

# Preface

Full-3D seismic waveform inversion (F3DWI) refers to inversions that seek to minimize the discrepancies between the observed and synthetic seismic waveforms, wiggle for wiggle, by solving the three-dimensional acoustic or (visco) elastic wave equations. Its development is important both for the theoretical foundations of modern quantitative seismology and for the practical applications of seismological methods in exploring the Earth's interior. Driven by the rapid advances in high-performance computing technology and efficient numerical methods for solving 3D wave equations, significant progresses in F3DWI have been made in the past decade, especially in large-scale structural studies that use passive sources. This book is derived from what I have learned in the past 10 years. F3DWI is by its very nature both a theoretical and a practical subject. It requires a certain level of understanding of the underlying mathematical formulation, a collection of parallelized software tools and a certain amount of practice. In this book, I try to give an integrated treatment of all three.

In Chap. 1, I give a brief introduction about the subject of this book and some discussions that motivates the development of F3DWI. Throughout this book, a parallelized finite-difference (visco)elastic wave-equation solver is used for demonstration purposes. The mathematical formulation and detailed instructions about how to set up and run this wave-equation solver for F3DWI purposes are summarized in Chap. 2.

The theoretical framework for F3DWI developed in Chaps. 3–5 is quite general and encompasses both the adjoint method (F3DT-AW), which back-propagates the misfits from the receivers to image structures, and the scattering-integral method (F3DT-SI), which sets up the Gauss-Newton normal equation by calculating and storing the sensitivity (Fréchet) kernel for each misfit.

The derivation of F3DT-SI in our previous publications requires the use of the reciprocity principle and the receiver-side Green's tensor (RGT). In Chap. 3, I generalize the formulation of F3DT-SI through adjoint analysis and show that the requirement on reciprocity can be removed by replacing the RGT with the time-reversed adjoint Green's tensor. This result may open up the possibility of applying the “scattering-integral-type” methods based on Green's functions to a larger class of inverse problems, in which the reciprocity principle may not hold. In Chap. 3, I

also derive the adjoint representation theorem and its application in Chap. 5 simplifies the derivation of the adjoint method for constructing the gradient of the objective function and also the Hessian-vector product.

In our previous publications of F3DT-SI, the data sensitivity (Fréchet) kernels were derived for the broadband cross-correlation delay time and amplitude misfits with respect to isotropic, elastic model parameters. In Chap. 4, I extend the kernel formulation to arbitrary misfits defined for individual receivers, receiver arrays, pressure and rotational sensors. In Chap. 4, I also derive the kernels for anisotropy and anelastic attenuation.

In Chap. 5, I examine both F3DT-SI and F3DT-AW in the context of numerical optimization. Possible extensions and some practical aspects of both types of methods are discussed briefly. Some more detailed discussions about the practical aspects can be found in Chap. 6, in which I give detailed descriptions about our 3D model for the crustal structure in southern California, CVM-S4.26, as well as the inversion that produced this model.

I started working on this model back in 2007 when I was a postdoc at the Lamont-Doherty Earth Observatory (LDEO) of Columbia University. After I moved to University of Wyoming in 2008, I kept working on it by myself until En-Jui Lee joined my research group in 2009. In the next 5–6 years, both En-Jui and I spent a lot of time developing this model. As shown in Chaps. 2 and 6 and also in our journal publications, CVM-S4.26 can fit a quite extensive collection of seismograms in southern California (more than 50,000 earthquake seismograms and ambient-noise Green's functions) from the first-arriving P-wave to about 30-sec after the surface wave, almost wiggle by wiggle. CVM-S4.26 reveals small-scale crustal heterogeneities that were not well imaged in previous crustal-scale tomography studies. Some of those small-scale features in CVM-S4.26 are highly consistent with geology and results from previous localized ray-theoretic travel-time tomography studies. In Chap. 6, I show many cross-sections throughout the entire model and discuss possible correlations with other independent geologic and seismic evidences. Materials in Chap. 6 complement our journal publications about this model.

Readers who are not particularly interested in the intricacies of the theoretical aspects of F3DWI can skip the mathematical formulations and start with descriptions of the software package, also named F3DWI. Those descriptions, instructions and worked examples of F3DWI are grouped into sections with the title “Software” throughout this book. I wrote most of the Fortran and C/C++ codes for F3DWI when I was doing my postdoc at LDEO in 2006–2007. The parallel finite-difference wave-equation solver, AWP-ODC, was provided by Yifeng Cui and Kim Olsen at the Southern California Earthquake Center (SCEC). I modified it to work with the rest of my kernel and inversion codes. During the development of CVM-S4.26, I wrote a command-line user interface using python to simplify and streamline the entire inversion process based on F3DWI. The scalable, parallel LSQR code, SPLSQR, for solving very large sparse linear systems associated with the Gauss-Newton normal equation in F3DT-SI was developed in collaboration with Liqiang Wang and his students and collaborators at the Computer Science Department in University of Wyoming. The software and other materials related to the book can

be requested from <http://pochenfullwave.ddns.net>. Like many other research codes, it takes some effort and practice to fully understand the behavior of these codes and to be able to effectively utilize these codes in realistic applications. Your comments, suggestions (of references), questions, corrections about the codes and the book are very much appreciated and please email them to [pochengeophysics@gmail.com](mailto:pochengeophysics@gmail.com) or [pchen@uwyo.edu](mailto:pchen@uwyo.edu).

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