S42J MCC: 3007 Thursday 1600h

Three-Dimensional Computational Waveform Modeling and Applications II

Presiding: **T S Anderson,** Cold Regions Research and Engineering Laboratory**; V F Cormier,** University of Connecticut

S42J-01 1600h

Waves on a Spherical Membrane

Carl H Tape[1] (6263956123; carl.tape@earth.ox.ac.uk)

John H Woodhouse[1] (441865272000; john@earth.ox.ac.uk)

[1] Oxford University, Dept. of Earth Sciences Parks Road, Oxford OX1 3PR, United Kingdom

The purpose of this study is to develop a numerical model for wave propagation on a spherical membrane and to compare the results with predictions made from ray theory. Such membrane waves are an analogue for seismic surface waves. The two-dimensional wave equation on a sphere is solved using a finite-difference method on a spherical grid of several thousand hexagonal faces. The spherical grid is first tested using a homogeneous phase velocity field with an initial Gaussian source. The resulting numerical solutions, $u(\theta, \phi, t)$, agree with analytical solutions for the homogeneous case. Next a heterogeneous phase velocity field, $c(\theta, \phi)$, is used; the solutions reveal the variation in amplitude and phase due to the lateral heterogeneity. Surface wave ray-tracing equations are then used to calculate the amplitude and phase anomalies for a set of source-receiver pairs. Exact ray theory calculates these values along the actual ray path, which may deviate considerably from the great-circle path between the source and receiver, which is the basis for the linearized ray theory calculations. We find that multipathing — multiple ray paths between a source and receiver — is quite common for the current resolution of long-period surface wave phase velocity maps, and it gives an indication of the divergence of linearized ray theory from exact ray theory. Using the results from the numerical model, we are able to examine the regimes under which ray theory predictions are invalid, and we discuss the results in terms of the ray theory validity condition, $\lambda \ll \Lambda$, where λ is the wavelength of the waves in the numerical model and Λ is the minimum scalelength of heterogeneity in the phase velocity map. We show that exact ray theory is better than linearized ray theory at predicting both phase and amplitude anomalies. We find that ray theory predictions of phase are quite stable. Predictions of amplitude, however, are valid only when the validity condition is well-satisfied.

S42J-02 1615h INVITED

Large Scale Parallel 3D Simulation of Regional Wave Propagation Using the Earth Simulator

Takashi Furumura (furumura@eri.u-tokyo.ac.jp)

Earthquake Research Institute, University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku 113-0032, Japan

This paper presents an efficient parallel code for seismic wave propagation in 3D heterogeneous structures developed for implementation on the Earth Simulator (5120 CPUs, 40 TFLOPS) at the JAMSTEC Yokohama Institute, a high-performance vector parallel system suitable for large-scale simulations. The equations of motion for the 3D wavefield are solved using a higher-order (8,16, 32 etc.) staggered-grid finite-difference method (FDM) in the horizontal (x,y) directions and a conventional fourth-order FDM in the vertical (z) direction. Compared to traditional Fourier pseudospectral method (PSM), the higher-order FDM achieves very good performance on vector processors as well as on the latest high-performance microprocessors (Intel Pentium 4, Itanium 2 etc.). The parallel computing is based on partition of the computational domain, with each subregion assigned to a node of the Earth Simulator. Message passing interface (MPI) inter-node communication is employed for data exchange between subregions. Small-scale heterogeneities such as low-velocity sedimentary basins are accounted for in large-scale models by adopting a multi-grid approach that combines a coarse mesh model with embedded finer mesh model. An accurate interpolation procedure, based on the fast Fourier transform (FFT), is used to combine the wavefield in the different grids. The results of application of the multi-grid, parallel FDM code on the Earth Simulator for modeling strong ground motions from recent large earthquakes are also presented. Events such as the 1993 Kushiro (Mj7.8) and 2000 Tottori-ken Seibu (Mj7.3) earthquakes were simulated using 3D structural models of northern and western Japan. The subsurface structures in Japan were derived by combining data from a number of reflection and refraction experiments, Bouguer anomaly data, and travel-time tomography studies of P and S waves. The scale of the 3D model is about 500 km by 1000 km by 350 km, which is divided into grid intervals of 0.5 to 1 km. The simulation required 128 to 364 Gb of computation memory, and computation took 1 to 2 h using 256 to 1408 processors of the Earth Simulator. Assuming a minimum shear wave velocity of Vs = 1.7 km/s, the modeling is capable of treating high-frequency seismic wave propagations of over 1 to 2 Hz. The volume rendering technique was employed to illuminate the 3D wavefield, and a set of snapshots was combined into a video sequence. The high-resolution 3D simulations for frequencies over 1 Hz provide a good representation of wave propagation in Japan during the large earthquakes. The computer simulation also matches the observations by the dense seismic array (K-Net and KiK-net, over 1700 stations) well, demonstrating the effectiveness of the simulation model. The combined studies of high-resolution computer simulation and dense seismic observation can therefore be expected to be highly valuable in understanding the complex seismic behavior associated with heterogeneities in the subsurface structure, and for predicting the pattern of ground motions expected for future earthquake scenarios.

S42J-03 1645h INVITED

Spectral-element simulations of seismic wave propagation

Jeroen Tromp[1] (jtromp@gps.caltech.edu)

Dimitri Komatitsch[1] (komatits@gps.caltech.edu)

Seiji Tsuboi[2] (tsuboi@jamstec.go.jp)

[1] Seismological Laboratory, California Institute of Technology, Pasadena, CA 91125

[2] Institute for Frontier Research on Earth Evolution, Japan Marine Science & Techmology Center, Yokohama 236-0001, Japan

We use a spectral-element method to simulate seismic wave propagation. The method is based upon a weak formulation of the equations of motion and combines the flexibility of a finite-element method with the accuracy of a global pseudospectral method. The finite-element mesh honors all first- and second-order discontinuities in the model. To maintain a relatively constant resolution throughout the model in terms of the number of grid points per wavelength, the size of the elements is increased with depth in a conforming fashion, thus retaining a diagonal mass matrix. In the solid portions of the model we solve the wave equation in terms of displacement, whereas in the fluid regions we use a formulation based upon a scalar potential. The domains are matched by honoring the continuity of traction and the normal component of displacement. The effects of attenuation, anisotropy, self-gravitation, rotation, and the oceans are incorporated. The method is implemented on parallel computers using a message-passing technique. We benchmark spectral-element synthetic seismograms against normal-mode and discrete wavenumber synthetics for laterally homogeneous models. The technique is used to assess strong ground motions in the Los Angeles basin, to investigate effects of full anisotropy on body and surface waves, to perform 3D centroid-moment tensor inversions, and to assess the quality of 3D mantle models. The basin simulations are performed on a Linux PC cluster, and some of the global simulations are performed on the Earth Simulator, the world's largest and fastest computer. On the Earth Simulator we use a very large mesh with 5.5 billion grid points (14.6 billion degrees of freedom) that requires 2.5 terabytes of memory. The vectorization ratio is 99.3%, and we reach a performance of 5 teraflops (30% of the peak performance) on 38% of the machine (243 out of 640 nodes, for a total of 1944 processors). The very high resolution of the mesh facilitates fully 3D calculations at seismic periods of 5 seconds.

S42J-04 1715h INVITED

Seismic FDTD Modeling of Surface Waves Over Grid-Transformed and Stair-Stepped Topographies

Stephen Ketcham[1] (603-646-4601; Stephen.A.Ketcham@erdc.usace.army.mil)

Mark Moran[1] (603-646-4275; Mark.L.Moran@erdc.usace.army.mil)

Thomas Anderson[1] (603-646-4751; Thomas.S.Anderson@erdc.usace.army.mil)

Roy Greenfield[2] (814-237-1810; roy@essc.psu.edu)

[1] US Army Engineer Research and Development Center, 72 Lyme Rd, Hanover, NH 03755, United States

[2] Greenfield Associates, 600 Mckee St, State College, PA 16803, United States

We are developing finite-difference time domain code to model 3D surface wave propagation caused by moving surface sources. Our applications require that we simulate surface wave propagation over real and sometimes steep terrain up to 1-km2 in area. Force inputs will have durations up to 1 minute and contain significant energy in the 15-45 Hz band. These features require that our code (1) have surface wave accuracy over topographical surfaces to ranges of several Rayleigh wavelengths, (2) be stable over long durations, and (3) run on supercomputers. We have implemented a grid transformation and the corresponding equations of motion and stress-strain-velocity. The transformation maps a rectangular, computational grid to a distorted grid with a topographical surface. The distorted grid conforms to the topographical surface. We have discretized the transformed equations of motion and stress-strain-velocity to calculate centered second order differences in space and time on the computational grid. We use conventional staggering of stress and particle velocity calculation points. To model a free surface, we adapt interface property averaging techniques to our transformed equations and approximate the stress release of a free surface by including a relatively thin layer of air above the ground. The ground-air interface is specified along the conformal topographical surface. Alternatively the interface can be located along a stair-stepped approximation of the topographical surface. The code therefore inherently allows for three transformation/free surface options: (1) transformed grid with ground-air interface that fully conforms to topography, (2) non-transformed rectangular grid with stair-stepped ground-air interface that discretely approximates topography, or (3) transformed grid with a hybrid interface, i.e., a conformal ground-air interface over part of surface and stair-stepped interface over the remainder. We have tested the accuracy and limitations of topography-conforming grid transformations by comparing results of surface-pulse-induced propagation over homogeneous elastic models with planar-sloped surfaces (slopes ranging from 0 to 1) to corresponding wavenumber-integration solutions. The comparisons show that receiver signal accuracy decreases with increasing slope and range. Acceptable accuracy is demonstrated in 25-percent-slope models out to 3-4 Raleigh wavelengths and in 50-percent-slope models out to 1-2 Raleigh wavelengths. Further comparisons with wavefields of models having non-transformed rectangular grids show that the topography-conforming grid transformations are more accurate for gentler slopes (e.g., 25 percent or less), while the fully rectangular grids with stair-stepped topography are best for steeper slopes, albeit with the well-recognized limitations of stair-stepped topographical models. These results suggest that using the hybrid topography modeling is desirable. e.g., we have synthesized a homogeneous elastic model with a grid-conforming 25-percent slope that is interrupted by a stair-stepped steep trench and a stair-stepped steep hill. Results from impulsive surface source analyses show underlying accuracy and minimal numerical noise, demonstrating the potential of the technique for surface sources on real topographies.

S42J-05 1745h

Sensitivity of Teleseismic Body Waveforms to Near-Source 3D Velocity Heterogeneity

Daejin Kang[1] (dkang@memphis.edu)

Charles A. Langston[1] (clangstn@memphis.edu)

[1] Center for Earthquake Research and Inforamtion, The University of Memphis 3890 Central Ave., Memphis, TN 38152, United States

There have been many source studies of teleseismic body waves using the approximation that structure near the source consists of plane layers. Although most authors of these studies will claim excellent results for their source models in terms of synthetic fits to observed waveforms, it is a general rule that there always exist anomalous data that do not seem to be explainable under the assumptions of the modeling study. Although there are many possibilities to explain this anomaly, it seems that near-source 3D velocity heterogeneity is an important factor in forming such teleseismic body waveforms. We address problems in near-source velocity heterogeneity for earthquake data sets to evaluate how such heterogeneity influences the Green's function and resulting source inversions. The teleseismic response of buried moment tensor sources in 3D media can be efficiently computed by using the result of the reciprocal problem of an incident P or S plane wave from beneath the structure. The finite-difference method is used for the plane wave response beneath the source structure and then the reciprocity theorem is applied to simulate the teleseismic body waves for the buried earthquake source(s). Teleseismic data sets from the 1994 Northridge and the 1971 San Fernando earthquakes are modeled to investigate the effect of San Fernando/Los Angeles basin structure on teleseismic waveforms. The frequency dependence of the near-source effect is investigated theoretically for proposed structure models and is constrained by detailed geological and geophysical studies in the literature.