Collaborative Research and Development (CRD) Grants Progress Report

Due Date: **(June 1, 2012)**
Covers the Period: **(May 1, 2011 – April 30, 2012)**

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

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

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Is the project information below correct?

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

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

File Number: CRDPJ 375142 - 08

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Collaborator(s):

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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.

Compressive acquisition and sparse recovery

Objectives*: Design and implementation is new seismic-data acquistion methodologies that reduced costs by exploiting structure in seismic data.*

We have worked towards these objectives with **Professor Ozgur Yilmaz** (co-PI) from both applied and theoretical perspectives. **Haneet Wason** (PhD student) worked with **Hassan Mansour** (PDF) on the development of new marine-acquisition schemes that are based on compressive sensing. This work was described at the Fall consortium meeting, and was presented by Hassan in his talk "A compressive sensing perspective on simultaneous marine acquisition" at the Brazililan SEG in Rio de Janeiro, and by Haneet in her talk "Sparsity-promoting recovery from simultaneous data: a compressive sensing approach" at the SEG in San Antonio. We also submitted the paper "Simultaneous-source marine acquisition with compressive sampling matrices", which will appear in Geophysical Prospecting. In this journal publication, we provide deeper theoretical insights that explain the peformance of simultaneous maringe acquisition from the perspective of compressive sensing; we also show that sequential data can be recovered from aquistions with a single source that fires at randomly-dithered times with a reduced time between the shots. This last approach is new, and has the potential to make acquisition cheaper. Our theoretical work is also new, and is the first step towards new acquisition guidelines that give the user control over the cost and quality of the recovery. We will present our latest findings on marine acquisition at the EAGE during the talk "Only dither: efficient simultaneous marine acquisition" at the Workshop: "Simultaneous Source Methods for Seismic Data".

Ozgur Yilmaz and Hassan also continued to work on the theoretical and practical aspects of weighted one-norm minimization, where approximate information on the support (i.e., location of significant transform-domain coefficients) is incorporated into the recovery process. We are very excited about this work because it is leading to significant improvements in the recovery problem. These results will be reported in "Weighted one-norm minimization for seismic data interpolation", which we plan to submit early this summer. Ozgur Yilmaz, Hassan Mansour, and **Navid Ghadermarzy** (1^{st} year MSc student) have recently extended this approach (based on incorporating approximate prior information into the recovery process) to sparse recovery methods based on non-convex optimization. This work will be reported in a journal paper that we plan to submit this summer.

We also extended our work towards recovery algorithms that exploit low-rank structure. This work, in collaboration with **Sasha Aravkin** (PDF), has resulted in the SEG abstract "Fast Methods for Rank Minimization with Applications to Seismic-Data Interpolation", authored with **Rajiv Kumar** (1^{st} year PhD student); we hope to present this work at this year's SEG. We are very excited about this work because it paves the way to solving extremely large seismic-data recovery problems using the latest developments from convex optimization and machine learning. We are working with proferssor Ben Recht from the Computer Science Department of the University of Wisconsin on this new topic.

Professor Michael Friedlander (co-PI) and Sasha Aravkin, in joint work with James Burke (Professor at University of Washington) are working on a matrix-free approach to general quadratic programming that can use second-order information. Because most of the sparse-recovery programs used in signal recovery can be formulated as quadratic programs (via a dual formulation), this approach has the potential to open the door to an entirely new generation of convex solvers. This is a distinctly different approach that is based on relaxing a polyhedral constraint set (e.g., the 1- or infinity-norms) by a differentiable object. This approach is mainly a technology of *reformulation*, and accommodates existing state-of-the-art nonlinear solvers to be used. We hope to finalize a report in this next period.

Finally, we are also happy to report that there is considerable uptake in industry regarding randomized acquisition and sparse recovery. For instance, WesternGeco has used some of our ideas to develop their coil sampling technology and they are working with us on the recovery. We are also aware that Conocophilips has done field trials with randomized sampling and sparse recovery on which they will report at the SEG. As we will show below, these techniques are not limited to seismic acquisition and can also be used to make seismic processing and inversion more efficient. The three PIs made these connection explicit in their paper "Fighting the Curse of Dimensionality: Compressive Sensing in Exploration Seismology", which recently appeared in IEEE Signal Processing Magazine. This paper was written for the broader signal-processing community and was desiged to raise a broader interest in exploration seismology in that community. To continue our momentum on this topic, we will add one more graduate student to the team, who will be looking at issues related to calibration, quality, and repeatability of surveys collected following the principles of compressive sensing. **Felix Oghenokohwo** (1st year PhD student) will also be working in this general area. In summary, we have made considerable progress towards the objectives and goals we set in the grant. We are now in the process to shift our attention to 3D seismic, which is challenging since this entails a two order-of-magnitude increase in the problem size.

Outcome: *Development of a new paradigm for seismic data acquisition and sparsity/low-rank-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.*

Free-surface removal

Objectives: *Wave-equation-based mitagation of the free surface by sparse inversion.*

Estimation of primaries. Tim Lin (PhD student) has worked on several fronts on our Robust formulation of Primary Estimation by Sparse inversion (REPSI). We solved this problem by extending the algorithm behind the SPGL1 solver, which was developed by Michael Friedlander (co-PI) and our former PhD student **Ewout van den Berg**. The new approach is based on block-coordinate descent, whereby iterations efficiently alternate between two subproblems: 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, which results in an improved scheme that yields highly encouraging results on challenging real data sets. Tim prepared a major update of the REPSI software, which uses our parallel extensions of SPOT, our object-oriented Matlab development environment pioneered by Professor Friedlander. Recent results of Tim's work have been presented during the SEG Post-Convention workshop on broad-band seismic in the talk entitled "Robust source signature deconvolution and the estimation of primaries by sparse inversion".

Jointly with the PI, Tim also finished the journal publication "Robust estimation of primaries by sparse inversion via one-norm minimization", currently under review. To remove REPSI's unfortunate reliance on working with full data matrices, **Bander Jumah** (MSc student, graduated 2011 and now with Saudi Aramco) and the PI use randomized singular-value decompositions in combination with hierarchical matrix representations to reduce the memory use and matrix-matrix multiplications costs. This work, "Dimensionality-reduced estimation of primaries by sparse inversion", was presented at the SEG by Bander and submitted for journal publication entitled "Dimensionality-reduced estimation of primaries by sparse inversion". We are excited about this work because it minimizes the reliance of iterative data-driven wave-equation based methods for multiple elimination to touch/on-the-fly interpolate all data during each iteration. More recently, we have begun exploiting possibilities to extend REPSI to 3-D sesimic problems.

Seismic interferometry. During a three-month visit by Joost van der Neut (PhD student supervised by Professor Wapenaar from the Delft University of Technology), we worked on using sparsity-promoting and sampling techniques to solve problems in seismic interferometry. This work resulted in the extended EAGE abstract "Up / down wavefield decomposition by sparse inversion", where sparsity-promoting techniques are used to stably compute decompostions of waves into up- and downgoing components. This development allows us to extend REPSI to ocean bottom data. For an intergated approach to the imaging and free-surface problem; see the subsection nonconventional imaging below.

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.*

Compressive modeling for imaging and inversion

Objectives: *Design and implementation of efficient wavefield simulators in 2- and 3-D.*

Particularly in the case of 3-D seismic, solving wave equations for large models has been extremely challenging.This is especially true in the context of inversion techniques that require the application of the migration operator (the adjoint of the Jacobian) and its adjoint (the linearized Born-scattering operator). Since time-stepping methods lead to complications, such as checkpointing and complexities of handling boundary conditions, we decided to use methods based on discretizations of time-harmonic wave equations. In 2-D, **Tristan van Leeuwen** (PDF) has implemented an object-oriented parallel-simulation framework in Matlab, which he described in the expanded abstract "A parallel, object-oriented framework for frequency-domain wavefield imaging and inversion.", submitted to the SEG. Aside from providing a simulator for the full wavefield, our environment also includes a matrix-free implementation for the linearized Born-scattering operator. Tristan extended this framework to include density variations; we are also working with Professor Min (visiting Professor from the Seoul National University) to extend our 2-D formulation to the elastic case. To overcome the challenges that come with wavefield simulations in 3-D, Tristan—in collaboration with Professors Dan and Rachel Gordon (University of Haifa and Technion)—has been working on preconditioned iterative solvers that can be parallelized relatively easily and extended to wave-equations with varying density, anisotropy, and elastic properties. We have a working prototype in parallel Matlab, which has a performance that is close to the original implementation, and is not too far from the performance of time-stepping methods (e.g., iWave, developed by Professor William Symes from Rice University).

This software has been released to the industry and has been made accessible to researchers at non-profit organizations. Tristan will talk about this exciting new development at the EAGE during his presentation entitled "Preconditioning the Helmholtz Equation via Row-projections". Currently we are working on incorporporating this simulator into our object-oriented framework for wave-equation based imaging and inversion. The proposed approach in 3-D is different from the approach we discussed in the DNOISE II proposal because it is simpler, more flexible, and no longer reliant of the knowledge of **Yogi Erlangga**, a former PDF. To arrive at this choice, we ran, with assistance from **Martin Pajchel** (summer COOP), comparisons with several alternartive approaches. To further optimize our implementation, **Art Petrenko** (1st year MSc student) has been added to the team and he will look at specific implementation issues to speed up the CARP-CG algorithm on which our preconditioner is based. Because extension to 3-D seismic requires a significant larger compute cluster (see discussion below), Art will also be involved in the design and implementation of a benchmark test suite to evaluate different types of hardware. Finally, we are also looking into ways to leverage alternative wavefield simulators and codes that are able to compute gradient updates (via the matrix-free action of the adjoint of the Jacobian). For this purpose, we have been in contact with Professor Mike Warner (Imperial College) and we are also looking for ways to bridge our wave-equation inversion framework to simulators developed by industry (see discussion under Parallel development environment).

Outcome: *Concrete implementation of a scalable object-oriented parallel simulation framework in 2- and 3-D for time-harmonic wave equations.*

Compressive wave-equation based imaging and inversion

Objectives: *Design and implementation of an efficient and robust wave-equation based inversion framework leveraging recent developments in machine learning, sparse recovery, robust statistics, and optimization.*

Linearized wave-equation based inversion:

Accelerated sparsity-promoting imaging. In this work, we used ideas from compressive sensing to mitigate the adverse effects of randomized source encoding (source crosstalk or migration noise due to the use of random amplitude-encoded supershots) by sparsity promotion (instead of by averaging as in batching, see below). To improve the efficiency of sparsity promotion via convex optimization, we adapted message-passing techniques that borrow from ideas from belief propagation, coding, and graph theory. This is joint work with **Xiang Li** (PhD student) and consisted of a case study on the synthetic Compass dataset provided to us by BG. This work was presented at the EAGE and was reported in the journal paper "Efficient least-squares imaging with sparsity promotion and compressive sensing", which appeared in Geophysical Prospecting. We showed that source crosstalk, caused by random source encoding, can be effectively mitigated by promoting curvelet-domain sparsity. We also showed that the convergence of our sparsity-promoting solver SPGL1 can be substantially accelerated by selecting new randomized supershots after each subproblem is solved. While the uplift of drawing new supershots can partially be explained by stochastic optimization—e.g., the stochastic gradient method employs a similar techniques—recent theoretical developments from message passing give a better insight into why renewals, in combination with sparsity promotion, are essential. We report on these exciting new developments at the coming EAGE meeting in the talk "Pass on the message: recent insights in large-scale sparse recovery", and during the SSP meeting in the talk "Approximate message passing meets exploration seismology"; we have also submitted the paper "Accelerated large-scale inversion with message passing" to the SEG. Xiang Li plans to extend our sparsity-promoting imaging approach to include imaging of density perturbations using convex-optimization techniques that promote joint sparsity. He will also study the effects of noise and extension to 3-D seismic. As an alternative, **Lina Miao** (1^{st} year MSc student), with the co-PI Michael Friedlander, is looking into replacing the first-order search directions in SPGl1 (our current sparsity-promoting solver) by second-order quasi-Newton based search directions, as is done in our code PQN. She showed that this replacement can lead to substantial speedups at the price of having to keep several model vectors in memory, which somewhat limits the applicability of this approach to large-scale problems. We hope to report on this development. Finally, in recent work, Ozgur Yilmaz, Hassan Mansour, and **Brock Hargreaves** (1^{st} year MSc student) are investigating a randomized "Kaczmarz-like" algorithm to solve linear systems of equations (not necessarily underdetermined) that have sparse or compressible solutions. Empirically, this new iterative algorithm is stable with repect to noise and model mismatch, computationally efficient, and shows robust convergence behaviour for both underdetermined and overdetermined systems. We are currently working on gaining a theoretical understanding of this algorithm as well on investigating its effectiveness in seismic imaging and inversion.

Preconditioned imaging by random matrix probing. Curt da Siva (1^{st} year MSc Math student) worked on preconditioning of the wave-equation Hessian using randomized probing techniques and fast parameterizations of pseudo-differential operators. This work was presented at the Fall consortium meeting and resulted in the paper "Matrix Probing and Simultaneous Sources: A New Approach for Preconditioning the Hessian", which will be presented at the EAGE. We are working on extending this method to include simultaneous sources and on incorporation this method into our sparsity-promoting imaging. We are also looking into how this method can be used to condition the linear Born-scattering operator such that it is conducive to message-passing techniques.

Migration with extended image volumes. Tristan van Leeuwen (PDF) worked on the formation of image volumes for the purpose of migration velocity analyses and linearized inversion on which he reported at several conferences (EAGE/SEG/Waves/ICIAM). See e.g., "Wave-equation extended images: computation and velocity continuation", which will be presented at the EAGE. While our ability to form matrix-free actions of extended image volumes is exiting, it is not trivial to develop this approach into a practical imaging and/velocity analysis tool. Therefore, **Rajiv Kumar** (1^{st} year PhD) will employ a simplified version of this technique (via angle gathers computed from extended images that are a function of the horizontal subsurface offset only) for linearized amplitude-versus offset inversion, while **Lina Miao** (1^{st} year MSc) will look into possibilities to develop convex penalty functionals to create hifi extended images from source-encoded data.

Unconventional imaging. Tu Ning (PhD student) made significant progress in developing imaging techniques for data with surface-related multiples. This work was presented at several meetings (EAGE/SEG) and has been very well received. We are particularly excited about two recent developments, namely a formulation where impulsive sources are replaced by areal sources, which allows us to remove expensive multidimentional convolutions and correlations, and where the convergence is signifantly improved by using ideas from message passing. With these two innovations, we were able to make significant improvements in quality, memory use, and speed of this unconventional imaging methodology. This work has been presented at several conferences including the SEG and EAGE, see e.g., "Migration with surface-related multiples from incomplete seismic data", and we hope to present "Imaging with multiples accelerated by message passing" at the SEG this Fall. This work has been implemented in software released to our sponsors. **Joost van der Neut** (visiting graduate student) worked on applying our sparse-recovery techniques to interferometric imaging, which he will present at the EAGE/SIAM/SEG meetings. We are particularly excited about combining interferometry with imaging, which we presented in the SEG abstract "Interferometric redatuming with simultaneous and missing sources using sparsity promotion in the curvelet domain", and which we plan to write up in a journal publication. This latter developments opens exciting new perspectives on problems related to monitoring of hydraulic fracturing and we will be looking to hire a experienced PDF and a graduate student to continue working on this topic.

Outcomes: *An efficient, concrete, and versatile imaging framework accelated by message passing and improved by curvelet-domain sparsity promotion and improved by leveraging the free surface and properties of extended image volumes.*

Nonlinear wave-equation based inversion:

Fast and robust full-waveform inversion. To overcome overwhelming data volumes and sensitivities related to errors in capturing the correct wave physics, Michael Friedlander (co-PI), **Sasha Aravkin** (PDF), and **Tristan van Leeuwen** (PDF) have worked on the theoretical development of batching techniques that control the error and that are robust with respect to modelling errors. This technology is based on the recent work of Friedlander and **Mark Schmidt** (PDF), published in the journal paper "Hybrid deterministic-stochastic methods for data fitting", which describes a measurement-sampling approach that can dramatically reduce the overall computational effort required for most data-fitting applications. This paper develops the theory needed to understand how to subsample data and still achieve steady convergence of most inversion procedures. The follow-up work of Aravkin, Friedlander, van Leeuwen, and the PI, combines the randomized sampling approach with ideas from robust statistics. Because only subsets of sources are used, this approach leads to significant improvement in the convergence as a function of the number of PDE solves. We reported our findings in a number of EAGE/SEG/ICASSP abstracts and in the following papers: "Robust inversion, dimensionality reduction, and randomized sampling", which will appear in Mathematical Programming and be presented at the ISMP in a plenary lecture; in "Robust inversion via semistochastic dimensionality reduction", which was presented at ICASSP, and "Fast waveform inversion without source encoding", which will appear in Geophysical Prospecting. The first of the two papers lays out the theoretical framework while the second paper addresses the issue that source-encoding techniques rely on fully-sampled data, which excludes marine acquisition. Extending full-waveform inversion to robust statistics required a similar technique since standard randomized source encoding is no longer applicable for other than two-norm misfit functionals. This work also has a concrete parallel software implementation in 2-D, which has been released to our industrial partners. We note that these batching and robust-statistics techniques are being incorporated in production codes of several companies including Total SA and WesternGeco. Currently, Tristan is extending this work to 3-D seismic, on which he plans to report soon.

Source estimation. Standard source-estimation techniques are no longer valid for non-two-norm data-misfit functionals. To overcome this difficulty, Tristan and Sasha extended source-estimation to include source estimation for robust data misfit functionals. This work entitled "Source estimation for frequency-domain FWI with robust penalties" will be presented at the EAGE.

Nonuniqness student's t misfit functionals. We address the issues of non-convexity of the student' t misift functionals in the SEG abstract entitled "On Non-Uniqueness of the Student's t-formulation for Linear Inverse Problems". This is a joint project between our group and Professor Kenneth Bube (University of Washington).

Full-waveform inversion with compressive sensing. Aside from relying on increasing the batch size to remove subsampling related errors by averaging, **Xiang Li** (PhD student) adapted our accelerated sparsity-promoting imaging techniques to speed up computations of Gauss-Newton updates of full wave-form inversion. This included an extension to marine data and was presented at several conferences (SIAM/EAGE/ICIAM/SPIE/SEG/ICASSP). Theoretical findings of this work were reported in the refereed SPIE proceeding "A modified, sparsity promoting, Gauss-Newton algorithm for seismic waveform inversion". Aside from several conference proceedings, we published this work to the geophysical community in the letter to Geophysics "Fast randomized full-waveform inversion with compressive sensing", which will appear in June. A concrete software implementation of this modified Gauss-Newton method has been released to the SINBAD consortium members. **Xiang Li** plans to study the incorporation of density variations, extension to 3D, and performance compared to batching as part of the remainder for his PhD work.

Source-side preconditioning. Professor Min, **Ning Tu** (PhD student), **Tristan van Leeuwen** (PDF) have worked on using subsurface wavefield deconvolution techniques (which correspond to certain approximations of the wave-equation Hessian) in full-waveform inversion and wave-equation based linearized inversion. We hope to report progress on this topic soon.

Elastic 2-D full waveform inversion. During her visit, Professor Min has worked on extending 2-D full-waveform inversion to the elastic case. We plan to incorporate some of her findings in our formulation of the full-waveform inversion problem. **Luz Mata** (1st year PhD) will be involved in this project.

Outcomes: *A fast and robust framework for full-waveform inversion that removes the impediments of computational complexity, by using randomized dimensionality-reduction techniques, and of reliance on accurate wave physics, by using misfit functionals derived from robust statistics.*

Parallel software environment.

Objectives: *Development and implementation of a scalable parallel interoperable development environment to test and dessiminate concrete software implementations of our algorithms to our industrial partners.*

Parallel SPOT (pSPOT) – a linear-operator toolbox for matlab. 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 (available at https://github.com/slimgroup/pSPOT). This extension, which is based on parallelized Kronecker products that allow us to seamlessely work with multidimensional arrays with dimensions that are contiguous or distributed, 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) released our implementation of Robust Estimation of Primaries by Sparse Inversion (REPSI) in this framework. We currently have our undergraduate **Frances Russell**, supported by an Undergraduate Student Research Award, working on the SPOT documentation this summer.

Object-oriented framework for physics-based optimization. Motivated by our experience developing SPOT and pSPOT, **Tristan van Leeuwen** (PDF) developed an object-oriented parallel environment for optimization problems that arise in inverse problems such as seismic imaging and full-waveform inversion. This software is build on top of pSPOT and allows us to formulate PDE-constrained optimization problems with (i) flexibility regarding the PDE, e.g., constant versus varying density, 2-D versus 3-D; (ii) flexibility regarding the misfit functional, e.g. two-norm versus student t misfit; (iii) matrix-free implementation of the Jacobian (linearized Born scattering operator) and its adjoint (migration operator), which makes our formulation conducive to linearized inversion (e.g., least-squares migration) and full-waveform inversion with Gauss-Newton Hessians; (iv) seamless integration with existing optimization codes such as L-BFGS and SPGL1; (v) unit tests that allow us to extensively test the different components of our optimization framework. Based on this framework, we released

- A parallel matrix-free framework for (linearized) acoustic modelling with the time-harmonic Helmholtz equation. [Demo] [Download]
- Fast imaging with surface-related multiples by sparse inversion [Demo] [Download]
- Fast full-waveform inversion with sparse updates [Demo] [Download]
- Fast full-waveform inversion with robust penalties and source estimation [Demo] [Download]

to our sponsors.

Seismic data container. The extreme large size of seismic data volumes makes the development of algorithms complicated because of memory requirements that often exceed memory of even the largest compute clusters. To address this issue, we have started the development of a data container that allows us to work seamlessly with very large multidimensional arrays in Matlab that are in-core or out-of-core. Our implementation not only allows us to extend (again through Kronecker products) pSPOT to include out-of-core dimensions, but is also allows us to keep track of meta data, e.g., sizes and header information. Because our implementation includes parallel IO, we limit overhead that comes with working with out-of-core dimensions. The first prototype of this software is made available at https://github.com/slimgroup/SeisDataContainer/. We plan to make this data container interoperable with our physics-based optimization framework.

Interoperable development environment. One of the major challenges the industry and our group are faced with is finding ways to facilitate the uptake of our technology by industry. Aside from the fact that each company may have its own propriatory software environment, the size of seismic data volumes and the nature of our problems makes it challenging for industry to incorporate our algorithms into their systems. To address these issues, we plan to work on the following fronts:

- Design of a serial IO interface between Matlab arrays and JavaSeis (and possibly other data formats) files using the JavaSeis (or equivalent) package. This activity includes the development of a low-level interface to read and write JavaSeis (or equivalent) files or their contiguous parts (slices) into serial Matlab arrays. This functionality requires the development and low-level implementation of Matlab's array methods using JavaSeis (or equivalent) functionality, rather then using intermediate Matlab arrays. The to-be-developed interface should be equivalent to current implementation of the Seismic data container that uses Matlab's native IO operations. The final goal of this project is to extend this interface to distributed matlab arrays, including distributed file access as implemented by JavaSeis (or equivalent).
- Design of an abstract interface, including a concrete implementation of an application interface between our object-oriented framework for physics-based optimization and implementations for wave simulators, gradients, Jacobians, and their adjoints by industry. This effectively replaces thefunctionality of our forward-modeling framework by a low-level industry-strength implementation. This activity will include the selection of an appropriate communication protocol (e.g., sockets) and a document outlining the

technical specifications the industry-strength implementations have to adhere to. This interface will be agnostic with regard to imlementation details of the forward-modeling framework from industry.

- Concrete implementation of an interface between the distributed arrays of matlab and Javaseis (or equivalent). This constitutes a two-way bridge between matlab and Seispace (or equivalent), a professional seismic-data processing package. This interface exposes our applications developed with pSPOT to SeisSpace (or equivalent) users while it also gives our parallel environment access to JavaSeis (or equivalent) 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.

Currently, we are talking to ConocoPhilips, Mathworks (the makers of Matlab), Landmark (Seispace), and IBM to explore possibilities for a pilot study towards the above goals. We have also been talking with BG Group and professor Mike Warner regarding the possibility to interface between our physics-based optimization framework and their implementations for 3-D wave simulators.

Outcomes: *A versatile, maintanable, and scalable development environment supporting concrete industry-strength implementations of the algrorithms developed as part of DNOISE II.*

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.).

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
Henryk-RA	3	65%	65%
Ian-RA	2	100%	100%
Aleksandr-PDF	3	100%	100%
Tristan-PDF	3	100%	100%
Hassan-PDF	3	100%	100%
Enrico-PDF	2	35%	35%
Tim-PhD	3	100%	100%
Ning-PhD	3	100%	32%
Haneet-PhD	3	100%	100%
Li-PhD	3	100%	32%
Mata-PhD	2	100%	43%
Navid-MSc	2	100%	100%
Brock-MSc	2	100%	100%
Rajiv-PhD	2	100%	100%
Lina-MSc	2	100%	100%
Artyom-MSc	2	100%	100%
Curt –Technician	1	100%	100%
Curt-MSc	2	100%	100%
Jiupeng-MSc	2	100%	100%
Felix O.-PhD	1	100%	100%
Siavash-Technician	1	100%	100%
Martin-technician	1	100%	100%
Yu Yang-technician	1	100%	100%
Shruti-technician	1	100%	100%
Sanyi-RA	2	100%	100%
Anais-visiting scholar	1	0%	0%
Yves-PhD	2	100%	0%
Gabriel-MSc	2	100%	0%
Peyman-PDF	1	100%	100%
Peyman-PhD	1	100%	100%
James-MSc	1	100%	100%
Nameet-technician	1	100%	100%
Rayan-PDF	2	100%	100%
Saman-technician	1	100%	100%
Trisha-technician	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	Refereed proceedings	Conference Presentations/ Poster	Other (including Technical Reports, Non-Refereed Articles, etc.)
Accepted/Published	12	26	56	2
Submitted	3	8		

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 Articles:

1. Efficient least-squares migration with sparsity promotion and compressive sensing. **F. J. Herrmann** and X. Li. Article first published online: 31 JAN 2012. DOI: 10.1111/j.1365-2478.2011.01041.x, 2012.
2. V. Kumar, J. Oueity, R. M. Clowes, **F. J. Herrmann**, Enhancing crustal reflection data through curvelet denoising, Tectonophysics, Volume 508, Issues 1–4, Pages 106-116, ISSN 0040-1951, 10.1016/j.tecto.2010.07.017, 20 July 2011.
3. T. van Leeuwen, A. Aravkin, and **F. J. Herrmann**. Seismic waveform inversion by stochastic optimization. 2011. International Journal of Geophysics, vol. 2011, 18 pages, doi:10.1155/2011/689041, 2011.
4. **X. Li**, A. Y. Aravkin, T. van Leeuwen, and **F. J. Herrmann**, "Fast randomized full-waveform inversion with compressive sensing". To appear as a letter in GEOPHYSICS, 2012.
5. **F. J. Herrmann**, **M. P. Friedlander**, and **O. Yilmaz** , "Fighting the Curse of Dimensionality: Compressive Sensing in Exploration Seismology", Signal Processing Magazine, IEEE, vol.29, no.3, pp.88-100, May 2012.
6. H. Mansour, H. Wason, T. T. Y. Lin, and **F. J. Herrmann**. "Randomized marine acquisition with compressive sampling matrices". To appear in Geophysical Prospecting, 2012.
7. A. Y. Aravkin, **M. P. Friedlander**, **F. J. Herrmann**, and Tristan van Leeuwen, "Robust inversion, dimensionality reduction, and randomized sampling". To appear in Mathematical Programming, 2012.
8. E. Haber and M. Chung and **F. J. Herrmann**. "An effective method for parameter estimation with PDE constraints with multiple right hand sides". To appear in SIAM Journal of Optimization, 2012.
9. T. van Leeuwen and **F. J. Herrmann**, "Fast waveform inversion without source encoding". To appear Geophysical Prospecting, 2012.
10. **M. P. Friedlander** and M. Schmidt, "Hybrid deterministic-stochastic methods for data fitting". To appear in SIAM Journal on Scientific Computing, 2012.
11. **M. P. Friedlander**, H. Mansour, R. Saab, and **O. Yilmaz**, "Recovering compressively sampled signals using partial support information". IEEE Trans. Inform. Theory, 58(2):1122--1134, 2012.
12. E. v. Berg and **M. P. Friedlander**, "Sparse optimization with least-squares constraints". SIAM Journal on Optimization, 21:1201--1229, 2011.

Submitted journal publications

1. T. T.Y. Lin and **F J. Herrmann**, "Robust estimation of primaries by sparse inversion via one-norm minimization". 2012.
2. B. Jumah and **F. J. Herrmann**, "Dimensionality-reduced estimation of primaries by sparse inversion". 2012.
3. P. P. Moghaddam, H. Keers, **F. J. Herrmann** and W. A. Mulder. "Randomized full-waveform inversion". 2012.

Reviewed conference proceedings

1. X. Li and **F. J. Herrmann**, "Efficient full-waveform inversion with marine acquisition geometry". In CSEG technical program. 2012.
2. H. Wason and **F. J. Herrmann**, "Only dither: efficient simultaneous marine acquisition". In CSEG technical program. 2012.
3. J. W. Oh, D. J. Min, and **F. J. Herrmann**, "Re-establishment of gradient in frequency-domain elastic waveform inversion". In CSEG technical program. 2012.
4. **F. J. Herrmann** and H. Wason, "Compressive sensing in marine acquisition and beyond", in EAGE technical program, 2012.
5. J. W. Oh, D. J. Min, and **F. J. Herrmann**, "Frequency-domain elastic waveform inversion using weighting factors related to source-deconvolved residuals", in EAGE technical program, 2012.
6. N. Tu and **F. J. Herrmann**, "Least-squares migration of full wavefield with source encoding", in EAGE technical program, 2012.
7. C. Da Silva and **F. J. Herrmann**, "Matrix Probing and Simultaneous Sources: A New Approach for Preconditioning the Hessian", in EAGE technical program, 2012.
8. H. Wason and **F. J. Herrmann**, "Only dither: efficient simultaneous marine acquisition", in EAGE technical program, 2012.
9. **F. J. Herrmann**, "Pass on the message: recent insights in large-scale sparse recovery", in EAGE technical program, 2012.
10. T. van Leeuwen, D. Gordon, R. Gordon, and **F. J. Herrmann**, "Preconditioning the Helmholtz equation via row-projections", in EAGE technical program, 2012.
11. A. Y. Aravkin, T. van Leeuwen, H. Calandra, and **F. J. Herrmann**, "Source estimation for frequency-domain FWI with robust penalties", in EAGE technical program, 2012.
12. J. van der Neut* and **F. J. Herrmann**, "Up / down wavefield decomposition by sparse inversion", in EAGE technical program, 2012.
13. T. van Leeuwen and **F. J. Herrmann**, "Wave-equation extended images: computation and velocity continuation", in EAGE technical program, 2012.
14. A. Y. Aravkin, **M. P. Friedlander**, T. van Leeuwen, "Robust inversion via semistochastic dimensionality reduction". ICASSP 2012.
15. H. Mansour and **O. Yilmaz**, "Support driven reweighted 1-norm minimization". ICASSP 2012.
16. H. Mansour and **O. Yilmaz**, "Adaptive compressed sensing for video acquisition". ICASSP 2012.
17. A. Y. Aravkin, X. Li, and **F. J. Herrmann**, "Fast seismic imaging for marine data", in proceedings of ICASSP, 2011.
18. H. Mansour and **O. Yilmaz,** "Weighted 1-norm minimization with multiple weighting sets". Proc. SPIE Wavelets and Sparsity XIV, vol. 8138, 813809 (2011), DOI: 10.1117/12.894165, 13 pages.
19. **F. J. Herrmann**, X. Li, A. Y. Aravkin, and T. van Leeuwen**, "A modified, sparsity promoting, Gauss-Newton algorithm for seismic waveform inversion", Proc. SPIE Wavelets and Sparsity XIV, vol. 8138, 81380V (2011), DOI:10.1117/12.893861, 14 pages. 2011.

20. H. Mansour, H. Wason, T. Lin and **F. J. Herrmann**. "A compressive sensing perspective on simultaneous marine acquisition", in proceedings of SBGF, 2011.
21. B. Jumah and **F. J. Herrmann**. "Dimensionality-reduced estimation of primaries by sparse inversion", in SEG Technical Program Expanded Abstracts, 2011, vol. 30, p. 3520-3525.
22. T. van Leeuwen and **F. J. Herrmann**. "Probing the extended image volume", in SEG Technical Program Expanded Abstracts, 2011, vol. 30, p. 4045-4050.
23. N. Tu, T. T.Y. Lin, and **F. J. Herrmann**. "Migration with surface-related multiples from incomplete seismic data", in SEG Technical Program Expanded Abstracts, 2011, vol. 30, p. 3222-3227.
24. H. Wason, **F. J. Herrmann**, and T. T.Y. Lin. "Sparsity-promoting recovery from simultaneous data: a compressive sensing approach", in SEG Technical Program Expanded Abstracts, 2011, vol. 30, p. 6-10.
25. A. Aravkin, T. van Leeuwen and **F. J. Herrmann**. "Robust full-waveform inversion using the Student's t-distribution", in SEG Technical Program Expanded Abstracts, 2011, vol. 30, p. 2669-2673.
26. Tim T.Y. Lin and **Felix J. Herrmann**, "Robust source signature deconvolution and the estimation of primaries by sparse inversion", in SEG Technical Program Expanded Abstracts, 2011, vol. 30, p. 4354-4359.

Submitted conference proceedings

1. **F. J. Herrmann**, "Accelerated large-scale inversion with message passing". 2012.
2. R. Kumar, A. Y. Aravkin, and **F. J. Herrmann**, "Fast Methods for Rank Minimization with Applications to Seismic-Data Interpolation". 2012.
3. N. Tu and **F. J. Herrmann**, "Imaging with multiples accelerated by message passing". 2012.
4. J. van der Neut*, **F. J. Herrmann**, and K. Wapenaar, "Interferometric redatuming with simultaneous and missing sources using sparsity promotion in the curvelet domain". 2012.
5. A. Y. Aravkin, T. van Leeuwen, K. Bube, and **F. J. Herrmann**, "On Non-Uniqueness of the Student's t-formulation for Linear Inverse Problems". 2012.
6. T. van Leeuwen and **F. J. Herrmann**, "A parallel, object-oriented framework for frequency-domain wavefield imaging and inversion". 2012.
7. X. Li and **F. J. Herrmann**, "Sparsity-promoting migration accelerated by message passing". 2012.
8. **F. J. Herrmann**, "Approximate message passing meets exploration seismology". 2012.

Conference Presentations/Posters:

1. **F. J. Herrmann.** Fighting the curse of dimensionality: compressive sensing in exploration seismology. Workshop: W-3 Compressive Sensing and Computation. SEG, September, 2011, San Antonio.
2. **F. J. Herrmann.** Modified Gauss-Newton with Sparse Updates, Brazilian Geophysical Society (SGBF), August, 2011, Rio de Janeiro*.
3. **F. J. Herrmann.** FWI with sparse recovery: a convex-composite approach. Workshop: Imaging and Inverse Problems, International Conference on Industrial and Applied Mathematics, July, 2011, Vancouver*.
4. **F. J. Herrmann.** Latest developments & open problems in compressive seismic-data acquisition. SINBAD Spring Consortium meeting. June, 2011, Vienna.

5. **F. J. Herrmann.** Efficient least-squares migration with sparsity promotion. EAGE, June 2011, Vienna.
6. **F. J. Herrmann.** Tackling the "data deluge": a dimensionality-reduction approach. Workshop: New Representations of Seismic Data - Aiming at Increased Information Density at Less Cost. EAGE, June, 2011, Vienna.
7. **F. J. Herrmann.** Randomized dimensionality reduction for full-waveform inversion. SIAM Optimization, June, 2011, Darmstadt.
8. **F. J. Herrmann.** Randomized dimensionality reduction in seismic inversion. Workshop: Seismology of Earth and Stars conference participants. Center for Theoretical Science. May, 2011, Princeton University.
9. **T. van Leeuwen**, M. Schmidt, M.P. Friedlander and F.J. Herrmann. A Hybrid stochastic-deterministic optimization method for waveform inversion, AMP Medical and Seismic imaging, July 14-16 2011, Vancouver.
10. **T. van Leeuwen**, W.A. Mulder and **F.J. Herrmann**. A correlation-based misfit criterion for wave-equation traveltime tomography, ICIAM, July 18-22 2011, Vancouver
11. A. Aravkin, **T. van Leeuwen** and F.J. Herrmann. Robust full waveform inversion using Student's t-distribution, ICIAM, July 18-22 2011, Vancouver.
12. **T. van Leeuwen** and F.J. Herrman. Probing the extended image volume for seismic velocity inversion, Waves, July 25-29 2011, Vancouver.
13. A. Aravkin, **T. van Leeuwen** and F.J. Herrmann. Robust full waveform inversion with Student's t-distribution, Waves, July 25-29 2011, Vancouver.
14. **T. van Leeuwen**. Recent advances in seismic waveform inversion, SCAIM Seminar, February 14 2012, Vancouver.
15. **A. Y. Aravkin**, Fast seismic imaging for marine data, ICASSP, Poster, Wed, March 28, 14:00 -16:00.Kyoto, Japan.
16. **A. Y. Aravkin**, Robust inversion via semistochastic dimensionality reduction, ICASSP, March 28, Kyoto, Japan.
17. **A. Y. Aravkin**, Robust inversion via semistochastic dimensionality reduction, TOTAL internal conference (Mathias), invited presentation, October 2011, Paris.
18. **A. Y. Aravkin**, Fast Robust Seismic Imaging. West Coast Optimization Meeting, October 2011, Kelowna.
19. **A. Y. Aravkin,** Robust full-waveform inversion using Student's t-distribution. Numerical Aspects of Waves, July 2011, Vancouver BC.
20. A. Y. Aravkin, Robust full-waveform inversion using Student's t-distribution. SIAM ICIAM, July 2011,Vancouver BC.
21. **A. Y. Aravkin**, Exploiting block tridiagonal structure to design efficient robust Kalman smoothers. SIAM ICIAM (invited presentation), July 2011, Vancouver, BC.
22. **A. Y. Aravkin**, Sparsity promoting formulations and algorithms for FWI. Applied Mathematics Perspectives 2011: Medical and Seismic Imaging (invited presentation), July 15. Vancouver, BC.
23. **A. Y. Aravkin**, Full-waveform inversion with compressive updates. SIAM Computational Science and Engineering, February 2011, Reno.
24. **X. Li** and F. J. Herrmann, "Efficient full-waveform inversion with marine acquisition geometry", CSEG, Calgary. 2012.
25. **H. Wason** and F. J. Herrmann, "Only dither: efficient simultaneous marine acquisition". CSEG, Calgary, 2012.
26. J. W. Oh, **D. J. Min**, and F. J. Herrmann, "Re-establishment of gradient in frequency-domain elastic waveform inversion", CSEG, Calgary, 2012.
27. **F. J. Herrmann** and H. Wason, "Compressive sensing in marine acquisition and beyond", EAGE, Copenhagen, 2012.
28. J. W. Oh, **D. J. Min**, and F. J. Herrmann, "Frequency-domain elastic waveform inversion using weighting factors related to source-deconvolved residuals", EAGE,

Copenhagen, 2012.

29. **N. Tu** and F. J. Herrmann, "Least-squares migration of full wavefield with source encoding", EAGE, Copenhagen, 2012.
30. **C. Da Silva** and F. J. Herrmann, "Matrix Probing and Simultaneous Sources: A New Approach for Preconditioning the Hessian", EAGE, Copenhagen, 2012.
31. **H. Wason** and F. J. Herrmann, "Only dither: efficient simultaneous marine acquisition", EAGE, Copenhagen, 2012.
32. **F. J. Herrmann**, "Pass on the message: recent insights in large-scale sparse recovery", EAGE, Copenhagen, 2012.
33. **T. van Leeuwen**, D. Gordon, R. Gordon, and F. J. Herrmann, "Preconditioning the Helmholtz equation via row-projections", EAGE, Copenhagen, 2012.
34. **A. Y. Aravkin**, T. van Leeuwen, H. Calandra, and F. J. Herrmann, "Source estimation for frequency-domain FWI with robust penalties", EAGE, Copenhagen, 2012.
35. **J. van der Neut** and F. J. Herrmann, "Up / down wavefield decomposition by sparse inversion", EAGE, Copenhagen, 2012.
36. **T. van Leeuwen** and F. J. Herrmann, "Wave-equation extended images: computation and velocity continuation", EAGE, Copenhagen, 2012.
37. **A. Y. Aravkin**, X. Li, and F. J. Herrmann, "Fast seismic imaging for marine data", ICASSP, Japan, 2011.
38. F. J. Herrmann, X. Li, A. Y. Aravkin, and **T. van Leeuwen**, "A modified, sparsity promoting, Gauss-Newton algorithm for seismic waveform inversion", Proc. SPIE 8138, 81380V (2011), DOI:10.1117/12.893861, San Diego, 2011.
39. **H. Mansour**, H. Wason, T. Lin and F. J. Herrmann. "A compressive sensing perspective on simultaneous marine acquisition", SBGF, Rio de janeiro, 2011.
40. **B. Jumah** and F. J. Herrmann. "Dimensionality-reduced estimation of primaries by sparse inversion", SEG San Antonio, 2011.
41. T. van Leeuwen and F. J. Herrmann. "Probing the extended image volume", SEG , Poster, San Antonio, 2011.
42. **N. Tu**, T. T.Y. Lin, and F. J. Herrmann. "Migration with surface-related multiples from incomplete seismic", data SEG San Antonio, 2011.
43. **H. Wason**, F. J. Herrmann, and T. T.Y. Lin. "Sparsity-promoting recovery from simultaneous data: a compressive sensing approach", SEG San Antonio, 2011.
44. **A. Aravkin**, T. van Leeuwen and F. J. Herrmann. "Robust full-waveform inversion using the Student's t-distribution", SEG San Antonio, 2011.
45. **Tim T.Y. Lin** and F. J. Herrmann, "Robust source signature deconvolution and the estimation of primaries by sparse inversion", SEG San Antonio, 2011.
46. **M.P. Friedlander**, "Deterministic-stochastic methods for data fitting", plenary talk at the IFIP TC7, Berlin, 2011.
47. **M.P. Friedlander**, "Data fitting and optimization with randomized sampling", Institute for Computational Mathematics, Stanford University, 2011.
48. **M.P. Friedlander**, "Algorithms for sparse optimization", SEG San Antonio, 2011.
49. **M.P. Friedlander**, "Incremental Newton-type methods for data fitting", SIAM Conference on Optimization, Darmstadt, 2011.
50. **M.P. Friedlander**, "Algorithms and applications of sparse optimization", tutorial lecture at SIAM Conference on Optimization, Darmstadt, 2011.
51. **O. Yilmaz,** "Sobolev duals of random frames and compressed sensing quantization", DARPA Mathematics Summit, 2012.
52. **O.Yilmaz**, "A popular overview of compressed sensing", SEG San Antonio, 2011.
53. **O. Yilmaz**, "Compressed sensing with partial support information – algorithms and theoretical guarantees", SPIE Wavelets and Sparsity XIV, 2011.
54. **O. Yilmaz**, "Noise-shaping quantizers for compressed sensing", International Conference on Applied Harmonic Analysis and Multiscale Computing, Edmonton, AB,

2011.

55. **O. Yilmaz,** “Compressed sensing with partial support information”, CMS Summer Meeting, Edmonton, AB, 2011.
56. O. Yilmaz, “Weighted 1-norm minimization for improved compressed sensing recovery”, Shanks Workshop, Vanderbilt University, 2011.

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

1. **Felix J. Herrmann**, Haneet Wason, and Tim T. Y. Lin. “Compressive sensing in seismic exploration: an outlook on a new paradigm”. CSEG Recorder, Vol 36, No. 4., p 19-33, April 2011.
2. **Felix J. Herrmann**, Haneet Wason, and Tim T. Y. Lin. “Compressive sensing in seismic exploration: an outlook on a new paradigm”. CSEG Recorder, Vol 36, No. 6., p 34-39, June 2011.

Presentations at Fall SINBAD/DNOISE consortium meeting

1. Felix J. Herrmann. Welcome and Overview of SINBAD & DNOISE
2. Felix J. Herrmann. Challenges and opportunities for Compressive Sensing in seismic acquisition
3. Ozgur Yilmaz. Compressed sensing with prior information
4. Haneet Wason. Only dither: efficient marine acquisition "without" simultaneous sourcing
5. Hassan Mansour & Haneet Wason. Why do curvelets work?
6. Felix J. Herrmann. Challenges and opportunities in sparse wavefield inversion
7. Tim T. Y. Lin. Inside the Robust EPSI formulation
8. Joost van der Neut. Interferometric redatuming by sparse inversion
9. Tu Ning. Migration from surface-related multiples
10. Bander Jumah. Dimensionality-Reduced EPSI
11. Felix J. Herrmann. To redraw or not to redraw: recent insights in randomized dimensionality reduction for inversion
12. Xiang Li. Efficient least-squares imaging with sparsity promotion and compressive sensing
13. Sasha Aravkin. Extensions to sparsity promotion
14. Tristan van Leeuwen. Towards extended modelling for velocity inversion
15. Michael P. Friedlander. Robust inversion with randomized sampling
16. Tristan van Leeuwen. Fast waveform inversion without source encoding
17. Sasha Aravkin. Robust FWI with Student's T and Robust Source Estimation
18. Shruti Kapoor. Demonstration new website
19. Curt da Silva. Recent Developments in Preconditioning the FWI Hessian
20. Xiang Li & Sasha Aravkin. A randomized, sparsity promoting, Gauss-Newton algorithm for seismic waveform inversion
21. Daisy Min. Parameter selection strategy for density in frequency-domain elastic waveform inversion
22. Tim Lin. SLIM's software design principles
23. Michael P. Friedlander & Tim Lin. SPGL1 for parallel matlab
24. Tristan van Leeuwen. Object-oriented FWI with parallel matlab-bridging the gap between academic and industry code bases
25. Ian Hanlon. General discussion for feedback and mentorship program

Presentations at Spring SINBAD/DNOISE consortium meeting

26. Felix J. Herrmann. Welcome and brief introduction to SINBAD & DNOISE
27. Felix J. Herrmann. Latest developments & open problems in compressive seismic-data acquisition
28. Tim Lin. Robust estimating primaries by sparse inversion in a transform domain
29. Felix J. Herrmann. Dimensionality-reduced estimation of primaries by sparse inversion
30. Ning Yu. Migration with illumination from surface-related multiples
31. Tristan van Leeuwen: FWI via stochastic optimization
32. Xiang Li: Modified Gauss-Newton with sparse updates
33. Sasha Aravkin: Robust Full-waveform inversion using Student's t-distribution
34. Tristan van Leeuwen: Probing the extended image volume

Presentations at companies

1. Compressive Sensing and Sparse Recovery in Exploration Seismology. ION, August, 2011, Houston.
2. Compressive Sensing and Sparse recovery in exploration Seismology. Petro China. June, 2011, Beijng.
3. Compressive Sensing and Sparse recovery in exploration Seismology. BGP. June, 2011, Beijng.

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 -

__X__ None Yet Filed/Issued

	Number of Patents				
Description	**CANADA**	**U.S.**	**EP**	**OTHER**	**TOTALS**
# of Patent Applications Filed					
# of Patents Issued					

# 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:

N/A

Patents Issued:

N/A

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

Our industrial partners get in return for their financial contributions royalty-free access to the IP developed as part of the SINBAD project. This is part of the SINBAD agreement, which arranges the industrial contributions that are matched by DNOISE II.

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

Consortium meetings

We organized two consortium meetings. One in the Spring, immediately following the EAGE in Vienna. This meeting was attended by Charles Jones and Jones Selvage from BG, John Washborne and Sandra Tegtmeier from Chevron, Djalma M. Soares Filho, Claudio Guerra Cardoso, and Carlos E. Theodoro from Petrobras, and Peter Vermeer, Ian Moore, Ali Ozbek, Raif Ferber, and Massimiliano Vassallo from WesternGeco/Schlumberger. As guests we had Nizare El Yadari from Fugro, and Rob Hegge from PGS. The Fall meeting in Whistler was attended by Sverre Brandsberg-Dahl Martin Frijlink, and Rob Hegge from PGS, Richard Coates, Kuang-Hung Liu, and Michel Schoneville from WesternGeco, Fuchun Gao from Total SA, Gilles Hennenfent and Kurt Nihei from Chevron, Charles Jones from BG, Chengbo Li and Morley, Larry Morley from ConocoPhillips, Nanxun Dai and Guoan Luo from BGP, and Adelson de Oliveira and Theodoro, Carlos Eduardo from Petrobras and Yu Zhou from BP. We also had Bernth, Henrik (Schlumberger; Childs, Paul (Schlumberger; Hobro, James (Schlumberger); Kaplan, Sam (ConocoPhillips); Lowrey, David (PGS); Long, Andrew (PGS); Mao, Weijian (Schlumberger); Rickett, James (Schlumberger); Vasconcelos, Ivan (Schlumberger); Veitch, Ben (Schlumberger) as confirmed participants of our webcast. Finally, we had Bloor, Robert (ION) and Zaicenco, Anton (Weir-Jones) as guests.

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.

Software releases

1. **Robust Estimation of Primaries with Sparse Inversion via one-norm minimization.** An iterative prestack surface demultiple method built upon solving a L1-minimization for the surface-free Green's function while simultaneously estimating the source wavelet. [Demo] [Download]
2. **Migration from surface-related multiples.** Fast imaging with surface-related multiples by sparse inversion [Demo] [Download]
3. **2D constant-density acoustic frequency-domain modeling, linearized modeling and imaging.** A parallel matrix-free framework for (linearized) acoustic modelling with the time-harmonic Helmholtz equation. [Demo] [Download]
4. **Modified Gauss-Newton full-waveform inversion.** Fast full-waveform inversion with sparse updates [Demo] [Download]
5. **Fast Robust Waveform inversion.** Fast full-waveform inversion with robust penalties and source estimation. [Demo] [Download]

Industry uptake
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 random sampling technology by WesternGeco and ConocoPhilips. Nick Moldoveanu who is the mastermind behind WesternGeco's full-azimuth 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. We are also aware that PGS and Petrobras, the PI gave a one-day course on Compressive Sensing at the Brazilian SEG, have a keen interest in applying concepts from Compressive Sensing to exploration seismology.
- interest in robust estimation of primaries by sparse inversion from PGS, who made an exciting real data set avaialble, and from BG and Chevron. **Tim Lin** will spend his internship at Chevron this summer working on this technology.
- implementation of our batching and robust statistics by Total SA during a visit by **Sasha Aravkin.** Our method has been implemented in their production code. **Anai Tamalet** is currently "on loan" from Total SA to work on this topic as a long-term visitor.

New website
Over the last year, we developed a complete new website

https://www.slim.eos.ubc.ca/

based on the open-source content management system drupal. Our efforts significantly improve access to our research findings, software, and people.

Outreach
To disseminate our research findings to broader academic and industrial communities we have written review articles that appeared in the Recorder, magazine of the CSEG, and in IEEE Signal Processing Magazine. We also participated in conferences in the field of signal processing (ICASSP and SSP) and computational mathematics (SIAM) to get more involvement from these communities.

5. Problems Encountered

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

x Technical or scientific problems
x Problems with direction of research or findings
x Equipment and facilities
x Staffing issues (including students)
- Funding problems
- Partner withdrew from project
- 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.

Technical or scientific problems
The project has not suffered any major setbacks. We have been making progress in developing our own wave simulator and we continue to work with Professor William Symes at Rice to use his iwave software package as comparison to our simulator, and we have been talking with Professor Mike Warner regarding the use of his 3-D elastic wave simlators. Despite these efforts, we are confronted with a serious lack of access to computational resources that are needed to make the step to 3-D seismic, which requires roughly a two-orders-of-magnitude increase in memory and computational capability (i.e., flops). Unfortunately, exisiting shared resources such as Westgrid are inadequate since these facilities are designed to run mature programs in batch mode, which is not suitable for the research and development of new algorithms. The latter requires more interactivity and immediate accessibility to the system. In addition, our calculations regarding the expected use required for 3-D development far exceed the capacity of Westgrid. To overcome this hurdle we have started

- steps towards raising funds for a local machine using from the Western Economical Diversification Fund. We are looking into way to leverage funding for DNOISE or to expand contributions from industry;
- steps towards exclusive collaboration with a company that would provide significant funding towards the computational resource;
- steps towards collaboration with other university groups (e.g., Professor Mike Warner at Imperial College) and companies towards a large computational facility in Brazil.

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 3-D, 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 Ian Hanlon who is working with Anton Kuipers (Dean's Office) to explore possibilities to get fuding from the Western Economical Diversification Fund.

Equipment and facilities

Given the size of our problems, we have by far reached the capacity of our compute cluster and we are looking for possibilities to augment our computational resources.

Staffing issues. While our current team is complete, we will have to plan for people, most notably experienced PDFs, leaving the team. Because we are active at a very high technical level, this will be challenging. Thereofore, we are starting active recruitment of new PDF talent.

6. 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
__x__ Partners were available for consultation
_____ Partners provided facilities
__x__ Partners participated in the training
_____ 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:__2____
__x__ Partners were involved in the research

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

The industry's collaboration involves the following:

- Attendance to our Consortium meetings that we organize twice a year. Once in BC 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 on a very sophisticated datasets provided by BG and WesternGeco. We also worked on datasets from PGS.
- Hiring our students as summer interns.
- Informal feedback during conversations at meetings.
- Formal feedback during conversations at the annual steering committee meeting at the end of the Consortium meeting in BC.

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?

______ Yes
__x__ 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	524,563	1,458,875
In-Kind		

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

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	189,725	153,557.16		337,381
Postdoctoral fellows	242,000	199,108.29		302,500
Technical/professional assistants	158,788	199,706.31		236,726
Other (specify)				
Equipment and Facilities				
Purchase or rental	6,000	45,498.91		14,500
Operation and maintenance costs	15,956			53,000
User fees	15,000			15,000
Materials and Supplies				
Materials and supplies	1,930	2,264.11		1,930
Travel				
Conferences	36,400	84,405.48		46,550
Field work				
Collaboration/consultation*	11,000			12,000
Dissemination Costs				
Publication costs	4,000			6,500
Other (specify)	22,000	31,554.31		22,000
Other (specify)				

Totals	702,799	716,094.57		1,048,087

* In our budget this item includes project-related travel and project meetings.

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 from May 1st, 2011 to April 30th 2012. The detailed expenses for this period are also included on the Form 300, which is attached to this report.

Overall the budget is right on target (1.89 % over). Regarding the **Salaries and Benefits**, we are slightly under in the student and PDF category and slightly over in the technical assistants category. This is still a resonance of starting up the grant in combination with a relatively large number of students who are on the grant but who are receiving fellowships. The overage for the technical staff is mostly due to the ramp-up investment we made in the beginning of the project towards development of our software environment with COOP students.

As for the **Equipment and Facilities**, we are slightly over because our estimates for renting facilities for our consortium meetings was budgeted too low. We experimented this year by hosting our meeting in Whistler, which was a great success because it raised the level of professionalism and created an environment very conducive to interactions between our group and representatives from industry. The timing of the event (the week after Thanksgiving in the US) was such that the extra costs were kept to an absolute minimum.

Unfortunately, we were not able to control the expenses related to **Travel** for the following reasons. First, there has been a significant increase in fuel surcharges, which we could not have foreseen. This led to a significant increase of the average airfare. Second, the international profile of our group has risen dramatically with the consequence that we are more regularly invited to talk at a wide variety of scientific meetings. While we are more often reimbursed for travel costs by the hosting academic organizations, this still has led to an increase in travel costs in particular by our PDFs and PIs. Third, while we have made several paid trips on invitation by industry we continue to incur costs related to efforts to recruit companies and to meet the increasing interest in our European Consortium meeting after the EAGE. To meet this increased interest for the Consortium meeting, we have been sending relatively more students and PDFs. Finally, we also organized a special session at the last SEG on Compressive Sensing, which gave rise to extra costs incurred by the co-PI's. Fourth, looking back at the original budget justification, we see that we seriously under estimated the cost of lodging, food, and conference fees. To give an example, we have not been able to find appropriate affordable lodging in the US and in Europe for $300 we mention in the grant. Fifth, conference fees have increased significantly. For instance, the registration fee for the EAGE is over $600 and $700 for the SSP meeting as opposed to the budgeted $480. While this does not affect the students, these fees apply to the PI's, PDF's, and RA's.

To mitigate the impact of these increased costs, we have applied widely to travel grants from professional organizations and within the University itself. We are pleased to inform you that we successfully secured roughly $10k. While this alliviated some of the current pressures, this is not a permanent solution and we hope to come to an arrangement how to accommodate these extra costs for the remainder of the grant.

Dissemination

Here, we went slightly over again due to increased costs of our Consortium meetings, which have been very well attended. While the industry affiliates cover their own travel and lodging costs, we cover costs for the facility, rental of LCD projection, audio, webcast equipment, and catering. This year we also paid for a group dinner to facilitate discussions between our group and the sponsors. We find that this sort of event give the companies an informal opportunity to provide feedback to our research team.To limit the extra costs of this event, we will seek sponsorship from one of the consortium members.