3D Imaging of Steep Dip Data

Wide Azimuth Acquisition and Complex structure

Summary

When dips are present in a Wide Azimuth 3D data-set, the velocity required to focus events to be stacked into a CMP varies with the source to receiver azimuth relative to the strike and dip of the structure. Even small dip rates can have serious deleterious effects on the stack response.

This is the well understood DMO effect, normally corrected for with multi-channel Dip Move-out, Pre-stack Time Migration or PSDM operators that smear any residual statics in the data that we are trying to resolve.

We need to correct these velocity variations early in the processing flow so that we can solve the residual statics/velocity analysis iterative sequence more confidently.

We use a structural interpretation and compute corrections using Levin’s NMO formula (1971), which takes into account the dip relative to the source/receiver azimuth to compute the correct NMO for each offset and time in a CMP. The Levin’s method will produce ‘zero dip velocities’ for superior focusing of dipping reflectors. The interpreted velocity model is lithologically consistent and is the preferred PSTM starting point. The dip field is also used for building robust local CMP super-gathers for residual statics analysis and velocity semblance displays.

Preamble

This issue arose from the recognition that on 2D data, dip and strike lines require different stacking velocities at the intersection. Levin’s NMO was not used in production processing because of the development of DMO shortly after, which is a better way of solving the velocity discrepancy and imaging issues, particularly for 2D marine data. Levin’s NMO was forgotten about with the advent of 3D until there were enough channels available for the wide azimuth recording we see now.

\[ DT = \left( T^2 + \frac{X^2}{V^2} \right) - T \]

Levin’s NMO

\[ DT = (T^2 + X^2/V^2 \cos^2 \theta)^2 - T \]

Conventional NMO

This is what it looks like from a depth perspective. The travel path in the dip direction is shorter than the travel path in the strike direction. The Levin’s NMO equation has a dip correction parameter included.
With a near vertical reflector, it can be seen that the near trace path and the far trace path are the same length, so have the same travel time, i.e., DT NMO is zero.

The long offset travel along strike has conventional NMO characteristics.

<table>
<thead>
<tr>
<th>Dip (degrees)</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>80</th>
<th>89.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>App dip ms/tr</td>
<td>5.4</td>
<td>10.6</td>
<td>15.2</td>
<td>19.2</td>
<td>22.6</td>
<td>25.4</td>
<td>29.8</td>
<td>31.5</td>
</tr>
<tr>
<td>RMS Velocity</td>
<td>7000 ft/sec</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Offset</td>
<td>5000 feet</td>
<td>1429 msec</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NMO DT (msec)</td>
<td>168.6</td>
<td>168.6</td>
<td>168.6</td>
<td>168.6</td>
<td>168.6</td>
<td>168.6</td>
<td>168.6</td>
<td>168.6</td>
</tr>
<tr>
<td>Dip vel (ft/sec)</td>
<td>7,108</td>
<td>7,449</td>
<td>8,083</td>
<td>9,138</td>
<td>10,890</td>
<td>14,000</td>
<td>40,311</td>
<td>Inf</td>
</tr>
<tr>
<td>Levin's DT (msec)</td>
<td>163.8</td>
<td>149.8</td>
<td>128.2</td>
<td>101.2</td>
<td>72.0</td>
<td>44.0</td>
<td>5.4</td>
<td>0.0</td>
</tr>
<tr>
<td>Levin's DT diff (msec)</td>
<td>4.8</td>
<td>18.8</td>
<td>40.4</td>
<td>67.4</td>
<td>96.7</td>
<td>124.7</td>
<td>163.2</td>
<td>168.6</td>
</tr>
<tr>
<td>% Velocity change</td>
<td>101.5</td>
<td>106.4</td>
<td>115.5</td>
<td>130.5</td>
<td>155.6</td>
<td>200.0</td>
<td>575.9</td>
<td>57295.8</td>
</tr>
</tbody>
</table>

This sheet shows the difference in DT between conventional NMO and Levin’s NMO for a range of dips. The model velocity here is 7000’/sec, with offset = depth of 5000’, the two way time is 1429 msec.

As the dip increases, the DT decreases dramatically. The stacking velocity also increases to infinity at 90 degree dip.

The apparent dip in the stack data goes to a max, in this case 31.5ms/trace at 90 degrees (with 110ft bins).
This is a synthetic CMP gather with random source-receiver azimuths, as expected in a 3D gather and corrected with conventional NMO at 7000 ‘/sec. To correct the traces recorded in the dip direction, the velocity would need to be 8083’/sec at 1500 msec.

Levin’s NMO does a perfect job of correcting all traces when there is access to the dip and strike database. This allows for superior cross-correlation performance in residual statics computations.
Zoom in to the one second event to see the effect of lower dip rates. Note that the wavelet here is a 25Hz Ricker, so is still very significant even at low dip rates.

Here is another way of visualizing the problem. This effect is orders of magnitude larger than Azimuthal Anisotropy. Again, Levin’s NMO is the solution, when dip and strike data are available.
We can now see clearly and correct for VTI Anisotropy using Fourth Order NMO corrections.

**Structural Dip Estimation:**

- Several ways to do this.
- We have automatic methods to pick in-line and cross-line dips. This is similar to dip the steering volumes that are used for curvature attributes, etc.
- As we are working on stack data that has rough velocities and no residual statics (initially), the data quality is often too poor to respond well to automatic dip picking.
- For practical reasons, we prefer to manually interpret the key horizons that define the gross structure.
- This can be refined after the initial iterations of residual statics and velocity analyses, when the stack data quality has improved.

**Dip conversion – step 1**

- Levin’s NMO formula requires true geologic dip.
- Our 3D implementation requires the geologic strike as well, so that we can compute the structural relationship to the source receiver Azimuth.
- First, we need to compute the apparent geologic dips in the in-line and cross-line directions. The picked horizons are converted by differentiation to a Msec/trace field for the volume.
- This dip in milliseconds per trace is converted to vertical distance using the best interval velocity field available. (Stacking velocities, smoothed) and converted to dip in degrees using the CMP bin spacing.

\[
\text{Apparent Dip (degrees)} = \arctan(\text{time dip} \times \text{Vel/bin size})
\]
Dip conversion – step 2

- This current apparent dip is apparent in two senses:
- It is oblique to the structure and is un-migrated. To compute the Migrated dip, we use the ‘Migrator’s Equation’ (from the days when data was hand migrated from 2D sections).

\[
\text{Migrated dip} = \sin^{-1}(\tan(\text{time dip}))
\]

- The Geologic dip is always greater than the apparent time dip from stacked data.

Dip conversion – step 3

From our hand interpreted (or automatic) horizons, we derive the true dip and strike at every CDP and time (interpolating between horizons). We need to have sufficient horizons defined to make this as sensible as possible.
This is the “Common Plane Problem” Two apparent dips in known directions (inline and crossline). What is the true Dip and Strike?

Fortunately, many have already worked this one out

Common Plane Calculator

<table>
<thead>
<tr>
<th>Data ID</th>
<th>In-line</th>
<th>Cross-line</th>
</tr>
</thead>
<tbody>
<tr>
<td>S&amp;D from 2 a.d.</td>
<td>Azimuth</td>
<td>dip</td>
</tr>
<tr>
<td>S&amp;D from 2 a.d.</td>
<td>134.000</td>
<td>40.930</td>
</tr>
<tr>
<td>Linear 1</td>
<td>Cos(alpha)</td>
<td>Cos(beta)</td>
</tr>
<tr>
<td>Linear 2</td>
<td>Cos(alpha)</td>
<td>Cos(beta)</td>
</tr>
<tr>
<td>Theta</td>
<td>0.543</td>
<td>-0.525</td>
</tr>
<tr>
<td>Angle(rad.s)</td>
<td>Theta</td>
<td>Angle(deg.s)</td>
</tr>
<tr>
<td>Angle(rad.s)</td>
<td>1.935</td>
<td>110.846</td>
</tr>
<tr>
<td>Cross-product</td>
<td>Cos(alpha)</td>
<td>Cos(beta)</td>
</tr>
<tr>
<td>3D</td>
<td>Cos(alpha)</td>
<td>0.118</td>
</tr>
<tr>
<td>Lower hemisphere</td>
<td>0.118</td>
<td>0.725</td>
</tr>
<tr>
<td>Plane</td>
<td>Strike azimuth</td>
<td>Dip</td>
</tr>
<tr>
<td>Plane</td>
<td>90.725</td>
<td>47.252</td>
</tr>
</tbody>
</table>

The values are from the yellow horizon in the previous image. Dip is 47 degrees, dip azimuth is 170 degrees.

For each trace and time sample in the CDP, we modify the θ in Levin’s NMO to account for the relative incident angle.
Super-gathering:

- Now that we have the Normal moveout issue solved, we use the basic time/dip field to adjust surrounding CDP data to the central CMP.
- For each CMP we time variantly shift each horizon to align the signal. Typically we would use a 3 or 5 bin radius, depending on the CDP Fold and data quality.
- This is so we can raise the useful fold for Residual statics calculations.
- This is appropriate for Pilot driven, Stack Power, or Raw Trace Correlation methods.
- For Velocity analysis, super gathering greatly improves the S/N ratio both for stack panels and semblance views, for a more robust interpretation.

The dips here are up to 20 degrees. Shown on the left are raw traces and right, with Levin’s NMO and dip alignment applied.
Levin’s NMO Applied + 1st Pass Residual statics

After a pass of residual statics and velocity analysis, this is the typical result. Now we can see the strike on the Time Slice.

We use this better quality data to modify the structural estimate (by hand, or automatically) for the next residual statics iteration.

Levin’s NMO Applied + 2nd Pass Residual statics
Another example:

2010 processing

2014 processing
Conclusions:

- Velocity focused CMP gathers permit superior Residual Statics Cross-correlation performance, with much higher resolution.
- We use the time dip information to construct useful supergathers for more robust Velocity Analysis and Residual Statics on both 2D and 3D datasets.
- We can now use a more open mute to increase stack fold and improve the long period residual statics resolution.
- The Velocity field now has the ‘dip effect’ removed, so are lithologically sensible, focused and stable.
- VTI Anisotropy can be more accurately estimated and corrected.
- These VTI dip corrected velocities provide a superior starting point for Pre-stack Time Migration and the initial velocity building for Pre Stack Depth Migration.