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Proper time-referencing for prestack Q estimation and compensation

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Summary

When applying attenuation compensation for prestack marine data, the traveltime spent in the water layer should be removed from the total traveltime because water practically does not attenuate acoustic waves. Current industry practices use either vertical water bottom time or offset water bottom time as the reference time. Both worked for certain water depths and targets, but failed in general to remove the water layer accurately. The relative timing error of improper timing referencing can be as large as 100%, which is directly translated into relative phase error of 100%. In this paper, I derived a simple analytical formula that can be used to remove the water layer from the total ray path with accuracy within 3% for all water depths and targets. The formula is essentially a modified form of the normal moveout velocity, thus can be readily incorporated into standard processing toolkits.

Introduction

Subsurface rocks are not perfectly elastic, they attenuation seismic waves. Seismic waves propagating in the viscous rocks are attenuated and dispersed, resulting in amplitude decay and phase delay. Compensating for the attenuation, commonly known as Q is an important step in seismic data processing to enhance seismic resolution and improve well-ties. It is well known that for all practical purposes water does not attenuate sonic waves, therefore Q-compensation should be applied to the ray path spent in the rocks, not in the water. Figure 1 illustrated the total ray path (Sw + Sr + Sr + Sw), out of which the water legs (Sw + Sw) should be excluded from the total ray path when applying Q-compensation.

For poststack marine data, removing water legs can be easily achieved by starting the Q-compensation from the water bottom. However, for prestack gathers acquired in a marine environment, the practices of excluding water legs from the traveltime varied widely. There are two generally accepted practices. One uses zero offset water bottom time (Zw+Zw in Figure 1) as the new reference time, the other uses flattened offset water bottom (Lw+Lw in Figure 1) as the reference time. The former works well for deep targets, but not as well for shallow targets; while the latter works well near the water bottom, but fails miserably away from the water bottom. Figure 3 showed the timing error introduced by the two approximations for the velocity model shown in Figure 2. For this particular model, the relative timing error can be as large as 100%. Recall the dispersion relationship (Kjartansson, 1979)

$$\gamma(\omega) = \frac{\omega \boldsymbol{t}}{\pi \boldsymbol{Q}} \ln\left(\frac{\omega}{\omega_0}\right), \qquad (1)$$

where ω is the angular frequency and ω_0 is the reference angular frequency, $\gamma(\omega)$ is the phase term. Equation (1) naturally leads to an expression for the relative phase error,

$$\frac{\delta\gamma}{\gamma} = \frac{\delta t}{t}, \tag{2}$$

which is equivalent to the relative timing error. Therefore both approximations illustrated in Figure 3 yielded the relative phase errors larger than 30% for most depths. It became obvious a better approximation is needed. In this paper, I derived a simple analytical formula that works equally well for all water depths and all targets with relative phase error within 3%. The algorithm I derived is a simple modification on current normal moveout (NMO) routines, making it easily adaptable.

Method

Since water does not attenuate waves, we can simply ray-trace through the earth model, and eliminate the time ray spent in the water. The resultant time should be properly time referenced, i.e., it reflects the actual time the ray spends on the attenuative rocks. All the derivation here assumed a locally 1D earth model. For simplicity, I further assumed a straight ray path.

Under the straight ray assumption, for a given offset $\boldsymbol{x}$ the time spent in the water for the ray path that reflects from two-way time $\boldsymbol{T}$ can be expressed as

$$\boldsymbol{T}_w(\boldsymbol{x},\boldsymbol{T}) \approx \frac{\boldsymbol{T}_{0w}}{\sqrt{1-(\frac{\boldsymbol{x}}{\boldsymbol{T}\boldsymbol{V}_{rms}})^2}}\ , \tag{3}$$

where $\boldsymbol{T}_{0w}$ is the zero-offset two-way water bottom time, $\boldsymbol{V}_{rms}$ is the normal moveout velocity at two-way time $\boldsymbol{T}$.

The time spent in the rocks $\boldsymbol{T}_{rock}$ then is simply

$$\boldsymbol{T}_{rock} = \boldsymbol{T} - \boldsymbol{T}_w(\boldsymbol{x},\boldsymbol{T})\,. \tag{4}$$

Recall the familiar hyperbolic moveout curve,

$$\boldsymbol{T}^2 \approx \boldsymbol{T}_0^{\,2} + \frac{\boldsymbol{x}^2}{\boldsymbol{V}_{rms}^{\;2}}\,. \tag{5}$$

Substituting Equation 5 into Equation 4, I obtained

$$\boldsymbol{T}_{rock} \approx \boldsymbol{T} - \boldsymbol{T}_{0w}\sqrt{1+\frac{\boldsymbol{x}^2}{\boldsymbol{V}_{rms}^{\;2}\boldsymbol{T}_0^{\,2}}}\ . \tag{6}$$

Equation 6 is the approximate expression for computing traveltime in the subsurface rocks. It depends on the normal moveout velocity, offset, zero offset water bottom time, zero offset event time and event time. Even though it can be implement in a moveout routine, I found a much simpler expression by adding zero offset water bottom time to $\boldsymbol{T}_{rock}$, the new time $\boldsymbol{T}_{rw}$ is

$$\boldsymbol{T}_{rw} = \boldsymbol{T}_{rock} + \boldsymbol{T}_{0w}\,. \tag{7}$$

Expanding Equation 7 with Equation 6 and ignoring the higher than second order terms, I obtained an expression for $\boldsymbol{T}_{rw}$,

$$\boldsymbol{T}_{rw} \approx \sqrt{\boldsymbol{T}_0^{\,2} + \frac{\boldsymbol{x}^2}{\boldsymbol{V}_{qrms}^{\;2}}}, \tag{8}$$

where $\boldsymbol{V}_{qrms}$ is defined as

$$\boldsymbol{V}_{qrms} = \frac{\boldsymbol{V}_{rms}}{\sqrt{1-\frac{\boldsymbol{T}_{0w}}{\boldsymbol{T}_0}}}, \tag{9}$$

Equation 8 is the same as equation 5 but with a modified normal moveout velocity $\boldsymbol{V_{qrms}}$ that depends only on the normal moveout velocity $\boldsymbol{V_{rms}}$, zero offset water bottom time and zero offset time for the events. Proper traveltime through the rocks can be obtained by taking out zero offset water bottom time from $\boldsymbol{T_{rw}}$. Appropriate Q estimation or compensation can then be reliably performed in this new reference time domain. A typical Q processing flow with proper time referencing may follow the sequence below:

1. Apply NMO correction on the gather with the given $\boldsymbol{V_{rms}}$ function.
2. Apply *reverse* NMO on the gather with the modified $\boldsymbol{V_{qrms}}$ function.
3. Apply static shift to remove $\boldsymbol{T_{0w}}$.
4. Perform Q estimation and/or apply Q compensation on the prestack gathers.
5. Apply NMO with $\boldsymbol{V_{qrms}}$.
6. Apply *reverse* NMO with $\boldsymbol{V_{rms}}$.

This workflow I presented above does not require any change to the existing NMO routines, only a modified RMS velocity ($\boldsymbol{V_{qrms}}$) needs to be supplied. Therefore this workflow can be readily adapted to any production processing toolkits.

Examples

To validate the expression derived in the above section, I tested it on a synthetic 1D model shown in figure 2. Figure 3 showed the two prevailing industry approximations, static shifts based on vertical water bottom time (dash dotted) and on flattened offset water bottom (dashed), against the exact ray tracing (solid). Noted that vertical water bottom approximation worked well at deep targets, but not so well at shallow depth; while the flattened offset water bottom approximation worked well near the water bottom, but quickly degraded as deeper events were encountered. The relative phase error ranged from 100% at 1 second to 5% at 5 seconds for the vertical water bottom approximation and from 0% at 1 second to 40% at depth slightly below 1 second. In contrast, the expression I derived in this paper worked equally well at all depths (Figure 4), with relative phase error well within 3%.

Even though what I have shown here is only one particular velocity model and water depth, experiments with a range of water depths and velocity models showed that negligible phase errors were observed with the new time reference formula.

Discussion and conclusions

In this paper I derived an analytic expression for effectively removing the water legs from the traveltime calculation. Even though I made the straight ray approximation and truncated higher order terms, the expression worked well for all depths of interests to exploration geophysics. The relative phase error was limited to within few percent, clearly showing advantage over current industry practices.

The properly time-referenced gathers can be analyzed for Q versus offset effects. Significant errors can be introduced if the gathers are not properly time-referenced.

Because the expression I derived is a simple modification of the normal moveout velocity, it does not require any change to the existing NMO routines, thus can be readily adapted for any production processing system.

The algorithm I proposed here is inherently limited by its 1D assumption. A more rigorous prestack depth migration with Q-compensation would take care of the time referencing problem automatically.

References

Kjartansson, E., 1979, Constant Q—wave propagation and attenuation: J.Geophys, Res., 84, 4737-4748.

Acknowledgements

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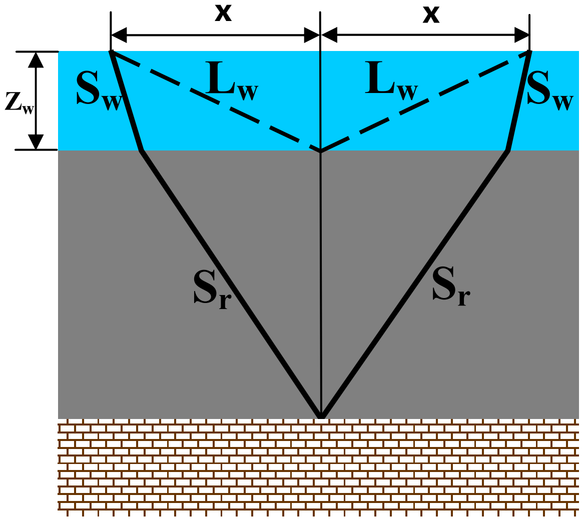

Figure 1. Schematics of the ray paths involved. The total ray path is Sw + Sr + Sr + Sw. One approximation simply removed Zw+Zw from the total ray path whereas the other one removed Lw+Lw from the total ray path.

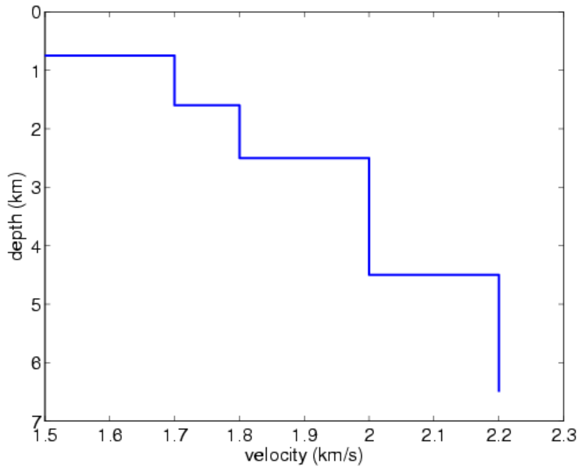

Figure 2. Synthetic velocity model used for the ray tracing.

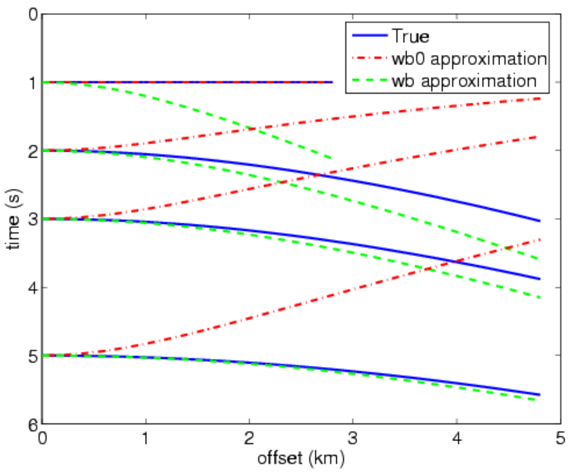

Figure 3. Two common industry approximations (dashed and dash dotted) attempting to remove the water legs from the ray path were compared with the true time referenced traveltime (solid).

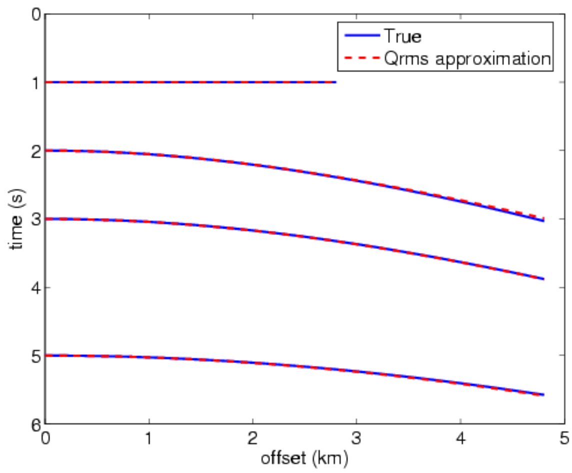

Figure 4. The approximation I derived (dashed) nearly matched the true traveltime (solid).