Flooding the topography: Wave-equation datuming of land data with rugged acquisition topography[*]

Dimitri Bevc

Formerly Stanford Exploration Project, Stanford University, Stanford, CA 94305; Presently 3DGeo Development Inc., 465 Fairchild Drive, Suite 226, Mountain View, CA 94043.

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ABSTRACT

Wave-equation datuming overcomes some of the problems that seismic data recorded on rugged surface topography present to routine image processing. The main problems are that (1) standard, optimized migration and processing algorithms assume data are recorded on a flat surface, and that (2) the static correction routinely applied to compensate for topography is inaccurate for waves that do not propagate vertically. Wave-based processes such as stacking, dip moveout correction, normal moveout correction, velocity analysis and migration after static shift can be severely affected by the non-hyperbolic character of the reflections.

To alleviate these problems, I apply wave-equation datuming early in the processing flow to upward continue the data to a flat datum, above the highest topography. This is what I refer to as "flooding the topography". This approach does not require a detailed a priori knowledge of the near-surface velocity, and it streamlines subsequent processing because the data are regridded onto a regularly sampled datum. Wave-equation datuming unravels the distortions caused by rugged topography, and unlike

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the static shift method, it does not adversely effect subsequent wave-based processing. The image obtained after wave-equation datuming exhibits better reflector continuity and more accurately represents the true structural image than the image obtained after static shift.

INTRODUCTION

Some of the last petroleum prospecting frontiers are in overthrust areas where rugged topography and irregular data coverage present significant processing challenges. The rugged terrain and complex structure make drilling very expensive, and since there is often little well control or a priori velocity information, it is critical to lower risk by extracting as much information out of the seismic data and providing the best possible image. Even when good quality data are recorded in these terrains, the processing challenges that arise due to topography, the presence of high-velocity rocks near the surface, and complex subsurface velocity can impede conventional processing and subsequent interpretation.

Seismic imaging algorithms are generally applied to data which is datumed to a planar surface. In regions of mild topography where the near-surface velocity is much slower than the subsurface velocity, a static shift is adequate for the transformation. However, when static shifts increases in magnitude and when the near surface velocity is comparable to the subsurface velocity, the static approximation becomes inadequate. Under these circumstances, a static shift distorts the wavefield and degrades the velocity analysis and imaging. In this case it is necessary to propagate the wavefield numerically to some level datum. This wave-equation datuming process may be used to “flood” the topography by filling it with a replacement velocity and upward continuing the data through it.

The concept of wave-equation datuming was first presented by Berryhill (1979) for poststack applications, and latter extended to prestack data (Berryhill, 1984). Unlike datuming with static shifts, wave-equation datuming removes the distortions caused by topography in a manner consistent with wavefield propagation. This insures that subsequent processing steps which assume hyperbolic form, or even more complicated trajectories consistent with wave propagation, can be accurately applied.

I demonstrate how wave-equation datuming can be used to improve and simplify the early stages of processing and imaging by applying the process to an overthrust data set from the Canadian Rockies. In this example, wave-equation datuming provides a clear improvement over conventional statics processing. Because the data are regridded onto a flat evenly sampled datum, further processing is streamlined and structural interpretations are easier to incorporate into the analysis.

Standard processing of overthrust data

Successful processing in overthrust areas has relied on heavy interaction between interpreters and processors (Burke and Knapp, 1995; Tilander and Mitchel, 1995). In recent years several advances have been made, not the least of which has been improved acquisition technology. Increased shothole depth, shot charge, and fold, go a long way towards increasing data quality. Data processing has generally consisted of early stage filtering and noise suppression followed by iterations of static shift and preliminary velocity estimation. The final output datum is usually set above the highest topography. However, during processing, data are often corrected to a local floating datum which is common midpoint (CMP) consistent. This is done to minimize nonhyperbolic distortions caused by large static shifts. When the assumption of vertical raypaths implicit to static corrections is invalid, CMP velocity analysis will suffer. In this case, it is better to apply wave-equation datuming rather than large static shifts.

Because of the nature of overthrust data, it is often difficult to pick velocity from CMP semblance analysis; therefore, velocity is often estimated from constant velocity stacks and post-stack migration. When constant velocity stacks and migration are used, the data are shifted to the final output datum. This shift is done primarily so that an interpreter's insight can be incorporated in the velocity estimation. As pointed out by Tilander and Mitchel, stacking to a floating datum in the presence of significant topography can introduce artificial structure. This hampers the interpreter's ability to use geological intuition in picking horizons and defining dominant structural style. The added benefit of shifting data to the final output datum is that fast and efficient algorithms can be applied to the estimation of migration velocity. If static shift is used to transform the data to the output datum and the assumption of vertical raypaths is not valid, the data will be distorted and the accuracy of the migration result will be compromised. If prestack wave-equation datuming is used instead of static shift, the event kinematics will not be distorted and the migrated image will be superior.

Refraction analysis is often used to determine low spatial frequency statics and to compensate for the weathering layer. The refraction statics solution is often used with a replacement velocity to correct data to either a floating or final datum. While this works well in regions of mild topography and well behaved weathering layer, the refraction model often does not match the geologic reality of mountainous terrain (Bevc, 1991). Although useful near-surface information may be gleaned from refraction analysis, it is often more accurate to apply wave-equation datuming to the recorded data rather than to apply static shifts based on refraction analysis for the final datum correction (Schneider et al., 1995).

For extremely poor signal-to-noise data, wave-equation datuming may not be appropriate because it is likely to generate strong artifacts. In such situations, judicious use of datum statics and residual statics is more likely to be successful. However, when the data quality is adequate, the incorporation of wave-equation datuming into the processing flow can offer significant benefits.

Related work on rugged topography and wave-equation datuming

Wiggins (1984) and Reshef (1991) implicitly include effects due to topography in their migration algorithms. Wiggins uses a Kirchhoff formulation to directly incorporate topography in prestack migration from a rugged surface. Reshef's phase-shift migration method is also used to directly migrate data. He performs downward extrapolation from a flat datum and adds data to the extrapolated wavefield each time the topographic surface is intersected. Both these methods allow direct migration of data recorded on a rugged topographic surface. Beasley and Lynn (1992) introduced an elegant and simple algorithm to correct for the error caused by the static time shift based on the "zero-velocity layer" concept. In their finite-difference migration, Beasley and Lynn migrate data after static shift by setting the velocity in the diffraction term to zero above the topography. Not only is the static shift required before the migration, but this technique cannot be applied to the computationally attractive phase-shift algorithms, because it includes the nonphysical characteristic of zero velocity.

Yilmaz and Lucas (1986) and Berryhill (1986) demonstrate how to compensate for the raypath bending effects of a rugged ocean bottom with severe velocity contrast. They call the technique prestack layer replacement. The method uses wave-equation datuming twice; first to downward continue the wavefield from an initial surface to a datum, using a known velocity, and second to upward continue the wavefield from the datum to the initial surface, using a different velocity.

Schneider et al. (1995) apply the same layer-replacement idea to replace the low-velocity layer for an overthrust data set. They use refraction analysis to estimate velocity in the weathering layer, followed by wave-equation datuming to downward continue the data to the base of the layer with the estimated velocity, and then upward continue with a replacement velocity. Their results show some improvement over refraction statics, but there is some error associated with the refraction velocity and layer determination. In portions of their final stack that correspond to topographic highs, static shift produces a better result than wave-equation datuming. This may be because their refraction model shows an unintuitive thickening of the low-velocity layer over a topographic high, which may result from the misidentification of tunneling or diving waves as refracted arrivals (Bevc, 1991).

In order for all of the above methods to work, the near-surface velocity must be known or reliably estimated. The more general and problematic situation is one for which the velocity structure is unknown. In this situation, I upward continue the data to some planar datum above the topography with a replacement velocity. This unravels the distortions caused by the rugged acquisition topography and allows standard velocity estimation and imaging techniques to be more accurately applied to the data.

STATIC SHIFT VS. WAVE-EQUATION DATUMING

The industry-standard method of datuming is to perform static shifts of data traces. This is adequate when the near-surface raypaths are nearly vertical or when the shifts are small. The static shift method is commonly applied to correct for near-surface velocity variations due to weathering layers and for topographic effects. In this section I will use simple synthetic examples to show that when static shifts are large and the assumption of vertical raypaths is not valid, the wavefield is distorted by the static shift so that velocity analysis, migration and any other wave equation based processing is severely degraded.

If the near-surface velocity structure is known, data can be downward continued through the near-surface velocity structure to some lower datum. In this type of situation, Shtivelman and Canning (1988) show the accuracy limitations of static shifting and the need to apply wave-equation datuming when differences in elevation are significant and the velocity model is complicated. For most land data, the near-surface velocity is not known. One method of eliminating distortions due to topography is to upward continue the data to an arbitrary datum above the highest topography. This is analogous to upward continuing marine data from the water bottom back to the original acquisition surface in marine layer replacement applications. The proper velocity to use for upward continuation should be close to the near-surface velocity. This choice of velocity is made so that excess ray bending is not introduced by the datuming process. Since near-surface velocity often varies along a seismic line, the datuming velocity is generally variable; however, for the examples shown here, a constant datuming velocity is used. Once the data have been upward continued to a higher datum, conventional velocity analysis can be performed. The result of velocity analysis, stacking, and migration after wave-equation datuming is superior to the result after static shift.

Thus, wave-equation datuming provides a way of extrapolating a distorted wavefield to a planar datum without requiring detailed knowledge of the near-surface velocity. Once the data is at the planar datum, the velocity structure can be determined.

All of the datuming examples in this paper are generated with a Kirchhoff wave-equation datuming algorithm. As depicted in Figure 1, each upward continued output trace P_j is calculated by summing over the input traces P_i:

$$P_j(\omega) \;=\; \sum_i A_{ij}\, \sqrt{-i\omega}\, P_i(\omega) e^{i\omega\tau_{ij}}. \tag{1}$$

A_{ij} is an amplitude term incorporating divergence and obliquity, ω is angular frequency, and τ_{ij} is the traveltime between input location i and output location j. For two-dimensional data, the amplitude term is given by

$$A_{ij} \;=\; \frac{\Delta x}{\sqrt{2\pi r_{ij} v}} \cos\theta_{ij},$$

where v is the datuming velocity, Δx is the spatial sampling interval, θ_{ij} is the angle between the normal to the input surface and the traveltime path r_{ij} connecting input location i and output location j. A detailed derivation of equation (1) is presented in Bevc (1995). Equation (1) can be applied directly to zero-offset data. Prestack wave-equation datuming is a two-step process: equation (1) is applied first to all common shot gathers, and then to all common receiver gathers (Berryhill, 1984).

The Kirchhoff method was selected over recursive methods such as phase shift and finite difference because it is the most efficient for application to prestack data, and because it can accommodate irregular acquisition geometry. The chief drawback of the recursive methods is that they require a regular computational grid. The Kirchhoff method is not confined to a regular grid, so for the irregular geometries of land data acquired in rugged terrain and for 3-D implementation considerations, the datuming algorithm based on the Kirchhoff integral is the operator of choice. Furthermore, the Kirchhoff implementation handles the exact topographic elevations, not some discretized representation.

Synthetic examples

To provide insight as to how wave-equation datuming compares to static shift, and for clarity of exposition, I will demonstrate a few concepts using zero-offset synthetic data.

The subsurface model for the synthetic data consists of an anticline, a syncline, and two point diffractors in a constant velocity medium of 2