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Micro-Physics and Modelling of Martian Dust Storms

Lorenzo Martinuzzo - 40th Cycle

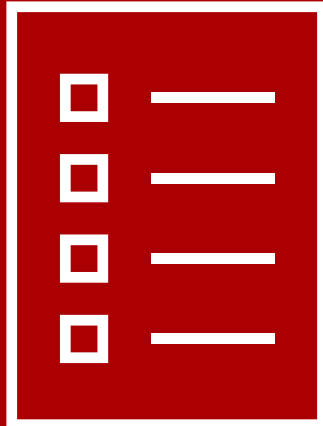
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Cosupervisor: Prof. Francesco Picano

Admission to the Second Year- 14/10/2025



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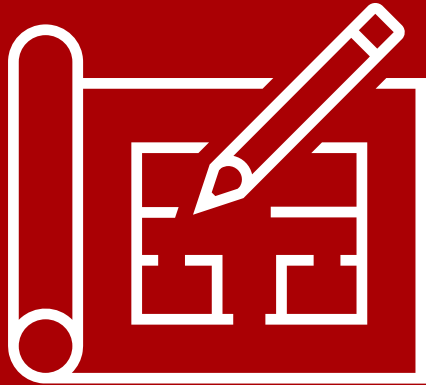


1. Introduction
2. Task 1: Particle-Resolved DNS
3. Task 2: Point-Particle DNS
4. Task 3: LES (Future Development)
5. Final Remarks





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1. Introduction

1.1. Project Motivations

1.2. Progress and Outlook

2. Task 1: Particle-Resolved DNS

2.1. Objectives

2.2. Implementation

2.3. Validation

2.4. Future Developments

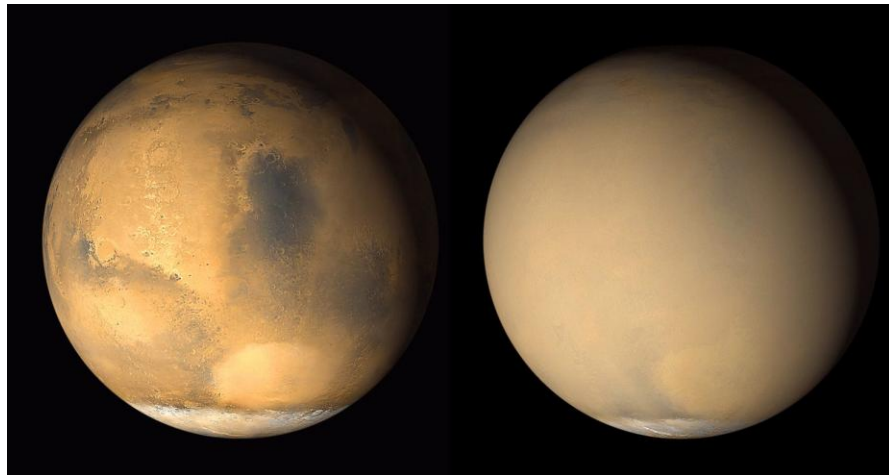


1.1. Project Motivations

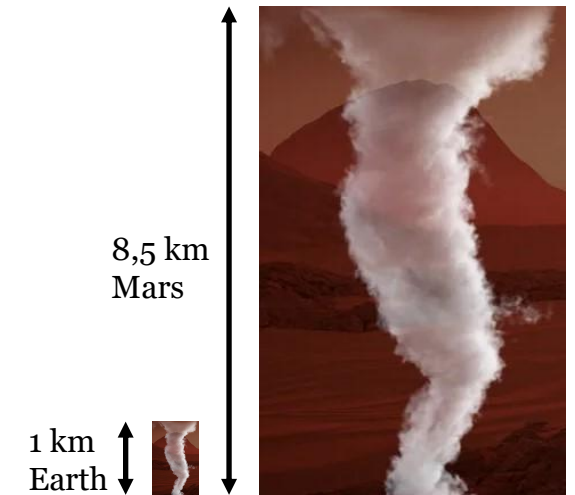
Recent years are showing an increasing interest in Martian exploration.

Dust storms can have a significant impact on both manned and unmanned missions on Mars, e.g.:

- Telecommunication attenuation;
- Solar radiation reduction on solar photovoltaic power systems.



NASA, Mars Global Surveyor, 2001



Dust Devils maximum observed height comparison between Earth and Mars.

Lift, suspension and sedimentation mechanisms require a detailed study of their micro-physics from a **computational** point of view, considering analogies and differences with respect to the Earth atmosphere



Particle-Resolved DNS

- ✓ Integration of IBM in a fluid solver with GPU;
- ✓ Validation of the implementation against literature data;
- Implementation of particle motion and collision (Y2);
- Analysis of the dataset and implementation of an *a priori* lift model (Y2).

Point-Particle DNS

- ✓ Implementation of the Point-Particle solver with GPU;
- ✓ Validation of the implementation through comparison with CPU;
- ✓ Simulations with gravity effects and thermal effects;
- Validation of the lift model through *a posteriori* simulations (Y2).

Large Eddy Simulations

- LES framework implementation for particle laden flows (Y2);
- LES simulation with models as further validation (Y3);
- LES with larger domains and more characteristic scenarios (Y3).



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3. Task 2: Point-Particle DNS

3.1. Objectives

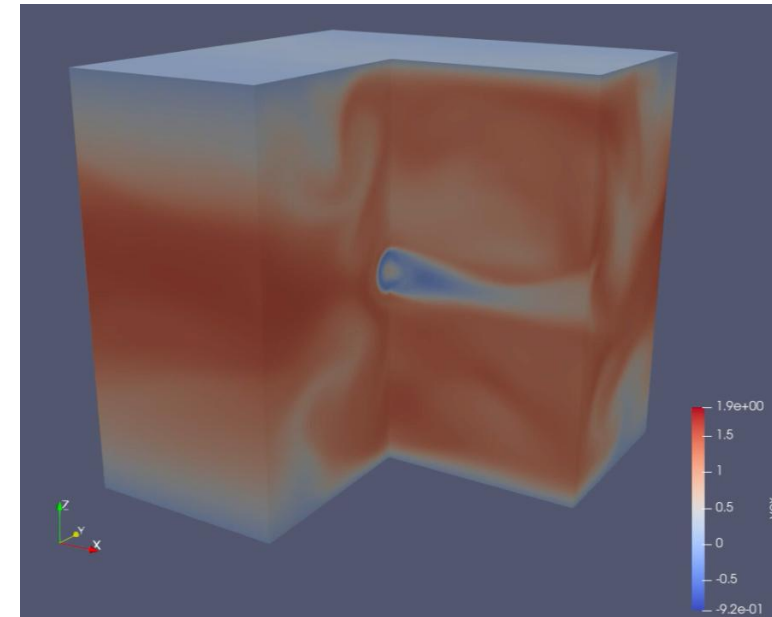
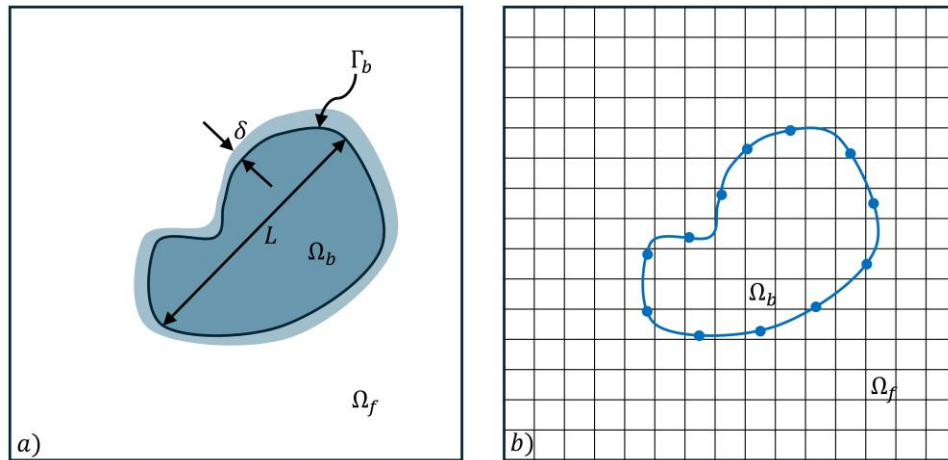
3.2. Implementation

3.3. Validation and Preliminary Results

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First task: high resolution Particle Resolved simulations of particle laden flows.



Objectives:

- Integration of the **particle solver** in a state-of-the-art flow solver;
- Analysis of the **micro-physics** of particle flow interaction;
- Development of a **lift model** for particles.

Numerical methods:

- High resolution **DNS** (Kolmogorov scale) for the flow phase;
- Flow-particle interface resolved with **IBM**;
- Newton-Euler equations integration for **particle motion**.



The flow solver is CaNS (Costa; CMA 2018):

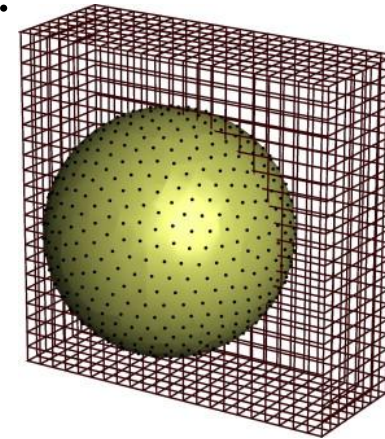
- Open source **DNS** numerical solver for incompressible, Newtonian flows;
- Massively-parallelized for multi **CPU and GPU**.

Navier-Stokes
equations in
conservative
form

$$\begin{cases} \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \\ \frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot \boldsymbol{\sigma} + \rho \mathbf{f} \end{cases} \quad \boldsymbol{\sigma} = \mu(\nabla \mathbf{u} + \nabla \mathbf{u}^T) - \frac{2}{3} \mu \nabla \cdot \mathbf{u} \mathbf{I}$$

Particle interface is resolved through a **multi direct forcing** Immersed-Boundary-Method (Breguem, JCP 2012) based on velocity interpolation on the particle **Lagrangian grid** over the particle surface and force spreading on the flow **Eulerian grid**:

$$\begin{aligned}
 \mathbf{U}_l^* &= \sum_{ijk} \mathbf{u}_{ijk}^* \delta_d(\mathbf{x}_{ijk} - \mathbf{X}_l^n) \Delta x \Delta y \Delta z \\
 \mathbf{F}_l^{n+\frac{1}{2}} &= \frac{\mathbf{U}_p(\mathbf{X}_l^n) - \mathbf{U}_l^*}{\Delta t} \\
 \mathbf{f}_{ijk}^{n+\frac{1}{2}} &= \sum_l \mathbf{F}_l^{n+\frac{1}{2}} \delta_d(\mathbf{x}_{ijk} - \mathbf{X}_l^n) \Delta V_l
 \end{aligned}$$



W.P. Breugem, 2012

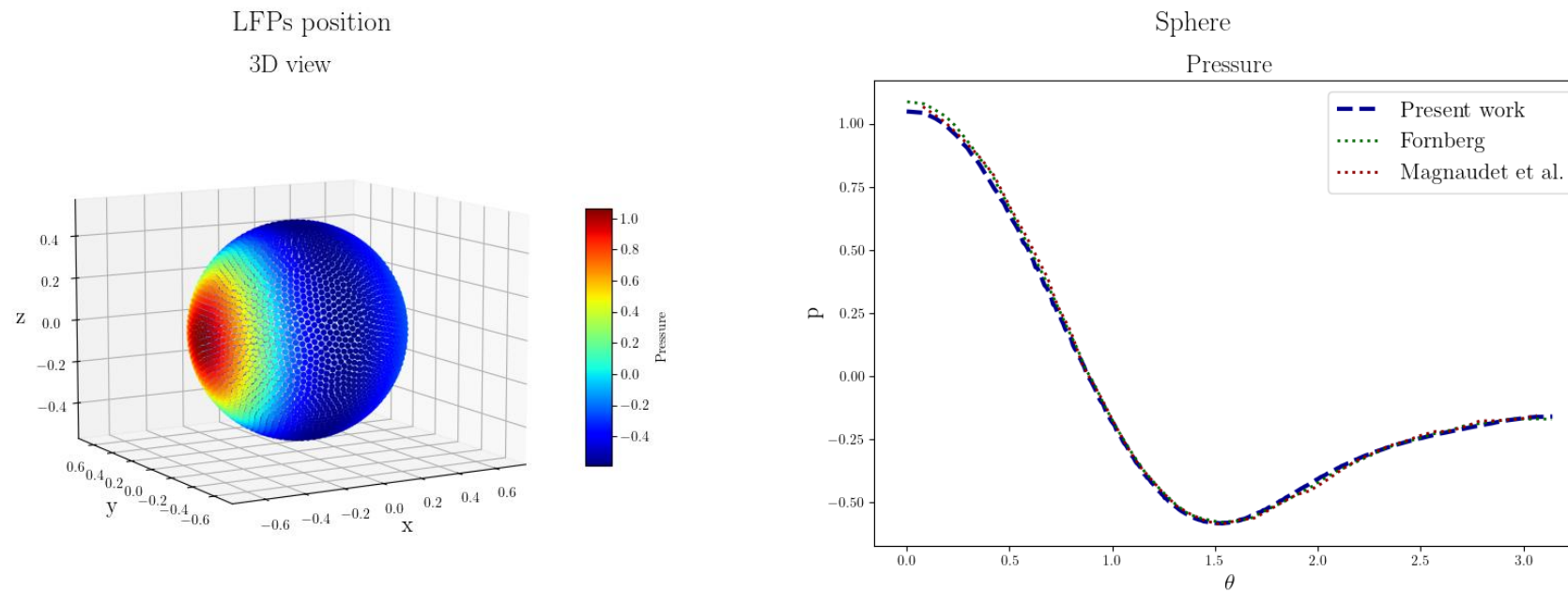
Particle motion is evolved through integration of **Newton-Euler equations**:

$$\begin{cases}
 \rho_p V_p \frac{d\mathbf{u}_c}{dt} = \oint_{\partial V} \boldsymbol{\tau} \cdot \mathbf{n} dA + (\rho_p - \rho_f) V_p \mathbf{g} + \mathbf{F}_c \\
 I_p \frac{d\boldsymbol{\omega}_c}{dt} = \oint_{\partial V} \mathbf{r} (\boldsymbol{\tau} \cdot \mathbf{n}) dA + \mathbf{T}_c
 \end{cases}$$

$$\boldsymbol{\tau} = -p\mathbf{I} + \mu(\nabla\mathbf{u} + \nabla\mathbf{u}^T)$$

We integrated the IBM method in the flow solver, taking into account GPU porting and performance.

The code was validated by simulating a uniform flow over a fixed **sphere**, and also GPU porting has been verified.



The **next steps** about the Particle Resolved simulations are:

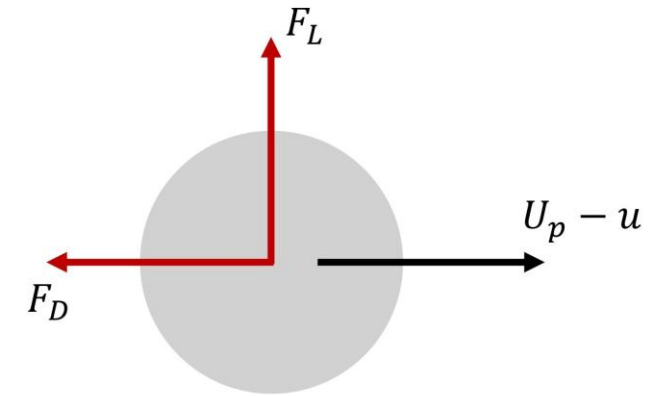
- Completing the integration of Particle motion;
- Running simulations;
- Development of a Lift Model.

Drag Models:

- Resistance force opposing to particle relative motion;
- Parallel and opposite to particle-flow relative velocity;
- Mainly function of Re_p and density ratio.

Lift Models:

- Transverse force deflecting particle trajectory;
- Perpendicular to particle-flow relative velocity;
- Mainly function of local flow vorticity and particle flow slip velocity.





2. Task 1: Particle-Resolved DNS

2.1. Objectives

2.2. Implementation

2.3. Validation

2.4. Future Developments

3. Task 2: Point-Particle DNS

3.1. Objectives

3.2. Implementation

3.3. Validation and Preliminary Results

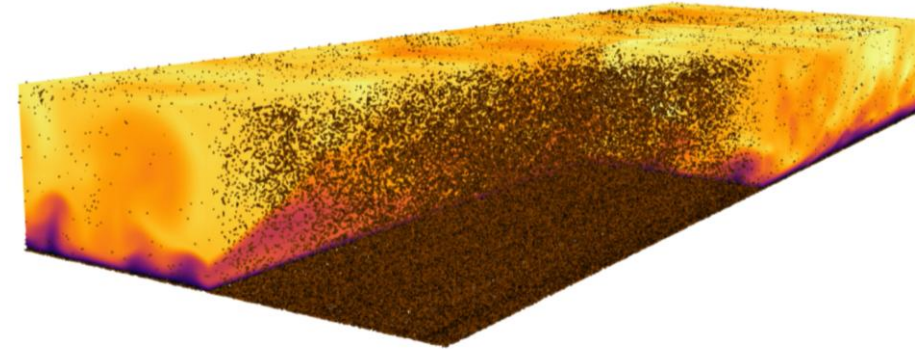
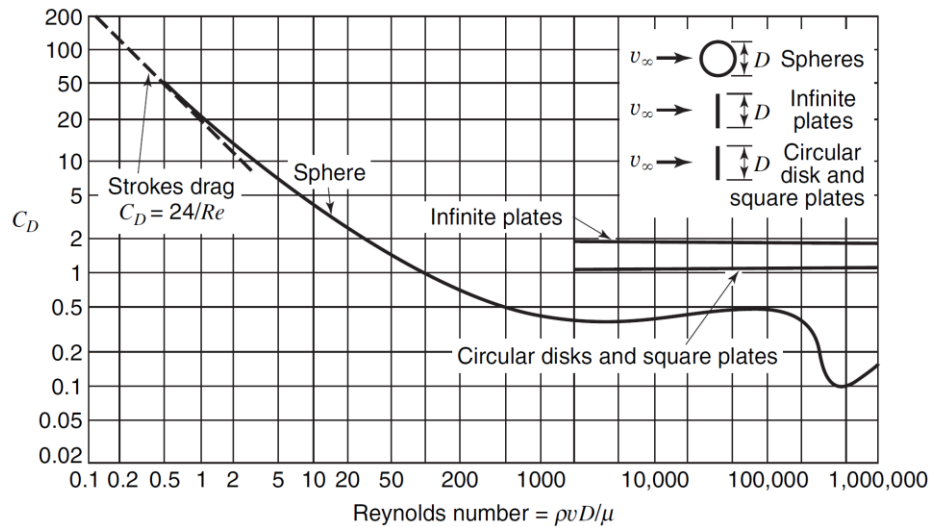
3.4. Future Developments

4. Task 3: LES (Future Development)

4.1. Objectives and Methodology



Second task: Point-Particle simulations of particle laden flows.



Objectives:

- Implementation of the point-particle solver in a state-of-the-art flow solver and GPU porting;
- Analysis of particle behaviour at larger scales;
- *A posteriori* validation of the lift model derived from PR-DNS.

The flow solver is the same used for Particle Resolved simulations on task 1.

Then, **particle equations** of motion are solved assuming a point mass, spherical particle and one-way coupling:

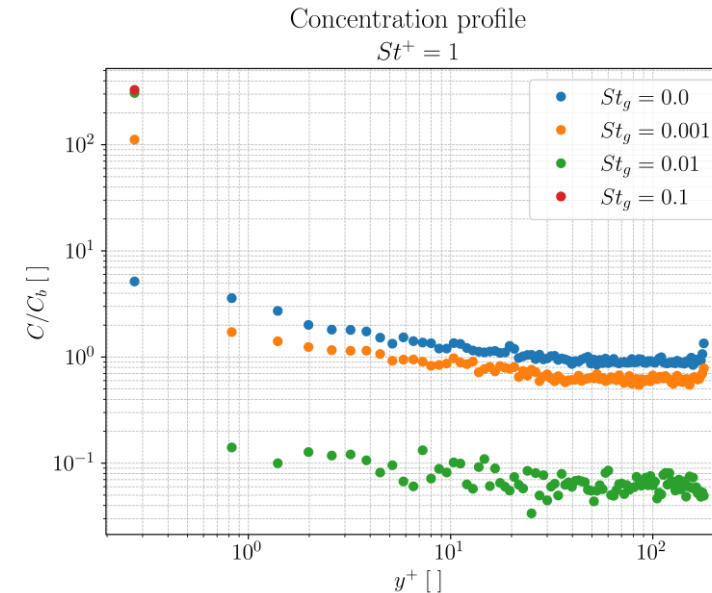
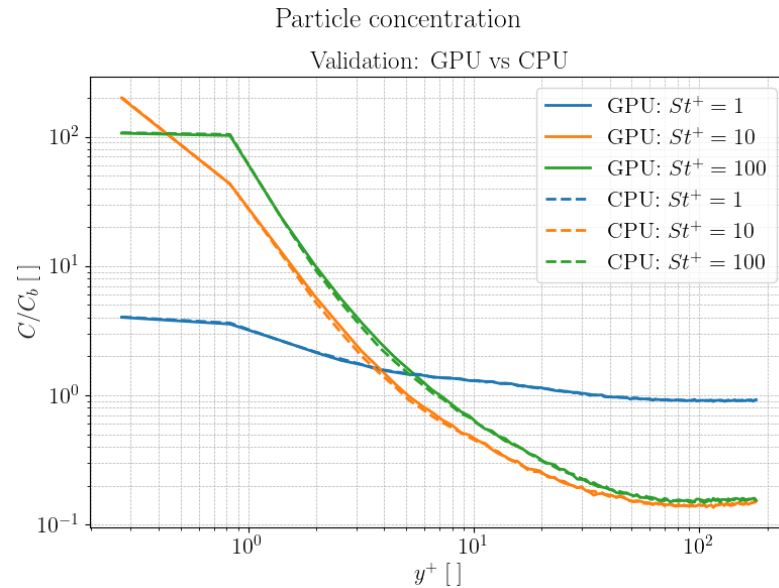
Particle equations:

$$\begin{cases} \frac{d\vec{U}_P}{dt} = (1 + 0,15Re_P^{0,687}) \frac{\vec{U} - \vec{U}_P}{\tau_P} + \vec{g} \\ \frac{d\vec{x}_P}{dt} = \vec{U}_P \end{cases}$$

So far, only a **drag model** has been considered, that is the first term of the right-hand side. It is the Schiller-Naumann (1933) model:

$$C_D = \frac{24}{Re_p} (1 + 0,15Re_p^{0,687})$$

The GPU implementation has been **validated** through comparison with the results obtained by the already validated CPU version of the code.



We also performed some preliminary simulations considering different particle sizes and gravity forces, which confirmed the **need for a lift model**.

The **next steps** about the Point-Particle simulations are:

- Implementing a state-of-the-art lift model in the code and analysing the results;
- Running simulations with the model obtained by the Particle resolved simulations;
- Simulation under unstable convection.

One of the most accurate lift model is the one proposed by Saffman (1965), which however can't predict correctly the near wall region:

$$F_L = 1,615J\mu|\omega|D^2 \sqrt{\frac{D^2|\omega|}{\nu} \frac{\omega \times U_s}{|\omega||U_s|}}$$



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3. Task 2: Point-Particle DNS

3.1. Objectives

3.2. Implementation

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4. Task 3: LES (Future Development)

4.1. Objectives and Methodology

5. Final Remarks



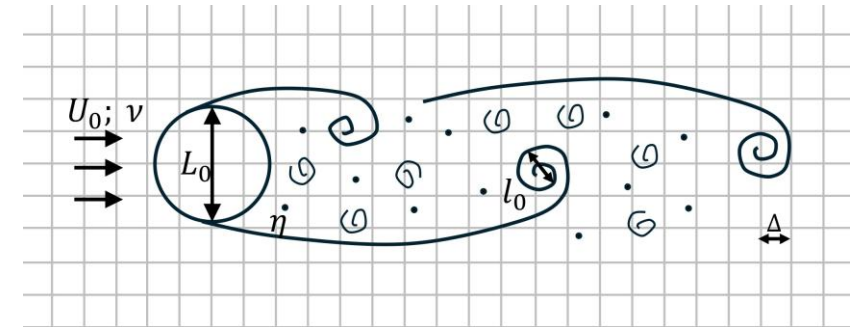
Third task: Large Eddy Simulations of particle laden flows.

Objectives:

- Simulation of **larger scales** of the Martian atmosphere;
- Simulation with realistic ground **morphology**.

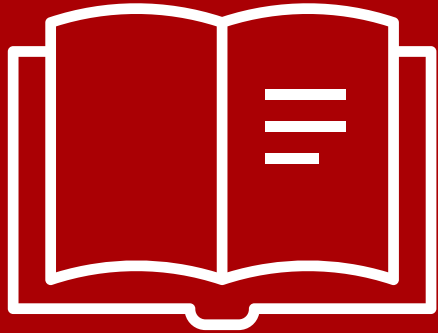
Methodology:

- Large Eddy Simulations \Rightarrow **lower computational cost** by modelling of smallest turbulent scale;
- IBM \Rightarrow modelling of **complex geometries**;
- Point Particle models \Rightarrow particle motion under flow effects.





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4. Task 3: LES (Future Development)
4.1. Objectives and Methodology

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5. Final Remarks

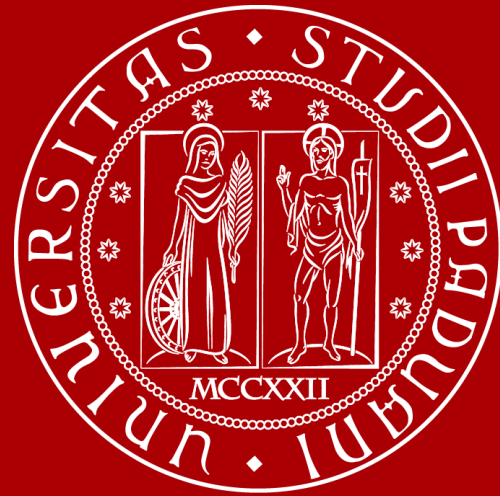


- The first year of the PhD program was mainly devoted to becoming familiar with Multi CPU and GPU programming and setting up of the numerical framework;
- The Particle-Resolved framework is completed for the IBM part and is going to be completed for Newton Euler equations integration;
- The Point-Particle framework is ready for GPU executions;
- Some preliminary simulations with Point Particle confirmed the need of a Lift model for particle motion;
- In the coming months PR simulation will be performed to create a database for definition of *a priori* lift model;
- In the meanwhile some PP simulations with state-of-the-art lift models will be performed, then validating *a posteriori* the proposed model;
- Later, LES will be employed to study more realistic configurations with reasonable computational cost.

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Thanks for the attention



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