The Prospect of Using Three-Dimensional Earth Models to Improve Nuclear Explosion Monitoring and Ground-motion Hazard Assessment

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INTRODUCTION

The past 10 years have brought rapid growth in the development and use of three-dimensional (3D) seismic models of Earth structure at crustal, regional, and global scales. In order to explore the potential for 3D seismic models to contribute to important societal applications, Lawrence Livermore National Laboratory (LLNL) hosted a Workshop on Multi-Resolution 3D Earth Models to Predict Key Observables in Seismic Monitoring and Related Fields on 6–7 June 2007, in Berkeley, California. The workshop brought together academic, government, and industry leaders in research programs developing 3D seismic models and methods for nuclear explosion monitoring and seismic ground-motion hazard assessment. The workshop was designed to assess the current state of 3D seismology and to discuss a path forward for 3D Earth models and techniques—how can they be used to achieve measurable increases in our capabilities for monitoring underground nuclear explosions and characterizing seismic ground-motion hazards? This paper highlights some of the presentations, issues, and discussions at the workshop and proposes two specific paths by which to begin quantifying the potential contribution of progressively refined 3D seismic models in critical applied arenas.

Seismic monitoring agencies are tasked with detection, location, and characterization of seismic activity in near real time. In the case of nuclear explosion monitoring or seismic hazard, decisions to further investigate a suspect event or to launch disaster relief efforts may rely heavily on real-time analysis and results. Because these are weighty decisions, monitoring agencies are regularly called upon to meticulously document and justify every aspect of their monitoring system. To meet this level of scrutiny and maintain operational robustness, only mature technologies are considered for operational monitoring systems, so operational technology necessarily lags contemporary research.

Current monitoring practice is to use relatively simple Earth models that generally afford analytical prediction of seismic observables (see "Examples of Current Monitoring Practice" below). Empirical relationships or corrections to predictions are often used to account for unmodeled phenomena, such as the generation of *S* waves from explosions or the effect of 3D Earth structure on wave propagation. This approach produces fast and accurate predictions in areas where empirical observations are available. However, accuracy may diminish away from empirical data. Further, much of the physics is wrapped into an empirical relationship or correction, which limits the ability to fully understand the physical processes underlying the seismic observation.

Every generation of seismology researchers works toward quantitative results, with leaders who are active at or near the forefront of what has been computationally possible. While recognizing that only a 3D model can capture the full physics of seismic wave generation and propagation in the Earth, computational seismology has, until recently, been limited to simplifying model parameterizations (*e.g.*, 1D Earth models) that lead to efficient algorithms. What is different today is the fact that the largest and fastest machines are at last capable of evaluating the effects of generalized 3D Earth structure at levels of detail significantly better than past efforts and with potentially wide application. Advances in numerical methods to compute travel times and complete seismograms for 3D models enable new ways to interpret available data. This includes algorithms such as the fast marching method (Rawlison and Sambridge 2004) for travel-time calculations; and full waveform methods such as the spectral element method (SEM; Komatitsch *et al.* 2002, Tromp *et al.* 2005), higher order Galerkin methods (Käser

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and Dumbser 2006; Dumbser and Käser 2006), and advances in more traditional Cartesian finite difference methods (*e.g.*, Pitarka 1999; Nilsson *et al.* 2007).

The ability to compute seismic observables using a 3D model is only half the challenge; models must be developed that accurately represent true Earth structure. Indeed, advances in seismic imaging have followed improvements in 3D computing capability (*e.g* Tromp *et al.* 2005; Rawlinson and Urvoy 2006). Advances in seismic imaging methods have been fueled in part by theoretical developments and the introduction of novel approaches for combining different seismological observables, both of which can increase the sensitivity of observations to Earth structure. Examples of such developments are finite-frequency sensitivity kernels for body-wave tomography (*e.g.*. Marquering *et al.* 1998; Montelli *et al.* 2004) and joint inversion of receiver functions and surface wave group velocities (*e.g.*, Julia *et al.* 2000).

Improvements in data quantity and quality have also greatly increased resolution and reduced uncertainty in seismic models. The EarthScope/USArray program (`http://www.earthscope.org`) and similar national and international efforts are collecting large high-quality data sets that will enable 3D imaging of regional Earth structure at unprecedented resolution. These efforts promise to sustain a march toward higher resolution and more accurate multi-scale 3D Earth models.

To date, the primary aim of 3D model development has been to improve the understanding of Earth structure and processes. Although a number of studies have demonstrated the utility of using 3D models for determining seismic locations (Antolik *et al.* 2003; Yang *et al.* 2004; Flanagan *et al.* 2007), the broader application of 3D models in operational monitoring systems has yet to occur. Changing operational practice is a serious matter for any monitoring agency, because operational changes are costly, and there are risks to operational robustness. Further, one of the primary benefits of a longstanding operational bulletin is consistency, which enables users to place current events in the context of an established bulletin. Therefore, the only operational changes that are considered are those that will, without doubt, improve operational performance significantly.

The purpose of the June 2007 workshop was to assess merits of incorporating 3D Earth-model techniques into monitoring systems. Here, we briefly summarize the current state of practice in nuclear explosion monitoring and seismic hazard analysis, then we present the current state of the art for developing 3D models and synthesizing associated 3D seismic wavefields. We conclude with two specific proposed paths forward that were defined during the workshop, with the goals of exploiting 3D models to improve nuclear explosion monitoring and earthquake hazard assessment, and to measure progress toward these goals.

EXAMPLES OF CURRENT MONITORING PRACTICE

The current practices for computing the many types of seismic observables are diverse and exhaustively describing them is beyond the scope of this report. Instead we provide some examples of how simple models are currently used to predict travel times and amplitudes.

Global Travel Times

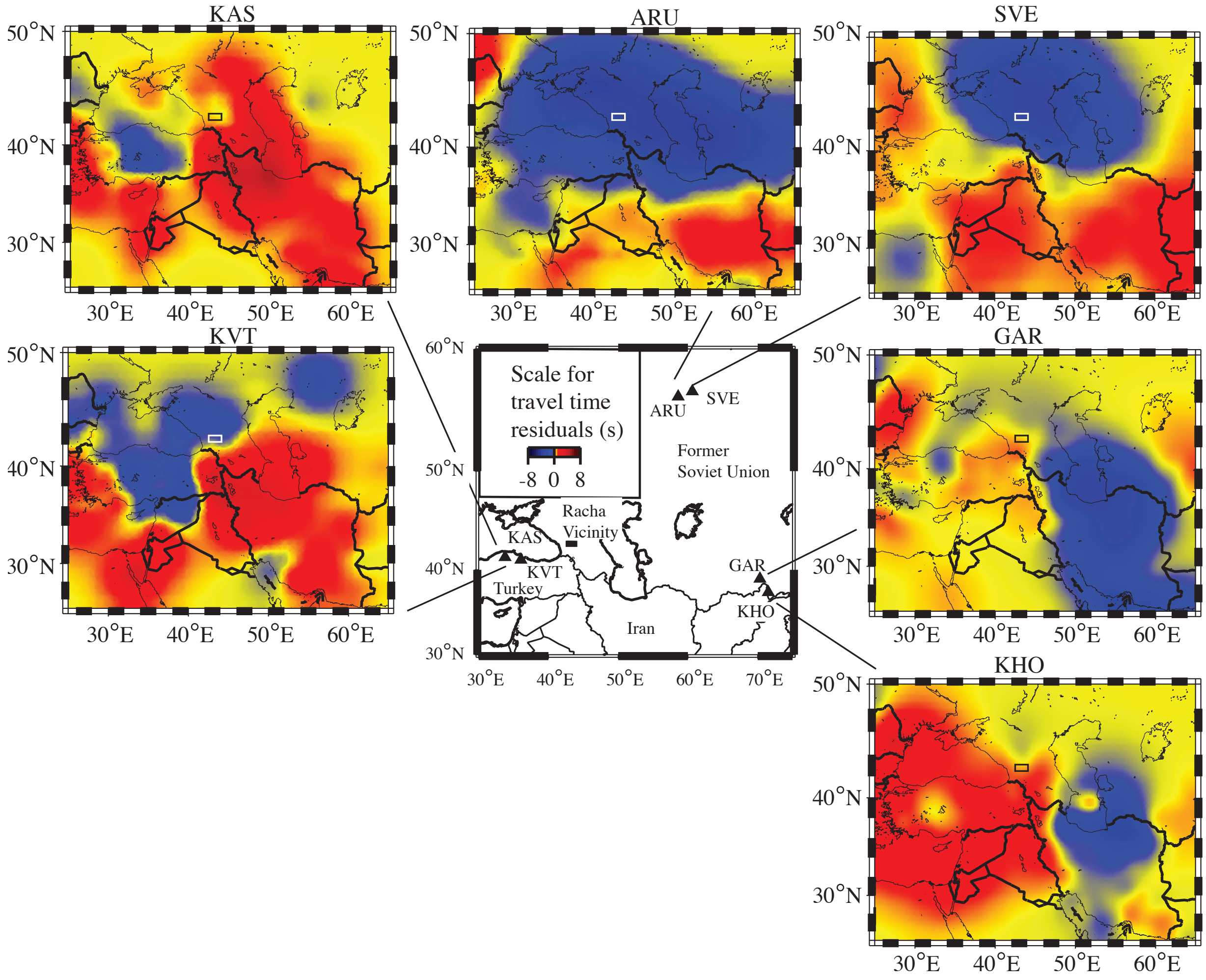
Nuclear explosion monitoring relies on one-dimensional (1D) Earth models (*e.g.*, Kennett and Engdahl 1991) to compute a "baseline" travel-time prediction. The 1D model parameterization enables the use of analytical travel-time approaches (*e.g.*, Buland and Chapman 1983) that are accurate to the extent that the model is accurate. However, the 1D model parameterization cannot capture the physics of wave propagation in the 3D Earth. Therefore, corrections to the baseline prediction due to any number of unmodeled effects (*e.g.*, station elevation, Earth ellipticity, 3D velocity perturbations) are accounted for with travel-time corrections. In the case of corrections to account for Earth ellipticity, the corrections may be model-based (Dziewonski and Gilbert 1976). In the case of corrections to account for unmodeled velocity structure, interpolation of empirical travel-time observations may be used to improve prediction accuracy and characterize uncertainty (*e.g.*, Figure 1; Myers and Schultz 2000). This approach works well where empirical observations are available and has proved robust in operational systems. However, prediction accuracy diminishes away from empirical observations (both laterally and with event depth), and considerable effort is needed to ensure consistency of corrections for all network stations. Capturing realistic Earth structure in a 3D model would not only consolidate our information about travel times and velocities into one "container" but would guarantee consistency of travel-time predictions for any and all seismic networks. Models can also be used to generate travel-time predictions when empirical data are sparse or unavailable, such as for a newly installed station.

Local Amplitudes

Ground motion calculations for seismic hazard typically rely on simple (1D) distance-dependent attenuation relationships to predict ground motions (*e.g.*, Joyner and Boore 1981) as shown in Figure 2, with corrections for site response and/or rupture directivity (*e.g.*, Abrahamson and Silva 1997). Site-specific corrections may be based on empirical data or generalized geotechnical corrections (*e.g.*, National Earthquake Hazards Reduction Program soil classifications; Building Seismic Safety Council 1998). However, these corrections typically do not account for path-propagation effects such as basin-generated surface waves that can have a large effect on long-period ground motions. Nor do these 1D calculations typically take into account the full time history of ground motions, such as duration of shaking, dynamic rupture, coupled structural response, and nonlinear effects.

STATE OF THE ART OF 3D SEISMOLOGY

Presentations at the workshop demonstrated that advances in numerical algorithms, inversion methods, computer performance, and seismic data quantity and quality are enabling the

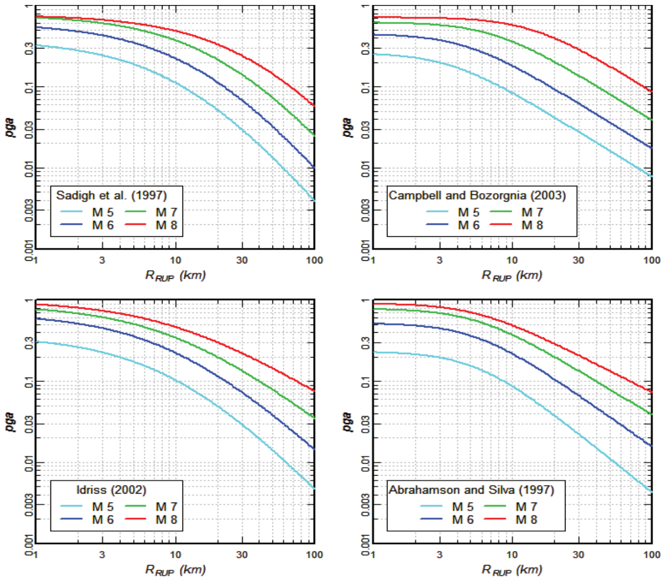


▲ **Figure 1.** Empirical travel-time correction surfaces relative to a 1D velocity model. The size of the corrections is indicated by color and ranges from approximately –6 to +4 seconds. Such corrections can account for tens of kilometers of location error (from Myers and Schultz 2000).

development and utilization of 3D models for routine prediction of seismic parameters. First and foremost, advances in computational performance—increases in computational power, parallel processing methods, and memory—enable prediction of seismic observables using 3D Earth models with unprecedented resolution. At present, routine 3D global-scale SEM calculations are feasible with modest-size computer clusters for periods as short as ~10–20 seconds (Komatitsch *et al.* 2002), and shorter-period calculations are possible on continental scales. Calculations for the entire globe have been performed at periods down to 3 seconds on supercomputers (Komatitsch *et al.* 2003). Simulations of strong motions on regional scales (~500 km) for large earthquake ruptures are possible to frequencies up to 1 Hz (*e.g.*, Olsen *et al.* 1997, 2006; Krishnan *et al.* 2006; Aagaard *et al.* 2008). Calculations of seismic attributes such as travel time (used for location) and scalar amplitude (used for magnitude and earthquake/explosion identification) are becoming fast enough to contemplate real-time computation in a monitoring system.

While it is clear that computational methods enable forward calculations using 3D models, these calculations are only as accurate (useful) as the 3D models used to represent Earth structure. At the workshop there was general concern from nuclear explosion and hazard organizations whether model resolution is or will become adequate to significantly improve prediction accuracy of seismic observables at relevant frequencies.

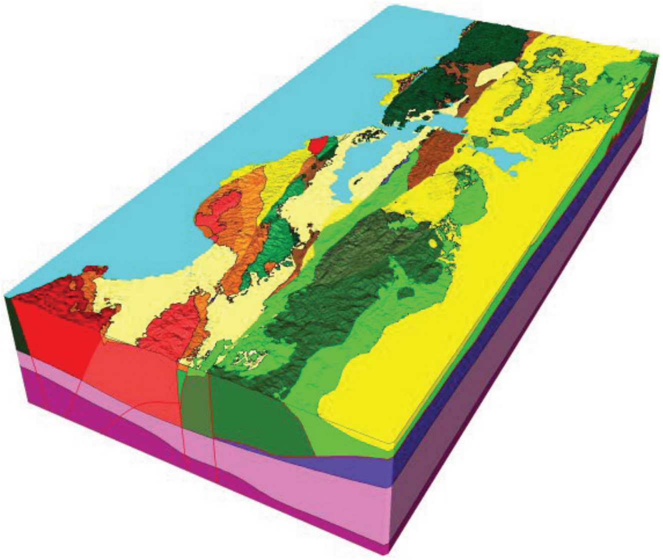
Several workshop speakers focused on model construction and inverse methods to improve model resolution. At local distances (event-station separation of <~100 km), geologic mapping and the use of seismic exploration methods (*e.g.*, seismic reflection/refraction and potential field analysis) have been used to resolve 3D structure of the upper crust and successfully improve prediction of seismic ground motion (workshop presentations by Tom Brocher, U.S. Geological Survey, and Jacobo Bielak, Carnegie Mellon University). There have been successful 3D model-building efforts in the seismic hazard community. The Southern California Earthquake Center (SCEC) Community Modeling Environment (SCEC Community Modeling Environment 2007) provides information tech-



▲ **Figure 2.** Peak ground acceleration (PGA) modeled as a 1D function of magnitude and distance using four attenuation formulas (Sadigh *et al.* 1997; Campbell and Bozorgnia 2003; I. M. Idriss, personal communication 2002; Abrahamson and Silva 1997). Figure from Chiou and Youngs 2006.

nology infrastructure for seismic hazard analysis (Jordan *et al.* 2003). This effort is both flexible and extensible and has resulted in state-of-the-art ground motion forward (Olsen *et al.* 2006) and inverse (Akcelik *et al.* 2003) calculations. The recently developed U.S. Geological Survey (USGS) 3D geologic and seismic velocity model of the San Francisco Bay area (Figure 3) successfully reproduces ground motions from moderate regional earthquakes (Rodgers *et al.* 2008) and the intensity data from the 1906 San Francisco earthquake (Aagaard *et al.* 2008). Furthermore, the open and collaborative nature of community modeling has given end users transparency into model construction.

While innovative, the data used in the construction of the Bay area model and SCEC community model (*i.e.*, high concentration of wells and well logs, very dense station spacing) are generally not available over the broader globe. At regional distances (~ 1,000 km) surface- and body-wave techniques can robustly resolve 3D aspects of crustal and upper-mantle structure (workshop presentations by Michael Pasyanos, LLNL; Charles Ammon, Pennsylvania State University; and Cliff Thurber, University of Wisconsin, Madison). Even so, broad areas of the globe (aseismic regions; oceanic regions and other areas that for political, economic, or logistical reasons do not have seismic stations) will be sampled only with limited body wave paths such as multiple surface reflections (*PP*, *PPP*, *SS*, etc.) and surface waves, which generally have lower resolution and may not be sensitive enough to discontinuities important for travel-time and amplitude prediction. Accordingly, several workshop talks focused on the advantages of developing seismic models using multiple constraints, including the gravity field (presentations by Pasyanos and Ammon). Discussion highlighted the importance of the starting model in these inversions, as well as ways of estimating model uncertainty. Probabilistic methods such as Markov chain Monte Carlo (*e.g.* Pasyanos *et al.* 2006) and neighborhood algorithm (*e.g.* Sambridge 1999) were discussed as possible estimators of uncertainty.

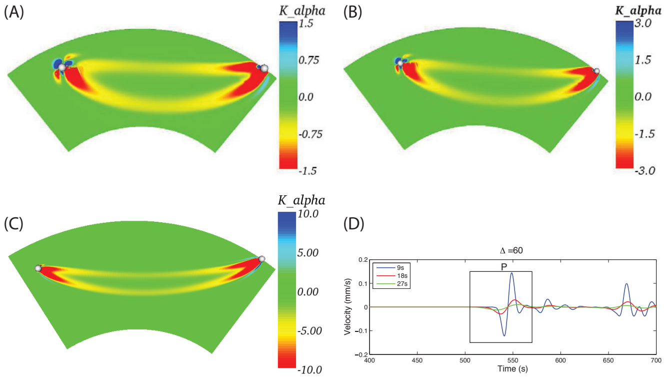


▲ **Figure 3.** USGS 3D geologic and seismic model of the San Francisco Bay area. Colors denote distinct geological units. Figure from Brocher 2005.

One recent advance is the use of seismic noise to extract interstation Green's functions, combined with traditional surface wave dispersion measurements, to determine 3D structure from the surface to several hundred kilometers depth, thus enabling model development in the absence of discrete seismic sources (workshop presentation by Michael Ritzwoller, University of Colorado, Boulder). At the global scale, free oscillations of the Earth and body-wave techniques are proven methods for improving Earth model accuracy (workshop presentation by Peter Shearer, University of California, San Diego). An exciting recent development is the application of adjoint methods to use the complete waveforms and finite-frequency sensitivities to update 3D structure (*e.g.*, Figure 4) using computationally intensive forward and back-projection calculations (workshop presentation by Jeroen Tromp, California Institute of Technology). Seismic tomography based on adjoint methods can be used to improve models at local, regional, and global scales and holds the promise of resolving the 3D structure needed for full waveform prediction.

DISCUSSION

The workshop included an open-floor discussion that we summarize here. Provided that model predictions are properly validated with appropriate empirical data, employing 3D Earth models has the potential to make major improvements in applying seismic technology to important societal issues. In nuclear explosion monitoring, for example, there is the possibility in the near term to use 3D Earth models based on simple tectonic regionalization (*e.g.*, Pasyanos *et al.* 2004; Johnson and Vincent 2002) to



▲ **Figure 4.** An example of an SEM method to compute adjoint kernels for estimating 3D structure. Red (–) and blue (+) show areas of sensitivity. Figure from Liu and Tromp 2008.

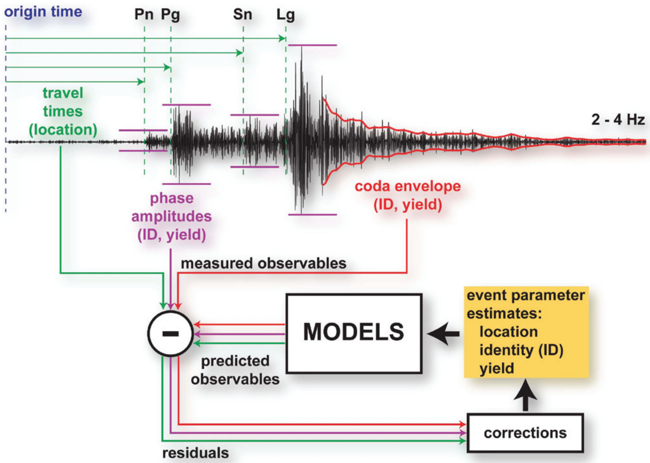
develop travel-time correction surfaces in regions where empirical ground-truth events are lacking, such as in north Africa and large portions of the former Soviet Union (*e.g.*, Flanagan *et al.* 2007). The use of 3D models has the additional advantage of reducing the non-stationarity of empirical corrections that are made relative to these models. If they are validated, 3D models can be developed to replace the current regionalized 1D models, making possible self-consistent calculations of travel times and waveforms from local to regional to teleseismic distances.

For studies of seismic hazard, 3D models can be used to improve event locations for defining seismicity and more importantly for first-principles calculation of ground motion for scenario earthquakes. This will allow modeling of ground-motion hazard for a large number of scenarios including variations in rupture directivity and path-propagation effects. Large ($M_W > 6.0$) damaging earthquakes are infrequent, and near-fault observations of ground-motion time series are limited to sparse numbers of recording stations. Consequently the database of recorded ground motions grossly undersamples the population of possible motions and near-fault locations. Simulations of ground motions in 3D models make it possible to compute estimates of the Earth's response anywhere for a wide range of potentially damaging earthquakes. The simulated ground-motion time series can feed directly into building response calculations for performance-based design of structures (Krishnan *et al.* 2006).

While the potential to improve monitoring using 3D models was not in question, monitoring agencies questioned the readiness of the technology for real-time applications. There are many well-known concerns/conditions that a 3D model approach would have to address (*e.g.*, Harris *et al.* 2007). Some of these were discussed at the meeting, particularly issues related to how best to parameterize models and exchange them between research groups (workshop presentation by William Menke, Lamont-Doherty Earth Observatory). In the next section we consolidate and summarize the major issues.

CONSIDERATIONS ON THE USE OF 3D MODELS

Model building using measurements derived from geophysical observables is conceptually simple, as illustrated in Figure 5.



▲ **Figure 5.** Models form the core of an iterative process of predicting observed signal characteristics (parameters, envelopes, waveforms) to detect, locate, identify, and characterize seismic events (from Harris *et al.* 2007).

In practice many questions arise when contemplating a transition from 1D, 2D, and 2½D models (restrictively parameterized 3D) to constructing and using 3D models (*e.g.*, Harris *et al.* 2007; Menke presentation at workshop and workshop discussion), among them:

1. Can a 3D geophysical model or a collection of 3D models provide measurably improved predictions of seismic monitoring observables over existing or planned 1D models, or 2D and 2½D models?
2. Is a single model that can predict all observables achievable, or must separate models be devised for each observable? How should joint inversion of disparate observable data be performed, if required?
3. What are the options for model representation? Can common and well-defined parameterizations be set to encourage quantitative exchanges of models between researchers? How does representation affect the accuracy and speed of observable predictions? Are multi-resolution models essential?
4. How should model uncertainty be estimated and represented, and how should it be used? Are stochastic models desirable? How are the models and their uncertainties to be validated in noncircular ways?
5. What data types should be used to construct the models? What quality control regime should be established? How do we best encourage researchers to make their underlying data available?
6. How will 3D models be used in operational practice? Will significant improvements in the basic functions (*e.g.*, detection, location, characterization) result from the use of 3D models? Will the calculation of observables through 3D models be fast enough for real-time use or must a strategy of precomputation, which limits the flexibility of the network, be employed?
7. What are the theoretical limits to 3D model development (resolution, uncertainty) and performance in predicting

monitoring observables? How closely can those limits be approached with projected data availability, station distribution, and inverse methods?

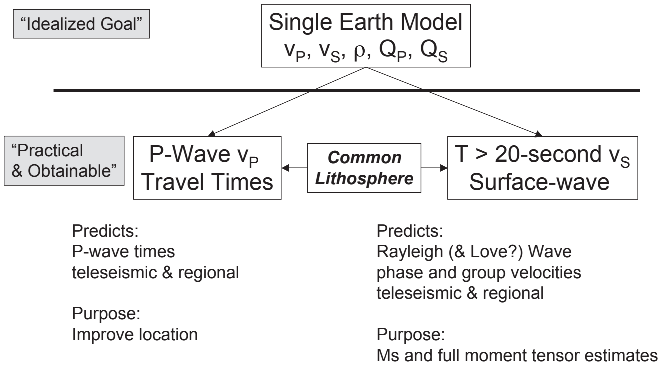
What priorities should be placed on the acquisition of event ground-truth information, deployment of new stations, development of new inverse techniques, exploitation of large-scale computing, and other activities in the pursuit of 3D model development and use?

These questions have many possible answers and provoked much of the discussion at the workshop. They leave open a very wide-ranging field of future research in 3D geophysical models. To reach the most practically useful results in the shortest possible time, we need a way to move toward community consensus among the possible paths forward, such as occurred in southern California with the SCEC Community Modeling Environment or in northern California with the USGS 3D Bay area model. The last part of the workshop addressed such specific proposals.

POSSIBLE PATHS FORWARD

There was a consensus that demonstration of prediction accuracy and robustness using 3D models was needed. Two specific proposals were considered and found to have merit during the “Path Forward” discussion at the workshop. The first was for the development of an Earth Model Framework Test Bed by the nuclear explosion monitoring community. A stated goal of such a model is to be relevant across all distance scales. Local and regional models are generally developed making simplistic assumptions about the deep Earth (*i.e.*, they commonly connect a detailed lithosphere smoothly onto a 1D model like *iasp91* at depth). Similarly, 3D models of the mantle make simplistic assumptions about the crust, usually employing a crustal model like CRUST5.1 (Mooney *et al.* 1998) or CRUST2.0 (Bassin *et al.* 2000). The result is an inconsistent model across the distance scale. There is a strong need to reconcile crustal/upper-mantle models and lower-mantle models, so that the resulting model consistently explains regional and teleseismic data.

The Earth Model Framework Test Bed would involve the construction of two models linked through a common crustal, lithospheric, and upper mantle discontinuity structure. The two velocity models would be intended to predict teleseismic and regional *P* travel times in order to improve event location estimates (the “*P* model”) and to predict surface-wave dispersion measurements and to estimate M_S (the “*S* model”). This is illustrated in the bottom half of Figure 6. The two models could be combined with density and attenuation for full waveform calculations, if necessary. The models were proposed to be both hierarchical and multi-resolution to provide increased resolution where justified by data coverage. A common format and shared structure would allow the models to be merged into a single model at some point in the future. The overriding consideration in development of such a model pair was to pick a practical goal as a starting point for a collaborative effort with sufficient flexibility to be extendable to more complex models, if warranted. There also were strong requirements to develop models immediately useful for monitoring objectives and performing noncircular validation. For example, a realistic goal of locating earthquakes would be to universally reduce the 2σ epicenter errors from 20 km to 5 km for a data set spanning regional and teleseismic distances, at least for events with $\mathbf{M} \geq 5.0$. A similar metric could be made for event identification. If the models perform adequately they could be combined and serve as a starting model for advanced imaging methods, such as joint inversion of multiple data types or seismic waveform tomography with adjoint methods.



▲ **Figure 6.** Proposal for the Earth Model Framework Test Bed.

An idealized goal is to have a single global 3D elliptical Earth model with Vp, Vs, ρ, Qp, Qs, and anisotropy parameters (along with corresponding uncertainty values) that is able to predict the spectrum of geophysical and seismological observations. The more modest current proposal is to develop a model that, while limited in scope, improves performance over current methods, works efficiently in an operational environment, and is flexible and expandable to accommodate future development (Figure 6). The near-term goal of such a model would be the ability to significantly improve the fit of derived seismic observables (*e.g.*, travel times, amplitudes) and predict waveforms at long periods. The long-term goal would be to improve the resolution and sophistication of such models (anisotropy, etc.) to predict waveforms at increasingly higher frequency.

A second proposed path forward was designed to specifically address one of the most critical challenges for explosion seismology, that is, to explain the frequency-dependent behavior of the *S* waves generated by explosions. It is widely observed that the ability to identify small explosions depends on the relative amplitude of regional P/S ratios above about 3 Hz. Existing 3D elastic wave propagation algorithms running on high-performance computing could be used to address this question; however, it is nearly impossible to obtain the correct characterization of the subsurface structure at the resolution required for such calculations. While full waveform calculations at regional distances may be challenging, it may be possible to evaluate the relative contributions of various factors by including more complete descriptions of the physics of explosions. These include rock fracture, spall, geologic heterogeneity, topographic scattering, tectonic stress release, and other effects. The objective of such an effort would be to create a physical model that is ultimately able to make predictions in new regions and under testing conditions for which no empirical data exists.

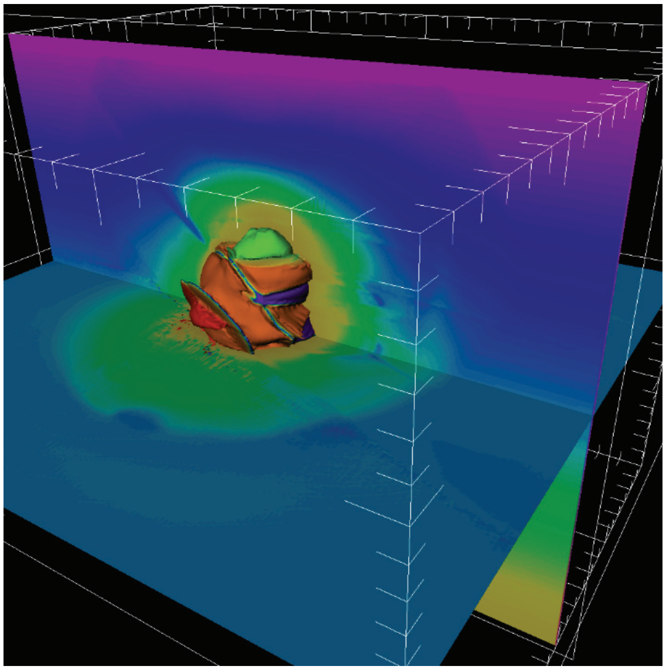
To accomplish this goal, sophisticated 3D models of the source region would need to be developed. If models with sufficient resolution are available, existing, well-developed modeling codes for nonlinear near-source effects (Figure 7), such as GEODYN (Lomov and Rubin 2003; Antoun *et al.* 2006), are available to compute the nonlinear effects of the explosion source out to the elastic radius. These could be leveraged to tie to existing local-scale seismic observations if three critical issues can be overcome. First, motions from the nonlinear source region codes need to be passed across domain boundaries to elastic (linear) finite difference or spectral element method codes and propagated to regional distances. Second, the large differences in spatial and temporal scales between the two methodologies needs to be handled. Third, 3D source region models around past nuclear tests with good empirical data need to be built, used in 3D calculations, and validated (matching available pressure and ground-motion data) to instill confidence in the results.

The ability to tie nonlinear source region modeling to seismic finite difference codes would allow many additional investigations of interest both to the seismic monitoring community and the earthquake hazard community. For example, a single set of codes that covered calculations from the nonlinear source region to the linear region where most seismic records are made allows a number of scenarios: 1) investigations of nonlinear source effects in earthquakes (*e.g.*, super-shear rupture, rupture induced fracture, triggering of rupture); 2) nonlinear source-structure interactions of critical importance to earthquake hazard analysis (*e.g.*, nonlinear soil response, liquefactions, soil-structure interactions); and 3) ties to existing seismic records for model development and validation.

CONCLUSION

As a result of recent advances in theory, data, and computational power, there are new prospects for developing and using 3D models for monitoring applications. Conditional to these developments, however, are the expectations that 1) the models will be built in a transparent manner using a variety of seismological and geophysical observations; 2) the 3D models represent a significant improvement over current methods (1D, 1D with corrections, and 2D, using community consensus metrics); and 3) implementation of the models will not be restrictively slow and difficult to use for realistic operations. Furthermore, these models would have to be cognizant of the issues raised in the "Considerations on the Use of 3D Models" section of this paper.

Two specific proposals were advanced during the workshop. The first is for development of a *P*- and *S*-wave model of the crust and mantle (down to the core), as well as methods for computing self-consistent travel times at local, regional, and teleseismic distances. This proposal is specifically limited in scope, resolution, and complexity and is meant to demonstrate capability in the monitoring arena in the near-term. The second proposal was for a model that would explain the frequency-dependent behavior of *S* waves generated by explosions. This would be accomplished by coupling codes for nonlinear source region modeling to seismic finite difference codes. Because they each try to address separate specific questions, they are not mutually exclusive proposals and could be advanced simultaneously if resources allow.



▲ **Figure 7.** A composite image from a 3D GEODYN simulation showing pressure contours superimposed on complex geologic features that characterize the cavity region of the Baneberry underground nuclear test. Different colors on the pressure isosurface indicate different materials, and the two diagonally slanting lines are faults that cut through the geology near the cavity. The image underscores the importance of material properties, heterogeneities, and geologic structure on nonlinear wave propagation through geologic media (from Lomov *et al.* 2003).

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