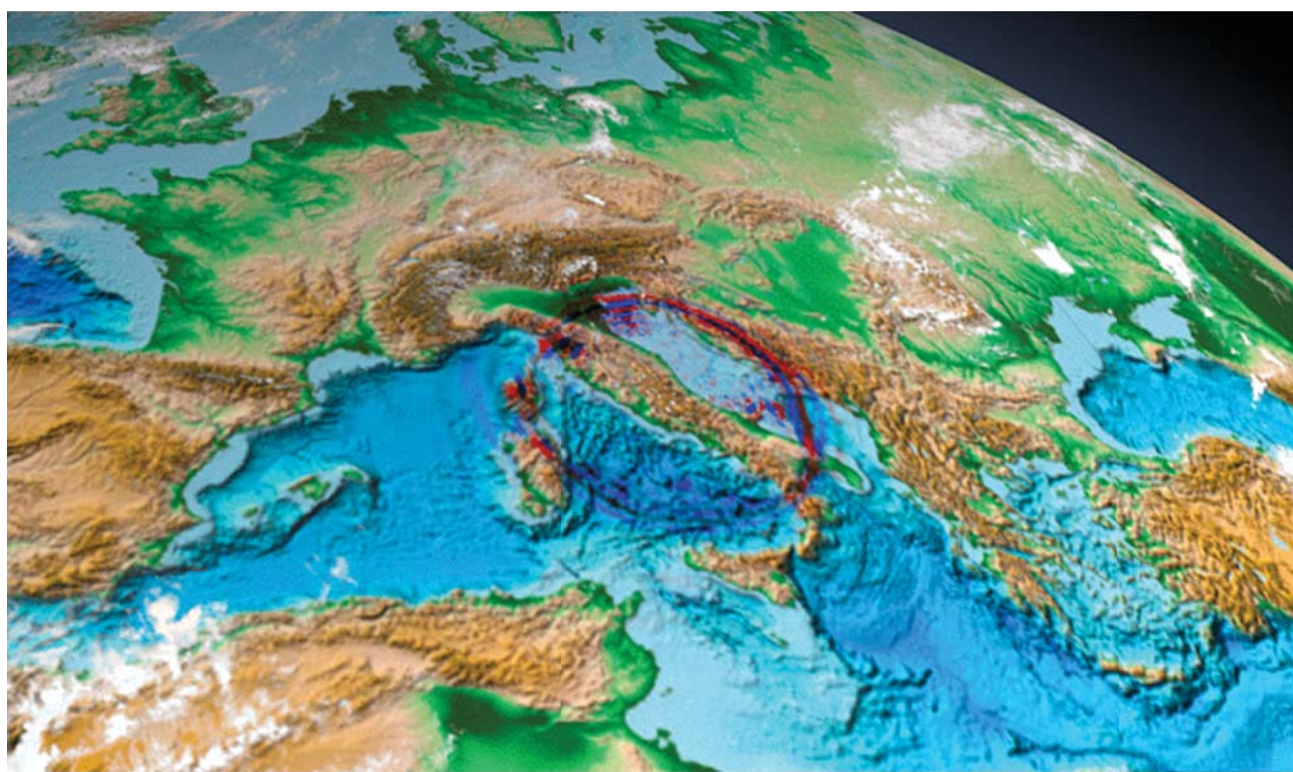




Computational Seismology: A Practical Introduction

Heiner Igel

OXFORD
UNIVERSITY PRESS

Contents

1	About Computational Seismology	1
1.1	What Is Computational Seismology?	1
1.2	What Is Computational Seismology Good For?	2
1.3	Target Audience and Level	4
1.4	How To Read This Book?	6
	Further reading	7
I	Elastic Waves in the Earth	9
2	Seismic Waves and Sources	11
2.1	Elastic Wave Equations	13
2.2	Rheologies	15
2.2.1	Viscoelasticity and Attenuation	16
2.2.2	Seismic Anisotropy	16
2.2.3	Poroelasticity	18
2.3	Boundary and Initial Conditions	18
2.3.1	Initial Conditions	18
2.3.2	Free Surface	19
2.3.3	Internal Boundaries	19
2.3.4	Absorbing Boundary Conditions	20
2.4	Fundamental Solutions	20
2.4.1	Body Waves	20
2.4.2	Gradient, Divergence, Curl	21
2.4.3	Surface Waves	22
2.5	Seismic Sources	23
2.5.1	Forces and Moments	23
2.5.2	Seismic Wavefield of a Double-Couple Point Source	26
2.5.3	Superposition Principle, Finite Sources	28
2.5.4	Reciprocity, Time Reversal	30
2.6	Scattering	31
2.7	Seismic Wave Problems As Linear Systems	33
2.8	Some Final Thoughts	35
	Further reading	36
	Exercises	37
3	Waves in a Discrete World	39
3.1	Classification of Partial Differential Equations	39
3.2	Strategies for Computational Wave Propagation	41

3.3	Physical Domains and Computational Meshes	43
3.3.1	Dimensionality: 1D, 2D, 2.5D, 3D	43
3.3.2	Computational Meshes	44
3.3.3	Structured (Regular) Grids	45
3.3.4	Unstructured (Irregular) Grids	45
3.3.5	Other Meshing Concepts	46
3.4	The Curse Of Mesh Generation	47
3.5	Parallel Computing	49
3.5.1	Physics and Parallelism	51
3.5.2	Domain Decomposition, Partitioning	51
3.5.3	Hardware and Software for Parallel Algorithms	52
3.5.4	Basic Hardware Architectures	53
3.5.5	Parallel Programming	54
3.5.6	Parallel I/O, Data Formats, Provenance	56
3.6	The Impact of Parallel Computing on Earth Sciences	58
	Further reading	59
	Exercises	59
II	Numerical Methods	61
4	The Finite-Difference Method	63
4.1	History	64
4.2	Finite Differences in a Nutshell	65
4.3	Finite Differences and Taylor Series	66
4.3.1	Higher Derivatives	67
4.3.2	High-Order Operators	68
4.4	Acoustic Wave Propagation in 1D	70
4.4.1	Stability	73
4.4.2	Numerical Dispersion	75
4.4.3	Convergence	76
4.5	Acoustic Wave Propagation in 2D	76
4.5.1	Numerical Anisotropy	77
4.5.2	Choosing the Right Simulation Parameters	78
4.6	Elastic Wave Propagation in 1D	81
4.6.1	Displacement Formulation	81
4.6.2	Velocity - Stress Formulation	82
4.6.3	Velocity - Stress Algorithm: Example	83
4.6.4	Velocity - Stress: Dispersion	85
4.7	Elastic Wave Propagation in 2D	86
4.7.1	Grid Staggering	86
4.7.2	Free Surface Boundary Condition	87
4.8	The Road to 3D	87
4.8.1	High-Order Extrapolation Schemes	88
4.8.2	Optimizing Operators	89
4.8.3	Minimal, Triangular, Unstructured Grids	90
4.8.4	Other Coordinate Systems	91
	Further reading	92

Exercises	93
5 The Pseudospectral Method	97
5.1 History	98
5.2 The Pseudospectral Method in a Nutshell	99
5.3 Ingredients	100
5.3.1 Orthogonal Functions, Interpolation, Derivative	100
5.3.2 Fourier Series and Transforms	102
5.4 The Fourier Pseudospectral Method	107
5.4.1 Acoustic Waves in 1D	108
5.4.2 Stability, Convergence, Dispersion	110
5.4.3 Acoustic Waves in 2D	111
5.4.4 Numerical Anisotropy	113
5.4.5 Elastic Waves in 1D	113
5.5 Infinite Order Finite Differences	115
5.6 The Chebyshev Pseudospectral Method	118
5.6.1 Chebyshev Polynomials	119
5.6.2 Chebyshev Derivatives, Differentiation Matrices	122
5.6.3 Elastic Waves in 1D	124
5.7 The Road to 3D	126
Further reading	129
Exercises	129
6 The Finite-Element Method	131
6.1 History	132
6.2 Finite Elements in a Nutshell	133
6.3 Static Elasticity	134
6.3.1 Boundary conditions	138
6.3.2 Reference Element, Mapping, Stiffness Matrix	138
6.3.3 Simulation Example	140
6.4 1D Elastic Wave Equation	142
6.4.1 The System Matrices	144
6.4.2 Simulation Example	146
6.5 Shape Functions in 1D	150
6.6 Shape Functions in 2D	152
6.7 The Road to 3D	153
Further reading	155
Exercises	156
7 The Spectral-Element Method	159
7.1 History	160
7.2 Spectral Elements in a Nutshell	161
7.3 Weak Form of the Elastic Equation	162
7.4 Getting Down to the Element Level	164
7.4.1 Interpolation with Lagrange Polynomials	167
7.4.2 Numerical Integration	169
7.4.3 Derivatives of Lagrange Polynomials	171
7.5 Global Assembly and Solution	173

7.6	Source Injection	174
7.7	The Spectral-Element Method in Action	175
7.7.1	Homogeneous Example	175
7.7.2	Heterogeneous Example	179
7.8	The Road to 3D	180
	Further reading	182
	Exercises	183
8	The Finite-Volume Method	185
8.1	History	186
8.2	Finite Volumes in a Nutshell	187
8.3	The Finite-Volume Method via Conservation Laws	188
8.4	Scalar Advection in 1D	193
8.5	Elastic Waves in 1D	196
8.5.1	Homogenous Case	198
8.5.2	Heterogeneous Case	200
8.6	Derivation via Gauss' Theorem	203
8.7	The Road to 3D	206
	Further reading	207
	Exercises	208
9	The Discontinuous Galerkin Method	211
9.1	History	212
9.2	The Discontinuous Galerkin Method in a Nutshell	214
9.3	Scalar Advection Equation	215
9.3.1	Weak formulation	217
9.3.2	Elemental Mass and Stiffness Matrices	219
9.3.3	The Flux Scheme	221
9.3.4	Scalar Advection in Action	223
9.4	Elastic Case in 1D	227
9.4.1	Fluxes in the Elastic Case	230
9.4.2	Simulation Example	231
9.5	The Road to 3D	234
	Further reading	235
	Exercises	236
III	Applications	239
10	Applications in Earth Sciences	241
10.1	Geophysical Exploration	243
10.2	Regional Wave Propagation	245
10.3	Global and Planetary Seismology	247
10.4	Strong Ground Motion and Dynamic Rupture	250
10.5	Seismic Tomography - Waveform Inversion	253
10.6	Volcanology	257
11	Current Challenges in Computational Seismology	259
11.1	Community Solutions	259

11.2 Structured vs. Unstructured: Homogenization	260
11.3 Meshing	261
11.4 Nonlinear Inversion, Uncertainties	261
A Community Software and Platforms in Seismology	263
A.1 Wave Propagation and Inversion	263
A.2 Data Processing, Visualization	265
A.3 Benchmarking	265
A.4 Ipython Notebooks	266
References	267