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ONERA
THE FRENCH AEROSPACE LAB

High performance numerical simulation at ONERA

Laurent CAMBIER
Scientific director « Advanced numerical simulation »

EUCASS meeting, Lille

Contribution to research and competitiveness
Grand challenge applications
ONERA strategy

Numerical simulation, third pillar of science

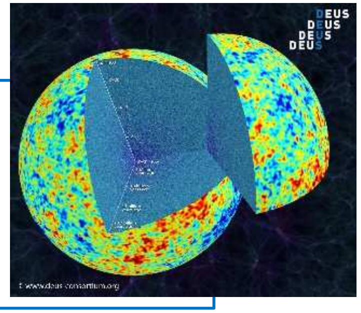
Integral part of science, added to theory and experimentation

- *Basic research* in astrophysics, climatology, biology…

DEUS Project CNRS

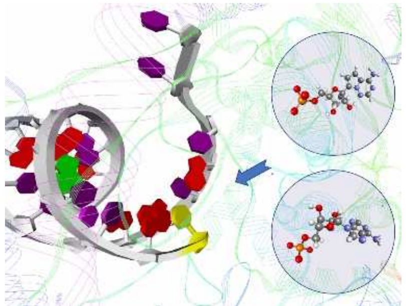
Cosmology: Evolution of the Universe

- **1st full simulations in the evolution of the structuration of the whole observable Universe, from the Big Bang to nowadays**
- **20 million core hours GENCI on Curie in 2012**

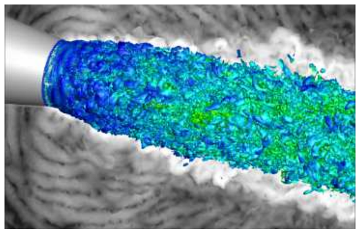


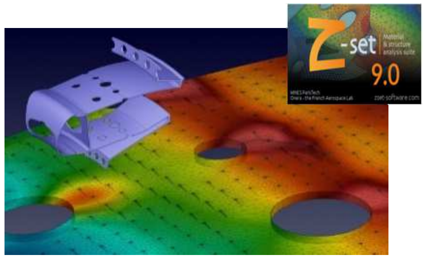
- Answer to *emergency situations :* earthquakes, tsunamis, epidemics…

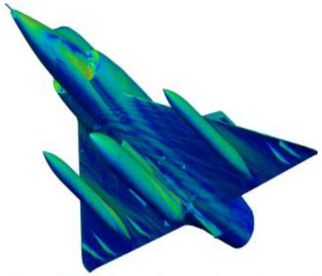
The COVID-19 HPC consortium in USA (600 Petaflops, 7 million cores)



- *Engineering sciences :* fluid mechanics, acoustics, structural mechanics, materials, electromagnetism…

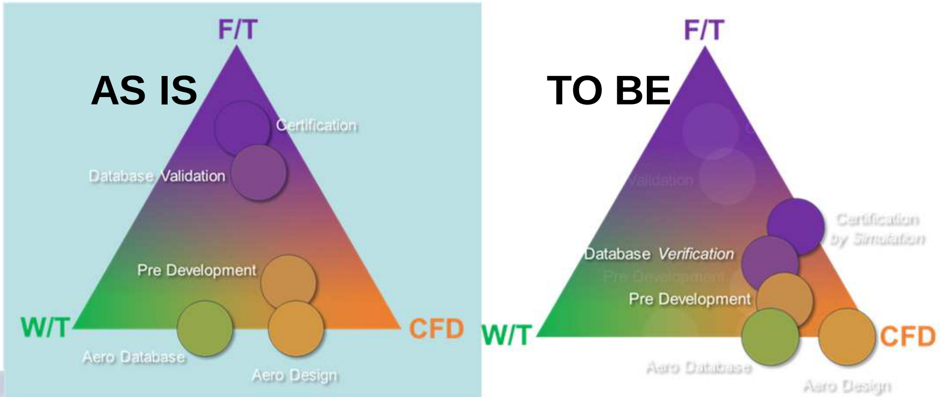






ONERA simulations

Numerical simulation in aerospace

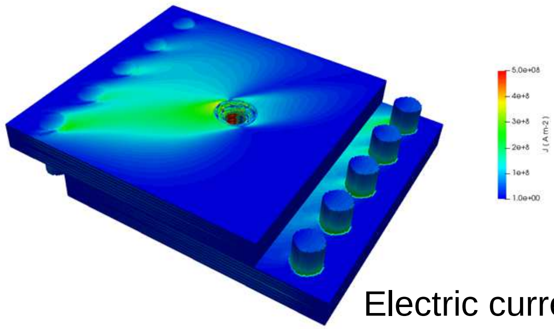


Airbus-Boeing talk (3AF 2019)

For competitiveness

- Productivity gains in design of new aircraft
- Study of breakthrough configurations

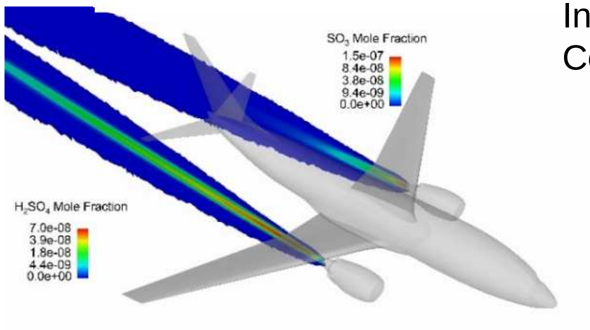
Configuration DRAGON @ONERA



Electric current distribution
In a structure struck by lightning
Code TARANIS @ONERA

For issues of general interest

- Safety : flight domain limits, icing problems, lightning effects…
- Environment : polluting emissions, climate impact, noise…



Contrail
Code CEDRE @ONERA

« Advanced Numerical Simulation » : a fifth scientific domain at ONERA since 2017

Dealing with all (possibly coupled) disciplines of physics

Aerodynamics	Materials
Aeroelasticity	Structural mechanics and dynamics
Aeroacoustics	Electromagnetism
Aerothermochemistry	Plasma
Conjugate heat transfer	Magnetohydrodynamics

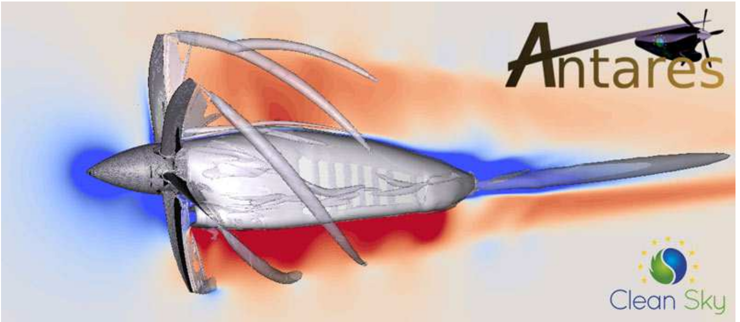
- For Aeronautics, Space and Defense
- Interacts with all ONERA research depts and the 4 other scientific domains
- Takes into account the important part of scientific and technical production corresponding to software
- Includes the whole range of involved research and development process

Modelling, algorithmics and applied mathematics, HPC, coupling of physics, reduced modelling, uncertainty management, software policy, development partnerships…

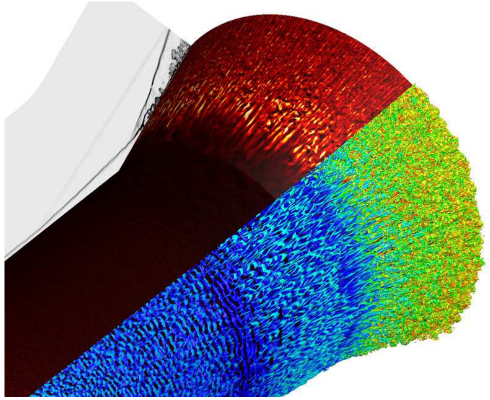
Grand challenge simulations

Many motivations

- « First of a kind » configurations
- Very high fidelity simulations to improve physical modeling
- Identification and solution of scientific issues
- Adaptation of methods and tools to new HPC hardware



***elsA* URANS simulation of a turboprop**



FASTS QDNS simulation
Hypersonic compression ramp

Extension ONERA Sator supercomputer (autumn 2021)

- Offered to ONERA young researchers during 2 months for grand challenges
- NEC, 43600 cores (extension : Intel Xeon Cascade Lake)
- LINPACK performance : 1,8 PFlop/s
- 21 million CPU hours attributed to 14 challenges

→ big success !

Grand challenge simulations : 4 examples from 4 different ONERA research departments

Electromagnetism

- Modeling of a scene of electromagnet. fields radiated by 4G/5G transmitters
- *Dept Electromagnetism and Radar* (R. Cranny & T. Volpert, DEMR)

Aeroacoustics

- LBM simulations for the direct prediction of the noise of a grid turbulence impacting a blade cascade
- *Dept Aerodynamics, Aeroelasticity, Acoustics* (M. Buszyk & T. Le Garrec, DAAA)

Energetics (CCRT)

- Fiber-regime atomization simulation for interfacial area quantification
- *Dept Multi-Physics for Energy* (J.C.Hoarau, L.H.Dorey, D.Zuzio, J.L.Estivalezes, DMPE)

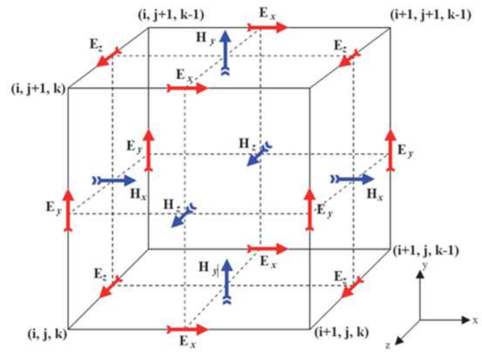
MDO with uncertainties

- Uncertainty propagation study of performances of a reusable launcher
- *Dept Information Processing and Systems* (M. Balesdent & L. Brévault, DTIS)

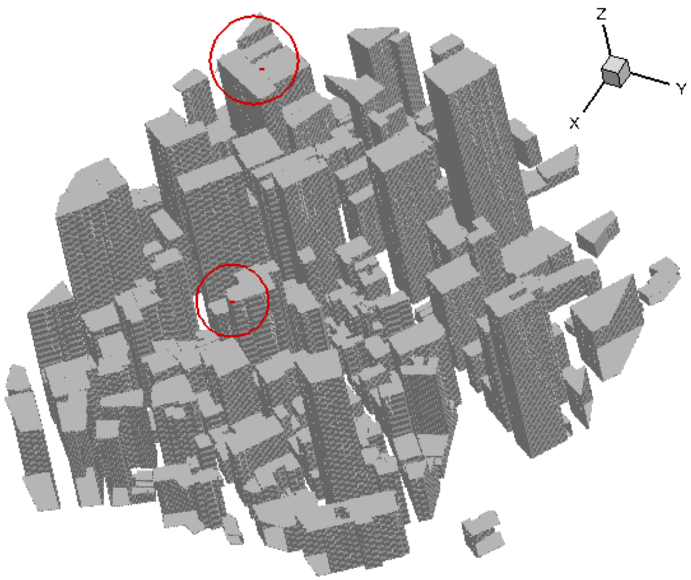
ElectroMagneticCompatibility (EMC) simulation : calculation of EM fields radiated by 2 transmitters (1/2)

Finite Difference Time Domain ALICE Code

- Developed by ONERA since the 90's initially for EMC applications
- Resolution of Maxwell's equations in time domain via the leap frog Yee' scheme
- Cartesian Grid
- Conductive and Dielectric materials
- Structured and unstructured wiring
- Plane wave and voltage/current generators
- MPI Parallel Code



$$\underline{\underline{\mu}} \frac{\partial \mathbf{H}}{\partial t} + \nabla \wedge \mathbf{E} = 0 \,,$$
$$\underline{\underline{\varepsilon}} \frac{\partial \mathbf{E}}{\partial t} - \nabla \wedge \mathbf{H} + \underline{\underline{\sigma}} \mathbf{E} + \mathbf{J}_s = 0 \,,$$
$$\nabla \cdot (\underline{\underline{\varepsilon}} \mathbf{E}) = \rho \,,$$
$$\nabla \cdot (\underline{\underline{\mu}} \mathbf{H}) = 0 \,.$$



Model characteristics (Manhattan district) :

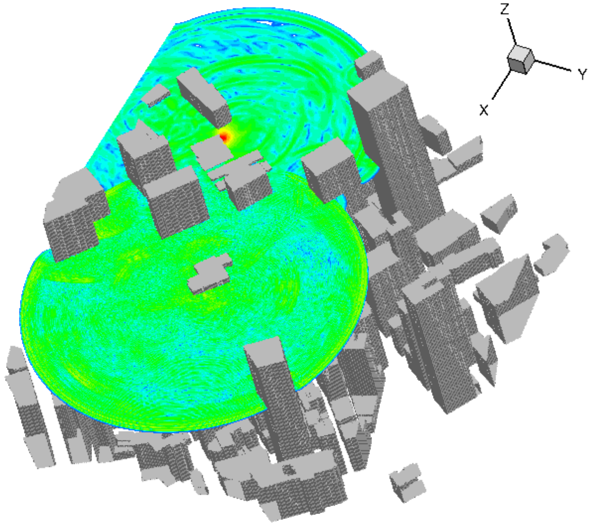
- Modelling area = 700m x 600m x 300m
- Cubic Cell size=10cm
- Frequency band of analysis=[10kHz – 500MHz]
- 126 billion cells, 82000 time iterations.
- Conductive materials
- 2 transmitters (on building roofs)

Run parameters (on ONERA HPC SATOR):

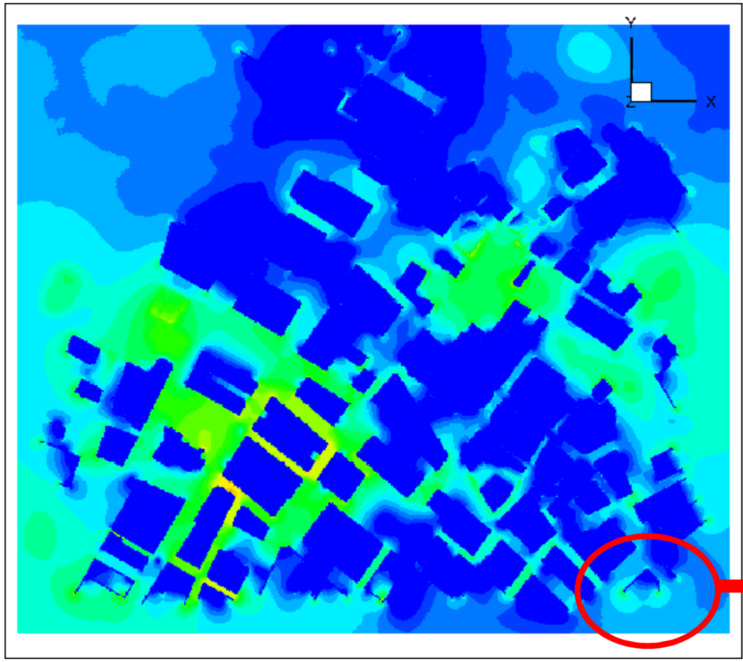
- 22 CPU hours on 11264 processors

ElectroMagneticCompatibility (EMC) simulation : calculation of EM fields radiated by 2 transmitters (2/2)

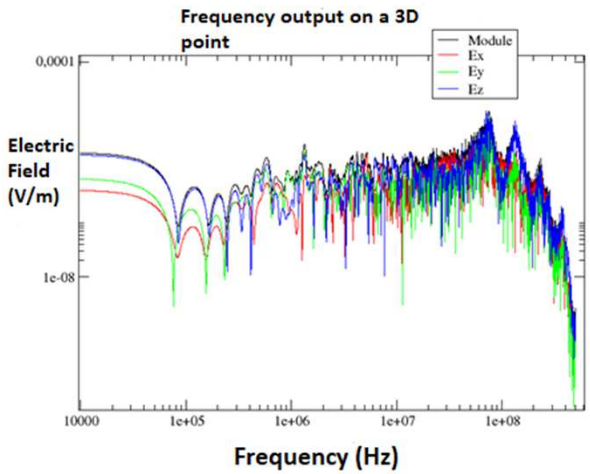
Time domain E-fields
Height=150m
Time=0.75 µs

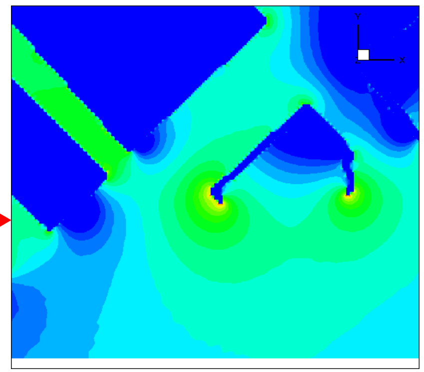


E-fields at 500MHz
Height=50m



Large band frequency output





Lessons learned :

- Dealing with very large meshes
- Post-processing of large amount of data
- Scalability tests > 10 000 procs

First of a kind simulation → application perspectives, such as :

Resistance of UAV to electromagnetic environments in urban operation

2 billion points LBM simulations for turbulence-airfoil interaction noise reduction

Munich Aeroacoustics · CERFACS · SAFRAN · ÉCOLE CENTRALE LYON · University of BRISTOL

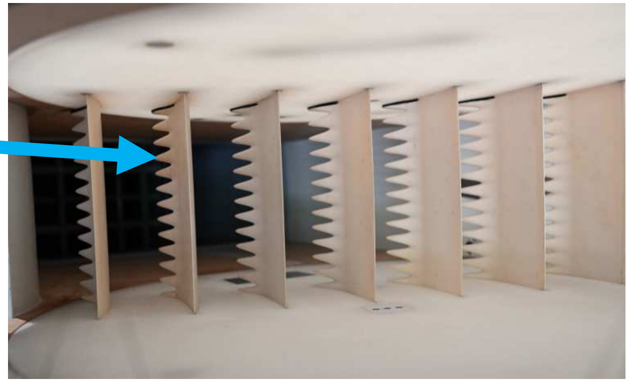
InnoSTAT – Innovative STATOR
EU project to design low-noise stators

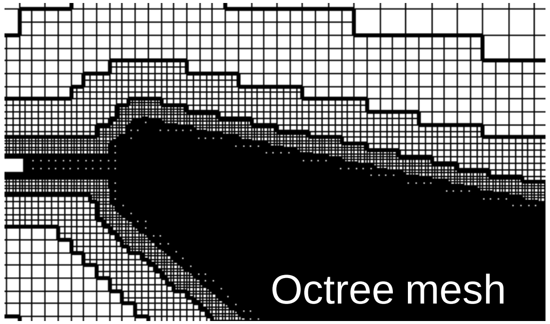
InnoSTAT

ONERA : - low-noise designs: **leading edge serrations**
- **lattice Boltzmann Method (LBM) simulations with ProLB (developed by a French consortium)**

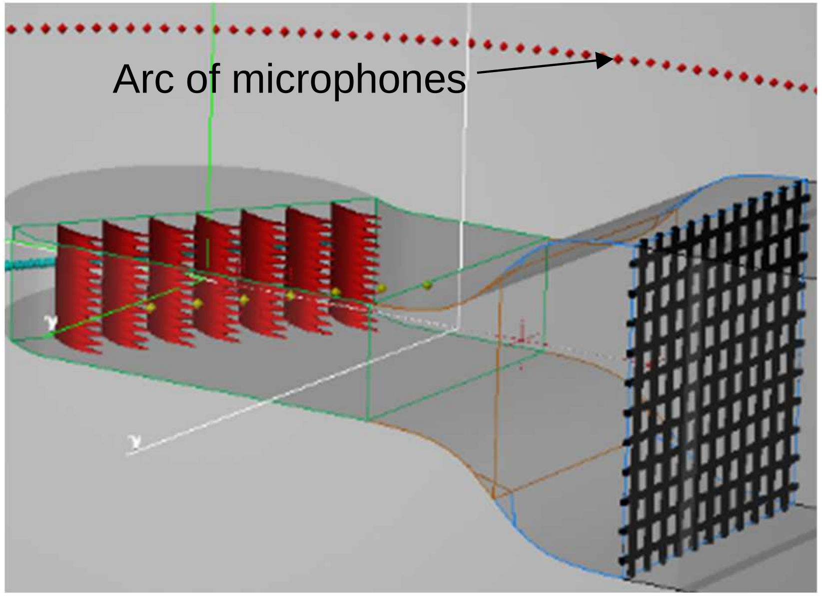
ProLB

Exp. (Ecole Centrale Lyon)





- Immersed boundary cond.
- Full **setup** with **full span airfoils**, **wind tunnel** walls and inlet **turbulence grid** generator



Cores	4000 / 8000
Restitution Time	≈ 2 / 4 days
CPU time	320 / 400 kh
Points	2 billion
Physical Time / Without transient	≈ 0.4 s / ≈ 0.2 s

0.2 s ≈ 192 chord/U

Very fine mesh (better mesh transitions in wake, points around blades X 2) → Improved physics description

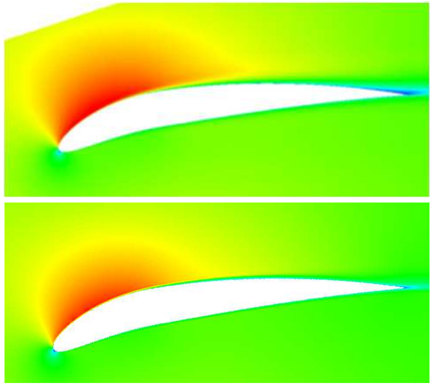
Aerodynamics performance

Prediction of broadband noise reduction

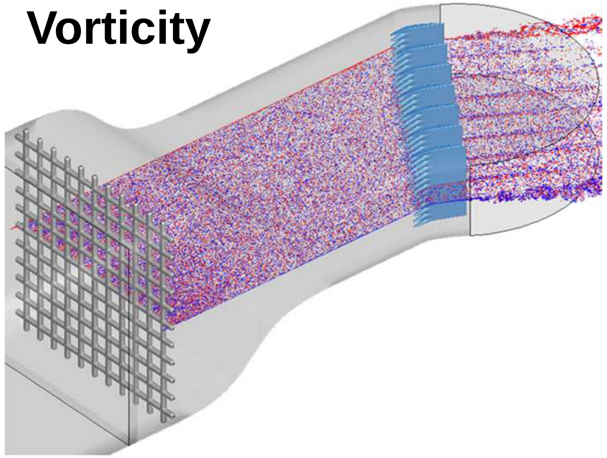
Mach (0.05 to 0.5)

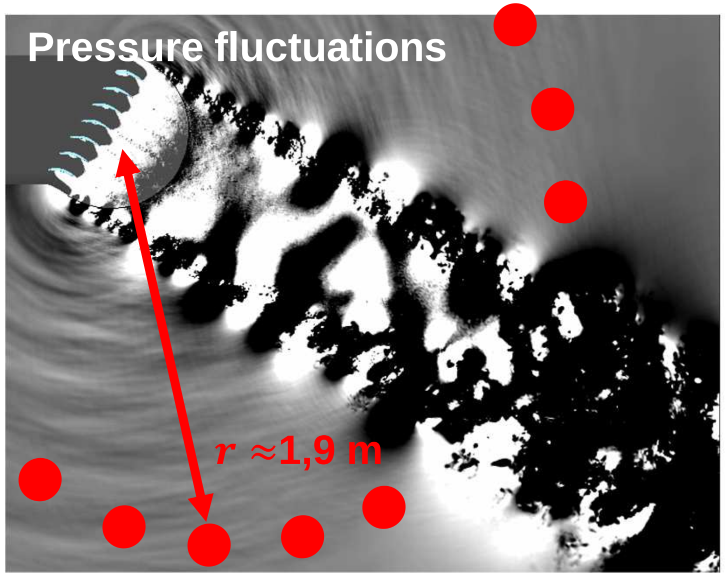
RANS
(1-channel)

LBM
(central vane)

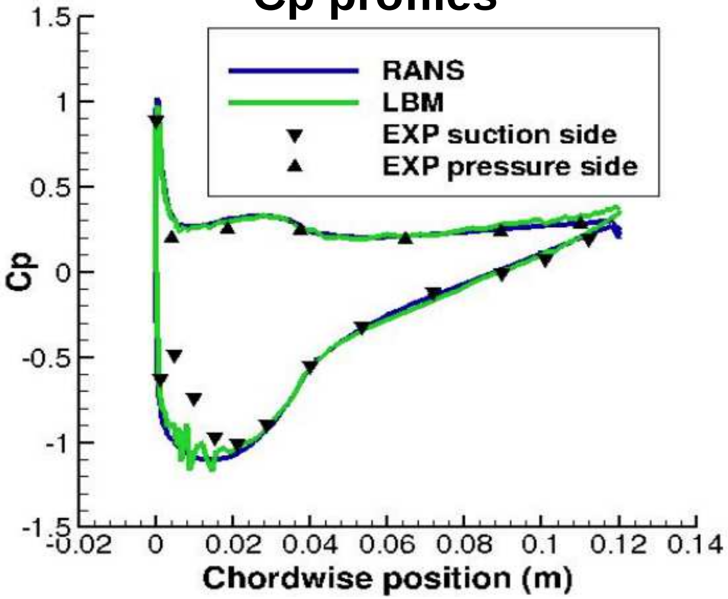


Vorticity

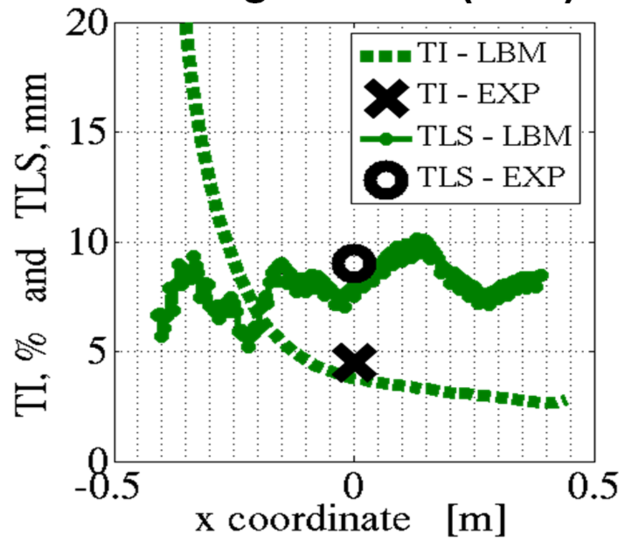




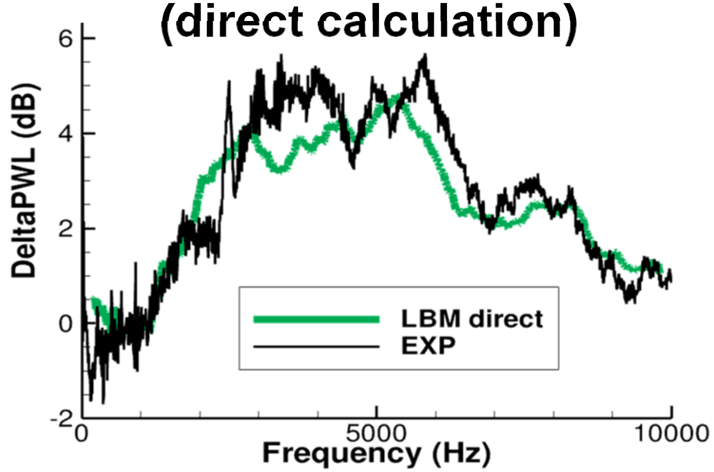
Cp profiles



Turbulence intensity (TI)
Turb. length scale (TLS)



Far-field acoustics (direct calculation)



Aerodynamics and Acoustics match very well with RANS and EXP !

Direct numerical simulation (DNS) of coaxial atomization

Fiber regime atomization in liquid rocket engine injection

Objectives of the DNS simulation

- Validation base for atomization modeling
- Visualization of the formation mechanism of droplets and their repartition

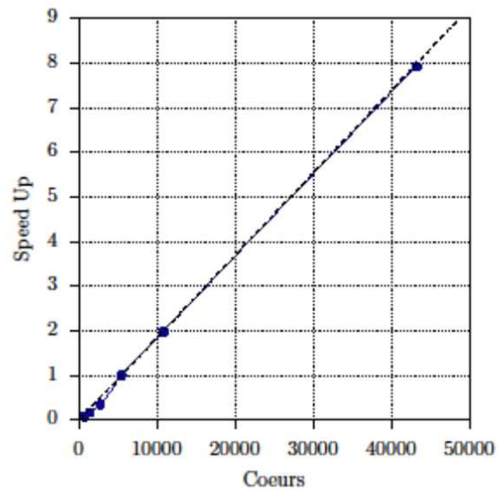
J. C. Hoarau, F. Granger, L. H. Dorey, D. Zuzio, J. L. Estivalezes

Two-phase simulation
(DYJEAT research software)

- Incompressible Navier-Stokes
- Sharp interface reconstruction (CLSVOF)
- Regular Cartesian mesh

Numerical setup

- 3 billion mesh points
- CCRT TOPAZE : 110 592 cores
- Use of 43200 / 86 400 cores
- 45 million CPU hours

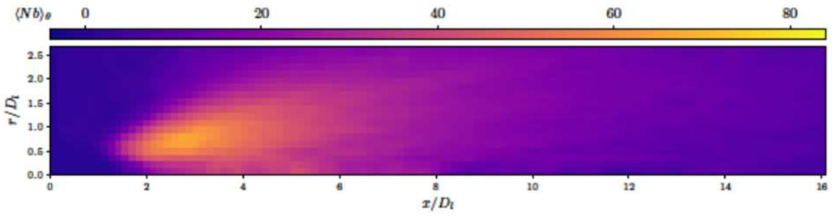


Direct numerical simulation (DNS) of coaxial atomization

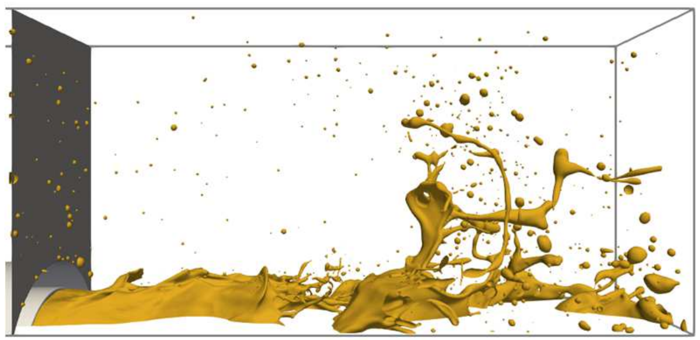
Fiber regime atomisation in liquid rocket engine injection

New results not available in experiments :

- Averaged number of droplets

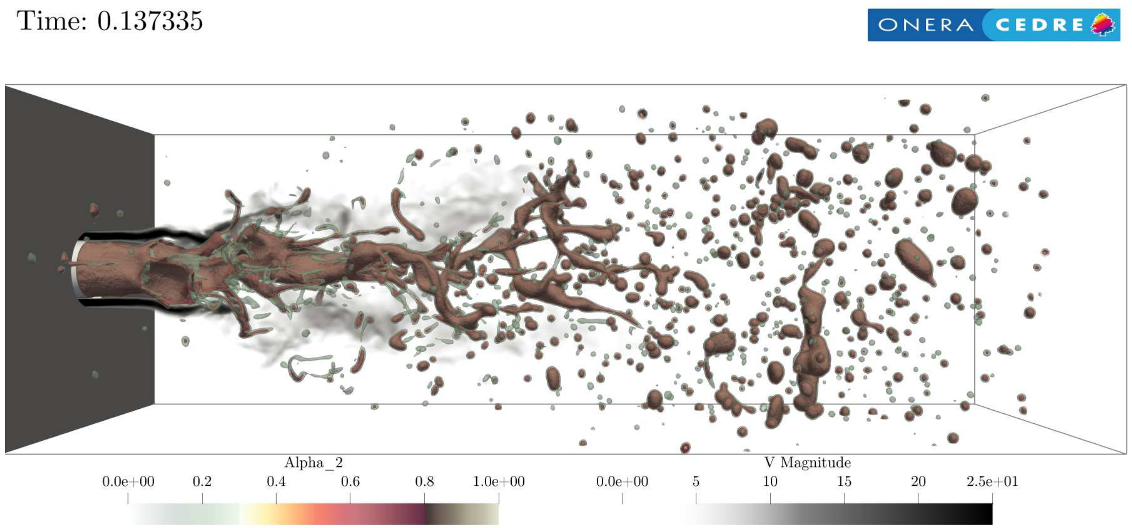


- Precise visualization of the atomisation process

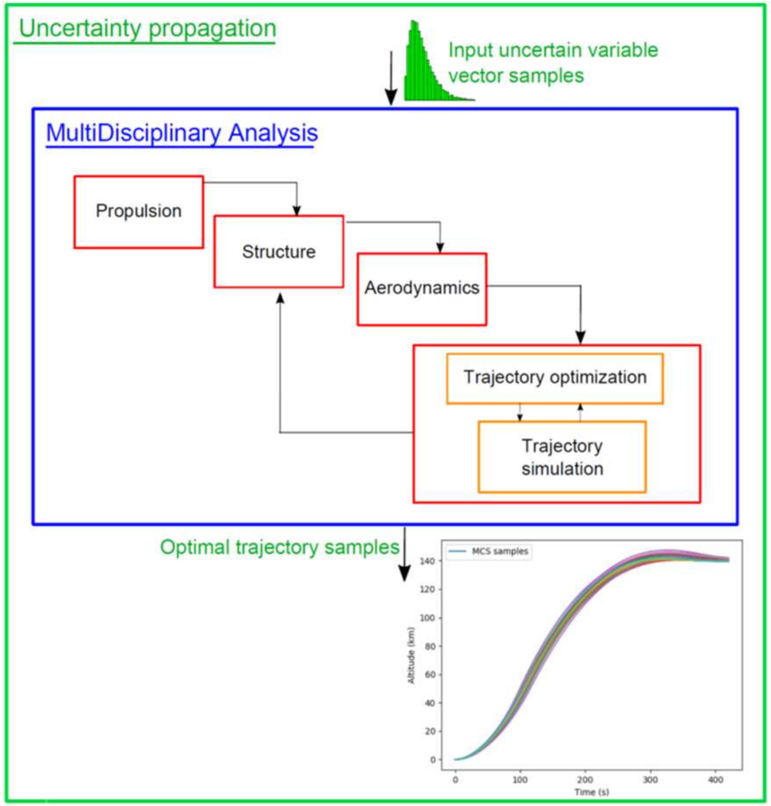


Validation database for LES simulation :

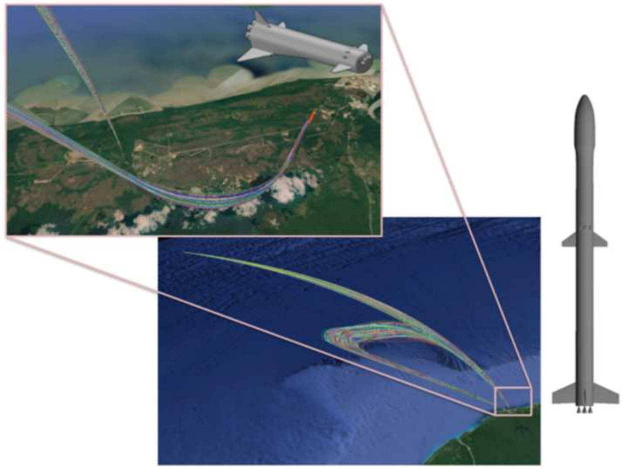
- Sub-grid modeling of the interface density transport
- Dynamic and repartition of the droplet creation

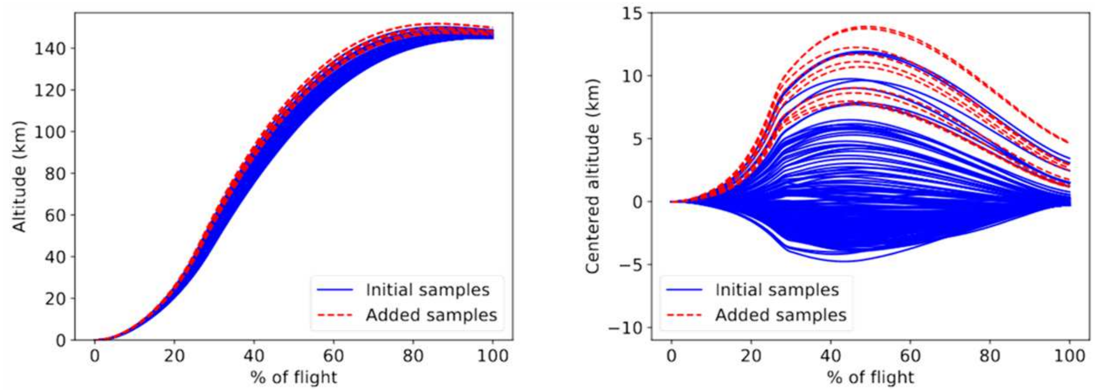


MDO under uncertainties :
Estimation of flight envelopes of launch vehicles



- Characterization **of flight envelopes of launchers under uncertainties by estimation of quantiles**
- Methodology based on combination of model reduction (Karhunen-Loève) and Gaussian process
- Devel. of an **adaptive enrichment strategy**
  → adaptive selection of CPU-costly multidisciplinary simulations to improve the accuracy of the estimation of quantiles





« ONERA HPC SATOR Grand challenges for young scientists » (November 2021)
→ 6×10^5h CPU on 4500 cores, use of OpenMDAO and OpenTURNS

ONERA strategy to deal with the major challenges of numerical simulation

Modeling, simulation & methodologies

1. **Multi-physics high fidelity and multi-fidelity**
2. ***Integration of the input of applied maths***
3. **Exploitation of large mass of data**
4. **Reduction of models for MDA and MDO**
5. **Uncertainty quantification**

HPC & software engineering

6. ***HPC efficiency, minimal dependency to computer evolution***
7. ***Exploitation of innovations for scientific software***
8. ***Interoperability and perennity of a set of evolutive scientific computer codes***

2. **Applied maths laboratory**

8. **Multiphysics simulation platform**

6.-7. **New CFD software project**

ONERA Applied Maths lab (LMA2S)

https://w3.onera.fr/lma2s

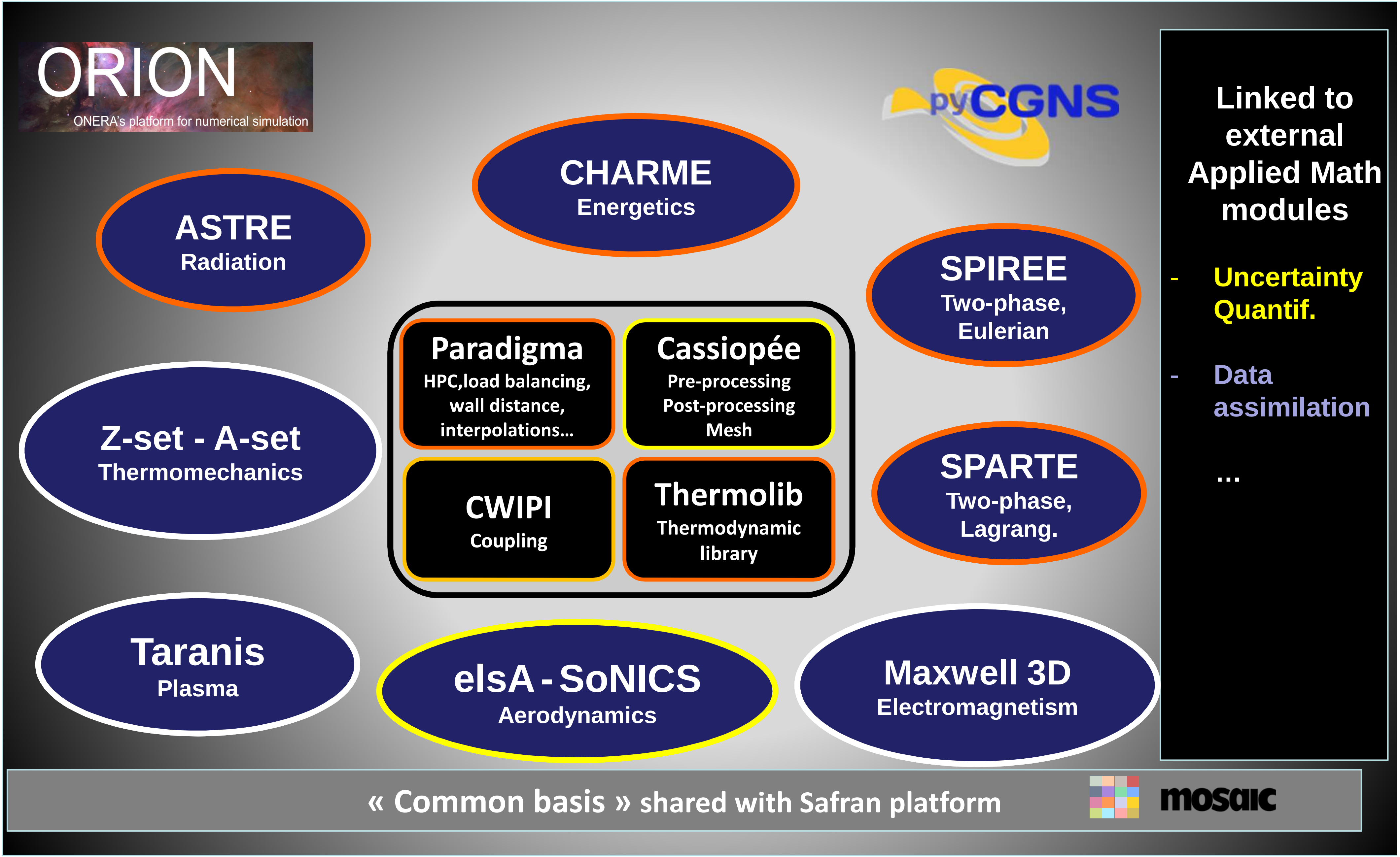
- **Recently created at ONERA to promote links and improve synergy between applied maths scientists belonging to « disciplinary departments »** (lab « without walls »)

- **8 scientific axes**

Waves
HPC (Linear algebra)
Multi-scales
Meshes and visualization
Optimization, control, identification
Uncertainty Quantification
CFD schemes
"White" axis (data based numerical simulation…)

- **An additional objective : providing disciplinary software with Maths apps software components of general interest**

ONERA project of multiphysics simulation platform (ORION) : synergy, mutualization, coupling



Software evolution with respect to hardware

- **Development time of large scientific software > Evolution time of hardware**

→ *Develop abstraction for agnosticity with respect to hardware evolution*

- **Do not let the gap widen between peak performances and real performances**

- **Promote openness to data science**

From the HPDA platform Jean Zay of GENCI to the near-coming exafllopic platform

One example of new generation scientific software in development at ONERA : CFD - from *elsA* to SoNICS (DGAC support, Safran partnership)

Operator graph generator

Code generator

Automatic graph differentiation

HPC layer

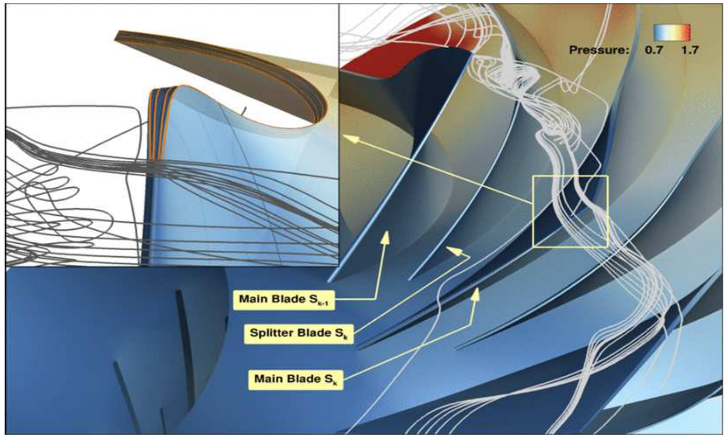
Operator graph

Operators

Data base for coupling

HPC scheduler

Some perspectives for high performance simulation



Aeroelastic simulation of a centrifugal compressor

- **Still tremendous progress to be done in representativity of the reality : need of more multi-physics**

- **Exaflopic HPDA architectures**
  - ➢ **Transition of « legacy» scientific software**
  - ➢ **HPC efficiency**
  - ➢ **Rely on data science without forgetting physics**

- **Better validate and qualify simulation results (certification)**

- **Need to associate a large variety of skills :**
  physical modeling, applied maths, numerical algorithms, data science, computer science, software development, aerospace engineering…

- **Rely on partnerships :**
  ONERA entered the OpenTURNS consortium for UQ in 2019

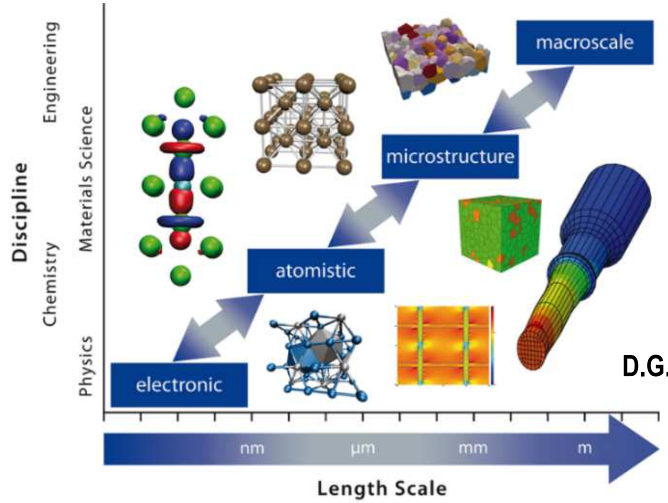
BACK UP

High performance computing needs in aerospace

- Increase in configuration size (for ex., from one blade to a full engine)

- Increase in geometrical fidelity

- Better representation of physics and range of scales
    - Turbulence in fluid mechanics
    - **Science of materials**
    - Electromagnetism

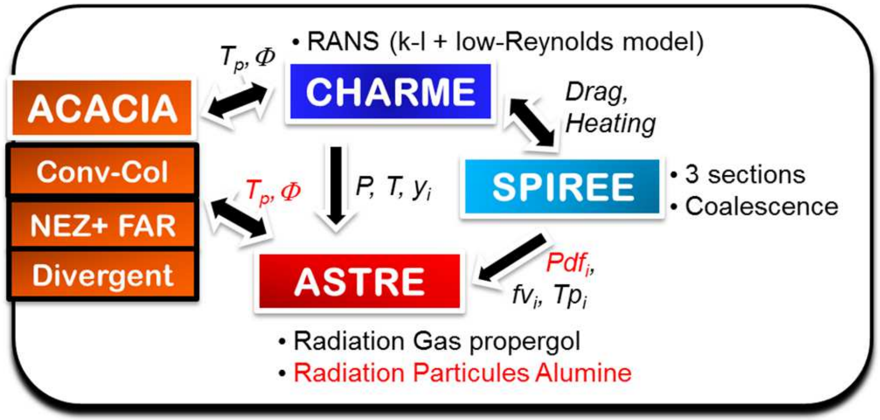


D.G. Pettifor, 1991

- Unsteady phenomena

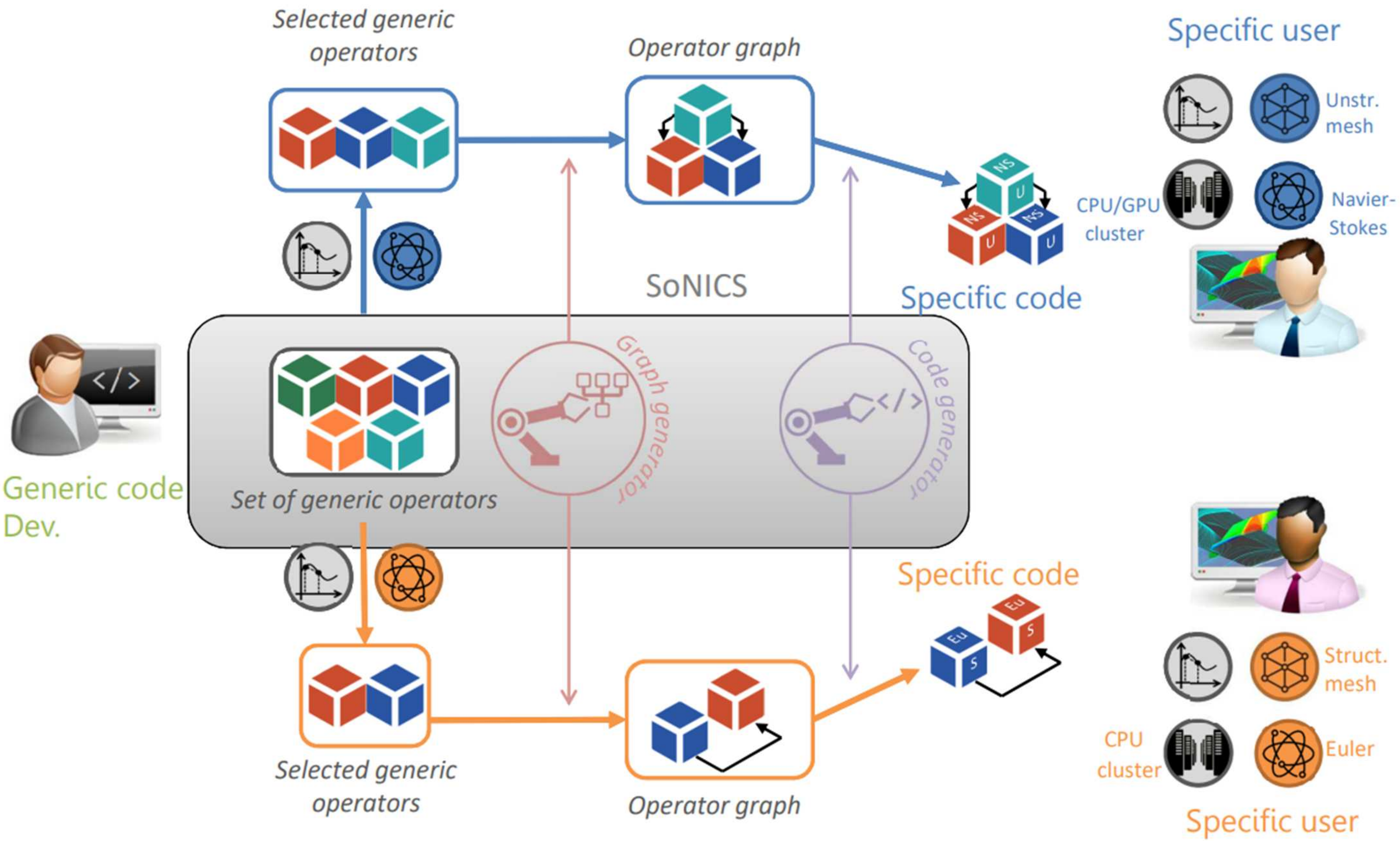
- **Multi-physics coupling**

- Optimization processes



Thermal behavior of a launcher nozzle CEDRE@ONERA

Software evolution with respect to hardware



Software evolution with respect to hardware

Building key components and achieving first milestones with SoNICS

- **Key SoNICS software components**

Operator graph generator

Code generator

Automatic graph differentiation

HPC layer

Operator graph

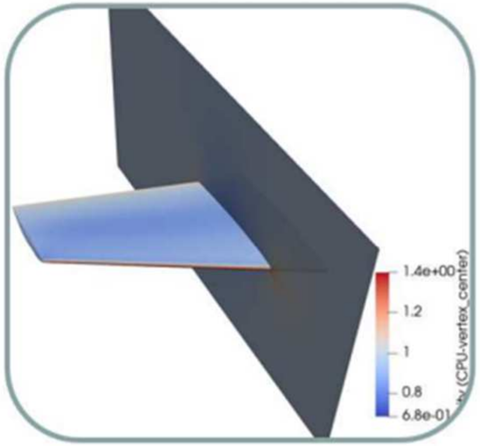
Operators

Data base for coupling

HPC scheduler

- **Achieved milestones**

- Cell centered on CPU
- Node centered on CPU
- Cell centered on GPU
- Notable performance speedups compared with elsA
  - *CPU X 14 speedup/ elsA*
  - *GPU X 100 speedup/ CPU (mono-proc)*



M6 wing, CPU, Node Centered

- **Next milestone**

- Rotor 37 use case / distributed parallel CPU+GPU
- TRL 2 → TRL 3 @Safran

Concluding remarks

Calcul et données. Nouvelles perspectives pour la simulation à haute performance. (2021, 58 p.) **Voir également 46ème forum ORAP *: Calcul haute performance : vers une hybridation avec l'IA***

6 recommandations :

- renforcer le développement de méthodes hybrides, associant physique de base et apprentissage

- s'appuyer sur des infrastructures matérielles convergées permettant à la fois le calcul scientifique et le traitement des données

- mieux valider, qualifier et expliquer les résultats des simulations

- organiser un meilleur partage des données entre utilisateurs potentiels

- promouvoir une formation hybride adaptée et bien reconnaître les métiers associés

- aider à la transition des grands codes de calcul scientifique déjà développés

La simulation numérique dans le secteur aérospatial : les défis à venir

Défis en termes de réduction de la consommation d’énergie, d’émission de polluants, de nuisances sonores

Objectif d’une aviation civile neutre en carbone en 2050

→ La simple évolution incrémentale des configurations ne suffira pas !

→ Concepts en forte rupture : abandon du « tube and wing », recours à l’hydrogène, avion plus/tout électrique…

⇒ Tirer parti de la révolution numérique et des progrès en science des données

Digitalisation croissante de l’ensemble des activités

Mise en place d’une forte continuité numérique
- **Tout au long du cycle de vie d’un produit (notion de jumeau numérique)**
- **Entre sociétés contributrices (co-conception entre industriels partenaires)**
- **Entre les différentes disciplines de la physique**

Progrès requis dans le domaine de la quantification des incertitudes (certification)

Importance croissante du *big data*

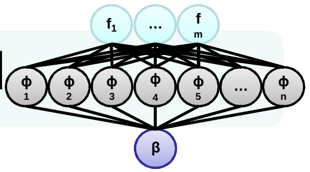
« Data driven modelling »

Apprentissage d’un modèle de type moyenne-fidélité RANS à partir de données de référence numériques :

Données haute fidélité (DNS, EXP)

Assimilation de données

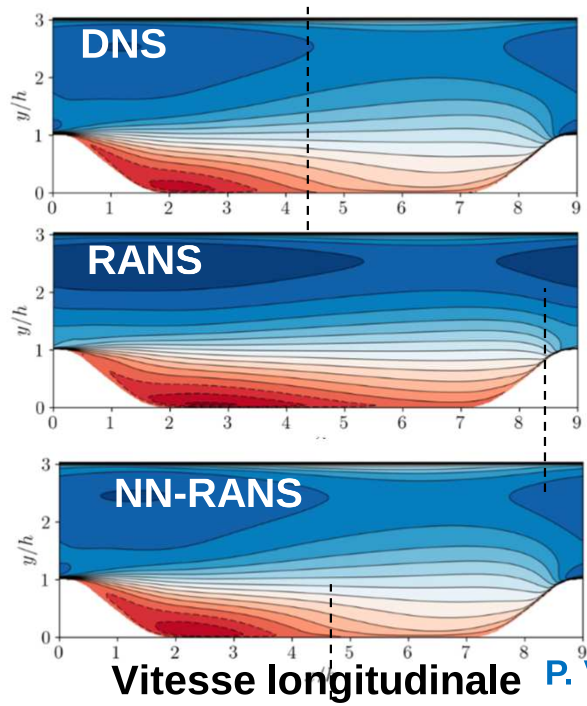
Apprentissage profond



Test du modèle RANS corrigé

NN-RANS testé sur d’autres configurations

Colline périodique (Re=5600)



Vitesse longitudinale P. Volpiani/ONERA

Sciences de l’ingénieur : besoin de données en quantité et de qualité pour l’apprentissage des modèles (small data)
Cf. Base de données ImageNet : 14 millions d’images annotées manuellement avec 20 000 étiquettes (big data)