Project-Team caiman

Calcul scientifique, modélisation et analyse numérique

Sophia Antipolis

THEME NUM

Activity Report

2004

Table of contents

1. Team

Caiman is a joint project-team with the "École Nationale des Ponts et Chaussées" (French national civil engineering school) through the CERMICS ("Centre d'Enseignement et de Recherche en Mathématiques, Informatique et Calcul Scientifique", Teaching and Research Center on Mathematics, Computer Science and Scientific Computing), the CNRS (French National Center of Scientific Research) and the Nice-Sophia Antipolis University (NSAU), through the Dieudonné Laboratory (UMR 6621).

Looking back at year 2004, we very sadly keep in our minds Frederic Poupaud, professor at NSAU and member of the project-team, who died in october 2004. He was a brilliant researcher and teacher, a cheerful and enthousiastic colleague. We enjoyed a rich, longlasting collaboration with him since the early 1990s. We miss him, badly.

Head of project-team
Serge Piperno [ICPC, ENPC]

Vice-head of project-team
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Administrative assistant
Sabine Barrère [administrative adjoint, ENPC]

Staff member Inria
Loula Fezoui [DR, INRIA]

Technical staff
Saïd El Kasmi [Junior technical staff, till 11/1]

Staff member Inria ENPC
Nathalie Glinsky-Olivier [CR Équipement, part-time 80%]

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Victorita Dolean [CMAP, Ecole Polytechnique]
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Ph. D. students
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Marc Bernacki [ENPC PhD grant]
Antoine Bouquet [FT R&D PhD contract, starting 10/1]
Martine Chane-Yook [INRIA PhD grant]
Hugo Fol [INRIA PhD grant]
Maud Poret [ATER, Valenciennes University]

Post-doctoral fellow
Christel Luquet-Piperno [till 7/1]
Gilles Scarella [starting 5/1]

Student intern
Grégory Beaume [Master student, Mecanum Master, UNSA, from 2/1 till 8/1]
Mondher Benjemaa [Master student, ENS Lyon, from 4/1 till 9/1]
Adrien Catella [ESSI Engineering school student, from 6/21 till 9/17]
Rudy Hayat [ENSHMG Engineering school student, from 3/8 till 6/25]

2. Overall Objectives

The project aims at proposing new and efficient solutions for the numerical simulation of physical phenomena related to electromagnetics and complex flows in interaction (fluid-structure interactions, epitaxy, etc.). Scientific activities sweep a large range from physical modeling to design and analysis of numerical methods. A particular emphasis is put on the validation of the methods proposed on realistic configurations and their algorithmic - possibly parallel - implementation.

Our research topics mainly concern wave propagation and fluid dynamics. In wave propagation, we investigate several aspects of integral equations for acoustics and electromagnetics in the frequency domain (fast multipole method, multi-layer models, coupling with volumic discretizations). In the time-domain, we construct numerical methods based on finite volumes or discontinuous finite elements. Current applications relate to heterogeneous electromagnetics, acoustics, propagation of acoustic waves in a non-uniform steady compressible flow (aeroacoustics) and geophysics. We also study the coupling of the Maxwell system or the Poisson equation with the transport of charges in rarefied gases. The main application is the spatial environment of satellites.

In the field of fluid dynamics, we study possible partitioned procedures for the transient solution of fluid-structure interactions, and more precisely the coupling in time between solvers for the fluid and the structure, aiming at constructing new, stable, and efficient algorithms (originally, applications to incompressible fluids were considered: wind engineering of structures and hemodynamics in biomedical engineering). These algorithms can be used also for time-subcycling by subdomain in wave propagation problems. Finally, in more standard compressible CFD, we consider viscous fluids with complex state laws and solve Navier-Stokes equations based on a perfect gas law solver modified using a relaxation method.

3. Scientific Foundations

3.1. Conservation laws and finite volume methods

Keywords: *ALE formulation*, *Riemann problem*, *computational fluid dynamics*, *discontinuous Galerkin finite element*, *electromagnetics*, *finite volume*, *monotonicity*, *moving variable mesh*, *unstructured mesh*.

Participants: Serge Piperno, Stéphane Lanteri, Loula Fezoui, Nathalie Glinsky-Olivier, Alexandre Ern, Marc Bernacki, Mondher Benjemaa, Hugo Fol, Maud Poret, Saïd El Kasmi, Stéphanie Lohrengel.

conservation law a conservation law is a partial differential balance equation of a scalar field (system of conservation laws for a vector field), where all terms are first-order space or time derivatives of functions of the unknown (for example, $\partial_t u + \partial_x f(u) = 0$).

Riemann solver a Riemann solver yields an exact or approximate solution of a local Riemann problem (initial value problem with two constant states). It is used in finite volume methods, for example in Godunov-type numerical fluxes.

finite volume methods numerical methods based on a partition of the computational domain into control volumes, where an approximate for the average value of the solution is computed. These methods are very well suited for conservation laws, especially when the problem solution has very low regularity. These methods find natural extensions in discontinuous finite elements approaches.

discontinuous finite element methods numerical methods based on a partition of the computational domain into finite elements, where the basis functions used are local to finite elements (absolutely no continuity between elements is required through element interfaces). These methods are also well suited for conservation laws. In general, they are more expensive than classical finite elements, but lead to very simple algorithms for the coupling of different choices of element types or for the use of locally refined, possibly non-conforming grids.

Many different PDEs are considered by team members. However, they are mainly similar to fluid dynamics equations, because they can be rewritten as hyperbolic systems of conservation laws or balance equations (Euler, Navier-Stokes, Maxwell equations). Fluid Dynamics equations are a non linear strictly hyperbolic system of conservation laws. Computational Fluid Dynamics started decades ago (see [50] for early references). The non-linearity leads to irregular (weak) solutions, even if the initial flow is smooth. Then the use of very low order finite elements was proposed and finite volumes were introduced to match the conservative nature of the initial physical system: the computational domain is partitioned in control volumes and the numerical unknowns are approximates to the mean values of the fields inside the control volumes (it is different from finite-difference methods, where unknowns are approximates to point-wise values, and from finite element methods where unknowns are coordinates relatively to a functional basis of solutions).

Finite volume methods can easily deal with complex geometries and irregular solutions [3]. They can simply lead to conservative methods (where for example no fluid mass is lost). They are based on numerical flux functions, yielding an accurate approximation of the variable flux through control volume interfaces (these interfaces separate two distinct average fields on the two control volumes). The construction of these numerical flux functions is itself based on approximate Riemann solvers [39] and interpolation and slope limitation can yield higher accuracy (outside discontinuity zones) [42].

These methods can be used in many application fields: complex CFD (with several species or phases), wave propagation in the time-domain in heterogeneous media [7] (acoustics, electromagnetics, etc). In wave propagation fields, the finite volume methods based on local Riemann solvers induce a numerical diffusion which pollutes the simulation results (the artificial dissipation is necessary for CFD, in order to build a viscous approximation of the problem, i.e. in order to obtain some monotonicity properties - ensuring that variables like density and pressure always remain positive!).

We have proposed a simple and very efficient finite volume method for the numerical simulation of wave propagation in heterogeneous media, which can be used on arbitrary unstructured meshes and compares well with the FDTD in terms of numerical properties [6] and computational efficiency. This method is currently extended to higher orders of accuracy with discontinuous Galerkin approaches.

Finally, we should recall here that finite volume methods can very simply deal with moving meshes (classically, for fluid-structure interaction simulations, Fluid Dynamics equations are rewritten in an Arbitrary Lagrangian-Eulerian (ALE) form, allowing the use of deforming meshes past a deforming structure). We currently make some effort to propose finite volume extensions on variable meshes (both the coordinates and the topology of the unstructured mesh vary), excluding classical remeshing of mesh adaptation [32].

3.2. High-performance parallel and distributed computing

Keywords: *distributed computing*, *domain partitioning*, *grid computing*, *message passing*, *object oriented programming*, *parallel computing*, *scientific visualization*.

Participants: Stéphane Lanteri, Loula Fezoui, Saïd El Kasmi, Victorita Dolean [CMAP, Ecole Polytechnique], Frédéric Nataf [CMAP, Ecole Polytechnique].

The efficient use of modern parallel computing platforms implies a careful adaptation of the underlying numerical algorithms. In practice, this translates into two main types of activities: most often, existing methods are parallelized with no modification to the numerical ingredients; however, in certain situations, new numerical methods have to be designed in order to fully benefit from the capabilities of these computers. The solution of the algebraic systems resulting from the discretization of partial differential equations is a classical context which is witnessing a large number of research activities worldwide that aim at developing new parallel solvers. These are for a great part based on domain decomposition principles [49][46]. Project-team Caiman is currently contributing to both aspects. On one hand, the finite volume and discontinuous Galerkin methods on unstructured tetrahedral meshes are parallelized using a classical SPMD (Single Program Multiple Data) strategy that combines a partitioning of the computational domain and a message passing programming model based on MPI (Message Passing Interface). On the other hand, we develop domain decomposition algorithms for the solution of general sparse linear systems.

Moreover, the popularity of the Internet as well as the availability of powerful computers and high-speed network technologies as low-cost commodity components is changing the way we use computers today. These technological opportunities have led to the possibility of using distributed computing platforms as a single, unified resource, leading to what is popularly known as grid computing [24]. Grids enable the sharing, selection and aggregation of a wide variety of resources including supercomputers, storage systems and specialized devices that are geographically distributed and owned by different organizations, for solving large-scale computational and data intensive problems in science, engineering and commerce. However this emerging grid computing concept also brings additional constraints on the development of scientific applications such as, heterogeneity (both in terms of CPUs and interconnection networks) and multi-localization. The development of scientific applications that fully exploit such distributed and heterogeneous computing platforms requires to bring together computer scientists from the grid computing community and computational mathematicians. The former are currently developing languages and tools relying on new programming paradigms, such as distributed oriented programming, that offer new perspectives of scientific applications. Since 2002, project-team Caiman is collaborating with project-team Oasis (also located at INRIA Sophia Antipolis) with the common aim of developing a problem solving environment that will allow an effective use of a heterogeneous, distributed, computing platform for the simulation of large-scale electromagnetics phenomena.

3.3. Coupling of models and methods

Keywords: *computational fluid dynamics*, *coupling*, *electromagnetics*, *finite element*, *finite volume*, *fluid-structure interaction*, *modelling*, *numerical analysis*, *unstructured mesh*.

Participants: Stéphane Lanteri, Loula Fezoui, Serge Piperno, Frédéric Poupaud, Martine Chane-Yook, Hugo Fol.

> **coupling:** interaction between several subsystems with simultaneous evolutions each depending on one-another. For example, a physical coupling can take place between different sub-systems. Similarly, different numerical methods solving different PDE can be coupled to solve a coupled physical problem.

> **coupling algorithm:** a particular algorithm, built for the numerical simulation of a coupled problem, allowing the modular use of existing numerical procedures. If no particular attention is paid to the construction of the algorithm, it does not inherit the numerical properties of the coupled procedures (in particular stability and accuracy).

Research themes in the team are widely spread: wave propagation, field-plasma coupling, fluid-structure interaction. All these research directions have in common the efficient, accurate coupling of different partial differential equations like the Maxwell system, the Vlasov and Poisson equations, the Navier-Stokes equations and equations for structural dynamics...

The coupled transient solution of different PDEs is still an open problem (from the theoretical and numerical points of view). The general approach is based on staggered algorithm (problems are solved separately and one after each other). This allows the use of existing codes and procedures. This kind of staggered partitioned procedure allows also the iterative solution of difficult coupled problems, when time scales are similar in different subsystems. Finally, one more and more important aspect of coupling is the transient coupling of numerical methods (the question of coupling the same method on several subdomains is still very interesting). All these works are motivated by the fact that the attention paid to the coupling algorithm can prevent numerical efficiency, stability, and accuracy breakdowns [4].

4. Application Domains

4.1. Wave propagation in electromagnetics

Keywords: *acoustics*, *antennas*, *biomedical engineering*, *electromagnetic compatibility*, *furtivity*, *plasma*, *satellites*, *telecommunications*.

We develop numerical methods and algorithms for the numerical solution (in the time or frequency domain) of electromagnetic wave propagation. They can be applied to many different physical settings and several very rich application domains, like telecommunications, biomedical and transportation engineering (optimum design of antennas, electromagnetic compatibility, furtivity, modelling of new absorbing media).

In the time domain, we aim at proposing accurate and efficient methods for complex geometries and heterogeneous materials (possibly with small elements like point sources, lines, etc). We first adapted existing finite volume methods, initially conceived for the solution of compressible fluid dynamics on unstructured grids. Their upwind nature [5] lead to numerical dissipation of the electromagnetic energy. We then proceeded with dissipation-free finite volume methods based on centered fluxes [6]. For the Maxwell system, they compared well with commonly-used finite difference methods [52]) in terms of accuracy and efficiency on regular meshes, but with spurious propagations on highly distorted meshes for example. At the same time, these methods could be coupled with Yee's FDTD method, in order to use different numerical methods in the context where they are the most efficient [47]. Finally, we are now developing software based on discontinuous element methods, which can be seen as high-order extensions of finite volume methods [22]. These methods can easily and accurately deal with highly heterogeneous materials, highly distorted meshes and non-conforming meshes as well! These methods are the robust and necessary bricks towards one of the goals we are aiming at: the construction of a complete chain of numerical methods, allowing the use of unstructured meshes and heterogeneous materials (for example for applications in biomedical engineering), based on explicit, time and space domain-decomposed schemes. We are considering applying the methods developed in the frequency domain.

In the field of plasmas, we are highly interested in the study of the plasmic and electromagnetic environment of artificial satellites. Satellites receive and emit high energy electromagnetic waves, have many different potential levels on different parts and are evolving in a cloud of charged particles (which may induce electric discharges and other severe problems). Although the physical context is rather electrostatic (the Vlasov-Poisson equations), we use our own experience on the Vlasov-Maxwell system to couple a finite element approach with particle methods, in order to provide meaningful numerical simulations of the plasmic environment of satellites, in the framework of a continuous collaboration with an industrial partner (France Telecom R&D), for which the physical meaning of both available experimental and numerical results is of great importance.

Finally, these methods are also used for other wave propagation problems in the time-domain. We currently consider aeroacoustics (propagation of flow perturbations inside a steady-state solution of Euler equations) and elastodynamics (propagation of seismic waves in a heterogeneous medium, and initiation of the waves by the rupture along a fault).

4.2. Computational fluid dynamics and related problems

Keywords: *biomedical engineering*, *civil engineering*, *combustion*, *coupling algorithm*, *finite element*, *finite volume*, *fluid-structure interaction*, *multiphase flow*, *real gas*, *telecommunications*, *unstructured mesh*.

We are interested in several physical problems where fluid dynamics are coupled with other phenomena: fluid-structure interactions, flows of real gases, aeroacoustics, etc.

In the field of fluid-structure interactions, many different application domains appear, like aerospace engineering, biomedical engineering, civil engineering. In aerospace engineering, the fluid flow is compressible and light compared with the structure. The stability properties of recent (both military and civil) airplanes is strongly dependent on the coupled behavior of the structure and the flow about it. Jointly with Charbel Farhat

(Colorado university at Boulder, Colorado) we have proposed criteria for the design of efficient, accurate and stable coupling algorithms in this context [4]. Cases involving incompressible flows are civil engineering (stability analysis of elementary bridge sections in uniform prescribed wind) and biomedical engineering (realistic simulation of highly deformable vessels). Ideas deriving from these criteria are currently reformulated for the domain decomposed solution of wave propagation in the time domain with different time-steps for each subdomain.

We are also interested in realistic flows (reactive flows of multiphase flows). For vapor phase epitaxy (industrial process of high importance for growing of single crystals in which chemical reactions produce thin layers of materials whose lattice structures are identical to that of the substrate on which they are deposited), we have developed a basic reactor simulator [37] based on a two-dimensional unstructured-grid formulation, where the flow cannot be considered as polytropic (the relation between the internal energy and the temperature is not linear) because of very high temperatures and a energy relaxation method [34] has been extended to the Navier-Stokes equations. This allows the use of a lightly modified version of a classical "perfect gas" solver.

Finally, in connection with the general problem of the simulation of wave propagation, we have started a new research direction in aeroacoustics. We have chosen to limit our investigations to a context (validated by industrials) where the steady flow is known and the goal is to propagate acoustic waves in a non-uniform flow (then, we do not consider the modelling of noise generation, using DNS or turbulent models for example). This requires numerical methods able to deal with heterogeneous propagation properties and producing very few numerical dissipation. The method developed in the framework of electromagnetics and classical acoustics is being extended to this context.

5. Software

5.1. MAXDG0/MAXDG1

Keywords: *Maxwell system*, *discontinuous Galerkin method*, *electromagnetics*, *finite volume*, *heterogeneous medium*, *parallel computing*, *time domain*.

Participants: Loula Fezoui, Stéphane Lanteri, Serge Piperno.

The team has developed the software MAXDG0/MAXDG1 for the numerical simulation of the three-dimensional Maxwell equations in time domain, for heterogeneous media and using tetrahedral unstructured grids. The two components of the software are respectively based on a finite volume method (cells centered on tetrahedra) and on a P1 Discontinuous Galerkin method, both with centered fluxes and a leap-frog explicit time-scheme. The parallelization is based on mesh partitioning and message passing using standard MPI. Many test-cases and post-processing developments have been recently added.

5.2. DGAA

Keywords: *Euler equations*, *aeroacoustics*, *discontinuous Galerkin method*, *parallel computing*, *time domain*.

Participants: Marc Bernacki, Stéphane Lanteri, Serge Piperno.

The team has developed the software DGAA for the numerical simulation in the domain of the three-dimensional propagation of waves inside a steady inviscid flow, using tetrahedral unstructured grids. The equations solved are the linearized Euler equations around a steady-state solution provided by an Euler equations solver developed at INRIA Sophia Antipolis. Then, the wave propagation (which is massively, yet smoothly heterogeneous) is modelled using a P1 discontinuous Galerkin method (also with centered fluxes and a leap-frog explicit time-scheme). The parallelization is based on mesh partitioning and message passing using standard MPI.

5.3. SPARCS_3D

Keywords: *Vlasov-Poisson equations model coupling*, *ionization*, *magnetosphere*, *plasma*, *plasmic propulsion*.

Participants: Martine Chane-Yook, Anne Nouri [LATP, CMI, Université de Provence], Frédéric Poupaud, Serge Piperno, Sébastien Clerc [Alcatel Space].

In collaboration with Alcatel Space, we study problems related to the electrostatic charge of satellites. These charges are received periodically from the sun and from the plasmic propulsors (which will be more used in a near future). The presence of these charged particles can lead to undesired potential gaps and eventually to electrostatic discharges (able to destroy some parts of solar energy generators). Following the pioneering work of Olivier Chanrion, which provided a software for the pseudo-transient two-dimensional axisymmetric Vlasov-Poisson equations, we have developed a three-dimensional prototype.

5.4. JEM3D

Keywords: *Grid computing*, *ProActive java library*, *high performance computing*, *parallel and distributed computing*, *time-domain Maxwell equations*.

Participants: Françoise Baude [project-team Oasis], Denis Caromel [project-team Oasis], Christian Delbe [project-team Oasis], Saïd El Kasmi, Fabrice Huet [project-team Oasis], Stéphane Lanteri, Romain Quilici [project-team Oasis].

As a first step towards the development of a numerical simulation tool for electromagnetic wave propagation problems that fully exploit a grid computing platform, we have developed JEM3D [15]- [29], a Java object-oriented time domain finite volume solver for the 3D Maxwell equations. This solver is built on top of a library of general classes for the development of numerical methods that rely on finite volume or finite element formulations on unstructured meshes. The underlying object-oriented model is able to deal with two-dimensional (2D) or three-dimensional (3D) problems, different types of discretization elements (triangles, quadrangles, tetrahedra and hexahedra), the main two families of finite volume formulations (vertex centered and element or cell centered formulations), etc. For the implementation of JEM3D, the Java language has been selected, mainly because of its intrinsic distributed computing features. Since the practical use of such features is not an easy task for the non specialists, we have set up a collaboration with the project-team Oasis in order to exploit the capabilities of their ProActive Java library. This library [30] greatly facilitates distributed programming through the concept of active objects. In order to improve the communication performances of the JEM3D software, the Ibis [27] has recently been interfaced with the ProActive library. Ibis is an efficient and flexible Java-based programming environment for Grid computing, in particular for distributed supercomputing applications, developed at the department of computer science of Vrije University.

6. New Results

6.1. Electromagnetics and wave propagation

6.1.1. *DGTD methods for the Maxwell equations on unstructured meshes*

Keywords: *Maxwell system*, *conforming mesh*, *discontinuous Galerkin method*, *finite volume method*, *locally refined mesh*, *non-conforming mesh*, *stability*, *structured mesh*, *time domain*.

Participants: Loula Fezoui, Stéphane Lanteri, Serge Piperno.

Electromagnetic problems often involve objects with complex geometries. Therefore, the use of unstructured tetrahedral meshes is mandatory for many applications. We have proposed [43] a Discontinuous Galerkin method for the numerical solution of the time-domain Maxwell equations over unstructured meshes (DGTD method). The method relies on the choice of a local basis of functions (for standard applications, P1 elements yield very satisfactory results), a centered mean approximation for the surface integrals and a second-order leap-frog scheme for advancing in time. The method is proved to be stable for a large class of basis functions and a discrete analog of the electromagnetic energy is also conserved. A proof for the convergence has been established for arbitrary orders of accuracy on tetrahedral meshes, as well as a weak divergence preservation

property [38]. We are now considering possible implementations of Discontinuous Galerkin methods on tetra-hedra beyond P1 elements. Fruitful discussions with Jan Hesthaven (Brown University) in summer lead us to a first extension to the P2-Lagrange nodal elements which is almost validated. We are currently investigating the possibility to consider modal elements, for which the local mass matrix is ill-conditioned, but with a well-known inverse.

6.1.2. DGTD methods for the Maxwell equations on locally refined meshes

Keywords: *Maxwell system*, *conforming mesh*, *discontinuous Galerkin method*, *finite volume method*, *locally refined mesh*, *non-conforming mesh*, *stability*, *structured mesh*, *time domain*.

Participants: Antoine Bouquet, Nicolas Canouet, Adrien Catella, Loula Fezoui, Serge Piperno, Stéphane Lanteri, Claude Dedeban [France Télécom R&D, center of La Turbie].

Electromagnetic problems often involve objects of very different scales. In collaboration with France Télécom R&D, we have studied Discontinuous Galerkin Time Domain (DGTD) methods for the numerical simulation of the three-dimensional Maxwell equations on locally refined, possibly non-conforming meshes. We had proposed an explicit scheme based on a classical Discontinuous Galerkin formulation which is able to deal with structured non-conforming grids [33]. The method relies on a set of local basis functions whose degree may vary at subgrid interfaces. We still use a centered mean approximation for the surface integrals and a second-order leap-frog scheme for advancing in time. We prove that the resulting scheme is stable and that it conserves a discrete analog of the electromagnetic energy.

The method is currently being reimplemented in a cartesian grid setting and numerical parallel acceleration of this implementation will be a part of the PhD thesis subject of Antoine Bouquet (completely funded by France Telecom R&D). Other interesting questions are the possibility to enhance accuracy and to couple with fictitious domain methods.

6.1.3. Finite volume and discontinuous Galerkin type methods for frequency domain electromagnetics

Keywords: *Maxwell equations*, *cell centered scheme*, *discontinuous Galerkin*, *finite volume*, *frequency domain*, *unstructured mesh*.

Participants: Hugo Fol, Stéphane Lanteri, Serge Piperno.

The goal of this study, which started in October 2003 with the doctoral thesis of Hugo Fol, is to extend the finite volume [6] and discontinuous Galerkin [43] methods, previously designed for the numerical simulation of time domain problems, to the solution of the frequency domain Maxwell equations. As for time domain applications, we are interested in numerical methods that can handle unstructured (tetrahedral) meshes. Such frequency domain finite volume and finite element methods lead to the inversion of a sparse (complex) linear system whose matrix operator may exhibit scale discrepancies in the coefficients due to the heterogeneity of the underlying medium as in the case of head tissues exposure to a radio-frequency field. Then, if an iterative solution method is preferred, it is necessary to devise appropriate preconditioners that take care of the matrix stiffness. This is an important component of our study that will lead us to investigate various strategies including domain decomposition based and algebraic multigrid preconditioning methods among others.

6.1.4. Computational bioelectromagnetics

Keywords: *MRI*, *Maxwell equations*, *finite difference time domain*, *finite element time domain*, *finite volume time domain*, *image processing*, *mobile-phone*, *numerical dosimetry*, *structured mesh*, *thermal effects*, *unstructured mesh*.

Participants: Nicholas Ayache [project-team Epidaure], Grégory Beaume, Isabelle Bloch [ENST Paris], Jasmin Burguet [ENST Paris], Olivier Clatz [project-team Epidaure], Maureen Clerc [project-team Odyssée], Garry Cohen [project-team Ondes], René De Seze [INERIS, center of Verneuil-en-Halatte], Claude Dedeban [France Télécom R&D, center of La Turbie], Hervé Delingette [project-team Epidaure], Najib Gadi [ENST Paris], Patrick Joly [project-team Ondes], Stéphane Lanteri, Steve Oudot [project-team Geometrica], Theodore

Papadopoulo [project-team Odyssée], Jean-Philippe Pons [project-team Odyssée], Serge Piperno, Gilles Scarella, Joe Wiart [France Télécom R&D, center of Issy-les-Moulineaux].

Project-team Caiman is the coordinator of the HEADEXP [26] (realistic numerical modelling of human HEAD tissues EXPosure to electromagnetic waves from mobile phones) cooperative research initiative started in January 2003 for a duration of two years. The ever-rising diffusion of mobile phones has determined an increased concern for possible consequences of electromagnetic radiation on human health. In fact, when a cellular phone is in use, the transmitting antenna is placed very close to the user's head where a substantial part of the radiated power is absorbed. In the last decade, several research projects have been conducted in order to evaluate the biological effects resulting from human exposure to electromagnetic radiation. In this context, it is widely accepted that a distinction must be made between thermal and non-thermal biological effects. Thermal effects such as headaches have been reported by numerous users.

Biological effects of microwave radiation have been investigated both from the experimental and numerical viewpoints. Concerning numerical modelling, the power absorption in a user head is computed using discretized models built from clinical MRI data. The great majority of such numerical studies have been conducted using the widely known FDTD (Finite Difference Time Domain) method. In this method, the whole computational domain is discretized using a structured (cartesian) grid. Due to the possible straightforward implementation of the algorithm and the availability of computational power, FDTD is currently the leading method for numerical assessment of human exposure to electromagnetic waves. However, limitations are still seen, due to the rather difficult departure from the commonly used rectilinear grid and cell size limitations regarding very detailed structures of head tissues as well as of a handset which might be essential for reliable compliance testing. So far, little attention has been paid to the application of numerical methods able to deal with unstructured grids that is, FETD (Finite Element Time Domain) and FVTD (Finite Volume Time Domain) methods.

The HEADEXP project aims at filling the gap between human head MRI images and the efficient and accurate numerical modelling of the interaction of electromagnetic waves emitted by mobile phones on biological tissues. This is made possible by the development of appropriate image analysis tools and automated unstructured mesh generation tools for the construction of realistic discretized human head models. Then, a first objective is to use the resulting head models to perform a dosimetric analysis of the radiated electromagnetic wave. In HEADEXP, this analysis relies on the FETD and FVTD solvers developed in the Caiman and Ondes project-teams. The results of these solvers are compared with those of the routinely used FDTD method for this task. A particular emphasis is put on the ability of the solvers to take into account the heterogeneity of the electromagnetic characteristics (conductivity, permittivity, permeability tensors) of the underlying media. Starting from the result of the numerical dosimetry analysis, a second objective of the HEADEXP project is to study the thermal effects induced by the dissipation of electric energy in the biological tissues. This requires the numerical solution of an appropriate bioheat equation that models heat transfers in biological tissues.

6.1.5. *Finite volume method for seismic wave propagation*

Keywords: *P-SV wave propagation*, *centered scheme*, *finite volume*, *velocity-stress system*.

Participants: Mondher Benjemaa, Nathalie Glinsky-Olivier, Serge Piperno, Jean Virieux [Géosciences Azur].

Numerical methods for the propagation of seismic waves have been studied for many years. Most of these numerical codes rely on finite-element or finite-difference methods. Among the most popular schemes, we can cite the staggered-grid-finite-difference scheme proposed by J. Virieux [51] and based on the first-order velocity-stress hyperbolic system of elastic waves equations which is an extension of the scheme derived by K.S. Yee for the solution of the Maxwell equations. The use of quadrangular meshes is a limitation for such codes especially when it is necessary to incorporate surface topography or curved interface. Then, our objective is to solve these equations by finite volume methods on unstructured triangular meshes. This work is done in close collaboration with J. Virieux (Géosciences Azur, CNRS, Sophia Antipolis).

To study the P-SV wave propagation in an heterogeneous medium, we solve the first-order hyperbolic system of elastic wave equations (Virieux, 1986) in a vertical 2D medium, supposed linearly elastic and isotropic (parameters for the medium are the density ρ and the Lamé coefficients λ and μ). This system having the same characteristics the Maxwell equations, we solve it using an adaptation of the second-order centered leap-frog scheme initially developed by M. Remaki [47]. The finite volumes are the elements of the triangular mesh.

The validation of this method has been continued by studying the P-SV wave propagation in an homogeneous medium with a horizontal free surface. Solutions have been compared to analytical seismograms for horizontal and vertical velocities [41]. This method also provides satisfying solutions of the weathered-layer test case (heterogeneous medium with a free surface). A new absorbing flux condition, coming from the methods dedicated to the Maxwell equations, has been implemented. A comparison of this technique with the absorbing boundary conditions of PML type is currently being performed.

We are also interested in the simulation of a fault, dynamic or preexistent. This problem has already been solved especially by finite-difference methods for which the fault is represented by a set of local sources following the fault's geometry. Using finite-volume methods, two techniques can be proposed. The first one considers the fault as a set of triangles and the solutions obtained have been validated by cofrontation with results of the finite-difference method. A second method, new and more original, consists of a representation of the fault by a set of segments instead of elements. A study of the total energy of the system provides a flux condition in the fault which is stable and accurate. Satisfying results have been obtained for a preexistent fault and we are now considering the case of a dynamic fault.

We are also interested in the application of discontinuous Galerkin type methods to the solution of these equations and in the extension to the three-dimensional case.

6.2. Computational fluid dynamics and related problems

6.2.1. *Acoustic waves propagation in a steady non-uniform flow*

Keywords: *L2 stability*, *absorbing boundary condition*, *centered fluxes*, *discontinous Galerkin method*, *finite volume method*, *leap-frog time scheme*, *linearized Euler equations*, *reflecting boundary condition*, *steady non-uniform flow*, *unstructured meshes*.

Participants: Marc Bernacki, Serge Piperno.

We are currently studying the propagation of acoustic waves in a steady inviscid flow. This subject is directly related to many research themes of the project-team. Starting from a steady solution of the Euler equations in a given configuration (geometry, mesh, flow), we aim at propagating acoustic waves in this continuously heterogeneous medium. This is done by simulating the propagation of very small perturbations, following the linearized Euler equations. We then apply in this context of wave-advection equations the same kind of dissipation-free numerical methods which were developed by the team for electromagnetics in the time domain.

A general discontinuous Galerkin framework has been introduced for the propagation of aeroacoustic perturbations of either uniform or non uniform, steady solution of the three-dimensional Euler equations [20]. An explicit leap-frog time-scheme along with centered numerical fluxes are used into the proposed Discontinous Galerkin Time Domain (DGTD) method. We have developed slip and absorbing boundary conditions. Stability is proved, under CFL-like stability condition on the time step for steady uniform flow. For steady non uniform flow, we dispose of energy estimations depending of the regularity of the flow. Tests cases illustrate the potential of our scheme [20]. We are considering the possibility to have a more accurate description for the supporting flow (it is currently constant over tetrahedra, and could simply be piecewise linear and continuous).

6.2.2. *Self-adaptive moving meshes*

Keywords: *TVD property*, *arbitrary Lagrangian-Eulerian formulation*, *arbitrary explicit-implicit scheme*, *computational fluid dynamics*, *finite volume*, *hyperbolic conservation laws*, *mesh adaptation*, *monotonicity*, *unstructured dynamic mesh*, *variable topology*.

Participants: Maud Poret, Serge Piperno.

We have considered dynamic self-adaptative mesh methods for solving hyperbolic linear or non-linear equations in one or two space dimensions. These methods are based on two approaches: the first relies on a moving mesh process without changing mesh topology, the second consists in local and dynamical grid refinement-coarsening. We employ a finite volume scheme based on variable grids (moving and refined) with numerical Godunov-type flows. The main originality consists in writing a finite volume method on a variable topology, hence introducing appearing or disappearing finite volumes (and writing finite volume formulations on possibly void control volumes).

The solutions adopted in one-dimensional problems [40] were chosen for their natural extension to two space dimensions. We have extended and generalized the one-dimensional tools in two space dimensions. The main difficulties are the handling of an unstructured topology with appearing and disappearing elements, and the application of constraints on mesh adaptation and motion to exclude the possibility for control volumes to become strictly negative (leading to more than one approximate values for some points). We have obtained interesting numerical results, for both steady and unsteady, supersonic and transsonic flows past fixed or rigidly moving airfoil profiles [45].

6.2.3. *Relaxation methods for the compressible Navier-Stokes equations*

Keywords: *Enskog-Chapman development*, *Navier-Stokes equations*, *entropy*, *finite volume*, *real gas*, *relaxation method*.

Participants: Nathalie Glinsky-Olivier, Alexandre Ern [CERMICS].

Gas flows arising in many engineering applications may be modeled using the compressible Navier-Stokes equations. These equations express the conservation of mass, momentum and energy and must be completed by a thermodynamic model providing the pressure and the temperature as functions of the conservative variables. The simplest model is that of a thermally perfect and calorifically perfect gas (TPCP, also referred to as polytropic ideal gas) in which, firstly, the pressure p is bilinear in the density ρ and the specific internal energy ε, $p = (\gamma - 1)\rho\varepsilon$, where $\gamma > 1$ is a constant (which is also the ratio between calorific capacities at constant pressure and volume) and secondly, the temperature T is linear in ε and does not depend on the density : $\varepsilon : T = (\gamma - 1)\,\varepsilon/R$, where R is a constant given by the universal gas constant divided by the molecular mass of the gas. Because of its relative simplicity, the TPCP gas model has often been considered in applications. Many robust Navier-Stokes solvers based on this assumption exist ; some of them involve finite volume discretizations in which the Riemann solver explicitly relies upon the TPCP gas model.

Many gas flows require a more elaborate thermodynamic model (for instance, polyatomic gas flows or high pressure flows). The pressure and the temperature are then nonlinear functions of the specific internal energy, while the pressure is still bilinear in the density and the temperature. Such gases will be referred to as thermally perfect (TP).

An attractive approach to incorporate complex pressure and temperature laws in the numerical simulation of gas flows is to consider a relaxation method. For the Euler equations, a relaxation method has been derived recently by Coquel and Perthame [34].

We have developed a relaxation method for the compressible Navier-Stokes equations. The main difference with the Euler equations is that because of the presence of diffusive fluxes, it is necessary to account not only for pressure relaxation but also for temperature relaxation. The new system is solved using a mixed finite volume/finite element method applicable to unstructured triangular meshes. The convective fluxes are evaluated using a Roe scheme of order 3, thanks to a combination of the MUSCL method and a β-scheme. For most complex test cases, a recent more robust limiter designed for the Euler equations [42] to yield fourth-order accuracy has also been implemented. The scheme is explicit in time and based on a four step Runge-Kutta method. The diffusive fluxes and the additional terms coming from the relaxation method are approximated by a P1 finite element interpolation technique.

Attention has been focused on the study of the interaction of a reflected shock wave with the incident boundary layer in a shock tube for two values of the Reynolds number $Re = 200$ and $Re = 1000$, and we have

compared our solutions with published results [35][48]... In all cases, the energy relaxation method is able to predict accurately the flow dynamics, even in the case $Re = 1000$ for which the flow is very complex. We have also investigated the case where the adiabatic exponent is temperature dependent and follows the vibrational model. Because of the strong temperature variations present in the flow, non-linearities arising in the adiabatic exponent yield a sizeable impact on the flow dynamics. The agreement between the results obtained with the relaxation method and those of an extended real gas Navier-Stokes code appears to be excellent.

6.3. Domain decomposition and coupling algorithms

6.3.1. *Convergence analysis of additive Schwarz for the Euler equations*

Keywords: *Euler equations*, *additive Schwarz*, *domain decomposition*, *finite volume*, *interface conditions*.

Participants: Victorita Dolean [Université d'Evry et CMAP, École Polytechnique], Stéphane Lanteri, Frédéric Nataf [CMAP, École Polytechnique].

We are interested here in the design, analysis and evaluation of domain decomposition methods for the solution of algebraic systems resulting from the discretization of hyperbolic or mixed hyperbolic/parabolic systems of partial differential equations such as those modelling compressible fluid mechanics problems. This activity is carried out in the context of a collaboration that was initiated during the doctoral thesis of Victorita Dolean [36]. This study is concerned with the convergence analysis of a domain decomposition method applied to the solution of the system of Euler equations. This method has previously been the subject of a numerical investigation in the context of the calculation of steady, 2D, compressible inviscid flows using a finite volume formulation on unstructured triangular meshes [2]. We recall that the proposed domain decomposition method relies on the formulation of a non-overlapping additive Schwarz algorithm which involves interface conditions that are Dirichlet conditions for the characteristic variables corresponding to incoming waves (often referred to as *natural* or *classical* interface conditions), thus taking into account the hyperbolic nature of the Euler equations. Here (see also [12]), the convergence of the additive Schwarz algorithm is first analyzed in the two- and three-dimensional continuous cases by considering the linearized equations and applying a Fourier analysis. We limit ourselves to the cases of two and three-subdomain decompositions with or without overlap and we obtain analytical expressions of the convergence rate of the Schwarz algorithm. Besides the fact that the algorithm is always convergent, surprisingly, there exist flow conditions for which the asymptotic convergence rate is equal to zero. Moreover, this behavior is independent of the space dimension. In a second step, we study the discrete counterpart of the non-overlapping additive Schwarz algorithm based on the implementation adopted [2] but assuming a finite volume formulation on a quadrangular mesh. We found out that the expression of the convergence rate was actually more characteristic of an overlapping additive Schwarz algorithm. Finally, updated numerical results confirmed qualitatively the convergence behavior found analytically.

6.3.2. *Time and space multi-scale approaches for the 1D and 2D Maxwell/acoustic equations*

Keywords: *centered flux*, *coupling algorithm*, *discontinuous Galerkin method*, *finite volume method*, *leap-frog time scheme*, *locally refined mesh*, *one-dimensional Maxwell system*, *stability*, *subcycling*, *time domain*, *two-dimensional acoustics equations*.

Participant: Serge Piperno.

Aiming at solving the Maxwell equations in the time domain with locally refined grids (structured or unstructured), we study the possibility of using both space and time locally refined subdomains. We are developing in two space dimensions for acoustics the numerical algorithms proposed in 1D [44]. We still consider coupling algorithms for time-subcycling by subdomain where no implicit solution is required. Some careful implementation details have to be taken into account to obtain a satisfying extension to two space dimensions.

6.3.3. *Plasmic environment of satellites*

Keywords: *Vlasov-Poisson equations model coupling*, *ionization*, *magnetosphere*, *plasma*, *plasmic propulsion*.

Participants: Martine Chane-Yook, Anne Nouri [LATP, CMI, Université de Provence], Frédéric Poupaud, Serge Piperno, Sébastien Clerc [Alcatel Space].

In collaboration with Alcatel Space, we study problems related to the electrostatic charge of satellites. These charges are received periodically from the sun and from the plasmic propulsors (which will be more used in a near future). The presence of these charged particles can lead to undesired potential gaps and eventually to electrostatic discharges (able to destroy some parts of solar energy generators). Following the pioneering work of Olivier Chanrion, which provided a software for the pseudo-transient two-dimensional axisymmetric Vlasov-Poisson equations, Martine Chane-Yook is aiming at developing a three-dimensional code, including the same features and starting from a basis developed by Sébastien Clerc at Alcatel. During the last year, the use of infinite elements at the outside boundary for the Poisson equation has been validated in three space dimensions. At the same time, we have examined the hypotheses under which the spatial volumic charge had to be taken into account or not. If needed, it is computed using a back-trajectories algorithm which is also used for the computation of currents impacting the surface of the satellite. Finally, an algorithm for the determination of the electric potential of conductors (starting from magnetospheric currents, themselves evaluated using back-trajectories) has been proposed, where relaxation has been added to improve iterative convergence [8].

6.4. High performance parallel and distributed computing

6.4.1. *Large-scale three-dimensional electromagnetics calculations*

Keywords: *MPI*, *aeroacoustics*, *cell centered scheme*, *discontinuous Galerkin*, *domain partitioning*, *electromagnetics*, *finite volume*, *message passing*, *parallel computing*, *time domain*, *unstructured mesh*.

Participants: Marc Bernacki, Loula Fezoui, Stéphane Lanteri, Serge Piperno.

The numerical simulation of realistic three-dimensional electromagnetics and aeroacoustics problems typically translates into the processing of very large amounts of data, especially for external problems. This is essentially the result of two antagonistic parameters: the characteristic space step of the mesh and the computational domain size. For high frequency phenomena, the space step can be very small while the artificial boundaries of the computational domain are located near the scattering object whereas an opposite situation is obtained for low frequency phenomena. Several numerical techniques can be considered in order to handle this problem to some extent such as, for instance, the reduction of the computational domain size through the use of perfectly matched layers. However, these numerical modelling adaptations are generally not sufficient and the computational power and memory capacity that are required for the simulation of realistic problems are such that the use of parallel computing platforms becomes essential. With respect to this need, we have developed parallel versions of our finite volume and discontinuous Galerkin methods for the solution of elctromagnetic and aeroacoustic wave propagation problems on unstructured tetrahedral meshes [9], using a SPMD (Single Program Multiple Data) strategy that combines a partitioning of the computational domain and a message passing programming model based on MPI (Message Passing Interface).

6.4.2. *Grid computing for the simulation of large-scale electromagnetic problems*

Keywords: *Grid computing*, *ProActive java library*, *high performance computing*, *parallel and distributed computing*, *time-domain Maxwell equations*.

Participants: Françoise Baude [project-team Oasis], Denis Caromel [project-team Oasis], Christian Delbe [project-team Oasis], Saïd El Kasmi, Fabrice Huet [project-team Oasis], Stéphane Lanteri, Romain Quilici [project-team Oasis].

For scientific applications such as those considered in project-team Caiman, the effective use of a heterogeneous, distributed, computing platform (i.e. a grid computing platform) requires new studies that must address several topics ranging from computer science concerns to more application related issues. This is for example the case for the development of numerical simulation tools that will be able to exploit several high performance computers (clusters of PCs, SMPs) geographically distributed. Indeed, from the computer science viewpoint,

it is necessary to devise new parallelization strategies that will take into account the heterogeneity of the computational nodes (CPUs) and the interconnection networks. This characteristics could also be considered at the numerical modelling level through the design of hierarchical PDE solvers based on domain decomposition principles. However, grid computing also motivates the development of new generation collaborative tools that will allow several people located in different sites, to follow or even act on a running numerical simulation. Such a tool will ideally be based on different modules (PDE solver, visualization server, geometric modeler, etc.) that will be coupled and distributed on special purpose computers (clusters of PCs, SMPs, high performance graphical server).

Both applications discussed above could be designed as component based distributed applications and, in order to do so, it would be necessary to adopt an appropriate programming paradigm. In 2002, we have initiated a collaboration with computer scientists from the project-team Oasis at INRIA Sophia Antipolis whose general objective is to apply distributed object-oriented programming principles to the context of computational electromagnetics applications. Two main activities have been considered so far.

For what concerns numerical simulation tools, we have developed JEM3D [29], an object-oriented time domain finite volume solver for the 3D Maxwell equations (see section 5.4 for more details).

Beside this activity, we are also working on the development of a collaborative tool for the interactive visualization of three-dimensional numerical simulation results [28]. Here, the objective is to define a framework that allows for the coupling of a parallel PDE solver with a visualization server. The visualization server is based on the VTK [31] (Visualization ToolKit). Ideally, this environment should be as generic as possible with regards to the characteristics of the parallel PDE solver. In practice, a client/server based paradigm is selected and implemented using a component based model. As previously, the development of this collaborative tool relies on the ProActive library.

7. Contracts and Grants with Industry

7.1. Assistance in parallelization of structured grid schemes on distributed memory platforms (INRIA-FT R&D)

Participants: Serge Piperno, Stéphane Lanteri, Claude Dedeban [France Télécom R&D, center of La Turbie], Antoine Bouquet.

France Télécom R&D (center of La Turbie) is developing its own FDTD-based software and exploits them on internal parallel machines. We help FT R&D with the transfer of time-domain software from shared to distributed memory parallel platforms. This collaborations also deals with some parallel and structured reprogramming of the experimental software developed by N. Canouet during his thesis.

7.2. Evaluation of the MAXDG0/MAXDG1 software (INRIA-CEA)

Participants: Stéphane Lanteri, Serge Piperno, Loula Fezoui.

The CEA/DAM (Division of Military Applications at CEA) takes part with EADS (for the DGA) in the development of a software for the numerical simulation of interactions of transient fields and particles. We share our experiences on Vlasov-Maxwell system and help CEA with numerical benchmarking of our software MAXDG0/MAXDG1.

7.3. Numerical methods for the time-domain solution of Maxwell or acoustics equations (INRIA-EADS)

Participants: Stéphane Lanteri, Serge Piperno, Hugo Fol.

EADS (CCR) has been supporting our research and development effort for many years, mainly concerning the Fast Multipole Methods and their multiple extensions. This ongoing collaboration allows the funding of

a PhD thesis on the frequency-domain version for our finite volume or discontinuous Galerkin approchaes, and on the coupling of boundary element and finite volume approaches. With this collaboration, we stay in touch with industrial concerns and EADS with one of the French groups working on time-domain acoustics and electromagnetics.

7.4. Electrostatic charge of satellites (INRIA-Alcatel)

Participants: Martine Chane-Yook, Frédéric Poupaud, Serge Piperno, Sébastien Clerc [Alcatel Space], Thierry Dargent [Alcatel Space].

In collaboration with Alcatel, we continue our effort on the numerical simulation of electrostatic charges and discharges of artificial satellites. After the PhD thesis of Olivier Chanrion, Alcatel has partially funded PhD thesis of Martine Chane-Yook, on the three-dimensional simulation of the Vlasov-Poisson equations around realistic satellites, starting from an Alcatel software basis from Sébastien Clerc.

7.5. Multilayer modelling and integral equations (INRIA-FT R&D)

Participants: Serge Piperno, Christel Luquet-Piperno, Claude Dedeban [France Télécom R&D, center of La Turbie].

France Télécom R&D (center of La Turbie) has developed an internal software for the numerical solution of three-dimensional electromagnetics in the frequency domain by integral equations. In this context, they have developed but not yet validated an approach allowing the simulation of multi-layered patch antennas, without discretization of all interfaces between different media. This software has been validated, extended to magnetic currents.

8. Other Grants and Activities

8.1. Regional collaborations

8.1.1. DGTD methods for Maxwell on locally refined cartesian grids (FT R&D)

Following the pioneering work of Nicolas Canouet, Antoine Bouquet has been hired as an internally funded PhD student on the same subject: transform inhouse software for the time-domain solution of Maxwell equations based on Yee's scheme (regular orthogonal structured grid) by replacing the finite difference algorithms by discontinuous Galerkin finite element methods. The goal is to obtain the flexibility and modularity of DGTD methods, while keeping existing pre- and post-processors.

8.1.2. Finite volume method for seismic wave propagation (Géosciences Azur)

Numerical methods for the propagation of seismic waves have been studied for many years. Most of these numerical codes rely on the finite-element or the finite-difference methods. Among the most popular schemes, we can cite the staggered-grid-finite-difference scheme proposed by J. Virieux [51] and based on the first-order velocity-stress hyperbolic system of elastic waves equations which is an extension of the scheme derived by K.S. Yee to the solution of the Maxwell equations. The use of quadrangular meshes is a limitation for such codes especially when it is necessary to incorporate surface topography or curved interface. Then, our objective is to solve these equations by finite volume methods on unstructured triangular meshes. This work is done in close collaboration with J. Virieux (Géosciences Azur, CNRS, Sophia Antipolis), whose laboratory is partially funding the PhD thesis of Mondher Benjemaa.

8.1.3. Plasmic environment of satellites (University of Provence)

In collaboration with Alcatel Space, we study the problems related to the electrostatic charge of satellites. These charges are received periodically from the sun and from the plasmic propulsors (which will be more used in a near future). The presence of these charged particles can lead to undesired potentials gaps and eventually to electrostatic discharges (able to destroy some parts of solar energy generators). Following the pioneering

work of Olivier Chanrion, Martine Chane-Yook is aiming at developing a three-dimensional code, including the same features and starting from a basis developed by Sébastien Clerc at Alcatel. This PhD thesis work is advised by Anne Nouri (LATP, CMI, Université de Provence).

8.2. National collaborations

8.2.1. Computational bioelectromagnetics (INRIA ARC HEADEXP)

Keywords: *MRI*, *Maxwell equations*, *finite difference time domain*, *finite element time domain*, *finite volume time domain*, *image processing*, *mobile-phone*, *numerical dosimetry*, *structured mesh*, *thermal effects*, *unstructured mesh*.

Participants: Nicholas Ayache [project-team Epidaure], Grégory Beaume, Isabelle Bloch [ENST Paris], Jasmin Burguet [ENST Paris], Olivier Clatz [project-team Epidaure], Maureen Clerc [project-team Odyssée], Garry Cohen [project-team Ondes], René De Seze [INERIS, center of Verneuil-en-Halatte], Claude Dedeban [France Télécom R&D, center of La Turbie], Hervé Delingette [project-team Epidaure], Najib Gadi [ENST Paris], Patrick Joly [project-team Ondes], Stéphane Lanteri, Steve Oudot [project-team Geometrica], Theodore Papadopoulo [project-team Odyssée], Jean-Philippe Pons [project-team Odyssée], Serge Piperno, Gilles Scarella, Joe Wiart [France Télécom R&D, center of Issy-les-Moulineaux].

Stéphane Lanteri is the coordinator of the HEADEXP [26] (realistic numerical modelling of human HEAD tissues EXPosure to electromagnetic waves from mobile phones) cooperative research initiative (see in section 6.1 for more details).

9. Dissemination

9.1. Scientific animation

9.1.1. Sophia Antipolis Club of parallel computing users

Stéphane Lanteri is co-chairing a regional initiative dedicated to parallel and distributed computing [23].

9.1.2. Grid5000@Sophia project

Stéphane Lanteri is the scientific coordinator of the Grid5000@Sophia project [25]. The INRIA Sophia Antipolis research unit has been selected by the French Ministry of Research, in the framework of the ACI GRID programme, to be one of the main nodes of the GRID'5000 computing infrastructure. The GRID'5000 initiative aims at building an experimental grid platform gathering less than a dozen of geographically distributed sites in France combining up to 5000 processors with a certain level of heterogeneity both in terms of processor and network types. The current plans are to assemble a physical platform featuring 8 clusters, each with between 100 to 1000 PCs connected by the Renater education and research national network. All clusters will be connected to Renater at 1 Gb/s (10 Gb/s is expected in a near future). This highly collaborative effort is funded by the French Ministry of Research, INRIA, CNRS and several regional councils. The Grid5000@Sophia project is built around scientific contributions from the Caiman, Coprin, Epidaure, Oasis and Smash project-teams that are concerned with object oriented middleware for distributed computing, algorithms for high performance computing on the grid (computational electromagnetics, computational fluid dynamics, optimal design of complex systems) and grid computing for medical applications.

9.1.3. Editing, scientific committees

Stéphane Lanteri is a nominated member of CNU 26th section at University Claude Bernard Lyon 1.

Serge Piperno is a supplementary elected member of INRIA's evaluation board and participated to the CR2 local admissibility board at Rocquencourt.

Serge Piperno is member of the editing committee of "Progress in computational fluid dynamics" (Inderscience).

Serge Piperno is member of the steering scientific committee of ONERA's federative research project "Couplage de Codes de Calcul Scientifique".

9.2. Teaching

- *Équations intégrales*, *Interactions fluide-structure*, Serge Piperno, "Mastère de Mécanique Numérique", École Nationale Supérieure des Mines de Paris (12h).
- Organization by Serge Piperno of an "opening week" at INRIA Sophia Antipolis for ENPC students.
- Organization by Anne Nouri, Frédéric Poupaud and Serge Piperno of "Journée simulation numérique pour les plasmas", at INRIA Sophia Antipolis, december 15-16.

9.3. Master and PhD students supervision

9.3.1. PhD thesis defended in 2004 in the project-team

1. Martine Chane-Yook, Modélisation et simulation 3D de la charge d'un satellite en environnement plasmique, université de Provence. Jury : Anne Nouri (advisor), Kazuo Aoki (reviewer), Stéphane Mischler (reviewer), Sébastein CLerc, Olivier Gues, Serge Piperno.

9.3.2. Ongoing PhD theses in the project-team

1. Marc Bernacki, Schémas en volumes finis avec flux centrés appliqués à l'aéroacoustique, ENPC.
2. Mondher Benjemaa, Simulation numérique de la rupture dynamique des séismes par des méthodes volumes finis en maillages non structurés, Université de Nice-Sophia Antipolis.
3. Antoine Bouquet, Adaptation de méthodes des domaines fictifs au schémas de type Galerkin discontinu avec sous-maillage, Université de Nice-Sophia Antipolis.
4. Maud Poret, Méthodes en maillages mobiles auto-adaptatifs pour des systèmes hyperboliques en une et deux dimensions d'espace - Application aux interactions fluide-structure, ENPC.
5. Hugo Fol, Couplage de schémas en volumes finis et de méthodes intégrales pour la propagation d ondes électromagnétiques, acoustiques et sismiques, Université de Nice-Sophia Antipolis.

9.3.3. Supervision activity

1. Serge Piperno is supervising the theses of Marc Bernacki, Antoine Bouquet and Maud Poret, and co-supervising the ones of Hugo Fol and Mondher Benjemaa.
2. Nathalie Glinsky-Olivier is co-supervising the thesis of Mondher Benjemaa.
3. Stéphane Lanteri is supervising the post-doctoral research of Gilles Scarella and is co-supervisor of the thesis of Hugo Fol. He has supervised the activity of Saïd El Kasmi.

9.3.4. Thesis reviewing activity

- Serge Piperno was reviewer for the PhD Thesis of Laurent Terzolo (ENSMP) and took part to the jury of Martine Chane-Yook (université de Provence) and Jeronimo Rodríguez-García (INRIA Rocquencourt).

9.4. Invitations, seminars, communications

- Seminars of Serge Piperno at ENST inside ARC HEADEXP intermediate meeting and at INRIA Rocquencourt (CRESPO).
- Presentations of Martine Chane-Yook and Serge Piperno during the "Journée sur les méthodes numériques pour les plasmas" at INRIA Sophia Antipolis.
- Seminar of Stéphane Lanteri at the workshop on "Linear solvers for coupled systems of PDEs" that took place at the Institut Henri Poincaré in May 2004.
- Communications of Serge Piperno at PIERS 2004, of Marc Bernacki and Martine Chane-Yook at the CANUM'2004.
- Presentation of Marc Bernacki in a closed "Computational Aeroacoustics Seminar" with EADS and inside a "Journée de rencontre aéroacoustique" at ENSTA.
- Participation de Stéphane Lanteri et Serge Piperno au CEMRACS 2004 (et au workshop IM2IM au sein de cette manifestation).

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[8] M. CHANE-YOOK. *Etude d'une équation cinétique liée à l'effet Compton. Modélisation et simulation 3D de la charge d'un satellite en milieu magnétosphérique*, Ph. D. Thesis, Université de Provence, décembre 2004.

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