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A scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences (RAS) was held on 26 January 2000 at the P L Kapitza Institute for Physical Problems, RAS. The following reports were presented.

(1) **Armand N A, Andrianov V A, Lukin D S, Chubinskiĭ N P** (Institute of Radio Engineering and Electronics, Fryazino, Moscow Region) "Scientific problems and the state of the art of surface radiolocation";

(2) **Reznikov A E, Kopeĭkin V V, Morozov P A, Shchekotov A Yu** (Institute of Terrestrial Magnetism, the Ionosphere, and the Radio-Wave Propagation, Russian Academy of Sciences, Troitsk, Moscow Region) "Development of apparatus and data processing methods for electromagnetic subsurface probing and experiments with their practical implementation".

A summary of the second paper is given below.

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Development of apparatus and data processing methods for electromagnetic subsurface probing and experiments with their practical implementation

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1. Development of radiophysical methods in geology

The theoretical foundations for application of radio waves in studies of geological structures were laid by H Lüowy and G Leimbach in 1910. In 1912, they demonstrated the possibility of mineral prospecting and groundwater exploration using radio-interference methods. In our country the first pilot surveying work using radio-signal methods was started by Petrovskiĭ in 1925 [1].

The effect of the reflection of pulse-modulated electromagnetic waves from undersurface irregularities was accidentally discovered by A H Waite at an ice airfield in the Antarctic when he noticed that an airplane's radio altimeter showed an altitude of 900 feet before take-off [2].

The use of standard radar equipment in geophysics turned out to be possible in only a limited number of cases, namely, when the attenuation of radio waves in a medium is low (for example, for probing dry sandstone, limestone and rock-salt). For the great majority of earth rocks, attenuation of radio waves is very high and, when using standard locators, the two-way travel time for reflected signals turns out to be so small that they are superimposed on the probing pulse and elude detection [3].

To increase the resolution and potential of a locator, attempts at using broadband signals with linear frequency modulation or spread-spectrum (noise-like) signals with phase modulation were made. Although these attempts persist to this day, locators based on this principle do not provide adequate resolution of underground irregularities, since in most practical cases the time base of a signal is greater than the wave-transit time for reflections from individual irregularities. This results in poor resolution of adjacent signals on the output of a data processing unit.

A way out was found when, instead of a standard radiolocation pulse with a high frequency carrier, a carrierless pulse was used. The latter consists of one or more current oscillations in an antenna and has a relative bandwidth approaching unity. Such a monopulse signal is best suited to georadar operations, since it provides maximum depth of probing and maximum resolution. Such a signal presents a limiting case of the transformation of a standard radio pulse when we reduce the carrier frequency with the aim of increasing the probing depth and simultaneously decrease the envelope duration with the aim of increasing resolution.

A method for forming such a pulse was proposed by Cook in 1960 and is used to the present day. This method, known as 'shock excitation of the antenna,' uses a voltage step which feeds into the transmitting antenna and forms a pulse [4].

The typical operating frequency range of present-day georadars is from 50 to 500 MHz, which is a 'tradeoff' between a probing depth of ones or tens of meters and a resolution of ones or tens of centimeters for actual geological structures. Higher-frequency radars with a maximum operating frequency of 40 GHz have received acceptance. These have a probing depth of ones or tens of centimeters and are mainly used for analysis of the state of concrete building constructions, so they can hardly be counted as geological devices.

The performance parameters of most georadars and their constructive design vary little. The basis of their operation is a method of stroboscopic transformation of the spectrum of a signal into a low-frequency region, where it is detected. The shock excitation of the antenna is accomplished by transistors operating in the avalanche mode with a voltage step of about 50 V.

The main technical problems associated with georadars of such design are the difficulty of providing a broad dynamic range, the constant amplitude-frequency and linear phase-frequency characteristics of stroboscopic transformation in

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the receiving channel that results in parasitic oscillations ('ringing') of the signal, and the masking of weak signals by stronger ones. The receiving channel 'ringing' is the chief cause of the low actual potential of radar, which usually lies in the range 40 – 50 dB. (The attenuation of a signal in a medium for which a radar is capable of detecting underground objects is taken as its actual potential. It should be noted that in georadar specifications one often indicates a value of the radar potential calculated as the ratio of the output power of the radar transmitter to the sensitivity of the radar receiver. This value does not allow one to estimate the actual potentialities of a device.)

In recent years in the United States and Australia work has been underway on the construction of a new type of georadar with frequency scanning. The motive for this work was the attempt to avoid signal 'ringing' in the receiving channel. Such a locator operates sequentially on a grid of frequencies and records the spectrum of the signal. Then this spectrum is normalized to the pre-recorded frequency characteristic of the receiving channel and transformed into the time region. This procedure allows one to clean 'ringing' from signals, however one fails to raise the actual potential of a locator, since a new problem arises — the necessity of detecting a weak reflected signal against the background of the uninterrupted operation of the transmitter of the locator.

2. Constructive features of present-day georadars

All known georadars can provide a probing depth of several meters only for low-absorption soils similar to dry sand in their parameters, so that they show little promise for the middle zone of Russia and other regions where clay soils are dominant.

When designing a new generation of georadars, we intended to solve the basic problem of achieving the maximum possible potential of these devices [5].

This is achieved by two basic methods: using a high-powered transmitter and detecting a signal in its own spectrum without its transformation into the low-frequency region. In other words, we have to eliminate most of the operations performed on a signal which can result in 'ringing' [6].

In order to provide the necessary parameters of object detection, we had to devise a small transmitter with a peak pulse power of 1 MW. It is a present-day version of the spark transmitters of Popov's and Marconi's times, which were used in the first radio-communication experiments.

The detection method used is based on the application of high-speed comparators which compare the incoming signal with a preset threshold. By varying the value of the threshold and the receiver gain, one can detect a signal in a broad range of magnitude. With the stroboscopic method, in one pulse radiated by the transmitter one records a value of the signal amplitude at one point in time, whereas in our method in one pulse one records the moments when a threshold is exceeded over the whole time axis.

The most suitable antenna, for both receiving and transmitting, turned out to be a resistive-loaded dipole in which part of the pulse energy is absorbed in resistors distributed along its arms. Selecting the proper resistors, one can provide near-total damping of the parasitic oscillations of a pulse. The optimal construction of a directional antenna operating under conditions of active and passive external interference turned out to be an 'anechoic' box containing no metallic details. It is a resistive-loaded dipole which is covered with a dielectric box filled by a carbon radio absorber which absorbs air waves.

The main technical characteristics of a base model of the georadar developed are as follow:

(1) frequency range from 3 to 500 MHz;

(2) pulse voltage at the transmitter output 5 kV;

(3) receiver sensitivity 75 μV;

(4) data discretization rate 1 ns;

(5) current consumed from a 12 V accumulator: 2 A in the recording mode, 0.5 A in the viewing mode;

(6) weight 10 kg.

The radar is equipped with a liquid-crystal display (128×256 elements) and has a built-in 4 MB memory. It can operate alone, that is, in the recording mode with information output on the display (if necessary, this information can be transferred to a computer through an RS-232 interface) as well as in combination with a notebook computer.

The actual potential of a georadar was measured in the following manner. The georadar was placed on floats and moved from the shore to the centre of a deep reservoir. In the process of moving, one records the depth at which the reflection of radio waves from the ground vanished because of their absorption by water. Using the records of the amplitude function, the specific attenuation was next determined as the ratio of the amplitude change to the depth difference. The actual potential was defined as the product of the specific attenuation by the depth at which the signal vanished. For georadars of this construction the actual measured potential was found to be not less than 120 dB.

3. Data processing methods

The radarograms obtained are practically free from the parasitic oscillations — apparatus 'ringing' — inherent in other georadars. For this reason we do not use the standard georadar data processing programs that are designed mainly for reducing the value of 'ringing' and separating the useable signal from the background using different types of filtering.

The method for reconstruction of a geological profile we have adopted is based on the use of a procedure known in seismology as the 'common point of excitation' (CPE).

First a radiolocation profile is recorded while moving along a route with a device in which the distance between the receiving antenna and the transmitting one is constant. From the radarogram one determines the points to be used to make the probing, that is, in line with the CPE method, to obtain time – distance (hodograph) curves from layers and objects. The hodograph is a function describing the signal delay from a layer (object) versus the distance between the receiving and transmitting antennae when they are moved symmetrically in different directions.

The hodograph allows one to determine both the true depth of a layer and the radio propagation velocity in this layer. In order to convert a radarogram into a geological section, it is necessary to eliminate multiple reflections from layers and transform the time axis into the spatial one specifying the propagation velocity in a layer. All needed information can be obtained from the hodograph.

The use of a quasi-seismical approach for reconstruction of a geological section cannot be considered to be satisfactory, since part of the information contained in the signal amplitude, its waveform, and polarization is not used. At the present time, mathematical algorithms for solving the inverse problem of radiolocation probing using an electrodynamic formulation are being developed.

The basis of the method consists in solving the direct electrodynamic problem for a sufficiently arbitrary model of a medium with varying dielectric permittivity and conductivity.

Further, on the basis of the modern variational calculus, a strategy for fitting medium parameters is carried out with the aim of minimizing discrepancies between the simulated and observed signals. To ensure the convergence of the iteration process and the uniqueness of the solution, the procedure of minimization is applied to definite classes of media. The result of the solution of the inverse problem is a corrected model of a medium (in a chosen class) for which the modeled response of the medium has a minimum discrepancy with the observed signal [7].

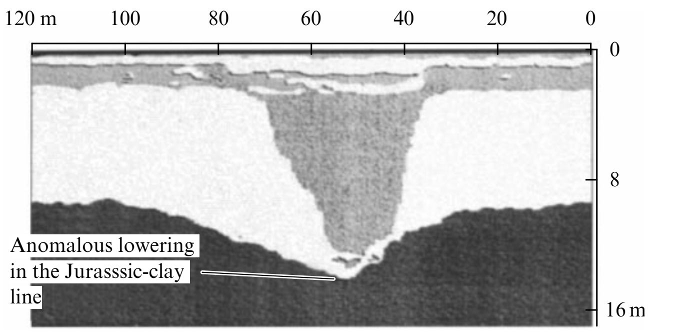

Figure 1. Georadar section of ground structure in the region of the subsidence at Bolshaya Dmitrovka Street.

4. Practical implementation of the method

Practical work on georadar investigation of underground structures is continually being carried out. In less than two years, 140 objects have been examined relating to subsidence and construction in conditions of complex underground communications.

As an illustration let us consider three results of our work (Figs 1 – 3).

(1) Georadar section of ground structure in the region of the subsidence at Bolshaya Dmitrovka Street in Moscow. The reason for the damage was that the geological project developed on the basis of data from borings did not take into account an anomalous lowering in the Jurassic-clay line. (At the order of the MKNT OAO.)

(2) Results of a georadar investigation of the territory around the excavations of the site of the ancient settlement Nastas'ino, Kolomna district, Moscow region. Based on the results obtained, a cultural layer with buried defensive ditches has been charted. (At the order of the Division of Conservation Works of the Institute of Archaeology, RAS).

(3) Georadar section of ground structure on the territory of the Aleksandrov citadel (city of Aleksandrov, Vladimir region). 'Objects' were found and charted according to their 'radiolocation images.' These included an arched underground passage or lengthy vault. According to the preliminary conclusions of the historians of the museum-preserve,

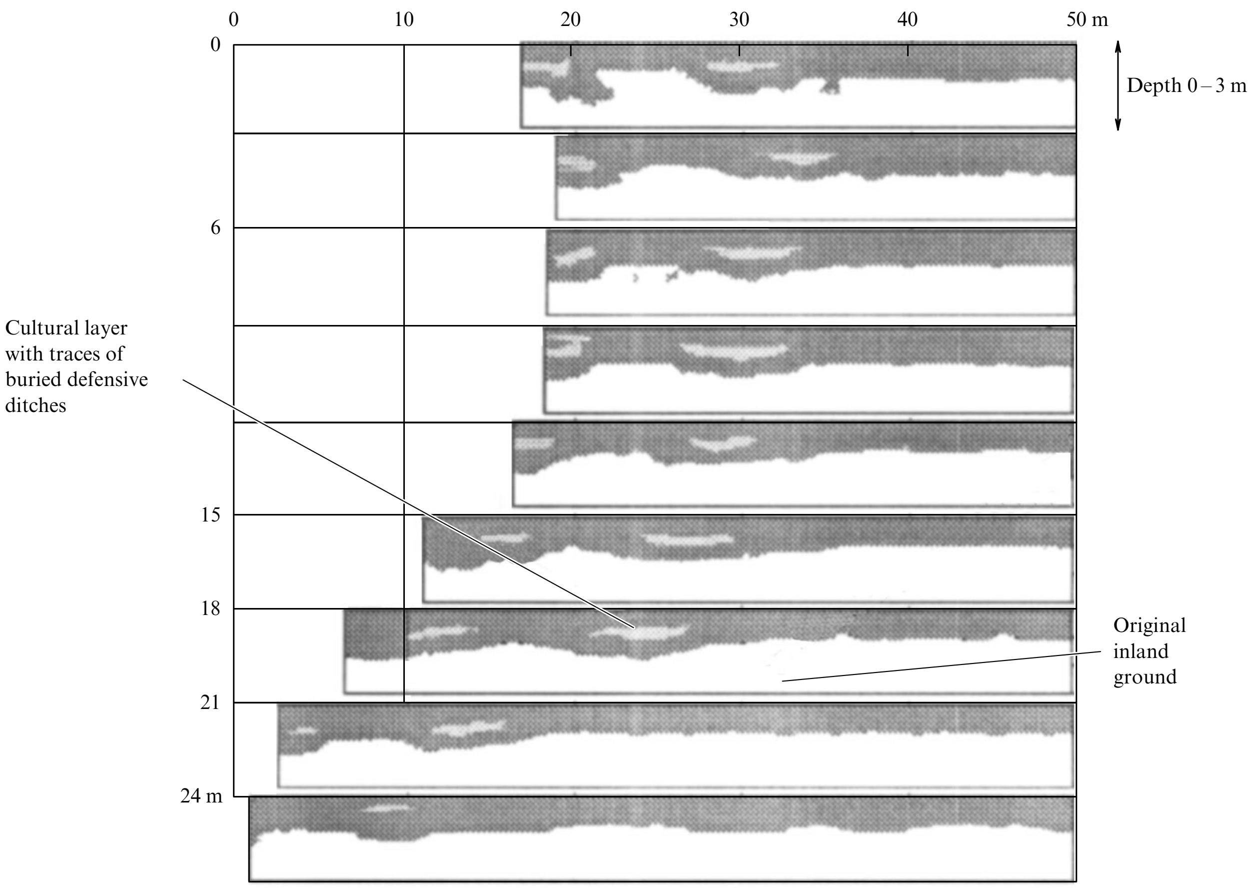

Figure 2. Results of the georadar investigation of the territory around the excavations of the site of ancient settlement Nastas'ino (4 – 3 century B.C.) Kolomna district, Moscow region.

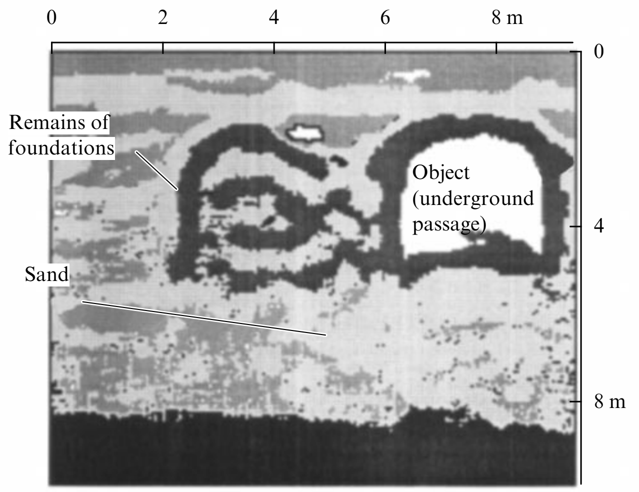

Figure 3. Georadar section of ground structure on the territory of the Aleksandrov citadel.

there are strong grounds to believe that these 'objects' date back to the age of Ivan the Terrible. (At the order of the management of the historico-architectural museum-preserve 'Aleksandrovskaya Sloboda'.)

5. Conclusions

By now there is positive operating experience with georadars in different regions of Russia including Siberia, Yakutia and the Far East. Practical results show that the actual potential of the georadars developed is sufficient to solve many problems with the probing of subsurface layers in the first ten meters even under clay-soil conditions near Moscow.

However, problems with probing to a depth of hundreds of meters can also be solved using radiolocation methods. To reach such a depth, radars operating in the frequency range of 1 – 50 MHz are required.

Investigations in this field are conducted in the Institute of Terrestrial Magnetism, the Ionosphere, and the Radio-Wave Propagation (IZMIRAN) and there has been positive experience in probing geological structures more than 100 m deep.

A primary factor hindering the widespread use of georadar technology is the complexity of data interpretation methods, which makes necessary the recruitment of highly skilled specialists. A possible way out is the development of mathematical procedures for solving the inverse problem of radiolocation probing, which will allow the involvement of an operator in obtaining the final results to be minimized and a maximum of information to be extracted from georadar data.

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