INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team Magique-3D

Modélisation avancée en Géophysique 3D

Futurs

THEME NUM

Activity Report

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1. Team

Magique3D is a joint project of INRIA Futurs, LMA (Laboratoire de Mathématiques Appliquées– CNRS UMR 5142, Université de Pau et des Pays de l'Adour) and MIGP (Laboratoire de Modélisation et d'Imagerie en Géosciences de Pau– CNRS UMR 5212, Université de Pau et des Pays de l'Adour)

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2. Overall Objectives

2.1. General setting

The MAGIQUE-3D project 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, the main purpose of this project is to establish a link between progress in high-resolution 3D scientific computing and various fields of geophysics. We wish on the one hand to develop sophisticated modeling tools (by integrating physical aspects of the phenomena under study) and to validate them in a rigorous way, and on the other hand to apply them to real cases of geophysical interest.

A first strength of this project is its intrinsically multi-disciplinary character. Moreover, the topics studied can lead to applications in fields other than seismology or seismic studies in the oil industry, for instance medical tomography, non destructive testing of materials or underwater acoustics.

A second strength of this project is that it is strongly related to the regional and national industrial environment, in particular regarding how to go from theoretical studies of relatively complex media to real applications of the methods developed for real cases encountered in the field. Our main industrial partner is TOTAL, whose main research center is located in Pau. We develop strong collaborations with this petroleum company. The project could also establish links with the industrial valorization unit of University of Pau (ValUPPA), which would ensure close contacts between the researchers of the project and the PME/PMI (small and medium-size companies) of the region of Pau.

Since the MAGIQUE-3D team has been created (January 2005), its overall objectives have been reorganized to answer to numerous questions from its main industrial partner TOTAL. MAGIQUE-3D is now a team-project (from july 2007) and its research program is composed of two main topics that structure the original parts of the activities of the group. The first topic, entitled ‘Depth Imaging’, is related to modeling of seismic wave propagation in complex geological structures, taking into account underlying physical phenomena. The main part of our research program has been defined jointly by working groups composed of members of MAGIQUE-3D and of our main industrial partner TOTAL. The second topic, that could be given the general title ‘Advanced modeling in wave propagation’, is related to the realistic numerical simulation of complex three-dimensional geophysical phenomena and its comparison with real data recorded in the field. We also participate in different research programs that allow us to work on other aspects of scientific computing in the context of external collaborations.

2.2. Highlights of the year

MAGIQUE-3D is a team-project since july 2007. The group has been selected to organize the next international congress on Mathematical and Numerical Aspects of Waves Propagation, the so-called WAVES09 conference which will take place from 22 till 26 June 2006 to the Palace Beaumont in Pau. The last edition took place to Reading in Great Britain and gathered more than 230 participants.

3. Scientific Foundations

3.1. Modeling

The main activities of Magique-3D in modeling concerns 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 wich are well-adapted to solve quickly and accurately problems set in very large or unbounded domains as it is generally the case in geophysics.

3.2. Depth Imaging

The research program of MAGIQUE-3D for depth imaging is divided into two topics that both deal with the solution of the wave equation in a complex 3D medium but that differ in terms of the methods that are used. The first topic is entitled "One-way and two-way models" and is based on numerical micro-local analysis. From a practical point of view, such investigations are supposed to lead to the solution of approximate wave equations but they have the advantage of giving rise to fast solution methods which, if not accurate in general situation, can provide approximate solutions that can subsequently be used as data to initialize implicit schemes for solving full wave equations. The second topic is entitled "High-performance methods for solving wave equations". It is more classical and deals with the development of methods of resolution that are innovative and based on finite element methods. We essentially focus on the development of mixed hybrid methods which are based on the combination of Lagrange polynomials and plane waves. By using finite element discretization, we can take the topography into account which allows us to outperform existing Reverse Time Migration methods based on finite difference methods.

3.3. Wave propagation in porous media

The propagation of waves in porous media is of interest in many gephysics applications. MAGIQUE-3D develops different axes of research on this subject. By using numerical methods like finite differences, finite elements or meshless techniques like the various boundary integral methods (Boundary Integral Method, Indirect Boundary Element Method, Meshless Galerkin Method...) we aim at solving the equations describing porous media. MAGIQUE-3D has started to work on Biot models. The first studies that we have undertaken were devoted to the mathematical analysis of a linear and nonlinear model coupling an elastic wave equation written in the solid structure and a diffusion equation written in the fluid. We currently work on numerical modeling of Biot's model, we develop a numerical method based on the one hand on the use of a three-dimensional spectral-element method for space discretization, which is a finite-element method with an exactly diagonal mass matrix, and on the other hand on an explicit scheme for time discretization.

3.4. High Performance methods for solving wave equations

Nowadays the wave equation can be solved with very good accuracy using finite-element methods but the main difficulty that remains is related to the very large amount of computer memory storage that is required, in particular in 3D. Moreover, the solution of the time dependent wave equation with classical finite elements requires the inversion of a very large mass matrix at each time step. To avoid this problem, we develop space-discretization methods such as spectral element methods or Discontinuous Galerkin methods which turn the mass matrix onto an easily invertible (block)-diagonal matrix. We also try to improve the time-discretization methods by using local time stepping schemes which enables us to use a small time step only on the part of the mesh it is needed and to use a coarse time step everywhere else. From a computational point of view, we dedicated a large part of our effort on parallel computing and we have established since the beginning of 2006 a collaboration with the Barcelona Supercomputing Center (BSC, Spain), where the fastest supercomputer for unclassified research in Europe is currently located.

3.5. Absorbing Boundary Conditions and Perfectly Matched Layers

In most of the problems of wave propagation we have to deal with unbounded domains. It is then helpful to define (artificial) boundaries defining the numerical model under study in order to reduce the computational costs.

Since the innovative work of [28], this question was addressed by using Absorbing Boundary Conditions (ABC) [26] or damping zones (sponge layers) [24]. In both cases, results are often not very satisfactory because spurious phases are reflected inside the computational domain, in particular at grazing incidence in the case of paraxial conditions, and at low frequency in the case of sponge layers. However these conditions are easy to include in numerical schemes and can be constructed such that they preserve the sparsity of the discrete matrix. This justifies MAGIQUE-3D works on the improvement of ABCs.

More recently, Bérenger [23] introduced an innovative condition for Maxwell's equations, which has the property of being perfectly adapted to the model, in the sense that no spurious phase is produced in the domain before discretization and use of a numerical scheme. The resulting model is called a Perfectly Matched Layer (PML). Because of its efficiency, the PML method quickly became very popular in electromagnetics. Next, based on an analogy between Maxwell's equations and linear elasticity written as a first order system in velocity and stress, several authors adapted the PML approach to the propagation of elastic waves in infinite domains (see e.g. [25], [27]). However, for instance in the case of elastodynamics (and *a fortiori* for porous media) and for Shallow Water equations, the classical PMLs are known to be unstable. Moreover the layers do not properly handle grazing rays which gives rise to spurious reflections. This is why MAGIQUE-3D develops new PML models both for elastodynamics, porous media and geophysical fluids.

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 that 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 needs 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. Sismology

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.

4.4. Submarine acoustics

The SPECFEM software package is able to simulate the propagation of waves in the context of time domain fluid-structure interaction. We have actually started to consider underwater acoustics in collaboration with P. Cristini (MIGP, UPPA) and F. Sturm (Laboratoire de Mécanique des Fluides et d'Acoustique, École Centrale de Lyon, France).

5. Software

5.1. Software

The MAGIQUE-3D project is based (in part) on existing software packages, which are already validated, portable and robust. The SPECFEM3D software package, developed at the California Institute of Technology (USA) by Dimitri Komatitsch and Jeroen Tromp, and which is still actively maintained by Dimitri Komatitsch and his colleagues from University of Pau, 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 has 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 will focus 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 installed and run successfully on a large number of platforms (for example IBM Power, Linux PC, SGI, HP Compaq DEC, NEC, Earth Simulator, Sun, CRAY), and is used on a daily basis by more than 100 academic institutions throughout the world.

6. New Results

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

Keywords: *Elastodynamics*, *Grazing Incidence*, *Perfectly Matched Layer*.

Participants: Dimitri Komatitsch, Roland Martin.

The Perfectly Matched Layer absorbing boundary condition has proven to be very efficient from a numerical point of view for the elastic wave equation to absorb both body waves with non-grazing incidence and surface waves. However, at grazing incidence the classical discrete Perfectly Matched Layer method suffers from large spurious reflections that make it less efficient for instance in the case of very thin mesh slices, in the case of sources located close to the edge of the mesh, and/or in the case of receivers located at very large offset. We show how to improve the Perfectly Matched Layer at grazing incidence for the differential seismic wave equation based on an unsplit convolution technique. The so-called Convolution-PML (CPML) has a cost that is similar in terms of memory storage to that of the classical PML. We illustrate the efficiency of this improved Convolutional Perfectly Matched Layer based on numerical benchmarks using a finite-difference method on a thin mesh slice for an isotropic material and show that results are significantly improved compared with the classical Perfectly Matched Layer technique. We also show that, as the classical model, the technique is intrinsically unstable in the case of some anisotropic materials.

6.2. An unsplit convolutional Perfectly Matched Layer improved at grazing incidence for the poroelasticity

Keywords: *Biot's Equations*, *Perfectly Matched Layer*, *Porous Medium*.

Participants: Dimitri Komatitsch, Roland Martin, Abdelaâziz Ezziani.

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 a previous article [5], 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. Here, we introduce 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.

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

Keywords: *Meshing*, *Parallel Computing*.

Participants: Roland Martin, Dimitri Komatitsch, Nicolas Legoff.

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 frequencies lying between 2 Hz and 15 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. We obtain actual simulations, which exhibit good scaling.

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

Keywords: *Local Time Stepping*, *Migration*, *Mixed hybrid method*.

Participants: Caroline Baldassari, Hélène Barucq, Henri Calandra [Expert Engineer, TOTAL], Julien Diaz.

We work on the development of a software for the Reverse Time Migration of acoustic waves which combines mixed hybrid elements in space and a local time stepping scheme. The discretization in space allows us to take the topography into account, which usually outperforms finite difference schemes. The local time stepping is used both to eliminate the dispersion effects and to optimize the computational cost. We implemented the method when the computational domain is bounded by a perfectly reflecting condition, hence we can not deal with unbounded domains and this is why we intend to include PMLs or ABCs into the equations. At present time, we are including absorbing boundary conditions into the model, which requires to adapt the time scheme because such conditions introduce a damping matrix which implies to change the approximation scheme.

6.5. Discontinuous Galerkin methods with plane waves basis for Helmholtz's equation in 3D

Keywords: *Perfectly Matched Layer*, *Smith factorization*, *Water Waves*.

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

We address the issue of deriving Perfectly Matched Layers (PML) for the linearized Shallow Water equation including the Coriolis force. Our approach is based on the Smith factorization as it was formerly proposed in [nataf] for the Euler equation. Since we take the Coriolis force into account, we can not apply the ideas of [nataf] directly. The factorization process gives rise to a first system which involves a fourth-order equation and whose numerical handling is quite difficult. We then propose another system which seems easier to handle numerically and involves the Klein Gordon equation. We show that the PML model is stable when the short waves are considered. At present time, the numerical handling is on going.

6.6. Discontinuous Galerkin methods with plane waves basis for Helmholtz's equation in 3D

Keywords: *Discontinous Galerkin Method*, *Helmholtz Equation*, *Plane Waves*.

Participants: Mohamed Amara, Magdalena Grigoroscuta.

The numerical approach of the Helmholtz equation is an area of large interest for the scientific computation: the challenge is to develop a robust method that avoids the numerical pollution appearing when using classical finite element method. We propose a new DG (discontinuous Galerkin) method in which the solution is approximated locally by plane waves. In order to enforce a weak continuity across element boundaries, we introduce suitable Lagrange multipliers.
This method has several advantages over the other ones which use plane waves as shape functions: it yields to a hermitian positive definite matrix, it presents the interest of being independent on the regularity of the mesh and it is easily adaptable to 3D.
A 2D code has been developed in order to test the method and to compare it to the existing ones, while the 3D code is in process.

6.7. Analytical computation of the Green's function of two layered stratified porous media

Keywords: *Cagniard-de Hoop*, *Green's function*, *porous media*.

Participants: Julien Diaz, Abdelaâziz Ezziani.

The Cagniard-de Hoop is particularly well known in the physics and engineering communities for calculating analytical solutions of time-dependent wave propagation problems in stratified media, especially in seismology. However, as far as we know, it has never been applied to the wave propagation in porous media. In order to validate the computational code of Abdelaâziz Ezziani we used this technique to compute the fundamental solution of the poroelastic equation in an infinite two layered media. Moreover we apply this method to the computation of the fundamental solution for time domain fluid-porous interaction.

6.8. Construction of new absorbing boundary conditions for the numerical simulation of the scattering by elongated obstacles

Keywords: *Dirichlet-to-Neumann operators*, *local conditions Mathieu and spheroidal functions*, *performance analysis*.

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

We address the issue of designing absorbing boundary conditions for elongated scatterers. We aim at constructing conditions which preserve the sparsity of the discrete finite element matrix and then which do not hamper the computational efficiency of the numerical method. We have constructed a new family of Dirichlet-to-Neumann (DtN) conditions for elliptical shaped scatterers which is quite general for applications in scalar acoustic problems. The conditions apply to a scalar acoustic problem governed by the Helmholtz equation. The DtN maps are designed to be local in order to keep the sparsity of the discrete finite element matrix. We have analyzed their performance at low and high frequencies by considering in a first time the radiator problem both for the two and the three-dimensional cases. This analysis allowed us to select the best DtN condition and is based on a modal analysis involving Mathieu functions (2D) or spheroidal wave functions (3D) . In a second time, we did the same comparisons by considering the scattering problem which is solved by using the On-Surface-Radiation-Condition method We can also enhance the effect of the eccentricity on the performance of the conditions. Next, we complete the theoretical study by comparing the efficiency of the DtN operators with Bayliss-Gunzburger-Turkel (BGT) operators which were formerly studied by Reiner et al. The comparison is done for the radiator and the scattering problems. We observed that the first-order (respect. second-order) DtN condition outperforms the first-order (respect. the second-order) BGT condition. In particular, when the eccentricity e is close to 1.and ka small, the performance of the DtN condtion of second order is very impressive for the scattering problems (2D and 3D).
Now we are considering the solution of the scattering problem when applying the new DtN conditions on the exterior boundary. We aim at analyzing how the location of the exterior boundary impacts the accuracy of the numerical solution and we intend to compare the performance of the new conditions with BGT conditions.

6.9. New mixed hybrid elements combining Lagrange polynomials and plane waves for the solution of the Helmholtz equation

Keywords: *Helmholtz Equation*, *Lagrange Multipliers*, *Oscillated Polynomials*.

Participants: Mohamed Amara, Hélène Barucq, Angela Bernardini, Rabia Djellouli.

We propose a new mixed-hybrid-type solution methodology to be applied for solving high-frequency Helmholtz problems. The proposed approach distinguishes itself from similar methods by a local approximation of the solution with *oscillated* finite elements polynomials *satisfying* the wave equation. The weak continuity of the solution across the element interfaces is enforced using Lagrange multipliers. A convergence analysis of the method has been performed an it shows the strong stability properties of this new discretization. Numerical results obtained in the case of two-dimensional waveguide problems illustrate the computational efficiency of the proposed solution methodology. Now, we are applying the new finite element method for solving the seismic wave equation.

7. Contracts and Grants with Industry

7.1. Contracts with TOTAL

- Modélisation et simulation numérique pour la migration terrestre par équations d'ondes tridimensionnelles.

  Period: 2007 January - 2009 december, Management: INRIA Futurs, Amount: 145000 euros.

- Résolution de l'équation d'Helmholtz 3D par une méthode de Galerkin discontinue DGM utilisant des bases d'ondes planes.

  Period: 2007 January - 2009 december, Management: INRIA Futurs, Amount: 139000 euros.
- Period: 2007 January - 2007 December, Management: INRIA Futurs, Amount: 60000 euros.
- Contrat annuel du Laboratoire de Modélisation et d'Imagerie en Géosciences (MIGP) CNRS UMR 5212 avec TOTAL.

  Period: January 1, 2006 - December 1, 2006, Management: CNRS, Amount: 170000 euros.

7.2. Contract with CSUN

In the context of the Associate Team MAGIC.

Period: 2006 January - 2008 December, Total Amount: 46000 USD

8. Other Grants and Activities

8.1. Competence Network on Wave Equations

Participants: Abderrhamane Bendali [INSA Toulouse and CERFACS], Serge Petiton [LIF, INRIA Futurs Lille], Serge Gratton [CERFACS], Jean Roman [Scalapplix, INRIA Futurs, Bordeaux], .

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. The current partners of the network were selected during a kickoff meeting held in Pau in June 2006. The main areas of interest and research topics of the program are now defined and a meeting will take place to Toulouse in Novembre, the 22th. Two Ph.D students advised by J. Roman and S. Petiton respectively will begin to work in january 2008 on computing aspects for optimizing the computational performances of our numerical methods.

The different partners plan to work jointly on topics dealing with solving wave equations. We intend to increase the numbers of participants and TOTAL wants to define jointly a research program and a mode of functioning which respects at the same moment the time necessary for the research and the industrial needs in fast results. At present time, MAGIQUE-3D is preparing a charter which will be propose to TOTAL in december. As far as funds are concerned, the current partners decided to use the ones from TOTAL to organize working groups and support Ph.D. and post-doctoral positions. Moreover, considering the main areas of interest and research topics of the program, links with ANR could be established and could provide an additional source of funding. To our knowledge, our 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.

8.2. ANR Project NUMASIS

MAGIQUE-3D participates in an ANR research program called NUMASIS managed by J.F. Méhaut (INRIA Rhône-Alpes, Grenoble). In this context we naturally collaborate with SCALAPPLIX and RUNTIME from INRIA futurs (Bordeaux). The main idea of the NUMASIS project is that multiprocessor machines of tomorrow will posses a NUMA architecture introducing multiple levels of hierarchy in computers (multi-modules, multi-core chips, multithreading systems, etc). To use them efficiently, parallel applications must have powerful tools making it possible to guide the distribution of execution and data flows without compromising their portability. The NUMASIS project proposes to evaluate the functionalities provided by current systems, to apprehend their limitations, to design and implement new management mechanisms for processes, data and communications within the basic software (operating system, libraries). The application field selected for NUMASIS is seismology, which appears to us to be representative of current needs in scientific computing.

Numerical modeling of seismic wave propagation in complex geological media is one of the significant research topics in seismology. Various approaches will be studied and their adequacy compared to specificities of NUMA machines will be evaluated. The various calculations will be based on modern numerical algorithms such as spectral elements, high-order finite differences or finite elements applied to realistic 3D models. The NUMASIS project will study problems of parallel algorithms (distribution, scheduling) making it possible to optimize the calculations based on these schemes by using as efficiently as possible the execution frameworks developed for these NUMA architectures.

The NUMASIS project was submitted in 2005 and accepted by the Calcul Intensif et Grilles de Calcul program of ANR. The project officially started on January 1, 2006 under reference ANR-05-CIGC-002. It will end on December 31, 2008. In the context of this project, MAGIQUE-3D has obtained 84000 euros for three years, which will be used mostly to fund the salary of a software engineer (David Michéa, who has joined MAGIQUE-3D on November 1, 2006) for two years.

8.3. 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. Collaborations have began with the Bordeaux team on the use of bandelet formalism for the seismic inversion.

8.4. Collaborations with other INRIA projects

MAGIQUE-3D participates in a ANR research program called NUMASIS and managed by J.F. Méhaut (INRIA Rhône-Alpes, Grenoble). In this context we naturally collaborate with SCALAPPLIX and RUNTIME from INRIA futurs (Bordeaux). We also collaborate with the team-project APICS from INRIA Sophia-Antipolis which manages the ANR project AHPI. At last, we will organize the WAVES09 conference with POEMS from INRIA Rocquencourt. A. Ezziani collaborates with this team-project and the group is supposed to participate to the competence network we are managing with TOTAL.

8.5. International collaborations

8.5.1. Visits

- Dimitri Komatitsch has spent one month at the Barcelona Supercomputing Center;
- Mounir Tlemcani has spent one month in june in MAGIQUE-3D to initiate collaborations with the University of Oran (Algeria);

- Christina Morency has spent on month in july in the framework of our collaborations with Caltech (USA);
- Rabia Djellouli has spent two weeks in july in the context of our associate team.

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 modelisation essentially. Two PhD. students from MAGIQUE-3D are participating to these works and they have the opportunities to be current visitors at CSUN. We are funding both by the DREI from INRIA and CSUN. From 12 till 14 december 2007, we organize a workshop whose program is available at http://uppa-inria.univ-pau.fr/m3d/WS07/.

8.5.3. New collaborations

Julien Diaz is now collaborating with Marcus Grote from the University of Basel (Switzerland).

9. Dissemination

9.1. Scientific animation

- In the context of depth imaging activities, MAGIQUE-3D has co-organized a congress on harmonic analysis, signal theory and meshless methods in April 2007 (see http://www.math.estia.fr/).
- In the context of the associate team, we organize a Workshop entitled: First Workshop on "Solution Methodologies for Direct and Inverse Scattering Problems: Recent Progress and Trends". It will take place from 12 till 14 december 2007 to the university of Pau (see http://uppa-inria.univ-pau.fr/m3d/WS07/)

9.2. Teaching

9.2.1. Lecture

- Lecture/course to Master students (39 hours) at University of Pau, France, on "Calcul Parallèle pour les Sciences de la Terre" ("Parallel computing in the Earth Sciences")
- Lecture/course to Master students (39 hours) at University of Pau, France, on "Modélisation en Géophysique" ("Geophysical modeling")
- Lecture/course to Master students (46 hours) at University of Pau, France, on "Propagation d'ondes et imagerie" ("Waves propagation and Imaging")

9.2.2. Training Courses

Tutorial (10 hours) on the Propagation of Seismic Waves in the context of the TAMTAM07 conference (from 16 till 18 April 2007)

9.3. Participation in Conferences, Workshops and Seminar

Caroline Baldassari

- *High-order multi-step one-way modeling*, 8th International conference on mathematical and numerical aspects of waves, WAVES 2007 (University of Reading, UK, 23-27 july 2007, http://www.waves2007.org/)

Hélène Barucq

- *Formulations One-Way pour la simulation des ondes sismiques*,Invited talk in the context of the TAMTAM07 Conference (Algeria, 2007, 16-18 April, http://tamtam07alger.ifrance.com).
- *Numerical micro-local analysis for seismic imaging of complex structures*, Invited talk in the context of the Workshop MASTHESTIA07 (France, 2007, 25-27 April, http://www.math.estia.fr).
- *One-way equations versus full wave equations for the propagation of acoustics waves*, Invited talk in the context of the first french-spanish congress of Mathematics (Spain, 2007, 9-13 july, http://www.unizar.es/ICHFM07)

Angela Bernardini

- *A new class of hybrid-mixed FEM for solving high frequency wave problems*,The 14th International Conference on Finite Elements in Flow Problem (Santa Fé, USA, March 2007) Santa Fé
- *A mixed-hybrid method for solving mid- and high-frequency Helmholtz problems*, 8th International conference on theoretical and computational acoustics, ICTCA 2007 (Heraklion, GREECE, 2-5 july 2007, http://www.iacm.forth.gr/ ictca07/)
- *A new discretization procedure using oscillating finite element polynomials for Helmholtz problems*, 8th International conference on mathematical and numerical aspects of waves, WAVES 2007 (University of Reading, UK, 23-27 july 2007, http://www.waves2007.org/)

Julien Diaz

- *Energy conserving explicit local time stepping for second-order wave equations*, 8th International conference on mathematical and numerical aspects of waves, WAVES 2007 (University of Reading, UK, 23-27 july 2007, http://www.waves2007.org/)
- *Explicit local time stepping for second-order wave equations*, International Conference on SCIentific Computation And Differential Equations, Scicade 2007 (Saint-Malo, France, 9-13 july 2007 http://scicade07.irisa.fr/)

Abdelaâziz Ezziani

- *Space-time mesh refinement and discontinuous Galerkin methods for symmetric first order hyperbolic systems*, 8th International conference on mathematical and numerical aspects of waves, WAVES 2007 (University of Reading, UK, 23-27 july 2007, http://www.waves2007.org/)

Roland Martin

- *An optimized Convolution-Perfectly matched layer (CPML) absorbing technique for 3D Poroelastic seismic wave propagation based on finite difference and spectral element methods*, EGU Meeting 16-21 April 2007, Vienna.
- *An unsplit Convolutional perfectly matched layer technique improved at grazing incidence for the differential anisotropic elastic wave equation: application to 3D heterogeneous near surface slices*, Joint Assembly AGU Meeting May 2007.

Anne-Gaëlle Saint-Guirons

- *Dirichlet-to-Neumann vs Bayliss-Gunzburger-Turkel operators for the modelling of elliptical scatterers at low frequency*, 8th International conference on theoretical and computational acoustics, ICTCA 2007 (Heraklion, GREECE, 2-6 july 2007, http://www.iacm.forth.gr/ ictca07/)
- *DtN-like boundary conditions for exterior elliptical shaped boundaries*, 8th International conference on mathematical and numerical aspects of waves, WAVES 2007 (University of Reading, UK, 23-27 july 2007, http://www.waves2007.org/)

10. Bibliography

Year Publications

Articles in refereed journals and book chapters

[1] H. BARUCQ, M. FONTES. *Well-posedness and exponential stability of Maxwell-like systems coupled with strongly absorbing layers*, in "J. Math. Pures Appl. (9)", vol. 87, n^{o} 3, 2007, p. 253–273.

[2] E. CHALJUB, D. KOMATITSCH, J.-P. VILOTTE, Y. CAPDEVILLE, B. VALETTE, G. FESTA. *Spectral Element Analysis in Seismology*, in "Advances in Wave Propagation in Heterogeneous Media", R.-S. WU, V. MAUPIN (editors), Advances in Geophysics, vol. 48, Elsevier - Academic Press, 2007, p. 365-419.

[3] A. GILLMAN, R. DJELLOULI, M. AMARA. *A Mixed Hybrid Formulation Based on Oscillated Finite Element Polynomials for Solving Helmholtz Problems*, in "J. of Computational and Applied Mathematics", vol. 204, n^{o} 2, 2007, p. 515–525.

[4] D. KOMATITSCH. *Comment on 'Multidomain Pseudospectral Time-Domain (PSTD) method for acoustic waves in lossy media' by Y. Q. Zeng, Q. H. Liu and G. Zhao, Journal of Computational Acoustics, vol. 12, no. 3, pp 277-299 (2004)*, in "J. Comput. Acoust.", vol. To appear, 2007.

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

[6] S. LEE, H. CHEN, Q. LIU, D. KOMATITSCH, B. 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.", vol. To appear, 2007.

[7] R. MARTIN, R. ZENIT. *Heat transfer resulting from the interaction of a vortex pair with a heated wall*, in "Journal of Heat Transfer", To appear, 2007.

[8] H. PUEBLA, R. MARTIN, J. ALVAREZ-RAMIREZ, R. AGUILAR-LOPEZ. *Controlling nonlinear waves in excitable media*, in "Chaos, Solitons and Fractals", 2007.

[9] J. TROMP, D. KOMATITSCH, Q. LIU. *Spectral-Element and Adjoint Methods in Seismology*, in "Communications in Computational Physics", vol. 3, n^{o} 1, 2007, p. 1-32.

Publications in Conferences and Workshops

[10] M. AMARA, H. BARUCQ, A. BERNARDINI, R. DJELLOULI. *On the numerical performance of a new discretization scheme for solving helmholtz problems*, in "Proceedings of the ICTCA 2007 Conference", submitted, 10 pages, 2007.

[11] H. BARUCQ, R. DJELLOULI, A.-G. SAINT-GUIRONS. *Dirichlet-to-Neumann vs Bayliss-Gunzburger-Turkel operators for the modelling of elliptical scatterers at low frequency*, in "Proceedings of the ICTCA 2007 Conference", submitted, 10 pages, 2007.

Internal Reports

[12] H. BARUCQ, R. DJELLOULI, A.-G. SAINT-GUIRONS. *Construction and performance analysis of local DtN absorbing boundary conditions for exterior Helmholtz problems. Part I : Elliptical shaped boundaries*, Technical report, n^{o} RR-6394, INRIA, november 2007, http://hal.inria.fr/inria-00180471.

[13] H. BARUCQ, R. DJELLOULI, A.-G. SAINT-GUIRONS. *Construction and performance analysis of local DtN absorbing boundary conditions for exterior Helmholtz problems. Part II : Prolate spheroid boundaries*, Technical report, n^{o} RR-6395, INRIA, november 2007, http://hal.inria.fr/inria-00180475.

Miscellaneous

[14] 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*, submitted to SIAM Journal on Numerical Analysis, 2007.

[15] H. BARUCQ, R. DJELLOULI, A.-G. SAINT-GUIRONS. *New DtN absorbing boundary conditions for exterior Helmholtz problems : derivation and performance analysis for elliptical and prolate spheroid boundaries*, submitted to APNUM, 2007.

[16] H. BARUCQ, R. DJELLOULI, A.-G. SAINT-GUIRONS. *Performance analysis of DtN absorbing boundary conditions for the scattering by prolate spheroid shaped obstacles*, submitted to JCAM, 2007.

[17] H. BARUCQ, B. DUQUET, F. PRAT. *True-Amplitude one-way propagation in heterogeneous media*, submitted to J. of Scientific Computing, 2007.

[18] J. DIAZ, M. J. GROTE. *Energy conserving explicit local time-stepping for second-order wave equations*, submitted to SIAM Journal on Scientific Computing, 2007.

[19] L. DUBOIS, K. L. FEIGL, D. KOMATITSCH, T. ÀRNADÒTTIR, F. SIGMUNDSSON. *Three-dimensional mechanical models for the June 2000 earthquakes sequence in the South Icelandic Seismic Zone*, submitted to Tectonophysics, 2007.

[20] A. EZZIANI, P. JOLY. *Local time stepping and discontinuous Galerkin methods for symmetric first order hyperbolic systems*, submitted to JCAM, 2007.

[21] R. MARTIN, D. KOMATITSCH, A. EZZIANI. *An unsplit convolutional perfecly matched layer improved at grazing incidence for the seismic wave equation. Part II: poroelastic media.*, Submitted to Geophysics, in revision, 2007.

[22] R. MARTIN, C. ORTIZ-ALEMAN. *Three-dimensional modelling for capacitance tomography using secondary potential formulation*, submitted to Computer Science and Engineering, 2007.

References in notes

[23] J. P. BÉRENGER. *A Perfectly Matched Layer for the absorption of electromagnetic waves*, in "J. Comput. Phys.", vol. 114, 1994, p. 185-200.

[24] C. CERJAN, D. KOSLOFF, R. KOSLOFF, M. RESHEF. *A nonreflecting boundary condition for discrete acoustic and elastic wave equation*, in "Geophysics", vol. 50, 1985, p. 705-708.

[25] W. C. CHEW, Q. LIU. *Perfectly Matched Layers for elastodynamics: a new absorbing boundary condition*, in "J. Comput. Acoust.", vol. 4, n^{o} 4, 1996, p. 341–359.

[26] R. CLAYTON, B. ENGQUIST. *Absorbing boundary conditions for acoustic and elastic wave equations*, in "Bull. Seismol. Soc. Am.", vol. 67, 1977, p. 1529-1540.

[27] F. COLLINO, C. TSOGKA. *Application of the PML absorbing layer model to the linear elastodynamic problem in anisotropic heterogeneous media*, in "Geophysics", vol. 66, n^{o} 1, 2001, p. 294-307.

[28] B. ENGQUIST, A. MAJDA. *Absorbing boundary conditions for the numerical simulation of waves*, in "Math. Comp.", vol. 31, 1977, p. 629-651.