High-resolution velocity model estimation by the RTH method

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Summary

The high-resolution velocity model estimation by the Reverse Time Holography (RTH) method is proposed. It is shown that the one of the new depth seismic attribute - RTH Velocity Residual, which is based on the estimated velocity, has spatial resolution of more than two times higher than resolution of the conventional Kirchhoff's depth migration. The data processing examples by RTH method for three types of spatial pixel size starting from 2 meters are presented. The new voxel-based classification of the seismic imaging methods based on the essence of formal operations on wave information at each point of the medium is proposed.

Introduction

The main idea of optical holography is based on the fixing the amplitude and phase of the wave scattered by object. The mechanism of such fixing uses the interference between scattered wave and some reference wave. The interference is "frozen" by a photographic plate, used when creating a holographic image (Gabor, 1948). Over 40 years ago, the ideas of optical holography were actively used when trying to create new methods for seismic data processing (Fitzpatrick et al., 1972). The Kirchhoff depth migration method, Reverse Time Migration (RTM) method (Baysal et al., 1983; McMechan, 1983) and Full Wave Inversion method (Tarantola, 1984; Virieux, et al., 2009) were developed during these way. Until now, some researchers continue to consider that, in a sense, seismic data is seismic holography (Robinson et.al, 2010). The method Reverse Time Holography (RTH) allows embodying the idea of optical holography to seismic (Erokhin et al., 2017, 2018a, 2018b; Erokhin, 2019). The RTH approach requires more computational power than the conventional RTM-based methods, but provides research on the structural, geological, and petro physical properties of medium at a new qualitative and quantitative level.

In this paper the high-resolution velocity estimation by RTH approach is proposed. It is shown that the image of the some new attribute, called RTH Velocity Residual, which is based on the high-precision velocity model estimation has a spatial resolution of more than two times higher than image, based on Kirchhoff's depth migration. The new voxel-based classification of the seismic imaging methods is proposed.

Method

The velocity estimation of the medium and other seismic attributes by the Reverse Time Holography (RTH) method is carried out in two stages: decomposition and synthesis. The first stage of the RTH consists in the development of some Vector Domain Common Image Gathers dataset (VDCIG). The creation of the VDCIG's repository is based on the full vector decomposition of two vector fields: direct and reversed in time (Erokhin et al., 2018a). There exist some conventional approaches for decomposition of forward and backscattered acoustic fields which use only pressure fields. The angles of incident and scattered waves are calculated using, for example, the Pointing vector (Yoon and Marfurd, 2006), which is accumulated on time. The RTH's VDCIG data power is significantly greater than the data power of conventional RTM or Angle Domain RTM methods.

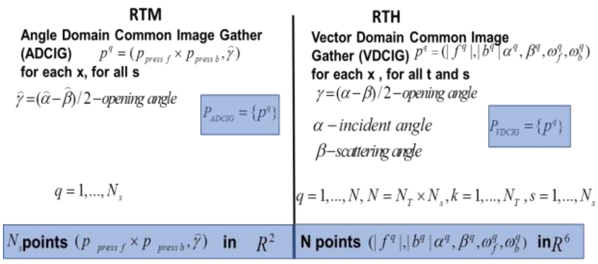

Figure 1: Data power comparison of RTM and RTH

The comparison between the Angle Domain Common Image Gathers (ADCIG) data power and VDCIG data power for some medium point is presented at Fig.1. Here the set $P_{ADCIG}=\{p^q\}$ describes the conventional RTM-based set ADCIG. The N_s is number of sources. The set $P_{VDCIG}=\{p^q\}$, where the $p^q=(|f^q|,||b^q|,\alpha^q,\beta^q,\omega^q{}_f,\omega^q{}_b)$ is a vector from R^6, describes the RTH-based set VDCIG. Here $\gamma=(\alpha-\beta)/2$ is Opening Angle , $\theta=(\alpha+\beta)/2$ is the Dip Angle, ω_f,ω_b are the instantaneous circular frequency of rotation of forward vector f and backscattering vector b (Hz, clockwise positive, versus negative). So, for each voxel of acoustic medium the set of vectors $\{p^q\}$ statistically describes the main characteristics of the forward wave and the back wave. It is very important to underline that the all components of the each vector p^q are interconnected. That is main prerequisite to decompose and designing the Imaging Condition based on VDCIG (Erokhin et al., 2017).

The second stage of the RTH approach is to synthesize an attributes based on the parameters evaluation for the VDCIG dataset. For this purpose we use the statistical estimation of the multidimensional distribution. The workflow of the RTH data processing is presented at Fig. 2.

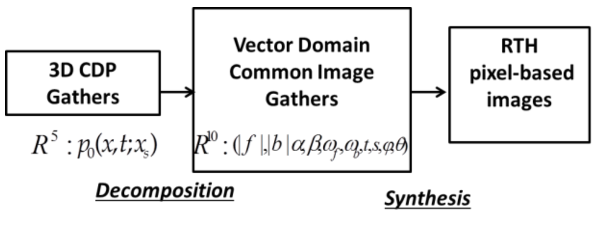

Figure 2: The RTH data processing workflow

One of the parameter, estimated for each voxel of the medium (pixel for 2D case) is the perturbation value of arrival time regarding to background velocity. It turns out that the RTH method allows one to estimate the velocity in the medium through a perturbation of the arrival time in each voxel of the medium The voxel size can be anything from 1-2 meters. Fig. 3 shows the result of velocity estimation (Fig. 2b, 2d) for the test with wavy velocity model (Fig. 3a, 3c). The background velocity is the gradient from 2 km/s up to 5 km/s. The parameters of this test are: the depth is 4 km, the length is 17 km, the step between receivers is 25 m, between sources - 50 m and the number of sources is 344.

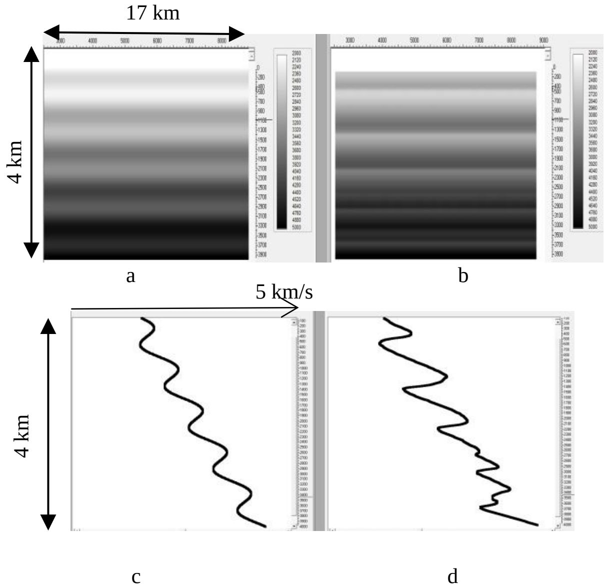

Figure 3: Mathematical modelling. The true velocity (a), (c), velocity estimation (b), (d)

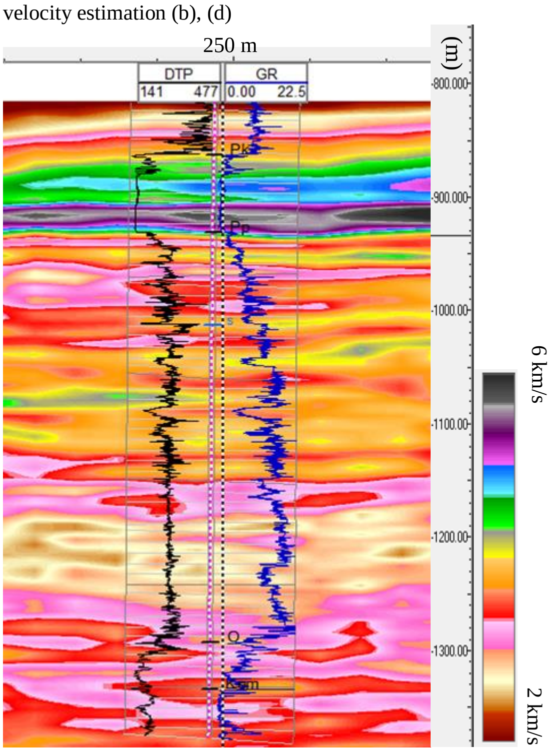

Figure 4: Comparison the RTH velocity and the logging data

The velocity estimation for the above model experiment was carried out on the basis of determining the first moment of the multidimensional statistical distribution of random events in each voxel of the medium by the parameter time. It is clear that a similar formal approach for the other ten distribution variables allows us to construct other seismic attributes, including all currently known. The difference between constructing RTH attributes from those obtained traditionally consists in their complete independence from each other and the possibility simultaneous creation all of them for each voxel of acoustic medium. This is the main voxel-based principle of the RTH method. The correctness of the attributes, obtained on the basis of the RTH method is confirmed by geological information, including logging data. So, at Fig. 4a the comparison of the RTH velocity with the data of acoustic logging and the gamma ray logging is presented. The voxel size here is 25 m lateral and 5 m deep. At depths of 800–900 meters, anomalies are observed in the RTH velocity and in the logging due to the high-velocity Permian deposits (Pk-Pp). The RTH velocity clearly captures the presence of Silurian deposits (1000 meters), Ordovician (1280 meters) and Cambrian (1320 meters), which are also observed on logging data.

Here we would like to make an important remark regarding the positioning of our RTH method with other seismic imaging methods and, possibly, further generalizing the RTH approach. From the point of view of the mechanism for creating seismic images, the RTH method has a fundamental difference from all previous methods of time and depth migration, such as Kirchhoff migration, PSTM, PSDM, RTM, CSPD, etc. This difference is concluded in other - statistical principles of the imaging of scattering medium, on the holographic-based principles by two-vectors decomposition of reference wave and scattering wave.

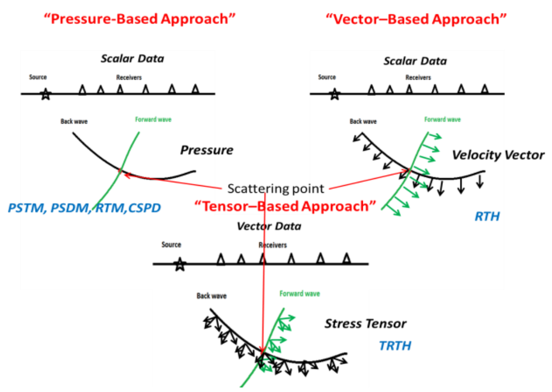

Figure 5: New classification of the seismic imaging methods

To be precise and build on the essence of formal operations on wave's data, performed by any method of seismic processing at each scattering point of the medium, then we can propose a next simple classification of all existing and developing seismic data processing methods (see Fig. 5). If

10.1190/segam2020-3410422.1

a method operates only with amplitude of wave for image of properties at each point of medium, then it can be called scalar-based method (PSDM, PSTM, CSPD, etc.). If a method uses both amplitude and phase of acoustic wave, then these method can be called vector-based method (RTH) and finally, if a method uses tensor information of elastic medium, then this type of seismic imaging method can be called tensor-based method (Tensor Reverse Time Holography - TRTH).

Examples

The examples of RTH data processing are presented below for three types of voxel size. Everywhere the step between receivers is 5 m, between sources - 25 m, time sampling - 2 millisecond, offset - 5 km. The all attribute estimations are calculated by massive supercomputer. The background velocity model is the simple gradient from 3 km/s up to 7 km/s (for the depth 10 km).

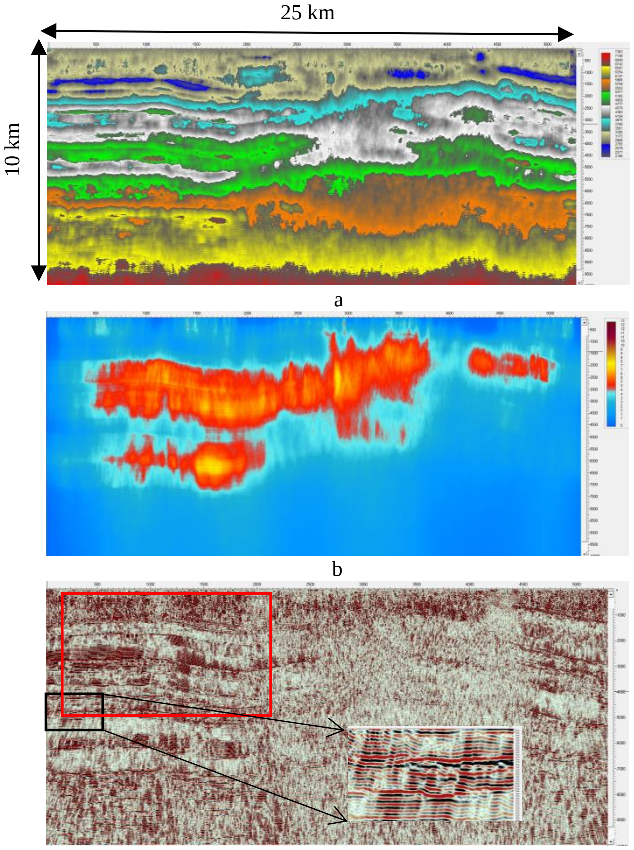

Figure 6: Long seismic profile. Voxel size is 25x5 m. RTH velocity - from 2190 m/s (bottom) to 7363 m/s (top) (a), Scattering Index (Diffractivity) (b), RTH Residual Velocity (c)

Fig. 6a - 6c depict the results of the estimation various attributes with the voxel size of 25x5 meters. In Fig. 6a shows the medium velocity. In the upper part of the depth section, the layer with reduced velocity can be observed (blue colour). At the depth of 4000 meters the inversion of the velocity is observed on the right side of the section (blue inclusions against a light grey background). Note that the RTH velocity is estimated with high detail up to depth of 10 km. Fig. 6b depicts the Scattering Index, which often characterizes the fracture value of the medium. At Fig. 6c an analogy of conventional Kirchhoff depth migration is presented by the attribute RTH Residual Velocity. The spatial resolution of the RTH depth section is 2-3 times higher than the analogous one. Fig. 7a-7b gives us the comparison of the Kirchhoff migration with the new attribute on an enlarged scale. The velocity for this section is presented without the gradient trend of the initial velocity model (see Fig. 7c).

Fig. 8a -8c demonstrate an even more detailed images of the same attributes, with the voxel size of 5x5 meters, but for the upper part of the depth section only. Here the low velocity inclusions are blue and high velocity layer is yellow. As we can see, the RTH method is capable of constructing a very high-resolution model. Fig. 9 depicts the results of the velocity calculation with the 2m voxel size. Such resolution is already quite sufficient as for horizontal well design and for geosteering too.

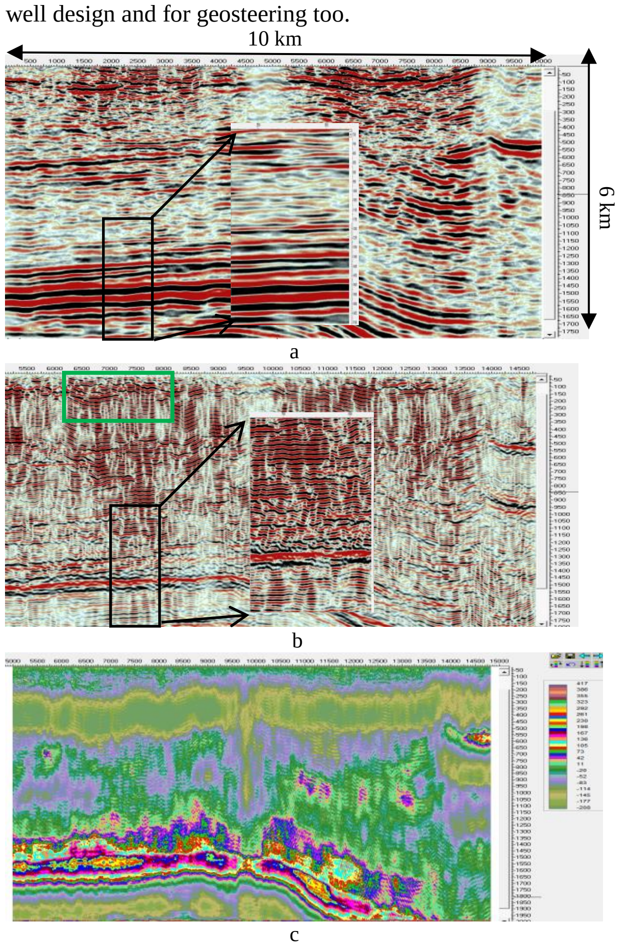

Figure 7: Zooming the red box at Fig. 6c. Voxel size is 5x5 m. The Kirchhoff Depth Migration (a), RTH Velocity Residual (b) and RTH velocity perturbation from -208 m/s (bottom) to 417 m/s (top) (c)

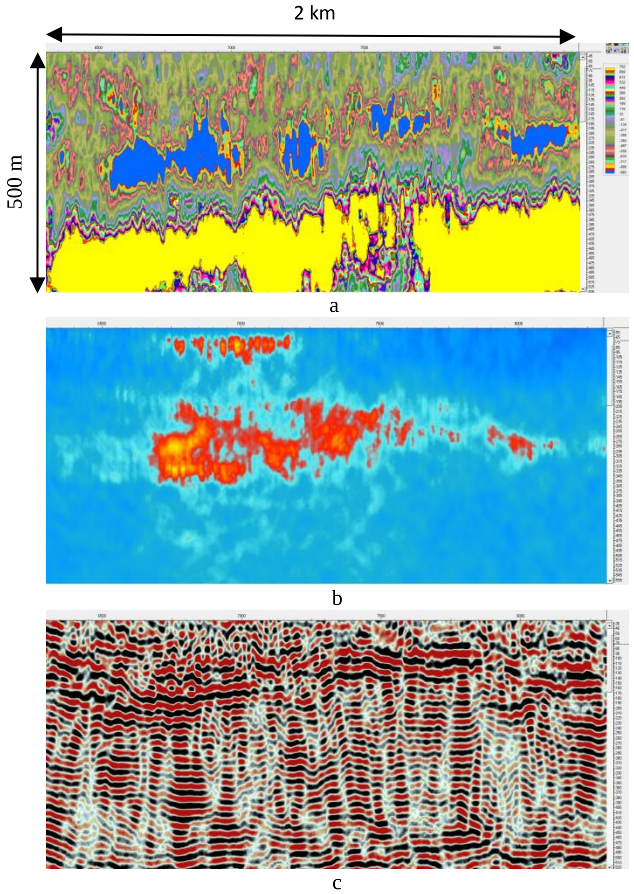

Figure 8: Zooming the green box at Fig. 7 (b). Voxel size is 5x5 m The RTH Velocity Perturbation from -883 m/s (bottom) to 782 m/s (top), Scattering Index (Diffractivity) (b), RTH Residual Velocity (c)

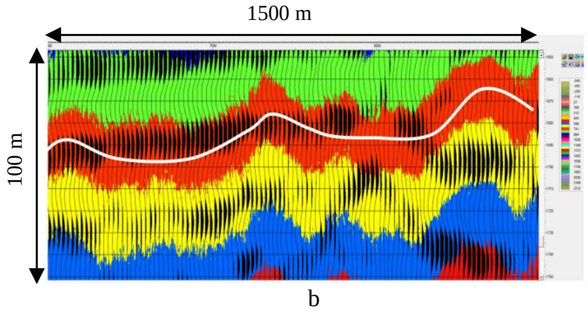

Figure 9: The RTH Velocity with RTM wiggle. Voxel size is 2x2 m. White line is proposed trajectory for horizontal well

Conclusions

The high-resolution velocity model estimation by the Reverse Time Holography method is proposed. It is shown that the one of the new depth seismic attribute, which is called the RTH Velocity Residual and which is based on the high-precision velocity model estimation has a spatial resolution of more than two-three times higher than Kirchhoff's depth migration. The data processing examples for three types of pixel size starting from 2 meters are presented. The new voxel-based classification of the seismic imaging methods based on the essence of formal operations on wave information at each point of the medium is proposed.

Acknowledgments

The authors thank colleagues and friends Alexander Yakovlev, Aleksander Danilin, Sergey Sergeev, Maksim Kozlov and Svetlana Shevchenko for help and useful participation. This work is supported by the Russian Science Foundation under grant 16-11-10027.

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