Released to public domain under Creative Commons license type BY (https://creativecommons.org/licenses/by/4.0).
Copyright (c) 2010 SLIM group @ The University of British Columbia.

Natural Sciences and Engineering Research Council of Canada
Conseil de recherches en sciences naturelles et en génie du Canada

350 Albert Street
Ottawa, Canada
K1A 1H5

350, rue Albert
Ottawa, Canada
K1A 1H5

TERMS AND CONDITIONS OF AWARD
Grant Summary

File: CRDPJ 375142 - 08

Project Title: Dynamic Nonlinear Optimization for Imaging in Seismic Exploration (DNOISE)

Principal Investigator: F.J. Herrmann, Earth and Ocean Sciences, British Columbia

Industry Partners:
J. Faroppa, BG Group (Canada)
Z. Yu, British Petroleum Oil
B. VerWest, CGGVeritas SA
G. Hennenfent, Chevron Canada Resources Ltd
E. Keskula, ConocoPhillips
M. Hall, INOVA Geophysical Equipment Ltd
E.L. de Faria, Petrobras
S. Jaffer, Total SA
D. Nichols, Schlumberger (WesternGeco LLC)

Co-applicants:
M.P. Friedlander, Computer Science, British Columbia
O.Y. Yilmaz, Mathematics, British Columbia

Collaborators:
E.Y. Haber, British Columbia
A.M. Powell, Vanderbilt University
M.A. Saunders, Stanford University
C.C. Stolk, University of Twente
E. Verschuur, Delft University of Technology

Project Start Date: 2010/08/01 ***Project End Date:*** 2015/07/31

Report Due Date(s):

Progress Report 1	2011/05/01
Progress Report 2	2012/05/01
Progress Report 3	2013/05/01
Progress Report 4	2014/05/01
Final Report	2015/09/30

	Amount of Award:		***Industrial Contribution:*** CASH	IN KIND
1/5	$277,729	2010/08/01	$351,622.00	$15,000
2/5	$336,925	2011/08/01	$409,187.00	$15,000
3/5	$507,899	2012/08/01	$524,563.00	$15,000
4/5	$507,615	2013/08/01	$524,563.00	$15,000
5/5	$511,959	2014/08/01	$524,563.00	$15,000

NSERC Program Officer
Theresa Anderson
Research Partnerships Programs

Telephone: (613) 943-7830
Fax: (613) 992-5337
E-mail: Theresa.Anderson@nserc-crsng.gc.ca

Canada

Natural Sciences and Engineering Research Council of Canada
Conseil de recherches en sciences naturelles et en génie du Canada

FORM 101
Application for a Grant
PART I

Institutional Identifier			
System-ID (for NSERC use only) 85267398			Date 2010/09/16
Family name of applicant: Herrmann	Given name: Felix	Initial(s) of all given names: J	Personal identification no. (PIN): **Valid** 264073

Institution that will administer the grant: British Columbia	Language of application: [X] English [ ] French	Time (in hours per month) to be devoted to the proposed research / activity: 145

Type of grant applied for: Collaborative Research and Development Grant	For Strategic Projects, indicate the Target Area and the Research Topic; for Strategic Networks indicate the Target Area.

Title of proposal
Dynamic Nonlinear Optimization for Imaging in Seismic Exploration II (DNOISE II)

Provide a maximum of 10 key words that describe this proposal. Use commas to separate them.
seismic imaging, compressive sensing, sparsifying transforms, one-norm optimization, seismic data acquisition, seismic data process, seismic modeling, seismic imaging, full-waveform inversion, adjoint-state methods

Research subject code(s)		Area of application code(s)	
Primary	Secondary	Primary	Secondary
4302	3002	300	1203

CERTIFICATION/REQUIREMENTS

If this proposal involves any of the following, check the box(es) and submit the protocol to the university or college's certification committee.

Research involving : Humans [ ] Human pluripotent stem cells [ ] Animals [ ] Biohazards [ ]

Does any phase of the research described in this proposal a) take place outside an office or laboratory, or b) involve an undertaking as described in Part 1 of Appendix B?

[X] NO [ ] If YES to either question a) or b) – Appendices A and B must be completed

TOTAL AMOUNT REQUESTED FROM NSERC

Year 1	Year 2	Year 3	Year 4	Year 5
292,729	351,925	522,899	522,615	526,959

SIGNATURES (Refer to instructions "What do signatures mean?")

It is agreed that the general conditions governing grants as outlined in the NSERC *Program Guide for Professors* apply to any grant made pursuant to this application and are hereby accepted by the applicant and the applicant's employing institution.

Applicant

Head of department

Applicant's department, institution, tel. and fax nos., and e-mail
Earth and Ocean Sciences
British Columbia
Tel.: (604) 822-8628
FAX: (604) 822-6088
fherrmann@eos.ubc.ca

Dean of faculty

President of institution
(or representative)

The information collected on this form and appendices will be stored in the Personal Information Bank for the appropriate program.
PROTECTED WHEN COMPLETED

Version française disponible

Canada

Personal identification no. (PIN)	Family name of applicant
Valid 264073	Herrmann

CO-APPLICANTS

I have read the statement "What do signatures on the application mean?" in the accompanying instructions and agree to it.

PIN, family name and initial(s)	Research/ activity time (hours/month)	Organization	Signature
290824, Yilmaz, O	40	British Columbia	
290611, Friedlander, M	40	British Columbia	
264073, Herrmann, F.J	145	British Columbia	

CO-APPLICANTS' ORGANIZATIONS AND/OR SUPPORTING ORGANIZATIONS (if organization different from page 1)

It is agreed that the general conditions governing grants as outlined in the NSERC *Program Guide for Professors,* as well as the statements "What do signatures on the application mean?" and "Summary of proposal for public release" in the accompanying instructions, apply to any grant made pursuant to this application and are hereby accepted by the organization.

Family name and given name of signing officer, title of position, and name of organization	Signature
Dr. Peter Haynes VP Exploration and Production BG Canada	
Dr. Zhou Yu Research scientist British Petroleum	
Dr. Thomas Koleszar Chief Geophysicist BP Canada Energy Company	
Dr. Andrew Deighan Principle Geophysicist BG Canada	

Personal identification no. (PIN)	Family name of applicant
Valid 264073	Herrmann

CO-APPLICANTS' ORGANIZATIONS AND / OR SUPPORTING ORGANIZATIONS (if organization different from page 1)

Family name and given name of signing officer, title of position, and name of organization	Signature
Dr. Mark Votier Chief Technology Officer BG Group	
Dr. Carlos Eduardo Theodoro Geophysicist Petrobras	
Dr. Sverre Brandsberg-Dahl Program Manager Petroleum Geo-Services (PGS)	
Dr. Dave Nichols Research Director WesternGeco	
Dr. Scott Morton Armada Hess Corporation	
Dr. Bruce Verwest Research Manager CGGVeritas	
Dr. Alexander Calvert Geophysicist ION - GX Technology	
Dr. Roald van Borselen Program Manager Petroleum Geo-Services (PGS)	
Dr. Gilles Hennenfent Geophysicist Chevron	

 Use additional page(s) if necessary. Version française disponible

Canada

PROTECTED WHEN COMPLETED

Personal identification no. (PIN)	Family name of applicant
Valid 264073	Herrmann

Before completing this section, read the instructions for the definition of collaborators in the Eligibility Criteria section of the Program Guide for Professors.

COLLABORATORS

PIN, family name and initial(s)	Research/ activity time (hours/month)	Organization / Department
Stolk, C		Twente University of Technolog,
Powel, A		Vanderbilt University,
Saunders, M		Stanford University,
Haber, E		British Columbia,
Erlangga, Y		Al-Faisal University,
Verschuur, D		Delft University of Technology,

Personal identification no. (PIN)	Family name of applicant
Valid 264073	Herrmann

SUMMARY OF PROPOSAL FOR PUBLIC RELEASE (Use plain language.)

This plain language summary will be available to the public if your proposal is funded. Although it is not mandatory, you may choose to include your business telephone number and/or your e-mail address to facilitate contact with the public and the media about your research.

Business telephone no. (optional): +1 (604) 822-8628
E-mail address (optional): fherrmann@eos.ubc.ca

DNOISE II: Dynamic Nonlinear Optimization for Imaging in Seismic Exploration is a multidisciplinary research project that involves faculty from the Mathematics, Computer Science, and Earth and Ocean Sciences Departments at the University of British Columbia. DNOISE II constitutes a transformative research program towards a new paradigm in seismic exploration where the acquisition- and processing-related costs are no longer determined by the survey area and discretization but by transform-domain sparsity of the final result. In this approach, we rid ourselves from the confinements of conventional overly stringent sampling criteria that call for regular sampling with sequentiual sources at Nyquist rates. By adapting the principles of compressive sensing, DNOISE II promotes a ground-up formulation for seismic imaging where adverse subsampling-related artifacts are removed by intelligent simultaneous-acquisition design and recovery by transform-domain sparsity promotion. This development---in conjunction with our track records in sparse recovery and time-harmonic Helmholtz solvers---puts us in an unique position to deliver on fundamental breakthroughs in the development and implementation of the next-generation of processing, imaging, and full-waveform inversion solutions.

Other Language Version of Summary (optional).

Personal identification no. (PIN)	Family name of applicant
Valid 264073	Herrmann

ACTIVITY SCHEDULE
(Refer to instructions to see if this section applies to your application. Use additional page(s) if necessary.)

Milestone	Description of activities	Anticipated starting date	Anticipated completion date
4.1.(i) Sparsifying transforms	We will conduct a theoretical and empirical study comparing different transform techniques such as contourlets, surfacelets, shearlets, and wave atoms, for recovery problems that involve missing traces, missing angular frequencies, and simultaneous shots.	2009-08-01	2014-07-31
4.1.(ii)(a) Multidimensional generalization of jitter sampli	We will design & implement multidimensional extensions of subsampling grids that reduce the imprint of coherent aliases.	2009-08-01	2012-07-31
4.1.(ii)(b) CS matrices for simultaneous acquisition	We will design & implement CS matrices that are both physically realizable and have fast matrix-free implementations. We will also work on theoretical performance estimates.	2009-08-01	2014-07-31
4.1.(iii) Development of parallel one-norm solvers	We will design & implement one-norm solvers for extremely large seismic problems including parallelization with domain decomposition.	2009-08-01	2014-07-31
4.1.(iv) Development of sparse recovery with reciprocity	We will design & implement a trace-interpolation method that exploits (approximate) source-receiver reciprocity.	2009-08-01	2010-05-31
4.1.(v)(a) One-norm recovery with joint-sparsity promotion	We will develop theory for joint sparsity recovery and apply these algorithms on data after DMO or imaging.	2009-08-01	2011-07-31
4.1.(v)(b) Design regularization functionals for joint spar	We will design & implement penalty functionals that exploit joint sparsity including focusing.	2009-08-01	2012-07-31
4.1.(v)(c) Development of joint sparsity-promoting solvers	We will design & implement norm-one solvers that exploit joint sparsity including focusing.	2009-08-01	2013-07-31

Personal identification no. (PIN)	Family name of applicant
Valid 264073	Herrmann

ACTIVITY SCHEDULE
(Refer to instructions to see if this section applies to your application. Use additional page(s) if necessary.)

Milestone	Description of activities	Anticipated starting date	Anticipated completion date
4.1.(vi) Development of non-convex sparsity-promoting solver	We will develop theory and concrete implementations for sparse recovery with non-convex sparsity norms.	2011-08-01	2013-08-31
4.2.(i)(a) Matched filtering with frequency regularization	We will implement a matched filter that includes penalties for across Fourier-domain fluctuations amongst the curvelet-domain matched-filter coefficients.	2009-08-01	2010-05-31
4.2.(i)(b) Matched-filtering with phase-space distances	We will design & implement regularization functionals that properly incorporate the phase-space distance (in position, angle, and scale) between curvelets.	2009-08-01	2010-05-31
4.2.(i)(c) Complex-valued curvelet-domain matched filtering	We will design & implement complex-valued matched filters volumes. This will allow for controlled phase corrections.	2009-08-01	2010-12-31
4.2.(i)(d) Curvelet-domain matched-filtering for 3-D data	We will implement our curvelet-domain matched filter for 3-D seismic lines.	2009-08-01	2010-08-31
4.2.(ii) Multi-term Bayesian wavefield separation	We will design & implement a multi-term separation scheme that uses n-1 multi-term predictions and the total data as input and produces estimates for n signal components by sparsity promotion.	2010-01-01	2010-12-31
4.2.(iii) Primary estimation by wavefield inversion	We will implement a methodology to estimate the free-surface impulse response with separable least squares	2010-04-01	2013-03-31
4.2.(iv) Sparsity-promoting primary estimation	We will implement a methodology to estimate the free-surface impulse response with separable least squares and sparsity promotion	2012-07-31	2014-03-31

Personal identification no. (PIN)	Family name of applicant
Valid 264073	Herrmann

ACTIVITY SCHEDULE
(Refer to instructions to see if this section applies to your application. Use additional page(s) if necessary.)

Milestone	Description of activities	Anticipated starting date	Anticipated completion date
4.2.(v) Surface-wave mitigation by wavefield inversion	We will implement a methodology estimate the free-surface impulse response with separable least squares and sparsity promotion	2009-08-01	2014-03-31
4.3.(i) Parallel Helmholtz solver 2D	Design & implementation of the parallel (over shot and frequency) implicit time-harmonic preconditioned Helmholtz solver in 2D based on the multilevel Krylov method.	2009-08-01	2010-12-31
4.3.(ii) Preconditioners for multiple right-hand sides	Design & implementation of an implicit time-harmonic multigrid preconditioner for system of equations with multiple right-hand sides.	2010-06-01	2014-07-31
4.3.(iii) Elastic Helmholtz solver	Design & implementation of an implicit time-harmonic Helmholtz solver for elastic wave propagation.	2011-07-01	2014-07-31
4.3.(iv) Simultaneous-source simulation	Design & implementation of full-waveform modeling using simultaneous sources and sparse recovery.	2009-08-01	2010-12-31
4.4.(i) Poststack migration based on time-harmonic Helmholtz	Design & implementation of parallelized poststack imaging using the adjoint-state methods for the time-harmonic Helmholtz equation.	2009-08-01	2010-08-31
4.4.(ii) Preconditioning of least-squares migration	Design & implementation of a preconditioner for the reduced Hessian based on curvelet-domain matched filtrering	2010-04-01	2011-03-31
4.4.(iii) Compressive poststack migration	Design & implementation of dimensionality reduction for post-stack least-squares migration. Included development of a large-scale Newton-type one-norm solver.	2010-07-01	2013-06-30

Personal identification no. (PIN)	Family name of applicant
Valid 264073	Herrmann

ACTIVITY SCHEDULE
(Refer to instructions to see if this section applies to your application. Use additional page(s) if necessary.)

Milestone	Description of activities	Anticipated starting date	Anticipated completion date
4.4.(iv) Integration of primary estimation	Design & implementation of gradient and Newton updates that include primary prediction. This involves the integration on our primary-prediction work in full-waveform inversion.	2010-02-01	2013-01-31
4.4.(v) Multiscale full-waveform inversion with sparsity	Design & implementation of compressive full-waveform with multiscale (joint) sparsity promotion. Investigate different options to compute the Newton updates.	2010-02-01	2013-01-31
4.4.(vi) Full-waveform with extensions	Design & implementation of full-waveform inversion based on extended modeling and focusing. This work involves extended modeling and focusing.	2010-05-01	2014-07-31
4.5.(i) SPOT: Reimplementation of Sparco	Design & implementation of SPOT -- A Linear-Operator Toolbox using object-oriented technology.	2009-08-01	2009-12-31
4.5.(ii) pSPOT --- A parallel Linear-Operator Toolbox	Design & implementation of our parallel object-oriented development environment based on SPOT	2010-01-01	2011-08-31
4.5.(iii) nSPOT -- A nonLinear Operator Toolbox	Design & implementation of an object-oriented toolbox for nonlinear operators to prototype PDE constrained optimization problems.	2010-04-01	2012-03-31
4.5.(iv) Application interface	We will design and implement and application interface of our parallel development environment to PROMAX.	2013-09-01	2014-07-31

Personal identification no. (PIN)	Family name of applicant
Valid 264073	Herrmann

See instructions for further details.

PROPOSED EXPENDITURES

	Year 1		Year 2		Year 3	
	Cash	In-kind	Cash	In-kind	Cash	In-kind
1) Salaries and benefits						
a) Students	118,015		189,725		337,381	
b) Postdoctoral fellows	242,000		242,000		302,500	
c) Technical/professional assistants	99,750	0	158,788	0	236,726	0
d)	0		0		0	
2) Equipment or facility						
a) Purchase or rental	35,500	0	6,000	0	14,500	0
b) Operation and maintenance costs	23,633		15,956		53,000	
c) User fees	15,000	0	15,000	0	15,000	0
d)	0		0		0	
3) Materials and supplies						
a) Office material	3,410	0	1,930	0	1,930	0
b)	0		0		0	
c)	0	0	0	0	0	0
4) Travel						
a) Conferences	25,855		36,400		46,550	
b) Field work	0	0	0	0	0	0
c) Project-related travel	6,000		6,000		7,000	
d) Project meeting	5,000		5,000		5,000	
5) Dissemination						
a) Publication costs	4,000		4,000		6,500	
b) Report+Meeting	8,500		22,000		22,000	
6) Technology transfer activities						
a) Field trials	0		0		0	
b) Prototypes	0		0		0	
c) Software development	0		0		0	
TOTAL PROPOSED EXPENDITURES	586,663		702,799		1,048,087	
Total support from industry	293,934		350,874		525,188	
Total support from university						
Total support from other sources						
AMOUNT REQUESTED FROM NSERC	292,729		351,925		522,899	

PROTECTED WHEN COMPLETED
Version française disponible

Canada

Personal identification no. (PIN)	Family name of applicant
Valid 264073	Herrmann

See instructions for further details.

PROPOSED EXPENDITURES

	Year 4		Year 5		
	Cash	In-kind	Cash	In-kind	
1) Salaries and benefits					
a) Students	337,381		337,381		
b) Postdoctoral fellows	302,500		302,500		
c) Technical/professional assistants	244,286	0	244,286	0	
d)	0		0		
2) Equipment or facility					
a) Purchase or rental	10,000	0	10,500	0	
b) Operation and maintenance costs	49,656		53,500		
c) User fees	15,000	0	15,000	0	
d)	0		0		
3) Materials and supplies					
a) Office material	1,930	0	1,930	0	
b)	0		0		
c)	0	0	0	0	
4) Travel					
a) Conferences	46,550		46,550		
b) Field work	0	0	0	0	
c) Project-related travel	7,000		7,000		
d) Project meeting	5,000		5,000		
5) Dissemination					
a) Publication costs	6,500		6,500		
b) Report+Meeting	22,000		22,000		
6) Technology transfer activities					
a) Field trials	0		0		
b) Prototypes	0		0		
c) Software development	0		0		
TOTAL PROPOSED EXPENDITURES	1,047,803		1,052,147		
Total support from industry	525,188		525,188		
Total support from university					
Total support from other sources					
AMOUNT REQUESTED FROM NSERC	522,615		526,959		

Personal identification no. (PIN)	Family name of applicant
Valid 264073	Herrmann

Before completing this section, read the instructions for contributions from supporting organizations and consult the *Use of Grant Funds* section in the NSERC *Program Guide for Professors* concerning the eligibility of expenditures for the direct costs of research and the regulations governing the use of grant funds, and *Guidelines for Evaluating Cost-Sharing Ratios and In-Kind Contributions in University-Industry Collaborations* regarding the eligibility of in-kind contributions.

Name of supporting organization

BG International

CONTRIBUTIONS FROM SUPPORTING ORGANIZATIONS

	Year 1	Year 2	Year 3	Year 4	Year 5
Cash contributions to direct costs of research (Transfer amounts to page five (5); except those for the Ship Time program.)	59,061	59,061	59,061	59,061	59,061
In-kind contributions to direct costs of research					
1) Salaries for scientific and technical staff	0	0	0	0	0
2) Donation of equipment, software	0	0	0	0	0
3) Donation of material	0	0	0	0	0
4) Field work logistics	0	0	0	0	0
5) Provision of services	0	0	0	0	0
6)	0	0	0	0	0
Total of in-kind contributions to direct costs of research	0	0	0	0	0
In-kind contributions to indirect costs of research (not leveraged)					
1) Use of organization's facilities					
2) Salaries of managerial and administrative staff	5,000	5,000	5,000	5,000	5,000
3)	0	0	0	0	0
Total of all in-kind contributions	5,000	5,000	5,000	5,000	5,000
Contribution to postsecondary institution overhead	8,438	8,438	8,438	8,438	8,438

Personal identification no. (PIN)	Family name of applicant
Valid 264073	Herrmann

Before completing this section, read the instructions for contributions from supporting organizations and consult the *Use of Grant Funds* section in the NSERC *Program Guide for Professors* concerning the eligibility of expenditures for the direct costs of research and the regulations governing the use of grant funds, and *Guidelines for Evaluating Cost-Sharing Ratios and In-Kind Contributions in University-Industry Collaborations* regarding the eligibility of in-kind contributions.

Name of supporting organization

British Petroleum

CONTRIBUTIONS FROM SUPPORTING ORGANIZATIONS

	Year 1	Year 2	Year 3	Year 4	Year 5
Cash contributions to direct costs of research (Transfer amounts to page five (5); except those for the Ship Time program.)	118,122	59,061	59,061	59,061	59,061
In-kind contributions to direct costs of research					
1) Salaries for scientific and technical staff	0	0	0	0	0
2) Donation of equipment, software	0	0	0	0	0
3) Donation of material	0	0	0	0	0
4) Field work logistics	0	0	0	0	0
5) Provision of services	0	0	0	0	0
6)	0	0	0	0	0
Total of in-kind contributions to direct costs of research	0	0	0	0	0
In-kind contributions to indirect costs of research (not leveraged)					
1) Use of organization's facilities					
2) Salaries of managerial and administrative staff	10,000	5,000	5,000	5,000	5,000
3)	0	0	0	0	0
Total of all in-kind contributions	10,000	5,000	5,000	5,000	5,000
Contribution to postsecondary institution overhead	16,875	8,438	8,438	8,438	8,438

Personal identification no. (PIN)	Family name of applicant
Valid 264073	Herrmann

Before completing this section, read the instructions for contributions from supporting organizations and consult the *Use of Grant Funds* section in the NSERC *Program Guide for Professors* concerning the eligibility of expenditures for the direct costs of research and the regulations governing the use of grant funds, and *Guidelines for Evaluating Cost-Sharing Ratios and In-Kind Contributions in University-Industry Collaborations* regarding the eligibility of in-kind contributions.

Name of supporting organization

Schlumberger

CONTRIBUTIONS FROM SUPPORTING ORGANIZATIONS

	Year 1	Year 2	Year 3	Year 4	Year 5
Cash contributions to direct costs of research (Transfer amounts to page five (5); except those for the Ship Time program.)	57,688	57,688	57,688	57,688	57,688
In-kind contributions to direct costs of research					
1) Salaries for scientific and technical staff	0	0	0	0	0
2) Donation of equipment, software	0	0	0	0	0
3) Donation of material	0	0	0	0	0
4) Field work logistics	0	0	0	0	0
5) Provision of services	0	0	0	0	0
6)	0	0	0	0	0
Total of in-kind contributions to direct costs of research	0	0	0	0	0
In-kind contributions to indirect costs of research (not leveraged)					
1) Use of organization's facilities					
2) Salaries of managerial and administrative staff	5,000	5,000	5,000	5,000	5,000
3)	0	0	0	0	0
Total of all in-kind contributions	5,000	5,000	5,000	5,000	5,000
Contribution to postsecondary institution overhead	9,813	9,813	9,813	9,813	9,813

Canada

Personal identification no. (PIN)	Family name of applicant
Valid 264073	Herrmann

Before completing this section, read the instructions for contributions from supporting organizations and consult the *Use of Grant Funds* section in the NSERC *Program Guide for Professors* concerning the eligibility of expenditures for the direct costs of research and the regulations governing the use of grant funds, and *Guidelines for Evaluating Cost-Sharing Ratios and In-Kind Contributions in University-Industry Collaborations* regarding the eligibility of in-kind contributions.

Name of supporting organization

CGGVeritas

CONTRIBUTIONS FROM SUPPORTING ORGANIZATIONS

	Year 1	Year 2	Year 3	Year 4	Year 5
Cash contributions to direct costs of research (Transfer amounts to page five (5); except those for the Ship Time program.)			57,688	57,688	57,688
In-kind contributions to direct costs of research					
1) Salaries for scientific and technical staff	0	0	0	0	0
2) Donation of equipment, software	0	0	0	0	0
3) Donation of material	0	0	0	0	0
4) Field work logistics	0	0	0	0	0
5) Provision of services	0	0	0	0	0
6)	0	0	0	0	0
Total of in-kind contributions to direct costs of research	0	0	0	0	0
In-kind contributions to indirect costs of research (not leveraged)					
1) Use of organization's facilities					
2) Salaries of managerial and administrative staff			5,000	5,000	5,000
3)	0	0	0	0	0
Total of all in-kind contributions	0	0	5,000	5,000	5,000
Contribution to postsecondary institution overhead		9,813	9,813	9,813	9,813

Personal identification no. (PIN)	Family name of applicant
Valid 264073	Herrmann

Before completing this section, read the instructions for contributions from supporting organizations and consult the *Use of Grant Funds* section in the NSERC *Program Guide for Professors* concerning the eligibility of expenditures for the direct costs of research and the regulations governing the use of grant funds, and *Guidelines for Evaluating Cost-Sharing Ratios and In-Kind Contributions in University-Industry Collaborations* regarding the eligibility of in-kind contributions.

Name of supporting organization

ION

CONTRIBUTIONS FROM SUPPORTING ORGANIZATIONS

	Year 1	Year 2	Year 3	Year 4	Year 5
Cash contributions to direct costs of research (Transfer amounts to page five (5); except those for the Ship Time program.)		57,688	57,688	57,688	57,688
In-kind contributions to direct costs of research					
1) Salaries for scientific and technical staff	0	0	0	0	0
2) Donation of equipment, software	0	0	0	0	0
3) Donation of material	0	0	0	0	0
4) Field work logistics	0	0	0	0	0
5) Provision of services	0	0	0	0	0
6)	0	0	0	0	0
Total of in-kind contributions to direct costs of research	0	0	0	0	0
In-kind contributions to indirect costs of research (not leveraged)					
1) Use of organization's facilities					
2) Salaries of managerial and administrative staff		5,000	5,000	5,000	5,000
3) Cash Contributions	0	0	0	0	0
Total of all in-kind contributions	0	5,000	5,000	5,000	5,000
Contribution to postsecondary institution overhead		9,813	9,813	9,813	9,813

Canadä

Personal identification no. (PIN)	Family name of applicant
Valid 264073	Herrmann

Before completing this section, read the instructions for contributions from supporting organizations and consult the *Use of Grant Funds* section in the NSERC *Program Guide for Professors* concerning the eligibility of expenditures for the direct costs of research and the regulations governing the use of grant funds, and *Guidelines for Evaluating Cost-Sharing Ratios and In-Kind Contributions in University-Industry Collaborations* regarding the eligibility of in-kind contributions.

Name of supporting organization

Petroleum Geo-Services (PGS)

CONTRIBUTIONS FROM SUPPORTING ORGANIZATIONS

	Year 1	Year 2	Year 3	Year 4	Year 5
Cash contributions to direct costs of research (Transfer amounts to page five (5); except those for the Ship Time program.)		58,313	58,313	58,313	58,313
In-kind contributions to direct costs of research					
1) Salaries for scientific and technical staff	0	0	0	0	0
2) Donation of equipment, software	0	0	0	0	0
3) Donation of material	0	0	0	0	0
4) Field work logistics	0	0	0	0	0
5) Provision of services	0	0	0	0	0
6)	0	0	0	0	0
Total of in-kind contributions to direct costs of research	0	0	0	0	0
In-kind contributions to indirect costs of research (not leveraged)					
1) Use of organization's facilities					
2) Salaries of managerial and administrative staff		5,000	5,000	5,000	5,000
3) Cash Contributions	0	0	0	0	0
Total of all in-kind contributions	0	5,000	5,000	5,000	5,000
Contribution to postsecondary institution overhead		9,188	9,188	9,188	9,188

Canada

Personal identification no. (PIN)	Family name of applicant
Valid 264073	Herrmann

Before completing this section, read the instructions for contributions from supporting organizations and consult the *Use of Grant Funds* section in the NSERC *Program Guide for Professors* concerning the eligibility of expenditures for the direct costs of research and the regulations governing the use of grant funds, and *Guidelines for Evaluating Cost-Sharing Ratios and In-Kind Contributions in University-Industry Collaborations* regarding the eligibility of in-kind contributions.

Name of supporting organization

Armada Hess

CONTRIBUTIONS FROM SUPPORTING ORGANIZATIONS

	Year 1	Year 2	Year 3	Year 4	Year 5
Cash contributions to direct costs of research (Transfer amounts to page five (5); except those for the Ship Time program.)			58,313	58,313	58,313
In-kind contributions to direct costs of research					
1) Salaries for scientific and technical staff	0	0	0	0	0
2) Donation of equipment, software	0	0	0	0	0
3) Donation of material	0	0	0	0	0
4) Field work logistics	0	0	0	0	0
5) Provision of services	0	0	0	0	0
6)	0	0	0	0	0
Total of in-kind contributions to direct costs of research	0	0	0	0	0
In-kind contributions to indirect costs of research (not leveraged)					
1) Use of organization's facilities					
2) Salaries of managerial and administrative staff			5,000	5,000	5,000
3) Cash Contributions	0	0	0	0	0
Total of all in-kind contributions	0	0	5,000	5,000	5,000
Contribution to postsecondary institution overhead			9,188	9,188	9,188

Personal identification no. (PIN)	Family name of applicant
Valid 264073	Herrmann

Before completing this section, read the instructions for contributions from supporting organizations and consult the *Use of Grant Funds* section in the NSERC *Program Guide for Professors* concerning the eligibility of expenditures for the direct costs of research and the regulations governing the use of grant funds, and *Guidelines for Evaluating Cost-Sharing Ratios and In-Kind Contributions in University-Industry Collaborations* regarding the eligibility of in-kind contributions.

Name of supporting organization

Chevron

CONTRIBUTIONS FROM SUPPORTING ORGANIZATIONS

	Year 1	Year 2	Year 3	Year 4	Year 5
Cash contributions to direct costs of research (Transfer amounts to page five (5); except those for the Ship Time program.)	59,063	59,063	59,063	59,063	59,063
In-kind contributions to direct costs of research					
1) Salaries for scientific and technical staff	0	0	0	0	0
2) Donation of equipment, software	0	0	0	0	0
3) Donation of material	0	0	0	0	0
4) Field work logistics	0	0	0	0	0
5) Provision of services	0	0	0	0	0
6)	0	0	0	0	0
Total of in-kind contributions to direct costs of research	0	0	0	0	0
In-kind contributions to indirect costs of research (not leveraged)					
1) Use of organization's facilities	0	0	0	0	0
2) Salaries of managerial and administrative staff	5,000	5,000	5,000	5,000	5,000
3)	0	0	0	0	0
Total of all in-kind contributions	5,000	5,000	5,000	5,000	5,000
Contribution to postsecondary institution overhead	8,438	8,438	8,438	8,438	8,438

 PROTECTED WHEN COMPLETED Version française disponible

Canada

Personal identification no. (PIN)	Family name of applicant
Valid 264073	Herrmann

Before completing this section, read the instructions for contributions from supporting organizations and consult the *Use of Grant Funds* section in the NSERC *Program Guide for Professors* concerning the eligibility of expenditures for the direct costs of research and the regulations governing the use of grant funds, and *Guidelines for Evaluating Cost-Sharing Ratios and In-Kind Contributions in University-Industry Collaborations* regarding the eligibility of in-kind contributions.

Name of supporting organization

Company Y

CONTRIBUTIONS FROM SUPPORTING ORGANIZATIONS

	Year 1	Year 2	Year 3	Year 4	Year 5
Cash contributions to direct costs of research (Transfer amounts to page five (5); except those for the Ship Time program.)	0	0	58,313	58,313	58,313
In-kind contributions to direct costs of research					
1) Salaries for scientific and technical staff	0	0	0	0	0
2) Donation of equipment, software	0	0	0	0	0
3) Donation of material	0	0	0	0	0
4) Field work logistics	0	0	0	0	0
5) Provision of services	0	0	0	0	0
6)	0	0	0	0	0
Total of in-kind contributions to direct costs of research	0	0	0	0	0
In-kind contributions to indirect costs of research (not leveraged)					
1) Use of organization's facilities	0	0	0	0	0
2) Salaries of managerial and administrative staff	0	0	5,000	5,000	5,000
3)	0	0	0	0	0
Total of all in-kind contributions	0	0	5,000	5,000	5,000
Contribution to postsecondary institution overhead	0	0	9,188	9,188	9,188

Personal identification no. (PIN)	Family name of applicant
Valid 264073	Herrmann

Complete this section if you are applying to the Research Tools and Instruments (Categories 2 and 3) Program **OR** if your project grant application includes the purchase of an equipment item or the installation of a facility costing $150,000 or more. Report total revenues in the appropriate section on page 5.

EXPECTED REVENUES FROM EQUIPMENT OR INSTALLATION

	Previous year	Current year	Year 1	Year 2	Year 3
1) User fees (internal source)					
2) User fees (external source)					
3) Cash contributions from university					
4) Other contributions to direct costs (specify). Do not include NSERC support.					
TOTAL REVENUES			0	0	0
In-kind contributions (specify)					

Give a detailed explanation of the user fee structure and other expected revenues. For "Cash contributions from university" category and for "In-kind contributions" category, identify each organization that is contributing to the facility and indicate the amount being contributed. Use one additional page if necessary.

Budget Justification

Industry support

Summary DNOISE II will run from August 1, 2009 to July 31, 2014. In year one DNOISE II seeks to match the established support from three oil companies and one service company. In later years, DNOISE II is projected to grow to four oil companies and two contractors in year two and to six oil companies and three contractors in year three to five. This amounts to a funding request of $294k for year one, of $351k in year two, and of $525k in years three to five, totaling to $2220k over five years. For this period, the funding from four companies is secured and the prospective growth is based on interest from particular companies (see below) towards DNOISE II. In case, we do not meet the prospected support level, we will scale back the budget accordingly. Where possible, the numbers in the budget were derived from actual expenditures incurred during the first DNOISE project.

Cash contributions Volatility in the world economy and oil price have had a detrimental impact on the level of support from industry towards academic research programs such as DNOISE. Despite the grim economy outlook, we have been able to secure support from industry and we have good reason to believe that this support will increase over the duration of this project. Refer to Table 1, and Form 101 for the current and projected support. We included the names of additional companies because these companies expressed interest in joining this project in the future.

The amounts listed in this proposal exclude 12.5% overhead charged by the University of British Columbia and other line items that can not be matched by NSERC. Because of these exclusions, the amounts stated by our industrial partners on the Form 183A may differ from the amounts included in our budget. Moreover, the fees for the companies are different depending on whether they are oil or surface companies or whether they need access to the Discrete Curvelet Transform Library ($5k annually, see user fee section in §2).

	Year				
Company	1	2	3	4	5
BP Group*	×	×	×	×	×
BG International	×	×	×	×	×
Chevron	×	×	×	×	×
WesternGeco/Schlumberger	×	×	×	×	×
ION	0	0	×	×	×
PGS	0	0	×	×	×
Company Y	0	0	×	×	×
ArmadaHess	0	0	0	×	×
CGGVeritas	0	0	0	×	×

Table 1: Actual and forecast industrial support

In-kind contribution The success of this project depends on applying our algorithms to real data. Our relationship with the supporting companies gives us access to such data. In addition, we will seek licenses from Landmark for their professional seismic-data processing software suite; these licenses are counted as in-kind contributions.

1 Salaries and benefits

Salaries and benefits details Students and postdoctoral fellows (PDFs) participate actively in all aspects of the proposed research. Students are expected to spend internships with the companies. These activities give rise to increased time pressure. Whenever possible, we try to relieve students from teaching-assistantships beyond that required by their program of study. Official starting dates for students are September 1 and January 1. Full-time equivalent (FTE) salaries are given in Table 2. The benefit rates are set according to UBC's policy. The number of students that will be supervised in each year is given in Table 3.

Category	Salary ($000s)	Benefit rate (%)
MSc	16.5	1
PhD	19.0	1
PDF	55.0	10

Table 2: Costs for students, postdoctoral fellows, and other scientific personnel

	Year				
Category	1	2	3	4	5
MSc	2	4	5	5	5
PhD	3	5	9	9	9
COOP	1	1	3	3	3
PDF	4	4	5	5	5

Table 3: Number of students postdoctoral fellows supervised

In order to bridge potential gaps in the hiring, whenever possible we will make our new students temporary research assistants before they formally enroll. The salaries that are expected to be spend for this bridging are reflected in the budgeted FTE. The detailed hiring schedule is given in Table 4.

The success of DNOISE II depends largely on our ability to rapidly prototype and disseminate our algorithms. To accomplish these tasks, a versatile software environment is needed that allows for code reuse, rapid parallel implementation, and for the creation of reproducible research. As part of reproducible research, source code is released as an integral part of the dissemination of our research findings. Inclusion of source code—a model advocated by Jon Claerbout and David Donoho—allows the research community to easily reproduce and build upon our research. Since the success of DNOISE II depends for a large part on the successful communication of our research, support personnel is essential to assist DNOISE II's researchers in the development, (parallel) implementation, and field testing of the algorithms and in the preparation of the reproducible reporting. The proposed support team consists of a *scientific/systems programmer*, whose main responsibility is the development and support of scientific software, and maintenance of the our compute cluster.

Category	Year 1	2	3	4	5
Herrmann					
MSc	2	2	3	3	3
PhD	2	3	4	4	4
COOP	1	1	1	3	3
PDF	3	3	4	3	3
Junior prog.	0.25	0.5	1	1	1
Scientific prog.	0.75	0.80	0.85	0.85	0.85
Research assoc.	0.5	0.5	0.75	0.85	0.85
System person	0	0.50	1	1	1
Yilmaz					
MSc	0	1	1	1	1
PhD	1	1	2.5	2.5	2.5
COOP	0	0	1	1	1
PDF	0.5	0.5	0.5	1	1
Friedlander					
MSc	0	1	1	1	1
PhD	1	1	2.5	2.5	2.5
COOP	0	0	1	1	1
PDF	0.5	0.5	0.5	1	1

Table 4: Time schedule for supervision of each PI

The *junior scientific programmer* and *summer COOPs* will assist DNOISE II team members with algorithm implementation in the object-oriented parallel software environment and with the technical aspects of preparing the reproducible research.

As DNOISE IIprogresses, the *research associate* will be primarily responsible for conducting real case studies using the technology that we develop. This person will also be responsible for project management and the distribution of our technology in the form of reproducible research to the sponsors and to the research community as a whole. This research associate will help coordinate our semi-annual meetings and workshops, and the field tests on the data sets provided by industry.

Salaries and benefit rates for non-student staff are given in Table 5 Cost of living adjustments are not included.

Category	Salary ($000s)	Benefit rate (%)
COOP	$25.2	8
Junior scientific programmer	25.2	8
Scientific programmer	70.0	18
Research associate	55.0	18

Table 5: Costs for non-student staff

2 Equipment or facility

Category	Year 1	Year 2	Year 3	Year 4	Year 5	Total
a) Purchase or rental	35,500	6,000	14,500	10,000	10,500	76,500
File server, RAID storage/backup	26,500	-	-	-	-	26,500
Desktops	6,000	6,000	14,000	10,000	10,000	46,000
LCD projector	3,000	-	500	-	500	4,000
b) Operation or maintenance	23,633	15,956	53,000	49,656	53,500	195,745
Cluster service contract	-	-	20,000	20,000	20,000	60,000
Back-up software	900	-	-	-	-	900
Replacements/repairs	1000	1500	2000	2500	2500	9,500
Parallel Matlab (cluster)	11,400	9,700	22,400	22,400	22,400	88,300
Cluster operating system	2,400	2,400	2,400	2,400	2,400	12,000
Desktop software	3,833	1,856	5,700	1,856	5,700	18,945
Desktops Operating sys. upgrades	3,000	500	500	500	500	5,000
Servers Operatings sys. upgrades	1100	-	-	-	-	1,100
c) User fees	-	-	-	-	-	-
Caltech license CurveLab Library	15,000	15,000	15,000	15,000	15,000	75,000

a) Purchase or rental Each member of the DNOISE II research team is provided with a personal workstation and centralized facilities for backup and printing. These personal workstations are intended for reporting, code development and small pilots. From our experience running DNOISE, the average life time of our workstations and centralized file-, printer-, and webservers is three to five years. Our budget is based on a scenario where equipment is gradually replaced and where there is room to deal with unforeseen calamities such as hardware failures. We will account for increases in maintenance fees due to the aging our equipment (see below). During DNOISE, we did not include the replacement of our equipment in our budget. This explains the relative large costs at the beginning of the project towards replacement. The desktops purchases are proportional to the new arrivals in the group. The semi-annual costs for the LCD projector cover replacement of the bulb.

The main expenses include: replacement of the our workgroup file/web Xserver ($5k), storage (RAID) array ($5k), and tape backup facility ($5k). We also plan to gradually replace our desktops, and printing facility.

The budget for the original DNOISE project contained a large line item in support of our compute cluster. Recently, we updated this IBM cluster from 36 computational nodes (144 CPU-cores) to 36 nodes with eight CPUs each (288 CPU-cored) through a $200 k Western Economical Diversification Grant. This upgraded facility meets our hardware requirements.

(b) Operation and maintenance costs The amounts requested for this budget item are based on costs we incurred during DNOISE. These costs include installation and maintenance of equipment; technical support for researchers; operational costs for print, file and network servers; printing and copying; and similar direct costs. Unfortunately, the Department of Earth and Ocean Sciences has and will not provide us with support towards these items. During DNOISE these costs amounted in total to $ 31k, and we expect, except for increasing hardware maintenance related to older equipment, these costs to remain roughly the same. However, there is a significant increase related to the license fees associated with the Parallel Matlab Library.

Our operational costs also include recurring license fees for the compilers suite on the cluster, and word processing, presentation software, and upgrades for the operating systems on our desktops and file/print/web servers. Depending on the license model, we strive towards sharing licenses and the number of shared licenses is based on the number of concurrent users. Each team member uses one matlab license ($1k per license) and $1/3$ Mathematica license. The academic license fees for iworks, MS Word, Adobe Acrobat Professional, and Mathematica range between $200-300 per individual license. The cost for the annual matlab license $ 300 and the cost for the Parallel Toolbox $ 350. This individual toolbox is used for *interactive* development and interactive testing of our algorithms on our desktops. After initial software development, we will run our algorithms for large-scale problems on the cluster. This will mostly be done in *batch mode* and requires a license for the Parallel Matlab Toolbox with a certain number of workers. These workers allow us to run Parallel Matlab jobs on many CPUs allowing us to solve problems that require many computations and that have a large memory imprint. The license fees of this Toolbox depend on the number of workers, i.e., the number of CPUs (see Table 6). Because the development and implementation of our paralell algorithms will need some time, we envision a gradual increase of the number of workers, and hence the requested license fees. These fees start at $ 11.4k serving 64 nodes to ramp up in year three towards 256 nodes at $ 22.4 k. These cost include three additional licenses to control large-scale jobs. This scenario also allow us to throroughly evaluate the use of Parallel Matlab as our development environment.

	Year				
	1	2	3	4	5
# of workers	64 ×	128 ×	256 ×	256 ×	256 ×
perpetual license costs (US $ 000s)	9.5	6.5	16	16	16
20% annual maintenance fee (US $ 000s)	1.9	3.2	6.4	6.4	6.4
Total (US $ 000s)	11.4	9.7	22.4	22.4	22.4

Table 6: License and annual licence costs for the Parallel Matlab Toolbox on the cluster

Finally, there are costs related to the PROMAX seismic-data processing software for which we are in the process of getting a license as part of an in-kind contribution. This in-kind contribution may not cover yearly maintenance fees for the external SQL database that is required by this software package.

Above amounts do not include the costs related to installation of these software packages and the maintenance of our compute systems that are taken care of by our junior and senior scientific programmers (see §1).

(c) User fees A large number of our algorithms use the Fast Discrete Curvelet Libary developed at the California Institute of Technology. To test our algorithms, our supporting companies need access to this software libary, which is not free for for-profit companies. The University of British Columbia Industrial Liaison Office negotiated an agreement with Caltech, which allows companies to run our software deliverables. The costs of this Library is $5k annually and gives companies that do not have a license the ability to test our software. However, this license does *not* give the companies the ability to use this Library outside of the scope of the DNOISE II project.

3 Materials and supplies

Category	Year 1	Year 2	Year 3	Year 4	Year 5	Total
a) Office material	$3,410	$1,930	$1,930	$1,930	$1,930	
Back-up tapes	$1,660	$180	$180	$180	$180	
Printing costs	$1,750	$1,750	$1,750	$1,750	$1,750	

(a) Office equipment including long-distance phone, photocopier, printing, poster reproducing costs and fax charges. Includes also basic office equipment such as a fax and copy machine, a stapler, etc. We also need a storage facility for DNOISE II's (financial) administration, reports, backup tapes, software etc.

4 Travel

Category	avg # trips/yr pp	Cost per trip	Year 1	Year 2	Year 3	Year 4	Year 5
Conferences			$25,855	$36,400	$ 46,550	$46,550	$46,550
Domestic–student	1	$1,250	$3,125	$5,625	$8,750	$8,750	$8,750
Domestic–other	1	$1,850	$7,400	$11,100	$12,950	$12,950	$12,950
Int'l–student	1	$1,660	$5,810	$5,395	$5,810	$5,810	$5,810
Int'l–other	1	$2,380	$9,520	$14,280	$19,040	$19,040	$19,040
Total conferences			$25,855	$36,400	$ 46,550	$46,550	$46,550
b) Field-work			-	-		-	-
c) Project-related travel			6,000	6,000	7,000	7,000	7,000
d) Project meeting			5,000	5,000	5,000	5,000	5,000
Sub-total			$36,855	$47,400	$58,550	$58,550	$58,550

(a) Conferences This includes travel for students, PDFs, and faculty. The students go to at least one conference annually. The travel expenses cover one or two domestic conferences per year and one international conference per year. The costs for domestic trips are based on $1250 ($250 lodging, $250 Food, $700 airfare, $50 conference fees) for students and $1850 ($500 lodging, $250 Food, $700 airfare, $400 conference fees) for non-students. The costs for international trips are based on $1660 ($300 lodging, $300 Food, $1000 airfare, $60 conference fees) for students and $2380 ($600 lodging, $300 Food, $1000 airfare, $480 conference fees) for non-students.

(c) Project related travel covers visiting academic collaborators and trips to industrial participants in DNOISE II. Since industry is sponsoring, they will typically not reimburse travel expenses of DNOISE II team members visiting their companies. $33k annually will cover these travel costs. These funds will NOT be used to support travel of people from the supporting companies.

(d) Project meeting covers the costs to organize the semi-annual meetings. One small meeting will be held in Europe. It is agreed with the advisory committee that there will be an annual meeting in Europe and a larger meeting in British Columbia. These meetings will bring at least one participant per company and will take place over one-to-two days and include lodging, conference room, and food. $5k annually will cover these travel costs.

5 Dissemination

	Year 1	Year 2	Year 3	Year 4	Year 5
a) Publication costs	$4,000.00	$ 4,000.00	$6,500.00	$6,500.00	$6,500.00
b) Annual report and webcast	$4,500.00	$4,500.00	$4,500.00	$4,500.00	$4,500.00
c) Annual meeting costs	$4,000.00	$17,500.00	$17,500.00	$17,500.00	$17,500.00
Sub-total	$12,500.00	$26,000.00	$28,500.00	$28,500.00	$28,500.00

(a) Publication costs The reporting as part of DNOISE is scheduled for *year 2* and *year 3*. $5k per annum covers the publication costs.

(b) Annual report and design website and webcast Electronic publication of the reproducible annual report and the webcasts are set to increase as the project ramps up. At the Seismic Laboratory for Seismic Imaging and Modeling (SLIM), we have had favorable experience with webcasts which save on travel expenses. The funding will be used to remove certain incompatibilities.

Annual meeting costs One of the main vehicles to desseminate our DNOISE II's research findings is the organization of an annual consortium meeting. During these meetings, each of the group members gives one or more presentation(s). These costs cover rental of the conference room and a social event. These cost will **not** cover the travel and lodging costs of our indutrial partners.

Relationship To Other Research Support

Relationship to other research: Dr. M. Friedlander

Dr. Friedlander currently holds a Natural Sciences and Engineering Research Council of Canada **NSERC** Discovery Grant of $22,000 per year, for the years 2004–2007. The title of the grant is "Large-Scale Nonlinear Optimization". This grant supports a broad research program for the development and analysis of algorithms for the solution of large-scale optimization problems. This grant currently supports one Ph.D. student who is working algorithms for PDE-constrained optimization problems. It also covers related equipment and travel expenses.

Relationship to other research: Dr. Ö. Yilmaz

Dr. Yılmaz currently holds a Natural Sciences and Engineering Research Council of Canada **NSERC** Discovery Grant of $16,000 per year, for the years 2004–2009. The title of the grant is "Approximation Theory of Quantization of Redundant Expansions". This grant funds Dr. Yılmaz's long term research program on establishing a comprehensive theory of quantization for redundant expansions. Currently, one M.Sc. student is being supported by this grant.

Relationship to other research: Dr. F. J. Herrmann

Dr. Herrmann currently holds a Natural Sciences and Engineering Research Council of Canada **NSERC** Discovery Grant of $ 19,000 per year, for the years 2006-2011. The title of the grant is "Multi-scale imaging and modelling of seismic reflectors". This grant funds Dr. Herrmann's long term research program on the detection and characterization of unconformities in the Earth subsurface. This funding is used to support a MSc. student, computer equipment and travel.

1 Research objectives

This proposal describes a comprehensive five-year continuation of our research program in dynamic nonlinear optimization for imaging in seismic exploration (DNOISE). DNOISE II builds on a proven track record of a multidisciplinary research team that conducts transformative research in the fields of seismic-data processing, imaging, and inversion. The overarching goal of the original DNOISE program can be summarized simply:

1) *"How to image more deeply and with more detail?"*

To help confront current pressures in the oil and gas industry, we continue to keep this focus, and add the additional question:

2) *"How to do more with less data."*

To answer these questions, we will develop a solid foundation for seismic data processing, imaging, and inversion from simultaneous source acquisition using ideas from compressive sensing (CS)—a research area according to whose principles we have and will continue to develop important breakthroughs in exploration seismology. With DNOISE II, we continue to adapt and expand developments in applied harmonic analysis and scientific computing, with an emphasis on acquisition design, sparsity-promoting recovery and seismic data processing, imaging, and inversion. We will integrate these results with PDE-constrained optimization based on our large-scale time-harmonic Helmholtz solver. With this approach, we will be able to robustly incorporate the physics and come up with concrete implementations for the next-generation of seismic processing, imaging, and inversion solutions.

2 DNOISE I: Status Report

Over three years, the first DNOISE project resulted in twelve journal publications (one in review), fifty expanded abstracts for the SEG/CSEG/EAGE, 70 talks (excluding our talks held during the Consortium meetings). During this project, four graduate (five MSc and one PhD), and two undergraduate students completed their degrees. (Two more PhD students will graduate within a year.) Two post-doctoral fellows (PDFs) finished their tenure, and two PDFs continue to be employed. DNOISE also employed two junior scientific programmers, two undergraduate coop students, and one senior programmer. Below we describe in detail our main successes (and fumbles), and new research areas that grew out of DNOISE and which we would like to pursue as part of DNOISE II. The following summary mirrors the outline of the original DNOISE proposal.

2.1 Construction of directional frames for seismic processing & imaging

As part of this project, we set out to address the following three questions. First, *can the principles of CS be used to construct and measure the effectiveness of certain redundant transforms for seismic applications?* DNOISE's success hinged largely on the ability of curvelets to solve a wide spectrum of problems in seismic data processing [36], including missing-trace interpolation [23,32], primary-multiple separation [37,74], and migration-amplitude recovery [30,33]. One of the outstanding open problems in the community is to understand why curvelets excel in so many seismic applications. For instance, curvelets work well for missing-trace interpolations. However, they are less effective for interpolation from missing angular frequencies; this is an example in which notions such as mutual coherence and sparsity do not provide satisfying answers [41].

Second, *can we design certain acquisition strategies that favor recovery by sparsity promotion?* Our jittered sub-Nyquist sampling approach [23] demonstrates that sparse-recovery techniques benefit from a sampling scheme that tames potentially harmful aliases into relatively harmless noise. In conjunction with curvelet-based recovery, this sampling scheme has been implemented and fully tested. This work is considered by industry to be transformative, and calls for commercialization have been made. Extensions of this methodology to higher dimensions [64, 65] and unstructured grids [19] remain mostly open. Aside from designing strategies for the design of acquisition grids according to the principles of CS, DNOISE has also established an important connection between recent developments in simultaneous-source acquisition [7] and CS [31, 49]. With DNOISE II, we plan to further expand on this exciting connection [42].

Third, *can we extend certain transform techniques to unstructured data?* We have partly answered this question by implementing and testing the nonequispaced curvelet transform [19, 22]. We have provided partial answers, though deep theoretical questions remain [40].

In summary: We made significant progress in answering each of these questions. Some important highlights include: calls from industry for commercialization; being featured as a "nugget" by the Institute of Pure and Applied Mathematics, which included a plenary talk at the NSF workshop "Cyber-Enabled Discovery and Innovation: Knowledge Extraction"; the EAGE Arie Van Weelden Award for our recent PhD graduate Gilles Hennenfent; and the plenary talk "Sub-Nyquist sampling and sparsity: getting more information from fewer samples" to presented by the PI during the Recent Advances and Road Ahead Session of this year's SEG [28]. Several important open problems remain, which will be addressed by DNOISE II: (i) multidimensional acquisition design to minimize imprint of sub-Nyquist sampling; (ii) extension of wavefield recovery to optimization problems that involve convex and nonconvex regularization functions that include prior information on the wavefield; and (iii) extension of these methods to recovery from compressively or simultaneously acquired/modeled data. In this last application, sub-sampling artifacts are removed using an approach similar to jittered sampling (in this case, simultaneous sources) that reduces interference, followed by a sparsity-promoting recovery.

2.2 Sparsity enhancement through convex programming

As part of this project, we set out to address the following questions. First, *can we design and implement extremely large-scale ℓ_1 solvers for matrix-free CS problems in exploration seismology?* The sheer size of problems in exploration seismology proved to be extremely challenging. However, we made significant progress on this important topic by developing two descent-based methods. The first is an iterative soft-thresholding algorithm with cooling [23, 32] (implemented as part of our trace-interpolation software released to industry). The second is SPGL1, a solver for large-scale sparse reconstruction problems based on a root finding method. SPGL1 is publicly available and has seen wide use. Both methods have proven to work well on the inversion of underdetermined systems that emerge in the field of CS. The ℓ_1-ℓ_2 Pareto curve [5] gives a unified framework for studying the effectiveness of sparse-recovery solvers [25]. Although SPGL1 has been demonstrated to be one of the most effective solvers available [4], further work is needed to scale this solver to problems that require out-of-core or parallelized in-core implementations. Our out-of-core 3-D interpolation results were obtained using our iterative thresholding algorithm.

Second, *can we use other sparsity-promoting norms, such as weighted-ℓ_1 and ℓ_p ($0 < p < 1$), to improve recovery?* This is a complicated question and a topic of current active research in the field of CS [10]. During DNOISE, we have been able to make progress in the following areas.

First, we have been able to derive a Bayesian sparsity-promoting wavefield-separation technique where the predictions for the to be separated signal components are used as weights for the ℓ_1 norms [57, 74]. This method was implemented by generalizing our soft-thresholding algorithm. We applied the resulting algorithm to successfully separate real 3-D data volumes, which we could achieve with only a few iterations. We also made theoretical contributions toward understanding sparse recovery via ℓ_p ($0 < p < 1$) norm minimization [56].

Third, *can we combine sparsity-promotion with other phase-space regularization functionals?* We made substantial progress in this area as part of our work on seismic amplitude recovery [33]. However, a number of open questions remain that include the relationship between ℓ_p and other energy functionals used in variational image processing (e.g., anisotropic diffusion), the choice of appropriate function spaces, and the design and implementation of methods that exploit the curvelet-coefficient phase-space structure exhibited by seismic data and images.

In summary: Sparsity-promotion, coupled with the curvelet tranform, has proven an essential innovation within DNOISE. Our use of the Pareto curve as an algorithmic tool gave us a powerful vehicle to study progress made by our solvers towards the ℓ_1 solution. Our findings showed that our adaptive iterative thresholding algorithm, and SPGL1, are effective and scalable. We have observed, however, that these (and many other) gradient-based methods can be extremely inefficient on problems that involve the inversion of matrices that do not adhere to the principles of CS, e.g., deconvolution problems. As part of DNOISE II, we plan to work on a new generation of solvers that are based on Newton-type methods that can accommodate preconditioning techniques. We will also work on the implementation of solvers that (i) exploit joint sparsity within prestack migration, (ii) can handle non-convex ℓ_p-norm problems with $0 < p < 1$, and (iii) solve nonlinear inverse problems with sparsity promotion.

2.3 Uniform uncertainty principles for seismic processing and imaging

2.3.1 Seismic data recovery and acquisition

We made substantial progress on developing the tools for sparse recovery from incomplete data. However, we did not fully develop wavefield reconstruction techniques that employ—aside from curvelet-domain sparsity—additional prior information regarding wave physics. This information is typically encapsulated in migration-like focusing operators such as the focal transform [8], NMO operators, or the full forward modeling operator. As part of DNOISE II, we propose to extend our recovery methodology to wavefield inversion [34] from incomplete data [34, 35]. The latter research direction emerged during DNOISE and which has applications that include recovery from simultaneous acquisition [31], and the formulation of imaging and inversion from incomplete data.

2.3.2 Coherent signal separation and prediction

This project addressed the following main questions. First, *can we come up with a coherent wavefield separation scheme that is moderately insensitive to location, phase, and frequency-content errors in the noise predictions?* Second, *can we come up with theoretical peformance estimates that predict the separability of the signal components?* We made significant progress on several fronts regarding the first question. The second remains open—however, we do know that it is related to the question of why curvelets perform so well on seismic data. We were able to derive, implement, and test two complementary methodologies for primary-multiple separation and surface-wave removal. Our first contribution involved the successful development of a stable curvelet-sparsity promoting separation scheme [29] through weighted ℓ_1. Because the original approach was too sensitive with regard to the weighting, we used a Bayesian reformulation [57, 74] where the estimation for the to be separated noise component(s) are constrained by the noise prediction(s). We implemented and successfully tested this approach on synthetic and real data for both primary-multiple separation (with the 2- and 3-D curvelet transforms) and surface-wave removal [76, 77] (with the 2-D curvelet transform). Our second contribution involved an adaptive curvelet-domain matched filter [36], which corrects for slowly varying errors in the noise predictions using phase-space smoothness. This method was also implemented and tested on synthetic and real data (using the 2-D curvelet transform) and is currently being evaluated for commercialization by Petroleum Geophysical Services. We also made progress in the prediction of the noise components using wavefield inversion [34, 35] with curvelet-domain sparsity promotion that eliminates the necessity to do extensive matching. Finally, we developed a framework for the prediction of primaries from simultaneous data [43]. During DNOISE II, we plan to (i) extend our Bayesian separation [57, 74] method to different types of wavefield components; (ii) improve multiple predictions using wavefield inversion techniques [34]; (iii) include migration-like operators, such as DMO, to limit the spatial frequency content and hence improve separation in areas of high curvature (e.g. near the apex); (iv) develop an SRME-type scheme for ground-roll removal using interferometric deconvolution; (v) exploit the "inverse-data" space [6] to remove and/or use surface-related multiples; and (vi) further development of our framework for prediction of primaries.

2.3.3 Preconditioning of imaging operators

This project addressed the question *can we use the invariance and sparsity of curvelets under the demigration-migration operator to correct the migration amplitudes and to precondition least-squares migration?* We worked on approaches that combine curvelet-domain sparsity and invariance under the demigration-migration operator [33]. Our activities included (i) the use of a reverse-time migration code developed by William Symes on the SEG/EAGE AA data set [62]; (ii) a derivation of a new curvelet-domain matched filter (also used in adaptive primary-multiple matching). In this case, the matched filter is used to estimate a curvelet-domain scaling (diagonal matrix) from a reference vector (typically the migrated image) and the remigrated reference vector; (iii) the development of curvelet-based preconditioners that lead to a faster convergence of CG-type methods such as LSQR [30].

Our work resulted in a theoretical result that bounds the error made by approximating the action of the demigration-migration operator by curvelet-domain scaling. We also derived a method to estimate the scaling from an image and a remigrated image through curvelet-domain matched filtering that is regularized by penalizing curvelet-to-curvelet variations in the scaling. We also developed a method to stably apply the correction via ℓ_1-norm regularized inversion of the scaled curvelet transform [33]. We plan to implement curvelet-domain matched filters for migration operators that are 3-D.

We were not able to extend our preconditioning to prestack imaging because a suitable prestack migration code was not available. We therefore shifted our attention to the design and implementation of our own prestack imaging code based on an implicit solver for the time-harmonic Helmholtz equation [18]. We leveraged this latest preconditioner [18] [15] based on a new multi-level Krylov method that guarantees, as opposed to previously proposed preconditioners [53], numerical convergence for fine mesh sizes and high angular frequencies. This work reduces the number of iterations for the implicit Helmholtz solver from $\mathcal{O}(n)$ down to $\mathcal{O}(1)$, and yet the cost of the preconditioner only grows as $\mathcal{O}(n \log n)$ as compared to the $\mathcal{O}(n^2)$ cost of the original operator. (Here, n is related to the size of the grid.) The result is a time-harmonic solver that has the same order of complexity as time-domain finite differences. We will use this solver to develop our own time-harmonic wave-equation migration code.

2.3.4 Compressed imaging

The main question addressed in this project was *how to reduce the numerical cost of imaging either by using invariance of curvelets under migration operators, or by reducing the size of seismic data volumes?* Our recent work on wavefield extrapolation [45] and simulation [30, 44] revealed that the second part of this question was prophetic. Both contributions extensively used results from CS to decrease the computational complexity of wavefield computation. The first contribution involved an explicit solver where the eigenfunctions of the Helmholtz equation were used as a measurement matrix. This approach leads (as subsequently confirmed by recent theoretical work [12]) to a natural parallelization and a reduction of the size of the operators that depends on the sparsity of the extrapolated wavefield. This work was presented as part of a plenary talk at the 2007 AMS von Neuman Symposium [1]. Some care is needed, however, because the sheer size of 3-D seismic problems precludes explicit solvers. Therefore, we shifted our attention towards preconditioned implicit solvers for the time-harmonic Helmholtz equation [15]. By establishing a direct connection between simultaneous-source acquisition [3, 49] and CS, we rigorously justified earlier work [7, 55]. We showed that with the appropriate choice of the simultaneous source functions, substantial gains can be made in reducing the number of shots (i.e., the number of source experiments) and the number of angular frequencies [31]. The amount of reduction is prescribed by CS theory and depends on transform-domain sparsity of the simulated wavefield.

These applications are examples of alternative methods to reduce the computational costs of solving PDEs, where we no longer seek to diagonalize the solution operator, and instead seek CS-like methods that reduce the dimensionality and exploit transform-domain sparsity. This can be interpreted as a form of diagonalization where the transform preserves sparsity for a whole class of solution operators. As a result, the solution can be subsampled with a rate that is on par with the transform-domain sparsity. This observation forms one of the key motivations of DNOISE II, where we plan to invoke these ideas throughout the work flow, starting from (simultaneous) acquisition design and processing of simultaneously acquired data, through to the process of imaging and inversion. This new compressive approach will yield a distinct advantage over traditional methods because the acquisition and computational costs will be comparable with the required amount of detail in the final result of the imaging/inversion procedure.

2.3.5 Seismic deconvolution and denoising

We worked on answering the following question: *how to exploit CS theory to solve the deconvolution problem for cases where the reflectivity can no longer be considered as a series of spikes?* We tackled this issue in two ways. First, we continued to use curvelet-domain sparsity as a prior that allowed use to solve this problem for a class of reflectivity models that sparsifies in this domain [11, 38]. (Kumar defended his MSc on this topic and the topic of curvelet-based denoising [39].) We used SPGL1 to solve the associated sparsity-promoting program, which led to a significant improved performance. We are also starting to work on blind-source deconvolution. Jointly with Dr. Beatrice Vedel, we investigated theoretical bounds for the detection and estimation of fractional-order transitions, which leads to a failure of classical one-norm based deconvolution. We were able to come up with a practical detection-estimation scheme that estimates the fractional-order of transitions. With these estimated orders, we were able to well tie the imaged opal-A (Amorphous) to opal-CT (Cristobalite/Tridymite) transition in the North Sea West of the Shetlands [46, 47]. We also came up with a singularity-preserving upscaling scheme [27].

2.3.6 Parallel development environment

We developed the SPARCO Matlab toolbox, which facilitates rapid prototyping with in-core matrix-free operators [69], and also developed the Python package SLIMPY, which implements out-of-core Unix pipe-based operators. The latter includes the development of a parallel file system in support of our windowed parallel curvelet transform [66]. SPARCO is used extensively by our sponsoring companies and our software releases have been used extensively to evaluate our algorithms. Finally, we also made some of our papers reproducible using the Madagascar package, and we developed a more flexible reproducible research system, REPRO [24], released to Sourceforge.

In summary: We made significant progress on many of DNOISE's milestones regarding the application of new transform-based techniques. Our software implementations have been tested against real data, and are now widely distributed along with reproducible documents. We would like, as part of DNOISE II, to expand these efforts. This will require continued development of our parallel development environment and investment in hardware. (Separately, we secured a $200k upgrade for our cluster.) In order to ensure that students can complete their implementations in reasonable time frames, we will migrate to the Parallel Matlab Toolbox.

3 DNOISE II

With the current surge in demand for oil and gas exploration, and the need for sustainable production, the seismic industry is struggling with two important questions: *How to cope with the increasing demand for seismic data, and the increasing data volumes that need to be processed? How to obtain more information from the observed waveforms?* As part of DNOISE II, we plan to tackle these important questions by completely redesigning seismic methods using the principles of CS. Our approach will follow two complementary design philosophies: the classical approach where seismic data is subjected to a number of processing steps; and the "holistic" approach of full-wave form inversion. Our main strengths lie in (i) our ability to take deep results in computational harmonic analysis and turn them into practicable and concrete ground-breaking solutions to vital problems in seismic exploration; (ii) our results on sparse recovery and simultaneous source modeling [31] to full-waveform inversion using adjoint-state methods that solve a compressively-sampled and sparsity-promoting PDE constrained optimization problem; and (iii) our ability to compare the redesigned processing flow with the "all-at-once" full-waveform methodology. These efforts will proceed in tandem with the following research topics.

3.1 Research objectives & outcomes

Compressive acquisition and sparse recovery: The monetary costs and turn-around times of seismic processing are crucial factors in modern-day exploration seismology. We will continue to leverage and adapt findings from CS towards a complete redesign of seismic acquisition and subsequent processing. In particular, we plan to improve on current acquisition design by incorporating our work on jitter sampling [23, 64, 65] and simultaneous-shot simulation [31]. We also plan to improve on sparse recovery, through selection and adaptation of multiscale and multi-directional transforms including wave-equation based techniques, and the design and implementation of large-scale solvers that promote joint sparsity. **Outcome:** A new methodology for exploration seismology where the costs of acquisition and processing are no longer dominated by the size of the survey area, but instead by the sparsity exhibited by seismic data volumes.

Free-surface removal: The presence of the free surface and a difficult to control source function represent two formidable challenges impeding the success of linearized seismic imaging. Failure to handle these challenges has detrimental effects on migration and migration velocity analysis. Therefore, we will continue to develop techniques that exploit transform-domain sparsity [74] and phase-space adaptation [37] to improve the removal of surface-related coherent noise components. Our activities will also include joint primary-impulse response prediction and source-function estimation based on separable least squares and sparsity promotion [43]. Our methodology will be applied to multiple and ground roll removal. **Outcome:** Wave-equation driven wavefield separation methodology that limits removal of primary energy through improved prediction, matching, and separation.

Compressive modeling for imaging and inversion: Access to a fast, parallel, and scalable modeling capability is key to the design of imaging technology, through linearization, and full-waveform inversion, through partial-differential-equation (PDE) constrained optimization [51,52]. Because imaging and inversion both rely on correlations of the time history, we will further develop our implicit time-harmonic Helmholtz solver [18] [15–17,44], including a parallel implementation for large models with $N \sim 1000^3$ grid points. We will include density-variations and extend our solver to elastic media. For scalability, we will generalize our preconditioned iterative solver to handle large numbers of shots (i.e., right-hand sides). This modeling capability will also include our recent work on simultaneous-source simulation [31] where the solution is subsampled deliberately according to the principles of CS. **Outcome:** A new implicit scalable time-harmonic full-waveform modeling utility with a numerical complexity comparable to time-domain finite differences, and additional cost reductions commensurate with the transform-domain sparsity of the solution.

Compressive wave-equation based imaging and inversion: The success of imaging and full-waveform inversion hinges on our ability to mitigate three key impediments, namely (i) the presence of (nonlinear) effects of the free surface and the source function, which either violate assumptions underlying linearized imaging, or lead to additional nonlinearities and calibration issues in inversion, (ii) the increasing size of seismic data volumes that call for increasing computational resources in a time where Moore's Law is under strain, and finally (iii) the non-uniqueness associated with the full-waveform inversion problem that is known to be multimodal. We tackle the first two challenges by integrating our free-surface removal technology [43], which extends and benefits from compressive sensing [28], into to-be-developed sparsity-promoting formulations for imaging and inversion. We plan to address the uniqueness problem of full-waveform inversion through a combination of continuation methods that sweep from coarse to fine scales [52] and focusing through mixed (1,2)-norm minimization [26]. **Outcome:** A imaging and full-waveform technology that leverages our contributions on simultaneous acquisition design, Helmholtz solvers, sparsity promotion for prestack migration, and a solver for PDE-constrained optimization.

Parallel development environment: The development and implementation of imaging and full-waveform inversion algorithms in 3D is a challenging task within an academic research environment. To meet this challenge, we plan to combine the development of a parallel version of

SPARCO [70], using the Matlab's Parallel Toolbox, with selective low-level implementations of our wave solvers. We will also continue to work with the development of our reproducible research environment. **Outcome:** An environment that allows us to disseminate our research findings and evaluate our algorithms on real data.

3.2 Research approach

This ambitious research program puts us in the unique position to contribute to fundamental problems in the current seismic processing flow, which is designed to process data such that it approximately adheres to the linearized forward model (Born approximation). Our approach offers a controlled pathway towards a formulation of full-waveform inversion according to the principles of CS. Our aim is to design new acquisition methodologies that bring acquisition and computational costs on par with the complexity or desired resolution of the end product. We will effect a gradual shift from sequence-based seismic processing towards a more holistic wave-equation driven approach. By combining joint-sparsity promotion with adjoint-state methods for the wave equation, we aim to mitigate the adverse effects of (deliberate) under sampling and non-uniqueness of full-waveform inversion. Our systematic effort requires integration of our software with commercial seismic-processing software and hardware to assess each component on real data.

3.3 Scientific team

Our core team of researchers consists of three tenured faculty members from the Department of Earth and Ocean Sciences, Mathematics, and Computer Science. Albeit our scientific backgrounds differ greatly, we have been able to build a tight-knit interdisciplinary group of (under)graduate students, post-doctoral fellows, scientific personnel, and international collaborators. These collaborators include Dr. Dirk-Jan Verschuur from the Delft University of Technology, Engineering Physics; Dr. Yogi Erlangga (PDF scheduled to leave in November) from Al-Faisal University, College of Sciences, Mathematics, Riyadh; Dr. Chris Stolk, University of Amsterdam, Mathematics; Dr. Alex Powell from Vanderbilt University, Mathematics; Michael Saunders from Stanford University, Management Science and Engineering.

Running a truly interdisciplinary team is always a challenge. During DNOISE, we have been able to overcome this challenge by a number of activities. These include the organization of a weekly joint seminar series; regular meetings amongst the PIs, co-advising of students, fostering of collaborations amongst the team memmbers, which has resulted in numerous publications; and the establishment of international research collaborations.

Our weekly meetings, which involve all DNOISE team members, particularly contributed towards the development of a common language and numerous instances of cross fertilization. These collaborations have resulted in a steady stream of publications and exposed our students to different disciplines. During DNOISE II, we plan to continue to expand our collaborations, and we are particularly excited with the arrival of Dr. Eldad Haber, NSERC Industrial Chair in Computational Geophysics, at UBC. Dr. Haber has expressed a keen interest in working with our group.

In summary, the DNOISE II project involves people from a wide variety of fields with complementary skill sets that vary from applied to theoretical. This combination of people with different backgrounds is unique in the field of exploration seismology.

3.4 General deliverables

DNOISE II aims to disseminate its research through refereed journal papers, expanded conference abstracts, reports and annual meetings with the supporting companies. To facilitate dissemination our papers and reports will be published in the form of reproducible research including the source codes necessary to reproduce the results. In addition, software releases will be prepared that include manuals of our software, test and field data cases.

4 The proposed research

The action items are bold-faced numbered and appear on the activity schedule of form 101.

4.1 Compressive acquisition and sparse recovery

Sparse recovery is the machinery that undergirds our research. It involves the inversion of underdetermined matrices through sparsity promotion. Its success hinges on the interplay of three key components: **(i)** a sparsifying transform that compresses seismic data and images; **(ii)** a subsampling strategy that reduces coherent aliases; and **(iii)** a recovery method by sparsity promotion. To further improve recovery—i.e., from fewer samples or with higher quality—we will also work on **(iv)** sparse recovery with source-receiver reciprocity; **(v)** joint-sparsity promotion with multiple measurements; and **(vi)** ℓ_p $(0 < p < 1)$ and other sparsity promoting functionals and solvers.

(i) According to CS, the recovery from incomplete data by sparsity promotion improves for transforms that attain a higher degree of compression—i.e., a higher decay rate for the amplitude-sorted transform-domain coefficients. By virtue of their phase-space localization capability, the curvelet transform has proven to be particularly well suited for exploration seismology, where the signals of interest contain multidirectional wavefront-like features with conflicting dips. This in part explains the success of curvelets in missing trace interpolation and wavefield separation (see section below). Curvelets are, however, not the only possible choice, and we will conduct a theoretical and empirical study comparing different transform techniques such as contourlets, surfacelets, shearlets, and wave atoms, for recovery problems that involve missing traces, missing angular frequencies, and simultaneous shots.

(ii) The design of appropriate CS matrices is critical for successful recovery. In seismic applications, this problem requires the design of sub-Nyquist acquisition grids—i.e., placement of source and geophones, and simultaneous source experiments. Both designs involve sub-Nyquist sampling, possibly along different coordinate axes with different physical meanings. Although there has been significant progress in the application of CS to important areas (e.g., MRI, radar imaging, and Fourier optics [54]), its application to exploration seismology remains in its infancy [49] [31], with the notable exception of early work on Fourier-based missing-trace interpolation [58]. We therefore plan to work on the following areas. **(a)** Generalization of our jitter sampling technique [23] to higher dimensions [64]. **(b)** The design of practical simultaneous source experiments [42]. To this end, we will work on **(c)** the design of random and fast-realizable simultaneous source experiments (i.e., CS matrices) through specialized Kronecker-type products [26, 31], including evaluation of their recovery properties.

(iii-iv) Under certain conditions, strictly sparse signals can be recovered by solving a convex one-norm minimization problem [9, 13] . Empirical findings support this claim, e.g., our work on missing-trace interpolation showed accurate results based on curvelet-sparsity promotion. These results were made possible by our large-scale solver SPGL1 [67], which represents a significant theoretical and algorithmic advance over current approaches. Further work is needed to specialize ℓ_1 solvers to large high-dimensional seismic-data volumes, and to parallelize ℓ_1 solvers using domain-decomposition techniques. Finally, we will design a recovery method that exploits (approximate) source-receiver reciprocity.

(v) Seismic data is redundant, a property that is apparent from similarities in the data after NMO or in the image after prestack migration. In both cases, we can expect the transform-domain coefficients to align—i.e., to exhibit *joint* sparsity. Therefore, we will work on the important generalization of sparse recovery that groups subsets of interrelated coefficients, and seeks solutions where all the coefficients in a group are simultaneously zero (below the noise level) or nonzero. This is often called the *joint-sparsity* problem [68], which can be used to recover signals that cannot be otherwise recovered by the usual techniques. The main challenges are development of: **(a)** a theory that gives conditions under which joint-sparsity techniques can be used to enhance signal recovery; **(b)** regularization functionals and norms that promote sparsity across groups [26], and **(c)** sparse-recovery algorithms for the resulting optimization problems.

(vi) According to CS, it is essential that sparsifying transforms be near orthogonal (which implies that they be "not too redundant") and compressible—i.e., seismic data and images enjoy sparse representations in the transform domain. These requirements are often in conflict, which poses a challenge that needs to be better understood. Moreover, recovery by one-norm minimization depends on certain properties of the transform matrix such as incoherence amongst its rows. For redundant transforms, this incoherence may not be sufficient and one-norm minimization can fail. In these cases, one alternative is to use p-(quasi-)norm minimization where $0 < p < 1$. Our recent work [56, 78] shows that such non-convex optimization methods are effective in situations where the one-norm fails. Because curvelet transforms are redundant (and thus coherent), this approach may improve on one-norm curvelet-based recovery. We will explore this possibility by developing solvers for large-scale non-convex minimization, and test these on seismic recovery problems. **Project leaders:** M. Friedlander (co-PI) and Ö. Yılmaz (co-PI) as co-leaders. **Project team:** R. Saab (PhD), E. van den Berg (PhD), and J. Johnson (MSc). MSc (two in years 2-5), PhD (one in year 1-2 and two in years 3-5), COOP (1 in years 3-5), Hassan Mansour (PDF), and PDF (2 in years 3-5).

In summary: With our track record consisting of contributions to various aspects of CS—ranging from theory development to the implementation of large-scale solvers and the solution of practical problems such as missing-trace interpolation [23, 32] and recovery from simultaneous data [31]—we are in a strong position to improve upon current, and often ad-hoc solutions to acquisition-related problems in exploration seismology.

4.2 Free-surface removal

We will follow two complementary approaches to handle effects related to the free surface, namely removal of coherent noise by noise prediction, followed by adaptation and separation, or by wavefield inversion. Our current methodology consists of an *adaptive* step to improve noise predictions, and a Bayesian *estimation* step that adds robustness to the separation. Applications include primary-multiple separation [74], and surface-wave removal [75]. Our first approach improves on the *adaptive* component of this project by: **(i)** continued development of curvelet-domain matched filters [60]. On the *estimation* component side, we will focus on **(ii)** Bayesian-separation for different classes of multiples [72]. Our second approach involves direct estimation of the surface-free impulse response from (simultaneous) data. **(iii)** We will research on how to reformulate our adaption [43] of recent work on primary estimation [71] using results from separable least-squares [20]; and **(iv)** incorporate the multiple-prediction operator into CS recovery; this works better because primaries are sparser than the total data, and multiples in the data are mapped to primaries. CS additionally permits significant dimensionality reduction, and leads to better computational costs. In both approaches, the seismic wavelet is estimated as a by product, except that the latter deconvolves the wavelet. Finally, **(v)** we will leverage our work on surface-related multiples towards the mitigation of surface waves.

(i-ii) We will work on curvelet-domain matched filters with **(i a)** regularization across different scales and frequencies [60]; **(i b)** incorporation of phase-space distance functions [61], **(i c)** extension to complex curvelets and inclusion of phase corrections in line with recent work by [48], and **(i d)** parallelization and extension to 3D. Our sparsifying estimation procedure for wavefield separation relies on the assumption that the curvelet supports of the components do not significantly overlap. We will improve the multiple elimination by **(ii)** multi-term [72] wavefield estimation that includes multi-term predictions for specularly-reflected and diffracted multiples. This application requires a generalization of our sparsity-promoting Bayesian estimation procedure with iterative thresholding [74].

(iii-v) We supplement our sparsity-promoting curvelet-domain wavefield inversion [34] with source-function estimation. We accomplish this by promoting curvelet-domain sparsity on the surface-free impulse response and Fourier-domain smoothness on the source function during a separable optimization procedure. First, **(iii)** we improve the convergence by using updates as in [20]. Second **(iv)**, we regularize this wavefield-inversion problem by imposing sparsity on the estimates for the primaries (in conjunction with Fourier-domain smoothness for the source function). To reduce the data volumes—i.e., the size of the full matrices involved with this wavefield-inversion procedure—we include compressive sampling in our formulation [43]. **Project leaders**: F. Herrmann (PI) is leader; Michael Friedlander, and Ö. Yılmaz are co-leaders. **Project team** MSc (Tim Lin and Jiupen Yan in year 1, and two in year 2-5), PhD (S. Bubshait fully funded with scholarship from Saudi Arabia), PhD (one in year 1-5), MSc (one year 3-5), and PDF (one in year 3-5).

In summary: Our expertise in coherent wavefield separation allows us to continue to improve our work on wavefield separation and apply it to surface-wave removal. We are particularly excited about our primary estimation by curvelet-based wavefield inversion.

4.3 Compressive modeling for imaging and inversion

By lack of proper preconditioning, implicit solvers for the time-harmonic Helmholtz solver did not, until very recently [15, 18], converge for the fine-mesh sizes and angular frequencies required by current-day exploration seismology. We leverage this exciting development by **(i)** a parallel implementation of preconditioned solver in 2-D (prototype nearly completed) and 3-D; **(ii)** simultaneous-source simulations; **(iii)** domain decomposition; **(iv)** including density variations; **(v)** multigrid preconditioners for multiple right-hand sides; and **(vi)** extension to the elastic case.

(i) Our time-harmonic Helmholtz solver offers embarrassing parallelization over frequencies and sources. To handle large 2-D and 3-D models, domain decompositions on the model are included. **(ii)** To guarantee scale up for multiple sources (right-hand sides), we will use recent work by Elman [14]. We will also extend our multigrid preconditioner to multiple right-hand sides. With this approach, we expect similar speedups as have been reported in the literature [21].

(iii) We will extend our Helmholtz solver to elastic waves. This extension requires a new type of preconditioner because there are now P- and S-waves with different wave speeds. **(iv)** Finally, we will incorporate our simultaneous acquisition scheme [31] to include compressive sampling along the sources and receivers. This additional subsampling will lead to further improvements. **Project leader**: F. Herrmann (PI). **Project team** Y. Erlangga (PDF and future collaborator), Tu Ning (PhD student on full scholarship from China), PhD (one in year 1-5), and PDF (2 in year 1, 1 in year 2).

In summary: Our expertise on Helmholtz solvers and compressive sampling puts us in the unique position to develop a new implicit scalable time-harmonic full-waveform modeling utility that will be competitive with time-domain finite differences. Common to time-harmonic solvers, our approach has distinct advantages, including the independence of the angular frequencies and the fact that correlations become simple multiplications in the frequency domain. More importantly, the inclusion of compressive sensing allows us to leverage transform-domain sparsity without having to define the modeling operators in the transformed domain.

4.4 Compressive wave-equation based imaging and inversion

Our proposal culminates in the Helholtz-based formulation of imaging and inversion that includes **(i)** "post-stack" (least-squares) migration, i.e., computation of gradient and Newton updates bases on the reduced Hessian; **(ii)** preconditioning for linearized inversion [30] to obtain "true amplitude" images and improved convergence for iterative Lanczos methods; **(iii)** dimensionality reduction by compressive sampling to expedite (least-squares) migration; **(iv)** integration of primary estimation into linearized (and full-waveform) inversion to remove imprints of the source and the free surface; **(v)** full-waveform inversion with multiscale sparsity promotion, which includes development of sparsity-promoting solvers for PDE-constrained optimization for the wave equation; **(vi)** compressive computation of image volumes ("pre-stack imaging") with sparsity promotion and focusing [26]; **(vii)** formulation of full-waveform inversion with extended modeling [63].

(i-iii) Our frequency-domain adjoint-state method [51, 52] combines three key technologies, **(i)** fine-grained parallelization (over shots and frequencies) for the gradient and Newton updates; **(ii)** preconditioning of the Hessian for the Newton updates based on curvelet-domain matched filtering; and **(iii)** system-size reduction by compressive sampling along the frequency and source axes. With this approach, we leverage the implicit Helmholtz solver by parallelization and compressive sampling over shots and frequencies. This in conjunction with preconditioning allows us to compute updates efficiently. Subsampling-related artifacts are mitigated by sparsity-promotion with a to-be-developed large-scale Newton-type ℓ_1 solver [59].

(iv-vi) The free surface and unknown source signatures cause major problems for imaging, migration velocity analysis [63], and full-waveform inversion [73]. **(iv)** By incorporating our work on primary prediction in the formulation of imaging and full-waveform inversion, we remove these surface-related effects by mapping the data to the surface-free impulse response. Our approach differs from existing methods of full-waveform inversion [73], where multiples are removed. This method requires inclusion of additional terms in the gradient and Newton updates and is made computational feasibly by applying compressive sampling to artificially reduce the size of the data volumes. Even though, this step removes an important complication, full-waveform inversion is still plagued by local minima [63]. Because of the dimensionality reduction by compressive sensing, our inversions also contains subsampling artifacts. **(v)** To address both issues, we develop a multiscale optimization procedure where curvelet-domain sparsity is promoted on the model for each scale starting at the coarsest. This approach leverages the multiscale structure of the curvelet transform, and requires development of a one-norm solver for nonlinear forward models. To exploit the redundancy of multiexperimental data, we will compute prestack image volumes from compressively sampled source and residual wavefields. These image volumes allow us to mitigate sub-sampling related artifacts through joint-sparsity promotion designed to penalize defocused energy [26]. **(vi)** Finally, we will include Symes' extension [63] in full-waveform inversion. The extended forward model will be solved with a "contrast" formulation where the nonlocal contributions of the extension act as secondary sources. Because the gradient of the corresponding PDE constrained optimization problem corresponds to prestack migration [63], we use joint-sparsity promotion to penalize unphysical defocused contributions. We believe that this formulation will remedy non-uniqueness that has plagued full-waveform inversion. **Project leaders**: F. Herrmann (PI) as leader; M. Friedlander (co-PI) as co-leader. **Project team** Y. Erlangga (PDF and future collaborator), T. Lin (PhD year 2-4), Li Xiang (on full scholarship from China), PhD (two year 2 and four year 3-5), COOP (one year 3-5), and PDF (one year 1-5 and two in year 3-5).

In summary: Combination of the latest developments in compressed sensing, scientific computing, seismic acquisition design, primary estimation, and extensions allows us to formulate a seismic imaging and inversion approach where the acquisition and computational costs are *decoupled* from the model size. By recognizing simultaneous acquisition as an instance of compressive sensing, we arrive at a formulation where the acquisition and processing costs depend on the transform-domain sparsity of the final product. This result entails a departure from the overly stringent paradigm of Nyquist sampling towards the new paradigm of compressed sensing. Applying this type of model-size reduction by compressive sampling will also hold the key towards making Symes' extension, where each model update corresponds to a "pre-stack" image volume, computationally feasible.

4.5 Parallel development and seismic data processing environment

Exploration seismology is challenging because of the extremely large multi-experimental data volumes involved. This challenge is exacerbated by the relative limited resources we have at our disposal in academia. For instance, our experience from DNOISE has taught us that it is difficult to quickly enough ramp-up graduate students so that they can engage in large-scale parallel computing, and fully exploit our compute cluster. The SPARCO and SLIMPY packages were initially developed to effectively implement Abstract Numerical Algorithms (ANAs [2, 50]) using *serial in-core* and *parallel out-of-core* operators. These prototyping environments have gone a long way towards addressing these challenges and ensuring that we maximally leverage the recent $200k upgrade of our compute cluster. However, these tools must continue to be improved if we are to meet the challenge of creating software environments that allow seamless transitions from serial to parallel implementations, and from in-core to out-of-core processing. We propose to take the following steps: **(i)** reimplement the SPARCO toolbox to take advantage of the more modern object-oriented functionality in recent releases of Matlab; **(ii)** implement parallelism using Matlab's Parallel toolbox, which will address memory allocation and computational complexity issues; **(iii)** support nonlinear operators; and **(iv)** develop an application interface for commercial seismic data processing and visualization.

(i-ii) The SPARCO Matlab toolbox was originally conceived as a testbed for sparse-recovery algorithms. However, the underlying operator library has proven to be an extremely flexible approach to prototyping. We have taken the very best ideas from SPARCO and reimplemented them using the more powerful object-oriented (OO) features available in late releases of Matlab. The resulting software toolbox, SPOT, the result of a complete redesign of SPARCO, is immensely more powerful and adaptible. Crucially, the flexibility of its OO design will allow us to integrate it with the Matlab's Parallel Computing toolbox, and ultimately, reduce valuable resources that are spent on low-level development effort. Also, we will more readily tap the parallel capabilities of our cluster, because we can easily implement most of our parallel algorithms with parallel SPOT. During prototyping in this environment, it is extremely important to move between the in-core Parallel Matlab representations of co-distributed arrays and in-core data structures such as Argonne's PETSc library for parallel arrays. This will allow us to implement algorithms that can efficiently use mixed *in-core* low-level implementations for our Helmholtz solvers and *in-of-core* solvers in Matlab. Combined with the expressiveness of Matlab extensions, the resulting environment will allow us to quickly implement algorithms for massively parallel computation. We expect that this package will have wide applicability to other scientific computing disciplines.

(iii-iv) The SLIMPY and SPARCO software architectures were designed for rapid prototyping of algorithms with linear operators on serial computers. We recognize that there is an increasing need to accommodate large scale linear and nonlinear operators within our iterative optimization algorithms. Therefore, SPOT's interface to block-diagonal operators will be generalized to allow for parallel definition of nonlinear operators. **Project leaders**: F. Herrmann (PI) and M. Friedlander (co-PI) as co-leaders; **Project team** Research Associate (one year 1-5, starting part time), junior programmer (one year 1-5), MSc (one year 1-5), PhD (one year 3-5).

In summary: Our experience in creating a versatile programming environment for algorithm development puts us in the position make the next step towards further integration. With this capability, we will be able to access our algorithms and disseminate our research findings.

5 Scientific-computing infrastructure

Software Our software environment consists of two main components, namely our parallel software development environment and our seismic data processing environments. Each component is complementary and we will use commercial packages to fit our needs.

To maximally utilize our cluster, we will switch to the Parallel Matlab Toolbox. This Toolbox has only become available recently and offers a functionality that will allow our students (already trained in matlab) to rapidly prototype and scale their algorithms. We reserve our desktops for interactive prototyping and our cluster for the large-scale number crunching. The Parallel Matlab Toolbox provides a framework allowing us to seamlessly migrate from desktop development to full-fletched batched processing on the cluster. In this proposal, we ask funding for licenses on desktops and on the cluster. The latter requires the purchase of a certain number of workers.

Seismic data processing, imaging and inversion require access to large data volumes and interactive input of parameter settings driven by visual quality control on the intermediate results. This type of work demands a high degree of interactivity, in particular because we conduct the quality control with several people in some visualization environment. This interactivity can only be offered by a commercial seismic data processing systems that allow us to process our data using vanilla processing technology and our own state-of-the art algorithms.

Hardware Regular upgrades and extensions of our dedicated parallel computer are a prerequisite for successful algorithm development and testing on large enough real datasets. Therefore, we replaced the current 36 computational nodes bought from IBM in early 2006 (with 4 CPU-cores per node), with the same number of nodes but with 8 CPU cores per node as well as increase the memory/CPU ratio. That effectively doubled the computational capability of our cluster. Even though our cluster is up to data, our files server, RAID, and backup facilities need replacement and so do a number of our desktop machines. Our file server also serves our website, which is frequently visited by our industrial partners, and by research institutions from around the world.

6 Training of HQP

Over the last three years, numerous undergraduate, graduate students, and postdocs have finished their degree as part of DNOISE at the UBC seismic laboratory for imaging and modeling (SLIM) and at the departments of the co-PIs. With its interdisciplinary nature, DNOISE II will continue to attract students, postdocs, and visiting faculty from diverse fields, including mathematics, computer science, electrical engineering, and geophysics.

Our students are exposed to many disciplines and receive broad training. They attend at least one conference yearly, participate in interdisciplinary programs such as those organized by UCLA's Institute of Pure and Applied Mathematics (IPAM), and by our own Pacific Institute for the Mathematical Sciences (PIMS). The students are also exposed to our industrial partners. We have an active exchange program in the form of student internships and onsite visits with industrial partners. The seismic laboratory for imaging and modeling is also frequented by people from industry, and long-term visitors are encouraged (such as faculty on sabbaticals). Regular meetings (at least annually), with research presentations expose our students and postdocs to the pressing scientific and engineering research challenges that are relevant to industry and academia. These formal meetings, coupled with frequent technical report releases and reproducible research constitutes an efficient vehicle for the dissemination of research carried out at SLIM.

7 Value of the results and benefit to Canada

DNOISE II is aimed at developing the next-generation of imaging and inversion tools for the seismic industry. These tools are vital for the entire seismic industry. They are also vital for Canada and its energy needs. Oil fields in Canada are difficult to image and problems vary from missing data, to multiples, to complicated overburdens. DNOISE II will lay the foundation for an active seismic research community of global standing. DNOISE II will create new commercial opportunities for Canadian oil and gas companies. Our industry funding has the explicit goal of bringing algorithms to market through a strategic alliance with existing and nascent companies. During the first DNOISE we received several calls from industry to commercialize our research findings. All intellectual property developed at the laboratory for seismic imaging and modeling belongs to the University of British Columbia as stated in our industrial research contracts.

The mathematical, computational, and (geo)physical techniques developed as part of DNOISE II are relevant not only to the oil industry but also to the many research disciplines that need to deal with incomplete data. These disciplines include remote sensing, (medical) imaging, data assimilation for weather forecasting, and machine learning. DNOISE II's technology is also applicable to global seismology where the sampling has and will always be a big issue.

Immediate outcomes of this project are research reports and software. The education of a competent work force of highly qualified personnel for the Canadian oil & gas industry is critical for longterm competitiveness of this industry. SLIM contributes towards the long-term enterprise of training the next generation of geoscientists which will be in high demand given the current oil price and the demographics of geoscientists in the industry.

[1] *Sparse representation and high-dimensional geometry*, 2007.

[2] R. Bartlett, *Thyra linear operators and vectors*, tech. rep., SAND2007-5984, Sandia National Laboratories, 2007.

[3] C. J. Beasley, *A new look at marine simultaneous sources*, The Leading Edge, 27 (2008), pp. 914–917.

[4] S. Becker, J. Bobin, and E. J. Candés, *Nesta: a fast and accurate first-order method for sparse recovery*, (2009).

[5] E. v. Berg and M. P. Friedlander, *Probing the Pareto frontier for basis pursuit solutions*, Tech. Rep. TR-2008-01, Department of Computer Science, University of British Columbia, January 2008. To appear in *SIAM J. Sci. Comp.*

[6] A. J. Berkhout, *Seismic processing in the inverse data space*, Geophysics, 71 (2006).

[7] ——, *Changing the mindset in seismic data acquisition*, The Leading Edge, 27 (2008), pp. 924–938.

[8] A. J. Berkhout and D. J. Verschuur, *Focal transformation, an imaging concept for signal restoration and noise removal*, Geophysics, 71 (2006).

[9] E. J. Candès, J. Romberg, and T. Tao, *Signal recovery from incomplete and inaccurate measurements*, Comm. Pure Appl. Math., 59 (2005), pp. 1207–1223.

[10] E. J. Candès, M. B. Wakin, and S. P. Boyd, *Enhancing Sparsity by Reweighted L1 Minimization*, Arxiv preprint arXiv:0711.1612, (2007).

[11] V. K. J. O. R. Clowes and F. Herrmann, *Curvelet denoising: application to crustal reection data*, Tech. Rep. TR-2009-4, the University of British Columbia, 2009. Submitted for publication.

[12] L. Demanet and G. Peyré, *Compressive wave computation*, 2008. Submitted for publication.

[13] D. Donoho, *Compressed sensing.*, IEEE Trans. Inf. Theory, 52 (2006), pp. 1289–1306.

[14] H. Elman, O. Ernst, D. P. O'Leary, and M. Stewart, *Efficient iterative algorithms for the stochastic finite element method with application to acoustic scattering*, Computer Methods in Applied Mechanics and Engineering, 18 (2005), pp. 1037–1055.

[15] Y. A. Erlangga and F. J. Herrmann, *An iterative multilevel method for computing wavefields in frequency-domain seismic inversion*, in SEG Technical Program Expanded Abstracts, vol. 27, SEG, August 2008.

[16] ——, *Migration with implicit solvers for the time-harmonic helmholtz equation*, EAGE, EAGE, 2009.

[17] ——, *Seismic waveform inversion with Gauss-Newton-Krylov method*, in SEG Technical Program Expanded Abstracts, vol. 28, SEG, 2009, pp. 2357–2361.

[18] Y. A. Erlangga and R. Nabben, *On multilevel projection Krylov method for the Helmholtz equation preconditioned by shifted Laplacian*, Tech. Rep. TR-2008-2, UBC EOS, 2008. To appear.

[19] L. Fenelon, *Nonequispaced discrete curvelet transform for seismic data reconstruction*, Master's thesis, Ecole Nationale Superieure De Physique De Strasbourg, August 2008. Visiting student.

[20] G. Golub and V. Pereyra, *Separable nonlinear least squares: the variable projection method and its applications*, in Institute of Physics, Inverse Problems, 2002, pp. 1–26.

[21] G. Haase and S. Reitzinger, *Cache issue of algebraic multigrid methods for linear systems with multiple right-hand sides*, SIAM J. Sci. Comput., 27 (2005), pp. 1–18.

[22] G. Hennenfent and F. J. Herrmann, *Seismic denoising with non-uniformly sampled curvelets*, Computing in Science and Engineering, 8 (2006).

[23] ——, *Simply denoise: wavefield reconstruction via jittered undersampling*, Geophysics, 73 (2008).

[24] G. Hennenfent and S. Ross-Ross, *TR2008-4 Repro: a Python package for automating reproducible research in scientific computing*, Seismic Laboratory for Imaging and Modeling, August 2008.

[25] G. Hennenfent, E. van den Berg, M. P. Friedlander, and F. J. Herrmann, *New insights into one-norm solvers from the Pareto curve*, Geophysics, 73 (2008).

[26] F. J. Herrmann, *Compressive imaging by wavefield inversion with group sparsity*, in SEG Technical Program Expanded Abstracts, vol. 28, SEG, SEG, 2009, pp. 2337–2341.

[27] ——, *Reflector-preserved lithological upscaling*, in SEG Technical Program Expanded Abstracts, vol. 28, SEG, SEG, 2009, pp. 3466–3470.

[28] ——, *Sub-nyquist sampling and sparsity: getting more information from fewer samples*, in SEG Technical Program Expanded Abstracts, vol. 28, SEG, 2009, pp. 3410–3415.

[29] F. J. Herrmann, U. Boeniger, and D. J. Verschuur, *Non-linear primary-multiple separation with directional curvelet frames*, Geophysical Journal International, 170 (2007), pp. 781–799.

[30] F. J. Herrmann, C. R. Brown, Y. A. Erlangga, and P. P. Moghaddam, *Curvelet-based migration preconditioning and scaling*, Geophysics, 74 (2009), p. A41.

[31] F. J. Herrmann, Y. A. Erlangga, and T. Lin, *Compressive simultaneous full-waveform simulation*, Geophysics, 74 (2009), p. A35.

[32] F. J. Herrmann and G. Hennenfent, *Non-parametric seismic data recovery with curvelet frames*, Geophysical Journal International, 173 (2008), pp. 233–248.

[33] F. J. Herrmann, P. P. Moghaddam, and C. C. Stolk, *Sparsity- and continuity-promoting seismic image recovery with curvelet frames*, Applied and Computational Harmonic Analysis, 24 (2008), pp. 150–173.

[34] F. J. Herrmann and D. Wang, *Seismic wavefield inversion with curvelet-domain sparsity promotion*, in SEG Technical Program Expanded Abstracts, vol. 27, SEG, August 2008.

[35] F. J. Herrmann, D. Wang, and G. Hennenfent, *Multiple prediction from incomplete data with the focused curvelet transform*, in SEG Technical Program Expanded Abstracts, vol. 26, SEG, 2007, pp. 2505–2509.

[36] F. J. Herrmann, D. Wang, G. Hennenfent, and P. P. Moghaddam, *Curvelet-based seismic data processing: a multiscale and nonlinear approach*, Geophysics, 73 (2008), pp. A1–A5.

[37] F. J. Herrmann, D. Wang, and D. J. Verschuur, *Adaptive curvelet-domain primary-multiple separation*, Geophysics, 73 (2008), pp. A17–A21.

[38] V. Kumar and F. J. Herrmann, *Deconvolution with curvelet-domain sparsity*, in SEG Technical Program Expanded Abstracts, vol. 27, SEG, August 2008.

[39] ——, *Incoherent noise suppression with curvelet-domain sparsity*, in SEG Technical Program Expanded Abstracts, vol. 28, SEG, 2009, pp. 3356–3360.

[40] S. Kunis and H. Rauhut, *Random sampling of sparse trigonometric polynomials*, Appl. Comput. Harm. Anal, 22 (2006), p. 2007.

[41] E. Lebed, *Sparse signal recovery in a transform domain*, Master's thesis, The University of British Columbia, August 2008.

[42] T. Lin and F. J. Herrmann, *Designing simultaneous acquisitions with compressive sensing*, EAGE, EAGE, 2009.

[43] ——, *Unified compressive sensing framework for simultaneous acquisition with primary estimation*, in SEG Technical Program Expanded Abstracts, vol. 28, SEG, 2009, pp. 3113–3117.

[44] T. Lin, E. Lebed, Y. A. Erlangga, and F. J. Herrmann, *Interpolating solutions of the Helmholtz equation with compressed sensing*, in SEG Technical Program Expanded Abstracts,

vol. 27, SEG, August 2008.

[45] T. T. Y. LIN AND F. J. HERRMANN, *Compressed wavefield extrapolation*, Geophysics, 72 (2007), pp. SM77–SM93.

[46] M. MAYSAMI, *Lithology constraints from seismic waveforms: application to opal-a to opal-ct transition*, Master's thesis, The University of British Columbia, Vancouver, BC Canada, 2008.

[47] M. MAYSAMI AND F. J. HERRMANN, *Lithological constraints from seismic waveforms: application to opal-a to opal-ct transition*, in SEG Technical Program Expanded Abstracts, vol. 27, SEG, August 2008.

[48] R. NEELAMANI, A. BAUMSTEIN, AND W. S. ROSS, *Adaptive subtraction using complex curvelet transforms*, in EAGE 70th Conference & Exhibition, Rome, G048, 2008.

[49] R. NEELAMANI, C. KROHN, J. KREBS, M. DEFFENBAUGH, AND J. ROMBERG, *Efficient seismic forward modeling using simultaneous random sources and sparsity*, 2008.

[50] A. D. PADULA, S. D. SCOTT, AND W. W. SYMES, *The standard vector library: a software framework for coupling complex simulation*, 2004.

[51] R.-E. PLESSIX, *A review of the adjoint-state method for computing the gradient of a functional with geophysical applications*, Geophysical Journal International, 167 (2006), pp. 495–503.

[52] G. PRATT, C. SHIN, AND HICKS, *Gauss-Newton and full Newton methods in frequency-space seismic waveform inversion*, Geophysical Journal International, 133 (1998), pp. 341–362.

[53] C. D. RIYANTI, Y. A. ERLANGGA, R.-E. PLESSIX, W. A. MULDER, C. VUIK, AND C. OOSTERLEE, *A new iterative solver for the time-harmonic wave equation*, Geophysics, 71 (2006), pp. E57–E63.

[54] J. ROMBERG, *Compressive sensing by random convolution*, (2008). Submitted for publication.

[55] L. A. ROMERO, D. C. GHIGLIA, C. C. OBER, AND S. A. MORTON, *Phase encoding of shot records in prestack migration*, Geophysics, 65 (2000), pp. 426–436.

[56] R. SAAB AND ÖZGÜR YILMAZYILMAZ, *Sparse recovery by non-convex optimization - instance optimality*, (2008).

[57] R. SAAB, D. WANG, O. YILMAZ, AND F. J. HERRMANN, *Curvelet-based primary-multiple separation from a Bayesian perspective*, in SEG Technical Program Expanded Abstracts, vol. 26, SEG, 2007, pp. 2510–2514.

[58] M. D. SACCHI, T. J. ULRYCH, AND C. WALKER, *Interpolation and extrapolation using a high-resolution discrete Fourier transform*, 46 (1998), pp. 31–38.

[59] M. SCHMIDT, E. VAN DEN BERG, M. P. FRIEDLANDER, AND K. MURPHY, *Optimizing costly functions with simple constraints: a limited-memory projected quasi-Newton algorithm*, in Proc. 12th Inter. Conf. Artificial Intelligence and Stat., April 2009, pp. 448–455.

[60] R. SHAHIDI AND F. J. HERRMANN, *Curvelet-domain matched filtering with frequency-domain regularization*, in SEG Technical Program Expanded Abstracts, vol. 28, SEG, 2009, p. 3645.

[61] H. F. SMITH, *A Hardy space for Fourier integral operators.*, J. Geom. Anal., 8 (1998), pp. 629–653.

[62] W. W. SYMES, *Reverse time migration with optimal checkpointing*, Geophysics, 72 (2007), pp. SM213–SM221.

[63] ——, *Migration velocity analysis and waveform inversion*, Geophysical Prospecting, 56 (2008).

[64] G. TANG, R. SHAHIDI, F. J. HERRMANN, AND J. MA, *Higher dimensional blue-noise sampling schemes for curvelet-based seismic data recovery*, in SEG Technical Program Expanded Abstracts, vol. 28, SEG, 2009, pp. 191–195.

[65] G. TANG, R. SHAHIDI, J. MA, AND F. J. HERRMANN, *Design of two-dimensional randomized sampling schemes for curvelet-based sparsity-promoting seismic data recover*, tech. rep., the University of British Columbia, 2009.

[66] D. Thomson, G. Hennenfent, H. Modzelewski, and F. J. Herrmann, *A parallel windowed fast discrete curvelet transform applied to seismic processing*, in SEG Technical Program Expanded Abstracts, vol. 25, SEG, 2006, pp. 2767–2771.

[67] E. van den Berg and M. P. Friedlander, *Probing the pareto frontier for basis pursuit solutions*, SIAM Journal on Scientific Computing, 31 (2008), pp. 890–912.

[68] ——, *In pursuit of a root*, Tech. Rep. TR-2009-7, Department of Computer Science, University of British Columbia, Vancouver, April 2009.

[69] E. van den Berg, M. P. Friedlander, G. Hennenfent, F. J. Herrmann, R. Saab, and O. Yilmaz, *Sparco: a testing framework for sparse reconstruction*, Tech. Rep. TR-2007-20, UBC Computer Science Department, 2007.

[70] E. van den Berg, M. P. Friedlander, G. Hennenfent, F. J. Herrmann, R. Saab, and O. Yilmaz, *Algorithm 890: Sparco: A testing framework for sparse reconstruction*, ACM Trans. Math. Softw., 35 (2008).

[71] G. J. A. van Groenestijn and D. J. Verschuur, *Estimating primaries by sparse inversion and application to near-offset data reconstruction*, Geophysics, 74 (2009), pp. A23–A28.

[72] D. J. Verschuur, D. Wang, and F. J. Herrmann, *Multiterm multiple prediction using separated reflections and diffractions combined with curvelet-based subtraction*, in SEG Technical Program Expanded Abstracts, vol. 26, SEG, 2007, pp. 2535–2539.

[73] D. Vigh and E. W. Starr, *3d prestack plane-wave, full-waveform inversion*, Geophysics, 73 (2008), pp. VE135–VE144.

[74] D. Wang, R. Saab, O. Yilmaz, and F. J. Herrmann, *Bayesian wavefield separation by transform-domain sparsity promotion*, Geophysics, 73 (2008).

[75] J. Yan and F. J. Herrmann, *Groundroll prediction by interferometry and separation by curvelet-domain matched filtering*, in SEG Technical Program Expanded Abstracts, vol. 28, SEG, 2009, pp. 3297–3301.

[76] C. Yarham, *Seismic ground-roll separation using sparsity promoting ℓ_1 minimization*, Master's thesis, The University of British Columbia, Vancouver, BC Canada, May 2008.

[77] C. Yarham and F. J. Herrmann, *Bayesian ground-roll separation by curvelet-domain sparsity promotion*, in SEG Technical Program Expanded Abstracts, vol. 27, SEG, August 2008.

[78] O. Yilmaz, *Stable sparse expansions via non-convex optimization*, in SINBAD 2008, 2008.

Personal identification no. (PIN)	Family name of applicant
Valid 264073	Herrmann

INTELLECTUAL PROPERTY

Complete this section if you need to discuss the plans for protecting and disposing of intellectual property arising from the grant. Do not exceed one page.

The IP is protected using two methods:

- Protection through publication. After consultation with UBC's Liaison Office (UILO) and the industrial partners it was agreed that our first line of defense for IP protection would be publication. This explains in part our extensive publication record of expanded proceedings for the SEG/CSEG/EAGE/SPIE meetings;

- Our second line of defense will be the filing of patents. We have been in contact with UILO on this issue as well. There are a number of key technologies which we intend to patent amongst which the curvelet transform for unstructured data and certain aspects of the application of uniform uncertainty principles to seismic data regularization;

All IP developed at the Seismic Laboratory of Seismic Imaging and Modeling will be owned by the University of British Columbia as stated in the research contract and in the grants in aid.

Natural Sciences and Engineering Research Council of Canada | Conseil de recherches en sciences naturelles et en génie du Canada

SEND ONE ORIGINAL ONLY DO NOT PHOTOCOPY

APPENDIX C
Referee Suggestions
(Form 101)

Complete Appendix C for all types of grants (except Discovery Grants, Research Tools and Instruments - Category 1, Major Resources Support Grants and Strategic Partnerships Workshops). Read the instructions before completing the appendix.

Date: 2010/09/16

Family name of applicant	Given name	Initial(s) of all given names	Personal identification no. (PIN)
Herrmann	Felix	J	**Valid** 264073

Title of proposal: Dynamic Nonlinear Optimization for Imaging in Seismic Exploration II (DNOISE II)

	Referee	Area(s) of expertise		PIN	Lang.
A	Pratt, Dr (Gerhard) Department of Earth Sciences University of Western Ontario 1151 Richmond St., London, ON CANADA N6A5B7 (519) 661-3513 gpratt2@uwo.ca	Full waveform inversion	1		
B	Symes, Dr (William) Department of Computational and Applied Mathemati Rice University Houston, TX UNITED STATES 77005 (713) 348-5997 symes@caam.rice.edu	Seismic imaging, PDE constrained optimization	2		
C	Donoho, Dr (David) Statistics Department Stanford Sequoia Hall Stanford, CA UNITED STATES 94305-221 (650) 23-3350 donoho@stat.stanford.edu	Compressive sensing	3		
D	Russell, Dr (Brian) Veritas DGC Inc (403) 266-3225 brian_russell@veritasdgc.com	Seismic exploration	4		
E	Sacchi, Dr (Mauricio) Department of Physics University of Alberta CEB Physics Building 11322 - 89 Avenue Edmonton, AL CANADA T6G2J1 (780) 492-1060 sacchi@phys.ualberta.ca	Seismic data processing and imaging	5		

NSERC reviewing committee	Committee reviewer	Personal identification no. (PIN)
	1st committee reviewer	
	2nd committee reviewer	
	3rd committee reviewer	

UBC FAS# F08-04568

"Seismic Imaging by Next-generation BAsis-function Decomposition (SINBAD)"

** Phase II **

CONSORTIUM MEMBERSHIP AGREEMENT FOR OIL COMPANIES

THIS AGREEMENT is made the 1st day of February, 2009.

BETWEEN

THE UNIVERSITY OF BRITISH COLUMBIA, a corporation continued under the *University Act* of British Columbia with offices at Suite 103 – 6190 Agronomy Road, Vancouver, British Columbia, V6T 1Z3; (the "University");

AND

BG INTERNATIONAL LIMITED., a corporation with a registered office at 100 Thames Valley Park Drive, Reading, Berkshire, RG6 1PT; (the "Participant")

(University and Participant are referred to in this Agreement individually as a "**Party**" and collectively as the "**Parties**")

WHEREAS

(1) It is the University's objective to exploit its technology for the public benefit, in harmony with its Global Access Principles launched by the University in November 2007 and as outlined at www.uilo.ubc.ca/global.asp, and to generate further research in a manner consistent with the University's status as a non-profit, tax exempt educational institution;

(2) The University has been engaged in research and development in the field of seismic imaging and has undertaken research into a project referred to as Seismic Imaging by Next-generation BAsis-function Decomposition **("SINBAD");**

(3) Software developed through SINBAD has incorporated software developed by the California Institute of Technology ("**Caltech**"), and to which the University has secured the rights to sublicense such software to Participant; and

(4) The Participant wishes to participate in continued research in and development of SINBAD (the "**Research**"), and the University wishes to undertake such research.

NOW, THEREFORE, the Parties agree as follows:

1. DEFINITIONS and INTERPRETATION

1.1 (a) "**Advisory Committee**" means the committee established to provide advice to the University on matters regarding the Research in accordance with Clause 4;

(b) "**Affiliate**" means any corporation, Limited Liability Company or other legal entity directly or indirectly controlled by Participant or its successors or assigns, or any successor or assign of such an entity. For the purpose of this Agreement, "control" shall mean the direct or indirect ownership of at least fifty percent (50%) of the outstanding shares or other voting rights of the subject entity to elect directors, or if not meeting the preceding, any entity owned or controlled by or owning or controlling at the maximum control or ownership right permitted in the country where such entity exists;

(c) “**California Institute of Technology**” means a not-for-profit California corporation, located at 1200 E. California Blvd., Pasadena, CA 91125.

(d) “**Caltech Software**” shall mean the curvelet software libraries and source code that: i) are available for download at www.curvelet.org or ii) may be obtained from Caltech by negotiating a commercial license.

(e) “**Caltech Patent**” shall mean the rights in and to any and all inventions which are disclosed in the U.S. and foreign patents and patent applications identified in Schedule 3 with respect to the Caltech Software and all counterparts, corresponding international and foreign patent applications, and patents resulting therefrom;

(f) "**Confidential Information**" means all information, regardless of its form that is disclosed by the University to the Participant or its Affiliates and which is clearly identified in writing as "Confidential" at the time of disclosure. If identified orally, a written notice must be sent to the Participant within ten (10) business days thereafter. “Confidential Information” does not include information:

(i) possessed by the Participant or its Affiliates prior to receipt from the University, other than through prior confidential disclosure by the University, as evidenced by the Participant`s business records;

(ii) published or available to the general public otherwise than through a breach of this Agreement;

(iii) obtained by the Participant or its Affiliates from a third party with a valid right to disclose it, provided that the third party is not under a confidentiality obligation to the University in respect of the same; or

(iv) independently developed by employees, agents or consultants of the Participant or its Affiliates who did not use the Confidential Information as evidenced by the Participant`s business records; or

(v) that must be disclosed pursuant to an order or a subpoena.

(g) “**Curvelet Transform Technology**” means the suite of programs, scripts, and procedures, including Executable Code and Source Code, which perform the Fast Digital Curvelet Transform referred to in Schedule 2, and that was developed at the California Institute of Technology;

(h) **"Derivative Works"** means any work consisting of revisions, annotations, elaborations, or other modifications to Software which, as a whole, represent an original work of authorship. Derivative Works includes any updates and new releases of the FDCT Software developed at the California Institute of Technology during the term of this Agreement, inclusive of backups, updates, or merged copies permitted hereunder including the file structures, programming instructions, user interfaces and screen formats and sequences;

(i) “**Effective Date**” means February 1, 2009;

(j) “**Executable Code**” means computer software programs, not readily perceivable by humans, and suitable for machine execution without the intervening steps of interpretation or compilation.

(k) **"Field"** means signal and image processing, including seismic data processing;

(l) "**Fast Digital Curvelet Transform**" means the transform described in Schedule 2 attached hereto. ;

(m) "**FDCT Software**" means the suite of programs, scripts, and procedures, including Executable Code and Source Code, received by Participant, which perform the Fast Digital Curvelet Transform;

(n) "**Foreground IP**" means the copyright (including the source code), design rights, trademarks and patents (whether registered or not and all applications for any of them) and other forms of intellectual property rights made or generated solely as a result of the research;

(o) "**Principal Investigator**" means Dr. Felix J. Herrmann of the Department of Earth and Ocean Sciences at The University of British Columbia;

(p) "**Software**" means copyright rights, as defined by United States copyright laws and applicable international treaties and/or conventions;

(q) "**Source Code**" means computer software programs, not in machine-readable format and not suitable for machine execution without the intervening steps of interpretation or compilation; and

(r) "**Start Date**" means April 1, 2009.

(s) "**University Background IP**" means any Intellectual Property Rights owned or under the control of the University prior to the date of this Agreement relating to the technology which is described in Schedule 1 attached to this Agreement, and excludes Caltech Patent and Curvelet Transform Technology;

2. RESEARCH WORK AND PUBLICATION

2.1 Subject to compliance by the Participant with its obligations under this Agreement, the University shall:

(a) carry out the Research in accordance with those policies, standards, procedures, conventions and techniques that are of a high recognized and acceptable professional standard in the scientific community and in accordance with the requirements of this Agreement;

(b) comply with all health and safety regulations applicable to any work carried out as part of the Research and otherwise comply with all relevant laws and regulations in the conduct of the Research;

(c) supply all equipment, materials and facilities as may be required to conduct the Research, which shall remain the property of the University after termination of this Agreement;

2.2 The University shall provide a representative to attend all meetings of the Advisory Committee, who shall be a person engaged in the management of the Research on behalf of the University.

2.3 The Participant acknowledges that the policies of the University require that the results of the Research be publishable. The Parties therefore agree that the Principal Investigator and other researchers engaged in the Research shall not be restricted from presenting at symposia, national, or regional professional meetings, or from publishing in abstracts, journals, theses, or dissertations, or otherwise, whether in printed or in electronic media, methods and results of the Research, provided however that the Principal Investigator provides the Participant with a copy of any proposed publication or presentation forty-five days in advance of publication or presentation, or in the case of software 12 months prior to a public release.

2.4 During the term of this Agreement, The University will keep the Participant informed, orally or in writing, as to the progress of the Research.

2.5 Any funds received by the University from the Participant under this Agreement are non-refundable, unless the University terminates this Agreement before its expiration.

3. OBLIGATIONS OF THE PARTICIPANTS

Subject to the University's compliance with the terms of this Agreement, the Participant shall pay the University funds in accordance with the schedule below (all funds in Canadian dollars):

- $72,500 Canadian due on or before June 1, 2009;
- $72,500 Canadian on each anniversary of the Start Date until termination.

3.2 The Participant may, at its own cost, provide a representative to attend meetings of the Advisory Committee.

3.3 Performance of the Research is dependent on the amount of funds received from Participants. The University reserves the right to suspend work on the Research or to terminate the Research and this Agreement by delivering written notice of same to the Participant if funds are not sufficient to carry out the Research.

3.4 The Participant may make payments by wire transfer to:
Pay Via: SWIFT MT100
Pay to: HSBC Bank Canada, Main Branch, Vancouver, BC – SWIFT Address HKBCCATT
Account number for Canadian dollars: 016-10020-437218-002
Beneficiary: The University of British Columbia
Payment Details: RTA, FAS #F08-0456

3.5 The University will retain title to any equipment purchased with funds provided by the Participant under this Agreement.

4. ADVISORY COMMITTEE

4.1 The Advisory Committee shall:

(a) provide advice to the University relating to the conduct of the Research;

(b) review the results and recommendations of any University Research reports;

4.2 The Advisory Committee shall consist of no more than one representative from Participant and at least one University representative.

4.3 Meetings of the Advisory Committee shall be held at Vancouver, British Columbia. Meetings shall be regulated as the University may decide from time to time.

4.4 The University shall call all such meetings and shall give at least 10 days' prior written notice thereof to the Participant.

5. CONFIDENTIALITY

5.1 Except as expressly provided herein, each Party agrees not to disclose any terms of this Agreement to any third party without the consent of the other Party; provided, however, that disclosures may be made as required by securities laws or other applicable laws, or to actual or prospective investors or corporate partners, or to a Party's accountants, attorneys or to the United States Government and or other professional advisors or to Affiliates, or to Caltech for the purpose of the University satisfying its obligations to Caltech under its license agreement for the Caltech Software and Caltech Patents.

5.2 The Participant will keep and use University Confidential Information in confidence and will not, without the University's prior written consent, disclose the University's Confidential Information to any person or entity.

5.3 If the Participant is required by judicial or administrative process to disclose the University's Confidential Information, it will promptly notify the University and allow it reasonable time to oppose the process before disclosing the Confidential Information.

5.4 Notwithstanding any termination or expiration of this Agreement, the obligations set out in this Article 5 survive and continue to bind the Parties, their successors and assigns until 7 years after such termination or expiration.

5.5 The Participant and its Affiliates will ensure that the Source Code to any Software or Confidential Information is not disclosed to any other third party. In the event of an unauthorized or accidental disclosure of the Source Code the Participant will immediately:

(a) notify the University and will provide to the University full particulars of all information in the Participant's possession or control regarding the circumstances of such unauthorized use or disclosure;

(b) take (in full consultation with the University) and at the Participant's sole cost and expense all reasonable steps deemed necessary to remedy any such unauthorized use or disclosure, and take all reasonable steps necessary to recover the Source Code and to prevent its unauthorized use by any third party.

6. INTELLECTUAL PROPERTY, INDEMNIFICATION & LIMITATION OF LIABILITY

6.1 All Foreground IP shall be the property of the University from the date of its creation.

6.2 The Participant indemnifies, holds harmless and defends the University, its Board of Governors, directors, officers, employees, faculty, students, invitees and agents against any and all claims (including all reasonable legal fees and disbursements) arising out of the receipt or use by the Participant or its Affiliates of any of the University's Confidential Information, University Background IP, Foreground IP, or any data or other results arising from such use including, without limitation, any damages or losses, consequential or otherwise, arising from or out of the Research.

6.3 The California Institute of Technology shall not be liable for any use of the FDCT Software or related know-how, and Participant hereby agrees to defend, indemnify and hold the California Institute of Technology and its employees harmless from any loss, claim, damage or liability, or whatever kind of nature, which may arise from this Agreement, or the use by Participant or its Affiliates of the Curvelet Transform Technology, FDCT Software, or any related know-how transferrred to the Participant or its Affiliates hereunder.

6.4 The University's total liability, whether under the express or implied terms of this Agreement, in tort (including negligence) or at common law, for any loss or damage suffered by the Participant or its Affiliates, whether direct, indirect or special, or any other similar damage that may arise or does arise from any breaches of this Agreement by the University, its Board of Governors, officers, employees, faculty, students or agents, is limited to $5,000.

6.5 Neither party will be liable for consequential or incidental damages arising from any breach or breaches of this Agreement.

6.6 Notwithstanding the termination or expiration of this Agreement, the rights and obligations in this Section 6 will survive and continue to bind the Participant and its successors and assigns.

7. GRANT OF RIGHTS

7.1 Subject to Section 6.2 (Indemnity), the University grants the Participant and its Affiliates a perpetual, worldwide, non-exclusive, non-transferable, royalty-free license to use and exploit University Background IP and Foreground IP for internal use only in the Field. Such internal use shall not include the provision of services or products to third parties. Internal use includes uses by Participant and its Affiliates as an "operator" in the field of oil and gas production and exploration.

7.2 Subject to Section 6.2 (Indemnity) and Section 6.3, the University grants the Participant and its Affiliates a worldwide, non-exclusive, non-transferable, royalty-free license to use and exploit the Caltech Patent, Caltech Software and the Curvelet Transform Technology for internal use in the Field and in conjunction with the University Background IP and/or Foreground IP, during the term of this Agreement.>

7.3 Neither the Participant nor its Affiliates will grant sublicenses of the University Background IP, Foreground IP or California Institute of Technology IP to any third party.

7.4 The Participant acknowledges and agrees that the University may use University Background IP and Foreground IP without charge in any manner for any purpose.

7.5 California Institute of Technology retains ownership of FDCT Software and Caltech Patent licensed under this Agreement.

7.6 Participant may not remove or obscure any visible copyright or trademark notices.

7.7 The FDCT Software shall not become subject to application for patent or copyright by Participant.

7.8 Participant may not install any copies of FDCT Software on computers that are not owned or leased by Participant or its Affiliates.

7.9 Participant agrees that it may make a reasonable number of copies of Software for archival and backup purposes.

7.10 Participant shall be the sole owner of any data output in any format or media derived from or obtained by use of the FDCT Software and may freely use and disclose such output to any third party.

8. <u>DISCLAIMER OF WARRANTY</u>

8.1 THE UNIVERSITY MAKES NO REPRESENTATIONS OR WARRANTIES, EITHER EXPRESS OR IMPLIED, REGARDING DATA OR SOFTWARE OR OTHER RESULTS ARISING FROM THE RESEARCH OR REGARDING CONFIDENTIAL INFORMATION THE UNIVERSITY MAY DISCLOSE TO THE PARTICIPANT. THE UNIVERSITY SPECIFICALLY DISCLAIMS ANY IMPLIED WARRANTY OF NON-INFRINGEMENT OR MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE AND THE UNIVERSITY WILL, IN NO EVENT, BE LIABLE FOR ANY LOSS OF PROFITS, BE THEY DIRECT, CONSEQUENTIAL, INCIDENTAL, OR SPECIAL OR OTHER SIMILAR DAMAGES ARISING FROM ANY DEFECT, ERROR OR FAILURE TO PERFORM, EVEN IF THE UNIVERSITY HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES. THE PARTICIPANT ACKNOWLEDGES THAT THE RESEARCH IS OF AN EXPERIMENTAL AND EXPLORATORY NATURE, THAT NO PARTICULAR RESULTS CAN BE GUARANTEED, AND THAT THE PARTICIPANT HAS BEEN ADVISED BY THE UNIVERSITY TO UNDERTAKE ITS OWN DUE DILIGENCE WITH RESPECT TO ALL MATTERS ARISING FROM THIS AGREEMENT.

8.2 NOTHING IN THIS AGREEMENT:

(A) CONSTITUTES A WARRANTY OR REPRESENTATION BY THE UNIVERSITY AS TO TITLE TO THE INTELLECTUAL PROPERTY LICENSED HEREUNDER, OR THAT ANYTHING MADE, USED, SOLD OR OTHERWISE DISPOSED OF UNDER THE LICENSE GRANTED IN THIS AGREEMENT WILL NOT INFRINGE THE PATENTS, COPYRIGHTS, TRADE-MARKS, INDUSTRIAL DESIGNS OR OTHER INTELLECTUAL PROPERTY RIGHTS OF ANY THIRD PARTIES, OR ANY PATENTS, COPYRIGHTS, TRADE-MARKS, INDUSTRIAL DESIGN OR OTHER INTELLECTUAL PROPERTY RIGHTS OWNED, IN WHOLE OR IN PART, BY THE UNIVERSITY, OR LICENSED BY THE UNIVERSITY TO ANY THIRD PARTIES;

(B) CONSTITUTES AN EXPRESS OR IMPLIED WARRANTY OR REPRESENTATION BY THE UNIVERSITY THAT THE PARTICIPANT HAS, OR WILL HAVE THE FREEDOM TO OPERATE OR PRACTICE THE INTELLECTUAL PROPERTY LICENSED HEREUNDER, OR THE FREEDOM TO MAKE, HAVE MADE, USE, SELL OR OTHERWISE DISPOSE OF ANY PRODUCTS; OR

(C) IMPOSES AN OBLIGATION ON THE UNIVERSITY TO BRING, PROSECUTE OR DEFEND ACTIONS OR SUITS AGAINST THIRD PARTIES FOR INFRINGEMENT OF PATENTS, COPYRIGHTS, TRADE-MARKS, INDUSTRIAL DESIGNS OR OTHER INTELLECTUAL PROPERTY OR CONTRACTUAL RIGHTS.

8.3 THE FDCT SOFTWARE IS EXPERIMENTAL IN NATURE AND IS BEING LICENSED "AS IS." IT IS PART OF AN ONGOING EXPERIMENTAL RESEARCH PROGRAM.

THE LICENSE OF THE FDCT SOFTWARE DOES NOT INCLUDE ANY TECHNICAL SUPPORT. THE CALIFORNIA INSTITUTE OF TECHNOLOGY AND UNIVERSITY MAKE NO WARRANTIES, REPRESENTATION OR UNDERTAKING WITH RESPECT TO THE UTILITY, EFFICACY, SAFETY, OR APPROPRIATENESS OF USING THE FDCT SOFTWARE.

8.4 THE FDCT SOFTWARE IS PROVIDED "AS-IS" WITHOUT WARRANTY OF ANY KIND INCLUDING ANY WARRANTIES OF PERFORMANCE OR MERCHANTABILITY OR FITNESS FOR A PARTICULAR USE OR PURPOSE (as set forth in UCC §§23212-2313) OR FOR ANY PURPOSE WHATSOEVER HOWEVER USED.

8.5 IN NO EVENT SHALL THE CALIFORNIA INSTITUTE OF TECHNOLOGY BE LIABLE FOR ANY DAMAGES AND/OR COSTS, INCLUDING BUT NOT LIMITED TO INCIDENTAL OR CONSEQUENTIAL DAMAGES OF ANY KIND, INCLUDING ECONOMIC DAMAGE OR INJURY TO PROPERTY AND LOST PROFITS, REGARDLESS OF WHETHER THE CALIFORNIA INSTITUTE OF TECHNOLOGY SHALL BE ADVISED, HAVE REASON TO KNOW, OR IN FACT SHALL KNOW OF THE POSSIBILITY.

8.6 PARTICIPANT BEARS ALL RISK RELATING TO QUALITY AND PERFORMANCE OF THE FDCT SOFTWARE USED BY THE PARTICIPANT OR ITS AFFILIATES.

9. <u>INSURANCE</u>

9.1 The Participant acknowledges the University's representation that it has liability insurance applicable to its directors, officers, employees, faculty, students and agents while acting within the scope of their employment by the University and that it has no liability insurance policy that can extend protection to any other person. Therefore, the Participant assumes the risks of personal injury and property damage attributable to the negligent acts or omissions of the Participant and its Affiliates and their directors, officers, employees and agents.

10. <u>TERM, TERMINATION AND WITHDRAWAL</u>

10.1 This Agreement starts on the Effective Date and continues for twelve months. This Agreement will be renewed automatically for further twelve-month periods, unless a notice of termination is given in writing by one Party to the other at least three (3) months before the end of this Agreement or the end of the latest renewal. If such a notice of termination is given, this Agreement will terminate with effect from the end of the twelve-month period during which the notice of termination was given.

10.2 If the Participant commits any breach or default of any terms or conditions of this Agreement and also fails to remedy such breach or default within thirty (30) days after receipt of a written notice from the University, the University may terminate this Agreement by sending a notice of termination in writing to the Participant. This termination will be effective as of the date of the receipt of such notice. The termination may be in addition to any other remedies available at law or in equity.

10.3 Upon the termination of this Agreement, the Participant will cease to use the University's Confidential Information and Curvelet Transform Technology in any manner whatsoever and upon the written request by the University, Participant agrees to destroy all of the University's Confidential Information in Participant's possession or control and certify the same to the University. In the event that such Confidential Information must not be destroyed pursuant to judicial proceedings, Participant will promptly notify the University.

10.4 Termination of this Agreement for any reason shall neither release any Party hereto from any liability which, at the time of such termination, has already accrued to the other Party or which is attributable to a period prior to such termination, nor preclude either Party from pursing any rights and remedies that it may have hereunder, at law or in equity and which accrued or is based upon any event occurring prior to such termination.

10.5 No termination of this Agreement, however effectuated, will release Participant from its rights and obligations under this Agreement including: Sections 1.0 (Definitions and Interpretations), 5.0 (Confidentiality), 8 (Disclaimer of Warranty), 10.3 (cessation of use of Confidential Information), 6 (Indemnity) and 10.4 (accrued liability).

11. GOVERNING LAW

11.1 This Agreement is governed by, and will be construed in accordance with, the laws of British Columbia and the laws of Canada in force in that province, without regard to its conflict of law rules. The Parties agree that by executing this Agreement, they have attorned to the exclusive jurisdiction of the Supreme Court of British Columbia.

12. ASSIGNMENT

12.1 Except by operation of law or the sale of that part of business to which the Research pertains, a Party may not assign this Agreement without the prior written consent of the other Party, which consent will not be unreasonably withheld or delayed.

13. TAXES

13.1 The Participant shall be responsible for payment of all applicable Value Added Taxes chargeable on goods or services supplied by the University.

14. NOTICES

14.1 All payments, reports and notices or other documents that a Party is required or may want to deliver to any other Party will be delivered:

(a) in writing; and

(b) either by personal delivery or by registered or certified mail (with all postage and other charges prepaid) at the address for the receiving Party as set out in Article 14.2 or as varied by any notice.

Any notice personally delivered is deemed to have been received at the time of delivery. Any notice mailed in accordance with this Article 14.1 is deemed to have been received at the end of the fifth day after it is posted.

14.2 Addresses for delivery of notices:

Participant	The University
Charles Jones Consulting Geophysicist Seismic Processing Operations BG ~~Group~~ International Ltd (JC) Telephone: +44 (0)118 929 2637	Managing Director University-Industry Liaison Office #103 – 6190 Agronomy Road The University of British Columbia Vancouver, British Columbia Canada V6T 1Z3 Telephone: (604) 822-8580 Fax: (604) 822-8589

14.3 The Participant may direct questions of a scientific nature or regarding financial matters to the University through the following contacts:

Scientific Matters:

Dr. Felix J. Herrmann
The University of British Columbia
Department of Earth and Ocean Sciences
6339 Stores Road
Vancouver, British Columbia
V6T 1Z4 CANADA
Telephone: (604) 822-8628
Facsimile: (604) 822-6088

Financial Matters:

Manager, Research and Trust Accounting
Office of Financial of Services
University of British Columbia

General Services Administration Building
2075 Wesbrook Mall
Vancouver, British Columbia
V6T 1Z1 CANADA
Telephone: (604) 822-6883
Telecopier: (604) 822-2417

15. COPYRIGHT MARKING

15.1 Participant will mark, in at least one conspicuous location, a notice that the some of the Software licensed hereunder are owned by California Institute of Technology and The University of British Columbia. All marking should include: © 2008 California Institute of Technology, Pasadena, California. ALL RIGHTS RESERVED. Based on Government Sponsored Research NAS7-03001 and © 2008 The University of British Columbia, British Columbia, Canada.

16. USES NOT PERMITTED

16.1 Participant agrees to utilize FDCT Software solely for the business purposes of Participant and its Affiliates. Any other uses are not permitted.

16.2 Except for distribution to its Affiliates, Participant agrees not to distribute the FDCT Software to any person external to Participant.

17. FORCE MAJEURE

17.1 Neither Party shall lose any rights hereunder or be liable to the other Party for damages or losses (except for payment obligations) on account of failure of performance by the defaulting Party if the failure is occasioned by war, strike, fire, Act of God, earthquake, flood, lockout, embargo, governmental acts or orders or restrictions, failure of suppliers, act of terrorism, or any other reason where failure to perform is beyond the reasonable control and not caused by the negligence or intentional conduct or misconduct of the nonperforming Party, and such Party has exerted all reasonable efforts to avoid or remedy such force majeure; provided, however, that in no event shall a Party be required to settle any labor dispute or disturbance.

18. EXPORT REGULATION

18.1 FDCT Software including technical data, are subject to U.S. export control laws, including the U.S. Export Administration Act as well as the Export Regulations in Participant's country and its associated regulations, and may be subject to export or import regulations in other countries. Participant agrees to strictly comply with all U.S. Export Control Regulations and acknowledges that it has the responsibility to obtain such licenses for FDCT Software as may be required after delivery to Participant. Participant agrees not to disclose or re-export any part of the FDCT Software received under this Agreement.

19. SUPPORT AND UPGRADES

19.1 No software maintenance support or training is provided as part of this Agreement.

20. GENERAL LEGAL PROVISIONS

20.1 Nothing contained in this Agreement is to be deemed or construed to create between the Parties a partnership or joint venture. No Party has the authority to act on behalf of any other Party, or to commit any other Party in any manner at all or cause any other Party's name to be used in any way not specifically authorized by this Agreement.

20.2 Subject to the limitations in this Agreement, this Agreement operates for the benefit of and is binding on the Parties and their respective successors and permitted assigns.

20.3 No condoning, excusing or overlooking by any Party of any default, breach or non-observance by any other Party at any time or times regarding any terms of this Agreement operates as a waiver of that Party's rights under this Agreement. A waiver of any term or right under this Agreement will be in writing signed by the Party entitled to the benefit of that term or right, and is effective only to the extent set out in the written waiver.

20.4 No exercise of a specific right or remedy by any Party precludes it from or prejudices it in exercising another right or pursuing another remedy or maintaining an action to which it may otherwise be entitled either at law or in equity.

20.5 Headings in this Agreement are for reference only and do not form a part of this Agreement and are not be used in the interpretation of this Agreement.

20.6 All terms in this Agreement which require performance by the Parties after the expiry or termination of this Agreement, will remain in force despite this Agreement's expiry or termination for any reason.

20.7 Part or all of any Article that is indefinite, invalid, illegal or otherwise voidable or unenforceable, may be severed from this Agreement and the balance of this Agreement will continue in full force and effect.

20.8 At the request of the University or Participant, the other Party will obtain the execution of any agreement or instrument (including from its employees, agents, contractors, consultants or representatives) that may be reasonably required to consummate the transactions contemplated in this Agreement, including assigning any rights, waiving any rights or perfecting any rights in such requesting Party's name.

20.9 This Agreement and the Schedules set out the entire understanding between the Parties and no changes to this Agreement are binding unless in writing and signed by the Parties to this Agreement. The Parties will be bound by the Schedules, except to the extent that they may conflict with the terms and conditions contained in this Agreement, in which case the terms and conditions of this Agreement will govern.

20.10 In this Agreement, unless the contrary intention appears, the singular includes the plural and vice versa and words importing a gender include other genders.

20.11 This Agreement may be executed in counterparts by the Parties, either through original copies or by facsimile. An executed copy of this Agreement delivered by facsimile will constitute valid execution and delivery of this Agreement.

20.12 Participant agrees that it shall not use the name of the California Institute of Technology, Jet Propulsion Laboratory, or JPL in any advertising or publicity material or make any form of representation or statement, which would constitute an express or implied endorsement by the California Institute of Technology of any licensed product, and that it shall not authorize others to do so, without first having obtained written approval from the California Institute of Technology, except as may be required by governmental law, rule or regulation.

20.13 University agrees that it will not use the name of Participant in any advertising or publicity material or make any form of representation or statement, which would constitute an express or implied endorsement by the Participant of any licensed product, and that University shall not authorize others to do so, without first having obtained written approval from Participant, except as may be required by governmental law, rule or regulation.

IN WITNESS WHEREOF the Parties have executed this Agreement on the day and year first above written.

SIGNED FOR AND ON BEHALF of
THE UNIVERSITY OF BRITISH COLUMBIA
by its authorized signatory:

Authorized Signatory MARIO A. KASAPI
Associate Director
University - Industry Liaison Office

LEGAL APPROVED IH

SIGNED FOR AND ON BEHALF of
BG INTERNATIONAL LIMITED.
by its authorized signatory:

Authorized Signatory JULIE CARN
BG Contract Ref: 107464CUT

I have read and understood the foregoing Agreement and understand my responsibilities as the Principal Investigator:

Signature: FOR
Dr. Felix J. Herrmann
Dept: Earth and Ocean Sciences, The University of British Columbia

Date: May 19, 2009

SCHEDULE 1

UNIVERSITY BACKGROUND IP

1 Wavefield reconstruction

1.1 Curvelet-based focal transform

Description: Seismic wavefield reconstruction based on the combination of the non-adaptive curvelet transform and the data-adaptive focal transform. This method involves the inversion of the curvelet-regularized focusing operator by a sparsity-promoting program that solves a large-scale norm-one optimization problem.

Packages:

SLIMpy.apps : source code

SLIMpy.demos : demo

1.2 Jittered undersampling

Description: In this paper, we present a new discrete undersampling scheme designed to favor wavefield reconstruction by sparsity-promoting inversion with transform elements that are localized in the Fourier domain. Our work is motivated by empirical observations in the seismic community, corroborated by recent results from compressive sampling, which indicate favorable (wavefield) reconstructions from random as opposed to regular undersampling. As predicted by theory, random undersampling renders coherent aliases into harmless incoherent random noise, effectively turning the interpolation problem into a much simpler denoising problem.

A practical requirement of wavefield reconstruction with localized sparsifying transforms is the control on the maximum gap size. Unfortunately, random undersampling does not provide such a control and the main purpose of this paper is to introduce a sampling scheme, coined jittered undersampling, that shares the benefits of random sampling, while offering control on the maximum gap size. Our contribution of jittered sub-Nyquist sampling proofs to be key in the formulation of a versatile wavefield sparsity-promoting recovery scheme that follows the principles of compressive sampling.

After studying the behavior of the jittered-undersampling scheme in the Fourier domain, its performance is studied for curvelet recovery by sparsity-promoting inversion (CRSI). Our findings on synthetic and real seismic data indicate an improvement of several decibels over recovery from regularly-undersampled data for the same amount of data collected.

Packages:

SoftReleaseSept07 : demo in Papers/Jitter

1.3 Surfacelet transform

Description: Here we compare the transform domain interpolation results on seismic data with missing traces. The two transform domains are curvelets and surfacelets. The interpolation algorithm is performed on two different examples, one synthetic, and one with real marine data. The interpolation problem is resolved via a large-scale solver with iterative cooling and soft thresholding for the -regularization minimization involved in the recovery.

Packages:

SoftReleaseSept07 : demo in MATLAB/SURFinterp

1.4 Seismic denoising with 3-D transform-domain sparsity

Description: The code performs Seismic denoising exploiting 3D-curvelet transform domain sparsity. The 3D curvelet transform exploits the three-dimensional structure of seismic data thereby yielding better results. The denoising problem is formed as an optimization problem and is solved by iterative Landweber method.

Packages:

SLIMpy.user_demos	: demo in vkumar/denoise3d

2 Wavefield separation

2.1 Curvelet-based primary-multiple separation from a Bayesian perspective

Description: A new primary-multiple separation scheme which makes use of the sparsity of both primaries and multiples in a transform domain, such as the curvelet transform to provide estimates of each. The proposed algorithm utilizes seismic data as well as the output of a preliminary step that provides erroneous predictions of the multiples. The algorithm separates the signal components, i.e., the primaries and multiples by solving an optimization problem that assumes noisy input data and can be derived from a Bayesian interpretation. More precisely, the optimization problem can be arrived at via an assumption of a weighted Laplacian distribution for the primary and multiple coefficients in the curvelet domain and of white Gaussian noise contaminating both the seismic data and the preliminary prediction of the multiples, which both serve as input to the algorithm.

Packages:

SLIMpy.ANAs	: source code
SLIMpy.apps	: source code
SLIMpy.demos	: demo

2.2 3D Curvelet-based primary-multiple separation from a Bayesian perspective

Description: Primaries multiples separation use the sparsity of both primaries and multiples in curvelet domain by solving an optimization problem that assumes noisy input data and can be derived from a Bayesian perspective.

Packages:

SLIMpy.ANAs	: source code
SLIMpy.user_demos	: demo in dwang/pms-bayes3D

2.3 Adaptive curvelet-domain primary-multiple separation

Description: In this paper we developed a new adaptive curvelet-domain matching filter in primary-multiple separation problem instead of using conventional least-squares windowed amplitude matching,we propose a data-adaptive method that corrects amplitude errors, which vary smoothly as a function of location, scale (frequency band) and angle. In that case, the amplitudes can be corrected by an element-wise curvelet-domain scaling of the predicted multiples.

Packages:

SLIMpy.ANAs	: source code
SLIMpy.apps	: source code
SoftReleaseFeb08	: paper in Papers/CurveMatchRep

2.4 Surfacelet-based primary-multiple separation

Description: Here we compare the transform domain primary-multiple separation on seismic data with simple thresholding in a transform domain. The transform domains

are curvelets and surfacelets. Simple thresholding is performed on the SRME predicted multiples and the subtraction is performed on a full 2D SAGA dataset, and the curvelet / surfacelet results are compared. It is important to note that this method highly relies on the accurate prediction of primaries / multiples, since inaccurate predictions will cause residual multiple energy in the result or may lead to a distortion of the primaries, or both.

Packages:

SoftReleaseSept07 : demo in MATLAB/SURF-Mult-Predict

2.5 Surfacelet-based primary-multiple separation from Bayesian perspective

Description: Here we compare the Bayesian wave-field separation algorithm in a transform domain. The transform domains are curvelets and surfacelets. The purpose of this demo is to compare which transform domain is better suited for the problem of primary-multiple separation from a Bayesian perspective. The algorithm is tested on a 2-dimensional dataset.

References: wang07rri

Packages:

SLIMpy.ANAs : source code

SLIMpy.apps : source code

SLIMpy.user_demos : demo in elebed/curv-surf

2.6 Ground-roll removal based on Curvelet Transform

Description: The demonstration of surface wave identification and separation through SLIMpy and pyct tools developed at SLIM. Two examples will be shown with real data to highlight the use of these tools relating to ground roll noise prediction, separation and the ability to perform multiple separations in sequence. This demo is fully reproducible through use of Madagascar and contains the appropriate tools, which can be modified to fit specific projects.

Packages:

SoftReleaseSept07 : demo in PYTHON/GroundRoll

2.7 Block coordinate relaxation and Bayesian surface wave separation

Description: This is a demonstration of surface wave identification and separation through SLIMpy and pyct tools developed at SLIM. Two examples will be shown with synthetic and real data to highlight the use of these tools relating to ground roll noise prediction, separation methods and their performance. Two different signal separation methods developed at SLIM will be used and the results can be compared. This demo is fully reproducible through use of Madagascar and contains the appropriate tools, which can be modified to fit specific projects.

Packages:

SLIMpy.ANAs : source code

SLIMpy.apps : source code

SLIMpy.user_demos : demo in cyarham/GroundRoll

3 Imaging

3.1 Curvelet Match Filtering for True Migration Amplitude Recovery

Description: This code estimates and applies the inverse of the diagonal of the normal operator in curvelet domain to the migrated image in the context of true amplitude recovery migration In these demos the migrated and de-migrated image are fetch from

ftp-server. These images should be generated before using this software.
The images in these examples are obtained using reverse-time migration-demigration, provided by William Symes at Rice university Inversion Lab and TOTAL E&P, Houston and are subjected to term and condition of these institutes.

Packages:

SoftReleaseFeb08 : Demo in PYTHON/CrvltMtchFlt4TrueAmpRecovery

4 Solvers

4.1 solvers

4.1.1 Iterative Soft Thresholding with cooling (ISTc)

Description: ISTc is a solver for large-scale one-norm regularized least squares. It is designed to solve any of the following two problems:

1. Basis pursuit denoise:

2. Basis pursuit:

ISTc relies only on matrix-vector operations *Ax* and .

Packages:

... : [SLIMpy.ANAs]: source code

4.1.2 SPGL1: A solver for large-scale sparse reconstruction

Description: SPGL1 is a solver for large-scale one-norm regularized least squares. It is designed to solve any of the following three problems:

1. Basis pursuit denoise:

2. Basis pursuit:

3. Lasso:

SPGL1 relies only on matrix-vector operations *Ax* and accepts both explicit matrices and functions that evaluate these products. In addition, SPGL1 supports the complex-variables case, and can solve each of these problems in the complex domain.

Packages:

SoftReleaseSept07 : demo in PYTHON/SPGL1 directory

4.2 solvers

4.2.1 LSQR

Description: Attempts to solve the least squares problem that minimizes . If **A** is inconsistent, it attempts to solve the system of linear equations **Ax=y**.

Packages:

SLIMpy.ANAs : source code

5 Transforms

5.1 Surfacelet transform with RSF data interface

Description: The Surfacelet transform (SurfeBox) is adapted to provide an interface to

read/write data using RSF (MADAGASCAR) file format.

Packages:

SurfBox.slim: source code
SLIM2RSFext : MADAGASCAR extension

5.2 Curvelets

5.2.1 2D and 3D Curvelet Transform with RSF data interface

Description: Two extensions to CurveLab are provided:

1. The 2D and 3D Curvelet code (CurveLab) is adapted to provide an interface to read/write data using RSF (MADAGASCAR) file format. The original in-core curvelet transforms were recorded into out-off-core MADAGASCAR applications.
2. Python wrapper was written to access in-core curvelet transforms.

Packages:

CurveLab-2.0.2-SLIM : source code
SLIM2RSFext : MADAGASCAR extension
pyCurvelab : Python wrapper

5.2.2 3D MPI Curvelet Transform with RSF data interface

Description: The original 3D MPI Curvelet code is adapted to provide an interface to read/write data using RSF (MADAGASCAR) file format. The utilized curvelet transform is in-core and can write either single or distributed (processor owned) files. The enclosed demonstration allows to compare the performance of 3D MPI RSF Curvelet transform to performance of SLIM's out-off-core serial implementation of 3D Curvelet transform.

Packages:

CurveLab-2.0.2-SLIM : source code
SLIM2RSFext-MPI : MADAGASCAR extension
SoftReleaseSept07 : demo in Other/FDCT-3D_MPI directory

6 Utilities

6.1 Jitter sampling

Description: The basic idea behind jittered undersampling is to regularly decimate the interpolation grid and subsequently perturb according to a discrete uniform distribution the coarse-grid sample points on the fine grid.

Packages:

SLIM2RSFext : MADAGASCAR extension

7 SLIMpy development/programming environment

Description: SLIMpy is a tool that interfaces Abstract Numerical Algorithms (ANAs) with a variety of lower lever software packages. SLIMpy uses operator overloading to build an abstract computational tree which can be applied to many other software environments such as MADAGASCAR (formerly RSF).

The main development in this release is SLIMpy's embarrassingly parallel capability. SLIMpy now takes advantage of multi core processors by running each independent command on a given number of threads. A more intuitive interface for adding plugin commands (e.g. MADAGASCAR) has replaces the old plugin system. A number of bugs have been fixed, stdin/out commands that have no stdin or stdout may now be run from SLIMpy. Currently in the development branch there is a Beta version which

expands SLIMpy's multi core to multi processor functionality by using rsh and keeping track of local vs. global data.
Plans for the next release include a scalar class as a complement to the vector class. The scalar class will become a part of the AST (Abstract Syntax Tree) so it algorithms may be built in entirety before execution. This will help with the dependency problem SLIMpy has with scalars and also enable more efficient parallel utilities.

Packages:

SLIMpy.core: source code

SCHEDULE 2

FAST DIGITAL CURVELET TRANSFORM

The Fast Digital Curvelet Transform software takes as input a two-dimensional Cartesian array and returns a table of curvelet coefficients. Each curvelet coefficient essentially extracts information about the digital array at a specific scale, along a specific orientation, and at a specific location. (As an analogy, the Fourier transform extracts information at specified frequencies). There is an inverse transformation which allows reconstruction of the original array by recombining its curvelet coefficients. Both transformations, the forward and inverse mappings, are stable. In addition, the run time is almost linear in the number of pixel values. The package contains two distinct implementations of the same algorithm, and also includes an extension of the software to three-dimensional arrays.

SCHEDULE 3

LIST OF CALTECH PATENTS

Caltech File #	Inventor(s)	Description	Patent #
4349	Emmanuel Candes, Laurent Demanet, and David Donoho	Caltech curvelet	US Patent application #: 11/400,048, published 2/15/2007 (US-20070038691-A1)

“Seismic Imaging by Next-generation BAsis-function Decomposition (SINBAD)”

** Phase II **

CONSORTIUM MEMBERSHIP AGREEMENT FOR OIL COMPANIES

BP Contract number BPO-08-03511

THIS AGREEMENT is made the 1st day of December, 2008.

BETWEEN

THE UNIVERSITY OF BRITISH COLUMBIA, a corporation continued under the *University Act* of British Columbia with offices at Suite 103 – 6190 Agronomy Road, Vancouver, British Columbia, V6T 1Z3; (the "University");

AND

BP AMERICA PRODUCTION COMPANY, a corporation incorporated under the laws of Delaware, with a registered office at 501 Westlake Park Blvd, Houston, TX 77079; (the "Participant")

(University and Participant are referred to in this Agreement individually as a "**Party**" and collectively as the "**Parties**")

WHEREAS

(1) It is the University's objective to exploit its technology for the public benefit, in harmony with its Global Access Principles launched by the University in November 2007 and as outlined at www.uilo.ubc.ca/global.asp, and to generate further research in a manner consistent with the University's status as a non-profit, tax exempt educational institution;

(2) The University has been engaged in research and development in the field of seismic imaging and has undertaken research into a project referred to as Seismic Imaging by Next-generation BAsis-function Decomposition **("SINBAD");**

(3) Software developed through SINBAD has incorporated software developed by the California Institute of Technology ("**Caltech**"), and to which the University has secured the rights to sublicense such software to Participant; and

(4) The Participant wishes to participate in continued research in and development of SINBAD (the "**Research**"), and the University wishes to undertake such research.

NOW, THEREFORE, the Parties agree as follows:

1. DEFINITIONS and INTERPRETATION

1.1 (a) "**Advisory Committee**" means the committee established to provide advice to the University on matters regarding the Research in accordance with Clause 4;

(b) "**Affiliate**" means any corporation, Limited Liability Company or other legal entity directly or indirectly controlled by Participant or its successors or assigns, or any successor or assign of such an entity. For the purpose of this Agreement, "control" shall mean the direct or indirect ownership of at least fifty percent (50%) of the outstanding shares or other voting rights of the subject entity to elect directors, or if not meeting the preceding, any entity owned or controlled by or owning or controlling at the maximum control or ownership right permitted in the country where such entity exists;

(c) "**California Institute of Technology**" means a not-for-profit California corporation, located at 1200 E. California Blvd., Pasadena, CA 91125.

(d) "**Caltech Software**" shall mean the curvelet software libraries and source code that: i) are available for download at www.curvelet.org or ii) may be obtained from Caltech by negotiating a commercial license.

(e) "**Caltech Patent**" shall mean the rights in and to any and all inventions which are disclosed in the U.S. and foreign patents and patent applications identified in Schedule 3 with respect to the Caltech Software and all counterparts, corresponding international and foreign patent applications, and patents resulting therefrom;

(f) **"Confidential Information"** means all information, regardless of its form that is disclosed by the University to the Participant or its Affiliates and which is clearly identified in writing as "Confidential" at the time of disclosure. If identified orally, a written notice must be sent to the Participant within ten (10) business days thereafter. "Confidential Information" does not include information:

(i) possessed by the Participant or its Affiliates prior to receipt from the University, other than through prior confidential disclosure by the University, as evidenced by the Participant's business records;

(ii) published or available to the general public otherwise than through a breach of this Agreement;

(iii) obtained by the Participant or its Affiliates from a third party with a valid right to disclose it, provided that the third party is not under a confidentiality obligation to the University in respect of the same; or

(iv) independently developed by employees, agents or consultants of the Participant or its Affiliates who did not use the Confidential Information as evidenced by the Participant's business records; or

(v) that must be disclosed pursuant to an order or a subpoena.

(g) "**Curvelet Transform Technology**" means the suite of programs, scripts, and procedures, including Executable Code and Source Code, which perform the Fast Digital Curvelet Transform referred to in Schedule 2, and that was developed at the California Institute of Technology;

(h) **"Derivative Works"** means any work consisting of revisions, annotations, elaborations, or other modifications to Software which, as a whole, represent an original work of authorship. Derivative Works includes any updates and new releases of the FDCT Software developed at the California Institute of Technology during the term of this Agreement, inclusive of backups, updates, or merged copies permitted hereunder including the file structures, programming instructions, user interfaces and screen formats and sequences;

(i) "**Effective Date**" means December 1, 2008;

(j) "**Executable Code**" means computer software programs, not readily perceivable by humans, and suitable for machine execution without the intervening steps of interpretation or compilation.

(k) **"Field"** means signal and image processing, including seismic data processing;

(l) "**Fast Digital Curvelet Transform**" means the transform described in Schedule 2 attached hereto. ;

(m) "**FDCT Software**" means the suite of programs, scripts, and procedures, including Executable Code and Source Code, received by Participant, which perform the Fast Digital Curvelet Transform;

(n) "**Foreground IP**" means the copyright (including the source code), design rights, trademarks and patents (whether registered or not and all applications for any of them) and other forms of intellectual property rights made or generated solely as a result of the research;

(o) "**Principal Investigator**" means Dr. Felix J. Herrmann of the Department of Earth and Ocean Sciences at The University of British Columbia;

(p) "**Software**" means copyright rights, as defined by United States copyright laws and applicable international treaties and/or conventions;

(q) "**Source Code**" means computer software programs, not in machine-readable format and not suitable for machine execution without the intervening steps of interpretation or compilation; and

(r) "**Start Date**" means April 1, 2009.

(s) "**University Background IP**" means any Intellectual Property Rights owned or under the control of the University prior to the date of this Agreement relating to the technology which is described in Schedule 1 attached to this Agreement, and excludes Caltech Patent and Curvelet Transform Technology;

2. RESEARCH WORK AND PUBLICATION

2.1 Subject to compliance by the Participant with its obligations under this Agreement, the University shall:

(a) carry out the Research in accordance with those policies, standards, procedures, conventions and techniques that are of a high recognized and acceptable professional standard in the scientific community and in accordance with the requirements of this Agreement;

(b) comply with all health and safety regulations applicable to any work carried out as part of the Research and otherwise comply with all relevant laws and regulations in the conduct of the Research;

(c) supply all equipment, materials and facilities as may be required to conduct the Research, which shall remain the property of the University after termination of this Agreement;

2.2 The University shall provide a representative to attend all meetings of the Advisory Committee, who shall be a person engaged in the management of the Research on behalf of the University.

2.3 The Participant acknowledges that the policies of the University require that the results of the Research be publishable. The Parties therefore agree that the Principal Investigator and other researchers engaged in the Research shall not be restricted from presenting at symposia, national, or regional professional meetings, or from publishing in abstracts, journals, theses, or dissertations, or otherwise, whether in printed or in electronic media, methods and results of the Research, provided however that the Principal Investigator provides the Participant with a copy of any proposed publication or presentation forty-five days in advance of publication or presentation, or in the case of software 12 months prior to a public release.

2.4 During the term of this Agreement, The University will keep the Participant informed, orally or in writing, as to the progress of the Research.

2.5 Any funds received by the University from the Participant under this Agreement are non-refundable, unless the University terminates this Agreement before its expiration.

3. OBLIGATIONS OF THE PARTICIPANTS

3.1 Subject to the University's compliance with the terms of this Agreement, the Participant shall pay the University funds in accordance with the schedule below (all funds in Canadian dollars):

- $72,500 Canadian due on or before December 31, 2008;
- $72,500 on each anniversary of the Start Date until termination.

3.2 The Participant may, at its own cost, provide a representative to attend meetings of the Advisory Committee.

3.3 Performance of the Research is dependent on the amount of funds received from Participants. The University reserves the right to suspend work on the Research or to terminate the Research and this Agreement by delivering written notice of same to the Participant if funds are not sufficient to carry out the Research.

3.4 The Participant may make payments by wire transfer to:
Pay Via: SWIFT MT100
Pay to: HSBC Bank Canada, Main Branch, Vancouver, BC – SWIFT Address HKBCCATT
Account number for Canadian dollars: 016-10020-437218-002
Beneficiary: The University of British Columbia
Payment Details: RTA, FAS #F08-0456

3.5 The University will retain title to any equipment purchased with funds provided by the Participant under this Agreement.

4. ADVISORY COMMITTEE

4.1 The Advisory Committee shall:

(a) provide advice to the University relating to the conduct of the Research;

(b) review the results and recommendations of any University Research reports;

4.2 The Advisory Committee shall consist of no more than one representative from Participant and at least one University representative.

4.3 Meetings of the Advisory Committee shall be held at Vancouver, British Columbia. Meetings shall be regulated as the University may decide from time to time.

4.4 The University shall call all such meetings and shall give at least 10 days' prior written notice thereof to the Participant.

5. CONFIDENTIALITY

5.1 Except as expressly provided herein, each Party agrees not to disclose any terms of this Agreement to any third party without the consent of the other Party; provided, however, that disclosures may be made as required by securities laws or other applicable laws, or to actual or prospective investors or corporate partners, or to a Party's accountants, attorneys or to the United States Government and or other professional advisors or to Affiliates, or to Caltech for the purpose of the University satisfying its obligations to Caltech under its license agreement for the Caltech Software and Caltech Patents.

5.2 The Participant will keep and use University Confidential Information in confidence and will not, without the University's prior written consent, disclose the University's Confidential Information to any person or entity.

5.3 If the Participant is required by judicial or administrative process to disclose the University's Confidential Information, it will promptly notify the University and allow it reasonable time to oppose the process before disclosing the Confidential Information.

5.4 Notwithstanding any termination or expiration of this Agreement, the obligations set out in this Article 5 survive and continue to bind the Parties, their successors and assigns until 7 years after such termination or expiration.

5.5 The Participant and its Affiliates will ensure that the Source Code to any Software or Confidential Information is not disclosed to any other third party. In the event of an unauthorized or accidental disclosure of the Source Code the Participant will immediately:

(a) notify the University and will provide to the University full particulars of all information in the Participant's possession or control regarding the circumstances of such unauthorized use or disclosure;

(b) take (in full consultation with the University) and at the Participant's sole cost and expense all reasonable steps deemed necessary to remedy any such unauthorized use or disclosure, and take all reasonable steps necessary to recover the Source Code and to prevent its unauthorized use by any third party.

6. INTELLECTUAL PROPERTY, INDEMNIFICATION & LIMITATION OF LIABILITY

6.1 All Foreground IP shall be the property of the University from the date of its creation.

6.2 The Participant indemnifies, holds harmless and defends the University, its Board of Governors, directors, officers, employees, faculty, students, invitees and agents against any and all claims (including all reasonable legal fees and disbursements) arising out of the receipt or use by the Participant or its Affiliates of any of the University's Confidential Information, University Background IP, Foreground IP, or any data or other results arising from such use including, without limitation, any damages or losses, consequential or otherwise, arising from or out of the Research.

6.3 The California Institute of Technology shall not be liable for any use of the FDCT Software or related know-how, and Participant hereby agrees to defend, indemnify and hold the California Institute of Technology and its employees harmless from any loss, claim, damage or liability, or whatever kind of nature, which may arise from this Agreement, or the use by Participant or its Affiliates of the Curvelet Transform Technology, FDCT Software, or any related know-how transferrred to the Participant or its Affiliates hereunder.

6.4 The University's total liability, whether under the express or implied terms of this Agreement, in tort (including negligence) or at common law, for any loss or damage suffered by the Participant or its Affiliates, whether direct, indirect or special, or any other similar damage that may arise or does arise from any breaches of this Agreement by the University, its Board of Governors, officers, employees, faculty, students or agents, is limited to $5,000.

6.5 Neither party will be liable for consequential or incidental damages arising from any breach or breaches of this Agreement.

6.6 Notwithstanding the termination or expiration of this Agreement, the rights and obligations in this Section 6 will survive and continue to bind the Participant and its successors and assigns.

7. GRANT OF RIGHTS

7.1 Subject to Section 6.2 (Indemnity), the University grants the Participant and its Affiliates a perpetual, worldwide, non-exclusive, non-transferable, royalty-free license to use and exploit University Background IP and Foreground IP for internal use only in the Field. Such internal use shall not include the provision of services or products to third parties. Internal use includes uses by Participant and its Affiliates as an "operator" in the field of oil and gas production and exploration.

7.2 Subject to Section 6.2 (Indemnity) and Section 6.3, the University grants the Participant and its Affiliates a worldwide, non-exclusive, non-transferable, royalty-free license to use and exploit the Caltech Patent, Caltech Software and the Curvelet Transform Technology for internal use in the Field and in conjunction with the University Background IP and/or Foreground IP, during the term of this Agreement.

7.3 Neither the Participant nor its Affiliates will grant sublicenses of the University Background IP, Foreground IP or California Institute of Technology IP to any third party.

7.4 The Participant acknowledges and agrees that the University may use University Background IP and Foreground IP without charge in any manner for any purpose.

7.5 California Institute of Technology retains ownership of FDCT Software and Caltech Patent licensed under this Agreement.

7.6 Participant may not remove or obscure any visible copyright or trademark notices.

7.7 The FDCT Software shall not become subject to application for patent or copyright by Participant.

7.8 Participant may not install any copies of FDCT Software on computers that are not owned or leased by Participant or its Affiliates.

7.9 Participant agrees that it may make a reasonable number of copies of Software for archival and backup purposes.

7.10 Participant shall be the sole owner of any data output in any format or media derived from or obtained by use of the FDCT Software and may freely use and disclose such output to any third party.

8. <u>DISCLAIMER OF WARRANTY</u>

8.1 THE UNIVERSITY MAKES NO REPRESENTATIONS OR WARRANTIES, EITHER EXPRESS OR IMPLIED, REGARDING DATA OR SOFTWARE OR OTHER RESULTS ARISING FROM THE RESEARCH OR REGARDING CONFIDENTIAL INFORMATION THE UNIVERSITY MAY DISCLOSE TO THE PARTICIPANT. THE UNIVERSITY SPECIFICALLY DISCLAIMS ANY IMPLIED WARRANTY OF NON-INFRINGEMENT OR MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE AND THE UNIVERSITY WILL, IN NO EVENT, BE LIABLE FOR ANY LOSS OF PROFITS, BE THEY DIRECT, CONSEQUENTIAL, INCIDENTAL, OR SPECIAL OR OTHER SIMILAR DAMAGES ARISING FROM ANY DEFECT, ERROR OR FAILURE TO PERFORM, EVEN IF THE UNIVERSITY HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES. THE PARTICIPANT ACKNOWLEDGES THAT THE RESEARCH IS OF AN EXPERIMENTAL AND EXPLORATORY NATURE, THAT NO PARTICULAR RESULTS CAN BE GUARANTEED, AND THAT THE PARTICIPANT HAS BEEN ADVISED BY THE UNIVERSITY TO UNDERTAKE ITS OWN DUE DILIGENCE WITH RESPECT TO ALL MATTERS ARISING FROM THIS AGREEMENT.

8.2 NOTHING IN THIS AGREEMENT:

(A) CONSTITUTES A WARRANTY OR REPRESENTATION BY THE UNIVERSITY AS TO TITLE TO THE INTELLECTUAL PROPERTY LICENSED HEREUNDER, OR THAT ANYTHING MADE, USED, SOLD OR OTHERWISE DISPOSED OF UNDER THE LICENSE GRANTED IN THIS AGREEMENT WILL NOT INFRINGE THE PATENTS, COPYRIGHTS, TRADE-MARKS, INDUSTRIAL DESIGNS OR OTHER INTELLECTUAL PROPERTY RIGHTS OF ANY THIRD PARTIES, OR ANY PATENTS, COPYRIGHTS, TRADE-MARKS, INDUSTRIAL DESIGN OR OTHER INTELLECTUAL PROPERTY RIGHTS OWNED, IN WHOLE OR IN PART, BY THE UNIVERSITY, OR LICENSED BY THE UNIVERSITY TO ANY THIRD PARTIES;

(B) CONSTITUTES AN EXPRESS OR IMPLIED WARRANTY OR REPRESENTATION BY THE UNIVERSITY THAT THE PARTICIPANT HAS, OR WILL HAVE THE FREEDOM TO OPERATE OR PRACTICE THE INTELLECTUAL PROPERTY LICENSED HEREUNDER, OR THE FREEDOM TO MAKE, HAVE MADE, USE, SELL OR OTHERWISE DISPOSE OF ANY PRODUCTS; OR

(C) IMPOSES AN OBLIGATION ON THE UNIVERSITY TO BRING, PROSECUTE OR DEFEND ACTIONS OR SUITS AGAINST THIRD PARTIES FOR INFRINGEMENT OF PATENTS, COPYRIGHTS, TRADE-MARKS, INDUSTRIAL DESIGNS OR OTHER INTELLECTUAL PROPERTY OR CONTRACTUAL RIGHTS.

8.3 THE FDCT SOFTWARE IS EXPERIMENTAL IN NATURE AND IS BEING LICENSED "AS IS." IT IS PART OF AN ONGOING EXPERIMENTAL RESEARCH PROGRAM.

THE LICENSE OF THE FDCT SOFTWARE DOES NOT INCLUDE ANY TECHNICAL SUPPORT. THE CALIFORNIA INSTITUTE OF TECHNOLOGY AN D UNIVERSITY MAKE NO WARRANTIES, REPRESENTATION OR UNDERTAKING WITH RESPECT TO THE UTILITY, EFFICACY, SAFETY, OR APPROPRIATENESS OF USING THE FDCT SOFTWARE.

8.4 THE FDCT SOFTWARE IS PROVIDED "AS-IS" WITHOUT WARRANTY OF ANY KIND INCLUDING ANY WARRANTIES OF PERFORMANCE OR MERCHANTABILITY OR FITNESS FOR A PARTICULAR USE OR PURPOSE (as set forth in UCC §§23212-2313) OR FOR ANY PURPOSE WHATSOEVER HOWEVER USED.

8.5 IN NO EVENT SHALL THE CALIFORNIA INSTITUTE OF TECHNOLOGY BE LIABLE FOR ANY DAMAGES AND/OR COSTS, INCLUDING BUT NOT LIMITED TO INCIDENTAL OR CONSEQUENTIAL DAMAGES OF ANY KIND, INCLUDING ECONOMIC DAMAGE OR INJURY TO PROPERTY AND LOST PROFITS, REGARDLESS OF WHETHER THE CALIFORNIA INSTITUTE OF TECHNOLOGY SHALL BE ADVISED, HAVE REASON TO KNOW, OR IN FACT SHALL KNOW OF THE POSSIBILITY.

8.6 PARTICIPANT BEARS ALL RISK RELATING TO QUALITY AND PERFORMANCE OF THE FDCT SOFTWARE USED BY THE PARTICIPANT OR ITS AFFILIATES.

9. INSURANCE

9.1 The Participant acknowledges the University's representation that it has liability insurance applicable to its directors, officers, employees, faculty, students and agents while acting within the scope of their employment by the University and that it has no liability insurance policy that can extend protection to any other person. Therefore, the Participant assumes the risks of personal injury and property damage attributable to the negligent acts or omissions of the Participant and its Affiliates and their directors, officers, employees and agents.

10. TERM, TERMINATION AND WITHDRAWAL

10.1 This Agreement starts on the Effective Date and continues for twelve months. This Agreement will be renewed automatically for further twelve-month periods, unless a notice of termination is given in writing by one Party to the other at least three (3) months before the end of this Agreement or the end of the latest renewal. If such a notice of termination is given, this Agreement will terminate with effect from the end of the twelve-month period during which the notice of termination was given.

10.2 If the Participant commits any breach or default of any terms or conditions of this Agreement and also fails to remedy such breach or default within thirty (30) days after receipt of a written notice from the University, the University may terminate this Agreement by sending a notice of termination in writing to the Participant. This termination will be effective as of the date of the receipt of such notice. The termination may be in addition to any other remedies available at law or in equity.

10.3 Upon the termination of this Agreement, the Participant will cease to use the University's Confidential Information and Curvelet Transform Technology in any manner whatsoever and upon the written request by the University, Participant agrees to destroy all of the University's Confidential Information in Participant's possession or control and certify the same to the University. In the event that such Confidential Information must not be destroyed pursuant to judicial proceedings, Participant will promptly notify the University.

10.4 Termination of this Agreement for any reason shall neither release any Party hereto from any liability which, at the time of such termination, has already accrued to the other Party or which is attributable to a period prior to such termination, nor preclude either Party from pursing any rights and remedies that it may have hereunder, at law or in equity and which accrued or is based upon any event occurring prior to such termination.

10.5 No termination of this Agreement, however effectuated, will release Participant from its rights and obligations under this Agreement including: Sections 1.0 (Definitions and Interpretations), 5.0 (Confidentiality), 8 (Disclaimer of Warranty), 10.4 (cessation of use of Confidential Information), 6 (Indemnity) and 10.5 (accrued liability).

11. <u>GOVERNING LAW</u>

11.1 This Agreement is governed by, and will be construed in accordance with, the laws of British Columbia and the laws of Canada in force in that province, without regard to its conflict of law rules. The Parties agree that by executing this Agreement, they have attorned to the exclusive jurisdiction of the Supreme Court of British Columbia.

12. <u>ASSIGNMENT</u>

12.1 Except by operation of law or the sale of that part of business to which the Research pertains, a Party may not assign this Agreement without the prior written consent of the other Party, which consent will not be unreasonably withheld or delayed.

13. <u>TAXES</u>

13.1 The Participant shall be responsible for payment of all applicable Value Added Taxes chargeable on goods or services supplied by the University.

14. <u>NOTICES</u>

14.1 All payments, reports and notices or other documents that a Party is required or may want to deliver to any other Party will be delivered:

(a) in writing; and

(b) either by personal delivery or by registered or certified mail (with all postage and other charges prepaid) at the address for the receiving Party as set out in Article 14.2 or as varied by any notice.

Any notice personally delivered is deemed to have been received at the time of delivery. Any notice mailed in accordance with this Article 14.1 is deemed to have been received at the end of the fifth day after it is posted.

14.2 Addresses for delivery of notices:

Participant	The University
Veronica Brown Senior EPT PSCM Specialist BP America Production Company Telephone: (281) 504-2258 Fax: (281) 504-2242	Managing Director University-Industry Liaison Office #103 – 6190 Agronomy Road The University of British Columbia Vancouver, British Columbia Canada V6T 1Z3 Telephone: (604) 822-8580 Fax: (604) 822-8589

14.3 The Participant may direct questions of a scientific nature or regarding financial matters to the University through the following contacts:

Scientific Matters:

Dr. Felix J. Herrmann
The University of British Columbia
Department of Earth and Ocean Sciences
6339 Stores Road
Vancouver, British Columbia
V6T 1Z4 CANADA
Telephone: (604) 822-8628
Facsimile: (604) 822-6088

Financial Matters:

Manager, Research and Trust Accounting
Office of Financial of Services
University of British Columbia

General Services Administration Building
2075 Wesbrook Mall
Vancouver, British Columbia
V6T 1Z1 CANADA
Telephone: (604) 822-6883
Telecopier: (604) 822-2417

15. **COPYRIGHT MARKING**

15.1 Participant will mark, in at least one conspicuous location, a notice that the some of the Software licensed hereunder are owned by California Institute of Technology and The University of British Columbia. All marking should include: © 2008 California Institute of Technology, Pasadena, California. ALL RIGHTS RESERVED. Based on Government Sponsored Research NAS7-03001 and © 2008 The University of British Columbia, British Columbia, Canada.

16. **USES NOT PERMITTED**

16.1 Participant agrees to utilize FDCT Software solely for the business purposes of Participant and its Affiliates. Any other uses are not permitted.

16.2 Except for distribution to its Affiliates, Participant agrees not to distribute the FDCT Software to any person external to Participant.

17. **FORCE MAJEURE**

17.1 Neither Party shall lose any rights hereunder or be liable to the other Party for damages or losses (except for payment obligations) on account of failure of performance by the defaulting Party if the failure is occasioned by war, strike, fire, Act of God, earthquake, flood, lockout, embargo, governmental acts or orders or restrictions, failure of suppliers, act of terrorism, or any other reason where failure to perform is beyond the reasonable control and not caused by the negligence or intentional conduct or misconduct of the nonperforming Party, and such Party has exerted all reasonable efforts to avoid or remedy such force majeure; provided, however, that in no event shall a Party be required to settle any labor dispute or disturbance.

18. EXPORT REGULATION

18.1 FDCT Software including technical data, are subject to U.S. export control laws, including the U.S. Export Administration Act as well as the Export Regulations in Participant's country and its associated regulations, and may be subject to export or import regulations in other countries. Participant agrees to strictly comply with all U.S. Export Control Regulations and acknowledges that it has the responsibility to obtain such licenses for FDCT Software as may be required after delivery to Participant. Participant agrees not to disclose or re-export any part of the FDCT Software received under this Agreement.

19. SUPPORT AND UPGRADES

19.1 No software maintenance support or training is provided as part of this Agreement.

20. GENERAL LEGAL PROVISIONS

20.1 Nothing contained in this Agreement is to be deemed or construed to create between the Parties a partnership or joint venture. No Party has the authority to act on behalf of any other Party, or to commit any other Party in any manner at all or cause any other Party's name to be used in any way not specifically authorized by this Agreement.

20.2 Subject to the limitations in this Agreement, this Agreement operates for the benefit of and is binding on the Parties and their respective successors and permitted assigns.

20.3 No condoning, excusing or overlooking by any Party of any default, breach or non-observance by any other Party at any time or times regarding any terms of this Agreement operates as a waiver of that Party's rights under this Agreement. A waiver of any term or right under this Agreement will be in writing signed by the Party entitled to the benefit of that term or right, and is effective only to the extent set out in the written waiver.

20.4 No exercise of a specific right or remedy by any Party precludes it from or prejudices it in exercising another right or pursuing another remedy or maintaining an action to which it may otherwise be entitled either at law or in equity.

20.5 Headings in this Agreement are for reference only and do not form a part of this Agreement and are not be used in the interpretation of this Agreement.

20.6 All terms in this Agreement which require performance by the Parties after the expiry or termination of this Agreement, will remain in force despite this Agreement's expiry or termination for any reason.

20.7 Part or all of any Article that is indefinite, invalid, illegal or otherwise voidable or unenforceable, may be severed from this Agreement and the balance of this Agreement will continue in full force and effect.

20.8 At the request of the University or Participant, the other Party will obtain the execution of any agreement or instrument (including from its employees, agents, contractors, consultants or representatives) that may be reasonably required to consummate the transactions contemplated in this Agreement, including assigning any rights, waiving any rights or perfecting any rights in such requesting Party's name.

20.9 This Agreement and the Schedules set out the entire understanding between the Parties and no changes to this Agreement are binding unless in writing and signed by the Parties to this Agreement. The Parties will be bound by the Schedules, except to the extent that they may conflict with the terms and conditions contained in this Agreement, in which case the terms and conditions of this Agreement will govern.

20.10 In this Agreement, unless the contrary intention appears, the singular includes the plural and vice versa and words importing a gender include other genders.

20.11 This Agreement may be executed in counterparts by the Parties, either through original copies or by facsimile. An executed copy of this Agreement delivered by facsimile will constitute valid execution and delivery of this Agreement.

20.12 Participant agrees that it shall not use the name of the California Institute of Technology, Jet Propulsion Laboratory, or JPL in any advertising or publicity material or make any form of representation or statement, which would constitute an express or implied endorsement by the California Institute of Technology of any licensed product, and that it shall not authorize others to do so, without first having obtained written approval from the California Institute of Technology, except as may be required by governmental law, rule or regulation.

20.13 University agrees that it will not use the name of Participant in any advertising or publicity material or make any form of representation or statement, which would constitute an express or implied endorsement by the Participant of any licensed product, and that University shall not authorize others to do so, without first having obtained written approval from Participant, except as may be required by governmental law, rule or regulation.

IN WITNESS WHEREOF the Parties have executed this Agreement on the day and year first above written.

SIGNED FOR AND ON BEHALF of
THE UNIVERSITY OF BRITISH COLUMBIA
by its authorized signatories:

MARIO A. KASAPI
Associate Director
University - Industry Liaison Office

Authorized Signatory

LEGAL APPROVED

Authorized Signatory

SIGNED FOR AND ON BEHALF of
BP AMERICA PRODUCTION COMPANY
by its authorized signatories:

T. P. Summers

Tim Summers
VP Imaging

I have read and understood the foregoing Agreement and understand my responsibilities as the Principal Investigator:

Signature:

Dr. Felix J. Herrmann
Dept: Earth and Ocean Sciences, The University of British Columbia

Date: 15-12-08

SCHEDULE 1

UNIVERSITY BACKGROUND IP

1 Wavefield reconstruction

1.1 Curvelet-based focal transform

Description: Seismic wavefield reconstruction based on the combination of the non-adaptive curvelet transform and the data-adaptive focal transform. This method involves the inversion of the curvelet-regularized focusing operator by a sparsity-promoting program that solves a large-scale norm-one optimization problem.

Packages:

SLIMpy.apps : source code
SLIMpy.demos : demo

1.2 Jittered undersampling

Description: In this paper, we present a new discrete undersampling scheme designed to favor wavefield reconstruction by sparsity-promoting inversion with transform elements that are localized in the Fourier domain. Our work is motivated by empirical observations in the seismic community, corroborated by recent results from compressive sampling, which indicate favorable (wavefield) reconstructions from random as opposed to regular undersampling. As predicted by theory, random undersampling renders coherent aliases into harmless incoherent random noise, effectively turning the interpolation problem into a much simpler denoising problem.

A practical requirement of wavefield reconstruction with localized sparsifying transforms is the control on the maximum gap size. Unfortunately, random undersampling does not provide such a control and the main purpose of this paper is to introduce a sampling scheme, coined jittered undersampling, that shares the benefits of random sampling, while offering control on the maximum gap size. Our contribution of jittered sub-Nyquist sampling proofs to be key in the formulation of a versatile wavefield sparsity-promoting recovery scheme that follows the principles of compressive sampling.

After studying the behavior of the jittered-undersampling scheme in the Fourier domain, its performance is studied for curvelet recovery by sparsity-promoting inversion (CRSI). Our findings on synthetic and real seismic data indicate an improvement of several decibels over recovery from regularly-undersampled data for the same amount of data collected.

Packages:

SoftReleaseSept07 : demo in Papers/Jitter

1.3 Surfacelet transform

Description: Here we compare the transform domain interpolation results on seismic data with missing traces. The two transform domains are curvelets and surfacelets. The interpolation algorithm is performed on two different examples, one synthetic, and one with real marine data. The interpolation problem is resolved via a large-scale solver with iterative cooling and soft thresholding for the -regularization minimization involved in the recovery.

Packages:

SoftReleaseSept07 : demo in MATLAB/SURFinterp

1.4 Seismic denoising with 3-D transform-domain sparsity

Description: The code performs Seismic denoising exploiting 3D-curvelet transform domain sparsity. The 3D curvelet transform exploits the three-dimensional structure of seismic data thereby yielding better results. The denoising problem is formed as an optimization problem and is solved by iterative Landweber method.

Packages:

SLIMpy.user_demos	: demo in vkumar/denoise3d

2 Wavefield separation

2.1 Curvelet-based primary-multiple separation from a Bayesian perspective

Description: A new primary-multiple separation scheme which makes use of the sparsity of both primaries and multiples in a transform domain, such as the curvelet transform to provide estimates of each. The proposed algorithm utilizes seismic data as well as the output of a preliminary step that provides erroneous predictions of the multiples. The algorithm separates the signal components, i.e., the primaries and multiples by solving an optimization problem that assumes noisy input data and can be derived from a Bayesian interpretation. More precisely, the optimization problem can be arrived at via an assumption of a weighted Laplacian distribution for the primary and multiple coefficients in the curvelet domain and of white Gaussian noise contaminating both the seismic data and the preliminary prediction of the multiples, which both serve as input to the algorithm.

Packages:

SLIMpy.ANAs	: source code
SLIMpy.apps	: source code
SLIMpy.demos	: demo

2.2 3D Curvelet-based primary-multiple separation from a Bayesian perspective

Description: Primaries multiples separation use the sparsity of both primaries and multiples in curvelet domain by solving an optimization problem that assumes noisy input data and can be derived from a Bayesian perspective.

Packages:

SLIMpy.ANAs	: source code
SLIMpy.user_demos	: demo in dwang/pms-bayes3D

2.3 Adaptive curvelet-domain primary-multiple separation

Description: In this paper we developed a new adaptive curvelet-domain matching filter in primary-multiple separation problem instead of using conventional least-squares windowed amplitude matching,we propose a data-adaptive method that corrects amplitude errors, which vary smoothly as a function of location, scale (frequency band) and angle. In that case, the amplitudes can be corrected by an element-wise curvelet-domain scaling of the predicted multiples.

Packages:

SLIMpy.ANAs	: source code
SLIMpy.apps	: source code
SoftReleaseFeb08	: paper in Papers/CurveMatchRep

2.4 Surfacelet-based primary-multiple separation

Description: Here we compare the transform domain primary-multiple separation on seismic data with simple thresholding in a transform domain. The transform domains

are curvelets and surfacelets. Simple thresholding is performed on the SRME predicted multiples and the subtraction is performed on a full 2D SAGA dataset, and the curvelet / surfacelet results are compared. It is important to note that this method highly relies on the accurate prediction of primaries / multiples, since inaccurate predictions will cause residual multiple energy in the result or may lead to a distortion of the primaries, or both.

Packages:

SoftReleaseSept07 : demo in MATLAB/SURF-Mult-Predict

2.5 Surfacelet-based primary-multiple separation from Bayesian perspective

Description: Here we compare the Bayesian wave-field separation algorithm in a transform domain. The transform domains are curvelets and surfacelets. The purpose of this demo is to compare which transform domain is better suited for the problem of primary-multiple separation from a Bayesian perspective. The algorithm is tested on a 2-dimensional dataset.

References: wang07rri

Packages:

SLIMpy.ANAs : source code
SLIMpy.apps : source code
SLIMpy.user_demos : demo in elebed/curv-surf

2.6 Ground-roll removal based on Curvelet Transform

Description: The demonstration of surface wave identification and separation through SLIMpy and pyct tools developed at SLIM. Two examples will be shown with real data to highlight the use of these tools relating to ground roll noise prediction, separation and the ability to perform multiple separations in sequence. This demo is fully reproducible through use of Madagascar and contains the appropriate tools, which can be modified to fit specific projects.

Packages:

SoftReleaseSept07 : demo in PYTHON/GroundRoll

2.7 Block coordinate relaxation and Bayesian surface wave separation

Description: This is a demonstration of surface wave identification and separation through SLIMpy and pyct tools developed at SLIM. Two examples will be shown with synthetic and real data to highlight the use of these tools relating to ground roll noise prediction, separation methods and their performance. Two different signal separation methods developed at SLIM will be used and the results can be compared. This demo is fully reproducible through use of Madagascar and contains the appropriate tools, which can be modified to fit specific projects.

Packages:

SLIMpy.ANAs : source code
SLIMpy.apps : source code
SLIMpy.user_demos : demo in cyarham/GroundRoll

3 Imaging

3.1 Curvelet Match Filtering for True Migration Amplitude Recovery

Description: This code estimates and applies the inverse of the diagonal of the normal operator in curvelet domain to the migrated image in the context of true amplitude recovery migration In these demos the migrated and de-migrated image are fetch from

ftp-server. These images should be generated before using this software.
The images in these examples are obtained using reverse-time migration-demigration, provided by William Symes at Rice university Inversion Lab and TOTAL E&P, Houston and are subjected to term and condition of these institutes.

Packages:

SoftReleaseFeb08 : Demo in PYTHON/CrvltMtchFlt4TrueAmpRecovery

4 Solvers

4.1 solvers

4.1.1 Iterative Soft Thresholding with cooling (ISTc)

Description: ISTc is a solver for large-scale one-norm regularized least squares. It is designed to solve any of the following two problems:

1. Basis pursuit denoise:

2. Basis pursuit:

ISTc relies only on matrix-vector operations *Ax* and .

Packages:

... : [SLIMpy.ANAs]: source code

4.1.2 SPGL1: A solver for large-scale sparse reconstruction

Description: SPGL1 is a solver for large-scale one-norm regularized least squares. It is designed to solve any of the following three problems:

1. Basis pursuit denoise:

2. Basis pursuit:

3. Lasso:

SPGL1 relies only on matrix-vector operations *Ax* and accepts both explicit matrices and functions that evaluate these products. In addition, SPGL1 supports the complex-variables case, and can solve each of these problems in the complex domain.

Packages:

SoftReleaseSept07 : demo in PYTHON/SPGL1 directory

4.2 solvers

4.2.1 LSQR

Description: Attempts to solve the least squares problem that minimizes . If **A** is inconsistent, it attempts to solve the system of linear equations **Ax=y**.

Packages:

SLIMpy.ANAs : source code

5 Transforms

5.1 Surfacelet transform with RSF data interface

Description: The Surfacelet transform (SurfeBox) is adapted to provide an interface to

read/write data using RSF (MADAGASCAR) file format.

Packages:

SurfBox.slim : source code

SLIM2RSFext : MADAGASCAR extension

5.2 Curvelets

5.2.1 2D and 3D Curvelet Transform with RSF data interface

Description: Two extensions to CurveLab are provided:

1. The 2D and 3D Curvelet code (CurveLab) is adapted to provide an interface to read/write data using RSF (MADAGASCAR) file format. The original in-core curvelet transforms were recorded into out-off-core MADAGASCAR applications.
2. Python wrapper was written to access in-core curvelet transforms.

Packages:

CurveLab-2.0.2-SLIM : source code

SLIM2RSFext : MADAGASCAR extension

pyCurvelab : Python wrapper

5.2.2 3D MPI Curvelet Transform with RSF data interface

Description: The original 3D MPI Curvelet code is adapted to provide an interface to read/write data using RSF (MADAGASCAR) file format. The utilized curvelet transform is in-core and can write either single or distributed (processor owned) files. The enclosed demonstration allows to compare the performance of 3D MPI RSF Curvelet transform to performance of SLIM's out-off-core serial implementation of 3D Curvelet transform.

Packages:

CurveLab-2.0.2-SLIM : source code

SLIM2RSFext-MPI : MADAGASCAR extension

SoftReleaseSept07 : demo in Other/FDCT-3D_MPI directory

6 Utilities

6.1 Jitter sampling

Description: The basic idea behind jittered undersampling is to regularly decimate the interpolation grid and subsequently perturb according to a discrete uniform distribution the coarse-grid sample points on the fine grid.

Packages:

SLIM2RSFext : MADAGASCAR extension

7 SLIMpy development/programming environment

Description: SLIMpy is a tool that interfaces Abstract Numerical Algorithms (ANAs) with a variety of lower lever software packages. SLIMpy uses operator overloading to build an abstract computational tree which can be applied to many other software environments such as MADAGASCAR (formerly RSF).

The main development in this release is SLIMpy's embarrassingly parallel capability. SLIMpy now takes advantage of multi core processors by running each independent command on a given number of threads. A more intuitive interface for adding plugin commands (e.g. MADAGASCAR) has replaces the old plugin system. A number of bugs have been fixed, stdin/out commands that have no stdin or stdout may now be run from SLIMpy. Currently in the development branch there is a Beta version which

expands SLIMpy's multi core to multi processor functionality by using rsh and keeping track of local vs. global data.
Plans for the next release include a scalar class as a complement to the vector class. The scalar class will become a part of the AST (Abstract Syntax Tree) so it algorithms may be built in entirety before execution. This will help with the dependency problem SLIMpy has with scalars and also enable more efficient parallel utilities.

Packages:

SLIMpy.core: source code

SCHEDULE 2

FAST DIGITAL CURVELET TRANSFORM

The Fast Digital Curvelet Transform software takes as input a two-dimensional Cartesian array and returns a table of curvelet coefficients. Each curvelet coefficient essentially extracts information about the digital array at a specific scale, along a specific orientation, and at a specific location. (As an analogy, the Fourier transform extracts information at specified frequencies). There is an inverse transformation which allows reconstruction of the original array by recombining its curvelet coefficients. Both transformations, the forward and inverse mappings, are stable. In addition, the run time is almost linear in the number of pixel values. The package contains two distinct implementations of the same algorithm, and also includes an extension of the software to three-dimensional arrays.

SCHEDULE 3

LIST OF CALTECH PATENTS

Caltech File #	Inventor(s)	Description	Patent #
4349	Emmanuel Candes, Laurent Demanet, and David Donoho	Caltech curvelet	US Patent application #: 11/400,048, published 2/15/2007 (US-20070038691-A1)

0050 0048649092

“Seismic Imaging by Next-generation BAsis-function Decomposition (SINBAD)”

** Phase II **

CONSORTIUM MEMBERSHIP AGREEMENT FOR OIL COMPANIES

CONSORTIUM MEMBERSHIP AGREEMENT

BETWEEN

THE UNIVERSITY OF BRITISH COLUMBIA, a corporation continued under the *University Act* of British Columbia with offices at Suite 103 – 6190 Agronomy Road, Vancouver, British Columbia, V6T 1Z3; (the "University");

AND

PETRÓLEO BRASILEIRO S/A - PETROBRAS, a public and private joint stock company, organized and existing under the laws of Brazil, enrolled as a corporate taxpayer (CNPJ) under number 33.000167/0001-01, with main offices at Av. República do Chile, 65, Rio de Janeiro, RJ, Brazil (the "Participant"), herein represented by Eduardo Lopes de Faria;

(University and Participant are referred to in this Agreement individually as a "**Party**" and collectively as the "**Parties**")

WHEREAS

(1) It is the University's objective to exploit its technology for the public benefit, in harmony with its Global Access Principles launched by the University in November 2007 and as outlined at www.uilo.ubc.ca/global.asp, and to generate further research in a manner consistent with the University's status as a non-profit, tax exempt educational institution;

(2) The University has been engaged in research and development in the field of seismic imaging and has undertaken research into a project referred to as Seismic Imaging by Next-generation BAsis-function Decomposition **("SINBAD")**; and

(3) The Participant wishes to participate in continued research in and development of SINBAD (the "**Research**"), and the University wishes to undertake such research.

NOW, THEREFORE, the Parties agree as follows:

1. DEFINITIONS and INTERPRETATION

1.1 (a) "**Advisory Committee**" means the committee established to provide advice to the University on matters regarding the Research in accordance with Section 4;

(b) "**Affiliate**" means any corporation, Limited Liability Company or other legal entity directly or indirectly controlled by Participant or its successors or assigns, or any successor or assign of such an entity. For the purpose of this Agreement, "control" shall mean the direct or indirect ownership of at least fifty percent (50%) of the outstanding shares or other voting rights of the subject entity to elect directors, or if not meeting the preceding, any entity owned or controlled by or owning or controlling at the maximum control or ownership right permitted in the country where such entity exists;

(c) "**Confidential Information**" means all information, regardless of its form that is disclosed by the University to the Participant or its Affiliates and which is clearly identified in writing as "Confidential" at the time of disclosure. If identified orally, a written notice must be sent to the Participant within ten business days thereafter. "Confidential Information" does not include information:

(i) possessed by the Participant or its Affiliates prior to receipt from the University, other than through prior confidential disclosure by the University, as evidenced by the Participant`s business records;

(ii) published or available to the general public otherwise than through a breach of this Agreement;

(iii) obtained by the Participant or its Affiliates from a third party with a valid right to disclose it, provided that the third party is not under a confidentiality obligation to the University in respect of the same;

(iv) independently developed by employees, agents or consultants of the Participant or its Affiliates who did not use the Confidential Information as evidenced by the Participant`s business records; or

(v) that must be disclosed pursuant to an order or a subpoena.

(d) "**Effective Date**" means the date of the last signature of the parties below;

(e) "**Executable Code**" means computer software programs, not readily perceivable by humans, and suitable for machine execution without the intervening steps of interpretation or compilation.

(f) **"Field"** means signal and image processing, including seismic data processing;

(g) "**Foreground IP**" means the copyright (including the Source Code), design rights, trademarks and patents (whether registered or not and all applications for any of them) and other forms of intellectual property rights made or generated solely as a result of the Research;

(h) "**Principal Investigator**" means Dr. Felix J. Herrmann of the Department of Earth and Ocean Sciences at The University of British Columbia;

(i) "**Software**" means copyright rights, as defined by Canadian copyright laws and applicable international treaties and/or conventions;

(j) "**Source Code**" means computer software programs, not in machine-readable format and not suitable for machine execution without the intervening steps of interpretation or compilation;

(k) "**Start Date**" means April 1, 2009; and

(l) "**University Background IP**" means any Intellectual Property Rights owned or under the control of the University prior to the date of this Agreement relating to the technology which is described in Schedule 1 attached to this Agreement, and excludes any software developed at the California Institute of Technology located in Pasadena, California.

2. RESEARCH WORK AND PUBLICATION

2.1 Subject to compliance by the Participant with its obligations under this Agreement, the University shall:

(a) carry out the Research in accordance with those policies, standards, procedures, conventions and techniques that are of a high recognized and acceptable professional standard in the scientific community and in accordance with the requirements of this Agreement;

(b) comply with all health and safety regulations applicable to any work carried out as part of the Research and otherwise comply with all relevant laws and regulations in the conduct of the Research;

(c) supply all equipment, materials and facilities as may be required to conduct the Research, which shall remain the property of the University after termination of this Agreement;

2.2 The University shall provide a representative to attend all meetings of the Advisory Committee, who shall be a person engaged in the management of the Research on behalf of the University.

2.3 The Participant acknowledges that the policies of the University require that the results of the Research be publishable. The Parties therefore agree that the Principal Investigator and other researchers engaged in the Research shall not be restricted from presenting at symposia, national, or regional professional meetings, or from publishing in abstracts, journals, theses, or dissertations, or otherwise, whether in printed or in electronic media, methods and results of the Research, provided however that the Principal Investigator provides the Participant with a copy of any proposed publication or presentation forty-five days in advance of publication or presentation, or in the case of software 12 months prior to a public release.

2.4 During the term of this Agreement, The University will keep the Participant informed, orally or in writing, as to the progress of the Research.

2.5 Any funds received by the University from the Participant under this Agreement are non-refundable, unless the University terminates this Agreement before its expiration.

3. OBLIGATIONS OF THE PARTICIPANTS

3.1 Subject to the University's compliance with the terms of this Agreement, the Participant shall pay the University funds in accordance with the schedule below (all funds in Canadian dollars):

- $67,500 Canadian due on or before 30 days after the date of the last signature below;
- $67,500 on each anniversary of the Start Date until termination.

3.2 The Participant may, at its own cost, provide a representative to attend meetings of the Advisory Committee.

3.3 Performance of the Research is dependent on the amount of funds received from Participants. The University reserves the right to suspend work on the Research or to terminate the Research and this Agreement by delivering written notice of same to the Participant if funds are not sufficient to carry out the Research.

3.4 The Participant may make payments by wire transfer to:
Pay Via: SWIFT MT100
Pay to: HSBC Bank Canada, Main Branch, Vancouver, BC – SWIFT Address HKBCCATT
Account number for Canadian dollars: 016-10020-437218-002
Beneficiary: The University of British Columbia
Payment Details: RTA, FAS #F08-04568

3.5 The University will retain title to any equipment purchased with funds provided by the Participant under this Agreement.

4. ADVISORY COMMITTEE

4.1 The Advisory Committee shall:

(a) provide advice to the University relating to the conduct of the Research;

(b) review the results and recommendations of any University Research reports;

4.2 The Advisory Committee shall consist of no more than one representative from Participant and at least one University representative.

4.3 Meetings of the Advisory Committee shall be held at Vancouver, British Columbia. Meetings shall be regulated as the University may decide from time to time.

4.4 The University shall call all such meetings and shall give at least 10 days' prior written notice thereof to the Participant.

5. CONFIDENTIALITY

5.1 Except as expressly provided herein, each Party agrees not to disclose any terms of this Agreement to any third party without the consent of the other Party; provided, however, that disclosures may be made as required by securities laws or other applicable laws, or to actual or prospective investors or corporate partners, or to a Party's accountants, attorneys or to the United States Government and or other professional advisors or to Affiliates.

5.2 The Participant will keep and use the Confidential Information in confidence and will not, without the University's prior written consent, disclose the Confidential Information to any person or entity.

5.3 If the Participant is required by judicial or administrative process to disclose the Confidential Information, it will promptly notify the University and allow it reasonable time to oppose the process before disclosing the Confidential Information.

5.4 Notwithstanding any termination or expiration of this Agreement, the obligations set out in this Section 5 survive and continue to bind the Parties, their successors and assigns until 7 years after such termination or expiration.

5.5 The Participant and its Affiliates will ensure that the Source Code to any Software or Confidential Information is not disclosed to any other third party. In the event of an unauthorized or accidental disclosure of the Source Code the Participant will immediately:

(a) notify the University and will provide to the University full particulars of all information in the Participant's possession or control regarding the circumstances of such unauthorized use or disclosure;

(b) take (in full consultation with the University) and at the Participant's sole cost and expense all reasonable steps deemed necessary by the University to remedy any such unauthorized use or disclosure, and take all reasonable steps necessary to recover the Source Code and to prevent its unauthorized use by any third party.

6. INTELLECTUAL PROPERTY, INDEMNIFICATION & LIMITATION OF LIABILITY

6.1 All Foreground IP shall be the property of the University from the date of its creation.

6.2 The Participant indemnifies, holds harmless and defends the University, its Board of Governors, directors, officers, employees, faculty, students, invitees and agents against any and all claims (including all reasonable legal fees and disbursements) arising out of the receipt or use by the Participant or its Affiliates of any of the Confidential Information, University Background IP, Foreground IP, or any data or other results arising from such use including, without limitation, any damages or losses, consequential or otherwise, arising from or out of the Research, however they may arise.

6.3 The University's total liability, whether under the express or implied terms of this Agreement, in tort (including negligence) or at common law, for any loss or damage suffered by the Participant or its Affiliates, whether direct, indirect or special, or any other similar damage that may arise or does arise from any breaches of this Agreement by the University, its Board of Governors, officers, employees, faculty, students or agents, is limited to $5,000.

6.4 The Participant acknowledges and agrees that the University will not be liable for consequential or incidental damages arising from any breach or breaches of this Agreement.

6.5 Notwithstanding the termination or expiration of this Agreement, the rights and obligations in this Section 6 will survive and continue to bind the Participant and its successors and assigns.

7. GRANT OF RIGHTS

7.1 Subject to Section 6.2 (Indemnity), the University grants the Participant and its Affiliates a perpetual, worldwide, non-exclusive, non-transferable, royalty-free license to use and exploit University Background IP and Foreground IP for internal use only in the Field. Such internal use shall not include the provision of services or products to third parties. Internal use includes uses by Participant and its Affiliates as an "operator" in the field of oil and gas production and exploration.

7.2 Neither the Participant nor its Affiliates will grant sublicenses of the University Background IP or Foreground IP to any third party.

7.3 The Participant acknowledges and agrees that the University may use University Background IP and Foreground IP without charge in any manner for any purpose.

7.4 Participant shall not remove or obscure any visible copyright or trademark notices.

7.5 Participant agrees that it may make a reasonable number of copies of Software for archival and backup purposes.

8. DISCLAIMER OF WARRANTY

8.1 THE UNIVERSITY MAKES NO REPRESENTATIONS OR WARRANTIES, EITHER EXPRESS OR IMPLIED, REGARDING DATA OR SOFTWARE OR OTHER RESULTS ARISING FROM THE RESEARCH OR REGARDING CONFIDENTIAL INFORMATION THE UNIVERSITY MAY DISCLOSE TO THE PARTICIPANT. THE UNIVERSITY SPECIFICALLY DISCLAIMS ANY IMPLIED WARRANTY OF NON-INFRINGEMENT OR MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE AND THE UNIVERSITY WILL, IN NO EVENT, BE LIABLE FOR ANY LOSS OF PROFITS, BE THEY DIRECT, CONSEQUENTIAL, INCIDENTAL, OR SPECIAL OR OTHER SIMILAR DAMAGES ARISING FROM ANY DEFECT, ERROR OR FAILURE TO PERFORM, EVEN IF THE UNIVERSITY HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES. THE PARTICIPANT ACKNOWLEDGES THAT THE RESEARCH IS OF AN EXPERIMENTAL AND EXPLORATORY NATURE, THAT NO PARTICULAR RESULTS CAN BE GUARANTEED, AND THAT THE PARTICIPANT HAS BEEN ADVISED BY THE UNIVERSITY TO UNDERTAKE ITS OWN DUE DILIGENCE WITH RESPECT TO ALL MATTERS ARISING FROM THIS AGREEMENT.

8.2 NOTHING IN THIS AGREEMENT:

(A) CONSTITUTES A WARRANTY OR REPRESENTATION BY THE UNIVERSITY AS TO TITLE TO THE INTELLECTUAL PROPERTY LICENSED HEREUNDER, OR THAT ANYTHING MADE, USED, SOLD OR OTHERWISE DISPOSED OF UNDER THE LICENSE GRANTED IN THIS AGREEMENT WILL NOT INFRINGE THE PATENTS, COPYRIGHTS, TRADE-MARKS, INDUSTRIAL DESIGNS OR OTHER INTELLECTUAL PROPERTY RIGHTS OF ANY THIRD PARTIES, OR ANY PATENTS, COPYRIGHTS, TRADE-MARKS, INDUSTRIAL DESIGN OR OTHER INTELLECTUAL PROPERTY RIGHTS OWNED, IN WHOLE OR IN PART, BY THE UNIVERSITY, OR LICENSED BY THE UNIVERSITY TO ANY THIRD PARTIES;

(B) CONSTITUTES AN EXPRESS OR IMPLIED WARRANTY OR REPRESENTATION BY THE UNIVERSITY THAT THE PARTICIPANT HAS, OR WILL HAVE THE FREEDOM TO OPERATE OR PRACTICE THE INTELLECTUAL PROPERTY LICENSED HEREUNDER, OR THE FREEDOM TO MAKE, HAVE MADE, USE, SELL OR OTHERWISE DISPOSE OF ANY PRODUCTS; OR

(C) IMPOSES AN OBLIGATION ON THE UNIVERSITY TO BRING, PROSECUTE OR DEFEND ACTIONS OR SUITS AGAINST THIRD PARTIES FOR INFRINGEMENT OF PATENTS, COPYRIGHTS, TRADE-MARKS, INDUSTRIAL DESIGNS OR OTHER INTELLECTUAL PROPERTY OR CONTRACTUAL RIGHTS.

9. INSURANCE

9.1 The Participant acknowledges the University's representation that it has liability insurance applicable to its directors, officers, employees, faculty, students and agents while acting within the scope of their employment by the University and that it has no liability insurance policy that can extend protection to any other person. Therefore, the Participant assumes the risks of personal injury and property damage attributable to the negligent acts or omissions of the Participant and its Affiliates and their directors, officers, employees and agents.

10. TERM, TERMINATION AND WITHDRAWAL

10.1 This Agreement starts on the Effective Date and continues for twelve months. This Agreement will be renewed automatically for further twelve-month periods, unless a notice of termination is given in writing by one Party to the other at least 3 months before the end of this Agreement or the end of the latest renewal. If such a notice of termination is given, this Agreement will terminate with effect from the end of the twelve-month period during which the notice of termination was given.

10.2 If the Participant commits any breach or default of any terms or conditions of this Agreement and also fails to remedy such breach or default within thirty days after receipt of a written notice from the University, the University may terminate this Agreement by sending a notice of termination in writing to the Participant. This termination will be effective as of the date of the receipt of such notice. The termination may be in addition to any other remedies available at law or in equity.

10.3 Upon the termination of this Agreement, the Participant will cease to use the University's Confidential Information in any manner whatsoever and upon the written request by the University, Participant agrees to destroy all of the University's Confidential Information in Participant's possession or control and certify the same to the University. In the event that such Confidential Information must not be destroyed pursuant to judicial proceedings, Participant will promptly notify the University.

10.4 Termination of this Agreement for any reason shall neither release any Party hereto from any liability which, at the time of such termination, has already accrued to the other Party or which is attributable to a period prior to such termination, nor preclude either Party from pursing any rights and remedies that it may have hereunder, at law or in equity and which accrued or is based upon any event occurring prior to such termination.

10.5 No termination of this Agreement, however effectuated, will release Participant from its rights and obligations under this Agreement including: Sections 1.0 (Definitions and Interpretations), 5.0 (Confidentiality), 8 (Disclaimer of Warranty), 6.2 (Indemnity),10.3 (cessation of use of Confidential Information) and 10.4 (accrued liability).

11. GOVERNING LAW

11.1 This Agreement is governed by, and will be construed in accordance with, the laws of British Columbia and the laws of Canada in force in that province, without regard to its conflict of law rules. The Parties agree that by executing this Agreement, they have attorned to the exclusive jurisdiction of the Supreme Court of British Columbia.

12. ASSIGNMENT

12.1 Except by operation of law or the sale of that part of business to which the Research pertains, a Party may not assign this Agreement without the prior written consent of the other Party, which consent will not be unreasonably withheld or delayed.

13. TAXES

13.1 The Participant shall be responsible for payment of all applicable Value Added Taxes chargeable on goods or services supplied by the University.

14. NOTICES

14.1 All payments, reports and notices or other documents that a Party is required or may want to deliver to any other Party will be delivered:

(a) in writing; and

(b) either by personal delivery or by registered or certified mail (with all postage and other charges prepaid) at the address for the receiving Party as set out in Section 14.2 or as varied by any notice.

Any notice personally delivered is deemed to have been received at the time of delivery. Any notice mailed in accordance with this Section 14.1 is deemed to have been received at the end of the fifth day after it is posted.

14.2 Addresses for delivery of notices:

Participant:

Carlos Eduardo Theodoro
PETROBRAS/CENPES/PDEXP/GEOF
Av. Horacio Macedo, 950
Cidade Universitária, Ilha do Fundao,
Rio de Janeiro, RJ
Brasil
21941-915
Telephone: 55-21-3865-7590
Fax: 55-21-3865-4739

The University:

Managing Director
University-Industry Liaison Office
#103 – 6190 Agronomy Road
The University of British Columbia
Vancouver, British Columbia
Canada V6T 1Z3
Telephone: (604) 822-8580
Fax: (604) 822-8589

14.3 The Participant may direct questions of a scientific nature or regarding financial matters to the University through the following contacts:

Scientific Matters:

Dr. Felix J. Herrmann
The University of British Columbia
Department of Earth and Ocean Sciences
6339 Stores Road
Vancouver, British Columbia
V6T 1Z4 CANADA
Telephone: (604) 822-8628
Facsimile: (604) 822-6088

Financial Matters: Manager, Research and Trust Accounting
Office of Financial of Services
University of British Columbia

General Services Administration Building
2075 Wesbrook Mall
Vancouver, British Columbia
V6T 1Z1 CANADA
Telephone: (604) 822-6883
Telecopier: (604) 822-2417

15. COPYRIGHT MARKING

15.1 Participant will mark, in at least one conspicuous location, a notice that the Software licensed hereunder is owned by The University of British Columbia. All marking should include: © 2008 The University of British Columbia, British Columbia, Canada.

16. FORCE MAJEURE

16.1 Neither Party shall lose any rights hereunder or be liable to the other Party for damages or losses (except for payment obligations) on account of failure of performance by the defaulting Party if the failure is occasioned by war, strike, fire, Act of God, earthquake, flood, lockout, embargo, governmental acts or orders or restrictions, failure of suppliers, act of terrorism, or any other reason where failure to perform is beyond the reasonable control and not caused by the negligence or intentional conduct or misconduct of the nonperforming Party, and such Party has exerted all reasonable efforts to avoid or remedy such force majeure; provided, however, that in no event shall a Party be required to settle any labour dispute or disturbance.

17. SUPPORT AND UPGRADES

17.1 No Software maintenance support or training is provided as part of this Agreement.

18. GENERAL LEGAL PROVISIONS

18.1 Nothing contained in this Agreement is to be deemed or construed to create between the Parties a partnership or joint venture. No Party has the authority to act on behalf of any other Party, or to commit any other Party in any manner at all or cause any other Party's name to be used in any way not specifically authorized by this Agreement.

18.2 Subject to the limitations in this Agreement, this Agreement operates for the benefit of and is binding on the Parties and their respective successors and permitted assigns.

18.3 No condoning, excusing or overlooking by any Party of any default, breach or non-observance by any other Party at any time or times regarding any terms of this Agreement operates as a waiver of that Party's rights under this Agreement. A waiver of any term or right under this Agreement will be in writing signed by the Party entitled to the benefit of that term or right, and is effective only to the extent set out in the written waiver.

18.4 No exercise of a specific right or remedy by any Party precludes it from or prejudices it in exercising another right or pursuing another remedy or maintaining an action to which it may otherwise be entitled either at law or in equity.

18.5 Headings in this Agreement are for reference only and do not form a part of this Agreement and are not be used in the interpretation of this Agreement.

18.6 All terms in this Agreement which require performance by the Parties after the expiry or termination of this Agreement, will remain in force despite this Agreement's expiry or termination for any reason.

18.7 Part or all of any Section that is indefinite, invalid, illegal or otherwise voidable or unenforceable, may be severed from this Agreement and the balance of this Agreement will continue in full force and effect.

18.8 At the request of the University or Participant, the other Party will obtain the execution of any agreement or instrument (including from its employees, agents, contractors, consultants or representatives) that may be reasonably required to consummate the transactions contemplated in this Agreement, including assigning any rights, waiving any rights or perfecting any rights in such requesting Party's name.

18.9 This Agreement and the Schedules set out the entire understanding between the Parties and no changes to this Agreement are binding unless in writing and signed by the Parties to this Agreement. The Parties will be bound by the Schedules, except to the extent that they may conflict with the terms and conditions contained in this Agreement, in which case the terms and conditions of this Agreement will govern.

18.10 In this Agreement, unless the contrary intention appears, the singular includes the plural and vice versa and words importing a gender include other genders.

18.11 This Agreement may be executed in counterparts by the Parties, either through original copies or by facsimile. An executed copy of this Agreement delivered by facsimile will constitute valid execution and delivery of this Agreement.

18.12 The University agrees that it will not use the name of the Participant in any advertising or publicity material or make any form of representation or statement, which would constitute an express or implied endorsement by the Participant of any licensed product, and that University shall not authorize others to do so, without first having obtained written approval from Participant, except as may be required by governmental law, rule or regulation. The Participant agrees that it will not use the name of the University in any advertising or publicity material or make any form of representation or statement, which would constitute an express or implied endorsement by the University of any licensed product, and that Participant shall not authorize others to do so, without first having obtained written approval from the University, except as may be required by governmental law, rule or regulation.

IN WITNESS WHEREOF the Parties have executed this Agreement.

SIGNED FOR AND ON BEHALF of
THE UNIVERSITY OF BRITISH COLUMBIA
by its authorized signatory:

Name: MARIO A. KASAPI
Title: Associate Director
University - Industry Liaison Office

LEGAL APPROVED
14

Date: Feb 5/09

SIGNED FOR AND ON BEHALF of
PETROBRAS CENPES/PDEXP/GEOF
by its authorized signatory:

Eduardo [illegible]

Name:
Title:

Date: Rio de Janeiro 15th May 2009.

I have read and understood the foregoing Agreement and understand my responsibilities as the Principal Investigator:

Signature:

Dr. Felix J. Herrmann
Dept: Earth and Ocean Sciences, The University of British Columbia

Date: 17-02-09

Witnesses:

1) Tatiana Lourenço Lopes

TATIANA LOURENÇO LOPES
CPF: 087.501.627-80
Mat. 343610

2)

JOÃO CARLOS R. DUARTE
Adminstrador
Mat.: 980333-5

SCHEDULE 1

UNIVERSITY BACKGROUND IP

1 Wavefield reconstruction

1.1 Curvelet-based focal transform

Description: Seismic wavefield reconstruction based on the combination of the non-adaptive curvelet transform and the data-adaptive focal transform. This method involves the inversion of the curvelet-regularized focusing operator by a sparsity-promoting program that solves a large-scale norm-one optimization problem.

Packages:

SLIMpy.apps	: source code
SLIMpy.demos	: demo

1.2 Jittered undersampling

Description: In this paper, we present a new discrete undersampling scheme designed to favor wavefield reconstruction by sparsity-promoting inversion with transform elements that are localized in the Fourier domain. Our work is motivated by empirical observations in the seismic community, corroborated by recent results from compressive sampling, which indicate favorable (wavefield) reconstructions from random as opposed to regular undersampling. As predicted by theory, random undersampling renders coherent aliases into harmless incoherent random noise, effectively turning the interpolation problem into a much simpler denoising problem.

A practical requirement of wavefield reconstruction with localized sparsifying transforms is the control on the maximum gap size. Unfortunately, random undersampling does not provide such a control and the main purpose of this paper is to introduce a sampling scheme, coined jittered undersampling, that shares the benefits of random sampling, while offering control on the maximum gap size. Our contribution of jittered sub-Nyquist sampling proofs to be key in the formulation of a versatile wavefield sparsity-promoting recovery scheme that follows the principles of compressive sampling.

After studying the behavior of the jittered-undersampling scheme in the Fourier domain, its performance is studied for curvelet recovery by sparsity-promoting inversion (CRSI). Our findings on synthetic and real seismic data indicate an improvement of several decibels over recovery from regularly-undersampled data for the same amount of data collected.

Packages:

SoftReleaseSept07 : demo in Papers/Jitter

1.3 Surfacelet transform

Description: Here we compare the transform domain interpolation results on seismic data with missing traces. The two transform domains are curvelets and surfacelets. The interpolation algorithm is performed on two different examples, one synthetic, and one with real marine data. The interpolation problem is resolved via a large-scale solver with iterative cooling and soft thresholding for the -regularization minimization involved in the recovery.

Packages:

SoftReleaseSept07 : demo in MATLAB/SURFinterp

1.4 Seismic denoising with 3-D transform-domain sparsity

Description: The code performs Seismic denoising exploiting 3D-curvelet transform domain sparsity. The 3D curvelet transform exploits the three-dimensional structure of seismic data thereby yielding better results. The denoising problem is formed as an optimization problem and is solved by iterative Landweber method.

Packages:

SLIMpy.user_demos : demo in vkumar/denoise3d

2 Wavefield separation

2.1 Curvelet-based primary-multiple separation from a Bayesian perspective

Description: A new primary-multiple separation scheme which makes use of the sparsity of both primaries and multiples in a transform domain, such as the curvelet transform to provide estimates of each. The proposed algorithm utilizes seismic data as well as the output of a preliminary step that provides erroneous predictions of the multiples. The algorithm separates the signal components, i.e., the primaries and multiples by solving an optimization problem that assumes noisy input data and can be derived from a Bayesian interpretation. More precisely, the optimization problem can be arrived at via an assumption of a weighted Laplacian distribution for the primary and multiple coefficients in the curvelet domain and of white Gaussian noise contaminating both the seismic data and the preliminary prediction of the multiples, which both serve as input to the algorithm.

Packages:

SLIMpy.ANAs : source code
SLIMpy.apps : source code
SLIMpy.demos : demo

2.2 3D Curvelet-based primary-multiple separation from a Bayesian perspective

Description: Primaries multiples separation use the sparsity of both primaries and multiples in curvelet domain by solving an optimization problem that assumes noisy input data and can be derived from a Bayesian perspective.

Packages:

SLIMpy.ANAs : source code
SLIMpy.user_demos : demo in dwang/pms-bayes3D

2.3 Adaptive curvelet-domain primary-multiple separation

Description: In this paper we developed a new adaptive curvelet-domain matching filter in primary-multiple separation problem instead of using conventional least-squares windowed amplitude matching,we propose a data-adaptive method that corrects amplitude errors, which vary smoothly as a function of location, scale (frequency band) and angle. In that case, the amplitudes can be corrected by an element-wise curvelet-domain scaling of the predicted multiples.

Packages:

SLIMpy.ANAs : source code
SLIMpy.apps : source code
SoftReleaseFeb08 : paper in Papers/CurveMatchRep

2.4 Surfacelet-based primary-multiple separation

Description: Here we compare the transform domain primary-multiple separation on seismic data with simple thresholding in a transform domain. The transform domains

are curvelets and surfacelets. Simple thresholding is performed on the SRME predicted multiples and the subtraction is performed on a full 2D SAGA dataset, and the curvelet / surfacelet results are compared. It is important to note that this method highly relies on the accurate prediction of primaries / multiples, since inaccurate predictions will cause residual multiple energy in the result or may lead to a distortion of the primaries, or both.

Packages:

SoftReleaseSept07 : demo in MATLAB/SURF-Mult-Predict

2.5 Surfacelet-based primary-multiple separation from Bayesian perspective

Description: Here we compare the Bayesian wave-field separation algorithm in a transform domain. The transform domains are curvelets and surfacelets. The purpose of this demo is to compare which transform domain is better suited for the problem of primary-multiple separation from a Bayesian perspective. The algorithm is tested on a 2-dimensional dataset.

References: wang07rri

Packages:

SLIMpy.ANAs : source code
SLIMpy.apps : source code
SLIMpy.user_demos : demo in elebed/curv-surf

2.6 Ground-roll removal based on Curvelet Transform

Description: The demonstration of surface wave identification and separation through SLIMpy and pyct tools developed at SLIM. Two examples will be shown with real data to highlight the use of these tools relating to ground roll noise prediction, separation and the ability to perform multiple separations in sequence. This demo is fully reproducible through use of Madagascar and contains the appropriate tools, which can be modified to fit specific projects.

Packages:

SoftReleaseSept07 : demo in PYTHON/GroundRoll

2.7 Block coordinate relaxation and Bayesian surface wave separation

Description: This is a demonstration of surface wave identification and separation through SLIMpy and pyct tools developed at SLIM. Two examples will be shown with synthetic and real data to highlight the use of these tools relating to ground roll noise prediction, separation methods and their performance. Two different signal separation methods developed at SLIM will be used and the results can be compared. This demo is fully reproducible through use of Madagascar and contains the appropriate tools, which can be modified to fit specific projects.

Packages:

SLIMpy.ANAs : source code
SLIMpy.apps : source code
SLIMpy.user_demos : demo in cyarham/GroundRoll

3 Imaging

3.1 Curvelet Match Filtering for True Migration Amplitude Recovery

Description: This code estimates and applies the inverse of the diagonal of the normal operator in curvelet domain to the migrated image in the context of true amplitude recovery migration In these demos the migrated and de-migrated image are fetch from

ftp-server. These images should be generated before using this software.
The images in these examples are obtained using reverse-time migration-demigration, provided by William Symes at Rice university Inversion Lab and TOTAL E&P, Houston and are subjected to term and condition of these institutes.

Packages:

SoftReleaseFeb08 : Demo in PYTHON/CrvltMtchFlt4TrueAmpRecovery

4 Solvers

4.1 solvers

4.1.1 Iterative Soft Thresholding with cooling (ISTc)

Description: ISTc is a solver for large-scale one-norm regularized least squares. It is designed to solve any of the following two problems:

1. Basis pursuit denoise:

2. Basis pursuit:

ISTc relies only on matrix-vector operations *Ax* and .

Packages:

... : [SLIMpy.ANAs]: source code

4.1.2 SPGL1: A solver for large-scale sparse reconstruction

Description: SPGL1 is a solver for large-scale one-norm regularized least squares. It is designed to solve any of the following three problems:

1. Basis pursuit denoise:

2. Basis pursuit:

3. Lasso:

SPGL1 relies only on matrix-vector operations *Ax* and accepts both explicit matrices and functions that evaluate these products. In addition, SPGL1 supports the complex-variables case, and can solve each of these problems in the complex domain.

Packages:

SoftReleaseSept07 : demo in PYTHON/SPGL1 directory

4.2 solvers

4.2.1 LSQR

Description: Attempts to solve the least squares problem that minimizes . If **A** is inconsistent, it attempts to solve the system of linear equations **Ax=y**.

Packages:

SLIMpy.ANAs : source code

5 Transforms

5.1 Surfacelet transform with RSF data interface

Description: The Surfacelet transform (SurfeBox) is adapted to provide an interface to

read/write data using RSF (MADAGASCAR) file format.

Packages:

SurfBox.slim: source code

SLIM2RSFext : MADAGASCAR extension

5.2 Curvelets

5.2.1 2D and 3D Curvelet Transform with RSF data interface

Description: Two extensions to CurveLab are provided:

1. The 2D and 3D Curvelet code (CurveLab) is adapted to provide an interface to read/write data using RSF (MADAGASCAR) file format. The original in-core curvelet transforms were recorded into out-off-core MADAGASCAR applications.
2. Python wrapper was written to access in-core curvelet transforms.

Packages:

CurveLab-2.0.2-SLIM : source code

SLIM2RSFext : MADAGASCAR extension

pyCurvelab : Python wrapper

5.2.2 3D MPI Curvelet Transform with RSF data interface

Description: The original 3D MPI Curvelet code is adapted to provide an interface to read/write data using RSF (MADAGASCAR) file format. The utilized curvelet transform is in-core and can write either single or distributed (processor owned) files. The enclosed demonstration allows to compare the performance of 3D MPI RSF Curvelet transform to performance of SLIM's out-off-core serial implementation of 3D Curvelet transform.

Packages:

CurveLab-2.0.2-SLIM : source code

SLIM2RSFext-MPI : MADAGASCAR extension

SoftReleaseSept07 : demo in Other/FDCT-3D_MPI directory

6 Utilities

6.1 Jitter sampling

Description: The basic idea behind jittered undersampling is to regularly decimate the interpolation grid and subsequently perturb according to a discrete uniform distribution the coarse-grid sample points on the fine grid.

Packages:

SLIM2RSFext : MADAGASCAR extension

7 SLIMpy development/programming environment

Description: SLIMpy is a tool that interfaces Abstract Numerical Algorithms (ANAs) with a variety of lower lever software packages. SLIMpy uses operator overloading to build an abstract computational tree which can be applied to many other software environments such as MADAGASCAR (formerly RSF).

The main development in this release is SLIMpy's embarrassingly parallel capability. SLIMpy now takes advantage of multi core processors by running each independent command on a given number of threads. A more intuitive interface for adding plugin commands (e.g. MADAGASCAR) has replaces the old plugin system. A number of bugs have been fixed, stdin/out commands that have no stdin or stdout may now be run from SLIMpy. Currently in the development branch there is a Beta version which

expands SLIMpy's multi core to multi processor functionality by using rsh and keeping track of local vs. global data.

Plans for the next release include a scalar class as a complement to the vector class. The scalar class will become a part of the AST (Abstract Syntax Tree) so it algorithms may be built in entirety before execution. This will help with the dependency problem SLIMpy has with scalars and also enable more efficient parallel utilities.

Packages:

SLIMpy.core: source code