Marie Curie Research Training Network

SPICE

Seismic wave Propagation and Imaging in Complex media: a European network

Coordinator: Heiner Igel

SPICE R&T Workshop II

ABSTRACT BOOK

September 4-10, 2005, Smolenice Castle, Slovakia

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Smolenice Castle, Slovakia

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ABSTRACTS

SURFACE WAVE SYNTHETIC DATA IN A 3D MODEL OF THE MID-MEDITERRANEAN REGION

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The Euro-Mediterranean area is a region with complex tectonic history where we can expect strong lateral heterogeneities. Such heterogeneities may cause multipathing and mode coupling, two phenomena which are not taken into account in classical tomographic studies. In order to evaluate the complexity we can expect in the waveforms for a realistic model of the region and in the view of preparing new tomographic methods, we generate synthetic surface wave data in the model of a recent study done by Marone et al. 2004. They used higher modes of surface waves as well as the fundamental mode and obtained a model of the upper-mantle under the Mediterranean region which shows variations in S-wave velocity of up to 20 % at a scale of about 500 km. They explained about 50 % of their data. Considering that they have selected data which are not too complex, we think that it is important to try to explain a larger part of the data at short periods in order to improve the lateral resolution of the model. We use a multiple scattering method for surface waves in 3D structures which takes into account mode coupling and multipathing. We focus on about 1500 km long wave paths from Greece, with high seismicity, to Switzerland and Southern Germany, with high density of seismological stations. These paths follow a very low velocity region under the Adriatic Sea, favoring multipathing and large amplitudes. The degree of complexity of the surface wave propagation in this region that we can expect from the roughness of the present tomographic models will be presented.

EARTHQUAKE DYNAMICS: BEYOND FRICTION

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New constraints on the scaling of source quantities, such as modern estimates of radiated energy and fracture energy, as well as an increasing interaction between seismology, fault zone geology and experimental rock mechanics, are driving the advent of novel paradigms of earthquake source dynamics. After reviewing the rich body of evidence for the scaling of fracture energy, I will motivate and present recent results of models of dynamic rupture that include off-fault dissipation. The physical models studied are simplified (fault zone visco-plasticity) to allow direct estimates of the scaling of energy dissipation and their relation to rupture parameters. These highly non-linear models are numerically solved with the spectral element method.

SISMOVI: A MULTIPLATFORM PRE-/POST-PROCESSING TOOL FOR SEISMIC WAVE MODELING ANALYSIS

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Seismic wave modeling analysis in complex geological structures is a task that requires three main phases: a pre-processing phase, a numerical simulation phase and a post-processing phase. In order to be effective, numerical simulation studies need the use of efficient computational algorithms and the use of pre- and post-processing tools based on computer aided modules. The ultimate goal of these tools is to facilitate the preparation of the geological models and to speed up the related definition process of the input data needed by the wave simulation codes. Moreover, they must help in the final analysis of the results obtained from the numerical experiments. In this work we present the last developments of SismoVi code. It is a pre-/post-processing tool based on the Python scripting language and on the wxPython graphics library for the GUI building. It has been developed specifically for the wave modeling needs. Being based on open source libraries it is portable on almost all computer platforms and its functionalities can be easily extended thanks to the various Python libraries that are available in different fields like graphics, data base management, scientific computations, image processing, and many others. Moreover, the full power of the language is available to the end user who can easily interact with the data on the fly, making transformations of them and viewing the results. To this end, the available array syntax in Python is very similar to that one available in FORTRAN 90 or Matlab and it is very efficient.

THE SPICE WWW STRUCTURE AND CODE LIBRARY

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One of the key deliverables of the SPICE project is a stable, manageable, user-friendly www structure that survives the project life time and can continue to be interactively used and modified. This hold particularly for the library of codes on seismic wave propagation that hopefully will be accepted and used widely by the scientific community. The growing request of adding content and also the need of dynamic pages (webforms, mailinglist etc.) forced us to switch from simple static webpages to a content management system (CMS). After evaluating different CMS's, we decided to use Zope and the add-in Plone. Zope (www.zope.org) is an object-orientated open-source web application framework, which is written primary in the Python programming language. One of the products to use with the Zope framework is the Plone CMS (www.plone.org). Plone features a powerful through-the-web development system, allowing you to develop and maintain your web site from anywhere in the world by just using any modern browser. Further features are a well grained user and right management, a complex workflow system and the possibility to extend the system for your needs very quickly. In the last month we adapted the layout from the old static pages and added new dynamic functionality, like publication management and the code library. The development is still in progress and will align with the growing interests and needs for the SPICE online presentation. It is important to note that the quality of the pages will heavily depend on the active use of all SPICE involved personnel, junior and senior researchers, task group leaders and administrators. Therefore we strongly urge you to USE, COMMENT and IMPROVE it!

SEISMICITY AND 3D VELOCITY STRUCTURE OF THE CAMPI FLEGREI (ITALY)

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The Campi Flegrei caldera is a complex volcanic structure located in the vicinity of Naples, in a highly populated area. It is occasionally the site of bradiseismic crises which are characterized by a large ground uplift accompanied by a high seismicity. The last unrest episode took place in 1982-1984 with a maximum vertical uplift of 1.8 m and about 15000 earthquakes. We examined about 800 earthquakes recorded by a temporary digital network with the aim to determine the spatial characteristics of the seismogenic structures and gain information about the caldera structure and volcano feeding system. The classification of earthquakes into multiplets indicates a surprising low amount of similar events, especially according to the clustered aspect of the seismicity. Using precise relocation technique, we were only able to identify 3 elongated patterns that may be interpreted as small faults. Most of the seismicity appears to be diffuse and generated along very small fractures. As an alternate and complementary approach to obtain high quality locations we proceed to a 3D tomographic joint inversion of both passive and active arrival times. We use a tomographic technique which relies on an improved theoretical travel time calculation using the finite difference computation scheme of Podvin and Lecomte (1991). Our first data set is composed of the earthquakes recorded in 1984 and the second of shots produced during the SERAPIS experiment in 2001. These 2 sets are complementary: the first one provides both Vp and Vs velocity models, as well as earthquake locations but has a low resolution, while the second has a high resolution but only provides P velocity and samples only shallow layers. By coupling the 2 sets we expect to obtain a high resolution velocity model for both P and S waves as well as an improved location for earthquakes. Finally, the improved earthquake locations will be used to detect converted phases. The modeling of those phases will allow identifying discontinuities and will provide a detailed knowledge of the structure of the Campi Flegrei.

UNDERSTANDING SUBSURFACE MASS MOVEMENT AT VOLCANOES: THE EU FP6 VOLUME PROJECT

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Volcanic eruptions are preceded by mass migration through a subsurface fracture network. A primary goal in *monitoring* active volcanoes is to capture, from the surface, measurements of sub surface mass movement. Such movements of multiphase fluids are generally detected at the surface in terms of changes in geophysical (ground deformation, seismicity) and geochemical observables. Such variations are therefore viewed with considerable interest in terms of early recognition of precursors to an eruption.

However, changes in the seismicity, ground deformation and/or geochemical tracers are not always related to the dynamics of magma bodies alone, and therefore do not necessarily indicate an eruption onset. Modern volcanology, even with abundant monitoring data, still does not identify diagnostic, unambiguous precursors to an eruption.

The rationale behind this **VOLUME** project is to increase our understanding of how subsurface mass movement manifests itself at the surface, in turn revealing the significance of such movements as precursors to impending eruptions.

An overview of **VOLUME** will be given in this presentation together with initial attempts to numerically model the coupled effects of liquid & gas migration and resulting seismic signatures.

3D NUMERICAL MODELING OF EARTHQUAKE MOTION IN COLFIORITO BASIN DURING THE UMBRIA-MARCHE, ITALY, SEISMIC SEQUENCE: I. DATA ANALYSIS

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On September 26, 1997, two moderate damaging earthquakes occurred in Umbria-Marche, northern Apennines, Italy. The epicenters were close (R<5 km) to a small (3-km wide) shallow sedimentary basin near Colfiorito. The two earthquakes were followed by the seismic sequence that lasted until April 8, 1998. Many earthquakes were recorded by the temporary four-station small-aperture array installed in the basin after the main events. The recorded motion makes a very good database for investigations of the effects the basin sediments may have on the earthquake motion. In order to estimate the properties of the motion, time-frequency, array and particle motion analyses were applied to the recorded motion. These analyses indicate the occurrence of a significant resonance of the soft sedimentary fill consisting of lateral debris fans mixed with lacustrine sandy-clayey deposits. While the resonance dominates the first part of the motion, laterally propagating waves generated at the basin's edge arrive at later times. The back azimuth of the diffracted waves is systematically different from that of the epicenter. Results of the detailed analysis are consistent with results published previously by Italian researchers.

ON THE RELEVANCE OF BORN THEORY IN CURRENT GLOBAL SEISMIC TOMOGRAPHY

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Tomographic inverse problems formulated in terms of ray theory (JWKB method) are implicitly grounded upon the high-frequency approximation. Regardless of the quality and coverage of seismic observations, this approximation limits the resolution of tomographic images; heterogeneities of extent smaller than, say, one wavelength cannot be properly mapped. Over the last two decades some authors have tried to overcome this limit via Born theory, i.e. accounting for single-scattering: the most relevant examples are perhaps the work of Snieder, Nolet and co-workers at Utrecht in the mid-1980s; the NACT method developed at Berkeley in the early 1990s; the recent series of "banana-doughnut" studies at Princeton. While the Born approximation is in principle more accurate than simple JWKB, it is not clear whether it leads to an effective improvement of tomographic images: comparisons between JWKB- and Born-theory-based maps are complicated by the inherent differences in the associated inverse problems, and their regularization; Born-theory methods are all implemented in the far-field limit, which might deteriorate resolution; last, it remains to be evaluated whether the current coverage and quality of global seismic databases is sufficient to achieve the progress that the application of Born theory might allow. I investigate these issues in the context of surface wave phase velocity tomography, at intermediate to long periods (away from the high-frequency limit); I apply the L-curve method and Akaike information criterion to evaluate quantitatively the improvement in resolution (if any) that Born theory provides in global tomography.

ASYMPTOTIC RAY THEORY IN SEISMOLOGY

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The contribution presents a brief outlook of the seismic ray method, based on the asymptotic high-frequency zero-order solution of the elastodynamic equation. The ray method is applicable to high-frequency body waves in complex, laterally varying, 2D/3D isotropic or anisotropic models. The ray synthetic wavefield is only approximate. Nevertheless, its accuracy is sufficient in solving many wave propagation problems of practical interest, which can hardly be treated by other techniques.

In the ray method, the high-frequency wavefield is expanded into elementary waves, which can be handled independently. Ray solution for each elementary wave has very simple form of the leading term of the so-called ray series. Equations for all the parameters of such a solution are strictly derived inserting the solution into
the equation of motion (elastodynamic equation). Namely they are: the eikonal equation and its solution by means of its characteristics (rays), which yields the travel time and amplitude polarization vectors, and the transport equation, yielding the scalar amplitude factors of individual waves. Most equations are derived both for isotropic as well as for anisotropic media.

Special attention is devoted to the calculation of rays, travel times and ray amplitudes across a structural interface. Equations for the ray solution in complex layered structures are presented and initial amplitudes (radiation functions) due to a point source are explained. Procedure to obtain ray synthetic seismograms is outlined.

The applicability conditions of the ray method are briefly discussed. The ray method is qualitatively compared to the finite-difference method, a representative technique which is able to yield a complete wavefield in 2D/3D structures.

IMPROVING MOMENT TENSOR INVERSION BY COMBINING FITS OF AMPLITUDE SPECTRA, FIRST MOTION POLARITIES AND DC COMPONENT

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Moment tensor inversion is often complicated, especially in the case of shallow events (h<35km), due to the lack of knowledge of the regional crustal structure and the usage of simplified Earth models. This effect, combined with the approximation in source depth estimation, may result critical for the inversion. Theoretical tests, as well as application to shallow earthquakes, show how in this case results of moment tensor inversion may be ambiguous and solutions often present anomalous characteristics, such as high percentage of CLVD or bad fit of observed polarities. In this study amplitude spectra moment tensor solution is improved by fitting at the same time amplitude spectra, observed first motion polarities and small CLVD components of the focal mechanism. The combined fit allows the resolution of ambiguities related with multiplicity of solutions at each depth and also solves the intrinsic ambiguity between pressure and tension axis which characterize the inversion in frequency domain. The method is applied to the case of shallow earthquakes in Spain using regional distances broadband data.

HIGH RESOLUTION SEISMIC IMAGING OF CRUSTAL REFLECTORS BY THE NON LINEAR INVERSION OF REFLECTION ARRIVAL TIME/ WAVEFORMS

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This study deals with the processing and modeling of a high quality seismic data-set acquired in 1999 in the Southern Apennine (Val d'Agri region), by Enterprise Oil Italiana and E.N.I., using a global offset acquisition 2D geometry.

A reliable velocity model is obtained by the tomographic inversion of first arrivals using the method proposed by Benz (1984) which solves the inversion problem with a linearized, perturbative approach.

To identify reflected/converted waves a velocity analysis, based on normalized crosscorrelation sum, is performed on data organized in CDP panels. This analysis allows computing stacking velocity panels then used to perform stack sections. These sections are used for the migration of reflectors using a new method for depth migrating reflected/converted phases. Using as background model the model retrieved by the tomographic inversion, this new method is based on the automatic, iterative phase searching and inversion using the maximum semblance criterion. The reflector is represented by a cubic spline curve and parameterized by a number of regularly spaced, control points. The best-fit interface parameters (depth coordinates of control points) are estimated by a global optimization technique (genetic algorithm) and by a multiscale approach aimed at maximizing the reflected/converted waveform lateral coherence.

ASSESSING FINITE DIFFERENCE METHODS FOR RUPTURE SIMULATIONS

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The spontaneously propagating shear crack on a frictional interface is a useful idealization of a natural earthquake. The corresponding nonlinear boundary value problems require computationally intensive numerical methods for their solution. Construction of effective numerical methods requires attention to problems of regularization, scale contraction, and numerical dispersion. Artificial viscosity regularizes certain ill-posed rupture dynamics problems. It also limits oscillations induced by numerical dispersion in low-order FD schemes, and can be a significant factor in achieving good performance with those methods. In addition, the addition of viscosity to a numerical scheme limits scale contraction, facilitating simulation of events which approach terminal rupture speed or undergo a transition to intersonic speed.

Assessing the convergence and accuracy of numerical methods is a further challenge, as we lack appropriate analytical solutions for comparison. One form of assessment is through comparisons of solutions obtained by different numerical methods. We have obtained nearly identical 3D rupture simulations by two very different numerical methods: a low-order finite difference (FD) method employing the split-node boundary formulation, and a boundary integral method employing spectrally formulated stress transfer functionals. Furthermore, the methods follow indistinguishable convergence rates when grid size is reduced, with the global error in rupture arrival times behaving as approximately grid-interval cubed in both cases. However, FD solution quality depends sensitively on the formulation of the fault discontinuities, and some alternative FD formulations show much poorer convergence than does the split-node FD formulation.

A complementary form of assessment is through scale-model earthquake experiments. FD simulations successfully capture the essential features of foam rubber earthquake experiments, including effects induced by stratified frictional strength properties. In addition, earlier FD simulations of rupture on a bimaterial interface predicted the essential features of rupture recently seen in spontaneously nucleated ruptures at a Homalite-polycarbonate interface in the laboratory experiments reported by Xia et al (2005). These features include asymmetric bilateral rupture and occurrence of intersonic velocity in one direction.

INCORPORATION OF REALISTIC ANELASTICITY IN ADER DG SCHEMES FOR WAVE PROPAGATION

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In the recent months ADER-DG (ADER - Discontinuous Galerkin) schemes have been tested as valid and efficient numerical methods for the simulation of elastic wave propagation. The accuracy achieved has been proved to be fully scalable and the use of unstructured meshes in its formulation makes it very well suited to handle complex geometries. However for the realistic simulation of seismic wave propagation turns out to be required the implementation of a realistic modelization of attenuating effects caused by the anelastic behavior of the media.

We present some approaches to this goal, as well as comparisons with other established methods to prove the suitability of ADER-DG schemes to this kind of attenuating effects.

MODELISATION OF THE SITE EFFECTS OF THE SANTIAGO BASIN: APPLICATION TO SEISMIC RISK ASSESSMENT

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Computer modeling and forecasting of strong motion in basins is a challenging and complex task. This complexity arises from their 3D geometry and the high heterogeneity of the structure in terms of wave-speed and density. Multiple spatial and temporal scales characterize the basin response. Many studies have shown that site effects caused by topography or local geological features, such as poorly consolidated sediments, can result in very significant amplification of the wave field. Such effects are intrinsically 3D and must be taken into account for a better seismic risk assessment. These complex phenomena illustrate the need for detailed basin models and accurate and flexible numerical techniques that can include in the same model different resolutions in time and space, and complex rheological behaviors.

To simulate ground motion in basins, we use the Spectral Element Method based upon the elastic-wave equation. This technique is highly accurate, in particular for interface and surface waves which play an important role in ground motion. Plane waves are widely used to characterize the basin response and the interaction between the surface waves and the sediments topography, responsible for ground motion amplification peaks. Classical methods impose an incident plane wave as an initial condition and let it propagate in the basin. In these cases, some diffraction phenomena can appear at the boundary where the wave can't be well defined. We present here a new way to implement plane waves. This method introduces a plane wave directly through its reaction at the interface between the bedrocks and the sediments, avoiding propagation problems. This also leads to a gain of calculation time which becomes an important parameter for realistic 2D and 3D simulations.

We illustrate the first applications within the framework of collaboration with the University of Santiago, Chile, for the 2D response of the Santiago basin. Preliminary results are presented and multi resolution extensions will be discussed.

KINEMATIC AND DYNAMIC SIMULATION OF THE 2000 TOTTORI EARTHQUAKE

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The goal of this study is to investigate the dynamic rupture propagation of the 2000 Tottori (Japan) earthquake. Numerous kinematic studies of this earthquake have been made. They come out with various slip distributions and rupture parameters. Nonetheless most of these results are not in agreement with the observed data and the friction law. It is therefore necessary to validate these models through a dynamic study. The dynamic rupture propagation is studied for a simple fault model. Rupture propagation is controlled by the properties of the friction law on the fault. In this study a simple slip-weakening friction law is used. We have observed that the rupture is controlled by a single nondimensional parameter K. For low values of K rupture does not occur. When K is larger than a critical value Kc, the rupture grows beyond the asperity. When K is considerably larger than Kc, the rupture front on the in-plane direction jumps to the speeds that are higher than the shear wave speed. An increase in Dc or Tu increases the rupture resistance. Conversely, an increase in the initial stress, favors the rupture. We apply these results to the Tottori earthquake. To estimate the initial stress field on the fault before the rupture starts, we use the slip distribution proposed by Holden et al. 2005. We are testing which friction parameters would allow a propagation of the rupture that would be similar to that of the kinematics. Finally synthetic seismograms computed for our final slip distribution model will be compared to the real seismograms in order to validate the results.

SEISMIC SURFACE WAVES IN THE LATERALLY HETEROGENEOUS EARTH: A FULL RAY THEORY APPROACH

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We have implemented the full ray theory method for surface wave propagation, which includes (1) wave excitation based upon the local Earth structure at the source; (2) seismic displacement dependent upon local Earth structure at the receiver; (3) full ray tracing, as a function of frequency, to determine the phase for each path; (4) corrections for off-great circle azimuths at the source and the receiver; (5) focusing/defocusing effects predicted by ray theory. Full ray theory allows the different parts of the wavefield - source, path and receiver - to be analysed independently. We present a theoretical and numerical study of the source, propagation and receiver terms as a function of the wave period, source mechanism and depth, for different Earth models. We find that taking into account the local structure at the source can significantly affect the surface wave source radiation pattern and the source spectra. Moreover, propagation in current tomography images predicts multipathing to be very common, even for shorter path lengths and for longer periods than usually observed. For the models with significant short scale structure, we find several examples of minor-arc multipathing for waves with period of T=200 s. This phenomenon is predicted to occur more frequently for Love waves than for Rayleigh waves. Lateral heterogeneity at the receiver only affects very slightly vertical component Rayleigh waves. Horizontal component surface waves are more affected, but, still, this effect is not larger than 15% for T=150 s surface waves.

SPECTRAL ELEMENT SIMULATIONS OF LABORATORY FRACTURE EXPERIMENTS

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The high-frequency generation during earthquake rupture dynamics is a major and widely debated problematic in seismology. Arrest phases and rupture velocity propagation is believed to be strongly influenced by the interaction between the dynamics and the fault geometry (kinks, jogs and forks). To the framework, recent studies from the laboratory experiments add new contributions to the understanding.

Numerical simulations of such a process require high resolution of the friction and the contact on the fault plane combined with a geometrical flexibility, which allows following the slope changes of the fault plane. Here, we analyze the nucleation and the propagation of the rupture along the kinks by using the spectral element technique and we show the influence of the slope on the rupture propagation.

INFERING THE RESOLUTION OF KINEMATIC INVERSION TECHNIQUES: A BLIND TEST

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Kinematic inversions of near-fault data allow for the retrieval of important global features of the rupture, such as the slip distribution and the rupture velocity. Today they are also a necessary step to move from observations to dynamic modeling of the fracture. Although several techniques have been developed since the last two decades, resolution of kinematic models is not yet clearly addressed. In fact, depending on the inversion strategy and on the assumptions done before the inversion (definition of the problem, fitness function, minimum search techniques, etc.), the final maps of slip and rupture velocity are generally different, sometimes incompatible among each other. With the aim of understanding advantages and limits of different techniques and inferring general properties of the kinematic inversion, we discuss a set-up of a blind test. It is a test in which the true solution exists but it is not known a-priori by the people performing the inversion. The benchmark is also a contribution of the Local Scale Group to the SPICE project.

GEMINI - A COMPUTER CODE FOR THE COMPUTATION OF GREEN FUNCTIONS FOR SPHERICALLY SYMMETRIC EARTH MODELS

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The computation of synthetic seismograms for a layered earth is one of the basic tools for inferring the 3D-structure of the earth. This is true from a theoretical point of view because most perturbation methods which attempt to compute synthetic seismograms for a 3D-heterogeneous earth use a spherically symmetric earth model as a reference. It is, however, also true from the observational point of view, since travel times of long-period body waves and phases of surface waves are often measured by cross-correlating the observed seismograms with synthetic ones.

Though the basic theory for this problem is well known since a long time, a numerical realization is still a non-trivial task and may require some computation time even on modern computers. An introduction will be given into the theoretical background of GEMINI and the way the calculation is numerically implemented. Some example calculations and comparisons with other methods are shown. Attendees of the workshop will have the opportunity to get the code and also run it. Appropriate input files are made available.

WAVEFORM SENSITIVITY KERNELS FOR GENERAL ANISOTROPIC PERTURBATIONS OF A SPHERICALLY SYMMETRIC EARTH MODEL

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Waveform sensitivity kernels allow a quantification of the influence of a structural anomaly on the synthetic seismogram for a given source, receiver and instant of time. They constitute the partial derivatives of the synthetic seismogram with respect to structure and are therefore essential for waveform inversion. Once evaluated, multiplication of the kernels with any structural perturbation and subsequent integration yield the signal scattered from the anomaly in the Born approximation. Since large amplitudes of the kernels correlate with the geometrical paths of the signals, they can also be used to characterize the nature of phases in a seismogram. By an appropriate integration over time, sensitivity kernels for travel time and amplitude can be derived from the waveform kernels.

We will present a sequence of waveform sensitivity kernels computed at time instants within the S- and SS-phases and the surface wavetrain for various anisotropic perturbations of a spherically symmetric earth model. Our purpose is to show that heterogeneous structure off the geometrical ray path significantly influences the waveforms. Moreover, we wish to demonstrate that sensitivity kernels can actually be used to map pseudo-Fresnel zones in three dimensions. Differences between kernels for anisotropic and isotropic perturbations and their implications for a waveform inversion will be discussed.

NUMERICAL BEHAVIOR OF THE FD-FE TRANSITION ZONE IN THE 3D HYBRID MODELING OF EARTHQUAKE MOTION

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We have developed a 3D hybrid modeling technique for relatively efficient simulation of both the dynamic rupture propagation on a fault, and seismic wave radiation and propagation in a surrounding heterogeneous viscoelastic medium in a single numerical calculation. The technique is based on the combination of the finite-element (FE) and finite-difference (FD) methods. In an arbitrarily shaped part of the whole computational region, the 2nd-order displacement FE method is used to simulate rupture propagation on a possibly non-planar fault (using the TSN method). The FE region may include the free-surface topography. The rest of the computational region, i.e., its major part, is solved by the 4th-order velocity-stress staggered-grid FD scheme. The use of spatial grid spacing h in the FE region and spatial grid spacing $2h$ in the FD region implies a. approximately the same frequency resolution in both regions, b. the computational efficiency of the technique. The schemes share the same time step. The FE and FD schemes communicate at each time level in the transition zone in which both spatial grids overlap.

It is obvious that the numerical behavior of the transition zone is a key feature of the hybrid technique. Therefore, we performed extensive numerical tests of the zone behavior. The tests address the questions of spatial definition of the transition zone, stability, spatial sampling ratio, time step, numerical integration, and material heterogeneity.

OPTIMALLY ACCURATE FINITE DIFFERENCE OPERATORS

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(Although the presentation at this conference is single-authored, the work reported here includes the contributions of Nozomu Takeuchi, Hiromitsu Mizutani, and Nobuyasu Hirabayashi. In this talk I hope to provide enough information so that participants will be able to be able to write their own optimally accurate finite difference (FD) codes.)

Finite difference methods for modeling elastic wave propagation have been used for many years. Since the earliest work, the error of the various numerical operators (e.g., fourth order in space or second order in time) has been routinely analyzed, but it is only relatively recently that a general framework for making formal error estimates for the synthetic seismograms has been available (Geller & Takeuchi, GJI, 1995, hereafter abbreviated GT95). GT95 developed a general criterion for optimally accurate numerical operators. This criterion essentially amounts to systematically introducing controlled errors into the spatial and temporal operators so that they cancel each other, rather than making each of the individual operators highly accurate.

Optimally accurate finite difference (FD) schemes have been developed for schemes which are second order in space and time, O(2,2); for schemes which are second order in time and fourth order in space, O(2,4); and for schemes which use the Spectral Element Method (SEM) in space and various temporal schemes). A comparison of the cost-performance of optimally accurate and conventional (non-optimally accurate) for several 1-D test models shows that optimally accurate schemes are clearly superior to conventional schemes. The considerations involved in choosing between various types of optimally accurate schemes are more subtle, but based on memory access “footprints” and ease of programming, optimally accurate O(2,2) schemes are probably preferable for most applications.

In “real” 2-D or 3-D problems, lithological discontinuities will generally not coincide with the regularly spaced grid used by optimally accurate FD schemes. To handle such cases we have derived special operators for elements containing inter-node lithological discontinuities. We also have formulated source representations for sources located between node points that allow synthetics to be computed with the same accuracy as for sources at nodes.

WAVEFORM INVERSION IN GLOBAL SEISMOLOGY

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Most waveform inversion studies in global seismology have parameterized the lateral dependence of the model using spherical harmonics. This is convenient for surface wave studies, where we have relatively uniform coverage of the Earth's surface. On the other hand, many studies of particular regions (e.g. D'', the layer immediately above the core-mantle boundary) use particular datasets of stations and sources (deep focus earthquakes), and coverage is limited to particular regions of the target depth. It is desirable to be able to invert seismic waveform data for such localized structure.

A theory for waveform inversion for localized structure was presented in the 1980s by Tarantola, who used finite difference synthetics. Geller & Hara (GJI, 1993) showed that by rearranging the order of sums and integrals in the usual formulation of inversion in global seismology, that it was basically equivalent to Tarantola's approach. To compute the kernels for the inverse problem we compute one set of forward synthetics for each source, and one set of back-propagated synthetics for each receiver. The forward and back-propagated synthetics are cross-correlated at each target pixel of the inversion.

We recently have begun a trial study of waveform inversion for anisotropic structure of D'' beneath Central America. We began this work by developing a forward modeling program for a spherically symmetric model using optimally accurate numerical operators. This program can also be used for shallow sources, and some of the computational issues are discussed in this talk. A beta version of this program is available for download at
http://www-solid.eps.s.u-tokyo.ac.jp/~dsm/

Some preliminary inversion results will be presented, and some of the issues arising will be discussed. A variety of issues remain, and computational requirements are substantial, but as computational resources become increasingly less expensive and as the dataset of seismic waveforms continues to increase in quality and quantity waveform inversion seems likely to become important as a tool of studying Earth structure on both global and regional scales.

MODELING REGIONAL SEISMIC WAVE PROPAGATION ACROSS A PASSIVE MARGIN: A COUPLED LOCAL-MODE APPROACH

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It is important to evaluate the effect of various geodynamical settings, upon wave propagation phenomena. We try here to evaluate the influence of a continental margin on the propagation of surface waves. Drastic changes of structure and of elastic properties through a passive margin modify very strongly the depth dependence of the modes eigenfunctions and may prevent using the asymptotic ray theory in intermediate and long-period synthetic seismograms calculations. Instead of propagating independently of each other, modes couple at strong and rapid lateral variations. We model their propagation by using an extension of the coupled local mode approach (e.g., Maupin 1988). We consider seismic propagation across a 2-dimensional waveguide; the local wavefield is expanded on the basis of local surface-wave modes, supplemented, for completeness, by the so-called improper eigenfunctions. The latter are the modes associated with body waves radiated in the half-space underlying the waveguide. All these modes (improper or not) strongly depend on the local elastic structure, and the lateral evolution of the waveguide structure controls the evolution of the amplitude of each of the modes. Broadband seismograms are then synthetised; specific attention is paid to the mode coupling for frequencies at which one of the normal modes of the structure goes to cut-off.

NUMERICAL SIMULATION OF SURFACE WAVES FORCED BY SLOW PRESSURE TRANSIENTS ON THE SEAFLOOR

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Ambient free infragravity waves in the oceans have periods of between 30 and 300 seconds and wavelength between 2 and 40 km.

They are excited by nonlinear interaction of high swell at coastal regions, mainly in the South Pacific and South Atlantic, and propagate long distances with amplitudes of a few mm only. Their propagation velocities depend on the depth of the ocean, and they are typically in the range between 30 and 140 m/s.

The dispersion relation of infragravity waves is well known so that measuring a pressure transient at a single station is sufficient to estimate the corresponding wavenumber.

Using this knowledge, the seafloor compliance method has been developed to study the response of the oceanic crust to slowly propagating infragravity waves. The seafloor compliance is sensible to variations in the shear modulus and thus the shear wave velocity.

During my diploma thesis a numerical method has been developed to simulate the seafloor compliance in response to infragravity waves. A Pseudo-Spectral method has been used.

Although this problem may be handled as a quasi-static problem for many cases, the introduction of soft uppermost seafloor layers with low shear wave velocity may justify full dynamic simulations as in our case.

The specific problems of the simulations are to stabilize the finite model when continuously propagating transients are forcing the system over long calculation times.

NON LINEAR KINEMATIC INVERSION OF THE 2000 TOTTORI EARTHQUAKE

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A nonlinear kinematic inversion method is applied to the Mw=6.8, October 2000, Tottori (Japan) earthquake. The earthquake region was well instrumented and provided a good strong motion data set that has been intensively studied. The algorithm used for our inversion is the Neighbourhood Algorithm. The method is applied to a set of 33 strong motion recordings located within 40 km of the epicenter. The fit between observed data and synthetics is mesured with an L^2 norm.

The first purpose of this study is to validate the inversion method and compare our results with those from linearised kinematic inversions by Yagi (2001), Sekiguchi (2002) and Semanne et al. (2005). Secondly, in order to satisfy the dynamic aspects of the rupture, the method will be applied to the same set of data with different initial parameters. The major changes will involve varying the hypocentral location that was badly constrained for that event, fixing the absolute timing of the data, and applying rigorous filters. Finally the kinematic results will be tested through a dynamic study of the computed final slip distribution.

AN EFFICIENT FDTD SOLUTION FOR SEISMIC PLANE-WAVE RESPONSES OF VERTICALLY HETEROGENEOUS VISCOELASTIC MEDIA

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Real Earth media disperse and attenuate propagating seismic waves. This anelastic behavior can be described well by a viscoelastic model. In this paper the Standard Linear model has been used to derive the viscoelastic wave equation for vertically inhomogeneous structure. For this purpose, viscoelastic coefficients are derived and a memory variable is introduced to incorporate the time dependent behavior of anelasticity. Plane-wave responses of vertically heterogeneous structure models (1-D media) are often computed in seismology. In this study we develop an efficient procedure to calculate the plane wave response of arbitrary 1-D viscoelastic media using the finite-difference method in time domain (FDTD). We first derive a viscoelastic wave equation for a plane-wave incidence problem for vertically heterogeneous media by applying the Snell's law to the 3-D wave equation. Then we discretized the velocity-stress formulation of the derived equation using a staggered-grid finite-difference scheme of fourth-order accurate in space and second order accurate in time. Low memory storage request, very high speed of calculation and incorporation of realistic attenuation are main advantages of this approach. We developed and revised a proper FORTRAN code for the calculation based on the code by Tanaka & Takenaka (2005) for the elastic case.

AN ARBITRARY HIGH ORDER DISCONTINUOUS GALERKIN METHOD FOR ELASTIC WAVES PROPAGATION ON UNSTRUCTURED MESHES

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We present a new numerical approach to solve the elastic wave equation in heterogeneous media with arbitrary high order accuracy in space and time on unstructured meshes. We combine a Discontinuous Galerkin Method with the ideas of the ADER time integration approach using arbitrary high order derivatives. In contrast to classical finite element methods we allow for discontinuities of the piecewise polynomial approximation of the solution at element interfaces. This way, we can use the well-established theory of fluxes across element interfaces based on the solution of Riemann problems as developed in the finite volume framework. In particular, we replace time derivatives in the Taylor expansion of the time integration procedure by space derivatives to obtain a numerical scheme of the same high order in time and space automatically. The method is specially suited for linear hyperbolic systems such as the heterogeneous elastic wave equations. The convergence analysis demonstrates that very high accuracy is retained even on strongly irregular meshes and by increasing the order of the ADER-Discontinuous Galerkin schemes very coarse meshes can be utilized, which is of particular importance for large 3-dimensional applications.

DETERMINISTIC SCENARIO STUDY FOR IRPINIA 1980 EARTHQUAKE AND POSSIBLE APPLICATION FOR CAMPANIA REGION (SOUTHERN ITALY) EARLY WARNING SYSTEM

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The November 23, 1980 (Ms=6.9) earthquake was a complex normal faulting event occurring along the southern Apenninic chain and characterized by three main rupture episodes.

The present work provides a post-event ground motion scenario of this destructive earthquake which is computed using a complex fault model and complete wave field Green functions in a layered velocity model.

The validation of the source/propagation model is performed through the matching of strong motion parameters (Peak Ground Acceleration, Peak Ground Velocity, displacement waveforms, duration after Trifunac and Brady) between synthetic and observed accelerograms. The shake maps have been calculated over the Campania region using a multiple-rupture source model described by the consecutive activation of three line sources .The parameters of the kinematic fault model (fault length, mechanism, rupture velocity, average final slip) have been assumed according to the Bernard and Zollo (1989)' fault model for the Irpinia earthquake.

The calculated shake maps have been used to simulate the macroseismic intensity field of the event and compare it with observed isoseismal maps.

SEISMIC SIGNATURE OF INFRACRUSTAL MAGMATIC INTRUSIONS IN THE EASTERN BETICS (INTERNAL ZONE), SE IBERIA

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Receiver functions at three broad-band stations located in the most easterly Inner Betics have been analyzed to investigate the structure of its underlying crust and uppermost mantle. These stations are located within a geologically distinctive block bounded by the Palomares/Alhama de Murcia faults, which is characterized by high heat-flow values, widespread strike-slip faulting and Neogene volcanism. Our analysis shows that a low velocity zone pervades the uppermost mantle beneath the stations, and that the overlying crust has a high Vp/Vs ratio and a prominent intracrustal low velocity zone (i) between the Palomares and Alhama de Murcia faults and (ii) east of Murcia, perhaps thermally perturbing the upper crust north and east of Cartagena. Independent studies show that the seismic velocities of the intervening mantle lid are normal beneath the stations, and we suggest that our observations result from rapidly ascending magma diapirs ponding at intracrustal levels within the distinctive block.

TRIANGULAR SPECTRAL ELEMENT METHOD FOR ELASTIC WAVE PROPAGATION USING UNSTRUCTURED GRIDS

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A Triangular Spectral Element Method (TSEM) is presented for elastic wave propagation using an unstructured triangulation of the geological domain. TSEM makes use of a variational formulation of elastodynamics based on unstructured straight-sided triangles that allow enhanced flexibility when dealing with complex geometries and velocity structures. The displacement field is expanded into a high-order polynomial spectral approximation over each triangular element and continuity between the elements is enforced by resorting to a Lagrangian interpolation built on the set of Fekete-points in the triangle. High-order accuracy is achieved leading however to a non diagonal mass matrix formulation. Comparison with classical spectral elements on quadrangles shows similar accuracy and stability even for long simulations. Surface and interface waves are accurately modeled even in the case of complex topography with the TSEM. Numerical results are presented for 2D canonical examples as well as more specific problems such as 2D elastic wave scattering by a cylinder embedded in a homogeneous half-space.

THE SPICE CODE VALIDATION

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The Southern California Earthquake Center (SCEC) organized the 3D Numerical Simulation Code Validation Project for wave propagation in the past years. Recently, SCEC organizes an earthquake source physics code validation/comparison exercise. The goal of both efforts is to validate 3D earthquake simulation methods and foster their application by engineering community. One set of computational models includes simple models of a homogeneous halfspace and layer over halfspace, as well as complex model of the San Fernando Valley / Los Angeles Basin region. The earthquake source validation set will similarly cover models starting from relatively simple ones up to complex real events.

Development of the earthquake motion numerical simulation methods is one of the primary goals of the Seismic Wave Propagation and Imaging in Complex Media: a European Network (SPICE), the EU FP6 project. SPICE provides a reasonable platform for a code validation effort in Europe.

We present a proposal of the SPICE Code Validation. The intention is to create a long-term basis for possible tests/comparisons/validation of numerical methods and codes for the earthquake motion simulation. The basis should serve even after the SPICE project is completed. The wave propagation subsets of models include simplest canonical models designed to test accuracy of the methods with respect to individual factors/features of the models including ABCs, canonical models combining two or more basic structural features, and realistic models. The source dynamics subsets of models are organized in a similar way. The models should reflect the recent development of the numerical methods as well as anticipated progress in a near future. Therefore, the plan also includes models for which reference solutions are not yet available and whose computational parameters will be specified in correspondence with the methodology development. Technically, the code validation process will be facilitated using the web-based interface.

MODELS OF SHEAR WAVE VELOCITIES AT A DRILLING SITE OF THE NINETYEAST RIDGE REGION INFERRED FROM THE INVERSION OF SCHOLTE WAVES

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The construction of shear wave velocity models of marine sediments down to 100m or more beneath the sea floor is important in a number of disciplines. One of the most significant trends in marine geophysics is to use interface waves to estimate shallow shear velocities which play an important role in determining the shallow crustal structure. In marine settings, the waves trapped near the fluid-solid interface are called Scholte waves, and this is the subject of the study.

In 1998, there were experiments on Ninetyeast Ridge (Central Indian Ocean) to study the shallow seismic structure at the drilled site. The data were acquired by both OBS (Ocean bottom seismograph) and OBH (Ocean bottom hydrophone). For OBS profiles, body and Scholte waves were excited by seafloor implosion source.

In this work, the Scholte waves are studied from real data. The dispersive analysis of Scholte wave is presented in order to yield phase velocity as a function of frequency (period). Shear wave velocities are inferred from the inversion of Scholte wave. Comparisons are made between the observed and synthetic seismograms by means of modeling using pseudo-spectral methods.

A WEB-BASED SYSTEM FOR STORAGE, CROSS-PLOT AND DISSEMINATION OF SYNTHETIC TIME HISTORIES

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Synthetic time histories from ground motion simulations or dynamic rupture models generally constitute large data sets which typically require gigabytes of storage capacity. For the same reason, getting access to a researchers simulation output, for example for an earthquake engineer to perform site analysis, or a seismologist to use a dynamic rupture model in ground motion simulations, can be a tedious procedure. To circumvent this problem we have developed a web-based "community model"" (websim3D) for the generation, storage, and dissemination of synthetic time histories. Websim3D allows user-friendly and fast access to view and download such simulation results, where the user selects an earthquake scenario or rupture model that brings up a map of the area where simulation data is available. Now, by clicking on an arbitrary site location, synthetic seismograms or fault slip histories can be displayed at fixed or variable scaling and/or downloaded. Websim3D relies on PHP scripts for the dynamic plots of the time histories. Finally, we use MATLAB's web server toolbox via PHP to contour distributions of rupture times from dynamic rupture models. Several time histories available at one site as well as rupture time distributions may be cross-plotted for comparison, an option useful for code validation and analysis of various earth model response.

MEMBRANE WAVES AND FINITE-FREQUENCY EFFECTS IN SURFACE WAVE TOMOGRAPHY

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Full numerical integration of the equations of motion in 3D is expensive. The membrane wave method presented here simplifies it by restriction to two dimensions.

Membrane waves are used, as an analogue for Love and Rayleigh waves, to study surface wave propagation in the Earth. They allow for detailed investigations of various aspects of elastic wave propagation such as e.g. scattering & caustic effects, wavefront healing, focusing on a global scale. We present here new finite-difference software running on a Beowulf cluster which models finite-frequency effects and compare our results with linear approximation theories.

A MODEL-BASED SIGNAL-PROCESSING APPROACH TO SEISMIC MONITORING: STOCHASTIC EARTH MODELS AND SPECTRAL ELEMENT METHOD SYNTHETICS

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Currently seismic monitoring of earthquakes and explosions relies heavily on detections of individual phases with signal-to-noise ratios above 2:1 and the interpretation of arrival times and amplitudes with approximate and inaccurate Earth models. We are testing the use of model-based (synthetic) seismograms as templates to detect, locate and identify events. This procedure will use information in the entire signal, rather than reduce the seismograms to arrival times and amplitudes of a few selected wave packets. Recent advances in correlation methods illustrate that weak signals can be detected using observed waveforms from previous events (empirical waveform templates). Detection performance can be improved by using a linear combination of empirical waveform templates, which accounts for variability in signals from small source region. We are advocating the use of model-based waveform templates. Rather than use a single "optimal" three-dimensional (3D) Earth model to compute the synthetic seismograms, we are using stochastic Earth models estimated with the Markov Chain Monte Carlo (MCMC)

method. This procedure allows us to determine a suite of 3D models from multiple data sets. Currently we are using models of East Asia based on surface wave group velocities, regional body-wave travel times, receiver functions and gravity. The variability of these models reflects the inconsistency and uneven resolution of the various data sets, errors in the data and errors in our assumptions to interpret the data. Synthetic seismograms are computed with the Spectral Element Method (SEM). The variability in the models produces different theoretical signals and reflects uncertainty in our estimates of the true 3D seismic velocity structure of the region. This variability is exploited when forming correlation detectors based on multiple waveform templates. We are currently computing a set of model-based SEM signals using a suite of MCMC models for a moderate (M ~5) earthquake in our test region. The source parameters are well known and fixed. The synthetics are valid to about 5-10 seconds and illustrate considerable variability in surface wave dispersion and duration, even at these intermediate periods. Correlations between the observed and model-based signals are promising and suggest that detection thresholds can be reduced relative to conventional methods.

SURFACE WAVE TOMOGRAPHY OF THE EUROPEAN REGION

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We present results of a surface wave tomographic study of the wide European and Mediterranean region, based on analysis of fundamental mode Rayleigh and Love waves. We use a two-step inversion, where data derived from dispersion measurements are first inverted to represent geographical variation of group velocity at different periods. Vertical variation of S wave speed is then obtained in each point of our Earth region by nonlinear inversion of local group velocity curves. Group velocity is a rather basic parameter, its measurements do not depend on an a priori model of the crust, and it represents a robust observable that can be taken even for moderate magnitude events, recorded at short distances. The two step inversion scheme allows separating the linear tomographic inversion for geographical variation, from the local nonlinear inversion for shear wave speed. Also, additional measurements can easily be added. Data coverage in this region in fact is not uniform, as it is highly influenced by the uneven distribution of seismic stations. We then combine our own wave dispersion data, measured at regional distance, with the global dataset of phase velocities measured by Ekstrom et al. (1997) to improve data coverage at the borders of our study region, and to warrant consistency with global models. The inclusion of measurements taken at short distances is however essential for achieving higher model resolution locally. The shear wave speed inversion is based on regional a priori models, consisting of PREM plus CRUST2.0, and an iterative nonlinear optimization scheme. We show and compare resulting Vsv and Vsh three-dimensional models with other results from the literature.

SIMULATION OF 3D GLOBAL WAVE PROPAGATION THROUGH GEODYNAMIC MODELS

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This project aims at a better understanding of the forward problem of global 3D wave propagation. We use the spectral element program "SPECFEM3D" (Komatitsch and Tromp, 2002a,b) with varying input models of seismic velocities derived from mantle convection simulations (Bunge et al., 2002). The purpose of this approach is to obtain seismic velocity models independently from seismological studies. In this way one can test the effects of varying parameters of the mantle convection models on the seismic wave field. In order to obtain the seismic velocities from the temperature field of the geodynamical simulations we follow a mineral physics approach. Assuming a certain mantle composition (e.g. pyrolite) we compute the stable phases for each depth (i.e. pressure) and temperature by system Gibbs free energy minimization. Elastic moduli and density are then calculated with different equations of state (EOS), depending on the mineral phase. For this we built a mineral physics database based on calorimetric experiments (enthalphy and entropy of formation, heat capacity) and EOS parameters.

A MULTIDOMAIN CHEBYSHEV METHOD FOR LARGE SCALE WAVE PROPAGATION PROBLEMS

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Modern massive parallel computers and computer clusters enable us to calculate synthetic seismograms with a realistic frequency content by directly solving the governing equations in three dimensions. However, their distributed memory architecture imposes restrictions on the applied algorithms in order to execute efficiently. In particular, the amount of inter-node communication is to be kept low and most operations have to be executed locally on each node. While finite difference methods are comparatively easy to optimize for these machines, they require a considerable amount of points per shortest wavelength in order to provide sufficiently good results. In addition, the implementation of accurate boundary conditions is problematic. Pseudospectral methods, on the contrary, provide accurate solutions with a comparatively small number of grid points but the global character of the discrete operator prevents an efficient implementation on distributed memory machines, because the inter-node communications would dominate the calculation. We investigate properties of an overlapping multidomain Chebyshev method, which combines the advantages of the pseudospectral approach and its spectral accuracy with the simplicity of a finite difference method. The decomposition of the entire computational domain into multiple Chebyshev subdomains enables us to distribute the computation among an arbitrary number of computational nodes. Communication costs reduce to only the data exchange across computational nodes that are required in order to couple the individual subdomains. The overlap of domains provides a robust coupling scheme, which ensures implicitly the continuity of field variables. A high scalability on massive parallel machines can be attained. Non-causal noise, which may be introduced by the global operator, is avoided. Boundary conditions can be easily imposed as in the standard Chebyshev approach. For regional scale studies, the grid is transform using a longitude-latitude mapping where the study region is centered around the equator. The grid for the global scale simulations is obtained by decomposing the globe using the Cubed Sphere approach.

3D FINITE-DIFFERENCE BODY WAVE TRAVEL TIMES AT REGIONAL AND TELESEISMIC DISTANCES

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Body wave travel times at teleseismic distances for 3D mantle models are often computed via ray bending methods, that are efficient and accurate for relatively smooth wave speed heterogeneity, and when however the true first arrival ray can be obtained by continuously perturbing the path traced in the average one dimensional model that is used for computing the first approximation. The influence of the initial 1D model on tomographic models has in fact been widely recognized and discussed in the literature. At the local scale, where wave speed heterogeneity can be strong and discontinuous, finite difference schemes are instead commonly used. We note that even at regional distance (say, up to 25 degree) discrimination of the correct first arrival is in fact complicated by the presence of structures like lithospheric slabs, and by vertical abrupt variations responsible for travel time branch triplications. We adapt the finite difference scheme, due to Podvin and Lecomte (1991), to work in spherical geometry, mapping Earth structure to epicenter-centered meshes via an azimuthal equidistant projection that preserves epicentral distances. Compared to travel time calculation methods for spherically-symmetric Earth models, such as tau-p, the finite difference scheme can be made very accurate by adjusting the grid size as needed for obtaining a model representation accurate enough. We test this scheme for realistic upper mantle structures, synthetic and obtained by actual travel time inversion, and compare paths and travel times calculated with different methods. Significant discrepancies in seismic rays can result. The whole finite difference scheme is well suited for implementation on parallel computers, and its use for massive tomographic inversions, such as required for upper mantle tomography, appears feasible.

ASSESSMENT OF FINITE-FREQUENCY THEORY FOR SURFACE WAVE TOMOGRAPHY

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Surface wave tomography, commonly based on ray theory, to date has reached the resolution limit given by the underlying theory. To more reliably map small scale heterogeneties, many recent works propose to go beyond ray theory by using more accurate finite-frequency propagation theories. However, while any finite-frequency theory is better than ray theory in forward modeling, it is not obvious that a finite-frequency theory might lead to a better imaging through an inversion process.

We present here a comparison between ray theory and finite-frequency surface wave tomography both for synthetic data and for a regional real dataset. Our finite-frequency theory is based on a linearized scattering theory. It only considers near forward, single scattering without mode coupling, which allows the 2D inversion of phase velocity data for local phase velocities. Moving from ray theory to finite-frequency theory also requires to revise the regularization of the inversion and particularly the choice of the a priori lateral smoothing. Indeed, the synthetic tests on noiseless finite-frequency data suggest that finite-frequency theory should be applied without lateral smoothing for better imaging of small scale structures. However, the finite-frequency theory we use does not lead to satisfactory results when applied to real data, likely because of the noise in the data. This result suggests that further improvements of the propagation theory are still required.

We plan to conduct tests on synthetic datasets computed with the much more accurate spectral element method. We thus hope to highlight the effects of shortcomings in our finite-frequency theory, and then to identify which still unmodeled propagation effects must be taken into account in surface wave tomography to make significant progress. Mode coupling, directional dependence of scattering, anisotropy are the first candidates to look at. In this study, we focus on 2D inversion of phase velocity data for local phase velocities. But some of the above improvements are also bound to need changes in the phase velocity data measurement procedure or even require 3D inversion for elastic parameters.

REGIONAL SPECTRAL ELEMENT MOMENT TENSOR FOR THE 2003, MW 5.3 BOLOGNA EARTHQUAKE

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Simulation of seismic wave propagation in realistic 3D earth models may be expected to improve the accuracy of the related inverse problems, compared to using average (1D) earth models. For regional moment tensor inversion, we may extend the usable band of waveforms to shorter periods, generally improving the signal-to-noise ratio for small events, and the depth resolution. We test regional 3D moment tensor inversion for a Mw 5.3 earthquake that occurred on September 14th 2003, 25 km south of the city of Bologna, Italy. We synthesize a preliminary 3D earth model for the complex Alpine-Apennine region from available geophysical studies on lithospheric structure, and use a spectral element code (Specfem3D, Komatitsch and Tromp, 2004) for numerical simulation of wave propagation. Using a rather coarse mesh, we run simulations on forty-nine 32bit x86 processors of the INGV Beowulf-Linux cluster, taking about 3h for solving for 300 second seismograms. Fréchet derivatives of waveforms with respect to the six moment tensor elements are computed at different trial depths, and full moment tensor inversion is done using seismograms from 22 regional stations out to 600 km epicentral distance. We show the precision of waveform matches in a broad period band (100s - 15s), and compare our moment tensor estimate to results given by routine long period moment tensor projects.

STRUCTURE OF THE TRANSITION ZONE FROM SURFACE-WAVES AND BODY-WAVES CONSTRAINTS

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The tomographic inversion of 100779 Rayleigh waveforms including higher modes has recently allowed us to constrain the SV-wave heterogeneities and azimuthal anisotropy in the upper mantle with a lateral resolution of a few hundred kilometers and a vertical resolution of a few tens of kilometers (Debayle et al. 2005). We are currently working to improve the resolution of our model in the transition zone by increasing the number and the accuracy of the higher modes measurements.

In addition to the large-scale constraints provided by surface-waves on the 3D distribution of shear-wave velocity and anisotropy, we aim to constrain the topography of the major seismic discontinuities by including the arrival times of converted/reflected body-wave phases. SS precursor phase analysis can efficiently complete the analysis of P-to-s and S-to-p receiver function dataset to achieve a global coverage of the transition zone seismic discontinuities.

We discuss preliminary results obtained from the analysis of each type of body-wave data set separately. The next step will consist to combine the body and surface waves/higher modes data sets in a simultaneous inversion for both the 3D distribution of SV-wave velocities and the depth of the seismic discontinuities in the transition zone. We discuss our strategy for the simultaneous inversion of all these data sets.

QUASI-SPHERICAL APPROACH FOR SEISMIC WAVE MODELING IN A 2D SLICE OF A LATERALLY HETEROGENEOUS WHOLE EARTH MODEL

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We propose a new method for calculation of seismic wavefield propagating in a global earth model includes lateral heterogeneity. While axisymmetric modeling is the most appropriate method in the field of global seismology, it cannot treat unaxisymmetrical structure with respect to the source axis. Furthermore since it assumes that the structure on the opposite side becomes the same as that on the target side concerning the axis, reflected and scattered waves occurred in the opposite side come into the target side and become numerical noise.

In order to overcome these problems, we here propose an ultra efficient approach for modeling 3D elastic wavefield. We solve the elastodynamic equation for spherical coordinates not in the conventional spherical domain but instead in the "quasi-spherical domain". This approach can simulate seismic wave propagation in a 2D slice of global earth model with an arbitrary lateral heterogeneity in similar computation time and storage as for 2D modeling. In addition it can correctly model 3D geometrical spreading effects and make it possible a direct comparison of real and synthetic waveform data. We show some numerical examples in this presentation.

VOLCANO SEISMOLOGY:
WHAT WE KNOW AND WHAT WE NEED TO KNOW

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Volcano seismology is the most prominent tool in early warning systems at active volcanoes. Recently, new techniques have been tested at different volcanoes all over the world (e.g., array techniques, active seismic monitoring, speech recognition). The key parameters for evaluating the state of unrest are the daily number of different event types, their location within the volcanoes edifice, their source mechanisms possibly related to different activity states and the evolution in time of these parameters.

In this presentation a brief overview of recent developments in volcano seismology will be given. However, the main focus will be on still unknown effects on seismic monitoring parameters and their impact on volcanic hazard mitigation. Topography, scattering properties of the propagation medium and external influences such as rain, to name a few, will often mask the direct insight into the volcanoes dynamic behavior. The final question to answer is: how can synthetic modeling help to solve immanent problems in early warning systems?

SEISMIC TOMOGRAPHY
AND FULLY NUMERICAL WAVE FIELD CALCULATIONS - FUTURE PROSPECTS AND PERSPECTIVES

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The aim of the talk will be to outline research issues, and to discuss research directions and the prospects for success in employing fully numerical wavefield calculations in global seismic tomography.

Current global tomographic models incorporate data from many tens of thousands of seismograms. Successful models are based not simply on modelling raw seismograms, but on identifying and isolating key features, which are not necessarily features which are largest amplitude.

If complete seismograms are taken, the dominant features are the fundamental mode surface waves. In the period range 30s to 500s, these are key data for constraining upper mantle structure. At shorter periods, data are complex and reflect strong crustal heterogeneities; these have not been used to a great extent in the construction of global models. Modelling depends upon using the surface ray-theory approach, which can potentially be extended using finite frequency Born-kernels. Key issues are the accuracy of forward calculations as a function of frequency and delay, the validity of the Born-kernel approach for the particular parameter ranges of interest.

Smaller in amplitude, but nevertheless of great importance in constraining both the upper mantle and the transition zone, are the overtone signals, which merge with long the multiply reflected long period body waves (particularly SS, SSS etc.). Numerical wavefield calculations are needed to evaluate the validity of ray-based approaches.

Lower mantle and core studies rely on large collections of absolute and differential travel times measured in long period body waves. Again, a key aspect, even if the analysis is not subsequently based on travel times alone, is to identify and isolate the portions of seismograms containing particular phases, so that they can enter into the inversion with appropriate weight. It is necessary to test the ability of fully numerical codes to reproduce such data with sufficient accuracy as a function of frequency.

Examples of comparisons between seismograms generated using the SPECFEM code of Komatitsch and Tromp and ones generated by other methods, in the range of frequencies and delay times relevant to global tomography, will be used to illustrate these issues.