

SEISMIC INTERFEROMETRY

Seismic interferometry is an exciting new field in geophysics that utilizes multiple scattering events to provide unprecedented views of the Earth's subsurface structures. This is the first book to describe the theory and practice of seismic interferometry with an emphasis on applications in exploration seismology.

The book is written at a level suitable for physical scientists who have some familiarity with the principles of wave propagation, Fourier transforms, and numerical analysis. Exercises are provided at the end of each chapter, and many chapters are supplemented by online MATLAB codes (available at www.cambridge.org/schuster) that illustrate important ideas and allow readers to generate synthetic traces and invert these to determine the Earth's reflectivity structure. Later chapters reinforce these principles by deriving the rigorous mathematics of seismic interferometry.

The book includes examples that apply interferometric imaging to both synthetic data and field data from applied geophysics, but examples and chapters devoted to earthquake applications are also incorporated. Presenting many new concepts for the first time, the book is a valuable reference for academic researchers and oil industry professionals seeking to learn more about this technique. It can also be used to teach a one-semester course for advanced students in geophysics and petroleum engineering.

Gerard Thomas Schuster received his Ph.D. in Geophysics from Columbia University in 1984. He took up a faculty position at the University of Utah in 1985, where he is currently Professor of Geophysics and the founder and director of the Utah Tomography and Modeling/Migration (UTAM) consortium of oil, gas, and mining companies. He served as Chief Editor of the journal *Geophysics* from 2004 to 2005, and was a co-recipient of the 2008 Eötvös prize from the EAGE for the best paper in the journal *Geophysical Prospecting*. Professor Schuster has been invited to give short courses in seismic imaging and signal processing methods to major petroleum exploration companies throughout the world, and was the invited Society of Petroleum Engineers (SPE) Distinguished Lecturer for 1998–1999.

Cambridge University Press
978-0-521-87124-2 - Seismic Interferometry
Gerard Schuster
Frontmatter
[More information](#)

SEISMIC INTERFEROMETRY

GERARD SCHUSTER

University of Utah, USA



CAMBRIDGE
UNIVERSITY PRESS

Cambridge University Press
978-0-521-87124-2 - Seismic Interferometry
Gerard Schuster
Frontmatter
[More information](#)

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo, Delhi

Cambridge University Press
The Edinburgh Building, Cambridge CB2 8RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9780521871242

© G. T. Schuster 2009

This publication is in copyright. Subject to statutory exception
and to the provisions of relevant collective licensing agreements,
no reproduction of any part may take place without
the written permission of Cambridge University Press.

First published 2009

Printed in the United Kingdom at the University Press, Cambridge

A catalog record for this publication is available from the British Library

ISBN 978-0-521-87124-2 hardback

Cambridge University Press has no responsibility for the persistence or
accuracy of URLs for external or third-party internet websites referred to
in this publication, and does not guarantee that any content on such
websites is, or will remain, accurate or appropriate.

Contents

<i>Preface</i>	<i>page ix</i>
1 Introduction	1
1.1 Seismic interferometry	1
1.2 Benefits and liabilities	12
1.3 Historical development of seismic interferometry	15
1.4 Organization of the book	18
1.5 Exercises	19
1.6 Appendix 1: Basics of exploration seismology	23
1.7 Appendix 2: Fourier identities	27
1.8 Appendix 3: Glossary	28
1.9 Appendix 4: MATLAB codes	29
2 Reciprocity equations of convolution and correlation types	30
2.1 Green’s functions	31
2.2 Reciprocity equation of convolution type	32
2.3 Reciprocity equation of correlation type	36
2.4 Stationary phase integration	40
2.5 Seismic migration	44
2.6 Interferometric migration	49
2.7 Summary	49
2.8 Exercises	50
2.9 Appendix 1: Causal and acausal Green’s functions	53
2.10 Appendix 2: Principal value contribution of dipoles	54
2.11 Appendix 3: Sommerfeld radiation conditions	56
2.12 Appendix 4: Adjoint operator	57
2.13 Appendix 5: Forward and backward wave propagation	58
2.14 Appendix 6: MATLAB codes	60

vi	<i>Contents</i>	
3	VSP → SWP correlation transform	61
3.1	Introduction	61
3.2	VSP → SWP correlation transform	62
3.3	Stationary phase analysis	63
3.4	Benefits	67
3.5	Liabilities	70
3.6	Numerical implementation	72
3.7	Numerical results	75
3.8	Summary	77
3.9	Exercises	79
3.10	Appendix 1: MATLAB codes	80
3.11	Appendix 2: Interferometric imaging = RTM	80
3.12	Appendix 3: Source wavefield deconvolution	82
3.13	Appendix 4: 3D reciprocity equation by quadrature	83
4	VSP → SSP correlation transform	86
4.1	VSP → SSP correlation transform	86
4.2	Benefits and limitations of the VSP → SSP transform	93
4.3	Truncation artifacts, VSP geometry, and model illumination	95
4.4	Numerical examples	98
4.5	Summary	105
4.6	Exercises	106
4.7	Appendix 1: Computer codes	108
5	VSP → SSP convolution transform	109
5.1	Introduction	109
5.2	VSP → SSP convolution transform	110
5.3	Transforming VSP traveltimes into SSP traveltimes	113
5.4	Numerical results	114
5.5	Summary	120
5.6	Exercises	120
5.7	Appendix 1: MATLAB codes	123
6	SSP → SSP correlation transform	124
6.1	Transforming SSP multiples into SSP primaries	125
6.2	Benefits	128
6.3	Interferometric interpolation of seismic data	131
6.4	Numerical examples	132
6.5	Summary	143
6.6	Exercises	144
6.7	Appendix 1: Computer codes	145

6.8	Appendix 2: Surface wave prediction by the SSP $\rightarrow$ SSP transform	146
7	VSP $\rightarrow$ VSP correlation transform	147
7.1	VSP $\rightarrow$ SSP $\rightarrow$ VSP correlation transform	147
7.2	VSP $\rightarrow$ SWP $\rightarrow$ VSP correlation transform	150
7.3	Interpolation and extrapolation of VSP and OBS data	152
7.4	Numerical results	156
7.5	Summary	160
7.6	Exercises	161
7.7	Appendix 1: Computer codes	161
8	SSP $\rightarrow$ VSP $\rightarrow$ SWP transforms	162
8.1	SSP $\rightarrow$ VSP correlation transform	162
8.2	SSP $\rightarrow$ SWP correlation transform	164
8.3	Natural Green's functions	165
8.4	Numerical examples	166
8.5	Summary	174
8.6	Exercises	176
9	Traveltime interferometry	177
9.1	Introduction	177
9.2	Theory	178
9.3	Numerical results	184
9.4	Summary	187
9.5	Exercises	187
10	Stochastic interferometry	189
10.1	Theory	190
10.2	Numerical examples	194
10.3	Summary	204
10.4	Exercises	205
10.5	Appendix 1: Processing steps for drill-bit data	208
10.6	Appendix 2: MATLAB codes	210
11	Interferometric source estimation	211
11.1	Source imaging condition	211
11.2	Summation imaging condition	215
11.3	Validation of super-resolution and super-stacking	221
11.4	Summation imaging condition and correlated traces	226
11.5	Summary	227
11.6	Exercises	228

Cambridge University Press
978-0-521-87124-2 - Seismic Interferometry
Gerard Schuster
Frontmatter
[More information](#)

viii	<i>Contents</i>	
12	Body wave earthquake interferometry	229
12.1	Introduction	229
12.2	Theory	234
12.3	Numerical tests	242
12.4	Summary	248
12.5	Exercises	248
	<i>References</i>	250
	<i>Index</i>	259

Preface

This book describes the theory and practice of seismic interferometry, with an emphasis on applications in exploration seismology. It is written at the level where it can be understood by physical scientists who have some familiarity with the principles of wave propagation, Fourier transforms, and numerical analysis. The book can be taught as a one-semester course for advanced seniors and graduate students in the physical sciences and engineering. Exercises are given at the end of each chapter, and many chapters come with MATLAB codes that illustrate important ideas.

Correlating a pair of recorded seismic traces with one another and summing the resulting correlogram for different shot records¹ is the basic processing step of seismic interferometry. This typically results in a new trace with a virtual source and/or receiver location, also known as a redatumed trace. The redatumed trace simulates a trace as if a real shot and/or receiver were at the new datum.

The redatuming procedure has been used by the exploration geophysics community since the early 1970s, except one of the traces in the correlation pair is computed by a numerical procedure such as ray tracing while the other trace is naturally recorded. Ray tracing, or more generally numerical modeling, uses an imperfect model of the Earth's velocity distribution which leads to defocusing errors in model-based redatuming. In contrast, seismic interferometry is free of such problems because it only uses recorded traces in the correlation.² This freedom also allows one to utilize all of the events in the trace, including higher-order multiples and coherent noise such as surface waves, leading to enhanced resolution, illumination, and the signal-to-noise ratio in the reflectivity image.

The key principles of interferometry are heuristically described in Chapter 1, and by its end the diligent reader will be using MATLAB code to generate synthetic traces, redatum these data by summed cross-correlations, and invert the redatumed

¹ The seismograms recorded for a single source are sometimes called a shot record.

² However, defocusing problems in interferometry arise because of the limited extent of the sources and receivers.

traces for the Earth's reflectivity structure. Later chapters reinforce these principles by deriving the rigorous mathematics of seismic interferometry. In particular, the governing equation of interferometry is known as the reciprocity equation of correlation type (Wapenaar, 2004). Many examples are presented that apply interferometric imaging to both synthetic data and field data. The terminology and examples mostly come from the applied geophysics community, but there are examples and chapters devoted to earthquake applications. The non-geophysicist will benefit by reading the brief overview of exploration seismology in Appendix 1 of the first chapter.

About 90 percent of the book deals with deterministic source interferometry where individual sources are excited with no temporal overlap in their seismic signals. This type of data is collected by applied geophysicists, and is also recorded by earthquake seismologists for strong teleseismic earthquakes. In contrast, diffuse wavefield interferometry introduced in Chapter 10 analyzes seismic wavefields with random amplitudes, phases, and directions of propagation. This topic has led to significant success for earthquake seismologists in inverting seismic surface waves recorded by passive earthquake networks. It will enjoy even more popularity as large arrays such as the USArray become more widely deployed. Diffuse wavefield interferometry in applied geophysics is undergoing vigorous scrutiny, but has not yet developed applications with widespread use. One of the dreams of exploration geophysicists is to monitor the health of oil reservoirs by passive seismic interferometry.

Finally, this book not only summarizes some of the most recent advances of seismic interferometry but also presents a partial road map for future research. It is my hope that the graduate-student reader will gain enough understanding so she or he can help complete and expand this road map.

Acknowledgments

The author wishes to thank the long-term support provided by the sponsors of the Utah Tomography and Modeling/Migration consortium. Their continued financial support through both lean and bountiful years was necessary in bringing this book to fruition. The American Chemical Society is acknowledged for their 2007–2009 grant ACS-45408-AC8 that resulted in the development of seismic source and reflectivity estimation with a natural Green's function. The National Science Foundation is also thanked for providing early seed grant money to study earthquake applications of seismic interferometry. Robert Nowack is to be thanked as a supportive co-principal investigator, and Jianming Sheng is acknowledged for his innovative work with earthquake interferometry. Jim Pechmann and Kris Pankow are thanked for their invaluable guidance in working with teleseismic data.

A crucial jumpstart in our interferometry research was the DOE grant given to us in the mid 1990s under the direction of Fred Followill and Lew Katz. They exposed the author to Katz' innovative method of 1D autocorrelogram imaging of VSP data. This was followed in 2000 with the generous invitation by Jon Claerbout to visit Stanford during four months of the author's sabbatical, which was crucial in putting together some pieces of the interferometry puzzle. Some of these pieces were given life by the expert computer implementation of Jianhua Yu, a pioneer of numerical VSP interferometry. His interferometry work during 2000–2004 yielded many VSP results that finally convinced the skeptics about its advantages over conventional VSP imaging. The early field data sets were provided by BP under the guidance of Brian Hornby. Drs. Hornby and Jianhua Yu (now at BP) pushed the practical application of VSP interferometry to new limits by applying these methods to important Gulf of Mexico data.

I also thank Sam Brown, Weiping Cao, Wei Dai, Steve Ihnen, Robert Nowack, Evert Slob, Yonghe Sun, Gerrit Toxopeus, and Dan Trentman, J. van der Neut, and Xin Wang for helping to edit portions of this manuscript. They made many valuable suggestions in both style and content that helped to improve the quality of this book. Robert Nowack and Yonghe Sun suggested many useful changes in every chapter. Dan Trentman is gratefully acknowledged for writing a Perl script that created the index in this book.

Finally, many thanks go to the following students or postdocs who generously donated their results or MATLAB codes to this book: Chaiwoot Boonyasiriwat, Weiping Cao, Shuqian Dong, Mark Fan, Sherif Hanafy, Ruiqing He, Zhiyong Jiang, Jianming Sheng, Yibo Wang, Yanwei Xue, Xiang Xiao, and Ge Zhan. Their diligent efforts have resulted in many interesting results, some of which are contained in this book.