An algorithm for semi-automated traveltime picking based on the non-hyperbolic moveout

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Summary

Accurate traveltime picking is a critical issue in terms of the input for the kinematical inversion (Jones, 2003). For the industrial processing, the procedure must also be an automated one to deal with large data volumes. We present a practical approach to the traveltime picking accounting for the fourth-order term in the CMP normal moveout formula. The method can be generalized for traveltime curves of any (even) order. The approach enables to split conventional two-dimensional optimization by the two successive one-dimensional optimization steps using the semblance operator. Once implemented as traveltime analysis software, the method prevents a geophysicist from interpreting two-dimensional spectra at each point of analysis.

Introduction

In most cases, the standard hyperbolic approximation for reflection moveouts in heterogeneous media is only accurate for short spread lengths. Numerous investigations, both theoretical and practical, during the past years have proven the necessity to account for higher order terms of a CMP normal moveout formula.

Reflection moveout curves are conventionally approximated with the hyperbolic formula:

$$t^2 = t_0^2 + al^2 . \qquad (1)$$

The reasons are simple: this more or less fits to the observed traveltimes for many datasets; the only parameter a is to be estimated and interactively controlled. Nevertheless, the traveltime curve differs from a hyperbola at far offsets even for the horizontally-layered medium. According to the Fermat principle, it is more flat than the hyperbola corresponding to the average velocity in the medium. The effect is more considerable in the case, where traveltime curves differ from hyperbolas dramatically, as for subsalt reflections.

Improving the accuracy of traveltimes at far offsets would result in considerable stabilizing the traveltime inversion. In addition, traveltimes that are more accurate provide better quality of a time section near a studied event.

In the present study, we use a generic form of a CMP traveltime curve

$$t^2 = t_0^2 + al^2 + bl^4 , \qquad (2)$$

where l is half a distance between the source and the receiver. The family of such functions, besides hyperbolas ($b = 0$), contains not only monotone functions, more or less steep than a hyperbola, but also non-monotone ones including those, where $t(L) < t(0)$. Besides, the method presented can be generalized on higher order polynomials, though we consider this useless because of instability of high order NMO analysis against noise events.

It may seem that the coefficients a and b in (2) can be easily determined by two-dimensional optimization. However, such an approach does not allow us to make computation and interpretation of velocity spectra the interactive procedures. In this case, the spectra become a set of two-dimensional maps rather than that of curves. Hence, model parameter estimates become much less stable in the case of field data processing. Thus, the problem consists in finding a method to apply successive steps of one-dimensional optimization. Obviously, the straightforward search for a followed by the search for b using only the formula (2) is incorrect, and we present and prove the formulas, which allow us to do the successive search of a and b.

Theory

In this section, we prove the possibility to split the two-dimensional optimization by the two successive one-dimensional optimization steps by the special decomposition of the formula (2). We also compute and estimate the parameter estimation errors.

Let the traveltime curve (2) be approximated by the curve $t^2 = t_0^2 + \hat{a}l^2$ in the interval $[0, l_1] \subset [0, L]$, where L is half a maximal offset shot-receiver. Let us minimize the objective

$$J(\hat{a}) = \int_0^{l_1} \left(al^2 + bl^4 - \hat{a}l^2 \right)^2 dl . \qquad (3)$$

From (3) it follows

$$\hat{a} = a + \frac{5l_1^2}{7} b . \qquad (4)$$

The estimate (4) is the LS one, but in practice, the coefficient standing at l^2 is determined based on the non-linear semblance operator (Neidell, Taner, 1971). This has the two consequences.

Firstly, it defines the recommended value of l_1, which should provide that the curve $t_0^2 + \hat{a}l^2$ was located within the central maximums of signals of the studied event. It is difficult to analytically prove this fact for an arbitrary signal shape and a semblance operator, but we have done this for simple analytical signal shapes. Secondly, because $\hat{a}$ is supposed to be estimated basing on velocity spectra computation followed by smoothing, editing, etc., the estimate will be never correct absolutely.

Let us denote by $\tilde{a}$ the estimate of the coefficient a we obtain with a semblance operator in the interval $[0, l_1]$

$$\tilde{a} = \hat{a} + \varepsilon = a + \frac{5l_1^2}{7}b + \varepsilon \ , \qquad (5)$$

where ε is the estimation error.
Substituting (5) into (2), we obtain

$$t^2 = t_0^2 + \tilde{a}l^2 + b\left(l^2 - \frac{5l_1^2}{7}\right)l^2 - \varepsilon \cdot l^2 \ . \qquad (6)$$

In order to determine the coefficient b with the given a priory NMO $t_0^2 + \tilde{a}l^2$, let us minimize the objective

$$J(b) = \int_0^L \left[b\left(l^2 - \frac{5l_1^2}{7}\right)l^2 - \varepsilon l^2 - \tilde{b}\left(l^2 - \frac{5l_1^2}{7}\right)l^2 \right] dx \ . \qquad (7)$$

From (7) it follows

$$\tilde{b} = b - \varepsilon \frac{L^2 - l_1^2}{\frac{7}{9}L^4 - \frac{10}{7}l_1^2 L^2 + \frac{5}{7}l_1^4} \ . \qquad (8)$$

Thus, we obtain the estimate of the sought-for CMP traveltime curve

$$\tilde{t}^2 = t_0^2 + \tilde{a}l^2 + \tilde{b}l^4 = t_0^2 + al^2 + bl^4 + \varepsilon \frac{\left(\frac{7}{9}L^2 - \frac{5}{7}l_1^2\right)L^2 - \left(L^2 - l_1^2\right)l^2}{\frac{7}{9}L^4 - \frac{10}{7}l_1^2 L^2 + \frac{5}{7}l_1^4} l^2$$

The analysis of the term standing at ε shows that the maximal offset L should not exceed l_1 more than in 1.5 –2 times.

Method

The practical algorithm consists of the following steps:

1. Pick a zero-offset time curve on a time stack.
2. Using the conventional NMO formula (1) and the mechanism of horizon-consistent velocity spectra, estimate the parameter a in the interval $[0, l_1] \subset [0, L]$, $l_1 \approx 0.5 \div 0.6L$.
3. Using the NMO formula (6) and the mechanism of horizon-consistent velocity spectra, estimate the parameter b in the interval $[0, L]$.
4. Restack using the NMO formula (6) and improve zero-offset time correlation if necessary.
5. If unable to achieve the hyperbolic fit in the interval $[0, \approx 0.6L]$ at Step 1, analytically compute the LS estimate of a in the whole spread length and repeat with Step 2.

Figure 1 illustrates the process of traveltime analysis.

Examples

An example of application of the algorithm to the marine dataset is shown in Figures 2 and 3. Figure 2 shows the result of the conventional velocity analysis, where it is impossible to fit event traveltimes with a hyperbola. Figure 3 shows the result of the non-hyperbolic analysis with the presented algorithm for the same event, where we find NMO parameters, which straighten the studied event. We can see that the algorithm using the fourth-order term is quite stable against the coherent noise.

Conclusions

The main feature of the presented algorithm is that it reduces two- (or multi-, in a general case) parameter optimization to the successive steps of one- parameter optimization. This allows implementing the algorithm as interactive software using horizon-consistent NMO spectra to search for traveltime curve parameters and providing the geophysicist with an interactive control on all sought-for parameters.

The improved traveltimes resulted from the analysis made with out method significantly improve stability of the traveltime inversion, as well as applying non-hyperbolic NMO provides better stack quality near non-hyperbolic events.

In combination with other processing techniques, such as prestack redatuming, the approach helps with processing in complex geological settings (salt bodies, basalt layers).

References

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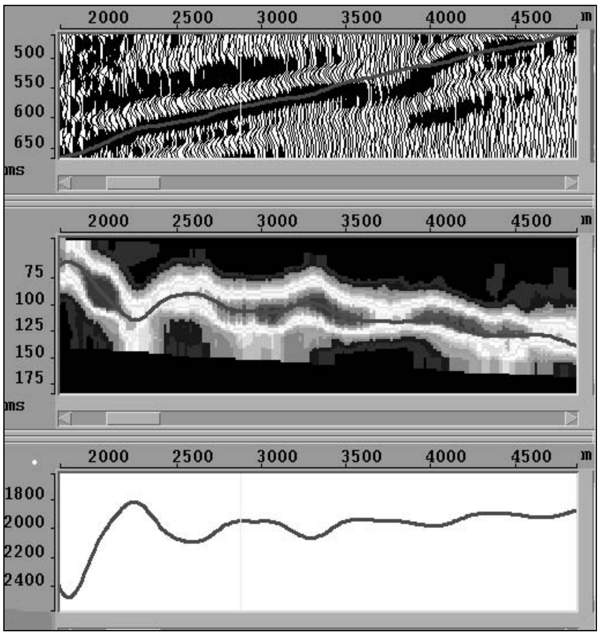

Figure 1. An example of horizon-consistent non-hyperbolic traveltime analysis.

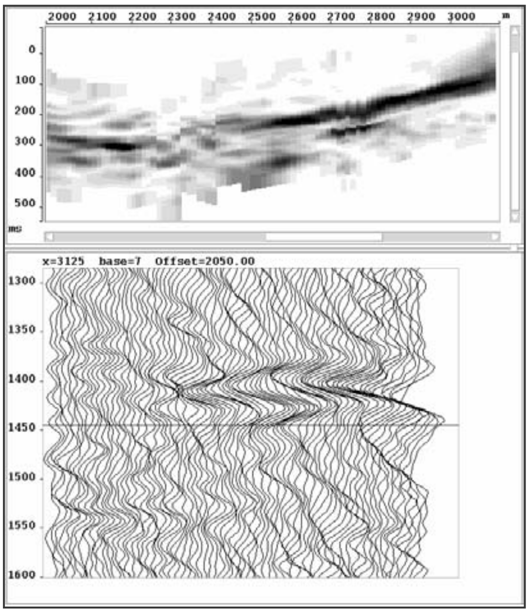

Figure 2. A best-fit hyperbolic NMO-corrected event

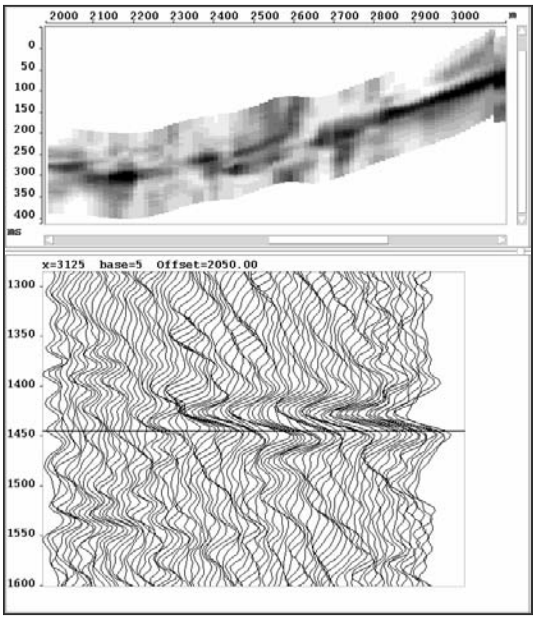

Figure 3. An event corrected with the fourth-order formula with its parameters estimated with the suggested method

Non-hyperbolic traveltime picking