Seismic advances

Current seismic exploration techniques are hampered by bottlenecks in data sampling and processing due to challenges in data collection, demand for more data and the increasing need to study highly complex geological settings. **Professor Felix J Herrmann**'s group is developing novel techniques to overcome these barriers which could greatly benefit the hydrocarbon industry

Would you begin with a broad overview of your aims and objectives?

Developments have recently been made in independent fields dealing with the notion of how you should collect and process data, and compressive sensing (CS) and large data analytics fall within that arena. My group aims to push the envelope on the technology in order to meet the challenges, and touches on many aspects of exploration seismology from the way field data is acquired, to the production of your final result. We want to improve data collection efficiency, but also how information is obtained from the data; which partly explains why we are working on so many fronts.

From what field did CS originate? Why is it salient to seismology?

CS emerged in 2004 during a thematic programme run at the Institute for Pure and Applied Mathematics at the University of California, Los Angeles, which I attended. An easy analogy to understand CS would be the workings of a camera. A picture is taken with many pixels and then it encodes that picture with a jpeg to reduce the size. A lot of data is collected and then unnecessary things are thrown away because it is a 'lossy' compression. CS samples less so you can obtain the same quality of picture back but without sampling all the pixels.

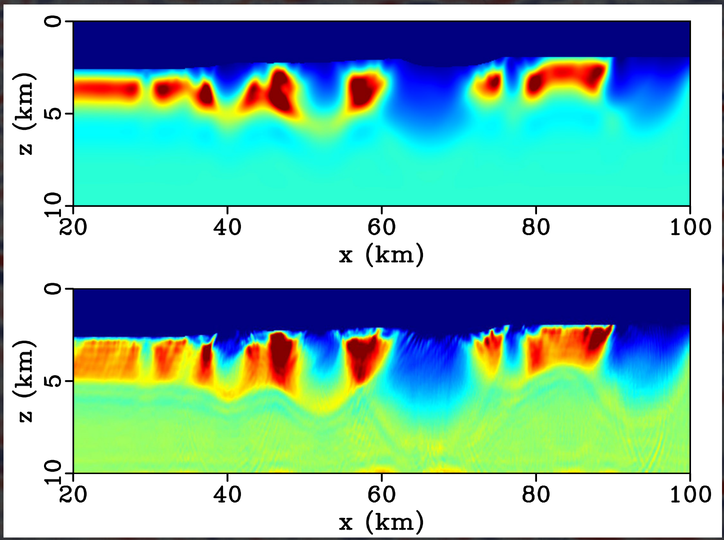


FIGURE 1. Results from a recent blind synthetic case study for the Gulf of Mexico put together by Chevron. **(Top)** Initial model obtained by travel-time tomography on first breaks. **(Bottom)** Full-waveform inversion result with curvelet-based modified Gauss Newton.

Although it is challenging to translate the ideas of CS to acquiring field data, taking fewer samples is extremely important because acquisition is very expensive, and more difficult to control because we are constrained by physics. We do not have a human-sized machine and are working on very large survey areas which make it more challenging. The industry has been picking this up slowly and we are one of the few groups adapting this technology for seismic applications.

Could you expand upon full-waveform inversion (FWI)?

To obtain information from this data is yet another challenge and forms the other aspect of our research. FWI is a transformative and disruptive technology. It was pioneered in the 1980s, but in those days there were limited computational resources and fundamentally it is hampered because the solution is not unique. For instance, it is relatively easy to find coefficients of a wave equation whose solution matches the data. However, these coefficients may not be unique and can be the result of getting stuck in a local optimal solution. So in order to make FWI more robust, we need to develop practical workflows that compensate for severe modelling errors and avoid the non-uniqueness. The latter may require fundamental changes in the problem formulation. My group is involved in all of the above.

Convex optimisation problems on the other hand, to which CS belongs, are 'easier' because their optimal points correspond to global minima and the solution is therefore unique. We adapt techniques from CS to sub-sample, reducing the cost of acquisition, and also to perform fewer computations. That is where the two research areas during CS and FWI meet.

Why is randomness in the mathematical sense important to improving seismic imaging?

One of the key aspects of CS is randomised sampling, which differs fundamentally from the previous sampling paradigm where we sample periodically on a regular grid. If you sample above Nyquist, periodic sampling is fine but if you sample below Nyquist, data becomes aliased – ie. damaging periodic phantoms emerge due to the periodicity of the sampling. However, if you randomise, you break this periodicity, and the harmful periodic aliases become relatively benign, incoherent noise that can be easily removed with sparse-recovery techniques.

Randomness therefore allows us to generate information in a much more effective way than we used to. Ideally, you want this sampling to correspond to the action of a Gaussian matrix – ie. a matrix with identically distributed Gaussian entries. While this may not be possible in the geophysical setting we tell industry to break periodicities in their sampling by random placements of sources and receivers or by firing sources at randomly dithered times. As in MRI, where CS has led to fivefold speedup, this randomisation will lead to more efficient acquisition. It is encouraging to see that companies like Schlumberger, with their random coil sampling, and ConocoPhilips, with their randomised land acquisition, are following my group's lead.

What are your long-term goals?

We have been very successful in developing 2D seismic techniques – making 2D images of the Earth's subsurface with 3D data input obtained from a source and receiver at the surface that move along a line and measures signals as a function of time. But we want to move to 3D seismic, which requires 5D data (two for the source, two for the receiver, and time) which leads to an explosion in dimensionality. More sources mean more waves and therefore greater problem sizes and an increase in computational demands by more than two orders of magnitude.

Next generation imaging technology

With the demand for hydrocarbon resources ever increasing, new and more efficient seismic exploration techniques are required. Researchers at the University of British Columbia are developing a new framework for wave-equation-based data mining combined with a dynamic nonlinear optimisation approach to create images in complex geological regions that until recently were unattainable

SEISMIC EXPLORATION IS concerned with obtaining data that can provide information about the structure and distribution of rock types. It involves the use and measurement of artificially generated seismic waves travelling through the Earth to locate features such as hydrocarbon deposits, geothermal reservoirs, groundwater and archaelogical sites, and to obtain geological information for engineering. Explosives and other energy sources are used to generate seismic waves, and arrays of seismometers or geophones detect the resulting wave motion of the Earth. Data is usually recorded in digital form so that computer processing can be used to enhance the signals with respect to the noise, extract the significant information and display the data in such a form that a geological interpretation can be readily carried out.

The basic technique of seismic exploration consists of generating seismic waves and measuring the time required for the waves to travel from the source to a series of geophones, usually positioned along a straight line directed toward the source. Based on a knowledge of travel times to the various geophones, and the velocity of the waves, researchers can attempt to reconstruct the paths of the seismic waves and thereby deduce information about the rocks from the observed arrival times together with variations in amplitude. Unfortunately, this ray-type of approach does not produces reliable high-resolution images in complex geological settings. Therefore, there has been a recent push by academia and industry to use information on the waveforms present in the data. This shift calls for wave-equation-based imaging, which is significantly more challenging because the physics is highly involved, demanding additional data and computational resources.

CURRENT SAMPLING LIMITATIONS

Many seismic exploration techniques rely on the collection of massive data volumes that are mined for information during processing. Whilst this approach has shown some success, current efforts toward higher-resolution images in increasingly complicated regions of the Earth continue to reveal fundamental shortcomings in the typical workflows of researchers working on seismic exploration. Moreover, current seismic data processing, imaging and inversion increasingly rely on computationally- and data-intensive techniques to meet society's continued demand for hydrocarbons. This approach is problematic because it leads to an exponential increase in cost as the size of survey areas grow.

Pressures for increased resolution make full sampling economically and physically unfeasible. This forces practitioners to sample below the required Nyquist sampling rate of at least twice the rate of the highest frequency in a signal. To mitigate the adverse affects of this undersampling, much research has focused on developing improved sampling schemes that randomise spatial locations and receivers or the sources firing times. Unlike periodic sampling, randomised techniques allow researchers to sample below Nyquist as long as the to-be-sampled signal has some type of structure that can be used to remove the now 'noisy', as opposed to coherent, subsampling artifacts.

COMPRESSIVE SAMPLING

The Seismic Laboratory for Imaging and Modeling (SLIM) at the University of British Columbia in Vancouver is a recognised world leader in the development of next generation seismic acquisition and imaging technology for the oil and gas industry. The SLIM team is carrying out research to develop alternative sampling strategies based upon compressive sampling (CS) towards seismic acquisition and processing for data that one would traditionally consider to be under sampled. CS is a novel, sampling paradigm for efficiently acquiring and nonlinearly reconstructing a signal, by finding solutions to underdetermined linear systems of equations. It is a technique that is effective for acquiring signals that have a sparse representation in some transform domain or can be represented by low-rank matrices, allowing them to be determined from relatively few measurements. CS is analogous to the game of Sudoku, where the rules allow the player to deduce the value of every point on the board, despite knowing just a few initial examples.

Led by SLIM Director Professor Felix J Herrmann, the team is reviewing basic facts about this new sampling paradigm that have already revolutionised various areas of signal processing and illustrate how it can be successfully exploited in various problems in seismic exploration to effectively tackle what it calls 'the curse of dimensionality'. Together with findings from earlier work in seismic data regularisation, trace interpolation, simultaneous marine acquisition, and phase encoding, the researchers are confronting this challenge with a randomised dimensionality-reduction approach that decreases the cost of acquisition and subsequent processing significantly.

Herrmann explains that while recent proposals to expedite seismic acquisition or computations through simultaneous sourcing have proven successful, the proposed methods lack a framework that would allow for the design of rigorous workflows. "By recognising these clever new sampling schemes as instances of CS, we are able to make a start towards sampling and computation strategies that employ structure in seismic data, which translates into transform-domain sparsity or low rank," he elucidates. "This attribute allows us to come up with sub-Nyquist sampling schemes, whose sampling is proportional to the sparsity or rank rather than to the dimensionality of the problem." It is worth noting that the success of these techniques hinges on subsamplings that break the periodicity of conventional ones.

DNOISE

Herrmann's team is currently working on seismic data acquisition, processing and imaging. Funded by the Natural Sciences and Engineering Research Council (NSERC) of Canada and industry they are researching dynamic nonlinear optimisation for imaging in seismic exploration (DNOISE). This five-year project aims to design the next generation of seismic imaging technology to address fundamental issues related to the quality and cost of seismic data acquisition, and the ability to invert exceedingly large data volumes. It also seeks to address the capacity to mitigate non-uniqueness of full-waveform inversion (FWI) – a technique that aims to estimate a model of the subsurface that minimises the difference between recorded seismic data and synthetic data simulated by the solution of the wave equation for that model.

The DNOISE project operates at the intersection of information, optimisation and seismic theory, and aims to provide answers to basic questions such as: 'what accuracy is attainable given a certain seismic acquisition'; and 'how we improve acquisition to obtain a certain accuracy' To answer these questions, Herrmann and his colleagues leverage the latest developments from information theory and machine learning. These developments constitute a new theoretical paradigm that the group is adapting to practical engineering principles that provide conditions under which seismic data can be recovered from deliberately subsampled and possibly noisy measurements. As part of DNOISE, the researchers plan to leverage these developments towards a broad spectrum of outstanding challenges in seismic imaging that range from mitigating the effects of the free surface, eg. multiples to wave-equation-based imaging and inversion using information on the amplitudes of the waveforms present in the data.

COLLABORATING WITH ACADEMIA AND INDUSTRY

The SLIM collaboration is highly interdisciplinary, and faculty members from Computer Science, Mathematics and Earth, Ocean and Atmospheric Sciences departments at the University of British Columbia are directly involved with the research. Although SLIM is well-connected with scientists locally and internationally, Herrmann is keen to further the project's collaborative approach: "In this field, you are only as good as your weakest link," he asserts. "This makes our research extremely challenging and while the industry has a very interesting working relationship with academia such as the SINBAD industry consortium – a joint industry project that I run at my university – the complex subject matter of wave-equation-based inversion calls for strategic collaboration with different academic institutions because the range of topics is becoming very broad. This is one of the biggest challenges my students and anyone in this field faces – you have to be a jack of all trades."

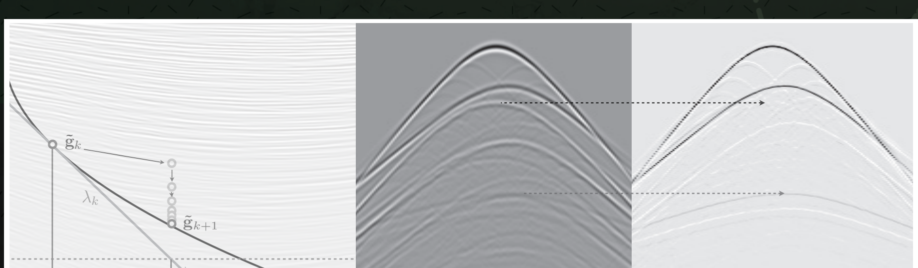
In SLIM's working relationship with industry, industry partners adapt technology developed by the team to capture information from the complex subsurface that was previously unresolvable. Such partners include BG Group, BGP, BP, Chevron, ConocoPhillips, PetroBras, PGS, Total SA and WesternGeco. Through active collaboration with industry and support from NSERC, SLIM is also a major hub for training the next generation of scientists critical to Canada's future sustainable resource management.

STRIKING A FINANCIAL BALANCE

In addition to working towards more strategic collaboration, Herrmann is striving to secure more financial commitment to the research: "One of the challenges I face in academia is that we do not have the computational resources, so I am strategically aligning my research programme to countries that are more willing to invest in research and development," he notes. "While Canada has made some investments in larger scale shared computational resources, it is not keeping pace with other countries. The shortfall comes in both strategic initiatives and resources around big data and the range of computational investments needed to capitalise on the variety of research that depend on these different types of resources. The field has evolved in a way that we should think about creating big data labs where traditional high-performance computing is combined with modern developments in analytics."

In Brazil, Herrmann's group, Imperial College

FIGURE 2. Schematic of multiple removal via Estimation of Primaries by Sparse Inversion. **(Left)** Solution path of the sparsity-promoting solver. **(Centre)** input data with multiples. **(Right)** output data without imprints of the source function and multiples.



Current seismic data processing, imaging, and inversion increasingly rely on computationally- and data-intensive techniques to meet society's continued demand for hydrocarbons

London and Brazilian partners are working to leverage the 1 per cent research and development levy of pre-salt from oil companies towards the industrialisation of FWI technology. "This is an interesting model for Canada to consider to ensure that intellectual property stays in Canada," notes Herrmann.

Although in Canada it is possible to match industry funding dollar for dollar, a significant amount more is required to perform computation to the degree required by FWI. "There has been a recent and dramatic shift in research funding in Canada, which while emphasising connections and commercialisation, has not systematically fostered the building of bridges across pure research, interdisciplinary research, and connections with industry. This has left some gaps to be filled, particularly in strategically making the connections across basic research to applied areas, which in the long term could be a potential disadvantage to Canada.

ANSWERING PRESSING QUESTIONS

By integrating broad geophysical insights with cutting-edge sampling and computational approaches, the SLIM team has achieved major improvements in seismic data acquisition, imaging and inversion. The main breakthrough of SLIM's approach will be a new technology framework for seismic acquisition, imaging and inversion with costs no longer determined by overly stringent sampling criteria. Instead, the costs will depend on transform domain sparsity or low rank of the final product and will therefore no longer grow uncontrollably with the dimensionality of the imaging problem.

Herrmann's results illustrate that his group is at the cusp of exciting new developments in the adaptation of CS for exploration seismology, where acquisition and processing workflows are not constrained by the fear of creating artefacts related to periodic subsampling. Instead, they are arriving at a workflow with control over these artefacts, and acquisition and computation processes are more efficient.

The combination of cross-disciplinary expertise and partnerships puts SLIM in an ideal position to address fundamental issues related to the quality and cost of seismic data acquisition, and to mine exceedingly large data volumes. Most importantly, the DNOISE project aims to resolve one of the most pressing issues in the oil and gas industry, namely how to image more deeply and with more detail. This question urgently needs to be answered if our energy-intensive society is to adequately address the increasing demand for conventional and unconventional (eg. shale gas) hydrocarbon resources.


HERRMANN AND STUDENTS

INTELLIGENCE

DYNAMIC NONLINEAR OPTIMIZATION FOR IMAGING IN SEISMIC EXPLORATION (DNOISE)

OBJECTIVES

DNOISE II constitutes a transformative research programme towards a new paradigm in seismic exploration where the acquisition- and processing-related costs are no longer determined by the survey area and discretisation but by transform-domain sparsity or low rank of the final result. The project promotes a ground-up formulation for wave-equation-based seismic inversion where adverse subsampling-related artifacts are removed by intelligent-acquisition design and recovery promoting transform-domain sparsity or low rank.

KEY COLLABORATORS

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