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Reverse time migration from irregular surface by flattening surface topography

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ABSTRACT

Prestack reverse time migration (RTM) is a powerful tool to provide high resolution structure images of crust and upper mantle in wide-angle seismic experiments. As a standard migration algorithm assumes that data are recorded on a flat surface, RTM meets severe challenge on the issue of complicated topography where many seismic surveys are carried out. Up till now, there are two popular techniques for handling elevation changes, i.e., elevation-static correction (or time shift) and wave equation datuming. Numerous studies demonstrate that the elevation-static correction is inaccurate for non-vertically traveling energy and subsequently may migrate reflectors to incorrect positions. Wave equation datuming is more accurate but more sophisticated and too computationally demanding for routine use. Here, we present an alternative scheme to deal with topography in prestack RTM that can migrate seismic data acquired in areas with irregular topography to the reflector positions directly without datuming or elevation static corrections. In this scheme, surface topography is flattened by a transformation of coordinates from Cartesian to curvilinear. Such a transformation is equivalent to map a rectangular grid onto a curved one, and is implemented by the introduction of boundary conforming grid. Then we use an explicit finite-difference scheme with second-order accuracy to discretize the elastic wave equations and perform the RTM in the curvilinear coordinate system. Moreover, a flux-corrected transport (FCT) algorithm, adapted from hydrodynamics, is incorporated in the RTM implementation, which can not only overcome problems of numerical dispersion that arise in finite difference algorithms, but also offer the opportunity to use a coarse grid to obtain the same accuracy as conventional finite difference methods on a dense grid. The FCTRTM method presented here has no limitations on surface irregularity, complexity of the subsurface structure, or velocity function. Extensive numerical examples demonstrate the feasibility and effectiveness of our method.

1. Introduction

Prestack reverse time migration (RTM) of wide-angle seismic data represents an extension of traditional imaging with near-vertical incidence data because it includes a larger component of the recorded wave field (e.g., Chang and McMechan, 1989; Chang et al., 1989; McMechan and Fuis, 1987). It has the potential to provide high resolution images of deep-crustal structures, particularly when closely spaced data are collected (Lafond and Levander, 1995; Zelt et al., 1998). However, as a standard, optimized migration algorithm assumes that data are recorded on a flat surface. RTM meets severe challenge with complicated topography where many seismic surveys are carried out (e.g., Robertsson and Holliger, 1997; Zhang et al., 2005a). For example, in deep seismic soundings to explore the crustal structure, seismic experiments are usually carried out across: (1) orogen belts for understanding the mechanisms involved therein (e.g., Carbonell et al., 2004; Kaila and Krishna, 1992); (2) basins to understand their formation mechanisms (e.g., Li and Mooney, 1998; Thybo et al., 2003); and (3) transition zones for the study of the interactions involved (e.g., Bayer et al., 2002; Z. Zhang et al., 2010).

Up to now, there are two popular techniques for handling elevation changes, i.e., elevation-static correction (or time shift) (e.g., Cox et al., 1999; Marsden, 1993; Yilmaz, 1987) and wave equation datuming (e.g., Berryhill, 1979, 1984; Bevc, 1997; Yang et al., 1999). Numerous studies demonstrate that in regions of mild topography where the near-surface velocity is much slower than the subsurface velocity and ray-path emergence angles are small, the elevation-static correction is adequate for the transformation (e.g., Marsden, 1993; Taner et al., 1974; Zhang et al., 2005b). However, when the near surface velocity is comparable to the subsurface velocity and ray-path emergence angles are large, the elevation-static correction is inaccurate and subsequently may migrate reflectors to wrong positions in depth (e.g., Berryhill, 1979; Cox et al., 1999; Reshef, 1991). Beasley and Lynn (1991) 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

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migration, the seismic data are migrated after static shift by setting the velocity in the diffraction term to zero above the topography. Not only is the static time shift required before migration, but this technique cannot be applied to the computationally attractive phase-shift algorithms due to the nonphysical characteristic of zero velocity (e.g., Bevc, 1997). The concept of wave-equation datuming was first presented in Berryhill (1979) for poststack applications, and later 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 wave-field propagation. This ensures that subsequent processing steps that assume hyperbolic form, or even more complicated trajectories consistent with wave propagation, can be accurately applied. However, the wave equation datuming is more sophisticated and too computationally demanding for routine use (e.g., Beasley and Lynn, 1991; Reshef, 1991).

Recently, methods allowing direct migration of seismic data recorded on a rugged topographic surface have been proposed. Wiggins (1984) used a Kirchhoff formulation to incorporate topography directly in prestack migration from a rugged surface. Reshef's (1991) phase-shift migration method was also used to migrate seismic data directly. He performed downward extrapolation from a flat datum and added data to the extrapolated wave field each time where the topographic surface is intersected.

Here, we present an alternative scheme to deal with topography in pre-stack RTM that can image seismic data acquired in areas with irregular topography directly without datuming or elevation static corrections. In this scheme, surface topography is flattened by a transformation of coordinates from Cartesian to curvilinear (Lan and Zhang, 2013a,b). Such a transformation is equivalent to map a rectangular grid onto a curved one, and is implemented by the introduction of boundary conforming grid. Then we use an explicit second-order accurate finite-difference scheme to discretize the elastic wave equations and perform RTM in the curvilinear coordinate system. In addition, a flux corrected transport (FCT) (e.g., Book et al., 1975; Boris and Book, 1973) technique is integrated into our method to reduce the numerical dispersion in the finite difference wave-field continuation.

2. Transformation between curvilinear and Cartesian coordinates

As to the topographic surface, the discrete grid must conform to the irregular surface to suppress artificial errors. Such a grid is named boundary conforming grid (Hvid, 1995; Thomson et al., 1985), and has been used in seismic wave simulation by a number of researchers (e.g., Appelö and Petersson, 2009; Fornberg, 1988; Lan and Zhang, 2011, 2012, 2013a,b; Zhang and Chen, 2006). A grid of this type is achieved by carrying out a transformation between the (curvilinear) computational space and the (Cartesian) physical space as illustrated in Fig. 1. By means of this transformation, the curvilinear coordinates q and r are mapped into Cartesian coordinates within the physical space, with both systems having a positive upward direction for the vertical coordinate. A boundary in the physical space is represented by a constant value of one of the curvilinear coordinates, either a curve in two dimensions or a surface in three dimensions (Hvid, 1995).

The boundary conforming grids are of two fundamental types: structured and unstructured (irregular). Structured grids are characterized by having a fixed number of elements along each of the coordinate directions. In 2-D, the generalized element is a quadrilateral. Neighboring elements in the physical space are also adjacent to one another in the computational space, which is one of the primary advantages of this type of grids. This property makes it relatively simple to implement in modeling (Hvid, 1995). A number of methods may be used to generate such grids, including Partial Differential Equation (PDE) methods, algebraic methods, co-normal mapping methods and variational methods (e.g., Thomson et al., 1985). Here, we use the PDE methods to generate our structured boundary conforming grids (for details see Hvid, 1995; Thomson et al., 1985).

After generating the boundary conforming grids, the Cartesian coordinates of each grid point can be determined from its curvilinear coordinates through the following equations (Lan and Zhang, 2011):

$$x = x(q,r), \tag{1a}$$

$$z = z(q,r). \tag{1b}$$

Then, we can express the spatial derivatives in the Cartesian coordinate system (x,z) from the curvilinear coordinate system (q,r) following the chain rule:

$$\partial_x = q_x \partial_q + r_x \partial_r, \tag{2a}$$

$$\partial_z = q_z \partial_q + r_z \partial_r. \tag{2b}$$

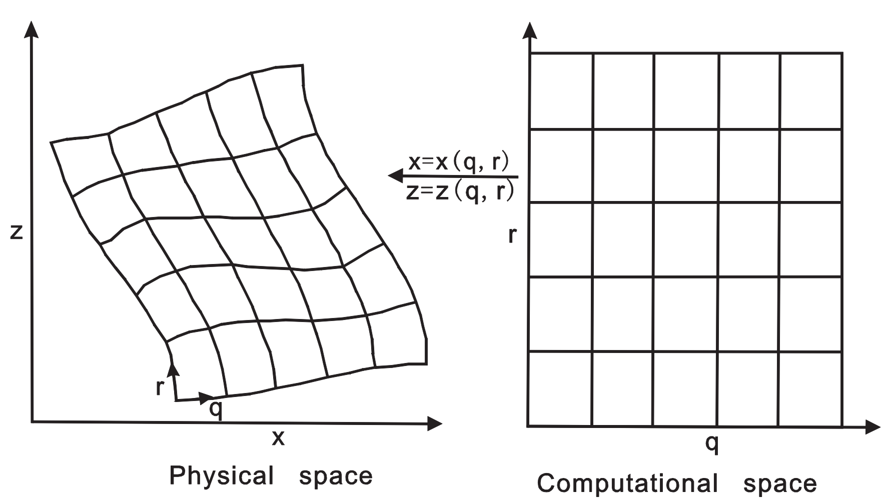

Fig. 1. Mapping between computational space and physical space in two dimensions.
From Lan and Zhang (2013a).