Consistent location of seismic reflection pulse sources

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Abstract. The original algorithm for constructing seismic images using only unambiguous and structurally stable solutions of direct kinematic seismic problems is proposed in the article. The sequence of small linear boundary line sections obtained by the consistent location of several closely located seismic reflection sources is smoothed out to construct the reflecting interfaces of medium depth profile. The consistent location has many advantages compared to well-known seismic imaging technologies.

1. Introduction
The article complements and develops the material about the location technology of seismic imaging published in [1]. The original algorithm that uses only unambiguous and structurally stable solutions of direct kinematic seismic problems (DKSP) is proposed in it. The approach motivates from the fact that the instability of the inverse kinematic seismic problem solutions may get to poor-quality seismic imaging [2].

It is necessary to have information about the depth, number and thickness of the layers of the geological environment, angles, curvature and other constructive forms of reflectors for the construction the high-quality seismic image [3].

The algorithm proposed earlier extracts this information from the coordinates of discrete seismic reflection pulses sources (RPS).

The consideration is conducted in the framework of geometric seismic of plane longitudinal reflected waves, using the basic 2D depth-velocity model of a layered sub-homogeneous medium. It assumes in the model that waves from a point source propagate in the form of a seismic pulse to the observation base receivers on the along the straight-line ray paths. This fact means that the propagation velocity of the seismic pulse along with the incident and reflected rays are constant. But for different pairs: shot point (SP) – receiver point (RP) the velocity fluctuations of seismic pulses in the layer can vary depending on the structural form of the reflecting boundary.

A discrete set of reflection points, which corresponding to the set of geophones of the observation base, can be distinguished on the reflecting boundary line. These points can be considered hypocenters of point sources of seismic reflection pulses. If at the seismic trace it is possible to detect reflection pulses and determine the coordinates of their hypocenters, then the coordinates of discrete seismic RPS is obtained.

The location (determination of coordinates) is performed by the previously proposed superresolution detection algorithm implemented based on a seismic digital antenna array (DAA).

Detection is a probabilistic procedure of hypothesis testing the presence of the desired signal
against a background of noise and interference [4]. The problems of detecting RPS of various nature are successfully solved in theoretical a practice field of radio engineering. In radiolocation and sonar, communication radio systems and other areas, passive and active multi-channel digital antenna systems- DAA are widely used. Based on them, various superresolution detection algorithms are implemented that provide the adaptation of the system to the directions on RPS. The directional patterns of such DAAs allow suppressing signals from interference sources while maintaining the desired signal as much as possible. Superresolution is based on the formation of a spatial criterion function (bearing relief) and is performed by scanning with a vector hypothesis the set of directions of the bearing sector. Analysis of the relief values allows DAA choosing the best direction on RPS instead of the single-direction receiving a signal with an ordinary locator [5 - 7].

2. Problem statement

The seismic RPS location, based on the idea of superresolution detection [1], is based on the arrival times found on seismic traces of waves reflected from the layer's boundaries.

The role of a seismic DAA is performed by a linear multi-channel seismic recording station [8]. The configuration of the observation system determines the directional pattern of the seismic antenna. Its focusing is carried out using a virtual location grid that simulates possible short straight segments of reflecting boundaries, and DKSP solutions in its nodes.

These solutions are found by a location algorithm called $L$ algorithm, which is a modification of the algorithm [9]. It calculates the propagation velocity in the given medium layer of the longitudinal reflected wave, its path from the SP to the RP and the coordinates of all reflection and refraction points along this path.

The reflection and refraction points coordinates serve to approximate the lines of the reflecting boundaries layer-by-layer from top to bottom, assuming that the kinematic parameters of the previous layers of the medium are known.

The reflection point coordinates from the lower boundary line of the given layer obtained by $L$ algorithm are the tangency point coordinates of the reflection isochrone (hereinafter referred to as isochrone) and this line.

An isochrone is an even-order curve symmetric concerning the centre of the segment connecting its focuses. In any layer of the medium, the isochrone is defined by one pair SP - RP of the observation base. The coordinates of these points determine the isochrone focuses on the first medium layer. The focuses of the isochrone in the deeper layer are the intersection points of the already known line of the lower reflecting boundary of the previous layer by the incident and reflected rays.

Within the framework of the basic depth-velocity model of the medium, the isochrone model is an ellipse, the canonical equation of which has two parameters. This is the focal length and the large axis of the ellipse, determined by the layer kinematic parameters: the velocity and time of wave propagation from one focus to another.

The search for the coordinates of a discrete seismic RPS reduced to the optimal choice of a location grid node (isochronetangency point) lying on a short segment of a straight line that simulates the lower reflecting boundary of the layer.

The original selection algorithm (superresolution detection) called the $S$ algorithm to provide the search. It is based on the relief construction and analysis, yet not born, but location relief. The difference lies in the fact that the location relief is specified not on the set of directions (bearings) but the set of tangents to isochrone.

Before the location of seismic RPS, estimates of the reservoir velocity of the wave propagation in the given layer and its thickness are performed.

Information about parameters of previous boundaries and the DKSP solution with the additional condition of the local velocities equality at the points of reflection from the underlying boundary are used for estimating the given reservoir velocity.

The thickness estimation is used for the initial centre positioning of the grid location.
Changes in the position and transformation of the virtual location grid determine the tangents set to the isochrone. On its basis the\textit{L}_algorithm finds the set of the tangency point coordinates to the isochrone. The\textit{S}_algorithm selects from this set the best tangency point, thereby fixing the best tangent to the isochrone.

Thus, the problem of locating a seismic RPS settled at the boundary of the given deep layer is solved.

Repeating the solution for all isochrones in the observation interval, we obtain a set of discrete seismic RPS. The coordinates of these sources can be used for polynomial approximation by the least-squares method of the given reflecting boundary line. The obtained boundary lines of all layers form a depth profile, attached in space to the observation profile.

Unfortunately, on account of objective computational reasons, the accuracy of polynomial approximation of a function using the least-squares method, performed over a large interval, does not always satisfy the highest requirements.

It is possible to significantly increase the approximation accuracy in such a situation by breaking a large interval into small parts and smoothing the sequence of linear trends of the function defined in these parts of the interval.

3. Theoretical justification

The application of location and selection algorithms for the cooperative processing of several successively arranged isochrones improves the quality of seismic imaging. We call the “consistent location” of seismic RPS the search of a common for them trend of the reflecting boundary specified on the group of sequentially located isochrones.

To implement a consistent location of seismic RPS, as well as to improve the resolution of DAA in a detection range, the observation system is divided into groups of sequentially located geophones. As a result of the application of a consistent location by all groups, the accuracy of the approximation and the reliability of the reflecting boundary line representation can be significantly increased.

The size of the group is determined by the number of isochrones necessary to locate a sufficiently small interval of the reflecting boundary, which can be approximately considered linear. The group is intended for the iterative coordinated location of a linear trend (\textit{l}_\text{trend}) of the reflecting boundary.

Each group geophone determines one isochrone and provides the selection (the choice of the best) of its tangent from the set specified by the location grid. Selection is carried out by the\textit{S}_algorithm which scans with a vector-hypothesis (\textit{S}_vector) the agency points set of the isochrone. The\textit{S}_vector is formed by an odd number (7) of sequentially located geophones.

Consider the iterative procedure for finding one \textit{l}_\text{trend} of the reflecting boundary of the given deep layer, illustrating the functioning of the location technology main elements.

The number of iterations is taken to be three. Within one iteration, the central node of the location grid is moved along a lateral three times.

The first iteration of the search for the \textit{l}_\text{trend} of a geophones group starts with the first accessible isochrone. Accessible is the isochrone for which there is a pathway from the SP to the RP passing through all superposed boundaries of the layers. The layer thickness estimation sets the initial central node depth of the location grid. Its initial distance from SP is equal to half the distance between the SP and the RP, corresponding to the first accessible isochrone.

Seismic DAA focuses on allisochrone tangents defined by the location grid. Focusing on a tangent means that a focus point (benchmark) is applied to it. The coordinates of each benchmark are the result of the \textit{L}_algorithm work with the input parameters: the coordinates of SP and the corresponding geophone \textit{S}_vector, arrival time of the reflected wave on it, superposed reflecting boundaries and tangent equations.

The central benchmark, which corresponds to the average (central) \textit{S}_vector geophone is allocated. The central benchmark becomes the discrete argument of the discrete spatial criterial function - the location relief. The values of the criterion function are calculated as the weighted sum of two
kinematic and one correlation criteria.

Kinematic criteria depend on the pathway from the SP to the RP of the incident and reflected rays, as well as the transit time of the seismic wave along with them. The calculation of the criteria ensures that the $L_\text{-algorithm}$ is applied to all $S_\text{vector}$geophones focused on the tangent.

For each $S_\text{vector}$geophone with number $i = j - n, ..., j + n$ difference $dT_i = T_i - T_{i,\text{real}}$ between the transit time of the wave $T_i$ received by the $L_\text{-algorithm}$ and the time $T_{i,\text{real}}$ recorded by the seismic trace is calculated. Based on the differences in the transit times to all geophones, two functionals $\eta_1, \eta_2$, are calculated. They allow the determination of kinematic criteria for each central benchmark. The first functional characterizes the inverse of the peak value. The second characterizes the inverse value of the time difference dispersion.

$$D_{1i} = 2e^{ad(T_i)}, \quad D_{2} = (dT_i)^2,$$

$$\eta_1 = 1/\text{mean}(D_{1i}), \quad \eta_2 = 1/\text{mean}(D_{2});$$

The correlation criterion for each central benchmark is a Semblance coherent estimate [10], which depends on the shape of the signals on the seismic traces:

$$\eta_{\text{Semblance}} = \frac{\sum_{i=1}^{T_n} (\sum_{i=j-n}^{j+n} x_i(t + \tau))^2}{\sum_{i=1}^{T_n} (\sum_{i=j-n}^{j+n} (x_i(t + \tau))^2),}$$

where $j$ is the number of the central $S_\text{vector}$ geophone in the observation system, $n$ is the number of $S_\text{vector}$ elements, $x_i$ - $i$-th seismic trace, $\tau$ is the time shift, integer $T$ is the pulse duration.

[1] For all lateral shifts of the location grid, location reliefs are constructed. Their analysis provides the choice of the best isochrone tangency point. The coordinates of the central benchmark, which has the maximum value among all location reliefs, determine this choice. The search continues until all isochrones tangency points of the geophones group are selected.

Through the selected isochrone tangency points of the geophones group, a polynomial of the first degree is constructed. The consistent (located on the same line) set of all isochrones tangency points of the geophones group is founded by the $L_\text{-algorithm}$ using this polynomial as a segment of the reflecting boundary.

This ends the current iteration.

The transition to the next iteration of the search for $l_\text{trend}$ is performed in order to clarify the depth of its occurrence. The step along the depth of the location grid is halved, the central node of the grid is located at the midpoint of the found set.

At alliteration, seismic DAA is focused, location reliefs are constructed, a consistent set of isochrone tangency points of the geophones group is obtained. Based on all sets of tangency points obtained at iterations, an approximation of the final $l_\text{trend}$ of the group is constructed.

Figure 1 shows the central benchmarks (markers) and $l_\text{trend}$s (lines) of three iterations. The line of the first iteration is shown by dots, the second by dash-dotted line, and the third by a dashed line. The final $l_\text{trend}$ is depicted by a thick line, the boundary by a thin line. The squares show the correspondence of the ends of the approximation interval and the approximated function.

Next, sequential processing is performed for the following groups of geophones.

The $l_\text{trend}$ sequence of all geophone groups of the observation system, subjected to smoothing, forms a complete line of the reflecting boundary of the given layer.
4. Experimental verification

Figure 2 shows a model example of the implementation of a consistent location seismic RPS.

A synthetic seismogram with the reflected wave lineups from four boundaries was processed.

The accuracy of reflecting boundary lines approximation is estimated. It is estimated by the standard deviation (STD). We received boundary lines (thick), true (thin lines). However, at the fourth boundary in the region of 2500 m, there is a noticeable deviation during the reconstruction of the boundary. This error is explained by the increase from border to border harmful effect of lateral disturbances in the superstratum on the DKSP decisions in the underlayers. Consideration and elimination of such influence is the subject of further research.

5. Discussion of results

The not prime but actual problem of constructing seismic images is the detection of the lateral disturbances of structural forms of reflecting layer boundaries.

The composition of the location technology includes a means of solving such problems, based on the consistent location of seismic RPS.

The third boundary in the region of 2500 m of the observation profile (Fig. 2) has a strong anticlinal form disorder, which is reproduced to the second boundary.

Figure 3 shows the exposure and approximation details of an anticlinal structural form disturbance of the second reflecting boundary. Here, the section of the reflecting boundary line is shown by dots,
intervals of straight lines represent \( l \)-trends, and dashed lines show the smoothed boundary line. The disturbance was reconnded trust quite accurately.

![Graph](image)

**Figure 3.** Anticlinal fragment of the boundary

### 6. Conclusion

The article describes a new approach to the construction of seismic images using stable and unambiguous solutions of DKSP. It is based on the constructing location of the seismic RPS, which is carried out by the seismic DAA, using a superresolution detection algorithm and a virtual location grid.

The sequence of small linear intervals of the boundary line obtained by the consistent location of several closely spaced RPSs is smoothed out to approximate the reflecting boundaries of the depth profile.

The consistent location has many advantages compared to well-known seismic imaging technologies. In particular, it is possible to lateral exposure disturbances of the structural forms of the layers reflecting boundaries, estimate reservoir velocities and remove multiple reflections from curved reflecting boundaries.

### References

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