New VSP Wavefield Separation Method. Wave-by-Wave Extraction

Emil Blias, Revolution Geoservices Inc., Calgary, Canada

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Summary

Wavefield separation is one of the main steps in processing VSP data. The purpose of this paper is to develop an optimization approach for VSP wavefield separation in the time domain. We model the actual wavefield as a sum of waves with unknown parameters. The wavefield separation problem is reduced to a nonlinear optimization problem with a small number (usually from two to four) of unknown waves with their wave shape functions, amplitudes and time-dependent time shifts.

Introduction:

Downgoing and upgoing P and S waves are used for different purposes. Downgoing waves are used to calculate seismic P and S velocities, to estimate the seismic anelastic quality factor Q, to build time-dependent filters, which allow us to recover high-frequency losses of seismic waves. (Sudha and Blias, 2002).

Upgoing wavefields are utilized to obtain VSP-CDP images. The idea of using a small number of waves with different apparent velocities for wave separation has been suggested by Nahamkin, Goltsman and Trojan (1966, 1967). Seeman and Horowicz (1983) and Esmersoy and Leaney (1989, 1990) suggested using a frequency domain optimization approach for zero-offset VSP wavefield separation. This approach was extended to obtain the anelastic parameter from VSP data (Blias, 1997). For 3-component VSP wavefield, an optimization approach in time domain was considered by Blias and Katkov (1990). The results of its applications were presented by Blias and Chavina (1999). Here I am describing an approach, which is quite close to what was presented in (Chopra et al., 2004) as the optimization inversion method.

Wavefield mathematical model

For the sake of simplicity (and space), we will describe a one-dimensional wavefield separation. Exactly the same approach can be applied to a two-dimensional or a three-dimensional wavefield. Let us consider several neighboring geophones, located at different depths, and let $U_i(t)$ be traces recorded at these geophones. Then we describe the borehole observation with a mathematical model:

$$U_i(t) = \sum_{k=1}^{n} a_{ki}\, f_k(t - \tau_{ij}(t)) + \xi_j(t), \quad i = 1, 2, \ldots, I;\;\; t=1,2, \ldots, T \qquad (1)$$

Here n is the number of regular waves, I is the number of traces, t are time samples; τ_{ij} are time shifts of the waves, a_{ki} is an amplitude of the k-th wave at the i-th receiver, $f_k(t)$ are wave functions and ξ_{ij} –stands for the random noise. In the equation (1), we assume that time shifts depend on time t, that is $\tau = \tau(t)$. This allows us to consider waves with non-parallel picks as we can see on offset VSP wavefields. We can mention that for downgoing waves τ is positive and for upgoing waves τ is negative.

In equation (1) we describe each wave with the wave shape function f(t), amplitude a_{ki}, which depends on the geophone level z_i and time function $\tau_k(t)$. If $\tau_k(t)$ is constant then we have a conventional description (Nahamkin and Trojan V., N., 1966, Goltsman and Trojan, 1967, Seeman and Horovicz, 1983, Leaney and Esmersoy, 1989, Leaney, 1990). As the amplitude of the wave cannot change rapidly from one depth to another, we will describe them as a linear combination of smooth functions $\psi(i)$:

$$a_i = \sum_{m=1}^{M} \alpha_m\, \varphi_m(i) \qquad (2)$$

Usually M = 2 or three and we use polynomial for the base functions $\varphi_m(i)$. Similarly we describe the time-delay functions $\tau(t)$:

$$\tau_i = \sum_{q=1}^{Q} \beta_q\, \varphi_q(i) \qquad (3)$$

To determine wave parameters we use the least-squares method, which leads us to minimize the function:

$$\Psi(\alpha,\beta,f) = \sum_{i,t} [U_i(t) - \sum_{k=1}^{n} a_{ki}\, f_k(t - \tau_{ki}(t))]^2 \qquad (4)$$

We use wave-by-wave iteration extraction, which has been suggested by Nahamkin and Troyan (1966) and Goltsman and Troyan (1967). Let w(t) be the difference between observed traces U(t) and all waves except the one number r:

$$w_i(t) = U_i(t) - \sum_{k\neq r}^{n} a_{ki}\, f_k(t - \tau_{ij}(t))$$

Then from (4), after flattening wave r, we can find the r-wave parameters by minimizing the objective function Φ_r:

$$\Psi_r = \sum_{t,i}[W_i(t + \tau_i(t)) - a_i f(t)]^2 \qquad (5)$$

where $a_i = a_{ri}$, $f(t) - f_r(t)$. It can be shown that for given time-dealay function $\tau(t)$ the problem can be reduced to eigen-value problem for the matrix **A**, which depends on the functions $w_i(t)$, $\varphi_q(t)$. Matrix **A** is given by the formula:

$$\mathbf{A} = (\mathbf{C}^{-1})^T\, \mathbf{B}\, \mathbf{C}^{-1}$$

where matrices **B** and **C** can be calculated from the formulas:

$$\mathbf{B} = \mathbf{\Phi}^T\, \mathbf{W}\, \mathbf{\Phi}; \qquad \mathbf{C} = \mathbf{\Phi}^T\, \mathbf{\Phi}$$

and matrices **W** and **Φ** are determined with the formulae:

$\varphi_{ik} = \varphi_k(t_j)$, $k = 1, 2, \ldots, M$, $j = 1, 2, \ldots, J$, J is a number of samples in (1).

$w_{km} = \sum_t w_k(t)\, w_m(t)$, $k, m = 1, 2, \ldots, I$.

The eigen-vector, corresponding to the biggest eigen-value of the matrix **A**, has coordinates, which are the coefficients α_m in the amplitude expansion (2). Knowing amplitudes α_k, the wave function is calculated from the formula:

$$f(t) = \sum_{k}^{n} \alpha_k\, Y_k(t) \Big/ \sum_{k}^{n} \alpha_k^2 \qquad (6)$$

For given time-delay function $\tau(t)$ the problem can be reduced to the eigen-value problem for the matrix **A**, which depends on the functions $w_i(t)$, $\varphi_q(t)$. To find coefficients β_q in the expansion (3), we use Newton's method. This implies that for each wave we use an iterative process to determine its parameters. First we fix the time-delay function and solve the eigen-value problem to find the amplitudes a_i and the wave function f(t). Then we fix found amplitudes and wave function and use the Newton's method to determine time-delay function$\tau(t)$ in the form (3).

Wave-by-wave decomposition

A wave-by-wave method has been developed to solve this problem. For each iteration, we fix the parameters of all waves except one. To determine the parameters of the wave, we use the above described approach. In the first step, we find the parameters of the first (dominant) wave. After that, we run an iteration process to improve parameters of the first and second waves together. We consequently create an objective function (5) for the first and second wave. This makes the second step of wavefield separation. For the third step, we change the parameters of three waves, doing iterations for each wave and so on.

Examples

First let us consider a near-zero-offset VSP data from Western Siberia. The described approach gives us tool to extract P waves although we cannot see this wave on the initial wavefield. Fig. 1a shows the near-zero offset (70m offset) VSP wavefield. The residual wavefield after two-wave separation is shown on fig. 1b, where we can see downgoing S waves, invisible on the initial wavefield. Fig. 2 shows the extracted PP upgoing, PS downgoing and PS upgoing waves. Fig. 2b clearly shows downgoing wavefield invisible on initial data. This wavefield allows us to calculate S velocities and use this information in AVO-Inversion problem.

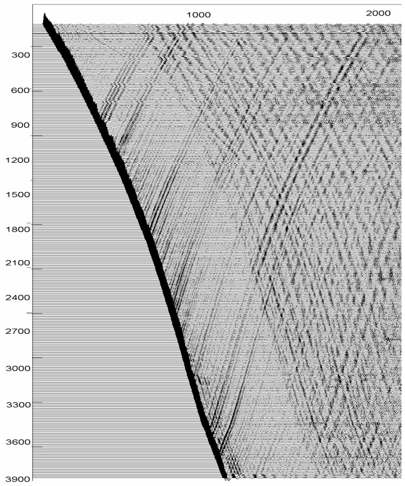

Fig. 1a VSP wavefield

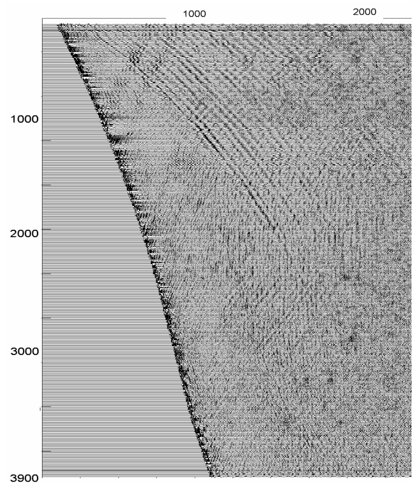

Fig. 1b. Residual wavefield after two-wave separation

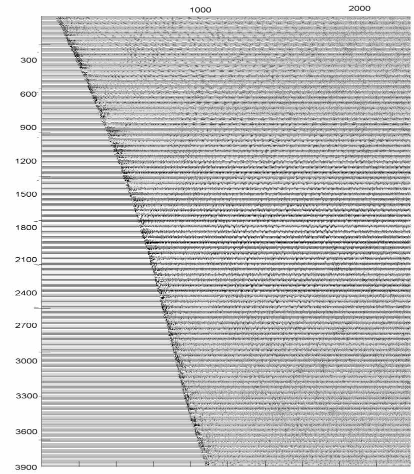

Fig. 1c. Residual wavefield after four-wave separation

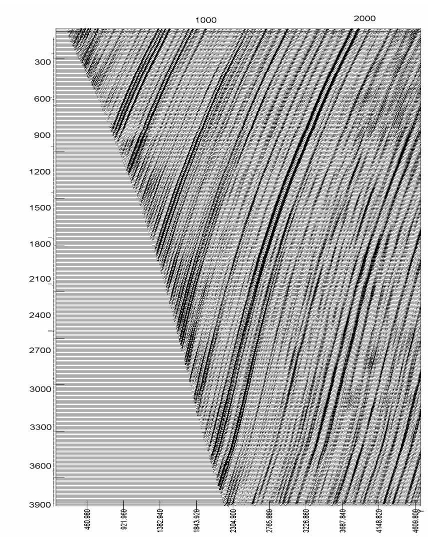

Fig. 2a. Upgoing PP wave

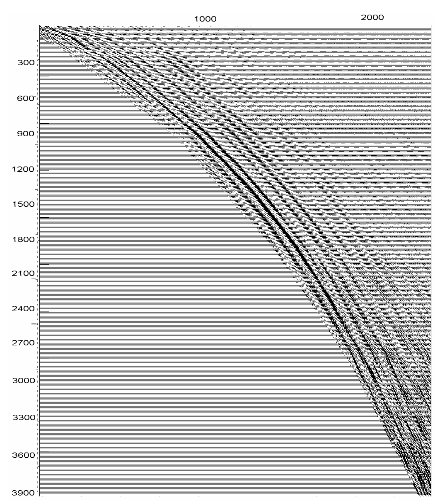

Fig. 2b. Downgoing PP wave

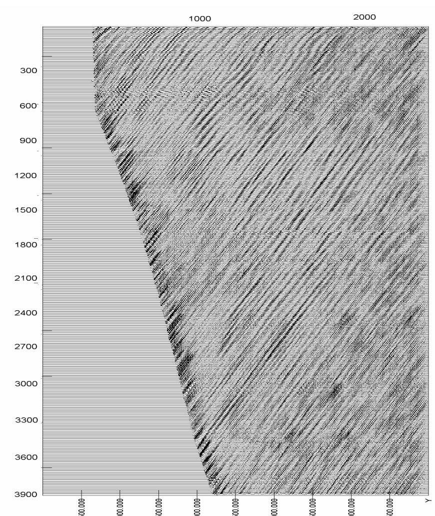

Fig. 2c. Upgoing PS wave

Now let's consider an example for a near-offset VSP wavefield separation with a tube wave. Fig. 3a shows initial VSP wavefield (after AGC applied) with the strong tube wave noise. The result of wavefield separation is shown on the fig. 3b – 3f. The residual wavefield has been increased by two times compared to its real value.

Conclusions.

An approach for VSP wavefield separation has been suggested. To extract downgoing and upgoing waves we use an optimization wave-by-wave extraction method. This method gives us tools to deal with complex wavefields. It allows extracting P waves even from a near-zero VSP offset. We are able to obtain information about seismic S wave velocities from z-component near-zero-offset VSP data.

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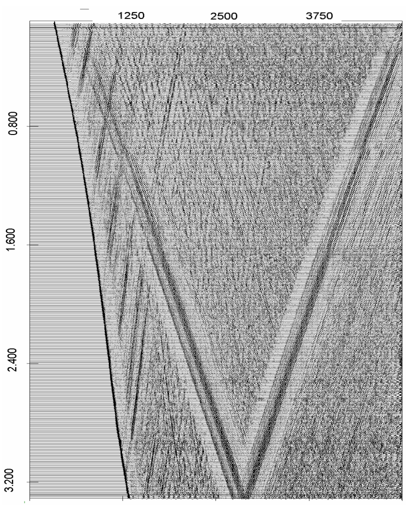


Fig. 3 a. VSP wavefield

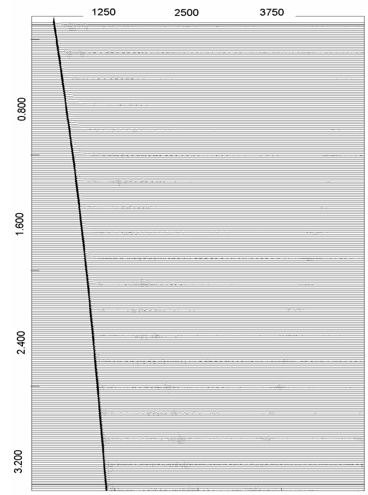
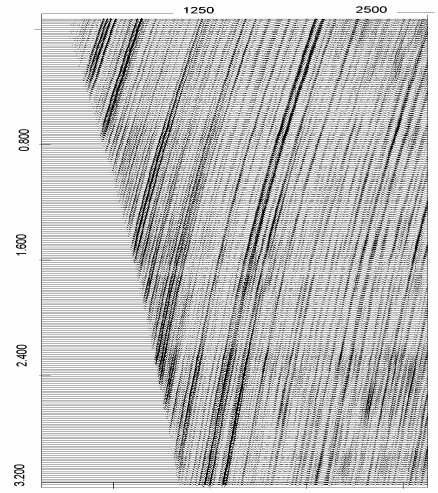


Fig. 3 b. PP downgoing wave Fig.



3 c. PP upgoing wave

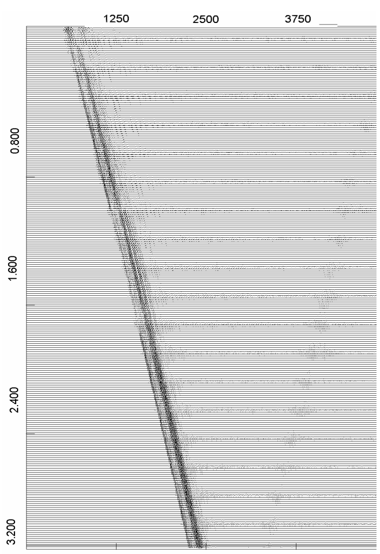


Fig. 3 d. Tube downgoing wave

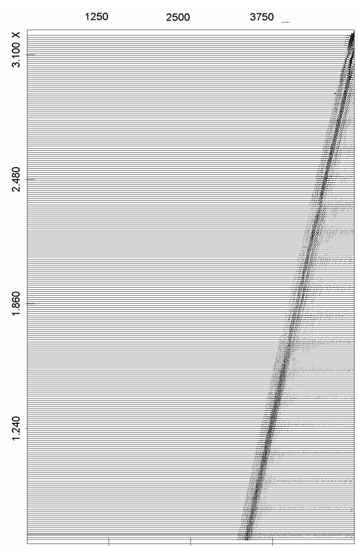
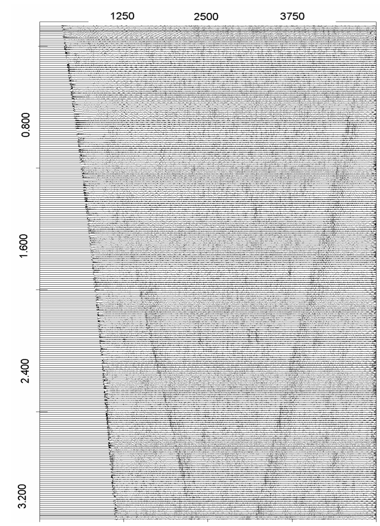


Fig. 3 e. Tube upgoing wave Fig.



3 f. Residual wavefield

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