Optimized 6th order NMO correction for long-offset seismic data

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Summary

The conventional 2nd order NMO assumes a small offset-to-depth ratio and straight raypaths. The accuracy for the travel-time calculations decreases significantly with increasing offset-to-depth ratio. The 2nd order NMO may be improved by extending the hyperbolic approximation with higher order (4th, 6th,) series. Conventional NMO is a small offset approximation, therefore, the explicit truncation of the higher order terms generates significant errors in the travel-time calculations at long offsets. Hence, the 2nd order approximation is not suitable for velocity analysis, AVO study, and CMP stack using long offset seismic data. In this paper, we introduce a more accurate travel-time approximation which we called the optimized 6th order NMO equation. The accuracy of the new and proposed equation is better than Taner's 6th order equation because the truncation error is smaller. Even though we truncate Taner's expansion to the 6th order, we take all other higher orders terms into account as well. The tests using synthetic and real data show that our optimized 6th order long offset NMO equation works well. The improvement at long offsets is more significant than Taner's 6th order truncation.

Introduction

Velocity analysis and CMP stack generally use a hyperbolic approximation for reflection travel-times (Dix, 1955). This approximation is accurate at small offset-to-depth ratios only. Many authors have proposed other schemes to improve conventional NMO (Causse et. al. 2000). A fourth order correction may be made by using a three term Taylor series expansion given by Taner and Koehler (1969) and Al-Chalabi, M.(1973). Using more than two terms in the Taylor series can improve velocity analysis and CMP stacking (Gidlow and Fatti 1990). However, a simple truncation generally causes a significant travel-time error at very large offset-to-depth ratios. To have a travel-time approximation with good accuracy at large offsets, we developed an optimized 6th order long offset NMO correction (LNMO). The definition and the coefficients for the first three terms are the same as given by Taner and Koehler (1969). But the coefficient for the fourth term is modified to make the travel-time error smaller. In this paper, we first introduce the new travel-time equation followed by a number of tests made using synthetic and real seismic data. We use synthetic data to compare and contrast the travel time accuracy among 2nd, 4th, 6th and our optimized 6th order equations. We also apply our optimized travel-time equation to real data to compare it with the conventional NMO correction results.

Theory and Method

For a horizontally layered earth, the two-way travel-time equation may be approximated as follows

$$T^2{}_x = c_1 + c_2 x^2 + c_3 x^4 + c_4 x^6 + \cdots \qquad (1)$$

$$c_1 = a^2{}_1$$

$$c_2 = \frac{a_1}{a_2}$$

$$c_3 = \frac{a^2{}_2 - a_1 a_3}{4a^4{}_2}$$

$$c_4 = \frac{2a_1 a^2{}_3 - a_1 a_2 a_4 - a^2{}_2 a_3}{8a^7{}_2}$$

$$a_1 = 2\sum_{k=1}^{n} \frac{d_k}{v_k}$$

$$a_2 = 2\sum_{k=1}^{n} v_k d_k$$

$$a_3 = 2\sum_{k=1}^{n} v^3{}_k d_k$$

$$a_4 = 2\sum_{k=1}^{n} v^5{}_k d_k$$

where x is the offset and c_k are cofficients for the Taylor's series expansion. Equation (1) may be truncated to the 4th, 6th or even higher orders for velocity analysis and NMO correction applications. No matter how high a truncation order is a truncation error is unavoidable. Generally more than a 6th order truncation is not practical in the evaluation of the coefficients. So, we perform the series expansion up to the 6th order. To consider the effect of higher orders beyond the 6th order, we rewrite Equation (1) as

$$
\begin{aligned}
T_x &= \sqrt{c_1 + c_2 x^2 + c_3 x^4 + c_4 x^6 + \cdots} \\
&= \sqrt{T^2{}_3 + c_4 x^6 + \cdots} \qquad\qquad (2) \\
&= T_3 \sqrt{1 + \frac{c_4 x^6 + \cdots}{T^2{}_3}} \approx T_3 + cc \frac{c_4 x^6}{2T_3}
\end{aligned}
$$

where $T_3 = \sqrt{c_1 + c_2 x^2 + c_3 x^4}$ and cc ,in Equation (2), is a constant. The modified 6th term takes some higher order beyond the 6th order effect into account. We call Equation (2) the optimized 6th order NMO equation.

Examples

A synthetic example in a multilayered medium

To validate and illustrate the performance of Equation (2), we present a synthetic example. Table 1 is a list of depths and velocities for the eight-layer 1D model used in the test. We generated a synthetic shot gather (Figure 1a) using an acoustic modeling method. The maximum offset used in the modeling was 8,150 m. We applied the 2nd, 4th, 6th and optimized 6th order NMO corrections (Figures 1b through 1e, respectively) to the prestack synthetic data set. The conventional second order NMO correction (Figure 1b) works satisfactorily for the near offsets. However, it has over corrected the data at far offsets in the time range of 2000 ms to 2820 ms approximately. The 4th order correction (Figure 1c) shows some under correction at far offsets due to c_3 (Equation 1) which is always negative. The 4th order correction is much better than the second order, but not as good as the 6th order correction (Figure 1d). It appears to be a convergent oscillating process as a function of the truncation orders. We can observe some over correction at the far offsets on the 6th order correction (Figure 1d). With our optimized 6th order correction (Figure 1e), we see a significant improvement over the 2nd, 4th and 6th order approximations in the three events. Signals at larger offsets can now be included into the CMP stack to yield an improved image. In addition, the better alignment will benefit long offset AVO analysis as well. This synthetic data set exercise demonstrates that our new travel-time equation is valid.

Table 1. 1D model parameters

Depth (m)	Vp (m/s)
10	1480
500	1780
1000	2000
1500	2800
3000	3500
3500	4000
4000	4500
4500	5000

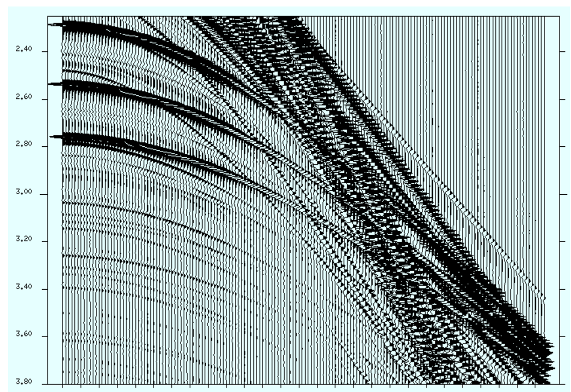

Figure 1a. Synthetic shot gather for the model defined in Table 1.

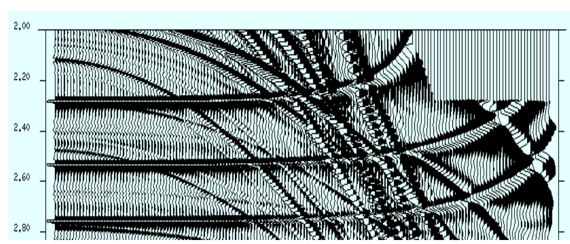

Figure 1b. The 2nd order NMO correction. The data are over-corrected at the far offsets.

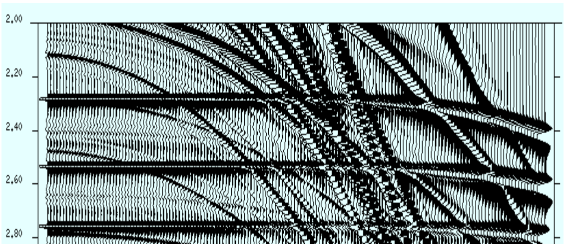

Figure 1c. The 4td order NMO correction. The data are under-corrected at the far offsets.

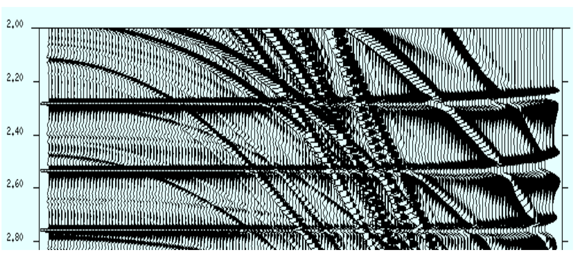

Figure 1d. The 6td order NMO correction. The data are over-corrected at the far offsets.

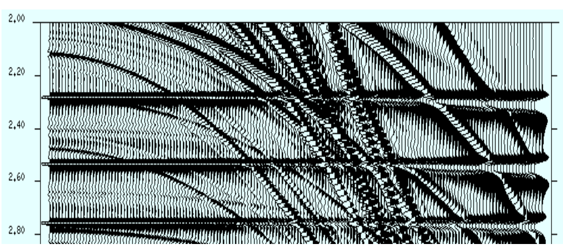

Figure 1e. The optimized 6td order NMO correction. An improvement has been achieved at the far offsets.

A field data example

Fig. 2 shows three CMP gathers from the Gulf of Mexico. These gathers were corrected with the conventional 2nd order NMO (left) and the optimized 6th order NMO (right) equations respectively. For this test, the same RMS velocity was used for both methods. The optimized 6th order NMO equation yields better results. The seismic events appear more coherent across the offsets unlike the result obtained with the 2nd order NMO equation which shows the events over- corrected at the far offsets.

Conclusions

The new proposed optimized 6th order NMO equation produces superior results when used to perform the NMO correction. The synthetic and field data examples shown in this contribution support this conclusion. Even though we truncate the NMO correction order to the 6th term, the new equation retains the accuracy of higher than 6th order terms. The traveltime calculations performed with the optimized 6th order equation approximate the ray tracing travel-times with high accuracy.

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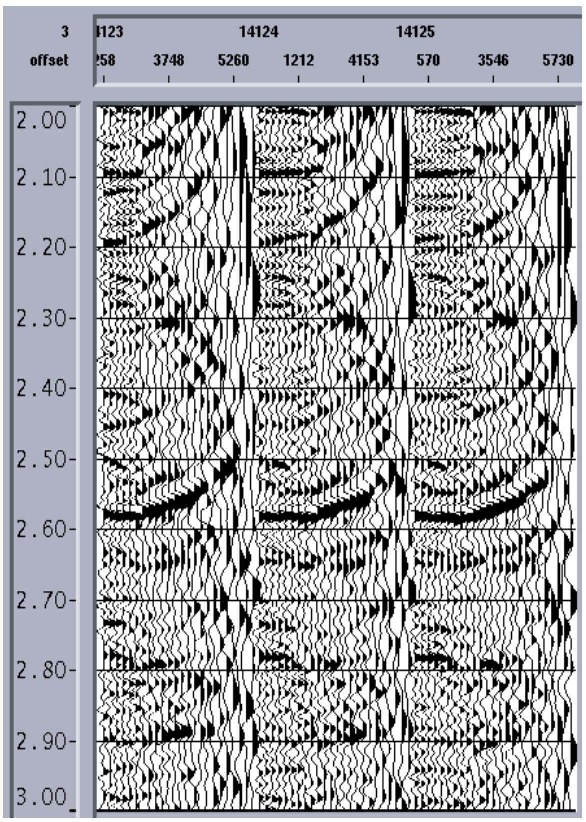

Fig. 2a. Real seismic data CMP gathers after the conventional 2nd order NMO correction.

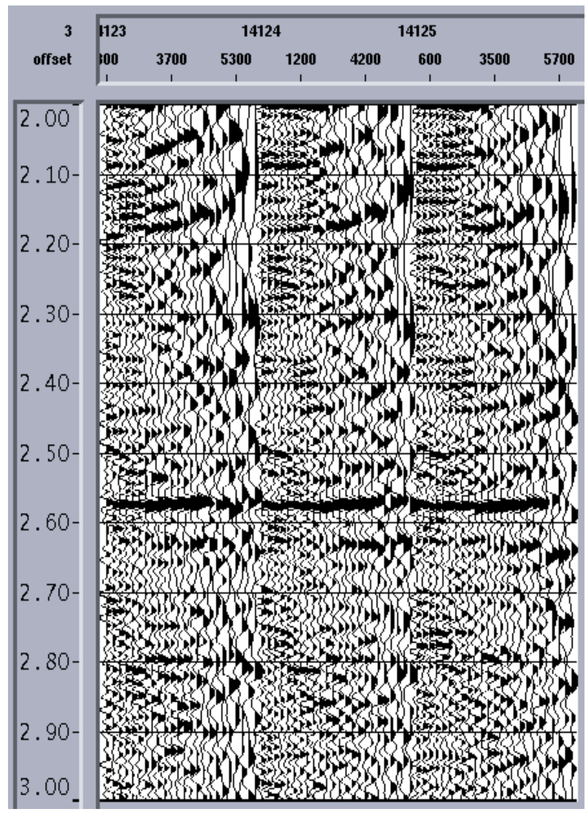

Fig. 2b. Real seismic data CMP gathers after the new optimized 6th order NMO correction.