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The Influence of the Type of Pulse on the Possibility of Logging Radiosounding

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Abstract—The successive application of the georadar method to a surface study of media pushes for the creation of a logging georadar. The tool operation conditions in a deep-seated medium with high absorption of electromagnetic waves (in a borehole) require optimization of the georadar technology for logging. Two possible approaches to GPR logging are discussed by the example of various georadars. We analyze the experimental data obtained with differently constructed MALA (Sweden) and GROT 12 (Russia) georadars under the same conditions during an international expedition. Conclusions are drawn that video pulses can be used for GPR logging.

Keywords: georadar; logging georadar; GPR

INTRODUCTION

The maximum depth of the currently used geophysical methods in the study of the near-borehole zone does not exceed the first few meters. Given the achievements of ground-penetrating radar technology, which in the tasks of subsurface sounding reaches depths of 100 m or more (Volkomirskaya et al., 2019), its adaptation for the purposes of logging seems relevant and promising.

Despite the conventionality of dividing probing pulses based on electromagnetic nature into radio pulses (which are based on quasi-monochromatic signals of different duration and modulation) and video pulses (which are based on short shock-type single oscillations of voltage and current in radiating antennas), their interactions with material substances differ significantly. Differences in the interaction of radio pulses and video pulses with material media affect the theoretical description of these processes. There are also significant design differences between devices that implement these sounding methods. Each of them has its own limitations on the sounding depth and the quality of the obtained experimental data.

Experimental and, later, theoretical results of recent decades in the study of natural media convincingly demonstrate the advantages of constructing equipment schemes for generating and recording aperiodic rather than quasi-monochromatic signals to achieve the maximum sounding depth. Furthermore, both the theory of ground-penetrating radar and the experiment developed independently, with rare exceptions. This leads to problems in the data interpretation and even public statements by some specialists that the experimental ground-penetrating radar data based on video pulses are “impossible to explain”. That is because some experimental results still do not have a qualitative and quantitative explanation within the framework of traditional solutions of Maxwell’s equations in continuous media, when they are represented as products of functions that depend either on coordinates or on time (separable solutions), usually studied using the Fourier transform. However, many of the experimental results become clearer if they are interpreted in the framework of analytical and numerical approaches to nonperiodic and nonstationary solutions of Maxwell’s equations.

The paper focuses on the natural advantages of using ultra wideband video pulses for sounding of natural media with strong absorption and proposes directions for the development of theory and technologies for interpreting experimental data. It shows the practicality of using aperiodic pulses for studying media with strong absorption, including logging radio sounding.

SPECIFIC FEATURES OF VIDEO PULSE PROPAGATION IN NATURAL MEDIUM

For the purposes of this work, it is important to compare the propagation of stationary, quasi-monochromatic, and nonstationary nanosecond pulses in stationary media with

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strong dispersion to justify the optimal signal shape in advanced subsurface and logging sounding. The deformation of a quasi-monochromatic pulse in a dispersive medium is traditionally described in the frequency domain using an expansion of the phase into a power series of the ratio of the spectral pulse width (Δω) to the carrier frequency (ω) (Landau and Lifshitz, 1984). However, this approach is inapplicable for video pulses, for which this ratio is not a small parameter.

If we abandon the traditional assumptions about the smallness and slowness of the field changes, then nonseparable exact analytical solutions will create a mathematical basis for describing rapidly varying nonperiodic fields and short pulses in dispersive media. In this case, the medium itself is assumed to be at rest and stationary, and the nonstationarity of the space–time structure of the propagating field is associated with a significant change in its envelope over a characteristic time determined by microscopic processes of formation of the field in the medium.

The physical foundations and mathematical apparatus of the theory of nonstationary wave processes were considered on the example of the problem of the electromagnetic field propagation in isotropic plasma (Shvartsburg, 1998). Theoretically, the problem statement is close to that considered later numerically in (Rudenchik et al., 2008; Volkomirskaya et al., 2013). It was shown in these works that an ultra wideband pulse both propagates and attenuates differently from a radio pulse. At the same time, it was found out that the same electromagnetic pulse will behave differently when interacting with media with different characteristic times of formation of the field, which is determined by the structure and composition of a particular medium characterized by electrical induction.

Thus, in some cases, the probe pulse will behave as “short”, and in others, as “long”, depending on the value of the ratio between the characteristic duration of the pulse and the characteristic time of formation of the field in the medium, which is determined by the microprocesses of the interaction of charges in the medium with an imposed external field. To achieve a sufficient compliance between the theoretical model and processes actually occurring in the medium, it is necessary to solve the problem in the kinetic approximation, which, even in natural media of simple composition, still seems unrealistic because of numerous difficulties.

The calculation of electrical induction, in particular for sinusoidal waves, is usually performed within the framework of the well-developed and well-known approximation of geometric optics, which assumes slow changes in the parameters of the medium and field. In contrast, the representation of alternating currents in a medium using nonseparable functions (Shvartsburg, 1998) makes it possible to calculate the electrical induction without using the indicated approximation.

MATHEMATICAL STATEMENT OF THE PROBLEM OF GEORADIOLOCATION FOR VIDEO PULSES

The electromagnetic field of the probing signal in the medium is defined by Maxwell’s equations:

$$\operatorname{div}\mathbf{D} = 0, \quad \operatorname{div}\mathbf{B} = 0, \tag{1}$$

$$\operatorname{rot}\mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}, \quad \operatorname{rot}\mathbf{H} = \frac{1}{c}\frac{\partial D}{\partial t} + \frac{4\pi}{c}\mathbf{J}\,. \tag{2}$$

Induction **D** is related to the electric field **E** and current **J** through the principle of causality—equation (3). It implies a relation between the real and imaginary parts of the dielectric permittivity, called the Kramers–Kronig formulas (Landau and Lifshitz, 1984):

$$\mathbf{D}(t) = \mathbf{E}(t) + \int_0^\infty f(\tau)\mathbf{E}(t-\tau)d\tau\,, \tag{3}$$

$$\mathbf{B} = \mathbf{H},$$

where $f(\tau)$ is a function that depends on the parameters of J, which specify the sounding signal by the spatial and temporal parameters of the medium. In models of signals with a limited spectrum, i.e., quasi-sinusoidal radio pulses, this relation is often violated, except for the case when the real part of the dielectric permittivity is an arbitrary constant, and the imaginary part is determined exclusively by conductivity, which in equation (3) corresponds to $f(\tau, x) = C_1(x)\delta(\tau) + C_2(x)\theta(\tau)$, where $\delta(\tau)$ is the Kronecker function, and $\theta(\tau)$ is the Heaviside function. In order not to violate the principle of causality, the dielectric permittivity can be parameterized by the coefficients of the real function $f(\tau, x)$ (Volkomirskaya et al., 2013).

Electric induction D, defined by formula (3), is related to the electric field E and the current J induced by this field and is determined, as is known, by the dynamic processes of the formation of the field in the medium. The contribution of these processes is described by the integral term in (3), the calculation of which for a number of fields and, in particular, for sinusoidal waves is usually performed within the approximation of slow changes in the parameters of both the medium and the field. For rapidly changing electromagnetic fields, the representation of alternating currents in a medium using nonseparable functions makes it possible to calculate the integral term in (3) in an explicit form, which leads to a complex dependence of the energy flux velocity on coordinates and time. In addition, the energy flux during the impact of the pulse on the medium depends on the shape and duration of the imposed video pulse (Shvartsburg, 1998).

Video pulses differ significantly in their model representation from the traditionally discussed modulated quasi-monochromatic signals with a rectangular or Gaussian envelope:

(1) The envelope of the video pulse contains one or several field oscillations, the shapes of which are far from sinu-

soidal both in amplitude and in the interval between the points of intersection of the zero potential axis;

(2) The leading and trailing edges of the pulse are asymmetrical.

Traditional models of the δ-function or the Heaviside step function, corresponding to zero signal duration and zero formation time, are not suitable for the problem under consideration. Application of more realistic models, such as modulated Gaussian or rectangular pulses, is limited by the assumption that the zero-crossing intervals are equal:

$$f_1 = \exp\left(-\frac{t^2}{2t_0^2}\right)\sin\omega t,\quad f_2 = \begin{cases}\sin\omega t, |T| \le \dfrac{T}{2}\\ 0, \quad |T| > \dfrac{T}{2}\end{cases}. \quad (4)$$

In contrast to this, in (Shvartsburg, 1998), flexible modeling of real video pulses containing one or several field oscillations was proposed based on the use of Laguerre functions (L_m).

$$L_m(x) = \frac{\exp(x/2)}{m!}\frac{d^m}{dx^m}\left[\exp(-x)x^m\right],$$
$$x = \frac{t - zc^{-1}}{t_0}. \quad (5)$$

where t_0 is the time scale of the signal.

The combination of nonseparable solutions of Maxwell's equations for fields in dispersive media and Laguerre representations of pulse fields outside these media forms an exactly solvable model of video pulse propagation within a homogeneous medium and in a one-dimensional approximation.

Signal reflection coefficients (6) are found, as usual, from the conditions of continuity of the electric and magnetic components of the fields at the boundary of the medium ($z - 0$):

$$R = -\frac{2\beta}{1 + 2\beta + \sqrt{1 + 4\beta}}, \quad (6)$$

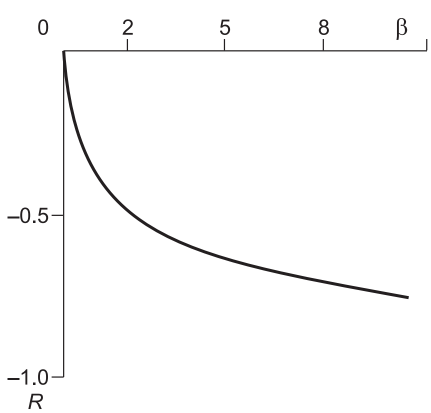

Fig. 1. Dependence of the reflection coefficient R of the video pulse on the characteristic times of the pulse and the medium.

where $\beta = \frac{t_0}{T}$, t_0 is the time scale of the signal; T is the time of the field formation in the medium.

$$T = \varepsilon_\infty / 2\pi\sigma. \quad (7)$$

The dependence of the reflection coefficient on the ratio of characteristic times is shown in Fig. 1. As can be seen, the reflection of pulses increases with an increase in the ratio $\beta = \frac{t_0}{T}$, which means that the same boundaries of media with different electrical properties become more contrasting for shorter pulses.

The obtained qualitative results can be used both for understanding and interpreting the experimental data systematically obtained in numerous experiments of the last decades. In particular, the results of an accurate calculation show that nonperiodic signals can attenuate in a conductive medium more slowly than sinusoidal waves. It should be added that the propagation of a signal in conducting media is accompanied by a distortion of its shape (Volkomirskaya et al., 2013). It is essential that nonstationary fields in a conducting medium are characterized by a natural time scale T (7). The decisive role of time parameters in the processes of pulse excitation of such fields in continuous media is shown in (Shvartsburg, 1998; Rudenchik et al., 2008).

COMPARISON OF EXPERIMENTAL DATA OF RAMAC AND GROT 12H GEORADARS

Let us consider the experimental data obtained when surveying the same profiles using devices of different designs to analyze the dependence of the propagation of pulsed signals of different shapes to the depth and the resolution of radio sounding. The described work was carried out within the framework of the Bykovsky spring 2017 project in Tiksi (Yakutia) under an agreement with the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI).

Joint research was carried out on freshwater Lake Gol'tsovoe by a group of Russian researchers with the GROT 12H georadar, manufactured by Timer LLC (Fig. 2),

Fig. 2. GROT 12H georadar with antennas of 2 m (75 MHz).

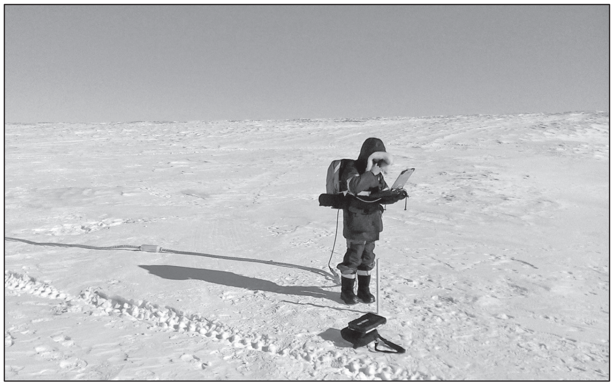

Fig. 3. Expedition member Michael Angelopoulos with the RAMAC georadar with antennas of 3 m (50 MHz).

and German researchers with a Swedish-made RAMAC georadar, made by MALA GeoScience, with antennas for rough terrain RTA 50 MHz (II) (Fig. 3). The values of 50 MHz (RAMAC) and 75 MHz (GROT 12H) determine the most efficiently transmitted and received frequency in the spectrum of each of the devices.

It is known that the receiving part of the georadar produced by RAMAC, one of the leading manufacturers of georadars on radio pulses, is based on the principle of frequency gating (Finkel'shtein et al., 1994), wherein, to restore the waveform, the received signal is transferred to the low-frequency domain for the further analog–digital transformation. For example, to display the reflected signal on a time scale which consists of 512 points with 1 ns intervals, 512 transmitter pulses are required. Therefore, one of the essential characteristics of georadars based on the gating principles is the pulse repetition frequency of the transmitter. Thus, for the RAMAC series georadars, the effective repetition frequency of the sounding pulses reaches 100 kHz per physical channel (https://www.guidelinegeo.com/wp-content/uploads/2016/03/MALA-RTA-Antennas.pdf). Along with introducing additional noise into the receiving path, frequency gating leads to a band-pass filtering of the reflected signal, which is responsible for the loss of low-frequency components and, therefore, for a decrease in the maximum achievable sounding depth.

Indeed, when sampling a signal in time, a stroboscopic converter takes one sample from each copy of the signal (as opposed to an ADC). This provides for converting the signal into a sequence of pulses, the envelope of which repeats the shape of the signal, and the duration can be much longer than the original. The period of the gate pulse T_{gp}, as a rule, exceeds the period of the signal T_s by the reading step Δt: $T_{gp} = m \cdot T_s + \Delta t$. When the coefficient $m > 1$, a number of signal periods are missed, usually $m = 1$. To obtain the shape of the entire signal at the period T_s, a minimum of n strobe pulse periods is required $n = T_s/\Delta t$ (each of the strobe pulses is shifted by a reading step). Then the total duration of the converted signal (a sequence of n strobe pulses modulated in amplitude by the input signal) is equal to $T_{cs} = n \cdot T_{gp}$, and the coefficient of temporal transformation (stretching of the time scale) is

$$K_{tt} = \frac{T_{cs}}{T_s} = \frac{n \cdot T_{gp}}{T_s} = \frac{T_{gp}}{\Delta t} \approx n .$$

The increase in K_{tt} is limited by the technical capabilities of the converter:

- the minimum step of reading;
- operation speed;
- stability of the reading step;
- the duration of the gate pulse.

Spreading a signal in the time domain is equivalent to narrowing it in the frequency-domain representation of the spectrum. Therefore, the concept of effective bandwidth is used, which depends on the maximum achievable gate-pulse repetition frequency. Usually it is linked with the minimum duration of the gate pulse τ_{gp} by the empirical relation

$$f_B = (0.45 - 0.60) / \tau_{gp} .$$

For the considered RAMAC equipment, the digitization of the reflected signal is carried out in $\Delta t = 2$ ns, and the speed of obtaining the waveform of the reflected signal allows recording 2–4 waveforms per second, depending on the settings.

The GROT 12H single-pulse georadar directly digitizes the reflected signal from one powerful (at least 1 MW) video pulse up to the entire depth of the estimated time delays, i.e., up to 20,000 ns (http://www.georadargrot.com/grot12h). The absence of gating allows digitizing in this range without narrowing the spectrum. In this case, the digitization error is determined by the characteristics of the ADC. The signal-to-noise ratio (SNR) is equal to the ratio of the root-mean-square value of the input signal V_{in} to the root-mean-square value of the noise magnitude V_{noise}, expressed in decibels: $SNR = 20 \lg V_{in}/V_{noise}$. The SNR value allows us to determine the proportion of noise in the measured signal in relation to the wanted signal. For an ADC with a certain resolution, it is the quantization noise that limits the converter capabilities by the theoretically best signal-to-noise ratio, which is defined as $SNR = 6.02N + 1.76$, where N is the ADC number of quantization bits. In particular, for the 12-bit ADC used in the GROT 12H SNR = 74 dB. The quantization noise can only be reduced by making measurements with an ADC with a greater number of bits. The increase in the dynamic range for the given characteristics of the ADC is reached by means of linear attenuators. The number of transmitter pulses is equal to the number of waveforms on the radargram. The measurement speed in both the pedestrian and transport versions is almost not limited by the pulse repetition frequency. The scheme of the device makes it possible to obviate the need for accumulation and averaging procedures, though it gives an opportunity to use them.

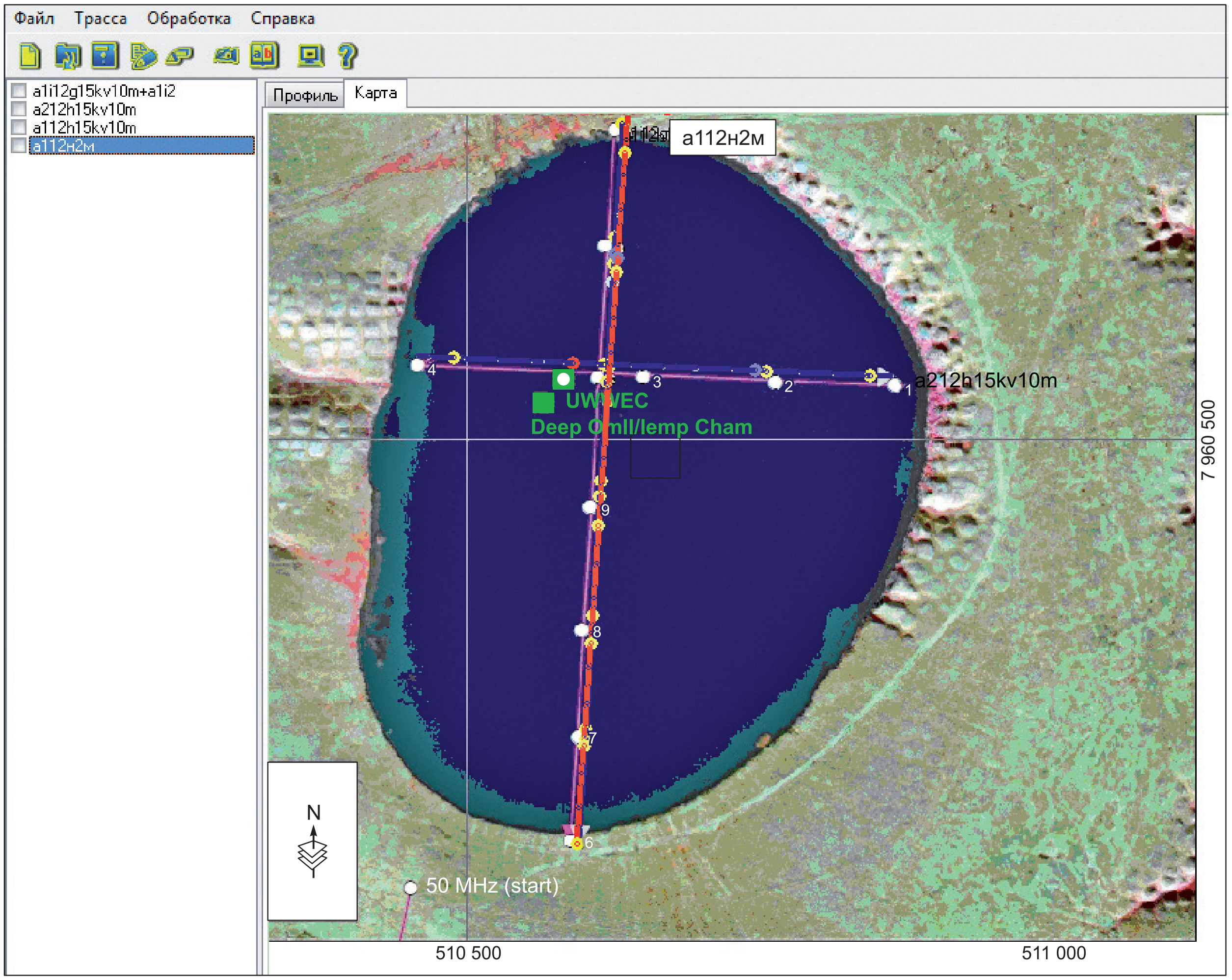

Fig. 4. Scheme of the GPR profiles on the map of Lake Gol'tsovoe in the window of the GROT processing program.

The main element in the formation of a video pulse signal is the transmitting and receiving antennas. For georadars of any design, they, among other purposes, act as filters for both the receiving and transmitting signals. A significant difference in the design of the GROT 12H and RAMAC is the implementation of the formation of signals of different shapes. The design of the GROT 12H series georadars using resistive load allows creating an aperiodic sounding pulse, the shape of which provides a large steepness of the front and the absence of additional oscillations associated with multiple reflections of the emitted and received signal from the ends of the antennas. The emitting antenna of GROT 12H dissipates almost half the transmitter signal power on load resistances, but the high power of a single ultra wideband aperiodic pulse, which can be easily formed by a gas-discharge or solid-state key element, permits obtaining a significant gain in the effective dynamic range of the entire device. In practice, the shock-excited voltage in the RAMAC georadar is 370 V, and in the GROT 12H georadar, no less than 5 kV. The technical characteristics of RAMAC RTA 50 MHz and GROT 12H are given on the manufacturers' sites (https://www.guidelinegeo.com and http://www.georadargrot.com/grot12h).

To compare the data of RAMAC and GROT 12H georadars, a GPR profile was chosen, on which studies were sequentially performed with two different georadars and antennas.

Figure 4 shows the relative position of the profiles on the surface of Lake Gol'tsovoe in the GROT program window. The red line marks the profile traversed from north to south on the lake ice using the GROT 12H georadar with 2-m antennas (which corresponds to the effective emitted central frequency of 75 MHz). For convenience of joint analysis, Figs. 5 and 6 show radargrams from both georadars obtained on the same profile.

We analyzed the radargrams in the SeiSee independent data processing program. It was originally designed for seismic data processing, but is quite applicable to the processing of radargrams obtained in georadiolocation. Besides, identical attenuation and filtration were applied.

Radargrams from both georadars obtained in the described experiment on the same profile under the same con-

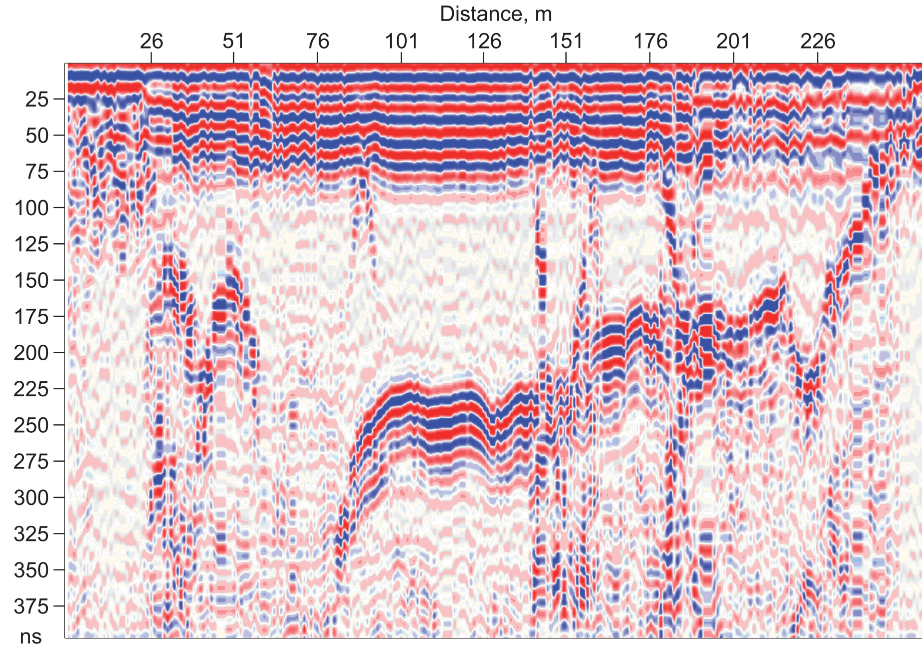

Fig. 5. Radargram of the profile surveyed from north to south using the GROT 12H georadar with 2-m antennas (center frequency 75 MHz) in the SeiSee program.

ditions represent the field of the reflected signal measured on the ice surface.

The appearance of the RAMAC radargram (Fig. 6) is smoother in comparison with the GROT 12H radargram (Fig. 5), but they represent the same geologic structures. The RAMAC time delay scale is limited by the number of points in accordance with the technical characteristics. Comparison of Figs. 5 and 6 shows that for a correct comparison of the data, it is necessary to combine the radargrams both along the profile and along the axis of time delays. To match the position of the boundaries of the reflected signal and, accordingly, to estimate the relative depth of sounding, it is necessary to shift the GROT 12H radargram down along the time delay axis by 50 ns.

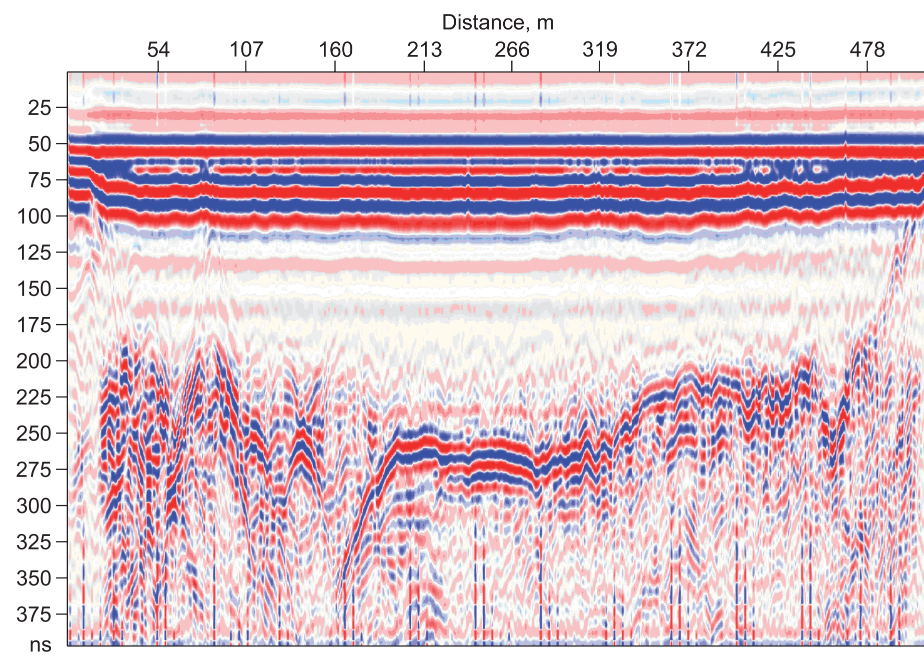

Fig. 6. Radargram of the same profile as in Fig. 5, surveyed with RAMAC RTA 50 MHz, in the SeiSee program.

COMPARISON OF THE EXPERIMENTAL DATA BASED ON ANALYSIS OF THE REFLECTED SIGNAL SPECTRA

In our experiment, data from two different georadars were obtained on the same profile at the same time. Therefore, the medium parameters can be considered the same. Considering that, let us analyze the data obtained to assess the features of the sounding pulses in both cases.

Let us compare the spectra of the reflected signals at the same points on the profile and apply the averaging procedure over the entire profile. In all the figures which show the spectra below the frequency is plotted along the horizontal axis, and the relative amplitude of the reflected signal is plotted along the vertical axis.

Figure 7 shows the amplitude–frequency characteristic (AFC) for two georadars for the same range of the time delays. The vertical axis shows the relative value of the amplitudes of the reflected signal harmonics in percentage of their presence, averaged over the entire profile; the frequency in MHz is along the horizontal axis. On the whole, the signal spectrum of RAMAC corresponds to the above estimates, and it has a smoother (averaged) pattern. The upper limit is bound to half in the frequency because of the two times lower sampling frequency. The border of the spectrum in the low-frequency region for RAMAC, as expected, is close to the central frequency of the antenna – 50 MHz. The spectrum features of the RAMAC signal are a consequence of the use of frequency gating in the receiver circuit. Indeed, the gating scheme (Finkel'shtein et al., 1994) leads to the fact that all three parameters (pulse repetition rate, the number of digitizing points on the time delay scale, and the scale length) are rigidly linked.

The depth resolution is determined by the high-frequency domain of the pulse spectrum. As it was shown in (Finkel'shtein et al., 1994), the depth resolution is determined by the pulse duration $\tau_{0.5}$ at the level of 0.5 of the maximum amplitude: The less $\tau_{0.5}$, i.e., the faster the amplitude falls to half its maximum, the higher the resolution. At the same time, the sounding depth is determined by the low-frequency part of the pulse spectrum. Thus, the spectrum width determines both the resolution and the depth of the GPR, that is, its real dynamic range, which is verified in practice.

Let us analyze the effective width of the reflected signal spectrum for the used georadars based on the data obtained (Fig. 7). The width of the spectrum of the received signal at the level A = 40% of the maximum amplitude is about 100 MHz for GROT 12H and about 225 MHz at the level A = 20%. For the RAMAC georadar, these values are 30 and 90 MHz, respectively.

In the high-frequency part of the spectrum for GROT 12H, the amplitude of the reflected signal converges in the limit to the value A = 10%; for RAMAC, to A = 0%. It was shown in (Kharkevich, 2013) that the rate of decrease in the amplitudes of harmonics in the spectrum depends on the structural properties of the signal: The coefficients will decrease the faster, the smoother the shape of the signal and its derivatives. If the signal has precipitous changes, which is typical for a single video pulse signal, the amplitudes of the harmonics in its spectrum tend to zero very slowly. The faster the Fourier coefficients decrease, the smoother the

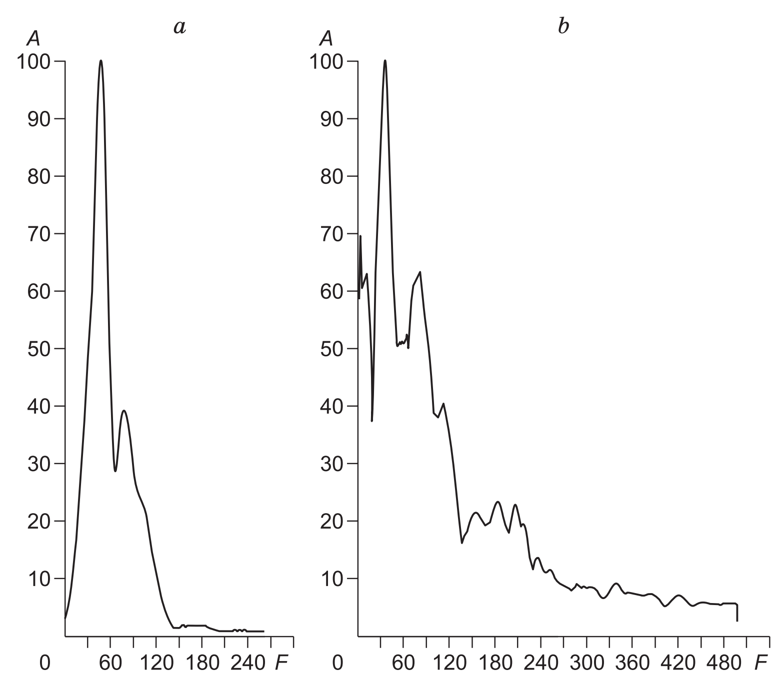

Fig. 7. Spectrum of the reflected signal for RAMAC (*a*). Spectrum of the reflected signal for GROT 12H (*b*). The horizontal scale is for the frequency *F* in MHz; the vertical scale is for the relative amplitude of harmonics *A*.

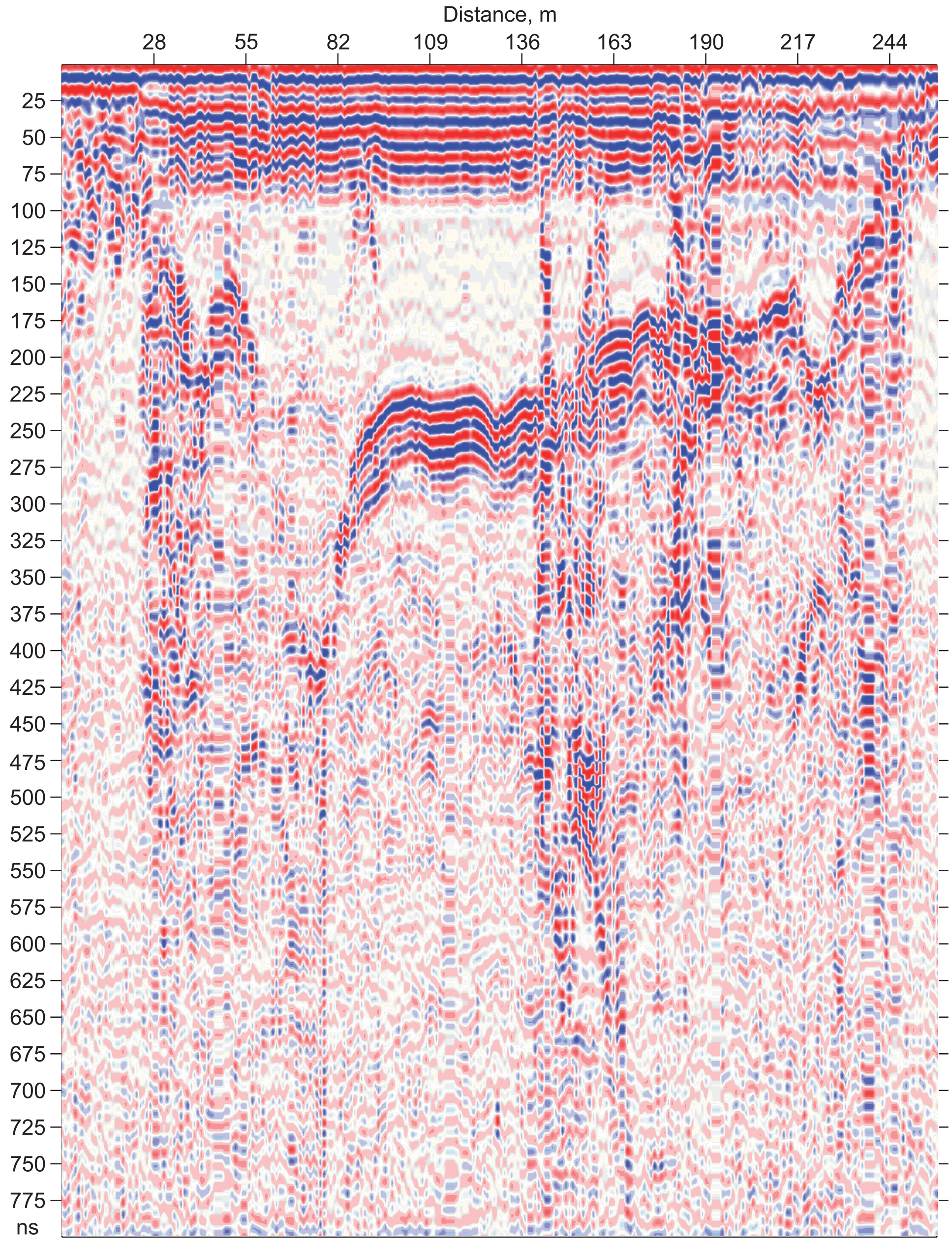

Fig. 8. Radargram of the GROT 12H profile in the SeiSee program. The signal spectrum corresponding to this radargram is shown in Fig. 9.

signal form, and the smaller the width of its spectrum. In the limit, the "smoothest" monoharmonic vibration is observed.

Thus, the recorded differences in the spectra represent the signal shape features in the considered georadars and indicate that the GROT 12H georadar has a video pulse signal, in contrast to the radio pulse signal in the RAMAC georadar.

The radargram of the profile surveyed using the GROT 12H georadar to the depths of time delays of 800 ns (Fig. 8) allows the analysis of the reflected signal to be continued at greater depths.

DISCUSSION

Comparison of radargrams in Figs. 5 and 8 shows that the visualization of the radargram with a twofold increase in the scale of time delays obtained using GROT 12H made it possible to locate zones of re-reflections of different origins up to time delays over 700 ns; for the RAMAC georadar, up to 400 ns.

On radargrams (Figs. 5 and 6), differences in reflection coefficients from irregularities are noticeable, for example, around the interval of time delays of 350–400 ns, which is expressed in the degree of contrast of the subsurface structures visualization. In general, the greater signal attenuation for the RAMAC georadar is observed. It should be noted that the central frequency of the RAMAC georadar is shifted to the low-frequency part of the spectrum by 25 MHz, in comparison with the central frequency of the GROT 12H. If all the characteristics of the devices were the same, this would lead to sounding at noticeably (approximately 1.5 times) greater depths for RAMAC (according to the classical concepts of the theory of geometric optics).

Let us note the differences in the dimensions of the antenna systems for practical application in logging radio sounding. Providing an in-line arrangement of the receiving and transmitting antennas for GROT 12H, as it is done in the ground version for the RAMAC RTA 50 MHz, the total length of the installation will be 5 m, while for the RAMAC RTA 50 MHz, the total length is 9.25 m. This difference for a georadar for a logging purpose is significant. It should be noted that, to provide radial resolution, the logging radar must contain at least one more receiving antenna (Gulevich et al., 2014), which will lead to an even greater overall length.

Comparison of the spectra in Fig. 7 reveals the following features:

(1) the presence of a significant low-frequency component in the GROT 12H spectrum and its absence in the RAMAC spectrum;

(2) a noticeable increase in both sides of the effective frequency band of the received signal for GROT 12H;

(3) significantly greater presence of high-frequency components in the spectrum of the GROT 12H.

The noted differences in the spectra under consideration represent the fact that the shape of the sounding signal of the RAMAC georadar is formed by a radio pulse (Kharkevich, 2013), and for the GROT 12H georadar, it corresponds to a video pulse. That is also verified by the significant presence of low-frequency components in the spectrum of the reflected signal of the video pulse and by the slow tendency to zero of the amplitudes of the harmonics of the high-frequency components.

With an increase in the scale of time delays for calculating the spectrum which corresponds to the radargram in Fig. 8, the amplitude–frequency spectrum unambiguously conveys the fact that the form of the signal of GROT 12H is close to the form of a classical video pulse with a steep leading edge (Kharkevich, 2013) (Fig. 9). Unfortunately, a fair model of the interaction of these pulses with highly absorbing and dispersive media, which makes it possible to carry out quantitative calculations, has not yet been created even for geological sections with known properties.

Generally, in natural media sounding with video pulses, which already have different applications in radiolocation and communication, the experiment is still noticeably ahead of the theory, allowing us to obtain practically significant results for many applications even with the achieved level of technology.

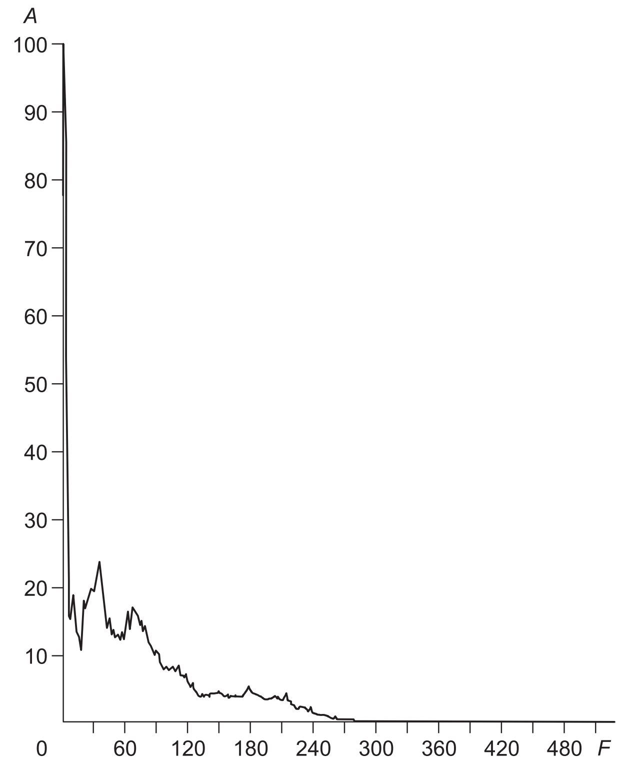

Fig. 9. Spectrum of the reflected signal of the GROT 12H georadar at the level of time delays of 800 ns. The horizontal scale is for the frequency *F* in MHz; the vertical scale is for the relative amplitude of harmonics *A*.

The experimental data considered in this work are based on theoretical models, which are still presented in very limited approximations. To shift to the solution of the problem considering the layering of the dispersed medium even in the one-dimensional approximation, it is necessary to use numerical methods. Today, we have no numerical solutions of the problem using nonseparable solutions of Maxwell's equations for the propagation of video pulses in dispersive media, in particular, for models of geological section of boreholes. Therefore, to obtain quantitative estimates of the advantages of logging sounding with video pulses, the considered comparison of experimental data may be of interest. In particular, the data obtained on a twofold increase in the sounding depth with an increase in resolution make it possible to assess the change in the maximum sounding distance in a borehole.

It should be noted that the problem in theoretical modeling of a pulsed electromagnetic field emitted from logging georadars is to take into account the effect of different designs of the emitting and receiving antennas, the logging probe cover, and the layer of drilling fluid present in a borehole on the amplitude and spectrum of the pulse emitted into the sounding medium and received inside the logging probe. In fact, the cover of the logging probe and the layer of drilling fluid should be considered electrodynamically as an element of the antenna, because they are located in the nearfield zone of the transmitters (Epov et al., 2008). These features should be taken into account when designing a logging video pulse georadar.

CONCLUSIONS

Comparison of the data of two georadars and theoretical conclusions in the works (Shvartsburg, 1998; Rudenchik et al., 2008; Volkomirskaya et al., 2013) make it possible to explain the higher efficiency of devices operating on video pulses with an aperiodic shape, in comparison to radio pulse devices. As an example, under the same conditions, the same international team of operators using the GROT 12H georadar with higher-frequency antennas received reflections from about two times greater depths than using the RAMAC georadar. When using video pulses, a lower attenuation of a signal in the medium in accordance with (Shvartsburg, 1998), a higher resolution, and better reflections from the boundaries of media with different electrical characteristics were observed.

The performed studies show that, to obtain quantitative estimates of attenuation and resolution, it is necessary to adequately describe the interaction of video pulses with the medium and derive a solution based on Maxwell's equations for rapidly changing nonperiodic fields. This is especially important in the problems of logging and crosshole radio sounding, where the medium is characterized by significant conductivity and frequency dispersion (Epov et al., 2011) and there are restrictions on the weight and size characteristics of the equipment. The study of specific models of oil and gas reservoir media based on numerical modeling of nonstationary nonseparable solutions of Maxwell's equations will help to optimize the design of a logging georadar and the shape of the video pulse to achieve the maximum possible sounding depth while maintaining high resolution. At present, the calculations have not yet been performed. Therefore, in comparison with exact solutions for the propagation of nonperiodic signals in the homogeneous medium, although experimental studies of the characteristics of devices created on different principles are qualitative, the authors think that they guide the development of logging radio sounding technology.

The practicability of carrying out experimental work of the use of video pulses for logging sounding is based primarily on the prospect of increasing the maximum depth of exploration of the near-borehole zone: up to tens of meters during sounding and up to hundreds of meters during crosshole radio sounding (according to preliminary estimates based on the capabilities of the prototype – the GROT 12H georadar in subsurface GPR).

In the absence of estimates based on numerical calculations of the problem of the video pulses propagation in a medium typical of geological models of the borehole zone, it seems useful to conduct a joint experiment to compare the data of the video pulse and radio pulse signals in equal conditions to determine the quantitative increase in the limiting depth of sounding of the borehole area when switching to video pulses.

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