Reverse Time Holography Approach based on the Vector Domain Common Image Gathers

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Summary

The Reverse Time Holography approach (RTH) for seismic processing is proposed. The RTH approach, like in optical holography, can "freeze» the information about amplitudes and phases of the scattered seismic waves reversed in time, with high precision, using a some “reference” wave. This information is saved in a Vector Domain Common Image Gathers (VDCIG) repository. The seismic imaging is based on the direct statistical evaluation of the VDCIG data set. The RTH method requires more computational power than the conventional Reverse Time Migration (RTM) method or its modifications basis Angle Domain CIG, but provides investigation on the structural, geological, and petrophysical properties of the environment at a new qualitative and quantitative level.

Introduction

Over 40 years ago, the ideas of optical holography (Gabor, 1948) were actively used when trying to create new methods for processing seismic data (Fitzpatrick et.al., 1972). The main idea of optical holography is in fixing the amplitude and phase of a wave scattered by some object, simultaneously with similar information from a certain reference wave on a photographic plate and in the subsequent use of this information when creating a holographic image. The Kirchhoff depth migration methods, RTM methods (Baysal et.al., 1983; McMechan, 1983) and Full Wave Inversion methods (Tarantola, 1984; Virieux, at.al., 2009) were developed during the processe of these studies. However the realiziation of the optical holography idea in its original form for seismic is failed.

Until now, some researchers continue to consider that, in a sense, seismic data is seismic holography (Robinson et.al., 2010). I am agree with this point of view. Indeed, it appears full numerical decomposition of two vector fields: the direct seismic field excited by the seismic source and the time-reversed, recorded on the surface of the land seismic field allows to embody the idea of optical holography in seismicity (Erokhin et.al., 2018a). The inversion is carried out by solving the adjoint problem for a vector acoustic equation based on the VPRTM (Vector Pair Reverse Time Migration) method (Erokhin et.al., 2017). Decomposition provides the formation of a certain set of events in the extended seismic data space Vector Domain Common Image Gathers (VDCIG). The mechanism of VDCIG formation is similar to the use of a “photographic plate” in optical holography for the fixation of the full amplitude-phase characteristics of two vector fields: the direct vector field and the scattered time-reversed vector field.

I have called this approach for seismic the Reverse Time Holography (RTH) to distinguish it from the conventional approach based on Imaging Condition in the RTM method. In essence, RTH is primarily a VDCIG extended seismic data storage technology, which includes, as a subset of Common Image Gathers, and some additional quantitative information regarding the relationship of the vector field, reversed in time, to the “reference” vector field. The tools of visualization of the properties of the geological environment in the RTH approach are based on multidimensional statistical evaluation of VDCIG data for each point of the geological environment and are more flexible and powerful than in the conventional RTM method based on the usual Imaging Conditions.

Method

A key point at the Reverse Time Holography approach is the formation of the VDCIG repository. The creation of VDCIG is based on the full vector decomposition of two vector fields: the direct and the reverse, created on the basis of the Vector Pair Reverse Time Migration (VPRTM) method. The mathematical formulation of the VPRTM problem basis the linearized acoustical wave by the couple $(p,\vec{i})$ where p is the pressure and $\vec{i}=\rho\vec{u}$ is the particle-impedance velocity vector, which satisfy the first order linear differential equations

$$\begin{aligned} & p^f{}_t - c^2 div(\vec{i}^{\,f}) = r(t)\delta(x-x_s) \\ & \vec{i}^{\,f}_t = \nabla p^f \\ & p^f\big|_{t=0}=0, \quad i^{\,f}\big|_{t=0}=0. \end{aligned} \qquad (1)$$

Here $r(t)\delta(x-x_s)$ is the source located at the boundary point $x_s \in \Gamma = \left\{x \in \mathbb{R}^n \middle| x^n = 0,\ n=2,3\right\}$ (δ is the Dirac function, and r is some wavelet), $\rho=\rho(x)$ density, $\vec{u}$ - particle velocity vector, $c=c(x)$ - medium velocity, T is the time of observation. The linearized acoustical wave (1) we obtained after disregard members $\langle\nabla\rho,\vec{i}\rangle/\rho$ .For simplicity, further we set the density $\rho=\rho(x)$ equal to 1. Let $p_0 = p^f\big|_{\Gamma\times[0,T]}$ be the “measured” pressure. The adjoint problem to (1) is written as follows

$$\begin{aligned} & p^b{}_t - c^2 div(\vec{i}^{\,b}) = 0 \\ & \vec{i}^{\,b}_t = \nabla p^b + p_0\delta(x^n)\vec{\nu}_\Gamma \\ & p^b\big|_{t=T}=0, \quad \vec{i}^{\,b}\big|_{t=T}=0, \end{aligned} \qquad (2)$$

where $\nu_\Gamma = (0,...0,1)$) is the unit normal vector to Γ . We call $(p^b,\vec{i}^{\,b})$ the back wave since it propagates in reversal time. So, forward and back waves, except pressure, include two impedance particle velocity vector fields: $\vec{i}^{\,f}(x,t;x_s)$ and $\vec{i}^{\,b}(x,t;x_s)$. Further we will use short notations $f=\vec{i}^{\,f}$, $b=\vec{i}^{\,b}$.

There exists the conventional approach for decomposition of forward and backscattered acoustic fields which uses only pressure fields. The angles of incident and scattered waves are calculated using, for example, Poynting vector (Yoon and Marfurd, 2006) which is accumulated on time. The result of such approach is obtaining two numbers: value of product of forward and backscsttered pressures and value of angle average near meeting time of forward and backscttered waves. Such approach is called the RTM-based Angle Domain Common Image Gathers (ADCIG). Is there exist the another, more detail and more informative approach for designing an undersurface gather like ADCIG? The answer is yes, if we will use the first order linear differential equations (1)–(2) and will be calculate not only pressure but the particle velocity vector too. Such approach has been proposed in papers by Erokhin et.al., 2017; Erokhin et.al., 2018a; 2018b. New seismic gathers have been called the Vector Domain Common Image Gather (Erokhin et.al., 2018a).

The images construction using the standard RTM method based on the Imaging Condition formula (Baysal et.al., 1983), as a rule, does not require large data storage capacities because for ADCIG, averaging is performed over time and sources, and as a result one or two values are stored for each point of the medium. Really, for 2D ADCIG case it is necessary to store only data set $R_{ADCIG} = \{d^q\}$, where $d^q = (\widehat{p}^q_{press\,f} \times \widehat{p}^q_{press\,b}, \widehat{\gamma}^q)$ $q = 1,...,N_s$, N_s - is the number of sources, $\widehat{\gamma}$ - opening angle, averaged by time, $\widehat{\gamma} = (\widehat{\alpha} - \widehat{\beta})/2$, $\widehat{\alpha}$ - incident angle, $\widehat{\beta}$ - scattering angle, $\widehat{p}^q_{press\,f}, \widehat{p}^q_{press\,b}$ forward and backscattering pressure from (1)-(2) , averaged by time. So, for each 2D medium point, after averaging by time and sources, we have to storage or one number - product of pressures either two number - product pressures and opening value.

The situation is quite different when forming a data set for VDCIG using the RTH method. For 2D case it is necessary to storage for each medium point already 6xN numbers, where, $N = N_T \times N_s$, N_T - is the number of time sampling, N_s - is the number of sources**.** So, for VDCIG we have storage data set $R_{VDCIG} = \{d^q\}$ **,**where $d^q = (|f^q|, |b^q| \, \alpha^q, \beta^q, \omega^q_f, \omega^q_b)$ is a vector from R^6,
$q = 1,...,N,\; N = N_T \times N_s,\; k = 1,...,N_T,\; s = 1,...,N_s$
ω_f, ω_b are the instantaneous circular frequency of rotation of the vectors f and b (Hz, clockwise positive, versus negative). So, VDCIG repository is much more huge then ADCIG repository. On real seismic data this power ratio can reach one or two thousands. Consequently, with a large fold and a high data sampling rate, considerable capacity of data storage for RTH is required. However, it seems that in the time of "Big Data", over time this will not be a big problem. Below we give a number of examples of using the RTH approach for various geological conditions.

Examples

The RTH approach allows building seismic attributes such as AVO, Dip, Opening Angle, Frequency, Relative Impedance, Amplitude Reflectivity, Amplitude and Phase Diffractivity, Velocity Tomography and other attributes related to structural, geological, and petro physical properties of the rocks. Fig. 1-11 shows a small part of the attributes, obtained simultaneously based on the statistical estimation of the data set from the VDCIG repository. In the examples below the computational grid is 5 meters and time step is 0.2 ms. The dominant frequency of Ricker's wavelet for case studies #1,#2 is - 40 Hz ; for the case study #3 – 200 Hz and for the case study #4 - 0.2 Hz .

<ins>Case Study #1. Long observation profile.</ins>

The length is 35,3 km, depth is 10 km. The step between the receivers is 5 m, between the sources - 25 m. The number of sources is 1015. The number of receivers for one source 1015. The computational domain for one source is 10000x10000 m. The pixel size when building images is 25x25 meters. The medium velocity at (1)-(2) is $c(z) = c_0 + \alpha z,\;\; c_0 = 3 km/s \;\;\; \alpha = 0.4 \;\; 1/s \;\;\; z \in [0,10]\, km$. The amount of VDCIG data is 26 TB.

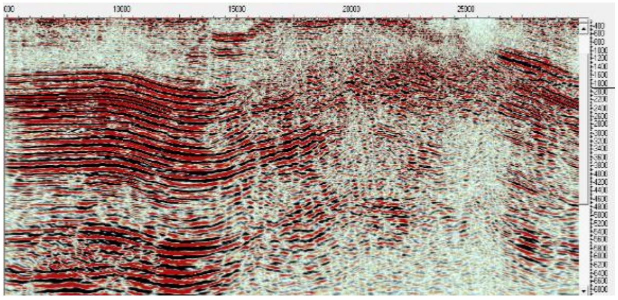


Figure 1: RTH Reflectivity

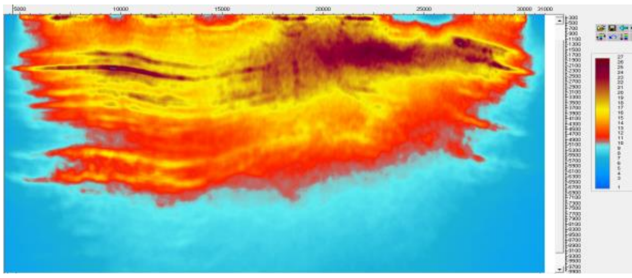


Figure 2: RTH Relative Impedance

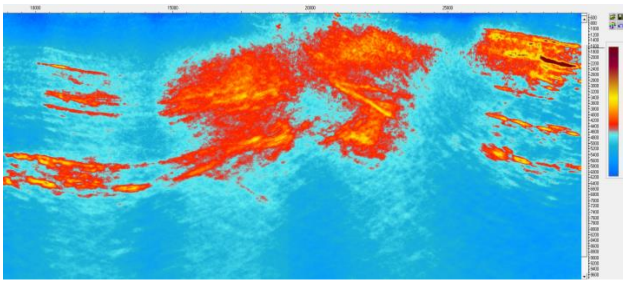


Figure 3: RTH Amplitude Diffractor

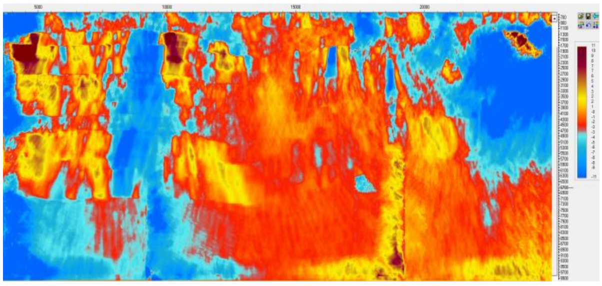


Figure 4: RTH Opening Angle. Angle scale from -11deg (blue) up to +11deg (red)

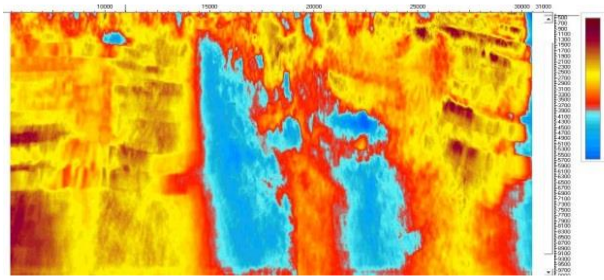
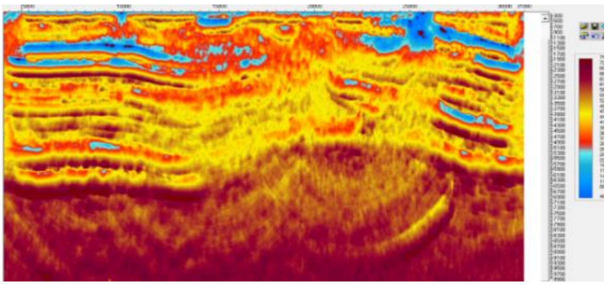


Figure 5: RTH Dip. Angle scale from -24 deg (blue) up to +24 deg (red)



b

Figure 6: RTH Velocity model. Velocity scale from 400 m/s (blue) up 7500 m/s (red)

Case Study #2. Comparing with well logging data.

The length is 22.5 km, depth is 4 km. The step between the receivers is 25 m, between the sources - 50 m. The number of sources is 344. The number of receivers for one source is 201. The computational domain for one source is 5000x4000 m. The pixel size when building images is 25x25 meters. The medium velocity at (1)-(2) is $c(z)=c_0+\alpha z,\quad c_0=2km/s\quad \alpha=1.0\quad 1/s\quad z\in[0,3]\,km$. The amount of VDCIG data is 1.8 TB.

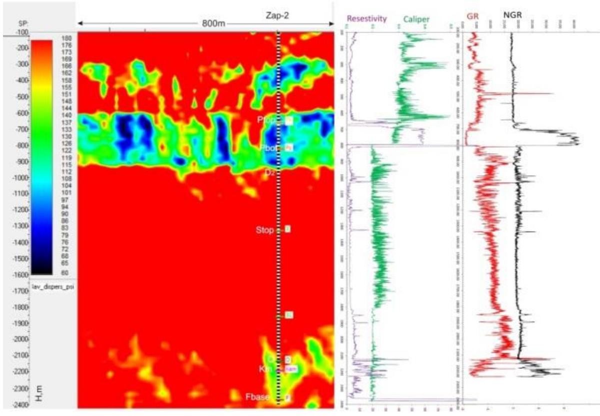


Figure 7: The Variance of Dip. Comparing with well logging data. Well logging data from left to right: resistivity log, caliper log, gamma ray log, neutron gamma log

Case Study #3. Near-surface layer: 3D velocity cube.

The size of the cube is 2300x2600x500 m. Parameters of acquisition system are: number of sources on X: 7; number of sources on Y: 72; spacing between sources on X: 300 m;Y spacing between sources: 25 m; number of receivers for one source on X: 41; the number of receivers for one source on Y: 5. The computational domain for one source is 1000x800x500 m. The medium velocity at (1)-(2) is $c(z)=2km/s\quad z\in[0,0.5]\,km$. The amount of VDCIG data is 1 TB. The pixel size when building images is 25x25 m laterally and 10 m on depth.

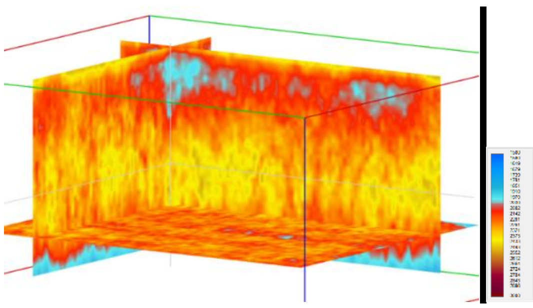


Figure 8: Near-surface layers: 3D velocity cube. Velocity scale from 1500 m/s (blue) up 3000 m/s (red)

Case Study #4. RTH attributes with wiggle overlay.

Fig. 10-12 shows some attributes with reflectivity overlay. The total length is 25 km, depth is 10 km. The step between receivers is 50 m, the step between sources is 50 m. The number of sources is 1200. The number of receivers for one source is 200. The computational domain for one source is 10000x10000 m. The pixel size when building images is 25x25 meters. The medium velocity at (1)-(2) is $c(z)=c_0+\alpha z,\quad c_0=2km/s\quad \alpha=0.6\quad 1/s\quad z\in[0,10]\,km$. The amount of VDCIG data is 1.5 TB.

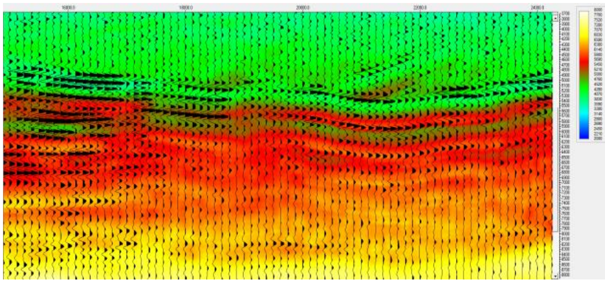


Figure 9: RTH Velocity model part with RTH Reflectivity wiggle overlay. Velocity scale – from 2000 m/s (blue) up 8000 m/s (yellow)

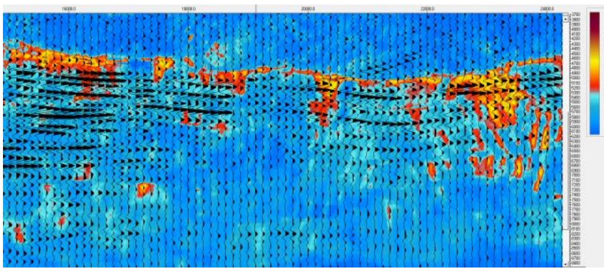


Figure 10: RTH Phase Diffractor part with RTH Reflectivity wiggle overlay.

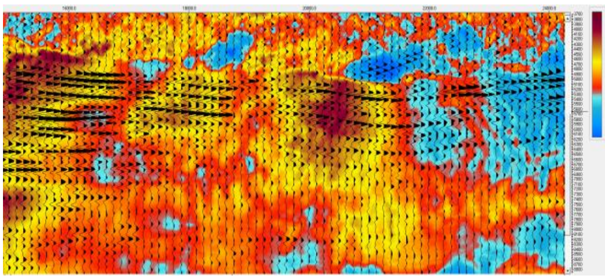


Figure 11: RTH Dip part with RTH Reflectivity wiggle overlay. Dip scale - from 18 deg (blue) up to +18 deg (red)

Conclusions

The RTH approach is proposed, consisting in the detailed vector decomposition of seismic data, recording of the received information in a VDCIG repository and statistical estimation of data set for obtaining the images of the geological medium on a new mathematical principles. The RTH approach requires more computational power than the conventional RTM method or its modifications based on ADCIG, but provides research on the structural, geological, and petro physical properties of the medium at a new qualitative and quantitative level.

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