A

Ground Motion Modeling of the 1906 Earthquake and Other Large Events on the Northern San Andreas Fault (poster)

Brad ***Aagaard*** *(U.S. Geological Survey, Menlo Park)*
Thomas Brocher (U.S. Geological Survey, Menlo Park)
David Dolenc (University of California, Berkeley)
Douglas Dreger (University of California, Berkeley)
Robert Graves (URS)
Stephen Harmsen (U.S. Geological Survey, Golden)
Stephen Hartzell (U.S. Geological Survey, Golden)
Shawn Larsen (Lawrence Livermore National Laboratory)
Kathleen McCandless (Lawrence Livermore National Laboratory)
Stefan Nilsson (Lawrence Livermore National Laboratory)
N. Anders Petersson (Lawrence Livermore National Laboratory)
Arthur Rodgers (Lawrence Livermore National Laboratory)
Bjorn Sjogreen (Lawrence Livermore National Laboratory)
Mary Lou Zoback (Risk Management Solutions)

Using five different wave propagation codes, we compute the ground motions for the 1989 magnitude 6.9 Loma Prieta earthquake using the Beroza (1991) and Wald et al. (1991) source models, and the 1906 magnitude 7.9 San Francisco earthquake using the Song et al. (2008) source model. The codes employ different simulation domains, discretization schemes, and fault implementations, but all of the simulations honor the source models as closely as possible and make use of the recently constructed 3-D geologic (Jachens et al., 2006) and seismic velocity (Brocher et al., 2006) models of northern California. For each of the events all of the simulations generate ground motions consistent with the observed large-scale spatial variations in shaking associated with rupture directivity and the geologic structure. We attribute the small variations among the synthetics to the minimum shear wave speed permitted in the simulations and how they accommodate topography.

For the Loma Prieta earthquake, our long-period simulations (T > 1-2 s), on average, under predict shaking intensities by about 1/2 MMI units (25-35% in PGV), while our broadband simulations (T > 0.1 s), on average, under predict the shaking intensities by 1/4 MMI units (16% in PGV). Discrepancies with observations arise due to errors in the source models and geologic models. At many sites we find greater consistency in the synthetic waveforms across the wave propagation codes for a given source model compared to across source models for a given wave propagation code. The synthetics for the Beroza source model reproduce the observed motions better than the Wald source model at some locations, whereas the synthetics for the Wald source model reproduce the observed motions better at other locations. This implies the uncertainty in the source parameters tends to exceed the uncertainty in the seismic velocity structure. Our estimates of the ground motions for the 1906 earthquake successfully reproduce the main features of the Boatwright and Bundock (2005) ShakeMap, but tend to overpredict the intensity of shaking by 0.1-0.5 MMI units. Although the new 3-D seismic velocity model improves upon previous velocity models, we identify two areas needing improvement, the La Honda basin southwest of San Jose and the area east of the Hayward fault associated with the Great Valley Sequence. Nevertheless, we find that the seismic velocity model and the wave propagation codes are suitable for modeling scenario events in the San Francisco Bay area.

PyLith 1.0: A Finite-Element Code for Modeling Quasi-Static and Dynamic Crustal Deformation (poster)

Brad Aagaard, USGS, Menlo Park
Charles Williams, Rensselaer Polytechnic Institute
Matthew Knepley, Argonne National Laboratory/CIG
Leif Strand, CIG
Sue Kientz, CIG

We have developed open-source finite-element software for 2D and 3D dynamic and quasi-static modeling of crustal deformation. This software, PyLith 1.0, combines the quasi-static modeling functionality of PyLith 0.8 and its predecessors (LithoMop and Tecton) and the dynamic modeling functionality of EqSim. The target applications contain spatial scales ranging from tens of meters to hundreds of kilometers with temporal scales for dynamic modeling ranging from milliseconds to minutes and temporal scales for quasi-static modeling ranging from minutes to hundreds of years. This software, PyLith 1.0, is part of the NSF-funded Computational Infrastructure for Geodynamics and runs on a wide variety of platforms, from laptops to Beowulf clusters (executables are available for OS X, Linux, and Windows). PyLith uses a general, parallel, graph data structure called Sieve for storing the finite-element mesh. This permits use of a variety of 2D and 3D cell types including triangles, quadrilaterals, hexahedra, and tetrahedra. Current features include kinematic fault interface conditions, Dirichlet (displacement) boundary conditions, linear elastic and Maxwell linear viscoelastic materials, and quasi-static and dynamic time-stepping. Future releases will add traction and absorbing boundary conditions, dynamic fault interface conditions (employing fault constitutive models), generalized Maxwell viscoelastic materials, and automated calculation of suites of Green's functions. We also plan to extend PyLith to allow coupling multiple simultaneous simulations. For example, this could include (1) coupling an interseismic deformation simulation to a spontaneous earthquake rupture simulation (each using subsets of the software), (2) coupling a spontaneous earthquake rupture simulation to a global wave propagation simulation, or (3) coupling a short-term crustal deformation simulation to a mantle convection simulation and an orogenesis and basin formation simulation.

Full Waveform Tomography for Seismic Velocity and Anelastic Losses in Heterogeneous Structures Including Model Uncertainties (talk)

Aysegul Askan
Civil Engineering Department, Middle East Technical University
Jacobo Bielak
Civil and Environmental Engineering Department, Carnegie Mellon University

We present a nonlinear waveform inversion method for determining the crustal velocity and intrinsic attenuation properties of sedimentary valleys in earthquake-prone regions starting from an initial model, by including a-priori information regarding the initial model parameters in the misfit function. We formulate the inverse problem as a constrained optimization problem, where the constraints are the partial and ordinary differential equations governing the anelastic wave propagation from the source to the receivers. We employ a wave propagation model in which the intrinsic energy-dissipating nature of the soil medium is modeled by a set of standard linear solids. To represent the modeling uncertainties, given a prior model, we include an L2-normed weighting term, in addition to the data misfit term in our objective function, which quantifies the model estimation errors independent of the measured data. We illustrate the methodology with pseudo-data from two-dimensional sedimentary models of the San Fernando Valley, using a source model with an antiplane slip function.

B

Numerical modeling of physical processes occurring during the spontaneous propagation of 3-D earthquake ruptures (talk)

*Andrea **Bizzarri** INGV - Sezione di Bologna (Italy)*

We present some solutions of the fundamental elasto-dynamic equation obtained by using a Finite Difference numerical code. We model the fully dynamic spontaneous propagation of truly 3-D earthquake ruptures on planar faults embedded in an elastic half-space. We implement the Traction-at-Split-Nodes fault boundary condition using different governing laws. To prescribe the traction evolution within the breakdown zone we can adopt either slip-dependent laws or rate- and state-dependent friction laws, which involve the choice of an evolution relation for the state variable(s). Our numerical procedure allows the use of oblique and heterogeneous distribution of initial stress and allows the rake rotation during rupture propagation. This implies that the two components of fault slip velocity and total dynamic traction are coupled together to satisfy the adopted constitutive law. It is possible to chose various strategy to force the rupture nucleation and absorbing boundary conditions are implemented in order to reduce the computational requests and time.
Among the various competing physical mechanisms occurring during faulting a special emphasis is given to the temporal variations of the effective normal stress, caused by thermal pressurization of pore fluids, for which an analytical solution is given. We also consider the evolution of the porosity, which is able to change the value of the so-called fracture energy. Finally, we study the effects of super-shear rupture speed on the high frequency content of S-waves. We demonstrate that crack tips governed by different friction laws propagating at super-shear speed have slip velocity functions with reduced high frequency content compared to crack tips traveling at sub-shear speeds. Additionally, we show that the Mach cone amplification of high frequencies overwhelms the deamplification of high frequency content in the slip velocity functions in super-shear ruptures. Consequently, when earthquake ruptures travel at super shear speed, a net enhancement of high frequency radiation is expected, and the alleged “low” peak accelerations observed for the 2002 Denali and other large earthquakes are probably not caused by diminished high frequency content in the slip velocity function, as has been speculated.

Dynamic Slip on a Rough Fault - Results from Discrete Element Method (DEM) Simulations. (poster)

*Steffen Abe & **Christopher Bean**, Seismology and Computational Rock Physics Lab., School of Geological Sciences, University College Dublin, Belfield, Dublin 4, Ireland.*

2D discrete element method (DEM) simulations are used to investigate the properties of the dynamic rupture on a heterogeneous fault. An intrinsic small-scale roughness of the fault surface is present as the fault model is constructed from randomly distributed spherical particles. Additionally, heterogeneity on a large length scale is introduced, generating asperity and non-asperity regions along the fault by varying the small-scale surface roughness. Contact friction is defined using a Coulomb Law. The model evolves from a stress-free initial state into stick-slip behaviour while a constant normal stress and a constant shear velocity are applied to the edges of the model. The resulting slip events show a number of properties similar to real seismic events. We observe qualitatively realistic source-time functions, realistic stress drops and rupture velocities including both sub- and super-shear. Our results indicate the importance of stress heterogeneity in controlling event size. A simple friction law coupled with geometrical complexity can yield many characteristic features seen in real rupture propagation.

The influence of near surface velocity structures on long-period (LP) volcano-seismic signals: simulated examples from Mt Etna. (poster)

***Christopher Bean,** Ivan Lokmer, Gareth O' Brien, Seismology and Computational Rock Physics Lab., School of Geological Sciences, University College Dublin, Belfield, Dublin 4, Ireland.*

Long Period (LP) signals with dominant periods in the range 0.2 – 2 Hz have received particular attention on volcanoes, as they are thought to be directly associated with moving fluids or resonating fluid-filled conduits. Consequently, in an effort to better understand fluid-driven processes, inverting for LP source mechanisms is becoming increasingly common. As the majority of LP events occur at shallow depths & have short path lengths and km-long wavelengths, the role of edifice heterogeneity is usually ignored. We use 3D full wavefield simulations in heterogeneous Mt Etna models with topography to generate synthetic Green's functions. Moment Tensor plus single force inversions of these synthetics demonstrate the extreme sensitivity of the solution for LP source forces to near-surface volcano structure. In particular, spurious forces and incorrect source geometries are obtained if the top 400 m is poorly constrained. Sensitivity kernels help to elucidate the details of the propagation effects which lead to poor source characterization and allow us to suggest an improved protocol for the inversion of real LP signals.

Full waveform inversion in the finite element setting – algorithmic concepts and numerical techniques (talk)

Carsten Burstedde
ICES, The University of Texas at Austin

In this talk I will focus on seismic inversion using the full wave equation in a finite element implementation. Integrating knowledge from seismology and recent techniques from numerical optimization leads to an inversion framework which is numerically robust and capable of relatively high resolution. The key idea borrowed from seismology is a multilevel continuation from low to high frequencies, possibly combined with modifications of the objective functional. The basic numerical algorithm is an inexact Krylov-Newton method combined with preconditioning and primal-dual techniques to handle constraints on the wave speed and steep jumps across layers. Numerical results will be included for 1D borehole data, and an outlook will be given on the development of our next-generation 3D inversion code.

C

Multi-scale issues and two scale homogenization solutions for the direct and inverse problem in seismology. (talk)

*Yann **Capdeville**[1], Laurent Guillot[1] and Jean-Jacques Marigo[2]*
1: Équipe de sismologie, Institut de Physique de Globe de Paris
2: Laboratoire de Modélisation en Mecanique, Université Paris 6

In many cases, in the seismic wave propagation modeling context, scales much smaller than the minimum wavelength are present in the earth model we wish to propagate in. For many numerical methods these small scales are a challenge leading to high numerical cost. The purpose of the work presented here is to understand and to build the effective medium and equations allowing to average the small scales of the original medium without losing the accuracy of the wavefield computation. We show that high order two scale homogenization provides a promising solution to this king of problem. The presentation will be mostly limited to the layered model case. In that case, it appears that the order 0 homogenization gives the result that was obtained by Backus in 1962 which implies that order 0 homogenized model is transversely isotropic even though the original model is isotropic. It appears the order 0 is not enough to obtain surface wave with correct group and phase velocities and that higher order homogenization terms up to 2 are often required, which implies to modify the wave equation and the boundary conditions. We show how to extend the theory from the periodic case to the non-periodic case. Examples in periodic and non-periodic medium are given. The accuracy of the results obtained by homogenization are checked against normal mode solution computed in the original media and shows a good agreement. Applications to numerical method like the spectral element method as well as preliminary results of homogenization in media varying rapidly in all directions will be presented.

CUBIT and Seismic Wave Propagation Based Upon the Spectral-Element Method: An Advanced Unstructured Mesher for Complex 3D Geological Media (talk)

*Emanuele **Casarotti,** Marco Stupazzini, Shiann Jong Lee , Dimitri Komatitsch, Antonio Piersanti, and Jeroen Tromp*

Unstructured hexahedral mesh generation is a critical part of the modeling process in the Spectral-Element Method (SEM). We present some examples of seismic wave propagation in complex geological models, automatically meshed on a parallel machine based upon CUBIT (Sandia Laboratory, cubit.sandia.gov), an advanced 3D unstructured hexahedral mesh generator that offers new opportunities for seismologist to design, assess, and improve the quality of a mesh in terms of both geometrical and numerical accuracy. The main goal is to provide useful tools for understanding seismic phenomena due to surface topography and subsurface structures such as low wave-speed sedimentary basins. Our examples cover several typical geophysical problems: 1) “layer-cake” volumes with high-resolution topography and complex solid-solid interfaces (such as the Campi Flegrei Caldera Area in Italy), and 2) models with an embedded sedimentary basin (such as the Taipei basin in Taiwan or the Grenoble Valley in France).

Effects of Fault Geometry on Rupture Dynamics (talk)

Victor M. ***Cruz-Atienza***[1] *and Jean Virieux*[2]
[1] *Department of Geological Sciences, San Diego State University, USA*
[2] *Géosciences Azur, Sophia-Antipolis, Valbonne, France*

Given the increasing amount of high quality laboratory and field earthquake data, more sophisticated models of rupture physics are needed to explain these observations. Various physical factors, as the fault geometry, may strongly affect the rupture process and therefore should now be integrated into our conceptual models. In recent years, several theoretical and numerical studies have been devoted to understanding the consequences of changes in the rupture geometry on both the rupture process and the corresponding off-fault (static and dynamic) effects. In this work we assume a slip-independent friction law and focus on the effect of tectonic loading and heterogeneities in the medium on rupture propagation and fracture energy. Our results show that fault geometry affects these parameters in a relevant way.
For this purpose we first introduce a new 3D dynamic-rupture, finite-difference model called the finite-difference, fault-element (FDFE) method (Cruz-Atienza et al., Geophysics, 2007). This method is based on a 3D methodology for applying dynamic-rupture boundary conditions along nonplanar faults within a partly-staggered regular lattice. The fault is discretized by a set of parallelepiped elements in which specific boundary conditions are applied. These conditions are applied to the stress tensor, once transformed into a local fault reference frame that matches the fault local geometry. Numerically determined weight functions multiplying particle velocities around each element allow accurate estimates of fault kinematic parameters (i.e., slip and slip rate) independent of faulting mechanism. Numerical criteria for rupture boundary conditions to model rupture processes accurately are determined experimentally finding consistency with those previously determined for the 2D case (Cruz-Atienza and Virieux, Geoph. J. Int., 2004). Given a spatial grid step for wave propagation, the number of grid nodes contained in each fault element should be adapted accordingly. The smaller the spatial step the greater the number of nodes should be.
Assuming a Coulomb-like slip-weakening friction law, a parametric study suggests that the FDFE method converges toward a unique solution, provided that the cohesive zone behind the rupture front is well resolved (i.e., four or more elements inside this zone). Solutions are free of relevant numerical artifacts for grid sizes smaller than approximately 70 m. We validate the FDFE method by comparing numerical solutions for spontaneous slip-weakening ruptures along planar and nonplanar parabola-shaped faults against those obtained with an independent semi-analytical boundary integral method (Aochi et al., PAGEOPH, 2000). This comparison shows that our finite-difference rupture model, based on a thick-fault source description, is accurate enough to perform these complex simulations. It confirms that finite-difference techniques still represent a viable and reliable way to model earthquake dynamics along nonplanar complexly shaped faults in three dimensions.

References:

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D

Multi-scale techniques in imaging and wave-equation tomography (talk)

Maarten V. de Hoop
R.D. van der Hilst, H. Smith, G. Uhlmann, C.C. Stolk
and F. Andersson

The Generalized Radon Transform (GRT) has been developed for imaging discontinuities and inverse scattering with single scattered phases; examples of phases used in imaging, at present, include ScS, SKKS and SS precursors. The GRT can be related to the (local) linearization of the nonlinear scattering problem. Using a frame of curvelets, the GRT can be represented by a matrix, mapping coefficients of the decomposition of the data into curvelets to curvelet coefficients from which the image can be composed. Curvelet coefficients are obtained by a curvelet transform; we establish a relation with (double) beamforming. The image and data representations compress, while the GRT matrix is sparse and a procedure for partial reconstruction of discontinuities with `incomplete' data (coverage) emerges. We also indicate, using curvilinear coordinates, how a wave-equation analogue (on manifolds) can be obtained. Furthermore, we summarize how curvelets can be used to construct Fr\'{e}chet derivatives for wave-equation tomography in wavespeed models of limited smoothness.

E

F

Seismic waveform tomography in the time-frequency domain with applications to the Australian upper mantle (talk)

Fichtner *and co-authors (H. Igel, B.L.N. Kennett and H.-P. Bunge).*

We present a novel approach to full waveform tomography based on misfits in the time-frequency domain and adjoint methods. Our focus is on theoretical developments and synthetic inversions for heterogeneities in the Australian upper mantle.

The centrepieces of our methodology are envelope and instantaneous phase misfits defined on time-frequency transforms of the seismograms. These misfits allow us to extract the maximum robust information from seismograms for the purpose of high-resolution tomography.

We derive Fréchet kernels for different definitions of the envelope and phase misfits using adjoint methods. The Fréchet kernels for instantaneous phase measurements agree with those obtained from waveform cross-correlation only in the special – though unrealistic – case of monochromatic waves. Examples of Fréchet kernels for data collected during the SKIPPY project are computed by means of a recently developed spectral element method.

With synthetic inversions we demonstrate that lateral heterogeneities can be determined efficiently by using instantaneous phase measurements of S waves and surface wave trains without explicitly dissecting the seismograms. Special attention is given to the following questions relating to the inversion, i.e., the misfit minimisation algorithm: 1) determination of the optimal step length for gradient methods, 2) acceptance/rejection criteria for the updated models and 3) the pre-conditioning of the steepest descent direction. Finally, we examine the possibility of using envelope or amplitude measurements and their corresponding Fréchet kernels for seismic waveform tomography.

Ground rotational motions: sensitivities and scattering effects *(poster)*

A. Fichtner, N.D. Pham, W. Suryanto, H. Igel
Department of Earth Sciences, Ludwig-Maximilians-University

With the recent advances in observing ground rotations (around a vertical axis) using ring laser technology we investigate the potential use of this observable to recover structural information. First, we employ the adjoint technique to derive sensitivity densities of rotational motions alone and the combined measurement of translations and rotations. It turns out that the ratio of rotation and translation leads to high sensitivities w.r.t. apparent shear velocities close to the receiver. This indicates the potential for recovering structural information by single-station measurements of translations and rotations. Synthetic examples illustrate these effects in a quantitative way. Second, we exploit the observation of rotational motions in the P-coda with the aim of recovering information on the scattering properties of the near-receiver structure. Assuming plane P-wave propagation and 1D structures, no rotational motions are expected. We perform synthetic simulations of plane P-waves through random crustal structures, examine the P-SH scattering and compare with observations.

G

Broadband Ground Motion Simulations for Mw 7.8 Southern San Andreas Earthquake (ShakeOut) (talk)

Robert W. ***Graves*** *(URS Corporation), Brad Aagaard (US Geological Survey, Menlo Park), Ken Hudnut (US Geological Survey, Pasadena)*

The Great Southern California ShakeOut is a NEHRP coordinated, multi-hazard response exercise based on a Mw 7.8 rupture scenario of the southern San Andreas Fault. The scenario event begins at Bombay Beach and ruptures 305 km northward through both the Coachella and Mojave segments, finally terminating at Lake Hughes. The slip distribution is derived by combining a slip-predictable model at long length-scales (> 30 km) with a stochastic model at short length-scales. A full kinematic rupture description is developed using empirical rules to govern the variation of rise time and rupture velocity across the fault surface, assuming a Brune slip pulse. We compute broadband ground motions using the hybrid procedure of Graves and Pitarka (2004). Low frequency (f < 1 Hz) motions are calculated using a 3D visco-elastic, finite-difference algorithm. Over 2 billion grid nodes are required to represent this model and the calculation was performed at USC's center for High Performance Computing and Communication (HPCC). From the low frequency calculation, ground motions are saved on a 2 km grid (25,000 sites), and then for each of these sites, high frequency ($f > 1$ Hz) ground motions are calculated and summed with the low frequency response to produce broadband (0-10 Hz) time histories. Finally, site-specific non-linear amplification functions are applied to these ground motions to account for local soil properties (via Vs30).

The ground motion simulations predict near fault PGA and PGV values generally ranging from 0.5 to 1.0 g and 100 to 250 cm/s, respectively. The largest near fault motions tend to correlate with large fault slip, although the ground velocities are also strongly influenced by rupture directivity. For the southern hypocenter assumed in this scenario, low frequency energy is efficiently channeled into the Los Angeles region along the string of basins (San Bernardino, Chino, San Gabriel, Los Angeles) lying south of the San Gabriel Mountains. This combination of rupture directivity and basin response produces a significant amplification of low frequency motions throughout the Los Angeles region, and has been identified in previous 3D San Andreas earthquake simulations. The great density of broadband time histories produced in this simulation facilitates the generation of ground motion maps and wave field animations. These products are useful for scientific investigation, as well as providing ground motion inputs that can be used for studies of damage potential and loss estimates.

H

Earthquake Source Modeling using Time-Reversal or Adjoint Methods (poster)

Vala **Hjorleifsdottir**, Qinya Liu and Jeroen Tromp, California Institute of Technology Seismological Lab

In recent years there have been great advances in earthquake source modeling. Despite the effort, many questions about earthquake source physics remain unanswered. In order to address some of these questions, it is useful to reconstruct what happens on the fault during an event. In this study we focus on determining the slip distribution on a fault plane, or a moment-rate density, as a function of time and space. This is a difficult process involving many trade offs between model parameters. The difficulty lies in the fact that earthquakes are not a controlled experiment, we don't know when and where they will occur, and therefore we have only limited control over what data will be acquired for each event. As a result, much of the advance that can be made, is by extracting more information out of the data that is routinely collected.

Here we use a technique that uses 3D waveforms to invert for the slip on a fault plane during rupture. By including 3D wave-forms we can use parts of the wave-forms that are often discarded, as they are altered by structural effects in ways that cannot be accurately predicted using 1D Earth models. However, generating 3D synthetic is computationally expensive. Therefore we turn to an `adjoint' method (Tarantola Geoph.~1984, Tromp et al.~GJI 2005), that reduces the computational cost relative to methods that use Green's function libraries. In it's simplest form an adjoint method for inverting for source parameters can be viewed as a time-reversal experiment performed with a wave-propagation code (McMechan GJRAS 1982). The recorded seismograms are inserted as simultaneous sources at the location of the receiver and the computed wave field (which we call the adjoint wavefield) is recorded on an array around the earthquake location.

Here we show, mathematically, that for source inversions for a moment tensor (distributed) source, the time integral of the adjoint strain is the quantity to monitor. We present the results of time-reversing synthetic seismograms computed for point sources and finite sources, building intuition for what to expect. We also show an example for a real event.

I

The SPICE Library: Codes, Training Material and Benchmarking in Computational Seismology (poster)

H. Igel (1)*, F. Gallovic (1), R. Barsch (1), P. Moczo (2), P. Pazak (2), P. M. Mai (3), Y. Qin (4)*

(1) Department of Earth Sciences, Theresienstr 41, Munich, 80333 Germany, (2) Department of Astronomy, Physics of the Earth and Meteorology, Comenius University, Mlynska dolina F1, Bratislava, 842 48 Slovakia, (3) Institute of Geophysics, ETH Hoenggerberg, CH-8093 Zurich, Switzerland, (4) Departement de Sismologie, Institut de Physique du Globe de Paris, Boite 89 - 4 place Jussieu, Paris, 752 52 France

Since 2004, the EU funded Marie Curie Training Network "Seismic wave propagation and imaging in complex media: a European network" joins 14 institutions and several associated partners in a project that aims at carrying out research in the field of computational seismology. One of the key deliverables of the project is an open www-based digital library with wave and rupture propagation codes, training material in numerical methods applied to the wave propagation problem and eventually simulation data. In 2005 the code library was initiated and several algorithms are now available to the scientific community. In addition to sophisticated, parallelized 3D wave propagation algorithms based on finite differences, finite elements or pseudospectral methods for local, regional, and global models, there are also simple training codes that help getting started with a particular method or can be used in tutorials. The software library also contains "classical" approaches like ray-theoretical approaches, the reflectivity and the normal mode methods. Furthermore, the library includes training material (including two books) covering a broad range of seismological topics. The goal of this paper is to present an update of the library, call for codes from outside of the SPICE community and also show links to the various SPICE benchmarking exercises, one of which offers an interactive web interface (developed by the Comenius University, Bratislava) to compare numerical and benchmarked test solutions. The library can be accessed through the project web pages http://www.spice-rtn.org.

J

K

Overview of the High-Order ADER-DG Method for Numerical Seismology (talk)

Käser, *M., Dumbser, M., de la Puente, J., Castro, C., Hermann, V.*

In geophysics and in particular in seismology, numerical modeling is becoming an important tool for understanding and analysing systematically the complex behaviour of a propagating seismic wave field. For practical use, a numerical scheme for solving the underlying hyperbolic system of the seismic wave equation is required to provide a wide range of capabilities. In the last years the introduction of the Discontinuous Galerkin Method in combination with the ADER time integration approach has led to remarkable progress towards satisfying many of these demands. The ADER-DG scheme is able to handle geometrically complex computational domains in three space dimensions, which typically have to be discretized by unstructured tetrahedral or hexahedral meshes to account for model boundaries and internal material interfaces. Furthermore, the generality of the velocity-stress formulation facilitates the treatment of different material properties, such as pure acoustic or elastic media, anisotropy, viscoelasticity and poroelasticity. These important physical properties are typically encountered in realistic simulations of earthquake scenarios. In fact, due to the formulation of the hyperbolic system, all these effects can be incorporated by modifying the Jacobian matrices and the coupling source term. Additionally, a variety of external source terms describing the generation of seismic waves through different physical source mechanisms have been included into the approach to enlarge the range of possible applications in many seismological fields. The development of the ADER-DG approach was continuously and strictly tested by convergence studies and comparisons to analytic and quasi-analytic solutions for a large number of test cases to confirm its arbitrary high order of accuracy in space and time. At the same time, the new numerical scheme was applied to different seismological problems and benchmark tests, where various numerical methods could be compared with respect to their accuracy and efficiency. Therefore, the scheme also had to be implemented for multi-processor computing using MPI and mesh partitioning strategies based on graph theory had to be used to divide the unstructured meshes in appropriate subdomains. Currently, the ADER-DG scheme has reached an application level which permits to use massively parallel hardware of modern high-performance computing centers and to enter the new era of GRID computing technology. Finally, we present selected results obtained by the new ADER-DG method for different problems of numerical seismology and give an outlook of future developments and extensions of the numerical scheme.

L

Rayleigh and Love wave tomography of the western United States from ambient seismic noise using USArray (poster)

*Fan-Chi **Lin**, Morgan P. Moschetti, and Michael H. Ritzwoller*

We present the most recent results of Rayleigh wave and Love wave tomography in the western United States using ambient seismic noise observed at 424 broadband stations from the EarthScope/USArray Transportable Array and regional networks. All available three-component time series between 1 October 2005 and 31 Aug 2007 have been cross-correlated to yield estimated empirical Rayleigh and Love wave Green's functions. Phase and group velocity dispersion curves for both Rayleigh and Love waves between 5 and 40 sec period are measured for each inter-station path by applying frequency-time analysis and are then used to invert for Rayleigh and Love wave speed maps. The significant velocity variations observed on the short period maps suggest that it may not be appropriate to use straight ray theory in these inversions. To investigate both the off-great-circle and finite-frequency effects, we apply a 2D finite difference wave propagation simulation combined with the adjoint method. We investigate the effects on ray geometry, travel time measurement, and tomography.

Constructing 3D sensitivity kernels and working towards 3D tomographic inversions based upon adjoint methods (talk)
*Qinya **Liu***

We apply adjoint methods popular in climate and ocean dynamics to calculate Frechet derivatives for tomographic inversions.

For illustrative purposes, we first construct the 3-D finite-frequency sensitivity kernel, relating the perturbation in the traveltime to the perturbation in the model parameters, by simultaneously computing the `adjoint' wave field forward in time and reconstructing the regular wave field backward in time. The adjoint wave field is produced by using the time-reversed velocity at the receiver as a fictitious source, while the regular wave field is reconstructed on the fly by propagating backward in time the last frame of the wave field saved by a previous forward simulation. The approach is based upon the spectral-element method, and is applied to both the regional 3D southern California velocity model as well as the global PREM model and the sensitivity kernels for various phases are computed.

We also generate `event' kernels by combining the traveltime measurements of various phases on all the receivers for a particular earthquake. It is a sum of weighted sensitivity kernels, with weights determined by the associated traveltime anomalies. By the nature of the 3-D simulation, every event kernel is also computed based upon just two simulations, i.e., its construction costs the same amount of computation time as an individual sensitivity kernel.

One can think of the sum of the event kernels for all available earthquakes, called the `misfit' kernel, as a graphical representation of the gradient of the misfit function. With the capability of computing both the value of the misfit function and its gradient, which assimilates the traveltime anomalies, we are ready to use an non-linear conjugate gradient algorithm to iteratively improve the velocity models.

M

THE FINITE-DIFFERENCE AND FINITE-ELEMENT IMPLEMENTATIONS OF THE TSN METHOD FOR THE DYNAMIC RUPTURE PROPAGATION (poster)
*Peter **Moczo** (1,2), Martin Galis (1,2), Jozef Kristek (1,2), Miriam Kristekova (2)*

(1) Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia
(2) Geophysical Institute, Slovak Academy of Sciences, Bratislava, Slovakia

The Traction-at-Split-Node (TSN) method for simulation of dynamic rupture propagation has been independently developed by Andrews (1973, 1999) and Day (1977, 1982). Day et al. (2005) showed very good level of agreement of the method with the boundary integral method. Dalguer & Day (2006) demonstrated its superior accuracy relative to the thick-fault method (Madariaga et al. 1998) and stress-glut method (Andrews 1999). We developed four implementations of the TSN method (Moczo et al. 2007): - the 2nd-order restoring-force e-invariants finite-element (FE) - FE-2; - velocity-stress (VS) staggered-grid (SG) finite-difference (FD) scheme, 2nd-order at grid points close to and grid points on the fault plane, 4th-order elsewhere - SG-FD-2; - VS SG FD scheme, 2nd-order at grid points close to the fault plane, 4th-order elsewhere (including grid points on the fault plane) - SG-FD-24; - VS SG FD scheme, 4th-order at all grid points - SG-FD-4. We performed a series of numerical simulations of spontaneous rupture propagation on a planar fault in a homogeneous unbounded elastic medium for the SCEC TPV3 model configuration and its modifications. We implemented an alternative configuration of the initialization zone and investigated its effect relative to the SCEC initialization on the rupture propagation for the initial traction parallel and oblique with respect to the coordinate axis. We numerically compared rupture propagation for the linear slip-weakening friction law and Ohnaka-Yamashita's friction law. We also compared convergence rates of all the four implementations. Based on our numerical results we suggested a modified version of the benchmark configuration.

N

1-D structure, 2-D space, 3-D wavefields: A spectral-element method for global tomography (talk)

Tarje ***Nissen-Meyer*** *(Princeton University),*
Alexandre Fournier (Universite Joseph-Fourier Grenoble),
Tony Dahlen (Princeton University).

Extracting observables out of any fraction of a seismogram (e.g. phases such as Pdiff) necessitates the knowledge of 3-D time-space wavefields that form the backbone of Frechet sensitivity kernels in tomographic inversions. Global reference models are at this point predominantly spherically symmetric such that alternatives to the full 3-D wave-equation solution (e.g., dynamic ray tracing) have been applied to construct sensitivity kernels. In most current global models, these methods however do not include non-geometric effects such as diffraction. To circumvent these limitations, we follow an idea which is based upon exploring symmetry considerations of the seismic-wave radiation patterns: Collapsing 3-D wave propagation to a series of six equivalent 2-D problems subject to different (multipole) source types while accounting for the full 3-D complexity of sensitivity kernels, the explicit computation and storage of highest-resolution, full wavefields become tractable even on moderate computational resources.

As, to our knowledge, no existing wave-propagation algorithm can handle this, we set out to implement a dedicated 2-D spectral-element method (SEM) for spherically symmetric earth models and full moment tensors. We will describe the SEM with our specific peculiarities such as axial discretization of seismic sources and focus on quantitative measures of meshing and parallelization in general spherical domains. Upon a dispersion analysis of the SEM, we also argue that the conventional second-order Newmark time extrapolation scheme is not efficient for all necessary cases of long propagation distances. Thus, we will present an easy-to-implement, non-dissipative alternative (symplectic fourth-order integration) at sufficient accuracy for all applications. Our SEM has been extensively tested against a variety of reference solutions such as elastostatics, source radiation, full wave propagation and energy conservation, exposing high accuracy and efficiency. We will also touch upon computational issues that are even faced in this

2-D case and suggest some remedies for data compression, before sketching the process to construct full time-space waveform sensitivity kernels from our 2-D wavefields.

O

Accuracy of spectral element methods for wave propagation Modeling (poster)

Saulo P. **Oliveira** and Geza Seriani

Spectral element methods have reached a great popularity in computational seismology. Assessing their accuracy is essential to set up a simulation and to validate improved spectral element formulations. This poster reviews a recent methodology to estimate the numerical dispersion of spectral element methods of arbitrary order for 1D, 2D, and 3D seismic wave propagation problems. This approach circumvents the issue of spurious modes of propagation and reduces to simple 1D calculations in Cartesian grids. We use this approach to study the effect of the time discretization on high-order spatial discretizations and to select the combination of consistent and lumped mass matrices that yields the lowest dispersion error. We further study numerical dispersion caused by mesh distortion.

P

A Green's Function Interpolation Approach for Fast Kinematic Source Inversion (poster)

F. **Pacchiani** [1], S. Heimann [3], G. Seriani [1], S. Cesca [2] and T. Dahm [3]
(1) OGS Trieste, Italy
(2) SZGRF Erlangen, BGR, Germany
(3) University of Hamburg, Germany

The increasing interest in obtaining fast, automated and reliable solutions for earthquake source parameters is currently requiring improved procedures to reduce computational time. The most time consuming step is typically the generation of Green's function databases, from where Green's functions are recovered during the application of the inversion technique. While automatic moment tensor solutions have been implemented and are now available for a wide range of earthquake magnitudes and using different seismic datasets, similar procedures for the retrieval of kinematic parameters are still not yet available. The Kinherd project's aim is to provide an automated inversion technique to retrieve parameters describing the characteristics of extended earthquake sources. The problem related to the Green's functions computation gets especially critical, when dealing with the inversion of kinematic parameters, since the Green's functions have to be evaluated on a dense grid in space and time. Such requirement arises from the necessity of resolving small-scale source characteristics while using a wide range of source-receiver configurations. Indeed, the amount of Green's functions to be computed increases dramatically with the number of source depths, epicentral distances and velocity models one wants to consider. To reduce the density of Green's functions in the initial databases, we propose to interpolate analytical Green's functions, considering the entire waveform. The technique we employ is the "generalized f-k trace interpolation method", a data adaptive interpolation method. The principle is to insert zero traces where interpolated traces are desired and to construct, in the frequency-wavenumber (f-k) domain, the interpolation operator using the low-frequency content of the stretched transforms of the original data. The interpolation becomes equivalent to complex number divisions in the f-k domain. This method has the advantages of being fast and adapted to 2D as well as 3D data, which suit well our objectives. We present results of the successful application of this method to synthetic and real data. Computation of the RMS show that the results are more precise compared to linear interpolation. Moreover the number of Green's function in the initial database can be reduced by at least 50%. Finally, we consider a synthetic earthquake and compare between the results obtained with and without interpolation.

Q

R

Wave Propagation Project (WPP): A New Open-Source Tool Supporting Computational Seismology at LLNL

*Arthur **Rodgers**[1], Anders Petersson[2], Bjorn Sjogreen[2], Daniel Appelo[2], Kathleen McCandless[3], David McCallen[4] and Tarabay Antoun[5]*

[1] *Seismology Group, Chemistry, Materials, Earth and Life Sciences Directorate*
[2] *Center for Applied Scientific Computing, Computations Directorate*
[3] *Computer Applications and Research Department, Computations Directorate*
[4] *Nonproliferation Division, Nonproliferation, Homeland and International Security Directorate*
[5] *Computational Physics Group, Materials, Earth and Life Sciences Directorate*
Lawrence Livermore National Laboratory, Livermore CA 94551

Lawrence Livermore National Laboratory performs research on a wide variety of seismic wave propagation problems in the national interest. These include seismic monitoring of underground explosions, computation of earthquake ground motion and building response and non-destructive evaluation. In order to advance research capabilities in these areas, LLNL has developed a new elastic finite difference code called Wave Propagation Program (WPP). This is a code is based on a node-centered second order formulation of the elastodynamic equations of motion and includes many important features. WPP simulates elastic wave propagation in fully 3D materials in a Cartesian geometry. 3D models can be specified in various ways, including binary raster and 'etree' (Carnegie Mellon University, http://www.cs.cmu.edu/~euclid/) formatted 3D models. The current distribution of the code has free-surface boundary conditions for a flat upper surface and non-reflecting (Clayton-Enquist) boundary conditions for interior boundaries. It can handle an arbitrary number of point force and moment tensor sources with several prescribed source-time functions. WPP outputs SAC (www.llnl.gov/sac) formatted seismograms as well as 2D slices of material properties and motions (e.g. snap shots of displacements or velocities and peak motions). WPP is freely available as open-source and is 'born parallel' for use on serial desktop machines, small LINUX clusters and massively parallel computers. Further developments are underway for future releases of the code, including mesh refinement, surface topography, attenuation and perfectly matched layer boundary conditions. This talk will briefly describe the underlying theory and features of the WPP code, as well as a description of the problems that motivate our development work. The WPP algorithms and software including a detailed user manual and examples can be found at: http://www.llnl.gov/CASC/serpentine/.

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S

Cross validation in inverse problems (talk)

M. Sambridge

Extracting information on structure or processes at depth within the Earth from surface observations results in an inverse problem. The data we measure only indirectly constrain the things of interest. Geophysicists are not alone in having to deal with such problems, as they occur in many areas of the physical sciences. Sooner or later Earth Scientists will try to fit a model to data and inevitably they ask the questions. Is the data fit good enough? Is the model representative of the true Earth? Are my conclusions justified by the data? If we seek a single favoured Earth model (defined somehow) then a ubiquitous feature of the inversion process is a trade off between fit to the data and complexity (or detail) in the model. As Earth models become more extravagant they fit the data better but we are suspicious that the additional detail is not justified. We often have to trade off our preference for simple models with the need for adequate data fit. Geophysicists have studied this problem for many years and developed a variety of approaches to deal with it. However many are problem specific and do not translate well to other scenarios. This talk will summarize some of these approaches and focus on an older (out of favour) method known as cross validation. This technique may be used to choose models along the trade-off in a self-consistent manner, and is easily adapted to particular problems. Cross validation has been seldom used in Geophysics largely because of the apparent high computational costs involved. However it is perfectly suited to parallelization and the widespread availability of cluster computing now makes it a viable approach for a range of problems. Here we show an example of its use in automatic detection of hyper-parameters in Earth source slip inversion.

Analytical evaluation of reflection coefficients for anelastic/anisotropic media and comparison with numerical simulations. (poster)

Rolf Sidler

Real earth media are in general both attenuating and anisotropic and conventional isotropic, elastic approximations prove increasingly inadequate for fully exploiting the information contained in modern seismic data. It is in part for this reason that the well-known but in part still unresolved problem of calculating reflection coefficients for interfaces between anelastic, anisotropic media based on the corresponding analytical expression is enjoying a significant renewed interest. To this end, we compare analytical plane-wave-type evaluations of the amplitudes and phases of reflection coefficients in transversely isotropic, anelastic media and compare them with the results from corresponding full-waveform synthetic seismograms based on numerical solution of the governing equations. Analytical evaluations of the reflection coefficients in anisotropic media inherently suffer from ambiguities related to the complex roots contained in the corresponding expressions, which lead to a large number of mathematically correct but physically unreasonable solutions. Indeed, it turns out that only one of these analytical solutions is physically correct and our results demonstrate that the corresponding numerical solution is an effective means for identifying it. Our results further indicate that this rather heureustic approach also turns out to be an effective means of exploring the analytical solution space more systematically by determining the correct sign of the root by analyzing the Riemann surface of the complex root. In the given context, we find that this approach proves to be quite effective for most intents and purposes. That said, we did, however, find that there are particular model parameter configurations which defy this approach as the correct integration path for the vertical slowness does not exist on the corresponding Riemann surface. Closer inspection then shows that these seemingly pathological cases can be readily resolved through an adequate switch on the Riemann sheet, which then results in a correct solution for all practical applications beyond the vicinity of the elastic equivalent critical angle.

Finite-frequency sensitivity of seismic observables to mantle anisotropy based upon adjoint methods.

A. ***Sieminski*** *(1), Q. Liu (2), J. Trampert (1), J. Tromp (2)*
(1) Utrecht University, Netherlands, (2) Caltech Seismological Lab, USA

We study the sensitivity of finite-frequency seismic waves to mantle anisotropy based upon kernels calculated by combining adjoint methods with spectral-element modeling of seismic wave propagation. We are mainly interested in surface-wave and SKS-splitting observables since these are the most popular data for studying mantle anisotropy. Anisotropy is described by the 21 elastic parameters naturally involved in asymptotic wave propagation in weakly anisotropic media. Our results illustrate the complexity of wave propagation in anisotropic models and emphasize the importance of full waveform modeling to accurately capture the sensitivity of finite-frequency data. The main characteristic of anisotropic sensitivity is a prominent path-dependence. For surface waves, significant effects due to mode coupling are also observed. They are a major feature for the higher modes. We investigate the sensitivity of SKS splitting through the 'splitting intensity', which characterizes the perturbation of the transverse signal. We show that this observable can efficiently be measured with a cross-correlation technique. SKS-splitting intensity 'senses' mantle anisotropy in a very different way than the surface waves. The sampling region of this observable is mainly confined to the upper mantle beneath the station, and it is sensitive to a much smaller number of elastic parameters.

CIG Science Gateways: SPECFEM3D_GLOBE, MAG, and Cigma (poster)

L. Strand (1), Y. Kim (2), J. Tromp (2), D. Komantitsch (3) W. Mi (1), P. Olson (4), L. Armendariz (1), S. Kientz (1)
1. Computational Infrastructure for Geodynamics (U.S.), 2. California Institute of Technology Seismological Lab (U.S.), 3. University of Pau (France), 4. Johns Hopkins (U.S.)

Computational Infrastructure for Geodynamics (CIG) has installed several of its open-source codes on the TeraGrid and is now developing several science gateways. Such an interface will streamline the process of using CIG software since it will enable users to easily start a new job using grid computing technologies. Installing a science gateway will work toward increasing resources available to the community for innovative research by offering a powerful yet more simplified interface to run and benchmark geodynamics applications. Starting with the seismology code SPECFEM3D_GLOBE, the geodynamo code MAG, and a new benchmarking code named Cigma that is a comparison tool that helps define numerical benchmarks for finite element models, CIG aims to support and encourage more of the geodynamics community to benchmark these codes, conduct training sessions on these applications, and encourage new users to try out the TeraGrid to see if it will work for their individual research.

T

CIG Geodynamics Software: Modeling Tools for the Earth Science Community (poster)

E. Tan (1), M. Gurnis (1), W. Landry (1), L. Hodkinson (2), M. Spiegelman (3), S. Kientz (1)
1. CIG (U.S.), 2. Victorian Partnership for Advanced Computing (Australia), 3. Columbia U. (U.S.)

Computational Infrastructure for Geodynamics (CIG) is a membership-governed organization that supports and promotes Earth science by providing state-of-the-art tools for computational geophysics using modern software development practices. CIG continues to develop successful applications like CitcomS, a finite element parallel code for modeling thermochemical convection in a 3D domain (e.g., within the Earth's mantle), now nearing version 3.0 which will include spherical compressible enhancements. CIG has also pursued improvements in Gale, a 2D/3D parallel code for long-term tectonics problems in orogenesis, rifting, and subduction. CIG has also committed to providing solutions for the magma community and is supporting development of a new code, the Magma Dynamics Demonstration Suite (Madds) that will aim to prove the feasibility of including magma dynamics in more general software.

Computational Aspects of Finite-Frequency Tomography (poster)

Yue Tian

Finite-frequency tomography is a new and promising approach to study the interior structure of the Earth. We report on an accurate and efficient software implementation of finite-frequency tomography, in a user-friendly form designed for distribution to seismologists. The major challenge for this implementation is to construct the finite-frequency sensitivity kernels and the associated matrix for the linear inverse problem not only accurately but also efficiently. We present codes for computing traveltime and amplitude sensitivity kernels for perturbations in seismic velocity and attenuation. For efficiency, we use the paraxial approximation and dynamic ray tracing to compute kernels, and use a local model parameterization in the form of a tetrahedral grid with linear interpolation in between grid nodes. We test the numerical precision and validity of the paraxial approximation against analytical expressions. The software accepts arbitrarily defined phases and 1D background models. The numerical precision of kinematic and dynamic ray tracing are optimized to produce traveltime errors under 0.1 sec, which requires a step size in trapezoidal integration of about 20 km for the most common seismic phases. Relative errors of kernel integrations are of the order of 1% for direct waves such as S, and a few percent for SS waves, with a typical integration step size of 50 km. These numerical errors are acceptable in view of common data uncertainties in global seismology. Larger errors of kernel integrations occur for minimax phases, such as SS waves with periods larger than 20 sec, where kernels become hyperbolic near the reflection point and the paraxial approximation breaks down at large distance from the ray. Effects of such errors may become noticeable at epicentral distances larger than 140 deg, especially for lower frequencies. We conclude that the paraxial approximation offers an efficient method for computing the matrix system for finite-frequency inversions in global tomography, though care should be taken near reflection points, and alternative methods are needed to compute the sensitivity near the antipode.

Synthetic seismograms for stagnant slab model

S. **Tsuboi** 1, H. Sugioka 1, M. Obayashi 1, Y. Fukao 1, Yuan Gao 2
1 IFREE/JAMSTEC; 2 China Earthquake Administration

We have shown that combination of Spectral-Element Method (SEM) and the Earth Simulator enables us to calculate synthetic seismograms for realistic three-dimensional Earth model with the accuracy of up to 3.5 sec (Tsuboi et al., 2003, 2005). SEM divides the Earth into 6 chunks and subdivides each chunk into slices. We may use only one chunk to have much finer mesh and calculate synthetic seismograms with accuracy of shorter period. Here we report our recent computation by using one chunk on the Earth Simulator. We divide the chunk to 64 X 64 =4096 slices and allocate one CPU of the Earth Simulator to each slice, which requires 512 nodes of the Earth Simulator. This mesh enables us to calculate synthetic seismograms which are accurate up to 2 second. We use global P-wave velocity tomographic model of GAP-P1 (Obayashi et al, 2006). S-wave velocity model is obtained with the scaling relation from P-model. We select the location of the chunk so that it includes Japanese Islands and calculate synthetic seismograms for deep earthquakes in Bonin Islands. We compare the synthetic seismograms with the observation for seismic stations in Eurasia. We will show that the effect of the stagnant slab, which is included in the tomographic model, is significant to the synthetic seismograms.

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Multi-mode 3-D Surface-wave Sensitivity Kernels in Radially Anisotropic Media (poster)

Ying Zhou
Department of Geosciences, Virginia Tech

We calculate the three-dimensional (3-D) sensitivities of low-order, multi-mode, surface-wave phase and amplitude measurements to the Earth's lateral heterogeneity in seismic velocity as well as radial anisotropy. The 3-D Born scattering sensitivity kernels are formulated for multi-mode measurements made between the data and mode-summed synthetic seismograms using a surface-wave mode- summation approach that fully accounts for interactions between simultaneous overtone arrivals. We derive sensitivity kernels for cross-spectral multi-taper measurements in radially anisotropic reference earth models. Our calculations of sensitivity kernels show that (1) in the presence of radial anisotropy, SH and SV waves are strongly coupled, and the sensitivities of Rayleigh waves to P wave velocities (PH and PV) become significant, when higher-mode surface-wave energy dominates in the measurement window; and (2) the windowing/tapering processes applied in making measurements have strong effects on the sensitivity kernels, especially for measurements made with short time windows. In general, multi-taper measurements are less sensitive to window selections compared to single-taper (e.g., cosine-taper or boxcar-taper) measurements. This multi-mode surface-wave approach opens the opportunity for imaging high-resolution structure of seismic velocity and radial anisotropy in the top 1000 km of the mantle.