An accurate and efficient hybrid method for poststack topographic datuming

Paul J. Fowler and Steve Schroeder, WesternGeco, Denver, Colorado*

Summary

Obtaining optimal migrated images from land data acquired in rugged terrain requires accurate correction for topographic relief. Wave-equation datuming to a flat reference surface before migration is significantly more accurate than static time shifting. Since the replacement velocity used for topographic datuming is usually laterally invariant, it is possible to design hybrid datuming algorithms that are both highly accurate and efficient. These datuming schemes can also be used for marine water-layer replacement.

Introduction

As migration algorithms improve, it is increasingly important to ensure high fidelity and efficiency in all processing steps applied prior to imaging. For seismic data acquired in areas with rugged terrain, imperfect treatment of surface topography can significantly degrade the quality of the final migrated image of the subsurface. Accurate datuming algorithms can help solve this problem.

Datuming for land data is used primarily to address two types of problems: topographic relief, and complex, heterogeneous near-surface layers. Ideally, one might want to apply datuming before stack to solve both types of problems. Some success has been reported in applying prestack datuming to 2-D data (e.g., Schneider et al., 1995; Bevc, 1997; Zhu et al., 1999). However, accurate and efficient prestack wavefield extrapolation in 3-D is much more problematic because of the coarse and irregular spatial sampling typical of 3-D data acquisition. Therefore, poststack datuming is much more common in practice.

Datuming through highly heterogeneous near-surface layers requires an algorithm that can accurately handle rapid lateral velocity variations. Such methods are computationally expensive, and it is an open question whether we can estimate near-surface velocities well enough to justify wave-equation datuming instead of applying cheaper and more robust static shifts (Salinas, 1996). Topographic relief, however, is usually handled by datuming upward using a laterally invariant velocity field. The simplicity of the velocity field can be exploited to implement a datuming scheme that is computationally more efficient than one that handles more complicated velocity fields. Thus, we focus here on efficient methods for poststack topographic datuming.

Some form of topographic datuming is nearly always applied either before or during migration of land data if any relief is present. Kirchhoff migration algorithms can directly handle data from topographic surfaces (Wiggins, 1984). Finite-difference methods can also be extended to include topography by using zero-velocity layers (Beasley and Lynn, 1992). However, incorporating topography in some wavenumber-domain methods (e.g., Beasley et al., 1988) is intrinsically more difficult. A separate, prior datuming step can provide a consistent and accurate solution to the handling of topography independent of the method used for subsequent migration.

The importance of topographic datuming

The most common approach to topographic datuming for land data is to extrapolate upward to a flat reference surface above the highest topographic point, using a replacement velocity roughly equal to the shallow sediment velocities. This is often implemented using simple static time shifts, but such an approach can cause significant vertical and lateral reflector positioning errors. These errors are most severe for large topographic relief and steep dips. A more accurate approach is to extrapolate the data using wave-equation methods.

Figures 1 to 5 illustrate the importance of accurate wave-equation datuming for a simple synthetic data example. Figure 1 shows a model containing a point diffractor and several reflectors below a dipping and undulating topographic surface. Figure 2 shows simulated zero-offset data from the topographic surface. Figure 3 shows the result of wave-equation datuming upward to a flat surface, followed by steep-dip migration. The flat and dipping reflectors and the isolated point scatterer are all imaged well. For comparison, Figure 4 shows the result of datuming using static time shifts, followed by the same migration. The dipping reflectors are now mispositioned, and the point scatterer is poorly focused. The apparent overmigration of the scatterer can be partially fixed by arbitrarily decreasing the migration velocity by 15%, as shown in Figure 5. However, the dipping beds are still seriously mispositioned. Although such ad hoc adjustments of the migration velocity are often made during routine processing, they can never fully compensate for the errors incurred by using static datuming.

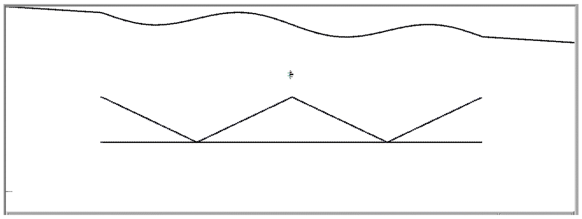
Figure 1: Model with topography

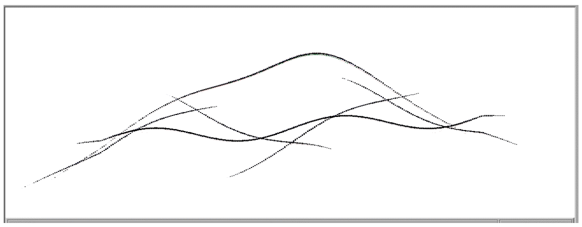
Figure 2: Synthetic data from topography

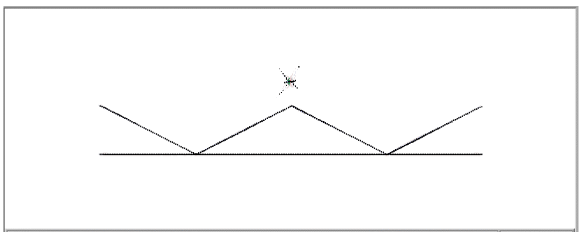
Figure 3: Migration after wave-equation datuming

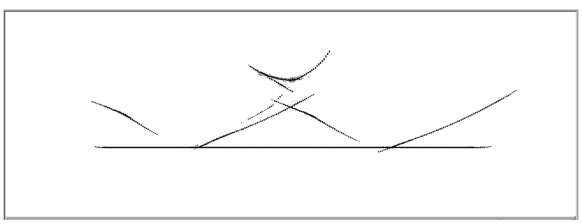
Figure 4: Migration after static time-shift datuming

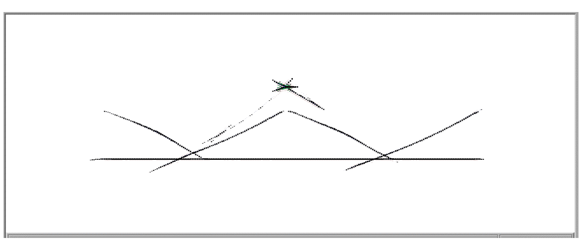
Figure 5: Migration with an incorrect, low velocity after static time-shift datuming

Wave-equation datuming methods

Basic integral equations for Kirchhoff datuming were presented by Berryhill (1979), Wiggins (1984), and Shtivelman and Canning (1988). The Kirchhoff extrapolation integral can be expressed in either the time or frequency domain. We use the latter because it can more easily and accurately incorporate the near-field terms, the differentiation filters, and the anti-aliasing filters that are all needed for high-accuracy datuming. The only significant approximation made is that of limited curvature on the topographic surfaces.

Non-recursive Kirchhoff datuming handles topography and data-sampling irregularity quite flexibly, and via ray tracing can be generalized to handle varying velocity fields. However, it can be costly to apply, particularly for large topographic relief. The cost of Kirchhoff datuming can be reduced somewhat by limiting the aperture of the extrapolation operators, since handling steep dips costs far more than lower dips. Other speedups, such as using cheaper approximations for weighting or for anti-aliasing, can compromise the accuracy of the result. Even using an efficient implementation, non-recursive Kirchhoff datuming can still cost as much or more than subsequent migration, raising a serious barrier to its routine use. A less computationally expensive solution is thus desirable.

Recursive extrapolation using frequency-space (*f-x*) operators provides an alternative to non-recursive Kirchhoff datuming (Ellis and Kitchenside, 1989). Topography on the initial surface can be handled by starting with a wavefield that is all zeroes, and then adding in the recorded data at each extrapolation step as one crosses the surface. Topography on the output surface can be treated similarly, by separately saving the wavefield values as this second horizon is reached. Similar treatments of topography in recursive extrapolation were also used for datuming by Yang et al. (1999) and MacKay (1994), and for depth migration by Reshef (1991). Recursive frequency-space extrapolation operators can be designed by using finite-difference approximations, by discretizing the Kirchhoff integral solution, or perhaps best, by optimal fitting of coefficients to the desired frequency-wavenumber extrapolator, as is commonly done for depth migration programs (e.g., Holberg, 1988; Blacquiere et al., 1989; Hale, 1991; Gaiser, 1994). Whatever method is used to design recursive *f-x* extrapolation operators, great care must be taken to preserve both stability and steep-dip accuracy. The recursive *f-x* approach is suitable for datuming through laterally varying velocity models, but unfortunately it is still comparatively expensive to apply. The lateral invariance of the velocity field used for topographic datuming can still be exploited to generate methods that are computationally less expensive.

Recursive frequency-wavenumber (*f-k*) phase-shift extrapolators provide very accurate and efficient solutions for datuming when the velocity is laterally invariant and the topography is flat. They can incorporate topography using essentially the same technique as for recursive *f-x* methods, by initiating the wavefield as the extrapolation crosses the first surface and saving new wavefield values as the second surface is reached (Ji and Claerbout, 1992). Since the extrapolation operators are applied via wavenumber-domain multiplication rather than by spatial convolution, they can be computationally very efficient.

Handling topographic relief does incur the extra cost of additional spatial Fourier transforms between domains at each depth step. However, the method can still be less expensive than space-domain methods, without the potential stability or accuracy problems of the latter.

The cost of recursive *f-k* datuming depends directly on the size of the depth step used. Using too large a step is equivalent to approximating the smoothly varying topographic surfaces by a series of discrete steps, thus degrading accuracy. This inaccuracy becomes visible when the depth step (converted to time units) becomes much larger than the time-sampling increment of the data. Larger depth steps can be used for lower frequencies, which can decrease the computational cost without damaging the result. However, for datuming large distances the cost of the many spatial Fourier transforms still remains greater than desired.

A fast hybrid datuming algorithm

A hybrid approach working alternately in wavenumber and space domains can run much faster than either approach alone while still retaining high accuracy. In this approach, we use *f-k* extrapolation to take large depth steps, and then use smaller, localized *f-x* extrapolators to handle topography as needed. This hybrid approach has the immediate advantage that only the *f-k* operators are applied recursively, so stability of the *f-x* operators is not a problem. The *f-x* operators will be small in size because they only have to extrapolate short distances, but they do have to be highly accurate so that they closely match the *f-k* operators.

The total cost of the *f-k* steps decreases as the step size gets larger. The cost of applying the *f-x* operators, however, increases with larger step size as the required aperture grows. The computational cost of this scheme therefore reflects a tradeoff between these two costs as step size increases. The optimum step size is usually many times larger than that used for the *f-k* method and the runtimes are correspondingly less. The actual minimum is a complicated function of many parameters, including survey size, time-sampling rate, bin size, replacement velocity, total datuming distance, and maximum dip limit. We have found in practice, though, that the tradeoff curve is usually quite flat in the region of the minimum, so enhanced performance can be achieved without excessive sensitivity to the precise choice of step size.

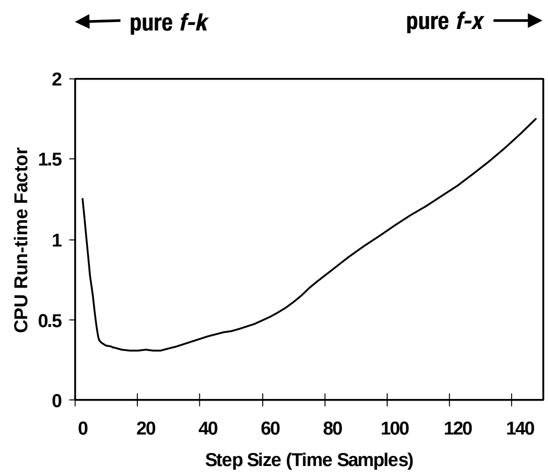

Figure 6: Measured cost tradeoff curve for hybrid datuming.

Figure 6 shows an example of a measured cost tradeoff curve for using the hybrid datuming algorithm on a 3-D field data set approximately 60 square kilometers in extent. The data were acquired in a rugged, mountainous region; the maximum datuming distance from topography up to a flat migration horizon was over 600 meters. Non-recursive *f-x* Kirchhoff datuming of this data set required 1.7 times the CPU time needed for a poststack time migration. Recursive *f-k* datuming using a fixed step size corresponding to the data time-sampling increment, Δt, reduced the relative run-time factor to 1.2 compared to time migration. Allowing the step size to vary inversely with frequency improved this further to a factor of 1.1. As can be seen in Figure 6, the optimal step size for the hybrid algorithm for this data set was approximately $20\Delta t$, giving a run-time factor of 0.32. However, using any step size between $10\Delta t$ and $30\Delta t$ gave run-time factors of 0.34 or less. For comparison, a high-accuracy recursive *f-x* poststack depth migration took approximately 11 times as long as the time migration. All timing tests were run with a 75° dip aperture, and with all other parameters chosen to ensure high fidelity. The results for all the datuming methods were of nearly identical high quality. The hybrid scheme thus achieved the goal of reducing the datuming run time to a fraction of the migration run time, while still retaining high accuracy.

Discussion and conclusions

The new hybrid space/wavenumber datuming algorithm described here provides an efficient and accurate implementation of poststack topographic datuming. It reduces computational costs sufficiently that it can replace static time-shift datuming in routine production processing, thus potentially improving the accuracy of any subsequent migration. It does require a laterally invariant replacement velocity, and works best for a constant velocity where many numerical factors can be precomputed and tabulated. The only other limitation is that computational efficiency is lost for dips beyond approximately 80°, since the required aperture of the *f-x* operators becomes too large. If high accuracy datuming of the very steepest dips is required, the *f-k* algorithm is appropriate and will still usually be faster than a Kirchhoff approach.

We have focused here on topographic datuming for land data, but the efficient datuming algorithms we have discussed can also be applied for marine water-layer replacement (Yilmaz and Lucas, 1986). In that case, one tries to lessen the effects of seafloor topography by extrapolating at water velocity down from the ocean surface to the seafloor, and then back up to the surface with a faster replacement velocity. To be most useful, this requires a hard seafloor with a jump to a sediment velocity significantly higher than water velocity, so this use of datuming to ameliorate topographic effects is less common than for land data.

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