

Preface

Avec tout ce que je sais, on pourrait faire un livre. Il est vrai qu'avec tout ce que je ne sais pas, on pourrait faire une bibliothèque.

Sacha Guitry

After working on research topics related to seismic tomography for a quarter of a century, I decided it was time to write down all I know about the topic – but not in a grand unifying tome that covers everything from first principles to numerical applications. First of all, I have little patience for mathematical niceties; second, and more importantly, I wrote this book for the *practitioners* of the craft of seismic tomography. Those who go out into the field to collect data usually have no time for proofs of convergence or existence. The intended reader of this book is therefore an observational seismologist or helioseismologist who is not interested in lengthy derivations nor in the subtleties that fascinate the theoreticians, but who wants to understand the assumptions behind algorithms, even if these are mathematically intricate, and develop an understanding of the conditions for their validity, which forms the basis of that priceless commodity: scientific intuition. The level is such that it could be used for a one-semester course at upper undergraduate or beginning graduate level, perhaps following up on an introductory course based on Shearer [307] or Stein and Wysession [343]. Despite covering a wide range of topics, I have tried to keep it short (hence the title), while not economizing on references that may provide more detail if needed. As for references, choice is inevitable, and I have generally given preference to easily accessible papers in the English language. I realize that this gives short shrift to articles from Eastern Europe, Japan and China. This is unfortunate and I offer my apologies to colleagues in these countries.

The book is roughly divided into three parts. The basic theory of wave propa-

gation and scattering needed to compute Fréchet (sensitivity) kernels for seismic tomography is expanded in the first half of the book. Although I made an attempt to write this as a self-contained part, even here I often steer away from lengthy derivations that the interested reader can find in the more general seismological literature, and strive instead to make results at least intuitively acceptable. I then discuss observations, paying attention to both the ambient noise and the capabilities of modern, digital, broadband instrumentation. The last part of the book is devoted to the tomographic inversion and imaging itself. I restrict the material to *transmission* tomography. The nonlinearities associated with reflection seismology form a topic apart, worthy of a monograph of equal or greater length than this book.

As a geophysicist, I have written this book from a ‘terrestrial’ viewpoint. Where the links with helioseismology are obvious, I have ventured onto the playing field of solar astronomy as well, mainly to demonstrate the large affinity between the two research fields and to help astronomers to recognize parallel developments more easily. However, geophysicists interested in the fascinating topics of helio- and astroseismology do well to consult other sources for an expert introduction into these fields. The lecture notes by Christensen-Dalsgaard [58] provide a general and very readable introduction to the theory of stellar oscillations. The ‘living review’ by Gizon and Birch [118] gives an up-to-date account of methods and results in local helioseismology. A special issue of *Astronomische Nachrichten* edited by Thierry Corbard, Laurent Gizon and Markus Roth [65] is an excellent source of information on current techniques and future plans and provides a wealth of further references.

If you are a student of the field, and undertake the journey of reading this book from first to last chapter, I hope that at the end you will not feel as though you have done the proverbial grand tour of six European cities in seven days. But I cannot deny that I try to cover a very large range of topics, each with its own jargon and notation. I have tried to stay close to notations one commonly finds in the literature. This implies that the same symbol is sometimes used with different meaning in different chapters. Usually, that meaning is clear from the context, but occasionally I have felt the need to explicitly comment on peculiarities in notation.

A special case is the notation of vectors, tensors and matrices. Throughout the book we deal with physical vectors such as the force $\mathbf{f} = (f_x, f_y, f_z)$, that have tensor-properties and are conceptually different from N -tuples such as the data ‘vector’ $\mathbf{d} = (d_1, d_2, \dots, d_N)$ that we encounter in the last few chapters. I use the same bold font for both, and avoid the transpose notation (e.g. \mathbf{d}^T) that toggles between row and column vectors. A dot product $\mathbf{a} \cdot \mathbf{b}$ denotes $\sum_i a_i b_i$, without the complex conjugation (if it is needed, as in the definition of an inner product for normal modes in Chapter 9, it is explicitly used in the notation, e.g. $\mathbf{a} \cdot \mathbf{b}^*$). A

matrix vector product such as $\sum_j A_{ij}b_j$ is written as $\mathbf{A}\mathbf{b}$, and quadratic products are therefore written as $\mathbf{a} \cdot \mathbf{A}\mathbf{b}$. The transpose of \mathbf{A} is written as \mathbf{A}^T .

During the writing of this book, I have become painfully aware that the half life of a typo or sign convention or even error in math must be measured in weeks or months, not days. In view of the many that have been found before submitting the manuscript, some will undoubtedly remain. I shall be very grateful for readers to contact me about these.

Software for the computation of finite-frequency kernels is publicly available at the software website of CIG (Computational Infrastructure for Geodynamics)[†]. In the text I refer to this as the *Software repository*.

Much of the research described in this book could never have been accomplished without the steady support of science foundations in a number of countries; in my own case the Dutch science foundation NWO and, over the last fifteen years, the National Science Foundation in the US. Program directors like Robin Reichlin at NSF, who remain largely anonymous and rarely share in the glory, play a crucial role in allowing science to advance in the best way possible and making sure taxpayers' money is well spent. The ESA/NASA Solar and Heliospheric Observatory was instrumental in the acquisition of very high quality data for solar seismology as witnessed by some of the illustrations in this book.

Both as a researcher and as a teacher of the topic, I always felt a strong need for one text that covers all important aspects of the multidisciplinary science of seismic tomography. I started to write this book during a sabbatical in 2005 with the intent to defy Richards' law (that one should multiply the expected time until submission – two years in my case – by π). That I succeeded is largely due to the help I received from many people. I wish to thank my colleagues at Geoazur of the Université de Nice/Sophia Antipolis, the Laboratoire de Géophysique Interne et Tectonophysique of the Université Joseph Fourier in Grenoble and the Institut de Physique du Globe in Paris, who all provided hospitable hiding space during the various stages of writing this book. A number of geoscientists and astronomers provided figures, valuable information, or commented on parts or all of earlier drafts of this book: Sebastien Chevrot, Jon Claerbout, Huub Douma, Adam Dziewon-ski, Bob Engdahl, Jim Fowler, Laurent Gizon, Brad Hindman, Shu-Huei Hung, Eystein Husebye, Alexander Kosovichev, Gabi Laske, Suzan van der Lee, Will Levandowski, Tolya Levshin, Guy Masters, Jean-Paul Montagner, Tarje Nissen-Meyer, Mark Panning, Jeroen Ritsema, Barbara Romanowicz, Géneviève Roult, Frederik Simons, Karin Sigloch, Roel Snieder, Toshiro Tanimoto, Albert Tarrantola, Yue Tian, Jean Virieux, Cecily Wolfe, and Ying Zhou. I am very grateful to them and wish to make clear that the responsibility for any errors that survive is

[†] <http://geodynamics.org/cig/software/packages/seismo/>

mine and mine alone. My beloved Julia Frey corrected more than a few prepositions and other peculiarities in my use of the English language. But mostly I am indebted to my close friend Tony Dahlen with whom I collaborated intensively at Princeton and who died before he could see the final version of this book. Without his sharp theoretical insight and intellectual driving force the field of seismic tomography would never have evolved as rapidly and actively as it has.