Seismic Imaging: Reconstruction of the Earth from Surface Recordings

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Summary: We build new and fast algorithms to reconstruct seismic velocities inside the Earth from data obtained from surface recordings of reflected waves. This is an important step in determining the Earth's substructure and locating petroleum resources.

Determining the velocity of propagating waves in the Earth is a crucial step in seismic imaging, which allows interpretation of structures in the Earth and aids in locating petroleum reserves. Vast supercomputing technologies are used to analyze massive amounts of data obtained by recording the reflection of sound waves off underground structures; this "seismic imaging" forms a critical stage in analyzing the Earth's makeup. A typical procedure is to tow an array of microphones and record waves reflecting off the various layers from carefully timed source events on the surface.

For many decades seismic imaging, known as “time migration”, was based on the assumption that the velocity inside the earth depends only on the depth and that the subsurface structures are horizontal or, at worst, planar with the same dipping angle. This procedure is considered adequate for the areas with mild lateral velocity variation, where the velocity depends mostly on vertical depth z and only slightly on the two horizontal directions x and y. However, even mild lateral velocity variations can significantly distort structures in time migrated images. Moreover, time migration produces images in time migration coordinates, which give the velocity at a depth point reached by ray from the Earth's surface at a given time. The relation between this somewhat unnatural coordinate system and the more appealing Cartesian coordinates can be nontrivial if the velocity varies laterally.

An alternative imaging approach, called "depth migration", is adequate for areas with lateral velocity variation, and produces seismic images in regular Cartesian coordinates. The major problem with this approach is that its implementation requires the construction of a "velocity model" for the seismic velocity v at the underground point (x,y,z). It is both difficult and time consuming to construct an adequate velocity model: an iterative approach of guesswork followed by correction is often employed.

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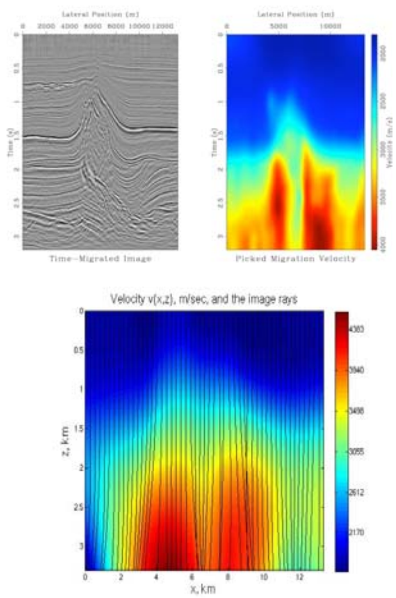
Our goal is fast and robust algorithms to (i) convert time migrated image coordinates to depth coordinates and (ii) convert migration velocities to depth velocities.

We have so far, been able to produce a relation theoretical relationship between the migration velocities and the true seismic velocities. This has allowed us to build a fast and robust algorithm for time-to-depth conversion of time migrated images, as well as two algorithms for achieving both of the above goals with some limitations.

The first algorithm converts time migration velocities to depth velocities, inspired by the Fast Marching Method, which is a Dijkstra-like procedure for computing the solution to the Eikonal equation, and gives the first arrivals for waves in a complex medium. However, in this case, the slowness field is unknown, so we must solve a coupled pair of equations: the first for waves propagating in a medium of unknown speed, and the second which gives the speed presuming one knows the position of the evolving wave. We have produced an O(N log N) way to produce the solution without iteration.

The two techniques for converting velocity data are themselves interesting: the first relies on ray-tracing, the second on a variant of level set methods. Each compute evolving fields using our newly discovered relationship between the waves and its evolving curvature. Both algorithms are stable, and give quite reasonable results for structures with significant lateral variation.

Below is a North Sea example, in which we image a salt dome with severe lateral variations. Top left shows the data; top right shows time migration data used to make this image; and the bottom shows reconstructed velocities in depth coordinates, together with the underlying characteristics.



J.A. Sethian, Level Set Methods and Fast Marching Methods, Cambridge Press, 1999.

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