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Activity Report 2012

Project-Team MAGIQUE-3D

Advanced 3D Numerical Modeling in Geophysics

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

RESEARCH CENTER
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THEME
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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, which is associated with CNRS. Gathering several researchers of different backgrounds in mathematics and scientific computing, MAGIQUE-3D team aims at developing sophisticated modeling tools, validating them in a rigorous way and applying them to real cases of geophysical interest. This project is intrinsically multi-disciplinary and is strongly related to the regional and national industrial environment. In particular, we develop strong collaborations with TOTAL but the topics studied can lead to applications other than petroleum engineering. Since it has been created, MAGIQUE-3D works 'Depth Imaging': this topic is related to modeling of seismic wave propagation in complex geological structures, taking into account underlying physical phenomena. It has been defined jointly by working groups composed of members of MAGIQUE-3D and of its main industrial partner TOTAL in order to make sure that actual results of interest in the context of the oil industry could be reached. One usually tackles such problems by adopting two different approaches. The first one consists in defining approximate models that lead to less expensive numerical methods (for example by decreasing the number of unknowns by means of an approximation of the original equations). The second approach is based on high-performance numerical methods applied to the full system, which lead to an accurate solution but implies a high computation cost. Both of these approaches are considered in the project.

Reagrding 'Advanced modeling in wave propagation', the team is involved in realistic numerical simulation of complex three-dimensional geophysical phenomena and its comparison with real data recorded in the field. One of the main issues is the choice of the numerical method, which implicitly defines the subset of configurations that can be studied. Comparisons with recorded seismic data for real geological cases have been carried out and then, numerical algorithms have been optimized and implemented on parallel computers with a large number of processors and a large memory size, within the framework of message-passing programming. We have reached a maximum resolution in terms of the seismic frequencies that can be accurately simulated on currently available supercomputers.

MAGIQUE-3D works on the development of optimized software for the simulation of 3D phenomena in geophysics. The team tackled this question addressing different and complementary issues such as the development of new discretization schemes, the construction of new boundary conditions used to reduce the size of the computational domain, the porting of our software on GPU to speed up their performances. All the algorithms we have proposed are compatible with high resolution techniques. More recently, we have begun to apply our knowledge on the direct problem to the solution of inverse problems. It is now a natural goal for the team since we develop a significant research program with Total, in particular in the context of the research program DIP (Depth Imaging Partnership), where the solution of inverse problems has become a big challenge for oil industry.

3. Scientific Foundations

3.1. Inverse Problems

- **Inverse scattering problems.** 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 [77]. Moreover the precision in the reconstruction of the shape of an obstacle strongly depends on the quality of the given far-field pattern (FFP) measurements: the range of the measurements set and the level of noise in the data. Indeed, the numerical experiments (for example [88], [91], [84], [85]) performed in the resonance region, that is, for a wavelength that is approximately equal to the diameter of the obstacle, tend to indicate that in practice, and at least for simple shapes, a unique and reasonably good solution of the IOP can be often computed using only one incident wave and *full aperture* far-field data (FFP measured only at a limited range of angles), as long as the aperture is larger than π. For smaller apertures the reconstruction of the shape of an obstacle becomes more difficult and nearly impossible for apertures smaller than $\pi/4$.
  This plus the fact that from a mathematical viewpoint the FFP can be determined on the entire sphere $S1$ from its knowledge on a subset of $S1$ because it is an *analytic* function, we propose [74], [75] a solution methodology to extend the range of FFP data when measured in a limited aperture and not on the entire sphere $S1$. It is therefore possible to solve the IOP numerically when only limited aperture measurements are available. The objective of MAGIQUE-3D is to extend this work to 3D problems of acoustic scatterin and to tackle the problem of elasto-acoustic scattering.
- **Depth Imaging in the context of DIP.** The challenge of seismic imaging is to obtain the best 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 most used technique of imaging is RTM (Reverse Time Migration), [76], which 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. The research program DIP has been defined by researchers of MAGIQUE-3D and engineers of TOTAL jointly. It has been created with the aim of gathering researchers of Inria, with different backgrounds and the scientific programm will be coordinated by MAGIQUE-3D. In this context, MAGIQUE-3D will contribute by working on the inverse problem and by continuing to develop 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 focus 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 Schemes in Space and Time.** 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. Obviously this results in increasing the number of unknowns of the discrete problem. Besides, the time step, whose value fixes the number of required iterations for solving the evolution problem, is linked to the space step through the 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 (and of multiplications by the stiffness matrix) will be. The method that we proposed in [11] allows for the use of local time-step, adapted to the various sizes of the cells and we recently extended it to deal with p-adaptivity [73]. However, this method can not yet handle dissipation terms, which prevents us for using absorbing boundary conditions or Perfectly Matched Layers (PML). To overcome this difficulty, we will first tackle the problem to used the modified equation technique [78], [90], [82] with dissipation terms, which is still an open problem.

We are also considering an alternative approach to obtain high-order schemes. The main idea is to apply first the time discretization thanks to the modified equation technique and after to consider the space discretization. Our approach involves p-harmonic operators, which 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 [68]. This new method seems to be well-adapted to p-adaptivity. Therefore, we now want to couple it to our local time-stepping method in order to deal with hp-adaptivity both in space and in time. We will then carry out theoretical and numerical comparisons between this technique and the classical modified equation scheme.
Once we have performant hp-adaptive techniques, it will be necessary to obtain error-estimators. Since we consider huge domain and complex topography, the remeshing of the domain at each time-step is impossible. One solution would be to remesh the domain for instance each 100 time steps, but this could also hamper the efficiency of the computation. Another idea is to consider only p adaptivity, since in this case there is no need to remesh the domain.

- **Mixed hybrid finite element methods for the wave equation.** The new mixed-hybrid-like method for the solution of Helmholtz problems at high frequency we have built enjoys the three following important properties: (1) unlike classical mixed and hybrid methods, the method we proposed is not subjected to an inf-sup condition. Therefore, it does not involve numerical instabilities like the ones that have been observed for the DGM method proposed by Farhat and his collaborators [80], [81]. We can thus consider a larger class of discretization spaces both for the primal and the dual variables. Hence we can use unstructured meshes, which is not possible with DGM method (2) the method requires one to solve Helmholtz problems which are set inside the elements of the mesh and are solved in parallel(3) the method requires to solve a system whose unknowns are Lagrange multipliers defined at the interfaces of the elements of the mesh and, unlike a DGM, the system is hermitian and positive definite. Hence we can use existing numerical methods such as the gradient conjugate method. We intend to continue to work on this subject and our objectives can be described following three tasks: (1) Follow the numerical comparison of performances of the new methods with the ones of DGM. We aim at considering high order elements such as R16-4, R32-8, ...; (2)Evaluate the performance of the method in case of unstructured meshes. This analysis is very important from a practical point of view but also because it has been observed that the DGM deteriorates significantly when using unstructured meshes; (3) Extend the method to the 3D case. This is the ultimate objective of this work since we will then be able to consider applications.
  Obviously the study we propose will contain a mathematical analysis of the method we propose. The analysis will be done in the same time and we aim at establishing a priori and a posteriori estimates, the last being very important in order to adopt a solution strategy based on adaptative meshes.
- **Boundary conditions.** The construction of efficient absorbing conditions is very important for solving wave equations, which are generally set in unbounded or very large domains. The efficiency of the conditions depends on the type of waves which are absorbed. Classical conditions absorb propagating waves but recently new conditions have been derived for both propagating and evanescent waves in the case of flat boundaries. MAGIQUE-3D would like to develop new absorbing boundary conditions whose derivation is based on the full factorization of the wave equation using pseudodifferential calculus. By this way, we can take the complete propagation phenomenon into account which means that the boundary condition takes propagating, grazing and evanescent waves into account, and then the absorption is optimized. Moreover our approach can be applied to arbitrarily-shaped regular surfaces.
  We intend to work on the development of interface conditions that can be used to model rough interfaces. One approach, already applied in electromagnetism [89], consists in using homogenization methods which describes the rough surface by an equivalent transmission condition. We propose to apply it to the case of elastodynamic equations written as a first-order system. In particular, it would be very interesting to investigate if the rigorous techniques that have been used in [70], [71] can

be applied to the theory of elasticity. This type of investigations could be a way for MAGIQUE-3D to consider medical applications where rough interfaces are often involved. Indeed, we would like to work on the modeling and the numerical simulation of ultrasonic propagation and its interaction with partially contacting interfaces, for instance bone/titanium in the context of an application to dentures, in collaboration with G. Haiat (University of Paris 7).

- **Asymptotic modeling**.

  In the context of wave propagation problems, we are investigating physical problems which involves multiple scales. Due to the presence of boundary layers (and/or thin layers, rough interfaces, geometric singularities), the direct numerical simulation (DNS) of these phenomenas involves a large numbers of degrees of freedom and high performance computing is required. The aim of this work is to develop credible alternatives to the DNS approach. Performing a multi-scale asymptotic analysis, we derive approximate models whose solution can be computed for a low computational cost. We study these approximate models mathematically (well-posedness, uniform error estimates) and numerically (we compare the solution of these approximate models to the solution of the initial model computed with high performance computating).

  We are mostly interested in the following problems.

  – 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;
  – ultrasonic wave propagation through bone-titanium media in medicine in collaboration with Inria Team MC2, and MSME;
  – asymptotic modeling of multi perforate plates in turbo reactors in collaboration with Cerfacs, INSA-Toulouse, Onera and Snecma in the framework of the ANR APAM.

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 calculus can be performed locally on each element of the mesh. The communications are ensured 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 to 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 should begin in 2013, in collaboration with Dider Rémy of SGI.

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 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.

5. Software

5.1. Hou10ni

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 is: 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 tetraedrons, 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. Now, it remains to compare the performances of Hou10ni to the ADER schemes.

Recently, we have extended the 2D version of Hou10ni for computing the solution of the harmonic wave equation (Helmholtz). 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.

5.2. Gar6more3D

Participant: Julien Diaz [correspondant].

This code computes 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 this code 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 [87]. They are freely distributed under a CECILL licence 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 one 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

6. New Results

6.1. Inverse Problems

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

Participants: Hélène Barucq, Rabia Djellouli, Élodie Estecahandy.

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:

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

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 [86] and the references therein, among others. We 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 Helmholtz equation is involved, that is the acoustic case by impenetrable scatterers [79]. The direct elasto-acoustic scattering problem defines an operator $F : \Gamma \to p_\infty$ 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 $\widetilde{p}_\infty(\widehat{x})$, corresponding to one or several given directions d and wavenumbers k, one can formulate IOPs as follows:

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

We propose a solution methodology based on a regularized Newton-type method to solve this inverse obstacle problem. 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. They are solution to the same boundary value problem as the direct problem with other transmission conditions. This work has been presented both in FACM11 and in WAVES 2011. A paper has been submitted.

6.1.2. hp-adaptive inversion of magnetotelluric measurements

Participants: Hélène Barucq, Julen Alvarez Aramberri, David Pardo.

The magnetotelluric (MT) method is a passive electromagnetic (EM) exploration technique that allows to determine the resistivity distribution in the subsurface of the area of interest on scales varying from few meters to hundreds of kilometers. Commercial uses include hydrocarbon (oil and gas) exploration, geothermal exploration, and mining exploration, as well as hydrocarbon and groundwater monitoring. MT measurements are governed by the electromagnetic phenomena, which can be described by Maxwell's equations. We solve those equations by a goal-oriented hp-adaptivity Finite Element Method (FEM).

In order to estimate the resistivity distribution in the Earth's subsurface, we solve an Inverse Problem. We define a Misfit Function that represents the difference between the measured and computed data for a particular resistivity distribution. By minimizing this misfit function using a gradient based approach with model reduction techniques, and hence solving the inverse problem, we are able to determine the properties of the subsurface materials.

6.2. Modeling

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

Participants: Hélène Barucq, Anne-Gaëlle Saint-Guirons, Sébastien 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 condition are classically considered in order to avoid spurious reflections. This year we have implemented and tested an exact condition based on a non local Dirichlet to Neumann operator in the context of the Helmholtz equation posed on an elongated domain.

6.2.2. Explicit computation of the electrostatic energy for an elliptical charged disc

Participants: Sophie Laurens, Sébastien Tordeux.

In [32], We have described a method to obtain an explicit expression for the electro- static energy of a charged elliptical infinitely thin disc. The charge distribution is assumed to be polynomial. Such explicit values for this energy are fundamen- tal for assessing the accuracy of boundary element method codes. The main tools used are an extension of Copson's method and a diagonalization, given by Leppington and Levine, of the single-layer potential operator associated with the electrostatic potential created by a distribution of charges on an elliptical disc.

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

Participants: Cyril Agut, Hélène Barucq, Henri Calandra, Julien Diaz, Florent Ventimiglia.

The new method involving p-harmonic operator described in section 3.2 has been presented in [17]. We have proved the convergence of the scheme and its stability under a CFL condition. Numerical results in one, two and three-dimensional configurations show that this CFL condition is slightly greater than the CFL condition of the second-order Leap-Frog scheme.

In the framework of the PhD thesis of Florent Ventimiglia, we are now considering the extension of this technique to the first order formulation of the acoustic and elastodynamic equations. A numerical analysis of performance in 1D indicates that, for a given accuracy, this method requires less storage than the High-Order ADER Schemes for and similar computational costs. We are now implementing this algorithm in 3D in order to confirm this analysis and to assess its performance in an RTM framework on realistic configurations.

6.2.4. Stability Analysis of an Interior Penalty Discontinuous Galerkin Method for the Wave equation

Participants: Cyril Agut, Hélène Barucq, Julien Diaz.

The Interior Penalty Discontinuous Galerkin Method [72], [69], [83] we use in the IPDGFEM code requires the introduction of a penalty parameter. Except for regular quadrilateral or cubic meshes, the optimal value of this parameter is not explicitely known. Moreover, the condition number of the resulting stiffness matrix is an increasing function of this parameter, but the precise behaviour has not been explicited neither. We have carried out a theoretical and numerical study of the pnealization parameter and of the CFL condition for quadrilateral and cubic meshes, this results have been presented in a paper accepted in M2AN [16]

6.2.5. Higher Order Absorbing Boundary Conditions for the Wave Equation

Participants: Hélène Barucq, Juliette Chabassier, Julien Diaz.

The numerical simulation of wave propagation is generally performed by truncating the propagation medium and the team works on new ABCs, trying to improve the performance of existing conditions. Following the analysis performed in [23], we have considered the issue of constructing high-order ABCs for the Helmholtz equation. Now, to derive conditions of order greater than two is really technical. In addition, when the coefficients representing the geological properties of the medium are not regular, the method of construction of ABCs is not completely justified. That is why we turned to the construction of conditions that take into account all the characteristics of the diffraction phenomenon and not only waves that propagate like in the case of standrad ABCs. This is what we call enriched ABCs. A research report is being written, an article should be submitted in 2013. During 2012, a publication for the acoustic wave equation has been accepted in M3AS [23] and a second one has been submitted.

6.2.6. Multiperforated plates in linear acoustics

Participants: Abderrahmane Bendali, M'Barek Fares, Sophie Laurens, Estelle Piot, Sébastien Tordeux.

Acoustic engineers use approximate heuristic models to deal with multiperforated plates in liners and in combustion chambers of turbo-engines. These models were suffering from a lack of mathematical justifications and were consequently difficult to improve. Performing an asymptotic analysis (the small parameter is the radius of the perforations), we have justified these models and proposed some improvement. Our theoretical results have been compared to numerical simulations performed at CERFACS (M'Barek Fares) and to acoustical experiments realized at ONERA (Estelle Piot). Two papers have been published in 2012 [27], [30].

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

Participants: Hélène Barucq, Rabia Djellouli, Élodie Estecahandy.

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 presented to ECCOMAS 2012 [44] and to two workshops [42] [43].

6.2.8. Operator Based Upscaling for Discontinuous Galerkin Methods

Participants: Hélène Barucq, Théophile Chaumont, Julien Diaz, Christian Gout, Victor Péron.

Scientists and engineers generally tackle problems that include multiscale effects and that are thus difficult to solve numerically. The main difficulty is to capture both the fine and the coarse scales to get an accurate numerical solution. Indeed, the computations are generally performed by using numerical schemes based on grids. But the stability and thus the accuracy of the numerical method depends on the size of the grid which must be refined drastically in the case of very fine scales. That implies huge computational costs and in particular the limitations of the memory capacity are often reached. It is thus necessary to use numerical methods that are able to capture the fine scale effects with computations on coarse meshes. Operator-based upscaling is one of them and we present in [22] a first attempt to adapt that technique to a Discontinuous Galerkin Method (DGM). We consider the Laplace problem as a benchmark and we compare the performance of the resulting numerical scheme with the classical one using Lagrange finite elements. The comparison involves both an accuracy analysis and a complexity calculus. This work shows that there is an interest of combining DGM with upscaling.

6.2.9. Asymptotic Modeling for Elasto-Acoustics

Participants: Julien Diaz, Victor Péron.

We present in [65] equivalent conditions and asymptotic models for the diffraction problem of elasto-acoustic waves in a solid medium surrounded by a thin layer of fluid medium. This problem is well suited for the notion of equivalent conditions : since the thickness of the layer is small with respect to the wavelength, the effect of the fluid medium on the solid is as a first approximation local. We derive and validate equivalent conditions up to the third order for the elastic displacement. These conditions approximate the acoustic waves which propagate in the fluid region. This approach leads us 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. Indeed, the boundary conditions have been integrated without changing the structure of the code Hou10ni.

This work has been presented in four international conferences and Workshops : Aquitaine-Euskadi Workshop on Applied Mathematics; First Russian-French Conference on Mathematical Geophysics, Mathematical Modeling in Continuum Mechanics and Inverse Problems; Workshop HPC-GA; Twelfth International Conference Zaragoza-Pau on Mathematics.

A paper with numerical results for the elasto-acoustic problem with a thin layer and a variable thickness is in preparation.

6.2.10. Asymptotic modeling in electromagnetism

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

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

In the paper [28], eddy current problems are addressed in a bidimensional setting where the conducting medium is non-magnetic and has a corner singularity. For any fixed skin depth we show that the flux density is bounded near the corner, unlike the perfect conducting case. Then as the skin depth goes to zero, the first two terms of a multiscale expansion of the magnetic potential are introduced to tackle the magneto-harmonic problem. The heuristics of the method are given and numerical computations illustrate the obtained accuracy.

In a forthcoming paper, 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 WCCM 2012.

6.2.11. Asymptotic models for penalization methods in porous media

Participants: Gilles Carbou, Victor Péron.

We investigate a Stokes-Brinkman problem with Beavers and Joseph transmission conditions, adapted to a penalization method in porous media. We exhibit a WKB expansion for the solution of the fluid-porous interface problem. The main interest is to derive equivalent models for the penalization method. We explicit the first terms of the WKB expansion for the flow and the pressure in the subdomains. Each asymptotics of the flow writes as a sum of a tangential boundary layer term plus a standard term in the porous region. From the benefits or these boundary layers, we infer a collection of elementary transmission problems satisfied by the standard parts of the asymptotics for the flow and the pressure. As a consequence of the penalization of the Laplacian operator which applies to the flow in the porous media, a degenerate operator of order zero applies to the elementary velocities appears in the porous region. The main difficulty concern the proof of elliptic regularity up to the interface for the solution of each elementary problem, since exotic conditions for the flow and the pressure appears along the interface. Our strategy consists to adapt a proof of elliptic regularity for the solution of a Darcy problem set in homogeneous media and developed by Boyer-Fabrie.

6.2.12. Asymptotic modeling in electromagnetism

Participants: Marc Duruflé, Victor Péron, Clair Poignard.

We investigate asymptotic models for 3D transmission problems in electromagnetism with homogeneous thin layers (uniform thickness). We exhibit Generalized Impedance Boundary Conditions of order 1 when the thin layer is symmetric and non-symmetric with respect to its mean surface. We present also a limit model for a resistive thin layer, and an equivalent model of order 1 for large contrast in conductivities through the thin layer. We write all these models in a general form. Questions regarding the implementation of the conditions have been addressed carefully. Numerical results with the high-order finite element library Montjoie illustrate the accuracy of the asymptotic models. A paper is in preparation.

6.2.13. Absorbing Boundary Conditions for Tilted Transverse Isotropic Elastic Media

Participants: Hélène 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 wavelenghts 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.

This ABC has been constructed for elliptic TTI media, where the slowness curve of the P-Wave is a rotated ellipse. Then, an appropriate change of variable can be applied in order to transform this ellipse into a circle. The main idea consists in imposing the isotropic ABC in the new system of coordinates and to apply the inverse change of variable in order to obtain the elliptic TTI ABC. We have compared numerically the reflections generated by this new ABC in TTI domain to the ones generated by the classical first order ABC in isotropic domains. The results show that the new ABC performs as well as the classical first order one. Moreover, this ABC seems to be also well-suited to non elliptic TTI media. These results have been presented at the Congrès Français d'Acoustique [35], at two workshops [39], [45].

6.2.14. 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 designed a new and efficient solution methodology for solving high-frequency Helmholtz problems. The proposed method is a least-squares based technique that employs variable bases of plane waves at the element level of the domain partition. A local wave tracking strategy is adopted for the selection of the basis at the regional/element level. More specifically, for each element of the mesh partition, a basis of plane waves is chosen so that one of the plane waves in the basis is oriented in the direction of the propagation of the field inside the considered element. The determination of the direction of the field inside the mesh partition is formulated as a minimization problem. Since the problem is nonlinear, we apply Newton's method to determine the minimum. The computation of Jacobians and Hessians that arise in the iterations of the Newton's method is based on the exact characterization of the Fréchet derivatives of the field with respect to the propagation directions. Such a characterization is crucial for the stability, fast convergence, and computational efficiency of the Newton algorithm. These results are part of the Master thesis of Sharang Chaudhry (student à CSUN) and have been presented to the 6th European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS, Vienna, 2012).

6.3. High Performance methods for solving wave equations

Participants: Lionel Boillot, Hélène Barucq, Henri Calandra, Julien Diaz, Emiljana Jorgji, Didier Rémy, Florent Ventimiglia.

We have recently optimized the DG code implemented in the DIVA plateform of Total by reducing the number of communications between each processors. Since this code is based on the first order formulation of the elastodynamic wave equation, we have to compute three velocities and six stresses at each degree of freedom of the mesh. One naive idea consists in communicating these nine values at each time step. On the other hand, the computation of the three velocities does not actually require the knowledge of the six stresses but of three linear combination of these stresses. Similarly, the computation of the stresses requires the knowledge of six linear combinations of the three velocities. The main idea of the optimization consists in computing the three linear combinations of the stresses and to communicate them to the other processors, while the three velocities are communicated before computing the linear computations. Hence the number of communications can be reduced to six at each time step.

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.

7. Bilateral Contracts and Grants with Industry

7.1. Contracts with TOTAL

- Depth Imaging Partnership (DIP)

  Period: 2010 January - 2012 december, Management: Inria Bordeaux Sud-Ouest, Amount: 3600000 euros. 150 000 euros have been devoted to hire an associate engineer (from Oct. 2010 to Sept. 2012).

- 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: 20November - 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.

8. Partnerships and Cooperations

8.1. Regional Initiatives

The PhD fellowship of Elodie Estecahandy is partially (50%) financed by the Conseil Régional d'Aquitaine.

The PhD fellowship of Vanessa Mattesi is partially (50%) financed by the Conseil Régional d'Aquitaine.

The Post-Doctoral fellowship of Juliette Chabassier is partially (50%) financed by the Conseil Général des Pyrénées Atlantiques.

The Post-Doctoral fellowship of Ángel Rodríguez Rozas is partially (50%) financed 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 and with the collaboration of Henri Calandra from Total, Magique-3D coordinates research activities dealing with the development of high-performance numerical methods for solving wave equations in complex media. This project involves French academic researchers in mathematics, computing and in geophysics, and is funded by Total. Currently, two project-teams are involved: Hiepacs and Nachos.

In the framework of DIP, three PhD students are working in Magique 3D and two new PhD students have been hired this year. One of them is shared with the project team Nachos (http://www-sop.inria.fr/nachos/). Moreover, one internship has been realized. Always in the framework of DIP, Magique-3D has a collaboration with Prof. Changsoo Shin who is an expert of Geophysics and works at the Department of Energy resources engineering (College of Engineering, Seoul National University). Jewoo Yoo, who is a first year PhD student advised by Prof.Changsoo Shin, has visited Magique-3D during four months, from November 2011 to February 2012.
The contract ends in 2012 and a second period will start in 2013. We aggreed with Total hat the new contract will be signed for five years and that Magique 3D will strenghten its collaboration with Professor J. Tromp at Princeton on the topic of full wave inversion.

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, pluridisciplinary 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.

8.3.2. Collaborations in European Programs, except FP7

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 the complementary skills in the field of wave propagation of two research teams which are respectively located in Pau and Bilbao. The main objective of this collaboration is to develop innovative numerical methods 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.

Joint project with the Matheon Research Center in Berlin funded by the European Union in the framework of the Procope 2012 Call. Total Amount: 4200 euros.

Program: PHC Procope 2012

Project acronym: Procope Inria - TU Berlin

Project title: Procope Inria - TU Berlin

Duration: January 2012 - December 2014

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.

8.4. International Initiatives

8.4.1. Inria International Partners

8.4.1.1. MAGIC

Title: Advance Modeling in Geophysics

Inria principal investigator: Hélène Barucq

International Partner:

Institution: California State University at Northridge (United States)

Laboratory: Department of Mathematics

Duration: 2006 - 2012

See also: http://uppa-inria.univ-pau.fr/m3d/Equipe-associee/index.html

The main objective of this collaboration is the design of an efficient solution methodology for solving Helmholtz problems in heterogeneous domains, a key step for solving the inversion in complex tectonics. The proposed research program is based upon the following four pillars:

1. The design, implementation, and the performance assessment of a new hybrid mixed type method (HMM) for solving Helmholtz problems. 2. The construction of local nonreflecting boundary conditions to equip HMM when solving exterior high-frequency Helmholtz problems. 3. The design of an efficient numerical procedure for full-aperture reconstruction of the acoustic far-field pattern (FFP) when measured in a limited aperture. 4. The characterization of the Fréchet derivative of the elasto-acoustic scattered field with respect to the shape of a given elastic scatterer.

8.4.2. Participation In International Programs

8.4.2.1. GEO3D

Joint project with the Novosibirsk state University in Russia funded by the Poncelet laboratory in the framework of the Inria Russia Call. Total Amount: 8000 euros for 2012.

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 - Yuri Laevsky

Duration: January 2012 to 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) in the context of geosciences. We are mainly interested to the derivation of numerical methods (discontinuous Galerkin approximation, space-time refinement), to the design of direct and inverse high performance solver, and to the modeling of complex media.

8.5. International Research Visitors

8.5.1. Visits of International Scientists

- Jewoo Yoo, Ph.D Student at Seoul University spent five months MAGIQUE-3D from December 2011 to April 2012.
- Rabia Djellouli spent one week in MAGIQUE-3D in November 2012.
- Patrick Dular (Université de Liège) is visiting MAGIQUE-3D from December 2012 to February 2013.

9. Dissemination

9.1. Scientific Animation

9.1.1. Conferences Organization

- In collaboration with the Institute of Numerical Mathematics and Mathematical Geophysics (Novosibirsk State University), Magique 3D organized the First Russian-French Conference on Mathematical Geophysics, Mathematical Modeling in Continuum Mechanics and Inverse Problems (June 18-22) in Biarritz. This conference was the kick-off meeting of the GEO3D project between the two teams. It focused on direct and inverse problems in mathematical geophysics, mathematical modeling in continuum mechanics, and wave propagation.

  Gathering well recognized specialists with a large spectrum of domain of expertise (geophysical modeling, wave propagation, numerical analysis, large scale problems, inverse problems...), it aimed at creating synergy resulting in theoretical and technological advances in these domains. It initiated discussions and defined joint research projects between French and Russian researchers.

  It gathered around forty participants.

  http://uppa-inria.univ-pau.fr/m3d/ConfFR/
- Magique 3d coorganized with the BCAM the Aquitanie-Euskadi Workshop on Applied Mathematics (October 29-31) in Biarritz. It was the closing workshop of the AKELARRE project (Aquitaine-Euskadi fundings), it focused on wave problems which were the subject of the joint project and take place in different areas of applied mathematics (control, finite elements, asymptotic analysis, boundary conditions, high performing computing, ...). and it gathered around 30 participants.

  http://uppa-inria.univ-pau.fr/m3d/ConfInriaBcam/

9.1.2. Administrative Activities

- Hélène Barucq is vice-chair of the Inria evaluation committee. From 2009 to 2012, she has been member of the panel of experts for the ANR programs "SIMI1 programmes blanc et jeunes chercheurs", http://www.agence-nationale-recherche.fr/programmes-de-recherche/recherches-exploratoires-et-emergentes/. She is the scientific leader of the strategic action Inria-TOTAL "DIP: Depth Imaging Partnership", http://dip.inria.fr/

- Julien Diaz is elected member of the Inria evaluation committee and member of the CDT (Commission de Développement Technologique of Inria Bordeaux Sud-Ouest.
- Victor Peron is member of the CJC (Commission Jeunes Chercheurs) of Inria Bordeaux Sud-Ouest
- Sébastien Tordeux is elected member of the 26th section of the CNU.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Master : Julien Diaz et Sébastien Tordeux, Introduction aux phénomènes de propagation d'ondes, 55 Eq TD, M2,

Master : Victor Peron et Sébastien Tordeux, Analyse numérique fondamentale, 110 Eq. TD, M1, UPPA, France,

Summer School : Sébastien Tordeux, Introduction à l'analyse mathématique de l'équation de Helmholtz, 12 Eq. TD, Ecole d'été de Jaca 2012, Espagne

9.2.2. Supervision

HdR : Sébastien Tordeux, Modélisation asymptotique pôur les problèmes de propagation d'ondes, Université de Pau et des Pays de l'Adour, January 2012.

PhD in progress : Julien Alvarez, hp-adaptive inversion of magnetotelluric measurements, October 2011, Hélène Barucq and David Pardo.

PhD in progress : Lionel Boillot, Propagateurs optimisés pour les ondes élastiques en milieux anisotropes, May 2011, Hélène Barucq and Julien Diaz.

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.

PhD in progress : Théophile Chaumont Frélet, , October 2012, Hélène Barucq and Christian Gout.

PhD in progress : Élodie Estecahandy, Sur la rśolution de problèmes de diffraction inverses avec des angles d'ouverture réduits, October 2010, Hélène Barucq and Rabia Djellouli.

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 hétérogéenéeités en acoustique et élastodynamique, October 2011, Hélène Barucq and Sébastien Tordeux.

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 jury member for the PhD defense of
  - Sébastien Impériale, Modélisation mathématique et numérique de capteurs piézoélectriques, January 2012 (Université de Paris Dauphine).
  - Sébastien Cambon, Méthodes d'élements finis d'ordre élevé et d'équations intégrales pour la résolution de problèmes de furtivité radar d'objets à symétrie de révolution, July 2nd 2012 (Université de Toulouse).
  - Mohamed Hansbo, Sur le modèle de Kerr-Debye pour la propagation des ondes électromagnétiques, October 1st 2012 (Université de Bordeaux).
  - Dimitri Nicolas, Couplage de méthodes d'échantillonnage et de méthodes d'optimisation de formes pour des problèmes de diffraction inverses, November 28th 2012 (École polytechnique).

- Sébastien Tordeux was jury member for the PhD defense of
  - Pierre-Henri Cocquet, Étude mathématique et numérique homogénéisé de métamatériaux, December 7th 2012 (Université de Toulouse).

9.3. Popularization

- Hélène Barucq, Lycée Cassin à Bayonne, conférence pour des classes de seconde, première et terminale, sur l'application des mathématiques dans la vie courante, April 6th 2012;
- Hélène Barucq, Médiathèque de Cambo-les-Bains, Cycle Café des Sciences, "Les mathématiques, ça sert!!!", April 6th 2012.

10. Bibliography

Major publications by the team in recent years

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Publications of the year

Doctoral Dissertations and Habilitation Theses

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