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NMO Application in VTI Media: Effective and Intrinsic Eta

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Summary

NMO or normal move-out is the time shift needed to correct for the effect of offset and velocity in a CMP gather. NMO equations approximate the time shift which would be computed by tracing a ray through a horizontally layered Earth. A few years ago the 2^{nd} order NMO equation, or hyperbolic NMO, was considered adequate in most cases. Today there are many options in the industry to apply higher order NMO which reduces the error in the approximation to the ray traced solution for longer offsets. There are two characteristics which are important when considering the application of a given NMO curve: 1) accuracy, how well the NMO curve approximates the ray traced solution, and 2) stability, how well the curve can tolerate small errors in the estimated velocity field (one would not want small errors in the estimated velocity field to cause large errors in the move-out time calculated).

If the data being processed is isotropic in nature, then the NMO equation will be dependent on velocity, v and offset x. If the data exhibits VTI (transverse isotropy with a vertical axis of symmetry) behavior, where the velocity of acoustic waves traveling horizontally is different from the velocity of acoustic waves traveling vertically, then the parameter η is used in the NMO equation in addition to v *and* x. *Effective η in the NMO equation expressed by Alkhalifah and Tsvankin (1995) is required to correct for both long-offset (non-hyperbolic) and VTI effects in seismic data. Since two effects are being handled by a single parameter, it is difficult to determine if a dataset exhibits VTI behavior solely on the need for an effective η (η_{eff}) parameter to NMO correct the cdp gathers. This leads to ambiguity in the interpretation of η_{eff} when performing velocity analysis and time imaging. An optimized 6^{th} order NMO equation separates the long-offset terms from the VTI term. The η parameter in this equation is needed only to correct the VTI effects and as such it represents intrinsic η (η_{int}). The use of these two equations has been compared in two case histories. In the first case history, η_{eff} is required but η_{int} is not required. As such, the data exhibits long-offset isotropic behavior. In the second case history, both η_{eff} and η_{int} are required in their respective NMO equations; therefore, the data exhibits VTI.*

Introduction

The use of η_{eff} in the NMO equation expressed by Alkhalifah and Tsvankin (1995) to correct for both long-offset and VTI effects in seismic data is well established in the industry. For the purposes of this discussion I will refer to this equation as "Alkhalifah". In cases where VTI exists, the magnitude of η_{eff} required to correct for the long-offset effects versus that needed to correct for VTI cannot be determined. In cases where the data is isotropic (VTI does not exist), η_{eff} is still required to correct for long-offset effects (Alkhalifah 1997). As such, it is difficult to determine if a dataset exhibits VTI behavior solely on the need for an η_{eff} parameter to correct CDP gathers using this equation. The optimized 6^{th} order NMO equation was originally proposed by Sun *et al*. (2002) and can be implemented as an isotropic long-offset NMO correction or a VTI term can be added to correct for VTI effects (Sun and Martinez, 2002). Because the long-offset effects and the VTI effects are handled in separated terms, the η parameter needed for this correction addresses only the VTI and represents η_{int}.

Theory

A ray-traced two-way travel time through a horizontally layered earth can be approximated by Taylor's series expansion (Taner and Koehler, 1969), which, if truncated at the 2nd order term, becomes the familiar hyperbolic NMO equation, equation (1), where x is offset, t_x is the two-way travel time for offset x, t_0 is the zero-offset travel time and v_{nmo} is the NMO velocity.

$$t_x = \sqrt{t_0^2 + \frac{x^2}{v_{nmo}^2}} \qquad (1)$$

Truncating the series at the 4th order term and solving for the coefficients yields the isotropic 4th order NMO equation also known as Long Offset NMO or LNMO.

$$t_x = \sqrt{t_0^2 + \frac{x^2}{v_{nmo}^2} + c_3 x^4} \qquad (2)$$

It is common to say that higher order NMO equations, such as equation (3), handle the "long offset effects" or "ray-bending" which is another way of saying it is a better approximation of the closed form of the Taylor's series expansion.

It is tempting to keep adding terms of the Taylor's series to increase accuracy. While additional terms do increase the accuracy of the equation, they also cause the equation to become unstable. Small errors in the estimation of v and x can cause large errors in t_x. This because taking offset, x, to large powers generates very large numbers.

To handle both long-offset errors associated with the truncation of the Taylor series (non-hyperbolic NMO) and errors caused by VTI, Alkhalifah and Tsvankin (1995) use an alternative to the 4th order truncation of the Taylor Series described above, shown here as equation (3).

$$t_x = \sqrt{t_0^2 + \frac{x^2}{v_{nmo}^2} - \frac{2\eta_{eff} x^4}{v_{nmo}^2\left[t_0^2 v_{nmo}^2 + \left(1+2\eta_{eff}\right)x^2\right]}} \qquad (3)$$

Having offset, x, in the denominator of the 4th order term adds stability to the equation. In equation (3), η_{eff} corrects for errors due to the truncation of the Taylor series (the long-offset effects) and that due to VTI. If η_{eff} were set to zero, equation (4) would become equation (2) as explained in Alkhalifah and Tsvankin (1995). Hence a non-zero η_{eff} would have to be chosen to correct for the long-offset effect irrespective of the existence of VTI. To eliminate this ambiguity and to improve the accuracy of the analytic NMO equation, Sun and Martinez (2002) implemented an optimized 6th order equation with a VTI term, equation (4).

$$t_x = \sqrt{\left(c_1 + c_2 x^2 + c_3 x^4\right)}\left(1 + \frac{CC}{2}\frac{c_4 x^6}{c_1 + c_2 x^2 + c_3 x^4}\right) - \Delta t_{VTI} \qquad (4)$$

where

$$\Delta t_{VTI} \approx \frac{C_{VTI}\, x^4}{2\sqrt{t_0^2 + \frac{x^2}{v^2}}} \qquad \text{and}$$

$$C_{VTI} = \frac{2\eta_{\text{int}}\, x^4}{v^2[t_0^2 v^2 + (1+2\eta_{\text{int}})x^2]}$$

Equation (4) is a 6th order solution to the original Taylor's series where c_k are the coefficients and CC is a constant designed to estimate the series' closed form. Like the Alkhalifah NMO equation, optimized 6th order NMO has offset, x, in the denominator of the higher order terms to make it stable. The VTI term is encapsulated in Δt_{VTI}. If we set η_{int} in equation (4) to zero, Δt_{VTI} becomes zero and the equation becomes the isotropic optimized 6th order NMO equation expressed by Sun *et al*. (2002). Hence η_{int} in equation (4) represents intrinsic η and not effective η as in equation (3).

Examples

The first case history is from offshore Brazil in the Santos basin. Here a 3-D true amplitude pre-stack time migration (TAPSTM) was performed using the isotropic optimized 6th order travel time equation described by Sun and Martinez (2002). The isotropic optimized 6th order NMO was removed and a residual velocity analysis was performed using equation (4) and a separate residual velocity analysis was performed on the same data using equation (5). Figure 1 shows a stack of the TAPSTM gathers generated from the velocity analysis using the Alkhalifah equation (equation 4). The stack is overlain by the η_{eff} field determined from the analysis. The magnitude of η_{eff} ranged from 0 to 0.145 with an average of 0.065. The residual velocity analysis using the optimized 6th order NMO equation yielded a null η_{int} field. This would suggest the data is isotropic. A comparison of a single TAPSTM gather moved out with various NMO curves can be seen in Figure 2. Here the gather was first moved out with a 2nd order NMO equation (Alkhalifah NMO with a null η_{eff} field); the classic "hockey sticks" seen on the far offsets might be interpreted as VTI effects. The next gather in Figure 2 is the same gather with an isotropic 4th order NMO applied. Here the data has been corrected and the "hockey sticks" are no longer evident.

The 3rd and 4th gather is the same gather moved out with Alkhalifah using the picked η_{eff} field and optimized 6th order NMO using a null η_{int} field respectively. The 4th order NMO, Alkhalifah and optimized 6th order NMO gave commensurate results, which is further evidence that the data is isotropic.

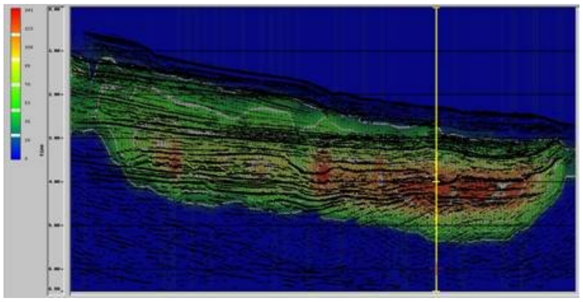

Figure 1: η_{eff} field underlain by the TAPSTM stacked subline from offshore Brazil. Values of η_{eff} range from 0 – 0.141. The η_{eff} field was determined by residual migration velocity analysis using the Alkhalifah NMO equation.

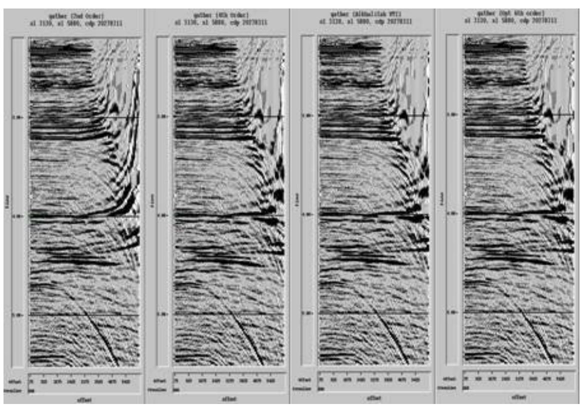

Figure 2: Unmuted TAPSTM gather from offshore Brazil moved out with 2nd order NMO, 4th order NMO, Alkhalifah NMO using η_{eff} and isotropic optimized 6th order NMO respectively.

The second case history is from offshore West Africa. As in the example from offshore Brazil, the data was migrated using TAPSTM and then the original velocity function was removed using inverse NMO. A velocity analysis was performed on a single CDP line using both Alkhalifah and optimized 6th order NMO with the VTI term. The results of this analysis can be seen in Figure 3. Figure 3(a) shows the stacked seismic line underlying the picked η_{eff} field using the Alkhalifah NMO equation. The average η_{eff} from this analysis was 0.057. Figure 3(b) shows the same stacked line underlying the picked η_{int} using the optimized 6th order NMO equation. The average η_{int} from this analysis was 0.012. The values of η_{eff} from the West Africa example are larger in magnitude and broader in range than that exhibited by η_{int} for the same data.

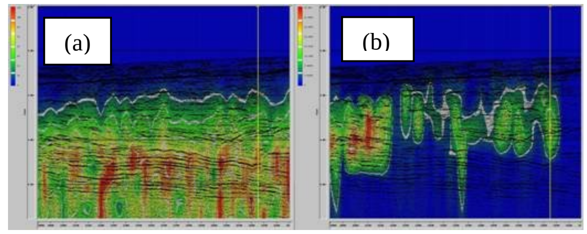

Figure 3: (a) η_{eff} field underlain by the TAPSTM stacked subline from offshore West Africa. The range of η_{eff} values are 0 – 0.125. The η_{eff} field was determined by residual migration velocity analysis using the Alkhalifah NMO equation.

(b) η_{int} field underlain by the TAPSTM stacked subline from offshore West Africa. The range of η_{int} values are 0 – 0.035. The η_{int} field was determined by residual migration velocity analysis using the Optimized 6th Order NMO equation.

Figure 4 shows a single TAPSTM gather from the West Africa example moved out with 2nd order NMO, 4th order NMO, Alkhalifah and Optimized 6th order NMO. The 2nd and 4th order NMO do not adequately correct the gather. Alkhalifah corrects the gathers to a greater extent and the optimized 6th order NMO improves the gather slightly further. An example of this improvement can be seen on the event circled in red in figure 4. The improvement of the optimized 6th order NMO over Alkhalifah is attributed to greater accuracy of the long-offset component of the optimized 6th order NMO equation.

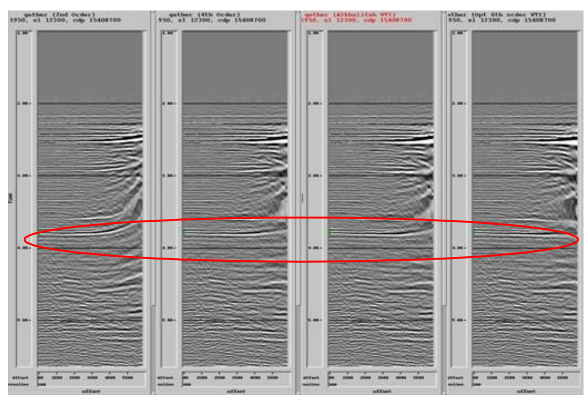

Figure 4: TAPSTM gathers from offshore West Africa moved out with 2nd order NMO, 4th order NMO, Alkhalifah NMO using η_{eff} and isotropic optimized 6th order NMO using η_{int} respectively. The event circled in red shows improved flattening using the Optimized 6th Order NMO correction with the $\eta_{int.}$

Conclusions

Effective η as required by the Alkhalifah NMO equation is used to address both long-offset effects due to the truncation of the Taylor series expansion and VTI. This leads to ambiguity in the interpretation of η_{eff} when performing velocity analysis and time imaging. The optimized 6th order NMO equation separates the long-offset terms from the VTI term. This allows for intrinsic η analysis in areas exhibiting VTI and isotropic velocity analysis in areas where only the long-offset effects are evident. The η_{int} fields generated from optimized 6th order NMO velocity analysis tend to exhibit smaller values with tighter distributions than that of η_{eff} generated from Alkhalifah NMO velocity analysis. This is due to the separation of the long-offset NMO and VTI effects in the optimized 6th order equation.

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