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Herrmann - CRDPJ 375142 - 08
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«Recipient_Family_Name» - «Program_ID» «App_ID_Comp_Year»

Collaborative Research and Development (CRD) Grants Progress Report

Due Date: (May 1, 2011)
Covers the Period: (August 1, 2010 to April 30, 2011)

Is your personal information below correct? (please enter an "x" in the appropriate box)

x	**Yes**
	No (please make the necessary corrections)

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Is the project information below correct?

	Yes
x	**No** (please make the necessary corrections)

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

File Number: CRDPJ 375142 - 08

Co-investigators(s):

M.P. Friedlander, Computer Science, British Columbia
O.Y. Yilmaz, Mathematics, British Columbia

Collaborator(s):

J. Burke, University of Washington
E.Y. Haber, British Columbia
A.M. Powell, Vanderbilt University
C.C. Stolk, University of Twente
E. van den Berg, Stanford University
E. Verschuur, Delft University of Technology

Supporting Organization(s):

G. Hennenfent, Chevron Canada Resources Ltd
Z. Yu, British Petroleum Oil
J. Faroppa, BG Group (Canada)
E. Keskula, ConocoPhillips Canada Resources Corp.
D. Nichols, Schlumberger Canada Limited
B.J. VerWest, CGGVeritas
G. Hauerl, Ion Geophysical Corporation - Canada

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E.L. De Faria, Petrobras
S. Jaffer, Total

1. Progress Towards Objectives/Milestones

Using approximately 5 pages, please provide in the box below:

- a brief description of the overall objectives of the research project as awarded;
- a description of the progress made towards each of these objectives during the period covered by this report; and
- a description and justification for any deviations from the original objectives and a discussion of the path forward.

The main thrust of the DNOISE project is focused on the following research themes:

- Seismic acquisition design and recovery from incomplete data with the goal to reduce acquisition costs while increasing the spatial bandwidth and aperture of seismic data;
- Removal of the `surface nonlinearity' by simultaneous estimation of the source signature and the surface-free Green's function by inverting the surface-related multiple prediction operator;
- Reduction of the computational complexity of full-waveform inversion (FWI) by randomized dimensionality reduction;
- "Convexification" of FWI to remove or at least diminish the adverse effects of non-uniqueness that has plagued FWI since its inception;

The first three themes are directed towards removing major impediments faced by FWI related to the costs of acquiring data, the computational costs of processing and inverting data, and to issues with source calibration and surface-related multiples. The final theme is more `blue sky' and tries to incorporate ideas from migration-velocity analysis into the formulation of full-waveform inversion. Aside from these themes, we will continue to work on seismic data acquisition schemes that favor sparsity-promoting recovery and on the development of large-scale solvers using recent developments in convex and stochastic optimization. Our efforts were organized into the following research topics:

- **Seismic-data acquisition based with compressive sensing.** We have worked with professor *Ozgur Yilmaz* (co-PI) on this topic from the applied and theoretical perspectives. *Haneet Waso*n (1st year MSc student who will likely upgrade to our PhD program) has started to work on shearlets, which could serve as an alternative to curvelets, and on the development of practical acquisition schemes based on compressive sensing. Haneet presented findings during last Fall's consortium meeting in her talk "Sequential source data recovery from simultaneous acquisition through transform-domain sparsity promotion - curvelet versus shearlet transform". Haneet also submitted jointly

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with the PI the expanded abstract entitled “Sparsity-promoting recovery from simultaneous data: a compressive sensing approach” to the SEG. On the theoretical front, *Rayan Saab* (PDF, who now works with Ingrid Daubechies, one of the world leaders in applied and computational Harmonic analysis) has worked on compressive sensing in high dimensions. His work will be important for the development of seismic acquisition schemes that are fundamentally high dimensional. Rayan presented this work during his talk entitled "Compressed sensing using Kronecker products" and he is working on a journal publication on this topic. *Hassan Mansour* (PDF) is working on weighted one-norm minimization, where approximate information on the support (read significant transform-domain coefficients) is incorporated in the recovery. His work will improve the recovery and his work will also be essential for parallel recovery schemes that make use of support estimates of neighboring slices (e.g., nearby offsets, frequencies, etc.). Hassan is currently incorporating his theoretical findings into our one solvers and he is preparing journal publications on this topic. For further details also see his talk "Recovering compressively sampled signals using partial support information", presented at the Fall industry-sponsor’s meeting. Jointly with the two co-PIs, this work was submitted for publication in the paper entitled “Recovery of compressively sampled signals using partial support information”. At least two new graduate students will be assigned to help out on these topics. **Outcome**: *Development of a new paradigm for seismic data acquisition and sparsity-promoting recovery that will allow us to acquire high-resolution wide azimuth seismic data volumes at significantly reduced costs. Our technology will be a key enabler for full-waveform inversion by pushing access to both the low and high end of the spectrum.*

- **Removal of the free surface and source calibration**. *Tim Lin* (PhD student) has worked on several fronts on our Robust formulation of Primary Estimation by Sparse inversion (REPSI). We solve this problem by extending the projected gradient method developed by professor *Michael Friedlander* (co-PI) to handle block-coordinate descents, during which the solution is found by alternating between the minimization of the one-norm on the curvelet coefficients of the surface-free Green's function and minimization of a weighted two norm on the Fourier spectrum of the source function. Tim also improved the scaling by incorporating a line search and the proper obliquity factor resulting in an improved scheme that yields highly encouraging results on a challenging real data set. Tim prepared a major update of the REPSI software, which uses our parallel extensions of SPOT, our object-oriented development environment in Matlab. Recent results of his work have been presented to the EAGE in the paper entitled "Estimating primaries by sparse inversion in a curvelet-like representation domain" and were also presented during the consortium meeting

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in his talk "Leveraging informed blind deconvolution techniques for the estimation of primaries by sparse inversion". Jointly with the PI he is finalizing a journal publication on this topic and he submitted the abstract “Robust source signature deconvolution and the estimation of primaries by sparse inversion” to the SEG Post-Convention workshop on broad-band seismic. To alleviate REPSI's reliance on an ideal surface-reflection operator, *Mufeed al Matar* (MSc) jointly with the PI extended our formulation to include a curvelet matching. His approach is designed to compensate for amplitude errors that are allowed to vary with position and dip. This adds robustness to errors induced by finite aperture and non-ideal surface reflections. Compared to SRME, the framework into which we introduced the curvelet matching originally, the inclusion of this matching in REPSI has the additional advantage that predicted multiples are matched to multiples rather than to the total data as in SRME. There are indications that this matching will also improve the convergence of REPSI. Mufeed presented this work at the Consortium meeting during his talk "Estimation of surface-free data by curvelet-domain matched filtering and sparse inversion". A report entitled "Estimation of surface-free data by curvelet-domain matched filtering and sparse inversion" and an MSc thesis entitled “Estimation of Surface-free Data by Curvelet-domain Matched Filtering and Sparse Inversion“, were written on this topic. *Bander Jumah* (1st year MSc student) has started to work on method to reduce the computational costs of REPSI by using techniques from stochastic optimization and compressive sensing. These techniques reduce the cost of the full matrix-matrix multiplies on which REPSI relies by dimensionality reduction. Bander reported jointly with the PI on his work in an abstract entitled “Dimensionality-reduced estimation of primaries by sparse inversion”, which has been submitted to the SEG. *Yiupeng Yan* finished his MSc thesis entitled “Groundroll prediction by interferometry and separation in curvelet domain”. We plan to put 2-3 new graduate students to work on this topic including extension to 3D and incomplete data. **Outcome**: *A robust framework for the estimation of surface-free Green's function and source signatures that serve as input to imaging, migration-velocity analysis, and full-waveform inversion.*

- **Imaging with surface-related multiples**. *Tu Ning* (PhD student) has worked jointly with the PI on including the surface-related multiple-prediction operator into our formulation of sparsity-promoting migration. This inclusion means that we can invert (incomplete) data with multiples to create high-resolution images by using curvelet-domain sparsity promotion. His tests on synthetic data are very encouraging and his results were presented during our Fall 2010 Consortium meeting during his talk "Sparsity promoting migration with surface-related multiples". The method works particularly well for missing data because the inversion of the multiple-prediction maps multiple energy to primaries that

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may not have been sampled. Tu Ning is currently working on a more realistic synthetic in preparation of a journal publication. Recent results of his method were jointly with the PI presented at the EAGE in the abstract entitled "Sparsity-promoting migration with surface-related multiples". He also submitted the abstract entitled "Migration with surface-related multiples from incomplete seismic data" to the SEG. Tuning's work is scheduled to be released in software by early Summer. As part of this project, Tu Ning plans to develop a workflow that includes obtaining an estimate for the velocity model, followed by imaging on a "blind" synthetic data example and later on a real data example. We are currently also working on plans to include source estimation in the formulation and to incorporate his approach in migration-velocity analysis (with *Tristan van Leeuwen,* PDF) and in full-waveform inversion. For the velocity analysis, we plan to use Tristan's work on correlation-based migration velocity analysis. Finally, we are also thinking about extensions to 3D for which we need to address issues related to reducing the computational costs. This project will involve 2-3 new graduate students. **Outcome**: *Improved high-resolution images from incomplete data by leveraging multiple energy and robust migration-velocity analysis that are no longer hampered by surface-related multiples and by poorly resolved reflectors.*

- **Dimensionality-reduced full-waveform inversion with stochastic optimization**. Least-squares migration and full-waveform inversion both require the solution of a large system of equations for each source. Unfortunately this leads to computational costs that become infeasible even for the largest compute clusters because the number of sources and system size increase exponentially. To address this issue, we use dimensionality-reduction techniques that reduce the number of PDE solves required to arrive at the solution. Motivated by recent results by Haber, Chung, and *Herrmann* in the paper "An effective method for parameter estimation with PDE constraints with multiple right hand sides", *Tristan van Leeuwen* (PDF) used techniques from stochastic optimization to analyze and improve ad hoc phase encoding methods that have been proposed to compute gradients efficiently. These methods combine large numbers of sequential sources into small collections of supershots by random superposition. Despite unavoidable source crosstalk, FWI can be carried out with these supershots by either choosing a single large enough collection of supershots to carry out the inversion or by choosing much smaller but different collections of supershots for each gradient update. In the machine learning community, the former is known as the stochastic average approximation (SAA), which has the advantage that it does not require changes for the solver. The latter is known as the stochastic gradient (SG), which has the advantage that allows us to work with a single or very few supershots for each gradient update. While SG can lead to significant speedups, the method is

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unstable with respect to noise. Tristan showed jointly with the PI that this sensitivity can be reduced by averaging amongst past models as prescribed by the theoretical findings of stochastic optimization. He presented these results during at the Consortium meeting in the talk "Waveform inversion by stochastic optimization" and in a paper submitted for publication entitled "Seismic waveform inversion by stochastic optimization". In this paper, we use recent for random-trace estimates to analyze the performance of the stochastic average approximation. This paper clearly establishes the connection between phase encoding in imaging and full-waveform inversion and stochastic optimization in machine learning. Jointly with professor *Michael Friedlander* (co-PI) and *Mark Schmidt* (PDF, who recently joined Ecole Normal Superieur in Paris), Tristan has worked on a new method where the number of supershots is increased during the inversion so that accuracy is increased as the algorithm converges to the solution. Tristan presented jointly with the PI the EAGE abstract "A hybrid stochastic-deterministic optimization method for waveform inversion" on this topic. Michael gave a presentation on this work at the 2011 SIAM Meeting on Optimization, and they also submitted the journal publication entitled "Hybrid Deterministic-Stochastic Methods for Data Fitting". Tristan is also extending his work to 3D where we expect the gains of his method to be even more significant. For this purpose, he is planning to use William Symes' iWave package as well well as a hybrid 3-D time-harmonic Helmholtz solver to be developed in our group using domain decompositions and Schur complements. We plan to put 2-3 new graduate students on this project. **Outcome**. *A formulation of FWI, which greatly reduces the number of sources that participate in the inversion and hence reduces the overall computational costs. Because our method hinges on the generic framework of parameter estimation with PDE constraints (e.g., the acoustic or elastic wave equation) where the PDEs are solved by indirect iterative methods, this methodology removes a major computational bottle-neck that has hampered extensions to 3D and to anisotropic elastic full-waveform inversion. Because of memory and computational requirements, direct solvers are infeasible for these large-scale problems.*

- **Dimensionality-reduced full-waveform inversion with compressive sensing**. *Xiang Li* (PhD student) has jointly with the PI worked on using sparsity promotion to recover migrated images and Gauss-Newton updates from small collections of supershots. His method exploits the fact that spectral-gradient solver (SPGL1) developed by *Ewout van den Berg* (former PhD, now a Stanford PDF) and *Michael Friedlander* (co-PI) solves a series of LASSO subproblems during which the one-norm of the solution is increased systematically. Because the solution is sparse after each problem is solved, this is a natural point at which to draw a new collection of supershots. We used this method to make

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sparsity-promoting imaging and full-waveform inversion more efficient because only small subsets of the data are required reducing the number PDE solves needed to arrive at the solution. In case of migration, the selection of the new batch of supershots coincides with the solution of the LASSO problem. This work “Efficient least-squares migration with sparsity promotion“ was presented by the PI at the EAGE. In case of FWI, the selection of the supershots coincides with the model updates and the new linearizations. This approach, where the `overdetermined' imaging and full-waveform inversion problems are solved by a series of dimensionality reduced sparsity-promoting subproblems, is based on two assumptions, namely that the trade-off curve between different selections of supershots and linearizations does not change significantly and that the gradient update is sparse in the curvelet domain. The latter assumption is justified because sedimentary basins are compressible in the curvelet domain and so are wavefields (curvelets act in the high-frequency limit as localized eigenfunctions of the wave equation) even for linearization with respect to a velocity model that is far from the true model. This work was presented jointly with the PI at the meeting in the talks "Compressive imaging" and "Full-waveform inversion with randomized L1 recovery for the model updates" and was also presented at the EAGE in "Efficient least-squares migration with sparsity promotion" and "Full-waveform inversion with randomized L1 recovery for the model updates". *Sasha Aravkin* (PDF) has worked jointly with the PI on formalizing our method by using convex-composite techniques that allow us to recast the nonlinear unconstrained least-squares problem of full-waveform inversion with sparsity promotion into a method where the Gauss-Newton updates are computed by solving sparsity-promoting programs on the linearized Gauss-Newton subproblems. Initial work on stylized examples have shown encouraging results and Sasha is working on more complicated examples and he also plans to include renewals. Sasha presented his work during two presentations at the Consortium meeting: "Introduction to convex composite optimization" and jointly with Tristan "Exloiting sparsity in full-waveform inversion: nonlinear basis pursuit denoise algorithm" and he presented jointly with the PI the abstract "A Nonlinear Sparsity Promoting Formulation and Algorithm for Full Waveform Inversion" at the EAGE. Sasha is also working on making our sparsity-promoting formulation more robust with respect to outliers by introducing a Hubert / student t norms replacing the two-norm on the data misfit (not on the model). This work was submitted to the SEG in the abstract entitled “Robust full-waveform inversion using the Student's t-distribution”. Jointly with the PI, also presented “Full Waveform Inversion with Compressive Updates” at the SIAM Computational Science and Engineering meeting. Finally, Sasha is working with professor James Burke (Department of Mathematics, University of Washington) and professor Friedlander (co-PI) on Newton-type one-norm solvers with complex-valued coefficient, which is an unresolved

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problem in the optimization community. We need these coefficients to be complex because this adds shift invariance and insensitivity to phase rotations to the curvelet transform. We plan to hire 2-3 new graduate students on this project. **Outcome**. *An efficient and robust formulation for wave-equation based imaging and full-waveform inversion based on a combination of stochastic optimization and compressive sensing. This formulation is designed to remove the exploding computational complexity of these problems in 3D and for situations that go beyond the scalar acoustic wave equation.*

Aside from these relatively short-term research topics, we are planning to work on the following long-term projects:

- **Compressive framework for Seismic Data Acquisition.** In this project, we will use the insights of compressive sensing to optimize seismic acquisition. Topics include the design of practical seismic acquisition scenarios, and issues related, and sigma-delta quantization. We will also look at experimental design in the context of full-waveform inversion. Professor *Ozgur Yilmaz* (co-PI) will take the lead on this topic. One of the main ingredients of compressive sampling theory is the requirement that samples are acquired in a way that is incoherent with the sparsity structure of the signals. In the seismic setting this amounts to the design of appropriate acquisition geometries and strategies that beat the Nyquist barrier. Our goal is to propose such geometries and quantization methods that are tailored to our compressive approach to seismic acquisition. The quantization aspect of this project will leverage the general-purpose compressive quantization theory developed by Saab and Yilmaz.
- **Stochastic optimization.** In this project, we will use insights in stochastic optimization to improve the numerical efficiency of our solvers and our formulation of the FWI problem. Traditionally there have been two approaches to stochastic approximation. The first approach is sample-average approximation (SAA), which reduces the overall size of a problem by sampling the function at relatively few points; the approximation is subsequently solved by a standard optimization method. The second approach is stochastic gradient (SG), which attempts to progress on the original problem by approximating the gradient. Each approach has its difficulties: with the SAA approach it is difficult to know apriori how to best sample the function in order to guarantee a certain accuracy; the SG approach may not converge. Our goal is to boostrap the theory developed by Friedlander and Schmidt, "Hybrid Deterministic-Stochastic Methods for Data Fitting", to solve the SAA problems, and to predict if further sampling is required. This project will involve all three PIs. Professor *Friedlander* has taken the lead on this.
- **Extension of Compressive Sensing to nonlinear operators.** In this project, we will seek to extend theoretical results from Compressive Sensing to PDE-

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constrained optimization. We will also investigate how ideas from Stochastic Optimization can be used in the context of compressive sensing and vice versa. This project will involve all three PIs.

- **FWI with extensions.** In this project, we will investigate a the performance of a "pre-stack" formulation of full-waveform inversion in which we incorporate focussing. This requires many of the above mentioned techniques and has the potential to address the non-uniqueness problem that continues to plague full-waveform inversion. Jointly with the PI, Tristan van Leeuwen (PDF) submitted the abstract entitled "Probing the extended image volume" to the SEG. In this work, he presents a new method to form the action of the extended image kernel on a vector without forming this kernel explicitly. He also presented work on waveform tomography "Multiscale aspects of waveform tomography at SIAM GeoSciences". This topic involves the PI.
- **Parallel software environment.** In this project, the PI, Michael Friedlander (co-PI), and Henryk Modzelewski worked on the design and implementation (by several summer COOP students) of our parallel extension of SPOT called pSPOT. This extension removes current limitations regarding the computational costs and storage requirements of our transform based algorithms that involve the solution of extremely large convex optimization problems. Because this environment exploits our parallel compute cluster, we are able to rapidly prototype and test our algorithms while this environment also leads to code that is readable and scalable to large problem sizes. Tim Lin (PhD student) releases our implementation of Robust Estimation of Primaries by Sparse Inversion (REPSI) in this framework. We plan to also release our implementations of compressive imaging and full-waveform inversion in this framework. Finally, we are also working with ConocoPhilips to build a bridge between Matlab (and the Distributed Parallel Toolbox that is used by pSPOT) and JavaSeis (the core of SeisSpace, which is a commercial seismic data processing package developed by Landmark). This interface exposes our applications developed with pSPOT to SeisSpace users while it also gives our parallel environment access to JavaSeis through overloading (with jSPOT, which gives matlab access to Java arrays) and through data containers that gives matlab parallel IO and access to large seismic data volumes. With these components in place, companies will be able to rapidly use our algorithms and this will lead to significant improved uptake of our technology.

2. Research Team

Please provide an overview of the participation in, and scientific contributions to, the project for each member of the research team (principal investigator, co-investigators, collaborators, company and government scientists, research associates, postdocs, students, etc.).

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This information is interwoven with the information provided under item 1.

3. Training

Please list **each** trainee (Undergraduate Students, Master's Students, Doctoral Students, Postdoctoral Fellows, Research Associates, Technicians …) on a separate line in the table below providing: a) the number of years they have been on the project, b) the percentage (%) of time each type of trainee spent on this project, and c) the percentage (%) of funding from this CRD grant (NSERC and industry contribution). If a trainee is fully paid from other sources, enter "0" in the "% of funding from this grant" column. Insert additional rows if necessary. (DO NOT INCLUDE FAMILY NAMES.)

Specify type of trainee (e.g. M.Sc., Ph.D. etc) (one trainee per line)	(a) Number of calendar years on the project	(b) % of research time spent on this project	(c) % of salary from this grant
Modzelewski, Henryk-RA	2	40%	40%
Modzelewski, Henryk-RA	1	65%	65%
Hanlon, Ian-RA	1	100%	100%
Aravkin, Aleksandr-PDF	2	100%	100%
Poor Moghadam, Peyman-PDF	1	100%	100%
Saab, Rayan-PDF	2	100%	100%
Van Leeuwen, Tristan-PDF	2	100%	100%
Mansour, Hassan Bader-PDF	2	100%	100%
Johnson, James-GRA	1	100%	100%
Kumar, Nameet-GRA	1	100%	100%
Lim, Tim Tai-GRA	2	100%	100%
Poor Moghaddam, Peyman-GRA	1	100%	100%
Tu, Ning-GRA	2	100%	100%
Wason, Haneet-GRA	2	100%	100%
Xiang, Li-GRA	2	100%	100%
Yan, Jiupeng-GRA	2	100%	100%
Lim, Tim Tai-UAA	2	100%	100%
Moradi Monfared, Saman-UAA	1	100%	100%
Lai, Yu Yang-UAA	1	100%	100%

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Roberson, Trisha Ann-UAA	**1**	**100%**	**100%**

4. Dissemination of Research Results and Knowledge and/or Technology Transfer

4.1 Please provide the number of publications, conference presentations, and workshops to date arising from the research project supported by the grant in the table below.

Publications, Conference Presentations, etc.

	None to date

- OR -

	Number of publications, presentations ...			
Status	**Refereed Journal Articles**	**Reviewed conference Proceedings**	**Conference Presentations/ Poster**	**Other (including Technical Reports, Non-Refereed Articles, etc.)**
Accepted/Published	**11**	**16**	**23**	**25**
Submitted	**5**			

4.2 Please provide the bibliographical reference data for the above publications, conference presentations and workshops under the corresponding headings. For publications, specify whether submitted, accepted or published.

REFEREED JOURNAL PUBLICATIONS (authors, title, journal, pages)

1. Nonequispaced curvelet transform for seismic data reconstruction: A sparsity-promoting approach. Gilles Hennenfent, Lloyd Fenelon, and **Felix J. Herrmann**, Geophysics 75, WB203-210 (2010), DOI:10.1190/1.3494032
2. Randomized sampling and sparsity: Getting more information from fewer samples **Felix J. Herrmann**, Geophysics 75, WB173-187 (2010), DOI:10.1190/1.3506147
3. Seismic waveform inversion by stochastic optimization. Tristan van Leeuwen, Aleksandr Aravkin, and **Felix J. Herrmann**. 2011. International Journal of Geophysics. In press., 2011.
4. Enhancing crustal reflection data through curvelet denoising. Vishal Kumar, Jounada Oueity, Ron M. Clowes, and **Felix J. Herrmann**. Technophysics. In Press, doi:10.1016/j.tecto.2010.07.01, 2010.
5. A.M.Powell, J.Tanner, Y.Wang, and **O.Yilmaz**. “Coarse quantization for random interleaved sampling of bandlimited signals”. *ESAIM MATHEMATICAL MODELLING AND NUMERICAL ANALYSIS.* In Press.
6. Daubechies, S. Gunturk, Y. Wang, and **O. Yilmaz.** " The golden ratio encoder". *IEEE TRANSACTIONS ON INFORMATION THEORY*. Vol. 56 (10) (2010), pp. 5097-5110.

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7. R. Saab and **O. Yilmaz.** “Sparse approximations via non-convex optimization – instance optimality.” *APPLIED AND COMPUTATIONAL HARMONIC ANALYSIS*. Vol. 29 (1), pp. 20-48.
8. J. Blum, M. Lammers, A. Powell and **O. Yilmaz**. “Sobolev duals for frames and sigma-delta quantization”. *JOURNAL OF FOURIER ANALYSIS AND APPLICATIONS*. Vol. 16 (3), pp. 365-381.
9. M. Lammers, A. Powell and **O. Yilmaz.** “Alternative dual frames for digital-to-analog conversion in sigma-delta quantization”. ADVANCES IN COMPUTATIONAL MATHEMATICS. Vol. 32 (1), pp. 73-102.
10. E. van den Berg and **M. P. Friedlander**, “Sparse optimization with least-squares constraints.” SIAM J. OPTIMIZATION, In Press.
11. E. van den Berg and **M. P. Friedlander.** “Theoretical and empirical results for recovery from multiple measurements.” IEEE TRANS. INFORMATION THEORY. 56(5):2516-2527, 2010.

Submitted journal publications

1. Eldad Haber, Matthias Chung, and **Felix J. Herrmann.** UBC-EOS Technical Report. TR-2010-04. An effective method for parameter estimation with PDE constraints with multiple right hand sides. In revision. 2010.
2. **M. Friedlander**, H. Mansour, R. Saab, and **O. Yilmaz**. “Recovery of compressively sampled signals using partial support information.” Submitted 2010.
3. **M. P. Friedlander** and M. Schmidt. “Hybrid deterministic-stochastic methods for data fitting.” Submitted 2011.
4. S. Gunturk, M. Lammers, A. Powell, R. Saab, and **O. Yilmaz**. “Sobolev Duals for Random Frames and Sigma-Delta Quantization of Compressed Sensing Measurements”. Submitted 2010.
5. **O. Yilmaz**, Y. Wang, and Z. Zhou. “Phase aliasing correction for robust blind source separation using DUET.” Submitted 2010.

Reviewed conference proceedings

1. Tim T.Y. Lin, **F. J. Herrmann**. Estimating primaries by sparse inversion in a curvelet-like representation domain. In the proceedings of the European Association of Geoscientists and Engineers (EAGE), Vienna, 2011.
2. Ning Tu, Tim T.Y. Lin, **F. J. Herrmann**. Sparsity-promoting migration with surface-related multiples. In the proceedings of the European Association of Geoscientists and Engineers (EAGE), Vienna, 2011.
3. Xiang Li, Aleksandr Aravkin, Tristan van Leeuwen, **F. J. Herrmann**. Full-waveform inversion with randomized L1 recovery for the model updates In the proceedings of the European Association of Geoscientists and Engineers (EAGE), Vienna, 2011.
4. Tristan van Leeuwen, Mark Schmidt, Michael Friedlander, **F. J. Herrmann**. A hybrid stochastic-deterministic optimization method for waveform inversion. In the proceedings of the European Association of Geoscientists and Engineers (EAGE), Vienna, 2011.
5. **F. J. Herrmann** and Xiang Li. Efficient least-squares migration with sparsity promotion In the proceedings of the European Association of Geoscientists and Engineers

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(EAGE), Vienna, 2011.

6. Aleksandr Y. Aravkin, Tristan van Leeuwen, James V. Burke, **F. J. Herrmann**. A Nonlinear Sparsity Promoting Formulation and Algorithm for Full Waveform Inversion. In the proceedings of the European Association of Geoscientists and Engineers (EAGE), Vienna, 2011.
7. Tim T.Y. Lin, Ning Tu, **F. J. Herrmann**. Sparsity-promoting migration from surface-related multiples. In the proceedings of the Society of Exploration Geophysicists International Exposition and Annual Meeting (SEG), Denver, 2010.
8. Peyman P. Moghaddam, **F. J. Herrmann**. Randomized full-waveform inversion: a dimenstionality-reduction approach In the proceedings of the Society of Exploration Geophysicists International Exposition and Annual Meeting (SEG), Denver, 2010.
9. Xiang Li, **F. J. Herrmann**. Full-waveform inversion from compressively recovered updates. In the proceedings of the Society of Exploration Geophysicists International Exposition and Annual Meeting (SEG), Denver, 2010.
10. Hassan Mansour, Haneet Wason, Tim Lin, **F. J. Herrmann**. A compressive sensing perspective on simultaneous marine acquisition. SBGF 2011.
11. Bander Jumah, **F. J. Herrmann**. Dimensionality-reduced estimation of primaries by sparse inversion. SEG 2011, San Antonio.
12. Tristan van Leeuwen, **F. J. Herrmann**. Probing the extended image volume. SEG 2011, San Antonio.
13. Ning Tu, Tim T.Y. Lin, **F. J. Herrmann**. Migration with surface-related multiples from incomplete seismic data. SEG 2011, San Antonio.
14. Haneet Wason, **F. J. Herrmann**, and Tim T.Y. Lin. Sparsity-promoting recovery from simultaneous data: a compressive sensing approach. SEG 2011, San Antonio.
15. Aleksandr Aravkin, Tristan van Leeuwen, **F. J. Herrmann**. Robust full-waveform inversion using the Student's t-distribution. SEG 2011, San Antonio.
16. Tim Lin, F.J. Herrmann. Robust source signature deconvolution and the estimation of primaries by sparse inversion. SEG Broadband Seismic Workshop, 2011, San Antonio.

Presentations at conferences:

1. **F. J. Herrmann.** Compressive sensing and sparse recovery in exploration seismology**.** BIRS Workshop: Sparse and Low Rank Approximation, 2011, March, 2011, Banff*.
2. **F. J. Herrmann.** Compressive Sensing and Sparse recovery in Exploration Seismology**.** Canadian Mathematical Society Meeting, November, 2010, Vancouver.
3. **O. Yilmaz.** Compressed sensing with partial support information**,** SPIE Wavelets XIV, San Diego, CA, Aug 2011 (scheduled).
4. **O. Yilmaz.** A/D conversion and compressive sampling, International Conference on Applied Harmonic Analysis and Multiscale Computing, Edmonton, AB, Jul 2011 (scheduled)
5. **O. Yilmaz.** Compressed sensing with partial support information, CMS Summer Meeting, Edmonton, AB, Jun 2011
6. **O. Yilmaz.** Weighted 1-norm minimization for improved compressed sensing recovery, Shanks Workshop, Vanderbilt University, Nashville, TN, May 2011.
7. **O. Yilmaz.** Sobolev duals of Gaussian frames and Sigma-Delta quantization for compressed sensing, Workshop on Sparsity and Computation, Hausdorff Center for

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Mathematics, Bonn, Germany, Jun 2010.

8. **O. Yilmaz.** Sigma-delta quantization for compressed sensing, Conference on Information Sciences and Systems (CISS), Princeton, NJ, Mar 2010.
9. **Sigma-delta quantization for compressed sensing,** Conference on Information Sciences and Systems (CISS), Princeton, NJ, Mar 2010.
10. **M. Friedlander.** Stochastic optimization for data fitting, 25th IFIP TC 7 Conference, Berlin, Germany, September 2011 (scheduled).
11. **M. Friedlander.** Tutorial on sparse optimization, SIAM Meeting on Optimization, Darmstadt, Germany. May 2011.
12. **M. Friedlander.** Deterministic-Stochastic methods for data fitting, SIAM Meeting on Optimization, Darmstadt, Germany. May 2011.
13. **M. Friedlander.** Sparse optimization: algorithms and applications, Institute for Pure and Applied Mathematics, UCLA. September 2010.
14. **F. J. Herrmann.** Compressive Sensing and Sparse Recovery in Exploration Seismology. MATHIAS 2010, Total SA, October, 2010, Paris.
15. **F. J. Herrmann.** Sub-Nyquist sampling and sparsity: getting more information from fewer samples. Presented at the 79th SEG Meeting, Houston. ExxonMobil. Corporate Research. Clinton, New Jersey, August 2009.*
16. **T. van Leeuwen.** Multiscale aspects of waveform tomography. Presented at SIAM GeoSciences 2011, Long Beach.
17. **S. Aravkin.** Full Waveform Inversion with Compressive Updates. Presented at SIAM Computational Science and Engineering, 2011, Reno.
18. **X. Li.** Full-waveform inversion from compressively recovered updates. Presented at the SEG 2010, Denver.
19. **N. Tu.** Sparsity-promoting migration from surface-related multiples. Presented at the SEG 2010, Denver.
20. **F. J. Herrmann.** Randomized full-waveform inversion: a dimensionality-reduction approach. Presented at the SEG 2010, Denver.

Other (Including Technical Reports, Non-Refereed Articles, etc.):

Presentations at Fall SINBAD/DNOISE consortium meeting

1. Felix Herrmann. Welcome and brief introduction to SINDBAD and DNOISE
2. Felix Herrmann. Compressive sensing and sparse recovery in exploration seismology
3. Ozgur Yilmaz (Math). Sparse approximations and compressive sensing: an overview
4. Haneet Wason. Sequential source data recovery from simultaneous acquisition through transform-domain sparsity promotion - curvelet versus shearlet transform
5. Chuck Mosher (ConocoPhillips). Operator localization with Generalized Windowed Transforms
6. Rayan Saab. Compressed sensing using Kronecker products
7. Hassan Mansour. Recovering compressively sampled signals using partial support

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information

8. Michael Friedlander (CS). Algorithms for Sparse Optimization
9. Tim Lin. Sparse optimization and the L1 norm
10. Aleksandr Aravkin. Introduction to convex composite optimization
11. Xiang Li. Compressive imaging
12. Tim Lin. Leveraging informed blind deconvolution techniques for the estimation of primaries by sparse inversion
13. Mufeed Al-Matar. Estimation of surface-free data by curvelet-domain matched filtering and sparse inversion
14. Ning Tu. Sparsity promoting migration with surface-related multiples
15. Randomized dimensionality reduction
16. Felix Hermann. Dimensionality reduction for full-waveform inversion
17. Mark Schmidt. Hybrid stochastic-deterministic methods
18. Peyman Moghaddam. Randomized full-waveform inversion
19. Tristan van Leeuwen. Waveform inversion by stochastic optimization
20. Xiang Li. Full-waveform inversion with randomized L1 recovery for the model updates
21. Aleksandr Aravkin and Tristan van Leeuwen. Exloiting sparsity in full-waveform inversion: nonlinear basis pursuit denoise algorithm.
22. Henryk Modzeleweski. Software releases and architechture
23. Michael Friedlander. Introduction to SPOT: a linear-operator toolbox
24. Sebastien Pacteau. Kronecker product optimization in SPOT
25. Nameet Kumar. Parallelizing operations with ease using Parallel SPOT

4.3 **Patents and Licences**

Please provide in the table below the **number** of patents (filed and issued) and licences to date arising from the research project supported by the grant in the table below. (Provide details in 4.4.)

	Not applicable

- OR -

	None Yet Filed/Issued

	Number of Patents				
Description	**Canada**	**U.S.**	**EP**	**Other**	**Totals**
# of Patent Applications Filed	**0**				
# of Patents Issued	**0**				

# of Licences		**(Provide details in 4.4.)**

4.4 Please provide details (titles, patent application number, patent number…) about the above listed patent applications, patents, and licences under the corresponding headings.

Patent Applications Filed:

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N/A

Patents Issued:

N/A

Licences: (licencees, exclusive/non-exclusive…)

SINBAD members get royalty-free access to the codes developed as part of the DNOISE/ SINBAD project.

4.5 Describe how the results achieved to date are being transferred to the user sector and the prospects for their commercial/industrial exploitation.

Prospects for the Transfer of the Results to the User Sector

Technology dissemination

Aside from presenting our results at professional meetings and at our twice-a-year Consortium meetings, we have been involved in the following initiatives to disseminate our research findings to our industrial partners:

- software releases with concrete parallel software implementations of our algorithms (see details below)
- development of our parallel development environment pSPOT and bridge to JavaSeis via jSPOT and our datacontainer that gives us access to the parallel IO of JavaSeis
- web casts during the meeting we plan to also organize these web casts on a more regular basis to present our research findings and to give tutorials for companies to use our software
- internships during which our students help our industrial partners with the application of our technology to solve their problems. This internship program has been very succesfull and allowed companies to evaluate our technology.

In addition to these activities, we also received lots of feedback from industry regarding the uptake (please remember that industry is not always in the position to disclose to us what they are doing with our research and what the impact is on their business) of our technology including

- application of our convex-optimization technology (developed by Michael Friedlander) within BP after Tim Lin spend a Summer with them as an intern. In the words of one of their researchers, Tim's presence advanced the career of one of their top research people by nearly a year. We have also seen an interest in this solver from other companies including WesterGeco and PGS (the latter is not yet a member of the consortium).

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- application of our random sampling technology by WesternGeco. Nick Moldoveanu who is the mastermind behind WesternGeco's Coil sampling used our sampling ideas and worked with us to interpolate missing data on well-designed synthetic. This exercise yielded very good results, which were presented by Nick at EAGE in Vienna.
- application of compressive full-waveform inversion to a dataset provided by BG. During this project, we applied our inversion technology with results that were received very favorably by BG. We greatly benefited from this feedback.

Software releases

Robust Estimation of Primaries by Sparse Inversion

This package implements an algorithm for simultaneous multiple removal and estimation of the source signature. It is based on the Estimation of Primaries by Sparse Inversion approach but reformulated via block- coordinate descent and convexification to L1 minimization. Both the primaries and the source signature are estimated in a data-consistent fashion using a biconvex alternating optimization scheme. We believe this approach is more robust to inversion instabilities, and should converge quicker and more reliably that the original formulation.

Planned Software releases for this Summer

Sparsity-promoting imaging with surface-related multiples

Compressive imaging

Full-waveform inversion

Compressive full-waveform inversion

Full-waveform inversion with stochastic optimization

5. Problems Encountered

Identify the main problems encountered during this instalment of the grant from the list below (select all that apply):

	Technical or scientific problems	Aside from a minor setback regarding the development of a 3D solver for Helmholtz, the project has not suffered any major setbacks. We have been making progress in developing our own solver and we established collaborations with other groups (William Symes at Rice and Jean Virieux/Stephane Operto at Nice) that can potentially give us this simulation capability. This will allow us to test our own solutions and gives a backup plan for our scale up to 3D.

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	Problems with direction of research or findings	Working with realistic field datasets in an academic environment is always challenging because of the large computational requirements and technical know how required to process field data. This, in conjunction with a push towards 3D, calls for delicate choices regarding what we can and cannot do not given our computer resources and experience working with real data. We hired a research associate who will work with us to expand our capabilities to work with real data and to see what the possibilities are to increase the capacity of our compute cluster.
	Equipment and facilities	Given the size of our problems, we have reached the capacity of our compute cluster and we are looking for possibilities to augment our computational resources.
	Staffing issues (including students)	Finding new students, PDFs, RA's, etc, has proven to be challenging and very time consuming. This has let to some delays but we are happy to report that we were able to hire several new PDFs and 6 new graduate students.
	Funding problems	None
	Partner withdrew from project	None
	Partner interaction issues	
	Other (specify)	

- OR -

	No problems occurred during this instalment of the grant

Briefly describe the main problems identified above and the steps taken to resolve each one.

1. **Collaboration with Supporting Organizations**

6.1 Who initiated this CRD project?

X	The university researcher		
	The industry partner		
	Shared initiation (university/ industry)		
	Other (specify)		

6.2 In what way were the partners directly involved in the project (select all that apply)?

	Partners were not involved in the project apart from their financial

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X	Partners were available for consultation
	Partners provided facilities
X	Partners participated in the training
X	Partners received training from university personnel
X	Partners discussed the project regularly with the university team
	Number of meetings during the period covered by this report: 1 Consortium meeting and many one-to-one conversations
X	Partners were involved in the research

6.3 Describe the partner's involvement and comment on the collaboration.

The industry's collaboration involves

- attendance to our Consortium meetings that we organize twice a year. Once in Vancouver and once in Europe. During these meetings, the industry partners give us feedback on our projects.
- releases of datasets to test our algorithms. For example, we worked o a very sophisticated datasets provided by BG and WesternGeco. We also worked on datasets provided by BP.
- hiring of summer intenrs.
- informal feedback during conversations at meetings.
- collaboration with ConocoPhilips to build a bridge between matlab (and our pSPOT) and JavaSeis, which give companies access to our algorithms and us access to large seismic data volumes. This project also involves participation from Mathworks the maker of Matlab.

6.4 Was the total amount of cash committed by the partner during the period covered by this report received?

x	Yes
	No

6.5 Was any in-kind received from the partner during the period covered by this report?

N/A	Yes
	No

6.6 For cash and in-kind received, please enter the amounts below, along with the amount of cash and in-kind committed in the original proposal. If no in-kind was received, please enter "0". Where in-kind was not committed enter "n/a".

	Amount Committed	**Total Amount Received to Date**
Cash		
In-Kind		

6.7 Describe the in-kind received and explain variations between commitment and actual cash and in-kind contribution if applicable.

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7. Financial Information

The purpose of this section is to provide additional project-specific detail; it cannot be substituted with a Statement of Account (Form 300).

Please provide the following financial information:

Budget Item	Budget for this instalment (as outlined in original proposal)	Actual expenditures for current instalment, up to Report due date	Projected expenditures from Report due date to end of this instalment	Planned expenditures for the next instalment
Salaries and Benefits				
Students	118,015	142,877.02	39,957	189,725
Postdoctoral fellows	242,000	206,573.45	66,250	242,000
Technical/professional assistants	99,750	111,021.21	61,111	158,788
Other (specify)		20,000		
Equipment and Facilities				
Purchase or rental	35,500	82,636.26		6,000
Operation and maintenance costs	23,633			15,956
User fees	15,000			15,000
Materials and Supplies				
Materials and supplies	3,410	6,543.08		1,930
Travel				
Conferences	25,855	77,094.04		36,400
Field work	0			
Project-related travel	6,000			6,000
Project meeting	5,000			5,000
Dissemination Costs				
Publication costs	4,000	14,385.95		4,000
Annual report and webcast	4,500			4,500
Annual meeting costs	4,000			17,500
Other (specify)				
Permits and Licenses		26,610.50		
Totals	**586,664**	**687,741.51**		**702,799**

Please provide detailed explanations for any deviation in the current period and in the budget for the coming year. (Note that deviations from the budget of greater than 20 per cent require pre-approval from NSERC.)

The numbers included in the above table under the “Actual expenditures” reflect our expenses

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from the beginning of the project, which is August 1st, 2009. The "Budget" in the first column reflects one-year period. The detailed expenses for the period of August 1st, 2010 until April 30th, 2011 are summarized on the Form 300, which is attached to this report. Our discussion regarding meeting the budget with 20% is based on combining the first and last column. We also rolled in expenses 3 months prior to the starting date of August 1st, 2009 as agreed with Theresa Anderson. These were expenses incurred during the bridging period between DNOISE I and II.

Overall one will notice that we are somewhat below the proposed expenditures. The reason for this include

- delays in student recruitment due university acceptance regulations and challenges finding suitable candidates. We are happy to report that 7 new MSC/PhD students will join the DNOISE II project September 1st, 2011. Aside from salary expenses, we will incur additional expenses for computer equipment etc.
- challenges in hiring a research associate in highly competitive market. We are happy to report that Ian Hanlon joined our group full time since March 15th, 2011.
- we hired successfully a number of PDFs and we are continuing our search for new candidates, which is challenging in a climate where industry is hiring aggressively.

Given our extensive recruiting efforts, we expect to meet our target soon for the remainder of the DNOISE II project. We also anticipate some additional HQP-related expenses whose costs will be posted retroactively to the grant. In coming year, we also expect the other budget items to increase in accordance with the growth of the research team.

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