Discovery at the Interface of Science and Engineering: Science Matters!

Computer and Information Sciences
Simulation Technologies

Large-Scale Seismic Inversion

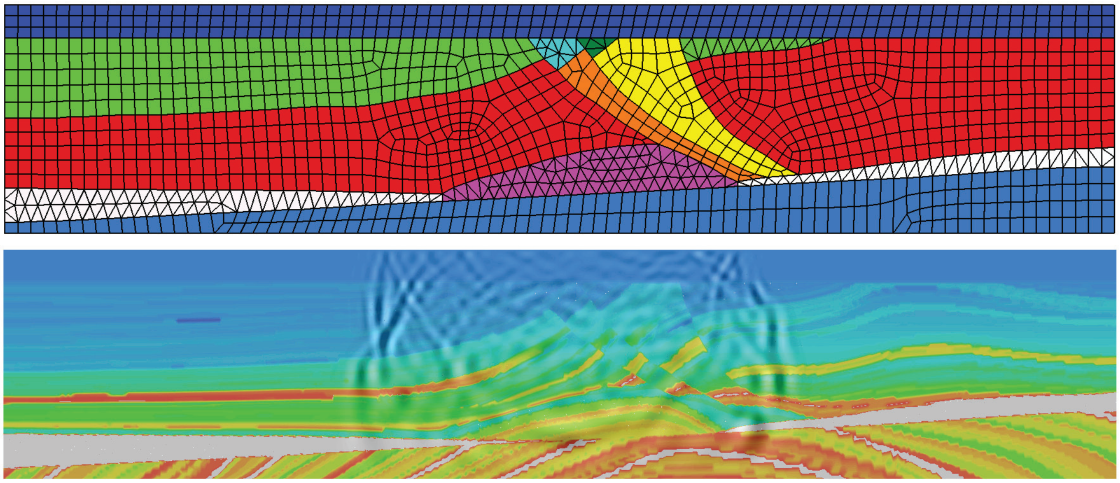

Figure 1: A hybrid triangular and quadrilateral unstructured mesh generated by Sandia's CUBIT for the Marmousi2 model (a standard seismic model with many layers, Reference 3) that conforms to geological interfaces (top), and simulated pressure waves propagating through the model (bottom).

Sandia is exploring new algorithmic approaches to modeling the complex geology of the earth's interior.

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Much of what is learned about the geology of the earth's interior is through seismic surveys that record reflected sound waves traveling through the various layers and structures. In "seismic inversion," one estimates the geologic structure and properties, density and wave speeds, and then simulates the seismic waves and surveys to produce synthetic recordings. These recordings are then compared to the actual field recordings to improve the initial estimates. This process is repeated until a sufficiently accurate earth model is obtained (Reference 2).

Advances in seismic inversion could have broad-reaching national impact for earthquake prediction, oil and gas exploration and production, carbon sequestration, nuclear-waste repositories, and nuclear non-proliferation monitoring. However, the process is a computational grand challenge. Discontinuous material interfaces, attenuation, and large-scale optimization are some of the major problems in the field today. Discontinuous material interfaces occur routinely in seismic surveys, such as the ocean bottom, salt structures, and faults (Figure 1 top). Sandia is leveraging advanced forward simulation methods, such as discontinuous Galerkin (DG) methods on unstructured meshes, along with adjoint-based inversion algorithms, to solve seismic inversion problems on distributed-memory parallel computers.

DG methods are a numerical approach to solve partial differential equations (PDEs). They use techniques from finite element and finite volume methods, and easily extend to higher-order approximations for the PDEs. The solution is continuous within the element, but across element boundaries it is discontinuous. To handle these discontinuities, solutions to the Riemann problem are used. DG methods are well-suited to hyperbolic PDEs which model physics with seismic wave-propagation. DG methods that conform to discontinuous material interfaces allow strong media changes to be modeled better, leading to more accurate simulations. One can also model the effects of attenuating material within the earth's interior with additional equations. However, these equations, along with the extremely large number of inversion parameters, create a tremendous burden on computational resources. Sandia is thus exploring new algorithmic approaches to help reduce these costs.

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Traditionally, discontinuous material interfaces have been smoothed to allow easy meshing of the computational domain as well as compatibility with high-order finite-difference methods for modeling wave propagation. However, with Sandia's unstructured DG methods, these interfaces can be better represented, producing more accurate results (Figure 1 bottom). As noted above, seismic wave attenuation, where wave energy is absorbed and experiences changes in waveform amplitude and shape, is complex and costly to model. It is very important to include, however, and Figure 2 illustrates the difference between a simulation with (right) and without (left) attenuation. These differences would affect the estimated earth properties obtained through inversion, leading to a potentially misleading prediction of the earth's interior.

The cost of inversion is directly related to the number of inversion parameters. Many inverse problems for engineering applications have at most tens of parameters. However, for seismic inversion one needs to invert for billions of field parameters (*e.g.*, density and bulk modulus for acoustic inversion) producing a tremendous computational challenge. Even with peta-scale computers, an inversion could take hundreds of CPU-days. An example acoustic inversion using the Sandia DG inversion tool is shown in Figure 3. The current work focuses on exploiting the flexibility of the DG method to further improve seismic inversion.

References

1. J. R. Krebs, J. E. Anderson, D. Hinkley, A. Baumstein, S. Lee, R. Neelamani, and M.D. Lacasse. Fast full wave seismic inversion using source encoding. SEG Technical Program Expanded Abstracts, 28(1): 2273–2277, 2009. doi: 10.1190/1.3255314. URL http://link.aip.org/link/?SGA/28/2273/1.
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3. G. S. Martin, R. Wiley, and K. J. Marfurt. Marmousi2: An Elastic Upgrade for Marmousi. The Leading Edge, 25:156–166, February 2006.

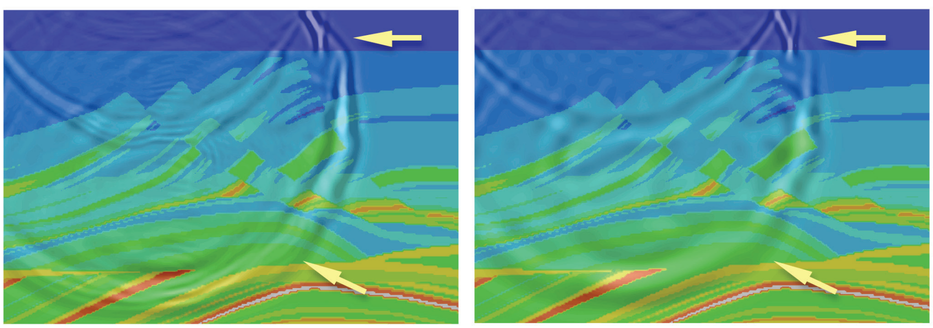

Figure 2: Simulated acoustic wave propagation without attenuation (left), and wave propagation with attenuation (right) through the Marmousi2 model.

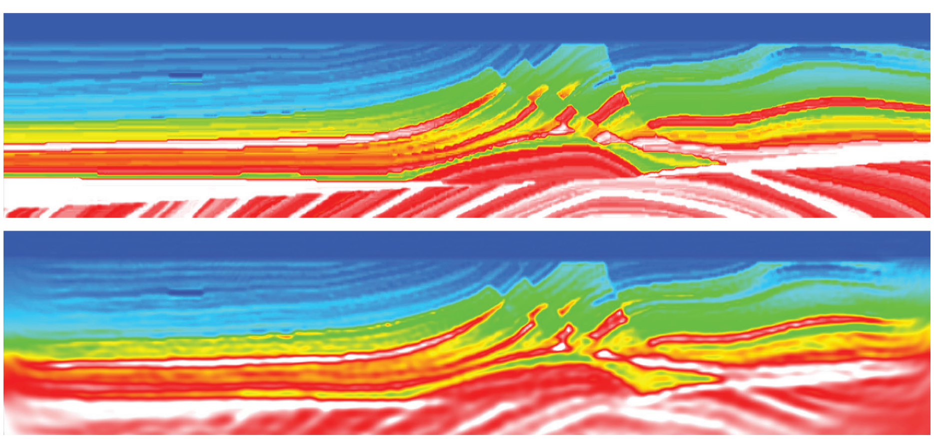

Figure 3: Inversion of the Marmousi2 model where the predicted sound-speed (bottom) is in good agreement with the true sound-speed (top). Conditions similar to those in Krebs et al. (References 1,2)

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