

Preface

Full waveform inversion is a novel variant of seismic tomography that is characterised by the numerical solution of the equations of motion, the exploitation of full waveform information and the iterative improvement of the tomographic images that accounts for non-linearity in the relation between model parameters and synthetic data. The numerical solutions ensure the accurate modelling of seismic wave propagation through realistically heterogeneous Earth models, thus making full waveform inversion the tomographic method of choice when the medium properties are highly variable. Thanks to the combination of numerical solutions and adjoint techniques, any type of waveform can be exploited for the benefit of improved tomographic resolution – without the need to identify particular waveforms in terms of classical seismic phases such as P or S.

The purpose of this book is to present the necessary ingredients for a full waveform inversion applied to real data. It is intended to serve as an accessible introduction to the topic for advanced students and professionals. The level is such that it could be used as a source of advanced teaching material for specialised seminars, courses and schools. Throughout the text we assume basic knowledge of elastic wave propagation in a seismological context, as it can be found, for instance, in the works of Båth (1979), Bullen & Bolt (1985), Lay & Wallace (1995), Udías (1999), Kennett (2001) or Aki & Richards (2002).

This book is organised in three parts that represent the major steps to be taken in order to solve a full waveform inversion problem.

Part I is dedicated to the numerical solution of the elastic wave equation. In the course of the past few decades many numerical methods for the discretisation of the wave equation have been developed – each being particularly well suited for specific applications. The choice to cover only finite-difference and spectral-element methods in detail has therefore been particularly difficult. In addition to being most frequently used in full waveform inversion, finite-difference and spectral-element methods also offer the opportunity to introduce many of the concepts that are fundamental in numerical wave propagation. Therefore, I hope that the content of Chaps. 2, 3, and 4 may serve as a useful basis for the understanding of numerical methods that I was not able to cover in a book that is focused on the solution of the inverse problem. Chapter 5 is concerned with the description and the numerical implementation of visco-elastic dissipation. Special attention is given to the concept

of memory variables and the construction of Q models with a specified frequency dependence. Efficient absorbing boundaries are of outstanding importance when the computational domain does not comprise the whole Earth. Chapter 6 therefore describes absorbing boundary conditions and absorbing boundary layer approaches such as the Gaussian taper method and perfectly matched layers (PML).

The subject of Part II is the solution of the full waveform tomographic inverse problem. Chapter 7 reviews the foundations of non-linear optimisation, including the concept of local and global minima, uniqueness, convexity, regularisation and a selection of gradient-based minimisation algorithms. The adjoint method, treated in Chaps. 8, 9 and 10, is one of the methodological cornerstones of full waveform inversion because it allows us to efficiently compute the partial derivatives of seismic observables that are needed in gradient-based minimisation schemes. The general operator formulation of the adjoint method, its application to the elastic wave equation, the extension to second derivatives and the derivation of explicit expressions for Fréchet and Hessian kernels are covered with particular detail. Of outstanding importance in full waveform inversion is the choice of suitable misfit functionals that extract as much waveform information as possible while conforming to the restrictions imposed by the data and the physics of wave propagation. Chapter 11 summarises several misfit functionals that have proven effective in applications to real data. Regardless of any technological advances, physical intuition remains the most important ingredient in the solution of any inverse problem. In the case of full waveform inversion, this intuition mostly comes from the interpretation of Fréchet kernels, a collection of which is presented in Chap. 12.

While full waveform inversion is still a comparatively young method, there is already an important conclusion to be drawn: Its application is highly problem-dependent! A numerical method that is efficient for the modelling of body waves on a regional scale may be inefficient for the simulation of global surface wave propagation. Misfit functionals that are well suited to image sharp reflectors may not be able to recover the long-wavelength structure of the Earth. Owing to this extreme problem dependence, Part III presents a collection of case studies where full waveform inversion has been applied successfully. Chapter 13 is concerned with a continental-scale problem, giving special emphasis to the numerical modelling, data selection and misfit quantification. A local-scale problem is described in Chap. 14, written by Florian Bleibinhaus, who used the acoustic wave equation to image the 2D velocity structure near the San Andreas fault. A highly efficient data reduction scheme applied to a synthetic problem at the global scale is the topic of Chap. 15, written by Yann Capdeville.

Writing a book on full seismic waveform modelling and inversion turned out to be more challenging than I expected, because it requires to cover a large variety of different topics without creating a monster that hardly anyone would attempt to read from the first to the last page. I have chosen the content such that it hopefully allows the reader to develop and apply his or her own full waveform modelling and inversion methods. My writing process was marked by many tough decisions concerning interesting topics that I was not able to present at all or not in detail. For instance, the large variety of numerical methods for the solution of the wave equation certainly

deserve at least one separate book. The same is true for the ample fields of non-linear optimisation and absorbing boundary methods that I had to present in a rather condensed form.

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