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Project-Team MAGIQUE-3D

Advanced 3D Numerical Modeling in Geophysics

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

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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 geophysics, physics, 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. During the period 2005-09, the research program of MAGIQUE-3D was mainly composed of two main topics that structured the original parts of the activities of the group. The first topic, entitled ‘Depth Imaging’, was 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 defining approximate models that either lead to less expensive numerical methods (for example by decreasing the number of unknowns by means of an approximation of the original equations), or to high-performance numerical methods applied to the full system, which leads to an accurate solution but implies a high computation cost. Both of these approaches have been considered in the project.

The second topic, that could be given the general title ‘Advanced modeling in wave propagation’, was related to the realistic numerical simulation of complex three-dimensional geophysical phenomena and its comparison with real data recorded in the field. One of the main issues was 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.

During the period 2005-2009, MAGIQUE-3D has worked 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. We now would like to continue working on the same subjects but also 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 [52]. 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 [68], [74], [63], [64]) 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 [44], [46] 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 scattering.
  We would like also to consider electrical impedance tomography, which is a technique to recover spatial properties of the interior of an object from measurements of the potential of the boundary of the object (see [48] by Liliana Borcea and [49] by Martin Hanke and Martin Brühl). In shape identification problems, the measured quantities do not depend linearly on the shape of the obstacle. Most popular approaches describe the objects by appropriate parameterizations and compute the parameters by iterative schemes based on Newton-type methods which require to solve a collection of direct problems. We plan to begin with this kind of approaches since we already have an efficient solver for the direct problem and these iterative schemes are known to be very successful in many cases. Their main disadvantage is that they are expensive since they must solve a direct problem at each step. We hope that our solver will be sufficiently optimized to limit this disadvantage.
- **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), [47], 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.
- **Tomography.** Seismic tomography allows one to describe the geometry and the physical characteristics of the heterogeneities inside the earth by analyzing the propagation speed of the seismic waves. The last past ten years have known a lot of developments like the introduction of sensitivity kernels which complete the rai theory which is often used in short period seismology. However the kernel sensitivity theory introduces very large matrices and the computations which are necessary to solve the inverse problem are very expensive. The idea would be to represent the kernels by a reduced number of parameters by using appropriate methods of compression. The wavelets of Haar

have been used by Chevrot and Zhao [51] but they do not seem to be optimal. We propose to address this kind of issue by aiming at giving parcimonious representations of kernels of sensitivity.

- **Potential techniques Inversion: parallel Hybrid local/global optimization.** In many applications, acoustic and seismic inversion are not enough to reconstruct multiphase component structures. Different potential techniques like electrical capacitance, resistivity, gravimetry and magnetometry are necessary. As potential techniques require the resolution of Poisson or Laplace-like equations, huge linear systems need to be solved using very large multi-CPU/multi-GPU clusters. Today, finite volume/conjugate gradient solvers are running on 200 processors for electrical capacitance and gravimetry problems at CINES/Montpellier supercomputing center as a proof of concept. The very promising results obtained lead us to run them on more than 2000 CPUs and perhaps 200 or 300 GPU clusters. By developing higher order versions we will be able to increase significantly the accuracy of the solutions and the speed of calculations. As the inversion process is performed iteratively, it should be worthwhile to incorporate at the same time local (least square methods) and global (neighborhood/very fast simulated annealing) optimization techniques. An acceptable model could then be taken as the new current model and at some degree, data compression will be used in order to compute an accurate sensitivity matrix for this current model computed with local/global optimization. Then, using local/global optimization, purely sensitivy matrix based inversion could be used to accelerate all the inversion processes. In the case of electrical capacitance tomography, the forward problem is accelerated by almost a factor of 100 when a GPU is preferred to a CPU. On a multiCPU/multiGPU, an asynchronous strategy of communications between processors and copies of informations between host (CPU) and device (GPU) is retained and will be implemented more properly. We plan to apply this to joint inversion at the regional and global earth scales. A collaboration with CAPS entreprises and GENCI has been approved in November 2009 for the multi GPU porting of a 3D finite volume code implemented using MPI by Roland Martin. On a signe GPU an acceleration factor of 23 has been already obtained. This collaboration is under its way. We have the intention to extend this to high order spectral element method in the context of AHPI ANR project in 2010 by taking the SPECFEM3D parallel code as a fundamental code that will be transformed into an elliptic large system solver.

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 [5] 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 [43]. 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 [53], [71], [58] 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 [37]. 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 [56], [57]. 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 [69], 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 [39], [40] 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 modelling 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 Ampre, 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.

\+ **Nonlinear problems in fluid dynamics.** In order to model heat transfers, fluid-solid interactions, in particular landslides and tsunamis induced by earthquakes, tremors induced by fluid motions in volcanoes, sharp solid-to-fluid transitions in some planets, it is of crucial importance to develop efficient parallel solvers on multicore/multi-processor supercomputing platforms. High order finite volumes introducing compact schemes or spectral-like integrations as well as high order finite elements and their related high order boundary conditions are needed to take into account, at the same time, discontinuities in geological structures, sharp variations and shocks in fluid velocities and properties (density, pressure and temperature), and the coupling between both codes. Discrete Galerkin techniques, spectral finite volumes or finite-volume techniques should be taken into account in compact schemes in order to reduce drastically the memory storage involved and compute larger models. Viscous compressible and incompressible codes need to be solved using non-conforming meshes between solid and fluid, and large linear systems need to be solved on very huge multi-CPU/multi-GPU supercomputers. Moving meshes close to the interface between solids and fluids should be taken into account by dynamic or adaptive remeshing. Furthermore we developped PML for the full compressible Navier-Stokes system of equations [66] using finite-differences discretization in curvilinear coordinates and we are planning to extend PML conditions to both compressible and incompressible viscous flows in the context of high order finite volumes or Discontinuous galerkin methods.

Another direction that we would like to consider would be the use of solitons in nonlinear problems. Indeed, a soliton is an interesting tool for modeling and explaining some nonlinear phenomena. For example tsumanis are sometimes explained by the emergence of solitons created by earth tremor. Strain solitons can be also used to explain the propagation of breaking in solids [70]. Therefore it would be interesting to investigate more this issue.

3.3. High Performance methods for solving wave equations

A tremendous increase of the sustained power of supercomputers has occurred in the last few years, in particular with the first ‘petaflops’ machines that have been built in the USA and also with new technology such as general-purpose computing on graphics cards (so-called ‘GPU computing’). Nowadays, one has access to powerful numerical methods that, when implemented on supercomputers, make it possible to simulate both forward and inverse seismic wave propagation problems in complex three-dimensional (3D) structures. Moreover, very spectacular progress in computer science and supercomputer technology is amplified by recent advances in High Performing Computing (HPC) both from a software and hardware point of view. One can in this respect say that HPC should make it possible in the near future 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. Our group has for instance already run simulations in parallel on 150,000 processor core, obtaining an excellent sustained performance level and almost perfect performance scaling [50].

We will therefore work on three HPC issues in the next few years. The first will be very large scale inversion of seismic model based on sensitivity kernels. In the context of a collaboration with TOTAL and also with Prof. Jeroen Tromp at Princeton University (USA), we will use adjoint simulations and sensitivity kernels to solve very-large scale inverse problems for seismology and for oil industry models, for instance deep offshore regions and/or complex foothills regions or sedimentary basins. The second issue is Graphics Processing Unit (GPU) computing: in the context of a collaboration with Prof. Gordon Erlebacher (Florida State University, USA) and Dr. Dominik Göddeke (Technical University of Dortmund, Germany) we have modified our existing seismic wave propagation software packages to port them to GPU computing in order to reach speedup factors of about 20x to 30x on GPU clusters (for instance at GENCI/CEA CCRT in Bruyères-le-Châtel, France). The third issue is porting our software packages to Symmetric Multi Processors (SMP) massive multicore computing to take advantage of future processors, which will have a large number of cores on petaflops or exaflops machine. In the context of a collaboration with Prof. Jesús Labarta and Prof. Rosa Badia from the Barcelona Supercomputing Center (Catalonia, Spain) we will use their ’StarSs’ programming environment to take advantage of multicore architectures while keeping a flexible software package relatively simple to modify for geophysicists that may not be computer-programming experts.

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. Seismology

We already applied our techniques to the study of strong ground motion and associated seismic risk in the Los Angeles basin area. This region consists of a basin of great dimension (more than 100 km × 100 km) which is one of the deepest sedimentary basins in the world (the sedimentary layer has a maximum thickness of 8.5 km underneath Downtown Los Angeles), and also one of the most dangerous in the world because of the amplification and trapping of seismic waves. In the case of a small earthquake in Hollywood (September 9, 2001), well recorded by more than 140 stations of the Southern California seismic network TriNet, we managed for the first time to fit the three components of the displacement vector, most of the previous studies focusing on the vertical component only, and to obtain a good agreement until relatively short periods (2 seconds).

We wish to improve these studies of seismic risk in densely populated areas by considering other regions of the world, for example the Tokyo basin, the area of Kobe or the Mexico City region. We also plan to generalize this type of calculations to the knowledge and modeling of site effects, i.e. of the local amplification of the response of the ground to seismic excitation. The study of such effects is an important observation in urban areas to be able to anticipate the damage to constructions and, if necessary, to plan the organization of search and rescue operations. It is also a significant element of the definition of paraseismic standards. Site effects can be determined experimentally, but that requires the installation of stations for a sufficient period of time to record a few tens of seismic events. Numerical modeling makes it possible to avoid this often long and difficult experimentation, assuming of course that one has good knowledge of the geological structure of the subsurface in the studied area. We thus propose in the MAGIQUE-3Dproject to use the numerical techniques mentioned above for instance to quantify the effects of topographic variations in the structure.

4.3. Non destructive testing, Medical Imaging

The problems of seismic imaging can be related to non destructive testing, in particular medical imaging. For instance, the rheumatologist are now trying to use the propagation of ultrasounds in the body as a noninvasive way to diagnose osteoporosis. Then, the bones can be regarded as elastodynamic or poroelastic media while the muscles and the marrow can be regarded as acoustic media. Hence the computational codes we use for seismic imaging could be applied to such a problem.

5. Software

5.1. SPECFEM3D

The MAGIQUE-3D project is based (in part) on existing software packages, which are already validated, portable and robust. The SPECFEM3D software package, developed by Dimitri Komatitsch and his colleagues in collaboration with Jeroen Tromp and his colleagues at the California Institute of Technology and at Princeton University (USA), and which is still actively maintained by Dimitri Komatitsch and his colleagues, allows the precise modeling of seismic wave propagation in complex three-dimensional geological models. Phenomena such as anisotropy, attenuation (i.e., anelasticity), fluid-solid interfaces, rotation, self-gravitation, as well as crustal and mantle models can be taken into account. The software is written in Fortran95 with MPI message-passing on parallel machines. It won the Gordon Bell Prize for best performance of the Supercomputing'2003 conference. In 2006, Dimitri Komatitsch established a new collaboration with the Barcelona Supercomputing Center (Spain) to work on further optimizing the source code to prepare it for very large runs on future petaflops machines to solve either direct or inverse problems in seismology. Optimizations have focused on improving load balancing, reducing the number of cache misses and switching from blocking to non-blocking MPI communications to improve performance on very large systems. Because of its flexibility and portability, the code has been run successfully on a large number of platforms and is used by more than 150 academic institutions around the world. In November 2008 this software package was again among the six finalists of the pretigious Gordon Bell Prize of the SuperComputing'2008 conference in the USA [50] for a calculation performed in parallel on 150,000 processor cores, reaching a sustained performance level of 0.16 petaflops.

5.2. 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 PhD. thesis of Caroline Baldassari and the 3D version should be implemented soon. 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). These functionalities will be soon implemented in the 3D code.

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 PhD. 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 it 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.

5.3. Gar6more3D

Participants: Julien Diaz [correspondant], Abdelaâziz Ezziani.

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/softwares.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 [67]. They are freely distributed under a CECILL licence and can be downloaded on the website http://web.univ-pau.fr/~jdiaz1/softwares.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 [65] 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 [55]. 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. Seismic data interpretation using the Hough transform and principal component analysis

Participants: M-.G Orozco-del-Castillo, Carlos Ortiz-Aleman, Roland Martin, Rafael Avila-Carrera, Alejandro Rodriguez-Castellanos.

In [29], two novel image processing techniques are applied to detect and delineate complex salt bodies from seismic exploration profiles: Hough transform and principal component analysis (PCA). It is well recognized by the geophysical community that the lack of resolution and poor structural identification in seismic data recorded at sub-salt plays represent severe technical and economical problems. Under such circumstances, seismic interpretation based only on the human-eye is inaccurate. Additionally, petroleum field development decisions and production planning depend on good-quality seismic images that generally are not feasible in salt tectonics areas. In spite of this, morphological erosion, region growing and, especially, a generalization of the Hough transform (closely related to the Radon transform) are applied to build parabolic shapes that are useful in the idealization and recognition of salt domes from 2D seismic profiles. In a similar way, PCA is also used to identify shapes associated with complex salt bodies in seismic profiles extracted from 3D seismic data. To show the validity of the new set of seismic results, comparisons between both image processing techniques are exhibited. It is remarkable that the main contribution of this work is oriented in providing the seismic interpreters with new semi-automatic computational tools. The novel image processing approaches presented here may be helpful in the identification of diapirs and other complex geological features from seismic images. Conceivably, in the near future, a new branch of seismic attributes could be recognized by geoscientists and engineers based on the encouraging results reported here.

6.1.3. Gravimetry Inversion

Participants: Roland Martin, Dimitri Komatitsch, Mark Jessel, Stéphane Perrouty, Vadim Monteiller.

In order to improve the subsoil images in regions which are not well covered by a dense seismic array or can not be well retrieved by using seismic imaging techniques alone (salty dome regions like in the Gulf of Mexico for instance), we have been developping new gravity imaging techniques using supercomputing. In regions like Ghana or the Chicxulub crater located in Yucatan plate (Mexico), 3D sensitivity kernels are calculated for gravity potential data sets measured over 2000 up to 10000 locations randomly distributed in space. The density anomaly computational domain covers a 250 km × 250 km × 20 km volume in these two regions. For instance for the Ghana region two resolutions are taken : 1 point each 2 kms in the horizontal plane and 200 m in the vertical direction in the less accurate configuration and one point each 500 m in the horizontal plane and one point each 100 m in the vertical direction for the most accurate configuration. The gravity anomalies are inverted using an optimized least-square method applied to a sensitivity kernel of 10^10 up to 4×10^11 elements . The least-square method using a L^2-norm or L^1-norm has been implemented on hybrid multi-CPU/multi-GPU Titane machines at CCRT of the French Nuclear Energy Agency. L^1 norm gives us sharper boundaries of the density structures when compared to L^2-norm solutions but these L^1 solutions are obtained at the expense of one order of magnitude in the number of iterations necessary to the inversion. The L^2-norm gives slightly smoother solutions but is much more faster than L^1 norm by at least one order of magnitude in terms of acceleration. The optimized CPU version has allowed us to reduce drastically the computation time form 5 hours on 512 processors to 25 minutes. Furtermore the multi-GPU version has decreased this computational time around 15 minutes. Our collaboration with geologists of IRD (Mark Jessell and Stephane Perrouty) has allowed us to determine a reallistic a priori model of Ghana with different resolutions in order to obtain more reallistic models after inversion. We are still optimizing the multi-GPU code, with the challenging goal of obtaining results lower than 10 minutes and then obtaining an acceleration factor of at least 4 when compared to the optimized multi-CPU iunversion code. By now the code is further optimized and more improvements are alreday in curse in terms of better preconditionning, automatic multi-resolution procedure implementation, gravimetry-seismic joint inversion and extension to the global earth imaging. An international article in a scientific peer-reviewed journal is in preparation.

6.2. Modeling

6.2.1. Local approximate DtN exterior boundary condition

Participants: Hélène Barucq, Rabia Djellouli, Anne-Gaëlle Saint-Guirons.

We investigate analytically the asymptotic behavior of high-order spurious prolate spheroidal modes induced by a second-order local approximate DtN absorbing boundary condition (DtN2) when employed for solving high-frequency acoustic scattering problems. We prove that these reflected modes decay exponentially in the high frequency regime. This theoretical result demonstrates the great potential of the considered absorbing boundary condition for solving efficiently exterior high-frequency Helmholtz problems. In addition, this exponential decay proves the superiority of DtN2 over the widely used Bayliss-Gunsburger-Turkel absorbing boundary condition. This work has been accepted for publication in Progress In Electromagnetics Research B. [19].

6.2.2. 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. In this paper, we investigate some properties of the Dirichlet to Neumann map posed on a spheroidal boundary in the context of the Helmholtz equation. We focus on the impedance coefficients defining the DtN condition and we aim at establishing suitable properties in order to propose an accurate numerical method for their computation. Then, we state the well-posedness of the corresponding mixed problem and propose a variational formulation adapted to a finite element discretization. This work has been submitted.

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

Participants: Cyril Agut, Hélène Barucq, Julien Diaz, Florent Ventimiglia, Roland Martin, Dimitri Komatitsch.

The new method involving p-harmonic operator described in section 3.2 has been presented in [13]. 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. We have also studied the penalization parameters involved in the new schemes and their influence of the CFL condition. These results are presented in the PhD. thesis of Cyril Agut [11]. 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 elastodynamic equations.

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

Participants: Cyril Agut, Hélène Barucq, Julien Diaz.

The Interior Penalty Discontinuous Galerkin Method [42], [38], [61] 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 CFL condition for quadrilateral and cubic meshes, which is presented in the Phd thesis of Cyril Agut [11]. These results were also presented at the peer-reviewed conference Waves 2011 (Vancouver, Canada, July 2011).

6.2.5. Higher Order Absorbing Boundary Conditions for the Wave Equation

Participants: Hélène Barucq, Julien Diaz, Véronique Duprat.

The numerical simulation of wave propagation is generally performed by truncating the propagation medium. Absorbing boundary conditions are then needed. We construct a new family of absorbing boundary conditions from the factorization of the wave equation formulated as a first order system. Using the method of M.E. Taylor, we show that we can generate an infinite number of boundary conditions which can not be obtained via the Niremberg's factorization method. The conditions can be applied on arbitrarily-shaped surfaces and involve second-order derivatives. We then propose a reduced formulation of the wave equation using an auxiliary unknown which is defined on the regular surface only. The reduced problem allows one to easily include the boundary conditions inside the variational formulation. The corresponding boundary value problem remains well-posed in suitable Hilbert spaces and we give a demonstration in a framework that is suitable to applications. We then study the long-time behavior of the wave field and we show that it tends to 0 as time tends to infinity. This provides a weak stability result that should be completed in the second part of this work. We have then decided to improve the stability result by performing a quantitative study of the energy. We have then shown that the energy is exponentially decaying if the obstacle is star-shaped and the external boundary is convex. This work has been published as INRIA Resarch Reports [34], [35] and two papers are submitted. We have next addressed the issue of enriching these ABCs by representing evanescent and damping waves. This has given rise to a work for the Hemlholtz equation and we have shown that the enriched ABCs performed better than standard ABCs. The xetension to the acoustic wave has led to new conditions involvin fractional derivatives. To the bast of our knowledge, it is the first time that fractional derivatives have been used for optimizing the performance of ABCs. These new results have been presented in two seminars (University of Bordeaux I and University of Genova) and in two conferences (FACM11 and WAVES 2011). A paper has been published [17] for the case of evanescent waves and two papers are in preparation. All these results are presented in the PhD thesis of Véronique Duprat [12].

6.2.6. Numerical methods combining local time stepping and mixed hybrid elements for the terrestrial migration

Participants: Caroline Baldassari, Hélène Barucq, Henri Calandra [Expert Engineer, TOTAL], Bertrand Denel [Research Engineer, TOTAL], Julien Diaz, Florent Ventimiglia.

In order to justify the use of our code IPDGFEM for the Reverse Time Migration, we have carried out a performance analysis of the Interior Penalty Discontinuous Galerkin method and of the Spectral Element Method. This analysis, which shows that IPDG performs as well as SEM, has been presented in [14].

Another aspect of the work concerns the design of local time-stepping algorithms. The local-time stepping strategy proposed in [5] allows for high-order time schemes where the time scheme is adapted to the various space step of the mesh. However, when the mesh contains both low-order and high-order cells, this method not allows for the adaptation of the order of the time-scheme to the order of the cells. We have then presented a new local time-stepping algorithm where both the order of the scheme and the time step vary in the different parts of the mesh. This method has been presented in [14] and at the peer-reviewed conferences Waves 2011 (Vancouver, Canada, July 2011) and DD20 (Domain Decompostion, San Diego, USA, February 2011).

The local-time stepping algorithm is not adapted to handle dissipation terms. A method has been proposed in [59], but it is based on an Adams-Bashworth scheme and it requires the storage of additional unknowns. We can not use this scheme for the simulation of seismic waves in very large heterogeneous domains due to memory limitation. We are now working on the design of alternative schemes which would not require the introduction of the auxiliary unknowns. This one of the topics of the PhD. thesis of Florent Ventimiglia.

6.2.7. Perfectly Matched Layers for the Shallow Water equations

Participants: Hélène Barucq, Julien Diaz, Mounir Tlemcani [Assistant Professor, University of Oran, Algeria].

In [45], we have proposed a new Perfectly Matched Layer for Shallow Water equations. This layer required the computation of an auxiliary variable in the whole computational domain. We are now considering a new strategy, which only requires the computation of the auxiliary variable inside the layer. Moeover, the new methodology seems to be well-adapted to the non-linear shallow water equations. We are now performing numerical tests to confirm this point.

6.2.8. 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 are in preparation.

6.2.9. Asymptotic modeling in electromagnetism

Participants: François Buret, Gabriel Caloz, Monique Dauge, Patrick Dular, Marc Duruflé, Erwan Faou, Laurent Krähenbühl, Victor Péron, Ronan Perrussel, Clair Poignard, Damien Voyer.

The following results rely on several problematics developed in section 3.2, item **Asymptotic modeling**.

We consider in [21] the equations of electromagnetism set on a domain made of a dielectric and a conductor subdomain in a regime where the conductivity is large. Assuming smoothness for the dielectric–conductor interface, relying on recent works we prove that the solution of the Maxwell equations admits a multiscale asymptotic expansion with profile terms rapidly decaying inside the conductor. This skin effect is measured by introducing a skin depth function that turns out to depend on the mean curvature of the boundary of the conductor. We then confirm these asymptotic results by numerical experiments in various axisymmetric configurations. We also investigate numerically the case of a nonsmooth interface, namely a cylindrical conductor.

We derive new thin layer models in electromagnetism, in [22]. We study the behavior of the electromagnetic field in a biological cell modeled by a medium surrounded by a thin layer and embedded in an ambient medium. We derive approximate transmission conditions in order to replace the membrane by these conditions on the boundary of the interior domain. Our approach is essentially geometric and based on a suitable change of variables in the thin layer. Few notions of differential calculus are given in order to obtain the first-order conditions in a simple way, and numerical simulations validate the theoretical results. Asymptotic transmission conditions at any order are given.

We present a numerical treatment of rounded and sharp corners in the modeling of 2D electrostatic fields in [36]. This work deals with numerical techniques to compute electrostatic fields in devices with rounded corners in 2D situations. The approach leads to the solution of two problems: one on the device where rounded corners are replaced by sharp corners and the other on an unbounded domain representing the shape of the rounded corner after an appropriate rescaling. Both problems are solved using different techniques and numerical results are provided to assess the efficiency and the accuracy of the techniques.

6.2.10. Operator Based Upscaling for Discontinuous Galerkin Methods

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

Realistic numerical simulations of seimic wave propagation are complicated to handle because they must be performed in strongly heterogeneous media. Two different scales must then be taken into account. Indeed, the medium heterogeneities are very small compared to the characteristic dimensions of the propagation medium. To get acccurate numerical solutions, engineers are then forced to use meshes that match the finest scale representing the heterogeneities. Meshing the whole domain with the fine grid leads then to huge linear systems and the computational cost of the numerical method is then very high. It would be thus very interesting to dispose of a numerical method allowing to represent the heterogenities of the medium accurately while computing on a coarse grid. This is the challenge of multiscale approaches like homoegenization or upscaling. In this work, we use an operator-based upscaling method. Operator-based upscaling methods were first developed for elliptic flow problems (see [41]) and then extended to hyperbolic problems (see [62], [73], [72]). Operator-based upscaling method consists in splitting the solution into a coarse and a fine part. The coarse part is defined on a coarse mesh while the fine part is computed on a fine mesh. In order to speed up calculations, artificial boundary conditions (ABC) are imposed. By enforcing suitable ABCs on the boundary of every cells of the coarse mesh, calculations on the fine grid can be carried out locally. The coarse part is next computed globally on the coarse mesh. Operator-based upscaling methods were so far developed in joint with standard finite element discretisation strategy. In this work, we investigate the idea of combining an operator based upscaling method with discontinous Galerkin finite element methods(DGFEM). To begin with, we have used use the interior penalty method as presented in [42] for elliptic problems and in [61], [60] for the wave equation. This is a quite natural way of addressing this issue because we can use a software package that has been already developed in the team. The first results that we have obtained seem to indicate that an DG operator based uspcaling method could be interesting essentially in case of staionnary problems. Nevertheless, the numerical analysis of the discretized problem must be continued. This work has been initiated during the internship of Theophile Chaumont-Frelet who was a fourth year engineer student at Rouen INSA. A paper dealing with the case of the Laplace operator will be submitted soon.

6.2.11. Discontinuous Galerkin Methods for Seismic Wave Propagation

Participants: Hélène Barucq, Caroline Baldassari, Lionel Boillot, Marie Bonnasse, Julien Diaz, Jérôme Luquel, Vanessa Mattesi, Florent Ventimiglia.

In the framework of our collaboration with Total, we are implementing a Discontinuous Galerkin formulation of the first order elastodynamic wave equations in the plateform Diva which is developed by Total. We consider the formulation proposed in [54] for isotropic media. During her post-doc, Caroline Baldassi has implemented a three dimensional code with Perfectly Matched Layers for this formulation. Jérôme Luquel has implemented the 2D version of this code during his internship. In the framework of the internship of Marie Bonnasse and the PhD thesis of Lionel Boillot, we have extended the formulation to Vertical Transverse Isotropic and Tilted Transverse Isotropic media in both 2D and 3D. The introduction of Absorbing Boundary Conditions or of PML is still an open problem for these types of media. It is one of the topics of the PhD thesis of Lionel Boillot.

The version of the code that we are using assumed that the properties of the media (density, velocity,...) are constant on each cells of the mesh. Discontinuous Galerkin methods allow for considering more general configurations, where these properties vary as polynomial functions inside each cells. Hence, it is not necessary to define the interfaces between the different media before constructing the mesh. The discontinuities are taken into account directly inside each cells. Moreover, we are able to consider smoothly varying media. In the framework of the internship of Vanessa Mattesi, we have implemented polynomial velocities in a Discontinuous Galerkin formulation. We have compared the results obtained with this method to the one obtained with piecewise constant properties. We have observed that the new formulation was more accurate and that it allowed for a simpler construction of the mesh. However, these gains do not counterbalance the increase of the computational induced by the new method. We have then concluded that considering piecewise constant properties was more appropriate to model seismic wave propagation.

6.2.12. Elastic surface waves in crystals

Participants: José Carcione, Fabio Cavallini, Dimitri Komatitsch, Nathalie Favretto-Cristini.

In [25], we present a review of wave propagation at the surface of anisotropic media (crystal symmetries). The physics for media of cubic and hexagonal symmetries has been extensively studied based on analytical and semi-analytical methods. However, some controversies regarding surfaces waves and the use of different notations for the same modes require a review of the research done and a clarification of the terminology. In a companion paper we obtain the full-wave solution for the wave propagation at the surface of media with arbitrary symmetry (including cubic and hexagonal symmetries) using two spectral numerical modeling algorithms.

In [27], we obtain the full-wave solution for the wave propagation at the surface of anisotropic media using two spectral numerical modeling algorithms. The simulations focus on media of cubic and hexagonal symmetries, for which the physics has been reviewed and clarified in a companion paper. Even in the case of homogeneous media, the solution requires the use of numerical methods because the analytical Green's function cannot be obtained in the whole space. The algorithms proposed here allow for a general material variability and the description of arbitrary crystal symmetry at each grid point of the numerical mesh. They are based on high-order spectral approximations of the wave field for computing the spatial derivatives. We test the algorithms by comparison to the analytical solution and obtain the wave field at different faces (stress-free surfaces) of apatite, zinc and copper. Finally, we perform simulations in heterogeneous media, where no analytical solution exists in general, showing that the modeling algorithms can handle large impedance variations at the interface.

6.2.13. Application of an elastoplastic spectral-element method to 3D slope stability analysis

Participants: Hom Nath Gharti, Dimitri Komatitsch, Oye Volker, Roland Martin, Jeroen Tromp.

In [26], we implement a spectral-element method for 3D time-independent elastoplastic problems in geomechanics. As a first application, we use the method for slope stability analyses ranging from small to large scales. The implementation employs an element-by-element preconditioned conjugate gradient solver for efficient storage. The program accommodates material heterogeneity and complex topography. Either simple or complex water table profiles may be used to assess effects of hydrostatic pressure. Both surface loading and pseudostatic seismic loading are implemented. In order to simulate elastoplastic behavior of slopes, a Mohr-Coulomb yield criterion is employed using an initial strain method (i.e., a viscoplastic algorithm). For large-scale problems, the software is parallelized based on domain decomposition using MPI (Message Passing Interface). Strong-scaling measurements demonstrate that the parallelized software performs efficiently.We validate our spectral-element results against several other methods, and apply the technique to simulate failure of an earthen embankment and a mountain slope.

6.2.14. Indirect Boundary Element Method applied to Fluid-Solid Interfaces

Participants: A. Rodriguez-Castellanos, E. Flores, F. J. Sánchez-Sesma, Carlos Ortiz-Aleman, M. Nava-Flores, Roland Martin.

In [31], scattering of elastic waves in fluid-solid interfaces is investigated. We use the Indirect Boundary Element Method to study this wave propagation phenomenon in 20 models. Three models are analyzed: a first one with an interface between two half-spaces, one fluid on the top part and the other solid in the bottom; a second model including a fluid half-space above a layered solid; and finally, a third model with a fluid layer bounded by two solid half-spaces. The source, represented by Hankel's function of the second kind, is always applied in the fluid. This indirect formulation can give to the analyst a deep physical insight on the generated diffracted waves because it is closer to the physical reality and can be regarded as a realization of Huygens' principle. In any event, mathematically it is fully equivalent to the classical Somigliana's representation theorem. In order to gauge accuracy we test our method by comparing with an analytical solution known as Discrete Wave Number. A near interface pulse generates scattered waves that can be registered by receivers located in the fluid and it is possible to infer wave velocities of solids. Results are presented in both time and frequency domain, where several aspects related to the different wave types that emerge from this kind of problems are pointed out.

6.2.15. Multiperforated plates in linear acoustics

Participants: Mohamed Amara, Sharang Chaudhry, Julien Diaz, Rabia Djellouli, Magdalena Grigoroscuta-Strugaru.

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 Newtonâs 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).

6.3. High Performance methods for solving wave equations

6.3.1. Forward and adjoint simulations of seismic wave propagation on fully unstructured hexahedral meshes

Participants: Daniel Peter, Dimitri Komatitsch, Yang Luo, Roland Martin, Nicolas Le Goff, Emanuelle Casarotti, Pieyre Le Loher, Federica Magnoni, Qinya Liu, Céline Blitz, Tarje Nissen-Meyer, Piero Basini, Jeroen Tromp.

In [30], we present forward and adjoint spectral-element simulations of coupled acoustic and (an)elastic seismic wave propagation on fully unstructured hexahedral meshes. Simulations benefit from recent advances in hexahedral meshing, load balancing and software optimization. Meshing may be accomplished using a mesh generation tool kit such as CUBIT, and load balancing is facilitated by graph partitioning based on the SCOTCH library. Coupling between fluid and solid regions is incorporated in a straightforward fashion using domain decomposition. Topography, bathymetry and Moho undulations may be readily included in the mesh, and physical dispersion and attenuation associated with anelasticity are accounted for using a series of standard linear solids. Finite-frequency Fréchet derivatives are calculated using adjoint methods in both fluid and solid domains. The software is benchmarked for a layercake model. We present various examples of fully unstructured meshes, snapshots of wavefields and finite-frequency kernels generated by Version 2.0 'Sesame' of our widely used open source spectral-element package SPECFEM3D.

6.3.2. Fluid-solid coupling on a cluster of GPU graphics cards for seismic wave propagation

Participant: Dimitri Komatitsch.

In [28], we develop a hybrid multiGPUs and CPUs version of an algorithm to model seismic wave propagation based on the spectral-element method in the case of models of the Earth containing both fluid and solid layers. Thanks to the overlapping of communications between processing nodes on the computer with calculation by means of non-blocking message passing, we obtain excellent weak scalability of this finite-element code on a cluster of 192 GPUs and speedup factors of more than one order of magnitude compared to the same code run on a cluster of traditional CPUs. This enables us to show a new geophysical phenomenon concerning wave propagation of diffracted shear waves in a layer called D" located at the base of the Earth's mantle, namely that in this layer the transverse and radial components of these waves can undergo a relative shift even in an isotropic Earth model, whereas this observation in real seismological data was interpreted until now as an indication of the presence of anisotropy in this layer.

7. 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. 50 000 euros have been devoted to hire an associate engineer (from Oct. 2010 to Sept. 2011).

- Optimisation de codes pour la migration terrestre d'ondes élastiques.

  Period: 2010 January - 2011 December, Management: INRIA Bordeaux Sud-Ouest, Amount: 60000 euros.

- 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 d'ondes élastiques en milieux anisotropes

  Period: 2011 November - 2014 October, Management: INRIA Bordeaux Sud-Ouest, Amount: 150000 euros.

7.2. Contract with CSUN

In the context of the Associate Team MAGIC.

Period: 2009 January - 2011 December, Total Amount: 15000 USD

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 PhD fellowship of Cyril Agut is financed by the Conseil Général des Pyrénées Atlantiques.

8.2. National Initiatives

ANR AHPI The endeavour of this project is to develop some methodology for modelling and solving certain inverse problems using tools from harmonic and complex analysis. These problems pertain to deconvolution issues, identification of fractal dimension for Gaussian fields, and free boundary problems for propagation and diffusion phenomena. The target applications concern radar detection, clinical investigation of the human body (e.g. to diagnose osteoporosis from X-rays or epileptic foci from electro/magneto encephalography), seismology, and the computation of free boundaries of plasmas subject to magnetic confinement in a tokamak. Such applications share as a common feature that they can be modeled through measurements of some transform (Fourier, Fourier-Wigner, Riesz) of an initial signal. Its non-local character generates various uncertainty principles that make all of these problems ill-posed. The techniques of harmonic analysis, as developed in each case below, form the thread and the mathematical core of the proposal. They are intended, by and large, to regularize the inverse issues under consideration and to set up constructive algorithms on structured models. These should be used to initialize numerical techniques based on optimization, which are more flexible for modelling but computationally heavy and whose convergence often require a good initial guess. In this context, the development of wavelet analysis in electrical engineering, as well as signal and image processing or singularity detection, during the last twenty years, may serve as an example. However, many other aspects of Fourier analysis are at work in various scientific fields. We believe there is a strong need to develop this interaction that will enrich both Fourier analysis itself and its fields of application, all the more than in France the scientific communities may be more separate than in some other countries.
The project was created in july 2007. Meetings were organized twice a year, alternatively in Orléans, Bordeaux, Sophia and Pau Collaborations have began with the Bordeaux team on the use of bandelet formalism for the seismic inversion and a post-doc, hired in october 2008, had in charge to analyze with us the feasibility of this approach. We have worked on the approximation of seismic propagators involving Fourier integral operators by considering different approaches. From November 2010 to November 2011, we have hired an associate engineer who has worked with us on the development of a software for the gravimetric inversion.

8.3. European Initiatives

8.3.1. 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.

8.4. International Initiatives

8.4.1. INRIA Associate Teams

8.4.1.1. MAGIC

Title: Advance Modelling in Geophysics

INRIA principal investigator: Hélène Barucq

International Partner:

Institution: California State University at Northridge (United States)

Laboratory: Department of Mathematics

Duration: 2006 - 2011

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

The main objective of this three-year research program 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 Fret derivative of the elasto-acoustic scattered field with respect to the shape of a given elastic scatterer.

8.4.2. Visits of International Scientists

- Chokri Bekkey spent one week in MAGIQUE-3D in April 2011.
- Yingxiang Xu, Post-doctoral student at Genova University, spent one week in MAGIQUE-3D in May 2011.
- Robert Kotiuga, Professor at Boston University, spent one month as invited Professor in MAGIQUE-3D in September 2011.
- Mounir Tlemcani spent two weeks in MAGIQUE-3Din September 2011 .
- Mohamed Lakhdar Hadji (University of Annaba, Algeria) spent one month in MAGIQUE-3D in December 2011.
- Jewoo Yoo, PhD student at Seoul University (Korea), is visiting us from october 2011 to February 2012.

In the framework of the Aquitaine/Euskadi programm, four scientists from the BCAM visited Magique 3D:

- Alejandro Pozo, PhD student, spent two weeksin MAGIQUE-3Din october 2011.
- Cristi Cazacu, PhD student, spent two weeks in MAGIQUE-3Din october 2011.
- Aurora Marica, Post-Doctoral student, spent one week in MAGIQUE-3Din november 2011.
- Javier Escartin, PhD student, spent two weeks in MAGIQUE-3Din december 2011 .

8.4.3. Participation In International Programs

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 . At the end of 2011, four PhD students have defended their PhD dealing with contributions to new numerical imaging methods that are based on the solution of the full wave equation. Two were working in Magique-3D and in November 2011, a Ph.D. student has been hired in Magique-3D. Moreover, four internships have been realized in Magique3D. Always in the framework of DIP, Magique-3D has started 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). At that moment, Jewoo Yoo, who is a first year PhD student advised by Prof.Changsoo Shin, is visiting Magique-3D during four months.
To our knowledge, this network is the first in the French research community to establish links between industrial and academic researchers in the context of a long-term research program managed by an INRIA team.

9. Dissemination

9.1. Animation of the scientific community

Hélène Barucq is vice-chair of the Inria evaluation committee.

Hélène Barucq and Julien Diaz were editors of the special issue for Waves 2009 in Communications in Computational Physics.

Hélène Barucq and Julien Diaz were members of the scientific committee of Waves 2011 (Vancouver, Canada).

Julien Diaz is elected member of the Inria evaluation committee.

Sébastien Tordeux is elected member of the 26th section of the CNU.

9.2. Teaching

Julien Diaz

Master : Introduction aux phénomènes de propagation d’ondes, 20 h, M2, Université de Pau, France

Victor Péron:

Licence :

Analyse 1, 39h, L1, Université de Pau et des Pays de l'Adour (UPPA), France;

Géométrie et calcul intégral, 48h , L2, UPPA, France;

Introduction à la variable complexe, 19h , L3, UPPA, France.

Master:

Analyse Numérique Fondamentale, 39h, M1, UPPA, France

Analyse Avancée Master Enseignement, 45h, M1, UPPA, France

Sébastien Tordeux

Master : Analyse numérique fondamental, 24h, M1, Université de Pau, France

Master : Introduction aux phénomènes de propagation d'ondes, 20h, M2, Université de Pau, France

PhD : Cyril Agut, Schémas numériques d'ordre élevé en espace et en temps pour l'équation des ondes, Université de Pau et des Pays de l'Adour, December 13th 2011, Hélène Barucq and Julien Diaz

PhD : Véronique Duprat, Conditions aux limites absorbantes enrichies pour l'équation des ondes acoustiques et l'équation d'Helmholtz, Université de Pau et des Pays de l'Adour, December 6th 2011, Hélène Barucq and Julien Diaz

PhD : Jonathan Gallon, Propagation automatique de Surface nD - Filtrage et traitement de la sismique avant stack , Université de Pau et des Pays de l'Adour, April 26th 2011, Hélène Barucq and Bruno Jobard

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

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

9.3. Participation in Conferences, Workshops and Seminar

Cyril Agut

- C. Agut, J.Diaz *Stability analysis of the interior penalty discontinuous Galerkin method for the wave equation*, 10th International conference on mathematical and numerical aspects of waves, WAVES 2011, Jul. 27, 2011, Vancouver, Canada, http://www.sfu.ca/WAVES/

Caroline Baldassari

- C. Baldassari, H. Barucq, H. Calandra, J. Diaz and F. Ventimiglia *Hybrid local-time stepping strategy for the Reverse Time Migration*, 10th International Conference on Mathematical and Numerical Aspects of Waves, WAVES 2011, July 25-29, 2011, Vancouver, Canada, http://www.sfu.ca/WAVES/).

Hélène Barucq

- H. Barucq, J. Diaz and V. Duprat *Enriched Absorbing Boundary Conditions for Acoustic Waves*, Eighth Annual Conference on Frontiers in Applied and Computational Mathematics, FACM 2011, Jun. 9, 2011, Newark, USA, http://m.njit.edu/Events/FACM11/.
- H. Barucq, *Analyse mathématique de conditions aux limites absorbantes enrichies pour l'équation des ondes acoustiques*, Université de Genève, 9 mars 2011.
- H. Barucq, *Nouvelles conditions aux limites absorbantes pour des équations d'ondes*, Université Bordeaux I, 23 juin 2011.

Véronique Duprat

- H. Barucq, J. Diaz and V. Duprat *Complete factorization of the wave equation for the construction of absorbing boundary conditions involving a fractional derivative*, Tenth International Conference on Mathematical and Numerical Aspects of Waves, WAVES 2011, July 25-29, 2011, Vancouver, Canada, http://www.sfu.ca/WAVES/.

Julien Diaz

- C. Baldassari, H. Barucq, and J. Diaz *Explicit hp-Adaptive Time Scheme for the Wave Equation*, 20th International Conference on Domain Decomposition Methods, DD20, Feb. 7-11, 2011, San Diego, USA, http://ccom.ucsd.edu/~dd20/.
- C. Agut and J. Diaz *Stability Analysis of an Interior Penalty Discontinuous Galerkin discretization of the wave equation*, Seminar of the Basque Center for Applied Mathematics (BCAM), May 4, 2011, Bilbao, Spain, http://www.bcamath.org/public_activities/ctrl_activities.php.

Élodie Estecahandy

- H. Barucq, R. Djellouli and É. Estecahandy *Analysis of the Fréchet differentiability with Respect to Lipschitz Domains for an Elasto-Acoustic Scattering Problem*, Eighth Annual Conference on Frontiers in Applied and Computational Mathematics, FACM 2011, Jun. 9-11, 2011, Newark, USA, http://m.njit.edu/Events/FACM11/.
- H. Barucq, R. Djellouli and É. Estecahandy *Characterization of the Fréchet derivative of the elastoacoustic field with respect to Lipschitz domains*, Tenth International Conference on Mathematical and Numerical Aspects of Waves, WAVES 2011, July 25-29, 2011, Vancouver, Canada, http://www.sfu.ca/WAVES/.

Victor Péron

- V. Péron *Electromagnetical Field in Biological Cells*, Séminaire de Mathématiques et de leurs Applications, LMAP, Pau, France, Feb. 2011.
- F. Buret, M. Dauge, P. Dular, L. Krähenbühl, V. Péron, R. Perrussel, C. Poignard, D. Voyer *Eddy currents and corner singularities*, Compumag 2011, Jul. 2011, Sydney, Australia, http://www.compumag2011.com/
- F. Buret, M. Dauge, P. Dular, L. Krähenbühl, V. Péron, R. Perrussel, C. Poignard, D. Voyer *2D electrostatic problems with rounded corners*, COMPUMAG 2011, Jul. 2011, Sydney, Australia, http://www.compumag2011.com/
- M. Duruflé, V. Péron, C. Poignard *Thin Layer Models for Electromagnetism*, WAVES 2011, Jul. 2011, Vancouver, Canada, http://www.sfu.ca/WAVES/
- M. Dauge, P. Dular, L. Krähenbühl, V. Péron, R. Perrussel, C. Poignard *Impedance condition close to a corner in eddy-current problems*, ACOMEN 2011, Nov. 2011, Liège, Belgium, http://www.compumag2011.com/

Sébastien Tordeux

- S. Tordeux, *Matching of Asymptotic Expansions for eigenvalues problem with two cavities linked by a small hole*, GDR Chant, Vienne, Autriche, 2011.
- S. Tordeux, *Parois perforées et multiperforées en acoustique*, Polariton 2011, CIRM, Marseilles
- S. Tordeux, *Perforated and multiperforated plates in linear acoustic*, Second International Workshop on Multiphysics, Multiscale and Optimization Problems 2011, University of the Basque Country, Bilbao
- S. Tordeux, *Matching of Asymptotic Expansions for an eigenvalue problem with two cavities linked by a small hole*, Institute of Computational Mathematics and Mathematical Geophysics, Novosibirsk State University, Russie, 2011.
- S. Tordeux, *Matching of Asymptotic Expansions for an eigenvalue problem with two cavities linked by a small hole*, Sobolev Institute of Mathematics, Novosibirsk State University, Russie, 2011.
- S. Tordeux, *Perforated and multiperforated plates in linear acoustic*, BCAM, Bilbao, Espagne, 2011.
- S. Tordeux, *Self-adjoint curl operator*, Anglet, journées Bordeaux-Pau-Toulouse, 2011
- S. Tordeux, *Parois multiperforées en acoustique*, Journée APAM, INSA-Toulouse, 2011
- E. Piot, S. Tordeux, *Modèles de parois perforées et multiperforées en acoustique*, sémianire MODANT, Grenoble, 2011
- S. Tordeux, *Modélisation multi-échelle des antennes microrubans*, Journée Modélisation et Calcul, Université de Reims, 2011

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[11] C. Agut. *Schémas numériques d'ordre élevé en espace et en temps pour l'équation des ondes*, Université de Pau et des Pays de l'Adour, December 2011.

[12] V. Duprat. *Conditions aux limites absorbantes enrichies pour l'équation des ondes acoustiques et l'équation d'Helmholtz*, Université de Pau et des Pays de l'Adour, December 2011.

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