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Answers to Program Managers Questions for SL17-Signal Propagation-NDD2Ab

1. **What scientific developments can be used to advance US explosion monitoring missions?**
   The major goal of the tasks undertaken under the program area Signal Propagation is to improve the predictions of the travel times, amplitudes, and frequency contents of the propagating signals and thereby improve event detection, location, and identification capabilities as well as magnitude/yield estimation. The following two scientific developments contributed significantly to that goal:

   a) We developed a high-quality 3D tomographic model of the *P*-wave velocity distribution in the Earth (SALSA3D) that significantly improves the accuracy and the precision of the event locations as compared to 1D radial velocity models.

   b) By developing GeoTess and LibCorr3D, we also provided a method to access the 3D model, predictions and uncertainties in a manner that meets operational USNDC event monitoring requirements. GeoTess is a model parameterization and software support system that implements the construction, population, storage and interrogation of data stored in 3D Earth models. LibCorr3D is a specific software implementation of GeoTess, which stores station-phase specific predictions of travel time and travel time uncertainty. Using this software, we have been able to precompute travel times and uncertainties for all stations and phases of interest and deliver them to our customers for use in their location algorithms. This software has been integrated into the operational software systems at the USNDC.

2. **What are the controlling technical limitations (and unknowns) that contribute to uncertainties in the R&D? How is error modeling and propagation (confidence/uncertainty) being developed?**
   For any tomographic inversion, factors contributing to uncertainties in the resulting model include errors of the travel-time picks, location accuracy of the events in the dataset, and ray path coverage. To minimize the effect of the event location accuracy, only events with epicenter accuracy of 25 km or better were used to develop SALSA3D. Also, during the development process of the model, in an iterative process, all the events in the dataset were relocated with the improved model, and a new model developed with the improved locations, etc. until the event locations and the final velocity model became consistent with each other. A very significant contribution achieved by this project was the calculation of path-dependent travel time prediction uncertainties using the full 3D model covariance matrix. The covariance matrix is computed directly from the tomography matrix and describes the variance and covariance of seismic slowness in the Earth. The diagonals are the uncertainty of the slowness of each grid node in our tomography model and the off-diagonal elements describe the

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covariance of all possible pairs of nodes in the model. While the mathematical description of these equations is straightforward, the calculation of the full covariance matrix is a daunting computational challenge. It involves computing the inverse of an $N \times N$ matrix where N is the number of nodes in the tomography model. SALSA3D is comprised of approximately 250,000 nodes. We accomplished the inversion of this matrix on a distributed cluster of computers consisting of approximately 400 computer cores. With the covariance matrix in hand, we were able to integrate the covariance along ray paths through our velocity model to produce robust estimates of the uncertainty of the travel times predicted for those same ray paths.

Unlike the solid Earth, in which changes are measured in millions of years, the atmosphere changes on a time scale of minutes. Therefore, the principal challenge in infrasound propagation is to characterize the state of the atmosphere at high temporal and spatial resolution. However, since operational models do not yet exist that are capable of realizing minute-scale phenomena such as gravity waves in the stratosphere and boundary layer dynamics near the Earth's surface, acoustic propagation is non-deterministic. This maps into uncertainties in the source location and signal strength from an infrasound event. At present, SNL is focused on characterizing the planetary boundary layer, the region of the atmosphere affected by the surface of the Earth. It has a strong influence on acoustic amplitudes for events at local distances (kilometers to tens of kilometers), yet is poorly resolved in operational weather forecast models.

3. **Is the research and development to be integrated into prototype software and if so how?**
   LocOO3D is an event location software that we developed, which has the capability of using our 3D velocity model. We use SALSA3D in LocOO3D to locate events more accurately and more precisely than what is possible with standard 1D velocity models.

4. **What future R&D scope is anticipated?**
   SALSA3D is a *P*-wave velocity model based on regional an teleseismic phases such as *P*, *Pn*, *PcP*, *PKPbc*, *PKPdf*, *PP*, and *pP*. We intend to develop a similar 3D velocity model for *S*-wave travel time prediction. We also plan on creating a local crustal velocity model in the near proximity of the state of Utah using nearly one million arrivals provided by the University of Utah Seismograph Stations. This, in an effort to determine the applicability of our tomography software and workflows to crustal scale structure. Finally, we intend to develop models based on full waveform tomography.

5. **What collaborations are currently in place and anticipated for future R&D?**
   SALSA3D is the result of a collaborative research involving Sandia National Laboratories and Los Alamos National Laboratories. We intend to intensify this collaboration in the future as we develop a 3D shear wave velocity model and models based on full waveform tomography. Also, a collaborative effort between SNL Team with DOE at the Nevada National Security Site (NNSS) is underway

in areas of relevance to applications of infrasound technologies to nuclear explosion monitoring. Specifically, the aim is to develop a method that leverages ambient urban infrasound to distinguish between different atmospheric regimes in the planetary boundary layer (PBL). The PBL is exceptionally dynamic, resulting in corresponding fluctuations in acoustic amplitude and propagation paths. It is also poorly resolved in operational weather models. Developing a means to characterize it using ambient noise will permit more effective mappings between acoustic amplitude and surface explosion yield.