Foreword

William W. Symes*

The inversion hypothesis suggests that a useful way to interpret reflection seismograms and other geophysical data is to create a detailed mechanical model of the earth which predicts them. Then the contents of the model provide a more immediate basis for interpretation than do the data themselves. This ambitious program has become thinkable in recent years as computers grow powerful enough to simulate seismic waves in believably complex multidimensional models. Judging the merit of the inversion hypothesis will require both a collection of functional algorithms to invert geophysical data, and a database of experience in using the resulting model based interpretations in an industrial setting. The latter is impossible without the former, and up to now the former has been lacking.

The central goal of The Rice Inversion Project is to render inversion of reflection seismograms feasible on an industrial scale: that is, to design efficient algorithms which produce inversion results of well understood reliability. We believe that several important obstacles standing in the way of this goal are essentially mathematical and computational in nature, and that we are well positioned to grapple with these. We also believe that contact with field data, and with people who apply seismology to solve industrial problems, is essential to keep our mathematical and computational work properly focused.

By the time of the last review meeting in summer 1993, TRIP had accomplished a number of its initial objectives, as decribed in the 1993 Annual Report. Chief of these was the development of a velocity inversion algorithm, differential semblance optimization, capable of estimating wave velocities directly from waveform data using efficient gradient based optimization methods - in fact the only method advanced so far which demonstrates these abilities for any significant class of real or realistic problems. The current domain of DSO consists of layered problems and 2D problems with mild structural features. Within this domain, DSO yields kinematically accurate velocity estimates using far fewer simulation and/or migrations than do alternative algorithms based on stochastic optimization techniques. The reader will find some progress toward extending the domain of DSO to arbitrary kinematic structures in this report.

The pages which follow present the accomplishments of The Rice Inversion Project over the past year. Some of the high points of 1993-94:

- development of efficient linearized viscoacoustic inversion, based on TRIP-developed finite difference simulator;

*The Rice Inversion Project, Department of Computational and Applied Mathematics, Rice University, Houston TX 77251-1892

- preliminary work on the Mobil AVO data set using acoustic and viscoacoustic linearized inversion;
- development of Kirchhoff simulation, migration, and linearized inversion tools based on accurate finite difference solution of the eikonal and transport equations;
- demonstration of an effective algorithm for incorporation of geologic/structural constraints in velocity models produced by differential semblance waveform inversion;
- extensive use of the DSO/PVM distributed implementation on workstation clusters;
- preliminary assessment of a *controlled illumination* variant of differential semblance for velocity estimation in complex structure;
- vastly improved understanding of the mathematical basis of velocity analysis, leading to designs for numerous algorithmic improvements in DSO.

Reports on these topics appear in the following pages, together with articles on various aspects of wave simulation, source estimation, reflection from caustics, and the object oriented design of inversion software.

During the spring TRIP sponsors received the 2.0 release of the project software package. This release contained several new features:

- on line documentation for all utility modules;
- documented examples for linear and nonlinear inversion;
- improved installation and maintenance tools;
- definition and auxiliary modules for IEEE disk image SEGY I/O, enabling data exchange with ProMAX on Sun and IBM platforms.

A new release, tentatively titled 3.2, is in the final testing and cleanup stages, and should ship to sponsors shortly. Notable new features of 3.2 include:

- Kirchhoff simulation, migration, and inversion capability, based on the work reported in this volume;
- 2D viscoacoustic finite difference simulation, migration, and inversion, also described in the following pages;
- DSO/PVM parallel distributed inversion for the primaries only constant density acousic model;
- further major improvements in installation and maintenance, including automated generation of all low-level makefiles and machine- or environment-dependent source.

While the course of research is intrinsically unpredictable, I can name a few topics to which TRIP will certainly devote some effort in the coming months:

- Further exploration of the Mobil AVO dataset and other field datasets: velocity control *via* DSO, inversion for source radiation pattern, multiparameter inversion for AVO interpretation;
- 3D Kirchhoff simulation, migration, and inversion;
- Improved finite difference simulators: automatic gridding and coefficient selection for maximal bandlimited accuracy, design for generic domain decomposition;
- Investigation of controlled illumination and other techniques for waveform inversion in the presence of multiarrivals and caustics;
- Automatic parameter selection, efficient gradient computation, and extended convexity properties of DSO through the dual formulation;
- Explicit object oriented implementation of the next generation of DSO using C++, greater variety of optimization tools;
- All-node and distributed/shared memory implementations of parallel DSO, hierarchical parallelism using domain decomposed finite difference schemes and parallelized Kirchhoff.

As always, the achievements of TRIP depend on the generous support of our sponsors: for 1994, Advance Geophysical, Amoco Research, Conoco Inc., Cray Research, Exxon Production Research Co, Interactive Network Technologies, Mobil Research and Development Co., and Texaco Inc.. We continue to enjoy additional vital support from several sources. The Office of Naval Research funds the work of several graduate research assistants on topics of interest both to the Navy and to industry (source estimation - Sue Minkoff; caustic reflection - Cliff Nolan; viscoelastic simulation and inversion - Joakim Blanch), through grant N00014-89-J1115. The Schlumberger Foundation helped defray the costs of the project over the last twelve months with a very generous gift. The State of Texas has provided significant support to the work on geophysical inversion at Rice for the past several years, through matching funds granted to the Geophysical Parallel Computation Project of the Center for Research in Parallel Computation, and NSF Science and Technology Center headquartered at Rice University. IBM will support a student to work on parallel aspects of seismic inversion software in 1994-1995, and the National Science Foundation has awarded a grant to support another student in theoretical work on wave propagation. The Shell Development Co. will support an undergraduate research associate to implement a parallel version of DSO under a shared/distributed memory system developed at Rice, through a gift to the Computer Science Department.

Rice University and the Department of Computational and Applied Mathematics have provided a supportive environment for TRIP. We are grateful to Dean Michael Carroll of the George R. Brown School of Engineering and to Dr. Jean Vorhaben of the Office of Sponsored Research for their help and encouragement. The staff of CAAM - Fran Mailan, Vivian Choi, Linda Neyra, and Michael Pearlman - give unstintingly of their time and labor and contribute greatly to the success of TRIP and all other ventures in the department. In particular, Michael Pearlman is responsible for the superb computing

environment which we enjoy, and Linda Neyra takes on each year the organization of the annual meeting with predictably gratifying results.

I offer the following pages to the reader in the hope that they will be found enjoyable and informative, and in the expectation that the work reported here will lead in the coming months to further progress towards resolving outstanding issues of applied geophysical inversion.

Who's Who in TRIP

The group is composed of a director, four post-doctoral associates and six graduate students. The following "Who is who" list, gives details about the current position, the professional and academic histories, the society affiliation and the research interests for each member of the group.

Name: William W. Symes
Current Position: Professor of Computational and Applied Mathematics, Chair of the Department, Rice University; Director of The Rice Inversion Project.
Employment history: 1974-1977, Lecturer, University of British Columbia, 1977-1979 Visiting Assistant Professor, University of Wisconsin; 1979-1984 Assistant Associate Professor, Michigan State University; 1983-present Rice University.
Academic history: 1971 A.B. University of California, Berkeley; 1975 Ph.D Harvard University.
Society Affiliation: SEG, SIAM, AMS.
Areas of professional interest: Inverse problems in seismology, mathematical/numerical analysis of wave propagation.

Name: Michel Kern
Current Position: Research Scientist, INRIA, France.
Employment history: 1988 - present Research Scientist, INRIA, France (on leave 1991-1993) 1991 - 1993 Rice University.
Academic history: 1984 Ecole des Mines de Paris; 1985 M.S University of Paris VI; 1987 Ph.D University of Paris IX.
Society Affiliation: SMAI, SEG
Areas of professional interest: Mathematical/Numerical Analysis of Wave Propagation, Inverse Problems, Scientific Computing.

Name: Alain Sei
Current Position: Research Scientist, Rice University.
Employment history: May 1988 - August 1988 Internship at Elf Aquitaine Company, France; September 1988 - October 1991 Ph.D Candidate at the French Petroleum Institute (IFP) Paris, France; January 1993 - present Research Scientist, Rice University.
Academic history: 1986 Bachelor in Mathematics, University of Pau, France; 1988 Masters in Mathematics, University of Pau, France; 1991 Ph.D in Applied Mathematics, University of Paris IX, France.
Society Affiliation: SIAM, AMS, SEG, MAA
Areas of professional interest: Mathematical and numerical analysis of wave propagation problems. Seismic modeling and inversion.

Name: Roelof Jan Versteeg
Current Position: Research Scientist, Rice University.
Employment history: September 1988 - October 1991 : Ph.D Candidate at the French

Petroleum Institute (IFP) Paris, France; January 1992 - September 1992 Research Scientist, Amoco Production Company; September 1992 - present Research Scientist, Rice University.
Academic history: 1988 M.Sc Geophysics, M.Sc Geology, State University of Utrecht, Netherlands; 1991 Ph.D in Geophysics, University of Paris VII, France.
Society Affiliation: SEG, EAEG, IAS.
Areas of professional interest: Migration, inversion, seismic interpretation.

Name: QUANG HUY TRAN
Current Position: Visiting Research Associate
Employment history: Institut Francais du Petrole
Academic history: Ecole des mines de Paris, Ph.D Ecole des Mines de Paris, June 1994.
Areas of professional interest: Scientific computing, numerical analysis, supercomputing.

Name: MAISSA ABD-EL MAGEED
Current Position: Graduate student, Rice University.
Employment history: 1983-1991 Teaching Assistant University of Alexandria, Egypt.
Academic history: 1983 A.B. Mathematics University of Alexandria; 1987 Masters, Image Processing University of Alexandria.
Areas of professional interest: Tomography, multi-path traveltime.

Name: JOAKIM OSCAR BLANCH
Current Position: PhD. Candidate, Rice University.
Employment history: Alfa-Laval, SAAB-Scania, ABB, SATTech.
Academic history: M. Sc. Uppsala University (Physics Engineering), University of Houston (Mechanical Engineering), Rice University (Geology and Geophysics/Computational Science and Engineering).
Society Affiliations: SEG, SIAM.
Areas of professional interest: Wave modeling, inverse problems.

Name: MARK STEVEN GOCKENBACH
Current Position: Research Associate, Department of Computational and Applied Mathematics, Rice University
Employment history: 1990 - 1992 Visiting Lecturer of Mathematics, Indiana University **Academic history**: 1985 B.S. University of Illinois at Urbana-Champaign; 1987 M.S. Illinois State University; Further graduate study at University of Illinois at Urbana-Champaign; 1994 M.A., Ph.D. Rice University
Areas of professional interest: Numerical algorithms for nonlinear programming. Inverse problems in seismology.

Name: SUSAN E. MINKOFF
Current Position: Graduate Student.

Employment history: 1988-1989 Senior Systems Analyst, Exxon Company, U.S.A; 1986-1988 Systems Analyst, Exxon Company, U.S.A.
Academic history: 1993 M.A. degree from the Dept. of Computational and Applied Mathematics, Rice University; 1986 B.S. degree in mathematics and computer science, Duke University.
Society Affiliation: AMS, SIAM.
Areas of professional interest: Partial differential equations, modeling.

Name: CLIFF NOLAN
Current Position: Graduate student, Rice University
Employment history: Numerous Summer jobs
Academic history: B.Sc. University College Galway, Ireland, M.Sc. Trinity College Dublin, Ireland.
Society Affiliation: SIAM, AMS.
Areas of professional interest: Inverse problems.

Name: HUA SONG
Current Position: Ph.D Candidate
Employment history: Aug. 1991 - present Research Assistant, Rice University; Oct. 1989 - Aug. 1991 Teaching Assistant, Ohio State University; Sept. 1987 - Oct. 1989 Research Assistant, Computing Center, Chinese Academy of Sciences, Beijing, PRC
Academic history: Aug. 1991 - present PhD program, Department of Computational and Applied Mathematics, Rice University; Oct. 1989 - Aug. 1991 PhD program, Department of Mathematics, The Ohio State University; July 1987 MS degree, Harbin Institute of Technology, Harbin, PRC; 1984 BS degree, Beijing Normal University, Beijing, PRC
Society Affiliation: AMS, SIAM.
Areas of professional interest: Inverse problems of PDEs, mathematical and numerical analysis of wave propagation phenomena.

List of Publications of TRIP

Title : A Family of Schemes for the Computation of Elastic Waves
Author : Alain Sei
Journal : SIAM Journal on Scientific Computing
Status : Accepted
Date : April 1994

Title : Error Analysis of Numerical Schemes for the Wave Equation in Heterogeneous Media
Authors : Alain Sei and W.W. Symes
Journal : Applied Numerical Mathematics
Status : Accepted
Date : May 1994

Title : Dispersion Analysis of Numerical Wave Propagation and its Computational Consequences
Authors : Alain Sei and W.W. Symes
Journal : Journal of Scientific Computing
Status : Submitted
Date : December 1993

Title : Computing the Gradient of the Traveltime Error without Ray-tracing
Authors : Alain Sei and W.W. Symes
Journal : Proceedings of the 64th SEG Meeting, Los Angeles, California
Status : Accepted
Date : July 1994

Title : Geologic Constraints on Seismic Inversion
Authors : Roelof Versteeg and W.W. Symes
Journal : Proceedings of the 64th SEG Meeting, Los Angeles, California
Status : Accepted
Date : July 1994

Title : Parallelizing a Seismic Inversion Code using PVM
Authors : Roelof Versteeg and W.W. Symes
Journal : Proceedings of the 64th SEG Meeting, Los Angeles, California
Status : Accepted
Date : July 1994

Title : Seismic Velocity Inversion via Regularization of a Related Problem
Authors : Mark S. Gockenbach, William W. Symes and Richard A. Tapia
Journal : Inverse Problems
Status : Submitted
Date : July 1994

Title : Inverting Waveforms in the Presence of Caustics
Author : William W. Symes
Journal : Journal of Geophysical Research
Status : Submitted
Date : May 1994

Title : Linear Inversion for 2D Viscoacoustic Media
Authors : Joakim Blanch and William W. Symes
Journal : Proceedings of the 64th SEG Meeting, Los Angeles, California
Status : Accepted
Date : July 1994

Title : Viscoelastic Modeling and Inversion of a Marine Data Set
Authors : Susan E. Minkoff and William W. Symes
Journal : Proceedings of the 64th SEG Meeting, Los Angeles, California
Status : Accepted
Date : July 1994

Title : Galerkin-Wavelet Modeling of Wave Propagation: Optimal Finite-Difference Stencil Design
Authors : J.O.A Robertsson, J.O Blanch, W. W. Symes and C.S Burrus
Journal : Mathematical and Computational Modeling
Status : Appeared, Vol 19, pp 31-38
Date : January 1994

Title : Modeling of a Constant Q: Methodology and Algorithm for an Efficient and Optimally
Author : J.O Blanch, J.O.A Robertsson and W. W. Symes
Journal : Geophysics
Status : Accepted
Date : June 1994

Title : Viscoelastic Modeling and Inversion of a Marine Data Set
Author : Sue Minkoff
Journal : Proceedings of the 64th SEG Meeting, Los Angeles, California
Status : Accepted
Date : July 1994

Title : Estimating the Energy Source and Reflectivity by Seismic Inversion
Author : Sue Minkoff
Journal : Proceedings of the SPIE 1994 International Symposium on Optics, Imaging, and Instrumentation
Status : Accepted
Date : July 1994

Table of Contents

1 - Foreword
William W. Symes

2 - Preliminary Results of Viscoelastic Inversion on the Mobil Dataset
William W. Symes, Roelof Versteeg, Joakim Blanch and Alain Sei

3 - Viscoelastic Modeling and Inversion of a Marine Data Set
Susan E. Minkoff and William W. Symes

4 - Geologic Constraints on Seismic Inversion
Roelof Versteeg and William W. Symes

5 - Estimating the Energy Source and Reflectivity by Seismic Inversion
Susan E. Minkoff and William W. Symes

6 - Linear Inversion for 2D Viscoacoustic Media
Joakim Blanch and William W. Symes

7 - Linear Inversion in Layered Viscoacoustic Media using a Time Domain Method
Joakim Blanch and William W. Symes

8 - Modeling of a Constant Q: Methodology and Algorithm for an Efficient and Optimally Inexpensive Viscoelastic Technique
Joakim Blanch, Johan Robertsson and William W. Symes

9 - Kirchhoff Simulation, Migration, and Inversion using Finite Difference Traveltimes and Amplitudes
Roelof Versteeg, William W. Symes, Alain Sei, and Quang Huy Tran

10 - Computing the Gradient of the Traveltime Error without Ray-tracing
Alain Sei and William W. Symes

11 - Error Analysis of Numerical Schemes for the Wave Equation in Heterogeneous Media
Alain Sei and William W. Symes

12 - Dispersion Analysis of Numerical Wave Propagation and its Computational Consequences
Alain Sei and William W. Symes

13 - Dispersion and Cost Analysis of some Finite Difference Schemes in One-Parameter Acoustic Wave Modelling
William W. Symes and Quang Huy Tran

14 - Galerkin-Wavelet Modeling of Wave Propagation: Optimal Finite-Difference Stencil Design
J.O.A Robertsson, J.O Blanch, W. W. Symes and C.S Burrus

15 - Implementation of the Conjuguate Gradient Algorithm in DSO
Susan E. Minkoff

16 - Inversion of Crosswell Seismogramms via Differential Semblance Optimization
Hua Song and William W. Symes

17 - On Crosswell Traveltime Tomography
Hua Song and William W. Symes

18 - Inverting Waveforms in the Presence of Caustics
William W. Symes

19 - Anomalous Reflections near a Caustic
Clifford J. Nolan

20 - An Abstract Analysis of Differential Semblance Optimization
Mark Gockenbach

21 - Convex Duality and Separable Inverse Problems in Wave propagation
William W. Symes

22 - Parallelizing a Seismic Inversion Code using PVM
Roelof Versteeg, Michel Kern and William W. Symes

23 - Object-oriented Desigh for Optimization and Inversion Software: a Proposal
Mark Gockenbach