Vérification, Validation et Quantification des incertitudes en simulation numérique (VVUQ)
Séminaire Aristote **Mardi 8 novembre 2016,** Amphithéâtre Becquerel,Ecole Polytechnique, Palaiseau

CFD industrial approach for space systems design

P. Brenner

AIRBUS SAFRAN LAUNCHERS

Scope

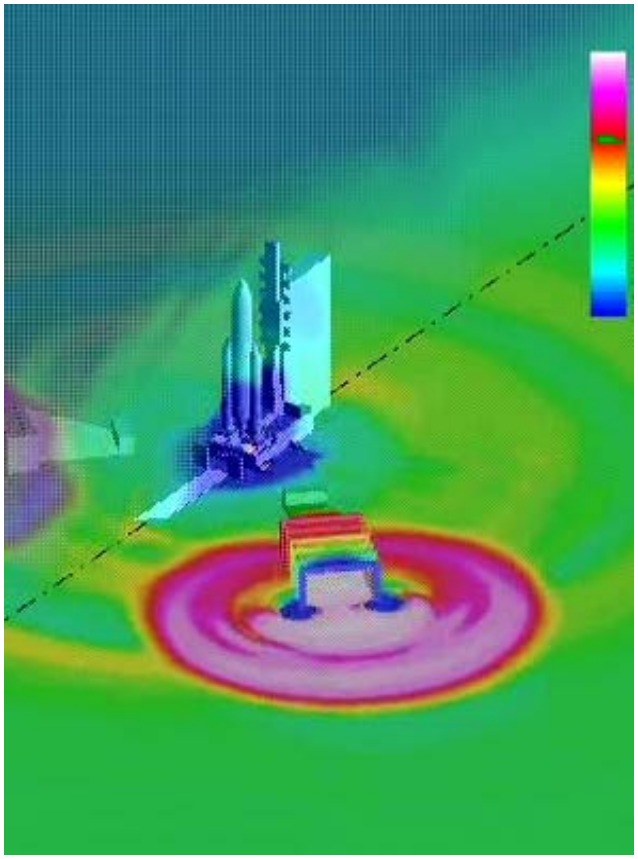
Transient/Unsteady flows

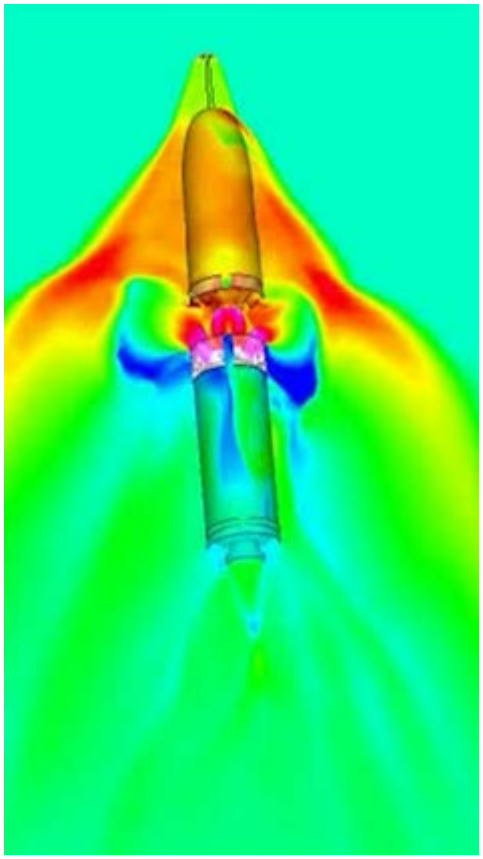
- **Engine Ignition** — Screech phenomenon, side loads, re-burning, Launch-pad, blast waves formation/propagation.
- **Stage separation** — Structural loads, flight mechanics.
- **Stability at re-entry** — Amplification/dumping of oscillatory motion (base flow features)
- **Unsteady eddy simulation** — Detached flows/ base flows

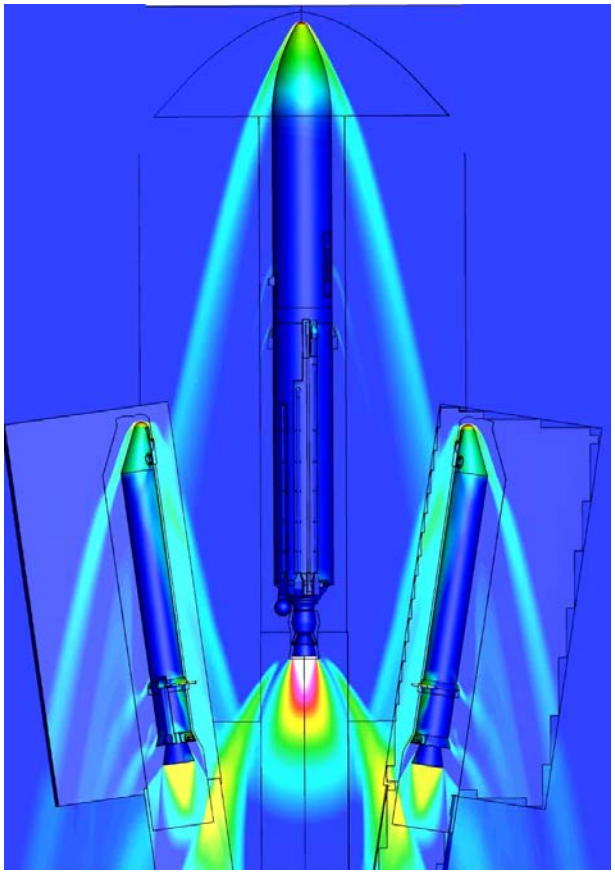
Steady flows

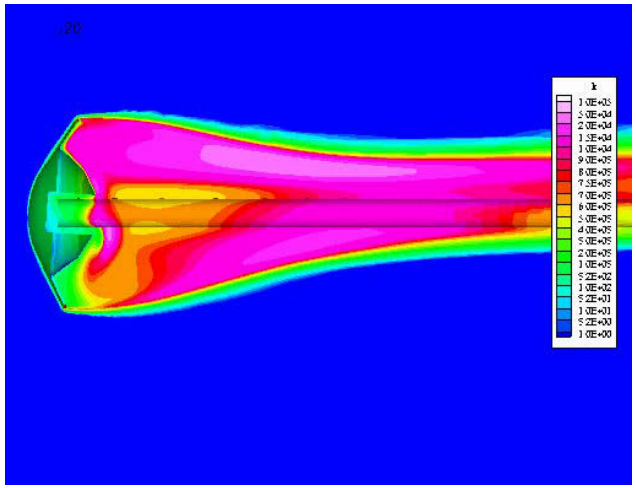
- **AEDB** — Flight mechanics (Sub/supersonic)
- **Hypersonic - ATDB** — Thermal loads, launchers, re-entry bodies...
- **Propulsive flows** — Base flows, engine flows, nozzles/plumes...

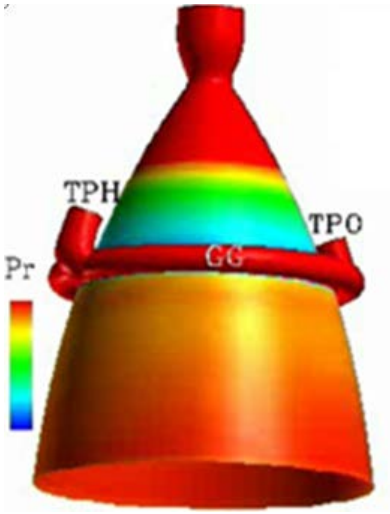
Transient/Unsteady flows

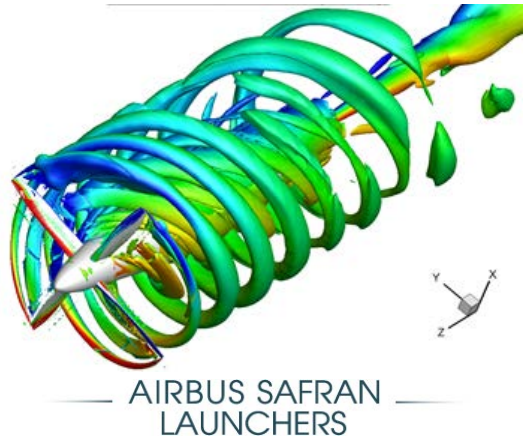












History

Ariane 5 (1987-1996)

• **Stage separation**	**R**educed/surrogate **M**odels - (Euler)
• **Take-off blast wave**	**RM** - (Euler).
• **AEDB**	**W**ind **T**unnel **T**ests - (Euler - RANS)
• **ATDB**	**WTT**

Huygens probe (1991-1997-2005)

• **Stability at re-entry**	**WTT** - Gunnery Flight Tests - (URANS)

Ariane 6 (2012-2020)

• **Stage separation**	URANS - **RM**
• **Take-off blast wave**	URANS
• **AEDB**	RANS => **WTT/3**
• **ATDB**	RANS => **WTT/3**

Industrial Requirements

Reliability

• **Robustness**	Stability-Conservativity-Positivity Realizability-Frame independency
• ***VERIFICATION***	Consistency-Truncation Error Assessment (A/M Solutions)
• ***VALIDATION***	Industrial Test Cases Data Base **=>** Certification
• **Uncertainty Quantification**	Mesh Convergence Reduced/surrogate Models + MC

Efficiency

• **Easy to use**	Meshing strategy-modification-GUI
• **Optimal algorithms**	Temporal integration strategy
• **Scalability**	HPC
• **Accuracy**	3^{rd} order for steady 4^{th} for unsteady Automated Mesh adaptation

Sustainability

• **Software engineering**	Git-Non regression DB
• **Adaptability to hardware evolutions**	Software architecture
• **Improvability**	idem

Complex physics

• **Moving bodies**	6DoF Motion/Connections
• **Turbulent models**	RANS-URANS-VLES
• **Particles modelling** (H2O,AL2O3…)	Dispersed Eulerian formulation
• **Chemical modelling**	ARRHENIUS / JANAF tables

Efficient Meshing strategy

• **Unstructured Hybrid meshes**	Canonical elements
• **Conservative CHIMERA**	Geometrical intersection
• **Automation**	CASCADES tool (+ Mesh adaptation)

Accurate and Robust numerical schemes

• **MUSCL approach**	Godunov Numerical Fluxes
• **High order reconstruction**	3rd order k-exact - Global 4th order
• **Adaptive Temporal Integration**	Explicit local time stepping
• **Implicit Temporal Integration**	Newton algorithm + GMRES-QR

Verification

Basic Models (convection, diffusion, production, coupling)

- **Euler-Laminar** — Algebraic solutions
- **Turbulence, Chemistry, Particles** — Algebraic/Manufactured solutions; Semi-empirical solutions

Complex issues

- **Boundary layer Shock interactions** — Semi-empirical solutions
- **Pathological behaviours (Carbuncle)** — Curative/avoidance process

Floating-point arithmetic & round-off errors

- **Computer arithmetic** — CADNA software (*Discrete Stochastic Arithmetic)*
- **Parallel Computing issues (non-deterministic behaviour)**

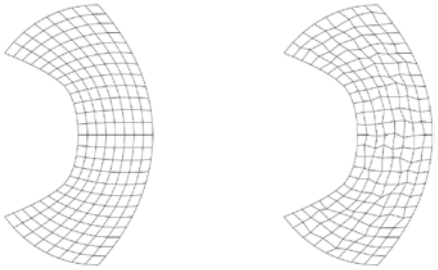
Computer Engineering

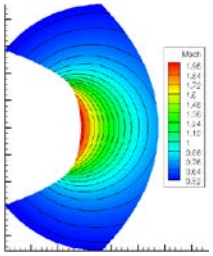
- **Compilers (option…)**
- **Non regression & Industrial Test Cases Data Base & HPC efficiency**

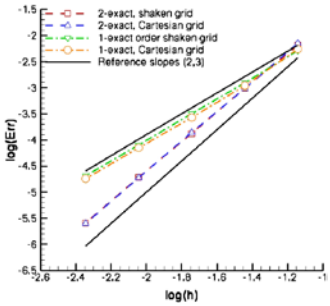
Verification

Basic Models

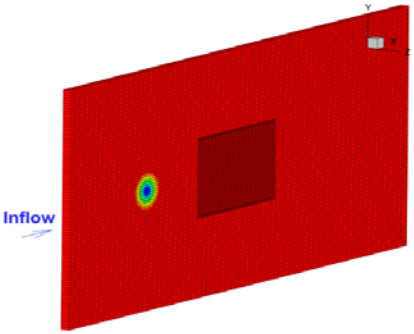
- Sub-Supersonic Ringleb's Flow (on distorted grids)

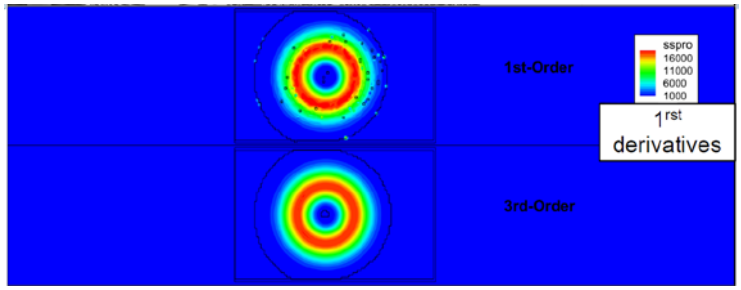


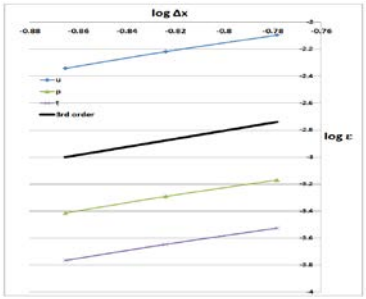




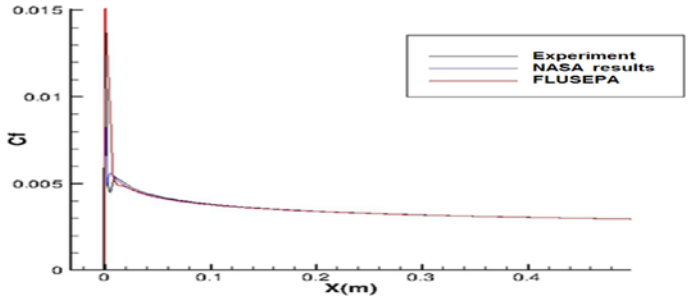
- Moving Vortex (with intersections & AMR)

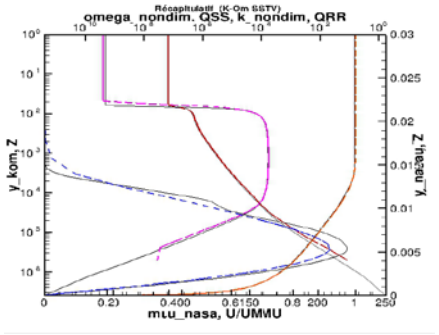






- Flat plates (NASA data bases)





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Complex issues

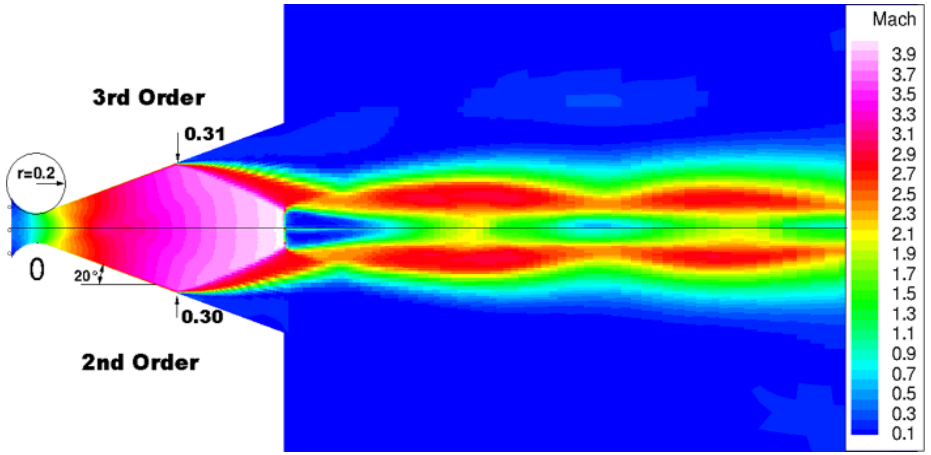
- Boundary Layer-shock interaction (Astier's Nozzle: Robustness)

Launder-Spalding k-ε

- Realizability constraint

Geometry:

- $Ø_{throat}$ = r = 0.2m
- $Ø_{exit}$ = 1.4m
- T_{Wall} = 2000K



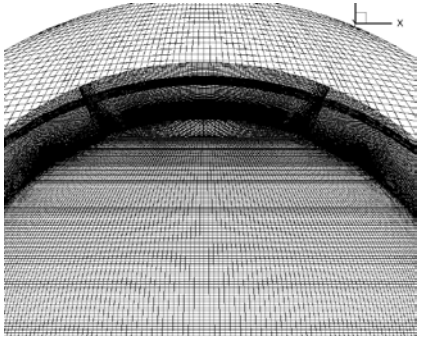
Chamber:

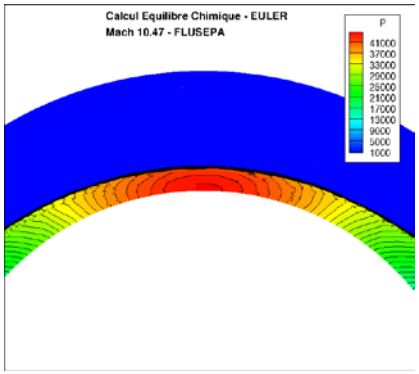
- P = 50bar, T = 3200K
- γ = 1.17, N = 32.8 mole/kg

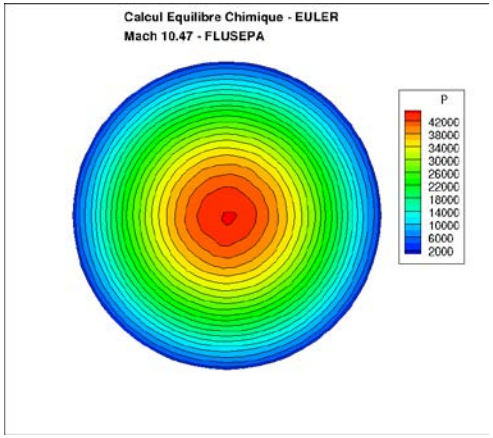
Atmosphere:

- P = 1bar, T = 300K
- γ = 1.4, N = 34.52mole/kg

- Hypersonic sphere (Carbuncle)







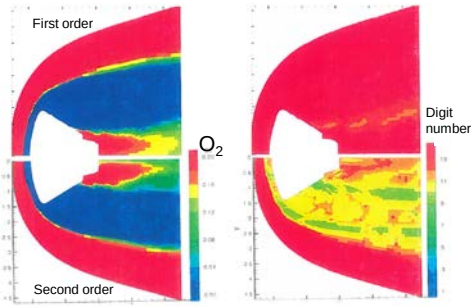
Verification

Floating-point arithmetic & round-off errors

- **Computer arithmetic**: CADNA software (*Discrete Stochastic Arithmetic)*

  ❑*2000-2001 Implementation of CADNA in FLUSEPA: Evaluation of round-off errors & numerical robustness for several models & numerical schemes:*

  - ✓ *1rst & 2d order convection scheme (Godunov-MUSCL)*
  - ✓ *Viscous & Turbulence model (Laminar – RANS k-ε)*
  - ✓*Temporal integration (Adaptive explicit – Newton implicit)*
  - ✓*Chemical reaction model & resolution*



  ❑*Future work?*

- **Parallel Computing issues** (non-deterministic behaviour)

  ❑*Performance drop to make reduction operations deterministic (Compiler – OpenMP – MPI libraries)*

Computer Engineering

- **Compilers** Enforce Usual Specification (trade-off btw Accuracy-Reproducibility-Performance)

Industrial Validation Issues

Complex Model

CPU cost

- **$RANS_{WL}$** (with Wall Law) — 15 mn (64 cores)
- **RANS** (without Wall Law) — x10 to 100
- **$RANS_{WL}$** + ***Chemistry*** — x 2 to 10
- **$RANS_{WL}$** + ***Particles*** — x 2 to 10

Unsteadiness

- **$URANS_{WL}$** — 1 day – 1 month
- **VLES** — 1 week – 1 year
- **LES** — 1 year – 1 life

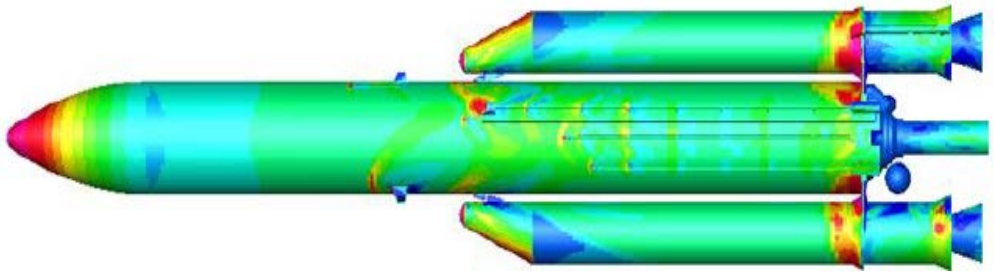
Industrial validation: minimum CPU requirement

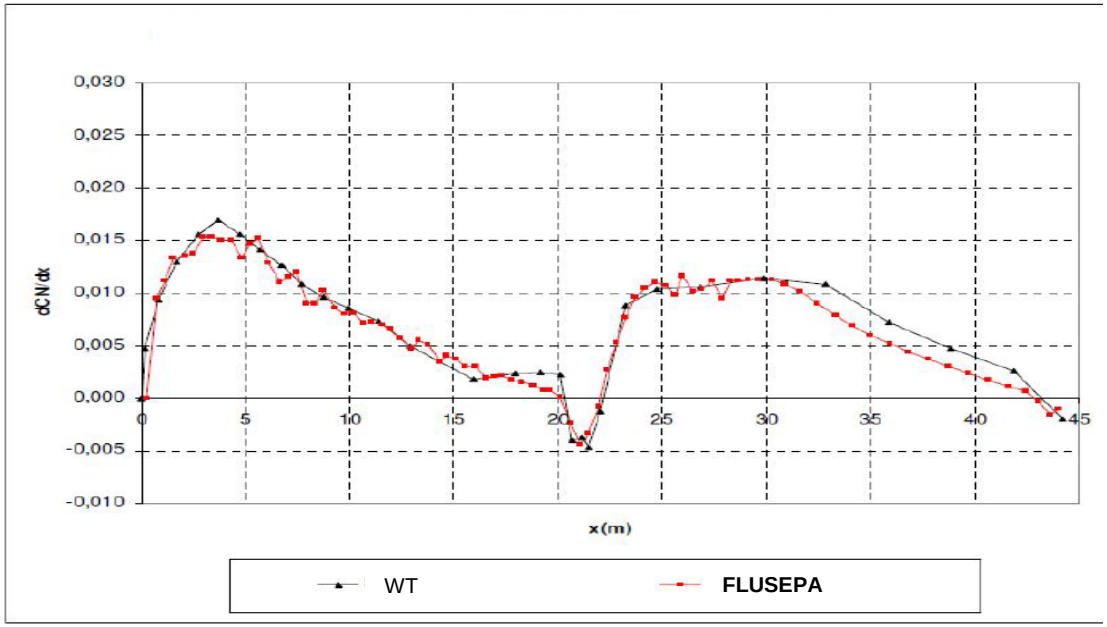
- **Best practices** — Model requirements
- **Empiricism** + **Automation** — Mesh libraries - AMR

CERTIFICATION

Validation

1-Aerodynamic Databases (AEDB)

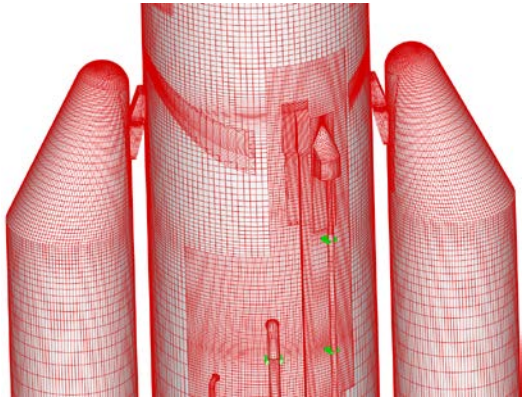


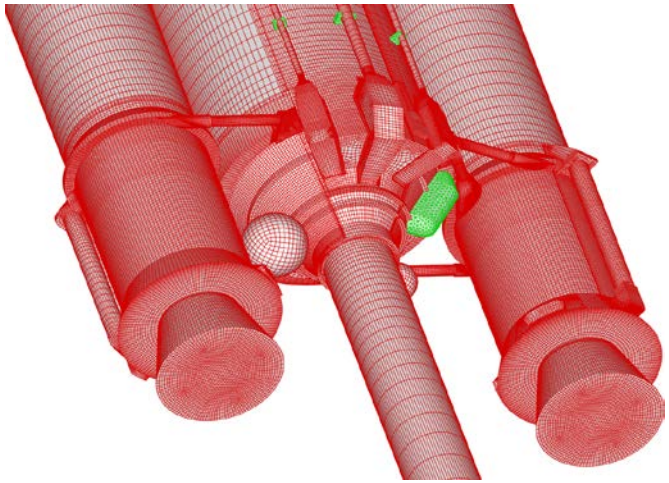


A5 Colombus wind tunnel model:
distributed gradient of lift coefficient (WTT vs CFD)

Cascades tool

Automated process





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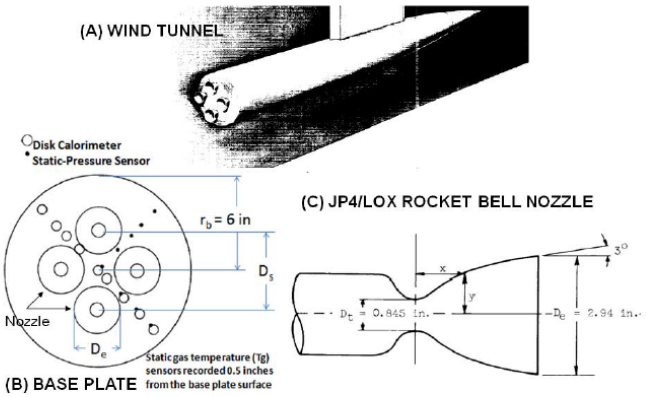
1-ATDB-Base Flows (NASA)



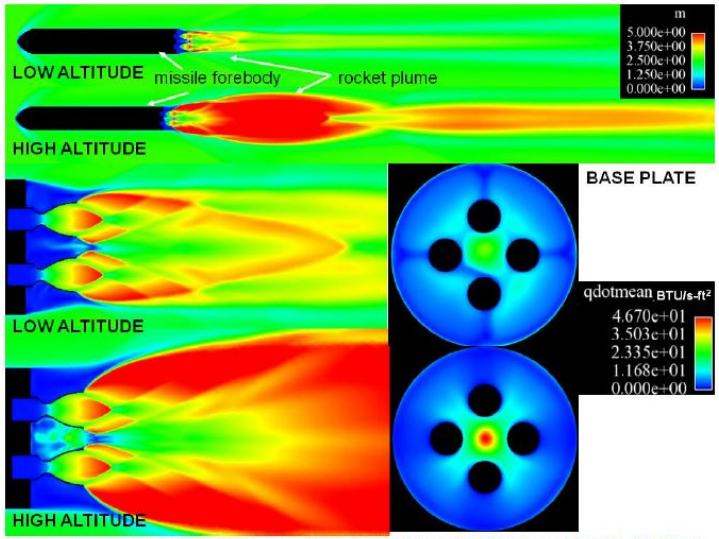
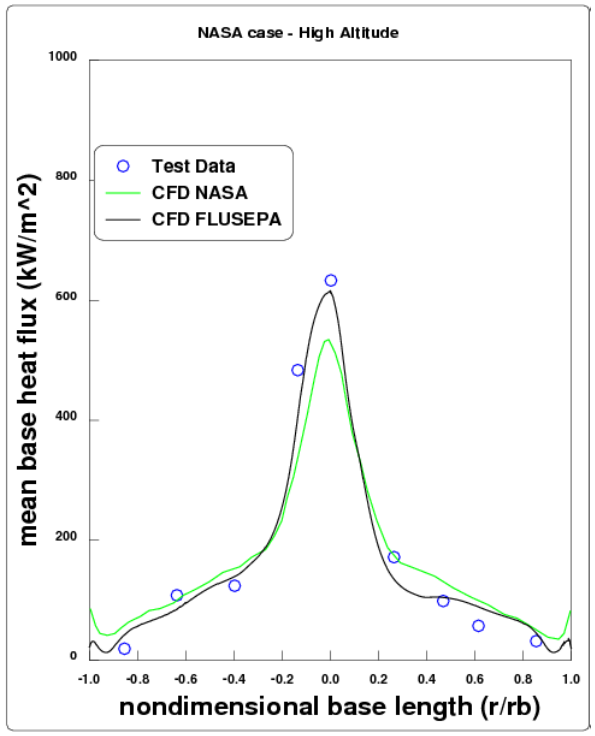
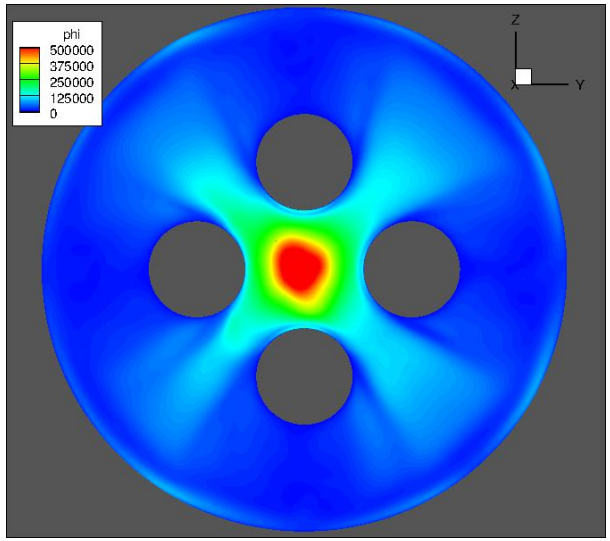
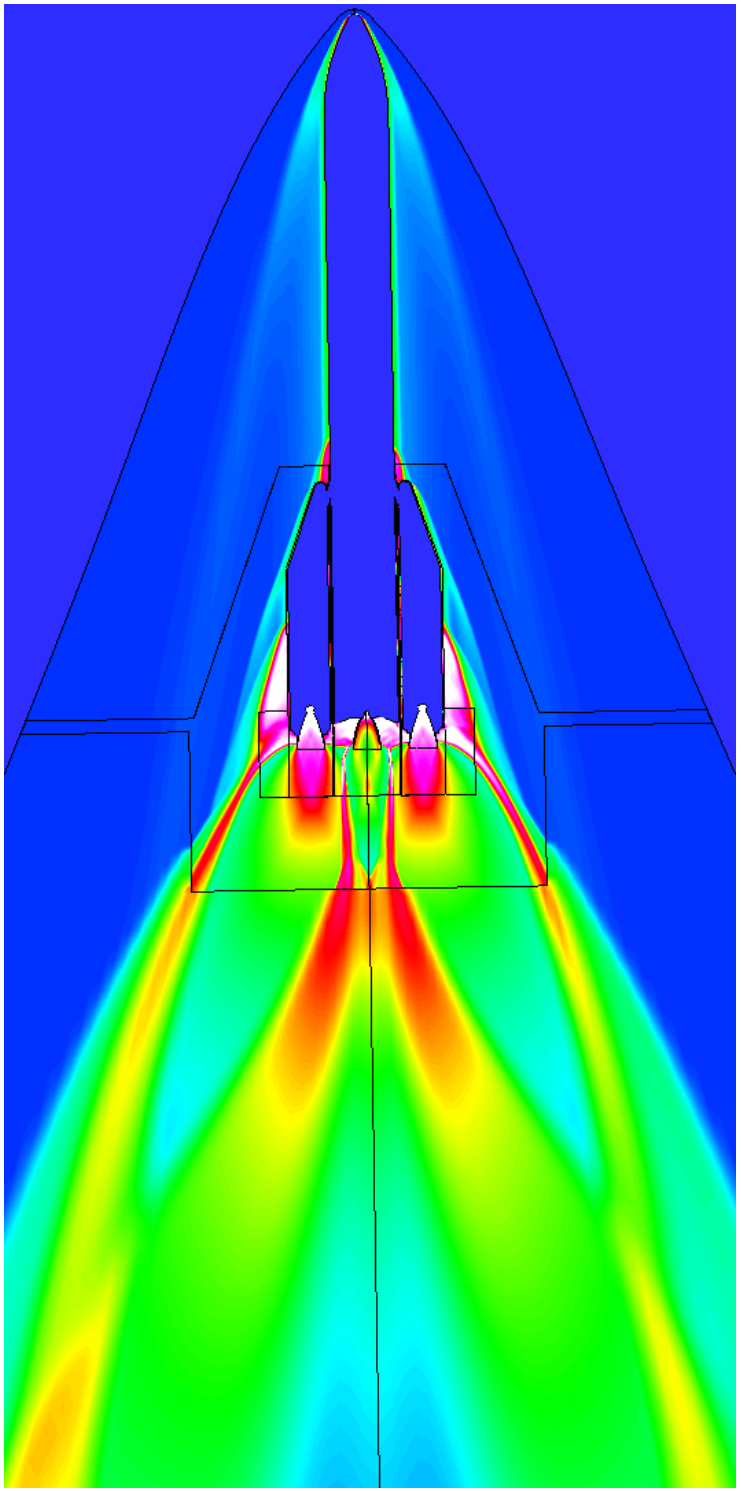


Figure 7. (Top) Full wind tunnel flow field domain (Mach contour); (Bottom left) Base flow field domain (Mach contour); (Bottom right) Base heat flux contours

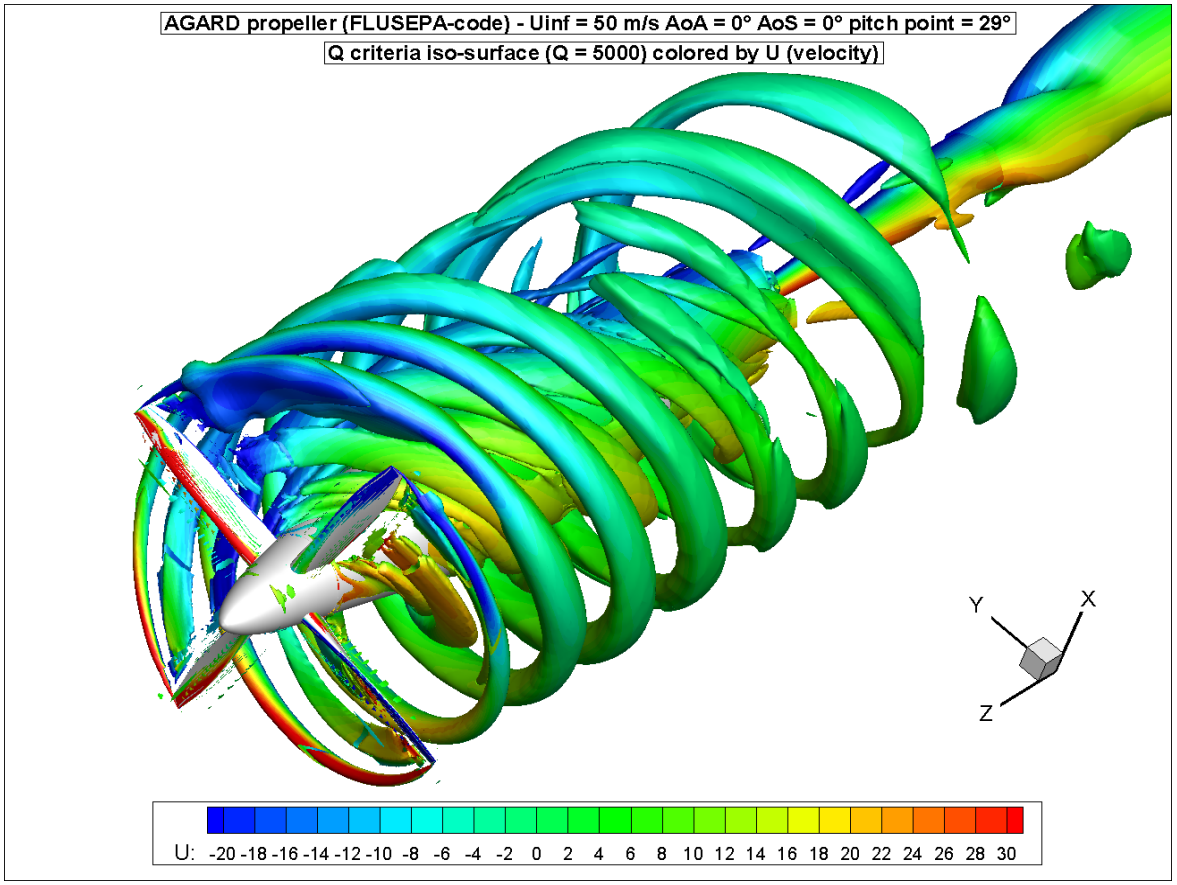


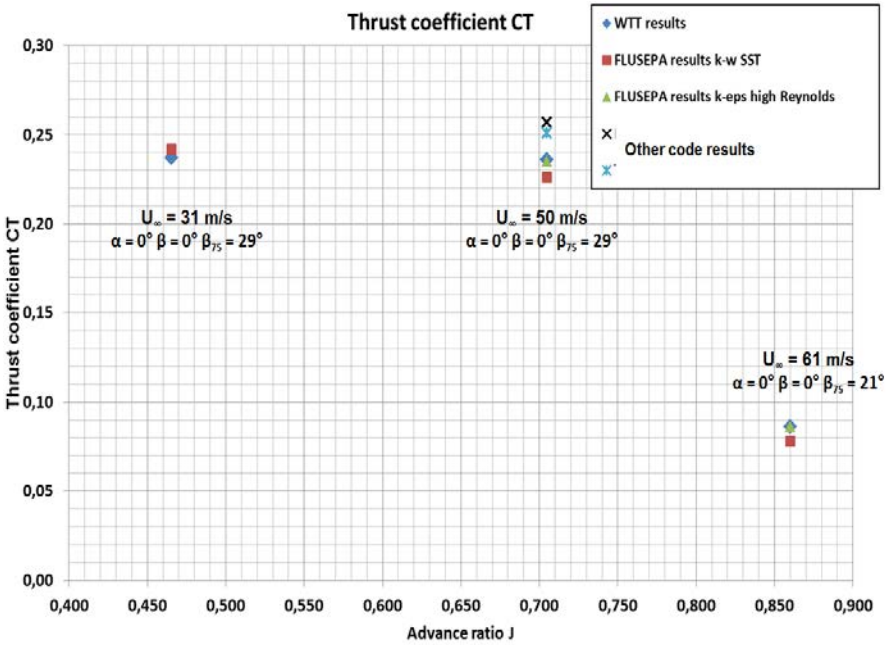


Plumes interaction



3b-Propeller Aerodynamics (AGARD)

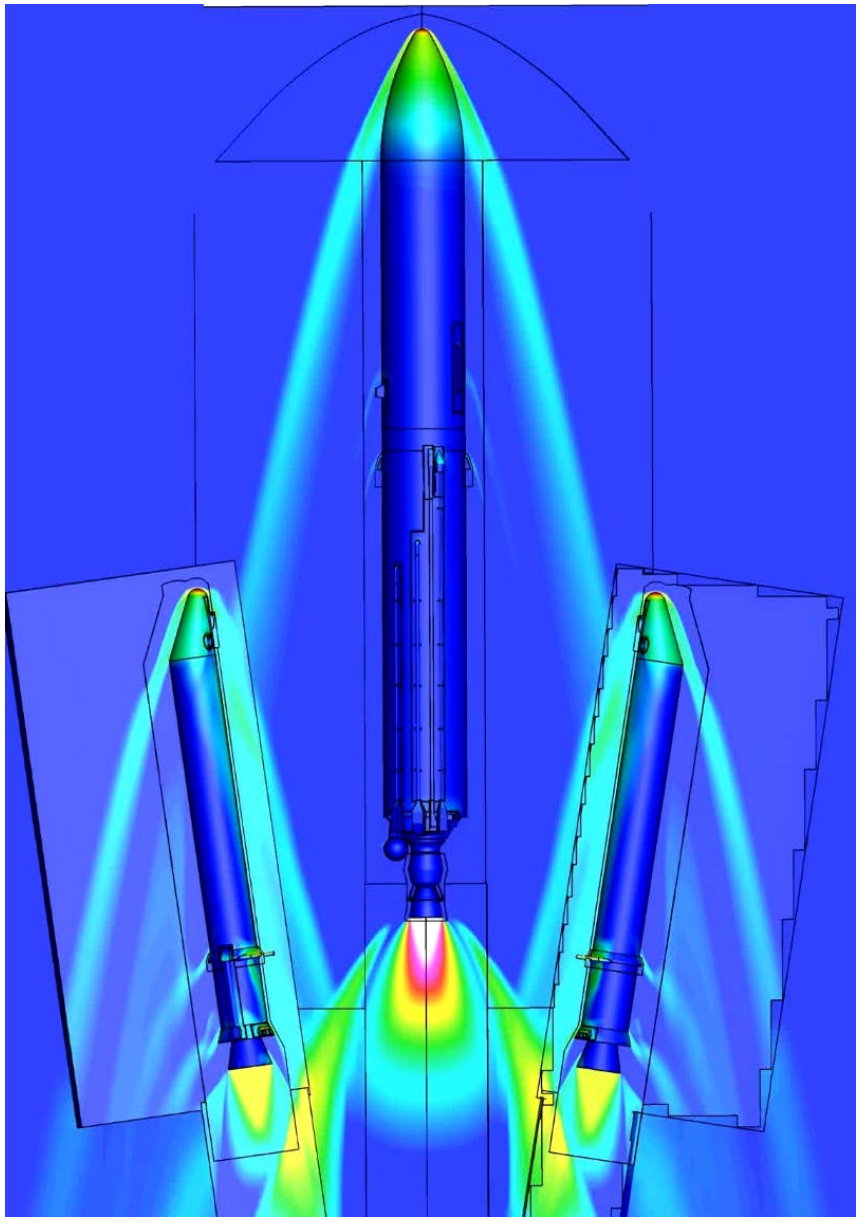


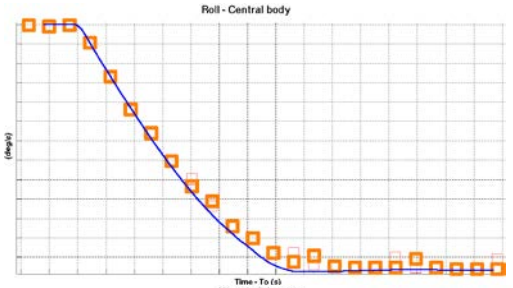


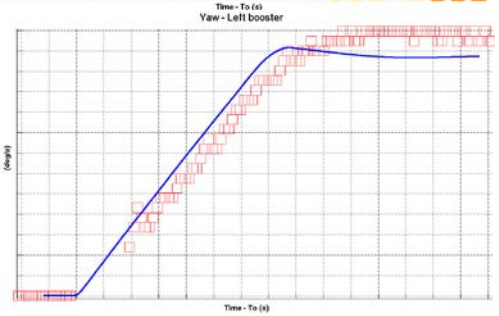
Validation of unsteady phenomena

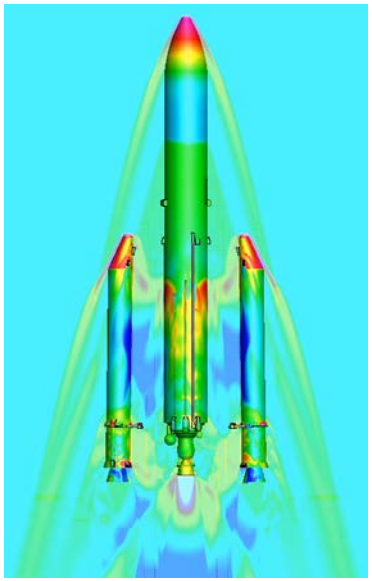
1-Stages Separations

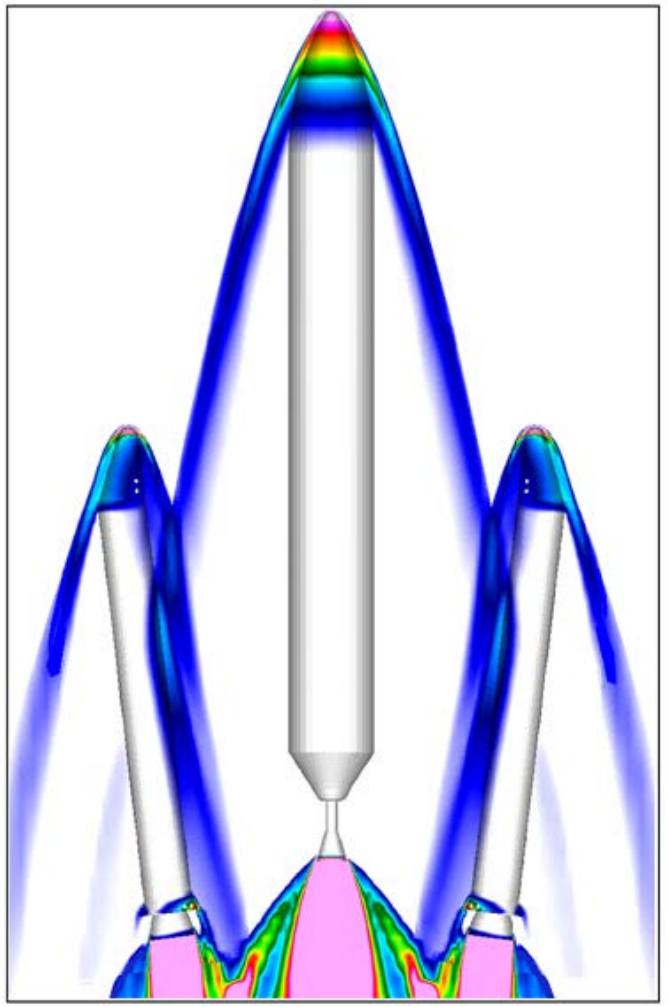
1995	**EULER**	90 K-cells
2016	**URANS**	14.5 M-cells











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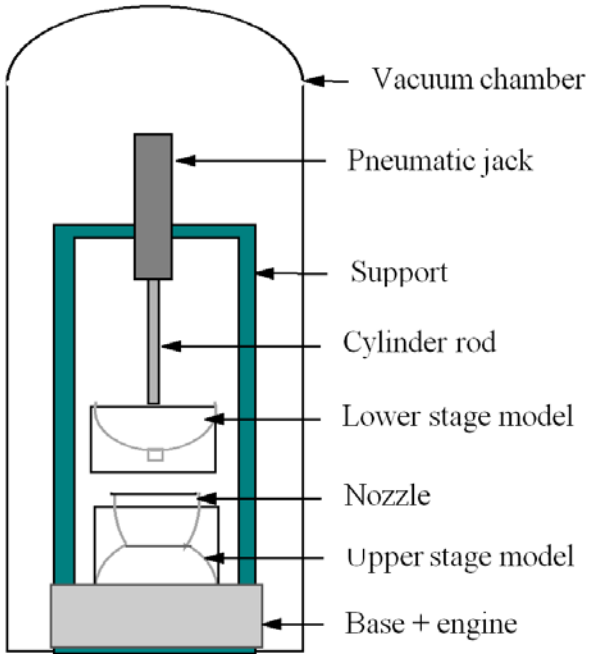
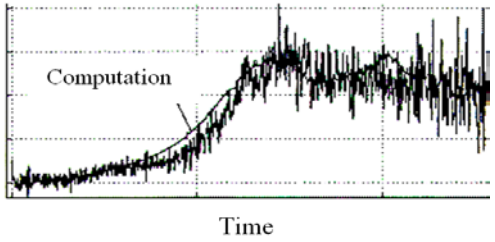
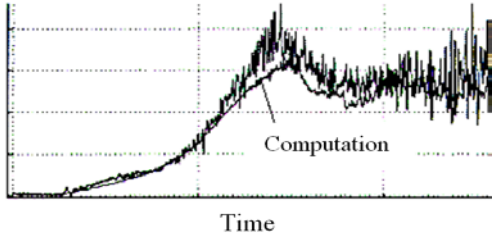
Validation of unsteady phenomena

1b-Stages Separations

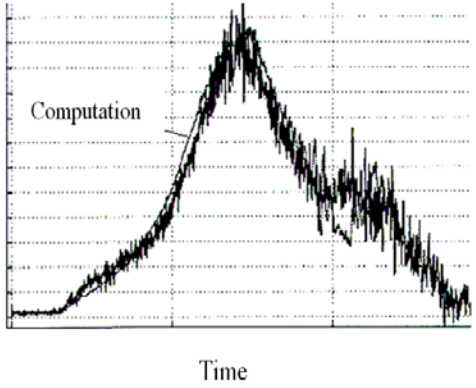


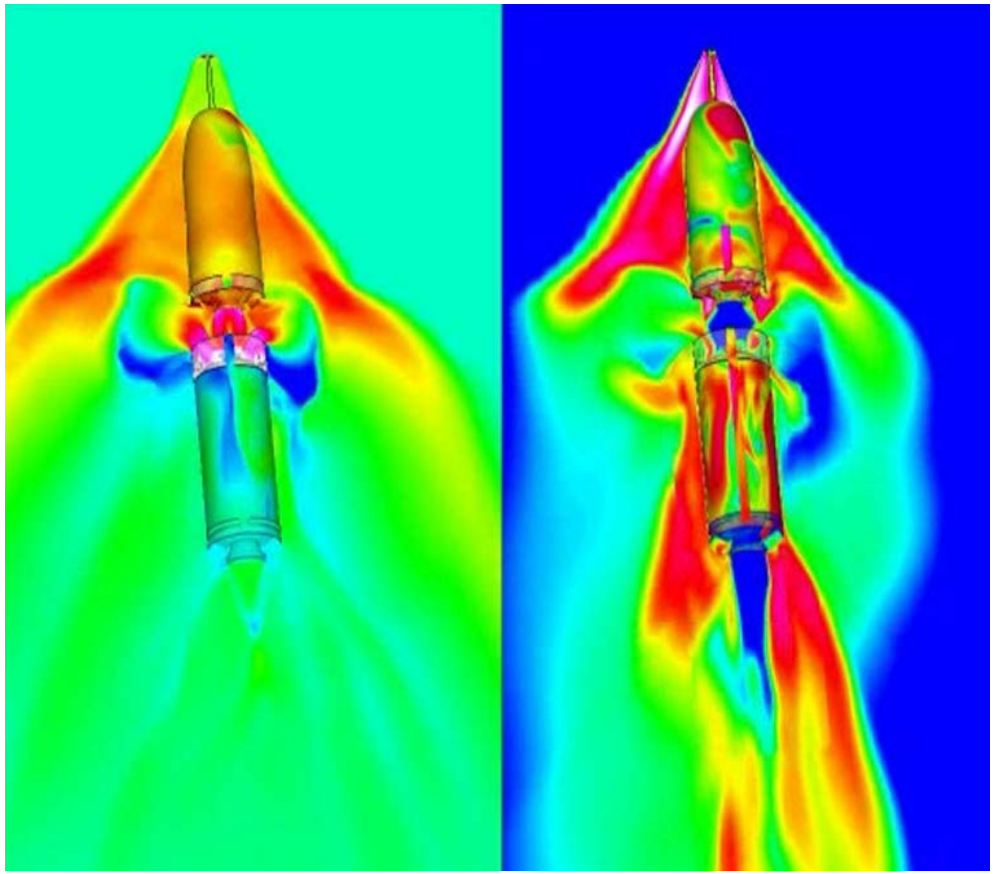


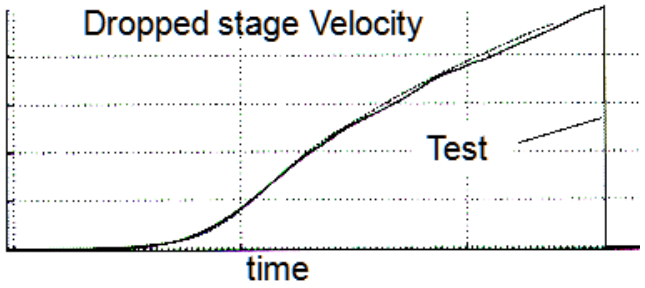
Pressure on the dropped stage



Pressure on the upper stage







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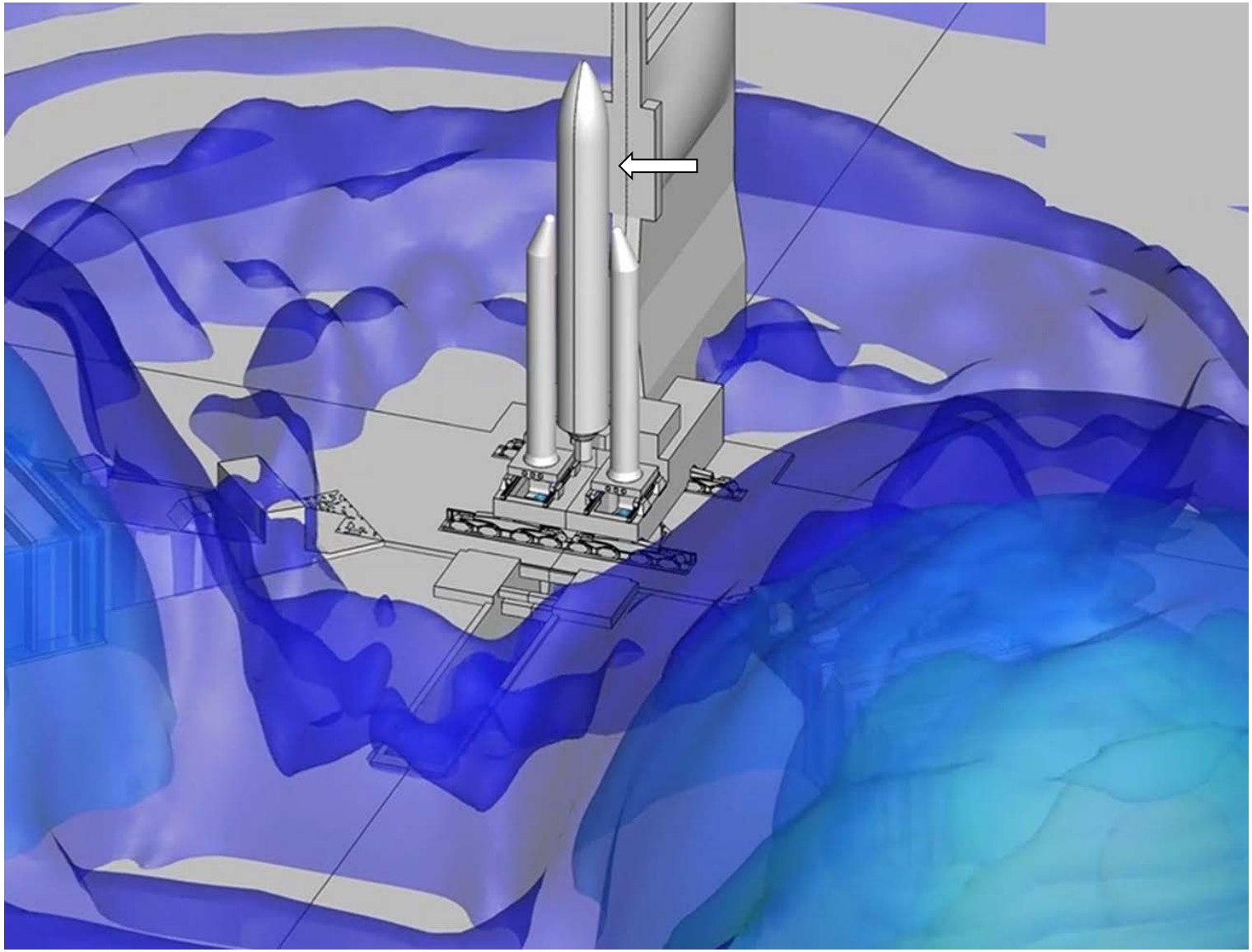
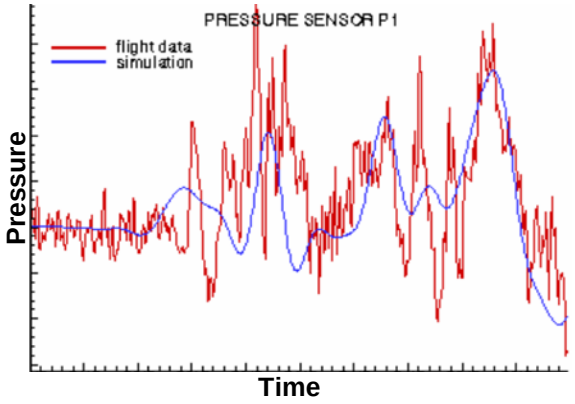
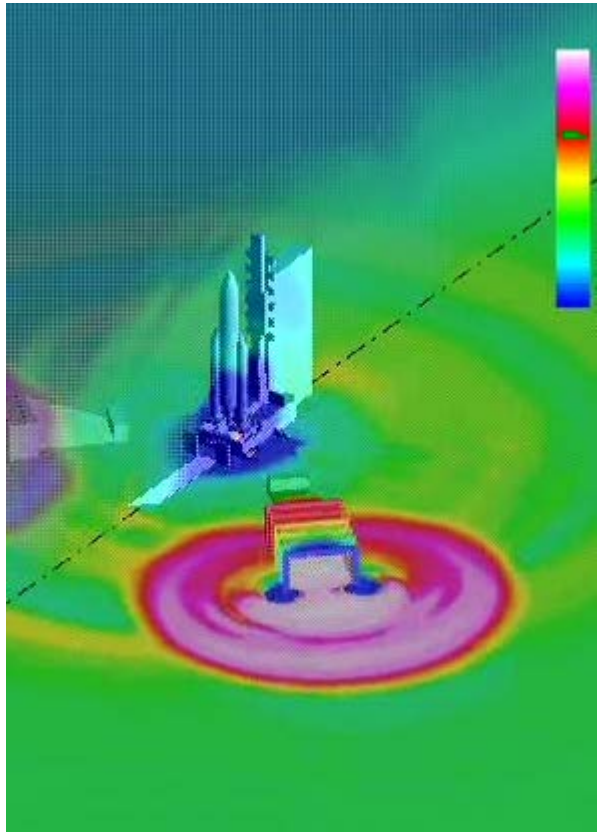
Validation of unsteady phenomena

2-Take-off – Blast-waves







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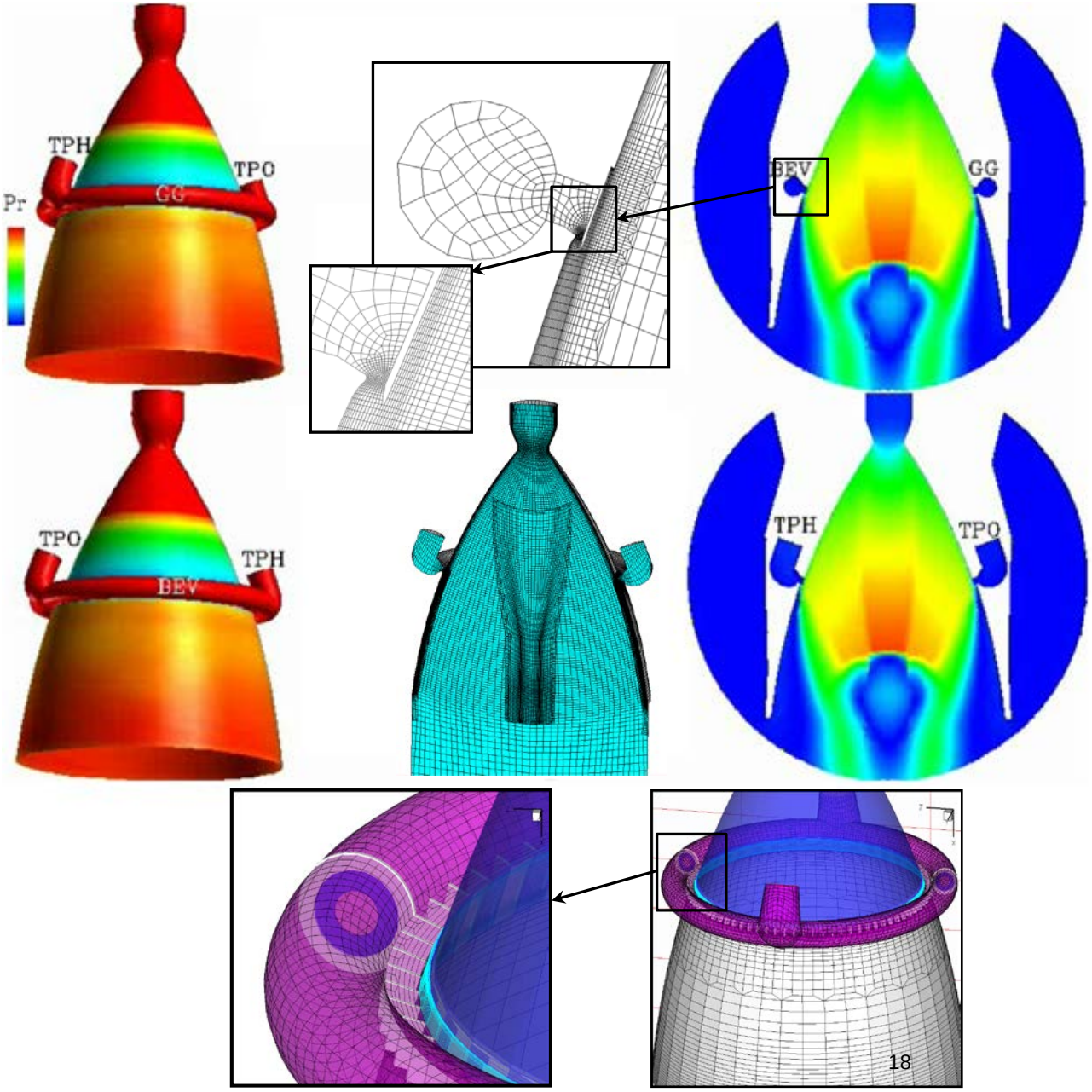
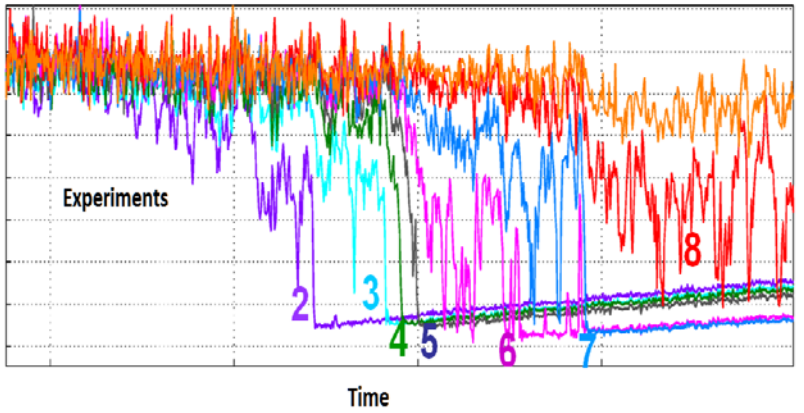
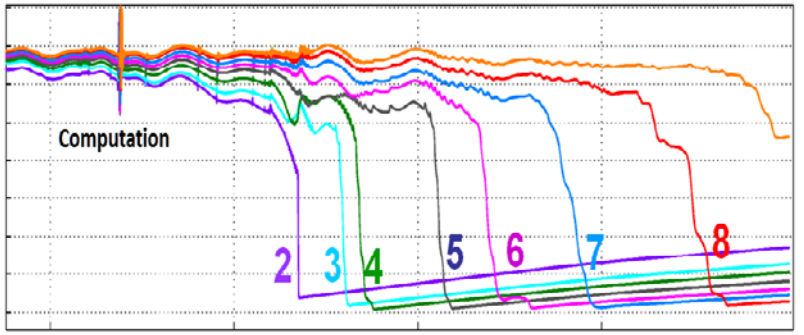
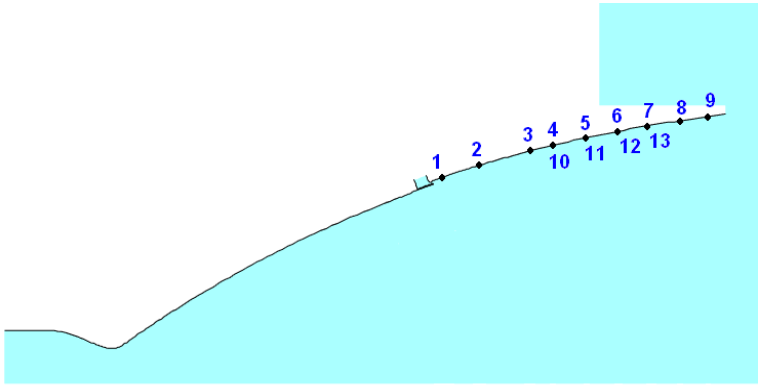
Validation of unsteady phenomena

2b-Engine ignitions









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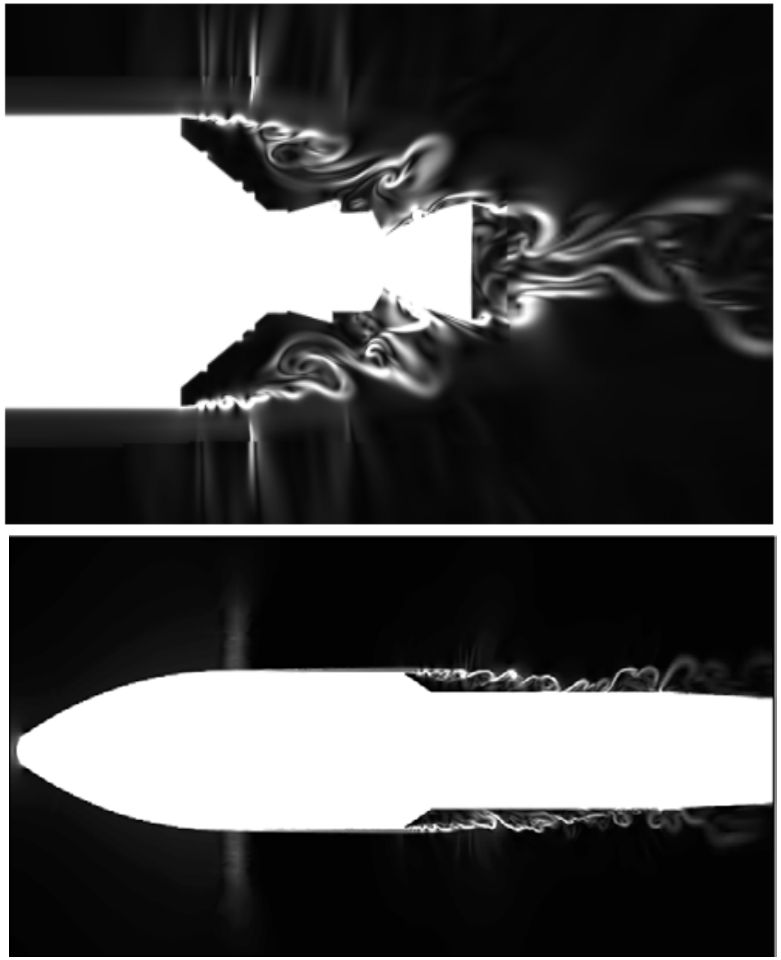
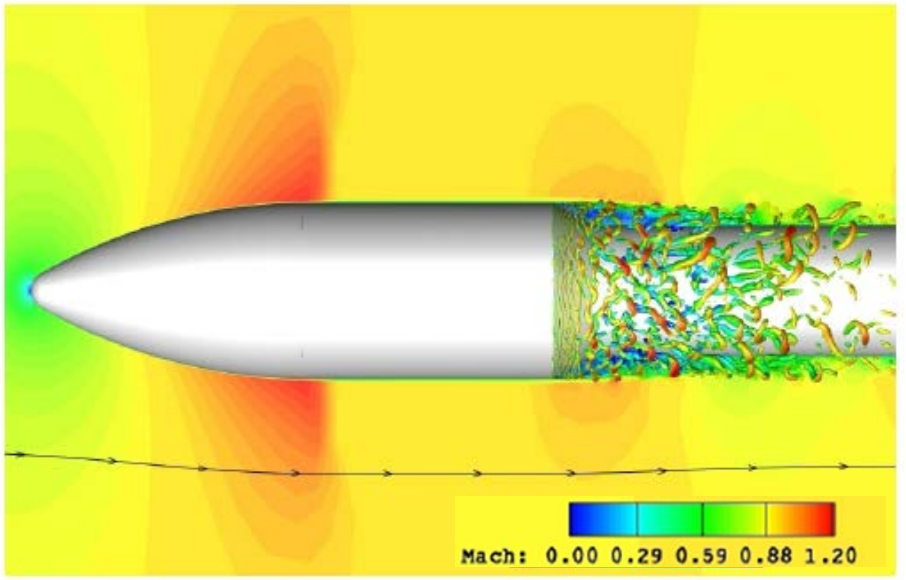
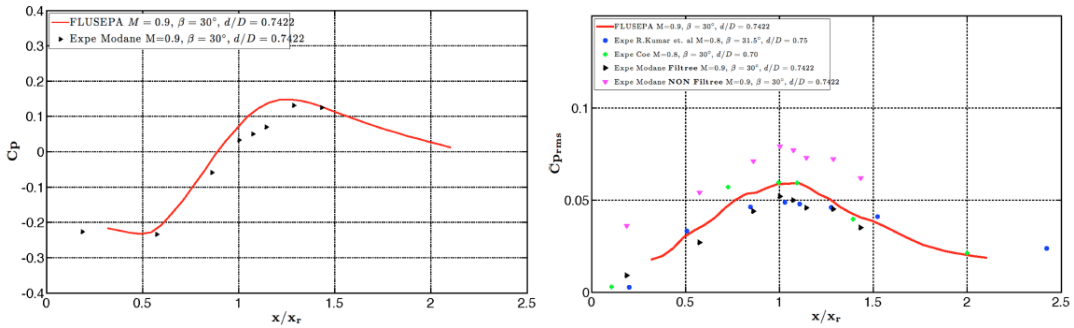
Validation of unsteady phenomena

4-Unsteady Eddy Simulations



A5 and A6 PPH VLES computations:
Instantaneous schlieren





A6 PPH : iso Q criterion colored by Mach Number(top) -
Comparison of Cp and Cprms with experiments (bottom)

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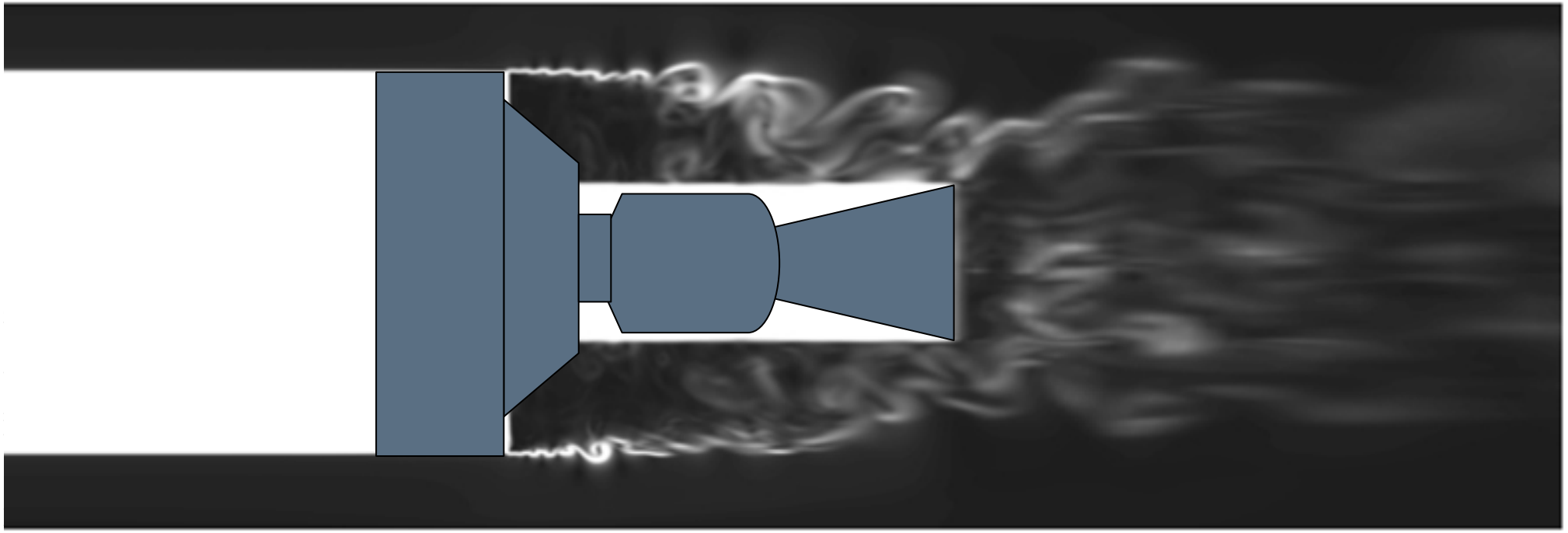
Validation of unsteady phenomena

4b-Unsteady Eddy Simulations (4 PhD+?)



Conclusions

Verification	**Implementation-(Algo-Num-Models)**
• **Sequential computing**	Achievable goal
• **Parallel computing**	Very Serious issues (no determinism)
• **Sustainability issues**	Software management (GIT non regression) Compilers – Libraries – Hardware
Industrial Validation (Certification)	**Small scale + flight measurements**
• **Steady configurations**	Fairly well controlled task
• **Unsteady simulations**	Painstaking work
• **Very Large Eddy simulations**	Tedious job
Outlook	
• **Automation**	Mesh & Model

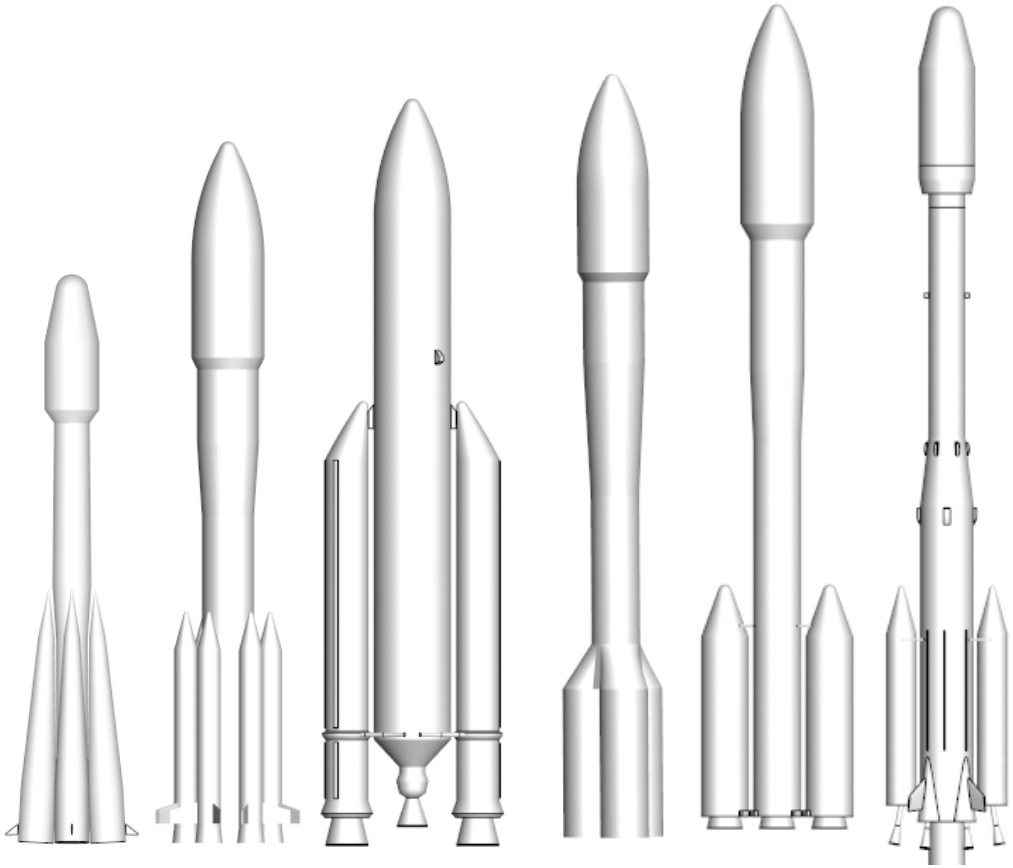
CASCADES Tool(1/3)

CASCADES designed to compute Aerodynamic database on nearly any kind of launcher.

Fully automatized :
- Auto building of hexahedral meshes
- Auto run of simulations
- Auto post-processing

Multi overlapping approach: complete launcher is made by merging of several (fully parameterised) elementary parts. No CAO needed in most of case.

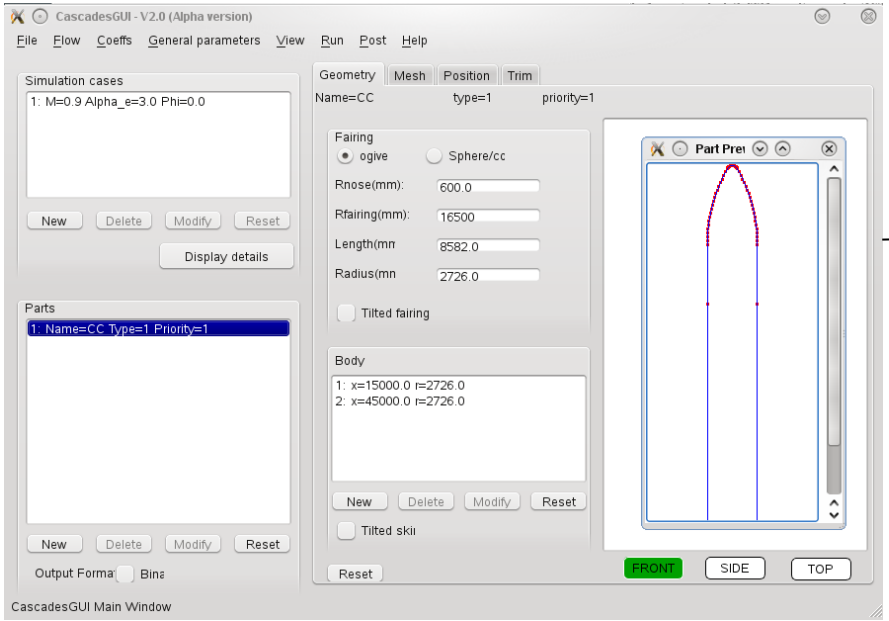
Very intensively used in Airbus DS : More than 100 different geometrical configurations since beginning 2013.

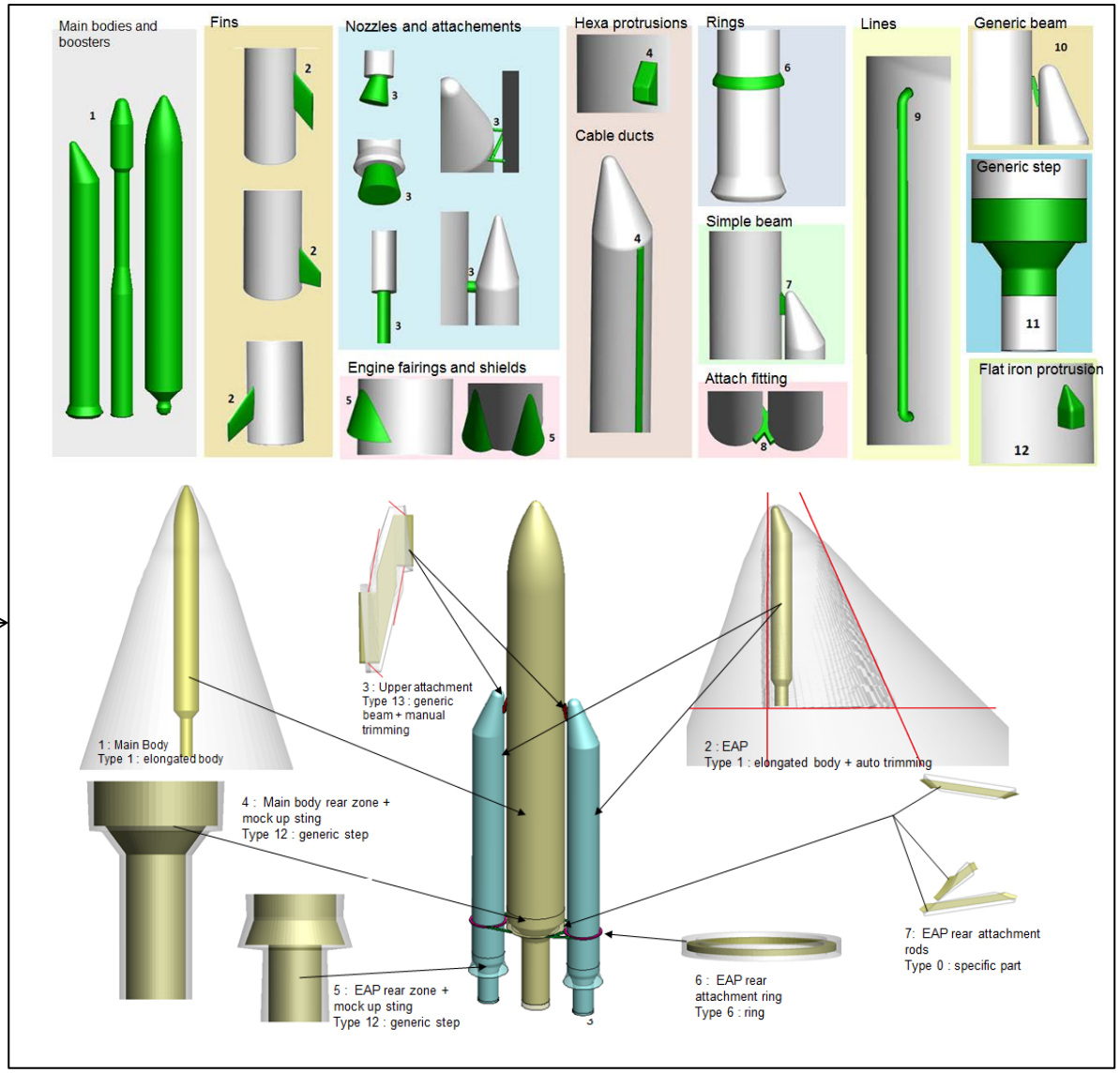


Examples of civil launchers modelled by CASCADES

CASCADES Tool(2/3)

CASCADES deals with a set of elementary parts. The user chooses how to build the launcher: which parts will be used and with what dimensions, positions and priority.
CASCADES makes automatically the volume meshes and the assembly.





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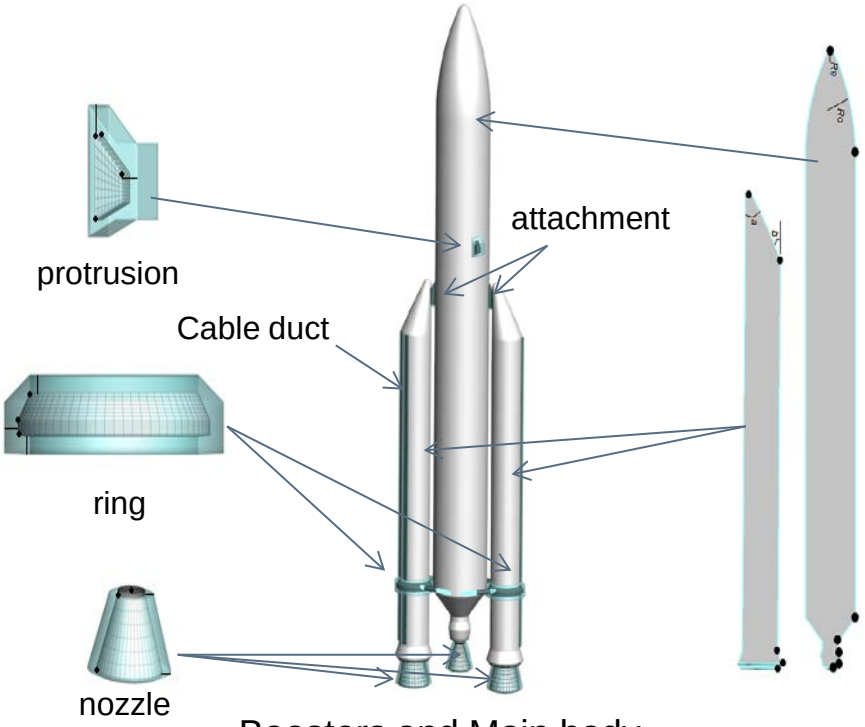
CASCADES Tool(2/3)

The meshes are built by multi-overlapping: the overall mesh is the addition of several simple submeshes.
No CAO files are needed.

CASCADES deals with a set of common elements. The user chooses which parts the launcher will be composed of and just gives the dimensions, number and positions. CASCADES makes automatically the volume meshes and the assembly.

Ex : simplified Ariane 5

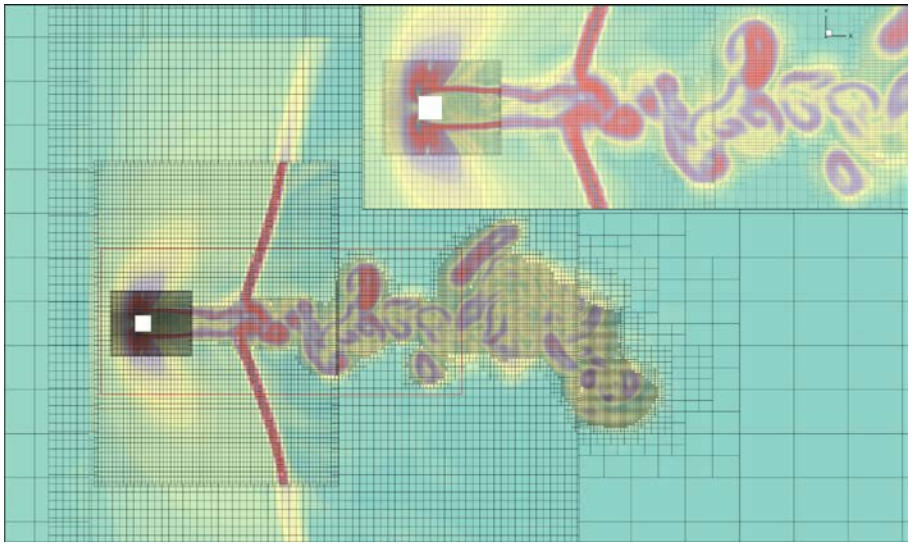


Boosters and Main body

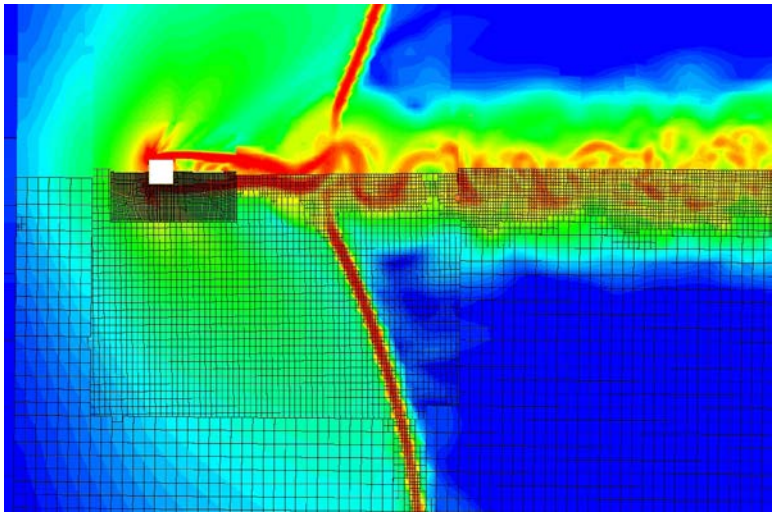
Outlook

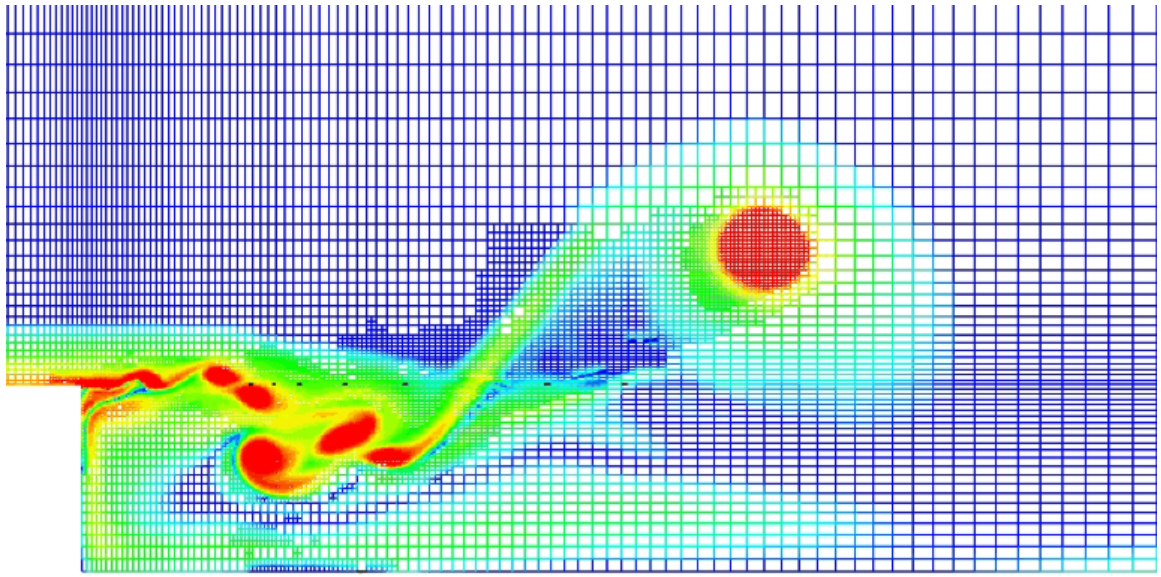
AMR

✓**Mesh refinement/coarsening**[28]



Octree (k-d tree)





Thank you
Any question?

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