Activity Report 2019

Project-Team FLUMINANCE

Fluid Flow Analysis, Description and Control from Image Sequences

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Project-Team FLUMINANCE

Creation of the Project-Team: 2009 July 01

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Other Research Topics and Application Domains:

B3.2. - Climate and meteorology
B3.3. - Geosciences
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1. Team, Visitors, External Collaborators

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  Huguette Bechu [Inria, Administrative Assistant]
Visiting Scientist
  Rudiger Brecht [Inria, from May 2019 until Aug 2019]

2. Overall Objectives

2.1. Overall Objectives

The research group that we have entitled FLUMINANCE from a contraction between the words "Fluid" and "Luminance" is dedicated to the extraction of information on fluid flows from image sequences and to the development of tools for the analysis and control of these flows. The objectives of the group are at the frontiers of several important domains that range from fluid mechanics to geophysics. One of the main originality of the FLUMINANCE group is to combine cutting-edge researches on data-assimilation and flow numerical modeling with an ability to conduct proper intensive experimental validations on prototype flows mastered in laboratory. The scientific objectives decompose in four main themes:

- **Fluid flows characterization from images**
  In this first axis, we aim at providing accurate measurements and consistent analysis of complex fluid flows through image analysis techniques.The application domain ranges from industrial processes and experimental fluid mechanics to environmental sciences. This theme includes also the use of non-conventional imaging techniques such as Schlieren techniques, Shadowgraphs, holography. The objective will be here to go towards 3D dense velocity measurements.

- **Coupling dynamical model and image data**
  We focus here on the study, through image data, of complex and partially known fluid flows involving complex boundary conditions, multi-phase fluids, fluids and structures interaction problems. Our credo is that image analysis can provide sufficiently fine observations on small and medium scales to construct models which, applied at medium and large scale, account accurately for a wider range of the dynamics scales. The image data and a sound modeling of the dynamical uncertainty at the observation scale should allow us to reconstruct the observed flow and to provide efficient real flows (experimental or natural) based dynamical modeling. Our final goal will be to go towards a 3D reconstruction of real flows, or to operate large motion scales simulations that fit real world flow data and incorporate an appropriate uncertainty modeling.

- **Control and optimization of turbulent flows**

We are interested on active control and more precisely on closed-loop control. The main idea is to extract reliable image features to act on the flow. This approach is well known in the robot control community, it is called visual servoing. More generally, it is a technique to control a dynamic system from image features. We plan to apply this approach on flows involved in various domains such as environment, transport, microfluidic, industrial chemistry, pharmacy, food industry, agriculture, etc.

- **Numerical models for geophysical flows simulation and analysis** Numerical models are very useful for environmental applications. Several difficulties must be handled simultaneously, in a multidisciplinary context. For example, in geophysics, media are highly heterogeneous and only few data are available. Stochastic models are often necessary to describe unresolved physical processes. Computational domains are characterized by complex 3D geometries, requiring adapted space discretization. Equations modeling flow and transport are transient, requiring also adapted time discretization. Moreover, these equations can be coupled together or with other equations in a global nonlinear system. These large-scale models are very time and memory consuming. High performance computing is thus required to run these types of scientific simulations. Supercomputers and clusters are quite powerful, provided that the numerical models are written with a parallel paradigm.

3. Research Program

3.1. Estimation of fluid characteristic features from images

The measurement of fluid representative features such as vector fields, potential functions or vorticity maps, enables physicists to have better understanding of experimental or geophysical fluid flows. Such measurements date back to one century and more but became an intensive subject of research since the emergence of correlation techniques [56] to track fluid movements in pairs of images of a particles laden fluid or by the way of clouds photometric pattern identification in meteorological images. In computer vision, the estimation of the projection of the apparent motion of a 3D scene onto the image plane, referred to in the literature as optical-flow, is an intensive subject of researches since the 80's and the seminal work of B. Horn and B. Schunk [67]. Unlike to dense optical flow estimators, the former approach provides techniques that supply only sparse velocity fields. These methods have demonstrated to be robust and to provide accurate measurements for flows seeded with particles. These restrictions and their inherent discrete local nature limit too much their use and prevent any evolutions of these techniques towards the devising of methods supplying physically consistent results and small scale velocity measurements. It does not authorize also the use of scalar images exploited in numerous situations to visualize flows (image showing the diffusion of a scalar such as dye, p ollutant, light index refraction, fluorescein,...). At the opposite, variational techniques enable in a well-established mathematical framework to estimate spatially continuous velocity fields, which should allow more properly to go towards the measurement of smaller motion scales. As these methods are defined through PDE's systems they allow quite naturally constraints to be included such as kinematic properties or dynamic laws governing the observed fluid flows. Besides, within this framework it is also much easier to define characteristic features estimation procedures on the basis of physically grounded data model that describes the relation linking the observed luminance function and some state variables of the observed flow. The Fluminance group has allowed a substantial progress in this direction with the design of dedicated dense estimation techniques to estimate dense fluid motion fields. See [7] for a detailed review. More recently problems related to scale measurement and uncertainty estimation have been investigated [61]. Dynamically consistent and highly robust techniques have been also proposed for the recovery of surface oceanic streams from satellite images [58]. Very recently parameter-free approaches relying on uncertainty concept has been devised [59]. This technique outperforms the state of the art.

3.2. Data assimilation and Tracking of characteristic fluid features

Real flows have an extent of complexity, even in carefully controlled experimental conditions, which prevents any set of sensors from providing enough information to describe them completely. Even with the highest levels of accuracy, space-time coverage and grid refinement, there will always remain at least a lack of resolution and some missing input about the actual boundary conditions. This is obviously true for the complex flows encountered in industrial and natural conditions, but remains also an obstacle even for standard academic flows thoroughly investigated in research conditions.

This unavoidable deficiency of the experimental techniques is nevertheless more and more compensated by numerical simulations. The parallel advances in sensors, acquisition, treatment and computer efficiency allow the mixing of experimental and simulated data produced at compatible scales in space and time. The inclusion of dynamical models as constraints of the data analysis process brings a guaranty of coherency based on fundamental equations known to correctly represent the dynamics of the flow (e.g. Navier Stokes equations) [11]. Conversely, the injection of experimental data into simulations ensures some fitting of the model with reality.

To enable data and models coupling to achieve its potential, some difficulties have to be tackled. It is in particular important to outline the fact that the coupling of dynamical models and image data are far from being straightforward. The first difficulty is related to the space of the physical model. As a matter of fact, physical models describe generally the phenomenon evolution in a 3D Cartesian space whereas images provides generally only 2D tomographic views or projections of the 3D space on the 2D image plane. Furthermore, these views are sometimes incomplete because of partial occlusions and the relations between the model state variables and the image intensity function are otherwise often intricate and only partially known. Besides, the dynamical model and the image data may be related to spatio-temporal scale spaces of very different natures which increases the complexity of an eventual multiscale coupling. As a consequence of these difficulties, it is necessary generally to define simpler dynamical models in order to assimilate image data. This redefinition can be done for instance on an uncertainty analysis basis, through physical considerations or by the way of data based empirical specifications. Such modeling comes to define inexact evolution laws and leads to the handling of stochastic dynamical models. The necessity to make use and define sound approximate models, the dimension of the state variables of interest and the complex relations linking the state variables and the intensity function, together with the potential applications described earlier constitute very stimulating issues for the design of efficient data-model coupling techniques based on image sequences.

On top of the problems mentioned above, the models exploited in assimilation techniques often suffer from some uncertainties on the parameters which define them. Hence, a new emerging field of research focuses on the characterization of the set of achievable solutions as a function of these uncertainties. This sort of characterization indeed turns out to be crucial for the relevant analysis of any simulation outputs or the correct interpretation of operational forecasting schemes. In this context, stochastic modeling play a crucial role to model and process uncertainty evolution along time. As a consequence, stochastic parameterization of flow dynamics has already been present in many contributions of the Fluminance group in the last years and will remain a cornerstone of the new methodologies investigated by the team in the domain of uncertainty characterization.

This wide theme of research problems is a central topic in our research group. As a matter of fact, such a coupling may rely on adequate instantaneous motion descriptors extracted with the help of the techniques studied in the first research axis of the FLUMINANCE group. In the same time, this coupling is also essential with respect to visual flow control studies explored in the third theme. The coupling between a dynamics and data, designated in the literature as a Data Assimilation issue, can be either conducted with optimal control techniques [68], [69] or through stochastic filtering approaches [62], [65]. These two frameworks have their own advantages and deficiencies. We rely indifferently on both approaches.

3.3. Optimization and control of fluid flows with visual servoing

Fluid flow control is a recent and active research domain. A significant part of the work carried out so far in that field has been dedicated to the control of the transition from laminarity to turbulence. Delaying, accelerating or modifying this transition is of great economical interest for industrial applications. For instance, it has been

shown that for an aircraft, a drag reduction can be obtained while enhancing the lift, leading consequently to limit fuel consumption. In contrast, in other application domains such as industrial chemistry, turbulence phenomena are encouraged to improve heat exchange, increase the mixing of chemical components and enhance chemical reactions. Similarly, in military and civilians applications where combustion is involved, the control of mixing by means of turbulence handling rouses a great interest, for example to limit infra-red signatures of fighter aircraft.

Flow control can be achieved in two different ways: passive or active control. Passive control provides a permanent action on a system. Most often it consists in optimizing shapes or in choosing suitable surfacing (see for example [60] where longitudinal riblets are used to reduce the drag caused by turbulence). The main problem with such an approach is that the control is, of course, inoperative when the system changes. Conversely, in active control the action is time varying and adapted to the current system's state. This approach requires an external energy to act on the system through actuators enabling a forcing on the flow through for instance blowing and suction actions [72], [64]. A closed-loop problem can be formulated as an optimal control issue where a control law minimizing an objective cost function (minimization of the drag, minimization of the actuators power, etc.) must be applied to the actuators [57]. Most of the works of the literature indeed comes back to open-loop control approaches [71], [66], [70] or to forcing approaches [63] with control laws acting without any feedback information on the flow actual state. In order for these methods to be operative, the model used to derive the control law must describe as accurately as possible the flow and all the eventual perturbations of the surrounding environment, which is very unlikely in real situations. In addition, as such approaches rely on a perfect model, a high computational costs is usually required. This inescapable pitfall has motivated a strong interest on model reduction. Their key advantage being that they can be specified empirically from the data and represent quite accurately, with only few modes, complex flows' dynamics. This motivates an important research axis in the Fluminance group.

3.4. Numerical models applied to hydrogeology and geophysics

The team is strongly involved in numerical models for hydrogeology and geophysics. There are many scientific challenges in the area of groundwater simulations. This interdisciplinary research is very fruitful with cross-fertilizing subjects.

In geophysics, a main concern is to solve inverse problems in order to fit the measured data with the model. Generally, this amounts to solve a linear or nonlinear least-squares problem.

Models of geophysics are in general coupled and multi-physics. For example, reactive transport couples advection-diffusion with chemistry. Here, the mathematical model is a set of nonlinear Partial Differential Algebraic Equations. At each timestep of an implicit scheme, a large nonlinear system of equations arise. The challenge is to solve efficiently and accurately these large nonlinear systems.

3.5. Numerical algorithms and high performance computing

Linear algebra is at the kernel of most scientific applications, in particular in physical or chemical engineering. The objectives are to analyze the complexity of these different methods, to accelerate convergence of iterative methods, to measure and improve the efficiency on parallel architectures, to define criteria of choice.

4. Highlights of the Year

4.1. Highlights of the Year

4.1.1. Awards

Best paper award 2019 Romain Schuster "Visualisation et mesure du flux d'aspiration d'une Sorbonne", ContaminExpert 2019. Paris, FR

Best Paper Award:

[43]

R. Schuster, D. Heitz, E. Mémin. *Visualisation et mesure du flux d'aspiration d'une Sorbonne*, in "ContaminExpert 2019", Paris, France, March 2019, pp. 1-8, https://hal.archives-ouvertes.fr/hal-02330348

5. New Software and Platforms

5.1. 2DLayeredMotion

Estimation of 2D independent mesoscale layered atmospheric motion fields

Functional Description: This software enables to estimate a stack of 2D horizontal wind fields corresponding to a mesoscale dynamics of atmospheric pressure layers. This estimator is formulated as the minimization of a global energy function. It relies on a vertical decomposition of the atmosphere into pressure layers. This estimator uses pressure data and classification clouds maps and top of clouds pressure maps (or infra-red images). All these images are routinely supplied by the EUMETSAT consortium which handles the Meteosat and MSG satellite data distribution. The energy function relies on a data model built from the integration of the mass conservation on each layer. The estimator also includes a simplified and filtered shallow water dynamical model as temporal smoother and second-order div-curl spatial regularizer. The estimator may also incorporate correlation-based vector fields as additional observations. These correlation vectors are also routinely provided by the Eumetsat consortium.

- Participant: Étienne Mémin
- Contact: Étienne Mémin
- URL: http://fluid.irisa.fr/index.html

5.2. 3DLayeredMotion

Estimation of 3D interconnected layered atmospheric motion fields

Functional Description: This software extends the previous 2D version. It allows (for the first time to our knowledge) the recovery of 3D wind fields from satellite image sequences. As with the previous techniques, the atmosphere is decomposed into a stack of pressure layers. The estimation relies also on pressure data and classification clouds maps and top of clouds pressure maps. In order to recover the 3D missing velocity information, physical knowledge on 3D mass exchanges between layers has been introduced in the data model. The corresponding data model appears to be a generalization of the previous data model constructed from a vertical integration of the continuity equation.

- Contact: Étienne Mémin
- URL: http://fluid.irisa.fr

5.3. DenseMotion

Estimation of 2D dense motion fields

Functional Description: This code allows the computation from two consecutive images of a dense motion field. The estimator is expressed as a global energy function minimization. The code enables the choice of different data models and different regularization functionals depending on the targeted application. Generic motion estimators for video sequences or fluid flows dedicated estimators can be set up. This software allows in addition the users to specify additional correlation based matching measurements. It enables also the inclusion of a temporal smoothing prior relying on a velocity vorticity formulation of the Navier-Stoke equation for Fluid motion analysis applications.

- Participant: Étienne Mémin
- Contact: Étienne Mémin
- URL: http://fluid.irisa.fr/index.html

5.4. Low-Order-Motion

Estimation of low order representation of fluid motion

FUNCTIONAL DESCRIPTION: This code enables the estimation of a low order representation of a fluid motion field from two consecutive images.The fluid motion representation is obtained using a discretization of the vorticity and divergence maps through regularized Dirac measure. The irrotational and solenoidal components of the motion fields are expressed as linear combinations of basis functions obtained through the Biot-Savart law. The coefficient values and the basis function parameters are formalized as the minimizer of a functional relying on an intensity variation model obtained from an integrated version of the mass conservation principle of fluid mechanics.

- Participants: Anne Cuzol and Étienne Mémin
- Contact: Étienne Mémin
- URL: http://fluid.irisa.fr

5.5. TYPHOON

KEYWORD: Fluid mechanics

FUNCTIONAL DESCRIPTION: Typhoon is a fluid motion estimator from image sequences. It is almost real-time dedicated to the measurement of LIDAR sequences, multi-scale, fast and precise to make a fine scale analysis of fluid flows with applications in the fields of energy, transport and environment.

- Participants: Christopher Mauzey, Étienne Mémin and Pierre Dérian
- Partner: CSU Chico
- Contact: Étienne Mémin
- URL: https://phys.csuchico.edu/lidar/typhoon/

5.6. H2OLab

KEYWORDS: Simulation - Energy - Contamination - Groundwater - Hydrogeology - Heterogeneity - Uncertainly - Multiscale

SCIENTIFIC DESCRIPTION: The software platform contains a database which is interfaced through the web portal H2OWeb. It contains also software modules which can be used through the interface H2OGuilde. The platform H2OLab is an essential tool for the dissemination of scientific results. Currently, software and database are shared by the partners of the h2mno4 project.

FUNCTIONAL DESCRIPTION: The software platform H2OLab is devoted to stochastic simulations of groundwater flow and contaminant transport in highly heterogeneous porous and fractured geological media.

-Modeling and numerical simulation of aquifers -Porous and fractured heterogeneous media -Flow with mixed finite elements -Solute transport with a Lagrangian method -Stochastic modeling for data uncertainty.

- Participants: Géraldine Pichot, Grégoire Lecourt, Jean-Raynald De Dreuzy and Jocelyne Erhel
- Partners: Université de Rennes 1 - CNRS - Université de Lyon - Université de Poitiers
- Contact: Jocelyne Erhel
- URL: http://h2olab.inria.fr/

5.7. PALMTREE

KEYWORD: Monte-Clarlo

FUNCTIONAL DESCRIPTION: We present an easy-to-use package for the parallelization of Lagrangian methods for partial differential equations. In addition to the reduction of computation time, the code aims at satisfying three properties:

simplicity: the user just has to add the algorithm governing the behaviour of the particles. portability: the possibility to use the package with any compiler and OS. action-replay: the ability of the package to replay a selected batch of particles.

The last property allows the user to replay and capture the whole sample path for selected particles of a batch. This feature is very useful for debugging and catching some relevant information.

- Authors: Lionel Lenôtre, Géraldine Pichot
- Contact: Géraldine Pichot

5.8. GRT3D

Global Reactive Transport in 3D

KEYWORDS: Geochemistry - Dispersion - Scientific calculation - Simulation - Advection

SCIENTIFIC DESCRIPTION: Participants : Édouard Canot, Jocelyne Erhel [correspondant] .

Version: version 2.0, April 2014

APP: registered

Programming language: C

Abstract: Reactive transport modeling has become an essential tool for understanding complex environmental problems. It is an important issue for MoMaS and C2S@EXA partners (see sections 8.2.5 , 8.2.3), in particular Andra. We have developed a method coupling transport and chemistry, based on a method of lines such that spatial discretization leads to a semi-discrete system of algebraic differential equations (DAE system). The main advantage is to use a complex DAE solver, which controls simultaneously the timestep and the convergence of Newton algorithm. The approach SIA uses a fixed-point method to solve the nonlinear system at each timestep, whereas the approach SNIA uses an explicit scheme.

The software suite GRT3D has four executable modules:

SIA1D: Sequential Iterative Approach for 1D domains,

GDAE1D: Global DAE approach for 1D domains,

SNIA3D: Sequential Non Iterative Approach for 1D, 2D or 3D domains.

GDAE3D: Global DAE approach for 1D, 2D or 3D domains. This module has three variants: the original one with logarithms, an optimized one still with logarithms, an optimized one which does not use logarithms.

Current work: extension of the chemistry module and parallelization.

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GDAE3D: Global DAE approach for 1D, 2D or 3D domains. This module has three variants: the original one with logarithms, an optimized one still with logarithms, an optimized one which does not use logarithms.

- Participants: Caroline De Dieuleveult, Édouard Canot, Jocelyne Erhel, Nadir Soualem and Souhila Sabit
- Partner: ANDRA
- Contact: Jocelyne Erhel

6. New Results

6.1. Fluid motion estimation

6.1.1. *Stochastic uncertainty models for motion estimation*
Participants: Musaab Khalid Osman Mohammed, Etienne Mémin.

This work is concerned with the design of motion estimation technique for image-based river velocimetry. The method proposed is based on an advection diffusion equation associated to the transport of large-scale quantity with a model of the unresolved small-scale contributions. Additionally, since there is no ground truth data for such type of image sequences, a new evaluation method to assess the results has been developed. It is based on trajectory reconstruction of few Lagrangian particles of interest and a direct comparison against their manually-reconstructed trajectories. The new motion estimation technique outperformed traditional optical flow and PIV-based methods used in hydrology [23]. This study has been performed within the PhD thesis of Musaab Khalid and through a collaboration with the Irstea Lyon hydrology research group (HHLY).

6.1.2. *Development of an image-based measurement method for large-scale characterization of indoor airflows*
Participants: Dominique Heitz, Etienne Mémin, Romain Schuster.

The goal is to design a new image-based flow measurement method for large-scale industrial applications. From this point of view, providing in situ measurement technique requires: (i) the development of precise models relating the large-scale flow observations to the velocity; (ii) appropriate large-scale regularization strategies; and (iii) adapted seeding and lighting systems, like Hellium Filled Soap Bubles (HFSB) and led ramp lighting. This work conducted within the PhD of Romain Schuster in collaboration with the compagny ITGA has started in february 2016. The first step has been to evaluate the performances of a stochastic uncertainty motion estimator when using large scale scalar images, like those obtained when seeding a flow with smoke. The PIV characterization of flows on large fields of view requires an adaptation of the motion estimation method from image sequences. The backward shift of the camera coupled to a dense scalar seeding involves a large scale observation of the flow, thereby producing uncertainty about the observed phenomena. By introducing a stochastic term related to this uncertainty into the observation term, we obtained a significant improvement of the estimated velocity field accuracy. The technique was validated on a mixing layer in a wind tunnel for HFSB and smoke tracers [39] and applied on a laboratory fume-hood [26], [30], [43]. This study demonstrated the feasibility of conducting on-site large-scale image-based measurements for indoor airflows characterization. The technique was also assessed in an outdoor flow

6.1.3. *3D flows reconstruction from image data*
Participants: Dominique Heitz, Etienne Mémin.

Our work focuses on the design of new tools for the estimation of 3D turbulent flow motion in the experimental setup of Tomo-PIV. This task includes both the study of physically-sound models on the observations and the fluid motion, and the design of low-complexity and accurate estimation algorithms. This year, we continued our investigation on the problem of efficient volume reconstruction via ensemble assimilation scheme. We have proposed a novel method for volumetric velocity reconstruction exploring the locality of 3D object space. Under this formulation the velocity of local patch was sought to match the projection of the particles within the local patch in image space to the image recorded by camera. The core algorithm to solve the matching problem is an instance-based estimation scheme that can overcome the difficulties of optimization originated from the nonlinear relationship between the imageintensity residual and the volumetric velocity. The proposed method labeled as Lagrangian Particle ImageVelocimetry (LaPIV) is quantitatively evaluated with synthetic particle image data. The promising results indicated the potential application of LaPIV to a large variety of volumetric velocity reconstruction problems [44].

6.2. Tracking, Data assimilation and model-data coupling

6.2.1. *Optimal control techniques for the coupling of large scale dynamical systems and image data*

Participants: Mohamed Yacine Ben Ali, Pranav Chandramouli, Dominique Heitz, Etienne Mémin, Gilles Tissot.

In this axis of work, we explore the use of optimal control techniques for the coupling of Large Eddies Simulation (LES) techniques and 2D image data. The objective is to reconstruct a 3D flow from a set of simultaneous time resolved 2D image sequences visualizing the flow on a set of 2D planes enlightened with laser sheets. This approach is experimented on shear layer flows and on wake flows generated on the wind tunnel of Irstea Rennes. Within this study we aim to explore techniques to enrich large-scale dynamical models by the introduction of uncertainty terms or through the definition of subgrid models from the image data. This research theme is related to the issue of turbulence characterization from image sequences. Instead of predefined turbulence models, we aim here at tuning from the data the value of coefficients involved in traditional LES subgrid models. A 4DVar assimilation technique based on the numerical code Incompact3D has been implemented for that purpose to control the inlet and initial conditions in order to reconstruct a turbulent wake flow behind an unknown obstacle [21]. We extended this first data assimilation technique to control the subgrid parameters. This study is performed in collaboration with Sylvain Laizet (Imperial College). In another axis of research, in collaboration with the CSTB Nantes centre and within the PhD of Yacine Ben Ali we will explore the definition of efficient data assimilation schemes for wind engineering. The goal is here to couple Reynolds average model to pressure data at the surface of buildings. The final purpose will consist in proposing improved data-driven simulation models for architects.

6.2.2. *Ensemble variational data assimilation of large-scale dynamics with uncertainty*

Participant: Etienne Mémin.

Estimating the parameters of geophysical dynamic models is an important task in Data Assimilation (DA) technique used for forecast initialization and reanalysis. In the past, most parameter estimation strategies were derived by state augmentation, yielding algorithms that are easy to implement but may exhibit convergence difficulties. The Expectation-Maximization (EM) algorithm is considered advantageous because it employs two iterative steps to estimate the model state and the model parameter separately. In this work, we propose a novel ensemble formulation of the Maximization step in EM that allows a direct optimal estimation of physical parameters using iterative methods for linear systems. This departs from current EM formulations that are only capable of dealing with additive model error structures. This contribution shows how the EM technique can be used for dynamics identification problem with a model error parameterized as arbitrary complex form. The proposed technique is used for the identification of stochastic subgrid terms that account for processes unresolved by a geophysical fluid model. This method, along with the augmented state technique, has been evaluated to estimate such subgrid terms through high resolution data. Compared to the augmented state technique, our method is shown to yield considerably more accurate parameters. In addition, in terms of

prediction capacity, it leads to smaller generalization error as caused by the overfitting of the trained model on presented data and eventually better forecasts [29].

6.2.3. *Reduced-order models for flows representation from image data*

Participants: Dominique Heitz, Etienne Mémin, Gilles Tissot.

During the PhD thesis of Valentin Resseguier we have proposed a new decomposition of the fluid velocity in terms of a large-scale continuous component with respect to time and a small-scale non continuous random component. Within this general framework, an uncertainty based representation of the Reynolds transport theorem and Navier-Stokes equations can be derived, based on physical conservation laws. This physically relevant stochastic model has been applied in the context of POD-Galerkin methods. This uncertainty modeling methodology provides a theoretically grounded technique to define an appropriate subgrid tensor as well as drift correction terms. The pertinence of this stochastic reduced order model has been successfully assessed on several wake flows at different Reynold number. It has been shown to be much more stable than the usual reduced order model construction techniques. Beyond the definition of a stable reduced order model, the modeling under location uncertainty paradigm offers a unique way to analyse from the data of a turbulent flow the action of the small-scale velocity components on the large-scale flow. Regions of prominent turbulent kinetic energy, direction of preferential diffusion, as well as the small-scale induced drift can be identified and analyzed to decipher key players involved in the flow. This study has been published in the Journal of Fluid Mechanics [15]. Note that these reduced order models can be extended to a full system of stochastic differential equations driving all the temporal modes of the reduced system (and not only the small-scale modes). This full stochastic system has been evaluated on wake flow at moderate Reynolds number. For this flow the system has shown to provide very good uncertainty quantification properties as well as meaningful physical behavior with respect to the simulation of the neutral modes of the dynamics. This study is pursued within a strong collaboration with the industrial partner: SCALIAN

6.2.4. *Learning of the dynamics of large scale geophysical systems using semi-group theory for data assimilation*

Participants: Etienne Mémin, Gilles Tissot.

The goal of this study is to propose new ensemble data assimilation methodologies to estimate oceanic and turbulent flows. In classical methods, from a distribution of initial conditions, an ensemble of simulations are computed and used for estimation. Ideally, from this solution, a new ensemble has to be generated to refine the estimation. However, due to large numerical costs and operational constraints, this iterative procedure is in practice intractable. In order to improve actual performances, we propose to take these limitations into account and to develop new methodologies able to better take advantage of the information contained in the ensemble and in the dynamical model. More precisely, we propose to learn the non-linear dynamical features of the system and to be able to reproduce it without having to run a new simulation. The formalism is based on two concepts: i) the reproducing kernel Hilbert spaces (RKHS) that are a basis of smooth functions in the phase space giving interpolatory properties ii) the Koopman operator, that is an infinite-dimensional operator able to propagate in time any observable of the phase space. These two elements allow to define a rigorous framework in which hypothesis classically done in ensemble methods appear naturally. Thus, classical methods enter in a special case of this new formalism, that allows us to generalise them in a way to improve the learning of the non-linear dynamical system. Numerical tests are performed using the Ginzburg-Landau equation and a quasi-geostrophic flow model.

6.2.5. *Estimation and control of amplifier flows*

Participant: Gilles Tissot.

Estimation and control of fluid systems is an extremely hard problem. The use of models in combination with data is central to take advantage of all information we have on the system. Unfortunately all flows do not present the same physical and mathematical behaviour, thus using models and methodologies specialised to the flow physics is necessary to reach high performances.

A class of flows, denoted "oscillator flows", are characterised by unstable modes of the linearised operator. A consequence is the dominance of relatively regular oscillations associated with a nonlinear saturation. Despite the non-linear behaviour, associated structures and dynamical evolution are relatively easy to predict. Canonical configurations are the cylinder wake flow or the flow over an open cavity.

By opposition to that, "amplifier flows" are linearly stable with regard to the linearised operator. However, due to their convective nature, a wide range of perturbations are amplified in time and convected away such that it vanishes at long time. The consequence is the high sensitivity to perturbations and the broad band response that forbid a low rank representation. Jets and mixing layers show this behaviour and a wide range of industrial applications are affected by these broad band perturbations. It constitutes then a class of problems that are worth to treat separately since it is one of the scientific locks that render hard the transfer of methodologies existing in flow control and estimation to industrial applications.

There exists a type of models, that we will denote as "parabolised", that are able to efficiently represent amplifier flows. These models, such as parabolised stability equations and one-way Navier-Stokes propagate, in the frequency domain, hydrodynamic instability waves over a given turbulent mean flow. We can note that these models, by their structure, give access to a natural experimental implementation. They are an ingredient adapted to represent the system, but have a mathematical structure strongly different from the dynamical models classically used in control and data assimilation. It is then important to develop new methodologies of control, estimation and data assimilation with these models to reach our objectives. Moreover, inventing new models by introducing the modelling under location uncertainties in these parabolised models will be perfectly adapted to represent the evolution and the variability of an instability propagating within a turbulent flow. It will be consistent with actual postprocessing of experimental data performed in similar flow configurations.

6.3. Analysis and modeling of turbulent flows and geophysical flows

6.3.1. *Geophysical flows modeling under location uncertainty*
Participants: Werner Bauer, Pranav Chandramouli, Long Li, Etienne Mémin.

In this research axis we have devised a principle to derive representation of flow dynamics under location uncertainty. Such an uncertainty is formalized through the introduction of a random term that enables taking into account large-scale approximations or truncation effects performed within the dynamics analytical constitution steps. Rigorously derived from a stochastic version of the Reynolds transport theorem [9], this framework, referred to as modeling under location uncertainty (LU), encompasses several meaningful mechanisms for turbulence modeling. It indeed introduces without any supplementary assumption the following pertinent mechanisms for turbulence modeling: (i) a dissipative operator related to the mixing effect of the large-scale components by the small-scale velocity; (ii) a multiplicative noise representing small-scale energy backscattering; and (iii) a modified advection term related to the so-called *turbophoresis* phenomena, attached to the migration of inertial particles in regions of lower turbulent diffusivity.

In a series of papers we have shown how LU modeling can be applied to provide stochastic representations of a variety of classical geophysical flows dynamics [12], [13], [14]. Numerical simulations and uncertainty quantification have been performed on Quasi Geostophic approximation (QG) of oceanic models. It has been shown that LU leads to remarkable estimation of the unresolved errors opposite to classical eddy viscosity based models. The noise brings also an additional degree of freedom in the modeling step and pertinent diagnostic relations and variations of the model can be obtained with different scaling assumptions of the turbulent kinetic energy (i.e. of the noise amplitude). For a wind forced QG model in a square box, which is an idealized model of north-Atlantic circulation, we have shown that for different versions of the noise the QG LU model leads to improve long-terms statistics when compared to classical large-eddies simulation strategies. For a QG model we have demonstrated that the LU model allows conserving the global energy. We have also shown numerically that Rosby waves were conserved and that inhomogeneity of the random component triggers secondary circulations. This feature enabled us to draw a formal bridge between a classical system describing the interactions between the mean current and the surface waves and the LU model in which the turbophoresis advection term plays the role of the classical Stokes drift.

Supported by funding from Inria-Mitacs Globalink, we hosted Ruediger Brecht, PhD student at Memorial University of Newfoundland, Canada, for a period of 3 months (May to August) in the Fluminance group. During his stay, Ruediger Brecht worked on the incorporation of a stochastic representation of the small-scale velocity component of a fluid flow in a variational integrator for the rotating shallow-water equations on the sphere, already developed within the first part of its PhD work. This work was based on an ongoing study in the group on a stochastic Quasi-geostrophic model and followed a series of works performed in the Fluminance group to define stochastic geophysical flow dynamics.

6.3.2. *Large eddies simulation models under location uncertainty*

Participants: Mohamed Yacine Ben Ali, Pranav Chandramouli, Dominique Heitz, Etienne Mémin, Gilles Tissot.

The models under location uncertainty recently introduced by Mémin (2014) [9] provide a new outlook on LES modeling for turbulence studies. These models are derived from a stochastic transport principle. The associated stochastic conservation equations are similar to the filtered Navier- Stokes equation wherein we observe a sub-grid scale dissipation term. However, in the stochastic version, an extra term appears, termed as "velocity bias", which can be treated as a biasing/modification of the large-scale advection by the small scales. This velocity bias, introduced artificially in the literature, appears here automatically through a decorrelation assumption of the small scales at the resolved scale. All sub-grid contributions for the stochastic models are defined by the small-scale velocity auto-correlation tensor. This large scale modeling has been assed and compared to several classical large-scale models on a flow over a circular cylinder at Re 3900 and wall-bounded flows. For all these flows the modeling under uncertainty has provided better results than classical large eddies simulation models. Within the PhD of Yacine Ben Ali we will explore with the CSTB Nantes centre the application of such models for the definition of Reynolds average simulation (RANS) models for wind engineering applications.

6.3.3. *Variational principles for structure-preserving discretizations in stochastic fluid dynamics*

Participants: Werner Bauer, Long Li, Etienne Mémin.

The overarching goal of this interdisciplinary project is to use variational principles to derive deterministic and stochastic models and corresponding accurate and efficient structure preserving discretizations and to use these schemes to obtain a deeper understanding of the conservation laws of the stochastic fluid dynamics investigated. The newly developed systematic discretization framework is based on discrete variational principles whose highly structured procedures shall be exploited to develop a general software framework that applies automatic code generation. This project will first provide new stochastic fluid models and suitable approximations, with potential future applications in climate science using the developed methods to perform accurate long term simulations while quantifying the solutions uncertainties. The generality of our approach addresses also other research areas such as electrodynamics (EDyn), magnetohydrodynamics (MHD), and plasma physics.

6.3.4. *Stochastic compressible fluid dynamics*

Participants: Etienne Mémin, Gilles Tissot.

Some work has been performed to extend the stochastic formulation under location uncertainty to compressible flows. The interest is to extend the formulation on the one hand to compressible fluids (for instability mechanisms involved in areoacoustics for instance, or for thermal effects in mixing layers) and on the other hand to geophysical flows where the Boussinesq equation is not valid anymore (density variations due to temperature or salinity gradients). A theoretical study has been performed that opens the door to numerical validations. In particular a baroclinic torque term has been identified that could have major effects in some situations.

6.3.5. *Stochastic hydrodynamic stability under location uncertainty*

Participants: Etienne Mémin, Gilles Tissot.

In order to predict instability waves propagating within turbulent flows, eigenmodes of the linearised operator is not well suited since it neglects the effect of turbulent fluctuations on the wave dynamics. To cope this difficulty, resolvent analysis has become popular since it represents the response of the linearised operator to any forcing representing the generalised stress tensors. The absence of information on the non-linearity is a strong limitation of the method. In order to refine these models, we propose to consider a stochastic model under location uncertainty expressed in the Fourier domain, to linearise it around the corrected mean-flow and to study resulting eigenmodes. The stochastic part represents the effect of the turbulent field onto the instability wave. It allows to specify a structure of the noise and then to improve existing models. Improvements compared to the resolvent analysis have been found for turbulent channel flow data at $\mathfrak{R}_\tau = 180$. This work is in collaboration with André Cavalieri (Instituto Tecnologico de Aeronautica, SP, Brésil).

6.3.6. *Singular and regular solutions to the Navier-Stokes equations (NSE) and relative turbulent models*

Participants: Roger Lewandowski, Etienne Mémin, Benoit Pinier.

The common thread of this work is the problem set by J. Leray in 1934 : does a regular solution of the Navier-Stokes equations (NSE) with a smooth initial data develop a singularity in finite time, what is the precise structure of a global weak solution to the Navier-Stokes equations, and are we able to prove any uniqueness result of such a solution. This is a very hard problem for which there is for the moment no answer. Nevertheless, this question leads us to reconsider the theory of Leray for the study of the Navier-Stokes equations in the whole space with an additional eddy viscosity term that models the Reynolds stress in the context of large-scale flow modelling. It appears that Leray's theory cannot be generalized turnkey for this problem, so that things must be reconsidered from the beginning. This problem is approached by a regularization process using mollifiers, and particular attention must be paid to the eddy viscosity term. For this regularized problem and when the eddy viscosity has enough regularity, we have been able to prove the existence of a global unique solution that is of class C? in time and space and that satisfies the energy balance. Moreover, when the eddy viscosity is of compact support in space, uniformly in time, we recently shown that this solution converges to a turbulent solution to the corresponding Navier-Stokes equations,carried when the regularizing parameter goes to 0. These results are described in a paper published in JMAA [24]

In the framework of the collaboration with the University of Pisa (Italy), namely with Luigi Berselli collaboration, we considered the three dimensional incompressible Navier-Stokes equations with non stationary source terms chosen in a suitable space. We proved the existence of Leray-Hopf weak solutions and that it is possible to characterize (up to sub-sequences) their long-time averages, which satisfy the Reynolds averaged equations, involving a Reynolds stress. Moreover, we showed that the turbulent dissipation is bounded by the sum of the Reynolds stress work and of the external turbulent fluxes, without any additional assumption, than that of dealing with Leray-Hopf weak solutions. This is a very nice generalisation to non stationnary source terms of a famous results by Foais. IN the same work, we also considered ensemble averages of solutions, associated with a set of different forces and we proved that the fluctuations continue to have a dissipative effect on the mean flow. These results have been published in Nonlinearity [19]. These results have been extended in the framework of POD for reduced models in [18].

In [55] we have shown the existence of a solution to a 1D Reynolds Averaged Navier-Stokes vertical model suitable in the atmospheric boundary layer, under suyitable assumption on the data. The paper is received for publication in thje journal Pure and Applied Functional Analysis (PAFA).

We also have introduced a turbulence model including a backscatter term, which has the same structure as the Voigt model. The additional term is derived in certain specific regimes of the flow, such as the convergence to stable statistical states. We get estimates for the velocity v in $L_t^\infty H_x^1 \cap W_t^{1,2} H_x^{1/2}$, that allow us to prove the existence and uniqueness of a regular-weak solutions (v, p) to the resulting system, for a given fixed eddy viscosity. We then prove a structural compactness result that highlights the robustness of the model. This allows us to pass to the limit in the quadratic source term in the equation for the turbulent kinetic energy k, which yields the existence of a weak solution to the corresponding Reynolds Averaged Navier-Stokes system satisfied by (v, p, k). These results are written in [47], a paper which is under revision in Non Linear Analysis.

Another study in collaboration with B. Pinier, P. Chandramouli and E. Memin has been undertaken. This work takes place within the context of the PhD work of B. Pinier. We have tested the performances of an incompressible turbulence Reynolds-Averaged Navier-Stokes one-closure equation model in a boundary layer, which requires the determination of the mixing length l. A series of direct numerical simulation have been performed, with flat and non trivial topographies, to obtain by interpolation a generic formula l = l(Re6, z), Re6 being the frictional Reynolds number, and z the distance to the wall. Numerical simulations have been carried out at high Reynolds numbers with this turbulence model, in order to discuss its ability to properly reproduce the standard profiles observed in neutral boundary layers, and to assess its advantages, its disadvantages and its limits. We also proceeded to a mathematical analysis of the model.

6.3.7. *Stochastic flow model to predict the mean velocity in wall bounded flows*

Participants: Roger Lewandowski, Etienne Mémin, Benoit Pinier.

To date no satisfying model exists to explain the mean velocity profile within the whole turbulent layer of canonical wall bounded flows. We propose a modification of the velocity profile expression that ensues from the stochastic representation of fluid flows dynamics proposed recently in the group and referred to as "modeling under location uncertainty". This framework introduces in a rigorous way a subgrid term generalizing the eddy-viscosity assumption and an eddy-induced advection term resulting from turbulence inhomogeneity. This latter term gives rise to a theoretically well-grounded model for the transitional zone between the viscous sublayer and the turbulent sublayer. An expression of the small-scale velocity component is also provided in the viscous zone. Numerical assessment of the results have been performed for turbulent boundary layer flows, pipe flows and channel flows at various Reynolds numbers [25][17].

6.3.8. *Numerical and experimental image and flow database*

Participants: Pranav Chandramouli, Dominique Heitz.

The goal was to design a database for the evaluation of the different techniques developed in the Fluminance group. The first challenge was to enlarge a database mainly based on two-dimensional flows, with three-dimensional turbulent flows. Synthetic image sequences based on homogeneous isotropic turbulence and on circular cylinder wake have been provided. These images have been completed with time resolved Particle Image Velocimetry measurements in wake and mixing layers flows. This database provides different realistic conditions to analyse the performance of the methods: time steps between images, level of noise, Reynolds number, large-scale images. The second challenge was to carry out orthogonal dual plane time resolved stereoscopic PIV measurements in turbulent flows. The diagnostic employed two orthogonal and synchronized stereoscopic PIV measurements to provide the three velocity components in planes perpendicular and parallel to the streamwise flow direction. These temporally resolved planar slices observations have been be used within a 4DVar assimilation technique, to reconstruct three-dimensional turbulent flows from data. The third challenge was to carry out a time resolved tomoPIV experiments in a turbulent wake flow. This work has been submitted to the Journal of Computational Physics.

6.3.9. *Fast 3D flow reconstruction from 2D cross-plane observations*

Participants: Pranav Chandramouli, Dominique Heitz, Etienne Mémin.

We proposed a computationally efficient flow reconstruction technique, exploiting homogeneity in a given direction, to recreate three dimensional instantaneous turbulent velocity fields from snapshots of two dimension planar fields. This methodology, termed as "snapshot optimisation" or SO, enables to provide 3D data-sets for studies which are currently restricted by the limitations of experimental measurement techniques. The SO method aims at optimising the error between an inlet plane with a homogeneous direction and snap-shots, obtained over a sufficient period of time, on the observation plane. The observations are carried out on a plane perpendicular to the inlet plane with a shared edge normal to the homogeneity direction. The method is applicable to all flows which display a direction of homogeneity such as cylinder wake flows, channel flow, mixing layer, and jet (axi-symmetric). The ability of the method is assessed with two synthetic data-sets, and three experimental PIV data-sets. A good reconstruction of the large-scale structures are observed for all cases. This study has been published in the journal "Experiments in Fluids" [21].

6.4. Visual servoing approach for fluid flow control

6.4.1. A state space representation for the closed-loop control of shear flows
Participants: Johan Carlier, Christophe Collewet.

The goal of this study is to develop a generic state representation for the closed-loop control of shear flows. We assume that the actuator acts at the boundaries. Our approach is based on a linearization of the Navier-Stokes equations around the desired state. Particular care was paid to the discrete approximation of the linear model to design a well-conditioned and accurate state matrix describing time evolution of disturbances evolving in parallel shear flow as long as these disturbances remain sufficiently small. A state matrix representation is obtained for the periodic channel flow and the spatially developing mixing layer flow. This approach has been validated through the representativity of our model in terms of linear stability. This work has been presented to the French Mechanics Congress CFM'2019 (https://hal.inria.fr/hal-02283161) [36].

6.4.2. Closed-loop control of a spatially developing shear layer
Participants: Christophe Collewet, Johan Carlier.

This study aims at controling one of the prototypical flow configurations encountered in fluid mechanics: the spatially developing turbulent shear layer occuring between two parallel incident streams with different velocities. Our goal is to maintain the shear-layer in a desired state and thus to reject upstream perturbations. In our conference IFAC paper (https://hal.inria.fr/hal-01514361) we focused on perturbations belonging to the same space that the actuators, concretely that means that we were only able to face perturbations of the actuator itself, like failures of the actuator. This year we enlarged this result to purely exogenous perturbations, in term of magnitude as well as in term of spatial dispersion. An optimal control law has been derived to minimize the influence of the perturbation on the flow. To do that, an on-line estimation of the perturbation (magnitude and spatial dispersion) has been developed to lead to an adaptive control law. Simple conditions to ensure the local asymptotic stability of the whole scheme have been derived. This work has been also presented to the French Mechanics Congress CFM'2019 (https://hal.archives-ouvertes.fr/hal-02189111) [37].

6.4.3. Design of a DBD plasma actuator for closed-loop control
Participants: Johan Carlier, Christophe Collewet.

The goal of this study is to design a DBD plasma actuator for closed-loop control. This kind of actuator is widely used in the flow control community however, it is more appropriate to force a flow than to control it. Indeed, to control a flow under a closed-loop fashion, the action must be proportional to the control signal provided by the control law. It is unfortunately not the case with these actuators. We have modified the classical DBD plasma actuator so that the action is almost a linear fonction of the control signal. Our approach have been validated by a prototype and by first experiments.

6.5. Coupled models in hydrogeology

6.5.1. Reactive transport in multiphase flow
Participant: Jocelyne Erhel.

Groundwater resources are essential for life and society, and should be preserved from contamination. Pollutants are transported through the porous medium and a plume can propagate. Reactive transport models aims at simulating this dynamic contamination by coupling advection dispersion equations with chemistry equations. If chemistry is at thermodynamic equilibrium, then the system is a set of partial differential and algebraic equations (PDAE). Space discretization leads to a semi-discrete DAE system which should be discretized in time. An explicit time scheme allows an easy decoupling of transport and chemistry, but very small timesteps should be taken, leading to a very large CPU time. Therefore, an implicit time scheme is preferred, coupling transport and chemistry in a nonlinear system. The special structure of linearized systems can be used in preconditioned Newton-Krlyov methods in order to improve efficiency. Some experiments illustrate the methodology and show also the need for an adaptive timestep and a control of convergence in Newton's iterations.

This work was presented at a workshop [31].

6.5.2. *Characterizations of Solutions in Geochemistry at equilibrium*
Participant: Jocelyne Erhel.

Geochemistry at thermodynamic equilibrium involves aqueous reactions and mineral precipitation or dissolution. Quantities of solute species are assumed to be strictly positive, whereas those of minerals can vanish. The mathematical model is expressed as the minimization of Gibbs energy subject to positivity of mineral quantities and conservation of mass. Optimality conditions lead to a complementarity problem. We show that, in the case of a dilute solution, this problem can also be considered as optimality conditions of another minimization problem, subject to inequality constraints. This new problem is easier to handle, both from a theoretical and a practical point of view. Then we define a partition of the total quantities in the mass conservation equation. This partition builds a precipitation diagram such that a mineral is either precipitated or dissolved in each subset. We propose a symbolic algorithm to compute this diagram. Simple numerical examples illustrate our methodology.

This work was published in the journal Computational Geosciences [22] and presented at an international conference [38].

6.5.3. *Mathematical models of kinetic reactions in geochemistry*
Participants: Jocelyne Erhel, Bastien Hamlat.

In geochemistry, kinetic reactions can lead to the appearance or disappearance of minerals or gas. We defined two mathematical models based first on a differential inclusion system and second on a projected dynamical system. We proposed a regularization process for the first model and a projection algorithm for the second one.

This work, supported by IFPEN, was presented at a conference [39] and a workshop [32].

6.6. Sparse Linear solvers

6.6.1. *Parallel GMRES*
Participant: Jocelyne Erhel.

Sparse linear systems $Ax = b$ arise very often in computational science and engineering. Krylov methods are very efficient iterative methods, and restarted GMRES is a reference algorithm for non-symmetric systems. A first issue is to ensure a fast convergence, by preconditioning the system with a matrix M. Preconditioning must reduce the number of iterations, and be easy to solve. A second issue is to achieve high performance computing. The most time-consuming part in GMRES is to build an orthonormal basis V. With the Arnoldi process, many scalar products involve global communications. In order to avoid them, s-step methods have been designed to find a tradeoff between parallel performance and stability. Also, solving a system with the matrix M and for multiplying a vector by the matrix A should be efficient. A domain decomposition approach involves mainly local communications and is frequently used. A coarse grid correction, based on deflation for example, improves convergence. These techniques can be combined to provide fast convergence and fast parallel algorithms. Numerical results illustrate various issues and achievements.

This work was presented at an international conference (invited talk) [31].

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

7.1.1. *Contract ITGA*
Participants: Dominique Heitz, Etienne Mémin.

duration 36 months. This partnership between Inria, Irstea and ITGA funds the PhD of Romain Schuster. The goal of this PhD is to design new image-based flow measurement methods for the study of industrial fluid flows. Those techniques will be used in particular to calibrate industrial fume hood.

7.1.2. Contract CSTB

Participants: Mohamed Yacine Ben Ali, Dominique Heitz, Etienne Mémin.

duration 36 months. This partnership between Inria, Irstea and CSTB funds the PhD of Yacine Ben Ali. This PhD aims to design new data assimilation scheme for Reynolds Average Simulation (RANS) of flows involved in wind engineering and buildings construction. The goal pursued here consists to couple RANS models and surface pressure data in order to define data driven models with accurate turbulent parameterization.

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. Comins'lab: SEACS : Stochastic modEl-dAta-Coupled representationS for the analysis, simulation and reconstruction of upper ocean dynamics

Participant: Etienne Mémin.

duration 48 months. The SEACS project whose acronym stands for: "Stochastic modEl-dAta-Coupled representationS for the analysis, simulation and reconstruction of upper ocean dynamics" is a Joint Research Initiative between the three Britanny clusters of excellence of the "Laboratoires d'Excellence" program: Cominlabs, Lebesgue and LabexMer centered on numerical sciences, mathematics and oceanography respectively. Within this project we aim at studying the potential of large-scale oceanic dynamics modeling under uncertainty for ensemble forecasting and satellite image data assimilation.

8.1.2. ANR BECOSE : Beyond Compressive Sensing: Sparse approximation algorithms for ill-conditioned inverse problems.

Participant: Dominique Heitz.

duration 48 months. The BECOSE project aims to extend the scope of sparsity techniques much beyond the academic setting of random and well-conditioned dictionaries. In particular, one goal of the project is to step back from the popular L1-convexification of the sparse representation problem and consider more involved nonconvex formulations, both from a methodological and theoretical point of view. The algorithms will be assessed in the context of tomographic Particle Image Velocimetry (PIV), a rapidly growing imaging technique in fluid mechanics that will have strong impact in several industrial sectors including environment, automotive and aeronautical industries. The consortium gathers the Fluminance and Panama Inria research teams, the Research Center for Automatic Control of Nancy (CRAN), The Research Institute of Communication and Cybernetics of Nantes (IRCCyN), and ONERA, the French Aerospace Lab.

8.1.3. IFPEN project

Participants: Jocelyne Erhel, Bastien Hamlat.

Contract with IFPEN (Institut Français du Pétrole et Energies Nouvelles) Duration: three years from October 2016. Title: Fully implicit Formulations for the Simulation of Multiphase Flow and Reactive Transport Coordination: Jocelyne Erhel. Contract with IFPEN (Institut FranÃ§ais du Pétrole et Energies Nouvelles). Duration: three years October 2016-September 2019. Title: Fully implicit Formulations for the Simulation of Multiphase Flow and Reactive Transport. Coordination: Jocelyne Erhel. Abstract: Modeling multiphase flow in porous media coupled with fluid-rock chemical reactions is essential in order to understand the origin of sub-surface natural resources and optimize their use. This project focused on chemistry models, with kinetic reactions. We developed a mathematical tool, which can be embedded into a reactive transport code.

8.1.4. GDR MANU

Participants: Yvan Crenner, Jocelyne Erhel, Bastien Hamlat.

Title: Mathematics for Nuclear industry
Duration: From 2016 to 2019
Coordination: C. Cancès
Webpage: http://gdr-manu.math.cnrs.fr/
Abstract: The working group MANU is a follow-up to the group MOMAS. It covers many subjects related to mathematical modeling and numerical simulations for problems arising from nuclear industry and nuclear waste disposal. We participated in a workshop on reactive transport (SITRAM), Pau, December 2019.

8.1.5. LEFE MANU: MSOM

Participants: Etienne Mémin, Long Li.

Title: Multiple Scale Ocean Model
Duration: From 2018 to 2021
Coordination: Bruno Deremble (CNRS LMD/ENS Paris)
Abstract: The objective of this project is to propose a numerical framework of a multiscale ocean model and to demonstrate its utility in the understanding of the interaction between the mean current and eddies.

8.2. International Initiatives

8.2.1. Inria International Partners

8.2.1.1. Informal International Partners

Imperial College, London (UK), Collaboration with Dan Crişan and Darryl Holm on Stochastic transport for the upper ocean dynamics

Chico California State University (USA), We have pursued our collaboration with the group of Shane Mayor on the GPU implementation of wavelet based motion estimator for Lidar data. This code is developped in coproperty between Inria and Chico.

8.2.1.2. International Initiatives

MATH-GEO

Title: MATHematical methods for GEOphysical flows

International Partners (Institution - Laboratory - Researcher):

Universidad de Buenos Aires (Argentina) - CIMA - Juan Ruiz

Universidad de la Republica Uruguay (Uruguay) - IMFIA, INCO

CMM (Chile) - Center for Mathematical Modeling - Axel Osses

Universidad San Ignacio de Loyola (USIL) (Peru) - Faculty of Engineering Alejandro Paredes

Duration: 2018 - 2019

Start year: 2018 http://mathgeo.cima.fcen.uba.ar

Nonlinear processes, such as advection and turbulent mixing, play a central role in geophysical sciences. The theory of nonlinear dynamical systems provides a systematic way to study these phenomena. Its stochastic extension also forms the basis of modern data analysis techniques, predictability studies and data assimilation methods. Contributions in the field of Topology and Dynamics of Chaos include methods conceived to unveil the structure organizing flows in phase space, building the gap between data and l ow-dimensional modeling. Low-order models in climate dynamics are highly desirable, since they can provide solutions in cases where high-resolution numerical simulations cannot be implemented, as in short-term wind forecasting. At the same time, the procedure provides a tool-kit for model validation, emulation or inter-model comparison, with interesting prospects in all fields of oceanographic and atmospheric sciences, including climate detection and attribution. The strategy constitutes an unprecedented and promising perspective, offering an original approach to the subject, with mathematical concepts that are not necessarily widespread in the geophysics scientific community. This proposal gathers specialists with a know-how in the most challenging aspects of the focused research field: coherent structure detection in fluid flows for the exploration and interactive visualization of scientific data (LIMSI France), data assimilation and fluid motion analysis from image sequences (Inria Rennes), numerical models and data assimilation (CMM-Chile) stochastic models for climate dynamics with application to El Niño Ocean models (USIL-Peru), mathematical methods for weather and climate (CIMA-UBA & IMIT / IFAECI, Argentina), geophysical flows and dynamical systems (LMD France), mixing structures and Lagrangian analysis of multisatellite data (LOCEAN France), marine and estuarine hydrodynamic and water properties numerical models (INCO & IMFIA-Uruguay), in situ measurements of oceanographic conditions (CEBC France, in program with CNES France and CONAE Argentina), global modelling technique and topological characterization of flows (CORIA with CESBIO, France).

8.3. International Research Visitors

8.3.1. Visits of International Scientists

- 1 week visit of Alejandro Paredes Universidad San Ignacio de Loyola (USIL) (Peru) to work with Etienne Mémin
- 1 week visit of André Cavaleri (Instituto Tecnologico de Aeronautica, SP, Brésil) to work with Gilles Tissot
- 3 months visit of Ruediger Brecht (May to August), PhD student at Memorial University of Newfoundland, Canada, supported by funding from Inria-Mitacs Globalink.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events: Selection

Jocelyne Erhel is member of

- the international advisory committee of the parallel CFD conferences (Antalya, May 2019).
- the program committee of the workshop Visualization in Environmental Sciences 2019 (co-event of EuroVis).
- the scientific Committee of the workshop "Parallel solution methods for systems arising from PDEs" (Marseille, September 2019).
- the scientific Committee of the conference SimRace (IFPEN, Rueil-Malmaison, scheduled in December 2019 and postponed in 2020).

9.1.2. Journal

9.1.2.1. Member of the Editorial Boards

Jocelyne Erhel
- member of the editorial board of ETNA.
- member of the editorial board of ESAIM:Proceedings and Surveys.

Etienne Mémin
- Associate editor for the Int. Journal of Computer Vision (IJCV)
- Associate editor for the Image and Vision Computing Journal (IVC)

9.1.2.2. Reviewer - Reviewing Activities

Jocelyne Erhel: Reviewer for the journals Computational Geosciences, SISC, M2AN, JCAM, PARCO
Dominique Heitz: Reviewer for Exp. in Fluids, AMI Région Auvergne Rhone Alpes
Etienne Mémin: Reviewer for Tellus-A, Quat. J. of the Roy. Met. Soc., Journ. of Fluid Mech., Im. Vis. Comp., Exp. in Fluids, Journ. of Comp. Phys.
Gilles Tissot: Reviewer for Journal of Sound and Vibration, Fluid Dynamics Research.

9.1.3. Invited Talks

Werner Bauer
- European Numerical Mathematics and Advanced Applications Conference 2019, Egmond aan Zee, The Netherlands.
- Seminar talk at IRMAR, University of Rennes, France.
- Seminar talk at the Journée Rennes-Nantes d'Analyse 2019, University of Nantes, France.

Jocelyne Erhel
- Workshop on "Reactive transport modeling", IPGP, Paris, June 2019.
- Workshop on "Parallel Solution Methods for Systems Arising from PDEs", Marseille, France, September 2019.
- Workshop on "Advances in the SImulation of reactive flow and TRAnsport in porous Media (SITRAM)",

Etienne Mémin
- Workshop Big data, data assimilation, and uncertainty quantification, IHP, Paris (France), 12-15 November 2019
- Workshop on stochastic parameterizations and their use in data assimilation 1-5 July 2019 Imperial College London
- Equadif 2019, Leiden The Netherland, July 2019
- EGU, Vienna, Austria, April 2019
- Workshop on Conservation Principles, Data & Uncertainty in Atmosphere-Ocean Modelling", Potsdam, Germany April 2019

9.1.4. Leadership within the Scientific Community

- J. Erhel is scientific coordinator of the website Interstices (since June 2012). https://interstices.info.

9.1.5. Scientific Expertise

- J. Erhel is a member of the scientific council of IFPEN, since April 2016.

9.1.6. Research Administration

Jocelyne Erhel
- the Inria administrative commission (CAP) for researchers, 2016-2019.
- the maths thesis committee of IRMAR, 2017-2019.
- the selection committee for PhD grants of OSUR, 2019.

Dominique Heitz
- Responsible of the Irstea ACTA Team
- Member of Irstea OPAALE research unit Executive Committee
- Member of Pôle Cristal scientific council
- D. Heitz is a member of scientific council of CSTB's Jules Verne Wind Tunnel

Roger Lewandowski
- President du Comité de liaison du groupe GAMNI-SMAI
- President of the Blaise Pascal award jury
- President of GAMNI-SMAI PhD thesis award
- Corresponding person of the SMAI in Rennes
- Responsible of the group "Mathematical modeling" of IRMAR
- Member of the scientific council of IRMAR,
- Member of Mathematical teaching council of U. Rennes I
- Member of the scientific council of the Henri Lebesgue Centre

Etienne Mémin
- Member of the scientific council of LEFE-MANU action of CNRS INSU
- Member of the comity GAMNI-SMAI

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Licence: Jocelyne Erhel, Optimisation, 12h, niveau L3, ENSAI Rennes
Licence : Dominique Heitz, Mécanique des fluides, 30h, niveau L2 INSA Rennes
Master: Jocelyne Erhel, arithmétique flottante, 4h, niveau M1, INSA Rennes
Master : Dominique Heitz, Mécanique des fluides, 25h, niveau M1, Dep GMA INSA Rennes
Master: Roger Lewandowski, Euler and the Navier-Stokes equations, M2, master « fondamental mathematics ».
Master : Etienne Mémin, Analyse du mouvement, Master Informatique, 15h, niveau M2, Université de Rennes 1.
Master : Etienne Mémin, Vision par ordinateur , 15h, niveau M2, ESIR Université de Rennes 1.
Master : Etienne Mémin, Motion analysis , 9h, Master 2 SISEA Université de Rennes 1.
Master : Gilles Tissot, mathematics for acoustics, 20h, niveau M1, Université du Mans.

9.2.2. Supervision

PhD in progress: Bastien Hamlat, University of Rennes 1, October 2016, co-advisors Jocelyne Erhel and A. Michel.
PhD in progress : Long Li, Data assimilation and stochastic transport for the upper ocean dynamics, started November 2017, Etienne Mémin.
PhD in progress : Yacine Ben Ali, Variational assimilation of RANS models for wind engineering, started November 2017, Dominique Heitz, Etienne Mémin, Gilles Tissot.
PhD in progress : Dinh Duong Nguyen, Regular and singular solutions of Navier-Stokes equations with eddy viscosity, started September 2017 , Roger Lewandowski.
PhD in progress : Robin Billard, Modelling of non-conventional perforated acoustic liners, Université du Mans, started December 2017, Gilles Tissot.

9.2.3. Juries

Jocelyne Erhel
- Etienne Ahusborde, HdR, Univ. Strasbourg (rapporteur)
- Benoit Pinier, PhD, Univ. Rennes (examinatrice)
- Quentin Tournois, PhD, Univ. Rennes (examinatrice)

Etienne Mémin

- Anthony Fillion, Ecoles des Ponts, U. Paris-Est (Rapporteur)
- Alban Farchi, Ecoles des Ponts, U. Paris-Est (Examinateur)
- Arthur Pajot, Sorbonne Université, (Rapporteur)

9.3. Popularization

9.3.1. Education

Jocelyne Erhel

- présidente du jury du rallye de mathématiques du CNED, since 2017.

9.3.2. Interventions

Jocelyne Erhel

- conference about spreading epidemics, "les amphis lycéens 2018-2019", March 2019.
- conference about spreading epidemics, "les amphis lycéens 2019-2020", December 2019. [46].

9.3.3. Creation of media or tools for science outreach

Jocelyne Erhel

- was scientific coordinator of the website Interstices (June 2012 - September 2019). She is now member of the editorial board, from October 2019.

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