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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 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 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. Inverse Problems

- **Inverse scattering problems.** The determination of the shape of an obstacle immersed in a fluid medium from some measurements of the scattered field in the presence of incident waves is an important problem in many technologies such as sonar, radar, geophysical exploration, medical imaging and nondestructive testing. Because of its nonlinear and ill-posed character, this inverse obstacle problem (IOP) is very difficult to solve, especially from a numerical viewpoint. The success of the reconstruction depends strongly on the quantity and quality of the measurements, especially on the aperture (range of observation angles) and the level of noise in the data. Moreover, in order

to solve IOP, the understanding of the theory for the associated direct scattering problem and the mastery of the corresponding solution methods are fundamental. Magique-3d is involved in the mathematical and numerical analysis of a direct elasto-acoustic scattering problem and of an inverse obstacle scattering problem. More specifically, the purpose of this research axis is to propose a solution methodology for the IOP based on a regularized Newton-type method, known to be robust and efficient.

- **Depth Imaging in the context of DIP.** The challenge of seismic imaging is to obtain an accurate representation of the subsurface from the solution of the full wave equation that is the best mathematical model according to the time reversibility of its solution. The Reverse Time Migration, [82], is a technique for Imaging which is widely used in the industry. It is an iterative process based on the solution of a collection of wave equations. The high complexity of the propagation medium requires the use of advanced numerical methods, which allows one to solve several wave equations quickly and accurately. Magique-3D is involved in Depth Imaging by the way of a collaboration with TOTAL, in the framework of the research program DIP which has been jointly defined by researchers of MAGIQUE-3D and engineers of TOTAL jointly. In this context, MAGIQUE-3D develops new algorithms in order to improve the RTM.

3.2. Modeling

The main activities of Magique-3D in modeling are the derivation and the analysis of models that are based on mathematical physics and are suggested by geophysical problems. In particular, Magique-3D considers equations of interest for the oil industry and focuses on the development and the analysis of numerical models which are well-adapted to solve quickly and accurately problems set in very large or unbounded domains as it is generally the case in geophysics.

- **Explicit High-Order Time Schemes.** Using the full wave equation for migration implies very high computational burdens, in order to get high resolution images. Indeed, to improve the accuracy of the numerical solution, one must considerably reduce the space step, which is the distance between two points of the mesh representing the computational domain. Another solution consists in using high-order finite element methods, which are very accurate even with coarse meshes. However, to take fully advantage of the high-order space discretization, one has to develop also high-order time schemes. The most popular ones for geophysical applications are the modified equation scheme [85], [100] and the ADER scheme [91]. Both rely on the same principle, which consists in applying a Taylor expansion in time to the solution of the wave equation. Then, the high-order derivatives with respect to the time are replaced by high order space operators, using the wave equation. Finally, auxiliary variables are introduced in order to transform the differential equation involving high-order operators into a system of differential equation with low order operators. The advantage of this technique is that it leads to explicit time schemes, which avoids the solution of huge linear systems. The counterpart is that the schemes are only conditionally stable, which means that the time step is constrained by a CFL (Courant-Friedrichs-Levy) condition. The CFL number defines an upper bound for the time step in such a way that the smaller the space step is, the higher the numbers of iterations will be. Magique-3D is working on the construction and the analysis of new explicit time schemes which have either larger CFL numbers or local CFL numbers. By this way, the computational costs can be reduced without hampering the accuracy of the numerical solution.
- **Implicit High-Order Time Schemes.** Solving wave propagation problems in realistic media and in time domain is still a challenge. Implicit numerical schemes are nowadays considered as too expensive because they require the inversion of a linear system at each time step, contrary to the explicit schemes. However, explicit schemes are stable only when conditions on the discretization parameters are fulfilled, which can be very difficult to satisfy in realistic contexts and lead to very expensive simulations. These conditions become less dramatic or even disappear in some cases when using implicit schemes. Our goal is to construct, justify and optimize analytically original implicit schemes that seem accurate to solve specific difficulties coming from realistic problems. Several directions could be followed. First, we will continue to develop a methodology to construct high

order implicit schemes for simple domains (conservative and homogeneous). For now (in [23]) we have used the modified equation technique on the classical θ -scheme, which leads to a parametrized family of numerical schemes that do not possess the same consistency error. Then, instead of choosing a time step that leads to a good precision for a given numerical scheme and spatial discretization, we reverse this standard reasoning and choose the best stable scheme, in the family of schemes that we just built, for a spatial and temporal given discretization. Stability is shown by energy techniques. It would be possible to continue this approach, leading to higher order schemes and better mastering the methodology. Crucial improvements to this work will be to adapt the methodology to dissipative media, heterogeneous media, realistic boundary conditions and model coupling. For instance, we aim at developing locally implicit schemes, for which the degree of implicitness would depend on the local characteristics of the media. Implicit-explicit schemes would be an application case of these new schemes, that could be used to optimize the global cost of simulation. Since computational efficiency is a priority, this theoretical seek will systematically be completed by the study of associated algorithms and their implementation on parallel architectures. We believe that locally implicit schemes will be well suited to the use of parallel algorithms.

- **Asymptotic methods for ultra short laser pulses propagation** In the long term goal of modeling an entire ultrashort laser chain, our first objective is to model the propagation of an ultrashort laser pulse in an isotropic third order nonlinear dispersive medium (as silica which is the material used for optical fibers or lenses). In other words, the optical index of the medium depends on the wavelength (dispersion phenomenon) but also on the electromagnetic field's intensity in a cubic way (Kerr effect). A first intuition is to use Maxwell's equations coupled with additional equations for the optical index. Current computing facilities allow us to solve such equations in parallel on small domains and during short time intervals, for instance using MONTJOIE software. The use of asymptotical methods that take advantage of the pulse's brevity leads to a family of equations written as evolution equations in the propagation direction (among which the nonlinear Schrödinger equation), and solved in frequency domain, which are much easier to solve. However, ultrashort pulses have large spectra, which contradicts another hypothesis currently done in usual asymptotic methods. This is why new models have to be derived, as well as numerical methods to solve them.

In fiber optics, the laser pulse propagates inside a waveguide called "optical fiber", in which the transversal spatial repartition of the electromagnetic field can be shown to be a linear combination of eigenmodes. A first idea will be to generalize the results obtained in 1d (see 6.2.12) to this more realistic application. We have good reasons to believe that a very efficient model will be derived and will compare very well with the global Maxwell system. An ultimate validation will be obtained by comparing the numerical results with experimental data.

Following this step, and in collaboration with CEA-CESTA, we wish to derive this kind of asymptotic models and associated numerical methods for general 3D open laser propagation.

- **Finite Element Methods for the time-harmonic wave equation.** As an alternative to Time-Domain Seismic Imaging, geophysicists are more and more interested by Time-Harmonic Seismic Imaging. The drawback of Time Domain Seismic Imaging is that it requires either to store the solution at each time step of the computation, or to perform many solutions to the wave equation. The advantage of Time Harmonic problems is that the solutions can be computed independently for each frequency and the images are produced with only two computations of the wave equation and without storing the solution. The counterpart is that one has to solve a huge linear system, which can not be achieved today when considering realistic 3D elastic media, even with the tremendous progress of Scientific Computing. Discontinuous Galerkin Methods (DGM), which are well-suited for hp -adaptivity, allow for the use of coarser meshes without hampering the accuracy of the solution. We are confident that these methods will help us to reduce the size of the linear system to be solved, but they still have to be improved in order to tackle realistic 3D problems. However, there exists many different DGMs, and the choice of the most appropriate one for geophysical applications is still not obvious. Our objectives are **a)** to propose a benchmark in order to test the performances of DGMs for seismic applications and **b)** to improve the most performant DGMs in order to be able to tackle realistic

applications. To these aims, we propose to work in the following directions :

1. To implement a 2D and 3D solver for time harmonic acoustic and elastodynamic wave equation, based on the Interior Penalty Discontinuous Galerkin Method (IPDGM). The implementation of this solver has started few years ago (see Section 5.1) for solving Inverse Scattering Problems and the results we obtained in 2D let us presage that IPDGM will be well-adapted for geophysical problems.
2. To develop a new hybridizable DG (HDG) [84] for 2D and 3D elastodynamic equation. Instead of solving a linear system involving the degrees of freedom of all volumetric cells of the mesh, the principle of HDG consists in introducing a Lagrange multiplier representing the trace of the numerical solution on each face of the mesh. Hence, it reduces the number of unknowns of the global linear system and the volumetric solution is recovered thanks to a local computation on each element.
3. To develop upscaling methods for very heterogeneous media. When the heterogeneities are too small compared with the wavelengths of the waves, it is necessary to use such techniques, which are able to reproduce fine scale effects with computations on coarse meshes only.

We also intend to consider finite elements methods where the basis functions are not polynomials, but solutions to the time-harmonic wave equations. We have already developed a numerical method based on plane wave basis functions [89]. The numerical results we have obtained on academic test cases showed that the proposed method is not only more stable than the DGM, but also exhibits a better level of accuracy. These results were obtained by choosing the same plane waves for the basis functions of every element of the mesh. We are now considering a new methodology allowing for the optimization of the angle of incidence of the plane waves at the element level.

Last, we are developing an original numerical methods where the basis functions are fundamental solutions to the Helmholtz equation, such as Bessel or Hankel functions. Moreover, each basis function is not defined element by element but on the whole domain. This allows for reducing the volumetric variational formulation to a surfacic variational formulation.

- **Boundary conditions.** The construction of efficient absorbing boundary conditions (ABC) is very important for solving wave equations. Indeed, wave problems are generally set in unbounded or very large domains and simulation requires to limit the computational domain by introducing an external boundary, the so-called absorbing boundary. This topic has been a very active research topic during the past twenty years and despite that, efficient ABCs are have still to be designed. Classical conditions are constructed to absorb propagating waves and Magique-3D is investigating the way of improving existing ABCs by introducing the modelling of evanescent and glancing waves. For that purpose, we consider the micro-local derivation of the Dirichlet-to-Neumann operator. The interest of our approach is that the derivation does not depend on the geometry of the absorbing surface.

ABCs have been given up when Perfectly Matched Layers (PML) have been designed. PMLs have opened a large number of research directions and they are probably the most routinely used methods for modelling unbounded domains in geophysics. But in some cases, they turn out to be unstable. This is the case for some elastic media. We are thus considering the development of absorbing boundary conditions for elastodynamic media and in particular for Tilted Transverse Isotropic media, which are of high interest for geophysical applications.

- **Asymptotic modeling.**

During the last 30 years, mathematicians have developed and justify approximate models with multiscale asymptotic analysis to deal with problems involving singularly perturbed geometry or problems with coefficients of different magnitude.

Numerically, all these approximate models are of interest since they allow to mesh the computational domain without taking into account the small characteristic lengths. this techniques lead to a reduction of the computation burden. Unfortunately, these methods do not have penetrated the numerical community since most of the results have been obtained for the two dimensional Laplacian.

The research activity of Magique 3D aims in extending this theory to three-dimensional challenging problems involving wave propagation phenomena. We address time harmonic and time dependent problems for acoustic waves, electromagnetic waves and elastodynamic wave which is a very important topic for industry. Moreover, it remains numerous open questions in the underlying mathematical problems.

Another important issue is the modeling of boundary layers which are not governed by the same model than the rest of the computational domain. It is rather challenging to derive and to justify some matching condition between the boundary layer and the rest of the physical domain for such multiphysical problems.

More precisely, we have worked in 2013 on the following topics:

- Eddy current modeling in the context of electrothermic applications for the design of electromagnetic devices, in collaboration with laboratories Ampère, Laplace, Inria Team MC2, IRMAR, and F.R.S.-FNRS;
- Multiphysic asymptotic modeling of multi perforate plates in turbo reactors in collaboration with Onera.
- Modeling of small heterogeneities for the three dimensional time domain wave equation. This reduced models is a generalization of the so called Lax-Foldy reduced model.

3.3. High Performance methods for solving wave equations

Seismic Imaging of realistic 3D complex elastodynamic media does not only require advanced mathematical methods but also High Performing Computing (HPC) technologies, both from a software and hardware point of view. In the framework of our collaboration with Total, we are optimizing our algorithms, based on Discontinuous Galerkin methods, in the following directions.

- **Minimizing the communications between each processor.** One of the main advantages of Discontinuous Galerkin methods is that most of the calculi can be performed locally on each element of the mesh. The communications are carried out by the computations of fluxes on the faces of the elements. Hence, there are only communications between elements sharing a common face. This represents a considerable gain compared with Continuous Finite Element methods where the communications have to be done between elements sharing a common degree of freedom. However, the communications can still be minimized by judiciously choosing the quantities to be passed from one element to another.
- **Hybrid MPI and OpenMP parallel programming.** Since the communications are one of the main bottlenecks for the implementation of the Discontinuous Galerkin in an HPC framework, it is necessary to avoid these communications between two processors sharing the same RAM. To this aim, the partition of the mesh is not performed at the core level but at the chip level and the parallelization between two cores of the same chip is done using OpenMP while the parallelization between two cores of two different chips is done using MPI.
- **Porting the code on new architectures.** We are now planning to port the code on the new Intel Many Integrated Core Architecture (Intel MIC). The optimization of this code has begun in 2013, in collaboration with Dider Rémy from SGI.
- **Using Runtimes Systems.** One of the main issue of optimization of parallel code is the portability between different architectures. Indeed, many optimizations performed for a specific architecture are often useless for another architecture. In some cases, they may even reduce the performance of the code. Task programming libraries such as StarPU (<http://runtime.bordeaux.inria.fr/StarPU/>) or DAGuE (<http://icl.cs.utk.edu/dague/index.html>) seem to be very promising to improve the portability of the code. These libraries handle the repartition of workloads between processors directly at the runtime level. However, until now, they have been mostly employed for solving linear algebra problems and we wish to test their performance on realistic wave propagation simulations. This is done in the framework of a collaboration with Inria Team Hiepac and Georges Bosilca (University of Tennessee).

We are confident in the fact that the optimizations of the code will allow us to perform large-scale calculations and inversion of geophysical data for models and distributed data volumes with a resolution level impossible to reach in the past.

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. Ultrashort Laser Pulses Propagation

One of the challenges in modern laser design is the improvement of the generation and manipulation of ultrashort pulses. These pulses are characterized by a short impulsion that typically lasts several femtoseconds. Recent innovations in ultrashort laser pulses open a wide range of possibilities in the interaction with matter and of applications. This scientific challenge is consequent, and has numerous applications : athermal micro-machining, imaging, optical surgery, meteorology, fundamental research For instance, the european project ELI (Extreme Light Infrastructure) aims at reaching tremendous peak powers of about 200 PW for fundamental physical experiments. Nowadays, numerical simulations can help to better understand physics by solving more and more elaborated models, simulate more and more realistic phenomena. They also provide an efficient and attractive tool for designing since they are less expensive than physical experiments. A laser chain consists of a set of optical components (e.g. lenses, optical amplifier, mirror, crystal, ...), which have various effects on the impulsion. An exact solution can be obtained by solving non-linear Maxwell's equations, but a direct numerical simulation is too costly because the computational domain may comprise from a thousand wavelengths until several millions of wavelengths in the direction of propagation. Current numerical tools are based on the resolution of non-linear Schrödinger models, where dispersive and non-linear effects (Kerr effect, Raman effect, N-wave mixing, ...) are mixed. Those models are becoming less and less accurate with modern pulses because the bandwidth becomes larger and because the intensity becomes higher. In the future, more robust models and numerical tools will be needed.

4.3. Modeling of Multiperforated plates in turboreactors

In the turbo-engine, the temperature can reach 2000 K inside the combustion chamber. To protect its boundary, “fresh” air at 800 K is injected through thousands of perforations. The geometry of the network of perforations is chosen in order to optimize the cooling and the mechanical properties of the chamber. It has been experimentally observed that these perforations have a negative impact on the stability of the combustion. This is due to the interaction with an acoustic wave generated by the combustion. Due to the large number of holes (2000) and their small sizes (0.5 mm) with respect to the size of the combustion chamber (50 cm), it is not conceivable to rely on numerical computations (even with supercomputers) to predict the influence of these perforations.

In collaboration with ONERA, we develop new models which allows to take into account these multiperforated plates at the macroscopic scale.

5. Software and Platforms

5.1. Hou10ni

Participant: Julien Diaz [correspondant].

5.1.1. Hou10ni-Time-Domain

This software, written in FORTRAN 90, simulates the propagation of acoustic waves in heterogeneous 2D and 3D media. It is based on an Interior Penalty Discontinuous Galerkin Method (IPDGM). The 2D version of the code has been implemented in the Reverse Time Migration (RTM) software of TOTAL in the framework of the Ph.D thesis of Caroline Baldassari. The 2D code allows for the use of meshes composed of cells of various order (p -adaptivity in space). For the time discretization, we used the local time stepping strategy described at section 3.2, item **High-Order Schemes in Space and Time** which permits not only the use of different time-step, but also to adapt the order of the time-discretization to the order of each cells (hp -adaptivity in time).

The main competitors of Hou10ni are codes based on Finite Differences, Spectral Element Method or other Discontinuous Galerkin Methods (such as the ADER schemes). During her Ph.D thesis, Caroline Baldassari compared the solution obtained by Hou10ni to the solution obtained by a Finite Difference Method and by a Spectral Element Method (SPECFEM). To evaluate the accuracy of the solutions, we have compared them to analytical solutions provided by the codes Gar6more (see below). The results of these comparisons are: a) that Hou10ni outperforms the Finite Difference Methods both in terms of accuracy and of computational burden and b) that its performances are similar to Spectral Element Methods. Since Hou10ni allows for the use of meshes based on tetrahedrons, which are more appropriate to mesh complex topographies, and for the p -adaptivity, we decided to implement it in the RTM code of TOTAL. Of course, we also used these comparisons to validate the code.

5.1.2. Hou10ni-Frequency-Domain

Recently, we have extended the 2D version of Hou10ni for computing the solution of the harmonic wave equation (Helmholtz), in the framework of the PhD thesis of Élodie Estécahandy. This new version is able to deal with both acoustic and elastodynamic media, but also to model elastoacoustic problems. The surfaces between the different media can be approximated by curved elements. We can use up to P^{15} elements when dealing with curved elements and element of arbitrary order (with of course a limitation depending on the machine precision) when dealing with non-curved elements. The construction of the global matrix is performed using OpenMP and the extension to hybrid MPI/OpenMP parallelism is on development. This code has been also implemented in a solver which determine the shape of an elastic obstacle from the knowledge of its scattered field.

The 3D version of Hou10ni-Frequency-Domain is under development. The code is now able to solve acoustic problems up to P^3 elements. It has been parallelized using MPI and is able to deal with partitioned meshes. Preliminary tests have been performed up to 16.000.000 unknowns. We are now considering the following features : hybrid MPI/OpenMP parallelism; extension to arbitrary polynomial degrees; extension to elastodynamic.

5.2. Gar6more2D and Gar6more3D

Participant: Julien Diaz [correspondant].

This codes compute the analytical solution of problems of waves propagation in two layered 3D media such as-acoustic/acoustic- acoustic/elastodynamic- acoustic/porous- porous/porous, based on the Cagniard-de Hoop method.

See also the web page <http://web.univ-pau.fr/~jdiaz1/software.html>.

The main objective of these codes is to provide reference solutions in order to validate numerical codes. They have been already used by J. Tromp and C. Morency to validate their code of poroelastic wave propagation [96]. They are freely distributed under a CECILL license and can be downloaded on the website <http://web.univ-pau.fr/~jdiaz1/software.html>. As far as we know, the main competitor of this code is EX2DELDEL (available on <http://www.spice-rtn.org>), but this code only deals with 2D acoustic or elastic media. Our codes seem to be the only ones able to deal with bilayered poroelastic media and to handle the three dimensional cases.

- ACM: J.2
- AMS: 34B27 35L05 35L15 74F10 74J05
- Programming language: Fortran 90

5.3. Montjoie

Participant: Marc Duruflé [correspondant].

Montjoie is a code developed by Marc Duruflé with contributions of students, including Juliette Chabassier during her PhD. It 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 in the context of Morgane Bergot's PhD. Several applications are currently available : wave equation, elastodynamics, aeroacoustics, Maxwell's equations. In 2013, an implementation of non-linear 1-D Maxwell's equations (non-linear Kerr effect) has been added as well as various 1-D non-linear Schrödinger-like equations. Thin layer models are also available for Maxwell's equations and elastodynamics.

See also the web page <http://montjoie.gforge.inria.fr>.

6. New Results

6.1. Inverse Problems

6.1.1. Reconstruction of an elastic scatterer immersed in a homogeneous fluid

Participants: H el ene Barucq, Rabia Djellouli,  Elodie Est ecahandy.

The determination of the shape of an obstacle from its effects on known acoustic or electromagnetic waves is an important problem in many technologies such as sonar, radar, geophysical exploration, medical imaging and nondestructive testing. This inverse obstacle problem (IOP) is difficult to solve, especially from a numerical viewpoint, because it is ill-posed and nonlinear. Its investigation requires as a prerequisite the fundamental understanding of the theory for the associated direct scattering problem, and the mastery of the corresponding numerical solution methods.

In this work, we are interested in retrieving the shape of an elastic obstacle from the knowledge of some scattered far-field patterns, and assuming certain characteristics of the surface of the obstacle. The corresponding direct elasto-acoustic scattering problem consists in the scattering of time-harmonic acoustic waves by an elastic obstacle Ω^s embedded in a homogeneous medium Ω^f , that can be formulated as follows:

$$\begin{aligned}
\Delta p + (\omega^2/c_f^2)p &= 0 && \text{in } \Omega^f \\
\nabla \cdot \sigma(u) + \omega^2 \rho_s u &= 0 && \text{in } \Omega^s \\
\omega^2 \rho_f u \cdot n &= \partial p / \partial n + \partial e^{i(\omega/c_f)x \cdot d} / \partial n && \text{on } \Gamma \\
\sigma(u)n &= -pn - e^{i(\omega/c_f)x \cdot d} n && \text{on } \Gamma \\
\lim_{r \rightarrow +\infty} r (\partial p / \partial r - i(\omega/c_f)p) &= 0 &&
\end{aligned} \tag{1}$$

where p is the fluid pressure in Ω^f whereas u is the displacement field in Ω^s , and $\sigma(u)$ represents the stress tensor of the elastic material.

This boundary value problem has been investigated mathematically and results pertaining to the existence, uniqueness and regularity can be found in [92] and the references therein, among others. We have obtained a new result proving the well-posedness of the problem when the fluid-solid interface is only lipschitzian. This has been published in the Journal of Mathematical Analysis and Applications [20]. We then propose a solution methodology based on a regularized Newton-type method for solving the IOP. The proposed method is an extension of the regularized Newton algorithm developed for solving the case where only the Helmholtz equation is involved, that is the acoustic case by impenetrable scatterers [86]. The direct elasto-acoustic scattering problem defines an operator $F : \Gamma \rightarrow p_\infty$ which maps the boundary Γ of the scatterer Ω^s onto the far-field pattern p_∞ . Hence, given one or several measured far-field patterns $\tilde{p}_\infty(\hat{x})$, corresponding to one or several given directions d and wavenumbers k , one can formulate IOP as follows:

$$\text{Find a shape } \Gamma \text{ such that } F(\Gamma)(\hat{x}) = \tilde{p}_\infty(\hat{x}); \quad \hat{x} \in S^1.$$

At each Newton iteration, we solve the forward problem using a finite element solver based on discontinuous Galerkin approximations, and equipped with high-order absorbing boundary conditions. We have first characterized the Fréchet derivatives of the scattered field and the characterization has been published in the Journal of Inverse and Ill-posed problems [18]. It is worth noting that they are solutions to the same boundary value problem as the direct problem with other transmission conditions. This work has been the object of several talks [63], [50], [36]. Elodie Estécahandy has defended her PhD thesis [14] in September 2013 and two papers will be submitted soon.

6.1.2. *hp-adaptive inversion of magnetotelluric measurements*

Participants: H el ene Barucq, Julien Alvarez Aramberri, David Pardo.

The magnetotelluric (MT) method is a passive electromagnetic exploration technique. It makes use of natural electric fields which propagate permanently into the Earth. Electric fields induce magnetic waves which can be detected at the surface to produce a map of the subsurface from the determination of the resistivity distribution. Magnetotelluric method is based on the mathematical relation between the magnetic and telluric variations which involve the electric resistivity of the subsurface. It is particularly relevant for the detection of metallic ores and for the study of geothermal sites. It is also used for oil and gas exploration because it provides information on sedimentary basins. It performs well on depth scales varying between a few tens of meters to hundred of kilometers, following the pioneering works of Tikhonov and Cagniard. Magnetotelluric measurements are governed by polarized Maxwell's equations in such a way that Helmholtz equations have to be solved. The geological mapping is constructed from the solution of an Inverse problem which requires computing the Impedance and/or the Resistivity distributions. In this work, we assimilate Earth with a horizontally layered model with possible 2D heterogeneities. Both the size of the direct problem and the required computational times may be excessively large. Indeed, on the one hand, the model of the source

requires defining a horizontally sufficiently large thick plate to avoid undesirable effects that could take place around the edges. On the other hand, the inversion of MT measurements typically requires the computation of an accurate solution at the receivers located at different positions. Since traditional hp-goal oriented techniques [98], [97] provide an accurate solution in one single point, we use a multi-goal-oriented algorithm [99] to obtain accurate solutions at all receivers. To get accurate quantities at several positions, it is necessary to increase the size of the mesh. This induces high computational costs in particular because the solution of the inverse problem is based on reiterated solutions of the direct problem. To decrease the computational costs required to perform the inversion, we propose an adaptive multi-dimensional inversion algorithm, which consists in increasing step by step the dimension in which the direct problem and the inversion are solved. At first step, we compute the 1D primary field with a semi-analytical solution and we invert the 1D problem. After that, we introduce the 2D heterogeneities. Regarding the direct problem, we compute the secondary field, thereby, drastically reducing the size of the computational domain for this problem. Then, we perform the inversion using the solution to the 1D Inverse Problem as a regularization term, increasing the robustness of the inversion algorithm.

6.1.2.1. Reverse Time Migration with Elastic Wave Equations

Participants: H el ene Barucq, Henri Calandra, Julien Diaz, J er ome Luquel.

Even if RTM has enjoyed the tremendous progresses of scientific computing, its performances can still be improved, in particular when applied to strong heterogeneous media. In this case, images have been mainly obtained by using direct arrivals of acoustic waves and the transition to elastic waves including multiples is not obvious, essentially because elastic waves equations are still more computationally consuming. We have thus chosen to consider high-order Discontinuous Galerkin Methods which are known to be well-adapted to provide accurate solutions based upon parallel computing. Now, one of the main drawback of RTM is the need of storing a huge quantity of information which is prohibitive when using elastic waves. For that purpose, we apply the Griewank algorithm [88] following Symes' ideas [101] for the acoustic RTM. The idea is to find a compromise between the number of wave equations to solve and the number of numerical waves that we have to store. This is the so-called Optimal Checkpointing. By reducing the occupancy of the memory, RTM should be efficient even when using elastic waves. The next step is the derivation of accurate imaging conditions, which could take advantage of all the information contained in the elastic wavefield. For acoustic media, Claerbout [83] proposed an imaging condition which is widely used and turns out to be sufficient to accurately reproduce interfaces. But Claerbout conditions do not take wave conversions into account and, since P-wave and S-wave interact with each other, it might be relevant to use an imaging condition including these interactions. This has been done successfully by J. Tromp and C. Morency [102] for seismology applications based upon the inversion of the global Earth. Their approach is based upon the adjoint state and it involves sensitivity kernels which are defined from the propagated and the back-propagated fields. Now, it has been shown in [93] that full wave form inversions using these sensitivity kernels may be polluted by numerical artifacts. One solution is to use a linear combination of the sensitivity kernels to delete artifacts. In this work, we propose then a new imaging condition which construction is inspired from [93] with some approximations required to keep admissible computational costs. We illustrate the properties of the new imaging condition on industrial benchmarks like the Marmousi model. In particular, we compare the new imaging condition with other imaging conditions by using as criteria the quality of the image and the computational costs required by the RTM. The results will be presented at the 2014 ECCOMAS conference in Barcelona.

6.2. Modeling

6.2.1. Implementation of a non-reflecting boundary condition on ellipsoidal boundary

Participants: H el ene Barucq, Anne-Ga elle Saint-Guirons, S ebastien Tordeux.

The modeling of wave propagation problems using finite element methods usually requires the truncation of the computational domain around the scatterer of interest. Absorbing boundary conditions are classically considered in order to avoid spurious reflections. This year we have proposed and tested a formulation which allows to take into account with no extra-cost a quasi-exact radiation condition based on a non local Dirichlet to Neumann operator.

6.2.2. Modeling of small heterogeneities in the context of the time domain wave equation

Participants: Vanessa Mattesi, Sébastien Tordeux.

We have proposed an approximate model to take into account small heterogeneities for the three dimensional time dependent wave equation. One of the most important result of this work is the generalization of the multipole theory (classically written for the Helmholtz equation) to the wave equation. This work has been presented at Waves 2013 and at JSA 2013 [58], [39]

6.2.3. A new modified equation approach for solving the wave equation

Participants: H el ene Barucq, Henri Calandra, Julien Diaz, Florent Ventimiglia.

In order to obtain high-order time-schemes, we are considering an alternative approach to the ADER schemes and to the modified equation technique described in section 3.2. The two first steps of the construction of the schemes are similar to the previous schemes : we apply a Taylor expansion in time to the solution of the wave equation and we replace the high-order derivatives with respect to the time by high order space operators, using the wave equation. The difference is that we do not use auxiliary variables and we choose to discretize directly the high-order operators in space. These operators can not be discretized by classical finite elements. For the discretization of the biharmonic operator in an homogeneous acoustic medium, both C1 finite elements, such as the Hermite ones, and Discontinuous Galerkin Finite Elements (DGFE) can be used, while in a discontinuous medium, or for higher-order operators, DGFE should be preferred [80]. We have applied this method to the second order wave equation [15] and the numerical results showed that this technique induced less computational burden than the modified equation scheme or the ADER scheme.

In the framework of the PhD thesis of Florent Ventimiglia, we have extended the new method involving p -harmonic operator to the first order formulation of the acoustic wave equation, which is the formulation discretized in the DIVA platform of TOTAL. In this case, the high order operators in space are not powers of the Laplace operator but powers of the gradient. Hence, we also had to adapt the space discretization, and we have extended the DG formulation with centered fluxes proposed in [87] to higher order operators. A numerical analysis of performance in 2D indicates that, for a given accuracy, this method requires less computational costs and less storage than the High-Order ADER Scheme. These results have been presented to the SMAI conference [49], Waves 2013 [61], Numerico IV [61] and HF2013 [34]. A paper has been accepted in ESAIM Proceedings [49].

6.2.4. Constructing and using Absorbing Boundary Conditions

6.2.4.1. Higher Order On-Surface Radiation Conditions for elastic scatterers

Participants: H el ene Barucq, Chokri Bekkey, Juliette Chabassier, Julien Diaz.

The numerical simulation of wave propagation is generally performed by truncating the propagation medium and the team works on new Absorbing Boundary Conditions (ABCs), trying to improve the performance of existing conditions. As we explained at Section 3.2, item **Boundary conditions**, we are developing ABCs for curved boundaries, based on the full factorization of the wave equation. These ABCs should take propagating, grazing and evanescent waves into account. In [17], we have considered the issue of constructing high-order ABCs taking into account both propagating and evanescent waves for the Helmholtz equation. In case of the simulation of acoustic waves diffracted by a solid immersed in a fluid, we investigate the performance of the new ABCs when used as On-Surface Radiation Conditions. The ABCs are set directly on the boundary of the solid. The unbounded problem is then replaced by a problem involving an acoustic pressure computed on the surface of the solid only. Preliminary results have been obtained by considering the toy problem where the scatterer is a disk. Analytic solutions are then available and we show that taking into account evanescent waves in the ABC could improve the accuracy of classical ABCs by two orders of magnitude at mid-frequency range, for ka between 1 and 100, k being the frequency and a the typical size of the diffracting obstacle. These results have been presented to the Waves 2013 conference [47].

6.2.4.2. Radiation boundary condition at high frequency

Participants: H el ene Barucq, Elodie Est ecahandy, Juliette Chabassier, Julien Diaz.

Regarding the solution of the Helmholtz equation at high frequency with finite element methods, it is current to refine the mesh in order to limit the effect of numerical pollution. It is then interesting to dispose of radiation boundary conditions which do not require to set the artificial boundary far from the scatterer. In this work, we have investigated the possibility of bringing closer the artificial boundary when standard conditions are enhanced by the modeling of grazing waves. The preliminary results we obtained show that this new ABC outperforms classical ABCs at high-frequency, for $ka > 50$, and that it is highly accurate, even when the boundary is very close to the scatterer. These results have been presented to the Waves 2013 conference [45]. Now, the next step is to consider an ABC taking the three types of waves into account.

6.2.4.3. *Absorbing Boundary Conditions for Tilted Transverse Isotropic Elastic Media*

Participants: H el ene Barucq, Lionel Boillot, Henri Calandra, Julien Diaz.

The simulation of wave propagation in geophysical media is often performed in domains which are huge compared to the wavelengths of the problem. It is then necessary to reduce the computational domain to a box. When considering acoustic or elastic isotropic media, this can be done by applying an Absorbing Boundary Condition (ABC) or by adding a Perfectly Matched Layer (PML). However, a realistic representation of the Earth subsurface must include anisotropy and, in particular, the so-called Tilted Transverse Isotropy. Perfectly Matched Layers are known to be unstable for this kind of media and, to the best of our knowledge, no ABC have been proposed yet. We have thus proposed a low-order ABC for TTI media. The construction is based on comparing and then connecting the slowness curves for isotropic and elliptic TTI waves. Numerical experiments illustrate the performance of the new ABC. They are performed by integrating the ABC in a DG formulation of Elastodynamics. When applied in a TTI medium, the new ABC performs well with the same level of accuracy than the standard isotropic ABC set in an isotropic medium. The condition demonstrates also a good robustness when applied for large times of simulation. These results have been presented to the Smari and to the Waves conferences [67], [68] and a paper has been submitted.

6.2.5. *Modeling of the damping factor of Multiperforated plates*

Participants: Estelle Piot, Vincent Popie, S ebastien Tordeux.

Multiperforated plates are classically used as a damping material. Melling has proposed in [94] a model to estimate the energy dissipated by these devices. However its well-known result should be corrected by a factor two to fit with experimental data. We have proposed a correct way to compute the energy dissipated by the multiperforated plates. This work has been presented at the Fifth International Scientific Conference and Young Scientists School "Theory and Computational Methods for Inverse and Ill-posed Problems.

6.2.6. *Performance Assessment of IPDG for the solution of an elasto-acoustic scattering problem*

Participants: H el ene Barucq, Rabia Djellouli,  elodie Est ecahandy.

We present a solution methodology for the direct elasto-acoustic scattering problem that falls in the category of Discontinuous Galerkin methods. The method distinguishes itself from the existing methods by combining high-order Discontinuous Galerkin approximations, local stabilizations for the coupled problem and the use of curved element edges on the boundaries. We present some numerical results that illustrate the salient features and highlight the performance of the proposed solution methodology on the resonance phenomenon existing in the elastic scatterer for simple geometries such as circles. Moreover, the designed method ensures a convergence order with a gain of two order of magnitude compared to polygonal boundaries, and a potential to address both mid- and high-frequency regimes. These results have been accepted for publication in International Journal for Numerical Methods in Engineering [19].

6.2.7. *On the influence of curvature on transmission conditions*

Participants: H el ene Barucq, Martin Gander, Yingxiang Xu.

Domain decomposition methods are both highly successful parallel solvers and also important modeling tools, since problems in subdomains can be treated by adapted methods to the physics in each subdomain. Subdomain boundaries are therefore rarely straight lines. The focus of this paper is to study the influence of curvature on transmission conditions used in optimized Schwarz methods. For straight interfaces and simple geometries, optimized interface conditions are typically determined using Fourier analysis. Asymptotically, these optimized conditions are still valid for curved interfaces. Since however the curvature is the most important information for a smooth curve, we want to study in this paper if and how the interface curvature influences the constants in the optimized parameters.

We consider the model problem

$$(\Delta - \eta)u = f, \quad \text{on } \Omega = \mathbb{R}^2, \quad \eta > 0, \quad (2)$$

and we require the solution to decay at infinity. We decompose Ω into two overlapping subdomains $\Omega_1 = (-\infty, a(y)) \times \mathbb{R}$ and $\Omega_2 = (b(y), \infty) \times \mathbb{R}$, where Γ_1 given by $a(y)$ and Γ_2 given by $b(y)$ are smooth curves satisfying $a(y) \geq b(y)$. A general parallel Schwarz algorithm is then given by

$$\begin{aligned} (\Delta - \eta)u_i^n &= f && \text{in } \Omega_i, \\ \mathcal{B}_i(u_i^n) &= \mathcal{B}_i(u_j^{n-1}) && \text{on } \Gamma_i, \quad 1 \leq i \neq j \leq 2, \end{aligned} \quad (3)$$

where $\mathcal{B}_i, i = 1, 2$, are transmission conditions to be chosen. If $\mathcal{B}_i, i = 1, 2$ are chosen as $\partial_{n_i} + DtN_i$, with DtN_i the Dirichlet to Neumann operators, the iterates will converge in two steps. These operators are however non-local, and thus difficult to use in practice. Therefore, local approximations are used in optimized Schwarz methods. We presented two different approaches to take the curvature of interfaces into account in the transmission conditions of optimized Schwarz methods: micro-local analysis, and analysis using a circular model problem. In both cases, we obtained curvature dependent transmission conditions. A preliminary comparison shows that the transmission conditions based on optimization perform better on the model problem, and that it could be important to take the curvature into account in transmission conditions. In our opinion it is however essential to do a more thorough theoretical and numerical study on more general geometry, where micro-local analysis is still applicable, before we can definitely draw conclusions. This work has been published in the peer-reviewed proceedings of the conference Decomposition Methods in Science and Engineering XXI [51].

6.2.8. Operator Based Upscaling for Discontinuous Galerkin Methods

Participants: H el ene Barucq, Th eophile Chaumont, Christian Gout.

Realistic numerical simulations of seismic wave propagation are difficult to handle because they must be performed in strongly heterogeneous media. Two different scales must then be taken into account. Indeed, the medium heterogeneities are currently very small compared to the characteristic dimensions of the propagation medium. To get accurate numerical solutions, engineers are then forced to use meshes that match the finest scale representing the heterogeneities. Meshing the whole domain with a fine grid leads then to huge linear systems and the computational cost of the numerical method is then too high to consider 3D realistic simulations. To dispose of a numerical method allowing to represent the heterogeneity of the medium accurately while computing on a coarse grid is thus relevant. This is the challenge of multiscale approaches like homogenization or upscaling. The ultimate objective of this work is to develop a software package for the Helmholtz equation set in heterogeneous domains. We focus on the operator-based upscaling method. Operator-based upscaling methods were first developed for elliptic flow problems (see [81]) and then extended to hyperbolic problems (see [90], [104], [103]). Operator-based upscaling method consists in splitting the solution into a coarse and a fine part. The coarse part is defined on a coarse mesh while the fine part is computed on a fine mesh. In order to speed up calculations, artificial boundary conditions (ABC) are imposed. By enforcing suitable ABCs on the boundary of every cells of the coarse mesh, calculations on the fine grid can be carried out locally. The coarse part is next computed globally on the coarse mesh. Operator-based upscaling methods were so far developed in joint with standard finite element discretization strategy.

In this work, we investigate the idea of combining an operator based upscaling method with discontinuous Galerkin finite element methods (DGFEM). During this year, we have performed the mathematical analysis of the Helmholtz equation set in a domain represented by a discontinuous velocity. The analysis has been achieved both for the continuous and the discretized problem which is based on a quadrature scheme which allows to take the discontinuities of the velocity into account. We get new stability results for stratified-like domains and numerical experiments show that in case of industrial benchmarks, the quadrature scheme leads to lower computational costs with a very good level of accuracy. A paper is in preparation and the results will be presented at the 2014 ECCOMAS conference in Barcelona.

6.2.9. Efficient solution methodology based on a local wave tracking strategy for high-frequency Helmholtz problems.

Participants: Mohamed Amara, Sharang Chaudhry, Julien Diaz, Rabia Djellouli, Steven Fiedler.

We have proposed a procedure for selecting basis function orientation to improve the efficiency of solution methodologies that employ local plane-wave approximations. The proposed adaptive approach consists of a local wave tracking strategy. Each plane-wave basis set, within considered elements of the mesh partition, is individually or collectively rotated to best align one function of the set with the local propagation direction of the field. Systematic determination of the direction of the field inside the computational domain is formulated as a minimization problem. As the resultant system is nonlinear with respect to the directions of propagation, the Newton method is employed with exact characterization of the Jacobian and Hessian. To illustrate the salient features and evaluate the performance of the proposed wave tracking approach, we present error estimates as well as numerical results obtained by incorporating the procedure into a prototypical plane-wave based approach, the least-squares method (LSM) developed by Monk and Wang [95]. The numerical results obtained for the case of a two-dimensional rigid scattering problem indicate that (a) convergence was achievable to a prescribed level of accuracy, even upon initial application of the tracking wave strategy outside the pre-asymptotic convergence region, and (b) the proposed approach reduced the size of the resulting system by up to two orders of magnitude, depending on the frequency range, with respect to the size of the standard LSM system. These results have been presented to the Waves 2013 [43] and in a Research Report [71]. A paper has been submitted.

6.2.10. Mesh Free Frontier-based Formulation (MF3) for High Frequency Helmholtz Problems.

Participants: Mohamed Amara, Julien Diaz, Rabia Djellouli.

We have proposed a novel approach for solving efficiently Helmholtz problems. The proposed solution method employs a boundary-type formulation without however involving Green functions and/or incurring singular integrals. In addition, this approach does not necessitate the use of a mesh. For these reasons, the method is named Mesh Free Frontier-based Formulation (MF3). Furthermore, the sought-after field is locally approximated using a set of basis of functions that consists of a Bessel kind function computed at a prescribed finite set of points. The number of the functions determines mainly the size of the resulting system, the complexity, as well as the computational cost of the proposed method. Preliminary numerical results obtained in the case of 2D-Helmholtz problems in the high-frequency regime are presented to illustrate the computational efficiency of MF3 (the method delivers results with high accuracy level, about 10^{-8} on the L^2 relative error, while requiring the solution of small linear systems). In addition, these results tend to suggest that MF3 is pollution free. These results have been presented to two conferences [32], [44]. A paper is in preparation.

6.2.11. Energy based simulation of a Timoshenko beam in non-forced rotation. Application to the flexible piano hammer shank.

Participants: Juliette Chabassier, Marc Duruflé.

A nonlinear model for a vibrating Timoshenko beam in non-forced unknown rotation is derived from the virtual work principle applied to a system of beam with mass at the end. The system represents a piano hammer shank coupled to a hammer head. An energy-based numerical scheme is then provided, obtained by non classical approaches. A major difficulty for time discretization comes from the nonlinear behavior of the kinetic energy of the system. Numerical illustrations are obtained by coupling this new numerical scheme to a global energy-preserving numerical solution for the whole piano. These numerical results show that the pianistic touch clearly influences the spectrum of the piano sound of equally loud isolated notes. These differences do not come from a possible shock excitation on the structure, nor from a changing impact point, nor a “longitudinal rubbing motion” on the string, since neither of these features are modeled in our study.

This work has been submitted for publication in Journal of Sound and Vibration [79]. discretization

6.2.12. *Simulating the propagation of ultra short laser pulses in a dispersive non linear medium.*

Participants: Juliette Chabassier, Marc Duruflé, Nayla Herran.

This collaboration with CEA-CESTA aimed at evaluating the limits of validity of the MIRÓ software provided by CEA. The MIRÓ software implements the propagation of laser pulses with a non-linear Schrodinger-like equation obtained from Maxwell’s equations in non-linear dispersive medium, assuming that the pulse spectrum is narrow and the non-linearity small enough. When considering intense ultra-short pulses, the spectrum bandwidth and the amplitude of the pulse may violate the constitutive assumptions of the model used by MIRÓ. This collaboration began with the internship of Nayla Herran (march 2013- august 2013). During this internship, different alternative models have been explored, and some of them were able to provide a solution much more accurate than MIRÓ’s models. The comparisons between alternative models and MIRÓ’s model have been performed in 1-D on small cases, for which the reference solution could be obtained from a direct numerical simulation of non-linear Maxwell’s equations. An efficient and accurate solver for non-linear Maxwell’s equations has been implemented in Montjoie software. This solver uses high order finite element in space, and high order Runge-Kutta-Nystrom scheme in time. The space grid moves with respect to the group velocity such that the computational domain stays relatively small and centered around the pulse. Thanks to this solver, we have been able to validate the different models and compare them. These 1-D promising results encourage us to continue this collaboration in order to obtain efficient and accurate numerical methods in 3-D. Our desire is also to be able to perform realistic cases involving physically relevant phenomena.

6.2.13. *Asymptotic Modeling for Elasto-Acoustics*

Participants: Julien Diaz, Victor Péron.

In the papers [31], [74], we derive equivalent conditions and asymptotic models for the diffraction problem of elastic and acoustic waves in a solid medium surrounded by a thin layer of fluid medium. Due to the thinness of the layer with respect to the wavelength, this problem is well suited for the notion of equivalent conditions and the effect of the fluid medium on the solid is as a first approximation local. We derive and validate equivalent conditions up to the fourth order for the elastic displacement. These conditions approximate the acoustic waves which propagate in the fluid region. This approach leads to solve only elastic equations. The construction of equivalent conditions is based on a multiscale expansion in power series of the thickness of the layer for the solution of the transmission problem.

Questions regarding the implementation of the conditions have been addressed carefully and the boundary conditions have been integrated without changing the structure of the code Hou10ni.

This work has been presented in two international conferences and Workshops : Workshop HPC-GA and WAVES’2013 [55].

A paper with numerical results for the elasto-acoustic problem with several configurations (a thin layer of variable thickness; coupling with an exterior "acoustic" medium) is in preparation.

6.2.14. *Thin layer models for electromagnetics*

Participants: Marc Duruflé, Victor Péron, Clair Poignard.

We have considered the transmission of electromagnetic waves through a thin layer. This thin layer can be replaced by transmission conditions. Media with thin inclusions appear in many domains: geophysical applications, microwave imaging, biomedical applications, cell phone radiations, radar applications, non-destructive testing. Our application concerns also media for which the conductivity drops inside the layer, such that the low-frequency regime has a different behavior from the mid-frequency regime. Different models are compared for these two regimes, drawbacks and disadvantages of each model are detailed. This work has been accepted for publication [27].

6.2.15. Corner Asymptotics of the Magnetic Potential in the Eddy-Current Model

Participants: Monique Dauge, Patrick Dular, Laurent Krähenbühl, Victor Péron, Ronan Perrussel, Clair Poignard.

The following results rely on a problematic developed in section 3.2, item **Asymptotic modeling**.

In the paper [25], we describe the magnetic potential in the vicinity of a corner of a conducting body embedded in a dielectric medium in a bidimensional setting. We make explicit the corner asymptotic expansion for this potential as the distance to the corner goes to zero. This expansion involves singular functions and singular coefficients. We introduce a method for the calculation of the singular functions near the corner and we provide two methods to compute the singular coefficients: the method of moments and the method of quasi-dual singular functions. Estimates for the convergence of both approximate methods are proven. We eventually illustrate the theoretical results with finite element computations. The specific non-standard feature of this problem lies in the structure of its singular functions: They have the form of series whose first terms are harmonic polynomials and further terms are genuine non-smooth functions generated by the piecewise constant zeroth order term of the operator. This work has been presented in the international conference JSA 2013 [38].

6.2.16. Finite Element Subproblem Method

Participants: Patrick Dular, Christophe Geuzaine, Laurent Krähenbühl, Victor Péron, Ronan Perrussel.

In the paper [26], we develop a finite element subproblem method to correct the inaccuracies proper to perfect conductor and impedance boundary condition models, in particular near edges and corners of conductors, for a large range of conductivities and frequencies. Successive local corrections, supported by fine local meshes, can be obtained from each model to a more accurate one, allowing efficient extensions of their domains of validity. This work has been presented in the international conference Compumag 2013 [57].

We develop also a finite element subproblem method for progressive eddy current modeling. The modeling of eddy currents in conductors is split into a sequence of progressive finite element subproblems. The source fields generated by the inductors alone are calculated at first via either the Biot-Savart law or finite elements. The associated reaction fields for each added conductive region, and in return for the source regions themselves when massive, are then calculated with finite element models, possibly with initial perfect conductor and/or impedance boundary conditions to be further corrected. The resulting subproblem method allows efficient solving of parameterized analyses thanks to a proper mesh for each subproblem and the reuse of previous solutions to be locally corrected. This work has been presented in the international conference ISEF'2013 [56].

6.3. High Performance methods for solving wave equations

6.3.1. Coupling the DG code with task programming libraries

Participants: Emmanuel Agullo, Lionel Boillot, Georges Bosilca, Henri Calandra.

Last year we optimized the DG code implemented in the DIVA platform of Total by reducing the number of communications between each processors. This optimization, coupled with the use of Hybrid MPI and OpenMP parallel programming has allowed to prove the scalability of the code up to 512 cores. We are now planning to extend these tests up to 4000 cores. However, preliminary results emphasized the limitations due to low level issues such as threads placement, data communications and cache utilization. Therefore, we are now considering the implementation in DIVA of task programming libraries such as StarPU (<http://runtime.bordeaux.inria.fr/StarPU/>) or DAGuE (<http://icl.cs.utk.edu/dague/index.html>). These libraries handle the low level issues directly at the runtime level and allow the programmer to focus on the algorithm itself. They are also provide a valuable help to improve the portability of the code from one architecture to another, which will allow us to port DIVA on heterogeneous architectures such as CPU/GPU and Intel Xeon Phi. We have already coupled DIVA and DAGuE on the Symmetric Multiprocessor System (SMP) of Plafirim (<https://plafirim.bordeaux.inria.fr>) and compared the performance of the code with MPI and an OpenMP implementations [66], [64].

7. Bilateral Contracts and Grants with Industry

7.1. Contracts with TOTAL

- Schémas en temps d'ordre élevé pour la simulation d'ondes élastiques en milieux fortement hétérogènes par des méthodes DG.
Period: 2010 November - 2013 October, Management: Inria Bordeaux Sud-Ouest, Amount: 150000 euros.
- Propagateurs optimisés pour les ondes élastiques en milieux anisotropes
Period: 2011 November - 2014 October, Management: Inria Bordeaux Sud-Ouest, Amount: 160000 euros.
- RTM en milieux hétérogènes par équations d'ondes élastiques
Period: 2011 November - 2014 October, Management: Inria Bordeaux Sud-Ouest, Amount: 160000 euros.
- Construction de milieux équivalents en vue de la simulation d'ondes élastiques harmoniques en milieux fortement hétérogènes par des méthodes DG
Period: 2012 October - 2015 October, Management: Inria Bordeaux Sud-Ouest, Amount: 165000 euros
- Simulation de la propagation d'ondes élastiques et visco-élastiques en régime harmonique par des méthodes Galerkin discontinues d'ordre élevé en maillage non structuré adaptées au calcul haute-performance.
Period: 2012 October - 2015 October, Management: Inria Bordeaux Sud-Ouest, Amount: 165000 euros

8. Partnerships and Cooperations

8.1. Regional Initiatives

The PhD fellowship of Elodie Estecahandy is partially (50%) funded by the Conseil Régional d'Aquitaine.
The PhD fellowship of Vanessa Mattesi is partially (50%) funded by the Conseil Régional d'Aquitaine.
The Post-Doctoral fellowship of Juliette Chabassier is partially (50%) funded by the Conseil Général des Pyrénées Atlantiques.

The Post-Doctoral fellowship of Ángel Rodríguez Rozas is partially (50%) funded by the Conseil Régional d'Aquitaine.

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 involves 2 other Inria Team-Projects (Hiepac 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 .

Since its beginning (2009), eight PhD students have been funded and Magique 3D has hired six of them, one being shared with the project team Nachos (<http://www-sop.inria.fr/nachos/>). Moreover, several internships have been realized. 2013 was a particular year for the project because Total decided to extend DIP for five years. It has been necessary to update the legal framework of the project which explains that the second phase of DIP will officially begin in 2014. Nevertheless, in order to preserve the dynamic of the project, Magique-3D has hired an internship, Wilfredo Salazar, coming from the Engineering school INSA at Rouen.

8.2.2. *Micro-local analysis of wave equations*

The numerical solution of wave equations most often requires to truncate the propagation domain to define a computational domain limited by an artificial boundary. Magique-3D is very involved in the construction and mathematical validation of boundary conditions which are set on the artificial boundary. Different techniques can be used for the design of such conditions and Magique-3D maintains a collaboration with Prof. Olivier Lafitte from the University of Paris 13 on the mathematical analysis of the Dirichlet-to-Neumann (DtN) operator for acoustic waves. This issue is addressed by applying micro-local analysis which enables us to consider the full DtN operator in the whole space of frequencies.

8.2.3. *Partnership with the department DMAE of ONERA*

title: Modeling of multiperforated plates

Coordinator: Sébastien Tordeux

Other partners: Department DMAE of ONERA

Abstract: In the aeronautic industry, there is a need of numerical models for the design of turboreactors of new generation. Magique-3D is cooperating with the department DMAE of ONERA to develop acoustic models of multiperforated plates which is an important component of the turboreactors.

This project is interdisciplinary, since it involves the experimental expertise of Estelle Piot (acoustician engineer of ONERA working on acoustic bench), the competences in mathematical modeling of Magique 3D. In parallel to the obtention of new theoretical results we are jointly developing a new numerical library based on the discontinuous Galerkin approximation which aims in interpreting experimental data.

This cooperation is formalized thanks to the common supervision of the PhD of Vincent Popie funded by ONERA and DGA and is a follow-up of the ANR APAM (2008-2011).

8.3. European Initiatives

8.3.1. *FP7 Projects*

8.3.1.1. *HPC-GA*

Title: High Performance Computing for Geophysics Applications

Type: PEOPLE

Instrument: International Research Staff Exchange Scheme (IRSES)

Duration: January 2012 - December 2014

Coordinator: Inria (France)

Others partners: BCAM (Basque Center of Applied Mathematics), Spain; BRGM (Bureau de Recherches Géologiques et Minières), France; ISTERre (Institut des Sciences de la Terre, France); UFRGS (Federal University of Rio Grande do Sul), Institute of Informatics, Brazil; UNAM (National Autonomous University of Mexico), Institute of Geophysics, Mexico;

See also: <https://project.inria.fr/HPC-GA/en>

Abstract: Simulating large-scale geophysics phenomenon represents, more than ever, a major concern for our society. Recent seismic activity worldwide has shown how crucial it is to enhance our understanding of the impact of earthquakes. Numerical modeling of seismic 3D waves obviously requires highly specific research efforts in geophysics and applied mathematics, leveraging a mix of various schemes such as spectral elements, high-order finite differences or finite elements.

But designing and porting geophysics applications on top of nowadays supercomputers also requires a strong expertise in parallel programming and the use of appropriate runtime systems able to efficiently deal with heterogeneous architectures featuring many-core nodes typically equipped with GPU accelerators. The HPC-GA project aims at evaluating the functionalities provided by current runtime systems in order to point out their limitations. It also aims at designing new methods and mechanisms for an efficient scheduling of processes/threads and a clever data distribution on such platforms.

The HPC-GA project is unique in gathering an international, multidisciplinary consortium of leading European and South American researchers featuring complementary expertise to face the challenge of designing high performance geophysics simulations for parallel architectures: UFRGS, Inria, BCAM and UNAM. Results of this project will be validated using data collected from real sensor networks. Results will be widely disseminated through high-quality publications, workshops and summer-schools.

Three members of MAGIQUE-3D (Julien Diaz, Victor Péron and Angel Rodríguez Rozas) participated to the second Workshop of HPC-GA in Bilbao on March 11th-15th, 2013, <http://www.bcamaath.org/en/workshops/second-workshop-of-the-hpc-ga-project>.

Manuela Longoni de Castro, Assistant Professor at UFRGS, spent one month in MAGIQUE-3D in January 2013.

8.3.2. Collaborations in European Programs, except FP7

8.3.2.1. AKELARRE

Joint project with BCAM (Basque Center of Applied Mathematics) funded by the Conseil Régional d'Aquitaine and the Basque Government in the framework of the Aquitaine-Euskadi Call. Total Amount: 14 000 euros.

Program: Fonds commun de coopération Aquitaine/Euskadi

Project acronym: AKELARRE

Project title: Méthodes numériques innovantes et logiciels performants pour la simulation de la propagation des ondes électromagnétiques en milieux complexes

Duration: février 2011 - février 2013

Coordinator: Hélène Barucq

Other partners: BCAM (Basque Center of Applied Mathematics), Spain

Abstract: This project brings together complementary skills of two research teams which are respectively located in Pau and Bilbao. The main objective of this collaboration is to develop innovative numerical methods in the field of wave propagation and to implement powerful software for the simulation of electromagnetic waves in complex media. These waves play an important role in many industrial applications and the development of such software is of great interest for many industrial enterprises located in the region. Theoretical and practical issues are considered. In particular, we focus on the mathematical analysis of boundary conditions that play a crucial role for accurate numerical simulations of waves.

8.3.2.2. *Procope Inria - TU Berlin*

Joint project with the Matheon Research Center in Berlin funded by the European Union in the framework of the Procope 2012 Call. Total Amount: 2800 euros.

Program: PHC Procope 2012

Project acronym: Procope Inria - TU Berlin

Project title: Procope Inria - TU Berlin

Duration: January 2012 - December 2013

Coordinator: Sébastien Tordeux

Other partners: Matheon Research Center, TU Berlin, Germany

Abstract: This project aims in funding trips between Pau and Berlin. The young research group of Kersten Schmidt and Magique 3D are both specialist of the modeling and the simulation of the wave propagation phenomena. During this program we focus on the modeling of multiperforate plates which are present in the combustion chambers; on the derivation of absorbing boundary conditions for stratified media and on the development of precise numerical methods in the context of the Hardy problem.

In this framework several members of Magique 3D visited the Matheon Research Center in Berlin :

- Julien Diaz, May 7th to May 10th
- Victor Péron spent one week in Berlin in November
- Juliette Chabassier spent one month in Berlin

and several members of Matheon Research Center visited Magique 3D :

- Kersten Schmidt spent one week in Pau in November
- Robert Gruhlke spent one week in Pau in November
- Philipp Kliewe spent one week in Pau in November
- Dirk Klindworth spent one week in Pau in December
- Maxim Zeinaliyev spent two weeks in Pau in December

8.4. International Initiatives

8.4.1. *Inria International Partners*

8.4.1.1. *MAGIC*

Program: Inria International Partner

Title: Advance Modelling in Geophysics

Inria principal investigator: Hélène Barucq

International Partner (Institution - Laboratory - Researcher):

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

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.

Élodie Éstécahandy defended her PhD thesis, *Contribution à l'analyse mathématique et à la résolution numérique d'un problème inverse de scattering élasto-acoustique*, on September 19th 2013. She has been coadvised by Hélène Barucq and Rabia Djellouli in the framework of MAGIC.

Rabia Djellouli visited MAGIQUE-3D in September 2013.

8.4.2. Participation In other International Programs

8.4.2.1. HOSCAR

Program: Inria-CNPq

Title: High performance cOmputing and SCientific dAta management dRiven by highly demanding applications

Inria principal investigator: Stéphane Lanteri (Nachos, Inria Sophia Antipolis-Méditerranée)

International Partners:

LNCC (Laboratório Nacional de Computação Científica), Brazil;

COPPE/UFRJ (Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa de Engenharia/Alberto Luiz Coimbra Institute for Graduate Studies and Research in Engineering, Universidade Federal do Rio de Janeiro), Brazil;

INF/UFRGS (Instituto de Informática, Universidade Federal do Rio Grande do Sul);

LIA/UFC (Laboratórios de Pesquisa em Ciência da Computação Departamento de Computação, Universidade Federal do Ceará).

Inria Teams :

NACHOS, Inria Sophia Antipolis - Méditerranée;

ZENITH, Inria Sophia Antipolis - Méditerranée;

MOAIS, Inria Grenoble - Rhone-Alpes;

HIEPACS, Inria Bordeaux - Sud-Ouest;

MOAIS, Inria Bordeaux - Sud-Ouest;

MAGIQUE 3D, Inria Bordeaux - Sud-Ouest;

Duration: 2012-2015

See also: <http://www-sop.inria.fr/hoscar/>

HOSCAR is a CNPq - Inria collaborative project between Brazilian and French researchers, in the field of computational sciences, also sponsored by the French Embassy in Brazil. It is coordinated by the team-project Nachos

The general objective of the project is to setup a multidisciplinary Brazil-France collaborative effort for taking full benefits of future high-performance massively parallel architectures. The targets are the very large-scale datasets and numerical simulations relevant to a selected set of applications in natural sciences: (i) resource prospection, (ii) reservoir simulation, (iii) ecological modeling, (iv) astronomy data management, and (v) simulation data management. The project involves computer scientists and numerical mathematicians divided in 3 fundamental research groups: (i) numerical schemes for PDE models, (ii) scientific data management, and (iii) high-performance software systems. Several Brazilian institutions are participating to the project among which: LNCC (Laboratório Nacional de Computação Científica), COPPE/UFRJ (Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa de Engenharia/Alberto Luiz Coimbra Institute for Graduate Studies and Research in Engineering, Universidade Federal do Rio de Janeiro), INF/UFRGS (Instituto de Informática, Universidade Federal do Rio Grande do Sul) and LIA/UFC (Laboratórios de Pesquisa em Ciência da Computação Departamento de Computação, Universidade Federal do Ceará). The French partners are research teams from several Inria research centers. *MAGIQUE-3D* is involved by the way of its research activities on finite element approximations which can be used for resource prospection and reservoir simulation. Several members of *MAGIQUE-3D* participated to the third workshop of the project in Bordeaux, Sep 2nd to 6th 2013 [69], [46], [60], [78]. In the framework of HOSCAR, Théophile Chaumont-Frelet who is a PhD student in *Magique-3D*, spent two weeks in August 2013 at the LNCC to initiate a collaboration with Prof. F. Valentin on the development of new finite element methods for the Helmholtz equation.

8.4.2.2. *GEO3D*

Program: Inria-Russia

Title: Models and numerical simulations in Geosciences: wave propagation in complex media

Inria principal investigator: Sébastien Tordeux

International Partner (Institution - Laboratory - Researcher):

Novosibirsk State University (Russia (Russian Federation)) - Institute of Numerical Mathematics and Mathematical Geophysics - Sébastien Tordeux

Duration: January 2012 - December 2014

See also: <http://uppa-inria.univ-pau.fr/m3d/ConfFR/participants.html>

GEO3D is a collaborative project between *Magique 3D* team-project (Inria Bordeaux Sud-Ouest) and the Institute of Numerical Mathematics and Mathematical Geophysics (Novosibirsk State University) and the Institute of Petroleum Geology and Geophysics, of in the context of geosciences.

We are mainly interested in the derivation of numerical methods (discontinuous Galerkin approximation, space-time refinement), the design of direct and inverse high performance solver, and the modeling of complex media.

More precisely, we are actually interested

1. in the computation of truncated Singular Value decomposition of very large matrix to analyze the inverse problem;
2. in the coupling of a discontinuous Galerkin method with a finite differences method for the direct problem;
3. in a spectral time stepping method for the direct problem;
4. in an algorithm to determine an impedance coefficient using indirect measurement.

Several researchers from the Institutes of Novosibirsk visited *MAGIQUE-3D* in 2013

- Serguey Kabanikhin spent one week in June 2013
- Maxim Shishlenin spent one month in June 2013 as invited Professor
- Vadim Lisitsa spent one month in September 2013
- Vladimir Tcheverda spent one month in September 2013

Several researchers from *MAGIQUE-3D* visited the Institute of Numerical Mathematics and Mathematical Geophysics in 2013

- Julien Diaz spent two weeks in February 2013
- Vanessa Mattesi spent three weeks in February 2013
- Sébastien Tordeux spent three weeks in February 2013
- Sébastien Tordeux spent two weeks in February 2013
- Vincent Popie spent two weeks in October 2013

8.5. International Research Visitors

8.5.1. Visits of International Scientists

- Patrick Dular (Université de Liège) spent two months MAGIQUE-3D between January 2013 and April 2013 as invited Professor.
- Manuela Longoni de Castro, Assistant Professor at UFRGS, spent one month in MAGIQUE-3D in January 2013.
- Serguey Kabanikhin spent one week in June 2013
- Maxim Shishlenin spent one month in June 2013 as invited Professor
- Vadim Lisitsa, Assistant Professor at Novossibirsk State University, spent one month in MAGIQUE-3D in September 2013.
- Vladimir Tcheverda, Professor at Novossibirsk State University, spent one month in MAGIQUE-3D in September 2013.

9. Dissemination

9.1. Scientific Animation

9.1.1. Administrative Activities

- Mohamed Amara is President of the Université de Pau et des Pays de l'Adour.
- Hélène Barucq is vice-chair of the Inria evaluation committee. She participated to the national jury of Inria competitive selection for Senior Researchers (DR2) and to the local jury of Inria competitive selection for Young Graduate Scientists (CR2) in Bordeaux. She participated to the selection committee for Research (Grant and Senior) Positions. She participated to the selection committee for a Professor position at the University of Rouen and at the University of Pau. She is member of the direction team of the Research Center of Bordeaux. She is member of the board of the Laboratory of Mathematics of Pau and of the research federation IPRA which are both under the administrative supervision of CNRS. She is the scientific head of the project DIP.
- Julien Diaz is elected member of the Inria evaluation committee. He participated to the local juries for Young Graduate Scientists (CR2) in Saclay and Sophia. He is elected member of the CLHSCT (Comité Local Hygiène et Sécurité) of Inria Bordeaux Sud-Ouest and appointed member of the CDT (Commission de Développement Technologique), of the CUMI (Commission des Utilisateurs des Moyens Informatiques) and of the Center Committee of Inria Bordeaux Sud-Ouest.
- Victor Péron is appointed member of the CJC (Commission Jeunes Chercheurs) of Inria Bordeaux Sud-Ouest. He was member of the committee to evaluate posters of PhD Students (in 2nd year), at Scientific School Doctoral 211 (Univ. of Pau), July 2013.
- Sébastien Tordeux is elected member of the 26th section of the CNU (Conseil National des Universités). He is also responsible of the first year of the Master of Applied Mathematics of Pau University.

9.1.2. Conferences

- H el ene Barucq and Julien Diaz were members of the scientific committee of Waves 2013 (<http://www.lamsin.tn/waves13/>)
- H el ene Barucq was member of the scientific committee of JSA 2013 (<http://jsa2013.sciencesconf.org/>)
- Julien Diaz was member of the organizing committee of the “Journ ee Ondes et probl emes inverses en g eophysique ” (<http://www.ensta-paristech.fr/~chaillat/MPT2013.html>).
- S ebastien Tordeux was member of the scientific committee of the Fifth International Scientific Conference and Young Scientists School "Theory and Computational Methods for Inverse and Ill-posed Problems"the (<http://conf.nsc.ru/tcmiip2013>)

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Licence: Victor P eron, Math ematiques pour les Sciences de la Mati ere, 19,5 Eq. TD, L2, UPPA, France,

Master: Victor P eron, Analyse num erique fondamentale, 75 Eq. TD, M1, UPPA, France,

Master: Victor P eron, Analyse, 28 Eq. TD, M1, UPPA, France,

Master : S ebastien Tordeux, Analyse num erique fondamentale, 36 Eq. TD, M1, UPPA, France.

Master : Julien Diaz : Transform ees, Fourth-year engineering students at ESTIA (Ecole Sup erieure des Technologies Industrielles Avanc ees), 16 Eq. TD.

Master: Julien Diaz and S ebastien Tordeux, Introduction aux ph enom enes de propagation d’ondes, 55 Eq TD, M2, UPPA, France.

ISAE (<http://www.isae.fr/>): H el ene Barucq, Introduction  a la simulation num erique des ondes, 5h Eq TD, Toulouse.

Master : Marc Durufl e, Algorithmique num erique, 60 Eq. TD, Enseirb-Matmeca, France.

Master : Marc Durufl e, Algorithmique et programmation, 32 Eq. TD, Enseirb-Matmeca, France.

Master : Marc Durufl e, Mini-projets de programmation, 28 Eq. TD, Enseirb-Matmeca, France.

Master : Marc Durufl e. Outils informatiques pour le calcul scientifique, 80 Eq. TD, Enseirb-Matmeca, France.

9.2.2. Supervision

PhD :  elodie Est ecahandy, Contribution  a l’analyse math ematique et  a la r esolution num erique d’un probl eme inverse de scattering  elasto-acoustique, September 19th 2013, H el ene Barucq and Rabia Djellouli.

PhD in progress : Julen Alvarez, *hp*-adaptive inversion of magnetotelluric measurements, October 2011, H el ene Barucq and David Pardo.

PhD in progress : Lionel Boillot, Propagateurs optimis es pour les ondes  elastiques en milieux anisotropes, May 2011, H el ene Barucq and Julien Diaz.

PhD in progress : Marie Bonnasse-Gahot, Simulation de la propagation d’ondes  elastiques et visco- elastiques en r egime harmonique par des m ethodes Galerkin discontinues d’ordre  elev e en maillage non-structur e adapt ees au calcul haute performance, October 2012, Julien Diaz and St ephane Lant eri (EPI Nachos, Inria Sophia Antipolis-M editerran ee).

PhD in progress : Th eophile Chaumont-Fr elet, October 2012, H el ene Barucq and Christian Gout.

PhD in progress : Aralar Erdozain, Fast inversion of 3D Borehole Resistivity Measurements using Model Reduction Techniques based on 1D Semi-Analytical Solutions, October 2013, H el ene Barucq, David Pardo and Victor P eron.

PhD in progress : Jérôme Luquel, RTM en milieu hétérogène par équations d'ondes élastiques, November 2011, Hélène Barucq and Julien Diaz.

PhD in progress : Vanessa Mattesi, Détection des hétérogénéités en acoustique et élastodynamique, October 2011, Hélène Barucq and Sébastien Tordeux.

PhD in progress : Vincent Popie, Septembre 2012, Investigation numérique et expérimentale du comportement acoustique de plaques perforées en vue de développement de modèles homogénéisés, Sébastien Tordeux and Estelle Piot

PhD in progress : Florent Ventimiglia, Schémas d'ordre élevé et pas de temps local pour les ondes élastiques en milieux hétérogènes, November 2010, Hélène Barucq and Julien Diaz.

9.2.3. Juries

- Hélène Barucq was referee for the PhD thesis defended by Rafael Lago at the Institut National Polytechnique de Toulouse, June 3th 2013, entitled "A study on block flexible iterative solvers with applications to Earth imaging problem in geophysics".
- Julien Diaz :
 - Jean-Baptiste Laurent (Université de Toulouse) "Raffinements locaux auto-adaptatifs dans une méthode Galerkin discontinue pour la résolution des équations de Maxwell", July 10th 2013.
 - Axel Modave (Université de Liège, Belgium) "Absorbing Layers for Wave-Like Time-Dependent Problems - Design, Discretization and Optimization", October 7th 2013.
 - Ludovic Moya (Université de Nice), Ludovic Moya, "Discontinuous Galerkin time domain method for electromagnetic wave propagation in biological tissues", December 16th 2013.

9.3. Popularization

- The short movie "Probing the invisible, from the earthquake to the model" realized by MAGIQUE-3D in 2010, has been presented at Unesco during the day "Mathematics for Planet Earth", on March 5th 2013 <http://mpe2013.org/fr/mpe-day-at-unesco/>. It is also part of the virtual exhibition "Mathematics of Planet Earth <http://imaginary.org/fr/node/134>"
- Hélène Barucq is member of the scientific board created for helping to the organization of a mobile exhibition in favor of the equality between girls and boys. The exhibition will be held in Pau in June 2014.
- Juliette Chabassier has written a short paper, "Simuler le son d'un piano" , on the website of Mathématiques de la planète Terre 2013, "Un jour, une brève", <http://mpt2013.fr/facteur-de-piano-numerique> [75].
- Juliette Chabassier has written a short paper, "Le piano rêvé des mathématiciens" , in the book "Mathématiques: l'explosion continue", <http://hal.inria.fr/hal-00913685>.
- Juliette Chabassier has published a website on the piano modeling, <http://modelisation.piano.free.fr>.
- Julien Diaz participated to the "Journées jeunes chercheurs en mathématiques du lycée de Navarre / UPPA" <http://univ-pau.fr/live/newsletter/newsletter-n46/journeesmaths?isPdf=1>, March 20th-22th, 2013.
- Julien Diaz has written an article, "Prospection pétrolière : le sous-sol révélé", in the TDC (Textes et Documents pour la classe) journal, for high-school teachers, <http://www.cndp.fr/tdc/tous-les-numeros/les-mathematiques-de-la-terre.html> [77].
- Julien Diaz has written a short paper, "Jeter un œil "Au centre de la Terre" , on the website of Mathématiques de la planète Terre 2013, "Un jour, une brève", <http://mpt2013.fr/jeter-un-oeil-au-centre-de-la-terre/> [76].
- Victor Péron participated to the "Journée d'Immersion des Lycéens à l'Université de Pau" and has given a talk "Probing the invisible, from the earthquake to the model", November 28th, 2013.

10. Bibliography

Major publications by the team in recent years

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- [3] C. BALDASSARI, H. BARUCQ, H. CALANDRA, J. DIAZ. *Numerical performances of a hybrid local-time stepping strategy applied to the reverse time migration*, in "Geophysical Prospecting", September 2011, vol. 59, n^o 5, pp. 907-919 [DOI : 10.1111/J.1365-2478.2011.00975.X], <http://hal.inria.fr/hal-00627603/en>
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