Stanford Exploration Project, Report 75, November 17, 1997, pages 181–202

Datuming by wavefield extrapolation

Lewei Mo[1]

keywords: *wave equation, velocity, boundary conditions, prestack, land, poststack*

ABSTRACT

This paper proposes a method of datuming that uses the exact two-way acoustic wave equation to do the wavefield extrapolation along with depth migration. Datuming is the process used to derive the wavefields at one datum from those at another datum. Poststack and prestack datuming regard the surface recorded wavefields as containing only subsurface primary reflections. In accord with this assumption, this paper points out that the surface recorded seismograms are the wavefields recorded at the earth surface, which is regarded as an absorbing boundary. According to the Huygens secondary-point-source principle, the surface recorded wavefields can also be regarded as a series of point sources. The datuming procedure I propose is implemented in the space-time domain by the finite-difference method. The recorded wavefields are taken as boundary conditions (sources) to drive the wave equation along the time axis in a rectangular strip containing the input and output datums. The desired wavefields at the output datum are the history wavefields at the output datum, with the four sides designed as absorbing boundaries. This method can handle any velocity variation between the two datums. In practical situations, one of the two datums is an irregular surface. This paper shows both upward and downward, poststack and prestack wave equation datuming. Tests with synthetic data show good results. The method has the potential for application to corrections of land data static and to migration in complex velocity areas.

INTRODUCTION

Datuming is the process of deriving wavefields at one datum from those at another datum. There is great utility in this process for land static correction (Berryhill, 1979, 1984; Shtivelman and Canning, 1988; Bevc, 1992) and for layer replacement in migration (Berryhill, 1979, 1984; Yilmaz, 1987). There are two ways to do it. One is by simple time shifting along individual traces, as in first-stage land data static correction. The other is by wavefield extrapolation based on the wave equation. Datuming

[1]**email:** not available

is closely linked to migration; both need to extrapolate the wavefields from one datum to another. Several methods of wavefield extrapolation have been developed for migration, among them, finite-difference methods (Claerbout, 1976, 1985), Kirchhoff-integral methods (French, 1975; Schneider, 1978), f-k methods (Gazdag, 1978; Stolt, 1978), and reverse-time migration methods (Baysal et. al., 1983; McMechan, 1983). For datuming, Berryhill (1979, 1984) applied the Kirchhoff-integral method to wavefield extrapolation. But his method is only easy to implement and accurate in a constant velocity medium. When the velocity of the medium varies, his method encounters various problems associated with the approximate solution to the wave equation and further difficulty in doing the ray tracing. Shtivelman and Canning (1988) presented an extrapolation scheme based on the asymptotics of the Kirchhoff-integral solution to the 2-D scalar wave equation. Their method is similar to that of Berryhill (1979), though more accurate. Bevc (1992b) implemented the datuming scheme given by Berryhill (1979) with the addition of being an anti-aliasing approximation to the Kirchhoff-integral. The inclusion of anti-aliasing of the Kirchhoff-integral has a low-cut filtering effect on the resulting wavefields. Ji et al. (1992) applied phase-shift method to perform datuming (Gazdag, 1978; Reshef, 1991); this method has the difficulty of implementing lateral velocity variations. Popovici (1992) applied phase-shift plus interpolation (PSPI) to perform datuming; but implementation of PSPI is clumsy in an irregular geometry.

This paper proposes a method of datuming that uses the exact two-way acoustic wave equation to do wavefield extrapolation along with depth migration. This method is implemented in the space-time domain by the finite-difference method. The paper first demonstrates upward and downward datuming for poststack data. It then demonstrates upward and downward datuming for prestack common-shot gather and common-receiver gather data and suggests application procedures for seismic data static correction for irregular land topography. Tests with synthetic data show good results. This method of datuming shows great promise for applications in land data static correction and migration in complex velocity areas.

POSTSTACK DATUMING

Poststack and prestack datuming, and various migration schemes, all take surface recorded data as containing subsurface primary reflections only. This means that the surface can be regarded as an absorbing boundary when recording the seismic wavefields. In poststack finite-difference reverse-time migration (McMechan, 1983), these surface recorded wavefields are taken as boundary conditions for running the two-way wave equation backward in time. The wavefield at time $t = 0$ is the subsurface reflectivity image, according to the imaging principle. The recorded wavefields can also be taken as the boundary condition for running the two-way wave equation forward or backward in time in a thin strip containing the two datums. The desired wavefields are the history wavefields at the output datum, with the four sides designed as absorbing boundaries. The wave equation runs forward in time (beginning from the minimum time) if one is extrapolating from a lower datum to a higher datum, and backward in time (from the maximum time) if one is extrapolating from a higher datum to a lower datum, because the actual earth wavefields expand up from the subsurface. The theory and results of datuming by the Kirchhoff-method can be found in Berryhill (1979, 1984) and Shtivelman and Canning (1988). Here I do the datuming by solving the two-way acoustic wave equation by the finite-difference method. Even though any recursive wavefield extrapolation method can be applied to accomplish datuming, I have chosen this particular method because it is more accurate and can honor arbitrary velocity models. The following sections describe upward and downward datuming with increasing degrees of complexity. The results show that a traveltime trajectory distorted by irregular recording topography can be corrected by datuming to a planar datum, either upward or downward.

Datuming from a planar datum to another planar datum, upward

To introduce datuming that uses a finite-difference method, let me first describe datuming from a lower planar datum to a higher planar datum. A scatterer is located at $(z = 0.15, y = 0.32)$ in a constant velocity $v = 1$ medium. The variables z and y denote depth and horizontal coordinates. I generate the synthetic zero-offset section in Figure 1 at the planar datum $z = 0.05$ by ray tracing, for which only the traveltime is correct. The apex of the hyperbola is at time $t = 0.1$. Then I use a grid in which $nz = 20, ny = 128$, $dz = 0.005, dy = 0.005$, and $dt = 0.001$ to run the two-way wave equation forward in time with the synthetic record as the boundary condition at the lower recording datum. The desired wavefields at the higher planar datum are the absorbing history wavefields at the top $iz = 1$ of the grid, or the history wavefields at the planar datum just one grid point below the top, so that the absorbing boundary conditions can be implemented efficiently. The results are shown in Figure 2. In this case, the datuming is done over $50m$. After the datuming process, the apex of the hyperbola is at time $t = 0.15$. The time period for running the wave equation must be larger than the original record length by an amount that is long enough to account for the propagation time from the lower datum to the higher datum, because the actual earth wavefields expand up from the subsurface. There is a light ghost following the main event, which results from the reverberations between the input datum and the output datum. The ghost reflection can be removed by implementing better absorbing boundary conditions at the output datum, and implementing the recorded wavefields as a series of point sources instead of simple boundary conditions.

Datuming from an irregular datum to a planar datum, upward

Let us now increase the degree of complexity and consider datuming from an irregular datum upward to a planar datum. As in the previous example, a scatterer is located at $(z = 0.15, y = 0.32)$ in a constant velocity $v = 1$ medium. And there is a supposedly irregular earth surface that can be expressed as the function $iz = 10 + 5sin(2. * 3.14 *$

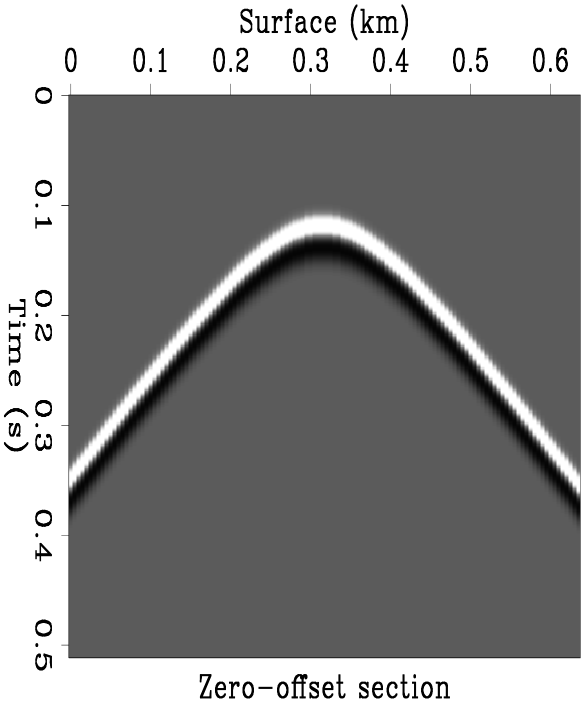

Figure 1: The wavefields recorded at the planar datum $z = 0.05$ mo1-d1 [ER]

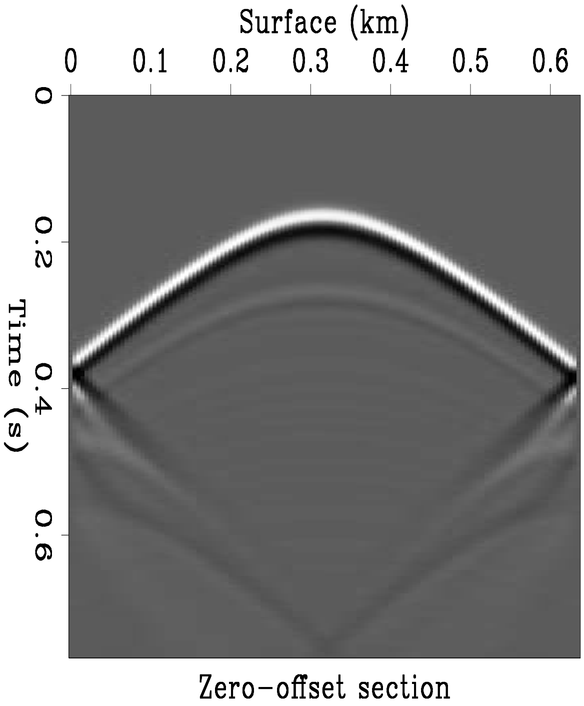

Figure 2: The extrapolated wavefields at the upper planar datum $z = 0$. The apex of the hyperbola has been shifted by the datuming. mo1-d1.2 [ER]

$2 * iy/ny)$. The maximum elevation difference is $50m$. The datuming geometry is shown in Figure 3. This kind of geometry is not unusual in land seismic surveys such as those of the mountainous regions in southwest China. The indices iz, iy are the depth and horizontal grid indices. I have chosen this particular surface for the sake of convenience. Any irregular surface can be used, as long as every boundary grid point as defined by the boundary has a recorded trace. No gaps can exist on the boundary grid. I generate the synthetic zero-offset section in Figure 4 at the irregular datum by ray tracing. The diffraction time curve deviates greatly from a perfect hyperbola because of the irregular recording surface.

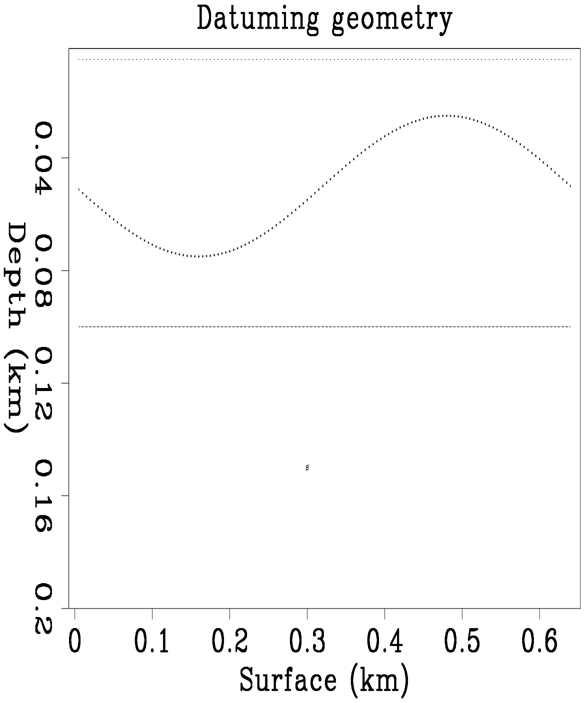

Figure 3: The datuming geometry of Figures 4, 5, and 6. The point S represents the position of the scatterer. The asterisk curve represents the field recording datum. The dotted and dashed lines represent the new datums for upward and downward datuming. mo1-Datum2.H [ER]

Then I use a grid with $nz = 20, ny = 128$, $dz = 0.005, dy = 0.005$, and $dt = 0.001$ to run the two-way wave equation forward in time, with the synthetic record as the boundary condition at the irregular recording surface, which is located inside the computational rectangle. The top and the two sides of the rectangle are designed as absorbing boundaries. The bottom boundary can be assigned any condition because it does not affect the computation. The desired wavefields at the new datum surface are the absorbing history wavefields at the top $iz = 1$ of the grid. The results are shown in Figure 5. The datuming is done by an average of $50m$. Now the diffraction time curve has been restored to a hyperbola, and the apex of the hyperbola is at time $t = 0.2$, and lateral position $y = 0.32$. Boundary reflection effects appear at the two sides, because in datuming to a higher datum the wave incidence angle upon the two sides increases, and the effects of absorbing boundary conditions (Clayton and Engquist, 1977) at large incidence angles are not as good as those at small incidence angles. By upward datuming to a planar datum whose elevation equals that of the highest point of the irregular topography, the edge reflection can be decreased. The other way to deal with boundary reflections is to pad with zeroed traces beyond the

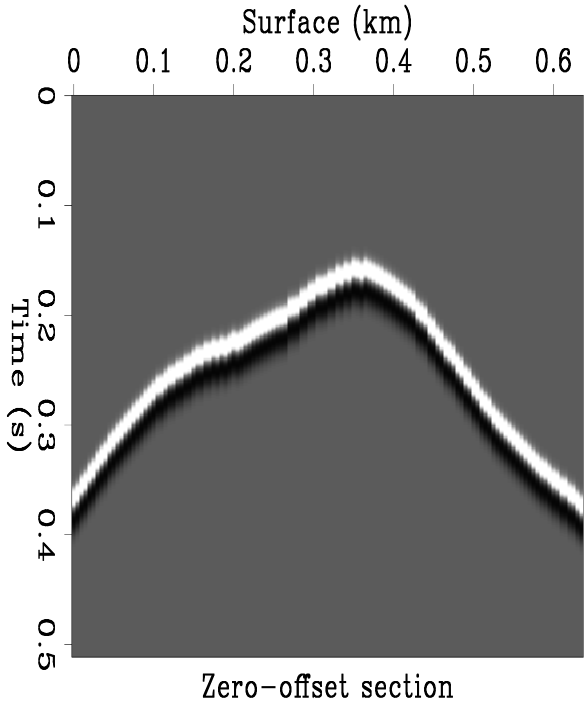

Figure 4: The wavefields recorded at the irregular surface datum. mo1-d2 [ER]

edge as placeholders for the energy that migrates out of the original grid during the datuming extrapolation process (Berryhill, 1984). There is a light ghost following the main hyperbola, which looks like the lateral reverse of the original diffraction curve. The ghost reflection results from the reverberations at the input datum. The ghost can be removed by implementing the recorded wavefields as a series of point sources instead of simple boundary conditions.

Datuming from an irregular datum to a planar datum, downward

This section describes datuming from an irregular datum downward to a planar datum. It uses a rectangular grid similar to that in the previous section, but now the wave equation is run backward in time from the recorded maximum time to time zero. And the desired wavefields at the new planar datum are taken as the history wavefields from the new datum grid points. At time zero, the wavefield left in the computational grid points between the old and the new datums is the reflectivity image in this strip. The downward datumed wavefields at the plane datum $z = 0.1$ are shown in Figure 6. In comparison to the upward datumed wavefields, there are no boundary reflections from the two sides; because, by datuming closer to the scatterer, the wavefields focus downward and the recording aperture increases so that the wave incidence angle upon the two edges decreases. Thus, the absorbing boundary conditions absorb more completely.

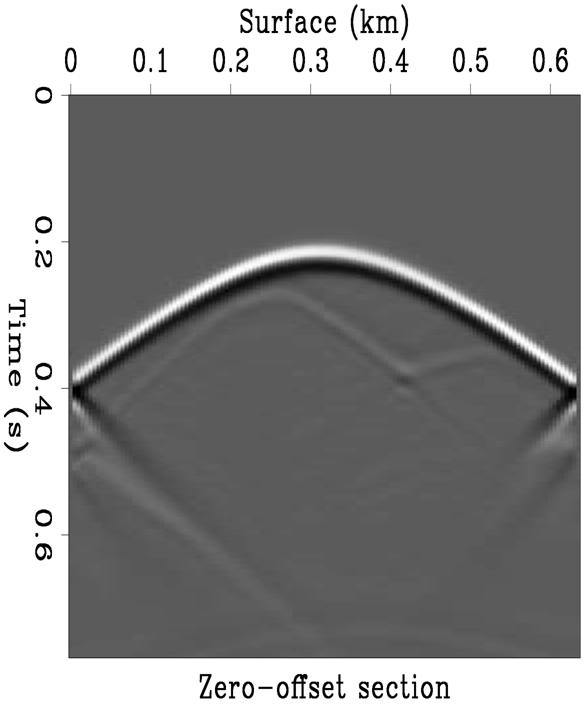

Figure 5: The extrapolated wavefields at an upper planar datum. mo1-d2.up [ER]

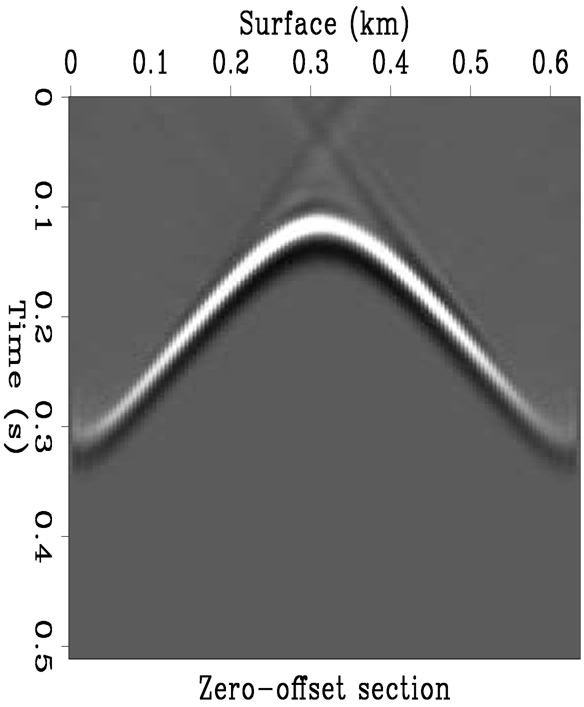

Figure 6: The extrapolated wavefields at a lower planar datum. The recording aperture increases. mo1-d2.down [ER]

Datuming from a planar datum to an irregular datum, downward

Datuming from a planar datum downward to an irregular datum has application in marine seismic survey environments, because it removes the effects the irregular seafloor topography has on subsurface reflections. Figure 7 is a depth reflectivity image, containing an irregular seafloor reflector and a deeper flat reflector. The spatial wavelet used is a Ricker wavelet with a fundamental wavenumber of 20 Hz(cycles/km). The velocity in the water layer is $1.5(km/s)$, and the velocity in the sediment is $2.5(km/s)$. I run the reverse-time migration (McMechan, 1983) in the modeling direction to generate the zero-offset section, which is shown in Figure 8. The planar reflector bears a distinct impression of the water bottom. By the use of a rectangular grid strip that contains the water bottom, the sea surface wavefields are downward datumed to the water bottom. The results are shown in Figure 9. The two sides and the bottom of the rectangular grid strip are designed as absorbing boundaries. Now the water bottom reflection has been flattened. Next, the water bottom wavefields are datumed upward to the sea surface using the constant sediment velocity; the results are shown in Figure 10. The reflection of the subsurface planar reflector is now flat. The whole section has a constant velocity that is equal to the sediment velocity. This process is called velocity layer replacement (Berryhill, 1979). The sea surface section is then migrated with a reverse-time depth migration scheme (McMechan, 1983). The results are shown in Figure 11. This migration image correctly depicts the original input reflectivity model.

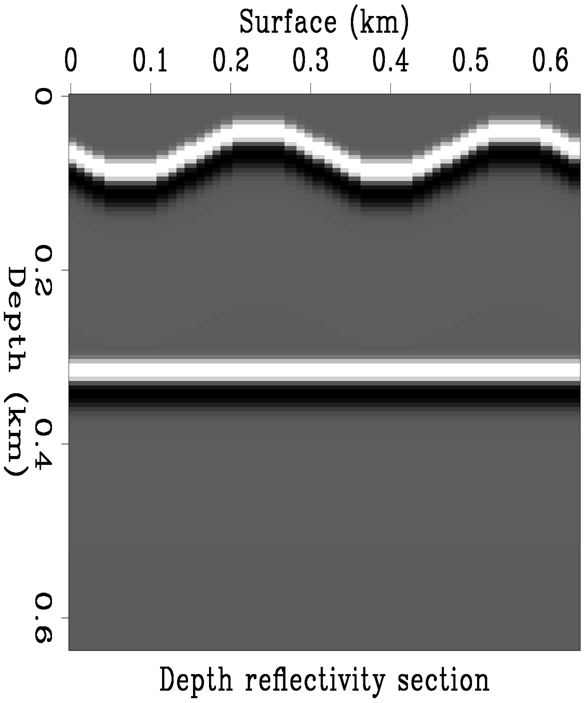

Figure 7: A marine model depth reflectivity section. mo1-depth.H [ER]

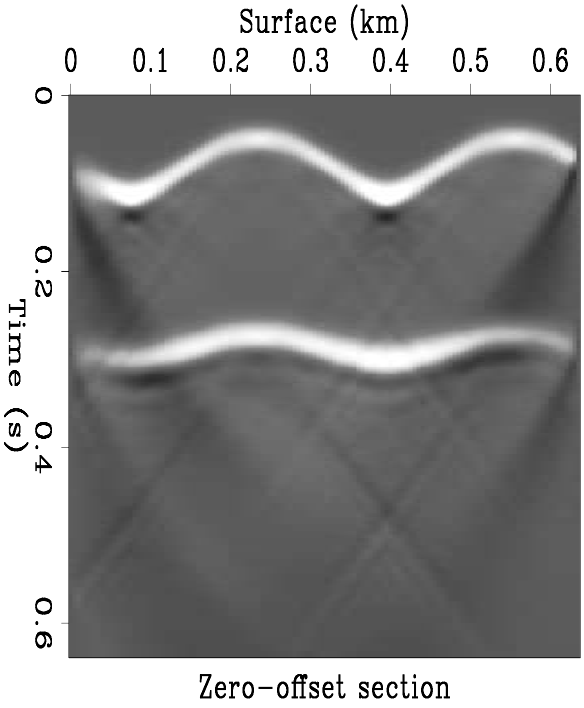

Figure 8: The recorded zero-offset section at the sea surface. The subsurface planar reflector bears a distinct impression of the water bottom. mo1-depth.H0 [ER]

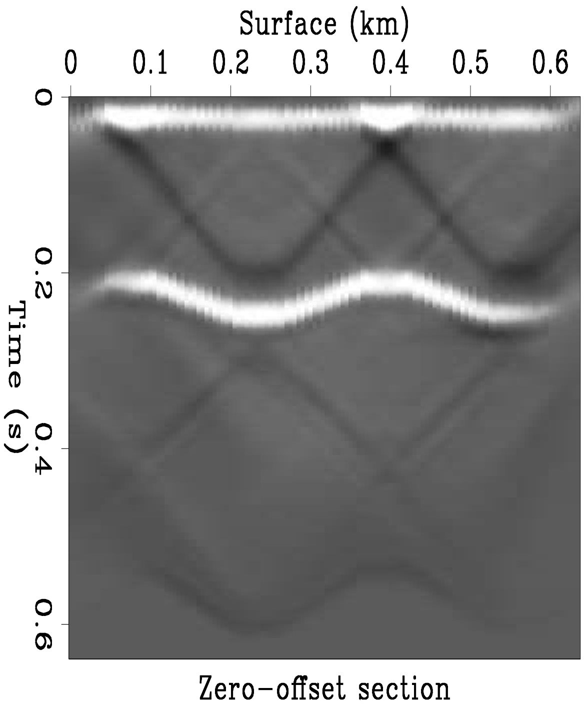

Figure 9: The extrapolated zero-offset section at the surface of water bottom. The reflection of water bottom has been flattened. mo1-depth.H01 [ER]

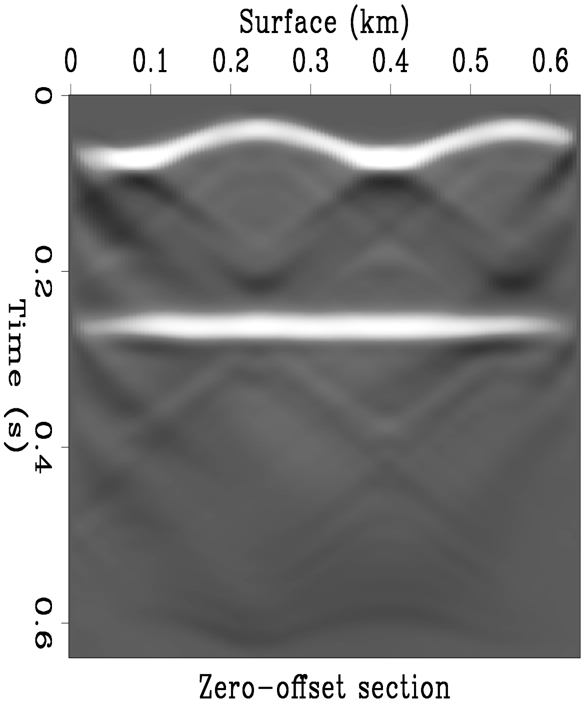

Figure 10: The new zero-offset section at the sea surface. The water layer velocity has been replaced by constant sediment velocity. mo1-depth.H010 [ER]

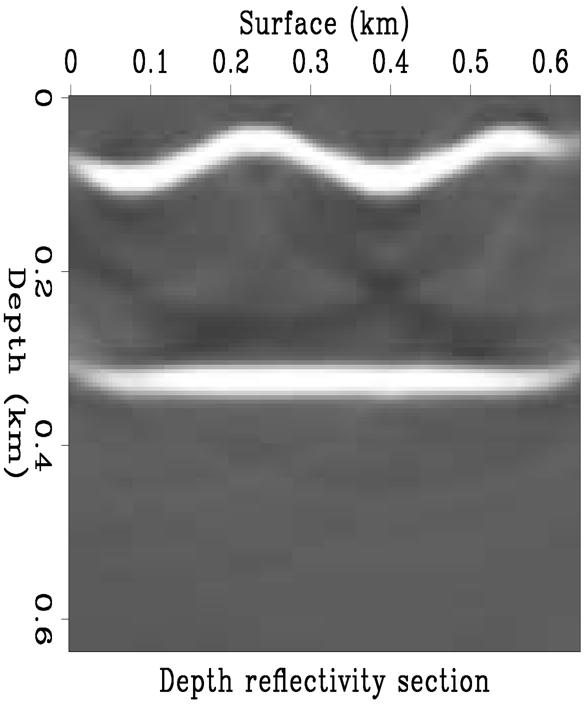

Figure 11: The constant velocity reverse-time migration depth reflectivity section. mo1-depth.H010mig [ER]

Datuming planar-to-planar datum through an irregular datum, downward

This section describes datuming from a planar datum downward to another planar datum through an irregular velocity contrast interface. By use of a rectangular strip, the sea surface wavefields in Figure 8 are downward datumed to a planar datum below the water bottom. The two sides and the bottom are designed as absorbing boundaries. By using the sea surface wavefields as boundary conditions, and running the wave equation backward in time, I obtain the subsurface reflection wavefields at the planar datum $z = 0.1$, which is shown in Figure 13, and the reflectivity image between the sea surface and this new datum (Shih and Levander 1988; Harris and McMechan, 1992), which is shown in Figure 12. A simple migration scheme can be used to image accurately the zero-offset section from this new datum.

This example demonstrates that we can use the sophisticated though expensive reverse-time migration to migrate across the complex datum of the velocity model. Beyond that, we can use a less sophisticated but fast migration scheme, such as finite-difference paraxial wave equation migration.

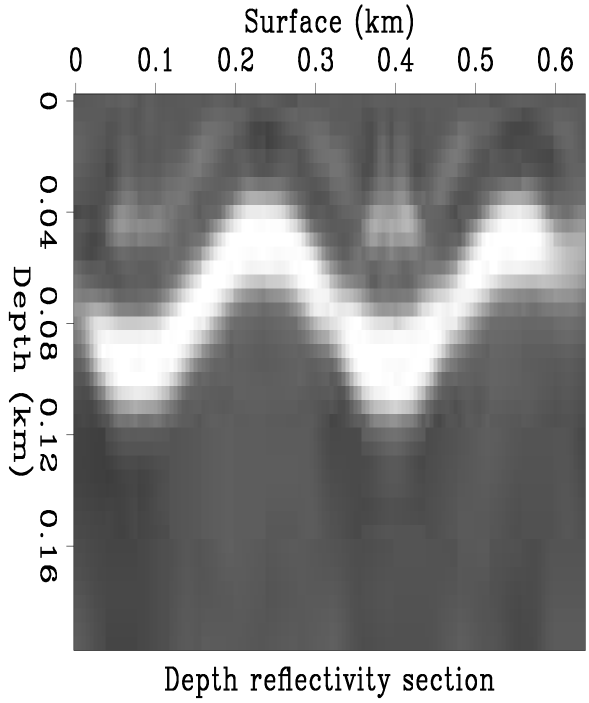

Figure 12: The depth reflectivity section between the sea surface and the lower planar datum. It contains the sea floor reflector. $\boxed{\text{mo1-Strip.H}}$ [ER]

PRESTACK DATUMING

Datuming of prestack seismic data is a simple extension of the poststack case. However, it has the potential for application to static correction of land data recorded over an irregular earth surface. The following sections first suggest application procedures for static correction by prestack datuming, and then demonstrate upward

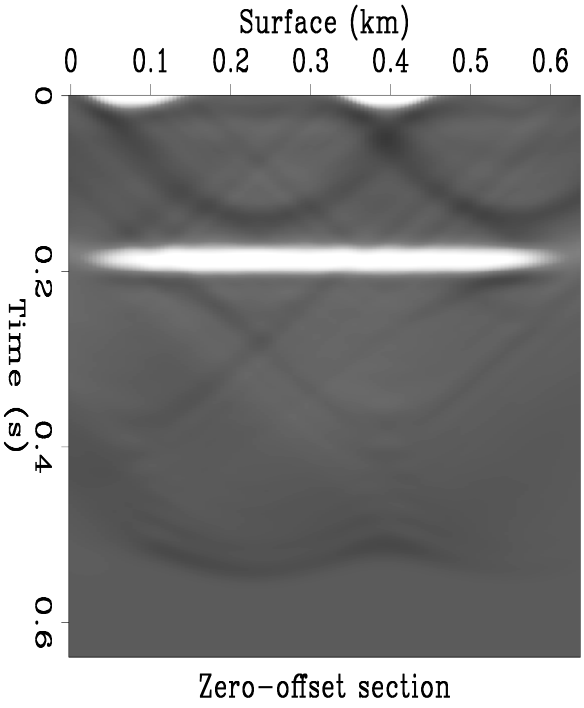

Figure 13: The extrapolated wavefields at the lower planar datum z=0.1 below the water bottom. These wavefields are free from the effects of the water bottom topography. mo1-depth.H02 [ER]

datuming from an irregular earth topography to a planar datum for common-shot gathers (CSG) and common-receiver gathers (CRG).

Static correction by prestack datuming

Land seismic data are usually recorded over an irregular surface, and static correction has long been a problem. There are two kinds of statics, long-wavelength (large time shift) and short-wavelength (small time shift) statics. They are solved in two separate stages. The first stage is datum correction, used to correct long-wavelength statics, by which simple vertical time shifts are applied to common-shot gathers and common-receiver gathers to datum from an irregular earth surface to a planar surface. This planar surface is either above, below, or through all the shot and receiver elevations, depending on the requirements of a survey area. The details of this datuming procedure can be found in seismic data processing manuals. Next, the sorted common midpoint (CMP) gathers are normal moveout (NMO) corrected and stacked to generate the zero-offset section. Then statistical residual static corrections are applied to the zero-offset stack section to flatten a user-predefined main reflection event, thus correcting the short-wavelength statics. Throughout the years, even though many methods have been developed to deal with this problem, static correction still remains a difficult unsolved problem. These methods are mostly designed for the stage of residual static corrections. Because in the first stage, the vertical time shift processing does not correspond to the wave equation, one might not expect that the second stage, statistical residual static corrections, which is designed for small time shifts, could do much better.

Static correction by wave equation datuming has been reported by several researchers, who all reported solving the wave equation by the Kirchhoff method. Berryhill (1979, 1984) demonstrated by the Kirchhoff method, and Shtivelman and Canning (1988) demonstrated by the asymptotic Kirchhoff method that wave equation upward and downward datuming can help solve the static correction problem. [Bevc (1991) described using refraction inversion to solve the problem of land static correction.] Bevc (1992) proposed upward continuing the data to some planar datum above the topography with some fictitious (appropriate) extrapolation velocity by the Kirchhoff method and anticipated that this operation could help solve the static correction problem. Bevc (1992b) implemented the datuming scheme given by Berryhill (1979) with the addition of being an anti-aliasing approximation to the Kirchhoff-integral. The inclusion of anti-aliasing of the Kirchhoff-integral has a low-cut filtering effect on the resulted wavefields. The problems with the different implementations of Kirchhoff-integral method, as mentioned in the introduction, are its approximate solution to the wave equation, the difficulty of doing ray tracing when the medium velocity varies, and the high cost of prestack implementation (Berryhill,1984).

In the research this paper describes, I replaced conventional datuming static time shift correction with wave equation datuming in order to correct from an irregular earth surface to a upper or lower planar surface (Dobrin, 1976). The upper planar surface must be above all the shot and receiver elevations and the lower planar surface below them in order to implement the wave equation datuming. The running of the wave equation is thus either forward or backward in time. At this stage, the long wavelength static has been removed, and the new datum wavefields are correct to the wave equation. From this point, one carries on the conventional seismic data processing sequence, which consists of NMO, brute stack, statistical residual static correction, and final stack. This paper shows only the results of upward extrapolation datuming, since the downward extrapolation is a similar procedure.

CSG datuming from an irregular datum to a planar datum, upward

I datum correct all the common-shot gathers and common-receiver gathers to a common planar datum just above all the shots and receivers (Dobrin, 1976) by employing the wave equation, using the finite-difference method with the near surface layer velocity, as in conventional static-shift correction. The near surface layer velocity can be obtained by well-shooting and tomographic inversion (Zhu and McMechan, 1988). Using the near surface layer velocity in the datuming avoids generating wild ray bending at the original lower datum surface as in the water bottom in marine survey.

The land surface supposedly has a sinusoidal topography, which is similar to that in the poststack case of Figure 3, with the same spatial oscillation frequency. Figure 14(a) is such a common-shot gather generated by the finite-difference modeling with the shot and receivers located on this topography. The earth model has two reflectors at depth. The land topography seriously distorts the traveltime trajectory of reflection events. With the recorded common-shot gather wavefields as boundary condition, I run the two-way wave equation forward in time to extrapolate the wavefields to a higher planar datum whose elevation equals that of the highest elevation point of the irregular topography. The new common-shot gather is shown in Figure 14(b). The reflection events have been restored to hyperbolas.

Next, the data are sorted into common-receiver gathers with the receivers located on the planar datum and the shots located on the original irregular datum. I also extrapolate the shots to the upper planar datum.

CRG datuming from an irregular datum to a planar datum, upward

To generate a common-receiver gather with the receiver located on an upper planar datum and the shots located on a lower irregular topography, based on the principle of reciprocity, I generate an equivalent common-shot gather with the shot located on the upper planar datum, and the receivers located on the lower irregular topography. The generated common-receiver gather is shown in Figure 15(a). Using the same scheme as that for extrapolating upward the receivers of the common-shot gather, I extrapolate the shots to the upper planar datum. The new common-receiver gather is shown in Figure 15(b). The reflection events have been restored to hyperbolas.

CSG datuming from an irregular datum to a planar datum, downward

As in static-shift datuming, I downward datum the prestack data from the irregular earth surface to a lower planar datum. I then carry out the conventional seismic data processing sequence (Stolt and Benson, 1986). This processing is in the realm of the prestack depth migration problem. Using the common-shot gather wavefields as boundary condition, I run the two-way wave equation backward in time, and collect the history wavefields at the new datum as the common-shot gather at this datum. According to the imaging principle that the source and receiver wavefields are time-coincident (Claerbout, 1971, 1976; Chang and McMechan, 1986; McMechan and Chen, 1990; Reshef, 1991), we can also obtain the depth reflectivity section between the old upper and the new lower datums.

CRG datuming from an irregular datum to a planar datum, downward

This procedure is similar to that of datuming a common-shot gather from an irregular datum downward to a planar datum.

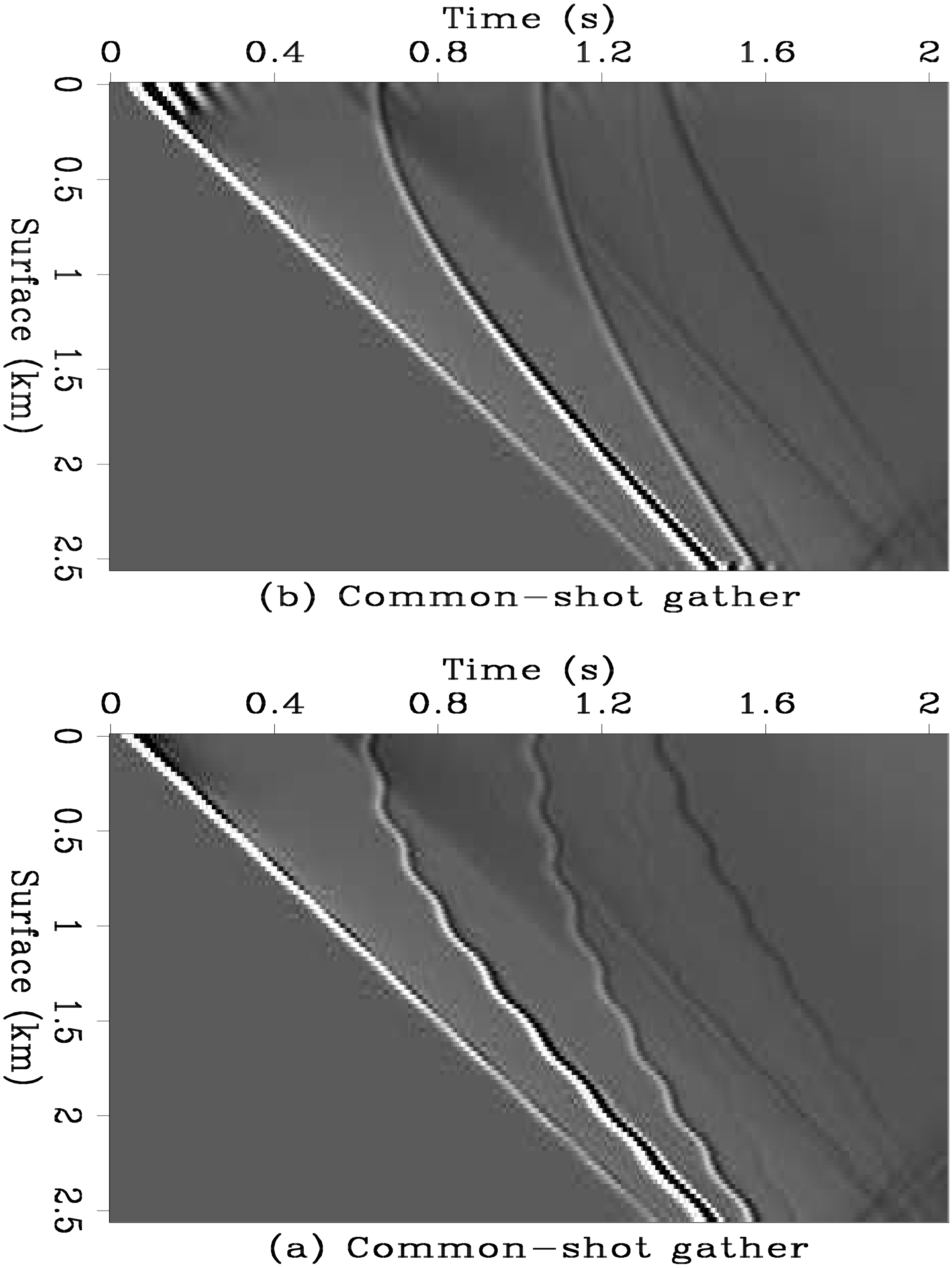

Figure 14: A common-shot gather, (a) recorded on an irregular earth surface showing the raw data without any processing, and (b) with the receivers upward datumed to a planar datum. mo1-CSG110 [ER]

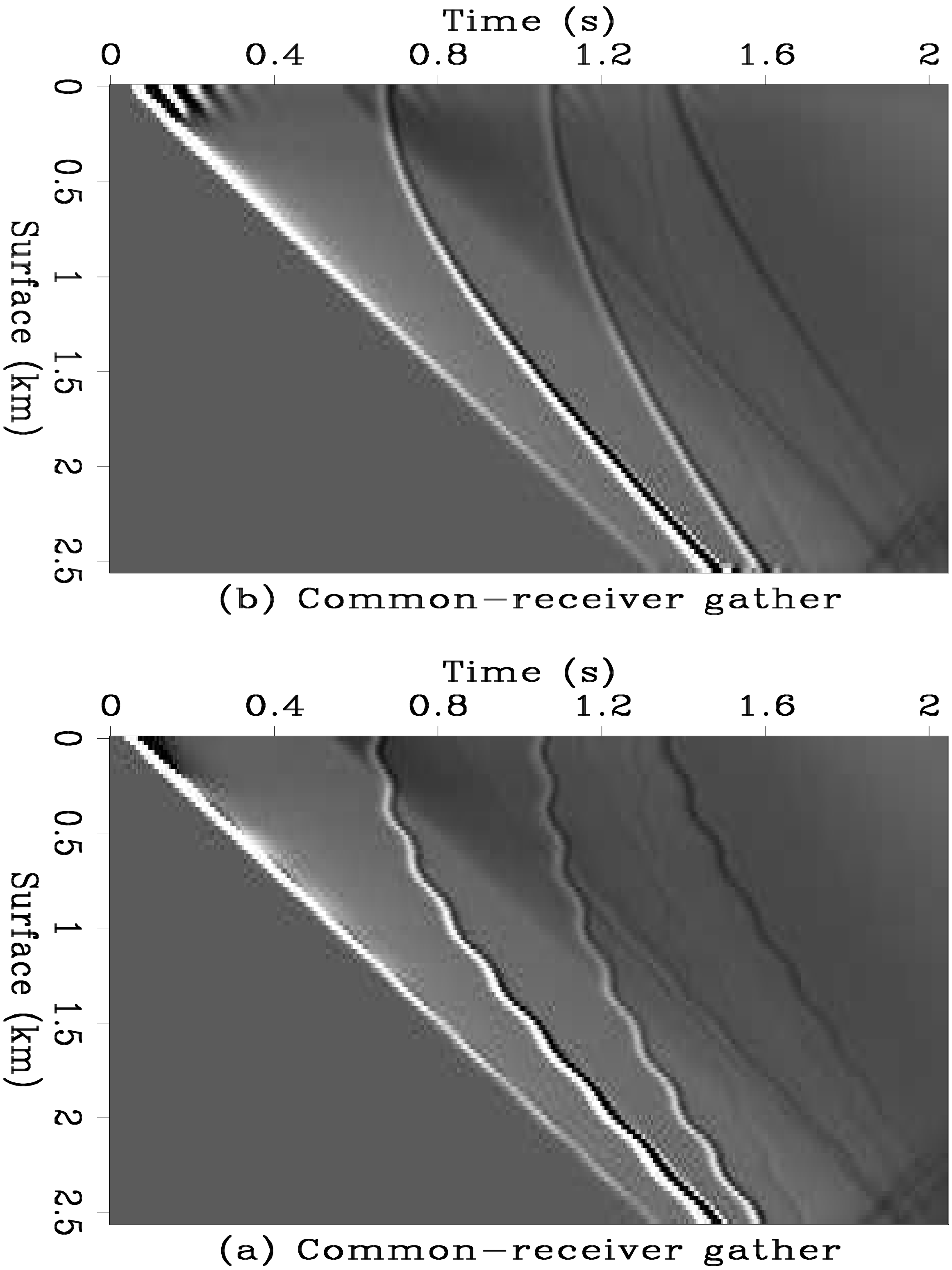

Figure 15: A common-receiver gather, (a) recorded on an irregular earth surface showing the raw data without any processing, and (b) with the shots upward datumed to a planar datum. $\boxed{\text{mo1-CRG110}}$ [ER]

TESTING ON FIELD DATA

Field data static correction

I need data from mountainous regions for testing static correction.

I solicit sponsors of SEP to provide field data to test the ideas.

Field data migration

I need data of an overthrust fault model for migration. The data can be either poststack or prestack.

I solicit sponsors of SEP to provide field data to test the ideas.

DISCUSSION

I have implemented second-order finite differencing to solve the wave equation for all the computations done in this paper. As for migration, there are various possible methods for wavefield extrapolation of datuming. The finite-difference two-way wave equation method I describe in this paper is just one of them. The other recursive wavefield extrapolation methods, like the one-way paraxial wave equation (Claerbout, 1976, 1985), the Kirchhoff-integral method (Berryhill, 1979, 1984), and the f-k phase shift method (Gazdag, 1978) are also workable. But an accurate method of datuming wavefield extrapolation must be based on the wave equation. Even for solving the two-way wave equation, one can use various numerical methods, such as the high-order finite-difference method (Dablain, 1986; Etgen, 1986) and the accurate pseudospectral method (Kosloff and Baysal, 1982). One simply chooses a sufficiently accurate and efficient method for the practical situation. The finite-difference method can process irregular topography efficiently and can honor arbitrary velocity structures. Two preferable methods of datuming wavefield extrapolation are the two-way wave equation implemented in the space-time domain by the finite-difference method (McMechan, 1983) and the one-way 45- and 65-degree paraxial wave equation implemented in the space-frequency domain by the finite-difference method (Claerbout, 1985).

High-order finite differencing reduces the number of spatial samples per wavelength for satisfactory numerical precision. And it can handle an irregular topography efficiently. In using a high-order finite-difference scheme to solve the wave equation, one should gradually drop the order of central finite differencing to the second-order near the recording boundary for the derivative perpendicular to the recording boundary, to avoid edge oscillation and ensure that the numerical solution conforms to the physical wave phenomena. This idea has been implemented in Mo (1992) for migration of crosswell seismic data. Another option suggested to me by John Etgen

(1992) is to pad with zero traces outside the recording datum, and let the high-order finite-differencing operators grab zero values outside the recording datum.

The 2-D descriptions here can be applied straightforwardly to the 3-D case. I am not so sure about application to datuming for multi-component data. In that case, one needs to solve the coupled elastic wave equations. But I do not see any barriers to doing so. I believe the surface reflection multi-component data can also be regarded as recorded at an elastic absorbing boundary, if one thinks the data contain only primary reflections.

CONCLUSIONS

I have shown that poststack and prestack datuming can be efficiently done by the use of finite-difference wavefield extrapolation. This method can handle any velocity variation between the two datums. And it is very efficient and accurate. It has great potential for applications in land-static correction and for migration in complex velocity areas. By cascading this datuming with simpler migration methods, one can obtain an accurate and fast migration scheme.

FUTURE RESEARCH

Two promising potential future research projects would be to demonstrate datuming with field data for applications to land data static corrections, and for migration in complex velocity areas. In deep marine seismic surveys, the removal of the water bottom multiples has long been a tricky problem. A likely solution is to datum all the common-shot and common-receiver gathers to a planar datum just above the water bottom, so that water bottom multiple travel-time period is short; conventional predictive deconvolution (Peacock and Treital, 1979) should work well, as in shallow water seismic surveys. Finite-difference datuming also has potential for applications in estimating background velocity by layer stripping procedures.

ACKNOWLEDGMENTS

My thanks to the sponsors of SEP and its director, Jon Claerbout, for their generous support. I would also particularly like to thank Martin Karrenbach and Dave Lumley for posing useful critical questions. I am grateful to Dr. James Berryman and Loren Rusk for carefully editing this paper.

REFERENCES

Baysal, E., Kosloff, D. D., and Sherwood, J. W. C., 1983, reverse-time migration: Geophysics, **48**, 1514–1524.

Berryhill, J. R., 1979, Wave-equation datuming: Geophysics, **44**, 1329–1344.

Berryhill, J. R., 1984, Wave-equation datuming before stack: Geophysics, **49**, 2064–2066.

Bevc, D., 1991, Refraction statics in mountainous terrain: SEP–**72**, 177–180.

Bevc, D., 1992, Wave-equation extrapolation of land data with irregular acquisition topography: SEP–**73**, 301–304.

Bevc, D., 1992b, Kirchhoff wave-equation datuming with irregular acquisition topography: SEP–**75**, 139–158.

Chang, W. F., and McMechan, G. A., 1986, Reverse-time migration of offset vertical seismic profiling data using the excitation-time imaging condition: Geophysics, **51**, 67–84.

Claerbout, J. F., 1976, Fundamentals of Geophysical Data Processing: McGraw-Hill.

Claerbout, J. F., 1985, Imaging the Earth's Interior: Blackwell Scientific.

Clayton, R. W., and Engquist, B., 1977, Absorbing boundary conditions for acoustic and elastic wave equations: Bull. Seism .Soc. Am., **67**, 1529–1540.

Dablain, M., 1986, The application of high-order differencing to the scalar wave equation: Geophysics, **51**, 54–66.

Dobrin, M. B., 1976, Introduction to Geophysical Prospecting: McGraw-Hill.

Etgen, J. T., 1986, High-order finite-difference reverse-time migration with the 2-way non-reflecting wave equation: SEP–**48**, 133–146.

Etgen, J. T., 1992, Personal communication.

French, W. S., 1975, Computer migration of oblique seismic reflection profiles: Geophysics, **40**, 961–980.

Gazdag, J., 1978, Wave equation migration with the phase-shift method: Geophysics, **43**, 1342-1351.

Harris, C. E., and McMechan, G. A., 1992, Using downward continuation to reduce memory requirements in reverse-time migration: Geophysics, **57**, 848-853.

Ji, J., and Claerbout, J., 1992, Phase shift datuming and migration from an irregular surface: SEP–**75**, 159–172.

Kosloff, D. D., and Baysal, E., 1982, Forward modeling by a Fourier method: Geophysics, **47**, 1402–1412.

McMechan, G. A., 1983, Migration by extrapolation of time-dependent boundary values: Geophys. Prosp., **31**, 413–420.

McMechan, G. A., and Chen, H. W., 1990, Implicit static corrections in prestack migration of common-source data: Geophysics, **55**, 757–760.

Mo, L., 1992, Migration of crosswell seismic data: SEP–**75**, 49–63.

Peacock, K. L. and Treitel, S., 1969, Predictive deconvolution: Theory and practice: Geophysics, **34**, 155–169.

Popovici, A., 1992, Wave-equation datuming in variable velocity media: SEP–**75**, 193–216.

Reshef, M., 1991, Depth migration from irregular surfaces with depth extrapolation methods: Geophysics, **56**, 119–122.

Schneider, W. A., 1978, Integral formulation for migration in two and three dimensions: Geophysics, **43**, 49–76.

Shih, R. C., and Levander, A. R., 1988, Multigrid reverse-time migration: 58th Ann. Internat. Mtg., Soc. Explor. Geophys., Expanded Abstracts, 988–990.

Shtivelman, V., and Canning, A., 1988, Datum correction by wave equation extrapolation: Geophysics, **53**, 1311–1322.

Stolt, R. H., 1978, Migration by Fourier transform: Geophysics, **43**, 23–48.

Stolt, R. H., and Benson, A. K., 1986, Seismic migration, theory and practice: Geophysical Press Limited.

Yilmaz, O., 1987, Seismic data processing: Soc. Expl. Geophys.

Zhu, X., and McMechan, G. A., 1988, Estimation of near-surface velocities by tomography: 58th Ann. Internat. Mtg., Soc. Explor. Geophys., Expanded Abstracts, 1236–1238.