Analysis of echo-pulse images of layered structures. The method of signal under space

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Abstract. A new approach to the analysis of pulse echo images is considered, which allows to increase the sensitivity of the analysis and provides the possibility of controlled compensation of the effect of multiple reflections. It is based on the use of the properties of eigenvectors of the correlation matrix of the spectral dependence of the signaling superposition that is being analyzed and the decomposition of the orthogonal space formed by the own vectors of the correlation matrix into two orthogonal subspaces: signaling and noise, that is, by searching for such a new coordinate system in which the informational harmonics of the spectral dependencies would be orthogonal within a given frequency interval. The results of experimental verification of the information capabilities of the method are presented. Probability of scientific positions is substantiated by experimental verification of developed models and methods, on examples of images with already known results (drilling of wells, etc.), which testifies the correspondence of theoretical and practical results.

Keywords: analysis of pulse, digital processing, mathematical model of the layered structure, analyzing pulse-echo images.

1 Introduction

The problem of processing echo-impulse images is very acute now, in order to improve their quality during visualization. It consists of analyzing superpositions of unknown pulse signals that make up these images. Methods of analysis, such as the inverse filtering method and the method of caps trial analysis, cannot be used in this area because of the number of constraints that they impose on incoming superpositions. Therefore, the development of such approaches and methods that are free of existing restrictions and based on the use of a priori information, such as the method of signal subspace in the spectral region, is relevant.

The method of processing ultrasound images, based on the method of signal subspace, aimed at neutralizing the influence of multiple re-rebounds, is resistant to the influence of measuring and structural noise and does not require a priori knowledge of the model of the analyzed structure.

The area of application of the method is to improve the quality of images obtained using ultrasound devices or seismograms.

2 Literature Review

The book [1] contains interesting findings of some state-of-the-art research in the field of signal and image processing. It covers a wide range of signal processing applications involving filtering, encoding, classification, segmentation, clustering, feature extraction, denoising, watermarking, object recognition, reconstruction and fractal analysis. Various types of signals including image, video, speech, non-speech audio, handwritten text, geometric diagram, ECG and EMG signals, MRI, PET and CT scan images, THz signals, solar wind speed signals (SWS) and photoplethysmogram (PPG) signals have been dealt with. It demonstrates how new paradigms of intelligent computing like quantum computing can be applied to process and analyze signals in a most precise and effective manner.

Development of a large number of algorithms for a plurality of arrival directions of signals is simultaneously active in work [2]. Advantages: a large number of methods are considered, including the signal subspace method, a comparative analysis of methods is carried out, the effectiveness of these methods is discussed.

Work [3] provides an authoritative account of the art and science of reflection seismology. It offers a clear explanation of the methods by which artificially created seismic waves are employed in the economic discovery of oil and gas, as well as their growing use in the exploitation of coal reserves and other energy resources.

The book [4] dedicated to the digital processing of seismic data and their interpretation. Benefits: examines procedures for improving data quality; seismic velocity analysis; principles of structural constructions, to extract geologically significant information, information theory is used.

In the work [5] has been given of the surface-related multiple problems by making use of the so-called feedback model. From the resulting equations it has been concluded that the proposed solution does not require any properties of the subsurface. The surface-related multiple removal algorithms have been formulated in terms of a Neumann series and in terms of an iterative equation. The iterative formulation also has the advantage that it can be integrated easily with other multiple removal methods. An algorithm for the removal of internal multiples has been proposed as well.

A systematic review of many new (at that time) methods of spectral analysis of time series are given in the [6] work. Advantages: such methods are described, such as the classical method based on the use of period grams, the Blackman-Tukey method, the autoregression method (maximum entropy), the moving average method, the maximum likelihood method, the autoregressive method - the moving average, the Prony method and the Pisarenko method; a summary table with a brief description of all the methods considered is given.

In the work [7] describes the methods of processing signals received on the sensor matrix to determine the location of the source. Mathematically, they represent forms of spectral estimation. Practical examples show Cramer-Rao accuracy for a variety of signals. Examples and comparisons with other methods of maximum probability and maximum entropy are included. An example is given of using MUSIC for time series to estimate multiple frequencies.

The work [8] devoted to digital spectral analysis using modern methods of spectral estimation. Such methods provide enhanced resolution with short sampling and the absence of false side lobes and, as a result, they can have a wide range of applications in radar, sonar, speech and music synthesis, image and seismogram processing, and many other areas. Advantages: programs that implement computational procedures for each of the considered methods are given.

The manual [9] a basic course on digital signal processing reviewed. Benefits: outlines the fundamentals of the theory of discrete signals and systems, discusses methods for spectral analysis and filtering of discrete signals, algorithms for the synthesis of discrete filters, the effect of quantization effects and finite computational accuracy on the operation of digital devices, describes modulation methods used to transmit digital information, discuss adaptive filters multi-speed signal processing.

In the work [10] an interference cancellation technique that combines a signal subspace approach with adaptive adjustment of the weight vector is derived. The weight vector is constrained to lie in a signal subspace computed by Eigen decomposition of the covariance matrix of the array outputs. The weight vector is rotated to maximize the output signal-to-interference ratio.

The article [11] reveals the meaning of the methods of the signal subspace, describes their features, application. Signal subspace methods are empirical linear methods for reducing dimension and noise level. The signal subspace is used in radio direction finding using MUSIC.

The objective of this paper [12] is threefold: to provide an extensive review of signal subspace speech enhancement; to derive an upper bound for the performance of these techniques; to present a comprehensive study of the potential of subspace filtering to increase the robustness of automatic speech recognizers against stationary additive noise distortions.

The book [13] outlines the elements of the classical theory of elastic waves in homogeneous and inhomogeneous media - ideal and real, isotropic and anisotropic, gives geological foundations and classification of seismic methods, analyzes the features of surface and linear hodographs of various waves, discusses the issues of modeling seismic fields. The chapters of the book study the techniques, methods and technology of modern fieldwork statistical theory, as well as the organization and economics of seismic exploration.

In work [14], various methods of reconstructing radio images reviewed, processing signals and images of the subsurface area and objects probed by ultra-wideband signals for their detection and interpretation during geophysical and archaeological research are considered; considered the specificity of the propagation of UWB signals in environments with pronounced attenuation and dispersion; describes various approaches to solving inverse problems of subsurface sounding; various organizations of subsurface sounding radar software (RPG) and methods of their use by the operator are given; The main characteristics of modern RPZs, especially the construction of radars, as well as the results of their use for solving a number of scientific and engineering-physical tasks are considered.

The manual [15] outlines the theory and basic methods for processing geophysical data using spectral and correlation and regression analysis, linear filters, a statistical theory of weak signal detection, classification algorithms and pattern recognition methods for complex analysis of geophysical observations.

In [16], spectral, correlation, and cepstral methods for isolating signals from interference, used in the original field and numerical experiments, are considered. Among them: the selection and measurement of signal parameters when the object is located in the light; time compression of a narrowband signal by transforming its spectrum; elimination of signal distortion caused by multipath, using only a distorted signal (blind reverb); method for determining the delay of the pulse, fluctuating in form; wave propagation using M-sequences and others

In [17], the possibility of predicting the spectrum of a seismic signal based on a priori data on the velocity section of the medium being examined is considered. The condition of broadband and uniform spectrum of the signal at the source, linear absorption of the medium and statistical dependence between the decrement of absorption and seismic velocity is accepted.

In a work [18], a theory is presented to account for the structure of seismograms. It is demonstrated mathematically that a sharp seismic disturbance gives rise to a traveling wavelet of shape determined by the nature of the earth's absorption spectrum for elastic waves, and that a seismogram is composed of a succession of these wavelets, generally overlapping but sometimes in the clear.

The monograph [19] contains a presentation of the theory and practice of frequency filtering algorithms, in which the decomposition coefficients of a noisy signal or image on the Fourier basis and wavelet basis are subject to processing. At the same time, much attention is paid to the choice of the parameters of the algorithms, based on the condition of the minimum mean-square filtering error. Fragments of Mathcad math package documents that implement the constructed filtering algorithms are given.

The handbook [20] contains information about the physics and kinematics of seismic waves. The equipment, work methods, processing and interpretation of seismic data are described. Considered the use of seismic prospecting in solving geological problems, the organization and planning of work.

A resource [21] provides complete coverage of signal modeling, optimum filtering, ratios of the acoustic impedances, and adaptive filtering. Many worked examples illustrate particular algorithms and techniques in use in practical settings.

In the work [22], which is based on the analysis of methods for processing echo-pulse images, the existing approaches were found to be flawed and two new methods were proposed. The developed methods and the software system based on them make it possible to increase the efficiency of visual analysis of medical and seismic ultrasound images. Disadvantages: similar software products for use in this subject area are not described.

The book [23] gives a systematic presentation of the results available in seismic surveys on linear transformations of seismic signals during their digital processing, as well as during the propagation of seismic waves in inhomogeneous media. The focus is on multi-channel and single-channel filtering of seismograms.

In the collection [24], the issues of construction and methods of application of seismic data processing algorithms for complex models of media and wave fields are considered. The results of the study of the processing procedures of the MOV and KMPV data, the continuations of the wave fields, the solution of direct dynamic and kinematic problems are presented. Advantages: great attention is paid to the efficiency and reliability of the algorithms, their stability in relation to various kinds of interference, including interference resulting from the computational structure of the algorithms

The book [25] describes the basics of processing and interpreting seismic data. Seismic exploration is one of the leading geophysical research methods with a variety of goals for the structure, structure and composition of rocks. Petroleum geology is the main and most effective field of application for seismic prospecting. The search and exploration of hydrocarbon deposits is currently difficult to imagine without the participation of seismic exploration.

The book [26] devoted to the use of the MATLAB matrix system in radio engineering calculations and in the simulation of electronic devices and systems. The newest versions of MATLAB with Simulink, Signal Processing Toolbox, Filter Design Toolbox, RF Toolbox and Blockset, Wavelet Toolbox, Control Systems, Sim Power Systems, etc. are described. The integration of MATLAB with modern digital radio measuring instruments and virtual oscillograms in semiactive radar is described.

The fundamental clinical guidelines are prepared by a team of leading ultrasound diagnostics specialists. The book [28] presents sections on ultrasound diagnostic systems, physical principles of ultrasound diagnostics.

In the work [29], methods of ultrasound imaging, widely used in modern medical diagnostic studies and non-destructive testing, are considered. For example, echo-pulse images of the biological tissue structure obtained in modern medical ultrasound diagnostics using the second harmonic are distinguished by an increased resolution due to the narrowing of the focal region of the second harmonic, lowering the side lobe level and suppressing reverberation noise compared to the fundamental frequency wave.

In the work [30], an algorithm was described for estimating arrival directions reviewed, delays, and Doppler shifts of the frequency of reflected signals in semi-active radar based on the signal subspace and the Esprit approach. Advantages: for semi-active radar, an algorithm for estimating arrival directions, delays and Doppler increments of the frequency of the reflected backlight signals received by a multi-element antenna array is described.

In the work [31], the accumulation effect was analyzed in estimating the correlation matrices formed in solving linear prediction problems using the least squares method. By analyzing the dependence of the perturbations of the weight coefficients on the perturbations of the elements of the correlation matrix, it was determined that the most optimal approach to increasing the resolution of the autoregressive methods of spectral analysis is to reduce the conditional number of the correlation matrix of the signal subspace. Coherent methods of preliminary data processing and the formation of their matrices are proposed, which provide the best conditionality of the systems of linear prediction equations and a smaller order of the autoregressive model.

In the work [32], algorithms were considered for the joint detection and direction finding of a variety of radio emission sources in a wide viewing band, developed on the basis of methods with frequency selection and on the basis of methods of signal subspaces. Estimates of the azimuth and quadrature components of the signals are presented when overlapping the spectra of real signals.

In the work [34], the importance of solving the problem of determining the direction of arrival of signals from multiple sources is noted. Advantages: describes a new approach to solving the problem under consideration, it is proposed to simulate signal sensors with a linear combination of noisy control vectors, depending on the parameters characterizing the direction of arrival of signals, is described according. iterative procedure and results of numerical simulation.

In the work [35], progress has been made in the development and application of methods that use the signal subspace and make it possible to estimate the arrival directions of a set of simultaneously acting signals. Advantages: a rather simple algorithm is proposed that allows finding the envelopes maximum of the angular spectrum, its description is given and the resolution is estimated, recommendations are made on the effective use of the proposed algorithm.

The analysis of the subject domain suggests that the development of the signal subspace method is a rather topical task. The works in question have the following disadvantages:

- in some papers [1,4,5,7,10,11,13,16,18,20,23,26,28-30,32] some basic methods used in the field of signal processing are not described in the exploration of minerals and seismic data;
- a number of drawbacks of these methods are connected with the use of linear lattices and the growth of errors in the increase of the range of arrival angles [2];
- in work [3] stable methods of easing the regular and irregular interference in seismic exploration are not considered, while the task of suppressing multiple waves is not considered;
- some [6, 24] of the methods considered are currently irrelevant;
- absence [8] comparative table of the efficiency of using the considered methods;
- are not reflected [9] or are superficially affected, questions concerning adaptive filtering, multi-speed sampling, frequency-time analysis and non-linear digital signal processing, the bases of multidimensional signal processing, the important issue of sampling noise, the noise of arithmetic and problems, associated with minimizing these noise and maximizing the dynamic range.
- it is not described [12] how to increase the residual noise level, the risk of deleting important signal information for the internal interface of the detector is reduced.

Finally, it has also not been shown that the subspaces filtering advantageously differs from the well-known method of spectral subtraction.

- New features of display and effective methods of interactive processing of three-dimensional data of subsurface radar sounding are not described [14];
- The requirement [15] of the FCC to limit the lower bandwidth of the UWB signal does not seem appropriate. It may be that in terms of solving specialized telecommunication tasks in the field of telecommunications, this requirement has a definite meaning, but the concept of the U.S.P signal, in general, should not be limited to the scope of technology, which today is called ultra-broadband;
- not considered [17] the problem of noise immunity estimation of absorption measurements or Q-factors according to the data of the GSP;
- Similar software products for use in this subject area have not been described [19, 22, 31];
- no [21] is illuminated by modern software allowing to simulate and process signals, produce filtering, spectrum estimation.
- unfortunately [25], for a number of reasons, it is not possible to display various colored pictures in the textbook, which substantially limits the possibilities of demonstrating all the results of modern seismic technologies;
- the disadvantages [34] of the existing methods for solving this problem are connected either with insufficient resolution or with difficulties encountered in the direction of coherent sources;
- although [32] the solution of the problem of determining the position of the angles spectral peaks, in the theoretical consideration, is not a difficult problem; in the processing of real data, due to the large dispersion of the latter, certain difficulties arise.

Therefore, the development of the signal subspace method is relevant.

3 Research methodology and analysis of echo-pulse images of layered structures

Echo-pulse image analyze is the main source of information in relation to the problems of geophysical prospecting of hydrocarbon reserves. By virtue of great practical importance, this problem has always paid special attention. Most often, a mathematical model of a local earth structure is considered as an analogue of a layered structure, which allows us to represent a separate seismic trace in the form of

$$s(t) = a(t)\nu \sum_{i=1}^{M} r_i \delta(t - t_i) + n(t)\,, \qquad (1)$$

where $a(t)$ is the initial impulse of seismic excitation; - reflection coefficients, characterized by the ratios of the acoustic impedance of the layer boundaries; t_i - time delays characterizing the acoustic thickness of the layers and their combinations; ν - convolution operation; $n(t)$- measuring and structural noise. Within the model (1), the main indicator of the presence of hydrocarbons is a local change in amplitude (the so-called “bright spot” model) [1], which, however, may contain false information due to the influence of interference effects caused by the influence of multiple reflections of seismic pulses between layers. This is expressed in the fact that in formula (1) the number of M observed pulses may absolutely not correspond to the number of significant layers of the L analyzed earth structure *(L≤M)*. In this connection, the development of methods for neutralizing the effect of multiple reflections is of particular importance from the point of view of increasing the sensitivity and reliability of visual analysis of echo-pulse images.

The most commonly used approach is based on direct fitting the parameters of the mathematical model of the layered structure to the measured seismic trace data. In this case, the known geometric model of the analyzed area is assumed, and the adjustment of parameters is carried out based on the use of a nonlinear least squares algorithm [2]. This approach is possible only if there is data from exploratory drilling (an extremely expensive operation), which predetermines its practical limitations. Another approach is based on the principles of backscattering theory and reduces to the summation of the Born backscattering series [3]. From a theoretical point of view, this method does not require a priori knowledge of the model of the geological structure, but by its very nature it belongs to the category of incorrect problems of mathematical physics, which, given the presence of significant measurement interference typical of tasks of exploratory geophysics, makes its practical application very problematic.

The purpose of this work is to analysis and development of the new method of neutralizing the influence of multiple reflections, which are resistant to the influence of measuring and structural noise, what will allow to increase the accuracy of determining the boundaries of deposits several times and do not require a priori knowledge of the parameters of the simulated geological structure, which are included in formula (1). As previously, it is assumed that the study area has a layered structure. The essence of the method is the transition to an information basis in which the useful (informative) and interfering subspaces are orthogonal, and the effect of multiple reflections is neutralized by the controlled choice of the dimension of the information subspace.

The basic idea of the proposed approach consists in the transition from the time domain of the initial measurements to the spectral domain of the Fourier transform, so

$$S(f)=\int_0^T s(t)\,exp(-j2\pi ft)dt = A(f)\sum_{i=1}^{M} r_i\,exp(-j2\pi t_i f)+N(f)\,,$$

$$f_L \le f \le f_T\,, \qquad (2)$$

where $S(f)$ is the spectral characteristic of the seismic trace; $A(f)$ - spectral characteristic of the probe pulse; $N(f)$ - spectral characteristic of noise. From consideration of expression (2) it can be seen that the time delays t_i in the function $S(f)$ are encoded by complex pulsations in the frequency domain (the period is inversely proportional to the value t_i), which makes it possible to use parametric adaptive spectral analysis methods [4] as applied to the tasks of compensating the effect of multiple reflections.

Regarding expression (2), one more remark needs to be made. Seismic measuring systems are low-frequency, their bandwidth is limited by the width of the spectral range $\Delta F = f_T - f_L$, where f_T and f_L , where and are the upper and lower frequencies of the range, respectively. Since the resolution in the time domain is limited by the ΔF magnitude, the use of parametric spectral analysis methods opens up an additional opportunity to increase the temporal resolution (also a very important practical task) of the analysis of pulse-echo images, but this issue will not be considered in this paper.

From a mathematical point of view, the method of suppressing multiple reflections in the spectral region, as noted above, is based on the idea of a signal subspace, first described in [5]. Such a choice is due to the high stability of the method to the influence of measuring noise and structural disturbances and, in particular, to the effect of changing the shape (and, consequently, the spectrum) of the probe pulse with depth.

Since the S(f) function can be assumed to be sufficiently smooth, its influence can be ignored in the framework of the signal subspace method. All processing is carried out on a computer (i.e. in discrete form) and expression (2) can be represented as

$$S(f_k) = \sum_{i=1}^{M} r_i \, exp(-j2\pi t_i f_k) + N(f_k) , \quad k = 1,...,K , \tag{3}$$

where is the K number of frequencies in the spectral $S(f)$ characteristic. In the vector-matrix form of the expression (3) has the form

$$S = Hr + N , \tag{4}$$

where is the H matrix characterizing the set of complex exponentials responsible for the time delays t_i in the spectral Fourier domain.

It is assumed that the $N(f)$ statistical characteristics of the interference satisfy the conditions:

$$E\{N_i N_j\} = \sigma^2 \delta(i-j); \quad E\{HN\} = 0 , \tag{5}$$

where E is the expectation operator.

The main idea of the signal subspace method is based on using the properties of the correlation matrix of the spectral characteristics of the analyzed seismic trace, so

$$R = E\{SS^T\} = Srr^T S^T + \sigma^2 I = SQS^T + \sigma^2 I , \tag{6}$$

where $Q = E\{rr^T\}$ is the correlation matrix characterizing the interrelation of complex harmonics in the spectral region; I - matrix unit.

As a new information orthogonal basis in the signal subspace method, we consider the linear vector space formed by the eigenvectors of the correlation matrix, which are found by solving the eigenvalue problem

$$R\Phi = \Lambda\Phi , \tag{7}$$

where $\left|\Phi_1 \Phi_2 ... \Phi_K\right|$ is the matrix of eigenvectors; Λ - diagonal matrix of eigenvalues, and $\lambda_1 \geq \lambda_2 \geq ... \geq \lambda_K$. By assumption, the *H* matrix is a superposition of complex exponentials, and their number is less than the number of samples of the spectral characteristics, so *K*≥*M*. Consequently, the rank of the matrix *R* is equal *N,* which allows you to split the diagonal matrix of eigenvalues into two parts:

$$\lambda_i = \lambda_{hi} + \lambda_{ni}; i = 1,...,M; \lambda_i = \lambda_{ni}; i = M+1,...,K \ , \tag{8}$$

where λ_{hi} and λ_{ni} are the eigenvalues corresponding to the SQS^T signal and σ^2 interference parts of the matrix *R*, respectively. Then, according to expression (8), the entire *K* dimensional space formed by the eigenvectors can be divided into two subspaces: *M* - the dimensional signal subspace formed by the first eigenvectors corresponding to the largest proper numbers, and (*K-M*) dimensional disturbance subspace formed by the remaining eigenvectors and orthogonal to the first, so

$$\Phi = \left\{\Phi_S^{(M)} | \Phi_N^{(K-M)}\right\}. \tag{9}$$

Taking into account the expression (7), the *R* matrix can be represented as

$$R = \sum_{i=1}^{M} \lambda_i \Phi_{si} \Phi_{si}^T + \sum_{i=M+1}^{K} \lambda_i \Phi_{ni} \Phi_{ni}^T = R_S + R_N \ , \tag{10}$$

those, the *R* correlation matrix can also be represented as a sum of two parts: the R_S signal and R_N interference. From expressions (6) - (8) it follows that

$$\Phi_N^T R \Phi_N = \sigma^2; \ \Phi_N^T R \Phi_N = \Phi_N^T SQS^T \Phi_N + \sigma^2 \Phi_N^T \Phi_N \ . \tag{11}$$

Since the eigenvectors are orthonormal, $\Phi_N^T \Phi_N = 1$ it follows from (11) that

$$\Phi_N^T SQS^T \Phi_N = 0 \ . \tag{12}$$

As by assumption *Q*≠*0*, it follows from expression (12) that

$$\Phi_N^T \left[s_1 s_2 ... s_M\right] = 0 \ . \tag{13}$$

Thus, from the consideration given it follows that, based on dividing the correlation matrix of the spectral characteristic of the recorded seismic trace into signal and interfering components, followed by projecting the spectral characteristic into a subdomain formed by the eigenvectors of the interfering space, it is possible to control the process of extracting significant harmonics, and thus also time delays in the time domain, which allows for a controlled process of suppressing multiple reflections.

From a practical point of view, instead of the expression (13), focused on the selection of zeros, it is more convenient to use the expression.

$$\frac{1}{s_i^T R_N s_i} \Rightarrow max\ ; i = 1,...,M\ . \qquad (14)$$

The features of seismogram analysis based on the expression (14) should include the following factors:

1. the analysis is carried out in the spectral region, but the result is obtained in the time domain, since the procedure of finding the spectrum from the spectrum;
2. the poles of expression (14) are visualized, and not the physical amplitudes as in the original $s(t)$ dependence;
3. since the actual number of significant layers is unknown, the selection of the reflections is carried out by varying the choice of values M in model (1);
4. from a mathematical point of view, the synthesis of a new seismogram based on expression (14) is a substantially non-linear process, which opens up additional possibilities for increasing the reliability and sensitivity of visual analysis of echo-pulse images.

4 Experimental results

The study of the informational capabilities of the new method was carried out using the example of a seismic image of a section of a gas condensate field, shown in fig.1a, the visual analysis of which is difficult due to the presence of numerous reflections that form a characteristic interference pattern. At the Fig.1b and Fig.1c are shown the results of applying the new method for the dimension of the signal subspace M = 10 and M = 20, respectively. Comparison of the results shows that the new method makes it possible to clearly distinguish the upper and lower boundaries of the gas-condensate collector. This result is especially clear when using pseudo color coding. The application of this approach to the data in Fig.1a did not give any positive results, whereas for the method of the signal subspace the result was excellent, which is apparently due to the essentially non-linear character of information display in this method.

The analysis of the results at the Fig.1 shows that the basic information stood out when the dimension of the signal subspace is 10. A further increase leads to the selection of subtle additional details (layers), but from the point of view of identifying the boundaries of the field, this no longer provides significantly new information.

Additional information about the features of the signal subspace method is provided by analyzing graphic image slices. So at the Fig.2a, a graph of the 100th column of the image in Fig.1a is shown, which clearly shows the effect of multiple reflections, which have a particularly negative effect on probing low-contrast areas with close values of impedances of the layer boundaries. Fig.2b presents the real part of the spectral characteristics of this path, which is the initial “raw material” for the signal subspace method. Fig.3a and 3b show the display in the time domain of the results of the signal subspace method (M = 10 and M = 20, respectively) for the data presented at the Fig.2a and 2b.

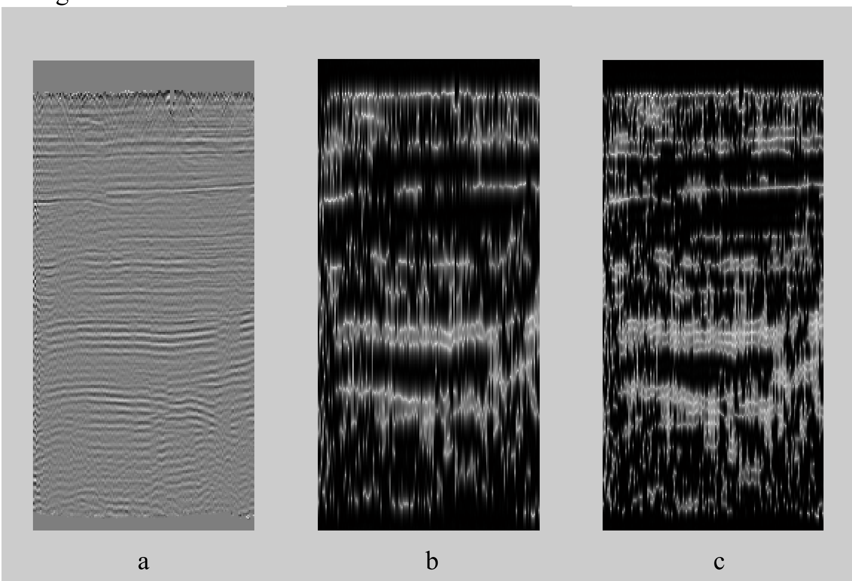

Fig.1. Echo-pulse images: a - the original image of the gas condensate field; b - the result of the signal subspace method (accounting for the 10 most significant signal components); c - the same, but for 20 signal components

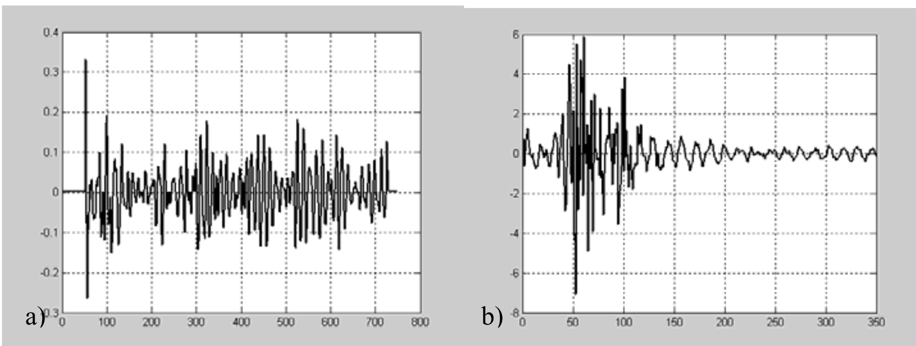

Fig.2. Graphic display of the results: a - the 100th column of the original image in Fig.1a; b - the real part of the spectral characteristics of the signal "a", which is the initial information for the method of the signal subspace.

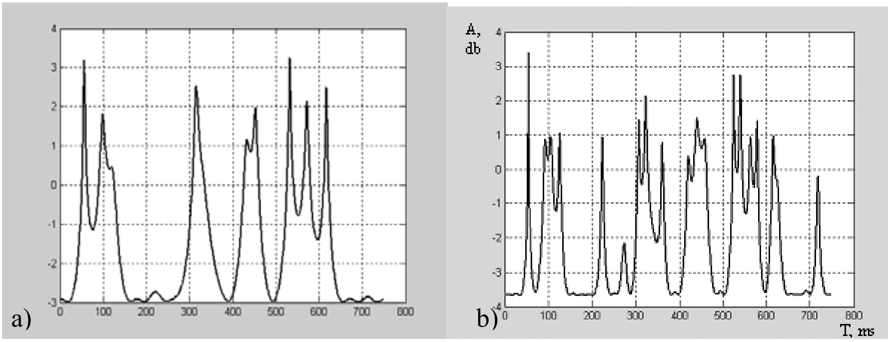

Fig.3. Results of the signal subspace method as applied to the data in Fig.2a: a is the dimension of the signal subspace M = 10; b - M = 20

Comparing the data at Fig.2 and Fig. 3, it follows that the signal subspace method allows one to effectively suppress multiple re-reflections by choosing the optimal value of the dimension of the signal subspace. The elimination of the effect of multiple reflections makes it possible to increase the reliability of visual analysis (compare Fig.2a and Fig.3a). An additional factor contributing to the informational significance of the method is, as noted above, the higher resolution of the analysis in the time domain, since the peaks in Fig.3 are sharper compared to the initial data at the Fig.2a. Comparing the data at Fig.3a, and Fig.3b clearly shows that increasing the dimension of the signal subspace leads to an increase in the sensitivity of the selection of image details, which can play an important role in the tasks of analyzing low-contrast seismic pulse-echo images.

5 Findings

1 The method of analyzing pulse-echo images of layered structures is a typical example of computer vision, because the visual analysis is based on the display of the poles of expression (14), and not on the physical amplitudes of the reflected signals.
2 A fundamentally important feature of the considered method of the signal subspace is the need to move from the time domain of the initial measurements to the spectral Fourier domain of the subsequent analysis.
3 The results of experimental studies show that the signal subspace method effectively neutralizes the effect of the negative effect of multiple reflections, which seriously complicates the visual analysis of pulse echo-images within the framework of traditional approaches.
4 Compensation of the effect of multiple reflections is carried out by optimizing the choice of the dimension of the signal subspace.
5 The new method has significant potential for further development and allows generalization to the field of other methods of echo-pulse diagnostics (ultrasound medical introscopy, ultrasonic non-destructive testing).
6 The effectiveness of the developed method (technically achieved):

- - reduction of re-reflections on the synthesized image in comparison with the original echo-pulse image - up to 3x (vector subtraction method was used);
- - a decrease in noise - due to the optimal selection of the size of the signal subspace, which approximate the signal.

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