IN PARTNERSHIP WITH:
**CNRS**

**Université de Pau et des Pays de l'Adour**

# Activity Report 2019

# **Project-Team MAGIQUE-3D**

## Advanced 3D Numerical Modeling in Geophysics

IN COLLABORATION WITH: Laboratoire de mathématiques et de leurs applications (LMAP)

RESEARCH CENTER
**Bordeaux - Sud-Ouest**

THEME
**Earth, Environmental and Energy Sciences**

# Table of contents

## Project-Team MAGIQUE-3D

*Creation of the Project-Team: 2007 July 01*

**Keywords:**

**Computer Science and Digital Science:**

A6. - Modeling, simulation and control
A6.1. - Methods in mathematical modeling
A6.1.1. - Continuous Modeling (PDE, ODE)
A6.1.4. - Multiscale modeling
A6.1.5. - Multiphysics modeling
A6.2. - Scientific computing, Numerical Analysis & Optimization
A6.2.1. - Numerical analysis of PDE and ODE
A6.2.7. - High performance computing
A6.3.1. - Inverse problems
A6.5. - Mathematical modeling for physical sciences
A6.5.1. - Solid mechanics
A6.5.4. - Waves

**Other Research Topics and Application Domains:**

B3. - Environment and planet
B3.3. - Geosciences
B3.3.1. - Earth and subsoil
B4. - Energy
B4.1. - Fossile energy production (oil, gas)
B5.2. - Design and manufacturing
B5.5. - Materials
B5.7. - 3D printing
B9.2.1. - Music, sound
B9.5.2. - Mathematics
B9.5.3. - Physics

# 1. Team, Visitors, External Collaborators

**Research Scientists**

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Julien Diaz [Inria, Senior Researcher, HDR]
Ha Howard Faucher [Inria, Researcher]
Yder Masson [Inria, Starting Research Position]

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Titly Farhana Faisal [Inria, Post-Doctoral Fellow]
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Alexandre Gras [Institut d'optique graduate school, PhD Student]
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Guillaume Castera [Inria, Intern, from Jun 2019 until Sep 2019]
Inga Girshfeld [California State University at Northridge, Intern, from Jun 2019 until Jul 2019]
Marin Pobel [Inria, Intern, from May 2019 until Jul 2019]
Alexis Thibault [Ecole Normale Supérieure Paris, Intern, from Apr 2019]
Vinduja Vasanthan [Inria, Intern, from Mar 2019 until Aug 2019]

# 2. Overall Objectives

## 2.1. General setting

MAGIQUE-3D is a joint project-team between Inria and the Department of Applied Mathematics of the University of Pau (LMAP), in partnership with CNRS. The main mission of MAGIQUE-3D is to develop and validate efficient solution methodologies for solving complex three-dimensional geophysical problems, with a particular emphasis on problems arising in seismic imaging, in response to the local industrial and community needs. Indeed, as it is well known, the region of Pau has long-standing tradition in the Geosciences activities. However, in spite of the recent significant advances in algorithmic considerations as well as in computing platforms, the solution of most real-world problems in this field remains intractable. Hence, there is a scientific need of pressing importance to design new numerical methods for solving efficiently and accurately wave propagation problems defined in strongly heterogeneous domains. More recently, MAGIQUE-3D has launched a research program in computational helioseismology. The idea is to apply seismic imaging techniques for understanding the interior of the Sun. This new research area will lead the team to develop new full waveform simulations of vector wave problems including new physical parameters like the gravity. Still in the spirit of widening its scope of applications from its skills in seismic imaging, MAGIQUE-3D has also developed a strong research partnership for the design of wind instruments based upon the solution of inverse problems.

MAGIQUE-3D program possesses an exceptional combination that is a prerequisite for accomplishing its mission: the investigator backgrounds, research interests, and technical skills complement to form a research team with a potential for significant impact on the computational infrastructure of geophysical, acoustical and astrophysical sciences. The research record of MAGIQUE-3D group covers a large spectrum of accomplishments in the field of wave propagation including (a) the design, validation, and performance assessment of a class of DG-methods for solving efficiently high frequency wave problems, (b) the construction, convergence analysis, and performance assessment of various absorbing-type boundary conditions that are key ingredients for solving problems in infinite domains, (c) the development of asymptotic models that are the primary candidate in the presence of heterogeneities that are small compared to the wave length, and (d) the development and analysis of high-order time schemes for solving time-dependent wave problems. Very recently, the team has also opened its research activities to laboratory experiments which help to improve wave modelling by giving a straightforward access to measurements that can be used for calibration. MAGIQUE-3D has built strong collaborations and partnerships with various institutions including (a) local industry (TOTAL), (b) national research centers (ONERA and CEA), and (c) international academic partnerships (e.g. Interdisciplinary Research Institute for the Sciences (IRIS) at California State University, Northridge, USA; University of Pays Basque and Basque Center of Applied Mathematics at Bilbao, Spain; University of California at Berkeley, Lawrence Berkeley National Laboratory, Max Planck Institute at Göttingen).

# 3. Research Program

## 3.1. Introduction

Probing the invisible is a quest that is shared by a wide variety of scientists such as archaeologists, geologists, astrophysicists, physicists, etc... Magique-3D is mainly involved in Geophysical imaging which aims at understanding the internal structure of the Earth from the propagation of waves. Both qualitative and quantitative information are required and two geophysical techniques can be used: **seismic reflection** and **seismic inversion**. Seismic reflection provides a qualitative description of the subsurface from reflected seismic waves by indicating the position of the reflectors while seismic inversion transforms seismic reflection data into a quantitative description of the subsurface. Both techniques are inverse problems based upon the numerical solution of wave equations. Oil and Gas explorations have been pioneering application domains for seismic reflection and inversion and even if numerical seismic imaging is computationally intensive, oil companies clearly promote the use of numerical simulations to provide synthetic maps of the subsurface. This is due to the tremendous progresses of scientific computing which have pushed the limits of existing numerical methods and it is now conceivable to tackle realistic 3D problems. However, mathematical wave modeling has to be well-adapted to the region of interest and the numerical schemes which are employed to solve wave equations have to be both accurate and scalable enough to take full advantage of parallel computing. Today, geophysical imaging tackles more and more realistic problems and we contribute to this task by improving the modeling and by deriving advanced numerical methods for solving wave problems.

MAGIQUE-3D research program is divided into four axes that are: (1) Imaging the Earth; (2) Exploring the Sun; (3) Detecting defaults in complex media; (4) Designing objects with a variety of shapes. Those applications stand out from the collaborations that we have established with interested end-user groups. It is worth noting that they share basic common methodologies which imparts consistency to our program despite they may appear quite distant. MAGIQUE-3D keep modeling and simulating geophysical phenomena for understanding the Earth interior and developing its resources sustainably, and our xperience with numerical geophysics may help us to address other challenging applications. We mainly used DG finite elements and spectral elements and both have demonstrated very good performance. However, in particular for reducing the computational costs and/or for better capturing the propagation characteristics, we are working on the development of hybrid solvers based on the coupling of different finite element methods. Other open questions deserve attention like the problem of numerical pollution or the poor scalability of decomposition domain techniques which are both significantly hampering computations in very large domains. For those purposes, we focus ourselves on the development of Trefftz-like approximations that are based on a particular computation of the fluxes by making a judicious use of an auxiliary numerical method (e.g. boundary integral equations, spectral elements, etc...). Those problems cannot be ignored and can be found in all of our research axes. In addressing those issues, we participate in the construction of new numerical schemes and for that purpose, we continuously need to improve our understanding of the underlying physics. By this way, we make our mathematical models evolve to more realistic representations of the wave propagation phenomenon. This motivated us to introduce experimental studies in our activities and to collaborate with geophysicists of the UPPA who own experimental devices adapted to our concerns. Moreover, we have hired recently Yder Masson who is an experienced researcher developing modeling and imaging methods to investigate the Earth's internal structure. This creates all the conditions for improving our mathematical representation of waves in complex media. It is worth noting that modeling is a concern for both geophysicists and mathematicians. Indeed, the Physics must be reproduced accurately and the underlying mathematical properties should be clarified. By this way, we can develop a numerical scheme respecting the main properties of the continuous problem of interest (energy conservation or attenuation, stability, well-posedness, etc...). Magique-3D proposes to define its research program from in-house accurate solution methodologies for simulating wave propagation in realistic scenarios to various applications involving trans-disciplinary efforts. The development of high-order numerical methods for wave simulations is serving as a basis for our contributions regarding applications. In particular, we pursue and strengthen our collaboration with HPC teams, in order to improve the scalability of our codes and to run them on very large heterogeneous architectures (using task based programming libraries as StarPU developed by Inria project-team Storm, improving the I/O by collaborating with UFRGS at Porto Alegre, using the metaprogramming framework Boast developed by Inria project-team Corse to produce portable and efficient computing kernels). We are also continuing our collaboration with Inria project team Hiepacs on the use of hybrid linear solvers, by considering the multiple Right-Hand Sides feature and by integrating appropriate transmission conditions between the various domains. During 2019, we have worked a lot on: (a) High-order numerical methods for modeling wave propagation in porous media: development and implementation; (b) Understanding the interior of the Earth and the Sun by solving inverse problems; (c) Full waveform inversion for the optimal design of wind musical instruments.

## 3.2. High-order numerical methods for modeling wave propagation in porous media: development and implementation

We aim at achieving the characterization of conducting porous media which are media favoring the conversion of seismic waves into electromagnetic waves.. This project is identified as a "New scientific challenge" which is a set of research projects funded by the E2S project of UPPA. The shape and form of porous media can vary depending on the size of the pore and the structure of the solid skeleton. Porous media are found in the nature (sandstone, volcanic rocks, etc) or can be manufactured (concrete, polyurethane foam, etc) as depicted in [68]. Instead of modeling such media as strongly heterogeneous, homogenization is used to describe the material on a macroscopic scale. Biot's theory describes the solid skeleton according to linear elasticity and adds to this the Navier-Stokes equation for a viscous fluid and Darcy's law governing the motion of the fluid [63], [61]. For simplified linear elasticity, there are one equation of motion and one constitutive law, with the unknowns being the displacement field in the solid and the solid stress. In poro-elasticity, the added unknowns are the fluid displacement relative to the solid and the fluid pressure. There are two equations of motion, coupled with two constitutive laws. By plane wave analysis, one obtains three types of waves: S wave, fast P wave and slow P wave (Biot's wave). While the first two types are similar to those existing in elastic solid, the existence of a third wave with drastically smaller speed adds to the complications already encountered in elasticity. This is obviously even more challenging for conducting poroelastic media where the three poroelastic waves are coupled with an electric field. In this case, it is not realistic to use a unique scheme for all the waves. Standard finite element methods coupled with time schemes have indeed difficulties to deliver accurate solutions because there is a need of adapting the mesh size to the smallest wave velocity and the time discretization to the largest wave velocity. It is then tricky to numerically reproduce the Biot's wave while approximating correctly the regular elastic waves P and S. Moreover, there is a challenging question about the boundary condition to be used for limiting the computational domain. We have launched a Ph.D project (Rose-Cloé Meyer) aiming at developing a new piece of software for the simulation of time-harmonic waves in conducting porous media.

This project is developed in collaboration with Steve Pride from the Lawrence Berkeley National Laboratory who has elaborated the corresponding physical theory [83], [87], [73], [74]. Next, once a new numerical method is developed, it is validated by comparing the numerical solution to an analytical one. This is a key step to us for assessing the accuracy of our simulations. Nevertheless, analytical solutions are not available for realistic media such as poroelastic or viscoelastic media represented by heterogeneous parameters. Engineers still argue that simulations may be inaccurate and could lead to wrong conclusions. Fortunately, it is possible to produce experimentally quite complex configurations where multi-physics measurements are used to monitor the wave propagation. There is thus a possibility of moving further on the validation of the numerical methods by comparing simulations and experiments. What is very exciting is that experiments are used to validate numerical methods which have the objective of simulating new phenomena that are not possible to reproduce in a lab. We have launched two Ph.D thesis (Chengyi Shen and Victor Martins Gomes) in collaboration with Daniel Brito (LFCR-UPPA) on the comparison of simulations with experiments. This topic is connected to another project that we have with Total on the use of waves for characterizing carbonates.

## 3.3. Understanding the interior of the Earth and the Sun by solving inverse problems

Even if the Earth and the Sun are actually very different media, their imaging is based on the same solution methodology [64]. However, our knowledge on Earth inversion is far more developed than for the Sun. Earth inversion is in the continuation of previous MAGIQUE-3D achievements while Sun inversion requires developing new technologies based on modeling, numerical analysis and implementation of a piece of software which is able to ask for new developments. For instance, we would like to develop a HDG software package for solving Galbrun and Linearized Euler equations. To the best of our knowledge, this has never be done and would be a major milestone for tackling vectorial equations. Regarding the modeling, we are pursuing our collaboration with the Max Planck Institute for Solar System Research (Göttingen, Germany) in the framework of the associate team ANTS. This partnership is essential to us for understanding a complex (and new to us) physics including gravity waves that we have never considered in the past. Even if we dispose of advanced solvers dealing with elasticity, the development of fast and accurate solvers for reproducing waves travelling in large 3D domains is still one of the positive developments towards realistic simulations. In particular, the techniques for the forward discretization and linear system solver must evolve accordingly to resolve large scale time-harmonic problems. For instance, we have elaborated a space-time Trefftz-DG formulation of the elasto-acoustic problem [58], which performs very well regarding the number of dofs and the order of convergence. We have also coupled spectral and DG elements to take advantage of both methods and we have performed some simulations which are very promising [57]. The formulation of FWI is in progress in the framework of Pierre Jacquet thesis launched in November 2017. Finally, we have also initiated research on seismology at the planetary scale, with the arrival of Yder Masson on the subject and new collaborators (such as Berkeley lab). This will further help widen our expertise on inverse wave problems and will feed all the four research axes of the future team-project. Regarding industrial partnerships, we have collaboration with Total and the SME RealtimeSeismic (Pau, France). We also continue to work with the UPV, the BCAM and the BSC, namely in the framework of Mathrocks project.

## 3.4. Hybrid time discretizations of high-order

Most of the meshes we consider are composed of cells greatly varying in size. This can be due to the physical characteristics (propagation speed, topography, ...) which may require to refine the mesh locally, very unstructured meshes can also be the result of dysfunction of the mesher. For practical reasons which are essentially guided by the aim of reducing the number of matrix inversions, explicit schemes are generally privileged. However, they work under a stability condition, the so-called Courant Friedrichs Lewy (CFL) condition which forces the time step being proportional to the size of the smallest cell. Then, it is necessary to perform a huge number of iterations in time and in most of the cases because of a very few number of small cells. This implies to apply a very small time step on grids mainly composed of coarse cells and thus, there is a risk of creating numerical dispersion that should not exist. However, this drawback can be avoided by using low degree polynomial basis in space in the small meshes and high degree polynomials in the coarse meshes. By this way, it is possible to relax the CFL condition and in the same time, the dispersion effects are limited. Unfortunately, the cell-size variations are so important that this strategy is not sufficient. One solution could be to apply implicit and unconditionally stable schemes, which would obviously free us from the CFL constraint. Unfortunately, these schemes require inverting a linear system at each iteration and thus needs huge computational burden that can be prohibitive in 3D. Moreover, numerical dispersion may be increased. Then, as second solution is the use of local time stepping strategies for matching the time step to the different sizes of the mesh. There are several attempts [65], [60], [82], [79], [71] and Magique 3D has proposed a new time stepping method which allows us to adapt both the time step and the order of time approximation to the size of the cells. Nevertheless, despite a very good performance assessment in academic configurations, we have observed to our detriment that its implementation inside industrial codes is not obvious and in practice, improvements of the computational costs are disappointing, especially in a HPC framework. Indeed, the local time stepping algorithm may strongly affect the scalability of the code. Moreover, the complexity of the algorithm is increased when dealing with lossy media [76].

Recently, Dolean *et al* [70] have considered a novel approach consisting in applying hybrid schemes combining second order implicit schemes in the thin cells and second order explicit discretization in the coarse mesh. Their numerical results indicate that this method could be a good alternative but the numerical dispersion is still present. It would then be interesting to implement this idea with high-order time schemes to reduce the numerical dispersion. The recent arrival in the team of J. Chabassier should help us to address this problem since she has the expertise in constructing high-order implicit time scheme based on energy preserving Newmark schemes [62]. We propose that our work be organized around the two following tasks. The first one is the extension of these schemes to the case of lossy media because applying existing schemes when there is attenuation is not straightforward. This is a key issue because there is artificial attenuation when absorbing boundary conditions are introduced and if not, there are cases with natural attenuation like in visco-elastic media. The second one is the coupling of high-order implicit schemes with high-order explicit schemes. These two tasks can be first completed independently, but the ultimate goal is obviously to couple the schemes for lossy media. We will consider two strategies for the coupling. The first one will be based on the method proposed by Dolean *et al*, the second one will consist in using Lagrange multiplier on the interface between the coarse and fine grids and write a novel coupling condition that ensures the high order consistency of the global scheme. Besides these theoretical aspects, we will have to implement the method in industrial codes and our discretization methodology is very suitable for parallel computing since it involves Lagrange multipliers. We propose to organize this task as follows. There is first the crucial issue of a systematic distribution of the cells in the coarse/explicit and in the fine/implicit part. Based on our experience on local time stepping, we claim that it is necessary to define a criterion which discriminates thin cells from coarse ones. Indeed, we intend to develop codes which will be used by practitioners, in particular engineers working in the production department of Total. It implies that the code will be used by people who are not necessarily experts in scientific computing. Considering real-world problems means that the mesh will most probably be composed of a more or less high number of subsets arbitrarily distributed and containing thin or coarse cells. Moreover, in the prospect of solving inverse problems, it is difficult to assess which cells are thin or not in a mesh which varies at each iteration.

Another important issue is the load balancing that we can not avoid with parallel computing. In particular, we will have to choose one of these two alternatives: dedicate one part of processors to the implicit computations and the other one to explicit calculus or distribute the resolution with both schemes on all processors. A collaboration with experts in HPC is then mandatory since we are not expert in parallel computing. We will thus continue to collaborate with the team-projects Hiepacs and Runtime with whom we have a long-term experience of collaborations. The load-balancing leads then to the issue of mesh partitioning. Main mesh partitioners are very efficient for the coupling of different discretizations in space but to the best of our knowledge, the case of non-uniform time discretization has never been addressed. The study of meshes being out of the scopes of Magique-3D, we will collaborate with experts on mesh partitioning. We get already on to François Pellegrini who is the principal investigator of Scotch (http://www.labri.fr/perso/pelegrin/scotch) and permanent member of the team project Bacchus (Inria Bordeaux Sud Ouest Research Center).

In the future, we aim at enlarging the application range of implicit schemes. The idea will be to use the degrees of freedom offered by the implicit discretization in order to tackle specific difficulties that may appear in some systems. For instance, in systems involving several waves (as P and S waves in porous elastic media, or coupled wave problems as previously mentioned) the implicit parameter could be adapted to each wave and optimized in order to reduce the computational cost. More generally, we aim at reducing numeric bottlenecks by adapting the implicit discretization to specific cases.

## 3.5. Full waveform inversion for the optimal design of wind musical instruments

Makers have improved wind musical instruments (as flutes, trumpets, clarinets, bassoons, ...) in the past by a “trial and error” procedure, where the final sound and ease of the instrument in playing conditions are the main criteria. Although the playing context should still be the final reference, we can consider intermediate measurements of the pipe entry impedance [75], [69], which quantifies the Dirichlet-to-Neumann map of the wave propagation in the pipe, and relies on mathematical simulations based on accurate and concise models of the pipe [84], [59] and the embouchure [77], [59], [55], [56], [86] in order to foresee the behavior of a given instrument, and therefore optimize it. A strong interaction with makers and players is necessary for defining both operable criteria quantified as a cost function and a design parameters space. We aim at building efficient musical instrument via handcrafted techniques but also modern tools as additive synthesis (3D printers). We plan to implement state-of-the-art numerical methods (finite elements, full waveform inversion, neuronal networks fed by numerical simulations, diverse optimization techniques...) that are versatile (in terms of models, formulations, couplings...) in order to solve the optimization problem, after a proper modeling of the linear and nonlinear coupled phenomena. We wish to take advantage of the fact that sound waves in musical instruments satisfy the laws of acoustics in pipes (PDEs), which leads to use FWI technique, in harmonic or temporal regime. We propose to implement an iterative process between instrument making and optimal design in order to build instruments that optimize tone quality and playability. We are currently collaborating with musical acoustics teams who have a strong experimental background on this question [66], [67] [DCY12, DF07, GPP98], we wish to strenghten the links we have with other teams [78], [72], [80], [81], [85], we will participate to professional clusters [ITE], and we are currently collaborating with makers and museums directly : Augustin Humeau (Dordogne) for the bassoon, Luc Gallois (Oise) and the Museum of Cité de la Musique - Philharmonie de Paris for the brass instruments. This research axis is surely the most exploratory of our research program and follows the successful ”Exploratory Research Program” Inria grant obtained in 2017. It could pave the way for significant progresses in inverse problem solving. Indeed, the problem depends on a few number of parameters unlike geophysical or astrophysical problems. We can thus use it to test different methods like neuronal networks, statistical methods, coupling with nonlinear phenomena, and decide if it could be applied to large scale applications.

# 4. Application Domains

## 4.1. Seismic Imaging

The main objective of modern seismic processing is to find the best representation of the subsurface that can fit the data recorded during the seismic acquisition survey. In this context, the seismic wave equation is the most appropriate mathematical model. Numerous research programs and related publications have been devoted to this equation. An acoustic representation is suitable if the waves propagate in a fluid. But the subsurface does not contain fluids only and the acoustic representation is not sufficient in the general case. Indeed the acoustic wave equation does not take some waves into account, for instance shear waves, turning waves or the multiples that are generated after several reflections at the interfaces between the different layers of the geological model. It is then necessary to consider a mathematical model that is more complex and resolution techniques that can model such waves. The elastic or viscoelastic wave equations are then reference models, but they are much more difficult to solve, in particular in the 3D case. Hence, we need to develop new high-performance approximation methods.

Reflection seismics is an indirect measurement technique that consists in recording echoes produced by the propagation of a seismic wave in a geological model. This wave is created artificially during seismic acquisition surveys. These echoes (i.e., reflections) are generated by the heterogeneities of the model. For instance, if the seismic wave propagates from a clay layer to sand, one will observe a sharp reflected signal in the seismic data recorded in the field. One then talks about reflection seismics if the wave is reflected at the interface between the two media, or talks about seismic refraction if the wave is transmitted along the interface. The arrival time of the echo enables one to locate the position of this transition, and the amplitude of the echo gives information on some physical parameters of the two geological media that are in contact. The first petroleum exploration surveys were performed at the beginning of the 1920's and for instance, the Orchard Salt Dome in Texas (USA) was discovered in 1924 by the seismic-reflection method.

## 4.2. Imaging complex media with ultrasonic waves

The acoustic behavior of heterogeneous or composite materials attracts considerable excitement. Indeed, their acoustic response may be extremely different from the single constituents responses. In particular, dispersions of resonators in a matrix are the object of large research efforts, both experimentally and theoretically. However it is still a challenge to dispose of numerical tools with sufficient abilities to deal with the simulation and imaging of such materials behavior. Indeed, not only acoustic simulations are very time-consuming, but they have to be performed on realistic enough solution domains, i.e. domains which capture well enough the structural features of the considered materials.

This collaboration with I2M, University of Bordeaux aims at addressing this type of challenges by developing numerical and experimental tools in order to understand the propagation of ultrasonic waves in complex media, image these media, and in the future, help design composite materials for industrial purposes.

## 4.3. Helioseismology

This collaboration with the Max Planck Institute for Solar System, Göttingen, Germany, which started in 2014, aims at designing efficient numerical methods for the wave propagation problems that arise in helioseismology in the context of inverse problems. The final goal is to retrieve information about the structure of the Sun i.e. inner properties such as density or pressure via the inversion of a wave propagation problem. Acoustic waves propagate inside the Sun which, in a first approximation and regarding the time scales of physical phenomena, can be considered as a moving fluid medium with constant velocity of motion. Some other simplifications lead to computational saving, such as supposing a radial or axisymmetric geometry of the Sun. Aeroacoustic equations must be adapted and efficiently solved in this context, this has been done in the finite elements code Montjoie. In other situations, a full 3D simulation is required and demands large computational resources. Ultimately, we aim at modeling the coupling with gravity potential and electromagnetic waves (MHD equations) in order to be able to better understand Sun spots.

# 5. Highlights of the Year

## 5.1. Highlights of the Year

Inria's Autumn school, November 4-8 2019, Inria Bordeaux Sud-Ouest co-organized by E. Agullo (HIEPACS), H. Beaugendre (CARDAMOM) and J. Diaz The school aimed at simulating a physical problem, from its modeling to its implementation in a high performance computing (HPC) framework. The school offered both plenary courses and hands-on sessions that involved many members of the three teams. The physical problem considered was the harmonic wave propagation.

The first day was dedicated to the modeling of the problem and its discretization using a Discontinuous Galerkin scheme. The following two days were dedicated to linear algebra for solving large sparse systems. Background on direct, iterative and hybrid methods for sparse linear systems were discussed. Hands-on on related parallel solvers were then be proposed. Has followed a session dedicated to advanced parallel schemes using task-based paradigms, including a hands-on with the starpu runtime system. The ultimate hands-on session was devoted to the use of parallel profiling tools. The school was closed with plenary talks illustrating the usage of such a workflow in an industrial context.

The hands-on session were conducted on the Federative Platform for Research in Computer Science and Mathematics (PlaFRIM) machine in a guix-hpc reproducible environment

The school was attended by about 40 participants mostly PhDs and postdocs from Inria teams.

# 6. New Software and Platforms

## 6.1. Elasticus

KEYWORDS: Discontinuous Galerkin - Acoustic equation - Elastodynamic equations - Elastoacoustic - 2D - 3D - Time Domain

SCIENTIFIC DESCRIPTION: Elasticus simulate acoustic and elastic wave propagation in 2D and in 3D, using Discontinuous Galerkin Methods. The space discretization is based on two kind of basis functions, using Lagrange or Jacobi polynomials. Different kinds of fluxes (upwind and centered) are implemented, coupled with RK2 and RK4 time schemes.

FUNCTIONAL DESCRIPTION: Elasticus is a sequential library, independent of Total plateform and developped in Fortran, to simulate wave propagation in geophysical environment, based on a DG method. It is meant to help PhD students and post-doctoral fellows to easily implement their algorithms in the library. Thus, readability of the code is privileged to optimization of its performances. Developped features should be easily transferred in the computing platform of Total. Elasticus manages arbitrary orders for the spatial discretization with DG method.

NEWS OF THE YEAR: In 2018, we implemented the coupling between hexahedra and tetrahedra and the coupling between Discontinuous Galerkin methods and Spectral Element methods in 2D and in 3D. We also introduced Perfectly Matched layers in the Spectral Element kernel.

- Participants: Julien Diaz, Lionel Boillot and Simon Ettouati
- Contact: Julien Diaz
- Publications: Spectral Element Method and Discontinuous Galerkin approximation for elasto-acoustic problems - Hybrid space discretization to solve elasto-acoustic coupling - On the coupling of Spectral Element Method with Discontinuous Galerkin approximation for elasto-acoustic problems - SEM-DG Approximation for elasto-acoustics

## 6.2. Hou10ni

KEYWORDS: 2D - 3D - Elastodynamic equations - Acoustic equation - Elastoacoustic - Frequency Domain - Time Domain - Discontinuous Galerkin

SCIENTIFIC DESCRIPTION: Hou10ni simulates acoustic and elastic wave propagation in time domain and in harmonic domain, in 2D and in 3D. It is also able to model elasto acoustic coupling. It is based on the second order formulation of the wave equation and the space discretization is achieved using Interior Penalty Discontinuous Galerkin Method. Recently, the harmonic domain solver has been extended to handle Hybridizable Discontinuous Galerkin Methods.

FUNCTIONAL DESCRIPTION: This software simulates the propagation of waves in heterogeneous 2D and 3D media in time-domain and in frequency domain. It is based on an Interior Penalty Discontinuous Galerkin Method (IPDGM) and allows for the use of meshes composed of cells of various order (p-adaptivity in space).

NEWS OF THE YEAR: In 2019, we have implemented the elasto-acoustic coupling and the poroelastic equations for the HDG formulation.

- Participants: Conrad Hillairet, Elodie Estecahandy, Julien Diaz, Lionel Boillot and Marie Bonnasse
- Contact: Julien Diaz
- Publications: Hybridizable discontinuous Galerkin method for the two-dimensional frequency-domain elastic wave equations - Convergence of seismic full waveform inversion and extension to Cauchy data - Convergence Analysis for Seismic Full Waveform Inversion - Stability and convergence analysis for seismic depth imaging using FWI - On the use of a laser ablation as a laboratory seismic source - Towards Energy-Efficient Storage Servers - Equivalent Robin Boundary Conditions for Acoustic and Elastic Media - Comparison of solvers performance when solving the 3D Helmholtz elastic wave equations over the Hybridizable Discontinuous Galerkin method - Comparison of solvers performance when solving the 3D Helmholtz elastic wave equations using the Hybridizable Discontinuous Galerkin method - Resolution strategy for the Hybridizable Discontinuous Galerkin system for solving Helmholtz elastic wave equations - Seismic imaging in laboratory trough laser Doppler vibrometry - Absorbing Boundary Conditions for 3D Elastic TTI Modeling, Application to Time-Based and Time-Harmonic Simulations - Shape and material parameter reconstruction of an isotropic or anisotropic solid immersed in a fluid - Modelling and advanced simulation of wave propagation phenomena in 3D geophysical media. - Multi-level explicit local time-stepping methods for second-order wave equations - Absorbing Boundary Conditions for 3D elastic TTI modeling - Modeling of elastic Helmholtz equations by hybridizable discontinuous Galerkin method (HDG) for geophysical applications - Performance Assessment on Hybridizable Dg Approximations for the Elastic Wave Equation in Frequency Domain - High-Order IPDG Approximations for Elasto-Acoustic Problems - High-order Discontinuous Galerkin approximations for elasto-acoustic scattering problems - Modelling of seismic waves propagation in harmonic domain by hybridizable discontinuous Galerkin method (HDG) - Absorbing Boundary Conditions for 3D Tilted Transverse Isotropic media - Performance comparison between hybridizable DG and classical DG methods for elastic waves simulation in harmonic domain - Polynomial speeds in a Discontinuous Galerkin code - Hybridizable Discontinuous Galerkin method for the simulation of the propagation of the elastic wave equations in the frequency domain - Discontinuous Galerkin methods for the simulation of the propagation of the elastic wave equations in the frequency domain - High order discontinuous Galerkin methods for time-harmonic elastodynamics - Hybridizable discontinuous Galerkin method for the two-dimensional frequency-domain elastic wave equations - Efficient DG-like formulation equipped with curved boundary edges for solving elasto-acoustic scattering problems - Numerical schemes for the simulation of seismic wave propagation in frequency domain - Performance analysis of DG and HDG methods for the simulation of seismic wave propagation in harmonic domain - Hybridizable Discontinuous Galerkin method for solving Helmholtz elastic wave equations - Discontinuous Galerkin methods for solving Helmholtz elastic wave equations for seismic imaging - Performance comparison of HDG and classical DG method for the simulation of seismic wave propagation in harmonic domain - Contributions to the mathematical modeling and to the parallel algorithmic for the optimization of an elastic wave propagator in anisotropic media - Contribution to the mathematical analysis and to the numerical solution of an inverse elasto-acoustic scattering problem
- URL: https://team.inria.fr/magique3d/software/hou10ni/

## 6.3. MONTJOIE

KEYWORDS: High order finite elements - Edge elements - Aeroacoustics - High order time schemes

SCIENTIFIC DESCRIPTION: Montjoie is designed for the efficient solution of time-domain and time-harmonic linear partial differential equations using high-order finite element methods. This code is mainly written for quadrilateral/hexahedral finite elements, partial implementations of triangular/tetrahedral elements are provided. The equations solved by this code, come from the "wave propagation" problems, particularly acoustic, electromagnetic, aeroacoustic, elastodynamic problems.

FUNCTIONAL DESCRIPTION: Montjoie is a code that provides a C++ framework for solving partial differential equations on unstructured meshes with finite element-like methods (continuous finite element, discontinuous Galerkin formulation, edge elements and facet elements). The handling of mixed elements (tetrahedra, prisms, pyramids and hexahedra) has been implemented for these different types of finite elements methods. Several applications are currently available : wave equation, elastodynamics, aeroacoustics, Maxwell's equations.

- Participants: Gary Cohen, Juliette Chabassier, Marc Duruflé and Morgane Bergot
- Contact: Marc Duruflé
- URL: http://montjoie.gforge.inria.fr/

## 6.4. tmodeling-DG

*Time-domain Wave-equation Modeling App*

KEYWORDS: 2D - 3D - Elastoacoustic - Elastodynamic equations - Discontinuous Galerkin - Time Domain

SCIENTIFIC DESCRIPTION: tmodeling-DG simulate acoustic and elastic wave propagation in 2D and in 3D, using Discontinuous Galerkin Methods. The space discretization is based on two kind of basis functions, using Lagrange or Jacobi polynomials. Different kinds of fluxes (upwind and centered) are implemented, coupled with RK2 and RK4 time schemes.

FUNCTIONAL DESCRIPTION: tmodelling-DG is the follow up to DIVA-DG that we develop in collaboration with our partner Total. Its purpose is more general than DIVA-DG and should contains various DG schemes, basis functions and time schemes. It models wave propagation in acoustic media, elastic (isotropic and TTI) media and elasto-acoustic media, in two and three dimensions.

NEWS OF THE YEAR: In 2018, we have coupled the code with a Reverse Time Migration algorithm.

- Participants: Julien Diaz, Lionel Boillot, Simon Ettouati and Hélène Barucq
- Partner: TOTAL
- Contact: Julien Diaz

## 6.5. OpenWind

*Open Wind Instrument Design*

KEYWORDS: Wave propagation - Inverse problem - Experimental mechanics - Image processing

FUNCTIONAL DESCRIPTION: Computes resonating pipes' impedance using one-dimensional finite element method with tonholes and fingering chart.

RELEASE FUNCTIONAL DESCRIPTION: account for toneholes as a pipe network using transmission matrices for pipe junctions [Chaigne & Kergomard]

- Authors: Robin Tournemenne, Juliette Chabassier, Alexis Thibault, Augustin Ernoult and Guillaume Castera
- Contact: Juliette Chabassier
- Publication: hal-01963674v2
- URL: https://gitlab.inria.fr/openwind/release

## 6.6. ffwi

*Frequency-domain Full Waveform Inversion*

KEYWORDS: 2D - 3D - Discontinuous Galerkin - Inverse problem - Frequency Domain - Acoustic equation - Elasticity

FUNCTIONAL DESCRIPTION: ffwi is developed in partnership with Total in the context of the Depth Imaging Partnership (DIP). It is devoted to perform seismic imaging using the Full Waveform Inversion method, in the frequency domain. It is based upon the software Fmodeling, which is itself dedicated to the forward problem. In FWI, the forward problem is solved using Hybridizable Discontinuous Galerkin Methods. The reconstruction of medium parameter is conducted with an iterative minimization scheme, which uses gradient descent techniques. The software can work with acoustic and elastic media, in two and three dimensions.

- Partner: TOTAL
- Contact: Florian Faucher

# 7. New Results

## 7.1. High-order numerical methods for modeling wave propagation in complex media: development and implementation

### *7.1.1. High order discretization of seismic waves-problems based upon DG-SE methods*

**Participants:** Hélène Barucq, Julien Diaz, Aurélien Citrain.

Accurate wave propagation simulations require selecting numerical schemes capable of taking features of the medium into account. In case of complex topography, unstructured meshes are the most adapted and in that case, Discontinuous Galerkin Methods (DGm) have demonstrated great performance. Off-shore exploration involves propagation media which can be well represented by hybrid meshes combining unstructured meshes with structured grids that are best for representing homogeneous media like water layers. Then it has been shown that Spectral Element Methods (SEm) deliver very accurate simulations on structured grids with much lower computational costs than DGms.

We have developed a DG-SEm numerical method for solving time-dependent elasto- acoustic wave problems. We consider the first-order coupled formulation for which we propose a DG-SEm formulation which turns out to be stable.

While the 2D case is almost direct, the 3D case requires a particular attention on the coupling boundary on which it is necessary to manage the possible positions of the faces of the tetrahedrons with respect to that of the neighboring hexaedra.

In the framework of this DG-SEm coupling, we are also interested in the Perfectly Matched Layer (PML) in particular the use of the SEm inside it to stabilize it in cases where the use of DGm leads to instabilities.

These results have been obtained in collaboration with Henri Calandra (TOTAL) and Christian Gout (INSA Rouen) and have been presented at Journées Ondes Sud-Ouest (JOSO) in Le Barp, the 14th International Conference on Mathematical and Numerical Aspects of Wave Propagation (WAVES) in Vienna (Austria) and MATHIAS conference in Paris [21], [26]

### *7.1.2. Isogeometric analysis of sharp boundaries in full waveform inversion*

**Participants:** Hélène Barucq, Julien Diaz, Stefano Frambati.

Efficient seismic full-waveform inversion simultaneously demands a high efficiency per degree of freedom in the solution of the PDEs, and the accurate reproduction of the geometry of sharp contrasts and boundaries. Moreover, it has been shown that the stability constant of the FWI minimization grows exponentially with the number of unknowns. Isogeometric analysis has been shown to possess a higher efficiency per degree of freedom, a better convergence in high energy modes (Helmholtz) and an improved CFL condition in explicit-time wave propagation, and it seems therefore a good candidate for FWI.

In the first part of the year, we have focused on a small-scale one-dimensional problem, namely the inversion over a multi-step velocity model using the Helmholtz equation. By exploiting a relatively little-known connection between B-splines ad Dirichlet averages, we have added the knot positions as degrees of freedom in the inversion. We have shown that arbitrarily-placed discontinuities in the velocity model can be recovered using a limited amount of degrees of freedom, as the knots can coalesce at arbitrary positions, obviating the need for a very fine mesh and thus improving the stability of the inversion.

In order to reproduce the same results in two and three dimensions, the usual tensor-product structure of B-splines cannot be used. We have therefore focused on the construction of (unstructured) multivariate B-spline bases. We have generalized a known B-spline basis construction through the language of oriented matroids, showing that multivariate spline bases can be easily constructed with repeated knots and that the construction algorithm can be extended to three dimensions. This gives the freedom to locally reduce the regularity of the basis functions and to place internal boundaries in the domain. The resulting mass matrix is block-dagonal, with adjustable block size, providing an avenue for a simple unstructured multi-patch DG-IGA scheme that is being investigated. With this goal in mind, more efficient quadrature schemes for multivariate B-splines exploiting the connection to oriented matroids are also being investigated.

A research report is in preparation.

### 7.1.3. Seismic wave propagation in carbonate rocks at the core scale

**Participants:** Julien Diaz, Florian Faucher, Chengyi Shen.

Reproduction of large-scale seismic exploration at lab-scale with controllable sources is a promising approach that could not only be applied to study small-scale physical properties of the medium, but also contribute to significant progress in wave-propagation understanding and complex media imaging at exploration scale via upscaling methods. We propose to apply a laser-generated seismic point source for core-scale new geophysical experiments. This consists in generating seismic waves in various media by well-calibrated pulsed-laser impacts and measuring precisely the wavefield (displacement) by Laser Doppler Vibrometer (LDV). The point-source-LDV configuration is convenient to model numerically. It can also favor the incertitude estimate of the source and receiver locations. Parallel 2D/3D simulations featuring the Discontinuous Galerkin discretization method with Interior Penalties (IPDG) are done to match the experimental data. The IPDG method is of particular interest when it comes to solve wave propagation problems in highly heterogeneous media, such as the limestone cores that we are studying.

Current seismic data allowed us to retrieve $V_p$ tomography slices. Further more, qualitative/quantitative comparisons between simulations and experimental data validated the experiment protocol and vice-versa the high-order FEM schemes, opening the possibility of performing FWI on dense, high frequency and large band-width data.

This work is in collaboration with Clarisse Bordes, Daniel Brito, Federico Sanjuan and Deyuan Zhang (LFCR, UPPA) and with Stéphane Garambois (ISTerre). Ii is one of the topic of the PhD. thesis of Chengyi Shen.

### 7.1.4. Simulation of electro-seismic waves using advanced numerical methods

**Participants:** Hélène Barucq, Julien Diaz, Ha Howard Faucher, Rose-Cloé Meyer.

We study time-harmonic waves propagation in conducting poroelastic media, in order to obtain accurate images for complex media with high-order methods. In these kind of media, we observe the coupling between electromagnetic and seismic wave fields, which is called seismokinetic effect. The converted waves are very interesting because they are heavily sensitive to the medium properties, and the modeling of seismo-electric conversion can allow to detect interfaces in the material where the seismic field would be blind. To the best of our knowledge, the numerical simulation of this phenomenon has never been achieved with high-order finite element methods. Simulations are difficult to perform in time domain, because the time step and the mesh size have to be adapted to the huge variations of wave velocities. To ease the numerical implementation, we work in the frequency domain. We can then include physical parameters that depend non-linearly on the frequencies. Then, we have developed a new Hybridizable Discontinuous Galerkin method for discretizing the equations. This allows us to reduce the computational costs by considering only degrees of freedom on the skeleton of the mesh. We have validated the numerical method thanks to comparison with analytical solutions. We have obtained numerical results for 2D realistic poroelastic media and conducting poroelastic media is under investigation.

Results on analytical solutions for poroelasticity are presented in the research report [44].

### 7.1.5. Quasinormal mode expansion of electromagnetic Lorentz dispersive materials

**Participants:** Marc Duruflé, Alexandre Gras.

We have studied the electromagnetic scattering of optical waves by dispersive materials governed by a Drude-Lorentz model. The electromagnetic fields can be decomposed onto the eigenmodes of the system, known as quasinormal modes. In [51], a common formalism is proposed to obtain different formulas for the coefficients of the modal expansion. In this paper, it is also explained how to handle dispersive Perfectly Matched Layers and degenerate eigenvectors. Lately, we have investigated the use of an interpolation method in order to compute quickly the diffracted field for a large number of frequencies.

### 7.1.6. A Hybridizable Galerkin Discontinuous formulation for elasto-acoustic coupling in frequency-domain

**Participants:** Hélène Barucq, Julien Diaz, Vinduja Vasanthan.

We are surrounded by many solid-fluid interactions, such as the seabed or red blood cells. Indeed, the seabed represents the ocean floors immersed in water, and red blood cells are coreless hemoglobin-filled cells. Hence, when wanting to study the propagation of waves in such domains, we need to take into account the interactions at the solid-fluid interface. Therefore, we need to implement an elasto-acoustic coupling. Many methods have already tackled with the elasto-acoustic coupling, particularly the Discontinuous Galerkin method. However, this method needs a large amount of degrees of freedom, which increases the computational cost. It is to overcome this drawback that the Hybridizable Discontinuous Galerkin (HDG) has been introduced. The implementations of HDG for the elastic wave equations, as well as partially for the acoustic ones, have been done previously. Using these, we have performed in this work the elasto-acoustic coupling for the HDG methods in 1D, 2D and 3D. The results are presented in Vinduja Vasanthan's master's thesis [54].

### 7.1.7. Absorbing Radiation Conidition in elongated domains

**Participants:** Hélène Barucq, Sébastien Tordeux.

We develop and analyse a high-order outgoing radiation boundary condition for solving three-dimensional scattering problems by elongated obstacles. This Dirichlet-to-Neumann condition is constructed using the classical method of separation of variables that allows one to define the scattered field in a truncated domain. It reads as an infinite series that is truncated for numerical purposes. The radiation condition is implemented in a finite element framework represented by a large dense matrix. Fortunately, the dense matrix can be decomposed into a full block matrix that involves the degrees of freedom on the exterior boundary and a sparse finite element matrix. The inversion of the full block is avoided by using a Sherman–Morrison algorithm that reduces the memory usage drastically. Despite being of high order, this method has only a low memory cost. This work has been published in [13].

### 7.1.8. Discontinuous Galerkin Trefftz type method for solving the Maxwell equations

**Participants:** Margot Sirdey, Sébastien Tordeux.

Trefftz type methods have been developed in Magique 3D to solve Helmholtz equation and it has been presented in [25].These methods reduce the numerical dispersion and the condition number of the linear system. This work aims in pursuing this development for electromagnetic scattering. We have adapted and tested the method for an academical 2D configuration. This is the topic of the PhD thesis of Margot Sirdey.

### 7.1.9. Reduced models for multiple scattering of electromagnetic waves

**Participants:** Justine Labat, Victor Péron, Sébastien Tordeux.

In this project, we develop fast, accurate and efficient numerical methods for solving the time-harmonic scattering problem of electromagnetic waves by a multitude of obstacles for low and medium frequencies in 3D. First, we consider a multi-scale diffraction problem in low-frequency regimes in which the characteristic length of the obstacles is small compared to the incident wavelength. We use the matched asymptotic expansion method which allows for the model reduction. Then, small obstacles are no longer considered as geometric constraints and can be modelled by equivalent point-sources which are interpreted in terms of electromagnetic multipoles. Second, we justify the Generalized Multiparticle Mie-solution method (Xu, 1995) in the framework of spherical obstacles at medium-frequencies as a spectral boundary element method based on the Galerkin discretization of a boundary integral equation into local basis composed of the vector spherical harmonics translated at the center of each obstacle. Numerically, a clever algorithm is implemented in the context of periodic structures allowing to avoid the global assembling of the matrix and so, reduce memory usage. The reduced asymptotic models of the first problem can be adapted for this regime by incorporating non-trivial corrections appearing in the Mie theory. Consequently, a change in variable between the two formulations can be made explicit, and an inherent advantage of the asymptotic formulation is that the basis and the shape can be separated with a semi-analytical expression of the polarizability tensors. A comparison of these different methods in terms of their accuracy has been carried out. Finally, for both methods and in the context of large numbers of obstacles, we implement an iterative resolution with preconditionning in a GMRES framework.

These results have been presented at Journées Ondes Sud-Ouest (JOSO) in Le Barp (France) and the 14th International Conference on Mathematical and Numerical Aspects of Wave Propagation (WAVES) in Vienna (Austria), see [22], [39]. Part of this work has been published in Wave Motion [17].

### *7.1.10. Boundary Element Method for 3D Conductive Thin Layer in Eddy Current Problems*

**Participant:** Victor Péron.

Thin conducting sheets are used in many electric and electronic devices. Solving numerically the eddy current problems in presence of these thin conductive sheets requires a very fine mesh which leads to a large system of equations, and becoming more problematic in case of high frequencies. In this work we show the numerical pertinence of asymptotic models for 3D eddy current problems with a conductive thin layer of small thickness based on the replacement of the thin layer by its mid-surface with impedance transmission conditions that satisfy the shielding purpose, and by using an efficient discretization with the Boundary Element Method in order to reduce the computational cost. These results have been obtained in collaboration with M. Issa, R. Perrussel and J-R. Poirier (LAPLACE, CNRS/INPT/UPS, Univ. de Toulouse) and O. Chadebec (G2Elab, CNRS/INPG/UJF, Institut Polytechnique de Grenoble). This work has been published in COMPEL - The international journal for computation and mathematics in electrical and electronic engineering, [16].

### *7.1.11. Asymptotic Models and Impedance Conditions for Highly Conductive Sheets in the Time-Harmonic Eddy Current Model*

**Participant:** Victor Péron.

This work is concerned with the time-harmonic eddy current problem for a medium with a highly conductive thin sheet. We present asymptotic models and impedance conditions up to the second order of approximation for the electromagnetic field. The conditions are derived asymptotically for vanishing sheet thickness where the skin depth is scaled like thickness parameter. The first order condition is the perfect electric conductor boundary condition. The second order condition turns out to be a Poincaré-Steklov map between tangential components of the magnetic field and the electric field. This work has been published in SIAM Journal on Applied Mathematics, [18].

## 7.2. Understanding the interior of the Earth and the Sun by solving inverse problems

### *7.2.1. Time-Domain Full Waveform Inversion based on high order discontinuous numerical schemes*

**Participants:** Hélène Barucq, Julien Diaz, Pierre Jacquet.

Full Waveform Inversion (FWI) allows retrieving the physical parameters (e.g. the velocity, the density) from an iterative procedure underlying a global optimization technique. The recovering of the medium corresponds to the minimum of a cost function quantifying the difference between experimental and numerical data. In this study we have considered the adjoint state method to compute the gradient of this cost function.

The adjoint state can be both defined as the adjoint of the continuous equation or the discrete problem. This choice is still under study and complementary results has been presented at WAVES 2019 conference in Vienna [38].

The FWI has been largely developed for time-harmonic wave problems essentially because of computational time which is clearly below the one of corresponding time-dependent problems. However, the memory cost in large 3D domain is overflowing the computer capabilities, which motivates us to develop a FWI algorithm in the time-domain. To fully exploit the information from the seismic traces, while preserving the computational cost, it is important to use an accurate and flexible discretization. For that purpose we study several time schemes such as Runge-Kutta 2/4 or Adam-Bashforth 3 and regarding the space discretization, we employ Discontinuous Galerkin (DG) elements which are well-known not only for their h and p adaptivities but also for their massively parallel computation properties.

In the work-flow of DIP a Reverse Time Migration (RTM) code has been developed in collaboration with Total using their Galerkin Discontinuous acoustic time domain solver. Then this code served as a prototype of the time domain FWI code called utFWI (Unstructured Time-Domain Full Waveform Inversion) (https://bil.inria.fr/fr/software/view/3740/tab). Thanks to this code, 2D acoustic multi-scale reconstructions has been performed. Several optimizers such as gradient descent, non linear conjugate gradient and limited BFGS have also been developed.

This work is a collaboration with Henri Calandra (TOTAL). The time domain FWI results has been presented at Total conference MATHIAS 2019 in Paris [37] and also during the Fall Meeting 2019 AGU in San Francisco [47].

#### 7.2.2. Box-Tomography imaging in the deep mantle

**Participant:** Yder Masson.

Box Tomography is a seismic imaging method (Masson and Romanowicz, 2017) that allows the imaging of localized geological structures buried at arbitrary depth inside the Earth, where neither seismic sources nor receivers are necessarily present. The big advantage of box-tomography over standard tomographic methods is that the numerical modelling (i.e. the ray tracing in travel time tomography and the wave propagation in waveform tomography or full waveform inversion) is completely confined within the small box-region imaged. Thus, box tomography is a lot more efficient than global tomography (i.e. where we invert for the velocity in the larger volume that encompasses all the sources and receivers), for imaging localized objects in the deep Earth. Following a successful, yet partial, application of box tomography to the imaging of the North American continent (i.e. Clouzet et al, 2018), together with Barbara Romanowicz and Sevan Adourian at the Berkeley Seismological Laboratory, we finished implementing the necessary tools for imaging localized structure in the Earth's lower mantle. The following tasks have been completed:

- Modify the global wave propagation solver Specfem_3D_globe in order to compute Green's functions in our current reference Earth model (SEMUCB).
- Modify the local wave propagation solver RegSEM_globe so that the wavefield can be recorded and stored at the surface of the modeling domain.
- Implement real-time compression for an improved management of computed data.

Preliminary results have been presented at the American geophysical union fall meeting 2019 [24]. In the near Future, the latest implementation of Box-Tomography will be deployed to investigate the deep structure under the Yellowstone hotspot down to 20 seconds period.

#### 7.2.3. Wave-propagation modeling using the distributional finite difference method (DFD).

**Participant:** Yder Masson.

In the last decade, the Spectral Element Method (SEM) has become a popular alternative to the Finite Difference method (FD) for modeling wave propagation in heterogeneous geological media. Though this can be debated, SEM is often considered to be more accurate and flexible than FD. This is because SEM has exponential convergence, it allows to accurately model material discontinuities, and complex structures can be meshed using multiple elements. In the mean time, FD is often thought to be simpler and more computationally efficient, in particular because it relies on structured meshed that are well adapted to computational architectures. This motivated us to develop a numerical scheme called the Distributional Finite Difference method (DFD), which combines the efficiency and the relative simplicity of the finite difference method together with an accuracy that compares to that of the finite/spectral element method. Similarly to SEM, the DFD method divides the computational domain in multiple elements but their size can be arbitrarily large. Within each element, the computational operations needed to model wave propagation closely resemble that of FD which makes the method very efficient, in particular when large elements are employed. Further, large elements may be combined with smaller ones to accurately mesh certain regions of space having complex geometry and material discontinuities, thus ensuring higher flexibility. An exploratory code allowing to model 2D and 3D wave propagation in complex media has been developed and demonstrated the interest of the proposed scheme. We presented numerical examples showing the accuracy and the interest of the DFD method for modeling wave propagation through the Earth at the EGU general assembly, 2019 and at the AGU fall meeting 2019 [41].

### 7.2.4. Time-harmonic seismic inverse problem

**Participants:** Hélène Barucq, Florian Faucher.

We study the inverse problem associated with the propagation of time-harmonic wave. In the seismic context, the available measurements correspond with partial reflection data, obtained from one side illumination (only the Earth surface is available). The inverse problem aims at recovering the subsurface Earth medium parameters and we employ the Full Waveform Inversion (FWI) method, which employs an iterative minimization algorithm of the difference between the measurement and simulation.

In particular, we investigate the use of new misfit functionals, based upon the *reciprocity-gap*. The use of such functional is only possible when specific measurements are available, and relates to Green's identity. The feature of the cost function is to allow a separation between the observational and numerical sources. In fact, the numerical sources do not have to coincide with the observational ones, offering new possibilities to create adapted computational acquisitions, and possibilities to reduce the numerical burden.

This work is a collaboration with Giovanni Alessandrini (Università di Trieste), Maarten V. de Hoop (Rice University), Romina Gaburro (University of Limerick) and Eva Sincich (Università di Trieste).

This work has given rise to a publication [11] and a preprint [53]. It has also been presented in several conferences [32], [35], [33], [34].

### 7.2.5. Convergence analysis for the seismic inverse problem

**Participants:** Hélène Barucq, Florian Faucher.

The determination of background velocity by Full Waveform Inversion (FWI) is known to be hampered by the local minima of the data misfit caused by the phase shifts associated with background perturbations. Attraction basins for the underlying optimization problems can be computed around any nominal velocity model and guarantee that the misfit functional has only one (global) minimum. The attraction basins are further associated with tolerable error levels which represent the maximal allowed distance between the (observed) data and the simulations (i.e., the acceptable noise level). The estimates are defined a priori, and only require the computation of (possibly many) first and second order directional derivatives of the (model to synthetic) forward map. The geometry of the search direction and the frequency influence the size of the attraction basins, and complex frequency can be used to enlarge the basins. The size of the attraction basins for the perturbation of background velocities in the classical FWI (global model parametrization) and the data space reflectivity (MBTT) reformulation are compared: the MBTT reformulation increases substantially the size of the attraction basins. Practically, this reformulation compensates for the lack of low frequency data.

This work is a collaboration with Guy Chavent (Inria Rocquencourt) and Henri Calandra (TOTAL). The results have been published in Inverse Problems [12] and in the Research Report [43].

### 7.2.6. Eigenvector representation for the seismic inverse problem

We study the seismic inverse problem for the recovery of subsurface properties in acoustic media. In order to reduce the ill-posedness of the problem, the heterogeneous wave speed parameter is represented using a limited number of coefficients associated with a basis of eigenvectors of a diffusion equation, following the regularization by discretization approach. We compare several choices for the diffusion coefficient in the partial differential equations, which are extracted from the field of image processing. We first investigate their efficiency for image decomposition (accuracy of the representation with respect to the number of variables and denoising). Next, we implement the method in the quantitative reconstruction procedure for seismic imaging, following the Full Waveform Inversion method.
This work is a collaboration with Otmar Scherzer (University of Vienna) and the results have been documented in [49].

### 7.2.7. Outgoing solutions for the scalar wave equation in Helioseismology

**Participants:** Hélène Barucq, Florian Faucher, Ha Pham.

We study the construction and uniqueness of physical solutions for the time-harmonic scalar wave equation arising in helioseismology. The definition of outgoing solutions to the equation in consideration or their construction and uniqueness has not been discussed before in the context of helieoseismology. In our work, we use the Liouville transform to conjugate the original equation to a potential scattering problem for Schrödinger operator, with the new problem containing a Coulomb-type potential. Under assumptions (in terms of density and background sound speed) generalizing ideal atmospheric behavior, we obtain existence and uniqueness of variational solutions.

Solutions obtained in this manner are characterized uniquely by a Sommerfeld-type radiation condition at a new wavenumber. The appearance of this wavenumber is only clear after applying the Liouville transform. Another advantage of the conjugated form is that it makes appear the Whittaker special functions, when ideal atmospheric behavior is extended to the whole domain. This allows for the explicit construction of the outgoing Green kernel and the exact Dirichlet-to-Neumann map and hence reference solutions and radiation boundary condition.

This work has given rise to a report of 135 pages, [45]. Some part have been extracted for a publication which has recently been accepted in ESAIM: M2AN.

Consequently to this work, ongoing research includes the fast construction of the Green's kernel, which is possible thanks to the family of special functions obtained from the previous analytical study, [36]. As part of the ANTS associate team, applications to helioseismology is also ongoing. This work is a collaboration with Damien Fournier and Laurent Gizon (Max Planck Institute at Göttingen). The "Ants workshop on computational helioseismology" has also been organized in this context.

### 7.2.8. Modeling the propagation of acoustic wave in the Sun

**Participants:** Hélène Barucq, Juliette Chabassier, Marc Duruflé, Nathan Rouxelin.

We study time-harmonic propagation of acoustic waves in the Sun in the presence of gravity forces.

Galbrun's equation, a Lagrangian description of acoustic wave propagation, is usually used in helioseismology. However, the discretization of this equation with high-order discontinuous Galerkin methods leads to poor numerical results for solar-like background flow and geometries. As better numerical results were obtained by using another model, the Linearized Euler's Equations, we investigate the equivalence between those two models.If compatible boundary conditions are chosen, it should be possible to reconstruct the solution of Galbrun's equation by solving the Linearized Euler's Equations and then a vectorial transport equation. It turns out that finding those boundary conditions is quite difficult and not always possible.

We also have constructed a reduced model for acoustic wave propagation in the presence of gravity. Under some additional assumptions on the background flow and for high frequencies, the Linearized Euler's Equations can be reduced to a scalar equation on the pressure perturbation. This equation is well-posed in a usual variational framework and it will provide a useful reference solution to validate our numerical methods. It also seems that a similar process could be used in more realistic cases.

### *7.2.9. Equivalent boundary conditions for acoustic media with exponential densities. Application to the atmosphere in helioseismology*

**Participants:** Juliette Chabassier, Marc Duruflé, Victor Péron.

We present equivalent boundary conditions and asymptotic models for the solution of a transmission problem set in a domain which represents the sun and its atmosphere. This problem models the propagation of an acoustic wave in time-harmonic regime. The specific non-standard feature of this problem lies in the presence of a small parameter $\delta$ which represents the inverse rate of the exponential decay of the density in the atmosphere. This problem is well suited for the notion of equivalent conditions and the effect of the atmosphere on the sun is as a first approximation local. This approach leads to solve only equations set in the sun. We derive rigorously equivalent conditions up to the fourth order of approximation with respect to $\delta$ for the exact solution $u$. The construction of equivalent conditions is based on a multiscale expansion in power series of $\delta$ for $u$. Numerical simulations illustrate the theoretical results. Finally we measure the boundary layer phenomenon by introducing a characteristic length that turns out to depend on the mean curvature of the interface between the subdomains. This work has been published in Applied Mathematics and Computation [15].

## 7.3. Hybrid time discretizations of high-order

### *7.3.1. Construction and analysis of a fourth order, energy preserving, explicit time discretization for dissipative linear wave equations.*

**Participants:** Juliette Chabassier, Julien Diaz.

A paper was accepted in M2AN [14]. This paper deals with the construction of a fourth order, energy preserving, explicit time discretization for dissipative linear wave equations. This family of schemes is obtained by replacing the inversion of a matrix, that comes naturally after using the technique of the Modified Equation on the second order Leap Frog scheme applied to dissipative linear wave equations, by an explicit approximation of its inverse. The series can be truncated at different orders, which leads to several schemes. The stability of the schemes is studied. Numerical results in 1D illustrate the good behavior regarding space/time convergence and the efficiency of the newly derived scheme compared to more classical time discretizations. A loss of accuracy is observed for non smooth profiles of dissipation, and we propose an extension of the method that fixes this issue. Finally, we assess the good performance of the scheme for a realistic dissipation phenomenon in Lorentz's materials. This work has been done in collaboration with Sébastien Imperiale (Inria Project-Team M3DISIM).

### *7.3.2. Space-Time Discretization of Elasto-Acoustic Wave Equation in Polynomial Trefftz-DG Bases*

**Participants:** Hélène Barucq, Julien Diaz.

In the context of the strategic action "Depth Imaging Partnership" between Inria and Total we have investigated to the development of an explicit Trefftz-DG formulation for elasto-acoustic problem, solving the global sparse matrix by constructing an approximate inverse obtained from the decomposition of the global matrix into a block-diagonal one. The inversion is then justified under a CFL-type condition. This idea allows for reducing the computational costs but its accuracy is limited to small computational domains. According to the limitations of the method, we have investigated the potential of Tent Pitcher algorithms following the recent works of Gopalakrishnan et al. It consists in constructing a space-time mesh made of patches that can be solved independently under a causality constraint. We have obtained very promising numerical results illustrating the potential of Tent Pitcher in particular when coupled with a Trefftz-DG method involving only surface terms.

In this way, the space-time mesh is composed of elements which are 3D objects at most. It is also worth noting that this framework naturally allows for local time-stepping which is a plus to increase the accuracy while decreasing the computational burden. The results of this work [28] have been presented during the ICIAM conference (Valencia, July 15-19).

## 7.4. Modeling and design of wind musical instruments

### *7.4.1. Full Waveform inversion for bore reconstruction of woodwind instruments*

**Participants:** Juliette Chabassier, Augustin Ernoult.

Several techniques can be used to reconstruct the internal geometry of a wind instrument from acoustics measurements. One possibility is to simulate the passive linear acoustic response of an instrument and to use an optimization process to fit the simulation to the measurements. This technique can be seen as a first step toward the design of wind instruments, where the targeted acoustics properties come no more longer from measurements but are imposed by the designer. We applied the FWI methodology, along with 1D spectral finite element discretization in space [19], to the woodwind instruments (with tone holes, losses and radiation). The algorithm have been implemented in Pyhton3 and is know operational to reconstruct the bore of real instrument. This functionality will be available in an upcoming version of the toolbox OpenWind.

### *7.4.2. Computation of the entry impedance of a wind instrument with toneholes and radiation*

**Participants:** Guillaume Castera, Juliette Chabassier, Augustin Ernoult, Alexis Thibault, Robin Tournemenne.

Modeling the entry impedance of wind instruments pipes is essential for sound synthesis or instrument qualification. Based on a one-dimensional model of acoustic propagation ("telegraphist's equations") we find approximate solutions using a high-order Finite Element Method (FEM1D). Contrary to the more standard semi-analytic Transfer Matrix Method (TMM), the FEM1D can take into account arbitrarily complex and variable coefficients [19]. It is therefore well-suited for the realistic cases involving boundary losses, smooth waveguide geometry, and possibly even a temperature gradient along the instrument's bore. We model toneholes as junctions of one-dimensional waveguides, and an acoustic radiation impedance models the radiation of all open tube ends. A global matrix is assembled to connect all these elements together, and solved for each frequency to compute the impedance curve. Source code is available in our Python3 toolbox OpenWind.

### *7.4.3. Time-domain simulation of a reed instrument with toneholes*

**Participants:** Juliette Chabassier, Augustin Ernoult, Alexis Thibault, Robin Tournemenne.

As part of the project aiming at providing practical tools for instrument design, we have been developing a sound synthesis module for reed instruments. We model a reed music instrument, such as the oboe or the bassoon, as a coupled system composed of a nonlinear source mechanism (the reed), and a linear resonating part (the air within the instrument's bore). Acoustic wave propagation inside of the instrument is reduced to a one-dimensional model, on which a variational approximation is performed, yielding high-order finite elements in space. Tone holes on the side of the instrument are taken into account using junctions of one-dimensional waveguides. The acoustic radiation impedance is written as a positive Padé approximation, so that it leads to a stable time domain model even when opening and closing holes during the simulation. For the reed, a one-degree-of-freedom lumped model is used, in which the reed opening follows a second order ODE and acts as a valve, modulating the flow that enters the pipe based on the pressure difference between the player's mouth and the inside of the instrument. Energy-consistent time discretization schemes have been derived for each component, so that it is possible to simulate instruments with an arbitrary geometry with good numerical accuracy and stability. The simulations have been implemented in Python3 and will be made available in an upcoming version of the toolbox OpenWind.

### *7.4.4. Time-domain simulation of 1D acoustic wave propagation with boundary layer losses*

**Participants:** Juliette Chabassier, Augustin Ernoult, Alexis Thibault.

Energy dissipation effects are of critical importance in musical acoustics. Boundary layer losses occurring in acoustic waveguides are usually modeled in the frequency domain, leading to slowly-decreasing kernels in the time domain similar to fractional derivatives. We have developed an energy-consistent time-domain model based on positive fraction approximation of the dissipative operators, leading to the use of $2N + 1$ additional variables per degree of freedom. Coefficients for these new variables depend only on $N$ so that they can be tabulated without any prior knowledge of the waveguide geometry. They are found with an optimization procedure. This model can be discretized using 1D finite elements [19], and an energy-consistent time-stepping scheme can be found. The resulting numerical scheme has been implemented numerically, and source code will be made available in an upcoming version of the toolbox OpenWind. An article is being written and will be submitted soon to JASA.

### *7.4.5. Numerical libraries for hybrid meshes in a discontinuous Galerkin context*

**Participants:** Hélène Barucq, Aurélien Citrain, Julien Diaz.

Elasticus team code has been designed for triangles and tetrahedra mesh cell types. The first part of this work was dedicated to add quadrangle libraries and then to extend them to hybrid triangles-quadrangles (so in 2D). This implied to work on polynomials to form functions basis for the (discontinuous) finite element method, to finally be able to construct reference matrices (mass, stiffness, ...).

A complementary work has been done on mesh generation. The goal was to encircle an unstructured triangle mesh, obtained by third-party softwares, with a quadrangle mesh layer. At first, we built scripts to generate structured triangle meshes, quadrangle meshes and hybrid meshes (triangles surrounded by quadrangles). In 2018, we have implemented the coupling between Discontinuous Galerkin methods (using the triangles/tetrahedra) and Spectral Element methods (using quadrangles/hexahedra). We have also implemented the PML in the SEM part, and we are now working on the local time-stepping feature.

# 8. Bilateral Contracts and Grants with Industry

## 8.1. Contracts with TOTAL

- Depth Imaging Partnership (DIP)
- Depth Imaging Partnership (DIP2)

  Period: 2014 May - 2019 April , Management: Inria Bordeaux Sud-Ouest, Amount: 120000 euros/year.
- Depth Imaging Partnership (DIP3)

  Period: 2019 May - 2021 December , Management: Inria Bordeaux Sud-Ouest, Amount: 120000 euros/year.
- Tent Pitcher algorithm for space-time integration of wave problems Period: 2019 November - 2022 October, Management: Inria Bordeaux Sud-Ouest, Amount: 165000 euros.
- Isogeometric analysis of sharp boundaries in fullwaveform inversion Period: 2019 January - 2021 December, Management: Inria Bordeaux Sud-Ouest, Amount: 55000 euros.
- FWI (Full Waveform Inversion) dans le domaine temporel utilisant des méthodes numériques hybrides pour la caractérisation de milieux élasto-acoustiques. Period: 2017 October - 2020 December , Management: Inria Bordeaux Sud-Ouest, Amount: 180000 euros.
- Petrophysics in pre-salt carbonate rocks

  Period: 2019 November - 2021 June, Management: Inria Bordeaux Sud-Ouest, Amount: 142000 euros.

# 9. Partnerships and Cooperations

## 9.1. Regional Initiatives

### 9.1.1. Partnership with I2M in Bordeaux supported by Conseil Régional d'Aquitaine

title: COFIMUS.

Coordinator:Juliette Chabassier

Other partners: I2M CNRS Université Bordeaux I

The objective is to develop a virtual workshop for wind musical instrument makers.

This project is supported by the Conseil Régional d'Aquitaine, for a duration of 2 years and has funded the postdoctoral position of Augustin Ernoult since March 2019.

## 9.2. National Initiatives

### 9.2.1. Depth Imaging Partnership

Magique-3D maintains active collaborations with Total. In the context of Depth Imaging, Magique-3D coordinates research activities dealing with the development of high-performance numerical methods for solving wave equations in complex media. This project has involved 2 other Inria Team-Projects (Hiepacs and Nachos) which have complementary skills in mathematics, computing and in geophysics. DIP is fully funded by Total by the way of an outline agreement with Inria .

In 2014, the second phase of DIP has begun. Lionel Boillot has been hired as engineer to work on the DIP platform. Six PhD students have defended their PhD since 2014 and they are now post-doctoral researchers or engineers in Europe. DIP is currently employing 2 PhD students and one post-doctoral researcher.

### 9.2.2. PRE Concert

Magique 3D is hosting an Inria "exploratory research project" (PRE) about modeling and designing wind musical instruments. This project has funded the post-doctoral position of Robin Tournemenne from July 2017 until July 2019.

### 9.2.3. ANR Num4Sun

The ANR has launched a specific program for supporting and promoting applications to European or more generally International projects. Magique-3D has been selected in 2016 after proposing a project to be applied as a FET project on the occasion of a call that will open in 2017 April. This project will gather researchers of the MPS (https://www.mps.mpg.de/en), of the BSC (https://www.bsc.es/), of the BCAM (http://www.bcamath.org/en/), of Heriot-Watt University (https://www.hw.ac.uk/) and Inria teams.
A kick-off meeting has been held in November 2016 in Strasbourg and a second one in Paris in July 2017. Thanks to this support, we have submitted a ETPHPC proposal in September 2017 The project is funded for 18 months starting from August 2016. The funding amounts 30000€.

### 9.2.4. Grant from Fondation Blaise Pascal

The project Louis 14.0 has been selected by the Fondation Blaise Pascal as one of their supported projects for 2019. See more about the project at https://project.inria.fr/louis14point0/, in french.

## 9.3. European Initiatives

### *9.3.1. FP7 & H2020 Projects*

*9.3.1.1. Mathrocks*

Title: Multiscale Inversion of Porous Rock Physics using High-Performance Simulators: Bridging the Gap between Mathematics and Geophysics

Program: H2020

Duration: April 2018 - March 2022

Coordinator: Universidad Del Pais Vasco (EHU UPV)

Partners:

- Bcam - Basque Center for Applied Mathematics Asociacion (Spain)
- Barcelona Supercomputing Center - Centro Nacional de Supercomputacion (Spain)
- Universidad Del Pais Vasco Ehu Upv (Spain)
- Universitat Politecnica de Catalunya (Spain)
- REPSOL SA (Spain)
- Pontificia Universidad Catolica de Valparaiso (Chile)
- Curtin University of Technology (Australia)
- The University of Texas System (USA)
- University Nacional de Columbia (Colombia)
- Pontificia Universidad Catolica de Chile (Chile)
- Universidad Central de Venezuela (Venezuela)
- University de Buenos Aires (Argentina)
- Macquarie University (Australia)

Inria contact: Hélène BARUCQ

We will develop and exchange knowledge on applied mathematics, high-performance computing (HPC), and geophysics to better characterize the Earth´s subsurface. We aim to better understand porous rocks physics in the context of elasto-acoustic wave propagation phenomena. We will develop parallel high-continuity isogeometric analysis (IGA) simulators for geophysics. We will design and implement fast and robust parallel solvers for linear equations to model multi-physics electromagnetic and elasto-acoustic phenomena. We seek to develop a parallel joint inversion workflow for electromagnetic and seismic geophysical measurements. To verify and validate these tools and methods, we will apply the results to: characterise hydrocarbon reservoirs, determine optimal locations for geothermal energy production, analyze earthquake propagation, and jointly invert deep-azimuthal resistivity and elasto-acoustic borehole measurements. Our target computer architectures for the simulation and inversion software infrastructure consists of distributed-memory parallel machines that incorporate the latest Intel Xeon Phi processors. Thus, we will build a hybrid OpenMP and MPI software framework. We will widely disseminate our collaborative research results through publications, workshops, postgraduate courses to train new researchers, a dedicated webpage with regular updates, and visits to companies working in the area. Therefore, we will perform a significant role in technology transfer between the most advanced numerical methods and mathematics, the latest super-computer architectures, and the area of applied geophysics.

## 9.4. International Initiatives

### *9.4.1. Inria Associate Teams Not Involved in an Inria International Labs*

*9.4.1.1. ANTS*

Title: Advanced Numerical meThods for helioSeismology

International Partner (Institution - Laboratory - Researcher):

Max Plank Institut für Sonnensystemforschung (Germany) – Department Solar and Stellar Interiors – Laurent Gizon.

Start year: 2019

See also: https://team.inria.fr/ants/

Magique-3D has started an Associate Team project, ANTS (Advanced Numerical meThods for helioSeismology), with the Max Planck Institute for Solar System Research (MPS), led by Laurent Gizon. This helps promote the collaboration between Magique3D and the Solar group at the Max Planck Institute for Solar System Research at Göttingen (MPS) for the direct and inversion of solar models from Doppler data obtained at the surface of the Sun. The scientific project benefits from the expertise of Magique-3D in seismic imaging, and the expert knowledge of the MPS group on Solar physics, in order to design accurate and efficient methodology. A joint workshop was held at Inria Bordeaux Sud-Ouest in December 2019: https://project.inria.fr/antsworkshop201912/.

### *9.4.2. Inria International Partners*

#### *9.4.2.1. New international partner: The Berkeley Seismological Laboratory, University of California, Berkeley.*

In September 2019, together with Barbara Romanowicz at the University of California Berkeley https://seismo.berkeley.edu/, we initiated a collaboration aiming at developing and deploying novel tomographic methods for imaging localized structures in the deep Earth that are either blurred out or not visible in the current global models.This effort is supported by the France-Berkeley Fund which granted our project for a period of 2 years. Amount: 11000€, Management: Berkeley University url: https://fbf.berkeley.edu/project/development-and-application-advanced-seismic-imaging-techniques-key-target-structures-deep

#### *9.4.2.2. Declared Inria International Partners*

##### 9.4.2.2.1. MAGIC2

Title: Advance Modeling in Geophysics

International Partner (Institution - Laboratory - Researcher):

California State University at Northridge (United States) - Department of Mathematics - Djellouli Rabia

The Associated Team MAGIC was created in January 2006 and renewed in January 2009. At the end of the program in December 2011, the two partners, MAGIQUE-3D and the California State University at Northridge (CSUN) decided to continue their collaboration and obtained the "Inria International Partner" label in 2013.

See also: https://project.inria.fr/magic/

The ultimate objective of this research collaboration is to develop efficient solution methodologies for solving inverse problems arising in various applications such as geophysical exploration, underwater acoustics, and electromagnetics. To this end, the research program will be based upon the following three pillars that are the key ingredients for successfully solving inverse obstacle problems. 1) The design of efficient methods for solving high-frequency wave problems. 2) The sensitivity analysis of the scattered field to the shape and parameters of heterogeneities/scatterers. 3) The construction of higher-order Absorbing Boundary Conditions. In the framework of Magic2, Rabia Djellouli (CSUN) visited Magique 3D in February 2018

## 9.5. International Research Visitors

### *9.5.1. Visits of International Scientists*

- Vianey Villamizar (Department of Mathematics, Brigham Young University) visited the team in September 2019

- Mounir Tlemcani (Université d'Oran, Algeria) visited Magique 3D in March 2019.
- Sevan Adourian (Univesity of California, Berkeley) visited Magique 3D for a week in June 2019, this visit has been sponsored by the France-Berkeley Fund.

### *9.5.2. Visits to International Teams*

*9.5.2.1. Research Stays Abroad*

- Nathan Rouxelin visited MPS at Göttingen in April 2019, during a month.
- Rose-Cloé Meyer visited prof. Steve Pride from Lawrence Berkeley National Laboratory in June 2019 during 1 month and in December 2019 during 3 weeks.
- In the framework of DIP, Pierre Jacquet visited Total Research Center at Houston, USA, in December 2019 during 1 week.
- Yder Masson, visited Barbara Romanowicz at the Berkeley Seismological Laboratory and Steve R. Pride at the Lawrence Berkeley Laboratory for two days the week following the AGU Fall Meeting Dec 9-13, 2019 , San Francisco, CA, USA)

# 10. Dissemination

## 10.1. Promoting Scientific Activities

### *10.1.1. Scientific Events: Organisation*

*10.1.1.1. Member of the Organizing Committees*

- Hélène Barucq co-organized committee of "Journées Ondes du Sud-Ouest" (JOSO 2019), March, 12-14. https://hal.archives-ouvertes.fr/JOSO2019
- Hélène Barucq, Florian Faucher and Ha Pham organized the "Ants workshop on computational helioseismology" in Bordeaux, December, 3-5, https://project.inria.fr/antsworkshop201912/
- Hélène Barucq coorganized a minisymposium on "Geophysical Applications" at ICIAM 2019 in Valence, July, 15-19, https://iciam2019.org/
- Julien Diaz and Sébastien Tordeux coorganized a minisymposium on "Advanced numerical tools for wave propagation simulation" at ICIAM 2019 in Valence, July, 15-19, https://iciam2019.org/
- Julien Diaz coorganized an autumn school on "High performance numerical simulation", https://project.inria.fr/hpcschool2019/, in Bordeaux, November, 4-8. This school gathered 30 participants, mainly PhD students and post-doc. It aimed at simulating a physical problem, from its modeling to its implementation in an high performance computing (HPC) framework. The physical problem considered was the harmonic wave propagation. The hands-on sessions were conducted on the Federative Platform for Research in Computer Science and Mathematics (PlaFRIM) machine.

### *10.1.2. Scientific Events: Selection*

*10.1.2.1. Member of the Conference Program Committees*

- Hélène Barucq and Julien Diaz were members of the scientific committee of Waves 2019 https://waves2019.at
- Sébastien Tordeux was member of the scientific committee of The international Russian-french workshop, Differential equations and Mathematical Modeling, Khanty-Mansiisk, Russia 25-29 août 2019

### *10.1.3. Journal*

*10.1.3.1. Reviewer*

Members of Magique 3D have been reviewers for the following journals:

- Computer Methods in Applied Mechanics and Engineering
- Geophysics
- Journal of Computational Physics
- Journal of Scientific Computing
- Numerical Methods in Engineering
- Geophysical Journal International
- Computational Geosciences (COMG)

### 10.1.4. Leadership within the Scientific Community

Hélène Barucq is elected member of the Liaison Committee of SMAI-GAMNI (Society of Applied and Industrial Mathematics - Group for promoting the Numerical Methods for Engineers).

### 10.1.5. Scientific Expertise

- Julien Diaz was expert for the evaluation of Millennium Science Initiative project for the government of Chile.
- Since 2017, Hélène Barucq has been chairwoman of a committee which evaluates research projects in Mathematics, Computer Science, Electronics and Optics to be funded by the Regional Council New Aquitaine
- Since 2018, Hélène Barucq has been scientific officer for E2S project. She participates in the evaluation of each E2S call. She is also member of a committee having in charge the recruitment of non permanent researchers for E2S.

### 10.1.6. Research Administration

- Julien Diaz is elected member of the Inria Technical Committee and of the Inria Administrative Board. Since 2018, he has been the head of the Mescal team of LMAP.
- Justine Labat is elected member of Laboratory Commitee of LMAP.
- Victor Péron is appointed member of the CER (Commission des emplois de recherche) of Inria Bordeaux Sud-Ouest.

## 10.2. Teaching - Supervision - Juries

### 10.2.1. Teaching

Master : Julien Diaz, Transformées, 24h Eq. TD, M1, EISTIA, France

Licence : Rose-Cloé Meyer, Mathématiques appliquées, 22.5h Eq. TD, L1, UPPA, France

Licence : Rose-Cloé Meyer, Développements limités, suites et séries, 19.5h Eq. TD, L2, UPPA, France

Licence : Marc Duruflé, Équations différentielles, 20h Eq. TD, L3, Enseirb-MatMeca, France

Licence : Marc Duruflé, Algorithmique Numérique, 50h Eq. TD, L3, Enseirb-MatMeca, France

Licence : Marc Duruflé, Outils Mathématiques 3-D, 37h Eq. TD, L3, Enscpb, France

Master : Marc Duruflé, Calcul scientifique en C++, 96h Eq. TD, M1, Enseirb-MatMeca, France

Licence : Marc Duruflé, Calcul scientifique en Fortran90, 20h Eq. TD, L3, Enseirb-MatMeca, France

Licence : Nathan Rouxelin, Mathématiques appliquées, 22.5h Eq. TD, L1, UPPA, France

Licence : Nathan Rouxelin, Modèles mathématiques pour l'informatique, 19.5h Eq. TD, L1, UPPA, France

Master : Florian Faucher, Inversion / optimisation, 10.5h Eq. Cours et TD, M2, Université de Pau et des Pays de l'Adour, France

Licence : Justine Labat, Algèbre pour l'informatique, 19.5h Eq. TD, L1, UPPA, France

Licence : Justine Labat, Introduction aux Probabilités, 12.5h Eq. TD, L2, UPPA, France

Licence : Victor Péron, Analyse 2, 39 Eq. TD, L1, UPPA, France

Licence : Victor Péron, Mathématiques appliquées, 15 Eq. TD, L1, UPPA, France

Licence : Victor Péron, Mathématiques appliquées, 19.5 Eq. TD, L1, UPPA, France

Licence : Victor Péron, Analyse numérique des systèmes linéaires, 48.75 Eq. TD, L3, UPPA, France

Licence: Géométrie analytique, 20h Eq. TD, UPPA, France

Master : Victor Péron and Sébastien Tordeux, Analyse numérique des EDP 1: différences finies, 75 eq. TD, Master1, UPPA, France

Master : Victor Péron and Sébastien Tordeux, Introduction aux phénomènes de propagation d'ondes, 38 eq. TD, Master 2, UPPA, France

Master : Robin Tournemenne, Math-Info, 64h eq. TD, L3+M1, ENSAM Bordeaux, France

### *10.2.2. Supervision*

PhD : Aurélien Citrain, Méthode d'éléments finis hybride pour la simulation des ondes sismiques : couplage des discrétisations Galerkine Discontinue et éléments spectraux, December 16th, Hélène Barucq and Christian Gout (Insa Rouen).

PhD : Justine Labat, Modélisation multi-échelle de la diffraction des ondes électromagnétiques par de petits obstacles, November 28th, Victor Péron and Sébastien Tordeux.

PhD in progress : Alexandre Gras, Hybrid resonance for sensing applications, IOGS, October 2017, Philippe Lalanne(IOGS), Marc Duruflé, Hélène Barucq (Magique 3D)

PhD in progress : Pierre Jacquet, Time domain Full Waveform Inversion involving hybrids numerical method to characterize elasto-acoustic media. ,October 2017, Hélène Barucq and Julien Diaz.

PhD in progress: Victor Martins Gomez, Experimental characterization and modeling of seismo-electromagnetic waves, Université de Pau et des Pays de l'Adour, October 2018, Hélène Barucq and daniel brito (LFCR)

PhD in progress : Rose-Cloé Meyer, Modeling of conducting poro-elastic media using advanced numerical methods , Université de Pau et des Pays de l'Adour, October 2018, Hélène Barucq and Julien Diaz

PhD in progress : Nathan Rouxelin, Advanced numerical modeling of acoustic waves propagating below the surface of the Sun, Université de Pau et des Pays de l'Adour, October 2018, Hélène Barucq and Juliette Chabassier

PhD in progress : Chengyi Shen, Approches expérimentale et numérique de la propagation d'ondes sismiques dans les roches carbonatées, October 2016, Julien Diaz and Daniel Brito (LFCR).

PhD in progress : Margot Sirdey, Méthode de Trefftz pour l'électromagnétisme, October 2019, Sébastien Tordeux and Sébastien Pernet (Onera).

PhD in progress : Vinduja Vasanthan, Tent Pitcher algorithm for space-time integration of wave problems, October 2019, Hélène Barucq and Julien Diaz.

PhD in progress : Stefano Frambati, Isogeometric analysis of sharp boundaries in full waveform inversion, January 2019, Hélène Barucq and Julien Diaz.

Master 2 internship : Ilyas Bouchni, Optimisation de maillage pour l'imagerie sismique, Université de Montpellier, Sept. 2019.

Master 2 internship : Vinduja Vasanthan, Couplage élasto-acoustique en domaine fréquentiel par des méthodes de type Galerkine Discontinues Hybride , Insa Rouen, Sept. 2019.

### *10.2.3. Juries*

- Victor Péron : Jérôme Tomezyk (Université Polytechnique Hauts-de-France), Résolution numérique de quelques problèmes du type Helmholtz avec conditions au bord d'impédance ou des couches absorbantes (PML), July 2nd 2019
- Julien Diaz : Soumaya Oueslati (Université de Cergy-Pontoise), "A new variational formulation for electromagnetic scattering problem using integral method with high order impedance boundary condition – Small perturbation of an interface for Stokes system", PhD thesis, June 12th 2019
- Julien Diaz : Aurélien Citrain (Insa de Rouen), "Méthode d'éléments finis hybride pour la simulation des ondes sismiques : couplage des discrétisations Galerkine Discontinue et éléments spectraux", PhD thesis, December 16th 2019

- Sébastien Tordeux : Pierre Schickele (Université de Toulouse),"Modélisation de l'émission EM de faisceaux de câbles complexes dans un environnement 3D", december 18th 2019

## 10.3. Popularization

### *10.3.1. Interventions*

- Justine Labat participated in scientific 'speed datings' during the 'Filles et Maths' day at Pau in February 2019.
- Juliette Chabassier participated to the festival Club Med'iation in May 2019.
- Juliette Chabassier participated to many interventions of Louis 14.0, a scientific and artistic show.
- Juliette Chabassier animated a workshop around the virtual piano in La Couronne in Nov 2019.
- Juliette Chabassier, Augustin Ernoult and Alexis Thibault participated to the "Articulations workshop" in Dec 2019.
- Juliette Chabassier participated to a workshop around the Meta-Piano-Teq with Jean Haury in Dec 2019.
- Sébastien Tordeux gave a talk on numerical analysis in the Cercle Sofia Kovalevskaïa of Toulouse in May 2019
- Sébastien Tordeux was member of the judging comittee for the "Tournois Français des Jeunes Mathématiciennes et Mathématiciens" in May 2019

### *10.3.2. Creation of media or tools for science outreach*

Juliette Chabassier co-created with the Ensemble Les Précieuses the show Louis 14.0 that presents how ancient instruments can be restored via numerical techniques, and played in real time in a musical and theatral show.

# 11. Bibliography

## Major publications by the team in recent years

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[9] A. CITRAIN. *Hybrid finite element methods for seismic wave simulation: coupling of Discontinuous Galerkin and Spectral Element discretizations*, Institut National des Sciences Appliquées de Rouen, 2019

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