S61B MCC: Hall C Saturday 0830h

Welcome to the Machine: Advances in Seismic Modeling, Methods, and Theory Posters

Presiding: **N Rawlinson,** Australian National University**; B Milkereit,** University of Toronto

S61B-1118 0830h POSTER

Generalized Radon Transform in Global Seismology: Focusing Selected Neighborhoods of the CMB

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Short period seismic body waves are modeled by a high-frequency single scattering approximation. In this paper we use methods from microlocal analysis and the theory of Fourier integral operators to develop a generalized Radon transform to carry out inversion to better characterize the multi-scale variations of acousto-elastic properties of the physical shell that encompasses Earth's lowermost mantle (the so called D" region), the Core Mantle Boundary(CMB), and Earth's outer core. We assume the structure of Earth's deep interior outside this shell is sufficeiently well known from seismic body wave transmission tomography and from Earth's free oscillations frequencies. With the methods developed in this paper, we propose to study selected neighborhoods of the CMB, and posibly assess outer core heterogeneity, using short-peroid records of reflected and scattered body waves.

S61B-1119 0830h POSTER

Wave Propagation on a Spherical Membrane in Comparison With Predictions From Ray Theory

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This study employs a simple model of wave propagation on a spherical membrane as a means of checking amplitude and phase predictions from surface wave ray theory. The two-dimensional wave equation on a sphere is solved using a finite-difference method on a spherical grid of approximately 8000 hexagonal faces (effects of dispersion are not considered). The main advantage of the grid of hexagons is that special boundary conditions are not necessary for high latitudes, as is the case with wave propagation on a grid of latitude-longitude cells. The solution to the wave equation is the displacement field $u(\theta, \phi, t)$, i.e., a seismogram for a fixed surface point, or a snapshot of the distorted spherical membrane for a fixed time. The spherical grid is first tested using a homogeneous phase velocity field with an initial Gaussian source. The resulting numerical solutions (HOM) agree with analytical solutions for the homogeneous case. Next a heterogeneous phase velocity field is used; the solutions (HET) reveal the variation in amplitude and phase due to the lateral heterogeneity.

Surface wave ray-tracing equations are used to calculate the amplitude and phase anomalies for a given source and receiver. These anomalies are applied to HOM by taking the Fourier transform of the HOM seismogram and then taking the inverse transform with the amplitude and phase correction obtained from the ray-tracing calculations. We attribute the remaining discrepancy between the HET seismogram and the ray-theory-corrected HOM seismogram to the approximations inherent in ray theory. The results give insights into the level of detail that surface wave ray theory is able to provide.

S61B-1120 0830h POSTER

ROBUST COMPUTATION OF GLOBAL SURFACE WAVE PHASE VELOCITY MAPS FROM MASSIVE DATASET BY THE CLASH

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The detection of seismic wave velocity heterogeneities enables to generate a present-day snapshot of the deep interior of the Earth. One *modus operandi* to compute a 3D body wave velocity model relies on the surface wave phase velocity measurements. Using a roller-coaster type algorithm, we determine the phase velocities of the fundamental and the first six overtone, integrated over the great circle epicenter-station paths. This new non-linear inverse approach tends to introduce the minimum number of *a priori* conditions. Every solution is tested and the model which achieves the best misfit function is retained. For each frequency of a given mode-branch, phase velocities are then expressed in terms of global heterogeneity maps. To this end, a new method, which includes azimuthal anisotropy in its comprehensive form, is developed and is reverently baptized the Computation of Large Anisotropic Seismic Heterogeneities (CLASH). The surface of the Earth is regularly discretized by means of a best fitting grid. Possible lacks of resolution due to an insufficient coverage are taken into account in the inverse resolution, which makes this method different from others. Several synthetic tests emphasize the robustness of this approach and the accuracy of the *a posteriori* uncertainties. Phase velocity maps of the Rayleigh fundamental and the first five higher modes are obtained from the processing a very large amount of seismograms recorded by global networks. The great similarity between the isotropic part of our models and previously published ones is encouraging in the project of using the CLASH to derive a new anisotropic shear wave velocity model of the Earth's mantle.

S61B-1121 0830h POSTER

3D Raytracing and Front Construction in Complex Media

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We present a fast and easy-to-implement 3D front-construction code for an isotropic medium. This comes from a combination of (1) a fast 3D ray-tracing method and, (2) a fast interpolation method to ensure a suitable density of rays to construct a piece of front. The 3D ray tracing (1) is a very simple shooting method implemented by solving the ray equations under the assumption that the local gradient of the squared slowness remains constant along the interval of parameterization. For (2) we introduce an innovative way of interpolating rays in 3D space that is similar to a topographic map where the surface is mapped using contours. In this case the surface to map is the front-surface, and the use of contours and the approach for connecting the contours (essentially a 2-D problem) avoids the search for nearby rays in 3D space to assess if ray density is appropriate. This code is implemented to be used in (a) typical regular-box model with topography, and (b) global Earth models, where the models are defined by a number of layers of any shape, such layers could be surface topography, Moho-topography, sediment-basins, etc., using longitude, latitude and depth from surface.

S61B-1122 0830h POSTER

Gaussian Beam Migration for Sparse Common-Shot and Common-Receiver Data

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We investigate the application of Gaussian beam migration for common-shot and common-receiver seismic data. The inversion of common-shot data is useful for seismic data where the receiver coordinates are well sampled, but the source coordinates are less well sampled. Since Gaussian beam migration uses smoothed, localized windowing of the data, it can provide more stable results for the inversion of sparsely sampled common-shot data. By reciprocity, this approach can also be applied to common-receiver data, such as from an OBS experiment where the source locations are dense but the receiver locations are sparse.

In order to test the common-shot Gaussian beam algorithm, a prestack data set was computed using the finite difference method for a slice from the SEG/EAGE salt model which has significant lateral velocity variations. For the generation of the synthetic data, no free surface multiples were included. Prior to the tracing of rays and beams through the model, smoothing of the velocity was performed. The phase times were then corrected using first-order perturbation theory. A receiver spacing of 20 m was used with an offset range of 13,400 m, and the shot spacing was allowed to vary. Comparing the Gaussian beam migration images with the true model, most of the features were well imaged. In particular, most features beneath the salt were imaged including steeply dipping events and a lower flat reflector. The Gaussian beam images also compared well with results from other methods.

S61B-1123 0830h POSTER

Applications of General Three-Dimensional Geographical Curve-Linear Library in Computational Seismology

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We developed a general library for handling a class of objects we call Geographical Curvilinear grids (GCLgrids). A GCLgrid can be viewed as topologically equivalent to a rectangular box divided into regular cubes with nodes at each corner of each cube. The actual grid can be arbitrarily distorted provided it can be mapped back into a uniform grid with no singularities. A simple example is a spherical shell divided along latitude, longitude, and depth. Two algorithms are the core of this library. First, we use Newton's method to search for a location in space from a starting point. This algorithm converges reasonably fast if the grid is not extremely distorted. Second, we interpolate the grid using methods known from finite analysis. A Jacobian matrix for an 8-node cube is computed to transform a distorted cube into a standard one. Shape functions are used to describe the actual object mapped to the standard cube. Once the transformation matrices are computed, we can interpolate n-element vectors as quickly as scalar data. We apply this technique to two computational seismology problems. First, in a plane wave migration procedure, we transform the seismic data from time to depth domain, and this approach provides a general solution to this complex mapping problem. Secondly, this approach allows us to utilize 3D travel time tables to locate events using 3D velocity models. This library may also have use in numerical modeling of regional scale geodynamic problems.

S61B-1124 0830h POSTER

Efficient Synthesis of Seismograms via Path Integration

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Global seismology is at a critical stage in its maturation as a field of study. With the advent of broadband digital seismic networks, we have been inundated with a wealth of high-quality data. This new data has brought global traveltime tomographic images close to their saturation point, i.e., the point at which additional measurements make a negligible difference in the major features observed, given present station coverage and the natural source distribution. More stringent seismic constraints on the details of the Earth's deep structure can be obtained only by including the additional information recorded in the seismic waveform. This valuable

information is most effectively extracted by the comparison of data with synthetic waveforms computed for a proposed structure model. The need for a practical and accurate method of generating these synthetics for the propagation of broadband seismic waves through realistic, 3-D models has never been greater.

However, at the present time practicality and accuracy are almost mutually exclusive. Practicality is achievable if one is willing to settle for high-frequency asymptotic solutions or for models with merely 1-D variations or for both. Until recent years, these "practical" methods were really the only methods available to seismologists, but now those who have plenty of computing power and memory, and plenty of patience, can generate very accurate seismograms up to frequencies that are approaching the range of low-frequency teleseismic S-waves.

Here we present an alternative approach, one that provides an adjustable compromise between computational speed and accuracy. We recast an existing path integral solution for acoustic wave propagation in a form that is immensely more amenable to numerical implementation. Several comparisons between the new path integral method and slower, established numerical methods for nontrivial 3-D media will be made.

S61B-1125 0830h POSTER

DSM Software for Computing Synthetic Seismograms in Transversely Isotropic Spherically Symmetric Media and Its Application

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The existence of anisotropy has been suggested in many regions in the Earth. Determining the anisotropic seismic velocity structure of the Earth can contribute to our understanding of geodynamics and rheology. Inversion of observed seismic waveforms is a promising approach for determining the Earth's anisotropic structure, but development of computational algorithms and software for computing synthetic seismograms in anisotropic media is required. Software for computing seismic waveforms in isotropic media based on the Direct Solution Method (DSM; Geller and Ohminato 1994, GJI) has previously been developed and is being used in data analysis, but DSM software for computing synthetic seismograms for anisotropic media has not yet been developed.

In this study, we derive algorithms and develop software for computing synthetics for transversely isotropic spherically symmetric media. Our derivation follows previous work for isotropic media (Takeuchi et al. 1996, GRL; Cummins et al. 1997, GJI). The displacement is represented using spherical harmonics for the lateral dependence and linear spline functions for the vertical dependence of the trial functions. The numerical operators derived using these trial functions are then replaced by optimally accurate operators (Geller and Takeuchi 1995, GJI; Takeuchi and Geller 2002, GJI, submitted). Although the number of elastic constants increases from 2 to 5, the numerical operators are basically identical to those for the isotropic case. Our derivation does not require approximations that treat the anisotropic or laterally heterogeneous structure as an infinitesimal perturbation to the isotropic structure. Only spherically symmetric models are considered in this paper, but when our methods can be extended to the 3-D case to permit computation of synthetic seismograms with the same accuracy as for spherically symmetric isotropic models. We present computational examples such as accuracy checks and also some applications to observed data.

S61B-1126 0830h POSTER

Modelling seismic waves in strongly heterogeneous media using a wavelet-based method

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Most numerical techniques for modelling seismic wave propagation encounter significant difficulties when confronted with media with strong heterogeneity. However, a wavelet-based approach can provide high accuracy and stability of spatial differentiation even in highly perturbed media. The wavelet-based method therefore allows the treatment of localized zones of strong contrast such as media with a fluid-filled crack. The accuracy of the method makes it possible to consider seismic waves in a medium with a weak systematic structure such as subduction zones, where slabs exhibit mild-velocity contrast to the background and therefore there can be significant interface waves on the surfaces of the slabs when the source is close to the slab. The wavelet-based method also allows an accurate treatment of the scattering effect of short-scale heterogeneity, as encountered in the crust. The results indicate that conventional finite difference methods are likely to overestimate scattering attenuation.

S61B-1127 0830h POSTER

Wavefront Evolution in Complex Layered Media Using the Fast Marching Method

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The Fast Marching Method (FMM) is a grid based numerical scheme for tracking the evolution of monotonically advancing interfaces via finite difference solution of the Eikonal equation. Like many other grid based techniques, the FMM is only capable of finding the first-arriving phase in continuous media. However, the FMM distinguishes itself by combining both unconditional stability and rapid computation, making it a truly practical scheme for velocity fields of arbitrary complexity.

We investigate the potential of the FMM for finding later arriving phases in layered media, with particular focus on reflections from smooth sub-horizontal interfaces that separate regions of continuous velocity variation. The presence of interfaces introduces two difficulties that need to be overcome. First, the FMM was originally devised for application to a regular grid of velocity nodes and needs to be adapted for the presence of irregularly spaced interface nodes. Second, the traveltime field will be multi-valued if reflections are sought. The irregular boundary node problem is dealt with by using a triangulation routine to locally suture the interface nodes to adjacent velocity nodes. The multi-valued traveltime field problem is solved by applying a two stage FMM; the first stage tracks the incident wavefront to all points on the interface surface and then stops; the second stage reinitializes the wavefront as a reflection by starting from the interface node with minimum traveltime.

A number of synthetic tests are carried out to assess the accuracy, speed and robustness of the new scheme. These include comparisons with analytic solutions and solutions obtained from a shooting method of ray tracing. Results from these tests indicate that wavefronts are accurately tracked, even in the presence of complex velocity fields and layer boundaries with high curvature. Incident wavefronts containing gradient discontinuities or shocks are also correctly reflected. Our two stage FMM for calculating reflection phases retains the desirable properties of rapid computation time and unconditional stability and suggests that other later arrivals such as multiples may be successfully located by further development of the wavefront reinitialization scheme.

URL: http://rses.anu.edu.au/∼nick/waves.html

S61B-1128 0830h POSTER

Monte Carlo Sampling of Solutions to Velocity Tomography Problem: A Quest for Imaging Accuracy

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The main drawback of the classical approach to seismic tomography is a lack of the robust method to estimate the accuracy of tomographic image. This difficulty can be overcome if the Bayesian inverse theory is applied to solve the tomography inverse problem. The method relies on the construction of the *posterior* probability over the space of all possible velocity images which gives the probability that a given model is the true one. Thus, it provides the mechanism to find not only estimators of the true velocity distribution, like the *Maximum Likelihood* or average models but also, to estimate the accuracy of the tomography imaging. However, as the tomography problems are highly dimensional, inspecting *posterior* probability requires Monte Carlo sampling. This paper presents the application of this technique to analysis of the tomography imaging accuracy.

S61B-1129 0830h POSTER

3D 4th-order Staggered-grid Finite-difference Modeling of Seismic Motion in Viscoelastic Media with Material Discontinuities

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We present a new 3D 4th-order staggered-grid finite-difference scheme for the viscoelastic heterogeneous media with material discontinuities. The scheme is a generalization of the recently developed scheme (Moczo et al., in press) for the perfectly elastic media, which was shown, using extensive numerical tests, to be more accurate than standard staggered-grid schemes. The generalization is based on two key approaches: a) We assume that a contact of two viscoelastic media with the GMB (generalized Maxwell body) rheologies can be approximated by an averaged medium with the GMB rheology. The quality factors are determined from volume harmonic averages of the complex, frequency-dependent torsion and bulk moduli. The quality factors are then used to determine anelastic coefficients of the averaged medium. b) We define anelastic functions in a new way, which allows both Days (1998) coarse spatial distribution (with a spatial period of 2h, h being a grid spacing) of the anelastic functions and accounting for all relaxation frequencies at any grid position of the anelastic function. This is important especially at the material discontinuities in order to avoid characterization of one medium by relaxation frequencies different from those, which characterize the other medium.

We compare synthetics calculated for a set of test models with those calculated using a recent approach by Graves and Day (2002) and confront both with the DWN (discrete wavenumber) solutions.

S61B-1130 0830h POSTER

Simulation of Seismic Wave Propagation Using Finite-Difference Method With Locally Variable Time-Step

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A finite-difference (FD) scheme using the locally variable time-step (LVTS) is developed for the efficient simulation of seismic wave propagation. Conventional simulation algorithms have used a constant time-step through the entire model region. Large contrasts in the velocity model often raise a problem of temporal oversampling in the region of smaller velocity as well as spatial oversampling in the region of larger velocity. As far as the spatial sampling is concerned, many efforts have been made to avoid the excessive fine sampling. They include the use of the nonuniform or discontinuous grid spacing. Those techniques reduce the computational overburden considerably. Besides the control of the spatial sampling, the use of a large time step can further shorten the computation time. However, researches on the time-step control are rarely found in the seismic modeling.

In this presentation, first-order velocity-stress formulations are used to calculate the spatial derivatives using finite-difference operators on a staggered grid. Field variables are staggered in both time and space. Temporal staggering between the velocity components and the stress components forces a larger time-step length to become odd-number times a smaller one. We use a three-times coarser grid in the high-velocity region compared with the grid in the low-velocity region to avoid spatial oversampling. Temporal steps corresponding to the spatial sampling ratio between the two regions are determined to satisfy the proper stability criteria. There exists a transition zone for time-marching between the two regions with different time-steps. The length of the transition zone depends on the accuracy of the spatial FD operator. While the second-order approximation requires the transition length of

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a half spatial grid-step of the larger grid spacing, the fourth-order approximation requires one and a half spatial grid-step. The wavefield in the margin of the region with smaller time-step are linearly interpolated in time using the values calculated in the region with larger one. The use of the proposed LVTS scheme with discontinuous grids results in remarkable saving of the computational time and memory requirement with dependency of the efficiency on the simulation model. This implies that large tasks such as the full waveform modeling using the domain-based methods enter on a new phase.

S61B-1131 0830h POSTER

An Efficient Finite-Difference Time-Domain Solution for Seismic Plane-Wave Incidence Problems of Vertically Heterogeneous Media

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Plane-wave responses of vertically heterogeneous structure models (1-D media) are often computed in seismology. For horizontally layered media, they can be calculated by semi-analytical methods such as the propagator matrix method. However, for the gradient velocity or randomly heterogeneous structures, we have to use numerical methods such as the finite-difference method. The conventional codes for the 2-D or 3-D finite-difference method require huge computer memory and long computation time even for calculating plane-wave responses of 1-D media. In this study we propose an efficient procedure to calculate plane-wave responses of arbitrary 1-D media using the finite-difference method.

We first derive an elastodynamic equation of plane-wave incidence problem for vertically heterogeneous media by applying the Snell's law to 3-D elastodynamic equation. We then discretize the velocity-stress formulation of the derived elastodynamic equation using a staggered-grid finite-difference scheme of fourth-order accurate in space and second-order accurate in time. We also investigate the implement of the stress-free surface condition for the scheme, and perform a stability check of the total scheme through actual computations using a Fortran code based on it.

We computed plane-wave responses of structure model with velocity gradient using the derived finite-difference method. We focused on the PS-converted phase and found a "offset" phase appearing between the PS-converted phases generated at the top and bottom boundaries of a velocity-gradient layer on the surface responses of a structure model with velocity gradient due to a P-wave incidence. This phase can be emphasized by calculating the receiver function from the radial and vertical waveforms. In this study we also investigate the "offset" phase attributed to the velocity gradient by numerical computations using the derived finite-difference method.

S61B-1132 0830h POSTER

Three Dimensional Sensitivity Kernels for Shear Wave Splitting in Transverse Isotropic Media

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The splitting intensity, a new seismological observable, which depends on the angle between the backazimuth of the earthquake and the direction of the symmetry axis and on the delay time between the two quasi shear waves, was introduced by Chevrot (2000). This parameter can be robustly determined from the seismic records and small variations of splitting parameters can then be measured.

Shear wave splitting observations are often used to constrain upper mantle anisotropy. However, their interpretation always implicitly relies on the geometric ray theory. We study the case of a plane shear wavefront propagating in a transverse isotropic medium. Using the Born approximation, it is possible to derive sensitivity kernels that relate linearly the splitting intensity to the elastic properties of the medium. The sensitivity kernels are given analytically and can be computed very efficiently. The amplitude and the shape of the kernels depend directly on the polarization and on the dominant period of the incoming wave. Moreover, we demonstrate analytically that the volume integral of the sensitivity kernels is constant as a function of depth and leads to the ray theoretical expression provided the near field contributions to the Green's tensor are taken into account. Sensitivity kernels established under the far field approximation are not valid in a depth interval going from the surface to approximately twice the dominant wavelength of the signal.

As an illustration, we present a numerical experiment on a two blocks model which demonstrates that lateral variations of anisotropy introduce complex and counter intuitive effects on shear wave splitting parameters measured at the surface.

S61B-1133 0830h POSTER

How do Petrophysical Scale Parameters Affect 3D Seismic Wave Propagation?

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In layered and heterogeneous media, the angular and frequency dependent seismic response point towards unique statistical distributions of physical properties. Investigations of the statistical nature of velocity and density perturbations provided useful insights into mechanisms governing wave propagation as there exists a strong correlation between the spatial properties of the velocity field of a reflective target and the lateral correlation length of the resulting seismic wave field. Here we present results from an integrated seismic modeling and borehole seismic acquistion project. Multi-offset vertical seismic profiling (VSP) techniques can be employed to image a target zone in a complex geological setting. The integration of borehole geophysical logs, offset VSPs, and 3D elastic modeling studies provide new insights in the scale dependent petrophysical parameters and the internal structure of the target zone. Scale-dependent elastic parameters are best determined in forward scattering (transmission) direction such as offset VSP and walkaway VSP experiments. Results from the 3-D modeling study were used for refine survey design and processing strategies of the VSP experiments. In our 3D modeling study, the target is characterized by strong variations in elastic parameters. Within the model, the Poisson's ratio varies from 0.15 to 0.48. Direct solutions of the elastic wave equation by finite differences (FD) must be obtained for complex fine-scale 3D subsurface models to better assess systematic variations of angular (amplitude-versus-offset) and other frequency dependent seismic attributes.

S61B-1134 0830h POSTER

An Efficient Mesh for Wavefront Construction Methods and its Numerical Properties for Anisotropic Media

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The wavefront construction method is an efficient way to model wave propagation in anisotropic media. This method is based on asymptotic ray theory, and it explicitly tracks the propagation of wavefronts through the earth model. The first step is to trace a fan of rays through the earth model, initializing the wavefront by constructing a mesh from the set of all ray points at a specified travel time. The wavefront is thus a mesh composed of quadrilateral cells defined by four neighboring rays. Rays are computed by kinematic ray tracing using Runge-Kutta methods. The basic geometry, or coordinate system, used to select the rays comprising the initial mesh has significant affects on the precision and performance of the numerical calculation. A common approach is to trace rays with regular increments in the azimuthal and declination takeoff angles. These two angles, along with travel time, define a ray coordinate system that is commonly used for implementations of conventional ray tracing for wavefront construction schemes.

While the ray coordinate system is straightforward to implement and has been used extensively, it has some drawbacks (Gibson et al., 2002). The most important is that the derivatives of Cartesian coordinates on the ray with respect to the azimuthal takeoff angle vanish near the poles of the coordinate system, leading to potential numerical errors. Our implementation applies paraxial methods, and the poor estimates of derivatives can seriously degrade the performance of the algorithm. Also, specifying an initial ray field with even increments in takeoff angles leads to large concentrations of rays near the poles, which is numerically inefficient.

To overcome these important limitations of the ray coordinate system, we apply a new mesh generation algorithm that utilizes a cubic gnomonic mesh. A cubic gnomonic mesh maps points chosen at regular intervals on the surface of a cube surrounding the source point to the focal sphere. In essence, the initial directions of the rays are defined by drawing a line segment from the source point through each initial mesh point on the cubic surface. Then all of the calculations of derivatives for the paraxial method are performed on the geometry defined by this new set of ray coordinates. The ray density is uniform in all directions, and the derivatives never vanish since there are no poles in the new ray coordinate system.

We will compare the numerical results of ray coordinate and cubic gnomonic coordinate systems to illustrate the advantages of the new system. We will also describe the implementation of the new scheme and show examples of applications to anisotropic earth models.

S61B-1135 0830h POSTER

Wide-Angle Complex Screen Propagator for Elastic Wave Propagation

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The complex screen method provides an efficient way to calculate the elastic wave propagation and primary reflection in heterogeneous model. The method is an elastic version of the phase screen method used for scalar wave propagation. The complex screen method is based on the one-way wave equation and local Born approximation, and usually accurate only for small scattering angle and for small to medium velocity perturbations (Wu, 1994, 1996; Wild and Hudson, 1998; Xie and Wu, 1996, 2001). In the current study, we extend the complex screen method to the wide-angle and large velocity perturbation cases.

Using the complex screen method, the interaction between the propagating waves and the heterogeneities is processed in two steps. The P- and S-wave couplings due to the heterogeneity are calculated first. Then, these waves propagate through the background medium independently. A correction based on the finite-difference method is used at the propagating stage to improve the wide-angle accuracy under large velocity perturbation for both P- and S-waves.

The resulted wide-angle elastic-wave propagator can be used in the forward propagation, reflection simulation and seismic migration in models with large velocity perturbations. Numerical examples related to these applications are presented.

S61B-1136 0830h POSTER

Analysis of Time-Lapse Seismic Technology Using a Physical Model of a Porous Channel Sand

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Time-lapse seismic has become an increasingly popular tool in the oil and gas industry as we move from exploration in new frontier basins to production in more mature basins. The goal of time-lapse seismic is to augment the information measured at injection and production wells by attempting to directly detect the movement of fluid fronts in an effort to more completely sweep hydrocarbons from the reservoir.

The reservoir in this study is represented by an idealized channel sand system. In the past few years there are very few physical or numerical model experimental studies. Numerical studies suffer from the computational cost of fully 3D elastic wave equation modeling. Physical models suffer from the limitation of materials where traditionally epoxies and resins having a Poisson's ratio of about 0.30 were used. Accommodating these challenges, idealized reservoir was modeled with sintered glass beads to replicate porous sand material having a Poisson's ratio close to 0.10. This study provides new experimental techniques and work flows in constructing a model with porous media, injecting the chosen media with fluid, and calibrating the transducer radiation patterns for AVO analysis.

Three 3D datasets over the channel model were acquired corresponding to different fluid distributions. Data was pre-processed and processed with relative-amplitude preserving flow, including 3D pre-stack time-migration. Channel fluid-front was delineated by extraction and comparison of seismic attributes of the datasets. Of these attributes, seismic coherence and AVO were able to better illuminate channel fluid-front than amplitude extraction, envelope, and instantaneous frequency.

S61B-1137 0830h POSTER

Computational Memory Reduction for Finite-Difference Elastic Wave Propagation Algorithms

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Numerical simulation of seismic wave propagation in three spatial dimensions may require substantial computational memory and execution time. A 3D time-domain finite-difference (FD) algorithm that solves the velocity-stress equations of isotropic elastodynamics requires at least 48N bytes of memory, where N is the number of spatial gridpoints. The earth model (P and S wavespeeds, mass density) is stored with 12N bytes and the elastic wavefield (3 velocity vector components and 6 independent stress tensor components) is stored with 36N bytes. In this study, three strategies for reducing computational memory demand are examined.

In the first approach, an earth model is represented by a finite number of homogeneous units or formations. The 3D spatial distribution of material properties is described by a single, integer-valued, pointer array. If 1-byte integer encoding is sufficient, the earth model is stored in N+12M bytes, where M is the number of model units. A second approach is applicable to earth models that are stratified in one predominant direction. The two spatial grid intervals normal to this direction may enlarged, yielding an elementary FD grid cell that is rectangular rather than cubic. This leads to a reduction in storage for both the earth model and the wavefield components. Finally, a non-uniform grid FD implementation of the velocity-stress equations achieves substantial memory savings (for both model and wavefield) in portions of the 3D grid that contain high seismic velocities. Such high velocity zones are spatially oversampled with conventional uniform grid FD algorithms.

Although each approach yields a reduction in memory, associated limitations and/or pitfalls should be recognized. Method 1 restricts material parameter variability; method 2 can enhance numerical dispersion and anisotropy, especially for rectangular grid cells with large aspect ratio. Finally, method 3 involves increased in code complexity, for both wave propagation and earth model construction algorithms. Representative synthetic seismograms demonstrate the feasibility and the limitations of each approach.

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S61B-1138 0830h POSTER

Frequency Domain Modelling by a Direct-Iterative Solver: A Space and Wavelet Approach

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Seismic forward modelling of wave propagation phenomena in complex rheologic media using a frequency domain finite-difference (FDFD) technique is of special interest for multisource experiments and waveform inversion schemes, because the complete wavefield solution can be computed in a fast and efficient way.

FDFD modelling requires the inversion of an extremely large matrix-equation $A \times x = b$, by either a direct or an iterative solver. The direct solver computes an effective inverse of A, called LU factorization. The main handicap is additional computer memory required for storing matrix fill-in coefficients, that are created during the factorization process. Iterative solvers are not limited by memory constraints (additional coefficients), but the convergence depends on a good initial solution difficult to guess before hand. For both solvers, available computer resources has limited widespread FDFD modelling applications to mainly two-dimensional ($2D$) and rarely three-dimensional ($3D$) problems.

In order to overcome these limits, we propose the combination of a direct solver and an iterative solver, called Direct-Iterative Solver (DIS). The direct solver is used to compute an exact wavefield solution on a coarse discretized grid. We use a multifrontal decomposition technique. The coarse-grid size is determined preliminary by limits of the available computer resources, rather than by the wave simulation problem. We project the exact coarse-grid solution on a fine-grid, and use it as an initial solution for an iterative solver, which convergences to an acceptable approximation of the desired fine-grid solution.

Two different DIS schemes have been implemented and tested for numerical accuracy and computational performance. The first approach, called the Direct-Iterative-Space Solver (DISS), projects the coarse-grid solution on the fine-grid by a bilinear interpolation. Though the interpolated solution nicely approximates the desired fine-grid solution, still for complex wave propagation phenomena spatial aliasing of interpolated fields is unavoidable and should be in principle corrected through V- and W-cycles used in multigrid techniques. This aliasing-error correction is costly and convergence cannot be guaranteed.

Therefore, we propose a wavelet-based FDFD strategy, called the Direct-Iterative-Wavelet Solver (DIWS). The wavelet basis transformation provides a decomposition of the signal on a sequence of resolution grids. Instead of bilinear interpolation, we formally recast the coarse-grid solution in the wavelet expansion of the desired fine-grid solution. The coarse-grid solution approximates the scaling coefficients in the fine-grid wavelet expansion, while all other fine-grid wavelet coefficients are unknown, therefore set to zero.

We construct the complex impedance matrix A and right-hand-side b in the wavelet domain. Then, the iterative solver is applied in the wavelet space, which fills-in all missing fine-grid wavelet coefficients. The final wavefield is obtained by an inverse wavelet transform. Additional V- and W-cycles, as required for the DISS approach, are unnecessary for the DIWS scheme. The formal expansion of fields into an orthogonal wavelet basis permits the construction of the true solution projected on each resolution grid, where all interactions between sub-grids of different resolution are accounted by the wavele decomposition.

We have implemented the DISS and DIWS strategy for the first-order hyperbolic system of equation, that allows SH-wave propagation simulations in structurally complex heterogeneous media. We illustrate the performance of both schemes for the complex Marmousi model.

S61B-1139 0830h POSTER

Computational Simulation of Reverse-Time Seismic Wave Propagation

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Reverse-time seismic wave propagation is readily demonstrated with a time-domain finite-difference (FD) algorithm that numerically solves the velocity-stress differential equations of 3D isotropic elastodynamics. True reverse-time propagation is achieved via a three-step procedure: (1) save velocity vector and stress tensor components of an outward propagating wavefield at a specified time T throughout a 3D volume, (2) supply these velocity and stress components to the FD algorithm as final wavefield conditions at time T, and (3) execute the FD algorithm with time decrementing from T toward earlier values. An alternate approach entails negating the particle velocity components from step (1), supplying these velocity (and unaltered stress) components to the FD algorithm as initial conditions at time zero, and executing the FD algorithm with time incrementing. In either case, the elastic wavefield converges toward the source location. The alternate procedure is properly referred to as back-propagation, rather than reverse-time propagation, since the FD algorithm executes forward in time. Back-propagation is also achieved by storing the outgoing wavefield, as a function of time, on a boundary that (wholly or partially) encloses the source. The stored traces are reversed in time, and are then used to initiate the FD algorithm via time-dependent boundary conditions.

In order to achieve exact time-reversal invariance of the initial outgoing wavefield, the seismic source wavelet must be time-shifted and reversed, and applied during the FD computational stage. The wavefield focuses at the source point and is annihilated. If the source wavelet is not supplied, the incoming wavefield forms a diffuse focal spot in the vicinity of the source position, propagates through this point, and subsequently diverges.

The reverse-time and back-propagation computational approaches are illustrated with 3D heterogeneous isotropic elastic earth models, and using a variety of different seismic energy sources (body force, body moments, surface traction). These methods may find application in determining various seismic source characteristics (location, waveform, type, orientation) by analysis of the converging, and subsequently diverging, wavefield.

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S61B-1140 0830h POSTER

Elastic Wave Scattering off a Fracture With Non-uniform Stiffness Distribution

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Elastic wave scattering by a fracture in rock has been commonly modeled using the seismic displacement discontinuity model (SDDM). This model uses a parameter called fracture stiffness that linearly relates small relative displacement across a fracture and the applied stress. Theoretically the fracture stiffness is frequency-independent, since the SDDM is essentially a static model. However, laboratory measurements on the static and dynamic stiffness of fractures in rocks and synthetic materials often exhibit significant discrepancies, the dynamic stiffness being much higher than the static stiffness.

In this study, we hypothesize that these discrepancies occur due to the violation of the assumptions of the SDDM: the characteristic dimension of the fracture such as roughness and contacting asperities should be much smaller than the seismic wavelength. To examine the effect of the random heterogeneous features on a fracture that alter the characteristics of the scattered seismic waves, we model the randomness as a distribution of fracture stiffness on the fracture plane. Using a semi-analytical, frequency-wavenumber domain technique based on the Fourier optics, the dynamic interaction between incoming plane waves and the fracture with random stiffness distribution can be computed to examine the frequency dependent (from static to high frequency dynamic) transmission and reflection coefficient of the fracture. It is noted that this approach is different from the Pyrak-Nolte et al (1990)'s work based on the geometrical optics. The presented technique provides not only statistical guidelines to correlate the dynamically measured stiffness of the fracture to the static stiffness but also a linear inversion scheme that images the distribution of fracture stiffness from measured seismic waves in the far field.

S61B-1141 0830h POSTER

Wave propagation in heterogeneous media by a least-squares one-way operator

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In seismic modeling and imaging, one-way operators are used to estimate wavefields $\psi_P(z + \Delta z)$ in the subsurface by extrapolating recorded wavefields $\psi_P(z)$. The most general one-way operator for isotropic media takes the form of a pseudo-differential operator

$$\psi_P(x, z + \Delta z) = \frac{1}{2\pi} \int \psi(y, z)\, \alpha(x, k, \Delta z) \times e^{-ik[x-y]} dk dy, \quad (1)$$

where x and y are spatial coordinates normal to the depth axis and correspond to input and output respectively, $k = \omega p$ are the Fourier duals of $[x - y]$, p is horizontal slowness, ω is temporal frequency and extrapolation symbol α is the complex exponential

$$\alpha(x, k, \Delta z) = e^{i\Delta z q(x,k)}, \quad (2)$$

where q is vertical slowness, and Δz is distance in depth from the recording location. It is assumed that q varies in the lateral coordinates x and y, but is invariant over Δz.

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Using **P** to represent extrapolation by the pseudo-differential operator (equation 1), we have the equality

$$\mathbf{P}\left(\frac{\Delta z}{2}\right)\psi(z) = \mathbf{P}\left(-\frac{\Delta z}{2}\right)\psi(z+\Delta z) \qquad (3)$$

from which a least-squares estimate of $\psi(z+\Delta z)$ can be derived:

$$\psi(z+\Delta z) = \left[\mathbf{P}^{\dagger}\left(-\frac{\Delta z}{2}\right)\mathbf{P}\left(-\frac{\Delta z}{2}\right)\right]^{-1} \times \mathbf{P}^{\dagger}\left(-\frac{\Delta z}{2}\right)\mathbf{P}\left(\frac{\Delta z}{2}\right)\psi(z)\,. \qquad (4)$$

Using a seismic modeling algorithm, we implement the one-way operator represented by equation (4) and extrapolate a point source through a strongly heterogeneous medium. We compare the resulting wavefield to wavefields obtained by several series approximations to equation (4) implemented as operators in the same modeling algorithm. We find that, for a minimal loss of accuracy, large increases in computational efficiency can be realized by implementing the approximate operators.

S61B-1142 0830h POSTER

3D Hybrid Simulation method Using Finite Difference and Discrete Wavenumber Method

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This study presents a 3D hybrid method for computation of 3D seismic motion inside basin. The hybrid method is based on the discrete wavenumber (DW) and fourth-order finite difference (FD) method. In the first step of the hybrid technique, DW method is used to calculate 3-component excitation on a finite difference grids surrounding 3D basin structure model. In the second step, FD method is used to compute the 3D wave propagation inside basin using the results obtain in the first step. The merits of this hybrid method are as follows. The first step computational model can locate the seismic source without the restriction of the finite difference grid point. The second step computational model needs less computer memory and time than the calculation using only FD method. The accuracy of the DW-FD hybrid method has been tested for homogeneous media. As the result of the test, the hybrid method solutions are in good agreement with the discrete wavenumber solutions for homogeneous media. Furthermore, we applied this method to simulation of strong ground motions from an actual earthquake, and showed the effectiveness of this method.

S61B-1143 0830h POSTER

Simulation of wavefields emanating from finite sources in anisotropic media

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The shallow crust is known to be anisotropic in most seismically active regions. Anisotropy manifests itself predominantly through shear-wave splitting which may considerably complicate the particle motion of shear wave trains. However, these arrivals may also be complicated by finite-source effects and noise.

The goal of this study is to classify and compare the effects of (weak) anisotropy and finite sources on the shear waveforms in the presence of realistic noise, and to discuss implications for the determination of source and medium properties. Three-dimensional numerical simulations are carried out using a finite-difference scheme for general anisotropic media.

Finite sources are simulated through a simple kinematic model, where rupture propagates with constant velocity in a symmetric manner from a hypocentre location to the edge of a circular fault. Regions swept by the rupture front begin to slip with a constant rate. An arrest front propagates backward from the predefined circular fault edge terminating the slip. Synthetic seismograms are calculated for a set of buried finite sources in a homogeneous half space.

We investigate the particle motion observed at the surface as a function of increasing anisotropy (from isotropic to 10% shear-wave anisotropy), increasing source area (from point source to finite source size), increasing noise, and various combinations of these factors. Particle motion effects are discussed as a function of propagation direction and frequency. We investigate whether the contributions of anisotropy and finite source size are separable in the model space considered.

S61B-1144 0830h POSTER

Coupling of Finite-Difference and Finite-Element Methods for Earthquake Source Simulations

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We investigate a scheme for interfacing Finite-Difference (FD) and Finite-Element (FE) models and apply it to dynamic rupture simulations. The more powerful but slower FE method allows for (1) unusual geometries (e.g. dipping and curved faults), (2) nonlinear physics, and (3) finite displacements. These capabilities are computationally expensive and limit the useful size of the problem that can be solved. Large efficiencies are gained by employing FE only where necessary in the near source region and coupling this with an efficient FD solution for the surrounding medium. Coupling is achieved through setting up and an overlapping buffer zone between the two methods. The buffer zone acts as mutual offset boundary conditions (BC). The buffer zone is itself divided into two regions; the interior portion of the buffer zone for each method corresponds to the exterior portion of the the buffer zone in the other method. Each interior buffer zone acts as a BC by passing field variables to the exterior buffer zone of the other method. This scheme eliminates the effect of the artificial boundaries at the interface and allows energy to propagate in both directions across the boundary. In general it is necessary to interpolate variables between the meshes and time discretizations used for each model, and this can create artifacts that must be controlled.

S61B-1145 0830h POSTER

Regularization Methods in Seismic Waveform Inversion

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Seismic waveform inversion is a highly challenging task. Nonlinearity, non-uniqueness, and robustness issues tend to make the problem computationally intractable. Regularization is critical for obtaining stable and geologically realistic solutions. We have developed a simple Gauss-Newton type algorithm for inversion of seismic data in which we evaluated several different existing regularization methods with application to field ocean bottom cable data. Although Engl's regularization criterion, based on a discrfepancy principle requires prior knowledge of noise in the data, we were able to obtain excellent results by trial and error choise of the noise estimates. The robustness and stability were further improved by allowing adaptivity in the choice of the regularization weight. The commonly used L-curve and GCV criteria were also used successfully in the inversion of field seismic gathers. We evaluated some existing methods of measuring the corner of the L-curve at each iteration of the algorithm and improved the performance when the L-curve was generated in linear rather than the conventional log-log scale. The GCV method requires more computaion time per iteration step but converges faster than an algorithm based on L-curve. We also developed a new approach in which we make an estimate of noise (for use in methods based on discrepancy principle) from the L-curve. We will demnostrate the relative performance of these methods with application to field ocean bottom cable data.

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S61C MCC: Hall C Saturday 0830h

Crustal Dynamics, Deep Crustal Imaging Posters *(joint with T)*

Presiding: **C M Snelson,** University of Nevada, Las Vegas**; R G Keller,** University of Texas at El Paso

S61C-1146 0830h POSTER

Deep Seismic Imaging of the Crust Through Las Cárceles and Bajada de Añelo, Neuquén Basin - Argentina (38° SL)

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Deep seismic sections were obtained by mathematical reprocessing of conventional vibroseis data recorded in the central sector of the Neuquén Basin. The lines involved linear upsweeps with frequency band of 12-65Hz and time-length of 8 sec. The field records were characterized by time-lengths of 13 sec and a sampling period of 4 msec . The Self-Truncating Extended Correlation algorithm was used to compute cross-correlation between the sweep and the records. The original frequency-band of 12-65 Hz was preserved for the first 5 sec of trace. However, this band was affected by an upper-frequency decreasing from 5 sec on, at a predicted linear-rate of 6.625 Hz/sec. Hence, correlated deep-records with a time-length of 11 sec and a final trace-band of 12-25 Hz were calculated. Depth-migration was implemented on the extended traces. Consequently, progressive models of crust velocity were iteratively matched with the corresponding migrated log. The iterative process was considered concluded when it was observed acceptable coincidence between the model and the depth-migrated horizons. The basin stratigraphy in the area consists of a continental sequence of initial sinrift (Precuyano) deposited on half-grabens, followed by strong cycles of marine and continental postrift units (Cuyo, Lotena, and Mendoza groups). The initial structuration is considered of Superior Triassic-Liasic age. While, the postrif phase would have extended until Early Cretaceous. The analysis in the area of Las Cárceles reveals the following:(1)The lower-crust top is placed at about 23-24 km;(2)An oblique reflector horizon between 16 and 18 km depth, is considered as a master shear that controlled the extensional system;(3)A submaster fault, between 8.5 and 12 km depth, is partially recognized in seismic sections;(4)The top of the rift basemen is characterized by irregular depths that, from W to E, fluctuates from 9 to 5 km;(5)Evident features of tectonic inversion, including sinrift as well as part of postrift sequences (i.e. Cuyo and maybe Lotena groups) are observed to the W of Los Chihuidos dorsal (this inversion episode was possibly initiated in the Callovian). In Bajada de Añelo, the study demonstrated that:(1)The top of the pre-liasic basemen is located at about 5 km depth, showing a smooth topographic relief;(2)In the central-western sector are detected features of bipolar inversion;(3)The middle level of the Cuyo group is characterized by oblique reflections related with a strong sedimentary progradation toward the west.

S61C-1147 0830h POSTER

Results from Shallow Seismic Refraction Surveys across Range-Bounding Faults in the Southern Rio Grande Rift

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