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Université de Pau et des Pays de l'Adour

Activity Report 2018

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

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Project-Team MAGIQUE-3D

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2. Overall Objectives

2.1. General setting

MAGIQUE-3D is a joint project-team between Inria and the Department of Applied Mathematics (LMA) of the University of Pau, in partnership with CNRS. The 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.

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 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, and (c) the development of asymptotic models that are the primary candidate in the presence of heterogeneities that are small compared to the wave length. 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 at Bilbao, Spain; University of Novosibirsk, Russia).

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 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 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 can contribute to this task by improving the modeling and by deriving advanced numerical methods for solving wave problems.
Magique-3D proposes to organize its research around three main axes:

1. Mathematical modeling of multi-physics involving wave equations;
2. Supercomputing for Helmholtz problems;
3. Construction of high-order hybrid schemes.

These three research fields will be developed with the main objective of solving inverse problems dedicated to geophysical imaging.

3.2. Mathematical modeling of multi-physics involving wave equations

Wave propagation modeling is of great interest for many applications like oil and gas exploration, non destructive testing, medical imaging, etc. It involves equations which can be solved in time or frequency domain and their numerical approximation is not easy to handle, in particular when dealing with real-world problems. In both cases, the propagation domain is either infinite or its dimensions are much greater than the characteristic wavelength of the phenomenon of interest. But since wave problems are hyperbolic, the physical phenomenon can be accurately described by computing solutions in a bounded domain including the sources which have generated the waves. Until now, we have mainly worked on imaging techniques based on acoustic or elastic waves and we have developed advanced finite element software packages which are used by Total for oil exploration. Nevertheless, research on modeling must go on because there are simulations which can still not be performed because their computational cost is much too high. This is particularly true for complex tectonics involving coupled wave equations. We then propose to address the issue of coupling wave equations problems by working on the mathematical construction of reduced systems. By this way, we hope to improve simulations of elasto-acoustic and electro-seismic phenomena and then, to perform numerical imaging of strongly heterogeneous media. Even in the simplest situation where the wavelengths are similar (elasto-acoustic coupling), the dimension of the discrete coupled problem is huge and it is a genuine issue in the prospect of solving 3D inverse problems.

The accurate numerical simulation of full wave problems in heterogeneous media is computationally intensive since it needs numerical schemes based on grids. The size of the cells depends on the propagation velocity of waves. When coupling wave problems, conversion phenomena may occur and waves with very different propagation velocity coexist. The size of the cells is then defined from the smallest velocity and in most of the real-world cases, the computational cost is crippling. Regarding existing computing capabilities, we propose to derive intermediate models which require less computational burden and provide accurate solutions for a wide-ranging class of problems including Elasto-acoustics and Electro-seismology.

When it comes to mathematical analysis, we have identified two tasks which could help us simulate realistic 3D multi-physics wave problems and which are in the scope of our savoir-faire. They are construction of approximate and multiscale models which are different tasks. The construction of approximate problems aims at deriving systems of equations which discrete formulation involves middle-sized matrices and in general, they are based on high frequency hypothesis. Multiscale models are based on a rigorous analysis involving a small parameter which does not depend on the propagation velocity necessarily.

Recently, we have conducted research on the construction of approximate models for offshore imaging. Elastic and acoustic wave equations are coupled and we investigate the idea of eliminating the computations inside water by introducing equivalent interface conditions on the sea bottom. We apply an On-Surface-Radiation-Condition (OSRC) which is obtained from the approximation of the acoustic Dirichlet-to-Neumann (DtN) operator [70], [49]. To the best of our knowledge, OSRC method has never been used for solving reduced coupling wave problems and preliminary promising results are available at [51]. We would like to investigate this technique further because we could form a battery of problems which can be solved quickly. This would provide a set of solutions which we could use as initial guess for solving inverse problems. But we are concerned with the performance of the OSRC method when wave conversions with different wavelengths occur. Anyway, the approximation of the DtN operator is not obvious when the medium is strongly heterogeneous and multiscale analysis might be more adapted. For instance, according to existing results in Acoustics and Electromagnetism for the modeling of wire antennas [61], multiscale analysis should turn out to be very efficient when the propagation medium includes well logs, fractures and faults which are very thin structures when compared to the wavelength of seismic waves. Moreover, multiscale analysis should perform well when the medium is strongly oscillating like porous media. It could thus provide an alternative to homogenization techniques which can be applied only when the medium is periodic. We thus propose to develop reduced multi-scale models by performing rigorous mathematical procedure based on regular and singular multiscale analysis. Our approach distinguishes itself from others because it focuses on the numerical representation of small structures by time-dependent problems. This could give rise to the development of new finite element methods which would combine DG approximations with XFEM (Extended Finite Element Method) which has been created for the finite element treatment of thin structures like cracks.

But Earth imaging must be more than using elasto-acoustic wave propagation. Electromagnetic waves can also be used and in collaboration with Prof. D. Pardo (Iker Basque Foundation and University of Bilbao), we conduct researches on passive imaging to probe boreholes. Passive imaging is a recent technique of imaging which uses natural electromagnetic fields as sources. These fields are generated by hydromagnetic waves propagating in the magnetosphere which transform into electromagnetic waves when they reach the ionosphere. This is a mid-frequency imaging technique which applies also to mineral and geothermal exploration, to predict seismic hazard or for groundwater monitoring. We aim at developing software package for resistivity inversion, knowing that current numerical methods are not able to manage 3D inversion. We have obtained results based on a Petrov-Galerkin approximation [46], but they are limited to 2D cases. We have thus proposed to reduce the 3D problem by using 1D semi-analytic approximation of Maxwell equations [74]. This work has just started in the framework of a PhD thesis and we hope that it will give us the possibility of imaging 3D problems.

Magique-3D would like to expand its know-how by considering electro-seismic problems which are in the scope of coupling electromagnetic waves with seismic waves. Electro-seismic waves are involved in porous media imaging which is a tricky task because it is based on the coupling of waves with very different wavelengths described by Biot equations and Maxwell equations. Biot equations govern waves in saturated porous media and they represent a complex physical phenomenon involving a slow wave which is very difficult to simulate numerically. In [68], interesting results have been obtained for the simulation of piezoelectric sensors. They are based on a quasi-static approximation of the Maxwell model coupled with Elastodynamics. Now, we are concerned with the capability of using this model for Geophysical Imaging and we believe that the derivation and/or the analysis of suitable modelings is necessary. Collaborations with Geophysicists are thus mandatory in the prospect of using both experimental and numerical approaches. We would like to collaborate with Prof. C. Bordes and Prof. D. Brito (Laboratory of Complex Fluids and their Reservoirs, CNRS and University of Pau) who have efficient experimental devices for the propagation of electromagnetic waves inside saturated porous media [50]. This collaboration should be easy to organize since Magique-3D has a long-term experience in collaborating with geophysicists. We then believe that we will not need a lot of time to get joint results since we can use our advanced software packages Hou10ni and Montjoie and our colleagues have already obtained data. Electro-seismology is a very challenging research domain for us and we would like to enforce our collaborations with IsTerre (Institute of Earth Science, University of Grenoble) and for that topic with Prof. S. Garambois who is an expert in Electro-seismology [76], [77], [65], [66]. A joint research program could gather Geophysicists from the University of Pau and from IsTerre and Magique-3D. In particular, it would be interesting to compare simulations performed with Hou10ni, Montjoie, with the code developed by Prof. S. Garambois and to use experimental simulations for validation.

3.3. Supercomputing for Helmholtz problems

Probing invisible with harmonic equations is a need for many scientists and it is also a topic offering a wealth of interesting problems for mathematicians. It is well-known that Helmholtz equations discretization is very sensitive to the frequency scale which can be wide-ranging for some applications. For example, depth imaging is searching for deeper layers which may contain hydrocarbons and frequencies must be of a few tens of Hertz with a very low resolution. If it is to detect hidden objects, the depth of the explored region does not exceed a few tens of meters and frequencies close to the kiloHertz are used. High performing numerical methods should thus be stable for a widest as possible frequency range. In particular, these methods should minimize phenomena of numerical pollution that generate errors which increase faster with frequency than with the inverse of space discretization step. As a consequence, there is a need of mesh refinement, in particular at high frequency.

During the period 2010-2014, the team has worked extensively on high order discontinuous Galerkin (DG) methods. Like standard Finite Element Methods, they are elaborated with polynomial basis functions and they are very popular because they are defined locally for each element. It is thus easy to use basis polynomial functions with different degrees and this shows the perfect flexibility of the approximation in case of heterogeneous media including homogeneous parts. Indeed, low degree basis functions can be used in heterogeneous regions where a fine grid is necessary while high degree polynomials can be used for coarse elements covering homogeneous parts. In particular, Magique-3D has developed Hou10ni that solves harmonic wave equations with DG methods and curved elements. We found that both the effects of pollution and dispersion, which are very significant when a conventional finite element method is used, are limited [52]. However, bad conditioning is persisting and reliability of the method is not guaranteed when the coefficients vary considerably. In addition, the number of unknowns of the linear system is too big to hope to solve a realistic 3D problem. So it is important to develop approximation methods that require fewer degrees of freedom. Magique-3D wishes to invest heavily in the development of new approximation methods for harmonic wave equations. It is a difficult subject for which we want to develop different tasks, in collaboration with academic researchers with whom we are already working or have established contacts. Research directions that we would like to follow are the following.

First, we will continue our long-term collaboration with Prof. Rabia Djellouli. We want to continue to work on hybrid finite element methods that rely on basis functions composed of plane waves and polynomials. These methods have demonstrated good resistance to the phenomenon of numerical pollution [47], [48], but their capability of solving industrial problems has not been illustrated. This is certainly due to the absence of guideline for choosing the plane waves. We are thus currently working on the implementation of a methodology that makes the choice of plane waves automatic for a given simulation (fixed propagation domain, data source, etc.). This is up-front investigation and there is certainly a lot of remaining work before being applied to geophysical imaging. But it gives the team the opportunity to test new ideas while remaining in contact with potential users of the methods.

Then we want to work with Prof. A. Bendali on developing methods of local integral equations which allow calculation of numerical fluxes on the edges of elements. One could then use these fluxes in a DG method for reconstructing the solution throughout the volume of calculation. This research is motivated by recent results which illustrate the difficulties of the existing methods which are not always able to approximate the propagating modes (plane waves) and the evanescent modes (polynomials) that may coexist, especially when one considers realistic applications. Integral equations are direct tools for computing fluxes and they are known for providing very good accuracy. They thus should help to improve the quality of approximation of DG methods which are fully flux-dependent. In addition, local integral equations would limit calculations at the interfaces, which would have the effect of limiting the number of unknowns generally high, especially for DG methods. Again, it is a matter of long-term research which success requires a significant amount of mathematical analysis, and also the development of non-trivial code.

To limit the effects of pollution and dispersion is not the only challenge that the team wants to tackle. Our experience alongside Total has made us aware of the difficulties in constructing meshes that are essential to achieve our simulations. There are several teams at Inria working on mesh generation and we are in contact with them, especially with Gamma3 (Paris-Rocquencourt Research Center). These teams develop meshes increasingly sophisticated to take account of the constraints imposed by realistic industrial benchmarks. But in our opinion, issues which are caused by the construction of meshes are not the only downside. Indeed, we have in mind to solve inverse problems and in this case it is necessary to mesh the domain at each iteration of Newton-type solver. It is therefore interesting to work on methods that either do not use mesh or rely on meshes which are very easy to construct. Regarding meshless methods, we have begun a collaboration with Prof. Djellouli which allowed us to propose a new approach called Mesh-based Frontier Free Formulation (MF3). The principle of this method is the use of fundamental solutions of Helmholtz equations as basic functions. One can then reduce the volumic variational formulation to a surfacic variational formulation which is close to an integral equation, but which does not require the calculation of singularities. The results are very promising and we hope to continue our study in the context of the application to geophysical imaging. An important step to validate this method will be particularly its extension to 3D because the results we have achieved so far are for 2D problems.

Keeping in mind the idea of limiting the difficulties of mesh, we want to study the method of virtual elements. This method attracts us because it relies on meshes that can be made of arbitrarily-shaped polygon and meshes should thus be fairly straightforward. Existing works on the subject have been mainly developed by the University of Pavia, in collaboration with Los Alamos National Laboratory [56], [57], [55], [53], [58]. None of them mentions the feasibility of the method for industrial applications and to our knowledge, there are no results on the method of virtual elements applied to the wave equations. First, we aim at applying the method described in [54] to the scalar Helmholtz equation and explore opportunities to use discontinuous elements within this framework. Then hp-adaptivity could be kept, which is particularly interesting for wave propagation in heterogeneous media.

DG methods are known to require a lot of unknowns that can exceed the limits accepted by the most advanced computers. This is particularly true for harmonic wave equations that require a large number of discretization points, even in the case of a conventional finite element method. We therefore wish to pursue a research activity that we have just started in collaboration with the project-team Nachos (Sophia-Antipolis Méditerranée Research Center). In order to reduce the number of degrees of freedom, we are interested in "hybrid mixed" Discontinuous Galerkin methods that provides a two-step procedure for solving the Helmholtz equations [69], [73], [72]. First, Lagrange multipliers are introduced to represent the flux of the numerical solution through the interface (edge or face) between two elements. The Lagrange multipliers are solution to a linear system which is constructed locally element by element. The number of degrees of freedom is then strongly reduced since for a standard DG method, there is a need of considering unknowns including volumetric values inside the element. And obviously, the gain is even more important when the order of the element is high. Next, the solution is reconstructed from the values of the multipliers and the cost of this step is negligible since it only requires inverting small-sized matrices. We have obtained promising results in the framework of the PhD thesis of Marie Bonnasse-Gahot and we want to apply it to the simulation of complex phenomena such as the 3D viscoelastic wave propagation.
Obviously, the success of all these works depends on our ability to consider realistic applications such as wave propagation in the Earth. And in these cases, it is quite possible that even if we manage to develop accurate less expensive numerical methods, the solution of inverse problems will still be computationally intensive. It is thus absolutely necessary that we conduct our research by taking advantage of the latest advances in high-performance computing. We have already initiated discussions with the project team HIEPACS (Bordeaux Sud-Ouest research Center) to test the performance of the latest features of Mumps http://mumps.enseeiht.fr/, such as Low Rank Approximation or adaptation to hybrid CPU / GPU architectures and to Intel Xeon Phi, on realistic test cases. We are also in contact with the team Algorithm at Cerfacs (Toulouse) for the development of local integral equations solvers. These collaborations are essential for us and we believe that they will be decisive for the simulation of three-dimensional elasto-dynamic problems. However, our scientific contribution will be limited in this area because we are not experts in HPC.

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 [62], [59], [75], [71], [64] 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 [67].

Recently, Dolean *et al* [63] 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 [60]. 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.

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. New Software and Platforms

5.1. 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

5.2. 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 2018, we have finished scalablity tests and performance comparison of Hou10ni/Mumps vs Hou10ni/Maphys on Plafrim, in the framework of the european project HPC4E. The code is now being ported on Turing, in order to extend the scability tests to the time-domain problem.

- Participants: Conrad Hillairet, Elodie Estecahandy, Julien Diaz, Lionel Boillot and Marie Bonnasse Gahot
- 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/

5.3. 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/

5.4. 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

5.5. OpenWind

Open Wind Instrument Design
KEYWORDS: Wave propagation - Inverse problem - Experimental mechanics - Image processing
FUNCTIONAL DESCRIPTION: -Computes resonating pipes' impedance using one-dimensional nite element method and the transfer matrix method -sound synthesis in the time domain (FDTD and FEM in space) - informatic interface for the usage of an input impedance measurement setup. -instrument bore extraction using tomographical image processing -inverse problem solving

- Contact: Juliette Chabassier

5.6. 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

6. New Results

6.1. Seismic Imaging and Inverse Problems

6.1.1. Shape-reconstruction and parameter identification of an elastic object immersed in a fluid

Participants: Izar Azpiroz Iragorri, Hélène Barucq, Julien Diaz.

We have developed a procedure to reconstruct the shape and material parameters of an elastic obstacle immersed in a fluid medium from some external measurements given by the so called far-field pattern. It is a nonlinear and ill-posed problem which is solved by applying a Newton-like iterative method involving the Fréchet derivatives of the scattered field. These derivatives express the sensitivity of the scattered field with respect to the parameters of interest. They are defined as the solution of boundary value problems which differ from the direct one only at the right-hand sides level. We have been able to establish the well-posedness of each problem in the case of a regular obstacle and it would be interesting in the near future to extend those results to the case of scatterers with polygonal boundaries. It requires to work with less regular Sobolev spaces for which the definition of traces is not obvious. We have also provided an analytical representation of the Fréchet derivatives in the case of a circle.

Next, we have introduced a series of numerical experiments that have been performed by applying two algorithms which propose two strategies of full reconstruction regarding the material parameters are retrieved simultaneously with the shape or not. It turns out that both work similarly delivering the same level of accuracy but the simultaneous reconstruction requires less iterations. We have thus opted for retrieving all the parameters simultaneously. Since realistic configurations include noisy data, we have performed some simulations for the reconstruction of the shape along with the Lamé coefficients for different noise levels. Other interesting experiments have been carried out using a multistage procedure where the parameters of interest are the density of the solid interior, the shape of the obstacle and its position. We have considered the case of Limited Aperture Data in back-scattering configurations, using multiple incident plane waves, mimicing a physical disposal of non-destructive testing.

We extended the solution methodology to the case of anisotropic media. Since the impact of some of the anisotropic parameters on the FFP is even weaker than the Lamé coefficients, the reconstruction of these parameters together with the shape parameters requires several frequencies and carefully adapted regularization parameters. It is in particular difficult to retrieve the Thomsen parameters ϵ and δ because their reconstruction requires to have an accurate adjustment on the rest of material and shape parameters. The recovery process is thus computationally intensive and some efforts should be done in the near future to decrease the computational costs. We were able to recover all the anisotropic parameters when the shape were assumed to be known. However, when trying to recover both shape and material parameters, we could only recover the shape and some of the physical parameters (namely the three most important ones : the density and the two velocities V_p and V_s).

These results have been obtained in collaboration with Rabia Djellouli (California State University at Northridge, USA) and are presented in Izar Azpiroz Ph.D thesis [1]

6.1.2. Time-harmonic seismic inverse problem with dual-sensors data

Participants: Hélène Barucq, Florian Faucher.

We study the inverse problem for the time-harmonic acoustic wave equation. The seismic context implies restrictive set of measurements: it consists of reflection data (resulting from an artificial source) acquired from the near surface area only. The inverse problem aims at recovering the subsurface medium parameters and we use the Full Waveform Inversion (FWI) method, which defines an iterative minimization algorithm of the difference between the measurement and simulation.

We investigate the use of new devices that have been introduced in the acoustic setting. They are able to capture both the pressure field and the vertical velocity of the waves and are called *dual-sensors*. For solving the inverse problem of interest, we define a new cost function, adapted to these two-components data. We first note that the stability of the problem can be shown to be Lipschitz, assuming the parameters to be piecewise linear.

The usefulness of the cost function is to allow a separation between the observational and numerical sources. Therefore, 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. We illustrate our approach with three-dimensional medium reconstructions, where we start with minimal information on the target models.

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). It has been presented in the GDR-Meca Wave conference [31].

6.1.3. Stability and convergence analysis for seismic depth imaging using Full Waveform Inversion

Participants: Hélène Barucq, Florian Faucher.

We study the convergence of the inverse problem associated with the time-harmonic wave equations. In the context of seismic, the inverse problem uses reflection data which can only be obtained from the near surface area. We consider the propagation of waves in a domain Ω and the forward problem is defined from the displacement vector field u, solution to

$$-\rho\omega^2 u - \nabla \cdot \sigma = g, \quad \text{in } \Omega, \tag{1}$$

where g stands for the source, ρ is the density and σ the stress tensor. The inverse problem aims at the recovery of the medium parameters (contained in the stress tensor) and can be solved with an iterative minimization algorithm: this is the Full Waveform Inversion (FWI) method. We study the convergence of the minimization by introducing the framework of *Finite Curvature/Limited Deflection* (FC/LD) problems. The idea is to obtain the FC/LD properties by restricting the model space to guarantee *strictly quasiconvex* attainable set. It allows us to numerically estimate the size of the basin of attraction depending on characteristics of the inverse problem such as the frequency or the geometry of the target. In particular, it allows a quantitative comprehension of frequency progression during the iterative scheme, which is an aspect that appeared mostly intuitive. It also allows a comparison of methods from a convergence point of view. This analysis is to relate with stability estimates in order to provide a consistent scheme where frequency progression is justified from the quantitative estimates. Eventually, we illustrate our approach with elastic medium reconstructions, starting from minimal information on the initial models; this also serves to illustrate the numerical requirement of the large scale optimization seismic experiments.
This work is a collaboration with Guy Chavent (Inria Rocquencourt) and Henri Calandra (TOTAL). The results have been presented in the conference “Reconstruction Methods for Inverse Problems” [15].

6.1.4. Quantitative localization of small obstacles with single-layer potential fast solvers

Participants: Hélène Barucq, Florian Faucher, Ha Howard Faucher.

In this work, we numerically study the inverse problem of locating small circular obstacles in a homogeneous medium using noisy backscattered data collected at several frequencies. The main novelty of our work is the implementation of a single-layer potential based fast solver (called FSSL) in a Full-Waveform inversion procedure, to give high quality reconstruction with low-time cost. The efficiency of FSSL was studied in our previous works. We show reconstruction results with up to 12 obstacles in structured or random configurations with several initial guesses, all allowed to be far and different in nature from the target. This last assumption is not expected in results using nonlinear optimization schemes in general. For results with 6 obstacles, we also investigate several optimization methods, comparing between nonlinear gradient descent and quasi-Newton, as well as their convergence with different line search algorithms.
The work is published in Journal of Computational Physics [9]. This work has been presented at GDR-Meca Wave conference in Fréjus *cf.* [21].

6.1.5. Time Domain Full Waveform Inversion Adjoint Studies

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. At each iteration the parameters are updated with the solution of an adjoint equation which can be defined either as the adjoint of the continuous equation or the discrete problem. Some studies have addressed the question of establishing what the best strategy is. The answer is still unclear and turns out to be strongly dependent on the problem under study.

The purpose of this study was to investigate several computations of the adjoint state as a preamble of a FWI method applied to the time-dependent acoustic wave approximated in a Discontinuous Galerkin framework involving Bernstein elements. We have considered different time schemes to feature the inherited properties of the computed adjoint state. By comparing the different discrete adjoint operators both from a mathematical and numerical point of view, we aim at defining the best option for computing the adjoint state with accuracy at least cost.

This work is a collaboration with Henri Calandra (TOTAL). It was presented at Total MATHIAS conference in Paris [28].

6.1.6. Seismic imaging of remote targets buried in an unknown media

Participant: Yder Masson.

Box Tomography:first application to the imaging of upper-mantle shear velocity and radial anisotropy structure beneath the North American continent: The EarthScope Transpotable Array (TA) deployment provides dense array coverage through- out the continental United States and with it, the opportunity for high-resolution 3-D seismic velocity imaging of the stable part of the North American (NA) upper mantle. Building upon our previous long-period waveform tomographic modeling, we present a higher resolution 3-D isotropic and radially anisotropic shear wave velocity model of the NA lithosphere and asthenosphere. The model is constructed using a combination of teleseismic and regional waveforms down to 40 s period and wavefield computations are performed using the spectral element method both for regional and teleseismic data. Our study is the first tomographic ap- plication of ‘Box Tomography’, which allows us to include teleseismic events in our inversion, while computing the teleseismic wavefield only once, thus significantly reducing the numerical computational cost of several iterations of the regional inversion. We confirm the presence of high-velocity roots beneath the Archean part of the continent, reaching 200–250 km in some areas, however the thickness of these roots is not everywhere correlated to the crustal age of the corresponding cratonic province. In particular, the lithosphere is thick (250 km) in the western part of the Superior craton, while it is much thinner (150 km) in its eastern part. This may be related to a thermomechanical erosion of the cratonic root due to the passage of the NA plate over the Great Meteor hotspot during the opening of the Atlantic ocean 200–110 Ma. Below the lithosphere, an upper-mantle low-velocity zone (LVZ) is present everywhere under the NA continent, even under the thickest parts of the craton, although it is less developed there. The depth of the minimum in shear velocity has strong lateral variations, whereas the bottom of the LVZ is everywhere relatively flat around 270–300 km depth, with minor undulations of maximum 30 km that show upwarping under the thickest lithosphere and downwarping under tectonic regions, likely reflecting residual temperature anomalies. The radial anisotropy structure is less well resolved, but shows distinct signatures in highly deformed regions of the lithosphere.

This is the first application to a real case study of a novel imaging method called "Box Tomography". These results were obtained through collaborations with Barbara Romanowicz (Berkeley Seimological Laboratory, UC Berkeley; Collège de France) and Pierre Clouzet (Institut de Physique du Globe de Paris). The results have been published in the Geophysical Journal International [11].

Additional developments are conducted in collaboration with Sevan Adourian and Barbara Romanowicz at the Berkeley Seismological Laboratory, UC Berkeley, in particular, to efficiently account for receivers located outside the imaged region. These new results have been presented in different international conferences [23], [19].

To strengthen existing collaborations, a proposal has been submitted to the France-Berkeley Fund (13000$ for travelling and living expenses). We propose a joint effort to further develop and apply a novel seismic tomographic approach, Box-Tomography, to image and characterize small scale structures of interest in the deep Earth, such as the roots of mantle plumes, ultra-low velocity zones, or the edges of large low shear velocity provinces. Our objective is to forge a long-term collaboration between applied mathematicians at Magique3D developing wave propagation modeling methods and the seismologists at the Berkeley Seismological Laboratory (UC Berkeley) using these methods to investigate the Earth's internal structure.

6.2. Mathematical modeling of multi-physics involving wave equations

6.2.1. Hybrid space discretization to solve elasto-acoustic coupling

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 SEM-DG numerical method for solving time-dependent elasto- acoustic wave problems. We consider the first-order coupled formulation for which we propose a SEM-DG formulation which turns out to be stable. In the 2D case, the coupling is quite straightforward due to the natural way of mixing triangles with quadrangles. 3D coupling is much more difficult and the interface between tetrahedra and hexahedra deserves a particular attention.

These results have been obtained in collaboration with Henri Calandra(TOTAL) and Christian Gout (INSA Rouen) and have been presented at the Fifth International congress on multiphysics, multiscale and optimization problems in Bilbao, the 13th World Congress on Computational Mecanics in New-York and MATHIAS conference in Paris [16], [17], [24].

6.2.2. Signal and noise in helioseismic holography

Participant: Hélène Barucq.

Helioseismic holography is an imaging technique used to study heterogeneities and flows in the solar interior from observations of solar oscillations at the surface. Holograms contain noise due to the stochastic nature of solar oscillations. Aims. We provide a theoretical framework for modeling signal and noise in Porter-Bojarski helioseismic holography. Methods. The wave equation may be recast into a Helmholtz-like equation, so as to connect with the acoustics literature and define the holography Green's function in a meaningful way. Sources of wave excitation are assumed to be stationary, horizontally homogeneous, and spatially uncorrelated. Using the first Born approximation we calculate holograms in the presence of perturbations in sound-speed, density, flows, and source covariance, as well as the noise level as a function of position. This work is a direct extension of the methods used in time-distance helioseismology to model signal and noise. Results. To illustrate the theory, we compute the hologram intensity numerically for a buried sound-speed perturbation at different depths in the solar interior. The reference Green's function is obtained for a spherically-symmetric solar model using a finite-element solver in the frequency domain. Below the pupil area on the surface, we find that the spatial resolution of the hologram intensity is very close to half the local wavelength. For a sound-speed perturbation of size comparable to the local spatial resolution, the signalto-noise ratio is approximately constant with depth. Averaging the hologram intensity over a number N of frequencies above 3 mHz increases the signal-to-noise ratio by a factor nearly equal to the square root of N. This may not be the case at lower frequencies, where large variations in the holographic signal are due to the individual contributions of the long-lived modes of oscillation. This work has been done in collaboration with Laurent Gizon, Damien Fournier, Dan Yang and Aaron C. Birch of the Max-Planck-Institut für Sonnensystemforschung at Göttingen (Germany) and published in Astronomy and Astrophysics [14]

6.2.3. *Sensitivity kernels for time-distance helioseismology. Efficient computation for spherically symmetric solar models*

Participant: Hélène Barucq.

The interpretation of helioseismic measurements, such as wave travel-time, is based on the computation of kernels that give the sensitivity of the measurements to localized changes in the solar interior. These kernels are computed using the ray or the Born approximation. The Born approximation is preferable as it takes finite-wavelength effects into account, although it can be computationally expensive. Aims.We propose a fast algorithm to compute travel-time sensitivity kernels under the assumption that the background solar medium is spherically symmetric. Methods. Kernels are typically expressed as products of Green's functions that depend upon depth, latitude, and longitude. Here, we compute the spherical harmonic decomposition of the kernels and show that the integrals in latitude and longitude can be performed analytically. In particular, the integrals of the product of three associated Legendre polynomials can be computed. Results. The computations are fast and accurate and only require the knowledge of the Green's function where the source is at the pole. The computation time is reduced by two orders of magnitude compared to other recent computational frameworks. Conclusions. This new method allows flexible and computationally efficient calculations of a large number of kernels, required in addressing key helioseismic problems. For example, the computation of all the kernels required for meridional flow inversion takes less than two hours on 100 cores. This work has been done in collaboration with Damien Fournier, Chris S. Hanson and Laurent Gizon of the Max-Planck-Institut für Sonnensystemforschung at Göttingen (Germany) and published in Astronomy and Astrophysics [13]

6.2.4. *Characterization of partial derivatives with respect to material parameters in a fluid-solid interaction problem.*

Participants: Izar Azpiroz Iragorri, Hélène Barucq, Ha Howard Faucher.

For a fluid-solid interaction problem with Lipschitz interface, we investigate the partial Fréchet differentiability of the solutions and the approximate far-field-pattern with respect to solid material parameters. Differentiability is shown in standard Sobolev framework, and the derivatives are characterized as solutions to inhomogeneous fluid-solid transmission problems. To validate the accuracy of the characterization, we compare analytical values with numerical ones given by Interior Penalty Discontinuous Galerkin (IPDG) in a setting with circular obstacles. Our comparisons also show that IPDG gives results with high precision and incurs almost no effect of discretization error accumulation. This work has been done in colllaboration with Rabia Djellouli (california State University at Northridge, USA). It has been published in [3].

6.2.5. *Asymptotic modeling of multiple electromagnetic scattering problems by small obstacles*

Participants: Justine Labat, Victor Péron, Sébastien Tordeux.

The detection of small conductive heterogeneities in three dimensional domains by non-destructive electromagnetic imaging is a real challenge. Basic finite element-based methods are very expensive in terms of computation time and memory burden, since they involve a huge number of degrees of freedom when the obstacles are very small compared to the testing wavelength. Using the matched asymptotic expansions method, we have developed a meshless reduced model, which consists of replacing the scatterers by equivalent point sources. This method has been numerically implemented in Matlab and its accuracy validated with analytical solutions in spherical geometries. The details of the results are given in [35] and were presented at the fifth International Congress on Multiphysics, Multiscale and Optimization Problems in Bilbao [18] and at ECCOMAS conferences in Glasgow [22]. Following the Born and Foldy-Lax models, we can extend the results for one obstacle to the multiple scattering problem, thus provide meshless methods in this case. Numerical simulations with thousands of small scatterers, up to 10000, were presented at the seminar of RWTH Aachen University [40].

6.2.6. *Discontinuous Galerkin Trefftz type method for solving the Maxwell equations*

Participant: Sébastien Tordeux.

Trefftz type methods have been developed in Magique 3D to solve Helmholtz equation. Theese 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 work has been achieved in the context of the Master trainee of Hakon Fure in collaboration with Sébastien Pernet of ONERA Toulouse.

6.2.7. Comparison between Galbrun and linearized Euler models in the context of helioseismology

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

Helioseismology aims to probe the Sun's internal structure thanks to surface observations and our knowledge of acoustic wave propagation. In this work we focus on modeling and simulating the propagation of waves below the surface of the Sun.

In the first part, we establish the equations for acoustic wave propagation by linearizing the Euler equations describing the fluid flow. We then compare two linearization processes based on the eulerian and lagrangian description of fluid dynamics.

In the second part, we solve those equations in time-harmonic domain using high order Discontinuous Galerkin methods. Those numerical methods seem to lack consistency and stability when applied to our problems. Specifically, we notice the presence of spurious modes in our numerical solutions.

To fully understand those results further investigations are needed. In particular, two questions seem to stand out : Is the acoustic wave propagation problem in time-harmonic domain well posed for a recirculating background flow ? Is this approach valid ? Can we really assume that the solar plasma solves the Euler equations ?

6.2.8. Asymptotic Models for the Electric Potential across a Highly Conductive Casing

Participant: Victor Péron.

We analyze a configuration that involves a steel-cased borehole, where the casing that covers the borehole is considered as a highly conductive thin layer. We develop an asymptotic method for deriving reduced problems capable of efficiently dealing with the numerical difficulties caused by the casing when applying traditional numerical methods. We derive several reduced models by employing two different approaches, each of them leading to different classes of models. We prove stability and convergence results for these models. The theoretical orders of convergence are supported by numerical results obtained with the finite element method. These results have been obtained with D. Pardo (UPV/EHU, BCAM, Ikerbasque) and Aralar Erdozain. It was published in Computers and Mathematics with Applications [12].

6.2.9. 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 accepted for publication in COMPEL - The international journal for computation and mathematics in electrical and electronic engineering. This work has been presented in the symposium IABEM 2018.

6.2.10. Model-based digital pianos: from physics to sound synthesis

Participant: Juliette Chabassier.

A review article has been published in IEEE Signal Processing Magazine on model-based digital pianos in collaboration with Balasz Bank [4] .

6.2.11. The virtual workshop : towards versatile optimal design of musical wind instruments for the makers

Participants: Juliette Chabassier, Robin Tournemenne.

Our project aims at proposing optimization solutions for wind instrument making. Our approach is based on a strong interaction with makers and players, aiming at defining interesting criteria to optimize from their point of view. After having quantified those criteria under the form of a cost function and a design parameters space, we wish to implement state-of-the-art numerical methods (finite elements, full waveform inversion, neuronal networks, diverse optimization techniques...) that are versatile (in terms of models, formulations, couplings...) in order to solve the optimization problem. More precisely, we wish to take advantage of the fact that sound waves in musical instruments satisfy the laws of acoustics in pipes (PDE), which gives us access to the full waveform inversion technique, usable in harmonic or temporal regime. The methods that we want to use are attractive because the weekly depend on the chosen criterion, and they are easily adaptable to various physical situations (multimodal decomposition in the pipe, coupling with the embouchure, ...), which can therefore be modified a posteriori. The goal is to proceed iteratively between instrument making and optimal design (the virtual workshop) in order to get close to tone quality related and playability criteria. In 2018 we have implemented a python 3 toolbox named OpenWind that includes the first simulation module. Next modules will be implemented next year. This work has been presented to the Congrès Français d'Acoustique [26].

6.2.12. Collaboration with Augustin Humeau, wind instrument maker

Participants: Juliette Chabassier, Robin Tournemenne.

We have initiated a strong collaboration with Augustin Humeau, bassoon maker in Dordogne, France. The goal is to develop practical tools for instrument design, in the realistic context of an artisanal workshop. Until now, an input impedance measurement setup has been developed in collaboration with Samuel Rodriguez, I2M Univ. Bordeaux. It is based on the use of five microphones and the need of one calibration. It has been specifically adapted to the small entrances of some wind instruments (bassoon, oboes). We have attended the JFIS (journées facture instrumentale et science) in November 2018, Le Mans, where the approach has been presented and demonstrated. Given the great interest showed by other instrument makers attendanting the conference, the future of this collaboration is in discussion and may integrate an Inria startup process.

6.2.13. Optimization of brass wind instruments based on sound simulations

Participant: Robin Tournemenne.

We exploited a new optimization method of the inner shape of brass instruments using sound simulations to derive objective functions. The novelties are the obtention of optimal bores for objective functions representative of the intonation but also of the spectrum of the instrument, and the possibility to include constraints in the optimization problem. A complete physics-based model, taking into account the instrument and the musician's embouchure, is used, in order to simulate sounds' permanent regimes using the harmonic balance technique. The instrument is modeled by its input impedance computed with the transfer matrix method under plane wave propagation and visco-thermal losses. Some embouchure's parameters remain variable during the optimization procedure in order to get the average behavior of the instrument. The design variables are the geometrical dimensions of the resonator. Given the computationally expensive function evaluation and the unavailability of gradients, a surrogate-assisted optimization framework is implemented using the mesh adaptive direct search algorithm (MADS). Two optimization examples of a Bb trumpet's bore (with two and ten design optimization variables) demonstrate the effectiveness of the approach. Results show that solvers can deal flawlessly with high dimensional problems, under constraints, improving significantly the value of the objective functions.

6.2.14. Energy based model and simulation in the time domain of linear acoustic waves in a radiating pipe

Participants: Juliette Chabassier, Robin Tournemenne.

We model in the time domain linear acoustic waves in a radiating pipe without damping. The acoustic equations system in formulated in flow and pressure, which leads to a first order space time equations system. The radiation condition is also written as a first order in time equation, and is parametrized by two real coefficients. Moreover, an auxiliary variable is introduced at the radiating boundary. The choice of this variable is adapted to the considered source type in order to ensure the model stability by energy techniques, under some conditions on the radiating condition. We then propose a stable space time explicit discretization, which ensures the dissipation of a discrete energy. The novelty of the discretization lies, on the one hand, in the variational nature of the space approximation (which leads to arbitrary order finite elements with no required matrix inversion), and on the other hand, on the definition of the auxiliary variable for any acoustic source type (which leads to the decay of a well defined energy). Finally, we quantify the frequential domain of validity of the used radiation condition by comparison with theoretical and experimental models of the literature. This is a collaboration with Morgane Bergot (Université Claude Bernard, Lyon 1). An article has been written and will be submitted soon. This work has been presented to the Congrès Français d'Acoustique [25].

6.2.15. Computation of the entry impedance of a dissipative radiating pipe

Participants: Juliette Chabassier, Robin Tournemenne.

Modeling the entry impedance of wind instruments pipes is essential for sound synthesis or instrument qualification. We study this modeling with the finite elements method in one dimension (FEM1D) and with the more classically used transfer matrix method (TMM). The TMM gives an analytical formula of the entry impedance depending on the bore (intern geometry of the instrument) defined as a concatenation of simple elements (cylinders, cones, etc). The FEM1D gives the entry impedance for any instrument geometry. The main goals of this work are to assess the viability of the FEM1D and to study and analyse the approximations necessary for the TMM in dissipative pipes. First, lossless Webster's equation in one dimension is studied with arbitrary radiation conditions. In this context and for cylinders or cones, the TMM is exact. We verify that the error made with FEM1D for fine enough elements is as small as desired. When we consider viscothermal losses, the TMM does not solve the classical Kirchhoff model because two terms are supposed constant. In order to overcome this model approximation, simple segments, on which are based the TMM, are decomposed into much smaller segments. We show that using the TMM actually amounts to solving a different equation than the original one, on each small segment. The FEM1D does not necessitate any model approximation, and it is possible to show that it solves the dissipative equation with any arbitrarily small error. With this in hand, we can quantify the TMM model approximation error. The methods are compared in terms of accuracy and computational burden. On realistic cases as the case of a trumpet, the FEM show a better efficiency. Moreover, unusual phenomena as a non constant air temperature can easily be tackle with the FEM. An article has been written and will be submitted soon. This work has been presented to the Congrès Français d'Acoustique [27].

6.2.16. 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 source for lab-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. 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 numerical schemes, opening the possibility of performing FWI on these high resolution data.

This work is in collaboration with Clarisse Bordes, Daniel Brito and Deyuan Zhang (LFCR, UPPA) and with Stéphane Garambois (ISTerre). It was presented at conference AGU [42].

6.3. Supercomputing for Helmholtz problems

6.3.1. 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.

6.4. Hybrid time discretizations of high-order

6.4.1. Space-Time Discretization of Elasto-Acoustic Wave Equation in Polynomial Trefftz-DG Bases

Participants: Elvira Shishenina, 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 have been published in the Applicable Analysis Journal [6], in the book of proceedings for European Conference on Numerical Mathematics and Advanced Applications (ENUMATH 2017) (due date April 27, 2019), and in the PhD thesis [2], as well as presented during the International Conference on Spectral and High-Order Methods (ICOSAHOM 2018, London - UK), the 13$^{\text{th}}$ World Congress on Computational Mechanics (WCCM 2018, New-York - USA), and during the annual seminar on Computational Science Engineering and Data Science organized by TOTAL (MATHIAS 2018, Serris - France).

6.4.2. Performance analysis of local time-stepping schemes for wave propagation

Participants: Julien Diaz, Rose-Cloé Meyer.

The efficiency of numerical simulation of wave propagation is highly dependent of the quality of the mesh. For complex simulations, the size of the cells in the mesh can strongly vary, either because of the geometry or because of the different propagation celerity of the waves. To ensure stability, explicit numerical schemes must match with the CFL conditions of every cells of the mesh. When significant disparities appear in the domain, the time step used on big cells is not optimal, which can cause heavy calculation cost and result in a loss of efficiency. To improve the performance of the programs, local time-stepping methods based on a spatial Discontinuous Galerkin discretization have been implemented. In this work, we compared three local time-stepping methods: a conservative method, a recursive method, and an asynchron method. The two first methods use local time steps that are fractions of the global time step, while the third method can use independent time steps on each cell of the mesh. The accuracy of the solution, the computation cost and the speedup of local-time stepping are presented on cases in two and three dimensions on configurations as fine slot or domains with geometric singularities. The results are presented in Rose-Cloé Meyer Master thesis [41]. This work has been achieved in collaboration with Guillaume Dufour and Xavier Ferrières (Onera)

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

Participants: Juliette Chabassier, Julien Diaz.

We submitted a paper to M2AN [37]. 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).

6.4.4. Construction and convergence analysis of conservative second order local time discretisation for wave equations

Participant: Juliette Chabassier.

In this work we present and analyse a time discretisation strategy for linear wave propagation that aims at using locally in space the most adapted time discretisation among a family of implicit or explicit centered second order schemes. The domain of interest being decomposed into several regions, different time discretisations can be chosen depending on the local properties of the spatial discretisations (mesh size and quality) or the physical parameters (high wave speed, low density). We show that, under some conditions on the time step, the family of time discretisations obtained combined with standard finite elements methods in space ensures a second order space-time convergence. This work has been done in collaboration with Sébastien Imperiale (Inria Project-Team M3DISIM). It has been submitted to Numerische Mathematik.

6.4.5. High-order locally implicit time schemes for linear ODEs

Participants: Hélène Barucq, Marc Duruflé, Mamadou N'Diaye.

In this work we have proposed a method that combines optimized explicit schemes and implicit schemes to form locally implicit schemes for linear ODEs, including in particular ODEs coming from the space discretization of wave propagation phenomena. This method can be applied to the following ODE

$$M_h \frac{dU}{dt} = K_h U + F(t)$$

Like in the local time-stepping developed by Grote and co-workers, the computational domain is split into a fine region and a coarse region. The matrix A_h is given as

$$A_h = M_h^{-1} K_h = A_h P + A_h (I - P)$$

where P is the projector on the fine region of the computational domain. Then the proposed locally implicit method is obtained from the combination of the A-stable implicit schemes we have developed in 2016 (Padé schemes or Linear-SDIRK schemes detailed in [8]) on the fine region and explicit schemes with optimal CFL number in the coarse region. The developed method has been used to solve the acoustic wave equation and we have checked the convergence in time of these schemes for order 4, 6 and 8.

This work is a chapter of the thesis defended by Mamadou N'diaye under the joint supervision of Hélène Barucq and Marc Duruflé. In 2018, the implemented method has been parallelized in Montjoie and 3-D numerical results have been obtained. An article is in preparation.

7. Bilateral Contracts and Grants with Industry

7.1. Contracts with TOTAL

- Depth Imaging Partnership (DIP)

  Period: 2014 May - 2019 April , Management: Inria Bordeaux Sud-Ouest, Amount: 120000 euros/year.
- Approximations hybrides par éléments finis discontinus pour l'élasto-acoustique

  Period: 2016 November - 2018 October, Management: Inria Bordeaux Sud-Ouest, Amount: 165000 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.
- Utilisation d'images 3D DRP à différentes échelles et résolutions pour vérifier l'applicabilité des problèmes acoustiques Period: 2017 November - 2019 October, Management: Inria Bordeaux Sud-Ouest, Amount: 170000 euros.
- Petrophysics in pre-salt carbonate rocks

  Period: 2017 December - 2019 November, Management: Inria Bordeaux Sud-Ouest, Amount: 190000 euros.

8. Partnerships and Cooperations

8.1. Regional Initiatives

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

title: Imaging complex materials.

Coordinator: Hélène Barucq

Other partners: I2M CNRS Université Bordeaux I

The detection, localization and monitoring of the defect evolution in composite materials, concrete and more generally heterogeneous materials is a challenging problem for Aeronautics and energy production. It is already possible to localize defects in homogeneous materials by using methods based on ultrasonic inspection and sometimes, they are usable in particular heterogeneous materials, most of the time in 2D. Classical methods rely on the correspondence between the distance and the propagation time of the wave traveling between the defect and the receivers. In complex media, such a correspondence may be lapsed, for instance when the velocity depends on the frequency (dispersion) or of the propagation direction (anisotropy). The defect signature can also be embedded in the acoustic field sent by the structure (multiple reflections). The complexity of the propagation in heterogeneous materials makes then difficult the accurate localization of the defect, in particular in 3D.

Topological imaging techniques can be applied to heterogeneous media. They can find the positions of defects from two simulations performed in a safe experimental medium. They have been developed at I2M laboratory to carry on 2D single/multi mode inspection in isotropic and anisotropic waveguides. They have also been applied to a highly reflecting medium observed with a single sensor. The objective of this work is to extend the technique to 3D problems. In particular, we are going to handle detection in composite plates and in highly heterogeneous media including a collection of small scatterers.

This project is supported by the Conseil Régional d'Aquitaine, for a duration of 2 years.

8.2. National Initiatives

8.2.1. 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.

8.2.2. PRE Concert

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

8.2.3. 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€.

8.2.4. ANR NonLocalDD

Magique 3-D is a partner of the ANR project entitled "Non Local Domain Decomposition Methods in Electromagnetics" that begins in october 2015. The aim of this project is to develop domain decomposition methods for the efficient solution of acoustics and Maxwell's equation either with boundary integral equations or finite element volume method. To obtain an exponential convergence of the iterative solution, non-local operators are studied and optimized to achieve a faster convergence. A post-doctoral student Marcella Bonazzoli has been hired by Magique 3-D in 2017 to study multi-domain integral equations for wave propagation. This student is supervised by Xavier Claeys, a partner of the NonLocalDD ANR project.

8.2.5. 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.

8.3. European Initiatives

8.3.1. H2020 Projects

8.3.1.1. 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.

8.4. International Initiatives

8.4.1. Inria International Partners

8.4.1.1. Declared Inria International Partners

8.4.1.1.1. 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

8.5. International Research Visitors

8.5.1. Visits of International Scientists

- José M. Carcione (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, OGS) visited Magique 3D in December 2018.
- Guy Chavent (Inria Rocquencourt, Emeritus professor) visited Magique 3D in December 2018.
- Barbara Romanowicz (Berkeley Seismological Laboratory, Collège de France) visited Magique 3D in November 2018
- Mounir Tlemcani (Université d'Oran, Algeria) visited Magique 3D in March 2018.
- Rabia Djellouli (CSUN) visited Magique 3D in February 2018.

8.5.2. Visits to International Teams

8.5.2.1. Research Stays Abroad

- Justine Labat visited Benjamin Stamm, RTWH Aachen University, Germany, in December 2018.
- In the framework of DIP, Pierre Jacquet visited Total Research Center at Houston, USA, in December 2018.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Journal

9.1.1.1. Reviewer

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

- Applicable Analysis
- Applied Numerical Mathematics
- Computers and Geosciences
- Geophysical Journal International
- IMA Journal of Numerical Analysis
- International Journal for Numerical Methods in Engineering
- Journal of Computational Physics
- Journal of Inverse and Ill-posed Problems
- SIAM Journal of Numerical Analysis
- SIAM Journal on Scientific Computing
- Wave Motion

9.1.2. 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).

9.1.3. 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 the committee which evaluates research projects in Mathematics, Computer Science, Electronics and Optics to be funded by the Regional Council New Aquitaine

9.1.4. Research Administration

- Julien Diaz is elected member of the Inria Technical Committee and of the Inria Administrative and Scientific Boards.
- Justine Labat is elected member of Laboratory Commitee of UPPA
- Justine Labat organized the seminar of PhD students of LMAP
- Juliette Chabassier is member of the Inria BSO Young Researcher Committee and of the Inria BSO Center Committee. She is member of the Workgroup for sustainable development at Inria Bordeaux Sud-Ouest.
- Victor Péron is appointed member of the CJC (Commission Jeunes Chercheurs) of Inria Bordeaux Sud-Ouest.
- Hélène Barucq is member of the monitoring and studies forward unit of Inria. She is the scientific head of the project DIP since its creation in 2009.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

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

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

Licence : Marc Duruflé, Algorithmique Numérique, 30h Eq. TD, L3, Enseirb-MatMeca, France

Licence : Marc Duruflé, Mathématiques pour les sciences du milieu naturel, 30h Eq. TD, L3, Ensegid, 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

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, Courbes et calcul intégral, 19.5 Eq. TD, L2, 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

9.2.2. Supervision

PhD : Izar Azpiroz Iragorri, Contribution to the Numerical Reconstruction in Inverse Elasto-Acoustic Scattering, February 28th, Hélène Barucq, Julien Diaz and Rabia Djellouli (CSUN).

PhD : Elvira Shishenina, Discrétisation espace-temps d'équations d'ondes élasto-acoustiques dans des bases TREFFTZ-DG polynomiales, December 7th, Hélène Barucq and Julien Diaz.

PhD in progress : Hamza Alaoui Hafidi, Imagerie ultrasonore tridimensionnelle dans les milieux hétérogènes complexes, October 2015, Marc Deschamps, Michel Castaings, Eric Ducasse, Samuel Rodriguez (I2M), Hélène Barucq, Marc Duruflé, Juliette Chabassier (Magique 3D).

PhD in progress : Aurélien Citrain, Déformation 3D de maillages en imagerie sismique, Méthodes d'inversion sismique dans le domaine fréquentiel , October 2016, Hélène Barucq and Christian Gout.

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, ,October 2017, Hélène Barucq and Julien Diaz.

PhD in progress : Justine Labat, Diffraction of an electromagnetic wave by small obstacles, Université de Pau et des Pays de l'Adour, October 2016, Victor Péron and Sébastien Tordeux

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).

Master 2 internship : Rose-Cloé Meyer, Analyse de performances de schémas à pas de temps locaux pour la simulation numérique de phénomènes de propagations d'ondes, Enseirb-Matmeca, Sept. 2018.

Master 2 internship : Nathan Rouxelin, Comparaison des modèles de Galbrun et d'Euler linéarisé dans le contexte de l'héliosismologie , Insa Rouen, Sept. 2018.

Master 2 internship: A discontinuous Galerkin Trefftz type method for solving the Maxwell equations, INSA Toulouse, Sept 2018

Master 2 internship : Auxence MBaimou: Models for plates and beams, application to the piano bridge, Marseille University, Sept. 2018.

L3 internship : Jérémy Martin, Sept. 2018.

9.2.3. Juries

- Hélène Barucq : (Insa de Rouen et ENSA d'Agadir (Maroc)) "De l'optimisation pour l'aide à la décision. Application au problème du voyageur de commerce probabiliste et l'approximation de données", PhD thesis, December 12th 2018
- Hélène Barucq : Bruno Weber (Université de Strasbourg) "Optimisation de code Galerkin discontinu sur ordinateur hybride. Application à la simulation numérique en électromagnétisme", PhD thesis, November 26th 2018

- Hélène Barucq : Florent Masmoudi (Université de Toulouse) "Non intrusive reduced order models", PhD thesis, July 9th 2018
- Hélène Barucq : Boris Caudron (Université de Nancy) "Couplages FEM-BEM faibles et optimisés pour des problèmes de diffraction harmoniques en acoustique et en électromagnétisme, PhD thesis, June 25th 2018
- Julien Diaz : Florian Monteghetti (Université de Toulouse), Analysis and Discretization of Time-Domain Impedance Boundary Conditions in Aeroacoustics, October 15th 2018
- Sébastien Tordeux: Hélène Canot (Université de Bretagne Sud) Méthodes d'homogénéisation et simulations numériques appliquées à la réponse électromagnétique des matériaux multi échelles
- Juliette Chabassier : Antoine Bensalah (Université Paris Saclay) Une approche nouvelle de la modélisation mathématique et numérique en aéroacoustique par les équations de Goldstein, 6 july 2018
- Victor Péron : Mostafa Shahriari (Basque Center for Applied Mathematics, BCAM), Fast One-Dimensional Finite Element Approximation of Geophysical Measurements, November 14th 2018

9.3. Popularization

9.3.1. Interventions

- Justine Labat participated in scientific 'speed datings' during the 'Filles et Maths' day at Pau in May 2018.
- Justine Labat animated the stand in Mathematics during 'Le Village des Sciences' day at Pau in October 2018.
- Sébastien Tordeux gave a talk on numerical analysis in the Cercle Sofia Kovalevskaïa of Toulouse in May 2018
- Juliette Chabassier participated to a movie - debate event in Cognac in march 2018.
- Juliette Chabassier animated a workshop around virtual piano during the Inria "10 years night" in september 2018.
- Juliette Chabassier animated a workshop around virtual piano during the Inria "fête de la science" in october 2018.
- Robin Tournemenne animated a workshop around virtual piano during the Inria "fête de la science" in october 2018.
- Juliette Chabassier animated a workshop around virtual piano during the Inria "open doors day" in october 2018.
- Juliette Chabassier welcomed L3 students around a virtual piano workshop in december 2018.

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