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A new 3D Eikonal solver for accurate traveltimes, take-off angles and amplitudes

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The finite-difference approximation to the eikonal equation was first introduced by J.Vidale in 1988 to propagate first-arrival times throughout a 2D or 3D gridded velocity model. Even today this method is still very attractive from a computational point of view when dealing with large datasets. Among many domains of application, the eikonal solver may be used for 2-D or 3-D depth migration, tomography or microseismicity data analysis.

The original 3D method proposed by Vidale in 1990 did exhibit some degree of travel time error that may lead to poor image focusing in migration or inaccurate velocities estimated via tomographic inversion. The method even failed when large and sharp velocity contrasts were encountered. To try and overcome these limitations many authors proposed alternative algorithms, incorporating new finite-difference operators and/or new schemes of implementing the operators to propagate the travel times through the velocity model.

If many recently published algorithms for resolving the 3D eikonal equation do yield fairly accurate travel times for most applications, the spatial derivatives of travel times remain very approximate and prevent reliable computation of auxiliary quantities such as take-off angle and amplitude. This limitation is due to the fact that the finite-difference operators locally assume that the wavefront is flat (plane wave). This assumption is in particularly wrong when close to the source where a spherical approximation would be more suitable. To overcome this singularity at the source, some authors proposed an adaptive method that reduces inaccuracies, however, the cost is more algorithmic complexity.

The objective of this study is to develop an efficient simple 3D eikonal solver that is able to: overcome the problem of the source singularity, handle velocity models that exhibit strong vertical and horizontal velocity variations, use different grid spacing in x, y and z axis of model. The final goal is of course to generate accurate travel times in order to compute auxiliary quantities such as take-off angle and amplitude on a velocity model with sharp and strong velocity contrasts.

Our scheme is very similar to many existing methods, in the sense that we use 1D, 2D and 3D local finite-difference operators to extrapolate travel time from one point to another. The accuracy of our scheme is achieved by combining two different extrapolation operators: a spherical one close to the source, and plane wave operator when we are far from the source. In this work, we briefly present the key point of our algorithm (plane and spherical wave extrapolation formulas); we illustrate the accuracy of our method by comparing with an analytical solution, and finally show that we are able to compute take-off angles and amplitudes on a velocity model with a sharp and strong velocity contrast.