1 Research interest keywords

- Nonlinear inverse problems for PDE,
- quantitative reconstruction,
- time-harmonic wave propagation,
- large scale optimization,
- Full Waveform Inversion,
- convergence and stability estimates,
- discontinuous Galerkin methods,
- High Performance Computing,
- geophysics,
- helioseismology.

2 Education

Supervisors: Hélène Barucq (Inria) and Henri Calandra (Total E&P).
* The thesis reviews can be found at the end of the CV.

| Master’s degree in applied mathematics and numerical methods.


3 Professional experience

Positions

10/2019–09/2021 Lise Meitner fellow, Faculty of Mathematics, University of Vienna, Austria.
Fellowship under the FWF (Austrian Science Fund) funding for my project “Viscoelastic inverse problems from seismic to medical scale”.
Allocation: 159,340 euros for 2 years position.

Expert research engineer in the framework of the Depth Imaging Partnership between Inria and Total E&P: research coordination on quantitative seismic inversion and software development under the Total platform in Houston.


2012 – 2014 Visiting scholar, Purdue University, West Lafayette, IN, USA.
Member of the Geo-Mathematics and Imaging Group (now at Rice University) led by Maarten V. de Hoop, under funding of Total E&P.


2010 Internship, Essilor International, Créteil, France.
| Surface optimization for glasses under constraint of adapted optics.
**Projects**

since 2014  **DIP**: *Depth Imaging Partnership* between Inria Magique 3D and Total E&P.


2019–2020 **GENCI** resource allocation: PI for the project AP010411013, entitled *harmoniC wAve propagatIon for extRa-terrestrial imagiNg using hybridizable Discontinuous Galerkin method* (CAIRN-DG).


**Visiting activities**

09-10/2016 Total E&P, Houston, TX, funded under the project GEAGAM.

06/2013 Lawrence Livermore National Laboratory, Berkeley, CA, USA.

**Teaching**

2018 – 2019 Université de Pau et des Pays de l’Adour

| Inversion/Optimization (M.Sc. level): lecture and computational exercises.

**Supervision of M.Sc. students**


**Language**

French: mother tongue; English: fluent; Spanish: advanced.

### 4 Software development

**Software**

- I am currently developing an open-source toolbox for quantitative time-harmonic inverse problems, using Hybridizable Discontinuous Galerkin discretization. The code is written in *Fortran90* using mpi and OpenMP parallelism for cluster deployment.

- **ffwi**: software developed in the Depth Imaging Partnership between Inria and Total E&P. I have written the Full Waveform Inversion method for seismic imaging using time-harmonic waves (acoustic, elastic, TTI). It is currently deployed by Total E&P in Houston.

**Programming skills**

- Excellent expertise in *Fortran* and Matlab; parallelism using mpi and OpenMP;
good expertise with cluster/supercomputers software programming (including makefiles), I am familiar with both slurm and LSF job schedulers;
- good knowledge of version-control system git; basic knowledge of svn;
- good knowledge of Python, C and C++; basic knowledge in Java and html;
- excellent expertise in \LaTeX{} and Beamer (with graphics using TikZ and PGF) for redaction;
- I am familiar with Linux, Windows (including Microsoft Office) and Mac OS.

5 Publications

The list of publications can be found at https://team.inria.fr/magique3d/team-members/florian-faucher/publications/

5.1 Peer-reviewed articles


Submitted articles


3
5.2 Peer-reviewed proceedings


5.3 Preprints and proceedings


5.4 Talks

The symbol † indicates invited talks.


[22] “Multi-level, multi-frequency, compressed full waveform inversion in 3D”. VI Meeting America, Total, Berkeley, USA (June 2013).


[26] “Seismic waves inversion in the frequency domain and 3D imaging”. VI Meeting America, Total, Montréal, Canada (Apr. 2012).
6 Thesis Reviews


The reports have been written by Prof. Samuli Siltanen of the University of Helsinki, and Prof. Jean Virieux, Emeritus at the University of Grenoble Alpes.
I am pleased to write this statement regarding the PhD thesis of Florian Faucher, entitled *Contributions to Seismic Full Waveform Inversion for Harmonic Wave Equations: Stability Estimates, Convergence Analysis, Numerical Experiments involving Large Scale Optimization Algorithms*.

I work as a Professor of Industrial Mathematics at University of Helsinki, Finland. My own scientific research concentrates on mathematical theory of inverse problems and on computational interpretation of indirect data. I feel confident about reporting on the present thesis as its subject matter is within my field of expertise. Also, let me state that I do not have any conflicts of interest regarding this task.

Seismic imaging is one of the fundamental application areas that drives the mathematical research on inverse problems. It importance ranges from fundamental science (recovering the inner structure of the Earth) through safety considerations (earthquake prediction) to very practical applications (prospecting for oil, water and minerals). Practitioners in the field use mostly classical imaging algorithms that are not based on latest mathematical findings. Recently, so-called Full Waveform Inversion (FWI) has become more practical due to two things: increased computational power and mathematical progress on inversion methods.

This manuscript is a *tour de force* in modern applied inverse problems mathematics, comparable in volume to at least two regular PhD theses. It is a significant contribution to both theory and practice of FWI.

Let me comment on the work chapter by chapter.

**Chapters 1–2** provide a thorough presentation of the physical and mathematical background of the topic, including review of models for the forward problem. The choice of working with a frequency-domain formulation is well justified. Regarding the direct problem, Mr. Faucher discusses several main methodologies, including finite differences, finite elements, and discontinuous Galerkin methods.

**Chapter 3** is devoted to the study of the stability of the chosen inverse problem formulation. For such a nonlinear and ill-posed inverse problem, it is especially valuable to have bounds for the stability constants, such as the ones provided by Mr. Faucher. Computational approximation of those bounds is a quite original and highly interesting detail in this work.
Chapter 4. Practical seismic inversion needs to be done in computational models having a huge amount of degrees of freedom. Such large-scale computation demands efficiency from the computational methods in terms of memory use and computational time. Mr. Faucher addresses these issues in Chapter 4, studying the definition and computation of first- and second-order derivatives needed in iterative minimisation methods used in the variational regularization approach.

Chapter 5 starts with an explanation of mathematical assumption under which the inversion algorithm can be proven to work. Mr. Faucher points out that, as is usual, one cannot expect the real-world seismic imaging problem to fulfil all of these assumptions. He then proceeds to analyse the limits for the computational model to be covered by theory. I have rarely seen such a profound and careful study probing the connection between the computational model and the inversion algorithm. In particular I like the computational comparison of Fréchet derivative condition numbers depending on the parametrization type in Figures 5.29, 5.34 and 5.46. Very nice work indeed!

Chapter 6. The use of realistic large-scale models is impressive. This also forces Mr. Faucher to concentrate on optimisation methods avoiding the use of the Hessian matrix. Also, he needs to adapt the resolution of the model to the frequency used; this also leads to a clever multi-level method where the result from the previous, lower-scale inversion serves as the initial guess for the next, larger problem. These kinds of adjustments are necessary for extending mathematical methods to problems with realistic scale. The reconstruction in Figure 6.36 is particularly interesting, showing that the methods are indeed providing high-quality reconstructions. As a whole, Chapter 6 serves as a comprehensive demonstration of the methodology with a variety of standard models. One important outcome is the good recovery of underground salt deposits.

Chapter 7 is about the practical case of having available a finite set of Cauchy data provided by modern dual measurement devices. A novel data discrepancy model is used to prove conditional stability of the inverse problem. This stability translates to robust behaviour of the inversion algorithm, which is demonstrated with a 3D computational example.

The thesis is well-written, and computational results are reported with carefully planned graphical illustrations. The connection to real-world models is remarkable. There is plenty of scientific novelty, and the work provides a significant advance in the field of underground prospecting and seismic inversion. In the future, I will use this thesis as a standard reference to seismic inversion in my research group.

Clearly, Mr. Faucher has acquired substantive and broad scientific understanding of both the application area and the related mathematical models, in part reflected by the extensive list of references in his work. He demonstrates good command of all three crucial skill sets of a modern applied mathematician: (1) capability of understanding cutting-edge mathematical theory and developing it further independently, (2) efficient scientific programming, and (3) teamwork in multidisciplinary teams.
I strongly and enthusiastically recommend approving the PhD thesis of Mr. Faucher.

Sincerely,

Samuli Siltanen
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Rapport sur le mémoire de thèse de Florian Faucher intitulé « Contributions to Seismic Full Waveform inversion for harmonic wave equations: stability estimates, convergence analysis, numerical experiments involving large scale optimization algorithms »

The manuscript is a very impressive investigation of high-resolution seismic imaging where both mathematical framework and numerical investigation on rather detailed realistic cases have been investigated. The manuscript is well-written and illustrates a high-quality work of the student with a rigorous mathematical writing. The work of Florian Faucher has been presented in different international workshops and conferences. One paper has been published in SIAM and two are on the way to be submitted.

The author has chosen to work in the frequency domain which allows some specific advantages (boundary conditions, attenuation, frequency decimation among others). It will be nice to hear more about drawbacks of such approach. I have appreciated the historical description of the wave theory which highlights recent progresses and difficulties. Maybe the name of Lamb and his theory of elasticity at the beginning of the XX century could be mentioned.

Wave propagation as the forward problem has required the attention of Florian Faucher and, obviously, he has acquired a deep expertise on the different techniques from the classical finite-difference method (FD) to the more involved continuous (FE/CG) and discontinuous (DG) finite-element method (Galerkin formulation) with its more or less recent hybridizable variation (HDG).

Chapter 1 described the differential formulation of the wave equation including anisotropy with the TTI description related to the so-called Bond transformation. Obviously, the author wanted to describe carefully the different hypothesis behind the wave propagation in elastic media with a rather complete list of textbooks. The different PDEs are well described and obviously Florian Faucher is aware, through this terminology, that wave propagation is not reduced to the scalar equation or the Helmholtz in the frequency domain. He takes benefit of the frequency formulation for introducing the attenuation as a model parameter related to complex velocity. Of course, it could be nice to mention that attenuation is related to a decrease of oscillations well described in this manuscript and representing waves. He has put some attention on boundary conditions and source conditions. Initial conditions are of importance as well for the uniqueness of the solution. Analytical solutions are provided in an homogeneous medium for underlining the geometrical decrease depending on the space dimension. It is well known that even spaces are more complex than odd spaces.
Unfortunately, the Earth is not homogeneous and the chapter 2 is devoted to numerical methods for solving wave propagation in heterogeneous media. I am impressed by the number of different techniques used by Florian Faucher from FD to HDG. Florian Faucher has taken benefit from previous intensive works of PhD students of the research project Magic3D led by Hélène Barucq, especially the work of Bonnasse-Gahot on HDG approach. Boundary conditions are mentioned making a difference between the physical one such as the free surface condition and the numerical one for mimicking a semi-infinite medium. Obviously Florian Faucher has no difficulties in the assimilation and in the use of these different approaches. As underlined at the end, the forward problem should be robust, efficient and fast. I guess this is the reason he has disregarded iterative methods to put his attention on direct solvers for solving the numerical discretized system.

Chapter 3 is a more mathematical analysis regarding the conditional Lipschitz stability of the non-linear and ill-posed inverse problem. The Calderón problem is formulated: it will be nice to connect it with one transformation usually done for the parabolic one-way Helmholtz equation by considering $p/\sqrt{\rho}$ which is related to the energy-flux condition. Of course, I would have wished to have more details regarding the generalization of the Calderón problem to the acoustic propagation. The stability condition is inspired with previous theoretical works and Florian Faucher has added intensive numerical analysis of such stability condition. This analysis drives him to wavelet description using Haar wavelets which is one way for considering piecewise constant velocity sampling. For Cauchy data, the extension could be for piecewise linear decomposition which allows more freedom. Aside the theoretical analysis, the important topic of the model parametrization is underlined: structured decomposition or unstructured decomposition (or mixed?). The problem one could identify should be the relation between this description of the model and the discretization needed for the forward modeling: a topic that should be considered by the author. This chapter results into an important result which provides some well-based formulation of the inverse problem. It is an illustration of the willingness of Florian Faucher to have a consistent formulation of the optimization. With my background, I have difficulties to understand the different steps in the demonstration procedure, but this has ended up with a publication which is a way to validate this analysis.

Chapter 4 is devoted to the Full Waveform Inversion (FWI) embedded in the vast literature on seismic imaging. Florian Faucher is aware of the different techniques and workflows for such image reconstruction. I appreciate, aside his extensive description, the fact that he is interested in dual sensors related to Cauchy data. It could be also considered for fixed-spread deployment where both hydrophones and geophones are collocated for marine acquisition. One may wonder how to overcome this issue for on-shore acquisition: suggestion for future acquisition could be very welcome. As the data is in the frequency domain, the gradient has to be estimated carefully with complex differentiation. It will be interesting to have expressions when considering attenuation because the model space will be also complex. Florian Faucher presents the now familiar adjoint formulation for deducing this gradient. Manipulations of the different PDEs allow a separation between operators involving spatial derivatives and those involving model parameters: a simplification which is not specific to the Helmholtz equation, leading to the simplification quoted by Florian Faucher. This question is of particular importance for the HDG formulation and the author has presented a careful analysis of the adjoint formulation for such formulation. Formal deduction of the Hessian-vector product is obtained as well as when considering the Gauss-Newton approximation, especially for multiple parameters. The Newton equation can be solved via a conjugate-gradient method using standard approaches, especially those related to the quadratic behavior of the Hessian operator. Florian Faucher mentions also possible higher-order adjoint formulation which should be setup inside the framework of FWI: is it related to the inversion problem beyond Newton equation requiring only second-order derivatives or is it related to an excursion toward more sophisticated diffraction approaches based on multiple scatterings? Without these perspectives, we stay with a formal description without no immediate objectives. Nethertheless, Florian Faucher has a complete understanding of the different algorithms (l-BFGS, step-length estimation) for handling such optimization while not forgetting the source inversion neither the complex frequency ingredient.
Numerical illustrations on the Marmousi model on the different variants of the descent algorithm show his intensive search for proper algorithms. Florian Faucher observes that the Hessian provides a more accurate reconstruction at least on synthetic data with another model as well. Let us mention that he has also investigated the influence of a variable density in relation with the joint inversion of the density and the bulk modulus: a challenge giving rise to various complementary questions such as the choice of the most pertinent set of parameters. This chapter by itself is an illustration of the vast amount of work achieved by Florian Faucher.

The chapter 5 is a crucial one, because Florian Faucher tackles the influence or sensitivity of the reconstruction with respect to frequency sampling, data availability (related to the acquisition design), parameter sampling and model geometry. Each question is quite difficult to answer and Florian Faucher has proceeded both theoretically and numerically. I read with interest the different analysis he has performed related to the basin attraction for least-squares problem. Simple geometries, frequency content of the data involved in the inversion, multiple parameters are few items which have been investigated numerically. Simple lessons are difficult to dress up, because of the number of possible linked effects. One point is the strategy from low-to-high frequencies while boundary conditions could provide more complex patterns requiring even low frequencies. One learning step is the importance of the parametrization of the model where the slowness (and its square related to diffraction kernel) is clearly preferred to the velocity. The complex patterns of the sensitivity kernel (Fréchet derivative) related to various parameter sets make general conclusions, but Florian Faucher has proposed few guidelines in his conclusion for better behaviours of the FWI, related to the data design feeding the inversion procedure as well as the model design related to the parameter setting. By doing so, Florian Faucher has reached a deep understanding of the non-linear behaviour of FWI, making this approach much more difficult to monitor than any migration strategy.

The chapter 6 is an impressive list of numerical experiments which are about 10 different realizations. Let us quote here the issues he analyzes in this chapter: effect of noise, the model compression, the variability of medium properties, especially high contrasts, the density insensitivity, the surface waves sampling the medium in a very specific way. I have noticed difficulties with complex frequencies when considering noise, although considering complex frequencies easy the convergence when properly handled, especially when considering the problem of salt dome reconstruction. The Louro model in 3D geometry is considered as well and illustrated that Florian Faucher has overcome computer challenges in his research investigation. Attenuation influence and surface waves impact are also widely illustrated. Even Florian Faucher has considered TTI parameters and he has found that some parameters are mostly used as garbage parameters while the ones related to kinematic information such as velocities are much better constrained. I may see this chapter has a learning investigation of how behaves the FWI in various conditions. It is again an illustration of the amount of work performed by Floriant Faucher during his PhD training.

The chapter 7 has attracted my interest because of the data considered related to Cauchy data, which means when having available a field and its derivative. What could we expect to achieve with this additional information? The introduction of a misfit function connected with the second Green identity seems to be very original as long as we have access to the pressure and its normal derivative with respect to the boundary: for marine experiment, it is related to the water surface and, therefore, to the vertical acceleration. Illustrations with mono-frequency and multi-frequency data are quite promising on one hand. On the other hand, the disconnection between observed and synthetic configuration could be also quite appealing. Moreover, Florian Faucher mentions perspectives for rotational seismology. Obviously, Florian Faucher has a broad knowledge of the different topics connected to seismic imaging.

The conclusion of his PhD research gives an idea of the work achieved by Florian Faucher who has considered both theoretical formulation and numerical analysis of the Full Waveform Inversion with...
detailed investigations of gradient, Hessian, multiple parameters, data manipulation. He has shown that he is interested both by analytical understanding and numerical illustrations. He has introduced new concepts, careful analysis of both theoretical results and numerical experiments. One may wish that he will go further toward real data by interacting with other people.

Following his impressive amount of work and his careful writing of a dense and exceptional manuscript, I recommend that Florian Faucher deserves the title of doctor of the Univ. de Pau et des Pays de l'Adour

Grenoble 2 October 2017

Jean Virieux
Professeur émérite de l'Université Grenoble Alpes
Jean Virieux