# WAVELET PROCESSING AND FILTERING
# OF THE RADARGRAM TRACE

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**Abstract** The paper considers the application of a discrete wavelet transformation to clear the noisy signals of the GPR path and filter of the radargram trace by complex Butterworth filters to remove extraneous frequencies from the signal.

**Key words:** wavelets, tresholding, filtering, multi-scale analysis, Stein criterion, signal spectrum, Butterworth filter.

**AMS Mathematics Subject Classification:** 60G35.

## 1    Introduction

Georadar tracking systems (georadars) are used for non-destructive testing and diagnostics in the field of construction of various objects, road surfaces (aerodromes) and exploration of minerals. The list of similar tasks is so large and covers a wide range of tasks of the national economy and the defense industry. The radar is capable of emitting electromagnetic signals into the survey environment, receiving and recording the reflected electromagnetic signals, then constructing a radargram based on the reflected electromagnetic signals. The radargram represents a time scan at the observation point. The main task of these experimental studies is to interpret the radargrams. The engineering and technical method of investigation consists in comparing the obtained radargrams with the standard forms in the database, as well as additional calculations based on the theory of wave propagation in the medium. Practical and theoretical methods of subsurface radar are described in the works of the authors of the far and near abroad [1] - [6]. There are a number of modifications of the device produced by different countries, they are designed to solve a wide range of problems and the instructions attached to them do not have a detailed description of the methods for interpreting radargrams. The quality of the interpretation of radargrams depends on the completeness of the available base of reflected signals from heterogeneities and the experience of geophysical reading skills, which introduces a substantially subjective character.

On the other hand, there is another direction in the interpretation of radargrams, namely, mathematical and computer simulation of the propagation and reflection of electromagnetic waves in a medium. The radargram carries information of the running time to the inhomogeneity, and in practice it is of interest to determine the physical characteristics of the inhomogeneity. In the case of reflected electromagnetic signals, the physical characteristics of the objects under study include: dielectric and magnetic

permeability, conductivity of media. To determine these coefficients, the theory of ill-posed and inverse problems, which developed rapidly in the 20th century, was widely used. The basis of this theory rises from the first works in this direction of Academician A.N. Tikhonov [7]. For a different class of problems, the theory of ill-posed and inverse problems was developed in the works of academicians Lavrentev M.M., Ivanov V.I. their pupils and followers [8] - [10]. Theoretical aspects, namely questions of uniqueness and stability in the class of well-posedness for inverse problems of mathematical physics, are set forth in the monograph by V.G. Romanov [11]. The theoretical foundations and problems of the numerical method for solving inverse problems for the geo-electric equation are described in detail in a monograph by V.G. Romanov, S.I. Kabanykhin [12]. The use of optimization methods for the solution of coefficient inverse problems is set forth in the monographs of S.I. Kabanykhin and K.T. Iskakov. [13]. Analysis of technical characteristics of common georadars and the application of information and communication technologies in the tasks of interpretation of georadar location data are reflected in the collective monograph [14]. As a rule, additional information is needed to solve the inverse coefficient problems. response of the medium at the observation point. In practice, georadar data are used, namely reflected signals from medium inhomogeneities that fix the receiver of the device. Thus, the georadar records the travel time of the reflected signals and then, using it as additional information, the embedded software (inverse problem solution), allows to determine the geoelectric section.

The result of the georadar survey is a set of single traces (signals) registered by the receiving antenna at each position of the radar. Usually this set of traces is displayed in the form of an image - a radargram [14-15]. The need for further processing of radargrams can be explained by several reasons. First, to solve engineering problems, it is necessary to have a dependence of the signal amplitude on the reflection depth, whereas the initial radargram is the dependence of the signal amplitude on the reflection time. Secondly, it is necessary to get rid of various kinds of interference that hide a useful signal. When processing radargrams, frequency filtering, averaging of signals, amplitude correction, Hilbert transform are used. The final stage in the processing of radargrams is the interpretation, on which the engineering task is directly solved. In interpreting, the main features of the wave pattern and its local features.

The digital signal is filtered using a discrete Fourier transform, and wavelet technology is used (Figure 1).
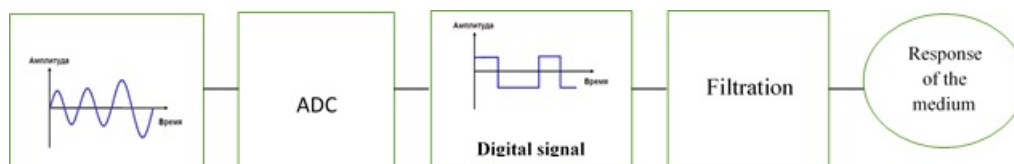


Figure 1: Filtering and clearing the signal

Based on the developed technical specification for the prototype georadiation sys-

tem, the technical characteristics of this system were obtained. The structural diagram of the meter is shown in (Figure 2).

The design and simulation of the circuit diagrams of the components of the prototype GPR were carried out using the Altium Designer high-speed electronic device design system [16].
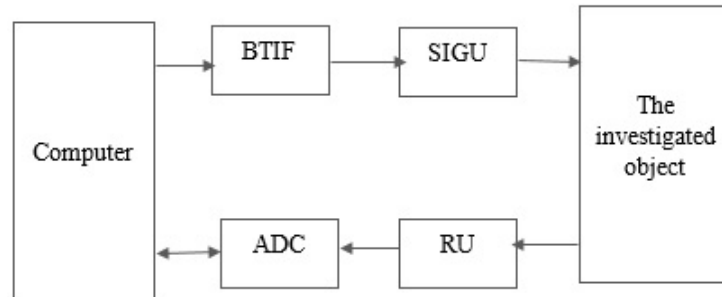


Figure 2: Structural diagram of the meter

The composition of the meter: block of time interval forming (BTIF); sounding impulse generation unit (SIGU; receiver unit (RU); analog-to-digital converter (ADC); power supply unit (PSU).

Figure 3a shows the state of the device in the connected state. Figure 3b shows the transmitting and receiving antennas, which are the main part of the georadar tracking system.



a) device in the connected state     b) receiving antenna and transmitting antenna

Figure 3: The device in the connected state and antennas

## 2    Test experiments with a prototype GPR

Test experiments were conducted in laboratory conditions with an experimental georadar to determine the maximum depth of sounding and resolution.

Figure 4a shows the result of an experiment with a metal reflecting plate. On the left of the monitor, the signal change from the transition boundary (changes in the

dielectric constant of the air-metal plate) is clearly visible. For more details, see Figure 4b.
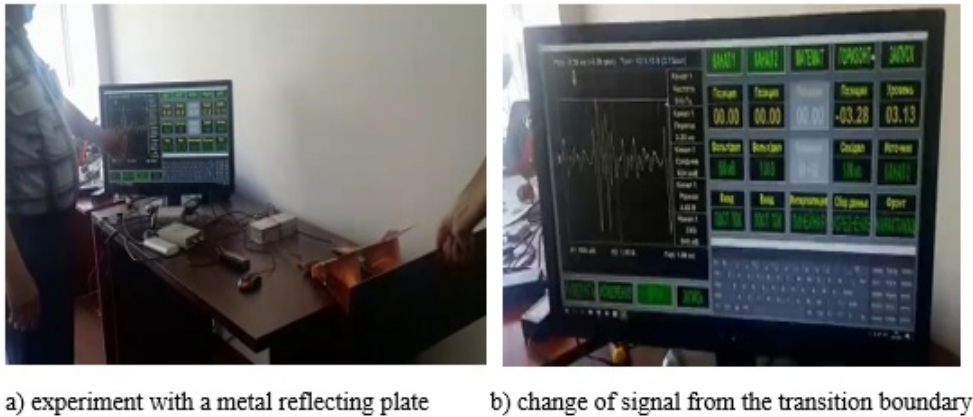


a) experiment with a metal reflecting plate    b) change of signal from the transition boundary

Figure 4: Carrying out an experiment with a metal plate

(Figure 5) shows the steps of assembling a prototype of a georadar.



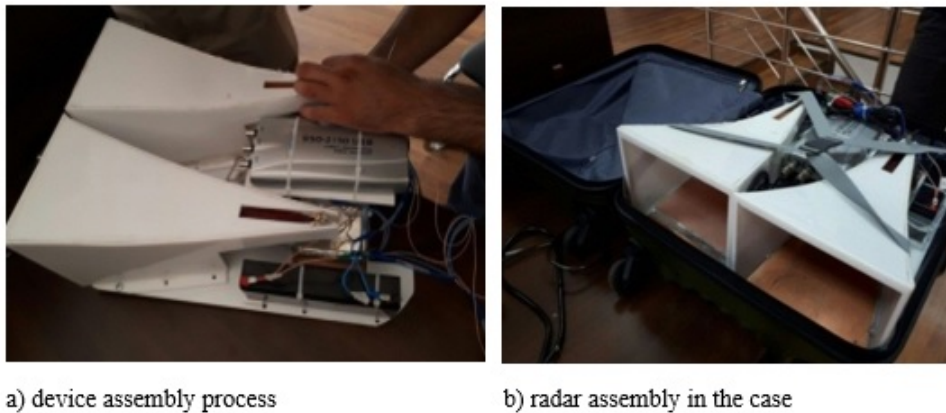a) device assembly process    b) radar assembly in the case

Figure 5: Stages of assembly and testing

Figures 5b show a radar assembly where the antenna is placed in a casing. The dimensions of the optimal location of the main radar nodes: the transmitter unit; receiver unit; a time interval generation unit; The power supply is selected based on 3D modeling.

To measure to a depth of about 20-23 meters, the following parameters were set: clock frequency 100 MHz, time interval - 10ns. This interval is divided into 256 parts, and the countdown timer is set in hardware with a step of 0.039 ns. With such parameters, the maximum number of intervals with a clock frequency of 100 MHz is 15 units, then the signal travel time is 3 meters with a return.

Thus, the depth of measurement with a clock frequency of 100 MHz is 45 meters with a return signal. Depending on the geoelectrical properties of the medium, the depth of the measurement changes in the direction of decreasing. You can change this setting if you change the device data. Thus, the depth of sounding depends on the

characteristics of the input data of the device. Antenna can also be tuned to other frequencies.

## 2  Experimental research in the field

The expedition was carried out with a visit to the training laboratory test site, located 76 km from Astana in the north-west direction, consisting of: employees of the Department of Computer Science of the Eurasian National University named after L.N. Gumilyov, Doctor of Physical and Mathematical Sciences. Iskakov K.T., senior lecturer of the department of Computing engineering Boranbaev S.A. , doctoral student of 2nd courses ENU named after. L.N. Gumilyov Uzakkyzy N.

Earlier, experimental studies were carried out and studied in the article [17], where on the basis of the interpretation of radargrams obtained with the help of the "Zond-12" device, approximate positions (according to the depth of occurrence) of artificial "targets" were established: the foam of ore, the metal barrel.

It has also been established that for qualitative interpretation of radargrams, conditions for the commensurability of the depth of occurrence of objects from the width of the excavation are necessary. To eliminate these errors, various targets were placed in the pit satisfying the following requirements: the size of the objects is four times smaller than the length of the excavation; two times less than the width of the excavation, as well as the depth of occurrence of about 1.5 times.

Similar studies were carried out using the Loza-B series georadar. A detailed analysis of the studies can be found in [18]. For carrying out measurements in the field, a prototype of a georadar was tested. (Figure 6) shows the process of measuring over the object - "Copper cable" in the field.



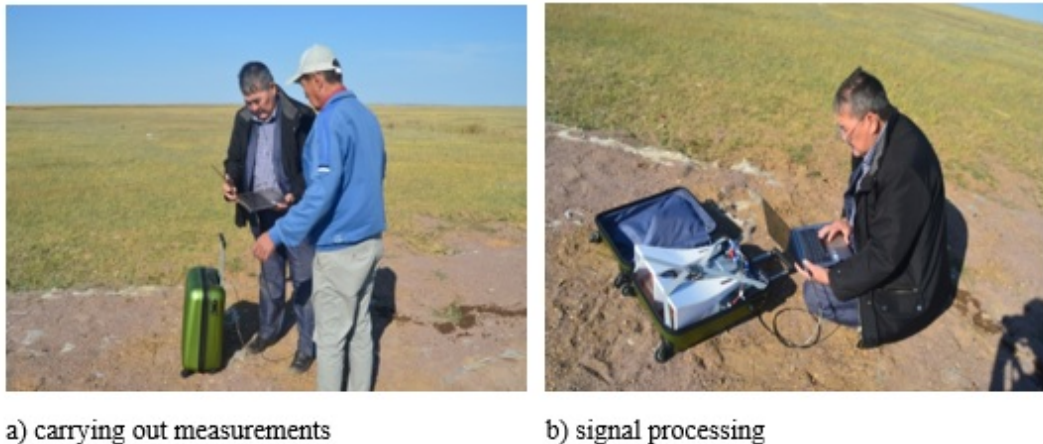a) carrying out measurements        b) signal processing

Figure 6: The process of conducting measurements in the field

The plot of the radargram trace of a given scan (Figure 7).
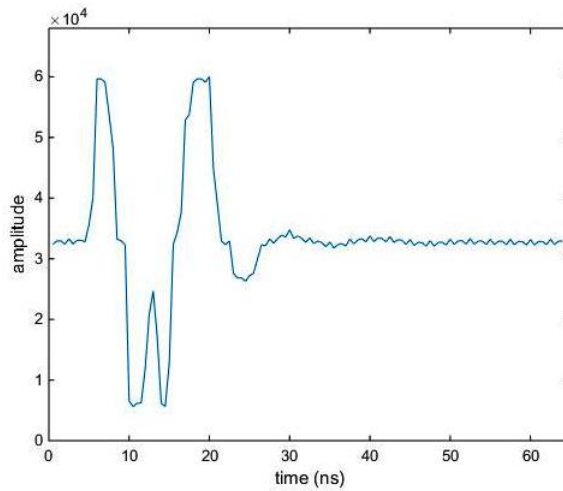
Figure 7: The graph of the radargram trace

In the future, for processing such a type of signals, pre-purification methods are used for wavelet analysis and filtration.

# 3    Clearing the path from noise using wavelet transformation

To improve the noise immunity of the georadar method, as a rule, preliminary processing of experimental measurements is carried out in order to extract informative signals. The essence of processing of georadar locating data consists, first of all, in allocation of a useful signal against a background of noise and noise. To distinguish useful signals, the characteristics of these signals differ from the corresponding characteristics of noise and interference waves [1,19].

One way to process the radargram is wavelet transformation. With the help of wavelet transformation of a digital signal in a radar picture, high-frequency components can be removed from the signal spectrum.

Wavelets Daubeshy db4 [20] were used to clean the signal from noise. Daubeshy wavelets have no analytical expression and are determined only by filters. In practical applications, approximating hk and gk-specific wavelet coefficients are used, without computing the specific form of wavelets [21]. For wavelets db4, these coefficients are as follows:

$$h_0 = 0.4829629131445341 \quad g_0 = h_3$$
$$h_1 = 0.8365163037378079 \quad g_1 = -h_2$$
$$h_2 = 0.2241438680420134 \quad g_2 = h_1$$
$$h_3 = -0.1294095225512604 \quad g_3 = -h_0$$

The decomposition into components of discrete wavelets of Daubeshy is carried out according to the formulas:

$$a_i = h_0 s_{2i-1} + h_1 s_{2i} + h_2 s_{2i+1} + h_3 s_{2i+2}$$

$$d_i = g_0 s_{2i-1} + g_1 s_{2i} + g_2 s_{2i+1} + g_3 s_{2i+2}, \, i\text{=1, 2,..., } n/2\text{-1}$$

$$a_{n/2} = h_0 s_{n-2} + h_1 s_{n-1} + h_2 s_0 + h_3 s_1$$

$$d_{n/2} = g_0 s_{n-2} + g_1 s_{n-1} + g_2 s_0 + g_3 s_1$$

Formulas (1) is a pyramidal algorithm for computing the wavelet coefficients of Malla [21]. With these formulas, the digital filter $h_n$ from the signal $s_k$ selects low frequencies, and the $g_n$ filter highlights the high frequencies. Applying the low-pass filter, we obtain the approximation coefficients $a_i$, the high-pass filter, we obtain the detailing coefficients $d_i$.

One way to reduce the noise level when processing signals using wavelet analysis technology is to program-controlled threshold processing of the detailing wavelet coefficients. This method was called tresholding. The main advantage of trsholding lies in the wide possibilities of variation of processing parameters by using different types, threshold processing methods and their parameters.

The wavelet transform possesses the redundancy property, which makes it possible to "cut" some or all of the wavelet coefficients of a certain level without losing information. The noise components are transferred at high frequencies and with wavelet analysis are contained in the detailing wavelet coefficients of the lower levels of signal decomposition. In trehshinging algorithms, the threshold of restriction can be adapted and set separately for each coefficient. When solving the noise reduction problem, it is necessary: to estimate the spectral composition of the noise component, to select the type of threshold processing (tresholding) and the criterion for calculating the threshold itself.

There are two main generally accepted rules for threshold cutoff of wavelet coefficients:

1) «hard» (hard thresholding): $d_i = \begin{cases} 0, & |d_i| \leq \lambda, \\ d_i & |d_i| > \lambda. \end{cases}$

2) «soft» (soft thresholding): $d_i = \begin{cases} 0, & |d_i| \leq \lambda, \\ sign(d_i)(|d_i| - \lambda), & |d_i| > \lambda. \end{cases}$

Here $\lambda$- is the value of the cutoff threshold (threshold value).

From the selection of the threshold level of the background (noise variance estimate), the noise quality of the signal, estimated as a signal-to-noise ratio, depends.

Setting small threshold values preserves the background in the detail coefficients and therefore only leads to a slight increase in the signal-to-noise ratio. For large threshold values, it is possible to lose coefficients that carry essential information. Finding the optimal value - the threshold value means finding a threshold that, with the smallest offset of the reconstructed signal, provides the highest value of the signal-to-noise ratio. The criterion of Stein's unbiased risk estimation (Stein's unbiased risk estimation) allows to determine the optimal value of the threshold corresponding to the level of decomposition of the signal [22].

$\lambda = \sigma\sqrt{2\ln n}$   $\sigma = \text{median}(|d_i|)/0{,}6475$

n - is the total number of samples of the processed signal at the current iteration level.

Multiple application of wavelet processing of a georadar signal is possible, which leads to an increase in the detail of the original signal up to the frequency of the wavelet
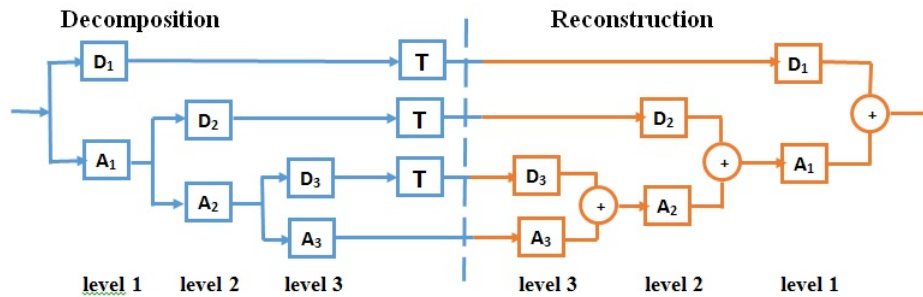
itself (Figure 8).



Figure 8: Stages of wavelet signal processing. A and D approximating and detailing coefficients, T - tresholding

In practice, excessive detailing makes the signal less visible. For most georadar tracking signals, 5 repetitions of wavelet processing are sufficient to increase the resolving power of the signal without loss of the envelope of the pulse.

For each level, a threshold is set and processing of the detailing factors is carried out. wavelet reconstruction using the approximating coefficients of the last level and the modified details of the previous levels (see Figure 5).

When the signal is reconstructed (reconstructed) by its wavelet coefficients, the process proceeds from large scales to small ones and is described at each step by the formulas:

$$a_1 = h_2 s_{\frac{n}{2}} + h_1 s_n + h_0 s_1 + h_3 s_{\frac{n}{2}-1}$$
$$a_2 = g_0 s_{\frac{n}{2}} + g_1 s_{\frac{n}{2}-1} + g_2 s_1 + g_3 s_n$$

$$a_i = h_2 s_{\frac{i-1}{2}} + h_1 s_{\frac{i-1}{2}+\frac{n}{2}} + h_0 s_{\frac{i-1}{2}+1} + h_3 s_{\frac{i-1}{2}+\frac{n}{2}-1} \quad i=3, 5, \ldots n/2 - 1 \text{ (odd)}$$
$$a_i = g_0 s_{\frac{i-1}{2}} + g_1 s_{\frac{i-1}{2}+\frac{n}{2}-1} + g_2 s_{\frac{i-1}{2}+1} + g_3 s_{\frac{i-1}{2}+\frac{n}{2}} \quad i=4, 6, \ldots n/2 \text{ (even)}$$

under the conditions that the detail coefficients of the previous levels are written in place of the signal values.

The results of the trace transformation by the Daubechies wavelets are shown in Figure 9.
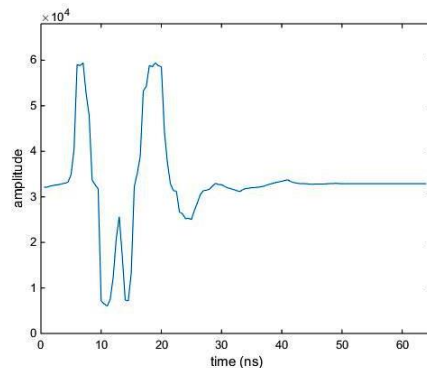


Figure 9: The plot of the radargram trace after the wavelet transformation.

# 4    Filtration of the radargram trace

Filtering consists in removing harmonics from certain frequencies from the signal. To remove and suppress radargrams from the route of frequencies that do not correspond to the frequency of the GPR antenna, we use the Butterworth Infinite Impulse Response (IIR) filter [23].

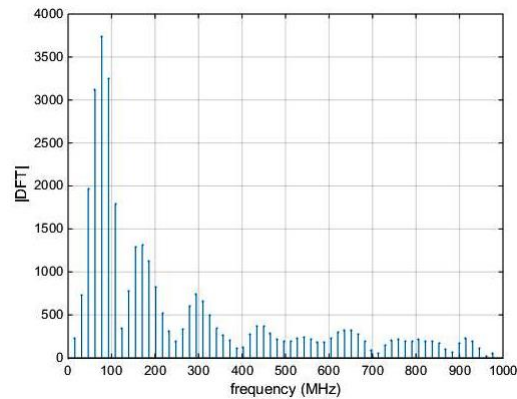The spectral composition of the original trace (Figure 7) is shown in Figure 10.



Figure 10: The spectrum of the original radargram trace.

Parameters for the synthesis of IIR low-pass filter Butterworth:
filter order: 4;
sample rate: 1 GHz;
bandwidth from 0 to 200 MHz;
delay band from 350 MHz.

The calculation of the Butterworth digital filter was carried out by the method of bilinear transformation (the method of invariance of frequency characteristics) [24].

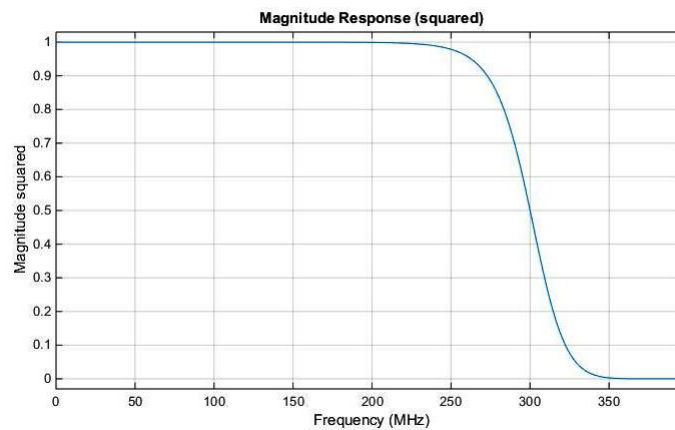The amplitude-frequency characteristic (AFC) of the obtained filter is shown in Figure 11.



Figure 11: Graph of the squared response of the Butterworth filter.

Transfer function of the filter:

$$H(z) = 0,67\frac{1 + 2z^{-1} + z^{-2}}{1 + 1.11z^{-1} + 0.57z^{-2}} + 0,51\frac{1 + 2z^{-1} + z^{-2}}{1 + 0,85z^{-1} + 0.21z^{-2}}$$
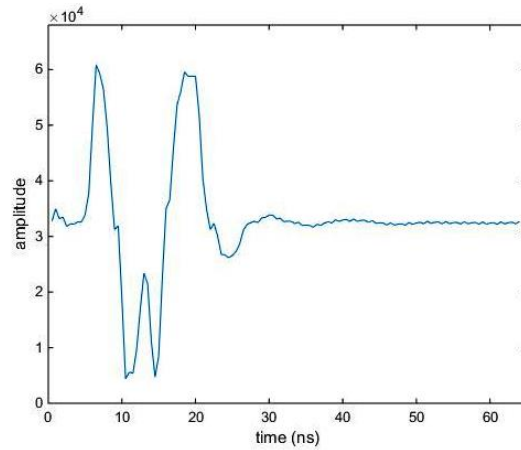
Figure 12 shows the graph of the filtered radargram trace.



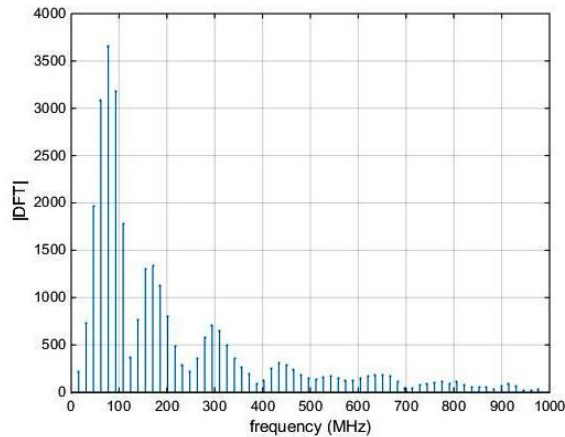Figure 12: The graph of the filtered radargram trace.



Figure 13: Spectrum of a filtered radargram trace.

# 5   Conclusion

Interpreting the results of georadar research is a complex and time-consuming process that requires a lot of experience and knowledge, as well as possible verification of results by other research methods. The basic methods of processing are aimed at suppressing, weakening or removing useless information and isolating, amplifying useful. Wavelet path conversion suppresses high-frequency noise, but does not remove from the signal. High-frequency interference is usually associated with working near radio stations or

transmitters. Frequency filtering of the radargram trace is performed in order to increase the signal / interference ratio by selectively removing the multipath interference in the trace spectrum.

Preliminary processing of the radargram trace for the removal of the useless and allocation of useful information was carried out.

1. By means of the wavelet transformation of the path, the high-frequency noise is reduced.

2. The filtration of the radargram trace by the Butterworth bandpass filter was performed to selectively remove the multipath interference in the trace spectrum.

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