EFFICIENT AND ACCURATE CALCULATON OF RAY THEORY SEISMIC TRAVEL TIME THROUGH VARIABLE RESOLUTION 3D EARTH MODELS

Sanford Ballard, James R. Hipp and Christopher J. Young,, Sandia National Laboratories

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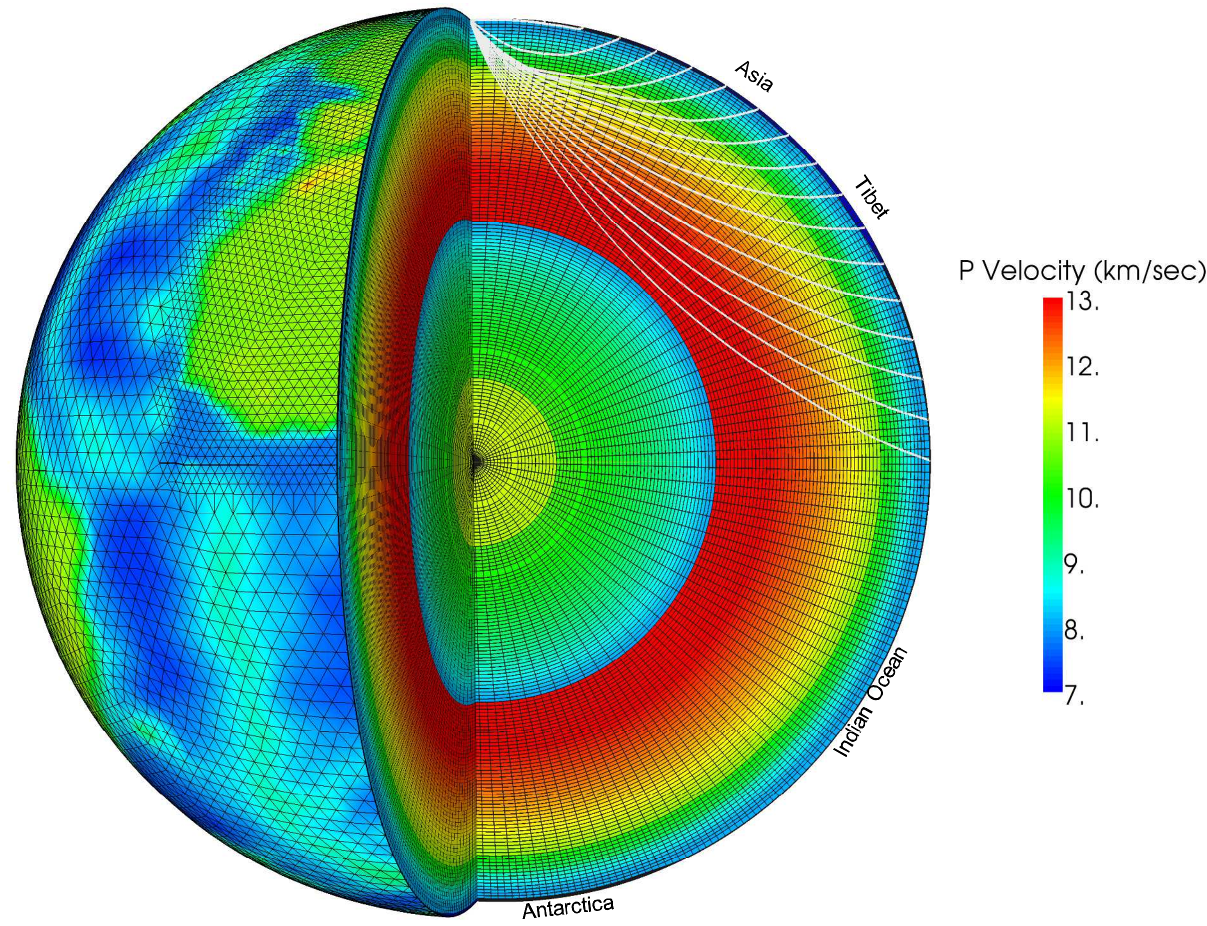
Introduction

Several studies have suggested that using 3D Earth models to locate seismic events can improve the accuracy and reduce the uncertainty of the computed locations. We describe a fully 3D global Earth model representation and a compatible travel time calculator based on the ray pseudo-bending algorithm of Um and Thurber (1987). Together, these codes provide a practical means to efficiently and accurately calculate travel times for infinite frequency rays through global, variable resolution 3D Earth models. Ray tracing in 3D is computationally expensive but we compensate by implementing our codes in a heterogeneous distributed computing environment.

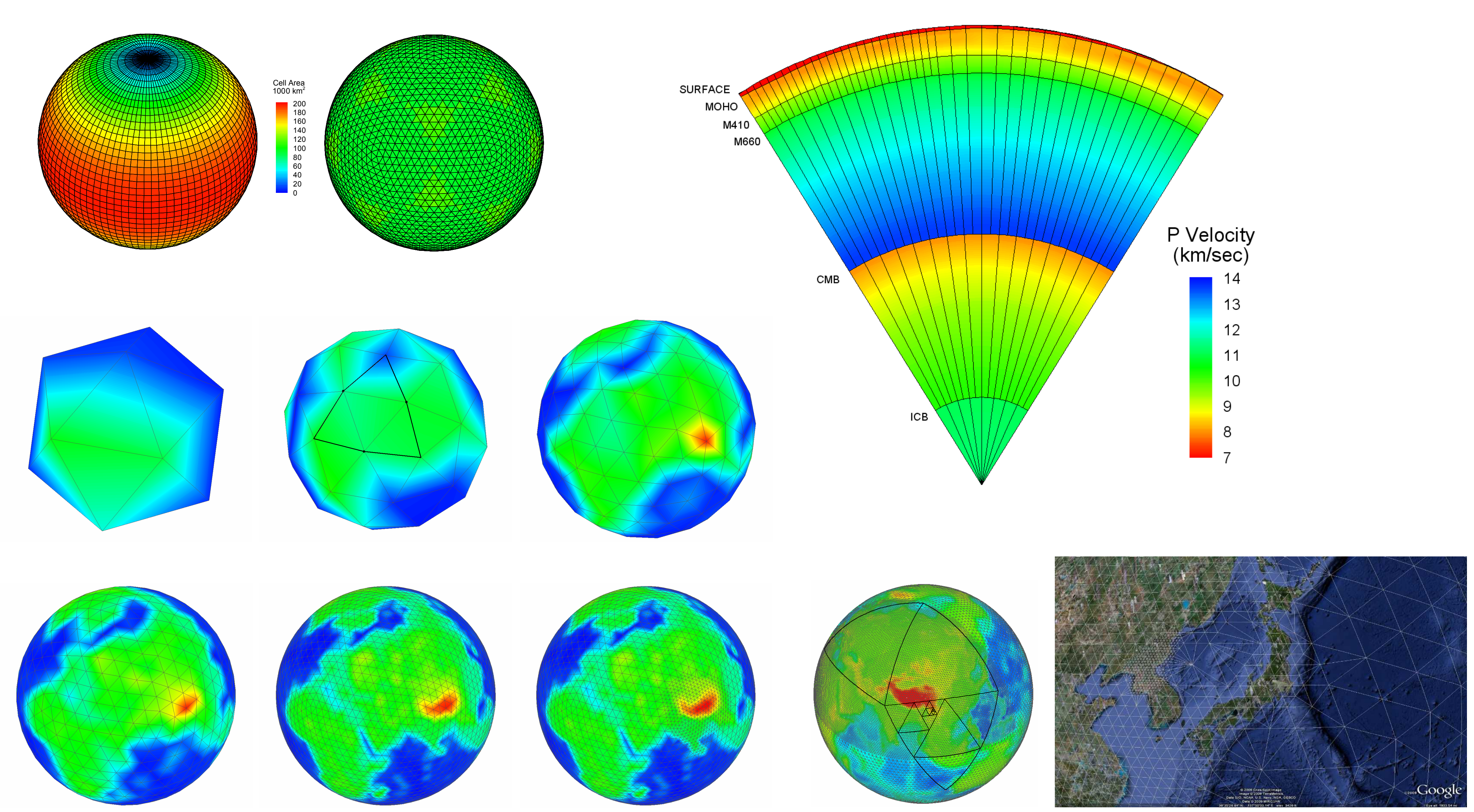
We are using these codes to evaluate published 3D models and to generate new models using tomographic inversion. We are currently modifying our seismic event location code and will soon be able to assess improvements in location capability that result from using 3D models.



3D Earth Model Representation

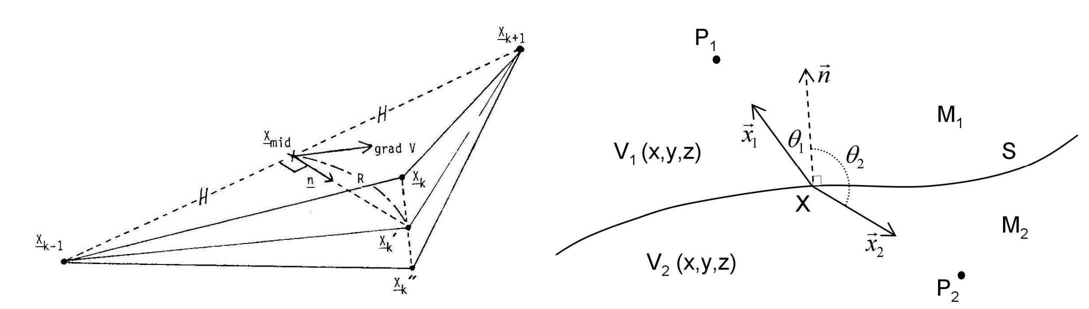
Regular latitude-longitude grids are not suitable for global models due to convergence of meridians at the poles. We construct a global tessellation of triangles by starting with a regular polyhedron (tetrahedron, octahedron, icosahedron or tetra-hexahedron) and recursively subdividing the triangles until the desired resolution is achieved. Variable resolution in the geographic dimension is achieved by only subdividing triangles where additional resolution is desired. Finding the triangle in which a given geographic position is located is efficiently implemented using a multi-level triangle walking algorithm.

At each node of the tessellation, a radial profile of Earth properties is defined. The radial positions of nodes are defined relative to the actual topography of the Earth referenced to the GRS80 ellipsoid, thereby removing the necessity to implement ellipticity and elevation corrections. Variable resolution in the radial direction is achieved by defining profiles from one of the major discontinuities in the model out to the topographic/bathymetric surface of the Earth.

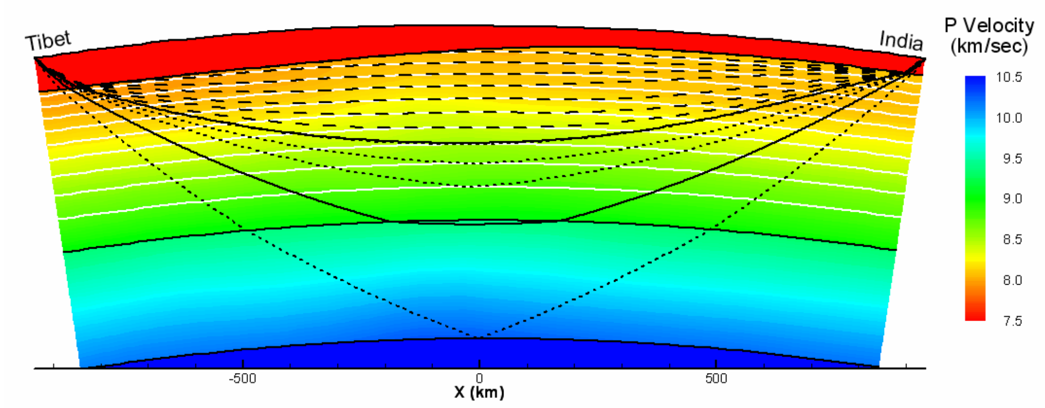


Ray Tracing

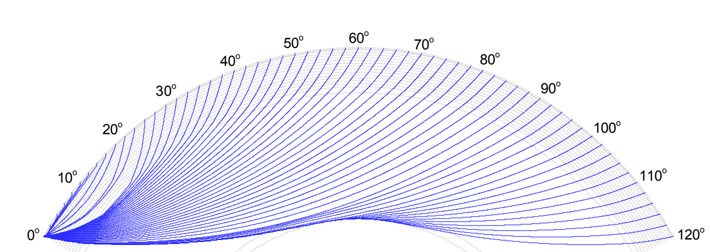
After considering Eikonal solvers, ray shooters and finite difference ray benders, we chose to implement the ray pseudo-bending algorithm described by Um and Thurber (1987) enhanced by Zhao et al. (1992) and Zhao and Lei (2004).

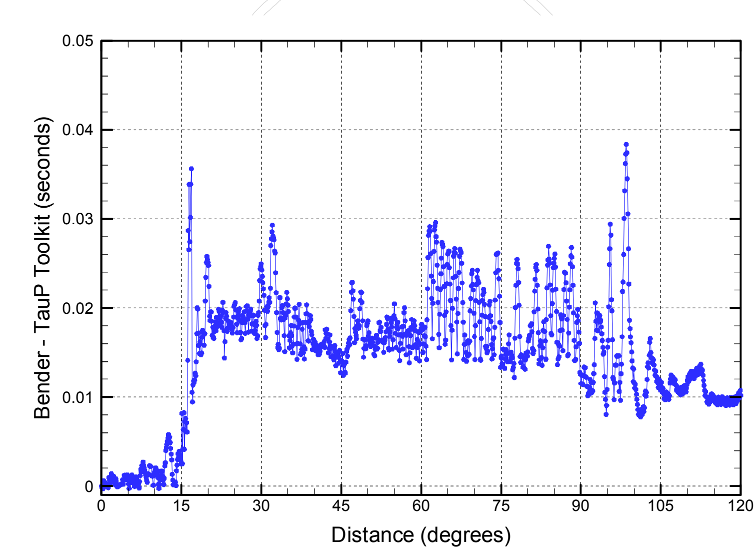


Our implementation reduces the likelihood that the pseudo-bending algorithm will return a local minimum by starting the ray calculation from several different starting rays. Specifically, interfaces are defined that include first order discontinuities plus additional interfaces at levels of the model where local minima are anticipated. Rays are computed that are constrained to bottom in each layer between these interfaces. The computed rays might be reflected off the top of the layer, turn within the layer, or diffract along the interfaces at the top and/or bottom of the layer. The computed ray that is seismologically valid and that has the shortest travel time is retained.



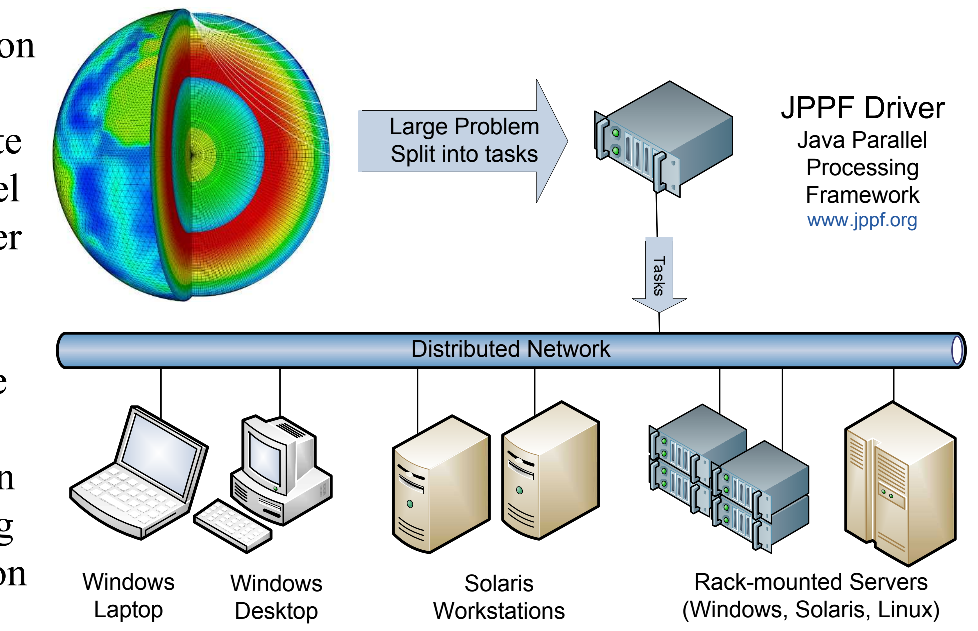
To verify the validity of the Bender we constructed a 3D version of the radially symmetric AK135 model (Kennett et al., 1995), using the successive tessellation subdivision method described above. The difference in travel time computed with the Bender and calculated using the 1D TauP travel time calculation algorithm (Buland and Chapman, 1983) as implemented in the TaupToolkit software (Crotwell et al., 1999) are compared below. The differences at all local, regional and teleseismic distances are at most a few hundredths of a second, indicating that the Bender is very accurate, even for long path lengths.





Distributed Computing

The ray bender requires on average approxim-ately 0.125 seconds to compute one source-receiver travel time on a single computer processor. To mitigate these negative performance impacts, we have multi-threaded the algorithm so it can be run in concurrent mode using all available processors on a single multiprocessor computer. We have also implemented our algorithm in a distributed computing environment using the Java Parallel Processing Framework (JPPF; www.jppf.org) allowing us to run many travel time calculations simultaneously on a heterogeneous cluster of multiprocessor PC, Mac, Unix and Linux computers. Our current configuration allows up to 200 travel time calculations to be run in parallel.

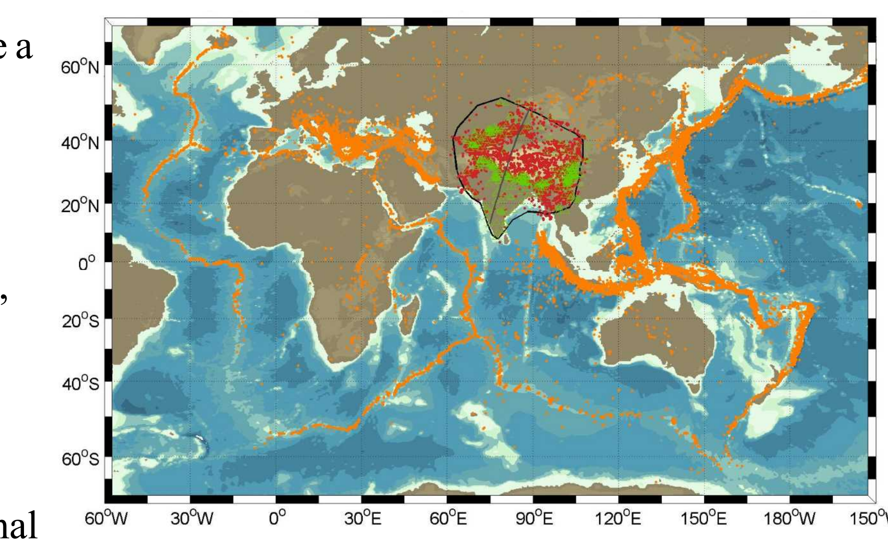


Travel Time Tomography

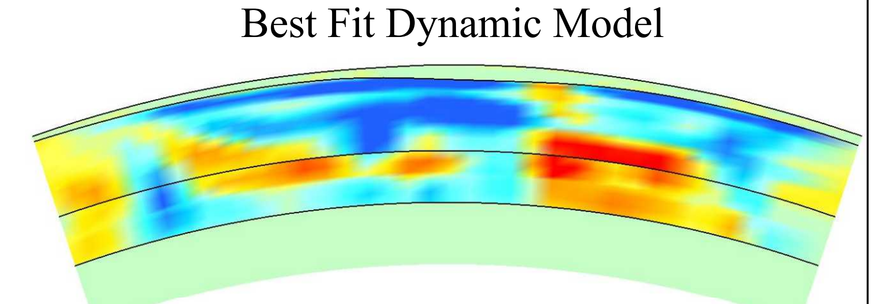
Our ultimate goal is to produce a global, seamless, 3D velocity model from the core-mantle boundary to the Earth's topographic / bathymetric surface. In pursuit of that goal, we have developed a tomographic inversion system based on the standard LSQR algorithm (Page and Saunders, 1982) and applied it to a regional tomography problem centered on the crust and upper mantle of the Indian Subcontinent and the Tibetan Plateau.

Tomography is highly non-unique. Our goal is to produce a model that achieves lower residuals in order to improve event location and reduce uncertainty, not to accurately image the Earth for the purpose understanding Earth dynamics.

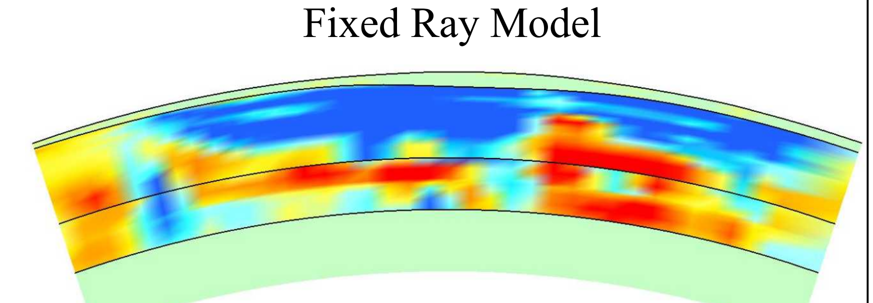
Important issues include: use of fixed vs. dynamic rays, inclusion of event and/or site terms in the inversion, selection of optimal damping and regularization parameters, and the selection of an appropriate starting model.



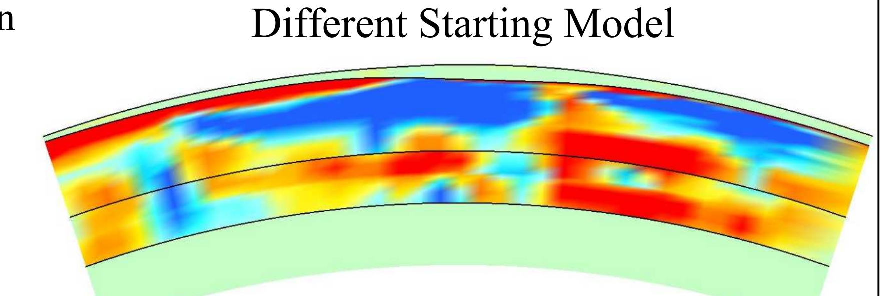
Best Fit Dynamic Model



Fixed Ray Model



Different Starting Model



Summary

We are developing the capability to compute seismic event locations using global, seamless, variable resolution 3D Earth models. A key goal of this work is to implement a system with computational performance that meets operational monitoring requirements.

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