Research Statement: Felix J. Herrmann

My long-term research objectives are (i) the development and implementation of the next-generation of (exploration) seismic data processing, modeling, imaging, and full-waveform inversion techniques that leverage recent developments in the field of theoretical signal processing known as "compressive sensing" where transform-domain sparsity promotion by one-norm minimization has led to sub-Nyquist sampling schemes with exciting implications for (simultaneous) seismic data acquisition design, imaging, and inversion algorithms. (ii) The introduction of new models that link onsets in connectivity of binary rocks, as a function of the volume fraction, to sudden changes in the elastic or fluid-flow transport properties. Combination of these two areas, which entails a diverse spectrum of topics ranging from nonlinear optimization, scientific computing and statistical mechanics, allows me to make new inferences from seismic data regarding the fine-structure and origin of unconformities that induce seismic reflections. This summary covers my primary areas of research since joining UBC, including new topics in collaboration with researchers from the Mathematics and Computer Science Department at UBC that include theoretical developments in sampling theory, design and implementation of extremely large-scale one-norm solvers and the development of new ways to compress wavefield extrapolation and imaging operators. The outcome of my industry-supported program includes improved images and understanding of processes responsible for seismic reflectors.

Research interests

With the continued increase in the worldwide demand for fossil fuels, seismic exploration has become increasingly more important. This increased demand is calling for innovations in seismic processing & imaging and a large part of my research is directed towards enhancing the current imaging algorithms by synthesizing, adapting and extending recent developments from other fields such as theoretical signal processing, harmonic analysis and information theory. In particular, I have been able to leverage new developments from the field of "compressive sampling" to the seismic imaging problem, which has resulted in new algorithms that range from the recovery of seismic data volumes from incomplete data to the separation of coherent signal components, the restoration of seismic-imaging amplitudes and compressed extrapolation of seismic wavefields. This technology is considered break-through by the oil & gas industry, which is currently in the process of evaluating my algorithms and is calling for commercialization of the algorithms I have developed. My research program focuses on three main questions:

1. *How to obtain better quality seismic images of the Earth's subsurface at reduced computational and data acquisition costs*—i.e., how to improve the signal-to-noise ratio and resolution of crustal and global-scale images. Improvements in the image quality are instrumental for (i) better understanding of the processes that take place in the Earth's subsurface and (ii) improved exploration and production of hydrocarbons and other resources.

2. *How to characterize what is in the image*—i.e., how to obtain a parameterization for the properties of seismic reflectors that can be accessed from seismic data. These parameterizations provide information on the fine structure of the major transitions in the Earth and help us constrain the physical and geological changes that are responsible for these transitions.

3. *How to understand why certain reflectors/transitions occur*—i.e., how to (physically) model seismic reflectors, using mixture models and percolation theory. This modeling gives me insight as to how changes in the rocks composition are translated into rapid changes in the seismic properties.

Research program and major research results

Improved seismic imaging and processing: The focus of this research program is to improve the quality of seismic images by incorporating the latest techniques from signal processing and inversion theory. These improvements are necessary because (i) recent increased efforts in data acquisition call for better imaging techniques; (ii) more details on the fine structure of the Earths subsurface are required to understand the physical processes driving the Earth's interior; (iii) exploration and production of oil & gas are shifting towards smaller and less accessible reservoirs.

Research outcomes: As part of this project significant progress has been made by applying the recently introduced curvelet transform (a multiscale and multi-directional transform) to various aspects of seismic processing including:

1. **Seismic data regularization** [Herrmann and Hennenfent, 2007] and **Sub-Nyquist jittered sampling techniques** [Hennenfent and Herrmann, 2007]. This work combines sparsifying transforms, one-norm solvers and random subsampling schemes that favor recovery from sub-Nyquist sampling;

2. **Coherent signal separation by transform-domain sparsity promotion** [Herrmann et. al., 2008, Herrmann et.al., 2006 and Saab et.al, 2007]. We contributed by improving on adaptive subtraction-based surface-related multiple elimination. Our transform-domain primary-multiple separation is robust w.r.t. to clutter and errors in the multiple prediction;

3. **Curvelet-domain matched filtering** [Herrmann et. al., 2008, Herrmann et.al., 2007]. In this work, we correct for smoothly varying amplitude errors in the predicted to-be-separated signal components through curvelet-domain scaling;

4. **Seismic-image amplitude recovery** [Herrmann et.al., 2007]. This work involves a rigorous bound on the accuracy of curvelet-domain diagonal approximations of zero-order pseudo-differential operators (high-frequency approximations of the normal operator of seismic imaging). This approximation is used to correct the image amplitudes through a scheme that promotes sparsity in the scaled curvelet domain;

5. **Compressed wavefield extrapolation** [Lin and Herrmann, 2007]. In this work, we developed a new algorithm where mutual incoherence amongst the eigenfunctions of the Helmholtz operator and curvelets is used to compressively sample (compress) one-way wavefield extrapolation operators.

6. **Preconditioning of the time-harmonic Helmholtz solver** [Erlangga and Herrmann, 2008] In this work, we present a new indirect type of preconditioning for the time-harmonic Helmholtz solver, which constitutes an order-of-magnitude improvement for both the computational complexity and memory imprint. This solver will form the basis on my future research efforts towards imaging and full-waveform inversion.

7. **Curvelet conditioning of least-squares migration** [Herrmann et. al., 2008, 2009] In this work, we introduce a method to condition least-squares reverse-time migration using a combination of Fourier, physical, and curvelet-domain scalings.

8. **Simultaneous full-waveform simulation** [Herrmann et. al 2008, 2009]. In this work, I established a direct connection between simultaneous-source acquisition and processing, and compressive sensing. With this connection, I am able to drastically reduce the computational costs of full-waveform modeling by reducing the number of right-hand sides by doing "simultaneous acquisition" during which all source fire. This work offers exiting perspectives towards a new imaging and full-waveform inversion methods where the numerical complexity is no longer determined by the size of the data acquisition and model but instead by its transform-domain sparsity.

9. **Compressive imaging by wavefield inversion with group-sparsity promotion** [Herrmann 2009]. In this work, I leverage the techniques of compressive sampling at the imaging step in the model space. By formulating the imaging step as a multi-dimensional wavefield deconvolution, I am able to significantly reduce the size of these wavefields. In combination with sparsity promotion and focusing towards the near offsets, this approach allows for a recovery from compressively sampled wavefields and leads to system-size reduction with sub-sampling rates, and hence modeling, and storage costs, that can be chosen in par with the sparsity of the object of interest.

Work part of item 1, 4 and 5 was recently presented as an invited talk at the 2007 von Neumann Symposium, "Sparse Representation and High-dimensional Geometry" (American Mathematical Society), at the NSF workshop "Cyber-Enabled Discovery and Innovation: Knowledge Extraction", hosted by the Institute for Pure and Applied Mathematics (IPAM), University of California, and at the Society of Industrial and Applied Mathematics (SIAM) Conference on Imaging Science. Aside from these academic achievements, I am also happy to report that there is a significant interest amongst my sponsors (BG Group, BP Production Company, Chevron, ExxonMobil and Shell) for software developed as part of items 1 and 2. My group is receiving numerous requests for assistance with the installation and evaluation of our software on numerous synthetic and real data sets. I consider this as a major achievement, given the relative short time span (three years) my consortium has been active. It is also encouraging to have received strong encouragements from industry other than our sponsors to bring our technology to market.

Future extensions: To address the (extremely) large size of seismic data, I am working on parallelization of our algorithms, including the introduction of a parallel curvelet transform (Thomson et.al, 2006), based on domain decomposition, and the parallelization of seismic wavefield extrapolation in collaboration with my postdoc Dr. Yogi Erlangga. This work involves preconditioners for the monochromatic Helmholtz operator. Finally, my Ph.D. student Gilles Hennenfent and I are working with Dr. Michael Friedlander on using the Pareto curve [Hennefent et.al., 2008] towards the solution of extremely large nonlinear one-norm solvers and their parallel implementation.

Seismic modeling and characterization: The goal of this project is to find a quantitative description for reflectors beyond their magnitude. The description is designed for use by geologists to help their interpretations and by reservoir engineers, rock physicists and mineralogists to constrain the elastic and transport properties of rocks.

Research outcomes: My contributions in this field include:

1. **Monoscale analysis method** [Herrmann, 2001]. In this work I introduced a more general mathematical parameterization for seismic transitions together with an inversion method.

2. **Seismic facies characterization** [Herrmann et.al., 2001]. I applied this method to the interpretation of facies in sedimentary basins;

3. **Percolation model for seismic singularities** [Herrmann and Bernabé, 2004]. This model describes the onset of connectivity amongst the stronger of the two components of a binary mixture. This work led to an alternative interpretation of upper-mantle discontinuities and to the explanation of laboratory measurements for the permeability and storativity of synthetic rocks consisting of mixtures of Quartz and Calcite [Bernabé et.al., 2004].

4. **Seismic-to-well tie**. Here, I continue to work on refining our parametric inversion methods with applications to the imaged opal-A (Amorphous) to opal-CT (Cristobalite/Tridymite) transition in the North Sea West of the Shetlands [Maysami and Herrmann, 2007,2008] and a MSc. thesis [Maysami, 2008]).

I continue to work on refining inverse methods to estimate the parameters of my model (see [Herrmann, 2005] and more recently in the proceedings of the EAGE [Maysami and Herrmann, 2007] and a MSc. thesis [Maysami, 2008]).

Future extensions: I plan to report on a new detection-estimation method that combines multiscale edge detection with a nonlinear least-squares method estimating the parameters of the smooth manifold defining the parameterization of seismic reflectors. I will also report on the use of this inversion method and the application of the percolation model to the Opal-Opal CT transition in a sedimentary basin near the Shetland Islands. With Dr. Beatrice Vedel, I am working on new theory for the recoverability of the proposed parameterization. With Dr. Bernabé, I continue to collaborate an our work including a new lithologic upscaling method that derives from our percolation model.

Other contributions: Because of the strong ties between my research program and industry, my body of work also includes a relative large number of four-page expanded refereed abstracts (59) in the proceedings of the annual meetings of the Society of Exploration Geophysicists (SEG), the European Association of Geoscientists and Engineers (EAGE) and the Canadian Society of Exploration Geophysicists (CSEG), and the organization of annual Industry Consortium Meetings with the companies that support my research.

Contributions to software development: To support the dissemination and implementation of my research findings, I undertook a concerted effort towards building a software environment that allows our sponsors to test our algorithms on realistic data sets. This effort consists of two separated but integrated activities, namely (i) the adaptation of MADAGASCAR (`http://rsf.sf.net`), a recently developed public-domain software package that implements utility programs defining seismic processing flows and which supports reproducible research, and (ii) the development of a new software package SLIMPy (`http://slim.eos.ubc.ca/SLIMpy`, to be released this Summer) that integrates these programs into the Python programming language. This "coarse-grained" compiler facilitates the implementation of abstract numerical algorithms (e.g. one-norm solvers) that scale to out-of-core and parallel implementations with minimal recoding. Aside from coordinating the implementation of this software, I supported the open-software community by organizing the workshop

"Reproducible Research in Computational Geophysics using Madagascar software package", Vancouver, 2006 and by putting together the mini-symposium "Software for Inverse Problems" during the First International Conference on Applied Inverse Problems, 2007. Finally, I have also been involved in the development of SPARCO (`http://www.cs.ubc.ca/labs/scl/sparco/`), a test suite for norm-one solvers aimed to address the current surge in scientific activity in the field of compressed sensing.

Long-term research interests

Aside from the negative impact of fossil fuels on global warming, we will be faced during our lifetime with challenges towards more sustainable use of our hydrocarbon resources. To address these issues, I plan to complement my research program towards the development of remote-sensing technology in support of CO_2 sequestration and in support of exploration of alternative energy resources such as the geotherm—i.e., the exploitable heat differential between the surface and the subsurface. I expect that the sophisticated imaging techniques developed in my group, in combination with my understanding of the rock physics, will be proof essential to meet these future challenges.

Connections at the University of Calgary

Amongst the oil & gas companies that support my group my research is considered as transformative, potentially leading to the next game change in seismic imaging and inversion techniques. My research interests overlap with numerous faculty at the University of Calgary. For instance, I talk regularly with Margrave, Fergunson, Lamoureux. Over the years, I have been able to establish connections by learning the language and concepts prevalent in a range of disciplines. As part of this process, I have organized a weekly seminar series at UBC with faculty and students (graduate and undergraduate) from five different departments. These meetings have led to exciting new research directions (e.g. the interdisciplinary research program DNOISE nucleated during this seminar series). I plan to do the same in Calgary, an activity that will certainly spark research along new and perhaps unexpected research directions. And, of course, last but not least I intend to interact with the CREWES consortium. I think I can bring new perspectives given my experience setting up the industry-supported SINBAD consortium at UBC.

Research funding

In order to confront the somewhat dire funding situation for basic research in Canada, I worked on a diversification of my funding portfolio by securing industry-supported research and by matching this support dollar-for-dollar through the Canadian NSERC Collaborative Research and Development (CRD) Grant program. These activities have grown into a relative large interdisciplinary research group with over twenty students, technical staff and postdocs. I lead this group, which includes two other faculty members from Mathematics and Computer Science and their students. The grant portfolio supporting this research effort includes:

NSERC Discovery grant (19 k[1]) " Multiscale imaging and modeling of seismic reflectors": The fundamental aspects of this research topic is part of my NSERC Discovery Grant. The more applied aspects of my research are organized in two industry-supported projects.

[1] Listed amounts are on a annual basis.

Industry grant (375 k) "Seismic Imaging by Next-generation BAsis-function Decomposition (SINBAD)": This three-year research contract aims at improving the quality of seismic images. This project was funded as part of the competition High Resolution Imaging of Hydrocarbon Reservoirs A Step Change, issued by Industry Technology Facilitator (`http://www.oil-itf.com/index.htm`). This project is supported by the following companies: BG Group (Canada), BP Production Company, Chevron, ExxonMobil and Shell Canada Ltd.

Industry grant (35 k) " Characterization And Reflector Modeling (ChARM)": This grant-in-aid supported by Chevron focuses on the characterization and modeling of seismic reflectors. In the sedimentary crust, this information can be used (i) to detect lithologic changes along major unconformities, (ii) to constrain my percolation model, and (iii) to do lithologic upscaling.

NSERC CRD Grant (231 k) "Dynamic nonlinear optimization for imaging in seismic exploration (DNOISE)": This NSERC Collaborative Research and Development Grant funds a multidisciplinary research project and focuses on one of the most pressing questions in the oil & gas industry namely—"How to image more deeply and with more detail?" This pressing question needs to be answered if our energy-intensive society is to address the current surge in demand for hydrocarbon resources adequately. DNOISE matches the industrial funding dollar-for-dollar as part of the SINBAD and ChARM projects.

Outcome: With this generous funding base, I have built an internationally recognized interdisciplinary research group, active in the geosciences and in the new field of compressive sampling at the crossroads of applied mathematics and computer science. The DNOISE group, including my own group at the Seismic Laboratory for Imaging and Modeling (SLIM), has hosted numerous visitors from academia and industry. My group has also interacted substantially with industry exposing the students to exiting new problems.

Teaching Statement: Felix J. Herrmann

Teaching philosophy:

During the course of my career, I have been involved in the supervision of several M.Sc. and Ph.D. student projects. From that experience and from my recent experience teaching undergraduate and graduate classes at UBC, I have learned how important it is to be able to share one's experience while working with students. I deliberately use the words "working with students" because it reflects my conviction that information is best communicated in active-process learning, which typically involves some project where students are encouraged to explore by themselves.

Recent insights on the student learning process have shown that the creation of an open collaborative environment where information is communicated in a shared and interconnected way has advantages over the classical linear and teacher-oriented method of teaching. In particular, initiatives such as Rices Connexions project (`http://cnx.rice.edu`) offer a unique new environment to e-learn. I have established contact with the founder Richard Baraniuk of Connexions and helped organize his visits to the e-learning community of UBC. I intend to use these contacts to develop e-learning modules to support my teaching. I am also looking into ways to assemble a core team of colleagues to help develop e-learning modules for the geophysics and geosciences communities. When I was chair of the Library Committee I was an advocate, as part of establishing the EOS Teaching and Learning Center, for a more active involvement of faculty towards generating e-content. I am happy to see that this is now an important component of the Carl Weiman initiative.

Over the time I have been at UBC, I have witnessed a steady decline in the "math" capability of students. This is a global trend with roots in western society that go back to primary school education. This trend adds a challenge to teaching material in geophysics that has traditionally been rich in mathematical content. To address this challenge, I enriched the lower-undergraduate level courses with real-life examples, explaining the importance of abstract geophysical concepts. At the upper-graduate level, I have made substantial changes to the courses that include the use of a more narrative textbook and the redesign of assignments and lectures. The feedback to my efforts has been positive and I will continue working at improving my courses. I also plan to incorporate ideas from the "The Index of Learning Styles", according to the Felder-Silverman model, in my teaching to help students assess their teaching styles and make adjustments so the students can optimize their learning experience within my courses.

Undergraduate teaching:

At UBC I have been involved in undergraduate teaching at all levels. I have taught the geophysics component of the first-year introductory service course EOSC 110 The Solid Earth - A Dynamic Planet. That experience has shown me how to explain abstract and quantitative concepts to a diverse student population with students from arts, science and engineering. This diversity amongst the students, and their interests, makes teaching this course a challenge in particular for a component of the material that is perceived as being difficult because it contains "math". By incorporating links to real-life events, such as the recent Sumatra earthquake and subsequent tsunami, I have been able to capture the attention of the students and give them a better understanding on the role of geophysics in the Earth Sciences and in society as a whole.

I have also taught EOSC 252 Introduction to Experimental Geophysics, wherein I face a similar situation with a spectrum of students that range from “fresh” second year geology students to far more experienced hydro-geologic engineers and unclassified students that are taking this course for their Professional Engineers and Geoscientists of BC degree. By completely redesigning the assignments for this course and the encouragement of active in-class participation, I have been able to find a good balance leaving enough of a challenge for the experienced students while keeping the material accessible for the less experienced students.

I have also taught two third year courses: EOSC 352 Geophysical Continuum Dynamics and EOSC 353 Seismology. These are courses that were designed as part of the core geophysics program. To address the issue of increasing “math illiteracy”, I completely overhauled the Seismology course last year. This redesign included the use of a more narrative book, new assignments and lectures that constitute a mix of powerpoint and blackboard presentations, as opposed to using the blackboard alone as I have done in the past.

As a final remark, I would like to mention my involvement with undergraduate students in my research group. This involvement began with Geophysics students doing their thesis topic with me and has grown into a continuous involvement with students coming in from the UBC engineering COOP program. Including undergraduate students has led to exciting collaborations, resulting in the publication of a journal paper and presentations at international conferences (this year I had two undergraduate students presenting at the SEG). Undergraduate students also play an important role in the development of our software infrastructure, including software releases to our industrial partners.

Graduate teaching:

Since my arrival at UBC, I have been actively involved in graduate teaching on different fronts, including (i) the development of a new Graduate Course EOSC 513 Imaging and Estimation with Wavelets, attended by on average $10 - 20$ students from several departments around campus including Computer Science (CS), Electrical and Computer Engineering (ECE), Engineering Physics and Physics, (ii) the coordination of an internship program for my graduate students as part of my industry collaborations, and (iii) the organization of a weekly Seminar Series with participation of all students and faculty involved in the Collaborative Research and Development Grant: DNOISE.

With my graduate course, I have been able to draw in students from different fields in science and engineering and interest them in theoretical aspects of signal processing and inversion theory as well as in the application of these concepts to seismology and to their Ph.D. research topics. With the in-class participation, in the form of selected journal paper and project presentations, and end-of-term projects, I have found a good balance between teaching students theory and acquainting them with cutting-edge research. This approach has led to interesting collaborations and class projects that have evolved into publications.

The DNOISE project involves a relatively large group of students who are all given the opportunity to participate in international conference and are asked to regularly report their work to our industrial sponsors in the form of presentations and concrete implementations of the algorithms developed as part of this project. I consider this focus as an important component of the student’s graduate education.