Activity Report 2016

Project-Team FLUMINANCE

Fluid Flow Analysis, Description and Control from Image Sequences

Table of contents

Project-Team FLUMINANCE

Creation of the Project-Team: 2009 July 01

Keywords:

Computer Science and Digital Science:

- 3. - Data and knowledge
- 3.3. - Data and knowledge analysis
- 3.4. - Machine learning and statistics
- 5.3. - Image processing and analysis
- 5.4. - Computer vision
- 5.9. - Signal processing
- 6. - Modeling, simulation and control
- 6.1. - Mathematical Modeling
- 6.2. - Scientific Computing, Numerical Analysis & Optimization
- 6.3. - Computation-data interaction
- 6.4. - Automatic control

Other Research Topics and Application Domains:

- 3.2. - Climate and meteorology
- 3.3. - Geosciences
- 5. - Industry of the future
- 5.2. - Design and manufacturing

1. Members

Research Scientists

Etienne Mémin [Team leader, Inria, Senior Researcher, HDR]
Jocelyne Erhel [Inria, Senior Researcher, HDR]
Christophe Collewet [IRSTEA, Researcher, HDR]
Dominique Heitz [IRSTEA, Researcher]
Cédric Herzet [Inria, Researcher]

Faculty Member

Roger Lewandowski [Univ. Rennes I, Professor]

Engineers

Yvan Crenner [Inria]
Lionel Lenôtre [Inria, until Jun 2016]

PhD Students

Pranav Chandramouli [Inria]
Benjamin Delfino [Inria, until Oct 2016]
Bastien Hamlat [IFPEN, from Oct 2016]
Musaab Khalid Osman Mohammed [IRSTEA]
Benoit Pinier [Univ. Rennes I]
Valentin Resseguier [Inria, granted by IFREMER]
Romain Schuster [ITGA]

Post-Doctoral Fellows

Pierre Derian [Inria]
Mamadou Diallo [Inria, from Oct 2016]
David Imberti [Inria, until Jul 2016]
Thibaut Tronchin [Inria, from May 2016]

Visiting Scientists
Shengze Cai [Zhejiang University, from Nov 2016]
Gisela Daniela Charo [University of Buenos Aires, from Sep 2016 until Oct 2016]

Administrative Assistant
Huguette Béchu [Inria]

Others
Jean-Raynald de Dreuzy [CNRS, Research Scientist, HDR]
Johan Carlier [Irstea, Research Engineer]

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 [47] 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 [57]. 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, pollutant, light index refraction, flurocein,...). 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 [8] for a detailed review. More recently problems related to scale measurement and uncertainty estimation have been investigated [51]. Dynamically consistent and highly robust techniques have been also proposed for the recovery of surface oceanic streams from satellite images [49].

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, the tools provided by the Bayesian theory play a crucial role since they encompass a variety of methodologies to model and process uncertainty. As a consequence, the Bayesian paradigm 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 [58], [59] or through stochastic filtering approaches [52], [55]. 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 [50] 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 [62], [54]. 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 [48]. Most of the works of the literature indeed comes back to open-loop control approaches [61], [56], [60] or to forcing approaches [53] 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. For example, high performance simulations were very helpful for finding out the asymptotic behaviour of the plume of solute transported by advection-dispersion. Numerical models are necessary to understand flow transfer in fractured media.

The team develops stochastic models for groundware simulations as well as for oceanic and atmospheric flows. Numerical models must then include Uncertainty Quantification methods, spatial and time discretization. Then, the discrete problems must be solved with efficient algorithms. The team develops parallel algorithms for complex numerical simulations and conducts performance analysis.

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. For example, steady-state flow simulations in porous media are discretized in space and lead to a large sparse linear system. The target size is 10^7 in 2D and 10^{10} in 3D. For transient models such as diffusion, the objective is to solve about 10^4 linear systems for each simulation. Memory requirements are of the order of Giga-bytes in 2D and Tera-bytes in 3D. CPU times are of the order of several hours to several days. Several methods and solvers exist for large sparse linear systems. They can be divided into three classes: direct, iterative or semi-iterative. Direct methods are highly efficient but require a large memory space and a rapidly increasing computational time. Iterative methods of Krylov type require less memory but need a scalable preconditioner to remain competitive. Iterative methods of multigrid type are efficient and scalable, used by themselves or as preconditioners, with a linear complexity for elliptic or parabolic problems but they are not so efficient for hyperbolic problems. Semi-iterative methods such as subdomain methods are hybrid direct/iterative methods which can be good tradeoffs. The convergence of iterative and semi-iterative methods and the accuracy of the results depend on the condition number which can blow up at large scale. 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.

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. Complex models are in general coupled multi-physics models. 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.

Approximation in Krylov subspace is in the core of the team activity since it provides efficient iterative solvers for linear systems and eigenvalue problems as well. The later are encountered in many fields and they include the singular value problem which is especially useful when solving ill posed inverse problems.

4. Application Domains

4.1. Introduction

By designing new approaches for the analysis of fluid-image sequences the FLUMINANCE group aims at contributing to several application domains of great interest for the community and in which the analysis of complex fluid flows plays a central role. The group focuses mainly on two broad application domains:

- Environmental sciences;
- Experimental fluid mechanics and industrial flows.

We detail hereafter these two application domains.

4.2. Environmental sciences

The first huge application domain concerns all the sciences that aim at observing the biosphere evolution such as meteorology, climatology or oceanography but also remote sensing study for the monitoring of meteorological events or human activities consequences. For all these domains image analysis is a practical and unique tool to *observe, detect, measure, characterize or analyze* the evolution of physical parameters over a large domain. The design of generic image processing techniques for all these domains might offer practical software tools to measure precisely the evolution of fluid flows for weather forecasting or climatology studies. It might also offer possibilities of close surveillance of human and natural activities in sensible areas such as forests, river edges, and valley in order to monitor pollution, floods or fire. The need in terms of local weather forecasting, risk prevention, or local climate change is becoming crucial for our tomorrow's life. At a more local scale, image sensors may also be of major utility to analyze precisely the effect of air curtains for safe packaging in agro-industrial.

4.3. Experimental fluid mechanics and industrial flows

In the domain of **experimental fluid mechanics**, the visualization of fluid flows plays a major role, especially for turbulence study since high frequency imaging has been made currently available. Together with analysis of turbulence at different scales, one of the major goals pursued at the moment by many scientists and engineers consists in studying the ability to manipulate a flow to induce a desired change. This is of huge technological importance to enhance or inhibit mixing in shear flows, improve energetic efficiency or control the physical effects of strain and stresses. This is for instance of particular interest for:

- military applications, for example to limit the infra-red signatures of fighter aircraft;
- aeronautics and transportation, to limit fuel consumption by controlling drag and lift effects of turbulence and boundary layer behavior;
- industrial applications, for example to monitor flowing, melting, mixing or swelling of processed materials, or preserve manufactured products from contamination by airborne pollutants, or in industrial chemistry to increase chemical reactions by acting on turbulence phenomena.

.

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: Etienne Memin
- Contact: Etienne Memin
- 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: Etienne Memin
- 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: Etienne Memin
- Contact: Etienne Memin
- 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: Etienne Memin and Anne Cuzol
- Contact: Etienne Memin
- URL: http://fluid.irisa.fr

5.5. TYPHOON

GPU implementation of wavelet based motion estimator for Lidar data. This code is developed in coproperty between Inria and Chico.
FUNCTIONAL DESCRIPTION Typhoon is a motion estimation software specialized in fluid motion estimation. It is based on a dense optical flow technique associated to a multiscale wavelet representation of the estimated motion.

- Participants: Pierre Derian, Christopher Mauzey and Etienne Memin
- Partner: CSU Chico
- Contact: Etienne Memin
- URL: http://phys.csuchico.edu/lidar/typhoon/

5.6. GRT3D

FUNCTIONAL DESCRIPTION Reactive transport modeling has become an essential tool for understanding complex environmental problems. It is an important issue for MoMaS and C2S@EXA partners, 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.

- Participants: Yvan Crenner, Jocelyne Erhel
- Partner: ANDRA
- Contact: Jocelyne Erhel
- URL: http://www.irisa.fr/sage/recherche/chemistry.html

5.7. H2OLab

KEYWORDS: Simulation - Multiscale - Uncertainly - Heterogeneity - Hydrogeology - Groundwater - Contamination - Energy
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: Jean-Raynald De Dreuzy, Jocelyne Erhel
- Partners: Université de Rennes 1 - CNRS - Université de Lyon - Université de Poitiers
- Contact: Jocelyne Erhel
- URL: http://h2olab.inria.fr/

5.8. PALMTREE

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.

- Participants: Lionel Lenotre
- Contact: Jocelyne Erhel

6. New Results

6.1. Fluid motion estimation

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

The objective consists here in relying on a stochastic transport formulation to propose a luminance conservation assumption dedicated to the measurement of large-scale fluid flows velocity. This formulation has the great advantage to incorporate from the beginning an uncertainty on the motion measurement. This uncertainty modeled as a possibly inhomogeneous random field uncorrelated in time can be estimated jointly to the motion estimates. Such a formulation, besides providing estimates of the velocity field and of its associated uncertainties, allows us to naturally define a linear multiresolution scale-space framework. It provides also a reinterpretation, in terms of uncertainty, of classical regularization functionals proposed in the context of motion estimation. This estimator, which extend a local motion estimator previously proposed in the team, has shown to improve significantly the results of the corresponding deterministic estimator. This kind method is assessed in the context of river hydrologics applications through a collaboration with an Irstea Lyon research group (HHLY). This study is performed within the PhD thesis of Musaab Mohammed.

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 the development of precise models relating the large-scale flow observations to the velocity, appropriate large-scale regularization strategies, and 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.

6.1.3. *3D flows reconstruction from image data*

Participants: Dominique Heitz, Cédric Herzet.

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 keep on our investigation on the problem of efficient volume reconstruction. Our work takes place within the context of some modern optimization techniques. First, we focussed our attention on the family of proximal and splitting methods and showed that the standard techniques commonly adopted in the TomoPIV literature can be seen as particular cases of such methodologies. Recasting standard methodologies in a more general framework allowed us to propose extensions of the latter: i) we showed that the parcimony characterizing the sought volume can be accounted for without increasing the complexity of the algorithms (e.g., by including simple thresholding operations); ii) we emphasized that the speed of convergence of the standard reconstruction algorithms can be improved by using Nesterov's acceleration schemes; iii) we also proposed a totally novel way of reconstructing the volume by using the so-called "alternating direction of multipliers method" (ADMM). In 2016, this work has led to the publication of a contribution in the international journal IOP Measurement Science and Technology.

On top of this work, we also focussed on another crucial step of the volume reconstruction problem, namely the pruning of the model. The pruning task consists in identifying some positions in the volume of interest which cannot contains any particle. Removing this position from the problem can then potentially allow for a dramatic dimensionality reduction. This year, we provide a methodological answer to this problem through the prism of the so-called "screening" techniques which have been proposed in the community of machine learning. In 2016, this work led to the publication of one contribution in the proceedings of the international conference on acoustics, speech and signal processing (ICASSP'16).

6.1.4. *Sparse-representation algorithms*

Participant: Cédric Herzet.

The paradigm of sparse representations is a rather new concept which turns out to be central in many domains of signal processing. In particular, in the field of fluid motion estimation, sparse representation appears to be potentially useful at several levels: i) it provides a relevant model for the characterization of the velocity field in some scenarios; ii) it plays a crucial role in the recovery of volumes of particles in the 3D Tomo-PIV problem.

Unfortunately, the standard sparse representation problem is known to be NP hard. Therefore, heuristic procedures have to be devised to access to the solution of this problem. Among the popular methods available in the literature, one can mention orthogonal matching pursuit (OMP), orthogonal least squares (OLS) and the family of procedures based on the minimization of sparsity inducing norms. In order to assess and improve the performance of these algorithms, theoretical works have been undertaken in order to understand under which conditions these procedures can succeed in recovering the "true" sparse vector.

This year, we contributed to this research axis by deriving conditions of success for the algorithms mentioned above when the amplitudes of the nonzero coefficients in the sparse vector obey some decay. In a TomoPIV context, this decay corresponds to the fact that not all the particles in the fluid diffuse the same quantity of light (notably because of illumination or radius variation). In particular, we show that the standard coherence-based guarantees for OMP/OLS can be relaxed by an amount which depends on the decay of the nonzero

coefficients. In 2016, our work has led to the publication of one paper in the journal IEEE Transactions on Information Theory.

We also investigated a new methodology to take sparsity into account into variational assimilation problems. We focussed on the problem of estimating of scalar transported by an unknown velocity field, when only low-resolution observations of the scalar are supposed to be available. The goal is to reconstruct both a high-resolution version of the scalar and the velocity field, assuming that these quantities admit a sparse decomposition in some proper frames. The associated optimization problem typically involves millions of variables and thus requires dedicated optimization procedures to be tractable. In 2016, we proposed a new assimilation scheme combining state-of-the-art optimization techniques (forward-backward propagation, ADMM, Attouch's procedure) to address this problem. Our algorithm is provably convergent while exhibiting a complexity per iteration evolving linearly with the problem's dimensions. This contribution has led to a journal publication in SIAM Journal on Imaging Science.

6.2. Tracking, Data assimilation and model-data coupling

6.2.1. *Stochastic fluid flow dynamics under uncertainty*
Participants: Pierre Derian, Etienne Mémin, Valentin Resseguier.

In this research axis we aim at devising Eulerian expressions for the description of fluid flow evolution laws under uncertainties. Such an uncertainty is modeled through the introduction of a random term that allows taking into account large-scale approximations or truncation effects performed within the dynamics analytical constitution steps. This includes for instance the modeling of unresolved scales interaction in large eddies simulation (LES) or in Reynolds average numerical simulation (RANS), but also uncertainties attached to non-uniform grid discretization. This model is mainly based on a stochastic version of the Reynolds transport theorem. Within this framework various simple expressions of the drift component can be exhibited for different models of the random field carrying the uncertainties we have on the flow. We aim at using such a formalization within image-based data assimilation framework and to derive appropriate stochastic versions of geophysical flow dynamical modeling. This formalization has been published in the journal Geophysical and Astrophysical Fluid Dynamics [10]. Numerical simulation on divergence free wavelets basis of 3D viscous Taylor-Green vortex and Crow instability have been performed within a collaboration with Souleymane Kadri-Harouna. Besides, we explore in the context of Valentin Resseguier's PhD the extension of such framework to oceanic models and to satellite image data assimilation. This PhD thesis takes place within a fruitful collaboration with Bertrand Chapron (CERSAT/IFREMER). This year we have more deeply explored several uncertainty representations of classical geophysical models for ocean and atmosphere. This study have led to very promising stochastic representation for the Quasi Geostophic approximation (QG) with noises of different energy.

6.2.2. *Free surface flows reconstruction and tracking*
Participants: Dominique Heitz, Etienne Mémin.

We investigated the combined use of a Kinect depth sensor and of a stochastic data assimilation method to recover free-surface flows. More generally, we proposed a particle filter method to reconstruct the complete state of free-surface flows from a sequence of depth images only. The data assimilation scheme introduced accounts for model and observations errors. We evaluated the developed approach on two numerical test cases: a collapse of a water column as a toy-example and a flow in an suddenly expanding flume as a more realistic flow. The robustness of the method to simulated depth data quality and also to initial conditions was considered. We illustrated the interest of using two observations instead of one observation into the correction step. Then, the performance of the Kinect sensor to capture temporal sequences of depth observations was investigated. Finally, the efficiency of the algorithm was qualified for a wave in a real rectangular flat bottom tank. It was shown that for basic initial conditions, the particle filter rapidly and remarkably reconstructed velocity and height of the free surface flow based on noisy measures of the elevation

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

Participants: Pranav Chandramouli, Dominique Heitz, Etienne Mémin.

In this axis of work we are exploring 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 plans enlightened with laser sheets. This approach will be experimented on shear layer flows and on wake flows generated on the wind tunnel of Irstea Rennes. Within this study we wish also 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. The longer-term goal is to learn empirical subgrid models directly from image data. An accurate modeling of this term is essential for Large Eddies Simulation as it models all the non resolved motion scales and their interactions with the large scales.

We have pursued the first investigations on a 4DVar assimilation technique, integrating PIV data and Direct Numerical Simulation (DNS), to reconstruct two-dimensional turbulent flows. The problem we are dealing with consists in recovering a flow obeying Navier-Stokes equations, given some noisy and possibly incomplete PIV measurements of the flow. By modifying the initial and inflow conditions of the system, the proposed method reconstructs the flow on the basis of a DNS model and noisy measurements. The technique has been evaluated in the wake of a circular cylinder. It denoises the measurements and increases the spatiotemporal resolution of PIV time series. These results have been recently published in the Journal of Computational Physics [7]. Along the same line of studies the 3D case is ongoing. The goal consists here to reconstruct a 3D flow from a set of simultaneous time resolved 2D images of planar sections of the 3D volume. This work has been mainly conducted within the PhD of Cordelia Robinson. The development of the variational assimilation code has been initiated within a collaboration with A. Gronskis, S. Laizé (lecturer, Imperial College, UK) and Eric Lamballais (institut P' Poitiers). A High Reynolds number simulation of the wake behind a cylinder has been recently performed within this collaboration. The 4DVar assimilation technique based on the numerical code Incompact3D is now implemented. We are currently trying to reconstruct a 3D turbulent flow from dual plane velocity observations. The control of subgrid parameterizations will be the main objective of the PhD of Pranav Chandramouli that is just starting.

6.2.4. *Ensemble variational data assimilation of large scale fluid flow dynamics with uncertainty*

Participant: Etienne Mémin.

This study is focused on the coupling of a large scale representation of the flow dynamics built from the location uncertainty principle with image data of finer resolution. The velocity field at large scales is described as a regular smooth component whereas the complement component is a highly oscillating random velocity field defined on the image grid but living at all the scales. Following this route we have assessed the performance of an ensemble variational assimilation technique with direct image data observation. Preliminary encouraging results have been obtained for simulation under uncertainty of 1D and 2D shallow water models.

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

Participants: Mamadou Diallo, Cédric Herzet, Etienne Mémin, Valentin Resseguier.

During the PhD thesis of Valentin Ressguier we 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 the POD-Galerkin method. The pertinence of this reduced order model has been successfully assessed on several wake flows. This study has been published in two conference papers and one journal article.

On the other hand, we investigated the problem of reduced-model construction from partial observations. In this line of search, our contribution was twofold. We first proposed a Bayesian framework for the construction of reduced-order models from image data. Our framework enables to account for any prior information on the system to reduce and takes the uncertainties on the parameters of the model into account. Interestingly, the proposed approach reduces to some well-known model-reduction techniques when the observations are not partial (i.e., the observation operator can be inverted). Second, we provided a theoretical analysis of our methodology in a simplified context (namely, the observations are supposed to be noiseless linear combinations of the state of the system). This result provides worst-case guarantees on the reconstruction performance which can be achieved by a reduced model built from the data. These contributions have led to the publications of one contribution in the proceedings of the international conference on acoustics, speech and signal processing (ICASSP'16). A journal version of these contributions has been submitted.

6.3. Analysis and modeling of turbulent flows

6.3.1. Singular and regular solutions to the Navier-Stokes equations (NSE) and relative turbulent models
Participant: Roger Lewandowski.

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 paid to the eddy viscosity term. For this regularized problem and when the eddy viscosity has enough regularity, we have 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 when, the regularizing parameter goes to 0. These results are described in a paper that will be soon submitted to the journal Archive for Rational Mechanics and Analysis (ARMA).

In the same direction, we also finalized a paper in collaboration with L. Berselli (Univ. Pisa, Italy) about the well known Bardina's turbulent model. In this problem, we consider the Helmholtz filter usually used within the framework of Large Eddy Simulation. We carry out a similar analysis, by showing in particular that no singularity occurs for Bardina's model.

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 considered the standard turbulent models involving the Navier-Stokes equations with an eddy viscosity that depends on the Turbulent Kinetic Energy (TKE), coupled with an addition equation for the TKE. The problem holds in a 3D bounded domain, with the Manning law at the boundary for the velocity. We have modeled a flux condition at the boundary for the TKE. We prove that with these boundary conditions, the resulting problem has a distributional solution. Then a serie of numerical tests is performed in a parallelepiped with a non trivial bottom, showing the accuracy of the model in comparison with a direct numerical simulation of the Navier-Stokes equations.

6.3.2. Turbulence similarity theory for the modeling of Ocean Atmosphere interface
Participants: Roger Lewandowski, Etienne Mémin, Benoit Pinier.

The Ocean Atmosphere interface plays a major role in climate dynamics. This interaction takes place in a thin turbulent layer. To date no sastifying universal models for the coupling of atmospheric and oceanic models exists. In practice this coupling is realized through empirically derived interaction bulks. In this study, corresponding to the PhD thesis of Benoit Pinier, we aim at exploring similarity theory to identify universal mean profile of velocity and temperature within the mixture layer. The goal of this work consists in exhibiting eddy viscosity models within the primitive equations. We will also explore the links between those eddy viscocity models and the subgrid tensor derived from the uncertainty framework studied in the Fluminance group. In that prospect, we have started to study the impact of the introduction of a random modeling of the friction velocity on the classical wall law expression.

6.3.3. *Hot-wire anemometry at low velocities*

Participant: Dominique Heitz.

A new dynamical calibration technique has been developed for hot-wire probes. The technique permits, in a short time range, the combined calibration of velocity, temperature and direction calibration of single and multiple hot-wire probes. The calibration and measurements uncertainties were modeled, simulated and controlled, in order to reduce their estimated values. Based on a market study the french patent application has been extended this year to a Patent Cooperation Treaty (PCT) application.

6.3.4. *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 carried 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 will be used in 4DVar assimilation technique, integrating Direct Numerical Simulation (DNS) and Large Eddies Simulation (LES), to reconstruct three-dimensional turbulent flows. This reconstruction will be conducted within the PhD of Pranav Chandramouli. The third challenge was to carried out a time resolved tomoPIV experiments in a turbulent wake flow. These temporally resolved volumic observations will be used to assess the algorithms developped in the PhD of Ioana Barbu and in the postdoc of Kai Berger. Then this data will be used in 4DVar assimilation technique to reconstruct three-dimensional turbulent flows. This reconstruction will be conducted within the PhD of Cordelia Robinson.

6.4. Visual servoing approach for fluid flow control

6.4.1. *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. As in all our previous works in flow control, we propose a vision-based approach to control this flow. We investigate the use of an optimal control based on a reduced linearized state space model of the Navier-Stokes equations. A steady desired state was first considered leading to a linear time-invariant system. The main problem consists to maintain the flow in his desired state in presence of unknown perturbation. Different strategies have been evaluated for different types of actuators and different cost functions. Even if our control law is based on a linearized approach, its efficiency has been validated on a realistic numerical Navier-Stokes 3D solver. This work has been submitted to the 20th World Congress of the International Federation of Automatic Control (IFAC).

6.5. Reactive transport

6.5.1. *Reactive transport in porous media*

Participant: Jocelyne Erhel.

In many environmental applications, transport of solutes is coupled with chemical reactions, either kinetic or at equilibrium. These reactions involve not only solutes, but also sorbed species and minerals. The mathematical model is a coupled set of nonlinear partial algebraic differential equations. A classical approach is to discretize first in space then in time. Since the problem is rather stiff, explicit time discretization suffers from a drastic CFL-like condition. On the other hand, implicit schemes allow large timesteps during some periods of simulation. Implicit Euler scheme is often used for monotonicity properties. The Jacobian is computed from the transport operator and the chemical operator. We have designed such a global approach and implemented it in our software GRT3D. We have done numerical experiments on the benchmark MoMaS.

Publications: 2 conferences and one journal article [15], [20], [21]

Grant: H2MNO4

6.5.2. *Reactive transport in fractured-porous media*

Participants: Yvan Crenner, Benjamin Delfino, Jean-Raynald de Dreuzy, Jocelyne Erhel.

Even in small numbers, fractures must be carefully considered for the geological disposal of radioactive waste. They critically enhance diffusivity, speed up solute transport, extend mixing fronts and, in turn, modify the physicochemical conditions of reactivity around possible storage sites. Numerous studies addressing various applications (e.g. radioactive waste storage, CO2 sequestration, geothermal storage, hydrothermal alteration) have shown that fractures cannot be simply integrated within an equivalent porous medium. Our objective is to develop a reactive transport model based on the separation of the fracture and matrix domains, with diffusion conditions differing between the fracture and in the matrix, appropriate flow-rock interactions at equilibrium in the matrix and fracture-matrix exchange conditions at their interface.

This year, we developed a numerical model for a chemical system with several minerals, which is representative of a storage site.

Publications: 2 conferences [28], [27]

Grant: ANDRA

6.6. Linear solvers

6.6.1. *Sparse linear solvers*

Participants: Jocelyne Erhel, David Imberti.

Sparse linear systems arise in computational science and engineering. The goal is to reduce the memory requirements and the computational cost, by means of high performance computing algorithms. We introduce a new variation on s-step GMRES in order to improve its stability, reduce the number of iterations necessary to ensure convergence, and thereby improve parallel performance. In doing so, we develop a new block variant that allows us to express the stability difficulties in s-step GMRES more fully.

Grants and projects: EXA2CT 8.2.1, EoCoE 8.2.2, C2S@EXA 8.1.7

Publications: 3 conférences [22], [23], [39]

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

7.1.1. *Contract CERSAT/IFREMER*

Participants: Etienne Mémin, Valentin Resseguier.

duration 36 months. This partnership between Inria and Ifremer funds the PhD of Valentin Resseguier, which aims at studying image based data assimilation strategies for oceanic models incorporating random uncertainty terms. The goal targeted will consist in deriving appropriate stochastic version of oceanic model and on top of them to devise estimation procedures from noisy data to calibrate the associated subgrid models.

7.1.2. Contract inter Carno IFREMER Inria

Participants: Etienne Mémin, Thibaut Tronchin.

duration 36 months. This contract aims at proposing image-based tools for the analysis of the hydraulic load of an immerged body. This project takes place within an inter Carnot cooperation between Ifremer and Inria.

7.1.3. 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 CIFRE PhD is to design new image-based flow measurement methods for the study of industrial fluid flows. Those techniques will used in particular to calibrate industrial fume hood.

7.1.4. ANDRA project

Participants: Yvan Crenner, Benjamin Delfino, Jean-Raynald de Dreuzy, Jocelyne Erhel.

Contract with ANDRA (National Agency for Nuclear Waste)
Duration: three years from November 2015.
Title: reactive transport in fractured porous media
Coordination: Jocelyne Erhel.
Partners: Geosciences Rennes.
Abstract: Even in small numbers, fractures must be carefully considered for the geological disposal of radioactive waste. They critically enhance diffusivity, speed up solute transport, extend mixing fronts and, in turn, modify the physicochemical conditions of reactivity around possible storage sites. Numerous studies in various fields have shown that fractures cannot be simply integrated within an equivalent porous medium with a simple enhancement of its petro-physical properties (porosity and permeability). We propose a combined numerical and experimental approach to determine the influence on reactivity of typical fracture patterns found in some radioactive waste applications.

7.1.5. IFPEN project

Participants: Bastien Hamlat, Jocelyne Erhel.

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.
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 extraction. This project aims to determine optimal strategies to solve the coupled transport and chemical reaction equations describing the physical processes at work in reactive multiphase flow in porous media. Three different formulations show great potential to accurately solve these equations. Two are fully implicit ("Reactive Coats" and "Semi-smooth Newton)" and one is an operator splitting approach. These formulations are still incomplete at the moment. The work will focus on extending the existing formulations to more complex physical phenomena, study their stability, convergence and theoretical equivalence. Another objective is to provide practical solutions to efficiently solve the resulting non-linear systems.

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, mathemathics 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 JCJC GERONIMO : Advanced GEophysical Reduced-Order Model construction from IMage Observations*
Participant: Cédric Herzet.

duration 48 months. The GERONIMO project which started in March 2014 aims at devising new efficient and effective techniques for the design of geophysical reduced-order models from image data. The project both arises from the crucial need of accurate low-order descriptions of highly-complex geophysical phenomena and the recent numerical revolution which has supplied the geophysical scientists with an unprecedented volume of image data. The project is placed at the intersection of several fields of expertise (Bayesian inference, matrix factorization, sparse representations, etc.) which will be combined to handle the uncertainties associated to image measurements and to characterize the accurate reduced dynamical systems.

8.1.3. *ANR BECOSE : Beyond Compressive Sensing: Sparse approximation algorithms for ill-conditioned inverse problems.*
Participants: Dominique Heitz, Cédric Herzet.

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.

8.1.4. *ANR-MN: H2MNO4 project*
Participants: Yvan Crenner, Benjamin Delfino, Jean-Raynald de Dreuzy, Jocelyne Erhel, Lionel Lenôtre.

Contract with ANR, program Modèles Numériques
Duration: four years from November 2012.
Title: Original Optimized Object Oriented Numerical Model for Heterogeneous Hydrogeology.
Coordination: Jocelyne Erhel and Géraldine Pichot, with Fabienne Cuyollaa.
Partners: Geosciences Rennes, University of Poitiers, University of Lyon 1, Andra, Itasca.
International collaborations: University of San Diego (USA), UPC, Barcelona (Spain)
Web page: http://h2mno4.inria.fr/

Abstract: The project H2MNO4 develops numerical models for reactive transport in heterogeneous media. It defines six mathematical and computational challenges and three applications for environmental problems with societal impact. We presented a poster at the ANR-day (rencontre du numérique, Parius, Nov. 2016)

8.1.5. INSU-LEFE: Toward new methods for the estimation of sub-meso scale oceanic streams
Participant: Cédric Herzet.

duration 36 months. This project tackles the problem of deriving a precise submesoscale characterization of ocean currents from satellite data. The targeted methodologies should in particular enable the exploitation of data of different nature (for example sea surface temperature or height) and/or resolutions. This 36-month project benefits from a collaboration with the Laboratoire de Météorologie Dynamique, Ecole Normale Supérieure, Paris.

8.1.6. INSU-LEFE: MODELER
Participant: Etienne Mémin.

duration 24 months. This project with MeteoFrance aims at exploring error modeling and stochastic parameterization in geophysical flow dynamics. The theory explored in this context should enable the construction of unified image data assimilation strategies.

8.1.7. Inria Project Lab: C2S@EXA project
Participants: Yvan Crenner, Jocelyne Erhel.

Title: C2S@EXA - Computer and Computational Scienecs at Exascale
Duration: from January 2012 until April 2017
Coordination: S. Lanteri, Nachos team.
Partners: Inria teams working on HPC; external partners: ANDRA and CEA.
Webpage: http://www-sop.inria.fr/c2s_at_exa/
Abstract: The C2S@Exa Inria Project Lab is concerned with the development of numerical modeling methodologies that fully exploit the processing capabilities of modern massively parallel architectures in the context of a number of selected applications related to important scientific and technological challenges for the quality and the security of life in our society. The team participated in several workshops.

8.1.8. GENCI: project on advanced linear solvers
Participants: Yvan Crenner, Jocelyne Erhel, David Imberti.

Title: Numerical models for hydrogeology
Duration: 2016
Coordination: J. Erhel
Webpage: http://www.genci.fr/
Abstract: To run large scale simulations, we defined a project, based on the platform H2OLab and on a new GMRES solver. We obtained and used computing time on machines located at GENCI supercomputing centers.

8.1.9. GDR MANU
Participants: Benjamin Delfino, Jocelyne Erhel.

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. The team participated in the conference JEMP2016.

8.2. European Initiatives

8.2.1. EXA2CT

Participants: Jocelyne Erhel, David Imberti.

Title: EXascale Algorithms and Advanced Computational Techniques

Programm: FP7

Duration: September 2013 - August 2016

Coordinator: S. Ashby, IMEC, Belgium

Partners:

Fraunhofer-Gesellschaft Zur Foerderung Der Angewandten Forschung E.V (Germany)

Interuniversitair Micro-Electronica Centrum Vzw (Belgium)

Intel Corporations (France)

Numerical Algorithms Group Ltd (United Kingdom)

Systems Solutions for Research (Germany)

Universiteit Antwerpen (Belgium)

Universita della Svizzera italiana (Switzerland)

Universite de Versailles Saint-Quentin-En-Yvelines. (France)

Vysoka Skola Banska - Technicka Univerzita Ostrava (Czech Republic)

Inria contact: Luc Giraud

Abstract: Numerical simulation is a crucial part of science and industry in Europe. The advancement of simulation as a discipline relies on increasingly compute intensive models that require more computational resources to run. This is the driver for the evolution to exascale. The EXA2CT project brings together experts at the cutting edge of the development of solvers, related algorithmic techniques, and HPC software architects for programming models and communication.

8.2.2. EOCOE project

Participant: Jocelyne Erhel.

Program: EINFRA-5-2015

Project acronym: EoCoE

Project title: Energy oriented Center of Excellence for computer applications

Duration: 36 months

Coordinator: CEA

Other partners: organisme, labo (pays) : 12 other partners

Abstract: the EoCoE objectives aims at firstly, to design, test and spread new methodological and organisational paradigms (Objectives 1, 3, and 4) driven by the users communities and, secondly, to contribute to mathematical and computer sciences challenges on the whole HPC tool chain (Objective 2).

8.3. International Initiatives

8.3.1. Inria Associate Teams Not Involved in an Inria International Labs

8.3.1.1. LFD-FLU

Title: Large-scale Fluid Dynamics analysis from FLow Uncertainty

International Partner (Institution - Laboratory - Researcher):

Universidad de Buenos Aires (Argentina) - Department of Computer Science and Electrical Engineering - Guillermo Artana

Start year: 2016

See also: http://www.irisa.fr/prive/memin/LFD-FLU/

The first objective of this associate team is primarily concerned with the establishment of efficient fluid flow image data analysis procedures. This concerns for instance data assimilation issues to reconstruct meaningful numerical representation of experimental fluid flows for analysis purpose. The second objective focuses on the incorporation of uncertainties in the flow dynamical evolution models

8.3.2. Inria International Partners

8.3.2.1. Informal International Partners

Imperial College (London, UK) We have initiated a collaboration with the Department of Aeronautics within the PhD thesis of Pranav Chandramoulli

Chico California State University (USA), We have pursue 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.

College of Control Science & Engineering of Zhejiang University We have initiated a collaboration with Prof. Chao Xu on the study of fluid motion estimator.

8.4. International Research Visitors

8.4.1. Visits of International Scientists

- 2 month sojourn of Gisela Charo (PhD student University of Buenos Aires) to work with Etienne Mémin and Valentin Resseguier within the associate team LFD
- 2 weeks visit of Alejandro Gronskis (Researcher Conicet Argentina) to work with Dominique Heitz, Etienne Mémin and Pranav Chandramouli within the associate team LFD
- Sojourn of 9 month of Shengze Cai PhD student in the College of Control Science & Engineering, Zhejiang University to work with Etienne Mémin
- 2 weeks visit of Prof. Luigi Berselli (U. Pisa) to work with Roger Lewandowski.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. General Chair, Scientific Chair

- J. Erhel organizes with J-R. de Dreuzy and T. Le Borgne the international conference CWMR (Saint-Malo, France, June 2018).

9.1.1.2. Member of the Organizing Committees

Etienne Mémin

- SWGEN (Vannes) program committee
- Scientific committee of the national colloqium on data assimilation, (Grenoble)

9.1.2. *Scientific Events Selection*

9.1.2.1. Member of the Conference Program Committees

Jocelyne Erhel

- international advisory committee of the parallel CFD conferences (Kobe, Japan, May 2016).
- program committee of the international conference CARI 2016.
- scientific committee of JEMP 2016.
- scientific committee of NLAA 2016.
- program committee of the workshop Visualization in Environmental Sciences 2016 (co-event of EuroVis)

9.1.3. *Journal*

9.1.3.1. 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)

9.1.3.2. Reviewer - Reviewing Activities

Jocelyne Erhel: Reviewer for the journals ADWR, ARIMA, JCAM, MATCOM
Dominique Heitz: Reviewer for Exp. in Fluids, ASME J. on Heat Transfer
Cédric Herzet: Reviewer for IEEE Tr. on Signal Processing, IEEE Tr. on Information Theory
Etienne Mémin: Reviewer for Tellus-A, IEEE Im. Proc., IEEE trans. Pat. Anal. Mach. Intel. , Im. Vis. Comp., Exp. in Fluids, Nonlinear Proc. in Geophysics., Journ. of Comp. Phys, Fluid Dynamics Research.

9.1.4. *Invited Talks*

Dominique Heitz

- Next generation transport aircraft workshop, Honolulu, Hawai, 22-25, February, 2016.
- Cap Aliment training "Les technologies douces de conservation des denrées alimentaires", Nantes, 13, October, 2016. Assisses du Génie des Procédés, région OUEST - Nantes, 9, november, 2016

Cédric Herzet

- GdR Isis « Algorithmes gloutons pour l'optimisation sous contrainte de parcimonie », Juin 2016

Roger Lewandowski

- Special Session on Above and Beyond Fluid Flow studies: In celebration of the 60th birthday of Prof. William Layton » within the Fall Western Sectional Meeting of the AMS, University of Denver, Denver, CO October 8-9, 2016.

Etienne Mémin

- E. Mémin. Représentation sous incertitude d'écoulements géophysiques, Huitième Ecole Interdisciplinaire de Rennes sur les Systèmes Complexes, Oct. 2016.

9.1.5. Leadership within the Scientific Community

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

9.1.6. Scientific Expertise

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

9.1.7. Research Administration

Jocelyne Erhel

- correspondent of Maison de la Simulation for Inria Rennes.
- correspondent of AMIES for Inria Rennes, from September 2015.
- member of the Inria national committee for secondment, 2016.
- member of the Inria local committee for health and safety (référent chercheur) from January 2016.
- member of the Inria administrative commission (CAP) for researchers, from January 2016.

Dominique Heitz

- Responsible of the Irstea ACTA Team
- Member of Pôle Cristal scientific council
- Member of Irstea OPAALE research unit Executive Committee
- Member of Irstea center of Rennes Executive Committee

Etienne Mémin

- Responsible of the "Commission Développement Technologique" Inria Rennes
- Member of the "Commission Personnel" Inria-IRISA Rennes

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Licence: Jocelyne Erhel, Optimisation, 24h, niveau L3, ENSAI Rennes

Licence : Dominique Heitz, Mécanique des fluides, 30h, niveau L2 INSA Rennes

Master: Jocelyne Erhel, modélisation et calcul scientifique, 12h, niveau M2, 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 : Cédric Herzet, Représentations parcimonieuses et compressed sensing, niveau M2, ENSAI, 12h

Master : Cédric Herzet, Représentations parcimonieuses et compressed sensing, niveau M2, niveau M2, INSA, 10h

Master: Roger Lewandowski, Euler and the Navier-Stokes equations, M2, master « fondamental mathematics ».

Master : Etienne Mémin, Analyse du mouvement, Mastere Informatique, 15h, niveau M2, Université de Rennes 1.

Master : Etienne Mémin, Vision par ordinateur , 15h, niveau M2, ESIR Université de Rennes 1.

9.2.2. Supervision

Master research work: C. Bonvoisin (ENS Cachan) February 2016 to June 2016, advisor R. Lewandowski

PhD in progress: B. Delfino, University of Rennes 1, November 2015, co-advisors J.-R. de Dreuzy and J. Erhel.

PhD in progress: P.-M. Gibert, University of Lyon, October 2015, co-advisors D. Tromeur-Dervout and J. Erhel.

PhD in progress: B. Hamlat, University of Rennes 1, October 2016, co-advisors J. Erhel and A. Michel.

PhD in progress : Benoit Pinier, Scale similarity and uncertainty for Ocean-Atmosphere coupled models, started 01/10/2014, supervisors: Roger Lewandowski, Etienne Mémin

PhD in progress : Valentin Resseguier, Oceanic models under uncertainty and image assimilitation, started 01/10/2013, Bertrand Chapron (Ifremer), Etienne Mémin

PhD in progress : Pranav Chandamouli, Turbulent complex flows reconstruction via data assimilation in large eddy models, started october 2015, Dominique Heitz, Etienne Mémin.

PhD in progress : Romain Schuster, Large-scale fluid motion estimation, started october 2016, Dominique Heitz, Etienne Mémin.

9.2.3. *Juries*

Jocelyne Erhel

- Rafife Nheili, PhD, Univ. Perpignan (rapporteur)

Etienne Mémin

- Laurent Cordier HDR, Univ. Poitiers.
- Nicolas Papadakis, HDR IMB, Univ. Bordeaux
- Yann Michel, HDR Meteofrance, Univ. Toulouse Paul Sabatier (Rapporteur)
- Van Linh Nguyen, PhD Univ. Lille (Rapporteur)
- Iliass Azijli, PhD TU Delft (Rapporteur),
- Raphael Legrand, PhD Meteofrance Univ. Paul Sabatier Toulouse (Rapporteur)

9.3. Popularization

Jocelyne Erhel

- présidente du jury du rallye de mathématiques du CNED, 2016.
- talk at day "au coeur des maths, enfermement ou liberté ?", LVN, May 2016.
- scientific responsible of the scientific culture web journal "Interstice" (https://interstices.info/)

Dominique Heitz

- Interview dans L'Usine Nouvelle, No 3479, pp. 30-31, 2016

10. Bibliography

Major publications by the team in recent years

[1] K. Burrage, J. Erhel. *On the performance of various adaptive preconditioned GMRES*, in "Numerical Linear Algebra with Applications", 1998, vol. 5, pp. 101-121

[2] J. Carrayrou, J. Hoffmann, P. Knabner, S. Kräutle, C. De Dieuleveult, J. Erhel, J. Van der Lee, V. Lagneau, K. Mayer, K. MacQuarrie. *Comparison of numerical methods for simulating strongly non-linear and heterogeneous reactive transport problems. The MoMaS benchmark case*, in "Computational Geosciences", 2010, vol. 14, n° 3, pp. 483-502

[3] R. CHOQUET, J. ERHEL. *Newton-GMRES algorithm applied to compressible flows*, in "International Journal for Numerical Methods in Fluids", 1996, vol. 23, pp. 177-190

[4] T. CORPETTI, D. HEITZ, G. ARROYO, E. MÉMIN, A. SANTA-CRUZ. *Fluid experimental flow estimation based on an optical-flow scheme*, in "Experiments in fluids", 2006, vol. 40, pp. 80–97

[5] J.-R. DE DREUZY, A. BEAUDOIN, J. ERHEL. *Asymptotic dispersion in 2D heterogeneous porous media determined by parallel numerical simulations*, in "Water Resource Research", 2007, vol. 43, n$^{\rm o}$ W10439, doi:10.1029/2006WR005394

[6] J. ERHEL, S. RAULT. *Algorithme parallèle pour le calcul d'orbites : Parallélisation à travers le temps*, in "Technique et science informatiques", 2000, vol. 19, n$^{\rm o}$ 5

[7] A. GRONSKIS, D. HEITZ, E. MÉMIN. *Inflow and initial conditions for direct numerical simulation based on adjoint data assimilation*, in "Journal of Computational Physics", 2013, vol. 242, pp. 480-497 [*DOI :* 10.1016/J.JCP.2013.01.051], http://www.sciencedirect.com/science/article/pii/S0021999113001290

[8] D. HEITZ, E. MÉMIN, C. SCHNOERR. *Variational Fluid Flow Measurements from Image Sequences: Synopsis and Perspectives*, in "Experiments in fluids", 2010, vol. 48, n$^{\rm o}$ 3, pp. 369–393

[9] H. HOTEIT, J. ERHEL, R. MOSÉ, B. PHILIPPE, P. ACKERER. *Numerical Reliability for Mixed Methods Applied to Flow Problems in Porous Media*, in "Computational Geosciences", 2002, vol. 6, pp. 161-194

[10] E. MÉMIN. *Fluid flow dynamics under location uncertainty*, in "Geophysical & Astrophysical Fluid Dynamics", 2014, vol. 108, n$^{\rm o}$ 2, pp. 119-146, http://dx.doi.org/10.1080/03091929.2013.836190

[11] N. PAPADAKIS, E. MÉMIN. *A variational technique for time consistent tracking of curves and motion*, in "Journal of Mathematical Imaging and Vision", 2008, vol. 31, n$^{\rm o}$ 1, pp. 81–103, http://www.irisa.fr/fluminance/publi/papers/Papadakis-Memin-JMIV07.pdf

[12] Y. SAAD, M. YEUNG, J. ERHEL, F. GUYOMARC'H. *A deflated version of the Conjugate Gradient Algorithm*, in "SIAM Journal on Scientific Computing", 2000, vol. 21, n$^{\rm o}$ 5, pp. 1909-1926

Publications of the year

Articles in International Peer-Reviewed Journals

[13] P. ARBOGAST, O. PANNEKOUCKE, L. RAYNAUD, R. LALANNE, E. MÉMIN. *Object-oriented processing of CRM precipitation forecasts by stochastic filtering*, in "Quarterly Journal of the Royal Meteorological Society", 2016 [*DOI :* 10.1002/QJ.2871], https://hal.inria.fr/hal-01378366

[14] I. BARBU, C. HERZET. *A new approach for volume reconstruction in TomoPIV with the alternating direction method of multipliers*, in "Measurement Science and Technology", 2016, vol. 27, 21 p. [*DOI :* 10.1088/0957-0233/27/10/104002], https://hal.inria.fr/hal-01419329

[15] J. ERHEL, S. SABIT. *Analysis of a global reactive transport model and results for the MoMaS benchmark*, in "Mathematics and Computers in Simulation", 2017, https://hal.inria.fr/hal-01405698

[16] C. HERZET, A. DRÉMEAU, C. SOUSSEN. *Relaxed recovery conditions for OMP/OLS by exploiting both coherence and decay*, in "IEEE Transactions on Information Theory", January 2016, vol. 62, n$^{\text{o}}$ 1, pp. 459-470 [*DOI :* 10.1109/TIT.2015.2490660], https://hal.inria.fr/hal-01058077

[17] C. HERZET, A. DRÉMEAU, C. SOUSSEN. *Relaxed Recovery Conditions for OMP/OLS by Exploiting Both Coherence and Decay*, in "IEEE Transactions on Information Theory", 2016, vol. 62, pp. 459 - 470 [*DOI :* 10.1109/TIT.2015.2490660], https://hal.inria.fr/hal-01419333

[18] P. HÉAS, A. DRÉMEAU, C. HERZET. *An Efficient Algorithm for Video Super-Resolution Based On a Sequential Model*, in "SIAM Journal on Imaging Sciences", 2016, vol. 9, n$^{\text{o}}$ 2, pp. 537-572, 37 pages [*DOI :* 10.1137/15M1023956], https://hal.inria.fr/hal-01158551

[19] S. NAKHOSTIN, H. CLENET, T. CORPETTI, N. COURTY. *Joint Anomaly Detection and Spectral Unmixing for Planetary Hyperspectral Images*, in "IEEE Transactions on Geoscience and Remote Sensing", 2016, vol. 54, pp. 6879 - 6894 [*DOI :* 10.1109/TGRS.2016.2586188], https://hal.archives-ouvertes.fr/hal-01377230

Invited Conferences

[20] J. ERHEL. *Un modèle mathématique de réactions chimiques et de transport réactif*, in "Calcul Scientifique et Modélisation Mathématique", Amiens, France, 2016, https://hal.inria.fr/hal-01405739

[21] J. ERHEL, S. SABIT, T. MIGOT. *Reactive transport simulations using a global approach*, in "computational methods in water resources (CMWR)", Toronto, Canada, 2016, https://hal.inria.fr/hal-01405708

[22] D. IMBERTI, J. ERHEL. *Parallel GMRES using a variable s-step Krylov basis*, in "SIAM Conference on Parallel Processing for scientific computing", Paris, France, 2016, https://hal.inria.fr/hal-01405733

[23] D. IMBERTI, J. ERHEL. *Varying the s in s-step GMRES*, in "Numerical Linear Algebra and Applications (NL2A)", Marseille, France, 2016, https://hal.inria.fr/hal-01405735

International Conferences with Proceedings

[24] C. HERZET, A. MALTI. *Safe screening tests for lasso based on firmly non-expansiveness*, in "IEEE International conference on acoustics, speech and signal processing (ICASSP'16)", Shanghai, China, March 2016, https://hal.inria.fr/hal-01419314

[25] P. HÉAS, C. HERZET. *Reduced-Order Modeling of Hidden Dynamics*, in "IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASPP)", Shangai, China, March 2016, pp. 1268–1272 [*DOI :* 10.1109/ICASSP.2016.7471880], https://hal.inria.fr/hal-01246074

Conferences without Proceedings

[26] N. COURTY, R. FLAMARY, D. TUIA, T. CORPETTI. *Optimal Transport for Data Fusion in Remote Sensing*, in "IGARSS", Beijing, China, July 2016, https://hal.archives-ouvertes.fr/hal-01377234

[27] B. DELFINO, J.-R. DE DREUZY, J. ERHEL, B. COCHEPIN, Y. MÉHEUST. *Impact of fractures on diffusively dominated reactive transport: application to radioactive waste storage studies*, in "Computational Methods for Water Resources (CMWR)", Toronto, Canada, 2016, https://hal.inria.fr/hal-01405716

[28] B. DELFINO, J. R. DE DREUZY, J. ERHEL. *Impact of fractures on diffusion dominated reactive transport in porous media: application to the study of a radioactive waste storage*, in "13èmes Journéess d'études des Milieux Poreux 2016", Anglet, France, October 2016, https://hal.archives-ouvertes.fr/hal-01394582

[29] S. NAKHOSTIN, N. COURTY, R. FLAMARY, T. CORPETTI. *Supervised Planetary Unmixing with Optimal Transport*, in "WHISPERS 8th workshop on Hyperspectral image and Signal Processing: Evolution in Remote Sensing", Los Angeles, United States, August 2016, https://hal.archives-ouvertes.fr/hal-01377236

[30] V. RESSEGUIER, E. MÉMIN, B. CHAPRON, P. DÉRIAN. *Stochastic parameterization of geophysical flows through modelling under location uncertainty*, in "Data Analysis and Modeling in Earth Sciences (DAMES) 2016", Hambourg, Germany, September 2016, https://hal.inria.fr/hal-01377719

[31] V. RESSEGUIER, E. MÉMIN, B. CHAPRON. *Likely chaotic transitions of large-scale fluid flows using a stochastic transport model*, in "9th Chaotic Modeling and Simulation International Conference (CHAOS2016)", Londres, United Kingdom, May 2016, https://hal.inria.fr/hal-01377702

[32] V. RESSEGUIER, E. MÉMIN, B. CHAPRON. *Randomized fluid dynamics based on subgrid transport*, in "Workshop on Stochastic Weather Generators", Vannes, France, May 2016, https://hal.inria.fr/hal-01377747

[33] V. RESSEGUIER, E. MÉMIN, B. CHAPRON. *Transport along stochatic flows in fluid dynamics*, in "Workshop - Statistical methods for dynamical stochastic models - DYNSTOCH 2016", Rennes, France, June 2016, https://hal.inria.fr/hal-01377723

Other Publications

[34] I. BARBU, A. GUIBERT, P. LOISEL, D. HEITZ. *Optical Flow Estimation out of Infrared Image Sequences of Biogas*, June 2016, The 17th International Symposium on Flow Visualization, Poster [*DOI :* 10.13140/RG.2.2.35868.28808], https://hal.archives-ouvertes.fr/hal-01416030

[35] I. BARBU, A. GUIBERT, P. LOISEL, D. HEITZ. *Validation d'une technique de vélocimétrie du gaz par imagerie infrarouge*, September 2016, CFTL2016, Poster [*DOI :* 10.13140/RG.2.2.11095.68006], https://hal.archives-ouvertes.fr/hal-01417131

[36] A. DRÉMEAU, C. HERZET. *DOA estimation in structured phase-noisy environments: technical report*, 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01394048

[37] C. HERZET, A. DRÉMEAU, P. HÉAS. *Model Reduction from Partial Observations*, 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01394059

[38] P. HÉAS, C. HERZET. *Low-rank Approximation and Dynamic Mode Decomposition*, 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01394064

[39] D. IMBERTI, J. ERHEL. *Vary the s in Your s-step GMRES*, July 2016, working paper or preprint, https://hal.inria.fr/hal-01299652

[40] S. KADRI HAROUNA, E. MÉMIN. *Stochastic representation of the Reynolds transport theorem: revisiting large-scale modeling*, November 2016, working paper or preprint, https://hal.inria.fr/hal-01394780

[41] V. RESSEGUIER, E. MÉMIN, B. CHAPRON. *Geophysical flows under location uncertainty, Part I Random transport and general models*, October 2016, working paper or preprint, https://hal.inria.fr/hal-01391420

[42] V. RESSEGUIER, E. MÉMIN, B. CHAPRON. *Geophysical flows under location uncertainty, Part II Quasi-geostrophy and efficient ensemble spreading*, October 2016, working paper or preprint, https://hal.inria.fr/hal-01391476

[43] V. RESSEGUIER, E. MÉMIN, B. CHAPRON. *Geophysical flows under location uncertainty, Part III SQG and frontal dynamics under strong turbulence conditions*, October 2016, working paper or preprint, https://hal.inria.fr/hal-01391484

[44] V. RESSEGUIER, E. MÉMIN, B. CHAPRON. *Oceanic models under uncertainty*, June 2016, CMG 2016 : 31st IUGG Conference on Mathematical Geophysics, Poster, https://hal.inria.fr/hal-01377710

[45] V. RESSEGUIER, E. MÉMIN, B. CHAPRON. *Stochastic subgrid tensor for geophysical flow modeling*, July 2016, 8th European Postgraduate Fluid Dynamics Conference, Poster, https://hal.inria.fr/hal-01377741

[46] V. RESSEGUIER, E. MÉMIN, D. HEITZ, B. CHAPRON. *Stochastic modelling and diffusion modes for POD models and small-scale flow analysis*, November 2016, working paper or preprint, https://hal.inria.fr/hal-01400119

References in notes

[47] R. ADRIAN. *Particle imaging techniques for experimental fluid mechanics*, in "Annal Rev. Fluid Mech.", 1991, vol. 23, pp. 261-304

[48] T. BEWLEY. *Flow control: new challenges for a new Renaissance*, in "Progress in Aerospace Sciences", 2001, vol. 37, pp. 21–58

[49] S. BEYOU, A. CUZOL, S. GORTHI, E. MÉMIN. *Weighted Ensemble Transform Kalman Filter for Image Assimilation*, in "TellusA", January 2013, vol. 65, n° 18803

[50] H. CHOI, P. MOIN, J. KIM. *Direct numerical simulation of turbulent flow over riblets*, in "Journal of Fluid Mechanics", 1993, vol. 255, pp. 503–539

[51] T. CORPETTI, E. MÉMIN. *Stochastic Uncertainty Models for the Luminance Consistency Assumption*, in "IEEE Trans. Image Processing", 2012, vol. 21, n° 2, pp. 481–493

[52] G. EVENSEN. *Sequential data assimilation with a non linear quasi-geostrophic model using Monte Carlo methods to forecast error statistics*, in "J. Geophys. Res.", 1994, vol. 99 (C5), n° 10, pp. 143–162

[53] J. FAVIER. *Contrôle d'écoulements : approche expérimentale et modélisation de dimension réduite*, Institut National Polytechnique de Toulouse, 2007

[54] J. FAVIER, A. KOURTA, G. LEPLAT. *Control of flow separation on a wing profile using PIV measurements and POD analysis*, in "IUTAM Symposium on Flow Control and MEMS", London, UK, September 19-22, 2006

[55] N. GORDON, D. SALMOND, A. SMITH. *Novel approach to non-linear/non-Gaussian Bayesian state estimation*, in "IEEE Processing-F", April 1993, vol. 140, n° 2

[56] A. GUÉGAN, P. SCHMID, P. HUERRE. *Optimal energy growth and optimal control in swept Hiemenz flow*, in "J. Fluid Mech.", 2006, vol. 566, pp. 11–45

[57] B. HORN, B. SCHUNCK. *Determining Optical Flow*, in "Artificial Intelligence", August 1981, vol. 17, n° 1-3, pp. 185–203

[58] F.-X. LE DIMET, O. TALAGRAND. *Variational algorithms for analysis and assimilation of meteorological observations: theoretical aspects*, in "Tellus", 1986, n° 38A, pp. 97–110

[59] J. LIONS. *Optimal Control of Systems Governed by Partial Differential Equations*, Springer-Verlag, 1971

[60] L. MATHELIN, O. LE MAÎTRE. *Robust control of uncertain cylinder wake flows based on robust reduced order models*, in "Computer and Fluids", 2009, vol. 38, pp. 1168–1182

[61] B. PROTAS, J. WESFREID. *Drag force in the open-loop control of the cylinder wake in the laminar regime*, in "Physics of Fluids", February 2002, vol. 14, n° 2, pp. 810–826

[62] I. WYGNANSKI. *Boundary layer flow control by periodic addition of momentum*, in "4th AIAA Shear Flow Control Conference", USA, June 29-July 2, 1997