The Seismic Wave Equation

The present book — which is the third, significantly revised edition of the textbook originally published by Elsevier Science — emphasizes the interdependence of mathematical formulation and physical meaning in the description of seismic phenomena. Herein, we use aspects of continuum mechanics, wave theory and ray theory to explain phenomena resulting from the propagation of seismic waves. The book is divided into three main sections: Elastic Continua, Waves and Rays and Variational Formulation of Rays. There is also a fourth part, which consists of appendices. In Elastic Continua, we use continuum mechanics to describe the material through which seismic waves propagate, and to formulate a system of equations to study the behaviour of such a material. In Waves and Rays, we use these equations to identify the types of body waves propagating in elastic continua as well as to express their velocities and displacements in terms of the properties of these continua. To solve the equations of motion in anisotropic inhomogeneous continua, we invoke the concept of a ray. In Variational Formulation of Rays, we show that, in elastic continua, a ray is tantamount to a trajectory along which a seismic signal propagates in accordance with the variational principle of stationary traveltime. Consequently, many seismic problems in elastic continua can be conveniently formulated and solved using the calculus of variations. In the Appendices, we describe two mathematical concepts that are used in the book; namely, homogeneity of a function and Legendre's transformation. This section also contains a list of symbols. Request Inspection Copy

This book describes the theory and practice of inverting seismic data for the subsurface rock properties of the earth. The primary application is for inverting reflection and/or transmission data from engineering or exploration surveys, but the methods described also can be used for earthquake studies. Seismic Inversion will be of benefit to scientists and advanced students in engineering, earth sciences, and physics. It is desirable that the reader has some familiarity with certain aspects of numerical computation, such as finite-difference solutions to partial differential equations, numerical linear algebra, and the basic physics of wave propagation. For those not familiar with the terminology and methods of seismic exploration, a brief introduction is provided. To truly understand the nuances of seismic inversion, we have to actively practice what we preach (or teach). Therefore, computational labs are provided for most of the chapters, and some field data labs are given as well.

Fundamentals of Seismic Wave Propagation, published in 2004, presents a comprehensive introduction to the propagation of high-frequency body-waves in elastodynamics. The theory of seismic wave propagation in acoustic, elastic and anisotropic media is developed to allow seismic waves to be modelled in complex, realistic three-dimensional Earth models. This book provides a consistent and thorough development of modelling methods widely used in elastic wave propagation ranging from the whole Earth, through regional and crustal seismology, exploration seismics to borehole seismics, sonics and ultrasonics. Particular emphasis is placed on developing a consistent notation and approach throughout, which highlights similarities and allows more complicated methods and extensions to be developed without difficulty. This book is intended as a text for graduate courses in theoretical seismology, and as a reference for all academic and industrial seismologists using numerical modelling methods. Exercises and suggestions for further reading are included in each chapter.

Wave equation travel time Tomography based on the adjoint method is an advanced and useful theory to simulate the wave propagation and inversion. More practices and applications need to be implemented widely. A real seismic survey project is been done as an example in this paper with the above theory implementation. Also the comparison results can be funded in this paper. Wave equation travel time Tomography based on the adjoint method is also a complex, long running, and repeated process. A desire to free hand from the inversion process needs to be met. Windows Workflow Foundation in .net 4.0 provides the feasibility to implement the inversion process automatically. The visual studio 2010 provides friendly platform for users to simply drag the function activity to design all kinds of workflow which also allowed both forward and backward workflow design. The benefits of the automatic implement the wave equation travel time inversion workflow is not limited to save the operating time, but also improves the inversion efficiency by reducing the un-continued running gap between each step.

Furthermore, the automatic process provides the feasibility to implement other inversion process and reduce the seismic imaging period. Wave Equation travel time tomography based on the adjoint method simulates the wave propagation path exactly in three-dimensional media which provides more accurate velocity model and much higher resolution image than the ray tracing theory which tracks the wave propagation path in two-dimensional media. That is also a big reason why the wave equation tomography is more accurate than the conventional tomography. Wave equation travel time Tomography based on adjoint method is not a new theory which was developed in 1980s but it was been limited by the requirements of large computing source which is used to calculate three-dimensional wave equations and to construct three-dimensional Fréchet kernel. Until recent years, following by the barge computing technology development, applying wave equation travel time tomography to large scale of earthquake and exploration become implementable. In the practice of wave equation travel time tomography based on the adjoint method, forward wave-field and adjoint wave-field are been calculated by using source time function instead of storing green function. For adjoint wave-field, the wave field source is been derived by using reversed time signal at receiver as simultaneous source which is based on reciprocity of the green function property. And also all the synthetic seismogram relative to one shot can be simulated simultaneously for each wave-field calculation. Three-dementional Fré?chet derivative is constructed by using both forward and adjoint wave-fields.

Without storing green function, large disk space could be saved. In the meanwhile the simulation of two wave-fields will double the memory required. Since Hessian is also not available in the calculation, inversion process needs to be solved iteratively.

In this book we study of the propagation of G type waves along the plane surface at the interface of two different types of media. The upper medium is taken as monoclinic magneto-elastic layer whereas the lower half space is inhomogeneous isotropic. Keeping terms up to first order, the Laplace transform of the displacement is obtained. Dispersion equation and condition for maximum energy flow near the surface are obtained in compact form. The dispersion equation is in assertion with the classical Love-type wave equation for the isotropic case. Effect of magnetic field and inhomogeneity on phase velocity and variation of group velocity with scaled wave number has been depicted by means of graphs. It is observed that inhomogeneity decreases phase velocity and the magnetic field has the favoring effect. A comparative study for the case of isotropic layer and monoclinic layer over the same isotropic inhomogeneous half space has been made through graphs

"Numerical simulation is an irreplaceable tool in earthquake ground motion research. Among all the numerical methods in seismology, the finite-difference (FD) technique is the most widely-used, providing the best balance of accuracy and computational efficiency. Now, for the first time, this book offers a comprehensive introduction to this method and its applications to earthquake motion"--

Recent progress in numerical methods and computer science allows us today to simulate the propagation of seismic waves through realistically heterogeneous Earth models with unprecedented accuracy. Full waveform tomography is a tomographic technique that takes advantage of numerical solutions of the elastic wave equation. The accuracy of the numerical solutions and the exploitation of complete waveform information result in tomographic images that are both more realistic and better resolved. This book develops and describes state of the art methodologies covering all aspects of full waveform tomography including methods for the numerical solution of the elastic wave equation, the adjoint method, the design of objective functionals and optimisation schemes. It provides a variety of case studies on all scales from local to global based on a large number of examples involving real data. It is a comprehensive reference on full waveform tomography for advanced students, researchers and professionals.

Full waveform inversion is an iterative optimization technique used to estimate subsurface physical parameters in the earth. A seismic energy source is generated in a borehole or on the surface of the earth which causes a seismic wave to propagate into the underground material. The transmitted wave then reflects off of material interfaces (rocks and fluids) and the returning wave is recorded at geophones. The inverse problem involves estimating parameters that describe this wave propagation (such as velocity) to minimize the misfit between the measured data and data we simulate from our mathematical model. The seismic velocity inversion problem is difficult because it contains sources of uncertainty, due to the instruments used to record the data and our mathematical model for seismic wave propagation. Using uncertainty quantification (UQ), we construct distributions of earth velocity models. Distributions give information about how probable an Earth model is, given the recorded seismic data. This rich information impacts real-world decision making, such as where to drill a well to produce oil and gas. UQ methods based on repeated sampling to construct estimates of the distribution, such as Markov chain Monte Carlo (MCMC), are desirable because they do not impose restrictions on the shape of the distribution. How ever, MCMC methods are computationally expensive because they require solving the wave equation repeatedly to generate simulated seismic wave data. This dissertation focuses on techniques to reduce the computational expense of MCMC methods for the seismic velocity inversion problem. Two-stage MCMC uses an inexpensive filter to cheaply reject unacceptable velocity models. The operator upscaling method, an inexpensive surrogate for the wave equation, is one such filter. We find that two-stage MCMC with the operator upscaling filter is effective at producing the same uncertainty information as traditional one-stage MCMC, but reduces the computational cost by between 20% and 45%. A neural network, in conjunction with operator upscaling, is another choice of filter. We find that the neural network filter reduces the computational cost of MCMC by 65% for our experiment, which includes the time needed to generate the training set and the neural

network. The size of the problem we can solve using two-stage MCMC is limited by the random walk sampler. Hamiltonian Monte Carlo (HMC) and the No-U-Turn sampler (NUTS) use gradient information and Hamiltonian dynamics to steer the sampler, thereby eliminating the inefficient random walk behavior. Discretizing Hamiltonian dynamics requires two user specified parameters: trajectory length and step size. The NUTS algorithm avoids setting the trajectory length in advance by constructing variable-length paths. We find that the NUTS algorithm for seismic inversion results in superior decrease in the residual over traditional HMC while removing the need for costly tuning runs. However, constructing the gradient for the seismic inverse problem is computationally expensive. In two-stage, neural network-enhanced HMC we replace the costly gradient computation with a neural network. Additionally, we use the neural network to reject unacceptable samples as in two-stage MCMC. We find that the two-stage neural network HMC scheme reduces the computational cost by over 80% when compared to traditional HMC for a 100-unknown layered problem.
Numerical Modeling of Seismic Wave PropagationGridded Two-way Wave-equation MethodsSEG BooksIntroduction to SeismologyCambridge University Press
Surface waves have drawn a significant attention and interest in the recent years in a broad range of commercial applications, while their commercial developments have been supported by fundamental and applied research studies. This book is a result of contributions of experts from international scientific community working in different

aspects of surface waves and reports on the state-of-the-art research and development findings on this topic through original and innovative research studies. It contains up-to-date publications of leading experts, and the edition is intended to furnish valuable recent information to the professionals involved in surface wave analysis and applications. The text is addressed not only to researchers but also to professional engineers, students, and other experts in various disciplines, both academic and industrial, seeking to gain a better understanding of what has been done in the field recently and what kind of open problems are in this area.

This book focuses on the mathematical potential and computational efficiency of the Boundary Element Method (BEM) for modeling seismic wave propagation in either continuous or discrete inhomogeneous elastic/viscoelastic, isotropic/anisotropic media containing multiple cavities, cracks, inclusions and surface topography. BEM models may take into account the entire seismic wave path from the seismic source through the geological deposits all the way up to the local site under consideration. The general presentation of the theoretical basis of elastodynamics for inhomogeneous and heterogeneous continua in the first part is followed by the analytical derivation of fundamental solutions and Green's functions for the governing field equations by the usage of Fourier and Radon transforms. The numerical implementation of the BEM is for antiplane in the second part as well as for plane strain boundary value problems in the third part. Verification studies and parametric analysis appear throughout the book, as do both recent references and seminal ones from the past. Since the background of the authors is in solid mechanics and mathematical physics, the presented BEM formulations are valid for many areas such as civil engineering, geophysics, material science and all others concerning elastic wave propagation through inhomogeneous and heterogeneous media. The material presented in this book is suitable for self-study. The book is written at a level suitable for advanced undergraduates or beginning graduate students in solid mechanics, computational mechanics and fracture mechanics.

Building on the success of T.J.T. Spanos's previous book The Thermophysics of Porous Media, The Physics of Composite and Porous Media explains non-linear field theory that describes how physical processes occur in the earth. It describes physical processes associated with the interaction of the various phases at the macroscale (the scale at which continuum equations are established) and how these interactions give rise to additional physical processes at the megascale (the scale orders of magnitude larger at which a continuum description may once again be established). Details are also given on how experimental, numerical and theoretical work on this subject fits together. This book will be of interest to graduate students and academic researchers working on understanding the physical process in the earth, in addition to those working in the oil and hydrogeology industries.

Seismic waves – generated both by natural earthquakes and by man-made sources –

have produced an enormous amount of information about the Earth's interior. In classical seismology, the Earth is modeled as a sequence of uniform horizontal layers (or sperical shells) having different elastic properties and one determines these properties from travel times and dispersion of seismic waves. The Earth, however, is not made of horizontally uniform layers, and classic seismic methods can take large-scale inhomogeneities into account. Smaller-scale irregularities, on the other hand, require other methods. Observations of continuous wave trains that follow classic direct S waves, known as coda waves, have shown that there are heterogeneities of random size scattered randomly throughout the layers of the classic seismic model. This book focuses on recent developments in the area of seismic wave propagation and scattering through the randomly heterogeneous structure of the Earth, with emphasis on the lithosphere. The presentation combines information from many sources to present a coherent introduction to the theory of scattering in acoustic and elastic materials and includes analyses of observations using the theoretical methods developed.

Authored by a geophysicist with more than 50 years of experience in research and instruction, Reflection Seismology: Theory, Data Processing and Interpretation provides a single source of foundational knowledge in reflection seismology principles and theory. Reflection seismology has a broad range of applications and is used primarily by the oil and gas industry to provide high-resolution maps and build a coherent geological story from maps of processed seismic reflections. Combined with seismic attribute analysis and other exploration geophysics tools, it aids geologists and geo-engineers in creating geological models of areas of exploration and extraction interest. Yet as important as reflection seismology is to the hydrocarbon industry, it's difficult to find a single source that synthesizes the topic without having to wade through numerous journal articles from a range of different publishers. This book is a one-stop source of reflection seismology theory, helping scientists navigates through the wealth of new data processing techniques that have emerged in recent years. Provides geoscientists and geo-engineers with a theoretical framework for navigating the rapid emergence of new data processing techniques Presents a single source of reflection seismology content instead of a scattering of disparate journal articles Features more than 100 figures, illustrations, and working examples to aid the reader in retaining key concepts Arms geophysicists and geo-engineers with a solid foundation in seismic wave equation analysis and interpretation

Developments in Solid Earth Geophysics 10: Transient Waves in Visco-Elastic Media deals with the propagation of transient elastic disturbances in visco-elastic media. More specifically, it explores the visco-elastic behavior of a medium, whether gaseous, liquid, or solid, for very-small-amplitude disturbances. This volume provides a historical overview of the theory of the propagation of elastic waves in solid bodies, along with seismic prospecting and the nature of seismograms. It also discusses the seismic experiments, the behavior of waves propagated in accordance with the Stokes wave equation, and wavelet functions and their polynomials. The book explains the laws of propagation of seismic wavelets and seismic ray paths, as well as the equations of wavelet propagation, the velocity-type seismic wavelet, and the spectrum of the wavelet. It discusses the motion of a mechanical seismograph disturbed by extraneous forces or motions. It also provides information on the differential equation describing the motion of a galvanometer, laboratory studies of wavelet contraction, and characteristics of a wavelet-contractor amplifier. Furthermore, the book explains the experimental studies of the primary seismic disturbance and internal friction. This monograph is a valuable source of information for physicists, students who want to pursue a career in geophysics or selenophysics, and those who actively working in these fields.

This book presents the formulations and solutions of the wave equation for the Earths free oscillations concerning the particular nodal, bifurcation, perspectival, and projective reference points within the framework of the three "great geometries" of Euclid, Lobachevsky, and Riemann. When studying the relationship between the propagation velocity of various types of bulk and surface seismic waves with radial, spheroidal, and torsional eigen oscillations of the Earth having corresponding periods, we are struck by the fundamental problem of obtaining reference points that allow physical meaning to be attributed to all these discrete oscillatory and continuous wave phenomena that occur in nature. Several unsuccessful attempts tried to unify the relationship of discrete oscillations and the velocity of waves and light occurring in seismology and other phenomena associated with gravity and matter, using a three-dimensional visual space-time model continuous Euclidean space. Using simple and illustrative examples for describing the free oscillations of the Earth and taking into account new visible event horizons related to the velocity of waves and light propagation, the author formulated and solved the fundamental wave equation of nature in the form of the three "great theorems" Galilean, Lorentz, and Poincare spatiotemporal transformations.

Accurate and efficient computer simulations of seismic wave propagation in realistic three-dimensional geological media are becoming increasingly important in seismology for improving our understanding of the earthquake rupture process that generates seismic waves and the geological medium through which seismic waves propagate. However, the accurate and computationally efficient numerical solution of the three-dimensional (visco)elastic seismic wave equation is still a very challenging task, especially when the material properties are complex and the modeling geometry, such as surface topography and subsurface fault structures, is highly irregular. We have successfully ported two different numerical methods for solving the three-dimensional elastic seismic wave equation from CPU platform to GPU platform. The first one is arbitrary high-order discontinuous Galerkin (ADER-DG) method which was designed for solving the three-dimensional elastic seismic wave equation on unstructured tetrahedral meshes. This ADER-DG implementation obtained a speedup factor of about 24.3 for the single-precision version of our GPU code and a speedup factor of about 12.8 for the double-precision version of our GPU code when compared with the serial CPU code running on one Intel Xeon W5880 core. By implementing the MPI technique and other optimization scheme, we further improved our ADER-DG code with parallelism capability which obtained a speedup factor of about 28.3 for the single-precision version of our codes and a speedup factor of about 14.9 for the double-precision version. To effectively overlap inter-process communication with computation, we separate the elements on each sub-domain into inner and outer elements and complete the computation on outer elements and fill the MPI buffer

first. While the MPI messages travel across the network, the GPU performs computation on inner elements and all other calculations that do not use information of outer elements from neighboring sub-domains. A significant portion of the speedup also comes from a customized matrix-matrix multiplication kernel, which is used extensively throughout our program. Preliminary performance analysis on our parallel GPU codes shows favorable strong and weak scalabilities. The second numerical method we ported is fourth order finite difference method. Within this implementation, we utilized the staggered grid, dual layer mesh grid, classical Perfect Match Layer (PML) and many GPU optimize technique to enhance the efficiency of our code. Compared with the double precision CPU code, our finite-difference implementation obtained a speedup factor of about 62 for the single-precision version of our GPU code and a speedup factor of about 31 for the double-precision version of our GPU code when compared with the serial CPU code running on one Intel Xeon W5880 core.
Authored by the internationally renowned José M. Carcione, Wave Fields in Real Media: Wave Propagation in Anisotropic, Anelastic, Porous and Electromagnetic Media examines the differences between an ideal and a real description of wave propagation, starting with the introduction of relevant stress-strain relations. The combination of this relation and the equations of momentum conservation lead to the equation of motion. The differential formulation is written in terms of memory variables, and Biot's theory is used to describe wave propagation in porous media. For each rheology, a plane-wave analysis is performed in order to understand the physics of wave propagation. This book contains a review of the main direct numerical methods for solving the equation of motion in the time and space domains. The emphasis is on geophysical applications for seismic exploration, but researchers in the fields of

earthquake seismology, rock acoustics, and material science - including many branches of acoustics of fluids and solids - may also find this text useful. New to this edition: This new edition presents the fundamentals of wave propagation in Anisotropic, Anelastic, Porous Media while also incorporating the latest research from the past 7 years, including that of the author. The author presents all the equations and concepts necessary to understand the physics of wave propagation. These equations form the basis for modeling and inversion of seismic and electromagnetic data. Additionally, demonstrations are given, so the book can be used to teach post-graduate courses. Addition of new and revised content is approximately 30%. Examines the fundamentals of wave propagation in anisotropic, anelastic and porous media Presents all equations and concepts necessary to understand the physics of wave propagation, with examples Emphasizes geophysics, particularly, seismic exploration for hydrocarbon reservoirs, which is essential for exploration and production of oil

Seismic modeling and imaging of the earth's subsurface are complex and difficult computational tasks. The authors present general numerical methods based on the complete wave equation for solving these important seismic exploration problems.

This book seeks to explore seismic phenomena in elastic media and emphasizes the interdependence of mathematical formulation and physical meaning. The purpose of this title - which is intended for senior undergraduate and graduate students as well as scientists interested in quantitative seismology - is to use aspects of continuum mechanics, wave theory and ray theory to describe phenomena resulting from the propagation of waves. The book is divided into three parts: Elastic continua, Waves and rays, and Variational formulation of rays. In Part I, continuum mechanics are used to describe the material through which seismic waves propagate, and to formulate a system of equations to study the behaviour of such material. In Part II, these equations are used to identify the types of body waves propagating in elastic continua as well as to express their velocities and displacements in terms of the properties of these continua. To solve the equations of motion in anisotropic inhomogeneous continua, the high-frequency approximation is used and establishes the concept of a ray. In Part III, it is shown that in elastic continua a ray is tantamount to a trajectory along which a seismic signal propagates in accordance with the variational principle of stationary travel time.

Concise textbook on seismic wave theory, with detailed derivations of formulas, clear explanations of topics, exercises, and selected answers.

Elastic Waves in the Earth provides information on the relationship between seismology and geophysics and their general aspects. The book offers elastodynamic equations and derivative equations that can be used in the propagation of elastic waves. It also covers major topics in detail, such as the fundamentals of elastodynamics; the Lamb's problem, which includes the Cagniard-de Hoop theory; rays and modes in a radially inhomogeneous earth and in multilayered media, which includes the Thomson-Haskell theory; the elastic wave dissipation; the seismic source and noise; and the seismographs. The book consists of 33 chapters. The first 16 chapters include basic material related to the propagation of elastic waves. Topics covered by these chapters include scalars, vectors, and tensors in cartesian coordinates, stress and strain analysis, equations of elasticity and motion, plane waves, Rayleigh waves, plane-wave theory, and fluid-fluid and solid-solid interfaces. The second half of the book covers various ray and mode theories, elastic wave dissipation, and the observations and theories of seismic source and seismic noise. It concludes by discussing earthquake seismology and different seismographs, like the pendulum seismometer and the strain seismometer.

Extrapolation of seismic waves from the earth's surface to any level in the subsurface plays an essential role in many advanced seismic processing schemes, such as migration, inverse scattering and redatuming. At present these schemes are based on the acoustic wave equation. This means not only that S-waves (shear waves) are ignored, but also that P-waves (compressional waves) are not handled correctly. In the seismic industry there is an important trend towards multi-component data acquisition. For processing of multi-component seismic data, ignoring S-waves can no longer be justified. Wave field extrapolation should therefore be based on the full elastic wave equation. In this book the authors review acoustic one-way extrapolation of P-waves and introduce elastic one-way extrapolation of P- and S-waves. They demonstrate that elastic extrapolation of multi-component data, decomposed into P- and S-waves, is essentially equivalent to acoustic extrapolation of P-waves. This has the important practical consequence that elastic processing of multi-component seismic data need not be significantly more complicated than acoustic processing of single-component seismic data. This is demonstrated in the final chapters, which deal with the application of wave field extrapolation in the redatuming process of single- and multi-component seismic data. Geophysicists, and anyone who is interested in a review of acoustic and elastic wave theory, will find this book useful. It is also a suitable textbook for graduate students and those following courses in elastic wave field extrapolation as each subject is introduced in a relatively simple manner using the scalar acoustic wave equation. In the chapters on elastic wave field extrapolation the formulation, whenever possible, is analogous to that used in the chapters on acoustic wave field extrapolation. The text is illustrated throughout and a bibliography and keyword index are provided.

This book provides an approachable and concise introduction to seismic theory, designed as a first course for undergraduate students. It clearly explains the fundamental concepts, emphasizing intuitive understanding over lengthy derivations. Incorporating over 30% new material, this second edition includes all the topics needed for a one-semester course in seismology. Additional material has been added throughout including numerical methods, 3-D ray tracing, earthquake location, attenuation, normal modes, and receiver functions. The chapter on earthquakes and source theory has been extensively revised and enlarged, and now includes details on non-double-couple sources, earthquake scaling, radiated energy, and finite slip inversions. Each chapter includes worked problems and detailed exercises that give students the opportunity to apply the techniques they have learned to compute results of interest and to illustrate the Earth's seismic properties. Computer subroutines and datasets for use in the exercises are available at www.cambridge.org/shearer.

Developments in Solid Earth Geophysics, 4: Mathematical Aspects of Seismology introduces studies of the more advanced parts of theoretical seismology. The manuscript first ponders on contour integration and conformal transformation, methods of stationary phase and steepest descent, and series integration. Discussions focus on Love waves in heterogeneous isotropic media, Laguerre's differential equation, Hermite's differential equation, method of steepest descent, method of stationary phase, contour integration in the complex plane, and conformal transformation. The text then examines series integration, Bessel functions, Legendre functions, and wave equations. Topics include general considerations of the wave equation, expansion of a spherical wave into plane waves, common features of special functions and special differential equations, applications of Legendre functions, Legendre polynomials, Bessel's differential equation, and properties of Bessel coefficients. The book explores the influence of gravity on wave propagation, matrix calculus, wave propagation in liquid media, integral equations, calculus of variations, and integral transforms. The text is a valuable source of data for researchers wanting to study the mathematical aspects of seismology.

This book is an introductory text to a range of numerical methods used today to simulate time-dependent processes in Earth science, physics, engineering, and many other fields. The physical problem of elastic wave propagation in 1D serves as a model system with which the various numerical methods are introduced and compared. The theoretical background is presented with substantial graphical material supporting the concepts. The results can be reproduced with the supplementary electronic material provided as python codes embedded in Jupyter notebooks. The book starts with a primer on the physics of elastic wave propagation, and a chapter on the fundamentals of parallel programming, computational grids, mesh generation, and hardware models. The core of the book is the presentation of numerical solutions of the wave equation with six different methods: 1) the finite-difference method; 2) the pseudospectral method (Fourier and Chebyshev); 3) the linear finite-element method; 4) the spectralelement method; 5) the finite-volume method; and 6) the discontinuous Galerkin method. Each chapter contains comprehension questions, theoretical, and programming exercises. The book closes with a discussion of domains of application and criteria for the choice of a specific numerical method, and the presentation of current challenges. Readers are welcome to visit the author's website www.geophysik.lmu.de/Members/igel for more information on his research, projects, publications, and other activities.

Seismic waves - generated both by natural earthquakes and by man-made sources - have produced an enormous amount of information about the Earth's interior. In classical seismology, the Earth is modeled as a sequence of uniform horizontal layers (or spherical shells) having different elastic properties and one determines these properties from travel times and dispersion of seismic waves. The Earth, however, is not made of horizontally uniform layers, and classic seismic methods can take large-scale inhomogeneities into account. Smaller-scale irregularities, on the other hand, require other methods. Observations of continuous wave trains that follow classic direct S waves, known as coda waves, have shown that there are heterogeneities of random size scattered randomly throughout the layers of the classic seismic model. This book focuses on recent developments in the area of seismic wave propagation and scattering through the randomly heterogeneous structure of the Earth, with emphasis on the lithosphere. The presentation combines information from many sources to present a coherent introduction to the theory of scattering in acoustic and elastic materials and includes analyses of observations using the theoretical methods developed. The second edition especially includes new observational facts such as the spatial variation of medium inhomogeneities and the temporal change in scattering characteristics and recent theoretical developments in the envelope synthesis in random media for the last ten years. Mathematics is thoroughly rewritten for improving the readability. Written for advanced undergraduates or beginning graduate students of geophysics or planetary sciences, this book should also be of interest to civil engineers, seismologists, acoustical engineers, and others interested in wave propagation through inhomogeneous elastic media.

The isotropic elastic wave equation governs the propagation of seismic waves caused by earthquakes and other seismic events. It also governs the propagation of waves in solid material structures and devices, such as gas pipes, wave guides, railroad rails and disc brakes. In the vast majority of wave propagation problems arising in seismology and solid mechanics there are free surfaces. These free surfaces have, in general, complicated shapes and are rarely flat.

Another feature, characterizing problems arising in these areas, is the strong heterogeneity of the media, in which the problems are posed. For example, on the characteristic length scales of seismological problems, the geological structures of the earth can be considered piecewise constant, leading to models where the values of the elastic properties are also piecewise constant. Large spatial contrasts are also found in solid mechanics devices composed of different materials welded together. The presence of curved free surfaces, together with the typical strong material heterogeneity, makes the design of stable, efficient and accurate numerical methods for the elastic wave equation challenging. Today, many different classes of numerical methods are used for the simulation of elastic waves. Early on, most of the methods were based on finite difference approximations of space and time derivatives of the equations in second order differential form (displacement formulation), see for example [1, 2]. The main problem with these early discretizations were their inability to approximate free surface boundary conditions in a stable and fully explicit manner, see e.g. [10, 11, 18, 20]. The instabilities of these early methods were especially bad for problems with materials with high ratios between the P-wave (C{sub p}) and S-wave (C{sub s}) velocities. For rectangular domains, a stable and explicit discretization of the free surface boundary conditions is presented in the paper

[17] by Nilsson et al. In summary, they introduce a discretization, that use boundary-modified difference operators for the mixed derivatives in the governing equations. Nilsson et al. show that the method is second order accurate for problems with smoothly varying material properties and stable under standard CFL constraints, for arbitrarily varying material properties. In this paper we generalize the results of Nilsson et al. to curvilinear coordinate systems, allowing for simulations on non-rectangular domains. Using summation by parts techniques, we show that there exists a corresponding stable discretization of the free surface boundary condition on curvilinear grids. We also prove that the discretization is stable and energy conserving both in semi-discrete and fully discrete form. As for the Cartesian method in, [17], the stability and conservation results holds for arbitrarily varying material properties. By numerical experiments it is established that the method is second order accurate.

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This book introduces a methodology for solving the seismic inverse problem using purely numerical solutions built on 3D wave equations and which is free of the approximations or simplifications that are common in classical seismic inversion methodologies and therefore applicable to arbitrary 3D geological media and seismic source models. Source codes provided allow readers to experiment with the

calculations demonstrated and also explore their own applications.
Seismic Wave Propagation in Stratified Media presents a systematic treatment of the interaction of seismic waves with Earth structure. The theoretical development is physically based and is closely tied to the nature of the seismograms observed across a wide range of distance scales - from a few kilometres as in shallow reflection work for geophysical prospecting, to many thousands of kilometres for major earthquakes. A unified framework is presented for all classes of seismic phenomena, for both body waves and surface waves. Since its first publication in 1983 this book has been an important resource for understanding the way in which seismic waves can be understood in terms of reflection and transmission properties of Earth models, and how complete theoretical seismograms can be calculated. The methods allow the development of specific approximations that allow concentration on different seismic arrivals and hence provide a direct tie to seismic observations.
Following the breakthrough in the last decade in identifying the key parameters for time and depth imaging in anisotropic media and developing practical methodologies for estimating them from seismic data, Seismic Signatures and Analysis of Reflection Data in Anisotropic Media primarily focuses on the far reaching exploration benefits of anisotropic processing. This volume provides the first comprehensive description of reflection seismic signatures and processing methods in anisotropic media. It identifies the key parameters for time and depth imaging in transversely isotropic media and

describes practical methodologies for estimating them from seismic data. Also, it contains a thorough discussion of the important issues of uniqueness and stability of seismic velocity analysis in the presence of anisotropy. The book contains a complete description of anisotropic imaging methods, from the theoretical background to algorithms to implementation issues. Numerous applications to synthetic and field data illustrate the improvements achieved by the anisotropic processing and the possibility of using the estimated anisotropic parameters in lithology discrimination. Focuses on the far reaching exploration benefits of anisotropic processing First comprehensive description of reflection seismic signatures and processing methods in anisotropic media