Activity Report 2014

Project-Team MAGIQUE-3D

Advanced 3D Numerical Modeling in Geophysics

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

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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-3Dis to develop and validate efficient solution methodologies for solving complex three-dimensional geophysical problems, with a particular emphasis on problems arising in seismic imaging, in response to the local industrial and community needs. Indeed, as it is well known, the region of Pau has long-standing tradition in the Geosciences activities. However, in spite of the recent significant advances in algorithmic considerations as well as in computing platforms, the solution of most real-world problems in this field remains intractable. Hence, there is a scientific need of pressing importance to design new numerical methods for solving efficiently and accurately wave propagation problems defined in strongly heterogeneous domains.

MAGIQUE-3D program possesses an exceptional combination that is a prerequisite for accomplishing its mission: The investigator backgrounds, research interests, and technical skills complement to form a research team with a potential for significant impact on the computational infrastructure of geophysical sciences. The research record of MAGIQUE-3D group covers a large spectrum of accomplishments in the field of wave propagation including (a) the design, validation, and performance assessment of a class of DG-methods for solving efficiently high frequency wave problems, (b) the construction, convergence analysis, and performance assessment of various absorbing-type boundary conditions that are key ingredients for solving problems in infinite domains, and (c) the development of asymptotic models that are the primary candidate in the presence of heterogeneities that are small compared to the wave length. MAGIQUE-3D has built strong collaborations and partnerships with various institutions including (a) local industry (TOTAL), (b) national research centers (ONERA and CEA), and (c) international academic partnerships (e.g. Interdisciplinary Research Institute for the Sciences (IRIS) at California State University, Northridge, USA; University of Pays Basque at Bilbao, Spain; University of Novosibirsk, Russia).

3. Research Program

3.1. 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, [71], is a technique for Imaging that 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. 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.

- **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 significantly 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 [75], [83] and the ADER scheme [79]. 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 and implicit 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.

- **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 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 efficient 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) [73] 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 [78]. 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 justified 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 2014 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.

– Modeling the propagation of ultrashort laser pulses in optical fibers.

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 achieve 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.** The goal is to test popular HPC architectures in the context of seismic imaging simulations. Current work concerns the new Intel Many Integrated Core Architecture (Intel MIC) of the Intel Xeon Phi co-processors and the upcoming stand-alone Intel processors.

• **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. One way to overcome this problem is to use task-based programming models through runtime libraries as StarPU (http://runtime.bordeaux.inria.fr/StarPU/ or PaRSEC (http://icl.cs.utk.edu/parsec/). However, until now, they have been mostly employed for solving linear algebra problems and our goal is to test their performances on realistic wave propagation simulations. This work is done in the framework of a collaboration with Inria Team Hiepacs 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. 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 allow to take into account these multiperforated plates at the macroscopic scale.

4.3. Helioseismology

This collaboration with the Max Planck Institute for solar system, which started in 2014, aims at designing efficient numerical methods for the wave propagation problems that arise in helioseismology in the context of inverse problems. The final goal is to retrieve information about the structure of the sun i.e. inner properties such as density or pressure via the inversion of a wave propagation problem. Acoustic waves propagate inside the sun which, in a first approximation and regarding the time scales of physical phenomena, can be considered as a moving fluid medium with constant velocity of motion. Some other simplifications lead to computational saving, such as supposing a radial or axisymmetric geometry of the sun. Aeroacoustic equations must be adapted and efficiently solved in this context, this has been done in the finite elements code Montjoie 5.2. In other situations, a full 3D simulation is required and demands large computational resources. Ultimately, we aim at modeling the coupling with gravity potential and electromagnetic waves (MHD equations) in order to be able to recover sun spots.

5. New Software and Platforms

5.1. Hou10ni

Participant: Julien Diaz [correspondant].

This software, written in FORTRAN 90, simulates the propagation of waves in heterogeneous 2D and 3D media in time-domain and in frequency domain. It is based on an Interior Penalty Discontinuous Galerkin Method (IPDGM) and allows for the use of meshes composed of cells of various order (p-adaptivity in space).

This year, we have implemented the 3D version for the simulation of elastodynamic waves. This version handles polynomials of arbitrary order while the previous one was only able to deal with polynomials of degree up to three.

We have also improved the parallelism by coupling the code to a mesh partitioner and we have totally rewritten the code to handle MPI parallelism both for the construction of the matrices and for the time scheme.

5.2. 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 2014, the implementation of linearized Euler equations and Galbrun's equation has been improved and extended to the axisymmetric case. Raman effect has been implemented in the 1-D non-linear Schrödinger equation.

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

5.3. Elasticus

Participant: Simon Ettouati.

Within the framework of the strategic action DIP, Magique-3D collaborates with Total to develop a computing platform, DIVA, meant to produce accurate images of the subsurface. To achieve this, approximate solutions of the first-order wave problem are computed thanks to a Discontinuous Galerkin (DG) Method. It is increasingly difficult to include new numerical schemes developed in the team in the industrial and highly parallel environment of Total.

Elasticus is a sequential library, independent of DIVA and developed in Fortran, to simulate wave propagation in geophysical environment, based on a DG method. It is meant to help PhD students and post-doctoral fellows to easily implement their algorithms in the library. Thus, readability of the code is privileged to optimization of its performances. Developed features should be easily transferred in the computing platform of Total. Contrary to DIVA which only computes approximate solutions with P1, P2 and P3 elements, Elasticus manages arbitrary orders for the spatial discretization with DG method. Matrices on the reference element for arbitrary orders are computed thanks to a library developed by J. Diaz.

5.4. DIVA-DG

Participants: Lionel Boillot, Marie Bonnasse-Gahot, Théophile Chaumont-Frelet, Jérôme Luquel.

DIVA-DG is the simulation code that we develop in collaboration with our partner Total. This year we have implemented

- 2D/3D anisotropic elastic Absorbing Boundary Conditions for time-domain.
- 2D elastic imaging conditions.
- 2D multiscale strategy to take into account fine scale heterogeneities on coarse meshes in frequency domain.
- Hybrydized Discontinuous Galekin method for 2D elastodynamic in frequency domain.

6. New Results

6.1. Inverse Problems

6.1.1. *Complex-frequency domain Full Waveform Inversion*
Participants: Florian Faucher, Maarten V. de Hoop, Henri Calandra.

We study the seismic inverse problem for the (complex) frequency-domain elastic isotropic wave equation; in particular the recovery of the Lamé parameters and density. We employ a Full Waveform Inversion where the iterative minimization is based on a gradient descent. The elastic inverse problem shows a Lipschitz-type stability where the Fréchet derivative has a strictly positive 'lower bound'. This bound is connected to the stability constant and can be approximated using the Gauss-Newton Hessian. The successive stability estimates provide a control of the convergence and decide the parameters of inversion. We develop a multi-level approach based on a structured domain partitioning of the sub-surface. The coefficients (Lamé parameters and density) are assumed to be piecewise constant functions following the domain partitioning, which is naturally defined with the successive stability estimates to maintain the radius of convergence, while refinement provides resolution. It allows us to start with minimal prior information for the coefficients and the algorithm is perfectly suitable for complex frequency. We have carried out numerical experiments in two and three dimensions; those results have been presented during the following conferences in 2014: [48], [49].

6.1.2. *Imaging of complex media with elastic wave equations*
Participants: Jérôme Luquel, Hélène Barucq, Henri Calandra, Julien Diaz.

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. The accuracy of numerical wave fields is obviously of great importance. 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 redhibitory when using elastic waves. For that purpose, we apply the Griewank algorithm following Symes' ideas 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. By this way, one may wonder if considering elastic waves including multiples in order to improve images of heterogeneous media is a valid option. It must involve a careful numerical analysis including the evaluation of the impact of the imaging condition. It is thus necessary to derive accurate imaging conditions, which could take advantage of all the information contained in the wavefield. For acoustic media, Claerbout 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 it is not clear wether conversions do or do not contain interesting information to get accurate images of heterogeneous media.

Since P-wave and S-wave interact with each other, it might be relevant to use an imaging condition including these interactions. In fact, this has been done successfully by J.Tromp and C. Morency for seismology applications based upon the inversion of the global Earth. Their approach is based upon the state adjoint and it involves sensitivity kernels which are defined from the propagated and the back-propagated fields. Now it has been shown that full wave form inversions using these sensitivity kernels may be polluted by numerical artefacts. One solution is to use a linear combination of the sensitivity kernels to delete artefacts. In this work, we propose then a new imaging condition which construction is inspired from 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. This work was presented at the the WCCM XI - ECCM V - ECFD VI - Barcelona 2014 Conference and SIAM Conference on IMAGING SCIENCE (SIAM-IS14) Hong Kong Baptist University[67].

6.1.3. *Helioseismology*

Participants: Juliette Chabassier, Marc Duruflé, Thorsten Hohage.

We have begun to write a software interface that allows to solve an inverse problem using adjoint and regularization methods (iTReg software) while using Montjoie software for the direct problem that must be solved at each iteration of the inversion process.

6.2. Modeling

6.2.1. *High-Order Time Schemes*

6.2.1.1. Fourth order energy-preserving locally implicit discretization for linear wave equations
Participants: Juliette Chabassier, Sébastien Imperiale.

A family of fourth order coupled implicit-explicit schemes is presented as a special case of fourth order coupled implicit schemes for linear wave equations. The domain of interest is decomposed into several regions where different fourth order time discretization are used, chosen among a family of implicit or explicit fourth order schemes derived in [72]. The coupling is based on a Lagrangian formulation on the boundaries between the several non conforming meshes of the regions. A global discrete energy is shown to be preserved and leads to global fourth order consistency. Numerical results in 1d and 2d illustrate the good behavior of the schemes and their potential for the simulation of realistic highly heterogeneous media or strongly refined geometries, for which using everywhere an explicit scheme can be extremely penalizing. Accuracy up to fourth order reduces the numerical dispersion inherent to implicit methods used with a large time step, and makes this family of schemes attractive compared to second order accurate methods in time. This work has been presented at the Franco-Russian workshop on mathematical geophysics, Sep 2014, Novosibirsk, Russia [58], at the and is the object of a submitted publication to International Journal for Numerical Methods in Engineering.

6.2.1.2. A new modified equation approach for solving the wave equation
Participants: Hélène 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.

In the framework of the PhD thesis of Florent Ventimiglia, we have extended this 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 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 [77] 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 AIMS conference [54]. A paper has been published in ESAIM Proceedings [19].

6.2.2. *Finite Element Methods for the time-harmonic wave equation.*

6.2.2.1. Goal-Oriented Adaptivity using Unconventional Error Representations

Participants: Vincent Darrigrand, David Pardo, Ignacio Muga, Hélène Barucq.

In the scope of subsurface modelling via the resolution of inverse problems, the so-called goal-oriented adaptivity plays a fundamental role. Indeed, while classical adaptive algorithms were first designed to accurately approximate the energy norm of a problem [69], [70], one requires a good approximation of a specific quantity of interest. An energy norm driven self-adaptive strategy can still be used for that purpose, although it often becomes sub-optimal and unable to provide an accurate solution for the required quantity of interest in a reasonable amount of time.

During the late 90's, to overcome this issue, the so-called goal-oriented strategy appeared, see for instance [82], [81]. The goal-oriented approach consists in expressing the error in the quantity of interest as an integral over the entire computational domain involving the errors of the original and adjoint problems, and then minimise an upper bound of such error representation by performing local refinements.

Most authors, using the adjoint problem, represent the approximation error in the quantity of interest via the global bilinear form that describes the problem in terms of local and computable quantities.

Our methodology, however, is based on the selection of an alternative bilinear form exhibiting better properties than the original bilinear form (e.g. positive definiteness). We represent the residual error functional of the adjoint problem through this alternative form. We can then compute new upper bounds of the error of the quantity of interest in a similar way than with the classical approach. Our main goal is to demonstrate that a proper choice of such alternative form may improve the upper bounds of the error representation.

Moreover, the method proposed here generalises the existing ones, since, in particular, we can select as the alternative bilinear form the one associated to the adjoint problem.

6.2.2.2. Hybridizable Discontinuous Galerkin method for the elastic Helmholtz equations

Participants: Marie Bonnasse-Gahot, Henri Calandra, Julien Diaz, Stéphane Lanteri.

We consider Discontinuous Galerkin (DG) methods formulated on fully unstructured meshes, which are more convenient than finite difference methods on cartesian grids to handle the topography of the subsurface. DG methods and classical Finite Element (FE) methods mainly differ from discrete functions which are only piecewise continuous in the case of DG approximation. DG methods are then more suitable than Continuous Galerkin (CG) methods to deal with hp-adaptivity. This is a great advantage to DG method which is thus fully adapted to calculations in highly heterogeneous media. Nevertheless, the main drawback of classical DG methods is that they are more expensive in terms of number of unknowns than classical CG methods, especially when arbitrarily high order interpolation of the field components is used. In this case DG methods lead to larger sparse linear systems with a higher number of globally coupled degrees of freedom as compared to CG methods with a same given mesh. In that case, we consider a hybridizable Discontinuous Galerkin (HDG) method which principle consists in introducing a Lagrange multiplier representing the trace of the numerical solution on each face of the mesh cells. This new variable exists only on the faces of the mesh and the unknowns of the problem depend on it. This allows us to reduce the number of unknowns of the global linear system. Now the size of the matrix to be inverted only depends on the number of the faces of the mesh and on the number of the degrees of freedom of each face. It is worth noting that for the classical DG method it depends on the number of the cells of the mesh and on the number of the degrees of freedom of each cell. The solution to the initial problem is then recovered thanks to independent elementwise calculation. The principle of the HDG method and 2D results were presented at the WCCM XI - ECCM V - ECFD VI - Barcelona 2014 Conference [41], the EAGE Workshop on High Performance Computing for Upstream [42], the Second Russian-French Workshop "Computational Geophysics" [43] and at the Réunion des Sciences de la Terre 2014 conference [53]. A comparison between HDG method and classical nodal DG method was given on a poster at the Journées Total-Mathias 2014 workshop [66].

6.2.2.3. Helioseismology

Participants: Hélène Barucq, Juliette Chabassier, Marc Duruflé, Damien Fournier, Laurent Gizon.

The finite element code Montjoie 5.2 has been used to solve Helmholtz equation in axisymmetric domain in the configuration of the sun. The efficiency of the code has been compared in three configurations : radial (1-D mesh and spherical harmonics), axisymmetric (2-D mesh), 3-D. The results have convinced our-selves and our partners of Max Planck Institute that the axisymmetric configuration is the most interesting for an inversion procedure, since 3-D computations are too expensive. A more realistic modeling of the sun requires the solution of time-harmonic Galbrun's equations (instead of Helmholtz equation), different formulations have been implemented and studied. It appeared that the different numerical methods are not able to converge to the correct solution for non-uniform flows. The lack of convergence is more obvious for flows with a larger Mach number. Such problems do not appear in Linearized Euler equations, as a result we have proposed simplified Galbrun's equations that converge correctly and provide the same solution as original Galbrun's equations for a null flow. These equations have been implemented in 2-D, axisymmetric and 3-D configuration.

6.2.2.4. *Scattering of acoustic waves by a disc - Hypersingular integral equations*
Participants: Leandro Farina, Paul Martin, Victor Péron.

Two-dimensional boundary-value problems involving a Neumann-type boundary condition on a thin plate or crack can often be reduced to one-dimensional hypersingular integral equations. Examples are potential flow past a rigid plate, acoustic scattering by a hard strip, water-wave interaction with thin impermeable barriers, and stress fields around cracks. In [29], we generalize some of these results to two-dimensional hypersingular integral equations. Thus, rather than integrating over a finite interval, we now integrate over a circular disc. Two-dimensional hypersingular equations over a disc arise, for example, in the scattering of acoustic waves by a hard disc; this particular application is described in Appendix A. We develop an appropriate spectral (Galerkin) method, using Fourier expansions in the azimuthal direction and Jacobi polynomials in the radial direction. The Hilbert-space arguments used by Golberg are generalized and a convergence theorem is proved by using tensor-product techniques. Our results are proved in weighted L^2 spaces. Then, Tranter's method is discussed. This method was devised in the 1950s to solve certain pairs of dual integral equations. It is shown that this method is also convergent because it leads to the same algebraic system as the spectral method.

6.2.2.5. *Finite Element Subproblem Method*
Participants: Patrick Dular, Christophe Geuzaine, Laurent Krähenbühl, Victor Péron.

In the paper [26], 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.

6.2.2.6. *High Order Methods for Helmholtz Problems in Highly Heterogeneous Media*
Participants: Théophile Chaumont-Frelet, Henri Calandra, Hélène Barucq, Christian Gout.

Heterogeneous Helmholtz problems arise in various geophysical application where they modelize the propagation of time harmonic waves through the subsurface. For example, in inversion problems, the aim is to reconstruct a map of the underground based on surface acquisition. This recovery process involves the solution to several Helmholtz problems set in different media, and high frequency solutions are required to obtain a detailed image of the underground. This obervations motivate the design of efficient solver for highly heterogeneous Helmholtz problems at high frequency.

The main issue with the discretization of high frequency problems is the so called "pollution effect" which impose drastic condition on the mesh. In the homogeneous case, it is known that one efficient way to reduce the pollution effect is the use of high order discretization methods. However, high order methods can not be applied as is to highly heterogeneous media. Indeed, they are based on coarser mesh and are not sensitive to fine scale variations of the medium.

We propose to overcome this difficulty by using a multiscale strategy to take into account fine scale heterogeneities on coarse meshes. The method is based on a simple medium approximation method, which can be seen as a special quadrature rule. Numerical experiments in two dimensional geophyscial benchmarks show that high order method coupled with our multiscale approximation medium stragey are cheaper than low order method for a given accuracy. Futhermore, focusing on one dimensional models, we were able to show from a theoretical point of view that our methology reduces the pollution effect even when used on coarse meshes with non-matching interfaces.

This work has been presented at the *WCCM XI - ECCM V - ECFD VI - Barcelona 2014* conference, the *Second Russian-French Workshop "Computational Geophysics"*. A poster has been presented at the *journées Total-Mathias 2014 workshop*. A paper has been submitted for publication to *Math. Of Comp.*.

6.2.3. *Boundary conditions.*

6.2.3.1. Absorbing Boundary Conditions for Tilted Transverse Isotropic Elastic Media
Participants: Lionel Boillot, Hélène Barucq, Julien Diaz, Henri Calandra.

The seismic imaging simulations are always performed in bounded domains whose external boundary does not have physical meaning. We have thus to couple the wave equations with boundary conditions which aim at reproduce the invisibility of the external boundary. The discretization of these conditions can be an issue. For instance, an efficient condition, once discretized, can induce huge computational costs by filling the matrix which has to be inverted. This is the case of the transparent boundary conditions which are approximated by local Absorbing Boundary Conditions (ABC) that do not increase to much the computational burden. However, the ABC has the drawback to introduce spurious numerical waves which can perturb the RTM results. It is possible to avoid this drawback by applying PML (Perfectly Matched Layers) but it proves to be unstable in anisotropic media. Last year, we proposed a way of construction leading to a stable ABC. The technique is based on slowness curve properties, giving to our approach an original side. We established stability results from long time energy behavior and we have illustrated the performance of the new condition in 2D numerical tests. This year, we extend all these results to 3D case and to arbitrary boundary shapes. The previous paper submission on 2D results has been accepted and released [18]. The recent results in 3D have been presented to the ECCOMAS conference.

6.2.3.2. Derivation of high order absorbing boundary conditions for the Helmholtz equation in 2D.
Participants: Hélène Barucq, Morgane Bergot, Juliette Chabassier, Élodie Estecahandy.

Numerical simulation of wave propagation raises the issue of dealing with outgoing waves. In most of the applications, the physical domain is unbounded and an artificial truncation needs indeed to be carried out for applying numerical methods like finite element approximations. Adapted boundary conditions that avoid the reflection of outgoing waves and provide a well-posed mathematical problem must then be derived. With ideal boundary conditions, the solution on the new mixed boundary valued problem in the truncated domain would actually be equal to the restriction of the mathematical solution in the unbounded domain. However, such ideal boundary conditions, called "transparent boundary conditions", can be shown to be nonlocal, which leads to dramatic computational overcosts. The seek of local boundary conditions, called "absorbing boundary conditions" (ABC), has been the object of numerous works trying to perform efficient conditions based on different techniques of derivation. Among them, the technique of micro-diagonalisation has been employed to the wave equation and more generally to hyperbolic systems in [76], leading to a hierarchy of absorbing local boundary conditions based on the approximation of the Dirichlet-to-Neumann map. A comprehensive review of different used strategies and higher order conditions can be found in [85]. One desirable property of ABCs is that the reflection of the waves on the artificial boundary generates an error of the same order as the one generated by the spatial discretization inside the domain. The computational effort is thus optimized in terms of modeling and numerical inaccuracies. Moreover, the ABC must fit the artificial boundary chosen by the user of the method. In the context of high order spatial discretization (spectral finite elements [74], Interior Penalized Discontinuous Galerkin [68]), there is nowadays a need for high order ABCs that can adapt on non flat geometries since these methods prove very efficient for capturing arbitrary shaped domains.

The aim of the present work is to develop high order ABCs for the Helmholtz equation, that can adapt to regular shaped surfaces. A classical way of designing ABCs is to use Nirenberg theorem [80] on the second order formulation of the Helmholtz equation, which enables us to decompose the operator as a product of two first order operators. Here our approach is to rewrite the Helmholtz equation as a first order system of equations before developing ABCs using M.E. Taylor's micro-diagonalisation method [84]. Then an asymptotic truncation must be performed in order to make the ABC local, and we will see that the high frequency approximation will lead to more usable ABCs than the one stating that the angle of incidence is small. During the process, while increasing the degree of the pseudo differential operator decomposition along with the order of asymptotic truncation, we retrieve classical ABCs that have been found with other techniques by other authors. For now, we have restricted ourselves to two dimensions of space, but despite the fact that 3D generalization should obviously generate more calculation, no further theoretical difficulties are expected.

This work has been the object of a technical report [61] and the obtained conditions have been implemented in Montjoie 5.2 and Houd10ni 5.1.

6.2.4. Asymptotic modeling.

6.2.4.1. Fast Simulation of Through-casing Resistivity Measurements Using Semi-analytical Asymptotic Models.
Participants: Victor Péron, David Pardo, Aralar Erdozain.

When trying to obtain a better characterization of the Earth's subsurface, it is common to use borehole through-casing resistivity measurements. It is also common for the wells to be surrounded by a metal casing to protect the well and avoid possible collapses. The presence of this metal case highly complicates the numeric simulation of the problem due to the high conductivity of the casing compared to the conductivity of the rock formations. In this study [47] we present an application of some theoretical asymptotic methods in order to deal with complex borehole scenarios like cased wells. The main idea consists in replacing the part of the domain related to the casing by a transmission impedance condition. The small thickness of the casing makes it ideal to apply this kind of mathematical technique. When eliminating the casing from the computational domain, the computational cost of the problems considerably decreases, while the effect of the casing does not disappear due to the impedance transmission conditions. The results show that when applying an order three impedance boundary condition for a simplified domain, it only generates a negligible approximation error, while it considerably reduces the computational cost. For obtaining the numerical results and testing the mathematical models we have developed a Finite Element Code in Matlab. The code works with Lagrange polynomials of any degree as basis functions and triangular shaped elements in two dimensions. The code has been adapted for working with the transmission impedance conditions required by the mathematical models.

6.2.4.2. Modeling the propagation of ultrashort laser pulses in optical fibers.
Participants: Mohamed Andjar, Juliette Chabassier, Marc Duruflé.

In order to model the propagation of an ultrashort laser pulse, the most natural idea is to solve Maxwell's equations in a nonlinear and dispersive medium. Given the considered optical periods (around 10^{-14} seconds), the associated wavelengthes (around 1 millimeter) and the propagation distances (several meters), the direct numerical simulation of these equations by usual numerical techniques (finite elements, explicit time schemes) is impossible because too expensive. The standard procedure is therefore to use approached equations obtained by exploiting legitimate hypotheses in the considered context (slowly varying pulse envelope, narrow spectrum, paraxial approximation ...). These new equations, among them the Nonlinear Schrödinger Equation, are significantly less expensive to solve and we can therefore provide realistic numerical simulations to physicists.

When the pulse propagates in an optical fiber, its spatial profile in the orthogonal plane to the propagation direction in very simple because optical fibers posses a finite (small, often equal to one) number of propagating modes. The equations that originally are stated on a 3D domain can then be written as one spatial dimension equations.

The scientific objective of this internship was to apply the approximation techniques mentioned above in this specific context, in order to obtain one or several equations (depending on the used hypotheses) that model the propagation of ultrashort laser pulses in optical fibers. A matlab code has been developed and integrated in the C++ code Montjoie 5.2. Numerical simulations have been led in order to observe classical situations of nonlinear fiber optics (Kerr effect, Raman effect, supercontinuum generation, ...).

6.2.4.3. Small heterogeneities in the context of time-domain wave propagation equation : asymptotic analysis and numerical calculation
Participants: Vanessa Mattesi, Sébastien Tordeux.

We have focused our attention on the modeling of heterogeneities which are smaller than the wavelength. The work can be decomposed into two parts : a theoretical one and a numerical one. In the theoretical one, we derive a matched asymptotic expansion composed of a far-field expansion and a near-field expansion. The terms of the far-field expansion are singular solutions of the wave equation whereas the terms of the near-field expansion satisfy quasistatic problems. These expansions are matched in an intermediate region. We justify mathematically this theory by proving error estimates. In the numerical part, we describe the Discontinuous Galerkin method, a local time stepping method and the implementation of the matched asymptotic method. Numerical simulations illustrate these results. Vanessa Mattesi has defended her PhD on this topic[14].

6.2.4.4. Theoretical and numerical investigations of acoustic response of a multiperforated plate for combustion liners
Participants: Vincent Popie, Estelle Piot, Sébastien Tordeux.

Multiperforated plates are used in combustion chambers for film cooling purpose. As the knowledge of the acoustic response of the chamber is essential for preventing combustion instabilities, the acoustic behaviour of the perforated plates has to be modeled. This can be done either by considering the transmission impedance of the plates, or their Rayleigh conductivity.

We have investigated the link between these two quantities thanks to matched asymptotic expansions. Especially the far-field or near-field nature of the physical quantities used in the definition of the impedance and Rayleigh quantity has been enlightened. Direct numerical simulations of the propagation of an acoustic plane wave through a perforated plate are performed and post-treated so that the assumptions underlying the definitions of impedance and Rayleigh conductivity have been checked. The results will be presented at the conference ASME Turbo Expo 2015.

6.3. High Performance methods for solving wave equations

6.3.1. *Coupling the DG code with task programming libraries*
Participants: Lionel Boillot, Emmanuel Agullo, George Bosilca, Henri Calandra.

The parallelization of the original code is based on a preliminary step of domain decomposition and then on the use of the MPI (Message Passing Interface) library. It is a common choice which works pretty well in most of the classical architectures. However, the parallel efficiency is not optimal and the performance decreases in hybrid architectures. Indeed, we know the number of operations that each sub-domain has to performed but this does not give us the exact time that the computations require. The cluster heterogeneity leads to various automatic optimizations (memory cache, parallel capability, . . .) which are difficult to measure. We have decided to tackle this problem by modifying the parallelism with the use of task programming. We have thus rewritten the DIVA algorithm in a graph of tasks without using the MPI library and we have left to the runtime PaRSEC the choice of when and where to execute each task. The numerical experiments we have performed have confirmed the significant improvement of the parallel efficiency on different architectures like ccNUMA machines or Intel Xeon Phi co-processors. Moreover, the proposed solution is portable on these architectures, this means that none or few modifications are required in the code, allowing to focus on algorithmic aspects in order to preserve the performance. These results have been presented to the EAGE HPC workshop and to the HPCC IEEE conference within a paper have been accepted.

7. Bilateral Contracts and Grants with Industry

7.1. Contracts with TOTAL

- Depth Imaging Partnership (DIP)

  Period: 2014 May - 2019 April , Management: Inria Bordeaux Sud-Ouest, Amount: 12000 euros/year.
- 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 Galerkine 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 Vanessa Mattesi is partially (50%) funded by the Conseil Régional d'Aquitaine.

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 (Hiepacs and Nachos) which have complementary skills in mathematics, computing and in geophysics. DIP is fully funded by Total by the way of an outline agreement wit 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. In 2014 the second phase of DIP has begun. Lionel Boillot has been hired as engineer to work on the DIP platform.

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 turbore-actors 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 turbore-actors.

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 & H2020 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.

Two members of MAGIQUE-3D (Julien Diaz and Victor Péron) participated to the last Workshop of HPC-GA in Grenoble on October 2014.

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.

In this framework, Rabia Djellouli visited Magique 3D in December 2014

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.

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, 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 in

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

An international workshop on "Computational Geophysics" gathering around 50 participants has been organized in Novosibirsk in the framework of GEO3D in September 2014

8.5. International Research Visitors

8.5.1. Visits of International Scientists

- Serguey Solovyev spent two months in MAGIQUE-3D in march 2014 and in December 2014.
- Mounir Tlemcani spent one month in MAGIQUE-3D in May 2014.
- Laurent Gizon
- Rabia Djellouli spent two weeks in MAGIQUE-3D in December 2014.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific events selection

9.1.1.1. responsable of the conference program committee

Sébastien Tordeux was member of the program committee of the 7th International Conference on Mathematical Modeling (ICMM-2014) that was held in Yakutsk, Russia.

9.1.2. Journal

9.1.2.1. reviewer

Juliette Chabassier has been reviewer for SIAM Journal on Scientific Computing (SISC), Acta Acustica united with Acustica and the Journal of the Acoustical Society of America.

Victor Péron has been reviewer for ESAIM : Mathematical Modelling and Numerical Analysis, Journal of Computational and Applied Mathematics, Zentralblatt MATH.

Lionel Boillot has been reviewer for ESAIM Proceedings, Congrès SMAI 2013, Volume 45, September 2014

Marc Duruflé has been reviewer for ESAIM : Mathematical Modelling and Numerical Analysis

9.1.3. 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 Lille. 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 Bordeaux and Lille. He participated to the selection committee for an Assistant-Professor position at the University of Toulouse. 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.

- 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.

- Victor Péron is appointed member of the CJC (Commission Jeunes Chercheurs) of Inria Bordeaux Sud-Ouest.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Licence : Vincent Darrigrand, Initiation à la modélisation statistique, 21h eqTD, L2, UPPA, France

Licence : Vincent Darrigrand, Suites et fonctions d'une variable, 24.38h eqTD, L1, UPPA, France

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

Licence : Victor Péron, Compléments d'analyse, 19,5 Eq. TD, L2, UPPA, France

Licence : Victor Péron, Calcul intégral, 19,5 Eq. TD, L3, UPPA, France

Licence : Victor Péron, Mathématiques pour les Sciences de la Matière, 19,5 Eq. TD, L2, UPPA, France

Master : Victor Péron, Analyse numérique fondamentale, 75 Eq. TD, M1, UPPA, France

Master : Victor Péron, Analyse, 28 Eq. TD, M1, UPPA, France

Master : Marc Duruflé, Outils informatiques pour le calcul scientifique, 80 Eq. TD, M1, Bordeaux INP, France

Master : Sébastien Tordeux, Analyse Numérique Fondamentale, 34 eqTD, M1, UPPA, FRANCE

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9.2.2. Supervision

PhD : Lionel Boillot, Contributions à la modélisation mathématique et à l'algorithmique parallèle pour l'optimisation d'un propagateur d'ondes élastiques en milieu anisotrope, UPPA, 12/12/2014, Hélène Barucq et Julien Diaz

PhD : Vanessa Mattesi, Propagation des ondes dans un milieu comprtant de petites hétérogénités: analyse asymptotique et calcul numérique , UPPA, 11/12/2014, Sébastien Tordeux

PhD : Florent Ventimiglia, Schémas numériques d'ordre élevé en temps et en espace pour l'équation des ondes du premier ordre. Application à la Reverse Time Migration, UPPA, 05/06/2014 Hélène Barucq and Julien Diaz.

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PhD in progress : Théophile Chaumont-Frélet, High Order Methods for Helmholtz Problems in Highly Heterogeneous Mediaitre, October 2012, Hélène Barucq and Christian Gout.

PhD in progress : Marie Bonnasse-Gahot, 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, October 2012, Julien Diaz and Stéphane Lantéri (EPI Nachos, Inria Sophia Antipolis-Méditerranée).

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

PhD in progress : Florian Faucher, Méthodes d'inversion sismique dans le domaine fréquentiel , October 2014, Hélène Barucq.

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9.2.3. *Juries*

Victor Péron : Aliénor Burel (Université Paris-Sud XI) "Contributions à la simulation numérique en élastodynamique : découplage des ondes P et S, modèles asymptotiques pour la traversée de couches minces", July 4th 2014

9.3. Popularization

Juliette Chabassier has written a contribution for interstices, "Le piano rêvé des mathématiciens" (see https://interstices.info/jcms/ni_76925/le-piano-reve-des-mathematiciens)

Juliette Chabassier has contributed to "Visages des Sciences", a series of postcards which are portraits of scientists.

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