INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team magique-3d

Advanced 3D Numerical Modeling in Geophysics

Bordeaux - Sud-Ouest

Theme : Observation and Modeling for Environmental Sciences

Activity Report

2010

Table of contents

MAGIQUE-3D is an INRIA Project-Team joint with University of Pau and Pays de l'Adour and CNRS (LMA, UMR 5142 and MIGP, UMR 5212)

1. Team

Research Scientists

Hélène Barucq [Team Leader, Senior Researcher, INRIA, HdR]
Julien Diaz [Junior Researcher, INRIA]
Taous-Meriem Laleg-Kirati [Junior Researcher, INRIA]

Faculty Members

Mohamed Amara [Professor, University of Pau and Pays de l'Adour, HdR]
Dimitri Komatitsch [Professor, University of Pau and Pays de l'Adour, HdR]
Victor Peron [Associate Professor, University of Pau and Pays de l'Adour, since September 2010]
Sébastien Tordeux [Associate Professor, University of Pau and Pays de l'Adour && INRIA, since September 2010]

External Collaborators

Henri Calandra [Research Expert Engineer, Total, France]
Sébastien Chevrot [Senior Researcher, CNRS, Observatoire Midi-Pyrénées - Toulouse]
Bertrand Denel [Research Engineer, TOTAL, France]
Rabia Djellouli [Proffessor, California State University at Northridge, USA]
Bruno Jobard [Assistant Professor, University of Pau and Pays de l'Adour, France]
Jesús Labarta [Professor, Barcelona Supercomputing Center, Spain]
Abdelaâziz Ezziani [Assistant Professor, University of Casablanca, Morocco]

Technical Staff

Caroline Baldassari [Associate Engineer, INRIA, since January 2010]
Pieyre Le Loher [Associate Engineer, INRIA, since November 2008, till November 2010]
Emiljana Jorgji [Associate Engineer, INRIA, since October 2010]
Vadim Monteiller [Associate Engineer, INRIA, since November 15, 2010]
Roland Martin [Research Engineer, CNRS, HdR]

PhD Students

Cyril Agut [Conseil Général 64, since October 2008]
Véronique Duprat [University of Pau and Pays de l'Adour, MESR grant, since October 2008]
Elodie Estecahandy [University of Pau and Pays de l'Adour, Conseil Régional d'Aquitaine, since November 2010]
Florent Ventimiglia [INRIA, CORDI/C INRIA - TOTAL, since November 2010]
Jonathan Gallon [TOTAL France, CIFRE, since January 2008]

Post-Doctoral Fellow

Céline Blitz [INRIA, since March 2009]

Visiting Scientists

Mounir Tlemcani [Assistant Professor, University of Oran, Algeria]
Rabia Djellouli [Professor, California State University at Northridge, USA]
Chokri Bekkey [Faculté des Sciences de Monastir & Laboratoire d'Ingénierie Mathématique, Ecole Polytechnique de Tunisie, Assistant Professor (MdC)]

Administrative Assistant

Josy Baron [INRIA]

Others

Jean-Michel Bart [Stagiaire, Elève Ingénieur INSA Toulouse]
Antony Vivier [Stagiaire, Elève Ingénieur EISTI]
Abal-Kassim Cheikh [Stagiaire, Elève Ingénieur EISTI]

Florent Ventimiglia [Stagiaire, University of Pau and Pays de l'Adour]

2. Overall Objectives

2.1. General setting

The MAGIQUE-3D project-team is associated to two laboratories of University of Pau (Department of Applied Mathematics - LMA associated with CNRS, and Department of Modeling and Imaging in Geosciences - MIGP, also 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 softwares 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.

2.2. Highlights

Dimitri Komatitsch was awarded the Bull-Joseph Fourier Prize 2010 for his work on the parallelization of codes to simulate global phenomena, as well as for the impact of his research, which enables the effects of earthquakes and their aftershocks to be predicted more effectively.

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 [91]. 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 [120], [128], [109], [110]) 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 [79],[13] 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 [83] by Liliana Borcea and [84] 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), [80], 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 [90] 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 $p - adaptivity$ [77]. 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 [92], [125], [99] 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 [52]. 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 [97], [98]. 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 [122], 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 [74], [75] 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).

+ **Approximation of one-way equations** Seismic migration techniques used in petroleum field are based on the resolution of the wave equation. We have considered the issue of computing the solution from a one way formulation of the wave equation. The numerical resolution of this problem is difficult and requires the approximation of a Fourier Integral Operator (FIO). Computing FIO is very heavy (long time computation and big storage space). An algorithm based on a Fourier transform representation of FIO was proposed in [124] where the symbol of the FIO was approximated by separation variables functions. Although this approach reduces the computational cost, it does not give good results in heterogenous media. The objective of this study consists in developing a fast and precise algorithm for FIO computation. Many studies have been devoted to a fast computation of FIOs and pseudo-differential operators. For instance, the paper of Lamoureux, Margrave [111] discusses some aspects of the computation of pseudo-differential operators. We can quote also the work of Bao and Symes [78] on the expansion of the principal symbol of the pseudo-differential operators (homogeneous of degree 0 in ξ). Several techniques based on the separation of the operator kernels have been also proposed for instance in [81]. A different approach to compressing operators is the partitioned separated method that consists in isolating off-diagonal squares of the operator kernel, and approximating each of them by low-rank matrix, for example: the partitioned SVD method described in [105] or the H-matrix for Hierarchical matrix [101] techniques. In [94] a method for discrete symbol calculus was introduced. A multiscale tool which is the curvelets [88] has also been proposed to speed up the computation of FIOs. As shown in [86], curvelets provide a parsimonious representation of FIOs which can lead to a fast computation of FIOs. Taking advantage of the parsimonious representation of FIOs in the Curvelets domain, curvelets have been already used in seismic migration for instance for multiple removal [102] and the restoration of migration amplitudes [103]. However and unfortunately, the direct computation of the curvelet representation of FIOs is not evident [93]. In [87], an algorithm based on the restriction of the FIO kernel to subsets of the temporal and frequency domains was proposed. Indeed, unlike the curvelets which work in the phase space (the product of the frequency and spatial spaces), this algorithm decomposes the FIO in the frequency domain. The FIO kernel is decomposed into two terms: a diffeomorphism which can be computed with a nonuniform Fast Fourier Transform FFT and a residual factor computed with a numerical separation of the spatial and frequency variables. The computational cost and the storage space in this case are considerably reduced.

+ **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 [24] 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 [123]. 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 [89].

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 $\times$ 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 [89] for a calculation performed in parallel on 150,000 processor cores, reaching a sustained performance level of 0.16 petaflops.

5.2. IPDGFEM

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 IPDGFEM 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 IPDGFEM 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 IPDGFEM 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 IPDGFEM allows for the use of meshes based on tetraedrons, which a 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 IPDGFEM to the ADER schemes.

5.3. Gar6more2D and Gar6more3D

The software GAR6MORE2D and GAR6MORE3D compute the analytical solutions to problems of wave propagation in infinite bilayered media respectively in two and in three dimensions. The medium can be composed of a) two acoustic layers; b) two poroelastic layers; c) two elastodynamic layers ; d) one acoustic and one poroelastic layers; or e) one acoustic and one elastic layers. The codes can also consider the case of homogeneous medium, either infinite or semi-infinite with Neumann or Dirichlet boundary conditions. They are written in FORTRAN90 and are based on the Cagniard-de Hoop method [85], [129], [95], [96], [14], [15].

The main objective of these codes is to provide reference solutions in order to validate numerical codes. They have been already used by J. Tromp and C. Morency to validate their code of poroelastic wave propagation [119]. 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.

6. New Results

6.1. Inverse Problems

6.1.1. Inverse acoustic problems

Participants: Chokri Bekkey, Hélène Barucq, Rabia Djellouli.

We have proposed a solution methodology to extend the range of FFP data when measured in a limited aperture and not on the entire sphere $S1$. Therefore it would be possible to solve numerically the IOP when only limited aperture measurements are available. However, due to the analyticity nature of the FFP, the reconstruction or the extension of the far-field pattern from limited measurements is an inverse problem that is *severely ill-posed* and therefore very challenging from a numerical viewpoint. Indeed, preliminary numerical results indicate that the reconstruction of the FFP using the discrete $L2$ minimization with the standard Tikhonov regularization is very sensitive to the noise level in the data. The procedure is successful only when the range of measurements is very large which is not realistic for most applications.
We propose a multi-step procedure for extending/reconstructing the FFP from the knowledge of limited measurements. The proposed solution methodology addresses the ill-posedness nature of this inverse problem using a *total variation* of the FFP coefficients as a penalty term. Consequently the new cost function is no longer differentiable. We restore the differentiability to the cost function using a perturbation technique [121] which allows us to apply the Newton algorithm for computing the minimum. The multi-step feature of the proposed method consists in extending the FFP at each step by an n degrees increment.
We investigate the effect of the frequency regime and the noise level of the performance of the proposed solution methodology. Preliminary results obtained in the case of two-dimensional sound-soft disk-shaped scatterer have been performed. They illustrate the potential of the solution methodology for enriching the FFP measurements for various frequencies and levels of noise. The solution methodology and the numerical results have been presented in a Research Report [79] and a paper has been submitted in November.

6.2. Modeling

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

Participants: Cyril Agut, Hélène Barucq, Julien Diaz.

The new method involving p-harmonic operator described in section 3.2 has been detailed in a reseach report [52] and in a submitted paper. We have proved the convergence of the scheme and its stability under a CFL condition. Numerical results in 1D and 2D show that this CFL condition is slightly greater than the CFL condition of the second-order Leap-Frog scheme. We are now considering 3D experiments to confirm this observation. We are also carrying out a theoretical analysis in order to obtain an explicit expression of the CFL condition. Our results have been presented at the peer-reviewed WONAPDE (Concepcion, January 2010) and Congrès Français d'Acoustique (Lyon, April 2010) conferences [34], [36] and a poster has been presented at the National Congress in Numerical Analysis (CANUM, Carcans-Maubuisson, 2010) [46].

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

Participants: Cyril Agut, Julien Diaz.

The Interior Penalty Discontinuous Galerkin Method [76], [73], [100] 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 the object of a research report [53]. The numerical study of the penalization parameter and of the CFL condition on triangular meshes has been the object of the internship of Jean-Michel Bart.

6.2.3. An unsplit convolutional Perfectly Matched Layer improved at grazing incidence for the seismic wave equation

Participants: Dimitri Komatitsch, Roland Martin.

The Perfectly Matched Layer (PML) absorbing technique has become popular in numerical modeling in elastic or poroelastic media because of its efficiency to absorb waves at non-grazing incidence. However, after numerical discretization, at grazing incidence large spurious oscillations are sent back from the PML into the main domain. The PML then becomes less efficient in the case of sources located close to an edge of the truncated physical domain under study, in the case of thin slices or for receivers located at large offset. In [107] we developed a PML improved at grazing incidence for the elastic wave equation based on an unsplit convolutional formulation for the seismic wave equation written as a first-order system in velocity and stress. This so-called Convolution-PML (CPML) has a cost that is similar in terms of memory storage to that of the classical PML. In [116] we introduced a similar technique for the two-dimensional Biot poroelastic equations and show its efficiency for both non dissipative and dissipative Biot porous models based on a fourth-order staggered finite-difference method used in a thin mesh slice. The results obtained are significantly improved compared to the classical PML. In [118] we applied our unsplit CPML to viscoelastic media, and in [117] we developed a variational formulation of the CPML. More recently, in [25] we developed a version called Auxiliary Differential Equation PML (ADE-PML) that is very well suited to higher-order time schemes. In [24] such a condition is studied for Navier-Stokes. In [71] we develop a stable variational formulation of these improved PMLs for fluid/solid models and for sensitivity kernel calculations. This will be compared to other techniques like the Indirect Boundary Element Method (IBEM) developped by [28] in 2011 to understand which are the fundamental modes excited in complex fluid-solid interface models. Furthermore CPML will be applied to model fluid-solid media in which fractures and salt domes are present and automatically retrieved by Hough Transform [27]. Finally, in [19] we developed an efficient absorbing boundary formulation for the stratified, linearized, ideal MHD equations based on an unsplit, convolutional perfectly matched layer and applied it to numerical models of the Sun.

6.2.4. Approximation of one-way equations

Participants: Hélène Barucq, Julien Diaz, Taous-Meriem Laleg-Kirati.

We have investigated different approaches but unfortunately we have not obtained satisfactory results for different reasons. We have first considered the curvelets but we have not tried to implement the method for the computation of FIOs because of the lack in time and -to the best of our knowledge- the non availability of numerical studies on the subject since 2004 when the theoretical results have been published. Then we have studied the decomposition of FIOs in the frequency domain [93]. The numerical results obtained in [93] and the first numerical tests that have been done are promising. However, due to the randomized character of the separation algorithm a direct inclusion of the algorithm in the GSP code should not be evident for the moment. Finally, we have considered the computation of the reflection coefficient using the inversion of an Helmholtz operator. This approach is still under consideration. This method should improve the computation of the reflection coefficient but we must apply a robust numerical method for weak elliptic problems. The ideas carried out in 6.2.8 should be considered.

6.2.5. Higher Order Absorbing Boundary Conditions for the Wave Equation

Participants: Hélène Barucq, Julien Diaz, Véronique Duprat.

We have constructed a new absorbing boundary condition taking into account propagating, evanescent and grazing waves for arbitrarily-shaped convex surfaces. The condition taking into account propagating and evanescent waves has been detailed in a submitted paper, while the complete condition, which involved a fractional derivative, has been presented at the peer-reviewed conferences WONAPDE (Concepcion, January 2010), Congrès Français d'Acoustique (Lyon, April 2010) and SIAM Annual Meeting (Pittsburgh, July 2010) [40], [42], [39] and at the National Congress in Numerical Analysis (CANUM, Carcans-Maubuisson, June 2010) [49]. The extension of this condition to Helmholtz equation and its performance analysis has been the object of the internship of Anthony Vivier.

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.

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 has been presented in a submitted paper and at the peer-reviewed conferences WONAPDE (Concepcion, January 2010) [37] and CANUM (Carcans-Maubuisson, Juin 2010) [31]. The local-time stepping method we have developed to optimize our code is the object of a submitted paper and has been presented at the ISFMA Symposium (Shanghaï, 2010) [38].

6.2.7. Perfectly Matched Layers for the Shallow Water equations

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

We have proposed a new Perfectly Matched Layer for Shallow Water equations, based on a transformation proposed by Hu [104]. The details of its construction, as well as numerical results illustrating its performances, are presented in [12]

6.2.8. Analytical computation of the Green's function of bilayered porous media

Participant: Julien Diaz.

The computation of analytical solution of wave propagation problems in acoustic/poroelastic media has been detailed in [14], [15]. These computations were implemented in Gar6more2D (for the 2D problem) and Gar6more3D (for the 3D problem).

6.3. High Performance methods for solving wave equations

6.3.1. Simulation of seismic wave propagation in an asteroid based upon a non-blocking MPI spectral-element method

Participants: Dimitri Komatitsch, Roland Martin, Céline Blitz.

In order to better understand the internal structure of asteroids orbiting in the Solar system, and then the response of such objects to impacts, seismic wave propagation in asteroid 433-Eros is performed numerically based on a spectral-element method at seismic frequencies from 0 Hz to 5 Hz. In the year 2000, the NEAR Shoemaker mission to Eros has provided images of the asteroid surface, which contains numerous fractures that likely extend to its interior. Our goal is to be able to propagate seismic waves resulting from an impact in such models. For that purpose we create and mesh both homogeneous and fractured models with a highly-dispersive regolith layer at the surface using the CUBIT mesh generator developed at Sandia National Laboratories (USA). The unstructured meshes are partitioned using the METIS software package in order to minimize edge-cuts and therefore optimize load balancing in our parallel non-blocking MPI implementation. In [115] and [82] we performed actual simulations and show that we can obtain good performance levels and good scaling when we implement overlapping of communications with calculations. Calculations were run at CINES in Montpellier, France.

6.3.2. Geological horizon propagation into large seismic volumes

Participants: Jonathan Gallon, Bruno Jobard, Hélène Barucq.

In the petroleum industry, seismic data is the starting point of many processes for the exploration for oil reservoirs. The dimensions of these *seismic cubes* keep increasing as the regions undergoing exploration keep growing and have increased spatial resolution. We have developed a new bricked cache system suitable [32] for propagating seismic horizons in such large volumes. To ensure the optimality of such surface extraction, the propagation algorithm must access randomly into the data volume. This lack of data locality imposes that the volume resides entirely in the main memory to reach decent performances. In case of volumes larger than the memory, we showed that using a classical brick cache strategy can also produce good performances until a certain size. As the size of these volumes increases very quickly, and can now reach more than 200GB, we demonstrated that the performances of the classical algorithm are dramatically reduced when processed on standard workstation with a limited size of memory (currently 8GB to 16GB). In order to handle such large volumes, we introduced a new slimming brick cache strategy where bricks size evolves according to processed data : at each step of the algorithm, processed data could be removed from the cache. This new brick format allows to have a larger number of brick loaded in memory. We further improved the releasing mechanism by filling in priority the holes that appear in the surface during the propagation process. With this new cache strategy, horizons can be extracted into volumes that are up to 75 times the size of the available cache memory.

6.3.3. High Performance Computing for the seismic wave equation at very high resolution

Participants: Dimitri Komatitsch, Roland Martin, Pieyre Le Loher.

With the very rapid evolution of personal computers, computer clusters, and supercomputers, nowadays the seismic wave equation can be solved with very good accuracy using very precise techniques implemented based on parallel computing in the context of so-called High-Performance Computing (HPC). This has been a central part of our research activity in the last few years and increasingly more in 2008 and 2009. In particular with some colleagues from the CINES supercomputing center in Montpellier (France) we have performed some very large scale calculations that are currently being published.

Using the high-order finite-element method implemented in our SPECFEM3D software package [126], we for instance studied the influence of topography modeled at very high resolution on seismic wave propagation in the region of Taipei in Taiwan [113] [112], [114].

We also applied the technique to model seismic wave propagation at very high frequency in the whole Earth [106], [127]. In November 2008 our SPECFEM3D software package was again among the six finalists of the pretigious Gordon Bell Prize of the SuperComputing'2008 conference in the USA [89] for a calculation performed in parallel on 150,000 processor cores, reaching a sustained performance level of 0.16 petaflops. And in June 2010 Dimitri Komatitsch won the first BULL Joseph Fourier Prize with it.

In the context of a collaboration with Gordon Erlebacher from Florida State University (USA) who visited us for a month in May-June 2010 and we ported our modeling algorithm to a NVIDIA graphics video card (Graphical Processing Units – GPU) using the CUDA language on top of a C implementation of our code. This technique is known as General-purpose Processing on Graphical Processing Units (GPGPU) and had never been used before for a high-order finite-element technique, which induces significant technical problems in particular regarding memory accesses. regarding memory accesses. In several recent articles [108][21], [20], [68] we used it to improve the speed of our code by a factor of 20 to 30 on large GPU clusters. In [26] we accelerated a 3D finite-difference wave propagation code by a factor between 20x and 60x using GPU graphics cards. In [22] we solved a very large problem on 6144 processor cores to study the splitting of shear waves at the bottom of the Earth's mantle. In [29] we used large scale 3D simulations to study the effects of 3D models of viscoelasticity in the full Earth, and in [30] we showed how such simulations can be performed in quasi-real time after a real earthquake and stored online in a catalog of seismograms for all large earthquakes worldwide.

Finally, in [17] we used a finite-element code to model the non linear behavior associated with large earthquakes, focusing on the study of parallel performance but also on a case study for the region of the city of Nice (French Riviera, France).

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).

- Propagation automatique de Surface nD Filtrage et traitement de la sismique avant stack Period: 2008 January - 2010 december, Management: INRIA Bordeaux Sud-Ouest, Amount: 45000 euros.

- Analyse méthodologique pour la génération de maillages irréguliers et de leur décomposition en sous-domaines sur calculateurs parallèles pour la propagation d'ondes sismiques en milieu géologiques complexes Period: 2009 May - 2010 April, Management: INRIA Bordeaux Sud-Ouest, Amount: 50000 euros
- Optimisation de codes pour la migration terrestre d'ondes élastiques.

  Period: 2009 January - 2010 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.

7.2. Contract with CSUN

In the context of the Associate Team MAGIC.

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

8. Other Grants and Activities

8.1. Regional Initiatives

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

8.2. European Initiatives

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.

8.3. 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 2009, two PhD students working in Magique-3D from 2007, have defended their PhD dealing with new numerical imaging methods that are based on the solution of the full wave equation. Two Ph.D students advised by J. Roman and S. Petiton respectively started to work in january 2008 on computing aspects for optimizing the computational performances of our numerical methods. They will defend their thesis in march 2011. A Ph.D. student has been hired in Magique-3D and a Master student will start working with Nachos in April. 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. A workshop has been organized in December, gathering INRIA teams, engineers from TOTAL and academic researchers (see http://uppa-inria.univ-pau.fr/m3d/Workshop_DIP).

8.4. ANR Project 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. A first meeting took place to Pau in october 2007 and a second one to Orléans in september 2008. 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 apporach. We have worked on the approximation of seismic propagators involving Fourier integral operators by considering different approaches. In November 2010, we have hired an associate engineer who will work with us on the development of a software for the gravimetric inversion.

8.5. International collaborations

8.5.1. Visits

- Dimitri Komatitsch, Pieyre Le Loher and Roland Martin spent two weeks at the Barcelona Supercomputing Center of the "Universitat Politecnica de Catalunya" in June 2010;
- Abal-Kassim Cheikh spent two weeks at Florida State University in July 2010.
- Mounir Tlemcani spent two weeks in July 2010 in MAGIQUE-3D.
- Chokri Bekkey spent two weeks in MAGIQUE-3D in April 2010.
- Rabia Djellouli spent one month in MAGIQUE-3D in May 2010.
- Julien Diaz spent two weeks at CSUN in November 2010.
- Emiljana Gorgji spent one week at the Barcelona Supercomputing Center of the "Universitat Politecnica de Catalunya" in November 2010.
- Gordon Erlebacher spent two weeks in MAGIQUE-3Din May 2010.
- Roland Martin spent one month at "Laboratorio de Flujos Complejos, Instituto de Ingenieria en Ciencias de Materiales, Universidad Nacional Autonoma de Mexico" in July 2010
- Roland Martin spent one month at 'Laboratorio de Paleomagnetismo, Instituto de Geofisica (UNAM)" in Mexico in August 2010.

8.5.2. Associate team MAGIC

Since january 2006, the team is associated to a team located at CSUN (California State University at Northridge) which is managed by R. Djellouli. Our common programm research takes part of the activities we develop in modeling essentially (see http://uppa-inria.univ-pau.fr/m3d/Equipe-associee/index.html).

8.5.3. New collaborations

Collaboration with BCAM (Basque Center of Applied Mathematics) in the framework of the Aquitaine Euskadi Call

9. Dissemination

9.1. Scientific animation

- In collaboration with the INRIA multimedia department, we realized a movie describing an example of the applications considered in the team. This movie, entitled "Sonder l'invisible: du seisme au modèle", focuses on the numerical simulation of earthquakes and is designed for the general public. It was played for the first time at "Fête de la Science" event which was held on October 20th, 2010 at Pau university. About thirty persons attended the event, a large part of them were students. Three conferences were also given during the event by Julien Diaz, Céline Blitz and Meriem Laleg about respectively: "seismic imaging", "simulation of wave propagation in the Asteroid Eros" and "modelling and analysis of the blood pressure for clinical diagnosis".
- Following our collaboration with the BCAM (Basque Center for Applied Mathematics), Hélène Barucq was one of the main organizers of the Workshop INRIA-BCAM, gathering researchers from BCAM and INRIA Bordeaux Sud-Ouest Research Center.
- Hélène Barucq coorganized a session at CFA 2010 (Congrès Français d'Acoustique, April 12-16 2010, Lyon, France) with Salah Naili (Professeur, Laboratoire de Mécanique Physique, Paris 12).

9.2. Teaching

9.2.1. Lecture

- Lecture/course to Master students (64 hours) at University of Pau, France, on "Calcul Parallèle et Modélisation en Géophysique" ("Parallel computing and geophysical modeling")
- Lecture/course to Master students (46 hours) at University of Pau, France, on "Propagation d'ondes et imagerie" ("Waves propagation and Imaging")
- Lecture/course (36 hours) to fourth-year engineering students at EISTI (Ecole Internationale des Sciences du Traitement de l'Information)
- Lecture/course (24 hours) to fourth-year engineering students at ESTIA (Ecole Supérieure des Technologies Industrielles Avancées).

9.3. Participation in Conferences, Workshops and Seminar

Cyril Agut

- C. Agut, J. Diaz and A. Ezziani *A new modified equation approach for high-order space and time discretizations of the wave equation*, Third Chilean Workshop on Numerical Analysis of Partial Differential Equations, WONAPDE 2010, 11th 15th January 2010, Concepcion (Chile), http://www.ing-mat.udec.cl/wonapde2010/.
- C. Agut and J. Diaz *High-order discretizations for the wave equation based on the modified equation technique*, 10ème Congrès Français d'Acoustique, CFA 2010, 12th 16th April 2010, Lyon (France), http://cfa.sfa.asso.fr/index.html.
- C. Agut, J. Diaz and A. Ezziani *Une nouvelle approche de type équation modifiée pour des discrétisations d'ordre élevé en espace et en temps de l'équation des ondes*, 40ème Congrès National d'Analyse Numérique, CANUM 2010, 31st May 4th June 2010, Carcans-Maubuisson (France), http://smai.emath.fr/canum2010/index.php
- C. Agut, J. Diaz and A. Ezziani *High-order discretizations for the wave equation based on the modified equation technique*, XIV Spanish-French Jacques-Louis Lions School, 6th 10th September 2010, A Coruna (Spain), http://dm.udc.es/ehf2010/

Hélène Barucq

- H. Barucq, C. Bekkey and R. Djellouli, *An efficient multi-step procedure for enriching limited two-dimensional far-field pattern measurements*, V International Conference on Inverse Problems, Control and Shape Optimization, PICOF 2010, Cartagena (Spain), April 7-9 2010 (http://picof.upct.es/).
- H. Barucq, J. Diaz and V. Duprat *Conditions aux limites artificielles enrichies pour l'équation des ondes acoustiques*, Séminaire du Laboratoire Jacques-Louis Lions, Paris, France, Apr. 9, 2010.
- H. Barucq, *Conditions aux limites modélisant la propagation d ondes acoustiques et électromagnétiques au voisinage de surfaces régulières arbitraires: construction et analyse mathématique*. Séminaire de l'EPI NACHOS, Sophia Antipolis, France, Aug. 27, 2010.
- H. Barucq, C. Bekkey and R. Djellouli, *An efficient multi-step procedure for enriching limited two-dimensional far-field pattern measurements*, IV European Conference on Computational Mechanics, ECCM 2010, Paris (France), May 16-21 2010 (http://www.eccm2010.org/).

Julien Diaz

- C. Baldassari, H. Barucq and J. Diaz *An hp-adaptive energy conserving time scheme for the wave equation*, Third Chilean Workshop on Numerical Analysis of Partial Differential Equations, WONAPDE 2010, Jan. 11, 2010, Concepcion, Chile, http://www.ing-mat.udec.cl/wonapde2010/).
- H. Barucq, J. Diaz and V. Duprat *Absorbing Boundary Condition Taking into Account the Grazing Modes*, 2010 SIAM Annual Meeting (AN10), Jul. 12, 2010, Pittsburgh, USA, http://www.siam.org/meetings/an10/
- H. Barucq, C. Baldassari and J. Diaz *High-Order Schemes with Local Time Stepping for Solving the Wave Equation in a Reverse Time Migration Algorithm* , 2010 ISFMA Symposium & Shanghai Summer School on Maxwell' equations: Theoretical and Numerical Issues with Applications, Jul. 25, 2010, Shanghaï, China.
- H. Barucq, C. Baldassari and J. Diaz *Schémas d'ordre élevé à pas de temps local pour la résolution de l'équation des ondes*, Séminaire du Groupe de Modélisation Mathématiques Mécanique et Numérique (GM3N), Caen, France, Oct. 11 2010.

Véronique Duprat

- H. Barucq, J. Diaz and V. Duprat *Enriched absorbing boundary conditions for the acoustic wave equation involving a fractional derivative*, WONAPDE 2010, 11th 15th January 2010, Concepcion (Chile), http://www.ing-mat.udec.cl/wonapde2010/.
- H. Barucq, J. Diaz and V. Duprat *Approximate boundary conditions based on a complete transparent condition for the acoustic wave equation*, CFA 2010, 12th 16th April 2010, Lyon, http://cfa.sfa.asso.fr/heber.html.
- H. Barucq, J. Diaz and V. Duprat *Factorisation complète de l'équation des ondes pour la construction de conditions aux limites absorbantes*, CANUM 2010, 31st May 4th June 2010, Carcans-Maubuisson, http://smai.emath.fr/canum2010/.
- H. Barucq, J. Diaz and V. Duprat *Development and optimization of absorbing boundary conditions for acoustic wave problems in complex media*, XIV Jacques-Louis Lions Spanish-French school on numerical simulation in physics and engineering, 6th 10th September 2010, A Coruna (Spain), http://dm.udc.es/ehf2010/.

Jonathan Gallon

- J. Gallon, S. Guillon, B. Jobard, H Barucq and N. Keskes *Slimming Brick Cache Strategies for Seismic Horizon Propagation Algorithms*, Eurographics/IEEE VGTC on Volume Graphics, 2th - 3th may 2010, Norrköping (Sweden), Dimitri Komatitsch

- F. Magnoni, E. Casarotti, A. Michelini, A. Piersanti, D. Komatitsch and J. Tromp, Spectral-element simulations of seismic waves and coseismic deformations generated by the 2009 L'Aquila earthquake, AGU Fall Meeting, San Francisco, USA, December 13-17, 2010.
- D. Komatitsch, Invited talk, Modélisation de la propagation des ondes sismiques en multi-GPUs, Groupe de travail du GDR Ondes, Lyon, France, November 9, 2010.
- D. Komatitsch, Invited talk, Eléments finis d'ordre élevé sur un réseau de cartes graphiques GPU pour la modélisation numérique des ondes sismiques, Académie des Sciences, Institut de France, Paris, November 2, 2010.
- D. Komatitsch, UNESCO ICTP Center in Trieste (Italy), Invited teaching class, The spectral-element method and three-dimensional seismology for the "Tenth Workshop on three-dimensional modeling of seismic wave generation, propagation and their inversion", September 27 - October 8, 2010.
- D. Komatitsch, Invited talk, A spectral-element seismic wave propagation algorithm on a large cluster of GPUs, University of Munich, Germany, July 2, 2010.
- D. Komatitsch, G. Erlebacher, D. Göddeke and D. Michéa, A spectral-element seismic wave propagation algorithm on a cluster of 192 GPUs, Invited talk, 6th International Workshop on Parallel Matrix Algorithms and Applications (PMAA'10), Basel, Switzerland, June 30 - July 2, 2010.
- D. Komatitsch, Simulation d'un tremblement de terre à l'échelle planétaire, Invited talk, Académie des Sciences, Institut de France, Paris, June 29, 2010.
- D. Komatitsch, D. Michéa, G. Erlebacher and D. Göddeke, Running 3D finite-difference or spectral-element wave propagation codes faster using a GPU cluster, 72nd European Association of Geoscientists & Engineers (EAGE) conference, Barcelona, Spain, June 14-17, 2010.
- D. Komatitsch, G. Erlebacher, D. Göddeke and D. Michéa, Modeling of seismic wave propagation using high-order finite elements with MPI on a cluster of 192 GPUs, Invited talk, 4th European Congress on Computational Mechanics (ECCM/ECCOMAS'2010), Paris, France, May 16-21, 2010.
- D. Komatitsch, D. Michéa, G. Erlebacher and D. Göddeke, Invited talk, Accelerating a 3D finite-difference wave propagation code and a spectral-element code using a cluster of GPU graphics cards, Annual meeting of the European Geophysical Union, Vienna, Austria, May 2-7, 2010.
- D. Komatitsch, Invited talk, Portage d'une application de propagation d'ondes sismiques en multi-GPUs, Aristote/OpenGPU workshop, Ecole Polytechnique, Paris, France, March 25, 2010.
- D. Komatitsch, Invited talk, Le calcul parallèle haute performance sur des clusters de cartes graphiques (NVIDIA GPUs) et certaines applications en sismique, sismologie et industrie pétrolière, Groupe Thématique Mathématiques Appliquées, Informatique, Réseaux, Calcul, Industrie de la Société de Mathématiques Appliquées et Industrielles (SMAI), France Télécom Orange Labs, Paris, France, March 19, 2010.

Taous-Meriem LALEG-KIRATI

- T.M. Laleg-Kirati, C. Médigue, B. Helffer, E. Crépeau and M. Sorine *Nouvelle technique d'analyse de la forme des signaux de pression artérielle basée sur une approche semi-classique*, Une demi-journée sur le cœur-Séminaire au laboratoire de mathématiques appliquées de l'université de Versailles Saint Quentin en Yvelines, 31 mars 2010.
- H. Barucq, J. Diaz and T.M. Laleg-Kirati, *Approximation des opérateurs one-way*, Réunion projet ANR Analyse Harmonique et Problèmes Inverses (AHPI), Université de Bordeaux, 19 janvier 2010
- T.M. Laleg-Kirati, E. Crépeau and M. Sorine *Analyse des signaux par quantication semi-classique. Application à l'analyse des signaux de pression artérielle*, Séminaire de l'Institut de Mathématiques de Bordeaux, Université de Bordeaux, 04 janvier 2010.

Pieyre Le Loher

- D. Komatitsch, P. Le Loher, D. Michéa, G. Erlebacher, D. Göddeke *Modeling of seismic wave propagation using high-order finite elements with MPI on a cluster of 192 GPUs*,ECCM European Conference on Computational Mechanics 2010, Paris, 17 mai 2010.
- D. Komatitsch, P. Le Loher, D. Michéa, G. Erlebacher, D. Göddeke *Running 3D Finite-difference or Spectral-element Wave Propagation Codes Faster Using a GPU Cluster*,EAGE European Association of Geoscientists and Engineers 2010, Barcelone, Espagnes, 16 juin 2010.
- D. Komatitsch, P. Le Loher, D. Michéa, G. Erlebacher, D. Göddeke *Running 3D Finite-difference or Spectral-element Wave Propagation Codes Faster Using a GPU Cluster*, QUEST workshop, Alghero, Italie, 23 septembre 2010.

Roland Martin

- R. Martin, D. Komatitsch, S. D. Gedney and E. Bruthiaux, *Convolution and non convolution Perfectly Matched Layer techniques optimized at grazing incidence*, 72nd European Association of Geoscientists & Engineers (EAGE) conference, Barcelona, Spain, June 14-17, 2010.
- R. Martin, D. Komatitsch, S. D. Gedney and E. Bruthiaux, *Convolution and non convolution Perfectly Matched Layer techniques optimized at grazing incidence for anisotropic, poroelastic or viscoelastic high-order wave propagation modelling*, 4th European Congress on Computational Mechanics (ECCM/ECCOMAS'2010), Paris, France, May 16-21, 2010.
- R. Martin, D. Komatitsch, E. Bruthiaux and S.D. Gedney. *Convolution and non convolution Perfectly Matched Layer techniques optimized at grazing incidence for high-order wave propagation modelling*. Vol. 12, EGU General Assembly 2010, Vienna, Austria.
- R. Martin, *Portage d'un code de volumes finis pour la gravimétrie sur GPU* , Aristote/OpenGPU workshop, École Polytechnique, Paris, France, March 25, 2010.

Victor Peron

- V. Péron *On the Influence of the Geometry on Skin Effect in Electromagnetism*, Rencontres de Mathématiques UPPA-UPV, Sep. 30 Oct. 1, 2010, Anglet (France).

10. Bibliography

Major publications by the team in recent years

[1] M. AMARA, R. DJELLOULI, C. FARHAT. *Convergence analysis of a discontinuous Galerkin method with plane waves and Lagrange multipliers for the solution of Helmholtz problems*, in "SIAM Journal on Numerical Analysis", 2009, vol. 47, p. 1038–1066.

[2] H. BARUCQ, J. DIAZ, M. TLEMCANI. *New absorbing layers conditions for short water waves*, in "Journal of Computational Physics", 2010, vol. 229, p. 58–72 [*DOI :* 10.1016/J.JCP.2009.08.033], http://hal.inria.fr/inria-00418317/en.

[3] H. BARUCQ, R. DJELLOULI, C. BEKKEY. *A multi-step procedure for enriching limited two-dimensional acoustic far-field pattern measurements*, in "Journal of Inverse and Ill-Posed Problems", 2010, vol. 18, p. 189-216, http://hal.inria.fr/inria-00527273/en.

[4] H. BARUCQ, R. DJELLOULI, A.-G. SAINT-GUIRONS. *Performance assessment of a new class of local absorbing boundary conditions for elliptical- and prolate spheroidal-shaped boundaries*, in "Applied Numerical Mathematics", 2008, http://hal.inria.fr/inria-00338494/en/.

[5] J. DIAZ, M. J. GROTE. *Energy Conserving Explicit Local Time-Stepping for Second-Order Wave Equations*, in "SIAM Journal on Scientific Computing", 2009, vol. 31, n^o 3, p. 1985-2014, http://hal.inria.fr/inria-00409233/en/.

[6] D. KOMATITSCH, G. ERLEBACHER, D. GÖDDEKE, D. MICHÉA. *High-order finite-element seismic wave propagation modeling with MPI on a large GPU cluster*, in "Journal of Computational Physics", 2010, vol. 229, n^o 20, p. 7692-7714 [*DOI :* 10.1016/J.JCP.2010.06.024], http://hal.inria.fr/inria-00528481/en.

[7] T.-M. LALEG-KIRATI, C. MÉDIGUE, Y. PAPELIER, F. COTTIN, A. VAN DE LOUW. *Validation of a semi-classical Signal analysis method for Stroke volume variation assessment: a comparison with the PiCCO technique*, in "Annals of biomedical engineering.", 2010 [*DOI :* 10.1007/S10439-010-0118-Z], http://hal.inria.fr/inria-00527442/en.

[8] R. MADEC, D. KOMATITSCH, J. DIAZ. *Energy-conserving local time stepping based on high-order finite elements for seismic wave propagation across a fluid-solid interface*, in "Computer Modeling in Engineering and Sciences", 2009, vol. 49, n^o 2, p. 163-189, http://hal.inria.fr/inria-00436429/en/.

[9] R. MARTIN, D. KOMATITSCH, A. EZZIANI. *An unsplit convolutional Perfectly Matched Layer improved at grazing incidence for the seismic wave equation in poroelastic media*, in "Geophysics", 2008, vol. 73, n^o 5, p. T51-T61, http://dx.doi.org/10.1190/1.2939484.

[10] R. MARTIN, D. KOMATITSCH. *An unsplit convolutional perfectly matched layer technique improved at grazing incidence for the viscoelastic wave equation*, in "Geophysical Journal International", 2009, vol. 179, n^o 1, p. 333-344, http://hal.inria.fr/inria-00528453.

Publications of the year

Articles in International Peer-Reviewed Journal

[11] H. BARUCQ, C. BEKKEY, R. DJELLOULI. *"Full aperture reconstruction of the acoustic Far-Field Pattern from few measurements"*, in "Communication in Computational Physics", 2010, http://hal.inria.fr/inria-00527346/en.

[12] H. BARUCQ, J. DIAZ, M. TLEMCANI. *New absorbing layers conditions for short water waves*, in "Journal of Computational Physics", 2010, vol. 229, p. 58–72 [*DOI :* 10.1016/J.JCP.2009.08.033], http://hal.inria.fr/inria-00418317/en.

[13] H. BARUCQ, R. DJELLOULI, C. BEKKEY. *A multi-step procedure for enriching limited two-dimensional acoustic far-field pattern measurements*, in "Journal of Inverse and Ill-Posed Problems", 2010, vol. 18, p. 189-216, http://hal.inria.fr/inria-00527273/en.

[14] J. DIAZ, A. EZZIANI. *Analytical solution for waves propagation in heterogeneous acoustic/porous media. Part I: the 2D case*, in "Communications in Computational Physics", 2010, vol. 7, n^o 1, p. 171-194 [*DOI :* 10.4208/CICP.2009.08.148], http://hal.inria.fr/inria-00404224/en.

[15] J. DIAZ, A. EZZIANI. *Analytical solution for waves propagation in heterogeneous acoustic/porous media. Part II: the 3D case*, in "Communications in Computational Physics", 2010, vol. 7, n^o 3, p. 445-472 [*DOI :* 10.4208/CICP.2009.08.149], http://hal.inria.fr/inria-00404228/en.

[16] F. DUPROS, F. DE MARTIN, E. FOERSTER, D. KOMATITSCH, J. ROMAN. *High-performance finite-element simulations of seismic wave propagation in three-dimensional non linear inelastic geological media*, in "Parallel Computing", January 2010, vol. 36, p. 308-325 [*DOI :* 10.1016/J.PARCO.2009.12.011], http://hal.archives-ouvertes.fr/hal-00537930/.

[17] F. DUPROS, F. DE MARTIN, E. FOERSTER, D. KOMATITSCH, J. ROMAN. *High-performance finite-element simulations of seismic wave propagation in three-dimensional non linear inelastic geological media*, in "Parallel Computing", 2010, vol. 36, n^o^ 5-6, p. 308-325 [*DOI :* 10.1016/J.PARCO.2009.12.011], http://hal.inria.fr/inria-00528479/en.

[18] G. DUPUY, B. JOBARD, S. GUILLON, N. KESKES, D. KOMATITSCH. *Parallel extraction and simplification of large isosurfaces using an extended tandem algorithm*, in "Computer-Aided Design / Computer Aided Design", 2010, vol. 42, n^o^ 2, p. 129-138 [*DOI :* 10.1016/J.CAD.2009.04.016], http://hal.inria.fr/inria-00436423/en.

[19] S. M. HANASOGE, D. KOMATITSCH, L. GIZON. *An absorbing boundary formulation for the stratified, linearized, ideal MHD equations based on an unsplit, convolutional perfectly matched layer*, in "Astronomy and Astrophysics", 2010, vol. 522, n^o^ A87, p. 1-8 [*DOI :* 10.1051/0004-6361/201014345], http://hal.inria.fr/inria-00528495/en.

[20] D. KOMATITSCH, G. ERLEBACHER, D. GÖDDEKE, D. MICHÉA. *High-order finite-element seismic wave propagation modeling with MPI on a large GPU cluster*, in "Journal of Computational Physics", 2010, vol. 229, n^o^ 20, p. 7692-7714 [*DOI :* 10.1016/J.JCP.2010.06.024], http://hal.inria.fr/inria-00528481/en.

[21] D. KOMATITSCH, D. GÖDDEKE, G. ERLEBACHER, D. MICHÉA. *Modeling the propagation of elastic waves using spectral elements on a cluster of 192 GPUs*, in "Computer Science Research and Development", 2010, vol. 25, n^o^ 1-2, p. 75-82 [*DOI :* 10.1007/S00450-010-0109-1], http://hal.inria.fr/inria-00528482/en.

[22] D. KOMATITSCH, L. P. VINNIK, S. CHEVROT. *SHdiff/SVdiff splitting in an isotropic Earth*, in "Journal of Geophysical Research", 2010, vol. 115, n^o^ B7, B07312 [*DOI :* 10.1029/2009JB006795], http://hal.inria.fr/inria-00528484/en.

[23] T.-M. LALEG-KIRATI, C. MÉDIGUE, Y. PAPELIER, F. COTTIN, A. VAN DE LOUW. *Validation of a semi-classical Signal analysis method for Stroke volume variation assessment: a comparison with the PiCCO technique*, in "Annals of biomedical engineering.", 2010 [*DOI :* 10.1007/S10439-010-0118-Z], http://hal.inria.fr/inria-00527442/en.

[24] R. MARTIN, C. COUDER-CASTANEDA. *An improved unsplit and convolutional Perfectly Matched Layer (CPML) absorbing technique for the Navier-Stokes equations using cut-off frequency shift*, in "Computer Modelling in Engineering and Sciences", 2010, vol. 63, n^o^ 1, p. 47-78, http://hal.inria.fr/inria-00528457/en.

[25] R. MARTIN, D. KOMATITSCH, S. D. GEDNEY, E. BRUTHIAUX. *A high-order time and space formulation of the unsplit perfectly matched layer for the seismic wave equation using Auxiliary Differential Equations (ADE-PML)*, in "Computer Modelling in Engineering and Sciences - CMES", 2010, vol. 56, n^o^ 1, p. 17-42, http://hal.inria.fr/inria-00528456/en.

[26] D. MICHÉA, D. KOMATITSCH. *Accelerating a 3D finite-difference wave propagation code using GPU graphics cards*, in "Geophys. J. Int.", 2010, vol. 182, n^o^ 1, p. 389-402 [*DOI :* 10.1111/J.1365-246X.2010.04616.X], http://hal.inria.fr/inria-00528487/en.

[27] M.-G. OROZCO-DEL-CASTILLO, C. ORTIZ-ALEMAN, R. MARTIN, R. AVILA-CARRERA, A. RODRIGUEZ-CASTELLANOS. *Seismic data interpretation using the Hough transform and principal component analysis*, in "Journal of Geophysics and Engineering", 2010, http://hal.inria.fr/inria-00545012/en.

[28] A. RODRIGUEZ-CASTELLANOS, E. FLORES, F. SÁNCHEZ-SESMA, C. ORTIZ-ALEMAN, M. NAVA-FLORES, R. MARTIN. *Indirect Boundary Element Method applied to Fluid-Solid Interfaces*, in "Soil Dynamics and Earthquake Engineering", 2010, n^{o} Accepted, http://hal.inria.fr/inria-00544999/en.

[29] B. SAVAGE, D. KOMATITSCH, J. TROMP. *Effects of 3D attenuation on seismic wave amplitude and phase measurements*, in "Bull. Seismol. Soc. Am.", 2010, vol. 100, n^{o} 3, p. 1241-1251 [*DOI :* 10.1785/0120090263], http://hal.inria.fr/inria-00528488/en.

[30] J. TROMP, D. KOMATITSCH, V. HJÖRLEIFSDOTTIR, Q. LIU, H. ZHU, D. PETER, E. BOZDAG, D. MCRITCHIE, P. FRIBERG, C. TRABANT, A. HUTKO. *Near real-time simulations of global CMT earthquakes*, in "Geophys. J. Int.", 2010, vol. 183, n^{o} 1, p. 381-389 [*DOI :* 10.1111/J.1365-246X.2010.04734.X], http://hal.inria.fr/inria-00528489/en.

Invited Conferences

[31] C. BALDASSARI, H. BARUCQ, H. CALANDRA, J. DIAZ. *Méthodes numériques pour l'imagerie sismique*, in "Congrès d'Analyse NUMérique", France Carcans-Maubuisson, June 2010, http://hal.inria.fr/inria-00527419/en.

[32] J. GALLON, S. GUILLON, B. JOBARD, H. BARUCQ, N. KESKES. *Slimming Brick Cache Strategies for Seismic Horizon Propagation Algorithms*, in "Eurographics/IEEE VGTC on Volume Graphics", Sweden Norrköping, R. WESTERMANN, G. KINDLMANN (editors), Eurographics/IEEE VGTC, 2010, p. 37-44 [*DOI :* 10.2312/VG/VG10/037-044], http://hal.inria.fr/inria-00533471/en.

[33] V. PÉRON. *On the Influence of the Geometry on Skin Effect in Electromagnetism*, in "Rencontres de Mathématiques UPPA-UPV", France Anglet, October 2010, http://hal.inria.fr/inria-00528308/en.

International Peer-Reviewed Conference/Proceedings

[34] C. AGUT, J. DIAZ, A. EZZIANI. *A new modified equation approach for high-order space and time discretizations of the wave equation*, in "Third Chilean Workshop on Numerical Analysis of Partial Differential Equations (WONAPDE 2010)", Chile Concepcion, 2010, http://hal.inria.fr/inria-00508590/en.

[35] C. AGUT, J. DIAZ, A. EZZIANI. *A New Modified Equation Approach for solving the Wave Equation*, in "Proceedings of the Tenth International Conference Zaragoza-Pau on Applied Mathematics and Statistics", Spain Jaca, 2010, http://hal.inria.fr/inria-00508629/en.

[36] C. AGUT, J. DIAZ, A. EZZIANI. *High-order discretizations for the wave equation based on the modified equation technique*, in "10ème Congrès Français d'Acoustique", France Lyon, April 2010, http://hal.inria.fr/inria-00527129/en.

[37] C. BALDASSARI, H. BARUCQ, J. DIAZ. *An hp-adaptive energy conserving time scheme for the wave equation.*, in "Third Chilean Workshop on Numerical Analysis of Partial Differential Equations, WONAPDE 2010", Chile Concepcion, 2010, http://hal.inria.fr/inria-00508541/en.

[38] C. BALDASSARI, H. BARUCQ, J. DIAZ. *High-Order Schemes with Local Time Stepping for Solving the Wave Equation in a Reverse Time Migration Algorithm*, in "2010 ISFMA Symposium & Shanghai Summer School on Maxwell' equations: Theoretical and Numerical Issues with Applications", China Shanghaï, 2010, http://hal.inria.fr/inria-00508634/en.

[39] H. BARUCQ, J. DIAZ, V. DUPRAT. *Absorbing Boundary Condition Taking into Account the Grazing Modes*, in "2010 SIAM Annual Meeting (AN10)", United States Pittsburgh, 2010, http://hal.inria.fr/inria-00508632/en.

[40] H. BARUCQ, J. DIAZ, V. DUPRAT. *Enriched absorbing boundary conditions for the acoustic wave equation involving a fractional derivative*, in "Third Chilean Workshop on Numerical Analysis of Partial Differential Equations (WONAPDE 2010)", Chile Concepcion, 2010, http://hal.inria.fr/inria-00508593/en.

[41] H. BARUCQ, J. DIAZ, V. DUPRAT. *High Order Absorbing Boundary Conditions for solving the Wave Equation by Discontinuous Galerkin Methods*, in "Proceedings of the Tenth International Conference Zaragoza-Pau on Applied Mathematics and Statistics", Spain Jaca, 2010, http://hal.inria.fr/inria-00508630/en.

[42] V. DUPRAT, J. DIAZ, H. BARUCQ. *Approximate boundary conditions based on a complete transparent condition for the acoustic wave equation*, in "CFA 10 10ème Congrès Français d'Acoustique", France Lyon, April 2010, http://hal.inria.fr/inria-00527158/en.

National Peer-Reviewed Conference/Proceedings

[43] C. AGUT, J. DIAZ, A. EZZIANI. *High-order discretizations for the wave equation based on the modified equation technique*, in "10ème Congrès Français d'Acoustique", France Lyon, Société Française d'Acoustique - SFA, 2010, http://hal.inria.fr/hal-00554448/en.

[44] H. BARUCQ, J. DIAZ, V. DUPRAT. *Approximate boundary conditions based on a complete transparent condition for the acoustic wave equation*, in "10ème Congrès Français d'Acoustique", France Lyon, Société Française d'Acoustique - SFA, 2010, http://hal.inria.fr/hal-00554446/en.

Workshops without Proceedings

[45] C. AGUT, J. DIAZ. *High-order discretizations for the wave equation based on the modified equation technique*, in "XIV Spanish-French Jacques-Louis Lions School", Spain A Coruna, September 2010, http://hal.inria.fr/inria-00527136/en.

[46] C. AGUT, J. DIAZ. *Une nouvelle approche de type équation modifiée pour des discrétisations d'ordre élevé en espace et en temps de l'équation des ondes*, in "CANUM 2010, 40e Congrès National d'Analyse Numérique", France Carcans-Maubuisson, June 2010, http://hal.inria.fr/inria-00527133/en.

[47] C. BALDASSARI, H. BARUCQ, J. DIAZ. *Schémas d'ordre élevé à pas de temps local pour la résolution de l'équation des ondes*, in "Séminaire du Groupe de Modélisation Mathématiques Mécanique et Numérique (GM3N)", France Caen, October 2010, http://hal.inria.fr/inria-00529641/en.

[48] V. DUPRAT, J. DIAZ, H. BARUCQ. *Development and optimization of absorbing boundary conditions for acoustic wave problems in complex media*, in "XIV Jacques-Louis Lions Spanish-French school on numerical simulation in physics and engineering", Spain A Coruna, September 2010, http://hal.inria.fr/inria-00527250/en.

[49] V. DUPRAT, J. DIAZ, H. BARUCQ. *Factorisation complète de l'équation des ondes pour la construction de conditions aux limites absorbantes*, in "CANUM 2010, 40e Congrès National d'Analyse Numérique", France Carcans Maubuisson, May 2010, http://hal.inria.fr/inria-00527161/en.

[50] T.-M. LALEG-KIRATI, E. CRÉPEAU, M. SORINE. *Analyse des signaux par quantication semi-classique. Application à l'analyse des signaux de pression artérielle*, in "Séminaire de l'Institut de Mathématiques de Bordeaux", France Bordeaux, 2010, http://hal.inria.fr/inria-00527763/en.

[51] T.-M. LALEG-KIRATI, C. MÉDIGUE, B. HELFFER, E. CRÉPEAU, M. SORINE. *Nouvelle technique d'analyse de la forme des signaux de pression artérielle basée sur une approche semi-classique*, in "Une demi-journée sur le coeur-Séminaire université de Versailles", France Versailles, 2010, http://hal.inria.fr/inria-00527760/en.

Research Reports

[52] C. AGUT, J. DIAZ. *New high order schemes based on the modified equation technique for solving the wave equation*, INRIA, July 2010, n^{o} RR-7331, http://hal.inria.fr/inria-00497627/en.

[53] C. AGUT, J. DIAZ. *Stability analysis of the Interior Penalty Discontinuous Galerkin method for the wave equation*, INRIA, December 2010, n^{o} RR-7494, http://hal.inria.fr/inria-00547862/en.

[54] M. AMARA, H. CALANDRA, R. DJELLOULI, M. GRIGOROSCUTA-STRUGARU. *A stabilized DG-type method for solving efficiently Helmholtz problems*, INRIA, November 2010, n^{o} RR-7461, http://hal.inria.fr/inria-00537983/en.

[55] T.-M. LALEG-KIRATI, C. MÉDIGUE, Y. PAPELIER, F. COTTIN, A. VAN DE LOUW. *Validation of a New Method for Stroke Volume Variation Assessment: a Comparaison with the PiCCO Technique*, INRIA, January 2010, n^{o} RR-7172, http://hal.inria.fr/inria-00429496/en.

Other Publications

[56] C. AGUT, J. DIAZ, A. EZZIANI. *High-Order Schemes Combining the Modified Equation Approach and Discontinuous Galerkin Approximations for the Wave Equation*, 2010, submitted.

[57] C. BALDASSARI, H. BARUCQ, H. CALANDRA, B. DENEL, J. DIAZ. *High-order Discontinuous Galerkin Method for the Reverse Time Migration*, 2010, submitted.

[58] C. BALDASSARI, H. BARUCQ, H. CALANDRA, J. DIAZ. *Numerical performances of a hybrid local-time stepping strategy applied to the Reverse Time Migration*, 2010, submitted.

[59] H. BARUCQ, J. DIAZ, V. DUPRAT. *Micro-differential boundary conditions modelling the absorption of acoustic waves by 2D arbitrarily-shaped convex surfaces*, 2010, submitted.

[60] A. BENDALI, A. MAKHLOUF, S. TORDEUX. *Field behavior near the edge of a microstrip antenna by the method of matched asymptotic expansions*, 2010, submitted, http://hal.inria.fr/inria-00531578/en.

[61] A. BENDALI, A. MAKHLOUF, S. TORDEUX. *Field behavior near the edge of a microstrip antenna by the method of matched asymptotic expansions*, 2011, In press.

[62] A. BENDALI, A. MAKHLOUF, S. TORDEUX. *Justification of the cavity model in the numerical simulation of patch antennas by the method of matched asymptotic expansions*, 2011, In press.

[63] F. BURET, M. DAUGE, P. DULAR, L. KRÄHENBÜHL, V. PÉRON, R. PERRUSSEL, C. POIGNARD, D. VOYER. *2D electrostatic problems with rounded corners*, December 2010, http://hal.inria.fr/hal-00549384/en.

[64] F. BURET, M. DAUGE, P. DULAR, L. KRÄHENBÜHL, V. PÉRON, R. PERRUSSEL, C. POIGNARD, D. VOYER. *Eddy currents and corner singularities*, December 2010, http://hal.inria.fr/hal-00549380/en.

[65] F. DUPROS, C. POUSA-RIBEIRO, H. AOCHI, J.-F. MÉHAUT, D. KOMATITSCH, J. ROMAN. *Efficient stencil computation on multicore architectures: Application to the finite-difference method for seismic wave propagation*, 2010, submitted.

[66] M. FARES, A. TIZAOUI, S. TORDEUX. *Justification of the cavity model in the numerical simulation of patch antennas by the method of matched asymptotic expansions*, 2011, In press.

[67] N. FAVRETTO-CRISTINI, D. KOMATITSCH, J. CARCIONE, F. CAVALLINI. *Elastic surface waves in crystals: Review of the physics and cross-check of two full-wave modeling methods*, 2010, submitted.

[68] D. KOMATITSCH. *Fluid-solid coupling on a cluster of GPUs for seismic wave propagation*, 2010, submitted.

[69] T.-M. LALEG-KIRATI, E. CRÉPEAU, M. SORINE. *Semi-classical signal analysis*, 2010, submitted, http://hal.inria.fr/inria-00495965/en.

[70] T.-M. LALEG-KIRATI, B. HELFFER. *On semi-Classical Questions Related to Signal Analysis*, 2010, submitted, http://hal.inria.fr/inria-00520773/en.

[71] R. MARTIN, D. KOMATITSCH, R. MADEC. *An improved perfectly matched layer for high-order finite element fluid-viscoelastic wave propagation and sensitivity kernel construction*, 2010, submitted.

[72] K. SCHMIDT, S. TORDEUX. *High order transmission conditions for thin conductive sheets in magneto-quasistatics*, 2010, submitted.

References in notes

[73] M. AINSWORTH, P. MONK, W. MUNIZ. *Dispersive and dissipative properties of discontinuous Galerkin finite element methods for the second-order wave equation*, in "Journal of Scientific Computing", 2006, vol. 27.

[74] X. ANTOINE, H. BARUCQ. *Approximation by generalized impedance boundary conditions of a transmission problem in acoustic scattering*, in "Math. Model. Numer. Anal.", 2005, vol. 39, n^{o} 5, p. 1041-1059.

[75] X. ANTOINE, H. BARUCQ, L. VERNHET. *High-frequency asymptotic analysis of a dissipative transmission problem resulting in generalized impedance boundary conditions*, in "Asymptotic Analysis", 2001, vol. 3, n^{o} 4, p. 257-284.

[76] D. N. ARNOLD, F. BREZZI, B. COCKBURN, L. D. MARINI. *Unified analysis of discontinuous Galerkin methods for elliptic problems*, in "SIAM J. Numer. Anal.", 2002, vol. 39, p. 1749–1779.

[77] C. BALDASSARI. *Modélisation et simulation numérique pour la migration terrestre par équation d'ondes*, Université de Pau et des Pays de l'Adour, 2009.

[78] G. BAO, W. SYMES. *Computation of pseudo-differential operators*, in "SIAM J. Sci. Comput.", 1996, vol. 17, n° 2, p. 416–429.

[79] H. BARUCQ, C. BEKKEY, R. DJELLOULI. *A Multi-Step Procedure for Enriching Limited Two-Dimensional Acoustic Far-Field Pattern Measurements.*, INRIA, 2009, RR-7048, http://hal.inria.fr/inria-00420644/en/.

[80] E. BAYSAL, D. D. KOSLOFF, J. W. C. SHERWOOD. *Reverse-time migration*, in "Geophysics", 1983, vol. 48, p. 1514-1524.

[81] G. BEYLKIN, M. J. MOHLENKAMP. *Numerical operator calculus in high dimensions*, in "Proc. Nat. Acad. Sci.", 2002, vol. 99, n° 16, p. 10246–10251.

[82] C. BLITZ, P. LOGNONNÉ, D. KOMATITSCH, D. BARATOUX. *Effects of ejecta accumulation on the crater population of asteroid 433 Eros*, in "Journal of Geophysical Research", 2009, vol. 114, E06006, http://hal.inria.fr/inria-00436421/en/.

[83] L. BORCEA. *Electrical impedance tomography*, in "Inverse Probl.", 2002, vol. 18, p. R99-R136.

[84] M. BRÜHL, M. HANKE. *Numerical implementation of two noniterative methods for locating inclusions by impedance tomography*, in "Inverse Probl.", 2000, vol. 16, p. 1029-1042.

[85] L. CAGNIARD. *Réflexion et Réfraction des Ondes Sismiques Progressives*, Gauthiers-Villars, Paris, 1939.

[86] E. J. CANDÈS, L. DEMANET. *Curvelets and fourier integral operators*, Académie des sciences/Éditions scientifiques et médicales, Elsevier, 2003.

[87] E. CANDÈS, L. DEMANET, L. YING. *A fast butterfly algorithm for the computation of fourier integral operators*, submitted.

[88] E. J. CANDÈS, D. DONOHO. *New tight frames of curvelets and optimal representations of objects with c^2 singularities*, in "Comm.Pure. Appl. Math", 2002, vol. 57, p. 219–266.

[89] L. CARINGTON, D. KOMATITSCH, M. LAURENZANO, M. TIKIR, D. MICHÉA, N. LE GOFF, A. SNAVELY, J. TROMP. *High-frequency simulations of global seismic wave propagation using SPECFEM3D_GLOBE on 62 thousand processor cores*, in "Proceedings of the ACM/IEEE Supercomputing SC'2008 conference", 2008, p. 1-11, Article #60, Gordon Bell Prize finalist article.

[90] S. CHEVROT, L. ZHAO. *Multiscale finite-frequency Rayleigh wave tomography of the Kaapvaal craton*, in "Geophys. J. Int", 2007, vol. 169, p. 201–215.

[91] D. COLTON, R. KRESS. *Inverse acoustic and electromagnetic scattering theory*, Applied Mathematical Sciences, Springer Verlag, 1992, n° 93.

[92] M. A. DABLAIN. *The application of high-order differencing to the scalar wave equation*, in "Geophysics", 1986, vol. 51, n° 1, p. 54-66.

[93] L. DEMANET, E. J. CANDÈS, L. YING. *Fast computation of fourier integral operators*, in "SIAM J. Sci. Comput.", 2006.

[94] L. DEMANET, L. YING. *Discrete symbol calculus*, to appear.

[95] J. DIAZ, A. EZZIANI. *Analytical Solution for Wave Propagation in Stratified Poroelastic Medium. Part I: the 2D Case*, INRIA, 2008, RR-6591, http://hal.inria.fr/inria-00305395/en/.

[96] J. DIAZ, A. EZZIANI. *Analytical Solution for Wave Propagation in Stratified Poroelastic Medium. Part II: the 3D Case*, INRIA, 2008, RR-6596, http://hal.inria.fr/inria-00305891/en/.

[97] C. FARHAT, I. HARARI, U. HETMANIUK. *A discontinuous Galerkin method with Lagrange multipliers for the solution of Helmholtz problems in the mid-frequency regime*, in "Comput. Methods Appl. Mech. Engrg.", 2003, vol. 192, p. 1389-1419.

[98] C. FARHAT, I. HARARI, U. HETMANIUK. *The discontinuous enrichment method for multiscale analysis*, in "Comput. Methods Appl. Mech. Engrg.", 2003, vol. 192, p. 3195-3209.

[99] J. C. GILBERT, P. JOLY. *Higher order time stepping for second order hyperbolic problems and optimal CFL conditions*, in "SIAM Numerical Analysis", 2006.

[100] M. J. GROTE, A. SCHNEEBELI, D. SCHÖTZAU. *Discontinuous galerkin finite element method for the wave equation*, in "SIAM J. on Numerical Analysis", 2006, vol. 44, p. 2408–2431.

[101] W. HACKBUSCH. *A sparse matrix arithmetic based on h-matrices. i. introduction to h-matrices.*, in "Computing", 1999, vol. 62, p. 89–108.

[102] F. HERRMANN, U. BÖNIGER, D. J. VERSCHUUR. *Non-linear primary-multiple separation with directional curvelet frames*, in "Geophys. J. Int", 2007, vol. 170, p. 781–799.

[103] F. J. HERRMANN, P. MOGHADDAM, C. C. STOLK. *Sparsity- and continuity-promoting seismic image recovery with curvelet frames.*, in "Applied and Computational Harmonic Analysis", 2008, vol. 24, p. 150–173.

[104] F. Q. HU. *A Stable Perfectly Matched Layer for Linearized Euler Equations in Unsplit Physical Variables*, in "J. Comput. Phys.", 2001, vol. 173, n^{o} 2, p. 455-480, http://dx.doi.org/10.1006/jcph.2001.6887.

[105] P. JONES, J. MA, V. ROKHLIN. *A fast direct algorithm for the solution of the laplace equation on regions with fractal boundaries*, in "J. Comput Phys", 1994, vol. 113, n^{o} 1, p. 35–51.

[106] D. KOMATITSCH, J. LABARTA, D. MICHÉA. *A simulation of seismic wave propagation at high resolution in the inner core of the Earth on 2166 processors of MareNostrum*, in "Lecture Notes in Computer Science", 2008, vol. 5336, p. 364-377.

[107] D. KOMATITSCH, R. MARTIN. *An unsplit convolutional Perfectly Matched Layer improved at grazing incidence for the seismic wave equation*, in "Geophysics", 2007, vol. 72, n^{o} 5, p. SM155-SM167, http://dx.doi.org/10.1190/1.2757586.

[108] D. KOMATITSCH, D. MICHÉA, G. ERLEBACHER. *Porting a high-order finite-element earthquake modeling application to NVIDIA graphics cards using CUDA*, in "Journal of Parallel and Distributed Computing", 2009, vol. 69, n^{o} 5, p. 451-460, http://hal.inria.fr/inria-00436426/en/.

[109] R. KRESS. *Integral equation methods in inverse acoustic and electromagnetic scattering*, in "Boundary Integral Formulation for Inverse Analysis", INGHMAN, WROBEL (editors), Computational Mechanics Publications, Southampton, 1997, p. 67–92.

[110] R. KRESS, W. RUNDELL. *Inverse obstacle scattering using reduced data*, in "SIAM J. Appl. Math.", 1999, vol. 59, p. 442–454.

[111] M. P. LAMOUREUX, G. F. MARGRAVE. *An introduction to numerical methods of pseudo-differential operators*, in "proc. CIME Workshop on Pseudodifferential Operators, Quantization and Signals", 2006.

[112] S.-J. LEE, Y. C. CHAN, D. KOMATITSCH, B.-S. HUANG, J. TROMP. *Effects of realistic surface topography on seismic ground motion in the Yangminshan region of Taiwan based upon the spectral-element method and LiDAR DTM*, in "Bulletin of the Seismological Society of America", 2009, vol. 99, n^{o} 2A, p. 681-693, http://hal.inria.fr/inria-00436427/en/.

[113] S.-J. LEE, H. W. CHEN, Q. LIU, D. KOMATITSCH, B.-S. HUANG, J. TROMP. *Three-Dimensional Simulations of Seismic Wave Propagation in the Taipei Basin with Realistic Topography Based upon the Spectral-Element Method*, in "Bull. Seismol. Soc. Am.", 2008, vol. 98, n^{o} 1, p. 253-264, http://dx.doi.org/10.1785/0120070033.

[114] S.-J. LEE, D. KOMATITSCH, B.-S. HUANG, J. TROMP. *Effects of topography on seismic wave propagation: An example from northern Taiwan*, in "Bulletin of the Seismological Society of America", 2009, vol. 99, n^{o} 1, p. 314-325, http://hal.inria.fr/inria-00436428/en/.

[115] R. MARTIN, D. KOMATITSCH, C. BLITZ, N. LE GOFF. *Simulation of seismic wave propagation in an asteroid based upon an unstructured MPI spectral-element method: blocking and non-blocking communication strategies*, in "Lecture Notes in Computer Science", 2008, vol. 5336, p. 350-363.

[116] R. MARTIN, D. KOMATITSCH, A. EZZIANI. *An unsplit convolutional Perfectly Matched Layer improved at grazing incidence for the seismic wave equation in poroelastic media*, in "Geophysics", 2008, vol. 73, n^{o} 5, p. T51-T61, http://dx.doi.org/10.1190/1.2939484.

[117] R. MARTIN, D. KOMATITSCH, S. D. GEDNEY. *A variational formulation of a stabilized unsplit convolutional perfectly matched layer for the isotropic or anisotropic seismic wave equation*, in "Comput. Model. Eng. Sci.", 2008, vol. 37, n^{o} 3, p. 274-304.

[118] R. MARTIN, D. KOMATITSCH. *An unsplit convolutional perfectly matched layer technique improved at grazing incidence for the viscoelastic wave equation*, in "Geophysical Journal International", 2009, vol. 179, n^{o} 1, p. 333-344, http://hal.inria.fr/inria-00528453.

[119] C. MORENCY, J. TROMP. *Spectral-element simulations of wave propagation in poroelastic media*, in "Geophys. J. Int.", 2008, vol. 175, p. 301–345.

[120] R. OCHS. *The limited aperture problem of inverse acoustic scattering: Dirichlet boundary conditions*, in "SIAM J. Appl. Math.", 1987, vol. 47, p. 1320–1341.

[121] J. PEDERSEN. *Modular Algorithms for Large-Scale Total Variation Image Deblurring*, Technical University of Denmark, 2005.

[122] J. R. POIRIER, A. BENDALI, P. BORDERIES. *Impedance boundary conditions for the scattering of time-harmonic waves by rapidly varying surfaces*, in "IEEE transactions on antennas and propagation", 2006, vol. 54.

[123] A. PORUBOVA, G. MAUGINB. *Improved description of longitudinal strain solitary waves*, in "Journal of Sound and Vibration", 2008, vol. 310, n^{o} 3.

[124] F. PRAT. *Analyse du Generalized Screen Propagator*, Université de Pau et des Pays de l'Adour, 2005.

[125] G. R. SHUBIN, J. B. BELL. *A modified equation approach to constructing fourth-order methods for acoustic wave propagation*, in "SIAM J. Sci. Statist. Comput.", 1987, vol. 8, p. 135–151.

[126] J. TROMP, D. KOMATITSCH, Q. LIU. *Spectral-Element and Adjoint Methods in Seismology*, in "Communications in Computational Physics", 2008, vol. 3, n^{o} 1, p. 1-32.

[127] S. TSUBOI, D. KOMATITSCH, C. JI, J. TROMP. *Computations of global seismic wave propagation in three dimensional earth models*, in "Lecture Notes in Computer Science", 2008, vol. 4759, p. 434-443.

[128] A. ZINN. *On an optimization method for full-and limited aperture problem in inverse acoustic scattering for sound-soft obstacle*, in "Inverse Problem", 1989, vol. 5, p. 239–253.

[129] A. T. DE HOOP. *A modification of Cagniard's method for solving seismic pulse problems*, in "Applied Science Research", 1960, vol. B8, p. 349-356.