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STRUCTURAL DECOMPOSITION OF THE WAVE FIELD IN THE SOLUTION OF INVERSE SEISMIC PROBLEMS

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ABSTRACT. This article discusses aspects of practical application of the solution to inverse seismic problems based on 1D elastic models of the medium. In order to better fit the 1D models to real observations we propose using a structural decomposition. It allows us to transform the wave field, corresponding to a 3D model, to the wave field, corresponding to a set of local 1D models with "ideal" conditions of seismic oscillations excitation and registration. As a result, a new system of observations in the form of "pseudo" seismograms, which are used during the transition into spectral domain for the solution of the corresponding inverse problem, can be available. In addition, the decomposition of waveforms corresponding to the target object is carried out in the spectral domain. This decomposition allows to eliminate variations in the waveform associated with the changes in the conditions of seismic oscillations excitation and registration, as well with the passage through the overlying medium. In particular, it takes into account the change in the waveform due to differences in the radiation patterns of the real source for different angles of arrival to the target object.

Keywords: seismic observations, seismic data transformation, 3D and 1D models, spectral domain, structural decomposition.

RESUMO. Este artigo discute aspectos da aplicação prática da solução de problemas inversos sísmicos, baseados em modelos elásticos 1D de meio. A fim de melhor ajustar os modelos a observações reais, propomos utilizar uma decomposição estrutural, que permite transformar o campo de onda, correspondente a um modelo 3D, ao conjunto de dados, correspondentes a modelos 1D locais, com condições "ideais" de excitação e registro das oscilações sísmicas. Formando novos dados na forma de "pseudo" sismogramas, que são usados durante a transição no domínio espectral para a construção da solução do problema inverso correspondente. Além disso, a decomposição de formas de ondas correspondentes ao objeto alvo é realizada no domínio espectral. Esta decomposição permite eliminar as variações na forma de onda, associadas a mudanças nas condições de excitação e registro das oscilações sísmicas, bem como com a passagem pela parte superior da seção geológica. Em particular, esta decomposição leva em conta a mudança na forma de onda, devido a diferenças nas características de orientação da fonte real para diferentes ângulos de chegada ao objeto alvo.

Palavras-chave: observações sísmicas, transformação de dados sísmicos, modelos 3D e 1D, domínio espectral, decomposição estrutural.

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INTRODUCTION

In our previous articles (see Mitrofanov et al., 2009b, 2009c) we have dealt with combination of spectra, based on the theoretical solution of the direct problem, with the spectra calculated from the observed seismograms. These issues are the fundamentals for implementation of the proposed algorithms in practice. However, there is another serious issue, resulting in a considerable difference between the real experiment and the theoretical solutions. In the theoretical solution of the direct problem we have assumed homogeneity of the overlying medium and the invariability of the conditions of excitation and registration of seismic signals. All these characteristics are not entirely feasible in a real experiment. In addition, the real medium is not horizontally layered, as it is assumed in the theoretical model. Therefore, a pre-processing of seismograms, which eliminates these differences, is necessary. Such treatments may be based on different procedures, the simplest one of them is the stacking procedure. In previous articles we have tried to note the major problem features associated with the existing dynamic processing of seismic data, and also indicated why not use the simplified scheme of seismic data processing when working with multi-component observations, when we need to consider the elastic models. In this article we propose a general scheme, which allows improving the dynamic processing of actually observed seismic data reflected from thin-layer target objects. It also allows to guarantee the solution of inverse dynamic problems for such objects in the spectral domain of the required input information within the horizontally layered elastic models.

This scheme is based on procedures for structural decomposition of the wave field, which can distinguish from the general structure of the registered wave field of reflected waves of required type (for example, PP and PS). They also take into account changes in the form of available signals associated with the heterogeneity, as regions of excitation and registration, and areas of propagation of the signals to thin-layer reflective object. These decomposition procedures give an opportunity to approach a model of the medium for the local target to a one-dimensional theoretical model. In a sense, this decomposition corresponds to the transformation of the initial wave field, corresponding to the elastic complex 3D models, to a set of local 1D models with ideal conditions of seismic oscillations excitation and registration. Such a transformation can be regarded as the development of ideas for changing the structure of observation system and processing of multi-component seismic data. The simplest example of such transformations is the transition from the ordinary data with common-shot gather to the data with common-middle gather. Such a transition is the basis of all the seismic data processing tools. The structural decomposition provides a transition to the data, corresponding to the reflection point from the local area of the medium and to a set of angles of arrival of reflected waves for the same area.

STRUCTURAL DECOMPOSITION OF THE SEISMIC WAVE FIELD

Examples of inverse problems and combination (similarity) of spectra, considered in previous works, were examined for synthetic seismograms, constructed in the framework of idealized models. In the examples we assumed one-dimensionality of the models, knowledge of the signal and the absent of any variation in its form, which is not related to the parameters of the target object. Therefore, studies have exceptional significance, but only in relation to the solution of the inverse problem on the algorithmic level, and only under the stated assumptions which have still to be provided. At the same time, we know that the real seismic experiment is fundamentally different from them. There are a number of reasons. It suffices to point on the impossibility of carrying out controlled field experiments, which would maintain the form of input seismic signal. In addition, real media differs greatly from one-dimensional models, even in such "ideal" geological basins, as the West-Siberian platform. The presence of such inadequacy of theoretical models for real media makes a serious instability in solving the inverse problem in the complete statement using the real data.

One possible way to overcome these difficulties is to decompose the medium model and the observed wave field into components corresponding to contrasting local features in the structure of the medium. This approach is associated with the heuristic argument, connected with the principle of locality, that the contrasting elements of the medium provide the most significant contribution to the wave field, and therefore their structure can be studied by selecting associated components in the wave field. Note that this argument is the basis of almost all methods of seismic data processing, aimed at the separation of certain reflections. All the methods of kinematic interpretation and the solution of inverse kinematic problems are based on it.

Under this approach, the inverse dynamic problem for the target local objects can be reduced to the following multi-level process in relation to the real observations and more realistic models.

The first level is the decomposition of the observed wave field with the extraction of its components associated with the target objects. It includes the construction of frame macro model, based on available *a priori* geological and seismic information. This allows using the ray tracing method to identify and allocate the required wave objects. At the same time it guarantees to take into account the geometry of rays in the area between the object being studied, as well as the key dynamic characteristics associated with a change of seismic energy in the process of propagation of selected waves as a function of the front divergence, the curvatures of borders, etc.

The second level is the decomposition of the form of seismic signals in multiplicative components corresponding to the influence of surface irregularities, as well as the area of signal propagation and the local reflecting object. As a result, a form of the incident seismic pulse and the spectral characteristics of the reflecting target object are estimated. It can be built as an operator, characterizing the influence of the upper part of geological section, which includes special features related to the heterogeneity of the conditions of seismic oscillations excitation and registration and to the area of signal propagation. It can be considered as a correction operator with respect to the form of signals for the isolated waves.

The third level is an immediate solution of the local inverse dynamic problem for a given structure of the reflecting object, including elastic models too. In this case, we can already use a locally one-dimensional description for the target object and the corresponding inverse problem in linearized or complete statement, which was considered in our previous article, see Mitrofanov et al. (2009b).

The general idea regarding proposed multi-level process for the solution of inverse dynamic problems for local targets using the real seismic data is presented in Figure 1. It can be seen that the use of structural macro model of the medium that defines a common “skeleton” model, and ray schemes constructed on the basis of this model for given types of waves and available systems of observations, reduces the general inverse problem to several inverse problems in relation to the target local objects. It is possible to transform the wave propagation in complex model for the individual observations (see Fig. 1(a)) in the process of wave propagation in locally one-dimensional models by selecting the appropriate observations, corresponded to the required angles of incidence and reflection points (see Fig. 1(b)). We use simultaneously with this approach effectively all the information that was obtained in the previous stages of processing and interpretation of multi-component data. In addition, this provides the separation and addition of two main approaches in the seismic research methods: kinematic and dynamic.

Let us consider the main points of this process. The kinematic interpretation the one among the main methods has been used for the construction of structural frame models of the medium. Therefore, during the processing of any real seismic data in modern processing tools there is always enough information to specify the structure of the model in some approximation. At this stage, the important point is the description and the construction of block models of media with the capability to automatically generate rays for different kind of waves and to analyze of loop situations, arising in ray tracing in models of this type. We earlier have solved these problems. Corresponding algorithms and programs in determining appropriate models and carrying out ray tracing for different types of waves had been created.

Figure 2 shows how to use these programs for the identification and selection of waves, PP (Fig. 2(a)) and PS (Fig. 2(b)), in the processing of real seismograms. It clearly shows a significant difference in between the selection of these waves, as by the structure of initial observations and by the initial wave field, on the real seismograms. The selected traces were used for formation of a “pseudo” seismogram.

The term *structural decomposition* reflects the essence of the proposed transformation of initial data while using the local one-dimensional models in the process of solving inverse seismic problems; where the structures of the macro model and observations to build the ray schemes have been used. Afterwards the ray schemes are used for the selection of observations that contain information about the local area of medium. Thus, the structure of the observations is modified in order to guarantee maximum focus on the local object. This can be represented as the decomposition of the observed wave field in the sum of waves corresponding to the fixed elements of the medium and ray parameter. The results of the decomposition, presented in the form of new sets of observations or the generalized seismograms, can be used to solve inverse problems. For example, using interpolation for the selected traces we can create “pseudo” seismograms, corresponded to the fixed zone of reflection and the normal ray. This allows us to pass on to the local one-dimensional problem in the time or spectral domain.

The decomposition of the form of seismic signals is used less in standard processing packages. Just recently it began to develop in the practical seismic exploration to distinguish the signal related to the local object and removing components, related to zones of seismic oscillations excitation and registration, as well as the influence of an intermediate medium (before and after reflection). We used the spectral-statistical method in various modifications, developed by authors of this article for a long period.

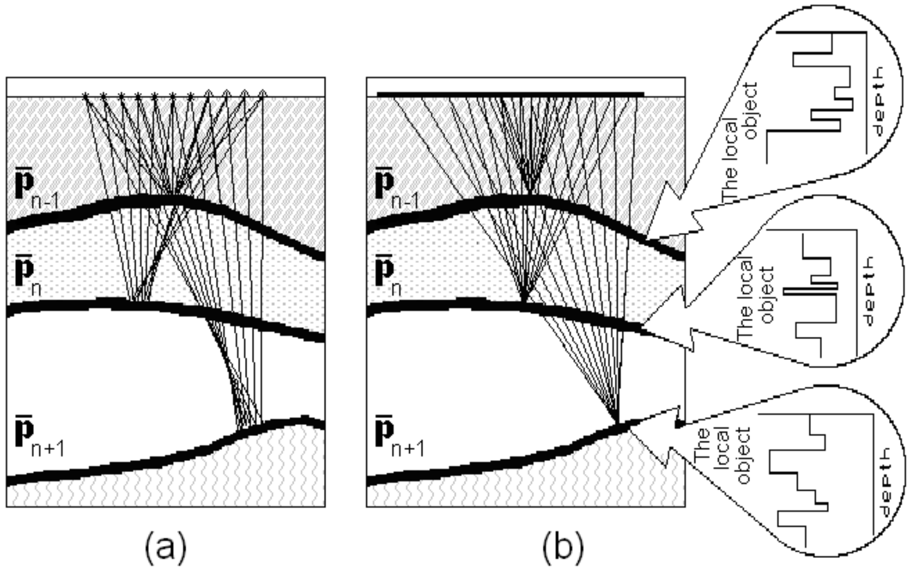


Figure 1 – General scheme of structural decomposition of seismic wave field: (a) structural macro model of the medium, defined by the vector of elastic parameters $\bar{\mathbf{p}}$, and ray schemes corresponded to the given observations; (b) selection of observations by the reflection point and angles. The structure of local objects, corresponded to the target horizons, is also shown.

This method also uses the relationship of variations of shape of the seismic signal to the structure of the observed wave field and the system of observations. The following issues can be stand out:

1. Accounting irregularities within the thick layers and contrasting elements of the medium along the signal path;
2. The solution of overdetermined systems of linear equations with a singular matrix;
3. Kind of *a priori* information required to construct a unique solution for these systems.

Consideration of the first issue was carried out in a geometric (ray) approximation, including caustics and diffraction. The second problem is an indispensable feature of the decomposition problems, solved for a range of special problems. Any change in the decomposition model and (or) system of observations provokes the need to restructure the algorithms for solving the problem and to redefine *a priori* data, needed to ensure the uniqueness of the solution. This made the development of a fairly general algorithm for finding the solution for any decomposition problem by finding the vectors of kernel matrix of the corresponding linear system. It is based on the consideration of factor models, which are relevant to various seismic problems. By virtue of the fact that many solutions have been previously obtained and published in various articles, we will not dwell on the details of the constructions carried out, but only give the basic concepts and results.

A representation, used in the spectral-statistical method for a part of the seismic trace $y_{ij}(t)$ containing the seismic signal or wave of a given nature, can serve as an example of a multiplicative factor model (Goldin & Mitrofanov, 1973):

$$y_{ij}(t) = s_i(t) \times r_j(t) \times u_{ij}^M(t) + \xi_{ij}(t) \qquad (1)$$

where $s_i(t)$, $r_j(t)$ are the impulse responses of excitation and registration zones of the seismic signal at the appropriate points of the profile line, and $\xi_{ij}(t)$ is the noisy component. The indices i and j uniquely determine the coordinates of the source and receiver, similar to the problem of static correction, and observation $y_{ij}(t)$ can be depicted in a generalized plane of observations. At the same time it is assumed that the impulse characteristics $u_{ij}^M(t)$ satisfy some additional conditions related to assumptions about the model. So, if assumed that the upper part of geological section is homogeneous and has no significant effect on the shape of the propagating seismic signal, corresponding to the wave reflected from the fixed boundary, then the very simple expression $G_{i+j}(t)$ for $u_{ij}^M(t)$ can be used, but the whole expression is rewritten as:

$$y_{ij}(t) = s_i(t) \times r_j(t) \times u_{ij}^M(t) + \xi_{ij}(t) \qquad (2)$$

Last representation is the multiplicative factor model for the part of the trace, which contains reflected wave, and it includes three

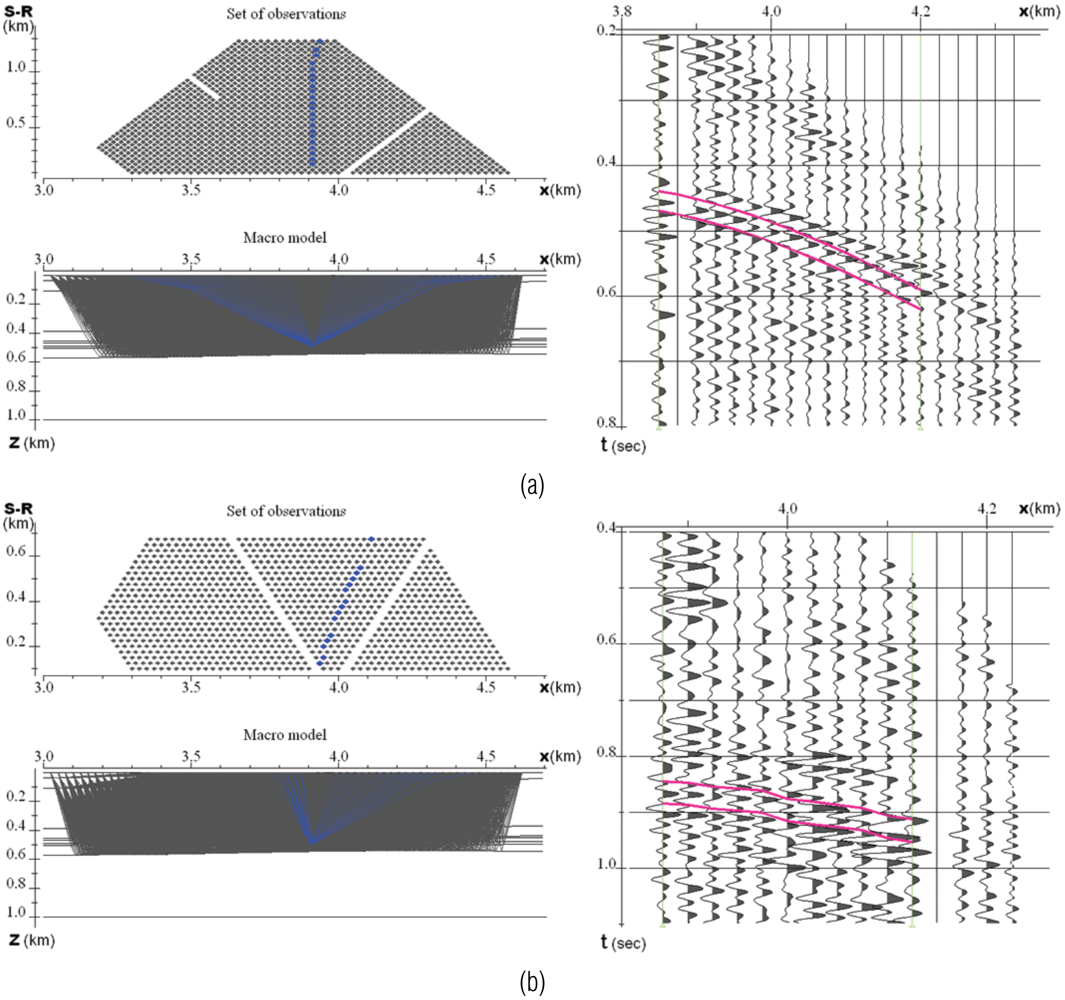


Figure 2 – Selection of the given types of waves: (a) PP and (b) PS on the basis of the developed procedures, using the ray method and the structural macro model. The system of observations is shown with the selected traces, macro model with ray schemes and "pseudo" seismograms formed on the basis of the selected traces. Selected observations and rays corresponded to reflections from a fixed point are identified in blue.

multiplicative factors: source, receiver and impulse response of the reflecting boundary. The operator, eliminating the influence of the upper part of geological section, can be simply defined as

$$R_{ij}^{Up^{-1}}(t) = s_i^{-1}(t) \times r_j^{-1}(t)$$

after determining $s_i(t)$, $r_j(t)$ by using the available observations $y_{ij}(t)$. The impact of this operator to the observation $y_{ij}(t)$ provides us an information about the target object, which can be used to solve the corresponding inverse problem. Obviously, for the real media and corresponding inverse problems the structure of the multiplicative factor model will be significantly more difficult, so the operator, eliminating the influence of the upper part of geological section, requires a more complex structure.

A general scheme of decomposition of the observed wave field on the multiplicative components was carried out for different description models of $u_{ij}^M(t)$. These included:

- Model of the spectral-statistical method (Goldin & Mitrofanov, 1975),

$$u_{ij}^M(t) = G_{i+j}(t) \times L_{i-j}(t),$$

- Efficient dynamic model (Mitrofanov, 1980),

$$u_{ij}^M(t) = g_{i+j}^{(0)}(t) \times g_{i+j,i-j}^{(2)}(t) \times \ldots \times g_{i+j,i-j}^{(2N)}(t),$$

- Effective ray model (Madatov et al., 1991),

$$u_{ij}^M(t) = A(\gamma_{ij}, \pi_{ij}) \times T(\gamma_{ij}, t),$$

- Model of head waves (Mitrofanov & Sergeev, 1986),

$$u_{ij}^M(t) = H_i^{(1)}(t) \times H_j^{(3)}(t) \times H^{(2)}(t, l_{ij}),$$

as well as models of target objects, including low-amplitude fault (Landa & Mitrofanov, 1979) and model of thin-layers objects, considered in our recent work, see Mitrofanov et al. (2009a).

An essential aspect of all the multiplicative factor models is their complete or partial linearization by passing to the logarithms of the spectral characteristics of intervals of traces $y_{ij}(t)$ containing selected waves. After linearization, any multiplicative model can be represented in conventional linear-algebraic form as:

$$\bar{z}(\omega) = \mathbf{A}\bar{\theta}(\omega) + \bar{\varepsilon}(\omega)$$

where $\bar{z}(\omega)$ is a vector of initial data, which are the logarithms of the spectral characteristics $y_{ij}(t)$, $\bar{\theta}(\omega)$ is the vector of unknown parameters, usually consisting of the logarithms of the spectral characteristics of multiplicative factors, $\bar{\varepsilon}(\omega)$ is noise vector, $\mathbf{A}$ is frequency independent matrix, whose form is determined by the type of model and structure of the observation system. This allows using modern methods of linear algebra to study the properties of these models and the construction of efficient algorithms for estimation of the parameters.

Such a transition is easily illustrated by a simple multiplicative factor model (2), which was used in the spectral-statistical method. After this transition, we obtain the expression:

$$\begin{aligned} z_{ij}(\omega) \; &= \alpha_i(\omega) + \beta_j(\omega) + \gamma_{i+j}(\omega) \\ &+ \lambda_{i-j}(\omega) + \varepsilon_{ij}(\omega) \end{aligned} \tag{3}$$

which represents a special case of the additive or linear factor model for each fixed frequency ω. Here $z_{ij}(\omega)$, $\alpha_i(\omega)$, $\beta_j(\omega)$, $\gamma_{i+j}(\omega)$, $\lambda_{i-j}(\omega)$ are the logarithms of the spectral characteristics $y_{ij}(t)$, $s_i(t)$, $r_j(t)$, $G_{i+j}(t)$, $L_{i-j}(t)$, respectively, and as well

$$\varepsilon_{ij}(\omega) = \ln\left(\frac{1 + \xi_{ij}(\omega)}{(S_i(\omega) \cdot R_j(\omega) \cdot G_{i+j}(\omega) \cdot L_{i-j}(\omega))}\right)$$

is a noise that has properties distinct from the original noisy component $\xi_{ij}(t)$ in Eq. (1). The properties of $\xi_{ij}(t)$ and the effective ways of constructing estimates in the linearized models were studied in (Mitrofanov et al., 2009b). The above transition leads us to a fairly common way of constructing estimates of factor models. Existing methods of estimating the parameters of linear systems allow constructing an optimal operator for selection of any of the components of $\bar{\theta}(\omega)$ or some combination of them. In general terms, any of the constructed operators will be linear, and obtained estimations can be represented as:

$$\bar{\theta}^*(\omega) = \mathbf{H}\bar{z}(\omega)$$

where $\mathbf{H}$ is a matrix. Then the component of our interest of the linearized model (or a fixed k-th component of $\bar{\theta}(\omega)$) can be represented as

$$\theta_k^*(\omega) = \sum_{l=1}^{N} h_{kl} \cdot z_l(\omega) \tag{4}$$

where h_{kl} are the elements of the matrix $\mathbf{H}$, and $z_i(\omega)$ are components of the vector $\bar{z}(\omega)$. This expression allows us to provide an estimate of the spectral characteristics of any multiplicative factor, included in the model, in the form:

$$L_k^*(\omega) = e^{\theta_k^*(\omega)} = \prod_{l=1}^{N} e^{h_{kl} \cdot z_l(\omega)} = \prod_{l=1}^{N} (\mathbf{Y}_l(\omega))^{h_{kl}} \tag{5}$$

where k and l specify the corresponding components of the vectors $\bar{\theta}(\omega)$ and $\bar{z}(\omega)$. Thus the estimate of the spectral component of the multiplicative model can be represented by an exponent product of the spectra of the parts of the traces, containing a signal from the local target object, and the properties of this product is completely determined by the properties and elements of the matrix $\mathbf{H}$.

After linearization of the above models of $u_{ij}^M(t)$, an analysis was carried out of the structure of the zero variety of the linear systems arising in the estimation of multiplicative components, which include components related to the upper part of geological section. This provided an opportunity to analyze *a priori* information needed to obtain a unique solution of the problem of separation of such components and construction of the operator taking into account the influence of the upper part of geological section. This analysis was conducted using procedures for the selection of vectors of zero variety of the corresponding matrices, proposed in Mitrofanov & Rachkovskaia (1996).

Obviously, for nontrivial kernel of the model, i.e., when there is no uniqueness in the definition of its components (in the presence of available variations), in the useful and noise components may appear spurious variations in the estimates of the factors that will have a fairly complex nature. Therefore, for practical purposes it is important to create the criteria indicating the presence of true variations both in a useful component of the field as a whole and in individual factors. Two types of such criteria were developed. The first type of criteria helps to assess the feasibility of using a specific factor model and procedures for the factor decomposition of the wave field. The second type indicates the significance of different factors variations. It allows us to adjust the factor model, and then if necessary, realize an effective adjustment of the initial data. We note that the question of the relevance of factors is a classic when working with multifactor models. We therefore used conventional approach based on F-statistics (Reyment & Joreskog, 1996), only by taking into account the probabilistic properties of the considered logarithms of the spectral characteristics of the linearized model.

The values of logarithms of spectra were used for linear estimation of the factors that determine the conditions of seismic oscillations excitation and registration, as well as the transmission and reflection characteristics of the medium for each of the waves used. Later, on the basis of this scheme and the mentioned algorithms a complete program will be developed to generate data for the solution of inverse dynamic problems using real multicomponent seismograms. Key elements of such a program and its prospects in the processing of multi-component seismograms, which correspond to more complicated than the one-dimensional model, are presented below in the framework of model experiments carried out for two-dimensional model of the medium.

RESULTS OF MODEL EXPERIMENTS FOR THIN-LAYER OBJECTS

A series of experiments, performed on the synthetic data, shows the importance and necessity of structural decomposition in the process of solving the inverse dynamic problems. At the same time, a macro model, corresponded to real seismic observations, was used as the basic model. Part of the corresponding macro model is shown in Figure 3. It shows the main reflecting horizons, as well as the position of two exploration wells, which were used to select models of thin-layer objects related to the target horizons. The locations of the three objects are identified in the figure in red. It also shows the variation of elastic parameters V_p, V_s, ρ, which will be consistent with thin-layer objects (blue-color variation V_p, red V_s and purple ρ). Models of objects in its structure correspond to two types of thin-layer models, and were used in our previous works (Mitrofanov et al., 2009b, 2009c). Also, the figure shows the values of elastic parameters for the thick layers of macro model.

The presented macro model and the models of local objects were used to calculate the synthetic seismograms. We used an effective method of solving the direct problem described in the paper (Mitrofanov et al., 2009a). In order to make structural decomposition of the wave field on the basis of macro model, there rebuild ray schemes used in the subsequent for the identification and selection of the reflected waves corresponding to target objects. An example of such schemes for the target object I, associated with the second boundary (horizon A) and located on the profile in the coordinates x = 23.0–23.5 km, was utilized. The schemes were calculated for two types of waves (PP, PSP) and corresponded to 48 multifold coverage for 21 sources. In this case the first source was located at a profile point with coordinates x = 22.0 km and the distance between the sources was 100 m. The distance between the receivers was equal to 25 m. Thus, the observing system covers all possible area of the target object, see Figure 4(a).

Constructed ray schemes enable us to determine the time of arrival of the waves. The corresponding times are presented in Figure 4(b). They not only provide accurate identification of each type of wave, as shown in the figure, but also determine the possible intervals of data analysis of waves. They also allow to specify the velocity characteristics of these waves, which can be used on the stages of the selection of waves, in particular, with the optimal F-K filtering.

Another important application aspect of ray schemes construction is the use of ray characteristics to calculate synthetic seismograms. These seismograms give us an opportunity to better understand the features of selected waves.

Figure 5 shows examples of the two calculated seismograms, corresponded to the specified system of observations. Using information about time of arrival of waves allows us to accurately identify all the observed signals on these seismograms. In this case we can analyze the amplitude and the dynamic features of these signals, in particular, the ratio of the amplitudes of different types of waves. For instance, the seismograms show when the signal amplitudes corresponded to the target converted waves PSP_2, would be comparable to the monotypic reflected waves, which have similar arrival times. This can have a significant impact on the selection of the initial seismic traces of the complete observations system.

Ray schemes provide an opportunity to consider the peculiarities of the target selected time intervals containing the reflected signal from the object. For example, if the proposed object, corresponded to the second boundary, is located at the point of a profile with coordinate x = 23.2 km, then we can analyze the structure of the selected observations for a given type of wave.

Thus, for a given system of observations, with a possible change of the reflection point along the horizon line $\pm$ 2 m of the coordinate x = 23.2 km, we need to select 16 seismic traces, where the corresponding signals will be observed. Selected observations are shown in Figure 6(a) in the left column. It clearly shows that the cone of selection of observations associated with the asymmetry of the hodograph of converted waves, and signals, corresponding to two types of waves (PP, PSP), will be related to different observations. At the same time in the selected observations (seismic lines), we will have only six sig-

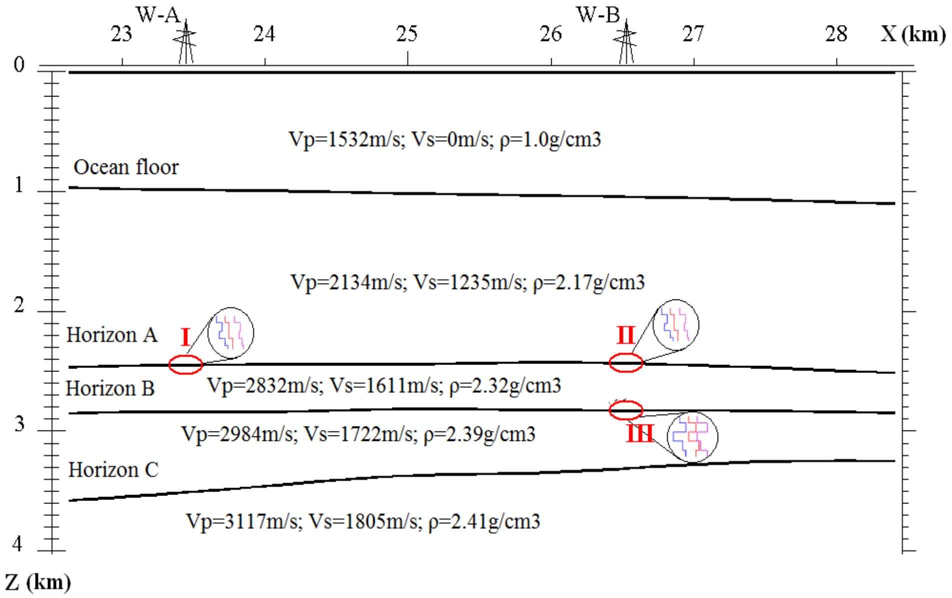


Figure 3 – Part of the macro model with the selected three target thin-layer objects, corresponding to the investigated horizons and the positions of the exploratory wells.

nals related to the reflected PP-wave, see Figure 6(b), left column. For the converted PSP_2-wave we can have a somewhat larger number of target signals, see Figure 6(c), left column. However, the small amplitude of converted waves at the near channels most likely will not get a good quality of these signals for the real data. Therefore, for the converted wave the number of the actually used signals will also be very small. This feature the selective procedure can have a significant impact on the stability of the solution, as in the problem of decomposition of waveforms, and the inverse problem in general. An essential factor in the selection of the data may be an extension of the domain containing reflections from the target object, which may include corresponding rays. The right column of Figure 6 shows the structure of selected observations, when the corresponding region has a variation of $\pm$ 100 m from the exact coordinate of the object. In this case the number of selected signals for each type of wave (the total number of possible signals exceeds 100) increases substantially. This expansion of the domain can be justified according to Fresnel zone, affecting the formation of the reflected signal. However, in real situations, we may be limited by *a priori* information on possible changes in the properties of the horizon for the broad reflected area. Therefore, when such information is available, we can use the constructed ray schemes to find the optimum width of the selection of the reflected signals, which allows to guarantee the greatest number of observations for the possible variations of the spatial coordinates along the boundary.

Selected observations, together with the ray characteristics, can simplify the selection of the required time intervals, containing the appropriate signals. Figure 7 shows examples of selected intervals for a given model experiment, when used a broad area of analysis of the reflected rays to the target. It is clearly seen that for seismograms corresponding to the source with coordinate $x = 22.5$ km (see Fig. 7(a)), the converted PSP_2-waves have high amplitude, which should provide the high signal-to-noise ratio for real traces. Therefore, they can be included in the input information. For the seismograms corresponding to a source with coordinate $x = 23.0$ km (see Fig. 7(b)), the situation is quite different. It makes sense to select only the PP-waves.

ANALYSIS OF INFLUENCE OF SOURCE RADIATION PATTERN

In the framework of the model experiments there was also carried out research on the integration of the incident pulse shape and characteristics of the orientation of source in the solution of inverse problems. In the experiments we used seismograms calculated for models of all three local objects, which are shown in Figure 3. Calculating seismograms was based on an effective method for solving the direct problem for the thin-layer elastic medium model (Mitrofanov et al., 2009a). The experiments show that ignoring the relevant characteristics of the calculated spectra of the generated seismograms and the individual reflected signals can lead to inaccurate or even incorrect solution of the inverse

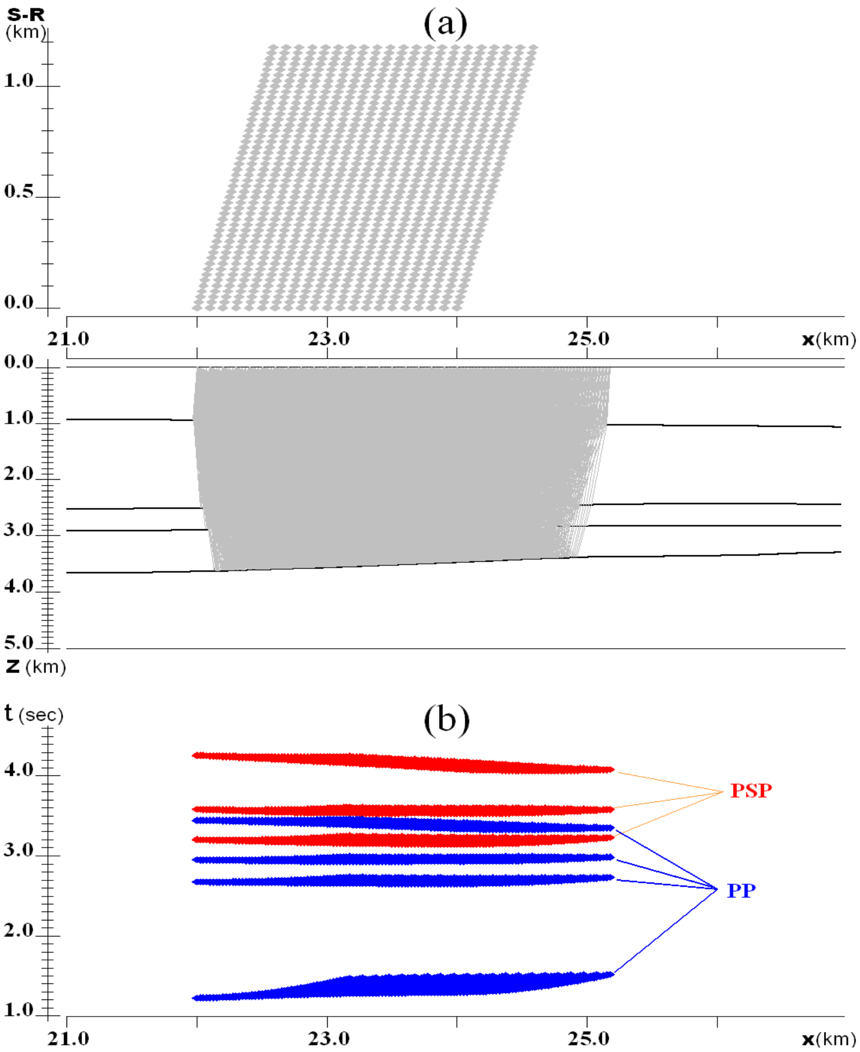
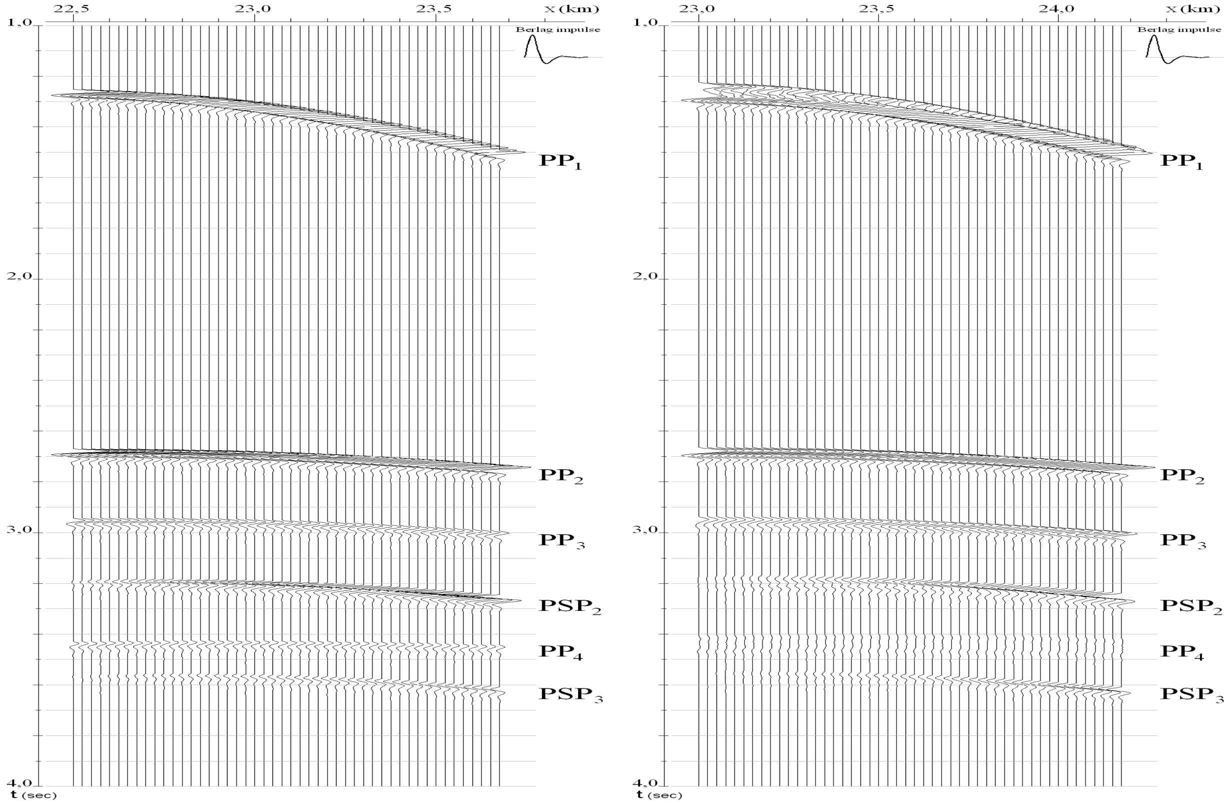


Figure 4 – Ray schemes for the given macro model: (a) system of observations with ray schemes corresponding to the two types of waves: PP, PSP; (b) hodographs of these waves, calculated for the given observations on the basis of the constructed ray schemes.

problem in the spectral domain. This is primarily associated with a significant difference between theoretical and calculated spectra, which significantly affects the properties of the minimized objective function (Mitrofanov et al., 2009b).

Experiments were carried out as follows: firstly, based on the model of the target object, model seismogram was calculated by using the complete solution of the direct dynamic problem in the spectral domain for a deepened source of the type of the center of expansion. Then constructed seismograms were used for the selection of signals corresponding to a specific target signals and the types of waves. Selected signals served as input data to determine the spectral characteristics. This approach fully corresponds to the dynamic inversion, widely used in practice, and can be considered in terms of the linearized solution of the inverse dynamic problem, proposed in our previous articles, see Mitrofanov et al. (2009b, 2009c). Essential here is that in the calculation of synthetic seismograms we use a complete solution that covers all the features of the generated wave field. A linearized solution, obtained on the basis of the potentials for certain types of waves, was utilized during the comparison of the calculated and theoretical spectra, and knowledge of the pulse shape incident on the local thin-layer object was also important. Thus, in the model experiment we could analyze some features that may occur in the processing of real multi-component data.



(a) (b)

Figure 5 – Examples of synthetic seismograms, calculated for multiple system of observations based on the ray method and containing only two types of reflected waves PP and PSP. The seismograms correspond to the sources located at the points of the profile with coordinates x = 22.5 km (a) and x = 23 km (b).

In constructing the model seismograms in all these experiments we used 24 channels array with the source position on the left side. In this, the first device is located directly above the source. The distance between geophones is 50 m; thus, the maximum distance is equal to 1150 m. The source signal was always the Berlage impulse that better corresponds to the signals observed in the real seismograms. The shape of this pulse is shown in Figure 5. The selection of the required reflections of the multi-component synthetic seismograms, corresponding to Z and X component, was carried out using ray tracing algorithms. As a rule, the start point of the selected interval, contained the analyzed signal, had a somewhat smaller value than the time by traced ray, see Figure 7. Example of selected intervals containing of PP and PSP waves reflected from the region of the second object is shown in Figure 8. These intervals were used to calculate the spectra, which are then compared with theoretical values.

In calculating the spectra for selected intervals of traces that contain reflections of certain types, we used optimal smoothing windows, providing sufficient accuracy of the spectral characteristics. Therefore, all the obtained deviations of the calculated spectra from the theoretical values could be attributed to inadequacies of model assumptions and the observed signals. It is important to note that according to the results of our previous studies (Mitrofanov et al., 2009a) the constructed linearized representation of the spectral characteristics of thin-layers series for a given type of reflection gives an error of no more than 2-3% with relatively small angles of incidence on the object. In our experiments, the latter condition, because of the relatively small size of source-to-receiver distance, was certainly achieved.

Figures 9-10 present some results of the analysis of the amplitude of the spectral characteristics of reflected signals for longitudinal waves. With the greatest simplicity, they provide a clear understanding of those features which may substantially affect the spectral characteristics of the observed signal in a real experiment.

Consider the results presented in Figure 9(a). Upper amplitude spectra are the result of the calculation performed on selected intervals of a synthetic seismogram. This simulation was carried out for the model of the object II. The following spectra (top to

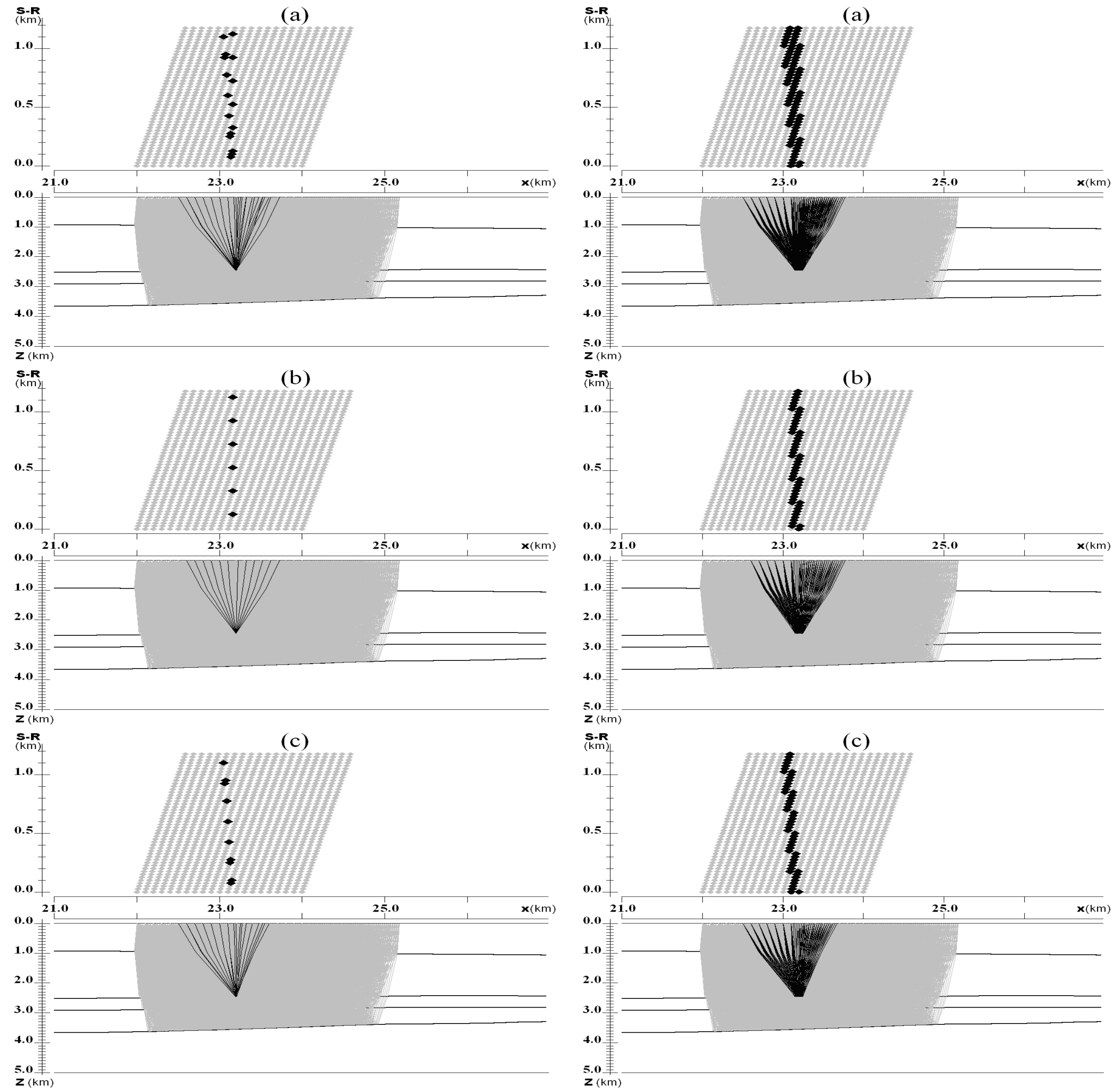
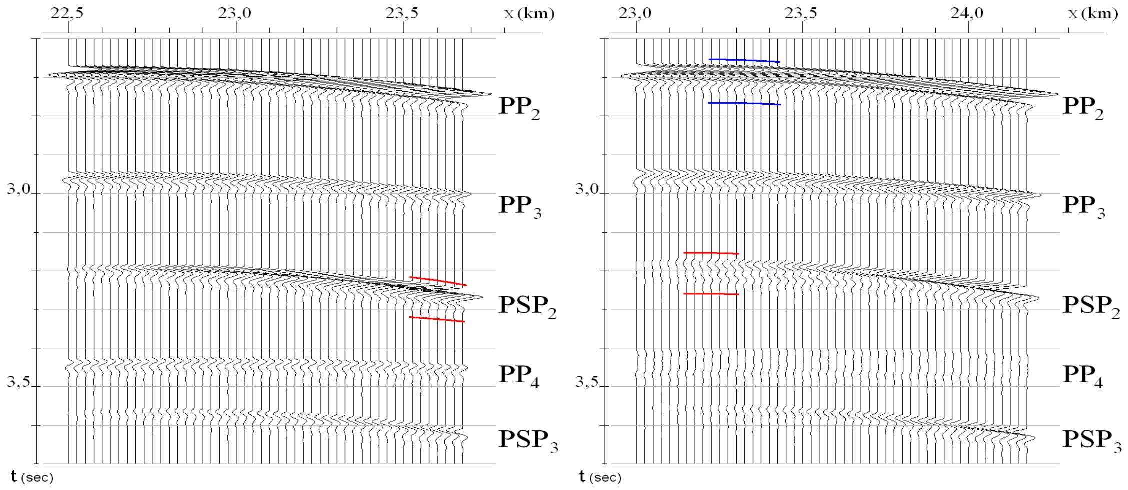


Figure 6 – Selection of the rays and observations, corresponding to the target object I at the point with coordinate x = 23.2 km (left column) and with an interval of 200 m from the center point x = 23.2 km (right column) for the complex of reflection waves $PP + PSP$ (a) as well as separately for the PP (b) and PSP (c) waves.

bottom in the figure) represents the theoretical spectral response of the thin-layer object, which was multiplied by the average spectrum of the smoothed signal, which serves as an estimate of the initial pulse incident on the given object. Similar estimates of the initial pulse are usually used in the real data processing. The third series of spectra (the lowest on the image) represents the difference between the first two spectra.

It is seen that the difference between the two spectra can reach significant values (in some cases, its value is 58%), and the value of the target functional, constructed on the basis of these spectra is equal to 0.31245. This is absolutely unacceptable value of the functional, because similar values are obtained by setting the wrong model of the object (Mitrofanov et al., 2009c). The fact that similar differences between theoretical spectra and calculated spectra are related to inaccurate definition of the incident pulse shape, was confirmed by the results presented in Figure 9(b). Here the top row of the spectra represents the relationship between the calculated or observed spectra and the theoretical spec-



(a) (b)

Figure 7 – Examples of the selection of intervals corresponding to the target object I, using the domain of 200 m with the center point x = 23.2 km for the complex of reflection waves $PP + PSP$ on synthetic seismograms. The intervals are related to the seismograms with sources located at the points with coordinates x = 22.5 km (a) and x = 23 km (b). Intervals with the reflected signals are shown in blue (for PP-wave) and in red (for PSP-wave).

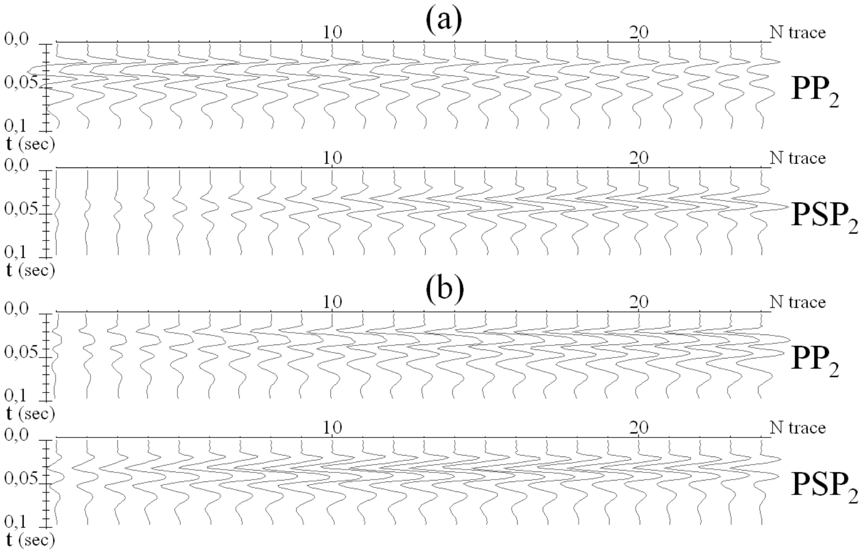


Figure 8 – Time intervals selected by the synthetic seismograms for Z-component (a) and X-component (b), which contained reflections from the region of the target object II.

tral characteristics for the given object. By definition, they must correspond to the spectral characteristics of the original pulse (it is shown in the middle part of the figure). But in practice, we have a significant difference between this ratio and the spectrum of the initial pulse. The size and structure of this difference is shown in the bottom of the figure.

The use of simplified decomposition procedures, specified the form of the initial pulse, which falls directly on the thin-layer object permits to improve the quality of the calculated spectra. This is confirmed by the results presented in Figure 10(b). This procedure takes into account the shape of the registered interference signal. As a result, we are able to better define the smooth spectrum of the initial pulse. However, despite the improvement of the quality of estimations of the spectral characteristics, they have some regular component, which changes the shape of the incident on the object pulse, depending on the source-to-receiver distance or the angle of incidence of corresponding wave at the target.

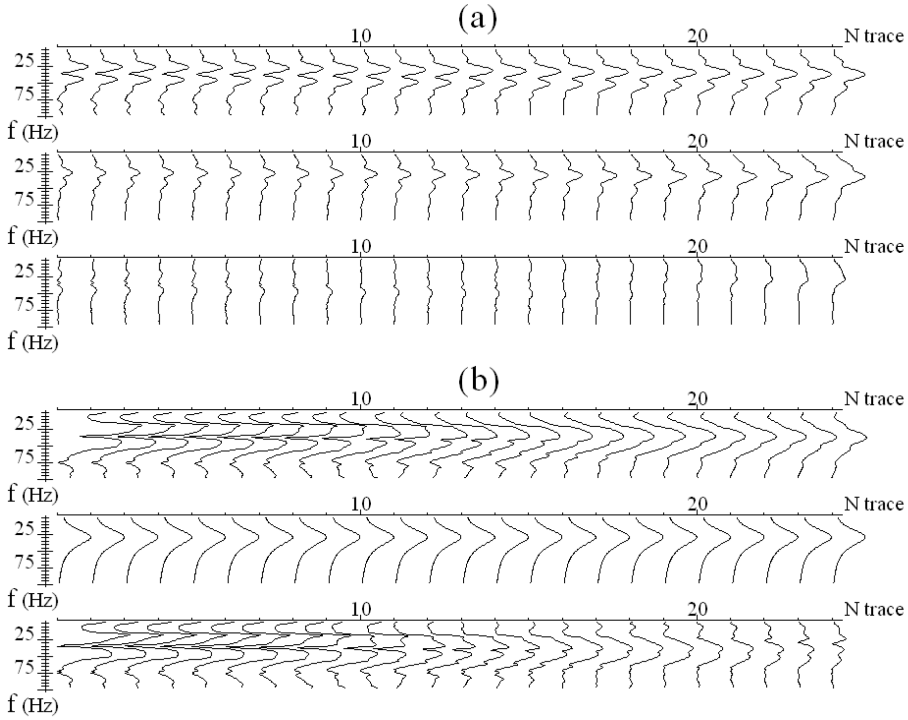


Figure 9 – Comparison of the calculated and theoretical spectra (a) for the reflected PP-waves in the case of the model for the target object II, as well as their relations with the spectrum of the initial pulse (b).

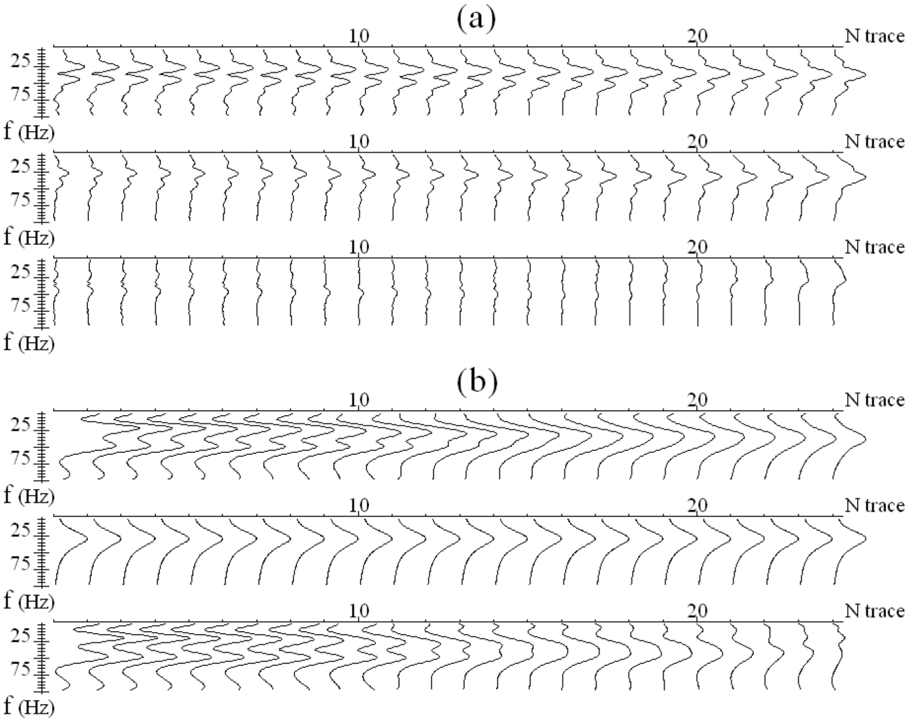


Figure 10 – Comparison of calculated and theoretical spectra (a) of reflected PP-waves in the case of the model II, and their relations with the spectrum of the initial pulse (b) after correction of the original signal form.

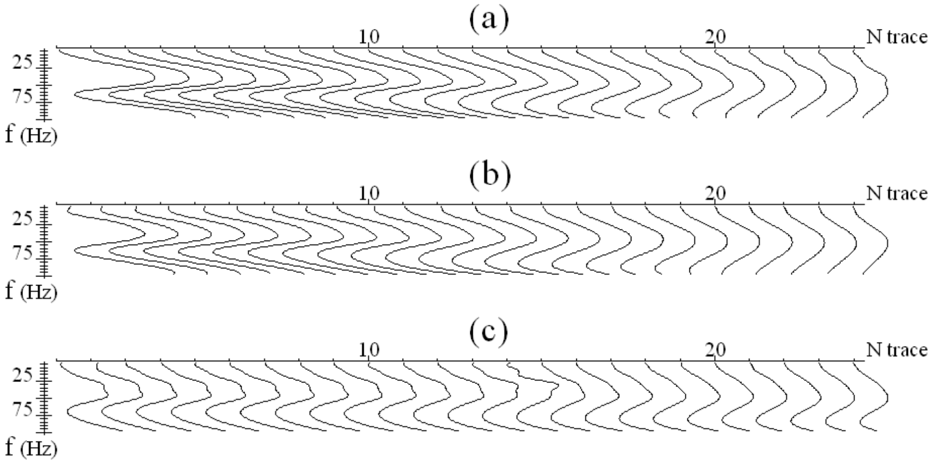


Figure 11 – Residual components in the spectra of reflected PP-waves in the case of models for objects: (a) I, (b) II, and (c) III.

The nature of these changes in shape and spectrum of the incident wave is related to the directional characteristics of a source, used in constructing the complete solution of the problem with a source of the type of the center of expansion, it is quite obvious from the physical point of view, and its manifestation in the synthetic data requires using more complex models of decomposition, which may take into account such changes. The model for the spectral-statistical method, in which the impulse characteristics $L_{i-j}(t)$ (or factors $\lambda_{i-j}(\omega)$) permit to determine changes in the waveform associated with different source-to-receiver distance, were quite suitable in our experiments.

Figure 11 shows the changes that were manifested by the specified radiation pattern of the source, in different calculated seismograms. It is evident that for objects I and II, which were associated with the same target horizon A and were located on near depths, these characteristics have a very similar structure. If we change the target horizon and its depth (that we have for the object model III) we observe a change in the corresponding radiation patterns. Thus, in a real experiment, when the characteristics of the source is unknown and may vary for different sources, its accounting is required in the procedures of decomposition. Taking into account this characteristic allowed us to provide near-perfect matching calculated and theoretical spectra, in addition to that, the value of the functional was equal to 0.01427.

CONCLUSIONS

In this paper, a structural decomposition of the observed wave fields and forms of seismic signals have been presented, which allows us to transform seismic data in the initial information for solving the inverse problem for a local target of a real medium. This transformation is crucial for the practical realization of inverse dynamic problems. It actually creates a certain methodology of constructing a solution of these problems in the case of elastic models of the medium where it is impossible to construct inverse algorithms for the whole model and the full wave field. For these cases, it allows us to make the transformation of seismic observations, which were obtained in complex models to the observations corresponded to locally horizontally layered model with respect to the target objects. It is important that in this case we are successful to take into account the characteristics of a real experiment, associated with the heterogeneity of regions of seismic oscillations excitation and registration, and also determine the form of the signal incident on the target object. It should be noted that this transformation is carried out by reduction of the reflection features to the points of normal rays. So, it can be implemented using both ray schemes and migration procedures.

This transformation defines the method of solution of inverse dynamic problems for modern multi-component observations. In the first stage there are distinguished local elements of the wave field (seismic signals) that are present in the various observed components, but related to the same target. Then, based on those elements of the field (reflected signals), the inverse problem is solved for the target object. Thus, we achieved several goals: first, adjustment of various observed components; second, using an additional information about the shape of the signal for refinement of an existing model of the medium, in order to more complete description of the target objects.

In principle, the proposed transformation can be realized for any parts of the medium, which may be defined as targets, i.e., its realization can be unified to create a common technology for solving inverse problems using the elements of the wave field.

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