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INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Team Magique3D

Modélisation avancée en Géophysique 3D

Futurs

THEME NUM

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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)

Team Leader

Hélène Barucq [INRIA Research scientist (on partial secondment) since september 2005, Assistant Professor LMA]

Research scientists

Dimitri Komatitsch [Professor, MIGP]
Nathalie Favretto-Cristini [CR CNRS MIGP]
Paul Cristini [CR CNRS MIGP]

Post-doctoral fellows

Roland Martin [Post-doc Total MIGP]
Frank Prat [Post-doc ERT LMA]
Patrick Saint-Macary [ATER, LMA]

Ph. D. students

Mathieu Fontes [MIGP, LMA]
Anne-Gaëlle Saint-Guirons [LMA]

Research scientists (partners)

Bertrand Duquet [IFP]
Christian Gout [MC, INSA Rouen]

2. Overall Objectives

2.1. Overall Objectives

Magique3D is a joint project between the LMA (Laboratoire de Mathématiques Appliquées, UMR 5142) and the MIGP laboratory (Laboratoire de Modélisation et Imagerie en Géosciences de Pau, UMR 5212), which are both CNRS units located at Université de Pau et des Pays de l'Adour (UPPA) and that are also part of Fédération de Recherche FR 2952 "Institut Pluridisciplinaire de Recherche Appliquée dans le domaine du Génie Pétrolier". It is a multidisciplinary research group whose activities are linked to issues of particular interest for the region of Pau. On the one hand, Pau is located in a mountainous region that is prone to earthquakes and therefore subjected to seismic hazard. On the other hand, Pau is also the city in which the French oil company TOTAL has its largest research center. The main research activities of Magique3D therefore deal for instance with the numerical simulations of complex phenomena such as earthquakes or the imaging of complex geological structures such as those involved in oil exploration.

>From a general point of view, Magique3D is interested in solving geophysical problems. Geophysics is a field that has benefited from rapid evolution in the last two decades. This is mainly due to metrological advances that have led to significant improvements in the quality and the quantity of observations. Nowadays one has access to powerful numerical methods that, when implemented on supercomputers, make the simulation of seismic wave propagation in complex three-dimensional geological structures possible. Magique3D aims at developing efficient software for the simulation of such phenomena of interest in 3D geophysics. By federating the work of researchers coming from different fields, the group aims at studying such problems in a complete fashion by including the modeling, mathematical analysis, numerical analysis and computing aspects.

3. Scientific Foundations

3.1. Modeling

The main activities of Magique-3D in modeling concern :

- the derivation of models that are based on mathematical physics for accounting on the principal characteristics of the physical phenomena considered.
- the mathematical analysis of models arising from geophysical problems and in particular, equations of interest for the petroleum industry.
- the development of boundary conditions that can be used in numerical models.

3.2. Wave propagation in porous media

The propagation of waves in porous media can be of interest in many 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 to solve the equations describing porous media. In a first attempt we will solve these equations by performing improvements of absorbing boundary conditions by using different alternative formulations like the Perfect Matched Layer techniques and high order paraxial methods.

3.2.1. Biot systems

Biot systems are used to model the porous media as a matrix filled with fluids. The equations of the wave propagation are close to the ones describing one component (solid or acoustic) materials but additional terms can be involved in the equations as viscous and pressure terms. These additional terms can be dependent on the porosity, the temperature and the displacement. Then, equations of conservation of partial densities (hence porosities), and partial temperatures need to be included [47]. New optimal absorbing conditions must take into account the varations of porosity, density and temperature. For this purpose, analogies to the resolution of boundary conditions used in Navier Stokes multiphase flow systems [46] are made and are guiding us to improve the existing methods.

3.2.2. Absorbing conditions

The development of absorbing conditions is a very important topic for the numerical simulation of the propagation of waves. They can be used for truncating the exact and infinite propagation domain or to select a computational region that is sufficient to simulate the phenomenon, according to physical considerations.
Magique-3D develops a research program on absorbing conditions based on pseudo-differential theory. This theory is well adapted to analyze the behavior of the waves micro-locally and has been applied successfully for the construction of Absorbing Boundary Conditions (ABC) in acoustics and electromagnetism. We intend to apply it :

1. to elastodynamics
2. to Biot systems
3. to compare ABC models to Perfectly Matched Layers

3.3. Imaging

The development of codes for imaging the subsurface is of interest for the petroleum industry. Such codes provide a cheap and helpful tool for prospecting. They can be constructed from different formulations of the problem and/or use different numerical methods. At present time, Magique-3D has already studied imaging problems from wave propagation and has analyzed different tools of imaging that were formerly introduced for medical imaging.

3.4. Seismic wave amplitude calculation in 3D

Usually, the amplitude of the P-waves recorded at the seismic receivers after being reflected on an interface are evaluated knowing the characteristics of the source and the reflection coefficient at the interface, and considering geometrical-spreading compensation. A survey of the literature brings to light that most calculations are generally performed with the concept of ray theory developed with the assumption of a wave propagating along a "mathematical" ray. Since it does not take into account the "physical rays" or the so-called (first) Fresnel volumes [38], [28], [24], [31] (i.e., the frequency-dependent spatial regions in the vicinity of the "mathematical ray" that are known to influence the propagation of the time-harmonic wavefields along the ray), this concept is known to be valid only in the limit of infinite frequency. However, seismic data are band-limited. Consequently, in order to correctly determine the wave amplitudes recorded at receivers, we have to pay attention to the frequency-dependent Fresnel volumes that depend on the position of the source and the receivers, and to pay attention to the Fresnel zones at the interface (IFZ). The latter, defined as sections of the Fresnel volumes by interfaces [23], [39] are essential to the formation of reflected and transmitted wavefields.

The real data recorded by the receivers are of course sensitive to the Fresnel volumes and the IFZ. The amplitude-versus-angle curve recorded is thus described by the curve obtained with the concept of band-limited-data. Nevertheless, one usually assumes that the curve recorded can be well described by the concept of infinite-frequency. The aim of this work is to emphasize the importance of using the cpncept of band-limited data, based on the IFZ in order to extract accurate information regarding media parameters from signals associated to reflected waves recorded at receivers.

3.5. Numerical methods

3.5.1. Spectral finite elements

During the 1990s, numerical modeling techniques that made it possible to study large 3D problems started to emerge. However, many research groups continued to carry out two-dimensional calculations because of the computational cost of these methods in 3D, and of the difficulty of implementing them (one needs to run them on large multiprocessor machines, based on specific programming techniques such as multitasking). In the last thirty years, several methods have been used for the numerical calculation of synthetic seismograms in complex geological models, first in two dimensions, and more recently in three dimensions. The finite-difference technique [51] is the most popular, and was applied successfully to local or regional models [41], [52]. Another largely used technique is the pseudospectral method, which uses global bases of Chebyshev or Legendre polynomials [21]. However, in many cases of practical interest, these traditional methods suffer from limitations such as numerical dispersion or numerical anisotropy. We thus have in recent years developed a new technique, called the spectral element method, which had been introduced initially in fluid dynamics [44], and that we applied for the first time to the propagation of waves in 3D structures (see for example [37], [35]. This work showed the superiority of the spectral element method over more traditional numerical techniques in terms of precision, weak numerical dispersion, and geometrical flexibility making it possible to adapt it to large and complex 3D models [33], [34]. Such precision is a crucial advantage for the resolution of forward or inverse problems in seismology.

The spectral element technique developed by Dimitri Komatitsch and his coworkers is based on a variational formulation of the wave equation, and combines the flexibility of a finite element method with the precision of a global pseudospectral method. The finite element grid is adapted to all major discontinuities of the geological model. In order to maintain a relatively constant grid resolution in the entire model in terms of the number of grid points per wavelength, and to reduce the computing time, the size of the elements is decreased with depth in a geometrically-conforming fashion, which allows us to preserve an exactly diagonal mass matrix in the method. The effects of attenuation and anisotropy are taken into account in the technique.

We applied this technique to a large number of real geophysical cases of practical interest, for example the study of strong ground motion and of the associated seismic risk in the densely-populated Los Angeles basin region. This area consists of a basin of great dimension (more than 100 km x 100 km) which is one of the deepest sedimentary basins in the world (the sedimentary layer has a maximum thickness of 8.5 km right underneath downtown Los Angeles), and therefore one of the most dangerous because of the resulting amplification of the seismic waves. In the case of a small recent earthquake in Hollywood (of magnitude MW = 4.2 on September 9, 2001), well recorded by more than 140 stations of the TriNet seismic network of Southern California, we managed for the first time to fit the three components of the vector displacement, while most of the previous studies concentrated on the vertical component only [42], [53], [43], while still obtaining a good fit to the recorded data down to relatively short periods (2 seconds). This study clearly showed how useful sophisticated 3D numerical modeling techniques can be in such a context [32].

Topography also plays a significant role for the characteristics of the "ground roll", i.e., surface waves recorded by the oil industry in field acquisition experiments, and its effects are essentially three-dimensional. We will use the 3D spectral-element code (SPECFEM3D) developed by D. Komatitsch and his coworkers to generate synthetic data for various 2D and 3D configurations. Some recent articles show that the presence of heterogeneities in the subsurface not only contributes to attenuate the recorded signal but also to delay coherent events. It is also difficult, under these conditions, to distinguish between a distribution of heterogeneities and a mere stratification of layers. We will also carry out 3D simulations with complex topographies. Effects of amplification due to conversions of body waves into Rayleigh surface waves in regions of sharp topography have been observed in the field. Amplitude variations of the signal of an order of magnitude can appear along the recording antenna [49], [40]. Because of diffraction phenomena, complex arrivals are also observed. We will try to reproduce these effects with our 3D numerical simulations of seismic wave propagation.

A few years ago, Dimitri Komatitsch started to work on this topic of the numerical modelling of the effect of topography on seismic wave propagation with Jacques Muller (TOTAL) and Patrice Ricarte (IFP) within the framework of the "Foothills" project of TOTAL. At the time, calculations were carried out exclusively in 2D because of the computer resources available. A very significant problem for the oil industry is indeed to study models located in foothill basins, in which the topography and the presence of the weathered surface layer (Wz) plays a crucial role on the quality of the seismic data recorded. It is now necessary to generalize such calculations, and obviously nowadays to carry them out in 3D using the seismic modelling tools that we have developed. Roland Martin is currently in the process of using such techniques to apply it to another real case in South America in which the very thin weathered zone makes the simulation very difficult to perform at high-frequency if classical numerical simulation techniques such as staggered finite-difference methods are used.

3.5.2. Numerical micro-local analysis

To simulate the propagation of acoustic waves, we propose to consider a model that comes from the factorization of the wave equation written as a first-order system. This model involves pseudo-differential operators whose representation naturally leads to the use of Fast Fourier Transforms. But we aim at developing a numerical method that is competitive compared to FDTD methods. Hence we have to use pseudo-differential approximation classes taht speed up the computations. Several approaches can be chosen. The first, which is the simplest one, consists in approximating the symbols of the pseudo-differential operators by functions whose variables are uncoupled. Then the number of FFTs required by the numerical method is considerably smaller. Unfortunately, while this approximation method is efficient when the medium is locally homogeneous, it fails when the velocity varies laterally. This is why we are investigating other techniques.

3.5.3. Parallel computing

Recently, researchers started to take advantage of the phenomenal increase in the computing power of personal computers (PCs) to transform them into parallel computing networks. Such clusters of PCs or "Beowulfs" often use standard computer components in order to reduce the cost of construction of the machine. The advantage of these machines is to make high resolution 3D calculations possible at low cost, but the disadvantage is that it is necessary to modify existing computing algorithms to explicitly use message-passing communication libraries (Message-Passing Interfaces - MPI, [29]) from a software programming point of view, because each PC has its own processor and its own memory (i.e., we are using a distributed-memory architecture, in which communications between components have to be handled and programmed explicitly).

We have therefore implemented our spectral-element algorithms on a parallel computer based on a message-passing technique (MPI) to handle the communications between processors, which allows us to reach a very high resolution in frequency while preserving very good performance in terms of computing cost. The corresponding software package, SPECFEM3D, has been successfully tested on many types of parallel and vectorial computers, and is currently used by more than 100 research groups in the world. In order to develop and test this software package, historically in a first stage we built at Caltech (USA) a large cluster of PC computers, comprising a total of 320 processors and 160 gigabytes of memory, and we optimized our parallel computing algorithms on this machine. Then, in 2002, a Japanese consortium opened to researchers a very large supercomputer called the "Earth Simulator". This machine was in 2004 the fastest computer of the world, with 5120 processors and 10000 gigabyt es of memory. We took advantage of this opportunity to carry out calculations at very high resolution on this machine. This supercomputer having a parallel architecture with distributed memory, but being equipped with vector processors, we had to optimize our algorithm to benefit from the vectorial structure. We then managed to calculate seismograms in the full 3D Earth down to periods of approximately 5 seconds, i.e., to high frequencies that had never been reached before [36]. These results illustrated the fact that, given a detailed model of an earthquake source, 3D models of the mantle and crust of the Earth, a precise numerical modeling technique such as the spectral element method, and a large computer, seismic waveforms covering an interval of amplitude of several orders of magnitude and a few decades in frequency can be accurately modeled.

The main disadvantage of numerical methods such as spectral finite elements is the relatively high cost of numerical calculations in the case of large 3D models. However, this technological limitation is only temporary: an extrapolation from 1993 to 2010 of the speed of the fastest computer in the world shows that we could reach a computer able to calculate at 1 petaflop = 10^{15} floating-point operations per second around the year 2010, or even sooner. Considering these technological developments, we are convinced that in the near future such algorithms will be used routinely to carry out calculations that will take into account the complexity of the 3D Earth. This project thus proposes to develop the tools necessary to calculate efficiently the propagation of seismic waves on such supercomputers.

We have also implemented a 3D finite-difference numerical modeling code for Maxwell's equations with PML based on the new PML model of section 4.1. Simulations that we wanted to perform based on this software package required typically between 10 and 15 gigabytes of memory, which is a relatively small amount that cannot be found on a PC, therefore parallel computing is required, but that can be found easily on shared-memory machines, and therefore we decided not to use MPI but rather use OpenMP compilation directives, which are easier to implement. We successfully ran large OpenMP simulations on 8 processors on the "Zahir" IBM Power4 supercomputer at IDRIS (Orsay, France).

4. New Results

4.1. Maxwell system in absorbing media

Participants: Hélène Barucq, Mathieu Fontes, Dimitri Komatitsch, Roland Martin.

Maxwell's equations are very commonly used in geophysics in particular in the context of atmospheric studies or radar interferometry and also in subsurface geophysics, in which georadars are used to image the properties of the first meters of the soil, for instance to study contamination or the conduct archaeological research (to detect metal or cavities).

An absorbing medium is described by a conductivity tensor whose coefficients are complex-valued. The description of the absorbing tensors is generally given in the frequency domain. We propose a time-dependent formulation of the problem that consists of the Maxwell system of equations coupled with two ordinary differential equations. We have developed a complete analysis of the problem. We have established an existence and uniqueness result based on the Hille-Yosida theorem and we have studied the long-time behavior of the solution. We can prove that if the computational domain is convex, the solution exponentially decays in time [15]. The extension of this result to the case of more general domains is currently under study. Numerical experiments are ongoing, based on the FDTD scheme proposed by Yee. We intend to analyze the effect of the coupling tensors to the absorption phenomenon.

This work has been followed by an analysis of the previous model. The question was the following : can we choose the coupling tensors such that the model is a PML model for the Maxwell system od equations? By developing a plane wave analysis, we proved that the coupling tensors represent pseudo-differential operators in time. Hence the mathematical analysis is more difficult. The existence and uniqueness of the solution is established but the time behavior of the solution is an open problem. Nevertheless we have performed numerical experiments after developing a code based on the 3D FDTD Yee's scheme [16]. They show the efficiency of the PML formulation except at grazing incidence. The question of optimizing the PML is currently under study.

A natural issue was then to study the well-posedness and the long-time behavior of the PML model involving pseudo-differential operators. As far as the existence and uniqueness are concerned, we obtained results by adapting the Hille-Yosida theory.

In 2006, we intend to go further into the comparison of the PML model with absorbing boundary conditions (ABC) models. We propose to decompose the PML model into one-way equations and then to analyze the behavior of any solution in the PML. This approach, initiated by Engquist and Majda was previously used for the construction of ABCs for hyperbolic systems. We then expect that, by applying the same process to the PML and the ABC models, we will be able to compare the two approaches.

4.2. PML for elastodynamics

Participants: Hélène Barucq, Mathieu Fontes, Dimitri Komatitsch, Roland Martin.

Absorbing conditions are a very important field in numerical geophysics, in particular in elastodynamics, i.e. when one studies seismic waves either in the viscoelastic, elastic or acoustic approximation. Historically, people have used Absorbing Boundary Conditions (ABCs) [26], [50], [30] that unfortunately are only approximate when the incidence is not normal, and that are inefficient at grazing incidence. Sponge layers have also been used [22] but lead to significant low-frequency reflections. Based on the work on PML for Maxwell's equations [20], some authors [25], [27] have extended the PML model to elastodynamics, but with two problems: the field has to be split, which increases the complexity and the cost of the calculations, and also after discretization the numerical PML is not perfect at grazing incidence. Recently, [48] have introduced an improved PML model for Maxwell's equations based on recursiv e numerical convolution, which they called the Convolutional-PML (C-PML). Based on similarities between the Maxwell's system of equations and the elastodynamics equations written as a first-order system in velocity and stress, we have derived a C-PML formulation for the 3D seismic wave equation. We are currently finishing the numerical tests, and so far the results have been very promising, showing a much improved behavior at grazing incidence. Next, we have considered the 2D elastodynamic equations coupled with the PML of Collino and Tsogka after discretization by the second-order finite difference scheme of Virieux and we have computed the four discrete coefficients of reflection. As expected, they are not zero and then, they have to be minimized to improve the almost perfect transmission at the interface between the effective medium and the PML one. We are currently looking for a minimization process that will be a good tradeoff between the possible situations. Indeed, we have to minimize four coefficients at the same time and their respective importance depends on the properties of the medium.

4.3. Mathematical analysis of Biot models

Participants: Hélène Barucq, Roland Martin, Patrick Saint-Macary.

We intend to model the propagation of waves in heterogeneous porous media. We began our investigations by analyzing several Biot systems where the unknowns are the pressure in the fluid and the displacement in the solid structure. The problem is described by two coupled parabolic hyperbolic equations. We have established existence and uniqueness results that are obtained based upon Galerkin methods. This approach allowed us to establish a priori estimates which will be helpful when considering numerical investigations. We have then analyzed the behavior of the solution with respect to the physical parameters and then to the time variable [3]. We have shown that the solution may converge to a stationary state that depends on the boundary condition we apply on the terminating boundary. Next, we have included a non linear term in the solid structure that describe some properties of rocks. We have performed a complete mathematical analysis in the one-dimensional case [5], [4].

In 2006, we intend to consider the complete Biot system for modelling the propagation of waves. The resulting system consists of two coupled wave equations applied to the displacements in the fluid and the structure. We will develop a mathematical analysis consisting of well-posedness results and a priori estimates. These results will be completed by numerical investigations. We have also decided to focus our attention on the construction of absorbing boundary conditions for this system. Indeed to our knowledge, there are few results concerning such conditions for the Biot system.

4.4. Seismic imaging based on numerical microlocal analysis

Participants: Hélène Barucq, Bertrand Duquet, Frank Prat.

The petroleum resources are quickly shrinking, which explains the necessity of improving the numerical methods that are helpful to locate possible oilfields before proceeding to any borehole. Imaging the subsurface is an important topic for the petroleum industry and classic numerical methods are either not efficient enough in case of heterogeneous media or too expensive to be useful for 3D problems. Recently M. De Hoop proposed a new model based on the decomposition of the wave field along the depth direction that is valid even when the velocity varies laterally and the multiple reflections can be separated from the primary ones. This is a very significant advance in the field of seismic imaging because it is the first model that can take the heterogeneities of the medium into account and that can simulate the multiples independently of the primary reflections. This decomposition is possible because it is set into the formalism of pseudodifferential operators. Generally speaking, the wave equation is replaced by a first-order hyperbolic system whose principal part is a diagonal system that describes the down-going and up-going propagation of waves. Then the zeroth-order part of the system is described by a matrix of operators accounting for the transmission and the reflection. For the decomposition of the wave equation, one uses classical pseudodifferential operators whose simplest representation involves the Fourier transform. Hence the most natural way of carrying out numerical experiments consists in using Fast Fourier Transforms (FFT) and J. Le Rousseau developed in 2001 a numerical code for the simulation of acoustic waves in a 2D medium. Then M. De Hoop and J. Le Rousseau focused their attention on the propagation and the reflection of waves and did not consider the transmission. We have developed a code for the 3D case. In a previous work, we have shown that if the medium is not smooth, the one-way method leads to results that are accurate at the kinematic level but that can be erroneous at the dynamic level. In 2005, we have tested several points that required investigations according to the numerical results we obtained. The first question we addressed was the pertinence of introducing the transmission terms into the model. Indeed, the numerical results we obtained for canonical cases were in good agreement with the solution of the full wave equation as far as the kinematic was concerned but the amplitudes of the one-way solution was erroneous. There exist two ways of including the transmission into the numerical model. The first consists in including the transmission terms into the principal part of the system as a zeroth-order perturbation. This results in changing the propagator of the problem and such an approach is quite close to that used by people like Bleistein or Plessix for factorizing the scalar full wave equation. The second idea keeps the principal part of the system and the transmission terms are included into the right hand-side of the

one-way system. Numerical tests have been performed to analyze the difference between the two approaches. Considering the simple case of a stratified medium, we have observed that :
(i) including the transmission terms is necessary to compute the amplitude of the wave filed correctly, even when the medium is simple
(ii) the best numerical results are always obtained by keeping the propagator as a full first-order operator and when the transmission terms are included into the right hand-side of the model.
Next we have tested the case of a complex medium by computing the solution in a medium that included a salt dome. We have observed that the numerical results deteriorate and we decided to analyze the propagation in the simple case of a medium with two layers separated by a sloping interface. The numerical results have been improved by computing the propagator from paraxial equations but we observed the well-known limitations of such equations by observing a deterioration of the results beyond a critical angle. These results have been summarized into [14].
In 2006, we have planned to organize our work as follows. First, we intend to improve the propagators by reconsidering their representation, at least numerically. At the beginning of our investigations, we decided to represent the operators in a specific class of symbols with disjoint variables. Such an approximation allowed us to speed up the computations in such a way the computational burden of the numerical method was very competitive compared to a FDTD method. Nevertheless, the accuracy of the method was lost as soon as the medium was heterogeneous. This is why we now focus our attention on representations involving curvelets. Such approximations seem very promising because they provide sparse representations of pseudodifferential operators, which should be competitive compared to the first approximation we used.
Second, since the one-way model is naturally adapted to parallel computing, we intend to construct propagators based on a finite-element method. In the work, we accept the idea that the numerical method will be expensive and we propose to overcome this difficulty by taking advantage of parallel computing to improve the numerical performance of the method. This subject will be at the center of the work of a post-doctoral researcher who will joint the team at the beginning of 2006.

4.5. Water waves

Participants: Hélène Barucq, Roland Martin, Anne-Gaëlle Saint-Guirons.

We have recently started to work on the simulation of water waves. We aim at developing a 3D software package that will lead to low computational cost.
We began by developing an unsplit PML model for the linearized shallow-water equations. We have used the same approach than the one proposed by Hu for the Euler system, which consists in recomposing the fields in split models. We have chosen to consider a split model proposed by Navon and its coworkers. Numerical experiments are currently being performed.
In a similar way, we use algebraic methods for the derivation of PML models. Such an approach has been used by Nataf for the linearized Euler system, based on the Smith factorization. The idea is the following: Using an algebraic decomposition of the given system, it is possible to analyze the nature of the different fields and to select which part needs to be absorbed. In the case of the Euler equation, PML models were known to induce numerical instabilities that were created by absorbing the complete field into the layer. An algebraic method like the Smith factorization shows that the solution to the Euler equation is composed of a two-way propagating part that must be absorbed and a part which, if absorbed, can generate instabilities into the PML. We are currently considering different algebraic methods because we aim at developing the analysis in the nonlinear case. For the non-linear case, recent efforts have also focused on the modeling of debris avalanche and granular flows taking into account compaction in the pressure and roughness terms via Mohr-Coulomb criteria. Without compaction we aim to model efficiently tsunamis and cyclones (Navon, Hesthaven etc....) locally and with Mohr-Coulomb friction terms we are modelling avalanches and pyroclastic flows on real topographies like Merapi-type volcano slopes. For such directed and regionally confined flows, the new optimized PML methods should allow us to reduce the computational cost and improve the accuracy of the solution comparing to the recent works of volcanologist teams [45].

4.6. Seismic wave amplitude calculation in 3D

Participants: Nathalie Favretto-Cristini, Paul Cristini.

Firstly we have performed 3D analytical calculations of the amplitude of P-waves recorded at receivers after specular reflection on a smooth interface between elastic media. These calculations have been performed by taking into account the band-limited property of the seismic source and thus the IFZ. In particular, the IFZ has been described by means of small angle variations about the incident angle that bound the Fresnel volume at the source point. We have then compared the variations in the reflected P-wave amplitude as a function of the incident angle obtained in the case of the infinite-frequency framework [19] and in the case of the band-limited-data framework, for three types of interface. For small incident angles, the reflectivity curves were almost identical, but large discrepancies appeared for greater incident angles. Finally, we have applied a quite simple inversion process to these reflectivity curves. We have shown that assuming that the curve reco rded by the receivers can be well described by the infinite-frequency concept leads to very inaccurate estimations of the media properties (estimation errors between 15% and 70%). Consequently, it is essential to use the band-limited-data concept, based on the IFZ, in order to develop a suitable inversion process to extract accurate information relative to media parameters from signals associated to reflected waves recorded at receivers [17].

We have also derived 3D analytical expressions for the reflected S-wave amplitude recorded at receivers, taking into account the IFZ. We are processing results.

4.7. Fault modeling in 3D complex geophysical data

Participants: Christian Gout, Dimitri Komatitsch, Roland Martin.

Such problems are of crucial interest in geosciences as they consitute an important exploration gap for reservoir characterization. Morevoer, it is well known that interpretation of faults in seismic data is a time consuming manual task and reducing time from exploration to production of an oil field has great economical benefits. More precisely, the fault extraction from 3D data is of crucial importance in reservoir characterization: detailed knowledge of the fault system may provide valuable information for production. In the exploration phase, the geological interpretation of seismic data is one of the most time consuming tasks. This is usually done manually by interpreters, and much time could be saved based on automatization of these tasks using a segmentation process. To do that, we have used segmentation methods (developed by Apprato, Gout, Le Guyader, Vese) previously used for medical applications during the Ph. D. thesis of Carole Le Guyader. We used classical tools such as deformable models, geodesic active contours or level set methods. The segmentation is performed with well data that are specific to geophysical applications. The Ph. D. thesis (CIFRE at the University of Pau and TOTAL) of Guilhem Dupuy "Création et manipulation de maillages de grandes tailles: applications aux géosciences" under the direction of Dimitri Komatitsch and Bruno Jobard (Pau, Laboratoire d'Informatique) is also strongly linked to this topic.

5. Contracts and Grants with Industry

5.1. Contracts with TOTAL

A research contract (C421883-ADERA) has supported the PhD thesis of F. Prat on the simulation of acoustic waves in heterogeneous media.

A research contract supports (TOTAL/MIGP) the work of Roland Martin.

6. Other Grants and Activities

6.1. Academic collaborations

Olivier Lafitte (University Paris 13 & CEA) collaborates at the program developed on seismic imaging. He is currently visiting the team and participates to the elaboration of numerical models for acoustics.

We also collaborate with Sébastien Chevrot (CR CNRS, Observatoire Midi-Pyrénées, Toulouse) on improved numerical modeling techniques to take into account anisotropy in geophysical media, in particular the upper mantle of the Earth. We have developed approaches to take into account sensitivity kernels in the forward problem.

6.2. Industrial collaborations

Magique-3D develops industrial collaborations with Total an IFP (Institut Français di Pétrole, Rueil-Malmaison) The main topic that we investigate concerns depth imaging. This is a collaboration with Henri Calandra (Head of the Depth Imaging project of Total) and Pierre Thore (Engineer at Total). Such a topic requires the development of efficient and fast direct solvers. This is also a collaboration with Bertrand Duquet from IFP. Recently Magique-3D has begun to collaborate with Patrick Lailly and Florence Delprat-Jeannaud (also from IFP) on a new method for solving the inverse problem in strongly heterogeneous media. This work will be developped in 2006 in the context of a PhD.

6.3. Collaborations with other INRIA projects

Magique-3D participates in a ANR research program that will begin in INRIA. It is called NUMASIS and is managed by J.F. Méhaut (INRIA Rhone-Alpes, Grenoble). Magique-3D will collaborate with Scalapplix and Runtime from INRIA Futurs (Bordeaux).

6.4. International collaborations

6.4.1. Northridge University

The team has a long term collaboration with Prof Rabia Djellouli, who moved from the University of Colorado at Boulder to the California States University at Northridge (CSUN) in 2004. We perform common research on inverse scattering problems. In 2005, we have benefited from the financial support of DREI at INRIA. We used these funds for the organization of four visits (H. Barucq and A.G. Saint-Guirons at CSUN, A. Gillman and R. Djellouli at Pau). We have submitted an Associate Team project and the proposal has been approved for 2006.

6.4.2. Polytechnical School of Tunis

We have developed a collaboration on waveguides with the Polytechnical Scool of Tunis (EPT). H. Barucq visited the School in November and began to supervise a PhD thesis in collaboration with C. Bekkey.

7. Dissemination

7.1. Scientific animation

The team has organized a Workshop at Pau (20-21 october 2005) on "Mesh creation, domain decomposition and parallel computing in 3D geophysics".
See WorkshopPau.html for more informations on this workshop.
The team participates actively to the seminar of the Laboratory of Mathematics. We invite speakers regularly (2 by trimester)

7.2. Teaching

We are very much involved in teaching because most of people in Magique-3D are permanent at the University. We give a list of the different lectures that permanent members gave during 2005 :

- Licence of Mathematics
- Licence of Geophysics
- Master of Mathematics
- Master of Applied Mathematics
- Master of Geophysics

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