2025 *Activity Report*

RESEARCH CENTRE: **Inria Centre at the University of Bordeaux**
IN PARTNERSHIP WITH: **Bordeaux INP**

Project-Team

CARDAMOM

Certified Adaptive discRete moDels for robust simulAtions of CoMplex flOws with Moving fronts

In collaboration with Institut de Mathématiques de Bordeaux (IMB)

Project-Team CARDAMOM

Creation of the Project-Team: 2016 June 01

Each year, Inria research teams publish an Activity Report presenting their work and results over the reporting period. These reports follow a common structure, with some optional sections depending on the specific team. They typically begin by outlining the overall objectives and research programme, including the main research themes, goals, and methodological approaches. They also describe the application domains targeted by the team, highlighting the scientific or societal contexts in which their work is situated. The reports then present the highlights of the year, covering major scientific achievements, software developments, or teaching contributions. When relevant, they include sections on software, platforms, and open data, detailing the tools developed and how they are shared. A substantial part is dedicated to new results, where scientific contributions are described in detail, often with subsections specifying participants and associated keywords. Finally, the Activity Report addresses funding, contracts, partnerships, and collaborations at various levels, from industrial agreements to international cooperations. It also covers dissemination and teaching activities, such as participation in scientific events, outreach, and supervision. The document concludes with a presentation of scientific production, including major publications and those produced during the year.

Keywords

Computer sciences and digital sciences

A6.1. – Methods in mathematical modeling
A6.1.1. – Continuous Modeling (PDE, ODE)
A6.1.4. – Multiscale modeling
A6.1.5. – Multiphysics modeling
A6.2. – Scientific computing, Numerical Analysis & Optimization
A6.2.1. – Numerical analysis of PDE and ODE
A6.2.8. – Computational geometry and meshes
A6.3. – Computation-data interaction
A6.3.4. – Model reduction
A6.3.5. – Uncertainty Quantification
A6.5.2. – Fluid mechanics

Other research topics and application domains

B3.3.2. – Water: sea & ocean, lake & river
B3.3.3. – Nearshore
B3.4.1. – Natural risks
B4.3.2. – Hydro-energy
B5.2.1. – Road vehicles
B5.2.3. – Aviation
B5.2.4. – Aerospace
B5.5. – Materials

Contents

1 Team members, visitors, external collaborators

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- Mario Ricchiuto [Team leader, INRIA, Senior Researcher, HDR]
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- Maria Kazolea [INRIA, Researcher, HDR]
- Martin Parisot [INRIA, Researcher]

Faculty Members

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- Victor Gonzalez Tabernero [Univ Corogne, from Aug 2025 until Sep 2025, from January 1st to January 31st 2025]
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- Joel Perez Villarino [Univ Corogne, from Aug 2025 until Sep 2025, from January 1st to January 31st 2025]
- Zhengfu Xu [UNIV MICHIGAN, from Feb 2025 until May 2025]

2 Overall objectives

CARDAMOM is a joint team of INRIA Bordeaux - Sud-Ouest, University of Bordeaux and Bordeaux Inst. Nat. Polytechnique) and IMB (Institut de Mathématiques de Bordeaux – CNRS UMR 5251, University of Bordeaux). `CARDAMOM` has been created on January 1^{st}, 2015 (website).

The CARDAMOM project aims at providing a robust modelling strategy for engineering applications involving complex flows with moving fronts. The term front here denotes either an actual material boundary (e.g. multiple phases), a physical discontinuity (e.g. shock waves), or a transition layer between regions with completely different dominant flow behaviour (e.g. breaking waves). These fronts introduce a multi-scale behaviour. The resolution of all the scales is however not feasible in certification and optimization cycles. Moreover, the full scale behaviour is not necessary in many engineering applications, while in others it is enough to model the average effect of small scales on large ones (closure models). We plan to develop application-tailored models obtained by a tight combination of *asymptotic PDE* (Partial Differential Equations) modelling, *adaptive high order PDE discretizations*, and a *quantitative certification* step assessing the sensitivity of outputs to both model components (equations, numerical methods, etc) and random variations of the data. The goal is to develop the necessary methods and models allowing to improve operational models used in parametric analysis and design cycles, by increasing both accuracy and confidence in the results. This is achieved by combining improved physical and numerical modelling, and assessment of output uncertainties. This requires a research program mixing of PDE analysis, high order discretizations, Uncertainty Quantification (UQ), and to some extend optimization and inverse modelling. These skills need to be also combined with some specific engineering know how to tackle applications of interest in real life.

2.1 Scientific context and challenges

The objective of CARDAMOM is to provide improved analysis and design tools for engineering applications involving fluid flows with moving fronts. In our applications *a front is either an actual material interface, a boundary of the domain, or a well identified transition region in which the flow undergoes a change in its dominant macroscopic character*. One example is the certification of wing de-anti icing systems, involving the predictions of ice formation and detachment, and of ice debris trajectories to evaluate the risk of downstream impact on aircraft components [86, 39]. Another application, relevant for space reentry, is the study of transitional regimes in high altitude gas dynamics in which extremely thin layers appear in the flow which cannot be analysed with classical continuous models (Navier-Stokes equations) used by engineers [46, 65]. A classical example relevant in coastal engineering is free surface flows. The free surface itself is a material interface, but we can identify also other fronts as e.g. the flooding line (wet/dry transition) or the transition between propagating and breaking waves, across which relevance of dissipation and vorticity changes dramatically [47]. For wave energies, as well as for aquifers, the transition between free surface and congested flows (below a solid surface) is another example [57]. Other similar examples exist in geophysics, astrophysics, aeronautic and aerospace engineering, civil engineering, energy engineering, material engineering, etc.

In all cases, computationally affordable, fast, and accurate numerical modelling is essential to allow reliable predictions in early stages of the design/analysis [88]. Such computational models are also needed for simulations over very long times, especially if changes in many variable input parameters need to be investigated.

To achieve this goal one needs to have a physically relevant Partial Differential Equation (PDE) model, which can be treated numerically efficiently and accurately, which means possibly with some adaptive numerical technique allowing to minimize the computational effort. To this end, the dynamics of some of the fronts can be modelled by appropriate asymptotic/homogenised PDEs, while other interfaces are explicitly described. Even in the best of circumstances in all practical applications the reliability of the numerical predictions is limited by the intrinsic uncertainty on the operational conditions (e.g. boundary/initial conditions, geometry, etc.). To this *aleatory* uncertainty we must add the structural *epistemic* uncertainty related possibly to the use of approximate PDE models. Besides the limited validity of the derivation assumptions, these models are often calibrated/validated with experimental data which is itself subject to errors and post-processing procedures (filtering, averaging, etc ..) [51, 78]. This is even worse in complex flows for which measurements are difficult or impossible to plan or perform due to the inherent exceptional character of the phenomenon (e.g. tsunami events), or technical issues and danger (e.g. high temperature reentry flows, or combustion), or impracticality due to the time scales involved (e.g. study of some new materials' micro-/meso- structure [52]). So the challenge is to construct computationally affordable models robust under variability of input parameters due to uncertainties, certification/optimization, as well as coming from modelling choices.

To face this challenge and provide new tools to accurately and robustly modelize and certify engineering devices based on fluid flows with moving fronts, we propose a program mixing scientific research in asymptotic PDE analysis, high order adaptive PDE discretizations and uncertainty quantification.

2.2 Our approach and objectives

We propose a research program mixing asymptotic PDE modelling, high order adaptive discretizations, and uncertainty quantification. In a standard approach a certification study can be described as a modelling exercise involving two black boxes. The first box is the computational model itself, composed of: PDE system, mesh generation/adaptation, and discretization of the PDE (numerical scheme). The second box is the main robust certification loop which contains separate boxes involving the evaluation of the physical model, the post-processing of the output, and the exploration of the spaces of physical and stochastic parameters (uncertainties). Many interactions exist in this process. Exploiting these interactions could allow to tap as much as possible into the potential of high order methods [68] such as e.g. h-, p-, r- adaptation in the physical model w.r.t. some parametric quantity/sensitivity non necessarily associated to the solution's smoothness.

Our objective is to provide some fundamental advances allowing to bring closer to the operational level modern high order numerical techniques and multi-fidelity certification and optimization algorithms, possibly using some clever paradigm different from the 2-black box approaches above, and involving tight interactions between all the parts of the play: PDE modelling, numerical discretization techniques, uncertainty quantification methods, mesh generation/adaptation methods, physical model validation/calibration, etc. The initial composition of the team provided a unique combination of skills covering all the necessary topics allowing to explore such an avenue. The questions that need to be tackled can be organized in the following main axes/scientific questions:

1. Continuous modelling: how to obtain the PDE description most suited for a given application, and make sure that on one hand its structure embeds sufficiently the physics sudied, and on the other the system is in a form suitable for efficient numerical discretization ?

2. Higher order adaptive discretization: what are the relations between PDE model accuracy (e.g. asymptotic error), PDE constraints (e.g. entropy inequalities, particular steady states, etc) and the scheme consistency ? how to account for additional constraints in the scheme ?

3. Parameter uncertainty and robust modelling: how to properly account when build models on one hand for the variability of physical states defining a process in realistic environments, and on the other of data possibly available for the process in consideration ? is it possible to couple the sampling in the space of parameters with the approximation in physical space ?

These themes are discussed in the following sections together with some challenges specific to the engineering applications considered:

- Aeronautics and aerospace engineering (de-anti icing systems, space re-entry, complex materials);
- Coastal engineering (coastal protection, hazard assessment etc.);
- Energy engineering with a focus on wave energy conversion
- Large scale models on manifolds with a focus on geophysics and some applications in astrophysics and relativity.

3 Research program

3.1 Continuous and discrete asymptotic modelling

In many of the applications we consider intermediate fidelity models can be derived using an asymptotic expansion for the relevant scale resolving PDEs, possibly combined with some form of homogenization or averaging. The resulting systems of PDEs are often very complex. One of the main challenges is to characterize the underlying structure of such systems: possible conservation laws embedded; additional constraints related to consistency with particular physical states (exact solutions), or to stability (entropy/energy dissipation); etc. A question of paramount importance in practical applications is also the formulation of the boundary conditions. The understanding of these properties is necessary for any new model. Moreover, different forms of the PDE may be better suited to enforce some of these properties at the numerical level.

Another issue when working with asymptotic approximations is that of closure. Indeed, important physical phenomena may be unaccounted for either due to some initial modelling assumptions, or because they involve scales much smaller than those modelled. A typical example is wave breaking in some depth averaged models. Another, relevant for our work, is the appropriate prediction of heat fluxes in turbulent flows.

So our main activities on this axis can be classified according to three main questions:

- what is the structure of the PDE model (exact solutions, stability and algebraic or differential constraints embedded, boundary conditions) ?
- what is the form of the model better suited to reproduce numerically certain constraints ?
- how to embed and design closure laws for relevant phenomena not modelled by the main PDE ?

3.2 High order discretizations on moving adaptive meshes

The efficient and robust discretization of complex PDEs is a classical and widespread research subject. The notion of efficiency is in general related to the combination of high order of accuracy and of some adaptation strategy based on an appropriate model of the error [80, 87].

This strategy is of course also part of our work. However, we are convinced that a more effective path to obtain effective discretizations consists in exploiting the knowledge of the PDE structure, embedding as much as possible the PDE structure in the discrete equations. This is related to the notion of enhanced consistency that goes in the direction of what is today often referred to as *constraint or property preserving* discretizations. For the type of PDE systems of our interest, the properties which are of paramount importance to be controlled are for example: the balance between flux divergence and forcing terms (so called well balanced of C-property [42, 77]) and the preservation of some specific steady states; the correct reproduction of the dispersion relation of the system, especially but not only for dispersive wave propagation; the preservation of some algebraic constraints, typically the non-negativity of some thermodynamic quantities; the respect of a discrete entropy/energy equality or inequality (for stability); the strong consistency with some asymptotic limit of the PDE (AP property); etc.

A fundamental issue is the efficient and accurate treatment of boundary and interface conditions. The idea is to have some approach which tolerates the use of non-conformal meshes, which is genuinely high order, and compatible with adaptation, and of course conformal meshing of the boundary/discontinuity. Techniques allowing the control of the geometrical error due to non-conformity is required. For discontinuities, this also requires an ad-hoc treatment of the jump condition. For wall boundaries, initial work using penalization has been done in CARDAMOM in the past [36, 73]. On Cartesian meshes several techniques exist to control the consistency order based on extrapolation/interpolation, or adaptive methods (cf e.g.[81, 72, 37, 50, 59, 54] and references therein). For discontinuities, we can learn from fitting techniques [43], and from some past work by Prof. Glimm and co-workers [49].

For efficiency, mesh adaptation plays a major role. Mesh size adaptation based on both deformation, r-adaptation, or remeshing h-adaptation, can be designed based on some error model representative. For unsteady flows, the capability to use moving meshes becomes necessary. A major question is what conservation means when geometry is modified. The geometrical conservation (GCL) needs of course to be added to the list of constraints to be accounted for [82, 69].

3.3 Applications in physics and engineering

As already mentioned, our focus is on four main classes of problems:

- Aeronautics and aerospace engineering (de-anti icing systems, space re-entry, complex materials)
- Coastal engineering (coastal protection, hazard assessment etc.)
- Energy engineering with a focus on wave energy conversion
- Large scale models on manifolds with a focus on geophysics (and possibly astrophysics).

There are several common aspects. One is the use of asymptotic vertically averaged approximations to produce efficient application-Taylored PDE models. Another common point is the construction of possibly high order constraint/property preserving numerical approximations. This entails the characterization of the underlying PDE models with a set of embedded properties, which go from classical conservation, to exact solutions (steady or moving), to the preservation of differential operators, to the thermodynamic admissibility (non-negativity, preservation of physical bounds). For all applications, the investigation of the parameter dependence of the results will take several forms from sensitivity analyses, to classical parametric studies to understand physical processes, to approximation in parameter space in the framework of hybrid PDE-meta-/reduced-order models.

4 Application domains

4.1 De-anti icing systems

Impact of large ice debris on downstream aerodynamic surfaces and ingestion by aft mounted engines must be considered during the aircraft certification process. It is typically the result of ice accumulation on unprotected surfaces, ice accretions downstream of ice protected areas, or ice growth on surfaces due to delayed activation of ice protection systems (IPS) or IPS failure. This raises the need for accurate ice trajectory simulation tools to support pre-design, design and certification phases while improving cost efficiency. Present ice trajectory simulation tools have limited capabilities due to the lack of appropriate experimental aerodynamic force and moment data for ice fragments and the large number of variables that can affect the trajectories of ice particles in the aircraft flow field like the shape, size, mass, initial velocity, shedding location, etc... There are generally two types of model used to track shed ice pieces. The first type of model makes the assumption that ice pieces do not significantly affect the flow. The second type of model intends to take into account ice pieces interacting with the flow. We are concerned with the second type of models, involving fully coupled time-accurate aerodynamic and flight mechanics simulations, and thus requiring the use of high efficiency adaptive tools, and possibly tools allowing to easily track moving objects in the flow. We will in particular pursue and enhance our initial work based on adaptive immerse boundary capturing of moving ice debris, whose movements are computed using basic mechanical laws.

In [40] it has been proposed to model ice shedding trajectories by an innovative paradigm that is based on CArtesian grids, PEnalization and LEvel Sets (LESCAPE code). Our objective is to use the potential of high order unstructured mesh adaptation and immersed boundary techniques to provide a geometrically flexible extension of this idea. These activities will be linked to the development of efficient mesh adaptation and time stepping techniques for time dependent flows, and their coupling with the immersed boundary methods we started developing in the FP7 EU project STORM [36, 73]. In these methods we compensate for the error at solid walls introduced by the penalization by using anisotropic mesh adaptation [56, 70, 71]. From the numerical point of view one of the major challenges is to guarantee efficiency and accuracy of the time stepping in presence of highly stretched adaptive and moving meshes. Semi-implicit, locally implicit, multi-level, and split discretizations will be explored to this end.

Besides the numerical aspects, we will deal with modelling challenges. One source of complexity is the initial conditions which are essential to compute ice shedding trajectories. It is thus extremely important to understand the mechanisms of ice release. With the development of next generations of engines and aircraft, there is a crucial need to better assess and predict icing aspects early in design phases and identify breakthrough technologies for ice protection systems compatible with future architectures. When a thermal ice protection system is activated, it melts a part of the ice in contact with the surface, creating a liquid water film and therefore lowering ability of the ice block to adhere to the surface. The aerodynamic forces are then able to detach the ice block from the surface [41]. In order to assess the performance of such a system, it is essential to understand the mechanisms by which the aerodynamic forces manage to detach the ice. The current state of the art in icing codes is an empirical criterion. However such an empirical criterion is unsatisfactory. Following the early work of [45, 39] we will develop appropriate asymptotic PDE approximations to describe the water runoff on the wing surface, also accounting for phase change, thus allowing to describe the ice formation and possibly rupture and detachment. These models will constitute closures for aerodynamics/RANS and URANS simulations in the form of PDE wall models, or modified boundary conditions.

In addition to this, several sources of uncertainties are associated to the ice geometry, size, orientation and the shedding location. In very few papers [75], some sensitivity analysis based on Monte Carlo method have been conducted to take into account the uncertainties of the initial conditions and the chaotic nature of the ice particle motion. We aim to propose some systematic approach to handle every source of uncertainty in an efficient way relying on some state-of-art techniques developed in the Team. In particular, we will perform an uncertainty propagation of some uncertainties on the initial conditions (position, orientation, velocity,...) through a low-fidelity model in order to get statistics of a multitude of particle tracks. This study will be done in collaboration with ETS (Ecole de Technologies Supérieure, Canada). The long-term objective is to produce footprint maps and to analyse the sensitivity of the models developed.

4.2 Modelling of wave energy converters

Wave energy conversion is an emerging sector in energy engineering. The design of new and efficient Wave Energy Converters (WECs) is thus a crucial activity. As pointed out by Weber [88], it is more economical to raise the technology performance level (TPL) of a wave energy converter concept at low technology readiness level (TRL). Such a development path puts a greater demand on the numerical methods used.

Our previous work [57][44] has shown the potential of depth-averaged models for simulating wave energy devices. The approach followed so far relies on an explicit coupling of the different domains involving the flow under the structure and the free surface region. This approach has the advantage to need efficient solvers of well-known system of equations (compressible and incompressible flow). However, the transmission condition between this two regimes is now always well understood, depending on the underlying PDE models. Moreover, several sources of numerical instabilities exist because of the different nature of the regions involved (compressible/incompressible). A different approach is proposed in [63, 62], and will be pursued in the coming years. The idea is to solve a unique model in the whole computational domain, with the effect of the structure being accounted for by means of an appropriate pressure variable playing the role of a Lagrange multiplier. Our numerical developments will be performed within the parallel platform `GeoFun`, based on the `Aerosol` library. In order to simulate the dynamic of the floating structures, we will consider the coupling with the open source code Chrono, an external code specialized in the resolution of the rigid body dynamics. The coupling is still under development. In parallel, we will add closure for other complex physical effects as e.g. the modelling of air pocket trapped under the structures. Several industrial processes (SeaTurns, Hace...) are based on chamber compressing air inside by the movement of the water surface. This strategy has the advantage of taking the turbines for energy production out of the water. The strategy is based on a polytropic modelling of the gas dynamics taking into account merging and splitting of the pockets, without a major impact on the efficiency of the simulation (robustness and numerical cost). This works benefits of the associated team LARME with RISE (C. Eskilson).

4.3 Coastal and civil engineering

Our objective is to bridge the gap between the development of high order adaptive methods, which has mainly been performed in the industrial context and environmental applications, with particular attention to coastal and hydraulic engineering. We want to provide tools for adaptive non-linear modelling at large and intermediate scales (near shore, estuarine and river hydrodynamics). We will develop multi-scale adaptive models for free surface hydrodynamics. Beside the models and codes themselves, based on the most advanced numerics we will develop during this project, we want to provide sufficient know how to control, adapt and optimize these tools.

We will focus our effort in the understanding of the interactions between asymptotic approximation and numerical approximation. This is extremely important in several ways. An example is the capability of a numerical model to handle highly dispersive wave propagation. This is usually done by high accuracy asymptotic PDE expansions of by means of multilayer models. In the first case, there is an issue with the constraints on the numerical approximation. Investigations of appropriated error models for adaptivity in the horizontal may permit to alleviate some of these constraints, allowing a reasonable use of lower order discretizations. Concerning multi-layer models, we plan can use results concerning the relations between vertical asymptotic expansions and truncation/approximation error to improve the models by some adaptive approach.

Another important aspect which is not understood well enough at the moment is the role of dissipation in the evolution of the free surface dynamics, and of course in wave breaking regions. There are several examples of breaking closure, going from algebraic and PDE-based eddy viscosity methods [67, 79, 74, 55], to hybrid methods coupling dispersive PDEs with hyperbolic ones, and trying to mimic wave breaking with travelling bores [85, 84, 83, 66, 58]. In both cases, numerical dissipation plays an important role and the activation or not of the breaking closure, as well as on the establishment of stationary travelling profiles, or on the appearance of solitary waves. These aspects are related to the notion of numerical dissipation, and to its impact on the resulting numerical solutions. These elements must be clarified to allow full control of adaptive techniques for the models used in this type of applications.

A fundamental issue that needs to be addressed is the proper discrete formulation of the boundary conditions for dispersive wave approximations. These conditions play of course a critical role in applications and remain an open problem for most Boussinesq models.

4.4 Geophysics and astrophysics

This is work is related to large scale simulations requiring the solution of PDEs on manifolds. Examples are tsunami simulations, as those performed in the past in the TANDEM project led by CEA [64], as well as some applications considered in the ANR LAGOON for climate change. In the framework of the MSCA project SuPerMan we started to look into applications in astrophysics which also involve similar issues. The idea is to consider both coordinate changes related to mesh movement, and in ALE formulations, as well as genuinely curved frames of reference [60], and combinations of both when for example considered mesh movement and adaptation in curvilinear coordinates [38]. Challenges are related to the appropriate PDE formulation, and the respect of continuous constraints at the discrete level.

The objective here is to devise the most appropriate manifold representation, and formulate the PDE system in the appropriate way allowing to embed as many continuous constraints as possible (well balancing, energy conservation, positivity preservation, etc). Embedding the ALE mapping will be necessary to envisage adaptive strategies, improving on [38] and [61].

5 Highlights of the year

- Laura del Río Martín has been hired as Chargée de recherche Inria, and joined CARDAMOM in October 2025;
- Firas Dhaouadi has been hired as Maître de Conférence at Bordeaux INP, and joined CARDAMOM in September 2025;

5.1 Awards

The MSCA proposal COPERNICUS, submitted by Laura del Río Martín, has been accepted and funded. The project official start has been set to February 2026.

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6 Latest software developments, platforms, open data

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6.1 Latest software developments

6.1.1 UHAINA

Keywords: Simulation, Ocean waves, Unstructured meshes, Finite element modelling

Scientific Description: Operational platform for near shore coastal application based on the following main elements:

- Fully-nonlinear wave propagation.

- Wave breaking handled by some mechanism allowing to mimic the energy dissipation in breakers.

- A high order finite element discretization combined with mesh and polynomial order adaptation for optimal efficiency.

- An efficient parallel object oriented implementation based on a hierarchical view of all the data management aspects cared for by middle-ware libraries developed at Inria within the finite element platform Aerosol.

- A modular wrapping allowing for application tailored processing of all input/output data (including mesh generation, and high order visualization).

- Spherical coordinates based on a local projection on a real 3D spherical map (as of 2021)

- Compilation with GUIX available (as of 2022)

- Homogenization and standardization of code outputs and hazard quatification (as of 2022)

- Correction of the management of dry/wet fronts in the presence of structures represented by a single high point (as of 2022)

- Use of FES for the calculation of the tide directly in UHAINA through an API. New compilation option for activation (as of 2022)

- Boundary conditions accounting tides from FES and corrected with the effect of the inverse barometer, for the simulation of the tidal propagation and the surge on domains at the regional scale (as of 2022)

- Hydraulic connections (e.g. sewers) in the simulation of urban flooding (as of 2022)

- Mass source term, for the injection of the volume of water overtopping structures not accounted in the elevation model during flooding episodes by sea surges (as of 2022)

Functional Description: Waves simulation

Contact: Mario Ricchiuto

Participant: 4 anonymous participants

Partners: EPOC, IMAG, IMB

6.1.2 AleVoronoi

Name: Direct Arbitrary Lagrangian Eulerian Finite Volume and Discontinous Galerkin schemes on VORONOI moving meshes with topology changes

Keywords: Finite volume methods, Discontinuous Galerkin, High order methods, Centroidal Voronoi tessellation, ALE, Fortran, OpenMP

Scientific Description: The implementation of AleVoronoi started in April 2018 as a collaboration between E. Gaburro, M. Dumbser (University of Trento, Italy) and W. Boscheri (University of Trento, then University of Ferrara, and now CNRS France). E. Gaburro (now U. Verona) is the main contributor, however, many parts of the code have been taken from existing codes of the other coauthors. Contributions to the code have been given by - S. Chiocchetti, starting from July 2019 (University of Trento, University of Stuttgart and now University of Cologne) , - W. Boscheri (CNRS) - M. Dumbser (U. Trento) - M Ricchiuto (Inria, cardamom) These developments include novel structure preserving numerical methods for hyperbolic balance laws.

Functional Description: Explicit, arbitrary high order accurate, one step (ADER), Finite Volume and Discontinuous Galerkin schemes on 2D moving Voronoi meshes for the solution of general first-order hyperbolic PDEs. Main peculiarity: the Voronoi mesh is moved according to the fluid flow using a direct Arbitrary-Lagrangian-Eulerian (ALE) method achieving high quality of the moving mesh for long simulation times. The high quality of the mesh is maintained thanks to a) mesh optimization techniques and b) the additional freedom of allowing topology changes. The high quality of the results is obtained thanks to the high order ADER schemes. The main novelty is the capability of using high-order schemes on moving Voronoi meshes with topology changes.

The code is written in Fortran + OpenMP.

News of the Year: The latest results concerning inria Cardamom are related to the implementation and validation of genuinely multidimensional finite volume fluxes, inspired by residual distribution methods. The schemes involve fluxes at corners of mesh cells. These fluxes depend on all the corner neighbours which allows the definition of genuinely multidimensional methods (in contrast to fluxes on mesh faces which only depend on 2 face neighbours).

Publications: hal-05124553, hal-04706736, hal-04706734, hal-03850196, hal-02411272

Contact: Elena Gaburro

Participant: 2 anonymous participants

6.1.3 AeroSol

Keywords: High order finite elements, Parallel computing

Functional Description: The AeroSol software is a high order finite element library written in C++. The code has been designed so as to allow for efficient computations, with continuous and discontinuous finite elements methods on hybrid and possibly curvilinear meshes. The work of the team CARDAMOM (previously Bacchus) is focused on continuous finite elements methods, while the team Cagire is focused on discontinuous Galerkin methods. However, everything is done for sharing the largest part of code we can. More precisely, classes concerning IO, finite elements, quadrature, geometry, time iteration, linear solver, models and interface with PaMPA are used by both of the teams. This modularity is achieved by mean of template abstraction for keeping good performances. The distribution of the unknowns is made with the software PaMPA , developed within the team TADAAM (and previously in Bacchus) and the team Castor.

News of the Year: Highlights for the year 2025 concern:

- Subcell limiting (Alessandro Del Piero)

- Coupling with mesh adaptation, computation of metrics (e.g. Hessian) time-dependent mesh adaptation (Dean Yuan)

- wet-dry handling for shallow water models (Dean Yuan)

- Improvements of PETSc usage (Filipe Forte Tenreiro)

- Refactorization of ICBC allocation in examples (Luca Cirrottola)

- Integration of functional test cases for Axisymmetric problems (Anthony Bosco, Vincent Perrier)

- documentation framework improvement (doxygen) (Luca Cirrottola)

- Maintenance and imrpovements of CMake compilation files and guix packaging (Luca Cirrottola)

- Preliminary tests on code coupling with OASIS (Andrea Filippini)

- Adaptation of the master branch to C++11 (Luca Cirrottola)

- Preparation of DM2 integration (Luca Cirrottola)

- Computation of spurious modes in low Mach number flows with pressure-centred fix (Ibtissem Lannabi)

- Development of code formatting rules and integration with CLANG (Luca Cirrottola)

- Several bug fixes (CI, functional tests, unit tests).

- Wiki and documentation improvement.

Contribution statistics: About 300 commits this year, organized in 16 merge requests that were opened and merged into the master branch this year.

URL: `https://team.inria.fr/cardamom/aerosol/`

Contact: Vincent Perrier

Participant: 11 anonymous participants

6.1.4 DM2

Name: Distributed Mesh and Data Manager

Keywords: HPC, Data parallelism, High order finite elements, Unstructured meshes, Hybrid meshes

Functional Description: DM2 is a C++ library for managing mesh and data on mesh in a MPI parallel environment. It is conceived to provide parallel mesh and data management in high order finite element solvers for continuum mechanics.

The user should provide a mesh file which is read by the library. Then DM2 is able to:

- Read the mesh, and read the data provided in the mesh file, possibly in parallel

- Redistribute the mesh in order to distribute the data on a given set of processors. This redistribution is made through a graph partitioner such as PARMETIS or PT-SCOTCH.

- Allocate the memory in parallel if a number of unknown by entity type is provided by the user.

- Centralize the data.

- Compute the halo required for a numerical method. The halo is adapted for each of the possible discretization.

- Renumber mesh elements for making a difference between mesh elements that need or need not communication.

- Aggregate a mesh based on a metric for developing a multigrid method.

Release Contributions: This version introduces overlap regions ("halos") among distributed mesh partitions. These halos are specialized for discontinuous or continuous schemes, but generic with respect to the (geometric) degree of the mesh cells. These halos allow to synchronize numerical data defined on a set of entities of the distributed mesh. Numerical data is again generic with respect to the degree of their polynomial approximation, the number and combinations of scalar/vector fields, and the size of the vector spaces.

News of the Year: Highlights for the 2025 years:

- Installation of DM2 as a standalone library.
- Library API.
- A specific *compound graph* with local and halo entities for each type of discretization.
- Use namespaces instead of type prefixes.
- Checkpoint restart.
- Vector NetCDF support.
- Code formatting checks with Clang.
- New Docker CI instead of the Cloudstack VMs.
- Refactorings: VTU, iterators, halo graph storage, template graph class, graph constructors, remove legacy code.
- Maintenance: Docker images, Guix time-machine, CMake.

Contributions statistics: about 31 merge requests that were merged into the master branch during the last year.

Contact: Vincent Perrier

Participant: 4 anonymous participants

6.1.5 CoPubli

Name: Co-Publications Inria

Keywords: Geolocation, HAL

Scientific Description: The pipeline consists of three software components.

One software extracts an Excel file from HAL using the AUREHAL APIs. Each record in the Excel file contains the following information: Teams, Research Centre, Author_FR, Co-author(s), Co-author Institution, Address, City, Country, AUREHAL_ID, EU (flag), Year, HalID, Domain(s), Keywords, Abstract. The output is reproducible for all of Inria's scientific output and can be applied to other time periods.

Another software retrieves the Latitude and Longitude based on the cities of the co-authors and adds this geolocation data to the Excel file.

A third software component enables user-friendly, interactive visualization of all or part of the Excel file through a web-based interactive dashboard. The dashboard allows filtering of co-publications by city, co-author institution, year, and Inria team.

Functional Description: It is possible to extract this information from HAL.

One limitation concerns the city. The city can be identified in the address, which is a free-text field in HAL's database. Therefore, a method will be needed to determine the city using its latitude and longitude based on the address provided.

Another limitation of the HAL database is that it does not require specifying the hierarchy of foreign institutions. For example, an author may affiliate their publication with the Dipartimento di Matematica (DiMa) without specifying that DiMa is under the supervision of the University of Genova (UniGe), or they may directly affiliate the publication with UniGe.

Release Contributions: stable

URL: `https://github.com/INRIA/datalake/tree/main/POC-RÃľseauxdecopublications`

Publication: hal-05432240v1

Contact: Luigi Liquori

Participant: 5 anonymous participants

6.1.6 Mmg

Name: Mmg Platform

Keywords: Mesh adaptation, Anisotropic, Mesh generation, Mesh, Isovalue discretization

Scientific Description: The Mmg platform gathers open source software for two-dimensional, surface and volume remeshing. The platform software perform local mesh modifications. The mesh is iteratively modified until the user prescriptions satisfaction.

The 3 softwares can be used by command line or using the library version (C, C++ and Fortran API) :

- Mmg2d performs mesh generation and isotropic and anisotropic mesh adaptation.

- Mmgs allows isotropic and anisotropic mesh adaptation for 3D surface meshes.

- Mmg3d is a new version af the MMG3D4 software. It remesh both the volume and surface mesh of a tetrahedral mesh. It performs isotropic and anisotropic mesh adaptation and isovalue discretization of a level-set function.

The platform software allows to control the boundaries approximation: The "ideal" geometry is reconstructed from the piecewise linear mesh using cubic Bezier triangular partches. The surface mesh is modified to respect a maximal Hausdorff distance between the ideal geometry and the mesh.

Inside the volume, the software perform local mesh modifications (such as edge swap, pattern split, isotropic and anisotropic Delaunay insertion...).

Functional Description: The Mmg plateform gathers open source software for two-dimensional, surface and volume remeshing. It provides three applications:

- mmg2d: generation of a triangular mesh , adaptation and optimization of a triangular mesh.

- mmgs: adaptation and optimization of a surface triangulation representing a piecewise linear approximation of an underlying surface geometry.

- mmg3d: adaptation and optimization of a tetrahedral mesh and isovalue discretization.

The platform software performs local mesh modifications. The mesh is modified iteratively until it meets user-defined prerequisites.

Release Contributions: - Robustification - Improved documentation

URL: `http://www.mmgtools.org`

Contact: Nicolas Barral

Participant: 5 anonymous participants

Partners: Université de Bordeaux, CNRS, IPB, UPMC

7 New results

7.1 Structure preserving numerical methods for evolutionary PDEs

Participants: Firas Dhaouadi, Laura Del Río Martín, Maria Kazolea, Martin Parisot, Mario Ricchiuto.

- Corresponding member: Mario Ricchiuto

In 2025, we have further pursued the research on novel numerical techniques for hyperbolic PDEs, with a strong focus on the design of stationarity preserving methods, and genuinely multi-dimensional discrete frameworks. The first property is related to the ability of a method to embed discrete approximations of truly multidimensional arbitrary stationary states. In one space dimension, this property is related to the so-called well balanced property, of which it is essentially a fully discrete version. In other words the methods we design preserve much more general stationary states than classical well balanced methods, but only an approximate/discrete form. In multiple space dimension this property cannot be achieved when using classical numerical methods based on one-dimensional Riemann solvers. The development of genuinely multidimensional methods sets our research path in the wake of the is a fundamental and rich development dating back to the early work by P.L. Roe, B. van Leer, H. Deconinck, and may others. We have written a thorough review on this aspect in [4]. This work involves many collaborations, in particular with U. Paris Cité/LJLL (M. Ciallella), CNRS (W. Barsukow), U. Roma La Sapienza (D. Torlo), U. Ziurich (R. Abgrall, Y. Liu), U. of Verona (E. Gaburro) and U. of Trento (M. Dumbser).

This year, the framework introduced in [6] to design stationarity preserving and involution preserving stabilized finite elements for homogenous linear hyperbolic PDEs has been extended to linear hyperbolic systems balance laws with very general source terms in [27]. The equations considered possess many multi-dimensional non-trivial steady states, which result from the equilibrium between derivatives of the unknowns in different directions, and the sources. Standard numerical methods include stabilization terms which are incompatible with such multi-dimensional solutions. This manifests itself in a diffusion of states that are supposed to remain stationary. In this novel "global flux quadrature" formulation, we introduce a transverse integration of each component of the conservative flux, and a cell integration of the source terms. This leads to the use of a so-called global flux, which can also be interpreted as a pointwise integral of the evolution operator over mesh sub-cells. All spatial derivatives and the sources are thus treated simultaneously. On Cartesian meshes, these methods are stationarity preserving. Additionally, when this formulation is combined with interpolation on Gauss-Lobatto nodes, consistency results can be obtained for the discrete equilibrium states, showing super-convergence properties. The numerical results confirm the theoretical predictions, and show the tremendous benefits of the new formulation.

A first extension to non-linear problems has been performed in [5] (accepted on J.Comput.Phys.). In this case we use the same ideas in the context of Finite Volume methods. Classical Finite Volume schemes for multi-dimensional problems include stabilization (e.g. via a Riemann solver), that is derived by considering several one-dimensional problems in different directions. Such methods therefore ignore a possibly existing balance of contributions coming from different directions, such as the one characterizing multi-dimensional stationary states. Instead of being preserved, they are usually diffused away by such methods. Stationarity preserving methods use a better suited stabilization term that vanishes at the stationary state, allowing the method to preserve it. This work presents a general approach to stationarity preserving Finite Volume methods for nonlinear conservation/balance laws. As the work done in the finite element setting, the new schemes use a multi-dimensional stationarity preserving quadrature strategy that allows to naturally introduce genuinely multi-dimensional numerical fluxes. In particular, instead of using face fluxes with two arguments (left and right state), we are led to introduce numerical fluxes at cell corners which are a function of multiple states (the number of corner neighbours of a cell). This is a novel setting which we plan to explore in depth in the future. The new methods are shown to significantly outperform existing ones even if the latter are of higher order of accuracy. This has been shown for linear acoustics, for the non-linear Euler equations and on the nonlinear shallow water equations, with and without source terms, on both stationary and even on non-stationary solutions.

The quadrature strategy used in [6, 27, 5] is currently limited to Cartesian meshes. Based on a different strategy, multidimensional Riemann solvers on general unstructured polygonal Voronoi-like tessellations have been introduced in [29]. In the reference, a general finite volume formulation based on corner multidimensional fluxes is put forward. As in [5], numerical fluxes depend on cell average states in all the corner neighbours. Two complete Riemann solvers are proposed in this setting. The first is a direct extension of the Osher-Solomon Riemann solver to multiple space dimensions. Here, the multidimensional numerical dissipation is obtained by integrating the absolute value of the flux Jacobians over a dual triangular mesh around each node of the primal polygonal grid. The required nodal gradient is then evaluated on a local computational simplex involving the d+1 neighbours meeting at each corner. The second method is a genuinely multidimensional upwind flux. By introducing a fluctuation form of finite volume methods with corner fluxes, we show an equivalence with residual distribution schemes (RD). This naturally allows us to construct genuinely multidimensional upwind corner fluxes starting from existing and well-known RD fluctuations. In particular, we explore the use of corner fluxes obtained from the so-called N scheme, i.e. the Roe's original optimal multidimensional upwind advection scheme. Both methods use the full eigenstructure of the underlying hyperbolic system and are therefore complete by construction. A simple higher order extension up to fourth order in space and time is then introduced at the aid of a CWENO reconstruction in space and an ADER approach in time, leading to a family of high order accurate fully-discrete one-step schemes based on genuinely multidimensional Riemann solvers. We present applications of our new numerical schemes to several test problems for the compressible Euler equations of gas-dynamics. The new methods were implemented in AleVoronoi, and the numerical results show that the proposed schemes can handle very strong shocks, they preserve certain stationary shear waves exactly, and have much reduced numerical dissipation compared to classical methods.

The schemes studied in the last work do not have any clear stationarity or involution preserving properties. However, besides the shear preserving property and the reduced numerical dissipation, they use CWENO polynomials to manage strong discontinuities. On the contrary, the multidimensional discretizations in [6, 27, 5] do not involve any non-linear mechanism to control oscillations. A first step to overcome this limitation has been done in collaboration with Y. Liu and R. Abgrall (U. of Zurich) in [25]. In this work, the stationarity preserving/global flux quadrature approach is combined with the active flux method. To manage discontinuities and preserve the non-negativity of densities (and water depth for shallow water) we blend the high-order stationarity preserving schemes with a first order local Lax-Friedrichs one. The blending is done based on previous work by [35]. Further control of oscillations is obtained using the oscillation eliminating filter by [76]. The compatibility with the stationarity preserving property is accounted for in the definition of the blending function. Numerical results confirm the possibility of combining stationarity preservation with oscillation free, solutions respecting the appropriate positivity constraints.

7.2 Efficient numerical modelling of free surface and non-linear waves

Participants: Firas Dhaouadi, Maria Kazolea, Martin Parisot, Mario Ricchiuto.

- Corresponding member: Maria Kazolea

We have continued our work on enhanced numerical modelling of free surface and non-linear waves. This is a multi-faceted activity involving PDE modelling and analysis, numerical analysis, validation and verification. The most challenging part of the work is the construction of efficient macroscopic models which appropriately account for small scales, and in particular for both wave dispersion, and dissipation effects, both of which may not be correctly modelled in the lowest order PDE approximations.

In this respect, the coupling of different models is often necessary. This requires the understanding of the well posedness of the coupling both on the theoretical and numerical level. In [30] we derive a new approach to analyze the coupling of linear Boussinesq and Saint-Venant shallow water wave equations in the case where the interface remains at a constant position in space. We propose a one-way coupling model as a reference, which allows us to obtain an analytical solution, prove the well-posedness of the original coupled model and compute what we call the coupling error-a quantity that depends solely on the choice of transmission conditions at the interface. We prove that this coupling error is asymptotically small for a certain class of data and discuss its role as a proxy for the full error with respect to the 3D water wave problem. Additionally, we highlight that this error can be easily computed in other scenarios. We show that the coupling error consists of reflected waves and argue that this explains some previously unexplained spurious oscillations reported in the literature. Finally, we prove the well-posedness of the half-line linear Boussinesq problem.

A standard technique to construct accurate and robust numerical approximations of multi-scale PDE models is to recast them in hyperbolic form. The advantage of this approach is that standard high order methods for hyperbolic PDEs can be used. In [28], we introduce novel approximate systems for dispersive and diffusive-dispersive equations with nonlinear fluxes. For purely dispersive equations, we construct a first-order, strictly hyperbolic approximation. Local well-posedness of smooth solutions is achieved by constructing a unique symmetrizer that applies to arbitrary smooth fluxes. Under stronger conditions on the fluxes, we provide a strictly convex entropy for the hyperbolic system that corresponds to the energy of the underlying dispersive equation. To approximate diffusive-dispersive equations, we rely on a viscoelastic damped system that is compatible with the found entropy for the hyperbolic approximation of the dispersive evolution. For the resulting hyperbolic-parabolic approximation, we provide a global well-posedness result.

Using the relative entropy framework [53], we prove that the solutions of the approximate systems converge to solutions of the original equations. The structure of the new approximate systems allows to apply standard numerical simulation methods from the field of hyperbolic balance laws. We confirm the convergence of our approximations even beyond the validity range of our theoretical findings on set of test cases covering different target equations. We show the applicability of the approach for strong nonlinear effects leading to oscillating or shock-layer-forming behaviour.

Hyperbolic relaxation techniques as the one discussed in the previous contribution are widely used to offset the cost of inverting time independent operators. To give an example the Serre-Green-Naghdi (SGN) equations provide a valuable framework for modelling fully nonlinear and weakly dispersive shallow-water flows. However, their standard formulation requires the inversion of an elliptic PDE which can considerably increase the computational cost compared to the Saint-Venant equations. To overcome this difficulty, hyperbolic models (hSGN) have been proposed that replace the elliptic operators with first-order hyperbolic formulations augmented by relaxation terms, which recover the original elliptic formulation in the stiff limit. Yet, as the relaxation parameter λ increases, explicit schemes face restrictive stability constraints that may offset these advantages. To mitigate this limitation, in [32] we introduce a semi-implicit (SI) integration strategy for the hSGN system, where the stiff acoustic terms are treated implicitly within an IMEX Runge-Kutta framework, while the advective components remain explicit. The proposed approach mitigates the CFL stability restriction and maintains dispersive accuracy at a moderate computational cost. Numerical results confirm that the combination of hyperbolization and semi-implicit time integration may provide an efficient and accurate alternative to both classical SGN and fully explicit hSGN solvers.

Still on the numerical side, in [8] we have proposed enhance semi-implicit methods for wave structure interaction problems with moving free surface, and large relative motions between the fluid and moving floating structures above water. As shown in our previous works [44, 62], the governing equations change type from hyperbolic below the free surface to elliptic below the moving floating object within the cells of the computational domain, the horizontal motion may exhibit a numerical instability that is not observed solely with the vertical heave motion. When a ship enters a new cell, the pressure at the bow increases and decreases sharply, leading to oscillations that can create an unphysical void below the vessel. After examining the origin of the problem, several measures were taken at the discrete level to reduce these spurious oscillations. All of these modifications were effective in controlling the oscillations, making numerical simulations with horizontal motion of moving floating objects more robust, stable and accurate. To enhance the range of application of the model, we also include some additional weakly dispersive terms. The same study is then performed in presence of these non-hydrostatic effects, showing a reliable and robust prediction of the interaction of moving bodies interacting with hydrostatic and non-hydrostatic (dispersive) waves.

In [33], we presents a novel approach for coupling a high-fidelity Navier-Stokes model with an asymptotic Boussinesq-type model. The proposed methodology aims to enhance the design and performance of wave energy converters, thereby supporting the broader integration of wave energy in addressing climate change and energy resource challenges. The numerical coupling strategy relies on overlapping subdomains with relaxation source terms transferred information from one model to the other. This framework improves the accuracy of local wave-structure interaction studies while maintaining computational efficiency over larger spatial domains. A series of case studies from the literature is carried out to illustrate the relevance and effectiveness of the approach.

All developments of new numerical methods or approximate models rely heavily on the availability of reliable, well documented, and relevant benchmarks. For this reason, in [26] we have proposed a comprehensive list of stationary solutions of different shallow water models. For each different case, we exhibit the form of the stationary solution and its conditions of existence for any set of boundary conditions on monotonic, bumped shaped and hollow shaped topographies. We find that in some cases and for supercritical flow at the inlet, two different stationary solutions can fulfilled the same set of boundary conditions. The solutions with shocks on increasing topography are sparsely documented and seem to be unstable. Eventually we consider a topography made of a succession of N decreasing bumps and prove in the subcritical case that up to 2^{N-1} solutions with discontinuities on decreasing topography only may coexist.

7.3 Advanced models of heat transfer and phase change phenomena

Participants: Héloïse Beaugendre.

- Participants: Héloïse Beaugendre, Alexis Cas
- Corresponding member: Héloïse Beaugendre

During atmospheric hypersonic re-entry, the heat distribution within the thermal protection system (TPS) is dampened by the in-depth chemical degradation of materials - called pyrolysis -, and by a surface physicochemical degradation - called ablation. The aim of Alexis Cas's PhD work work is to preserve the mass and energy conservation and to investigate the numerical tools used during the pyrolysis-thermal coupling of heat shield under deformations. First, an overview of macroscopic modeling of pyrolysis is done. Arrhenius laws are employed for the modeling of density variation. Thermal expansion, swelling and shrinkage are taken into account as a consequence of material degradation. This analysis explores a pyrolysis-thermal model that preserves physical properties and a number of numerical methods, focusing on numerical conservation and method efficiency. Finally, ablation and swelling test cases are studied, in order to validate and compare the numerical methods. The simulation results are in reasonable agreement with reference data and experimental data. Some numerical methods result in a trade-off between mass or energy conservation and a faster computational time.

7.4 High order embedded and immersed boundary methods

Participants: Héloïse Beaugendre, Benjamin Constant, Mario Ricchiuto.

- Corresponding member: Héloïse Beaugendre

We studied several steady-state turbulent flow simulations of the NASA High Lift Common Research Model on Cartesian grids at increasing angles of attack. The Reynolds Averaged Navier-Stokes equations are solved with the one-equation Spalart-Allmaras model, while the presence of a geometry is accounted for by an immersed boundary method based on a ghost cell direct forcing approach. A wall model is applied to deal with the inherent impossibility of isotropic cells to properly capture the near-wall flow physics at high Reynolds number. This work validates the recent developments brought to the Cartesian methodology based on a geometric regularization of the forcing point location around the immersed geometry. New developments are presented to improve the pre- and post-processing for this type of 3D applications. Comparisons are made with state-of-the-art solutions from the reference literature on body-fitted meshes, both structured and unstructured. A 2D multi-element airfoil is also studied to facilitate the analysis of the solutions obtained on the full aircraft in high lift configuration. For higher angles of attack, more detailed investigations are proposed to discuss the physics closer to the stall phenomenon, especially near the wing tip.

We also introduced a novel data-driven wall modeling strategy for Reynolds-Averaged Navier-Stokes (RANS) simulations. The method reformulates wall laws as a Dirichlet-to-Neumann map applied at a specific height within the boundary layer. This map is learned using neural networks trained on data from wall-resolved RANS simulations. While the approach shares similarities with the work of Romanelli et al. (2023), it is significantly faster, as it eliminates the need for iterative resolution of the skin friction inherent in the implicit relation $u^+ = f(y^+, p^+)$. The model's accuracy has also been improved through enhanced treatment of the turbulent variables and by incorporating additional input parameters that better describe the boundary layer state. The method is demonstrated on attached turbulent flows across various Reynolds numbers and wall pressure gradients. After training the neural networks on a subset of reference cases, their ability to generalize to both familiar and unseen conditions is evaluated. The model is further validated on a completely different setup (an airfoil), where it is compared to two existing analytical wall models, showing better accuracy and robustness with respect to pressure gradient conditions. This work also introduces an efficient extrapolation-detection algorithm that could be used either to ensure that the model is always applied within its validity domain or to trigger an automated adaptive learning strategy of the wall-law or, in a zonal context, to select between wall-resolved/wall-modeled regions. Overall, our method provides a new practical intermediatefidelity, cost-effective framework that displays an attractive balance between accuracy and computational efficiency, bridging the gap between the more computationally intensive approach of Romanelli et al. (2023) and the limited accuracy of conventional analytical wall models.

7.5 Adaptation techniques

Participants: Nicolas Barral, Héloïse Beaugendre, Luca Cirrottola, Corentin Prigent, Mario Ricchiuto, Fabien Salmon, Ishak Tifouti.

- Corresponding member: Nicolas Barral

MMG Consortium the anisotropic meshing library MMG is supported by a consortium of industrial and academic partners. After restarting in 2024, the consortium has continued its activities of maintaining MMG, following the consortium roadmap. In September, a new version of the website was published, with an extensive documentation of the code. In June 2025, the consortium met to update the roadmap. Following this meeting, a new Python interface is being developped, while a continuous effort to improuve robustness and reliability is ongoing.

Mesh adpatation for sea ice modelling. The collaboration with Institut des Géosciences de l'Environnement, Grenoble, with Fabien Salmon's. Three axes were followed. First, the performance of parMMG2D was further assessed and improved. Second, a substantial effort to integrate MMG in the state-of-the art sea-ice model NeXtSim, and merge the changes upstream in the main version of the code. Finally, a theoretical study of error estimators for quasi isotropic and/or quasi uniform meshes was carried out, resulting in new metrics to guide MMG in the context of sea-ice modelling.

Coupling mesh adaptation with model reduction.

In [18], we propose a localized automated nonlinear model reduction framework for rapid and reliable solution of parameterized shock-dominated flows. Our formulation exploits the adaptive procedure of [Barral et al, JCP, 2024] and a clustering technique to devise a piecewise Lagrangian approximation of the solution to the parametric problem: the application of clustering is designed to cope with parameter-induced shock-topology changes that hinder the effectiveness of standard (monolithic) Lagrangian approximations. We rely on (i) metric-based mesh adaptation to generate an accurate mesh for a range of parameters, (ii) parametric registration for the computation of a bijection Φ that tracks moving features of the solution field, and (iii) projection-based model reduction to rapidly and reliably estimate the mapped solution; finally, we develop (iv) a clustering technique to partition the parameter domain in subregions where the shock topology does not change. We present numerical investigations for a two-dimensional supersonic inviscid flow past a Gaussian bump to illustrate the many features of the methodology: in more detail, we display the performance of three clustering techniques, and we compare our approach with monolithic Lagrangian approximations.

Finally, a *goal-oriented* approach encompassing MOR and mesh adaptation was designed. While goal-oriented methods are well established in mesh adaptation and shape optimization, their use in model reduction is much less common. We developed an automated goal-oriented adaptive multi-fidelity training algorithm that produces goal-oriented registration-based reduced models tailored to specific outputs of interest. Two goal-oriented mesh adaptation strategies were considered: (i) an anisotropic approach based on an a priori goal-oriented error estimator, and (ii) an isotropic approach derived from an a posteriori goal-oriented estimator. Both methods were adapted to our parametric setting. We compared them in terms of mesh quality, solution accuracy, and accuracy of the associated outputs, with a feature-based anisotropic mesh adaptation approach. As expected, parametric solutions obtained with goal-oriented adapted meshes are less accurate than those built on feature-based meshes. However, goal-oriented meshes are refined in significantly smaller regions of the computational domain, specifically those relevant to the outputs of interest, thereby reducing the relative output error compared to the feature-based approach. For the supersonic flow past a bump, we found that isotropic goal-oriented meshes yield better accuracy in the output error, whereas anisotropic goal-oriented meshes provide improved resolution of the adjoint solution by following its spatial variations.

7.6 Modeling of flows in aquifers

Participants: Manon Carreau, Martin Parisot.

- Corresponding member: Martin Parisot

In [9], we focus on the formal derivation of a unified model for groundwater and surface water flow, combining the shallow water model and the Dupuit-Forchheimer model. The primary goal of the model is to describe the dynamics of water table, which represents the level below which the medium is fully saturated, while disregarding unsaturated regions. The unified shallow-water/Dupuit-Forchheimer model provides a single set of equations across the domain. It transitions to the shallow water model in areas where the porous medium is absent and to the Dupuit-Forchheimer model when the water table remains below the surface. The derivation is carried out in two steps: first, a vertical integration separates the ground and surface media, followed by the application of a low-permeability limit in the ground layer. The model ensures conservation of both mass and energy. A numerical scheme that preserves these properties at the discrete level, along with several numerical experiments, demonstrates the robustness and efficiency of the approach.

8 Bilateral contracts and grants with industry

8.1 Bilateral Contracts

CEA-CESTA

Participants: Héloïse Beaugendre.

- Title: Development of models and numerical methods for the degradation of a pyrolysable material
- Type: contrat d’accompagnement for Alexis Cas’s PhD.
- Duration: 36 months
- Starting date : 1st October 2023
- Coordinator: Heloise Beaugendre Celine Baranger and Simon Peluchon(CEA)
- Summary: During re-entry into the atmosphere, a spacecraft is subjected to considerable mechanical stress and heat flows. These heat flows, applied to the vehicle’s wall, cause the heat shield to heat up significantly. The heat shield is made up of materials that chemically degrade under the effect of heat to limit the temperature rise inside the vehicle. These reactions are known as pyrolysis. Similarly, on the surface, these materials undergo physical degradation known as ablation. Understanding these two phenomena is essential for the design of heat shields. The design of such a shield requires precise numerical simulations of the airflow that is created around the vehicle throughout its trajectory. This airflow must be coupled with ablation and pyrolysis phenomena.

EDF

Participants: Bastien Jouy, Mario Ricchiuto.

- Title: Numerical modelling of Favre waves and undular bores in channels with banks
- Duration: 36 months
- Starting date : 08 November 2021
- Coordinator: Mario Ricchiuto
- Summary: The collaboration with EDF (Eleectricité de France) focuses on the improvement of their in house code TELEMAC-Mascaret, initially for the advection of passive scalars (pollutant transport), and more recently for the simulation of hydrostatic and dispersive (undular) bore dynamics in networks of channels (application to abrupt closing/opening of valves). The past work on advection schemes has been done with J.M. Hervouet (retired) and R. Ata (riadh.ata@edf.fr - currently at FLOW-3D) was an informal collaboration. The ongoing collaboration on bore dynamics is with D. Violeau (damien.violeau@edf.fr) is object of a CIFRE contract. This work aims at increasing the capabilities of EDF's code to simulate the undulating bores studied in [48].

Airbus

Participants: Nicolas Barral, Clarisse Chabaud, Mario Ricchiuto.

- Title: Curvilinear Mesh Adaptation for Aircraft Design
- Duration: 36 months
- Starting date : 1st October 2024
- Coordinator: Nicolas Barral
- Summary: The aim of this thesis work is to develop a mesh adaptation strategy compatible with the high-order numerical methods in Airbus' code CODA. Of particular interest will be the consideration of complex curved geometric shapes found in aeronautics. The success of this work will be measured by the ability of the chosen strategy to control the numerical error near curved boundaries. To this end, a curvilinear mesh generation tool for the automatic mesh adaptation process by metric specification will be developed in the Flowsimulator environment. A method for correcting the geometric error during spatial integration at wall level will also be developed in the CODA tool. On the basis of these two main technologies, a high-order mesh adaptation process will then be developed, enabling reliable control of the numerical error. The range of applications targeted will be the simulation of highly loaded supercritical wings and hyper-supported configurations in icing conditions.

IFPEN

Participants: Martin Parisot, Sebastien Erdocio.

- Title: Monarc
- Duration: 36 months
- Starting date : 1st November 2024
- Coordinator: Martin Parisot

- Summary: This project is a collaboration with Benoit Chauveau, Leo Argelas and Arnaud Pujol, from IFPEN, to supervised the PdH of Sebastien Erdocio. The objective is to propose a model for the dynamics of unsaturated (Vadose area) and saturated (water table) groundwater. To avoid costly 3D simulations, the strategy is based on a 2D-horizontal Dupuit-Forchheimer model for the dynamics of the water table and several (one by horizontal mesh cell) 1D-vertical infiltration equation. The main issue of the project is the coupling between the water dynamics preserving the physical conservation, i.e. mass and energy conservation. In a second phase, perched water, confined water and exchanges with the surface will be considerated.

9 Partnerships and cooperations

9.1 International research visitors

Other international visits to the team

- Victor Gonzalez Tabernero (U. da Coruna, Spain) has visited the team for two months this year to work with M. Ricchiuto on genuinely multidimensional well balanced discretizations for the shallow water equations with source terms.
- Valerio Orlandini (U. di Roma La Sapienza, Italy) hs visited the team for three months to work with M. Ricchiuto on efficient discretization of viscous terms in the compressible Navier-Stokes equations.
- Joel Perez Villarino (U. da Coruna, Spain) has visited the team for two months this year to work with M. Ricchiuto on efficient time stepping methods for discontinuous Galerkin approximation of dispersive PDEs.
- Jens Visbech (DTU Compute, Denmark) has visited the team for one month to work with M. Ricchiuto on high order embedded boundary methods for wave propagation.
- Prof. Zhengfu Xu (Michigan Tech, US) has visited the team for a duration of three months co-funded by the Visiting Scientist program of the Bordeaux University. During his stay Prof. Xu collaborated with M. Ricchiuto and R. Loubere on high resolution well balanced methods for hyperbolic problems.

Several colleagues visited the team for much shorter stays (about one week): A. Chertock (NC State, USA), E. Gaburro (U. di Verona, Italy), D. Ketcheson (KAUST, Saudi Arabia), A. Kurganov (U. of Shenzhen, China), E. Pimentel-García (Universidad Malaga, Spain), H. Ranocha (Mainz University, Germany), D. Torlo (La Sapienza, Italy).

9.1.1 Visits to international teams

Research stays abroad

Several short visits (up to one month) to international teams have taken place this year:

- Maria Kazolea visited the Edanya team at the University of Malaga in the framework of the Picasso Program from September 27 to October 4. The objective of the visit was to work latest on high order fully well balanced WENO discretizations. She also visited the University of Crete for 4 weeks in July to work on the modelling of river flows with a Boussinesq approach.
- Martin Parisot visited the Edanya team at the University of Malaga from October 27 to November 1st to share latest advances in modeling and numerical schemes for dispersive models with a projection structure. Visit performed in the framework of the Picasso Program
- Mario Ricchiuto visited the math department of the University of Valladolid in September 15-20 to work on the behaviour of hyperbolic approximations of disperssive and parabolic PDEs. He also visited the math department of the Technical University of Clausthal (Germany) in October 20-24 to work on the stability of stationarity preserving numerical discretizations.

9.2 European initiatives

9.2.1 Horizon Europe

RESCUER

Title: Resilient Solutions for Coastal, Urban, Estuarine and Riverine Environments

web: RESCUER project on cordis.europa.eu

Duration: From February 1, 2024 to January 31, 2028

Partners:

- INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET AUTOMATIQUE (INRIA), France
- COMUNE DI SENIGALLIA (COMUNE), Italy
- UNIVERSIDAD DE ZARAGOZA (UNIVERSIDAD DE ZARAGOZA), Spain
- STATENS VEGVESEN (STATENS VEGVESEN VEGDIREKTORATET), Norway
- Águas da Figueira, S.A. (Águas da Figueira, S.A.), Portugal
- UNIVERSITE DE PAU ET DES PAYS DE L'ADOUR, France
- Hydronia Europe SL (Hydronia Europe SL), Spain
- UNIVERSITA DEGLI STUDI ROMA TRE (UNIROMA3), Italy
- TRUSTEES OF COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK, United States
- UNIVERSIDADE DE COIMBRA (UNIVERSIDADE DE COIMBRA), Portugal
- COWI AS (KAMPSAX GEODAN GEOPLUS KAMPSAX DATA GEOPLAN GEOMASTERS GEODATAAGRINOVA INTERNATIONAL KAMPSAX INTERNATIONAL KAMPSAX TEKNIK), Denmark
- KARLSRUHER INSTITUT FUER TECHNOLOGIE (KIT), Germany
- UNIVERSITE DE BORDEAUX (UBx), France
- FUNDACION AZTI - AZTI FUNDAZIOA (AZTI), Spain
- UNIVERSITA POLITECNICA DELLE MARCHE (UNIVPM), Italy
- AALBORG UNIVERSITET (AAU), Denmark
- UNIVERSITETET I BERGEN (UiB), Norway
- SUEZ EAU FRANCE, France

Inria contact: Maria Kazolea

Coordinator: Prof. H. Kalisch, University of BERGEN

Summary: The Doctoral Network (DN) "RESCUER" (Resilient Solutions for Coastal, Urban, Estuarine and Riverine Environments) will focus on the training of young researchers (Fellows) in the general area of coastal oceanography, hydraulic and coastal engineering, applied mathematics, and scientific computation. The network will leverage advances in the numerical treatment of hydrodynamic equations in the past decade to create multi-physics models able to address pressing needs in practical modeling of various phenomena in the coastal zone with the goal of improving overall safety of coastal areas.

Ensuring the safety of property and commercial developments onshore and offshore requires an integrated approach, including phase-resolving wave modeling, tracking and mitigation of morphological changes, potential flooding in urban areas and monitoring of water quality. While protective structures and emergency plans for catastrophic storm waves and storm surges are well established, the confluence of global warming and sea level rise with other known natural risk factors and increasing human activity create a new set of hazards and requires new thinking in coastal modeling and the planning of mitigation strategies.

To address the challenges outlined above, we will rely on numerical techniques which are in each case tested against existing models and validated with experiments and field measurements. In our work with consulting companies and government agencies, we have identified a trend towards coupled models instead of traditionally used stand-alone models and a need for operational capabilities. These needs will be answered using new multi-physics models, state-of-the-art numerical methods, image recognition algorithms and innovative programming techniques such as GPU programming. The synergistic interplay of physical modelling, numerical analysis and large-scale simulation with lab experiments and field work plays an essential role in this network. Our project goes beyond the state of the art by improving existing numerical models, employing GPU programming and super-resolution techniques and building a unified suite of solvers that will allow us to address the multi-physics problems in coastal, estuarine, riverine and urban areas.

9.3 National initiatives

ANR LAGOON

Participants: Maria Kazolea, Ralph Lteif, Martin Parisot, Vincent Pilorget, Mario Ricchiuto.

Title: Large scale global storm surge simulations

Type: ANR

Duration: 48 months

Starting date : 1st Oct 2021

Coordinator: Vincent Perrier (U.Pau et des Pays de l'Adour)

Abstract: The aim of the project is to develop an all-scale shallow water storm-surge model simulating different features of oceanic flows: from large scale linear waves in open ocean to small scale non-linear flows in coastal areas, and using high resolution by combining novel numerical approaches on unstructured grids and high performance computing.

PERPR IRIMA ROM

Participants: Nicolas Barral, Maria Kazolea, Mario Ricchiuto, Dean Yuan.

Title: Seismo-volcanic, tsunami and hydro-climatic risks in overseas France

Type: ANR

Duration: 48 months

Starting date : 1st Oct 2024

Inria Contact: Maria Kazolea

Coordinator: Anne Le Friant (IPGP)

Abstract: The PC Outermer project focuses on the intense and frequent telluric and hydro-meteorological hazards faced by overseas and intertropical populations, such as earthquakes, volcanic eruptions, tsunamis, gravity instabilities, flooding/submersions and coastal erosion in connection with cyclones and climate change. It is essential to take into account the geographical and societal particularities of overseas and intertropical areas (distance from the hexagone, insularity, lack of connection and size of territories, high proportion of the total population of the territory exposed to one or more hazards, diversity of cultural and historical practices, social and political tensions), which require a specific understanding of local capacities for risk prevention and management, as well as adaptation and resilience. Innovative management strategies therefore need to be developed and tested in terms of feasibility/acceptability/inclusivity, taking into account the political and social status of these territories. Knowledge of telluric and hydrometeorological hazards, and of the vulnerabilities of these territories, is essential because of the active observation conditions they offer, and above all in order to meet the challenges of risk and crisis management. However, all our scientific achievements show that there are still limits to our ability to detect changes in the phase of activity as early as possible, to the resilience of our networks, and to our capacity to develop integrated risk management models that can characterize the issues and assess their vulnerability to different hazards. The risks to which overseas populations are exposed need to be reconsidered in order to accurately qualify and model cascading phenomena and forcing processes, and the superposition of hazards and vulnerabilities on the same territories, in order to reduce the consequences of major disasters and help develop relevant risk and resilience policies.

This project aims to: 1/ identify new observables for the study of natural hazards and their anthropogenic impact on large spatio-temporal scales, 2/ develop holistic and integrated models of complex processes, taking into account the uncertainties associated with climate change projections and the integration of coupled predictive models, 3/ to develop integrated risk management strategies adapted to overseas and intertropical areas, and capable of dealing with the consequences of extreme and cascading events that induce multiple risks (eruptions, instabilities, tsunamis, floods). Inria is participating in WP2 which is devoded in on estimating the damage and socio-economic impact of tsunami hazards, applying our methodologies to Mayotte in the Indian Ocean.

Inria Action Exploratoire: AM^{2}OR

Participants: Nicolas Barral.

Title: AM^{2}OR: Adaptive meshes for Model Order Reduction

Type: Inria Action Exploratoire

Duration: 48 months

Starting date : 1st October 2022

Coordinator: Nicolas Barral

Partner: Tommaso Taddei (Inria MEMPHIS)

Abstract: Mesh adaptation and Model Order Reduction both aim at reducing significantly the computational cost of numerical simulations by taking advantage of the solution's features. Reduced Order Modelling is a method that builds lighter surrogate models of a system's response over a range of parameters, which is particularly useful in the solution of design and optimization inverse problems. Reduced-order models rely on a high-fidelity (e.g., finite element) approximation that should be sufficiently accurate over the whole range of parameters considered: in presence of structures such as shocks and boundary layers, standard mesh refinement techniques would lead to high-fidelity models of intractable size. In this project, we propose a novel adaptive procedure to simultaneously construct a high-fidelity mesh (and associated discretisation) and a reduced-order model for a range of parameters, with particular emphasis on inverse problems in computational fluid dynamics.

I MPT 2023

Participants: Nicolas Barral, Fabien Salmon.

Title: Parallel mesh adaptation for sea ice dynamic

Type: Appels à projets Institut de Mathématiques pour la Planète Terre

Duration: 25 months

Starting date : September 2023

Coordinator: Nicolas Barral

Abstract: In this project we work with the sea ice model neXtSIM, developed at Nansen Environmental and Remote Sensing Center (Bergen, Norway) and Institute of Environmental Geosciences (Grenoble, France). This new model aims at modelling complex sea ice dynamics across scales, in order to be used for both local short-term predictions and global climate prediction simulations. The specificity of neXtSIM is the use of a purely Lagrangian advection formalism on fully unstructured meshes, coupled with a novel rheological framework, that has given promising results. Such a Lagrangian approach results in strongly deformed meshes over time, in particular in the vicinity of cracks in the ice resulting from the mechanical forces coming from winds and currents, and where large drift of the ice can occur. A remeshing step is thus necessary to locally replace stretched or invalid mesh elements and restore the quality of the mesh. However, unlike the rest of the code that was parallelised recently for distributed memory architectures using MPI, the remeshing stage remains sequential, thus strongly impacting the performance of the code. Besides, the current remeshing does not yet take advantage of modern anisotropic mesh adaptation techniques that aim at optimising the size and orientation of the mesh elements to minimise a certain numerical error estimate and makes it possible to reduce the computational cost while increasing the accuracy. The goal of the collaboration is to leverage these methods to accelerate simulations, and thus be able to perform ensembles of large-scale high-resolution (kilometric) simulations of the sea ice, and to study ice trajectories from a statistical perspective.

9.4 Regional initiatives

Participants: Maria Kazolea, Martin Parisot, Mario Ricchiuto.

P SGAR CORALI

Title: COnnaissances inteRdisciplinaires pour meilleure Adaptation face aux risques LIttoraux

Type: Programmes Scientifiques de Grande Ambition Régionale

Duration: 48 months

Starting date : December 2024

Coordinator: Prof. Aldo Sottolichio

Abstract: The aim of PSGAR CORALI is to provide the multidisciplinary scientific knowledge needed to better forecast coastal changes and developments, and to better anticipate societal adaptations to the natural risks of erosion and submersion at the land-sea interface. The research proposed will be fundamental and international in scope, with direct application to regional sites in New Aquitaine. To achieve this, the PSGAR will implement a series of research and expert assessments (observation, modeling, analysis and decision support) to accelerate the transition towards a society capable of adapting to and becoming more resilient and sustainable in the face of current and future changes in open and semi-enclosed coastlines. To meet this challenge, heightened by climate change, interdisciplinary research will be encouraged and stimulated. This holistic, integrative approach to knowledge brings together the geosciences, environmental sciences, human and social sciences, and engineering. These disciplines, although involved in these issues, still too often work without direct interaction with society. The PSGAR proposes to integrate them more fully and to encourage the co-construction and transfer of knowledge to public and private coastal stakeholders. The PSGAR CORALI is built around a consortium federating the major universities of New Aquitaine and leading research organizations in the field of natural and environmental risks, already grouped around the regional research network (R3) RIVAGES, dedicated to the specific theme of coastal risks.

10 Dissemination

10.1 Scientific events: organisation

- Maria Kazolea is a member of the organizing Committee of the international workshop Sunhype 2026
- Mario Ricchiuto has co-organized the workshop B'Waves25, focusing on various aspects of wave breaking, with accent on free surface waves. This is the sixth edition of the B'Waves series started with a 2014 workshop aiming at serving as a platform for interactive exchange between scientists.

10.2 Journal

Member of the editorial boards

- Maria Kazolea served as guest editor in Computers and Fluids on the special issue Innovations in Modeling and Numerical Methods for Evolutionary PDEs: Theory and Applications
- Martin Parisot is Managing Editor for SMAI - Journal of Computational Mathematics
- Mario Ricchiuto is a member of the following boards
  - Journal of Computational Physics, Elsevier (Associate Editor)
  - Computers & Fluids, Elsevier (Associate Editor)
  - Water Waves, Springer (Editor)
  - Numerical Methods for Partial Differential Equations, Wiley (Editor)

Reviewer - reviewing activities

- Martin Parisot served as a reviewer in: Applied Mathematics and Computation, Computers and Fluids (x3), Journal of Computational Physics

10.3 Invited talks

- Martin Parisot has provided invited talks at the following events
  - Climath, 25-27/11
  - Digest, 13/11
  - Hydraumath, 16-25/06
  - JEMP, 04-06/11
  - NumHyp, 09-13/06
  - Cimav, 11-16/05
- Mario Ricchiuto has provided invited talks or lectures at the following events

  - Workshop on bedload and sedimentation processes: experiments, modelling and numerical simulation, Sevilla (Spain), January 2025
  - 1st PICASSO Workshop (France-Portugal-Spain), Malaga (Spain), March 2025
  - SHARK-FV 2025 workshop, Minho (Portugal), June 2025
  - Aria workshop 2025, Bidart (France), September 2025
  - ETNA Workshop Efficient Time-Stepping Numerical Approaches for PDEs, Catania (Italy), November 2025

10.4 Leadership within the scientific community

- H. Beaugendre is member of the following committees
  - Scientific committee of Forum des jeunes mathématiciennes et mathématiciens (JMM2025, november 2025, Bordeaux)
  - Scientific Committee of CANUM 2026
- Mario Ricchiuto is member of the following committees
  - Scientific Committee of the International Conference on Computational Fluid Dynamics – ICCFD
  - Scientific Committee of the Terre et Énergies, Réseau Thématique 2166 du CNRS Mathématiques – RT CNRS Terre et Énergies

10.5 Scientific expertise

- H. Beaugendre has been an expert for the evaluation of the research project PRF TRICEPS related to in-flight icing, in ONERA Toulouse, january 2025.
- Martin Parisot served as an expert for the evaluation of the ECOS SUD CHILI research project, related to collaboration between French and Chilean researchers.

10.6 Research administration

- Since September 2024, H. Beaugendre has been Director of Research, Innovation and Technology Transfer at ENSEIRB-MATMECA, Bordeaux INP.
- Since January 2025, Maria Kazolea has been serving as the Scientific Correspondent for the International Relations Department of the Inria Center at the University of Bordeaux. As such she has contributed participated to the creation of the software coPubli. CoPubli is a minimal software pipeline to extract, browse and geolocalise HAL coauthors. This tool visualises Inria's international network and partnerships. CoPubli extract an Exel file containing for each Inria Centre (respectively, Inria Team, or Inria Researcher) a list of foreign co-publishing researchers along with their research institutions, city, and country, information that could not be easily extracted by HAL without using data fusion and aggregation techniques [34].
- Since January 2025, Martin Parisot has been serving as referent of the Inria Center of Bordeaux for the Inria+Alumni community.

10.7 Teaching - Supervision - Juries - Educational and pedagogical outreach

10.7.1 Teaching

- Nicolas Barral
  - Licence: Calcul Scientifique en Fortran 90, 22h, L3, ENSEIRB-MATMÉCA, France
  - Licence : TP Fortran 90, 44h, L3, ENSEIRB-MATMÉCA, France

  - Licence : TP C++, 48h, M1, ENSEIRB-MATMÉCA, France
  - Master : Calcul Haute Performance (OpenMP-MPI), 45h, M1, ENSEIRB-MATMÉCA et Université de Bordeaux, France
  - Master : Théorie du maillage, 9h, M1, ENSMAC, France
  - Master : Meshing for computational science, 24h, M2, ENSEIRB-MATMÉCA et Université de Bordeaux, France
  - Master : projet professionnel et suivi de stages, 14 h, ENSEIRB-MATMÉCA, France
  - Master : responsable des stages 2A, 20 h, ENSEIRB-MATMÉCA, France

- Héloïse Beaugendre
  - Licence: Encadrement de projets sur la modélisation du biomimétisme ou le chaos, 20h, L3, ENSEIRB-MATMECA, France
  - Master : Calcul Haute Performance (OpenMP-MPI), 20h, M1, ENSEIRB-MATMECA et Université de Bordeaux, France
  - Master : Responsable du parcours CHP de 3ème année, 20h, M2, ENSEIRB-MATMECA, France
  - Master : Calcul parallèle (MPI), 39h, M2, ENSEIRB-MATMECA, France
  - Master : Encadrement de projets de la filière Calcul Haute Performance, 10h, M2, ENSEIRB-MATMECA, France
  - Master : Modélisation des écoulements turbulents, 29.5h, M2, ENSEIRB-MATMECA, France
  - Master : Encadrement de projets sur la quantification d'incertitudes et la sensibilté au maillage, 20h, M1, ENSEIRB-MATMECA, France
  - Master : Projet fin d'études, 4h, M2, ENSEIRB-MATMECA, France

- Firas Dhaouadi
  - Licence : Équations différentielles Ordinaires, 18h, L3, ENSEIRB-MATMECA, France
  - Licence : Analyse numérique, 24h, L3, ENSEIRB-MATMECA, France
  - Licence : Encadrement d'un projet sur la simulation numérique d'un impact laser en Lagrangien, L3, 25h,ENSEIRB-MATMECA, France
  - Master : Encadrement de projets de la filière Calcul Haute Performance, 6h, M2, ENSEIRB-MATMECA, France
  - Master : Projet fin d'études, 4h, M2, ENSEIRB-MATMECA, France

- Martin Parisot
  - Licence: Encadrement de projets sur la modélisation de l'AMOC, 10h, L3, ENSEIRB-MATMECA, France
  - Master: Encadrement de projets sur la modélisation de la formation et déformation des vagues, 10h, M1, ENSEIRB-MATMECA, France
  - Master : Cours magistral de modélisation et méthodes numériques pour les processus hydrauliques, 29.5h, M2, ENSEIRB-MATMECA, France

10.7.2 Supervision

PhDs supervised by the members of the team :

- Tony Bonnet (Bordeaux INP), co-supervised by M. Parisot
- Alexis Cas (CEA), co-supervised by H. Beaugendre
- Clarisse Chabaud (Airbus), co-supervised by N. Barral and M. Ricchiuto

- Sebastien Erdocio (IFPEN), co-supervised by M. Parisot
- Maxime Jannin (CEA), co-supervised by M. Ricchiuto
- Filipe Forte Tenreiro (BRGM), co-supervised by M. Kazolea
- Alessandro Del Piero (Inria, RESCUER Doctoral Network), , co-supervised by M. Kazolea
- Vincent Pilorget (BRGM), co-supervised by M. Ricchiuto
- Ishak Tifouti, co-supervised by N. Barral

10.7.3 Juries

- H. Beaugendre has been reviewer for Abdoulaye Ouattara (PhD thesis, Pprime Poitiers, june 2025); Pablo Elices Paz (PhD thesis, Polytechnic Montreal and ONERA Toulouse, september 2025); Antoine Motte (PhD thesis, CEA Saclay, october 2025). She has been examiner for Zeina Chehade (PhD thesis, Inria Carmen, june 2025); Chloé Mimeau (HDR thesis, CNAM, november 2025).
- M. Kazolea has been reviewer for Guillaume Coulaud (PhD thesis, Ecole national des ponts et de chaussees,November 2025)
- M. Ricchiuto has been reviewer for the following evaluations: Marco Gambarini (PhD thesis, Politecnico di Milano); Dr. Zheng Sun (tenure, University of Alabama) ; Jésus Ganzález Sieiro (PhD thesis, Universidad Pais Vasco, December 2025); Yu-Hsi Lin (PhD thesis, U. Aix-Marseille, June 2025)

10.8 Popularization

N. Barral, M. Kazolea and M. Ricchiuto participated in the article À Bordeaux, ces chercheurs qui simulent numériquement des tsunamis of the regional newspaper SudOuest.

11 Scientific production

11.1 Major publications

[1] R. Abgrall, P.-H. Maire and M. Ricchiuto. ‘Embedding General Conservation Constraints in Discretizations of Hyperbolic Systems on Arbitrary Meshes: A Multidimensional Framework’. In: *Mathematical Models and Methods in Applied Sciences* (12th Dec. 2025). DOI: `10.1142/S0218202526400014`. URL: `https://inria.hal.science/hal-05441079`.

[2] W. Barsukow, M. Ricchiuto and D. Torlo. ‘Structure preserving nodal continuous Finite Elements via Global Flux quadrature’. In: *Numerical Methods for Partial Differential Equations* 41.1 (21st Jan. 2025). URL: `https://hal.science/hal-04779510`.

[3] M. Carreau and M. Parisot. ‘A unified modeling of underground-surface hydraulic processes’. In: *Multiscale Modeling and Simulation: A SIAM Interdisciplinary Journal* 24.1 (29th Jan. 2025), pp. 68–98. DOI: `10.1137/25M1731733`. URL: `https://hal.science/hal-04918607`.

11.2 Publications of the year

International journals

[4] R. Abgrall, P.-H. Maire and M. Ricchiuto. ‘Embedding General Conservation Constraints in Discretizations of Hyperbolic Systems on Arbitrary Meshes: A Multidimensional Framework’. In: *Mathematical Models and Methods in Applied Sciences* (12th Dec. 2025). DOI: `10.1142/S0218202526400014`. URL: `https://inria.hal.science/hal-05441079` (cit. on p. 17).

[5] W. Barsukow, M. Ciallella, M. Ricchiuto and D. Torlo. ‘Genuinely multi-dimensional stationarity preserving Finite Volume formulation for nonlinear hyperbolic PDEs’. In: *Journal of Computational Physics* (2026). DOI: 10.1016/j.jcp.2025.114633. URL: https://hal.science/hal-05337761. In press (cit. on pp. 17, 18).

[6] W. Barsukow, M. Ricchiuto and D. Torlo. ‘Structure preserving nodal continuous Finite Elements via Global Flux quadrature’. In: *Numerical Methods for Partial Differential Equations* 41.1 (21st Jan. 2025). URL: https://hal.science/hal-04779510 (cit. on pp. 17, 18).

[7] S. Bhat, N. Barral and M. Ricchiuto. ‘Error-based efficient parameter space partitioning for mesh adaptation and local reduced order models’. In: *Computer Methods in Applied Mechanics and Engineering* 435 (Feb. 2025), p. 117649. DOI: 10.1016/j.cma.2024.117649. URL: https://inria.hal.science/hal-04851883.

[8] C. Brutto, M. Dumbser, M. Parisot and M. Ricchiuto. ‘Introduction of dispersive effects and treatment of horizontally moving pressurized regions in a semi-implicit fluid–structure interaction model’. In: *Computers and Fluids* 300 (Sept. 2025), p. 106756. DOI: 10.1016/j.compfluid.2025.106756. URL: https://hal.science/hal-05216832 (cit. on p. 19).

[9] M. Carreau and M. Parisot. ‘A unified modeling of underground-surface hydraulic processes’. In: *Multiscale Modeling and Simulation: A SIAM Interdisciplinary Journal* 24.1 (29th Jan. 2025), pp. 68–98. DOI: 10.1137/25M1731733. URL: https://hal.science/hal-04918607 (cit. on p. 22).

[10] A. Cas, C. Baranger, H. Beaugendre and S. Peluchon. ‘Conservative models and numerical methods for pyrolysis-thermal coupling of heat shield degradation and deformations’. In: *International Journal of Heat and Mass Transfer* 256 (Mar. 2026), p. 127962. DOI: 10.1016/j.ijheatmasstransfer.2025.127962. URL: https://inria.hal.science/hal-05442240.

[11] S. Gavrilyuk and M. Ricchiuto. ‘A geometrical Green-Naghdi type system for dispersive-like waves in prismatic channels’. In: *Journal of Fluid Mechanics* 1014 (26th June 2025), A5. DOI: 10.1017/jfm.2025.10274. URL: https://inria.hal.science/hal-04889204.

[12] M. Kazolea, C. Parés-Madronal and M. Ricchiuto. ‘Approximate well-balanced WENO finite difference schemes using a global-flux quadrature method with multi-step ODE integrator weights’. In: *Computers and Fluids* 296 (30th June 2025). DOI: 10.1016/j.compfluid.2025.106646. URL: https://inria.hal.science/hal-04890566.

[13] H. Lharti, D. Lacanette, F. Salmon, J. Riss, M. Mauriac and C. Sirieix. ‘Influence of geological heterogeneities on thermal behaviour of Lascaux Cave for conservation purposes’. In: *International Journal of Heat and Mass Transfer* 242 (23rd Feb. 2025), p. 126863. DOI: 10.1016/j.ijheatmasstransfer.2025.126863. URL: https://hal.inrae.fr/hal-04998057.

[14] H. Lharti, C. Sirieix, A. Marache, J. Riss, F. Salmon, C. Verdet and D. Lacanette. ‘3D modelling of rock mass heterogeneities in unsaturated karst using geophysics, clustering and geostatistics’. In: *Engineering Geology* 350 (May 2025), p. 107994. DOI: 10.1016/j.enggeo.2025.107994. URL: https://hal.inrae.fr/hal-04997958.

[15] H. Ranocha and M. Ricchiuto. ‘Structure-preserving approximations of the Serre-Green-Naghdi equations in standard and hyperbolic form’. In: *Numerical Methods for Partial Differential Equations* 41.4 (21st June 2025). DOI: 10.1002/num.70016. URL: https://inria.hal.science/hal-04888829.

[16] M. Romanelli, S. Beneddine, I. Mary, H. Beaugendre, M. Bergmann and D. Sipp. ‘Efficient and accurate data-driven wall modelling strategy for Reynolds averaged Navier–Stokes simulations’. In: *Journal of Computational Physics* 538 (Oct. 2025), p. 114128. DOI: 10.1016/j.jcp.2025.114128. URL: https://inria.hal.science/hal-05282661.

[17] J. Visbech, A. Engsig-Karup and M. Ricchiuto. ‘A spectral element solution of the Poisson equation with shifted boundary polynomial corrections: influence of the surrogate to true boundary mapping and an asymptotically preserving Robin formulation’. In: *Journal of Scientific Computing* 102.1 (2025), p. 11. DOI: 10.1007/s10915-024-02713-z. URL: https://inria.hal.science/hal-04829220.

Invited conferences

[18] I. Tifouti, N. Barral and T. Taddei. ‘Registration-based model reduction with local reduced order bases’. In: AIAA Scitech 2025 -. Orlando (FL), United States, 6th Jan. 2025. URL: `https://inria.hal.science/hal-05065511` (cit. on p. 21).

International peer-reviewed conferences

[19] B. Constant, A. M. D. Jost, S. Péron, C. Benoit and H. Beaugendre. ‘Steady-State Turbulent Flow Simulations of the NASA High Lift Common Research Model in an Immersed Boundary Context’. In: *AIAA AVIATION FORUM AND ASCEND 2025*. AIAA AVIATION Forum and ASCEND 2025. Las Vegas, United States: American Institute of Aeronautics and Astronautics, 2025. DOI: `10.2514/6.2025-3791`. URL: `https://hal.science/hal-05190236`.

Conferences without proceedings

[20] M. P. Basile, R. Milani, J. Peter, F. Renac and M. Ricchiuto. ‘Maximum principle preserving and entropy stable time implicit DGSEM for degenerate parabolic equations’. In: ICOSAHOM 2025 - 15th International Congress on Spectral and High Order Methods. Montréal, Canada, 2025. URL: `https://hal.science/hal-05241586`.

[21] A. Cas, C. Baranger, H. Beaugendre and S. Peluchon. ‘Numerical methods for pyrolysis-thermal coupling of heat shield degradation during hypersonic RE-entry’. In: FAR 2025 - 3d International Conference on Flight vehicles, Aerothermodynamics and Re-entry. Arcachon, France, 2025. URL: `https://inria.hal.science/hal-05282905`.

[22] A. Cas, C. Baranger, H. Beaugendre and S. Peluchon. ‘Numerical methods for pyrolysis-thermal coupling of heat shield degradation during hypersonic re-entry’. In: HiSST 2025 - 4th International Conference on High-Speed Vehicle Science & Technology. Tours, France, 22nd Sept. 2025. URL: `https://inria.hal.science/hal-05282959`.

[23] A. Cas, C. Baranger, H. Beaugendre and S. Peluchon. ‘Conservative numerical modeling of an ablative charring heat shield under deformations’. In: 15th Ablation Workshop. Las Cruces, United States, 18th Nov. 2025. URL: `https://inria.hal.science/hal-05442277`.

Doctoral dissertations and habilitation theses

[24] I. Tifouti. ‘Construction of reduced-order models with mesh adaptation’. Université de Bordeaux, 20th Nov. 2025. URL: `https://theses.hal.science/tel-05408853`.

Reports & preprints

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