Seismic Inversion

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About the Author

Gerard Schuster is currently a professor of geophysics at King Abdullah University Science and Technology (KAUST) and an adjunct professor at University of Utah and University of Wyoming. He was the founder and director of the Utah Tomography and Modeling/Migration consortium from 1987 to 2009 and is now the co-director and founder of the Center for Fluid Modeling and Seismic Imaging at KAUST. Schuster helped pioneer seismic interferometry and its practical applications in applied geophysics through his active research program and through his extensive publications. He also has extensive experience in developing innovative migration and inversion methods for both exploration and earthquake seismology.

Schuster has an MS (1982) and a PhD (1984) from Columbia University and was a postdoctoral researcher there from 1984–1985. From 1985 to 2009, he was a professor of geophysics at University of Utah. He left Utah to start his current position as professor of geophysics at KAUST in 2009. He received a number of teaching and research awards while at University of Utah. He was editor of GEOPHYSICS 2004–2005 and was awarded SEG's Virgil Kauffman Gold Medal in 2010 for his work in seismic interferometry. He was the SEG Distinguished Lecturer in 2013.

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Preface

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. I have written this book with the hope that it will be largely comprehensible 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 (e.g., Snell's law and ray tracing). For those not familiar with the terminology and methods of seismic exploration, a brief introduction is provided in the Appendix of Chapter 1. Computational labs are provided for most of the chapters, and some field data labs are given as well.

MATLAB and Fortran labs at the end of some chapters are used to deepen the reader's understanding of the concepts and their implementation. Such exercises are introduced early and geophysical applications are presented in every chapter. For the non-geophysicist, geophysical concepts are introduced with intuitive arguments, and their description by rigorous theory is deferred to later chapters.

The lab exercises in the Computational Toolkit can be found at http://csim.kaust.edu.sa/web/SeismicInversion and http://utam.gg.utah.edu/SeismicInversion/; the exercises can be accessed using the login Paulina and the password Brozina.

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I also thank the following reviewers who provided very valuable edits: Abduhlrahman Alshuhail, Abdullah AlTheyab, Pawan Bharawadj, Chaiwoot Boonyasiriwat, Derrick Cerwinsky, Yuqing Chen, Wei Dai, Li Deng, Craig Douglas, Gaurav Dutta, Zongcai Feng, Shihang Feng, Bowen Guo, Sherif Hanafy, Libo Huang, Kai Lu, Veronika Pelletier, Mrinal Sinha, Ahmad Tarhini, Xin Wang, Han Yu, Ge Zhan, Zhendong Zhang, and Sanzong Zhang. The last two chapters on image-domain inversion are modified versions of Sanzong Zhang's dissertation, and the description of the viscoacoustic gradient in Chapter 15 is a modified version of an appendix in Gaurav Dutta's dissertation. The derivation of the VTI adjoint equations are from Mrinal Sinha and Bowen Guo. I also thank Yue Wang and Ken Bube for their derivation of the adjoint of the viscoelastic wave equation in Chapter 22. Bowen Guo also helped generalize the gradient equation for inverting trim statics with the wave equation. Zongcai Feng scrupulously checked the accuracy of the equations in Chapters 20 through 23.

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Notation Convention

- $\mathbb{R}^N$ denotes the N-dimensional real vector space.
- $\mathbb{C}^N$ denotes the N-dimensional complex vector space.
- A column vector will be denoted by boldface lower-case letters. For example, $\mathbf{x} = [x_1, x_2, ..., x_N]^T$ represents the $N \times 1$ vector where x_i is the i^{th} element of $\mathbf{x}$.
- A matrix will be denoted by boldface upper-case letters. For example, $\mathbf{A} \in \mathbb{R}^{M\times N}$ represents an $M \times N$ real matrix whose ij^{th} element is denoted by A_{ij}.
- An order-of-magnitude estimate of a variable whose precise value is unknown is an estimate rounded to the nearest power of ten.
- A scalar will be denoted by lower-case letters.
- Subscripts are usually used to denote the element index of a vector or matrix.
- Superscripts with parentheses are used to denote an iterate of a vector or matrix. For example, $\mathbf{x}^{(k)}$ denotes the k^{th} iterate of an iterative scheme.
- $\mathbf{x} \cdot \mathbf{y} = \mathbf{x}^T\mathbf{y} =< \mathbf{x}, \mathbf{y} >= \sum_{i=1}^N x_i^* y_i$ represents a dot product or an inner product between finite-dimensional vectors $\mathbf{x}$ and $\mathbf{y}$.
- MATLAB syntax is sometimes used to represent vectors or matrices. For example, $[a \;\; b; c \;\; d]$ denotes the matrix

$$\begin{bmatrix} a & b \\ c & d \end{bmatrix}.$$

- $||\mathbf{x}||_1$ denotes the 1-norm of the $N \times 1$ vector $\mathbf{x}$ which is equal to

$$||\mathbf{x}||_1 = \sum_{i=1}^N |x_i|.$$

- $|\mathbf{x}| = ||\mathbf{x}||_2$ denotes the 2-norm or Euclidean norm of the $N \times 1$ vector $\mathbf{x}$ which is equal to

$$||\mathbf{x}||_2 = \sqrt{\sum_{i=1}^N x_i^2}.$$

  If the subscript is missing then the 2-norm is indicated, l_2 for a discrete vector and L_2 for a well-behaved function of a continuous variable.

- The length of a vector $\mathbf{x}$ will often be denoted as $|\mathbf{x}|$ rather than $||\mathbf{x}||_2$.
- $||\mathbf{x}||_p$ denotes the p-norm or Euclidean norm of the $N \times 1$ vector $\mathbf{x}$ which is equal to

$$||\mathbf{x}||_p = \left(\sum_{i=1}^N x_i^p \right)^{\frac{1}{p}}.$$

- $\hat{\mathbf{x}} = \frac{\mathbf{x}}{|\mathbf{x}|}$ denotes the unit vector.
- $\mathbf{A}^*$ denotes the complex conjugate of the matrix $\mathbf{A}$.
- $\mathbf{A}^T$ denotes the transpose of matrix $\mathbf{A}$. We will often insist it also means the transpose and complex conjugated matrix $\mathbf{A}$.
- $\mathbf{A}^\dagger$ denotes the conjugated and transposed matrix $\mathbf{A}$.
- $\star$ denotes temporal convolution. For example, assuming $f(t)$ and $g(t)$ are real continuous functions of the scalar variable t and are square integrable then

$$f(t) \star g(t) = \int_{-\infty}^{\infty} f(t-\tau)g(\tau)d\tau = \int_{-\infty}^{\infty} f(\tau)g(t-\tau)d\tau. \tag{1}$$

- $\otimes$ denotes temporal correlation. For example, assuming $f(t)$ and $g(t)$ are real continuous functions of the scalar variable t and are square integrable then

$$f(t) \otimes g(t) = f(-t) \star g(t) = \int_{-\infty}^{\infty} f(\tau)g(t+\tau)d\tau. \tag{2}$$

- $\mathcal{F}[f(t)] = F(\omega)$ denotes the Fourier transform of $f(t)$ and $\mathcal{F}^{-1}[F(\omega)]$ is the inverse Fourier transform of $F(\omega)$. For example,

$$F(\omega) = \mathcal{F}[f(t)] = \int_{-\infty}^{\infty} f(t)e^{-i\omega t}dt,$$

$$f(t) = \mathcal{F}^{-1}[F(\omega)] = \frac{1}{2\pi}\int_{-\infty}^{\infty} F(\omega)e^{i\omega t}d\omega,$$

$$\frac{d^n f(t)}{dt^n} = \frac{1}{2\pi}\int_{-\infty}^{\infty} (i\omega)^n F(\omega)e^{i\omega t}d\omega,$$

$$f(-t) = \mathcal{F}^{-1}[F(\omega)^*],$$

$$\mathcal{F}[f(t) \star g(t)] = F(\omega)G(\omega),$$

$$
\begin{aligned}
\mathcal{F}[f(t) \otimes g(t)] &= \mathcal{F}[f(-t) \star g(t)] = F(\omega)^* G(\omega), \\
f(t) \star g(t) &= \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega) G(\omega) e^{i\omega t} d\omega, \\
f(t) \otimes g(t) &= \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega)^* G(\omega) e^{i\omega t} d\omega, \\
f(t) \otimes g(t)|_{t=0} &= \int_{-\infty}^{\infty} f(\tau) g(\tau) d\tau \\
&= \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega)^* G(\omega) d\omega, \\
f(t) \otimes f(t)|_{t=0} &= \int_{-\infty}^{\infty} f(\tau)^2 d\tau = \frac{1}{2\pi} \int_{-\infty}^{\infty} |F(\omega)|^2 d\omega.
\end{aligned} \tag{3}
$$

- The Dirac delta function $\delta(t)$ is a generalized function (Zemanian, 1965) that is zero everywhere on the real line, except at $t = 0$. The Dirac delta function has a broadband spectrum with the constant amplitude 1:

$$
\delta(t - t') = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{i\omega(t-t')} d\omega. \tag{4}
$$

For a smooth function $f(\tau)$, the delta function has the sifting property:

$$
f(t) = \int_{-\infty}^{\infty} f(\tau) \delta(\tau - t) d\tau. \tag{5}
$$

Abbreviations

ABC	absorbing boundary condition
ADCIG	angle-domain common image gather
CAG	common angle gather
CFL	Courant-Friedrichs-Lewy
CG	conjugate gradient
CIG	common image gather
CMG	common midpoint gather
COG	common offset gather
CSG	common shot gather
DFP	Davidon-Fletcher-Powell
DM	diffraction-stack migration
DOD	domain of dependence
DSO	differential semblance optimization
EWT	early arrival wave equation tomography
FD	finite difference
FE	finite element
FWI	full waveform inversion
GCV	generalized cross validation
GDM	generalized diffraction-stack migration
GDSO	generalized differential semblance optimization
GIDI	generalized image domain inversion
GOM	Gulf of Mexico
IDI	image domain inversion
KM	Kirchhoff migration
LSM	least squares migration
LSRTM	least squares reverse time migration
MD	migration deconvolution
MVA	migration velocity analysis
NLCG	nonlinear conjugate gradient
NMO	normal moveout
PDE	partial differential equation
PML	perfectly matched layer
PSTM	prestack time migration
QN	quasi-Newton
RTM	reverse time migration
SD	steepest descent
SE	spectral element
SLS	standard linear solid
SPD	symmetric positive definite
SSP	surface seismic profile
SV	singular vector
VSP	vertical seismic profile
WT	wave equation traveltime tomography
WTW	wave equation traveltime and waveform tomography
ZO	zero offset

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