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Токторалиев Э.Т.
22.12.2023г.

ISSN 0747-9239, Seismic Instruments, 2015, Vol. 51, No. 1, pp. 53–64. © Allerton Press, Inc., 2015.
Original Russian Text © P.V. Ilyichev, V.V. Bobrovsky, 2014, published in Seismicheskie Pribory, 2014, Vol. 50, No. 2, pp. 5–19.

Application of Pseudonoise Signals in Systems of Active Geoelectric Exploration (Results of Mathematical Simulation and Field Experiments)

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Abstract—Applications of features of pseudonoise signals (PNS) in systems of active geoelectric exploration are investigated by mathematical simulation and experimentally under actual field conditions using a special measuring complex. A significant gain in the output signal/noise ratio (of about 100 times) is obtained with a measuring system using PNS compared with conventional electric exploration systems because of the use of the correlation processing of special PNS. It ensures a high accuracy of the transient signal recording, especially for large time periods. As a result, it becomes possible to measure electrical parameters of the Earth's crust in a wider range of depths at a lower power of the sounding device.

Keywords: pseudonoise signals, geoelectrical exploration, correlation signal processing, synchronous signal accumulation

DOI: 10.3103/S0747923915010089

INTRODUCTION

The idea of the application of pseudonoise signals (PNS) in geophysical investigations of the Earth's crust, in particular the use of active geoelectric exploration methods, emerged a few decades ago, but its implementation encountered technical and technological difficulties associated with the formation and processing of such signals. Thus, in 1980, in *Geophysics,* Canadian researchers reported the use of PNS in electromagnetic sounding of the Earth's crust (Duncan et al., 1980). A 20 km sounding electric dipole and receiving centers with magnetic field sensors (magnetometers) separated by a significant distance were used. On the receiving side, the cross correlation function (CCF) between the recorded signal and a copy of the sounding signal were calculated with a subsequent computation of the CCF frequency spectrum, which was used to determine the one-dimensional dependence of the apparent resistivity of rocks on the depth. The geoelectric section structure was determined based on the analysis of this dependence.

Among domestic publications related to the use of PNS in geoelectric exploration a patented invention should be noted (Velikin, 2009). This invention provides the methods and devices for geoelectric exploration using the transient electromagnetic method (near- and far-field transient electromagnetic sounding) using PNS. The work of Canadian researchers (Duncan et al., 1980) was considered the prototype. In the opinion of the author of the invention (Velikin, 2009), the prototype has several disadvantages, the main of which is the fact that the method proposed by the Canadian researchers is characterized by a low accuracy of measurements during near-field geoelectric section sounding. This is due to the fact that measurements are conducted against the background of the primary field. Therefore, interference caused by the current pulse generator introduces errors that reduce method sensitivity. To address this shortcoming, it was proposed to expose sounding bipolar M-sequences of current pulses to additional pulse modulation and to carry out measurements both during the effects of modulating pulses and in the pauses between them. With this sounding method, additional modulation distortions of signals recorded at the receiving side occur. The inventor (Velikin, 2009) proposes to eliminate their influence by the application of the modulation of sounding signals by pulses with a random distribution law of their repetition period and the corresponding digital processing of signals recorded on the receiving side.

A review of the methods of noise control during electromagnetic sounding of the Earth's crust can be found in (Sidorin and Ostashevskii, 1996). These authors also performed a series of studies aimed at excluding the accumulation of coherent noise during the sounding. For this purpose, different modulations of sounding signals, in particular pulse-width and phase modulations, were used (Ostashevskii and Sidorin, 1990). It was noted that the modulation law can be changed. Thus, the use of pseudo-random sequences, such as Walsh sequences, was suggested.

In (Gar'yanov et al., 1999), a device for controlling the operation of the powerful generator set MUZA-PM developed by the authors was described (Ostashevskii et al., 1997). This device made it possible to generate powerful current pulses with a random distribution of their duration in the current electric dipole. An experiment on the synchronous reception of these pulses at a distance of 16 km from the current dipole was successfully conducted.

According to the authors of this paper, any additional modulation of signals extends signal spectrum and adds many problems to their digital processing. Effects associated with the modulation distortion of signals during digital processing lead to a complication of the shaping and processing algorithms of such signals, and all, as a rule, measures taken to eliminate the undesirable effects of modulation do not solve all problems.

Note also one of the latest works of B.S. Svetov et al. (Svetov et al., 2011), which also dedicated to the use of PNS in geoelectricity. The authors of this paper were able to develop an efficient algorithm for PNS processing without using correlation signal filtering. At the same time, a theoretical gain was obtained by increasing the signal/noise ratio on the receiver side of the electric exploration system by about five times compared with traditional methods of sensing using deterministic sequences of pulses with a fixed duration and repetition period. This gain is significantly inferior to the values expected when using PNS correlation processing (100 or more times inferior).

In this paper we made another attempt to improve the efficiency of the use of PNS in geoelectric exploration equipment. The authors hope to embody the proposed idea in a specific physical implementation, i.e., in a modern-hardware and -software electric exploration measurement system for the electromagnetic sounding of the Earth's crust.

BACKGROUND OF THE PNS APPLICATION IN ACTIVE GEOELECTRIC EXPLORATION

The application of PNS in active geoelectric exploration can be based on expressions valid for linear systems

$$Y(t) = X(t) \otimes g(t), \tag{1}$$

$$R_{XY}(t) = R_{XX}(t) \otimes g(t), \tag{2}$$

wherein $R_{XX}(t)$ is an autocorrelation function (ACF) of the input PNS $X(t)$, $g(t)$ is the impulse response (IR) of the studied object (the Earth's crust), $R_{XY}(t)$ is the cross correlation function between the input (sounding) $X(t)$ and the received $Y(t)$ signals, and $\otimes$ is the integral convolution of two signals.

In all existing active geoelectric exploration systems it is assumed that the investigated medium (the Earth's crust) is linear, i.e., its electrical properties are independent of the parameters of sounding signals. In the case of the application of PNS, the linearity condition is not violated. Moreover, it is even improved, because the levels of sounding pseudonoise signals are assumed to be significantly lower than in the case of traditional electric exploration methods.

With the proper choice of pseudonoise signals $X(t)$ it is possible to obtain conditions when $R_{XX}(t)$ will approach $\delta(t)$, which is the Dirac δ function. In this case, according to (2), it can be expected that the CCF $R_{XY}(t)$ at the output of the correlation receiver will approach the sought IR of the Earth's crust. Thus, the use of the correlation receiver and expression (2) with an appropriate choice of the PNS form makes it possible to obtain the IR of the studied object by direct calculation of the CCF between its output $Y(t)$ and input $X(t)$ (the Earth's crust) without resorting to the differentiation of the transient response (TR), which is usually obtained in standard methods of the electromagnetic sounding of the Earth. It is also clear that the IR is more sensitive to local inhomogeneities in the Earth's crust and changes of its electrical parameters compared with the TR, which is particularly important in problems of electromagnetic monitoring.

Binary pseudorandom sequences have found wide application as PNS in digital systems. So-called M sequences (maximum-length pseudorandom sequences) are most widely used. These are the sequence of signals (pulses) of a rectangular (or other) shape the amplitude (or other parameters) of which can take a finite number of values (2, 3, ..., p are prime numbers). The physical implementation of binary M sequences is the simplest one (for $p = 2$, the amplitude of pulses is +1 and –1).

M-sequence generators can be quite simply implemented using digital circuits and devices. For example, an M sequence with a length of N bits can be formed using an n-bit shift register with feedbacks through the multi-input logical operation XOR (Ilyichev, 2012).

Figure 1 shows plots of binary M sequences $X(t)$ of various lengths ($N = 2^n - 1 = 63, 255, 1023$) and of approximately the same duration (10080, 10200, 10230 of relative time units), their frequency spectra $S(f)$ and autocorrelation functions $R_{xx}(t)$. The greater the M-sequence length, the greater its frequency spectrum and the more its ACF similar to the Dirac δ function. It should be noted that the ACF of a single M sequence has side spikes in addition to the main (principal) lobe. These spikes limit the use of the correlation processing of single M sequences in geoelectric exploration despite the fact that with increasing M-sequence length the level of lateral fluctuations of its ACF declines (see Fig. 1). This is clearly demonstrated in (Svetov et al., 2011). Therefore, the authors of this work associate the use of PNS in electric exploration equipment with the known remarkable property of binary M-sequence that recur without pauses, which consists in the lack of lateral fluctuations of their ACF (Varakin, 1985).

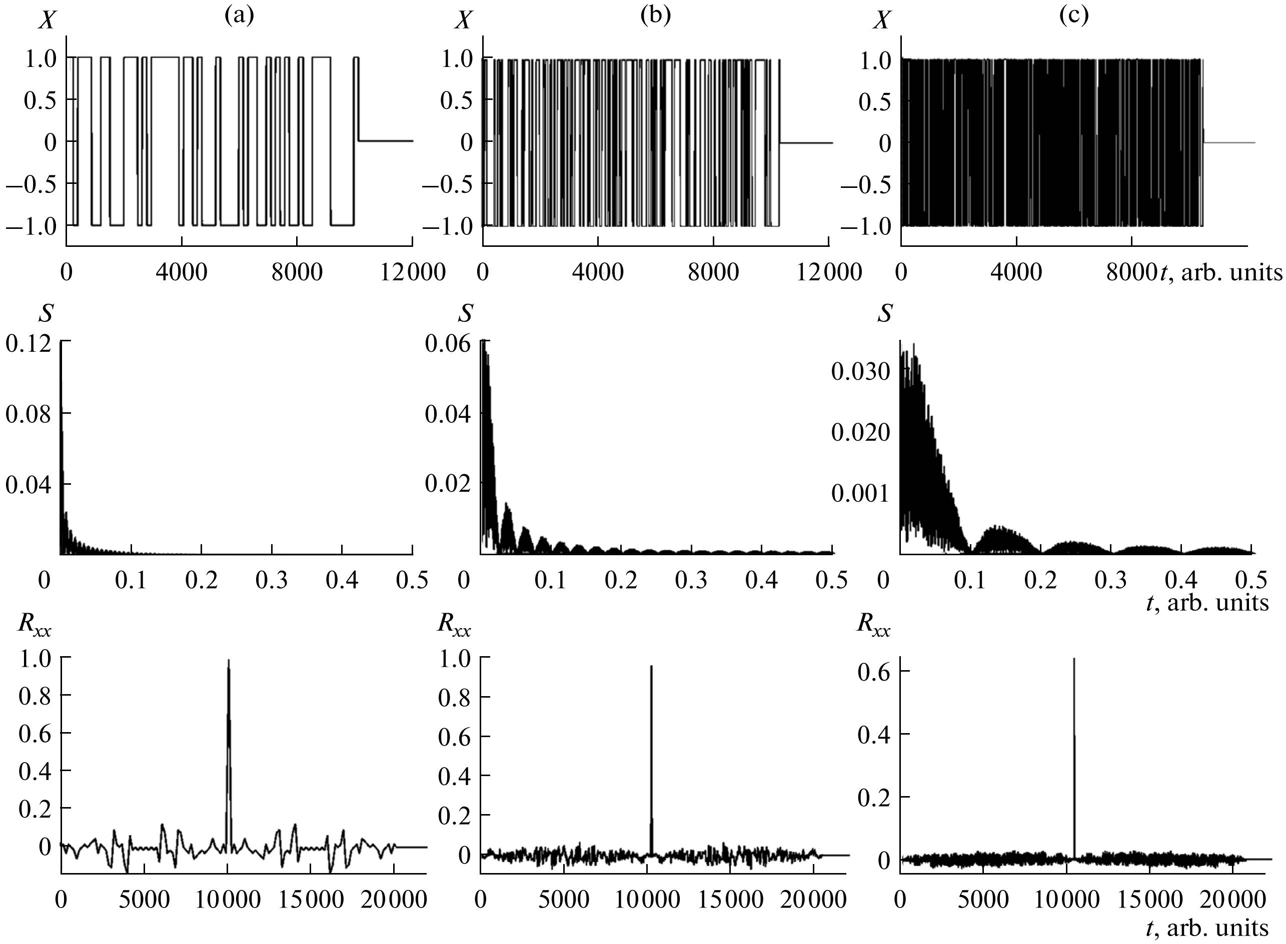

Fig. 1. Example of binary M sequences $X(t)$ of different lengths: $N = 63$ (a), $N = 255$ (b), $N = 1023$ (c); their frequency spectra $S(f)$ and autocorrelation functions $R_{xx}(t)$.

Figure 2 shows an example of changing the shape of the ACF of the binary M sequence during its periodic repetition. According to Fig. 2, in the case of repetition of the M sequence beginning with the second period, its ACF has no lateral fluctuations. At the same time, between the main lobes of the ACF a small constant negative bias is observed. The bias level is N times less than the main lobe level, where N is the M-sequence length. At the end of the last repetition period lateral fluctuations of the ACF reappear. Obviously, there will be no lateral fluctuations in the CCF computed between the received and sounding signals of the electric exploration system. This property of M sequences makes it possible to obtain an environmental IR by carrying out PNS correlation processing. In this case, after correlation processing, further accumulation of periodic CCF signals is possible, apart for signals from the first and last M sequences, which allows for further improvement of the signal/noise ratio. In fact, significant new advantages are added to the existing ones of the conventional accumulation of deterministic signals because of the use of PNS-correlation processing.

MATHEMATICAL SIMULATION OF THE SYSTEM WITH PNS

In 2011, a mathematical simulation of the electric exploration system with the application of PNS in comparison with the standard system in which bipolar sequences with a constant pulse duration are used for sensing was conducted at the Research Station of the Russian Academy of Sciences (Ilyichev, 2012). Two main problems were solved in the simulation: (1) CCF proximity to the IR environment in the case of PNS correlation processing was investigated, (2) the gain in noise reduction obtained during the correlation signal processing in the system with PNS compared with a standard system with deterministic signals and their simultaneous accumulation was assessed.

Simple IR environmental models in the form of the homogeneous conductive half-space and inertial integral element of the first order were used to show that the CCF computed between the received and sounding pseudonoise signal almost exactly coincided with IR environments in shape. The exceptions were two

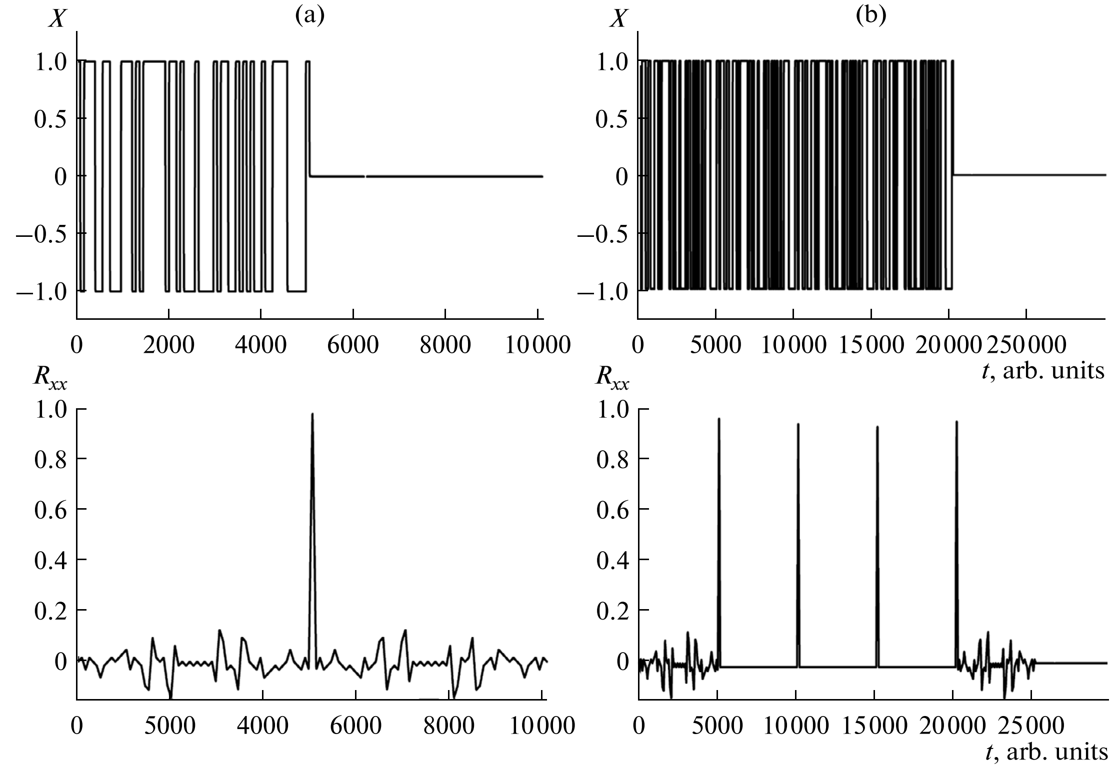

Fig. 2. Changing the shape of ACF of pseudonoise signals in the case of their periodic recurrence: a single M sequence $X(t)$ and its autocorrelation function $R_{xx}(t)$ (a), recurrent M sequence $X(t)$ (four periods) and its correlation function $R_{xx}(t)$ with single M sequence (b).

narrow bands at the beginning and end of the time interval in which these functions were determined. The width of these bands is determined by the minimum pulse time in the sounding M sequence. The presence of bands with a large error of approximation of CCF to IR can be explained by the differences between the ACF of the periodically repeated binary M sequence from the ideal Dirac δ function. Duration reduction of the minimum pulse in the M sequence approximates the CCF to the IR environment, but at the same time the analyzed transient time interval decreases. In order to obtain a good approximation of the CCF to the IR environment in a wide range of times, it is necessary to further increase M-sequence length.

In assessing the gain in noise reduction in a system with PNS correlation processing compared with a standard system with deterministic signals, the same normal noise with a given mean-square value was simultaneously fed to the input of models of the system with PNS and with deterministic signals in the absence of sounding signals. Next, the signal (noise) obtained on the receiving side was processed with a focus on the selection of useful signals from the background noise. In order to ensure the same energy of sounding signals in both models regardless of the specified M-sequence length, approximately constant durations of a single M-sequence and bipolar pulses was provided in the deterministic sequence by changing the minimum duration of the pulse in the M sequence.

As a result of processing, the RMS noise levels at the outputs of two models, coefficients of noise reduction, and reduction gain obtained in the model with the PNS correlation processing compared with the standard one were calculated. The results of simulation and signal processing are presented in Table 1.

Table 1 shows that with equal energies of sounding signals it is possible to achieve a significant gain (by 10 or more times) in the reduction of noise produced at the output of the system with PNS compared with standard systems even at short lengths of M sequences.

Figure 3 gives a model of signal extraction from noise for output of a system with PNS correlation processing compared with a system with deterministic signals, which shows a significant gain (of about 100 times) in improving the signal/noise ratio for output of a system with PNS with the length of the sounding M sequences of 255 cycles. In order to obtain the same signal/noise ratio improvement in a system with deterministic signals, it is necessary to increase the duration of a sounding pulse sequence by approximately 800 times, which indicates the expected high performance of the application of PNS in electric exploration systems.

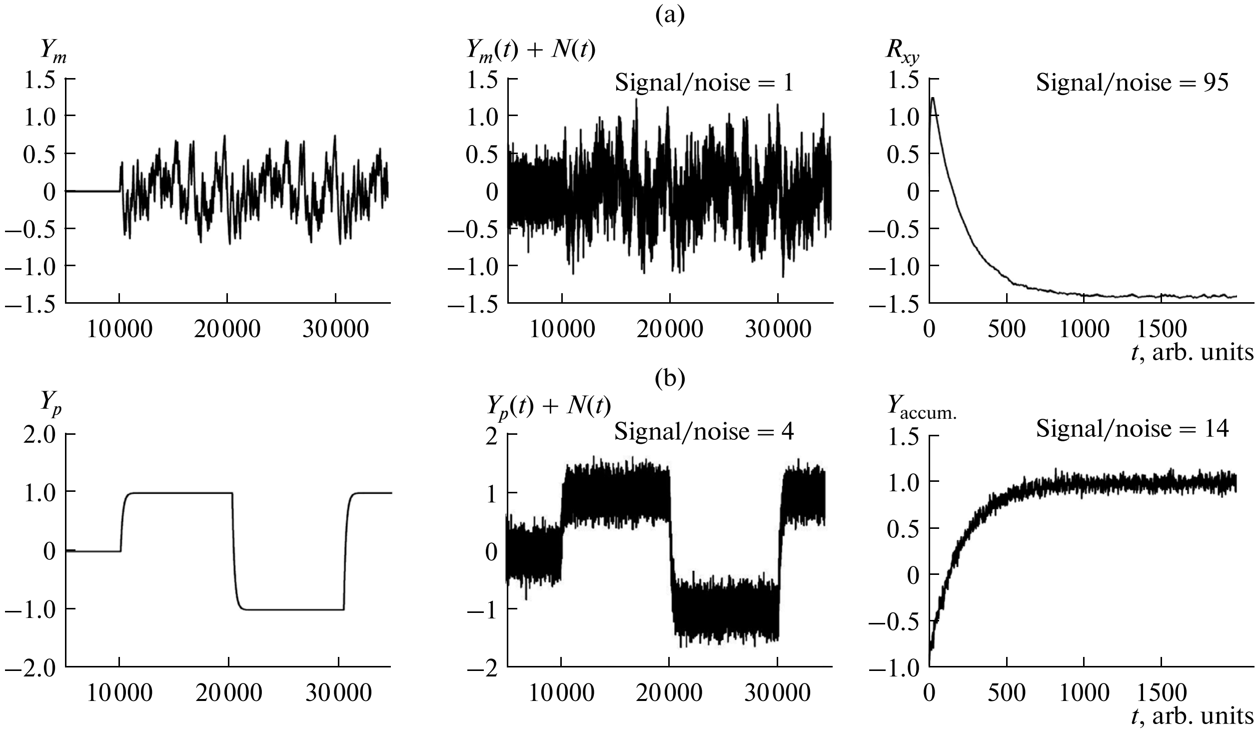

Fig. 3. Example of extraction of useful signal on background of noise in systems with PNS correlation processing (a) and with the accumulation of deterministic signals (b) (length of M sequence is 255, number of cycles is 16, cycle length is 40, time constant of environmental model is 200).

$Y_m(t)$ and $Y_p(t)$ are output signals of an environmental model (first segments) for a sounding with periodically recurring pseudonoise signals in the form of a bipolar pulse M sequence and a deterministic bipolar sequence of pulses of a fixed duration, respectively; $Y_m(t) + N(t)$, $Y_p(t) + N(t)$ are the output signals of the model of the investigated environment complicated by additive normal noise; $R_{xy}(t)$ is the result of the correlation signal processing in the channel with the PNS; and $Y_{\text{accum.}}(t)$ is the result of the synchronous accumulation in the channel with deterministic signals.

FIELD EXPERIMENT ON THE APPLICATION OF PNS IN GEOELECTRIC EXPLORATION EQUIPMENT

A special research electric exploration measuring system with pseudonoise signals (EEMS PNS) was developed and produced at the Research Station of the Russian Academy of Sciences in Bishkek with the direct participation of the authors of this paper for further investigation of application features of PNS in the geoelectric exploration equipment. Figure 4 shows the structural and functional layout of the complex and its appearance.

The measurement system consists of a sensing inductive loop (IL), a generator of sensing signals (GSS), a current limiting unit (CLU), an inductive signal sensor (ISS), the calibration signal generator (CSG), a unit of amplification and filtering of signals (UAFS), a unit of control and recording of signals (UCRS), and a personal (field) computer (PC). Sensing current pulses produced in the GSS are fed through the CLU designed as a configurable set of noninductive resistors to a single-turn inductive square loop arranged horizontally on the surface of the Earth. An inductive sensor that converts a vertical component of the alternating magnetic field into an electric signal is mounted in the geometric center of the loop. The signal from the inductive sensor output is fed to the UAFS input, where it is amplified and filtered out from noise and interference from various origins (natural and artificial). The useful signal S, partially filtered from noise and amplified, arrives at the UCRS, where it is transformed into a digital form with the given sampling rate using an analog-to-digital converter. Digital samples of the recorded signal are saved and accumulated in the UCRS. The UCRS controls the operating modes of the measuring complex: the calibration mode of the measuring channel, the sounding mode with deterministic periodic sequences of current pulses, and the sounding mode with pseudonoise signals. In addition, control signals (MNG) that ensure GSS operation are generated in the UCRS. In the calibration mode of the measuring channel, the control signal GR generated in the UCRS is converted into calibrated current pulses, using the CSG, that are supplied to the ISS calibra-

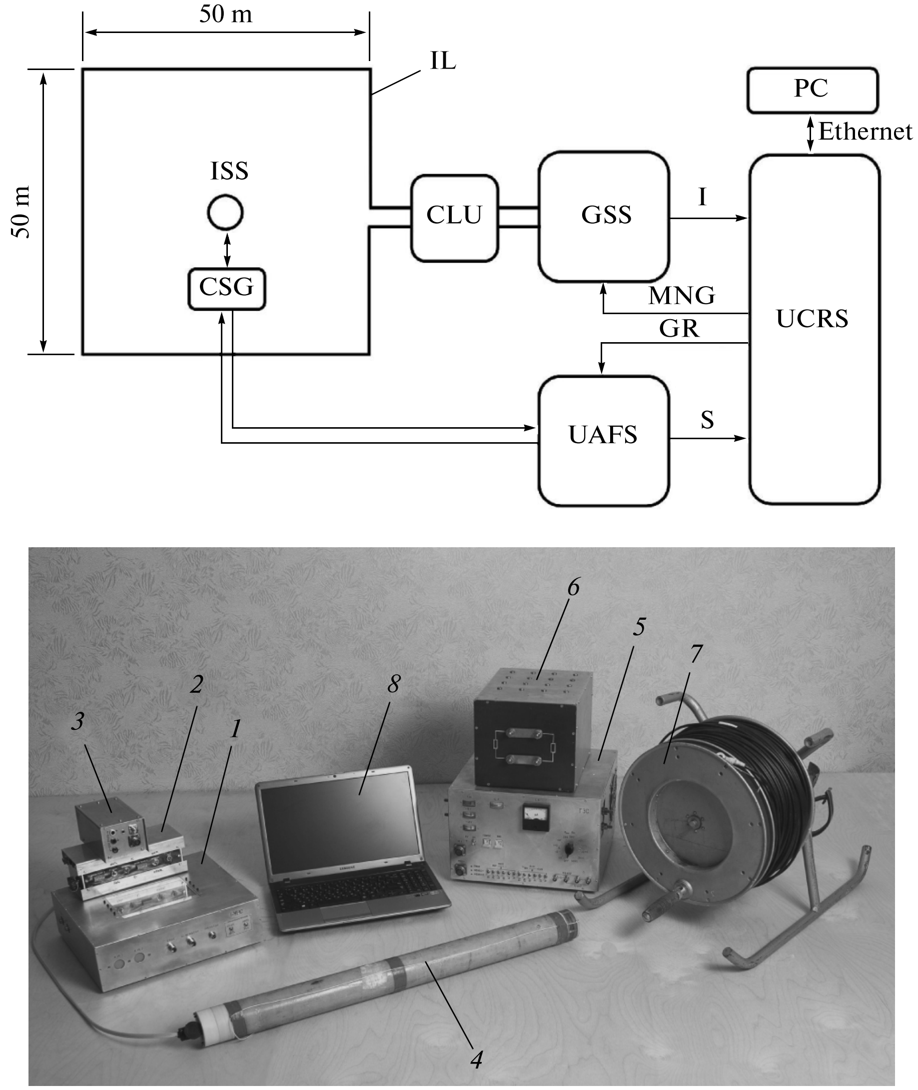

Fig. 4. Structural and functional layout and appearance of geoelectric measuring complex with pseudonoise signals. IL is sensing inductive loop (*7*), ISS is inductive signal sensor (*4*); UCRS is unit of control and recording of signals (*1*); UAFS is unit of amplification and filtering of signals (*2*); GSS is generator of sensing signals (*5*); CLU is the current limiting unit (*6*); CSG is calibration signal generator (*3*); PC is the personal (field) computer (notebook, *8*).

tion coil. In sounding modes, in addition to the signal from the ISS, a synchronous recording and accumulation of the signal "I" of the current sensor is carried out. This sensor is part of the GSS. It controls the current pulse shape in the sensing inductive loop. The personal (field) computer, which is part of the measuring complex, provides the mathematical processing of the recorded signals and technological setting (programming) of the UCRS. Table 2 shows the main technical parameters of the experimental measurement complex.

In the fall of 2013, the first field experiments with the EEMS PNS were held. The complex was deployed in the territory of the Bishkek geodynamic polygon. Noise and transient signals obtained in two sounding modes (pseudonoise signals and deterministic signals with constant duration and repetition period) were recorded and processed.

In order to evaluate the efficiency of the reduction of interference and noise in PNS correlation processing compared with standard processing methods of deterministic signals, a series of field records of noise and interference in the absence of sounding signals were conducted the same way as was done in the mathematical simulation. Next, the noise recorded was processed in order to extract useful signals from background noise in two modes: a correlation-processing mode with subsequent simultaneous accumulation in a time window corresponding to the CCF repetition period (PNS mode) and a mode of synchronous weight accumulation of periodic sequences of deter-

Table 1. The comparison of noise reduction in the PNS correlation processing and in the standard accumulation of deterministic signals according to mathematical simulation

Parameter	Number of accumulation periods (M-sequence repeats)														
	4			16			32			64			128		
N	63	255	1023	63	255	1023	63	255	1023	63	255	1023	63	255	1023
T_0	160	40	10	160	40	10	160	40	10	160	40	10	160	40	10
t_M	10080	10200	10230	10080	10200	10230	10080	10200	10230	10080	10200	10230	10080	10200	10230
σ_I	0.5576	0.55661	0.55831	0.55734	0.55984	0.56056	0.55778	0.55886	0.55724	0.56021	0.55999	0.55856	0.55933	0.55951	0.55949
σ_c	0.0101	0.00944	0.00803	0.01000	0.00947	0.00812	0.00991	0.00946	0.00805	0.01006	0.00952	0.00807	0.00993	0.00946	0.00810
σ_{c-a}	0.0098	0.00938	0.00784	0.00281	0.00279	0.00230	0.00187	0.00173	0.00154	0.00114	0.00115	0.00103	0.00086	0.00087	0.00071
σ_a	0.3135	0.31104	0.31044	0.15578	0.15710	0.15573	0.11098	0.11008	0.11001	0.07715	0.07905	0.07739	0.05635	0.05553	0.05545
σ_I/σ_a	1.778	1.789	1.798	3.578	3.564	3.599	5.026	5.077	5.065	7.261	7.084	7.217	9.926	10.076	10.090
σ_I/σ_c	55.413	58.987	69.528	55.738	59.105	69.036	56.282	59.098	69.227	55.688	58.829	69.196	56.330	59.165	69.107
σ_I/σ_{c-a}	56.962	59.323	71.196	198.194	200.417	243.714	297.569	322.625	355.624	491.817	486.057	540.140	651.784	640.886	791.168
σ_a/σ_{c-a}	32.0	33.2	39.6	55.4	56.2	67.7	59.2	63.5	71.6	67.7	68.6	74.8	65.7	63.6	78.4

N is the M-sequence length in cycles (the number of code patterns in the M-sequence); T_0 is the minimum pulse duration (one cycle) in the M sequence in relative units (increments of time); t_M is the length of the M sequence and bipolar pulses of the deterministic sequence in increments of time; σ_I is RMS noise at the input of the measuring channel of the receiving equipment; σ_c is RMS noise at the output of the correlation filter (CCF calculation for an ensemble of M sequences); σ_{c-a} is RMS noise after correlation filter and subsequent accumulation of CCF; σ_a is RMS noise at the output of a standard processing channel (simultaneous accumulation of bipolar pulses); $K_{rc} = \sigma_I/\sigma_a$ is noise reduction coefficient in standard processing channel (simultaneous accumulation of bipolar pulses);σ_I/σ_c is coefficient of noise reduction using correlation filter; $K_{rc} = \sigma_I/\sigma_{c-a}$ is coefficient of noise reduction in the correlation processing channel; PG = σ_a/σ_{c-a} is the gain in noise reduction in the correlation processing channel in comparison with the standard one.

Table 2. Technical parameters of the EEMS PNS

No.	Parameter	Measurement unit	Value	Note
1	Amplitude of current pulses in the sensing induction loop	A	0.3–7.0	Depends on R_{CLU} and U_{AB}
2	Accumulator battery voltage (UAB) of the power supply unit	V	12–200	Determined by the amplitude of sounding pulses
3	Minimum current pulse front time in sensing induction loop	μs	10	If $R_{CLU} = 120$ Ohm, $L_P = 0.4$ mH
4	Conversion factor of the signal inductive sensor	mV/nT	0.1	
5	Integration constant of the signal inductive sensor, not less than	s	0.3	
6	Inlet measurement channel bandwidth by level –3 dB	Hz	0.6–8000	ISS + UAFS
7	Inherent noise level of the inlet measurement channel (RMS value), not more than	uV	0.4	
8	Sampling frequency of recorded signals	kHz	51–54	Depends on the operating mode
9	Dynamic range of recorded signals, not less than	dB	96	

Table 3. Noise reduction for PNS correlation processing and deterministic signal accumulation

Parameter	Modes of measurement and signal processing					
	PNS, correlation processing + accumulation			PS, accumulation		
	$M = 11$ $T_M = 0.15$ s $N = 398$	$M = 12$ $T_M = 0.31$ s $N = 190$	$M = 13$ $T_M = 0.63$ s $N = 92$	$T_P = 0.16$ s $N = 372$	$T_P = 0.32$ s $N = 184$	$T_P = 0.64$ s $N = 92$
σ_{in}, mV	61.72	62.56	61.84	62.53	63.05	61.95
σ_{CCF}, mV	0.954	0.674	0.505	–	–	–
σ_{out}, mV	0.0481	0.048	0.0489	3.051	4.162	5.884
σ_{in}/σ_{CCF}	65	93	122	–	–	–
$K = \sigma_{in}/\sigma_{out}$	1284	1302	1264	21	15	11
$PG = K_{PNS}/K_{PS}$	63	86	120	–	–	–

M is the length (bit depth) of the pseudonoise M sequence; T_M is the length of a single M sequence; T_P is pause length (of the pulse) in a deterministic periodic sequence of pulses; N is the number of accumulated M sequences (pauses in a periodic sequence of pulses); σ_{in} is the RMS level of recorded noise; σ_{CCF} is the RMS level of noise after correlation processing without accumulation; σ_{out} is the output RMS noise level; K is the noise reduction ratio; and PG is the gain in noise reduction under the PNS mode compared with the PS mode.

ministic signals in pauses between sounding pulses as in standard electric exploration systems (PS mode).

Since in standard electric exploration systems received signals are usually accumulated in pauses between sounding pulses, the record time of these signals was set to be twice as long in order to obtain approximately the same conditions with the PNS mode in terms of the number of accumulated repetition periods of signals and their power. The results of the data processing of the field recording are listed in Table 3.

Table 3 shows that in the case of the correlation processing and the subsequent synchronous accumulation of signals in the PNS mode a significant (of more than 1200 times) continuous interference reduction is achieved. The accumulation processing used in sounding with periodic sequences of pulses of constant duration (PS mode) given that the energies of sounding signal sequences are equal provide significantly less interference reduction (10–20 times). At the same time, the gain in noise reduction in the PNS mode compared with the PS mode increases with the increase of the length (bit depth) of the used pseudonoise M-sequence.

Figures 5 and 6 show standard examples of the reduction of interference and noise recorded under

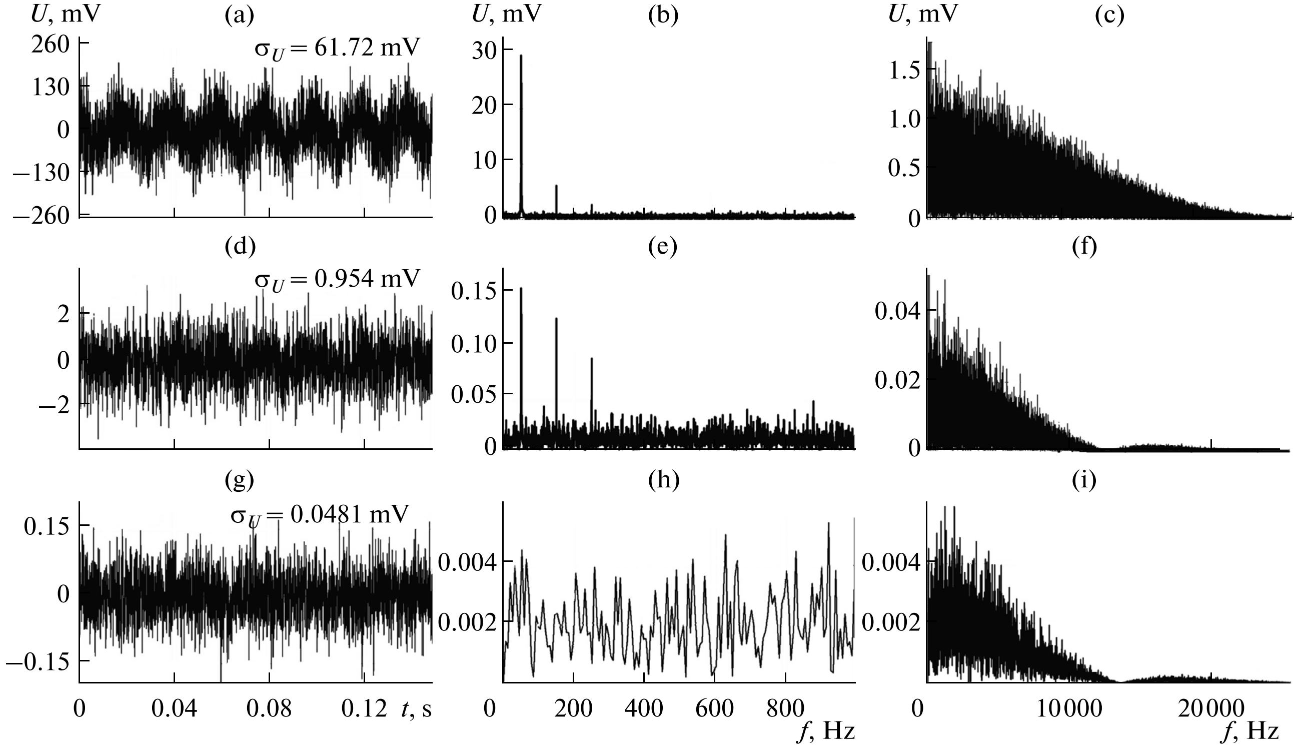

Fig. 5. Reduction of interference and noise in PNS mode ($M = 11$, $N = 398$, $T_M = 0.15$ s). Segment of noise record (raw data) (a); spectrum of initially recorded noise (b, c); noise after correlation processing (d); noise spectrum after correlation processing (e, f); noise after correlation processing and accumulation (g); noise spectrum after correlation processing and accumulation (h, i).

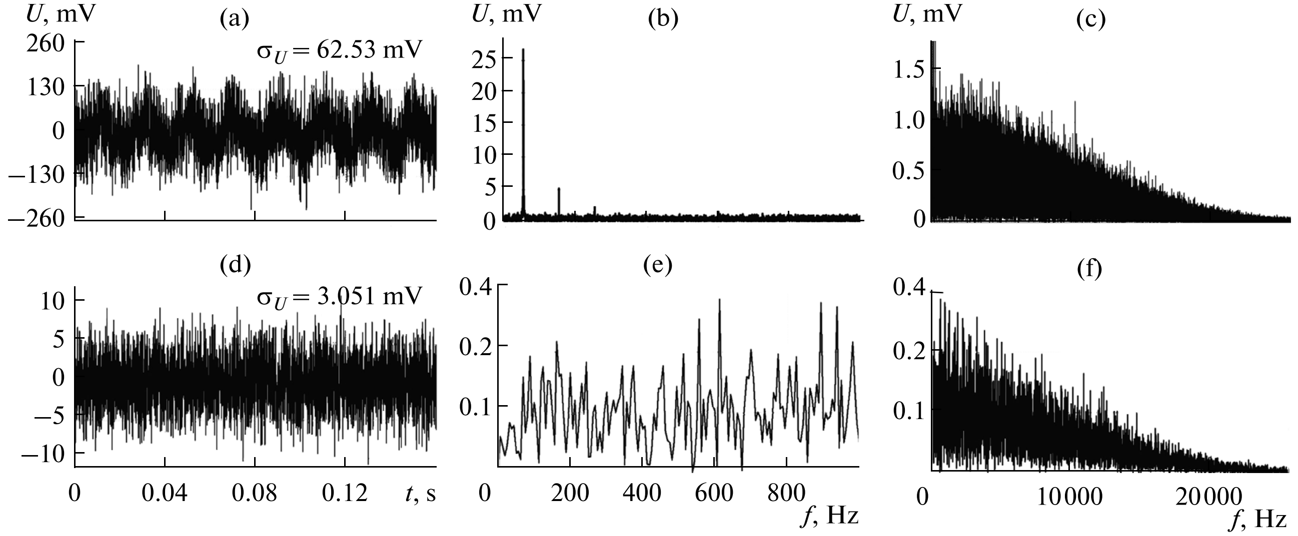

Fig. 6. Reduction of interference and noise in PS mode ($T_P = 0.16$ s, $N = 372$). Noise record sample (raw data) (a); spectrum of initially recorded noise (b, c); noise after simultaneous weight accumulation (d); the spectrum of noise after simultaneous weight accumulation (e, f).

field conditions after being processed in two modes (PNS mode, Fig. 5, and PS mode, Fig. 6).

According to Figs. 5a–5c and Figs. 6a–6c, field interference and noise are an additive mixture of low-frequency interference and wideband noise. In the amplitude spectrum of recorded interference, characteristic peaks are observed at frequencies of 50, 150, and 250 Hz (Figs. 5b and 6b) corresponding to odd harmonics of industrial power systems. The decaying spectrum of the noise (broadband) component of the

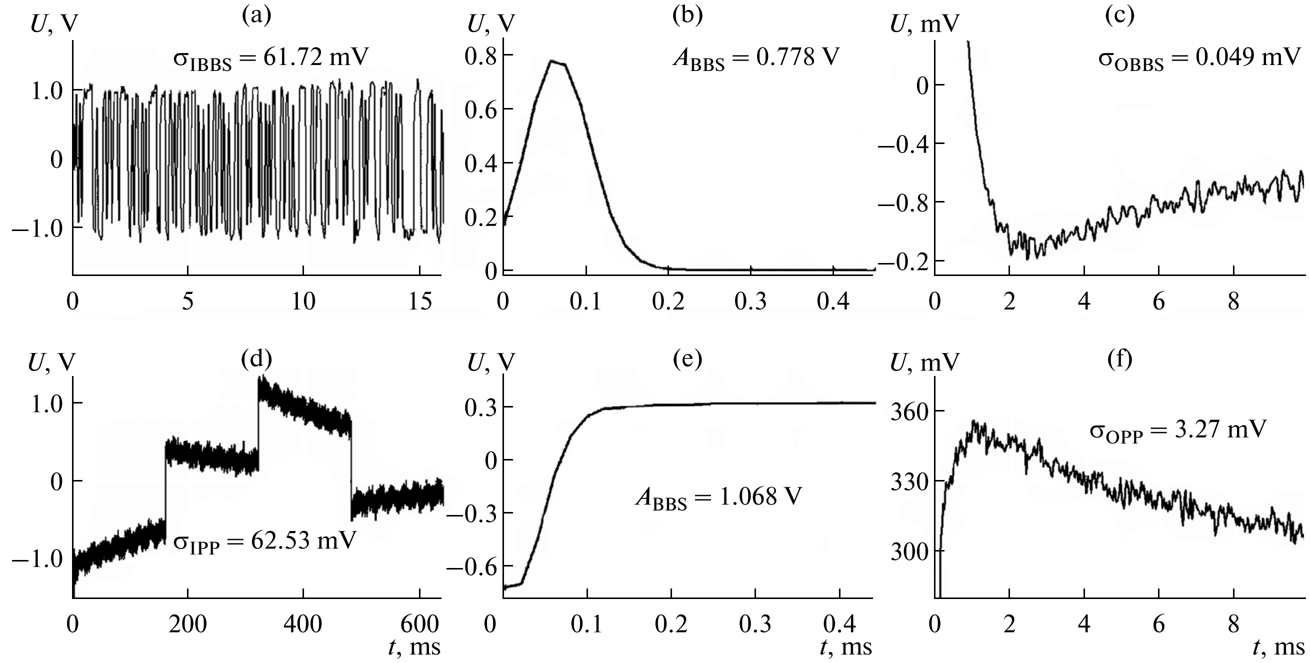

Fig. 7. Example of extraction of useful signal on background of interference and noise in field experiment using EEMS PNS (amplitude of sensing current pulses of 0.6 A). Segment of received signal in case of sounding using pseudonoise M sequence of pulses ($M = 11$, $N = 398$, $T_M = 0.15$ s) (a); specific segments (sections) of signal after correlation processing and subsequent accumulation in PNS mode (b, c); segment (one period) of received signal in case of sounding with periodic sequence of pulses with pause ($T_P = 0.16$ s, $N = 372$) (d); characteristic segments (sections) of signal after synchronous weight accumulation in PS mode (e, f).

recorded interference (Figs. 5c and 6c) is determined by the peculiarities of the spectral density of telluric interference, the intrinsic noise of the measuring channel, and its frequency response.

As a result of correlation processing a significant (of about 65 times) reduction of both tonal components and broadband noise interference is observed (Fig. 6d). The noise spectral composition also changes, in addition to a reduction inaa the overall noise level. The level of high frequency components becomes significantly lower (Fig. 5f).

Further accumulation of signals after correlation processing (398 CCF periods) contributes to noise reduction even more (Figs. 5g–5i). For the best reduction of tonal noise remaining after correlation processing, the length of the single binary M-sequence used for the correlation signal processing that is chosen is a multiple of an odd number of half-cycles of the noise in the further synchronous accumulation. As a result, the total reduction of noise in correlation processing with subsequent accumulation according to Fig. 5 was approximately 1280 times (62 dB).

In the PS mode, the reduction of both tonal and broadband continuous noise is carried out by applying the algorithm of synchronous weight accumulation of signals. In this case, the magnitude of reduction of broadband noise and interference depends on the number of accumulated time periods. For the best reduction of tonal noise and all its harmonics, the duration of the time window of accumulation is taken as a multiple of the integer of periods of the tonal noise. According to the plots in Figs. 6b and 6e, the spectral components of tonal noise nearly disappear during the accumulation, and the level of broadband noise is reduced, but significantly less so than in the case of correlation signal processing. At the same time, the shape of the spectrum of broadband continuous noise does not change. According to Fig. 6, total reduction of interference and noise in the PS mode was of about 20 times (26 dB).

Thus, the gain in noise reduction in the PNS mode compared with the PS mode was 64 times (36 dB).

In the course of fieldwork, a series of comparative experiments was conducted on the recording of transient signals under two sounding modes (PNS and PS) at different amplitudes of the sensing current pulses. The signals recorded under the PNS mode were subjected to correlation processing with a subsequent accumulation of obtained recurrent CCFs, and under the sensing mode with a deterministic sequences of pulses with constant parameters, signals were processed using the synchronous weight accumulation algorithm. Comparative qualitative and quantitative analyses of the data were conducted.

Figure 7 shows an example of the extraction of useful transient signals against the background of noise at the output of the system with the PNS correlation processing compared with the system with deterministic signals.

Data recorded using specially developed signal processing software were used to calculate amplitudes of signals in the A_{BBS}, A_{PP} sensing modes as well as the root-mean-square (RMS) level of the input σ_{IBBS}, σ_{IPP}, and σ_{OBBS}, σ_{OPP} (postprocessing) noise. According to Fig. 7, the input signal-to-noise ratio can be defined as $A_{PP}/\sigma_{IPP} \approx 17$ for the PS sensing mode and as $A_{BBS}/\sigma_{IBBS} \approx 13$ for the PNS mode, while output levels will be $A_{PP}/\sigma_{OPP} \approx 326$ and $A_{BBS}/\sigma_{OBBS} \approx 15813$, respectively.

Thus, in the case of sensing by pseudonoise signals the signal/noise ratio improvement after processing was 1216 times, and in the case of energy equivalent sensing by periodic sequence of bipolar rectangular pulses with a constant duration and pauses between them, the improvement was only 19 times.

It should also be noted that in the case of PNS correlation processing the calculated CCF coincides in form with the measurement system IR, which consists of the sensing device IR, the researched environment (Earth's crust) IR, and measurement channel IR. In plots in Fig. 7b, 7e, 7c, and 7f, it can be clearly seen that the maximum (minimum) of the CCF (Figs. 7b and 7c) is obtained at a maximum rate of change of the step response function (SRF) obtained under the PS mode (Figs. 7e and 7f), and the transition of the CCF through zero occurs at the maximum SRF value (Figs. 7c and 7f). Thus, the CCF obtained in the correlation processing is proportional to the change rate of the SRF obtained in the PS mode. It confirms the results obtained in the mathematical simulation of the system with the PNS.

DISCUSSION OF RESULTS AND CONCLUSIONS

Mathematical simulation and experimental studies conducted at the Research Station of the Russian Academy of Sciences has made it possible to identify a number of important features and advantages of the use of pseudonoise signals in the geoelectric exploration equipment. In particular, the effective application of the PNS in the geoelectric exploration requires the correct choice of PNS. Not all types of pseudonoise signals are suitable for this purpose. The main criterion for the selection of PNS is the maximal proximity of the autocorrelation function of the PNS to the ideal Dirac δ function, which provides direct acquisition of the impulse response of the studied environment (Earth's crust) by calculating the cross-correlation function between the detected response and sounding signals. These conditions are satisfied perhaps by the only kind of pseudonoise signals in the form of continuous recurrent pulse sequences of maximum length, the so-called binary M sequences. A distinctive feature of such signals is the lack of side spikes in their ACF perceived as noise.

The use of PNS makes it possible to obtain a significant gain (of 100 or more times) in the output signal/noise ratio compared with traditional geoelectric exploration systems because of the correlation signal processing. In this case, the said gain increases with the increase of the length of the M sequence of sounding pulses used.

A high level of reduction of noise and interference in the measurement system with PNS makes it possible to record very weak signals observed for large transient periods. Thus, it becomes possible to measure the electrical parameters of the Earth's crust in a wider range of depths at lower power of the sounding device.

Thus, the first positive results of the use of PNS in the active geoelectric exploration obtained at the Research Station of the Russian Academy of Sciences suggest that in the short term there can be developed a modern measuring complex with a wide range of investigated depths the Earth's crust and reduced energy consumption (power of the sounding electropulse system) compared with existing geoelectric exploration measuring systems, while maintaining high accuracy, noise immunity, and reliability.

ACKNOWLEDGMENTS

We are grateful to Boris Sergeevich Svetov, Doctor of Technical Sciences, for his assistance, theoretical advice, and solutions proposed to problems that arose in the course of our work; Vadim Nikolaevich Klyuchkin, Candidate of Technical Sciences, for technical advice and assistance in the development of hardware of the measuring complex EEMS PNS; management of the Research Station of the Russian Academy of Sciences in the person of the Director Anatolii Kuz'mich Rybin, Doctor of Physical and Mathematical Sciences, and First Deputy Director Gennadii Grigor'evich Schelochkov for the organizational and financial support of our work; academic adviser Vitalii Dmitrievich Bragin, Candidate of Physical and Mathematical Sciences, for scientific advice on the developed subject; members of the Laboratory of Advanced Instrumental Developments of the Research Station of the Russian Academy of Sciences Oleg Aleksandrovich Lashin, Dmitrii Sergeevich Myasnikov, and Evgeniya Aleksandrovna Plisovitskaya for active participation in and practical contribution to the research.

This work was conducted under the Program of Basic Scientific Research of State Academies of Sciences for 2013–2020, paragraph 80, subject "Development of Hardware and Software and Fundamentals of Electromagnetic Monitoring of Geodynamic Processes in Seismically Active Areas and Hazard Assessment," project no. 0120.0713073.

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Translated by O. Pismenov