SOFTWARE REVIEW

GEORADAR-EXPERT
AUTOMATED PROCESSING OF GPR DATA

SOFTWARE REVIEW

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The idea of developing the GEORADAR-EXPERT software arose as a result of the generalization of many years of experience in professional activities in the field of GPR research. Practical skills acquired at all stages of investigations with GPR (communication with the customer, development of field survey methods and their implementation, GPR data processing and the creation of a technical report) allowed the developers of GEORADAR-EXPERT to form their opinion on what capabilities should have modern software for processing GPR data and in what form should the final result of this processing be presented.

As a result, three main areas of software development for GPR were identified. The first is the development and implementation of algorithms that serve to increase the depth of GPR research and increase the resolution of GPR data. The second direction concerns the final result of processing GPR data. This is a refusal to present GPR data on the subsurface environment as a set of amplitudes of the reflected signals in the form of a radarogram and the transition to the final processing result in the form of a section that contains the characteristics of this environment. The third area is the minimization of the influence of the human factor on the process of processing GPR information and the automation of this process, which is important for growing volumes of GPR research from year to year, worldwide.

The GEORADAR-EXPERT software was developed taking into account all these aspects. This software includes both standard options for processing GPR data implemented in applications from numerous manufacturers of GPR software, as well as algorithms and methods developed specifically for GEORADAR-EXPERT that increase the informativeness and depth of GPR research. The main such development is the automated analysis of the BSEF (Back-Scattering Electromagnetic Field). The final result of processing GPR data by the BSEF automated analysis method are sections of the attributes of the electrophysical characteristics of the subsurface environment and the wave field recorded by GPR.

**Automated BSEF Analysis**

Professionals using ground penetrating radars may encounter a situation where the quality of the results of GPR profiling differs for the worse from the samples presented in advertising materials of manufacturers of geophysical equipment. On such advertising radarograms, one can easily find the boundaries between the layers, as well as diffracted reflections from local objects, by which it is easy to determine the speed of propagation of waves in a subsurface subsurface environment and permittivity. As a rule, such results can be obtained during the GPR study of subsurface with low losses and the presence of sharp changes in the
electrophysical characteristics in the contact zone of the layers. In practice, one has to study not only low-loss subsurface, but also subsurface environment that have high absorption of electromagnetic energy, without sharp boundaries, with various interferences. And as a result of such a field study, there may be something like this radarogram:

The above example is the result of GPR profiling of bulk soil with a 200 MHz antenna. Due to the strong attenuation of the GPR probe pulses in this bulk soil, weak reflections from the bottom of the embankment are masked by more intense interference. Application to this GPR profile of standard methods of digital signal processing, such as subtracting average GPR traces and frequency filtering in order to suppress noise, did not lead to a positive result. The boundary between bulk and bedrock is still not visible. There are also no diffracted reflections from local objects in the soil, from which it would be possible to determine the wave velocities and permittivity in different parts of the GPR profile in order to rely on these values, at least roughly calculate the position of the boundary between bulk and primary soils. Visual analysis of the processed GPR profile gives practically no useful information:

The following shows the result of processing this GPR profile using BSEF automated analysis in the form of a section of the attribute "The real part of the complex relative permittivity" This is the most commonly used attribute. Undoubtedly, the information content of the result is significantly higher than that of the
radarogram. The section can be easily divided into two layers. The top layer is bulk soil. On a section, this layer has colors ranging from light blue to dark red. The bedrock is represented by shades of blue.

By studying the change in the color gamut of the section, one can learn about changes in the electro physical characteristics of the soil inside each layer. For a more accurate representation of changes in the attribute of a section, you can use the statistical module implemented in the GEORADAR-EXPERT software and obtain data for each layer, for each layer boundary, or for the entire section as a whole in the form of graphs and tables by twelve statistical indicators. The figure below shows a graph of the changes in the average permittivity in a layer of bulk soil. The area of the graph that exceeds the user-defined threshold is colored in red:
Obviously, the transition from the presentation of data on the subsurface environment in the form of a set of amplitudes of the reflected signals (in the form of a radarogram) to the characteristics of this subsurface obtained as a result of applying the BSEF automated analysis method (in the form of an attribute section) significantly increases the informativeness of the GPR study and makes the result of this study more understandable as geoscientist and the customer of the GPR study. Exporting the processing results to graphic formats, spreadsheet formats and a grid data format allows you to work with these results in computer programs to visualize numerical arrays and create drawings, such as Surfer, AutoCAD or similar.

The full list of section attributes in GEORADAR-EXPERT is quite wide - the entire list can be found in the GEORADAR-EXPERT user manual, which is available on THIS LINK >>. As an example, the figures below show sections along the GPR profile of the attributes of humidity and the Q-factor (the ratio of the center frequency of the signal spectrum to its width). Q-factor is often used to identify loose areas in the ground or areas of reduced strength in building structures.
The indisputable advantage of BSEF automated analysis is the ability to study subsurface environment, the electro physical characteristics of which change smoothly, without sudden jumps that form reflective boundaries. On the radarogram obtained in the study of such a subsurface, the boundaries of the layers are not visible - as in the figure below to the left. The figure on the right shows a permittivity section along this GPR profile, created in the GEORADAR-EXPERT software:

In the example under consideration, the GPR profile crosses a dried-up stream, the middle of the channel of which is located at a distance of 25 m from the beginning of the profile. The section clearly shows the boundary between dense soil and loose sediments, which, as a result of channel processes, has acquired a funnel-like shape and reaches a depth of 7 meters. An area of high humidity is also clearly visible in the depth range from 2 to 6 meters, which is characterized by increased values of the permittivity and is colored in a
dark blue color. The lower part of this area is also funnel-shaped and fairly symmetrical about the middle of the stream. The application of the BSEF automated analysis method to this GPR profile made it possible to obtain much more useful information than the GPR profile could provide before this method was applied.

The runtime spent on performing automated BSEF analysis and creating attribute section is relatively small. For example, the processing of this GPR profile was carried out for several minutes on a computer with a processor frequency of 2.4 MHz. Significant time savings occur in the case of processing a large amount of the same type of GPR data - for example, such as roads or railway profiling results. The user, having configured the parameters of automated processing and starting the processing, can switch to other tasks, and GEORADAR-EXPERT will independently load GPR profiles and save the processing results to the computer's hard disk.

Using the BSEF automated analysis method has the following advantages over other methods of digital processing of GPR signals:

- The depth of GPR research is increasing - the data processing algorithm by the BSEF automated analysis method has high noise immunity and works well in areas of strong noise of signals located in the lower zone of the GPR profile;

- The information content of GPR studies increases - a attribute section according to the results of an automated BSEF analysis allows obtaining information on the structure of the investigated subsurface environment even in the conditions of a smooth change in the electrophysical characteristics of this environment, i.e. in the absence of layer boundaries on the radarogram. If these boundaries are present, then a change in the electrophysical characteristics inside each layer also represents undoubted benefit;

- Significantly increases the speed of processing GPR data, which is important for constantly increasing volumes of GPR works, especially in the road and railway industries;

- The areas of application of the GPR method are expanding and the list of tasks to be solved with the help of this method is increasing;

- The influence of the human factor on the processing and interpretation of GPR data is reduced;

- Provides greater opportunities for the study of complexly constructed subsurface environments.

**Summing Sections or Cross-Sections of 3D Assemblies**

The GEORADAR-EXPERT software contains a fairly wide range of wave field attributes and characteristics of the subsurface environment intended for various purposes. There are frequent cases when information about the object under study is not contained in full by one section of the attribute, but is distributed over the sections of several attributes. In this case, summing a set of attributes allows you to combine disparate information about an object within a single summary section.

The figure below shows images of the GPR profile obtained during the study of the buried valley, a set of attribute sections for summation obtained because of an automated BSEF analysis of this GPR profile and
the result of summing these sections. At the same time, as a result of the summation, artifacts caused by the accumulation of errors in the process of collecting and processing GPR information are eliminated.

The considered GPR profile is not very informative at depths of more than two meters, and the depth of the buried valley, according to a priori information, exceeds this value. On the sections of the attributes, some details of the buried relief are noticeable; however, each of the sections separately does not provide complete information about the structure of the studied subsurface environment. The summation operation made it possible to bring these disparate useful signals into one whole. The relief of the buried valley in the total section is well traced along its entire length. In the figure, the relief of the valley is marked with a dotted line. This example shows how the use of the summation module made it possible to effectively solve the problem of insufficient information content of the GPR profile and individual sections of attributes along this profile.

**Digital Signal Processing GPR Profile**

Along with automated BSEF analysis and creation of sections containing the properties of a subsurface environment or GPR wave field, GEORADAR-EXPERT implements a complete set of data processing methods that should be present in every software for processing GPR information. These are various types of filtering and other standard options for digital signal processing; GPR profile geometry control; work with user-defined layer boundaries, etc. - In a word, everything that a geophysicist is used to working with. The entire functionality of the GEORADAR-EXPERT software is described in detail in the user manual, which can be downloaded on [THIS LINK >>](#). In addition to the foregoing, GEORADAR-EXPERT implements algorithms and signal processing methods specially developed for this software. For example, the B-Detector (Boundaries Detector) method.

The B-Detector method is designed to detect reflections from the boundaries of layers in the wave pattern of a GPR profile, suppress interference that overlaps these reflections, and increase the vertical resolution of GPR data. Using the B-Detector, the user manages the frequency and width of the spectrum of the signals, thereby changing their duration and degree of detail of the radarogram.
As an example of the application of the B-Detector method, consider the GPR profile that was obtained during a survey of the highway with a 1200 MHz antenna - see the figure below on the left. Starting from the mark of 5 meters from the beginning of the GPR profile, asphalt concrete pavement consists of two layers. The upper layer of asphalt concrete has an average thickness of 0.04 m, the lower boundary of the second layer of asphalt concrete lies in the depth range from 0.12 to 0.15 m from the surface. Under the asphalt concrete there is a layer of crushed stone base with an average thickness of about 0.15 m. But not all of these boundaries are visible on the GPR profile. For example, the boundary between the layers of asphalt concrete is not visible. This fact allows us to conclude that the resolution of the 1200 MHz antenna is not enough to detect the boundaries of the structural layers of the pavement.

In addition, determining the exact position of the boundaries on the wave pattern of a given GPR profile vertically is also difficult, because phase displacements of signals as a result of superposition of reflections from the neighboring boundaries of the layers introduce distortions. Regardless of how the user will determine the position of the boundaries - by the extrema of the same phases of the signals or by the line of changing the sign of the amplitude of the signals, or something else - these phase distortions will affect the accuracy of positioning.

In such a situation, it would be logical to use an antenna with a higher frequency to emit a probe pulse of shorter duration, which would lead to an improvement in the resolution of the signals. But then the depth of the GPR study would decrease. The fact is that the damping coefficient of the radio pulse in the subsurface environment increases in proportion to the increase in the frequency of the radio pulse. For this reason, at the hardware level, it is impossible to achieve an increase in signal resolution without reducing the depth of the GPR study. At the software level, it is possible to partially overcome this contradiction using the B-Detector method. The figure below on the right shows the result of applying this method to the GPR profile under consideration:

The resolution of the signals after applying the B-Detector method increased markedly, reflections from all the boundaries of the layers of the pavement became clearly visible. The phases of these reflections have normalized, reflections become more compact in the time domain, distortions caused by the mutual influence of reflections from nearby boundaries are eliminated. All of the above minimizes errors in determining the position of the boundaries of the layers. Reflections from these boundaries have become well adapted to the automated positioning of boundaries, which is also implemented in GEORADAR-EXPERT. This is important for processing large volumes of data obtained during roads or railway GPR studies.
Below, as another example, shows the result of GPR profiling of a highway with a 400 MHz antenna. In the upper figure - the raw data, in the lower figure - the result of processing by the B-Detector method:

B-Detector treatment allowed us to confidently detect the lower boundary of the pavement, the depth of which varies around the 0.2 meter mark, and this boundary is difficult to completely detect on an untreated GPR profile. In the figure below, on the left is the amplitude-frequency spectrum of the raw signals of the GPR profile, on the right is the spectrum of these signals after applying the B-Detector method:

As a result of applying the B-Detector method, the central frequency of GPR profile signals increased by about 3.5 times - from 264 MHz to 911.4 MHz. The width of the signal spectrum increased by 3.7 times - from 74.7 MHz to 277 MHz (the wider the spectrum of the pulse, the shorter its duration, which means better vertical resolution of the radarogram). About the GPR profile, after applying the B-Detector method,
we can say that this GPR profile was recorded using a imaginary GPR with an antenna 400 * 3.5 = 1400 MHz, but at the same time the penetration depth of the probe pulse of this imaginary high-frequency GPR same as a real GPR with a 400 MHz antenna.

Most often, during a GPR survey of the road, it is necessary to obtain two radarograms along the same profile. One radarogram is recorded using a high-frequency GPR antenna with a depth of about 1 meter. This radarogram is used to study the road surface and its base. The second radarogram is recorded using a mid-frequency GPR antenna with a depth of 3 - 5 meters, which is used to study the subbase and subgrade.

If the GPR used for road research does not have the ability to simultaneously record several GPR profiles, then in order to obtain two radarograms it is necessary to go through the same profile two times with different antennas. In this case, using the B-Detector method makes it possible to abandon the high-frequency antenna and record not two, but only one GPR profile of the road using a mid-frequency antenna. For example, 400 MHz - as in this example. In this case, the volume of field and cameral work will be halved. Considering the significant volume of GPR profiling in road research, this is a tangible saving. Even in the case of using a multi-channel GPR, which allows you to simultaneously record more than one GPR profile, using the B-Detector method reduces the amount of cameral work and improves the quality of processing GPR data.

Another argument in favor of using the B-Detector method. A small design and surveying company company may not have a complete set of GPR units that cover the entire frequency range used in georadiolocation. The purchase of a large amount of this equipment requires significant financial costs. In this case, the application of the B-Detector method will compensate for the absence of high-frequency antennas by using low-frequency antennas in those areas of GPR research in which high-frequency antennas are used. Thus, the range of tasks to be expanded, which will lead to an increase in the number of GPR research customers.

Along with the B-Detector method, increasing the resolution of GPR profiling results in the GEORADAR-EXPERT software can be done using wavelet decomposition of GPR signals. The wavelet decomposition uses special functions - wavelets, the graph of which resembles a probing GPR pulse in shape. During wavelet processing, the user sets the order of the wavelet and the level of decomposition. Low-frequency decomposition levels are discarded, after which the GPR profile signals are restored. Thus, on the GPR profile, the central frequency of the signals and the width of their spectrum increase. Below is a comparison of the results of applying the B-Detector methods (top image) and wavelet decomposition of signals to the same GPR profile.
Each of these methods has its advantages. The user, depending on the features of the GPR profile signals and the tasks of the GPR study, can choose which of these methods to use in each case.

One of the problems a geophysicist encounters when processing GPR data is the suppression of reflections from objects located on the ground surface. These so-called air reflections can have a high level of amplitudes and effectively mask useful signals, crossing them with their inclined fragments. Using shielding for GPR antennas may not give the expected effect. The results of profiling by dipole low-frequency antennas, for which shielding is not provided, are most susceptible to this interference. Also, diffracted reflections from contrasting local objects located in a subsurface medium can be a source of interference. These reflections can also mask less intense reflections from the boundaries of the layers.

The spatial filter implemented in the GEORADAR-EXPERT software allows solving this problem. Consider a GPR profile that crosses tram tracks. The figure below, on the left, shows this GPR profile before processing. Profile obtained by GPR with a 150 MHz low-frequency antenna. On this profile, intense reflections from metal rails and infrastructure objects of tram tracks cross weaker reflections from the boundaries of layers in the ground and mask them. The result of spatial filtering is shown on the right. As a result of filtering, the interference in the form of diffracted reflections removed; instead of this interference, reflections from the boundaries of the layers became visible.
Options for digital processing of GPR profile signals, of which there are more than two dozen in GERADAR-EXPERT, allow to solve practically the whole range of problems that users face during GPR data processing. Automation of the user’s actions frees him from the obligation of constant presence at the computer. The user can save the sequence of data processing procedures to a file and apply this sequence in the future. In batch processing mode, the user only needs to select a group of GPR data files, after which the load, processing and saving of the result is performed automatically, without user intervention. For a complete description of the capabilities of the GEORADAR-EXPERT software, see the user manual, which can be downloaded ON THIS LINK >.

**Graphical User Interface**

The graphical user interface of the GEORADAR-EXPERT software is a set of tabs, each of which serves for specific tasks and contains panels with controls for these tasks. Tabs are located in the main program window. At the top of this window is the standard menu bar. The user can change the aspect ratio of the tabs or hide them. GEORADAR-EXPERT provides two modes of the main program window - 2D and 3D. 2D mode is designed to work with two-dimensional data - GPR profiles and sections created by the results of an automated BSEF analysis. The 3D mode is used to visualize the three-dimensional volume of GPR data, as well as slices of this volume. The three-dimensional volume is formed from attribute sections created by the BSEF analysis of a set of GPR profiles obtained during the areal GPR surveying. The main window mode changes automatically, depending on the type of data loaded into GEORADAR-EXPERT.

The following shows the main window of the GEORADAR-EXPERT software in 2D mode. The upper group of tabs serves to visualize two-dimensional data, graphs of the spectrum of signals and statistical information. In this example, the section visualization tab is active. Nearby are inactive tabs for visualizing the GPR profile and the amplitude-frequency spectrum of the signals of this profile. To activate a tab, the user needs to click on this tab, after which the data on this tab will be available, and the data on the other tabs from this group will be hidden.
In the left part of the GEORADAR-EXPERT main window there are tabs intended for graphical presentation of the BSEF analysis results, as well as controls for creating and visualizing the section based on the results of this analysis. In the lower part of the main window there is a group of tabs intended for placing control elements for displaying the radarogram, GPR profile properties and profile processing settings. All three groups of tabs are separated by two separators - vertical and horizontal, which contain buttons for controlling the size of the tabs.

The main window of GEORADAR-EXPERT with the active tab for visualizing the GPR profile is shown below. Unlike the previous example, the ratio of the tab groups has been changed - the size of the left tab group has increased due to a decrease in the size of the upper and lower groups:
The main window of the GEORADAR-EXPERT with the active tab for displaying the amplitude-frequency spectrum of GPR profile signals is shown below. The sizes of the upper and lower groups of tabs are increased by reducing the size of the left group of tabs:

The tab of the section created with the terrain correction is shown below. The last tab is active in the left group of tabs. The area of this tab is only partially occupied by the settings panels for creating and visualizing the section:
The section visualization tab with terrain correction in the attribute visibility constraint mode is shown below. In this mode, section areas containing attribute values that go beyond the boundaries of a user-defined range are not rendered. Hidden areas are not taken into account in the process of statistical analysis and analysis of the spatial distribution of attribute values. Thus, the user can exclude part of the section from these calculations, if necessary.

To work with the results of the areal GPR surveying, the 3D mode of the main window of the GEORADAR-EXPERT software is intended. This mode is used to visualize three-dimensional assembly of sections created on the basis of the results of BSEF automated analysis of GPR profiles of unequal length and arbitrary orientation. When forming a 3D assembly of sections, it is possible to take into account the position of GPR profiles in GPS coordinates. In 3D mode, the left group of tabs available in 2D mode is hidden. The upper group of tabs is intended for visualization of 3D volume, mutually perpendicular slices and arbitrary custom sections of 3D volume. The lower group of tabs is used to place 3D visualization controls.

The figure below shows the main window of the GEORADAR-EXPERT software in 3D mode with the active tab for visualizing the volume of 3D assembly. The volume is divided into parts by three orthogonal slices - one horizontal and two vertical. The result is eight sub-volumes - four lie above the horizontal slice and four are located below this slice. You can resize sub-volumes by moving orthogonal slices along their respective axes. In the presented example, one upper quarter of the 3D assembly volume is cut out (made transparent):
The user can control the already existing by default 3D orthogonal slices of the 3D assembly - change their position, average the specified thickness of the 3D volume in all three XYZ directions and present the result as orthogonal slices, create user sections of any shape, save these sections to a file and load them in 3D assembly from a file. The figure below shows the main window of GEORADAR-EXPERT with the active tab for visualizing 3D volume containing three orthogonal slices and one user section:

The tab below shows the development of this curved user section. Vertical lines indicate the position of the nodal points of the curve through which this section passes. The names of the points are located on the upper boundary of the section. For each point, it is possible to obtain a logging curve and a table of its values.
The user can save a series of images of orthogonal slices of 3D volume in the computer’s hard disk in automatic mode with a specified step along the corresponding axis. Compared to the manual mode for saving slices, automatic mode saves time. In manual mode, you first need to perform actions to move the slice to the desired point on the axis, and then interact with the save dialog box. When the number of slices is several tens, or even hundreds, the manual saving process is extended for a long time. The figure below shows a Windows Explorer window with a directory for saving a set of horizontal slices of 3D volume.
In 3D mode, all the necessary options for visualizing GPR information are provided, including the ability to control the transparency of elements included in the 3D assembly volume. This allows for greater visibility in the presentation of the results of the GPR study. The figure below shows an example of 3D visualization, which includes isosurfaces and the volume of 3D assemblies with varying degrees of transparency. In the translucent volume of the 3D assembly, interstratified layers of rocks are visible in the form of areas of red shades. The boundaries of soil anomalies are represented by isosurfaces of blue color. Translucent isosurfaces do not overlap each other, and this allows us to observe the shape of these anomalies completely.

Below is a variant of visualization of the 3D assembly volume, in which full transparency is defined by the user-specified range of attribute values, and the isosurface is the boundary between the transparent and opaque regions:
If the 3D assembly contains isosurfaces, then these isosurfaces divide the volume of the 3D assembly into parts. The user can create isosurfaces so that they pass along the contact boundaries of the layers of the investigated subsurface. The ability to obtain information about the volume of these layers is of undoubted practical interest. GEORADAR-EXPERT provides this opportunity. The figure below on the left shows the axes of the 3D assembly from the previous example, on which orthogonal slices and two isosurfaces are placed - one yellow, the other purple. The values through which these isosurfaces pass are shown in the lower left corner of the image in the rectangles of the corresponding colors. The right-hand side of the image shows an automatically generated table of volumes bounded by these isosurfaces. Similarly, you can get information about layer area in square meters in 2D mode. Only in this case the layers do not limit the isosurfaces, but the lines of the boundaries of the layers.

Below is an example of a 3D assembly, which was created taking into account the coordinates of the GPS positioning system. In a three-dimensional view, the positions of GPR profiles and vertical slices along these profiles are visualized. An isosurface passes through the 3D assembly volume, showing the contact position of soils with various electro physical characteristics. For isosurface and 3D assembly volume, various degrees of transparency are specified.
Undoubtedly, GEORADAR-EXPERT, developed as a result of summarizing many years of experience in processing GPR data, is an effective tool for solving a wide range of GPR tasks, including in cases where the use of software for processing GPR data from other manufacturers does not lead to positive results. High informativeness and quality of cameral work performed using the GEORADAR-EXPERT software will help to attract new customers and ensure stable competitiveness in the geophysical services market.

Similarities and Differences from Other Manufacturers Software

**Similarity**

The GEORADAR-EXPERT software implements a complete set of data processing options, which should be present in each software for processing GPR information. These are various types of filtering and other standard options for digital signal processing, managing GPR profile parameters, working with user-defined layer boundaries, etc. That is, everything that a specialist in processing GPR data is used to using in his professional activity.

**Differences**

The main difference of GEORADAR-EXPERT from other manufacturers' software is the increased informativeness of GPR data processing results and the low level of human factor influence on the final processing result. The ability to batch process data and automate user actions provides good processing speed for large volumes of information. Algorithms and methods implemented in the GEORADAR-EXPERT
software provide more opportunities for researching complexly constructed subsurface environments. GEORADAR-EXPERT includes the following options specially designed for this software:

- Automated BSEF (Back-Scattering Electromagnetic Field) electromagnetic field analysis. Carries out the transition from the presentation of data on the subsurface in the form of a set of amplitudes of the reflected signals in the form of a radarogram to the characteristics of this subsurface in the form of an attribute section. Such a presentation makes the result of processing GPR data more understandable both to geophysicists and to specialists in related fields. For example, geologists or design-and-planning engineers. BSEF analysis works well in areas of strong noise located at the bottom of the GPR profile, which allows increasing the depth of GPR research. Along with this, the BSEF analysis provides information on the structure of the investigated subsurface environment even under conditions of a smooth change in its electrophysical characteristics, i.e. in the absence of layer boundaries on the radarogram.

- B-Detector Method (Boundaries Detector). This method is designed to detect reflections from the boundaries of layers in the wave pattern of a GPR profile, suppress interference that overlaps these reflections, and increase the vertical resolution of GPR data. Using the B-Detector, the user manages the frequency and width of the spectrum of the signals, thereby changing their duration and degree of detail of the radarogram. As a result of processing by the B-Detector GPR method, the profile obtained by the low-frequency antenna looks as if the frequency of the GPR antenna during recording of this profile was several times higher. The resolution of signals on this GPR profile is also several times higher. If necessary, it is possible, and vice versa, to lower the central frequency of the radarogram signals.

- Method for decomposing a radarogram into components. This is not a wavelet decomposition of signals, although it is also implemented in the GEORADAR-EXPERT. This method converts a signals matrix of GPR profile into a set of matrices. Each matrix from this set contains only one unique type of reflected waves. The user discards the matrices with those types of waves, which he defined as interference, and then summarizes the remaining matrices. Thus, interference are excluded from the GPR profile signals. Using the same method, it is possible to remove diffracted reflections, including air ones, leaving behind only the boundaries of the layers on the radarogram. This is useful, for example, for road research. Or vice versa, you can remove all the boundaries of the layers, leaving only diffracted reflections. For example, to better detect reinforcement in a concrete structure.

- Statistical analysis module. This module is intended to summarize the results of GPR profiling and to better presentation the variability of the electrophysical characteristics of the GPR profile. Using the results of statistical analysis, presented in the form of tables and graphs, it is possible to establish a relationship between the physicomechanical characteristics of the investigated subsurface environment (for example, soil or building structures) and various statistical indicators. Thus, a feature set is created that can be used in the future to assess the state of similar objects. Statistical data sources are GPR profiles, attribute sections, which are calculated based on the results of BSEF automated analysis, and slices of the 3D assembly. If the user has drawn the boundaries of the layers on the GPR profile, on the attribute section or on the 3D assembly slice, the statistical indicators are calculated inside each layer, along the boundary of each layer and for the whole object, without
regard to separation into layers. Using the statistical analysis module implemented by GEORADAR-EXPERT raises the quality of GPR research results to a new, higher level.

- Cluster analysis. Cluster analysis of attributes is used to rapid assessment the structure of the subsurface environment in a given approximation. The number of clusters determines the degree of approximation. The result of cluster analysis is a section of the attribute in the form of a combination of blocks of various shapes (clusters). Within a cluster, attribute values are the same. Through clusters, the section is divided into characteristic areas, each of which has its own features.

- Flaw detection module of building structures. Flaw detection of concrete and reinforced concrete building structures is based on the identification of zones on the section with abnormal deviations of the values of the Q-factor attribute. Flaw detection results are saved in the form of a section of the attribute, on which the defective zones are highlighted, and a defective list, in which for each GPR profile a quantitative and qualitative assessment of the state of the object is given, during the study of which one or another profile is obtained.

- 2D data summation module. Designed to summarize sections of heterogeneous attributes or cross-sections of a 3D assembly. As a result of summation, artifacts caused by the accumulation of errors in the process of collecting and processing GPR information are eliminated, and the model of the subsurface medium is restored from summation elements (attribute sections or cross-sections of a 3D assembly), each of which contains only some of the useful information.

**Useful Links**

The site of the GEORADAR-EXPERT software in English:

The user manual of the GEORADAR-EXPERT software package in English can be downloaded from the download page at the following link:

Video tutorials in English can be viewed and downloaded from the following link:

The information booklet in English with a brief overview of the GEORADAR-EXPERT software package can be downloaded from the following link:

Technical support: ge_soft@mail.ru