**Herrmann - CRDPJ 375142 - 08**

**Collaborative Research and Development (CRD) Grants Progress Report**

**Due Date: (May 1, 2013)**
**Covers the Period: (May 1, 2012 to April 30, 2013)**

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

__X__ **Yes**
____ **No** (please make the necessary corrections)

Dr. F.J. Herrmann
Dept. of Earth and Ocean Sciences
University of British Columbia
2207 Main Mall
VANCOUVER BC V6T 1Z4

Tel.: (604) 822-8628
E-mail Address: fherrmann@eos.ubc.ca

**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):**
E.Y. Haber, British Columbia
A.M. Powell, Vanderbilt University
J.V. Burke, University of Washington
C.C. Stolk, University of Twente
E. Verschuur, Delft University of Technology
Ben Recht, University of Wisconsin, Madison

## Supporting Organization(s):

S. Kaplan, Chevron Canada Resources Ltd
Z. Yu, British Petroleum Oil
C. Jones, BG Group (Canada)
E. Keskula, ConocoPhillips Canada Resources Corp.
D. Nichols, Schlumberger Canada Limited
B.J. VerWest, CGG (CAN)
C.E. Theodoro, Petrobras
S. Jaffer, Total
S. Brandsberg-dahl, Petroleum Geo-Services

## 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.

**Executive summary.** *As we enter the second half of the DNOISE II project, we are happy to report that we have made significant progress on several fronts. Firstly, our work on seismic data acquisition with compressive sensing is becoming widely recognized, reflected in adaptations of this technology by industry and in this year's SEG Karcher award, which went to Gilles Hennenfent, who was one of the researchers who started working in this area in our group. As this report shows, we continued to make progress on this topic with numerous presentations, publications, and software releases. Secondly, our work on large-scale optimization is also widely adapted and instrumental to the different research areas on the grant. In particular, we are excited about new directions that go beyond sparsity promotion and which allow us to exploit other types of structure within the data, such as low-rank. Over the near future, we expect to see a body of new research based on these findings touching acquisition as well as the wave-equation based inversion aspects of our research program. Thirdly, we are also very happy to report that we continued to make substantial progress in wave-equation base inversion. In particular, we would like to mention successes in the areas of acceleration of sparsity-promoting imaging with source estimation and multiples and in theoretical as well as practical aspects of full-waveform inversion. We derived a highly practical and economic formulation of 3-D FWI and we also came up with a complete new formulation of FWI, which mitigates issues related to cycle skipping. Finally, we made a lot of progress applying our algorithm to industrial datasets, which has* *been well received by industry. Our findings show that FWI is still an immature technology calling for more theoretical input and for the development of practical workflows. Finally, we are happy to report that we have been joined by several new companies, namely, ION Geophysical, CGG, and Woodside.*

*At this midpoint of the Grant, we are also happy to report that we are well on schedule to meet the milestones included in the original proposal. Given our wide range of expertise and our plans to replace our compute cluster, we continue to be in an excellent position to make fundamental contributions to the fields of seismic data acquisition, processing, and wave-equation based inversion.*

*In the section below, we give a detailed overview of the research and publication activities of the different members of the group and how these relate to the objectives of the grant, to industrial uptake, and to outreach. We refer to the publication section for a complete list of our presentations, conference proceedings, and journal publications. We also refer to our mindmap, which clearly establishes connections between the different research topics we have embarked upon as part of the DNOISE project.*

**Compressive acquisition and sparse recovery**

**Objectives**: *Design and implementation of 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, now at Mitsubishi Electric Research Laboratories, Mass., USA) on the development of new marine-acquisition schemes that are based on compressive sensing. This work was presented at our Spring and Fall consortium meetings and at the 2012 EAGE in Copenhagen by **Haneet** in the talk entitled "Only dither: efficient simultaneous marine acquisition" and by **Professor Felix J. Herrmann** (PI) in the talk "Compressive sensing in marine acquisition and beyond" at the EAGE Workshop: "Simultaneous Source Methods for Seismic Data". **Haneet** demonstrated in her talk that high-quality seismic data volumes can be recovered from marine acquisition where the average intershot time is reduced significantly. While this reduction leads to overlapping shots, the random-time dithering, in conjunction with the shot separation by curvelet-domain sparsity promotion, allows us to recover high quality data volumes. The paper "Simultaneous-source marine acquisition with compressive sampling matrices" on this topic has appeared in Geophysical Prospecting. In this journal publication, we provide deeper theoretical insights that explain the peformance of simultaneous marine 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. In her latest abstract for the EAGE, **Haneet** discusses connections between random time dithering and jittered sampling in space in her paper entitled "Ocean bottom seismic acquisition via jittered sampling", which also has been released in a software package to our sponsors. Former PDF **Reza Shahidi** (now at Memorial University) finalized his work in our group on jitter sampling entitled "Application of randomized sampling schemes to curvelet-based sparsity-promoting seismic data recovery", which will appear in Geophysical Prospecting. Finally, **James Johnson** (MSc student) finished his master's with his thesis "Seismic wavefield reconstruction using reciprocity". In this work, **James** incorporates reciprocity in curvelet-domain recovery by introducing projections on symmetric matrices in sparsity-promoting one-norm minimization.

**Felix Oghenokohwo** ($2^{nd}$ year PhD student) has been working on how our randomized sampling techniques could lead to new insights in 4-D acquisition. The premise of compressive sensing is that one potentially does not have to worry about exactly reproducing the acquisition as long as the randomized acquisition is carried our with the same avarage sampling density. **Felix** presented early work on this at this year's Canadian GeoConvention (CSEG) in a presentation entitled "Assessing the need for repeatability in acquisition of time-lapse data".

**Ozgur Yilmaz** and **Hassan Mansour** 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 appear in GEOPHYSICS in "Improved wavefield reconstruction from randomized sampling via weighted one-norm minimization" by **Hassan Mansour**, **Felix J. Herrmann**, and **Ozgur Yilmaz**. **Ozgur Yilmaz**, **Hassan Mansour**, and **Navid Ghadermarzy** ($2^{nd}$ year MSc and soon to become PhD student) have 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 **Navid's** MSc Thesis (to be completed by August 2013) and also in "Sparse recovery with partial support information via non-convex optimization", a journal paper that we plan to submit this summer. In addition, **Navid** recently worked on sparse recovery using "approximate message passing algorithms" and

devised a way of incorporating prior information to these algorithms (which are in certain cases significantly faster and more accurate than other methods). This work will be presented in Navid's thesis and also will be submitted to a conference for publication as a conference proceedings paper.
**Ozgur Yilmaz** and **Hassan Mansour** worked on generalizing the Kaczmarz algorithm, a classical row-action method to solve overdetermined linear systems. Specifically they considered overdetermined systems with a sparse solution. In this case, they devised a Kaczmarz-type algorithm called "Sparse Randomized Kaczmarz Algorithm" that solves such systems in significantly fewer iterations as compared with the classical randomized Kaczmarz method. This algorithm is presented in "A fast randomized Kaczmarz algorithm for sparse solutions of consistent linear systems", which will soon be submitted as a journal paper.

**Tim Lin** (PhD student) worked on applying recent alternatives to transform-domain sparsity promotion. He presented this work at our Consortium meeting and is schedule to give the following presentation "Cosparse seismic data interpolation" at the 2013 EAGE in London. Together with **Ozgur Yilmaz**, **Brock Hargreaves** (2nd year MSc student) also worked on transform-domain sparsity promotion. Specifically, he investigated ways of incorporating prior information to recovery algorithms based on promoting "analysis-sparsity". He devised an original algorithm that in certain cases outperforms existing methods. This work will be submitted to for publication as a conference proceedings paper. **Brock** will work on this topic during his internship at Total in Houston.

We also extended our work towards recovery algorithms that exploit low-rank structure. This work, in collaboration with **Sasha Aravkin** (PDF, now at IBM-Watson Research, NY, USA) and **Ben Recht** (professor at the University of Wisconsin at Madison), has resulted in "Seismic data interpolation and denoising using SVD-free low-rank matrix factorization", which will be presented at the EAGE by **Rajiv Kumar** (2nd year PhD student), and has been submitted in the following abstract to the 2013 SEG: "Reconstruction of seismic wavefields via low-rank matrix factorization in the hierarchical-separable matrix representation". In the latter, we introduce hierarchical separable matrices in combination with reordening of the data in the midpoint-offset domain as a "transform" to increase the decay of the singular values and to increase the incoherence of the sampling. The latter makes the recovery from missing shots or receivers conducive to recovery by SVD-free nuclear-norm minimization. We also submitted the paper "A robust SVD-free approach to matrix completion, with applications to interpolation of large scale data", with applications to machine learning (i.e., the Netflix problem) and to seismic missing-trace interpolation, for publication in the mathematical literature. This paper introduces a large-scale SVD-free optimization framework that is robust w.r.t. outliers, and that uses information on the "support". These extensions are new and the latter corresponds to a generalization of our work on weighted one-norm minimization to matrix completion problems. We extended the SPGl1 framework, by **Michael Friedlander** and **Ewout van den Berg** (former PhD student, now at IBM Research), to incorporate matrix completion problems and robust norms. We released this software to our sponsors. We are very excited about this work because it paves the way to solving extremely large seismic-data recovery problems (including the recovery of 3D seismic data volumes) using the latest developments from convex optimization and machine learning. Aside from working on matrix-completion problems relevant to missing-trace interpolation, we also started a research program extending these ideas to tensor completion problems. In this way, we hope to truly exploit the multi-dimensional structure of seismic data. **Curt da Silva** (1$^{nd}$ year PhD student enrolled from our MSc program) has made significant progress on this topic using and extending recent (theoretical) work on hiearchical Tucker decompositions. **Curt** is scheduled to present this work entitled "Hierarchical Tucker Tensor Optimization - Applications to 4D Seismic Data Interpolation" at the 2013 EAGE and shortly thereafter at the prestigious bi-annual SAMPTA meeting in a talk entitled "Hierarchical Tucker Tensor Optimization - Applications to Tensor Completion". **Curt's** contribution has been to extend the current theoretical framework for these decompositions so that he is able to solve tensor completion (i.e., missing-trace recovery problems on four dimensional frequenct slices) problems using large-scale optimization techniques, which makes his approach ameneable to seismic applications. Because there are indications that this work removes some of the impediments related to the "curse of dimensionality", we plan to use these techniques in the future to compute exended image volumes. Aside from applying matrix and tensor optimization problems to the recovery of incomplete data, we plan to use matrix-type norms as penalty functions ifull-waveform inversion. This application is suported by recent theoretical developments in this field.

**Professor Michael Friedlander** (co-PI) and **Sasha Aravkin**, in joint work with **professor James Burke** (Math department University of Washington) are working on a matrix-free approach to general quadratic and semidefinite programming. Because all of the sparse-recovery programs used in signal recovery can be formulated as as one of these types (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 the difficult nonsmooth sparisty constraint set (e.g., the 1- or nuclear-norms) into a differentiable object. This approach is mainly a technology of *reformulation*, and allows existing state-of-the-art nonlinear solvers to be used. The theoretical results of this approach are described in "Variational properties of value functions, which will appear in the SIAM J. on Optimization.

Although this last reformulation approach provides a way for handling the nonsmoothness inherent in sparse optimization, we continue to face the challenge of the scale of our optimization problems, which are tied to the ambient dimension of the signal of interest. To that end, **Michael Friedlander** and **Ives Macedo** (PhD student) are designing a dual approach that works in a space “dual” to the original one, with the benefit that this dual problem has only as many variables as *measurements*, which is logorithmic in the ambient dimension. The smoothing approach described above can now be used on this problem, or a nonsmooth large-scale bundle method can be applied. Results for this framework are presented at an invited talk at the Annual Meeting of the Canadian Operations Research Society. **Nathan Krislock** (PDF) is working on the extensions of this approach to nuclear-norm regularization.

To keep the momentum in compressive sensing and large-scale optimization, we have hired **Oscar Lopez** (PhD student), **Rongrong Wang** (PDF, PhD from University of Maryland), and **Ernie Esser** (PDF at UCLA). We also hope to hire **Ting Kei Pong** (PDF, PhD at University of Waterloo).

**Industry uptake and outreach.** We are also happy to report that there is considerable uptake in industry regarding randomized acquisition and sparse/low-rank recovery. For instance, WesternGeco continues to use our ideas to develop their coil sampling technology and they are working with us on the recovery. Schlumberger, the parent company of WesternGeco, also organized a special one-day seminar on compressive sensing in Cambridge Mass., which was attended by their CTO and top researchers, and by leading researchers in the fields of compressive sensing, convex optimization, optics, medical imaging, and exploration seismology. This by-invitation-only meeting was attended by **Michael Friedlander**, **Felix J. Herrmann**, our alumnus **Gilles Hennenfent** (Chevron), and one of our sponsors Chuck Mosher (ConocoPhillips). We are also aware that Conocophilips are conducting extensive field trials with randomized sampling and sparse recovery on which they reported extensively at the EAGE and SEG. Finally, there is a lot of interest from Fugro, a company recently purchased by CGG, who have now joined the SINBAD Consortium. 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. This research was featured in the recent article “Seismic advances”, which appeared in *International Innovation*. This journal reaches a wide audience acoss many fields in science & enginerring. **Felix J. Herrmann** also presented a plenary lecture entitled “Randomized sampling in exploration seismology” at the workshop Big Learning: Algorithms, Systems, and Tools as part of the annual meeting of the Neural Information Processing Systems (NIPS). NIPS is one of the largest machine learning conferences frequented by researchers from academia and from "big data" industry.

In summary, we have made excellent progress towards the objectives and goals we set in the grant and there is a considerable tangible uptake of our technology. Over the last year, we have been able to shift our attention to 3D seismic. While our parallel algorithms are all capable of recovering 3D seismic data volumes, having access to large-scale computing has now become the main impediment. For a discussion on our computer needs, please refer to section HPC at the end of this section of the report, where we provide a rational for the replacement of our compute system.

**Outcomes**. *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** has continuerd to work on this topic and his activities include (i) implementation of EPSI on 3D sail lines during an internship at Chevron; (ii) dealing with the missing near offset problem. Jointly with the **PI**, **Tim** also finished the journal publication "Robust estimation of primaries by sparse inversion via one-norm minimization", which will appear in GEOPHYSICS. 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** proposed the use of low-rank approximations based on randomized singular-value decompositions in combination with hierarchical matrix representations. These techniques allow us to reduce the memory use and matrix-matrix multiplications costs. This work, entitled "Dimensionality-reduced estimation of primaries by sparse inversion", will appear in Geophysical Prospecting. We are excited about this work because it is tightly connected to our more recent matrix factorization work. While these techniqued drastically reduce the computational needs of REPSI, extending these ideas to 3D seismic has been challenging because of lack of adequate computational resources.

**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 SEG abstract "Interferometric redatuming with simultaneous and missing sources using sparsity promotion in the curvelet domain", where sparsity-promoting techniques are used to stably compute decompostions of waves into up- and downgoing components. We extended this work to include imaging, which appeared as the express letter "Interferometric redatuming by sparse inversion", which appeared in Geophysical Journal International. While we are well on schedule on this topic, we have plans to extend this work to 3D and to a continuous monitoring system for 4D seismic or for hydraulic fractoring. While we are in an excellent position to make fundamental breakthroughs applying this technology to "small" 3-D field data, our current computational resources are inadequate to embark on this crucial step. See section **HPC needs** at the end of this section, for a detailed discussion on our computational needs for this application.

**Industry uptake and outreach.** The industry has shown a keen interest in these topics and especially in REPSI. While we made good progress to implement 2-D REPSI in a quasi 3-D environment, the real challenge will be to implement this algorithm on 3-D seismic, which is extremely challenging because of the high computational demands and "everything talks to everything" type of parallellism that is required. We are exploring possibilities to work with industry to make this happen but we are somewhat hampered by lack of access to a large-scale machine to prototype our algorithms at UBC.

**Outcomes**. *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 (with 1 billion parameters) has been extremely challenging.This is especially true in the context of iterative wave-equationn based 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, soon at CWI, the Netherlands) has implemented an object-oriented parallel-simulation framework in Matlab, which he described in the technical report "A parallel matrix-free framework for frequency-domain seismic modelling, imaging and inversion in Matlab". Software for the 3-D extension of this work were recently released as part of 3D acoustic full-waveform inversion. Aside from providing a 2- and 3-D simulators for the full wavefield, our environment also includes a matrix-free implementation for the linearized Born-scattering operator. As we further explain under the section in FWI, our time-harmonic formulation of forward modeling is very suitable for FWI because it does not rely in delicate parameter settings and offers maximal control over the accuracy by limiting the number of iterations. As we show below, this leads to a computational efficient formulation of 3-D FWI. **Tristan** extended this framework to include density variations, **Xiang Li** (PhD student) included anisotropy while **Bas Peters** (1st year PhD student) has made good progress to extend our forward modelling capability to include full elasticity (with all 21 coefficients). While our versatile preconditioner, based on Kaczmarz row-projections, shows indications to deliver on its premise that this preconditioner should work for any wave equation irrespecitve the physics (acoustic, varying density, anisotropy, etc.), the size of the systems in 3-D rapidly exceeds the capability of the nodes of our compute cluster. To give an example, due to the exisitence of low-shear velocity zones, the computational needs of elastic FWI easily grows a thousand fold. To address some of these issues, we purchased a Maxeler Inc. workstation with 100 GB of memory and with streaming FPGAs. This workstation allowed us to run small 3D acoustic FWI (see details below) and to start working on a native implementation of our row-based preconditioner that employ capabilities of the streaming FPGA's. Aside from analyzing the performance of row-based Kaczmarz on conventional hardware, summarized in "Software acceleration of CARP, an iterative linear solver and preconditioner" that will be presented at the HPCS 2013 in Toronto and hopefully at the SEG, **Art Petrenko** (MSc student) has embarked on this ambitious project. Even though our preconditioner is extremely simple, porting this code to a streaming FPGA proves to be extremely challenging since it involves a completely different programming paradigm that requires a lot of domain-specific knowledge. To overcome these challenges, we have actively been seeking collaborations with research groups in Electrical and Computer Engineering at UBC. **Art** has also been involved in the design and implementation of a benchmark test suite to evaluate different types of hardware as part of the Brazil initiative (see below).

Aside from our efforts to evaluate exotic new types of hardware, we also put together a matlab-license free version of modeling and FWI (see discussion under FWI and under Parallel development environment). 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 continued to be 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). We also plan to conduct an exhaustive study to compare the pros and cons of time-stepping or time-harmonic approaches in the context of reverse-time migration and FWI. Because FWI on field data often relies on coordinated time-domain manupulations of the input and simulated data, we will also investigate how techniques from compressive sensing can be employed to implement these techniques for time-harmonic solvers.

In summary, we have met and even exceeded the expectations of the grant. However, as we mentioned before, lack of access to adequate computational resources to extend and test to our formulation to 3D now forms a major impediment. Finally, we have started to extend the Kaczmarz preconditioner towards the inversion of the data-augmented system, consisting of the Helmholtz equation and the picking operator, that appears in our new penalty formulation of wave-equation based inversion (see below). **Sebastien Pacteau** ($1^{st}$ year PHD student) and **Bas Peters** ($1^{st}$ year PhD student) are investigating whether techniques from *randomized* linear algebra can be used to solve this moderately overdetermined but possibly inconsistent augmented system. To preserve momemtum on this research topic, we recruited **Rafael Lago** (PDF, PhD from CERFACS Toulouse), who is an expert on indirect large-scale Helmholtz solvers with multiple right-hand-sides.

**Industry uptake and outreach.** At this time, most companies use time-stepping wave simulators for their imaging and FWI needs while we prefer to work with time-harmonic approaches. While timestepping approaches may seem more natural and faster, they are much more challenging when one wants to implement proper Jacobians that pass the adjoint and gradient tests—a preriquisite for iterative (linearized) wave-equation based inversion. As shown by **Tristan** in "A parallel matrix-free framework for frequency-domain seismic modelling, imaging and inversion in Matlab", erroneous implementations can lead to serious errors in optimization-driven inversions. **Tristan** presented this work at a high-performance computing (HPC) meeting in Houstin that was mainly organized for the oil & gas industry, which is seeing an enormous resurgence in HPC activity mainly driven by developments in wave-equation based inversion technology. Given these increased needs and challenges, we organized a HPC luncheon during our Fall Consortium meeting, which was attended by representatives from major HPC players. Since access to HPC and adequate formulations of (linearized) forward modeling are both essential for progress in this field, we plan to continue to show to industry how important it is to properly implement (linearized) forward modeling for any iterative wave-equation based inversion scheme. Finally, we also plan to make these codes a central part of the *I*nternational *I*nversion *I*nitiative–a long-term multi-million dollar supercomputer initiative in Brazil, which is funded from their one-percent R&D levy, in support of industrialization of FWI. We have worked extensively with BG Group (one of our sponsors) on this initiative, which also involves **professor Mike Warner** from Imperial College London. For further details, we refer to section **HPC needs** below.

**Outcomes:** *Concrete implementation of a scalable virtually parameter-free object-oriented parallel simulation framework in 2- and 3-D for time-harmonic wave equations including explicit control of simulation accuracy, matrix-free definition of the linearized Born scattering operator (the Jacobian) and its adjoint the reverse-time migration operator (adjoint of the Jacobian).*

**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:**

**Fast sparsity-promoting imaging.** In this work, we continue to use ideas from compressive sensing and approximate message passing to accelerate the convergence of sparsity-promoting imaging. This work was reported in the journal paper "Efficient least-squares imaging with sparsity promotion and compressive sensing", which appeared in Geophysical Prospecting, and which was presented at the 2012 EAGE and SEG conferences by **Xiang Li**, **Ning Tu**, and **Felix J. Herrmann** during our talks "Sparsity-promoting migration accelerated by message passing", "Imaging with multiples accelerated by message passing", and "Accelerated large-scale inversion with message passing". In retrospect, this work proved to be somewhat prophetic given its connections to the new field of *randomized* linear algebra. In particular, our approach has connections with randomized (block) Kaczmarz and new least-squares solvers such as Blendenpik and LSRN. This is exciting news because it will hopefully allow us to theoretically analyze and improve the performance of our efforts to accelerate the convergence of our sparsity-promoting solver SPGL1 by selecting new randomized supershots after each Pareto subproblem is solved. **Xiang Li** prepared software implementing sparsity-promoting reverse-time migration based on our 2D Helmholtz equation in the software release Efficient least-squares imaging with sparsity promotion and compressive sensing. While the uplift of drawing new supershots can partially be explained by stochastic optimization—e.g., the stochastic gradient method employs a similar technique—recent theoretical developments from message passing and randomized (block) Kaczmarz give a better insight into why renewals, in combination with sparsity promotion, not only improve the convergence but also lead to more robustness with respect to linearization errors in imaging, as recently reported by **Ning Tu** in the expanded abstract "Controlling linearization errors in $\ell$1 regularized inversion by rerandomization", which we hope to present at the SEG. **Ning** plans to submit a journal publication on this exciting result as well. Jointly with **Ozgur Yilmaz, Navid Ghadermarzy**, **Curt da Silva**, and **Brock Hargreaves** (2st year MSc student), we are investigating how to analyze and improve these "Kaczmarz-like" algorithms for linearized sparsity-promoting wave-equation based imaging and augmented wave-equation solves. To help continue this research direction, we recruited **Polina Zheglova** (PDF, PhD from Rensselaer now at Memorial), who has experience in geophysical imaging.

**Source estimation.** The success of wave-equation based imaging relies on knowledge of the source signature. **Sasha Aravkin** and **Tristan van Leeuwen** introduced a method to estimate the source function by using a *variable projection* method. **Ning Tu** adapted this method to sparsity-promoting wave-equation based imaging problem, which he will present at the ICASSP meeting in the presentation entitled "Sparse seismic imaging using variable projection". The outcome of this paper is exciting because it allows us to estimate the wavelet accurately as part of our formulation of sparsity-promoting reverse-time migration. **Ning** prepared the software release "Fast imaging with wavelet estimation by variable projection", which contains a concrete implementation of this approach.

**Imaging with surface-related multiples. Ning Tu** continued to make significant progress in developing imaging techniques for data with surface-related multiples. This work has been presented at several meetings (EAGE/SEG) and has been very well received. We are particularly excited about the following contributions: (i) rigorous proof of principle that shows that imaging of surface-related multiples can be accomplished by simply replacing *impulsive* sources by *areal* sources (read simulatenous sources given by the upgoing wavefield); (ii) a significant improvement in the computational efficiency since replacing these sources allows us to have the wave-equation solver carry out the expensive multi-dimensional convolutions implicitely; (iii) our abillity to clearly show the limitations of methods to mitigate the effects of surface-related multiples based on deconvolutional imaging conditions. These contributions were presented at the EAGE in the presentation "Migration with surface-related multiples from incomplete seismic data", at the SEG "Imaging with multiples accelerated by message passing", and **Ning Tu** also hopes to present Limitations of the deconvolutional imaging condition for two-way propagators at the SEG this Fall. **Ning Tu** is about to finalize the manuscript "Fast imaging with surface-related multiples" and also plans to write up his other contributions as journal publications.

**Migration with extended image volumes. Tristan van Leeuwen** (PDF) continued to work on efficient computations of full-subsurface offset image volumes for the purpose of migration-velocity analyses and linearized amplitude-versus-angle inversion on which he reported at several conferences. See e.g., "Wave-equation extended images: computation and velocity continuation", presented at the 2012 EAGE. While our ability to form matrix-free actions of extended image volumes is exiting, if it were not for the fact that our approach reduces the required computional resources by orders of magnitude, it has been challenging to turn this technology into tangible applications. Fortunately, we made a lot progress on this topic recently resulting in the extended abstract "AVA analysis and geological dip estimation via two-way wave-equation based extended images", which **Rajiv Kumar** hopes to present at the 2013 SEG. As far as we know, this paper is the first attempt to create true two-way wave-equation image volumes and to use these to construct amplitude-versus-ray-parameter panels that are corrected for the local geological dip. **Tristan** also finalized a first implementation of migration-velocity analysis based on these extended image volumes in combination with a commutation relation. Again, as far as we know this is the first example of automatic migration-velocity analysis, based on two-way full subsurface offset image volumes. **Tristan** is about to finalize the draft "Extended images in action" to be submitted as a journal publication.

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

**Nonlinear wave-equation based inversion:**

**FWI with phase encoding and stochastic optimization.** Our former graduate student and postdoc **Peyman Moghaddam** (now at TGS in Houston) published work he did in our group entitled "New Optimization Approach For Source Encoding Full-Waveform Inversion", which appeared in GEOPHYSICS.

**Frugal full-waveform inversion.** To overcome overwhelming data volumes and sensitivities related to errors in capturing the correct wave physics, **Michael Friedlander**, **Sasha Aravkin** (PDF), **Tristan van Leeuwen** (PDF), and **Felix J. Herrmann** developed a theoretical framework that allowed us to guarantee convergence by controlling subsampling related errors in the misfit and gradient calculations. In this work, we show that convergence is guaranteed as long as we grow the sample size in such a way that its error decays commenserate the convergence rate of theoptimization. We reported our findings in a number of

EAGE/SEG/ICASSP/SIAM abstracts and in the following papers: "Robust inversion, dimensionality reduction, and randomized sampling", which appeared in Mathematical Programming, and has been presented as a semi-plenary lecture at the Inter. Symp. on Math. Prog. in Berlin, and in "Fast waveform inversion without source encoding", which will appear in Geophysical Prospecting. The first of the two papers lays out the theoretical framework; the second paper addresses the issue that source-encoding techniques rely on fully-sampled data, which excludes marine acquisition where the receivers change for each source. **Michael Friedlander** and **Gabriel Goh** (2nd-year PhD student) recently refined these theoretical results by introducing probabilistic tail bounds in their paper "Tail bounds for stochastic approximation", which has been sent for review. This work gives a solid theoretical foundation that guarantees the success of stochastic-approximation methods with "overwhelming" probability; this approach applies to any optimization problems where the objective is given by a sum that can me approximated by a sample mean. Translation of these theoretical results to a practical algorithm has been challenging since the constants appearing in the expressions for the convergence are generally not known beforehand. To overcome these practical challenges, **Tristan van Leeuwen** and **Felix J. Herrmann** came up with an heuristic formulation of FWI where the misfit and gradient calculations only call for additional data and wave-simulation accuracy when needed by the optimization–i.e., then FWI makes sufficient progress. This leads to significant savings, especially in the beginning of the optimization or during the solution of ill-posed problems, where progress towards the solution is only made slowly. This work was presented at the SEG 2013 Workshop: "Full Waveform Inversion: From Near Surface to Deep" and has been submitted for publication in the paper "3-D frequency-domain seismic inversion with controlled sloppyness". We are also about to finalize "Frugal full-waveform inversion: from theory to a practical algorithm" intended for the a broad non-technical geophysical audience. Our frugal approach is based on 3-D simulations with our indirect time-harmonic solver preconditioned with Kaczmarz row projections. The software "3-D acoustic full-waveform inversion" was part of our most recent software release. We are excited about this work because it allows us to run 3D acoustic FWI for a small problem on a relatively "small" 100 GB workstation. While these sort of cost savings are significant, they are not enough to make 3-D FWI feasible on exisiting hardware available within academia for the following reasons: (i) the presented acoustic only example is very small 5 X 5 X 2 km and therefore unrealistic and still it needs losts memory not available on current cluster configurations available to us; (ii) application to field data need, except for the need to run relatievly large models, the inclusion of at least some form of anisotropy, which doubles the computational and storage needs; and (iii) even with our data– and model-side paralellization, we would immediately overwhelm academic HPC resources, including Westrgrid, that are available to us. Please

refer to section **HPC needs** for a more detailed discussion on this topic.
**Robust FWI.** Because *"getting the wave physics right"* really is essentially an oxymoron, FWI requires a formulation that is less sensitive to noise, outliers in the data, and scaling by the source function. While we made good progress in the formulation of FWI using penalty functionals that derive from the Student's t distribution, unmodelled, e.g., elastic, phases are not spiky and coherent with modelled (acoustic) phases rendering robust penalty functionals ineffective. By formulating the misfit in the Fourier domain, where elastic phases can be expected to relatively sparse, we have been able to invert elastic data with an acoustic code. We will present this work entitled: "In which domain should we measure the misfit for robust full waveform inversion?" at the next EAGE. Because data-side robust penalty formulations are not the only alternative to deal with unmodelled phases, **Xiang Li** (PhD student) and **Anais Tamalet** (long-term visitor from Total) wrote the extended abstract "Optimization driven model-space versus data-space approaches to invert elastic data with the acoustic wave equation, which we hope to present at the next SEG. In this work, we compare model-space curvelet-domain one-norm regularization with Fourier-domain student's t.

**FWI with the penalty method.** While considerable progress has been made in the development and application of wave-equation based inversion technology, demands for computational resources and sensitivity to starting models remain major challenges. To overcome these challenges **Tristan van Leeuwen** and **Felix J. Herrmann** derived a completely new adjoint-free penalty formulation of FWI that shares the computational advantages of the reduced unconstrained adjoint-state formulation, where the contstraints are eliminated by explicitely solving the forward and adjoint wave equations, and the "all-at-once" constrained formulation, which involves iterations of the sparse KKT system. While the reduced system has the advantage that it has limited memory requirements, it involves dense matrices (the Jacobian and (Gauss-Newton) Hessian are both dense) and a highly non-linear releationship between the unknown medium properties and the data. The "all-at-once" method, on the other hand, is much more mundane and is bi-linear in the source and medium properties (for the Helmholtz equation at least). Moreover, solutions of this approach involve iterations on sparse systems. More importantly, since the "all-at-once" method optimizes over updates of the forward, adjoint wavefields, and medium properties, it entails more degrees of freedom, allowing the optimization to sidestep local minima. Unfortunately, the "all-at-once" method is inpractical because it needs to store both wavefields for all sources, which is computationally infeasible. By replacing the PDE-constraint with a penalty, we overcome this problem by solving a data-augmented wave equation, consisting of a wave-equation block—e.g., the Helmholtz equation on the left and the source on the right-hand-side, and a data block consisting of a restriction operator on the left, restricting the solution to the receiver positions, and observed data on the right. By giving the PDE block infinite weight, we arrive at the constraint formulation. Because we solve the augmented system, we share the advantage of the reduced formulation, which allows us to cummulate gradients and Gauss-Newton Hessians amongst the source experiments, while retaining the enlarged search space of the "all-at-once" method. Aside from the computational benefit of ommitting the need of explicitely solving for the adjoint wavefield, the penalty method has the additional advantage of being less sensitive to the accuracy of the starting model. The latter feature, which we were able to confirm on stylized synthetic examples, is highly desired by FWI. We summarized our results in the broad audience paper "Mitigating local minima in full-waveform inversion by expanding the search space" with technical details appearing in the more technical paper "A penalty method for PDE-constrained optimization". We are extremely excited about this new—and as far as we know unique—formulation of FWI, which does not depend on the specifics of the PDE, which is confirmed by early results with this metnod on an EM and optical problem. Finally, to ensure continuety on this topic, we recruited PDF **Ernie Esser**, who is an expert on augmented Lagrangian methods, which are connected to the penalty method. We also recruited PDF **Rafael Lago**, who has experience in FWI.

**Industrial uptake and outreach.** We have made considerable progress on various fronts of wave-equation based inversion and these developments have not gone unnoticed by industry and have resulted in numerous invitations and other signs of direct impact and uptake. For instance, **Sasha** and **Tristan** visited Total SA in Pau to help them implement our batching robust methodology resulting in a joint abstract at the EAGE. **Anais Tamalet**, long-term visitor from Total, has been working with us on various aspects of FWI, which is leading to a rapid uptake of our algorithms in her organization. Through the grapevine, we are also aware that Schlumberger/WesternGeco and PGS have implemented our source estimation and batching techniques in their FWI. **Tristan** visited BGP, PGS, BP, Schlumberger and ConocoPhillips, in Houston, Feb 25 - March 1, 2013, and **Xiang Li** visited BGP and CGGVeritas to discuss our results on the Chevron GOM dataset, obtained with our modified Gauss-Newton method. We also understand that there is also a keen interest for our sparsity-promoting migration with source encoding from several sponsors. Finally, BG group has been working extensively with our and **professor Mike Warner's** group from Emperial College to start a FWI initiative in Brazil aimed at industrialization of FWI technology. See details below.

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

**Case studies: Wave-equation based inversion on industrial data**

Over the last year, we have worked extensively on case studies provided to us by industry. We did this work with **Brendan Smithyman** (a Phd student of **Professor Ron Clowes**), **professor Andrew Calvert** (SFU), and **professor Eric Takam Takougang** (University of Western Australia) and several team members from our group.

**Gulf of Mexico Data Set.** Over the summer we worked on the Chevron GOM Full Waveform Inversion Synthetic, a dataset designed to challenge FWI by being extremely complex and by lacking long offsets and low frequencies. We presented our results at the SEG Post-Convention workshop during the talk "FWI from the West Coasts: lessons learned from "Gulf of Mexico Imaging Challenges: What Can Full Waveform Inversion Achieve?". To meet the challenges of this dataset, we developed the following workflow: (i) starting model building by first-break traveltime tomography by picking 600k traces; (ii) curvelet-domain denoising to improve the signal quality at the low-end of the spectrum; (iii) FWI with nonlinear smoothing of the model updates using our modified Gauss-Newton method. From our expererience working with this complicated salt-model dataset, we learned that (i) curvelet-domain denoising of the data was essential; (ii) data-space regularization via offset and Laplace parameter continuation were insufficient to deal with strong elastic phases in the data. (iii) model-space curvelet-domain sparsity promotion of our modified Gauss-Newton method was able to prevent FWI from getting stuck in local minima as was the case with our l-BFGS quasi-Newton and Pratt's nonlinear conjugate gradient method; (iv) this somewhat large 2-D synthetic already proves to be almost too large for our compute cluster to handle.

Of the academic contributions to the Gulf Of Mexico Challenge, which nearly all consisted of hands-off FWI—as opposed to extremly hands-on conventional velocity building workflows utilized by industry—our group did reasonably well certainly compared to Pratt and Chin's group who also presented. Other academic groups made attempts but gave up. The best non-anonymous industrial contribution came from CGGVeritas, who were able, after months of highly interactive reflection tomography, interactive gradient updates, and salt floading, to produce a reasonable image of the top and medium depth (about 4km) salt. Since then we improved our results and we are getting closer to their results by following an automatic non-interactive, and therefore fast, procedure. While the initial results are encouraging, there is lots of room for improvement including: (i) obtaining better starting models or less sensitivity to the quality of the initial model. While first-break traveltime inversion gave us a reasonable starting model for shallow depths, it failed to provide sufficient accurate velocity information to recover the long-wavelength components of the salt. Because the offsets are only 20 km and there is no reasonable data quality below 2 Hz, FWI is not able to recover the bottom of the salt; (ii) incorporation of more wave physics to explain the elastic phases in the data; (iii) having access to computational resourses to test different starting models and to explore various parameter settings.

**North Sea Data Set.** More recently, we have also started work on a 2-D line extracted from the Machar field data set by BP. So far, we have been able to create an image with our reverse-time migration code using their velocity model. We also have early results of our curvelet-domain sparsity-promoting migration, which are encouraging, but which reveal certain imaging problems in the target zone near the salt dome. We also plan to test (i) our REPSI and migration with surface-related multiples approaches on this ocean-bottom dataset. For this we need to decompose the wavefield in its up- and down-going compenents from the geo- and hydro-phone data; (ii) we plan to test our FWI code on this dataset. Since the data is anisotropic, this will be memory intensive even for this 2-D line. Finally, we also started working on inverting the 3-D BG Compass dataset with our frugal FWI technology on the new workstation.

**Industrial uptake and outreach.** Throught a concerted effort of our research team and collaborators we have been able to make good progress working on complex industrial synthetics. There has been a keen interest from our sponsors in our work on the GOM dataset and we are also very gratefull to BP and others to make data available to us to evaluate our technology. We have been invited to speak at two post-convention SEG workshops on our work on FWI. We are also excited by the interest we received from CGG for our GOM results (presented by Xiang Li during a recent visit in Houston). We plan to continue to work on new datasets, which will continue to allow us to evaluate our technology and also to raise interesting scientific questions. With proper access to computational resources and integration of seismic data processing software, we plan to continue to work on interesting case studies.

**Outcomes:** We made a good start in evaluating our FWI technology on realistic industrial data. Our experience so far showed that our FWI framework provides a solid low-handson approach to FWI yielding reproducible results. Our experience also showed that FWI is not yet a versatile technology and in need of development of robust workflows or alternative FWI formulations that are less sensitive to starting models.

**Parallel software environment**

**Objectives:** *Development and implementation of a scalable parallel interoperable development environment to test and desseminate concrete software implementations of our algorithms in 2- and 3-D to our industrial partners.*

**Parallel SPOT (pSPOT) – a linear-operator toolbox for matlab.** Over the last year, we continued to design, implement, and optimize SLIM's parallel extension of SPOT called pSPOT (available at https://github.com/slimgroup/pSPOT). This extension of SPOT, 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 continue to be able to rapidly prototype and test our algorithms. This environment also leads to code that is readable and scalable to large problem sizes. During his internship at Chevron, **Tim Lin** validated that this approach to data (see below) and operator abstractions scales to large industrial scale problems. Unfortunately, we have not been able to replicate **Tim's** work at Chevron internally since we do not have access to a large enough machine. We also worked on a seamless integration of this operator abstaction and our data container and object-oriented framework for physics-based optimization.

**Seismic data container and data handling.** One of the main challenges of seismic data processing and inversion are (i) finding the proper levels of abstractions giving access to or hiding relevant meta data and (ii) dealing with extemely large data volumes. For instance, solvers for linear problems should only care about compatability of implicit mat-vec products while code to setup Helmholtz matrices or to compute penalty functions should have awareness of the physical units and dimensions. Moreover, solvers should not have to be aware that the vector is out of core but operators that work across out of core dimensions certainly do. To start to tackle these complicated problems, we developed a seismic data container that is tighly integrated (i.e., transparent or detail hiding when appropriate) with our abstract linear operator framework pSPOT. This framework allows us to work seamlessly with very large multidimensional arrays in Matlab that are in-core or out-of-core. Our implementation allows us to extend (again through Kronecker products) pSPOT to include out-of-core dimensions, and 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. This software is made available at https://github.com/slimgroup/SeisDataContainer/. We have plans to make this data container interoperable with our physics-based optimization framework. We also are also looking into fundamental new ways of handling data by either bringing the computations to the data, as in hadoop used in "big-data" machine learning community to solve massive map-reduce problems; and (ii) new methods that feed dimensionality-reduced wave-equation inversions with data rather than responding to requests for data. With this work, we hope to jump on the wave of new developments in truly scalable "big-data" handling.

**Object-oriented framework for physics-based optimization**. We continued our work on an object-oriented parallel environment for optimization problems. Our activities focussed on (i) extension of 2-D FWI to 3-D FWI by **Tristan van Leeuwen**, entailing a significant jumb in problem size and data handeling; and (ii) development of a stand-alone virtually matlab-free data-parallel version of 3-D FWI. As before, this object-oriented framework 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 the following applications

- 2D ocean-bottom marine acquisition via jittered sampling – a new type of marine acquisition scheme including curvelet-based recovery with one-norm minimization;
- Efficient least-squares imaging with sparsity promotion and compressive sensing – fast reverse-time migration with phase encoding and curvelet-domain sparsity promotion;
- Fast imaging with wavelet estimation by variable projection – reverse-time migration with curvelet-domain sparsity promotion and source-wavelet estimation;
- Seismic trace interpolation using weighted one-norm minimization – recovery of missing traces by weighted curvelet-domain sparsity promotion
- 3D acoustic full-waveform inversion – extension of our full-waveform inversion framework to 3-D;
- Application of simultaneous seismic data interpolation and denoising

using factorization based low-rank optimization – missing-trace interpolation using low-rank matrix factrorizations and nuclear norm minimization;

Aside from these specific applications, we also worked extensively on extending the capability of our spectral-projection solver SPGl1, which now includes (i) SVD-free nuclear norm minimization; more general misfits, such as student t, (iii) weighted one norms, and (iv) variable projection, e.g., to do on-the-fly source estimation. These capabilities are used implicitly by some of the above applications, which all benefit from our abstractions that allow us to develop clean, succinct, code that includes unit testing on most levels.

During last Fall's Consortium meeting, we discussed our software approach with representatives from Mathworks, the maker of MATLAB, who sent three representatives to our meeting, and they gave us very supportive feedback, which shows that we are on the right track. We also discussed Mathworks' pricing policies for parallel matlab and they are aware of the challenges this paradigm faces to be widely adapted by industry. Mathworks license policy is perceived as prohibitively expensive and it also does not offer sufficient resilience w.r.t. failing nodes, to support scale up to industrial size problems.

To overcome our dependence on MATLAB, we have only a "limited" number of workers, we investigated alternative approaches. 3-D full-waveform we relied on Swift parallel scripting language and worked with researchers in UBC Electrical and Computer Engineering to expose this agnostic parallel capability to MATLAB. As a result, we are now able to run 3-D FWI from a single MATLAB session (if necessary this need could be removed as well), which drives the computations required for the misfit and gradient calculations by calling compiled MATLAB programs. Swift enters into the mix because it offers fault-tolerance capability needed to scale FWI to thousands of nodes without the need of having to invoke thoussands of MATLAB workers. We plan to run the first tests of this framework early this summer on the systems of "Bitbrains", a Dutch big-data IT company that has cycles to spare and is interested to learn the HPC aspects of exploration seismology. We also plan to expose this functionaliy to SPOT so we can extend this framework to FWI with Gauss-Newton approaches or to other large-scale linear problems. While this approach offers an exciting perspective of being able to run large-scale problems, this approach (i) calls for compute nodes that have lots of memory; and (ii) it does not easilly support model-space parallelism to distribute the wave simulations over multiple cores/nodes. Unfortunately, item (i) can only be pushed that far (elastic problems become simply too large) and is not very conducive to academic hardware, which generally does not have access to large amounts of fast memory. To address item (ii) we have been looking into ways to parallellized CARP-CG (our row-based preconditioner) using MPI.

**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 worked 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'ss 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). So far, we implemented a prototype for this interface, which we plan to integrate with our seismic data container.
- Design of an abstract interface, including a concrete implementation of an application interface between our object-oriented framework for physics-based optimization and other 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 included the selection of an appropriate communication protocol, which for now is the protocol of Swift. This interface is agnostic with regard to imlementation details of the forward-modeling framework. So far, we prioritized on building a standalone version of 3-D MATLAB-based FWI. Since this design shares a lot of functionality with our interface to Swift, we are confident that we can make this wave-simulator agnostic.
- 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 would expose our applications developed with pSPOT to Seispace (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. Unfortunately, we made little progress on this very technically involved project. One of the main challenges if to find programmers that have sufficient experience and understanding of geophysics and these are very difficult to come by. In addition, the call for a stand-alone version of 3D FWI took priority. While important, we plan to revisit this ambitious project when the need arises for a framework that allows for all-to-all communications such as transposes. Finally, we were not able to come to an agreement with Haliburton for license of their SeisSpace.

**Seismic data processing environment.** As our capability to process and invert seismic data is growing, we are shifting our focus towards testing our algirithms on 2- and 3-D seismic field datasets. This means that we need access to professional seismic data processing software with 3-D capabilities. WesternGeco has kindly offered the use of their Omega software as an in-kind donation, which will allow us to pre- and post-process field data. Unfortunately, our current computational resources are too limited to allow for 3-D seismic data processing. In the **HPC needs** section below, we propose a plan to purchase a new computational fascility that is able to process small 3-D via a combination of funding from NSERC, UBC, and possibly the Western Economical Diversification Fund, matching industrial cash and this and other in-kind contributions. To meet our immediate needs for seismic data processing and to gain familiarity with this complex software package, we will purchase a $13k interactive workstation.

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

**HQP-related activities.**

Aside from regular activities between students, PDFs, and their advisors, the **PI's** organize a weekly seminar (directied studies course) on topics pertinent to the grant. While the PDFs help with the week-to-week organization, the **PI's** have been responsible for selecting the topics and providing our students and PDFs context so they are able to relate the often technical topics to their research part of the DNOISE project. This course is also regularly attended by students. PDFs, and Faculty from other department including Computer Science, Mathematics, Physics, and Electrical and Computer Engineering.
To coordinate our case-studies related activities, we also have a weekly

meetings with group members and collaborators.

**HPC needs**

As we mentioned at several instances throughout this section, we arrived half-way in to the DNOISE II grant at a critical point where progress is being hampered by lack of access to computational resourses. So far, the computational intensive research as part of the DNOISE II Grant has been carried out on a nine-year old refurbished (in 2009) 288 core cluster, which is now out of warranty. While access to this machine has been instrumental to the progress we have made so far, it is now outdated and impedes our progress because it (i) does not offer sufficient cycles that 3-D and large 2-D seismic data call for, (ii) does not have sufficient memory and disk space, and (iii) it does not allow us to run a professional data-processing package to handle massive 3-D field datasets.

We have carefully evaluated different alternatives to meet our current and future demands (five-year plan) and we found that at this point the only viable option is to replace our current hardware with a new machine. We reached this decision since current shared resources, such as the ones offered by the mainly CFI-funded Compute Canada, of which Westgrid is a subsidiary, can not meet our computational demands and can not offer flexible solutions that meet our specific needs. Moreover, our demands far exceed what commerical cloud solutions, such as the amazon cloud, can offer at financially reasonable rates. Our needs include

- Large numbers of compute nodes with large amounts of memory and diskspace. Traditional HPC is not data intensive and the current shared academic facilities focus on cycles only, which makes this type of hardware unsuitable for our applications. Even if we were to distribute our problems over various nodes, our demands for memory would lead to highly inefficient, if not infeasible demands, for hardware – something that can not be accomodated within the current systems. In addition, seismic date volumes are very large, and would farily easily overwhelm IO and available diskspace of current shared systems.
- Highly interactive code development required for research and algorithm development of wave-equation based inversion, which needs reasonable turn-around times of jobs entered into the batch system. The size and number of concurrent projects of the DNOISE Grant would immediately overwhelm available shared systems and will lead to unmanagable long turn-around times.
- Testing and development of practical workflow for FWI on field data call for multiple runs with different parameter settings and on-th-fly QC.

Aside from issues with data integrety, multiple case studies even on 2-D data would easily overwhelm the current systems.

- Algorithms that involve all-to-all communications, such as Estimation of Primaries by Sparse Inversion. This type of algorithms are by far the most challenging because they involve lots of data movement, which in case of 3-D seismic lead to substantial turnaround times for even the largest compute clusters.

Industry has responded to the increased needs for data-intensive HPC by purchasing several greater-than-1 petaflop machines over the last year. FWI and other wave-equation bases inversion techniques are responsible for this resurgence in HPC needs. This resurgence is also a clear sign that industry is adapting this type of technology and they are looking to us for the next-generation of this technology. It is therefore important, we continue to have access to adequate resources.

To give our industrial partners the opportunity to give feedback to their and our current and future needs, we invited representatives from the HPC to join a luncheon at our Fall Consortium meeting in Whistler. This luncheon was attended by representatives from Cray Inc., IBM, Intel, Mathworks, and Maxeler Inc. During the meeting it became clear that (i) we are still missing software tools that allow for fast prototyping and fast uptake by industry; (ii) the Intel-processor based HPC will not provide the speeds required by visco-/poro-elastic FWI. The latter easily entails a 1000 fold increase in computational needs. Maxeler made a point that their streaming FPGA solution may offer the cycles but their programming paradigm is very challenging to say the least. As for the software tools, we are on the right track but many challenges remain.

The conclusion of this all is that we need to find alternatives to meet our HPC needs at UBC and we have undertaken the following actions

- We looked at Compute Canada and found that their resources do not meet our daily needs nor our need to run occasional large-scale jobs. Groups in the US we are competing with have access to world fastest machine in Oakridge to run their FWI code. While our dimensionality reduction techniques should not make it necessary to resort to these large machines, still Compute Canada, with its current HPC configurations, will not able to meet our needs. Unfortunately, there is a moratorium on HPC funding in Canada until Compute Canada has finalized its reorganization, which may take several years.
- We contacted representatives from the Western Economic Diversification Fund (WED) and we submitted a preliminary proposal for feedback. During our meeting with their representatives, it became clear that WED

is looking to support local companies and is reluctant to support HPC. In addition, they were in stalemate in anticipation of the BC elections. At that point, we aborted our attempts and decided to wait for better times for a possible late in the game matching from WED. Calls for funding from the WED need approval from the UBC administration. While we have support from higher up in the administration, the Department of Earth, Ocean, and Atmospheric Sciences, and the Dean of the Faculty of Science, has not been as active as the VP Research Office.

- Upon invitation by IBM Canada, we are part of the initial stages of a Canada-wide Business-lead National Network of Excelence driven by IBM with the title “Next-generation Computing”. During the organizational meeting in Toronto it became clear that there is a lot of interest and expertise on FPGA’s in Canada. Jointy with **professor John Chen,** from University of Calgary and who is active in the field reservoir engineering, we submitted a proposal for a joint HPC system. While this certainly may offer a long term solution, NCE’s are highly competitive and there will also be competition amongst the participants of this Grant if funded.
- For several years, the **PI** has been involved with BG Group and **professor Mike Warner** from Imperial College London, in a supercomputer project in Brazil funded by Brazil’s one-percent R & D levy. As part of this activity, we have started the long-term *I*nternational *I*nversion *I*nitiative, which involves a to-be-formed consortium for companies that have obligations under the one-percent levy in Brazil. The purpose of this project, that will include a $10–40 M computer, is to make FWI into a mature technology. While the long-term outlook of this project are fantastic regarding access to HPC for FWI, this project will not solve our immediate needs and will also not offer a solution to our day-to-day HPC needs. Moreover, the one-percent R & D levy allows for funding of HPC in Brazil only so this would not resolve the HPC situation at UBC. However, the high visibility of this project will likely strengthen our position to get in-kind contributions for local HPC hardware.

To address our immediate needs and to create a long-term solution to our HPC needs we propose the following:

- Designate $100k annually to our HPC needs. This will be funded from contributions from two new companies (beyond the contributions from the ten companies matched by the DNOISE II Grant), who recently signed.
- Match this new industrial funding and in-kind contributions from Western-Geco (Omega) and from the HPC vendor. This should provide sufficient funding for a local system, described below, that would fit our needs.
- Work with UBC to get additional matching. We have been working with

the UBC administration using the argument that it is in their best financial interest to offer help replacing our old cluster. Not only will this cut the power consumption considerably, and thereby providing an incentive for the administration to replace old HPC equipment, but the new system will also have a smaller environmental footprint per cycle. We are working with IBM to develop a campus wide policy and we expect good progress on this project by the end of the summer.

**Description of the proposed computational resource.** To address our needs for the duration of the DNOISE II Grant, we propose the following HPC configuration:

- **Hardware**: a 736-core cluster with 16 Giga Byte of RAM per core and about 0.5 Peta Byte disk space that reaches approximately 30 Terra FLOPS. This machine will allow us to run small 3D seismic problems. IBM, one of the anticipated vendors, has offered to donate 50 percent of the purchase price towards supporting services including software.
- **Software:** seismic processing software that allows us to pre- and postprocess 3D seismic data volumes. WesternGeco have offered a licence to their Omega processing software. This is the first time that this professional software package has been offered to an academic institution. The total commercial value for a license for our compute cluster of Omega is $6.355 M with an additional service fee of 20% per annum.

## 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.).

For participation and contribution by team members, please refer to section 1 above, and the publications section 4 below. We have had key external collaborations this year with **professor Andrew Calvert's** group at Simon Fraser University, **professor Mike Warner's** group at Imperial College London, **Professor William Symes** at Rice, and **professor Eric Takam Takougang** at University of Western Australia. Participation of company scientists is extremely extensive and is described in section 1 and in section 6.

**Changes in research team:** The DNOISE team underwent several changes this year. PDF **Sasha Aravkin** joined IBM Watson Research, NY, USA, PDF

**Hassan Mansour** joined Mitsubishu, Mass., USA, and PDF **Tristan van Leeuwen** went to the CWI, Amsterdam. To replace these PDFs, we undertook an extensive recruitment search which led to the hire of **Ernie Esser** from UCLA, **Rafael Largo** from CERFACS, **Rongrong Wang** from the University of Maryland, and **Polina Zheglova** from Memorial University. We also hired graduate students **Oscar Lopez**, **Mathias Laboutin**, and **MengMeng Yang** who will start September 1st. New PhD students Bas Peters, Sebastien Pacteau, and Zhilong Fang joined the group in September of 2012.

**Rayan Saab** (former PhD student of Yilmaz and SLIM member) will complete his tenure at Duke University as a Banting Postdoctoral Fellow in the Fall of 2013. In July Saab will start as a tenure-track assistant professor in the Mathematics Department of University of California, San Diego.

**Sasha Aravkin** (former PDF at SLIM) has started as a permanent research staff at IBM Watson Research Laboratory.

**Ewout van der Berg** (former PDF at SLIM, now at Stanford) will also start as a permanent research staff at IBM Watson Research Laboratory.

**Hassan Mansour** (former PDF at SLIM) has started as a permanent research staff at Mitsubishi Electric Research Laboratories (MERL).

**James Johnson** (MSc student) now works for Schlumberger in Calgary.

**Gilles Hennenfent** (former PhD, now at Chevron) is this year's recipient of the 2013 recipient of the J. Clarence Karcher Award, which is given in recognition of significant contributions to the science and technology of exploration geophysics by a young geophysicist.

**Peyman Moghaddam** (former PhD & PDF at SLIM) has started at TGS in Houston.

**Michael Friedlander** (co-PI) won the Canadian Association of Computer Science "Outstanding researcher prize", which is awarded nationally each year to 3 computer scientists who are within 10 years of their PhD.

Undergraduate co-op programmer **Shruti Kapoor** has continued to a placement with Honeywell, and co-op programmer **Thomas Lai** will soon take up an internship with Facebook.

## 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)**<br><br>**(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** |
|---|---|---|---|
| Shruti – Undergraduate Co-Op Student | .4 | 100% | 100% |
| Thomas – Undergraduate Co-Op Student | .75 | 100% | 100% |
| Arnold – Undergraduate Co-Op Student | .3 | 100% | 100% |
| Michelle – Undergraduate Summer Student | .3 | 100% | 100% |
| Ming – Undergraduate Summer Student | .3 | 100% | 100% |
| Lina – MSc | 3 | 100% | 100% |
| Art – MSc | 3 | 100% | 100% |
| Brock – MSc | 3 | 100% | 100% |
| Navid – MSc | 3 | 100% | 100% |
| Curt – MSc | 3 | 100% | 100% |
| Sebastien – PhD | .75 | 100% | 100% |
| Bas – PhD | .75 | 100% | 100% |
| Zhilong – PhD | .75 | 100% | 100% |
| Felix – PhD | 2 | 100% | 100% |
| Rajiv – PhD | 3 | 100% | 100% |
| Tim – PhD | 4 | 50% | 0% |
| Xiang – PhD | 3 | 100% | 10% |
| Haneet – PhD | 3 | 100% | 100% |
| Tuning – PhD | 3 | 100% | 10% |
| Gabriel – PhD | 1 | 100% | 100% |
| Ives – PhD | 2 | 100% | 20% |
| Julie – PhD | 1 | 20% | 0% |
| Anais – Visiting Industrial Intern | 2 | 100% | 0% |
| Sanyi – Visiting Research Associate | 2 | 100% | 100% |

| | | | |
|---|---|---|---|
| Hassan – PDF | 3 | 100% | 100% |
| Aleksandr – PDF | 3 | 100% | 100% |
| Tristan – PDF | 3 | 100% | 100% |
| Enrico – PDF | 3 | 20% | 20% |
| Nathan – PDF | 1 | 33% | 33% |
| Henryk – Scientific Programmer/Systems Admin | 3 | 60% | 60% |
| Harsh – Junior Programmer | .25 | 100% | 100% |
| Barbara – Scientific Programmer | .8 | .25 | 25% |
| Ian – Research Associate | 3 | 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** | **Conference Presentations/ Poster** | **Other (including Technical Reports, Non-Refereed Articles, etc.)** |
| **Accepted/Published** | 14 | 13/32 | 56 |
| **Submitted** | 5 | 9 | |

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. **M. P. Friedlander**, M. Schmidt, Hybrid deterministic-stochastic methods for data fitting. SIAM J. Scientific Computing, 34(3), 2012
2. A. Y. Aravkin, J. V. Burke, **M. P. Friedlander**. Variational properties of value functions. To appear in SIAM J. on Optimization, 2013.

3. H. Mansour, **F. J. Herrmann**, **O. Yilmaz**. Improved wavefield reconstruction from randomized sampling via weighted one-norm minimization. Accepted for publication in GEOPHYSICS, 2013.

4. T. T.Y. Lin and **F J. Herrmann**. “Robust estimation of primaries by sparse inversion via one-norm minimization”. 2012. Accepted for publication in GEOPHYSICS.

5. B. Jumah and **F. J. Herrmann**. “Dimensionality-reduced estimation of primaries by sparse inversion”. 2012. Accepted for for publication in Geophysical Prospecting.

6. P. P. Moghaddam, H. Keers, **F. J. Herrmann** and W. A. Mulder. “A new optimization approach for source-encoding full-waveform inversion. GEOPHYSIS, Vol 78, No. 3, p. R125-R132, April 2013.

7. R. Shahidi , G.Tang, J. Ma and **F. J. Herrmann**. Design of two-dimensional randomized sampling schemes for curvelet-based sparsity-promoting seismic data recovery. Accepted for publication in Geophysical Prospecting.

8. J. van der Neut and **F. J. Herrmann**. Interferometric redatuming by sparse inversion. Geophysical Journal International, Vol 192, Issue 2, p 666-670. 2012. (Express letter)

9. X. Li, A. Y. Aravkin, T. van Leeuwen and **F. J. Herrmann**. “Fast randomized full-waveform inversion with compressive sensing”. doi: 10.1190/ geo2011-0410.1. Geophysics, May 2012 v. 77no. 3 p. A13-A17.

10. **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.

11. H. Mansour, H. Wason, T. T. Y. Lin and **F. J. Herrmann**. “Randomized marine acquisition with compressive sampling matrices”. Geophysical Prospecting, 2012. Volume 60, Issue 4, pages 648–662, July 2012.

12. A. Y. Aravkin, **M. P. Friedlander**, **F. J. Herrmann** and T. van Leeuwen. “Robust inversion, dimensionality reduction, and randomized sampling”. Mathematical programming, August 2012, Volume 134, Issue 1, pp 101-125.

13. E. Haber, M. Chung and **F. J. Herrmann**. “An effective method for parameter estimation with PDE constraints with multiple right hand sides”. 2012, http://dx.doi.org/10.1137/11081126X. SIAM Journal of

Optimization, 22(3), 739–757. (19 pages).

14. T. van Leeuwen and **F. J. Herrmann**. “Fast waveform inversion without source encoding”. Geophysical Prospecting, 2012. Article first published online: 10 JUL 2012. DOI: 10.1111/j.1365-2478.2012.01096.x

**Submitted journal publications**

1. Tristan van Leeuwen and **Felix J. Herrmann**, “A penalty method for PDE-constrained optimization”. 2013.
2. Tristan van Leeuwen and **Felix J. Herrmann**, “Mitigating local minima in full-waveform inversion by expanding the search space”. 2013.
3. Tristan van Leeuwen and **Felix J. Herrmann**, “3D frequency-domain seismic inversion with controlled sloppyness ”. 2013.
4. Aleksandr Y. Aravkin, Rajiv Kumar, Hassan Mansour, Ben Recht, and **Felix J. Herrmann**, “A robust SVD-free approach to matrix completion, with applications to interpolation of large scale data” 2013.
5. Felix J. Herrmann, Andrew J. Calvert, Ian Hanlon, Mostafa Javanmehri, Rajiv Kumar, Tristan van Leeuwen, Xiang Li, Brendan Smithyman, Eric Takam Takougang, and Haneet Wason. “Frugal full-waveform inversion: from theory to a practical algorithm”, 2013

**Reviewed conference proceedings**

1. Curt Da Silva and Felix J. Herrmann, “Hierarchical Tucker Tensor Optimization - Applications to Tensor Completion”, In proceedings SAMPTA technical program, 2013.
2. Curt Da Silva, **F. J. Herrmann**. “Hierarchical Tucker Tensor Optimization - Applications to 4D Seismic Data Interpolation”, In proceedings EAGE technical program, 2013.
3. Rajiv Kumar, Aleksandr Y. Aravkin, Hassan Mansour, Ben Recht, **F. J. Herrmann**. “Seismic data interpolation and denoising using SVD-free low-rank matrix factorization”, In proceedings EAGE technical program, 2013.
4. Tim Tai-Yi Lin, **F. J. Herrmann**. “Cosparse seismic data interpolation”, In proceedings EAGE technical program, 2013.
5. Ning Tu, Aleksandr Y. Aravkin, Tristan van Leeuwen, **F. J. Herrmann**. “Fast least-squares migration with multiples and source estimation”. In proceedings EAGE technical program , 2013.
6. Tristan van Leeuwen, Aleksandr Y. Aravkin, H. Calandra, **F. J. Herrmann**. “In which domain should we measure the misfit for robust full waveform inversion?”, In proceedings EAGE technical program, 2013.
7. Haneet Wason, **F. J. Herrmann**. “Ocean bottom seismic acquisiton via jittered sampling”, In proceedings EAGE technical program, 2013.
8. **F. J. Herrmann**. “Accelerated large-scale inversion with message passing”. In proceedings SEG technical program, 2012.

9. N. Tu and **F. J. Herrmann**. "Imaging with multiples accelerated by message passing". In proceedings SEG technical program,2012.
10. J. van der Neut, **F. J. Herrmann** and K. Wapenaar. "Interferometric redatuming with simultaneous and missing sources using sparsity promotion in the curvelet domain". In proceedings SEG technical program, 2012.
11. 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". In proceedings SEG technical program, 2012.
12. X. Li and **F. J. Herrmann**. "Sparsity-promoting migration accelerated by message passing". In proceedings SEG technical program, 2012.
13. **F. J. Herrmann**. "Approximate message passing meets exploration seismology". In proceedings IEEE Statistical Signal Processing Workshop, 2012.

### Submitted conference proceedings

1. Rajiv Kumar, Tristan van Leeuwen, and **Felix J. Herrmann**, "AVA analysis and geological dip estimation via two-way wave-equation based extended images", SEG. 2013.
2. Ning Tu, Xiang Li, and **Felix J. Herrm**ann, "Controlling linearization errors in ℓ1 regularized inversion by rerandomization", SEG. 2013.
3. Ning Tu, Tristan van Leeuwen, and **Felix J. Herrmann**, "Limitations of the deconvolutional imaging condition for two-way propagators", SEG. 2013.
4. Xiang Li, Anais Tamalet, Tristan van Leeuwen, and **Felix J. Her**rmann, "Optimization driven model-space versus data-space approaches to invert elastic data with the acoustic wave equation", SEG. 2013.
5. Rajiv Kumar, Hassan Mansour, Aleksandr Y. Aravkin, and **Felix J. Herrmann**, "Reconstruction of seismic wavefields via low-rank matrix factorization in the hierarchical-separable matrix representation", SEG. 2013.
6. Art Petrenko, Tristan van Leeuwen, and **Felix J. Herrmann**, "Software acceleration of CARP, an iterative linear solver and preconditioner", SEG. 2013.
7. Curt Da Silva and **Felix J. Herrmann**, "Structured tensor missing-trace interpolation in the Hierarchical Tucker format", SEG. 2013.
8. Haneet Wason and **Felix J. Herrmann**, "Time-jittered ocean bottom seismic acquisition", SEG. 2013.
9. Felix Oghenekohwo and **Felix J. Herrmann**, "Time-lapse seismics with randomized sampling", SEG. 2013.

## Conference Presentations/Poster:

1. **F. J. Herrmann** ”Randomized sampling in Exploration Seismology”. KAUST, 2013, Saudi Arabia.
2. **F. J. Herrmann** “Recent Developments in Wave-equation Based Inversion Technology” Presented at SEG Full-Waveform Inversion Workshop, 2013, Muscat, Oman.
3. **F. J. Herrmann** “Dimensionality reduction in FWI” Presented at the SIAM Conference on Computational Science & Engineering, 2013, Boston, USA.
4. **F. J. Herrmann** “Randomized Sampling in Exploration Seismology”. Presented during the workshop: Big Learning: Algorithms, Systems, and Tools” as part of the annual meeting of the Neural Information Processing Systems Foundation, December 2012, Lake Tahoe
5. **H. Mansour** “Reweighted algorithms for sparse signal recovery”. SCAIM seminar series, October 2012.
6. **F. J. Herrmann** “Approximate message passing meets exploration seismology”. IEEE Statistical Signal Processing Workshop, August 2012, Ann Harbor, USA.
7. **N. Ghadermarzy** “Non-convex compressed sensing using partial support information”. PIMS Joint AB/BC Seminar, August 2012.
8. **H. Mansour** “Beyond l1-norm minimization for sparse signal recovery”. PIMS Joint AB/BC Seminar, August 2012.
9. **H. Mansour** “Beyond one-norm minimization for sparse signal recovery”, Statistical Signal Processing Workshop (SSP), August 2012.
10. **F. J. Herrmann** “Compressive sensing in marine acquisition and beyond”. EAGE Workshop 03 Simultaneous source methods for seismic data, June 2012, Copenhagen, Denmark.
11. **F. J. Herrmann** “FWI from the West Coasts: lessons learned from "Gulf of Mexico Imaging Challenges: What Can Full Waveform Inversion Achieve?" Presented at Post-Convention workshop at the SEG, Las Vegas, 2012.
12. **F. J. Herrmann** “Accelerated large-scale inversion with message passing”. Presented at SEG, Las Vegas, 2012.
13. **M.P. Friedlander** “Robust inversion and randomized sampling”. Semi-plenary at the Intern. Symp. on Math. Prog., Berlin, 2012.
14. **M.P. Friedlander** “Robust inversion and randomized sampling”. Invited speaker at IBM Research, New York, 2012.
15. **M.P. Friedlander** “Stochastic-approximation in imaging”. Inter. Conf. on Imaging Science, Hong Kong, 2012,.
16. **Ning Tu** “Imaging with multiples accelerated by message passing”. Presented at SEG, Las Vegas, 2012.
17. **Joost van der Neut** “Interferometric redatuming with simultaneous and missing sources using sparsity promotion in the curvelet domain”.

Presented at SEG, Las Vegas, 2012.

18. **Sasha Aravkin** "On Non-Uniqueness of the Student's t-formulation for Linear Inverse Problems". Presented at SEG, Las Vegas, 2012.
19. **Xiang Li** "Sparsity-promoting migration accelerated by message passing". Presented at SEG, Las Vegas, 2012
20. **F. J. Herrmann** "Approximate message passing meets exploration seismology". Presented at IEEE Statistical Signal Processing Workshop, Ann Harbor, 2012.
21. **F. J. Herrmann** "Compressive Sensing and Sparse Recovery in Exploration Seismology". Wisconsin Institutes for Discovery, August 2012, Madison, USA.
22. **Joost van der Neut** "Interferometric seismic imaging by sparse inversion". Presented at SIAM Meeting on Imaging Science, 2012, Philidelphia, USA.
23. **Xiang Li** "Efficient full-waveform inversion with marine acquisition geometry". Presented at CSEG, 2012.
24. **Haneet Wason**"Only dither: efficient simultaneous marine acquisition". Presented at CSEG, 2012.
25. **F. J. Herrmann** "Compressive sensing in marine acquisition and beyond". Presented at EAGE, 2012.
26. **Ning Tu** "Least-squares migration of full wavefield with source encoding". Presented at EAGE program.
27. **Curt da Silva** "Matrix Probing and Simultaneous Sources: A New Approach for Preconditioning the Hessian". Presented at EAGE, 2012.
28. **Haneet Wason** "Only dither: efficient simultaneous marine acquisition". Presented at EAGE, 2012.
29. **F. J. Herrmann**"Pass on the message: recent insights in large-scale sparse recovery". Presented at EAGE, 2012.
30. **Tristan van Leeuwen** "Preconditioning the Helmholtz equation via row-projections". Presented at EAGE, 2012.
31. **Sasha Aravkin** "Source estimation for frequency-domain FWI with robust penalties". Poster presented at EAGE, 2012.
32. **Joost van der Neut** "Up / down wavefield decomposition by sparse inversion". Presented at EAGE technical program, 2012.

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

### Presentations at Fall SINBAD/DNOISE consortium meeting

1. **Ozgur Yilmaz**. Weighted methods in sparse recovery
2. **Haneet Wason**. Ocean bottom seismic acquisition via jittered sampling
3. **Enrico Au-Yeung**. Compressed sensing, random Fourier matrix and

jittered sampling**Tim Lin**. An introduction to cosparse signal reconstruction

4. **Navid Ghadermarzy**. Non-convex compressed sensing using partial support information
5. **Hassan Mansour**. Seismic trace interpolation via sparsity promoting reweighted algorithms
6. **Brock Hargreaves**. Analysis versus synthesis in weighted sparse recovery
7. **Felix Oghenekohwo**. Assessing the need for repeatability in acquisition geometry of 4D (time lapse) seismic data
8. **Rajiv Kumar**. Seismic data interpolation using SVD-free Pareto Curve based Low-Rank Optimization
9. **Curt Da Silva**. Hierarchical Tucker Tensor optimization - applications to 4D seismic data interpolation
10. **Okan Akalin**. Large scale seismic data interpolation with matrix completion (via web-link)
11. **Tristan van Leeuwen**. 3D Frequency-domain waveform inversion using a row-projected Helmholtz solver
12. **Art Petrenko**. CARP-CG: a computational study
13. **Bas Peters**. Frequency domain 3D elastic wave propagation in general anisotropic media
14. **Michael Friedlander**. Randomized sampling: How confident are you?
15. **Sasha Aravkin**. Estimating nuisance parameters in inverse problem
16. **Anais Tamalet**. Variance parameters estimation - application to full-waveform inversion
17. **Felix J. Herrmann**. Fast sparsity-promoting imaging with message passing
18. **Xiang Li**. Fast Gauss-Newton full-waveform inversion with sparsity regularization
19. **Tristan van Leeuwen**. Yet another perspective on image volumes
20. **Lina Miao**. Acceleration of sparsity-promoting recovery and its benefits in seismic application
21. **Tim Lin**. Recent developments on the robust estimation of primaries by sparse inversion
22. **Ning Tu**. Fast imaging with multiples
23. **SINBAD Meeting Large-scale optimization (Chair: M. Friedlander)**
24. **Sasha Aravkin**. Generalized SPGL1: from theory to applications
25. **Nathan Krislock**. Wireless sensor network localization
26. **Xiang Li**. Wave-equation based inversion with joint sparsity promotion
27. **Felix J. Herrmann**. Our findings on the Chevron benchmark dataset
28. **Mike Warner**. Anisotropic 3D full-waveform inversion of the Tommeliten Alpha field

29. SLIM's perspective on HPC & big data by **Felix J. Herrmann**, **Tristan van Leeuwen**, and **Tim Lin** (SLIM)
30. High performance data-intensive computing in oil & gas: the fusion of HPC and Big Data by **Geert Wenes** (Cray Inc)
31. IBM forecast for HPC in seismic data processing by **Peter Madden** (IBM Canada)
32. The fastest way to Elastic FWI and RTM through Dataflow computing by **Bob Clapp** (Maxeler)
33. Matlab as a key development tool for research and production algorithms by **Andrew Willard & Jill Reese** (Mathworks)
34. Presentation by **Shane Story** (Intel)
35. Panel discussion moderated by **Ian Hanlon** (SLIM)
36. **Haneet Wason**. Randomized marine acquisition for ocean-bottom surveys.
37. **Felix J. Herrmann**. Latest developments in seismic-data recovery.
38. **Tristan van Leeuwen**. An overview of recent FWI developments at SLIM
39. **Sasha Aravkin**. Inverse Problems Using Student's t.
40. **Curt da Silva**. Recent Developments in Preconditioning the Wave-Equation Hessian.
41. **Felix J. Herrmann**. Supercool(ed) least-squares imaging
42. **Ning Tu**. Fast imaging with multiples

**Presentations at companies**

1. **F. J. Herrmann.** "*Compressive* sensing in Seismic *Acquisition* and *Computations*", Schlumberger Doll Research, 2012, Cambridge. Mass., USA.
2. **M.P. Friedlander.** "*Sampling approaches for data fitting*", Schlumberger Doll Research, 2012, Cambridge. Mass., USA.
3. **Tristan van Leeuwen.** "Recent advances in seismic waveform inversion; robust norms, source estimation, fast optimization and 3D frequency-domain inversion", BGP, 2013, Houston, USA.
4. **Tristan van Leeuwen.** "Recent advances in seismic waveform inversion; robust norms, source estimation, fast optimization and 3D frequency-domain inversion", PGS, 2013, Houston, USA.
5. **Tristan van Leeuwen.** "Recent advances in seismic waveform inversion; robust norms, source estimation, fast optimization and 3D frequency-domain inversion", BP, 2013, Houston, USA.
6. **Tristan van Leeuwen.** "Recent advances in seismic waveform inversion; robust norms, source estimation, fast optimization and 3D frequency-domain inversion", WesternGeco/Schlumberger, 2013, Houston, USA.
7. **Tristan van Leeuwen.** "Recent advances in seismic waveform inversion; robust norms, source estimation, fast optimization and 3D frequency-

domain inversion”, ConocoPhillips, 2013, Houston, USA.

8. **Tristan van Leeuwen.** “Preconditioning the Helmholtz equation via row-projections”, Total, 2012, Paris, France.
9. **Xiang Li.** “Sparsity promoting seismic imaging and full-waveform inversion”, BGP, 2013, Houston, USA.
10. **Xiang Li.** “Sparsity promoting seismic imaging and full-waveform inversion”, Total SA, 2013, Houston, USA.
11. **Xiang Li.** “Sparsity promoting seismic imaging and full-waveform inversion”, PGS, 2013, Houston, USA.
12. **Xiang Li.** “Sparsity promoting seismic imaging and full-waveform inversion”, CGG, 2013, Houston, USA.
13. **Tim Lin.** “Estimation of Primaries by Sparse Inversion”, Chevron, 2012, San Ramon, USA.
14. **Sasha Aravkin.** “Estimating nuisance parameters for inverse problems”, 2012, ”, Total, 2012, Paris, France.

## 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** | | 1 | | | 1 |
| **# of Patents Issued** | | 1 | | | 1 |

**# of Licences** 12 **(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:**

US Provisional Patent Application No. 61/815,533 entitled "A Penalty Method for PDE-Constrained Optimization with Applications to Wave-Equation Based Seismic Inversion"

**Patents Issued:**

(WO2011160201) METHOD AND SYSTEM FOR DETERMINING AN ESTIMATED MODEL PARAMETER FROM A MEASURED FIELD by Eldad Haber and Felix J. Herrmann, 2011.

**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.

DNOISE II was joined by three new companies in April of this year, namely CGG, ION, and Woodside.

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**

We have avid participation from our sponsors and our upcoming semi-annual Consortium Meeting (to be held Jun 14 at Royal School of Mines, Imperial College London in association with EAGE meeting) has record registration from our sponsor R&D personnel, as listed below and see our meeting website https://www.slim.eos.ubc.ca/SINBADSpring2013/.

We also had an extremely well attended and successful 2013 annual Fall

Consortum meeting (attendees listed below), and Spring 2012 meeting (attendees listed below).

**Spring Consortium meeting Jun 14, 2013, London:**
**Currently registered to attend:**
Raymond Abma (BP America), Aria Abubakar (Schlumberger-Doll Research), Paul Brettwood (ION Geophysical), John Brittan (ION Geophysical), Paul Childs (Schlumberger Gould Research), Nanxun Dai (BGP), Kristof DeMeersman (CGG) Carlos Eduardo Theodoro (Petrobras), Camila Franca (BG-Group) David Fraser Halliday (Schlumberger Gould Research), Rob Hegge (Petroleum Geo-Services) Jon-Fredrik Hopperstad (Schlumberger Gould Research), Clement Kostov (WesternGeco GeoSolutions, Schlumberger), Andrew Long (Petroleum Geo-Services), Hamish Macintyre (BG-Group), Fabio Mancini (Woodside), Ian Moore (WesternGeco), Gordon Poole (CGG), Tom Ridsdill-Smith (Woodside), Jonas Rohnke (CGG), Risto Siliqi (CGG) Djalma Soares (Petrobras), Paulo Terenghi (Petroleum Geo-Services), John Washbourne (Chevron) Yu Zhang (CGG), Andrew James Carter (Statoil - Guest)

**Fall Consortium meeting December 2nd – 5th 2012, Whistler, BC:**

**Industry attendees:**
Brandsberg-Dahl, Sverre (PGS), Childs, Paul (Schlumberger), Coates, Richard (WesternGeco), Dai, Nanxun (BGP), Gao, Fuchun (Total SA), Hegge, Rob (PGS), Kaplan, Sam (Chevron), Klaedtke, Andreas (PGS), Li, Chengbo (ConocoPhillips), Liu, Zijian (PGS), Morley, Larry (ConocoPhillips), Ramos Martinez, Jaime (PGS), Schonewille, Michel (SLB), Selvage, James (BG Group), Tegtmeier-Last, Sandra (Chevron), Theodoro, Carlos Eduardo (Petrobras), Yu, Zhou (BP America), Zhang, Wei (BGP), Akalin, Okan (PhD, Wisconsin Institutes for Discovery, via video), Clapp, Bob (Maxeler), Hall, Mike (Fugro Seismic Imaging), Iakovlev, Alex (LARGEO LLC), Kasapi, Mario (UBC UILO), Kuipers, Anton (UBC Science), Madden, Peter (IBM), Paquette, Claude (Cray), Reese, Jill (MathWorks), Smithyman, Brendan (PhD, UBC EOAS), Story, Shane (Intel), Yu, Winston (MathWorks), Warner, Michael (Imperial College London, via video),Wenes, Geert (Cray), Willard, Andrew (MathWorks)

**Webcast participants:**
Beydoun, Wafik (Total), Bones, Debbie (Chevron), Calandra, Henri (Total), Citlali Ramirez, Adriana (Statoil), Crook, Howard (BG Group), Dracott, Richard (Dracott Associates), da Cunha Filho, Carlos Alves (Petrobras), Faroppa, James (BG Group) ,Guerra Cardoso, Claudio (Petrobras), Jones, Charles (BG Group), Keith, Graeme (DONG Energy), Macintyre, Hamish (BG Group), Moldoveanu, Nick (WesternGeco/Schlumberger), Morton, Scott (Hess) Mosher, Chuck (ConocoPhillips), Nemeth, Tamas (Chevron), Oriato, Diego (Maxeler)

Ricoux, Philippe (Total), Ridsdill-Smith, Tom (Woodside), Santos de Oliveira, Adelson (Petrobras), Stork, Christof (Halliburton), Thierry, Philippe (Intel), Valasek, Paul Allen (Maerskoil), Vyas, Madhav (BP), Wallon Pizarro, Heidi Ursula (IBM), Zheng, Chong (BGP)

**Spring Consortium meeting June 8th 2012, Copenhagen:**

**Industry attendees:**
Aria Abubakar (WesternGeco/Schlumberger), Peeter Akerberg (Chevron), Sverre Brandsberg-Dahl (PGS), Henri Calandra (Total SA), Nizar Chemingui (PGS), Nanxun Dai (BGP), Carlos Eduardo Theodoro (Petrobras), Rob Hegge (PGS), James Hobro (Schlumberger), Jon-Fredrik Hopperstad (WesternGeco/Schlumberger), Stuart Long (BP), Hamish Macintyre (BG Group), Chuck Mosher (ConnocoPhillips), Einar Otnes (PGS), Ali Ozbek (WesternGeco/Schlumberger), James Selvage (BG Group), Ivan Vasconcelos (WesternGeco/Schlumberger), John Washbourne (Chevron), Xander Campman (Shell), Evert Kramer (Logica/Shell), Dmitri Lokshtanov (Statoil), Tony Martin (Hess), Scott Morton (Hess), Michael Perrone (IBM), Adriana Citlali Ramirez (Statoil), Leen Roozemond (Shell). Ivan Stekl (Imperial), Tim Seher (Fugro Seismic Imaging), Adrian Umpleby (Imperial)

**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:

1. software releases with concrete parallel software implementations of our algorithms (see details below)
2. 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
3. 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
4. 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.

**Cummulative 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]

2. **Migration from surface-related multiples.** Fast imaging with surface-related multiples by sparse inversion [Demo]
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]
4. **Modified Gauss-Newton full-waveform inversion.** Fast full-waveform inversion with sparse updates [Demo]
5. **Fast Robust Waveform inversion.** Fast full-waveform inversion with robust penalties and source estimation. [Demo]
6. **2D ocean-bottom marine acquisition via jittered sampling** – a new type of marine acquisition scheme including curvelet-based recover with one-norm minimization;
7. **Efficient least-squares imaging with sparsity promotion and compressive sensing** – fast reverse-time migration with phase encoding and curvelet-domain sparsity promotion;
8. **Fast imaging with wavelet estimation by variable projection** – reverse-time migration with curvelet-domain sparsity promotion and source-wavelet estimation;
9. **Seismic trace interpolation using weighted one-norm minimization** – recovery of missing traces by weighted curvelet-domain sparsity promotion
10. **3D acoustic full-waveform inversion** – extension of our full-waveform inversion to 3-D;
11. **Application of simultaneous seismic data interpolation and denoising using factorization based low-rank optimization** – missing-trace interpolation using low-rank matrix factrorizations and nuclear norm minimization;

**Outreach**

To disseminate our research findings to broader academic and industrial communities we have written review articles that International Innovation and in IEEE Signal Processing Magazine. We also participated in conferences in the field of signal processing (ICASSP and SSP), machine learning (NIPS) and computational mathematics (SIAM) to get more involvement from these communities. We also mentioned outreach throughout section 1.

## 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)
X 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 simulators. 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 started a number of initiatives as outlined in the section **HPC need**s above.

**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 are very glad that WesternGeco has been willing to donate their Omega seismic data processing software to our project. For details on this multi-million dollar software package, refer to the description above.

**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. See **HPC needs** section above.

**Staffing issues.** While our current team is complete, we will have to plan for people, most notably experienced PDFs, leaving the team. In particular, **Sasha** Aravkin (PDF) and **Hassan** Mansour (PDF), who were both talented and productive PDFs, left 9 months before their end-of-contract in order to take permanent positions at IBM Research and Mitsubishi Research, respectively. While we have been able to hire three new PDFs in a highly competitive market, we are still somewhat understaffed in that area, which we hope to resolve by Januay 1st, 2014. **Michael Friedlander** is now part of a 3-year PIMS Collaborative Research Grant in Optimization, which providees 40% funding for a PDF for next year. Because a PIMS fellowship is prestigious, we will use this as an opportunity to recruit a fourth talented PDF.

## 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: app. 20
__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, BGP, BP, Chevron, and 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.
- Meetings and discussions at geophysical industry conferences
- Case studies on synthetic and field data

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?

__X__ 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** | $2,220,372 | $1,776,875 |
| **In-Kind** | 0 | Estimated commercial value $6,355,000 |

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

In-Kind contribution from WesternGeco: Omega seismic data processing software, accurately and efficiently processes:

1. land, marine, and transition zone environments
2. time or depth data
3. 2D, 3D, and 4D surveys
4. isotropic and anisotropic (TTI and VTI) velocity fields
5. multicomponent data
6. reservoir-to-basin scale projects.

It's four major components make it a completely flexible and scalable system:

1. **Interactive desktop** Manage seismic data and seismic projects, build processing workflows, view QC processing results, visualize and analyze seismic data, and interactively generate statics and velocity solutions.
2. **Omega Infrastructure** A database-driven project model, automated data management, and detailed history, enable you to concentrate on the geophysics.
3. **Geophysical Algorithms** Over 400 algorithms in three packages: Foundation, Time, and Depth are available. Additional advanced algorithms are available, including reverse time migration (RTM), adaptive beam, Gaussian packet migration, and 3D GSMP generalized surface multiple prediction.
4. **Omega Integration** Integrate the compute power and algorithm base of the Omega system with the visualization canvas of Petrel software for more advanced geophysical workflows.

## 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 | 337,381 | 221,396 | 86,250 | 377,050 |
| Postdoctoral fellows | 302,500 | 126,356 | 22,000 | 354,400 |
| Technical/professional assistants | 236,726 | 150,988 | 47,300 | 233,400 |
| Other (Specify) | | | | |
| **Equipment and Facilities** | | | | |
| Purchase or rental | 14,500 | 47,666 | 2,000 | 10,000 |
| Operation and maintenance costs | 53,000 | 41,360 | 15,000 | 49,656 |
| User fees | | | | |
| **Materials and Supplies** | | | | |
| Materials and supplies | 1,930 | 3360 | 500 | 1,930 |
| **Travel** | | | | |
| Conferences | 46,550 | 38,698 | 16,600 | 46,550 |
| Field work | | | | |
| Collaboration/consultation | | | | |
| Project related travel | 7,000 | 3,505 | 3,000 | 7,000 |
| Project meeting | 5,000 | | 2,500 | 5,000 |
| **Dissemination Costs** | | | | |
| Publication costs | 6,500 | 4,765 | 1,000 | 6,500 |
| Other (specify) – Report + Meeting | 22,000 | 27,534 | 1,000 | 22,000 |
| **Other (specify)** | | | | |
| | | | | |
| | | | | |
| **Totals** | 1,033,087 | 665,628 | 197,150 | 1,113,486 |

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.)

We experienced unexpected loss of two postdocs midway through project Yr3 to industry positions. It was not possible to immediately replace these as PDFS usually start in Sept following graduation. Aggessive hiring has resulted in 4 new PDFs to start Jul – Sept 2013. We are expecting to obtain another PDF partially co-funded by fellowship as well. As a result our PDF expense has been underbudget for Yr 3, and is expected to be overbudget for Yr 4.

We will be aggressively seeking out a talented new Senior scientific programmer to advance progress more quickly through Yr 4. This was approved in the DNOISE budget for Yr 3, 4, 5 but we have been unable to fill this gap as yet.

We purchased a Maxeler workstation containing 100 GB of memory and with streaming FPGAs at a massive discount of 60%, which greatly advanced our computer capabilities.

We expect our research activities to increase greatly next year due to the talented new members joining our team, and due to the increased research capacity of co-PIs Michael Friedlander and Ozgur Yilmaz. We expect to fully spend our available budget for Yr 4.