Some Applications of Computational Fluid Dynamics to Entry and Landing of the Mars Science Laboratory

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Aerospace and Ocean Engineering Seminar

February 9, 2015

Outline

- Mars Science Laboratory (MSL) mission profile
- Computational Method
- Capsule flows*
  - Database calculations
  - Mass jettison
- Descent and landing
  - Parachute canister mortar launch
  - Rocket plumes with plume-plume interaction
  - Rocket plumes in proximity to the ground
- Conclusions

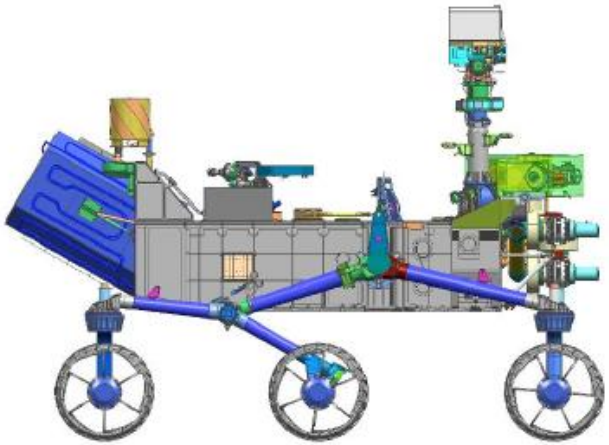
* Reference: M. Schoenenberger, A. Dyakonov, P. Buning, W. Scallion, and J. Van Norman, "Aerodynamic Challenges for the Mars Science Laboratory Entry, Descent and Landing," AIAA-2009-3914, June 2009.

MSL Mission Profile

- Mission characteristics
  - Goal: “Explore and quantitatively assess a local region on Mars as a potential habitat for life, past or present”*
  - Cost: $1.7B
- Curiosity rover characteristics
  - Mass: 900 kg (MER Spirit & Opportunity were 170 kg)
  - Range: 20 km+ (MER spec was 600 m)
  - Duration: 2 yr (MER spec was 3 mo)
- Mission dates
  - Launch: November 26, 2011
  - Landing: August 6, 2012

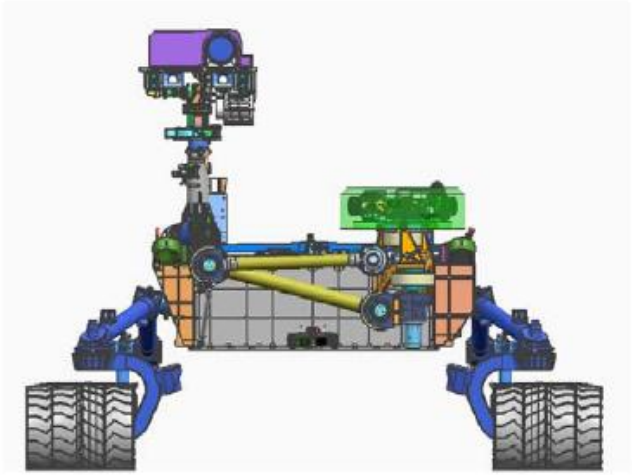
*Mission goal and following slides from “NASA's Next Rover: The 2009 Mars Science Laboratory,” a presentation by Dr. Alberto Behar (JPL), International Forum “SPACE: Science and the Challenges of the XXI Century,” Oct. 1-5, 2007, Moscow – St. Petersburg. http://arc.iki.rssi.ru/oct4/2007/ppt/02_07_Alberto_Behar.pdf

Size Comparison



JPL 2009 MSL Rover

2005 MINI Cooper S



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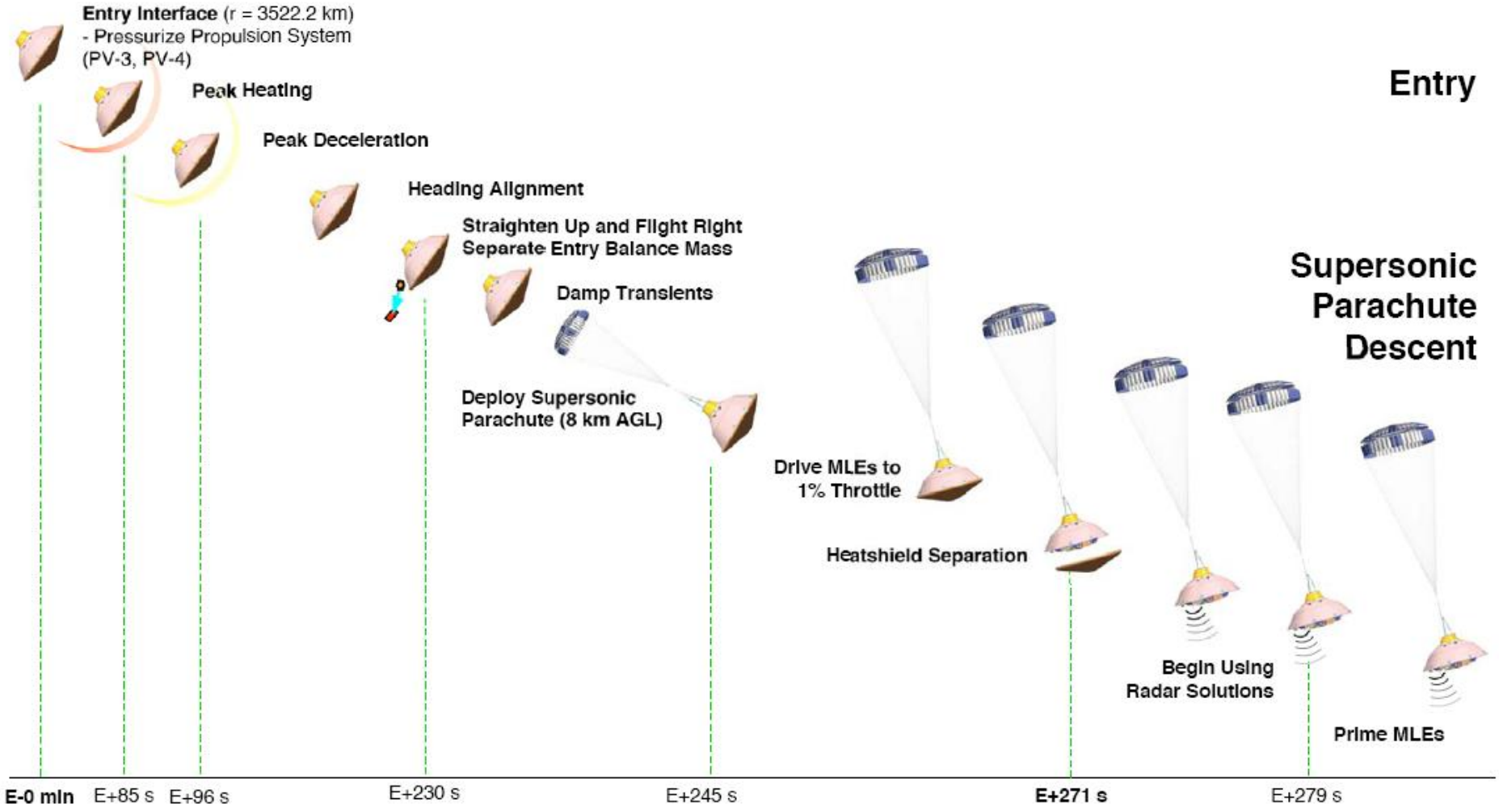
EDL Timeline (1 of 2)



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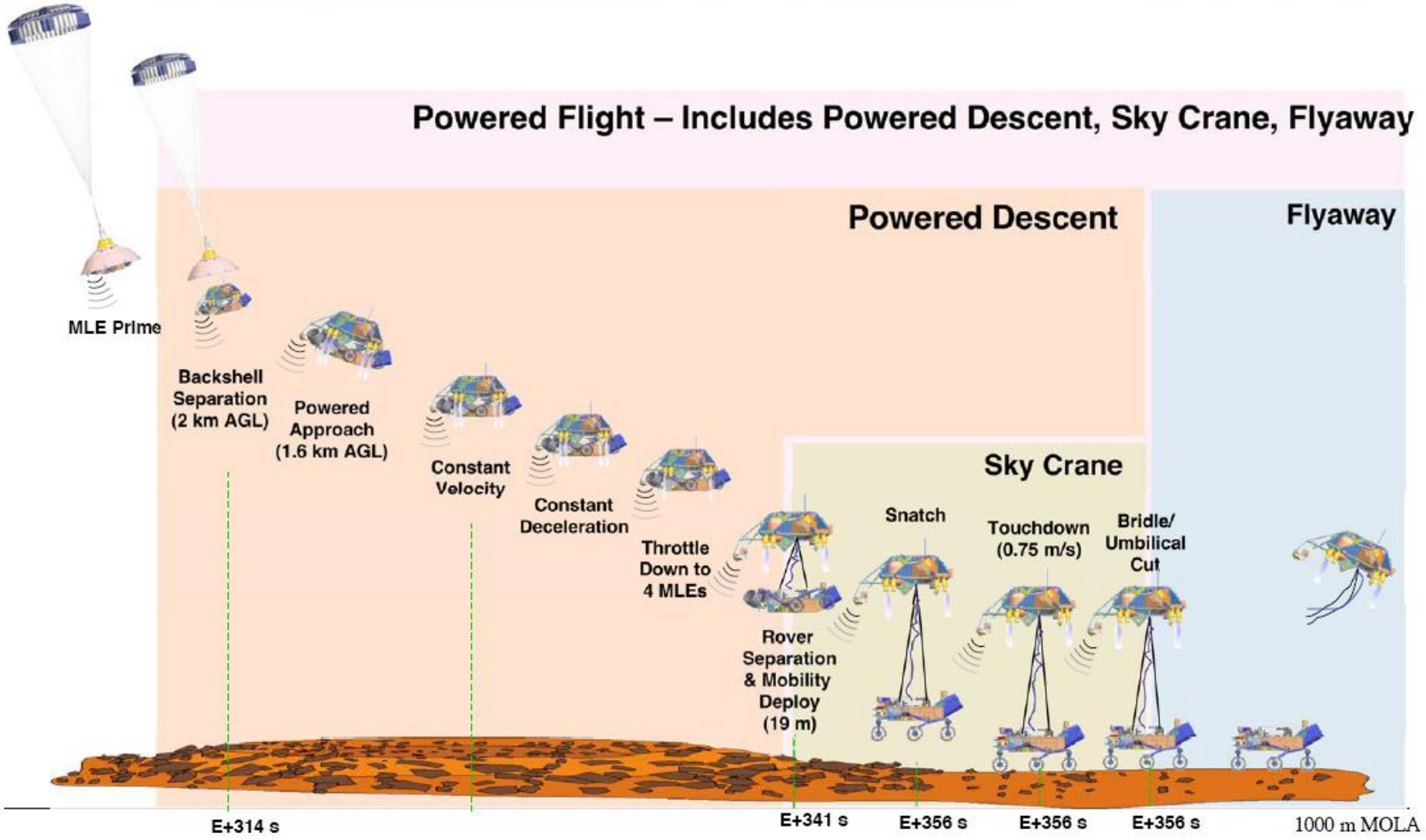
EDL Timeline (2 of 2)



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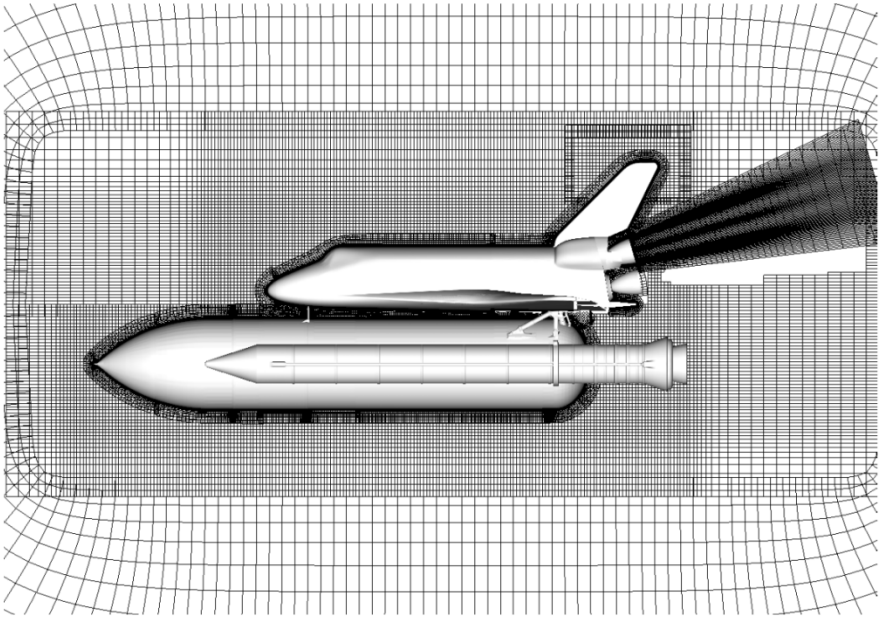
Computational Method: OVERFLOW Code

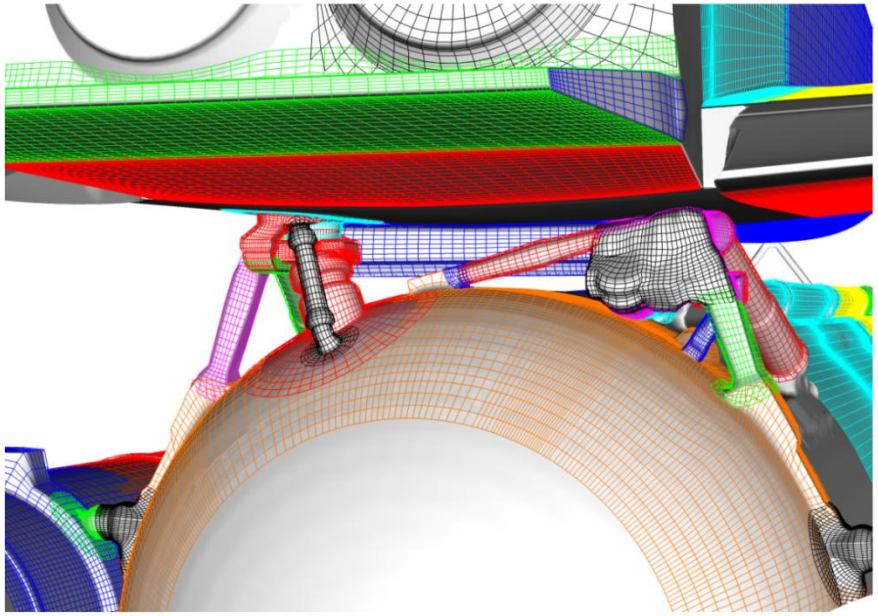
- NASA-developed CFD code
  - Reynolds-averaged Navier-Stokes solver
  - Compressible flow (subsonic through supersonic)
- Overset, structured “Chimera” grids (Steger, Benek, Dougherty)
- Developed for multi-body and moving body simulations

Domain Decomposition of Volume



The Grid Guys 1993 AIAA-93-0533

Surface Grid Topology of Aft Attach Region



The Grid Guys 1993 AIAA-93-0533

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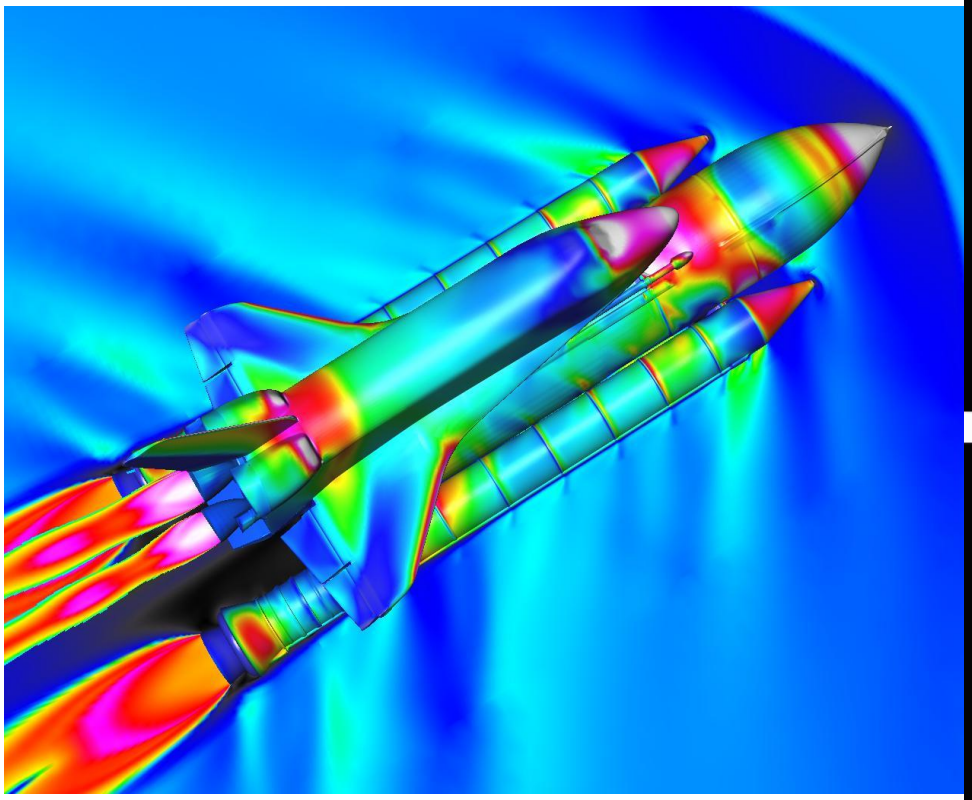
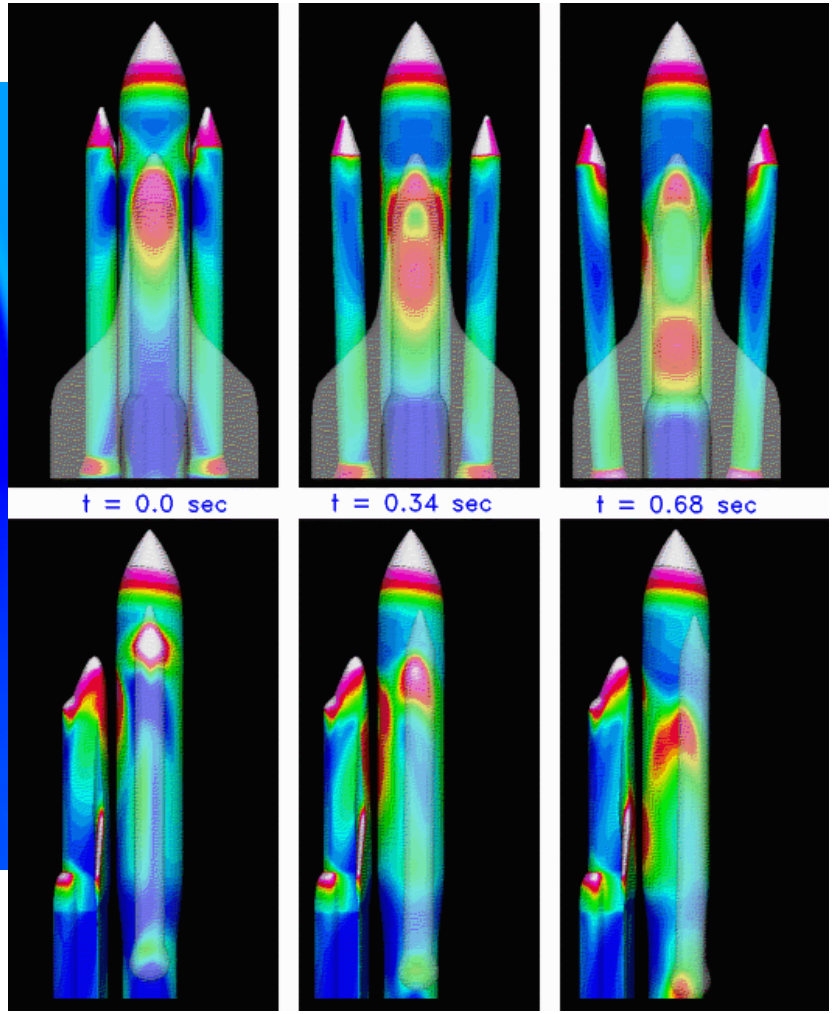
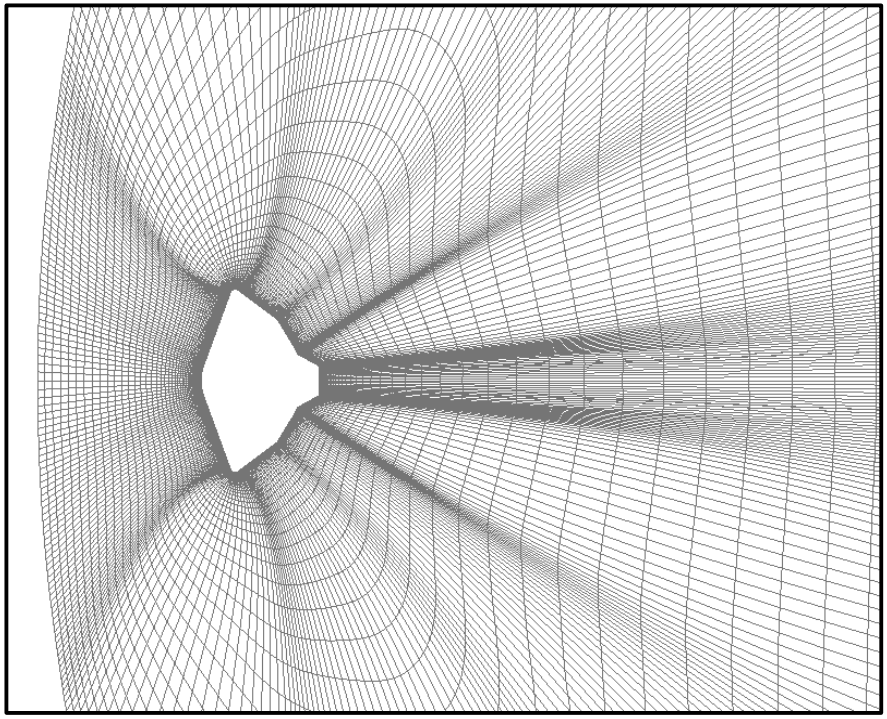




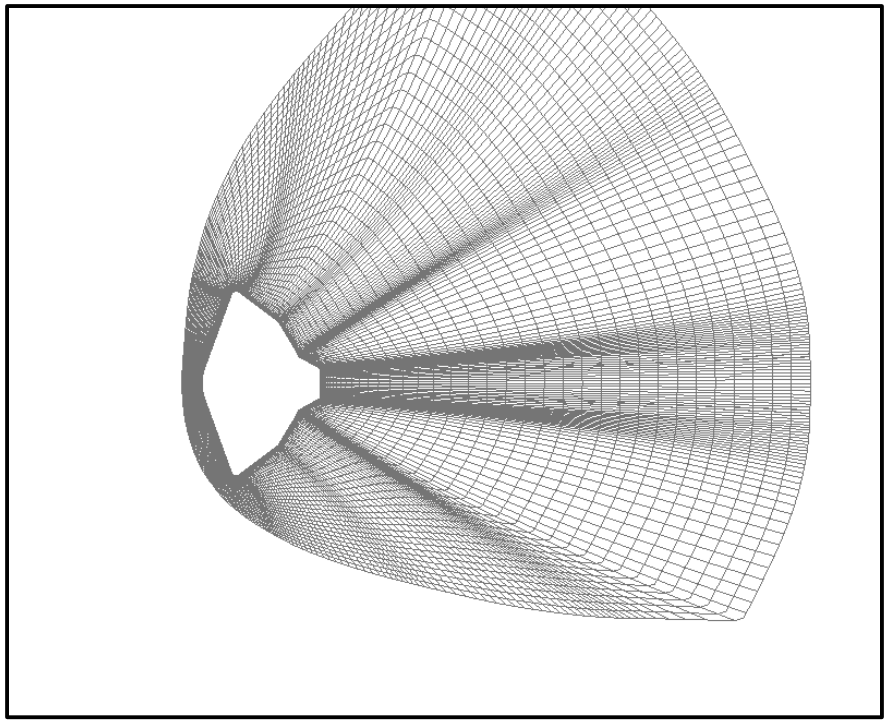
Supersonic Aero Database Calculations

- Database calculations
  - Mach 2-6, alpha 0-24 deg
  - LAURA grid (unadapted)
- Design issues:
  - Backshell pressure contribution to drag
  - Trim angle (pitching moment)
- Solver issues:
  - Effect of grid adaption on bow shock capturing
  - Grid adaption effect on convergence

LAURA Capsule Grids for MSL

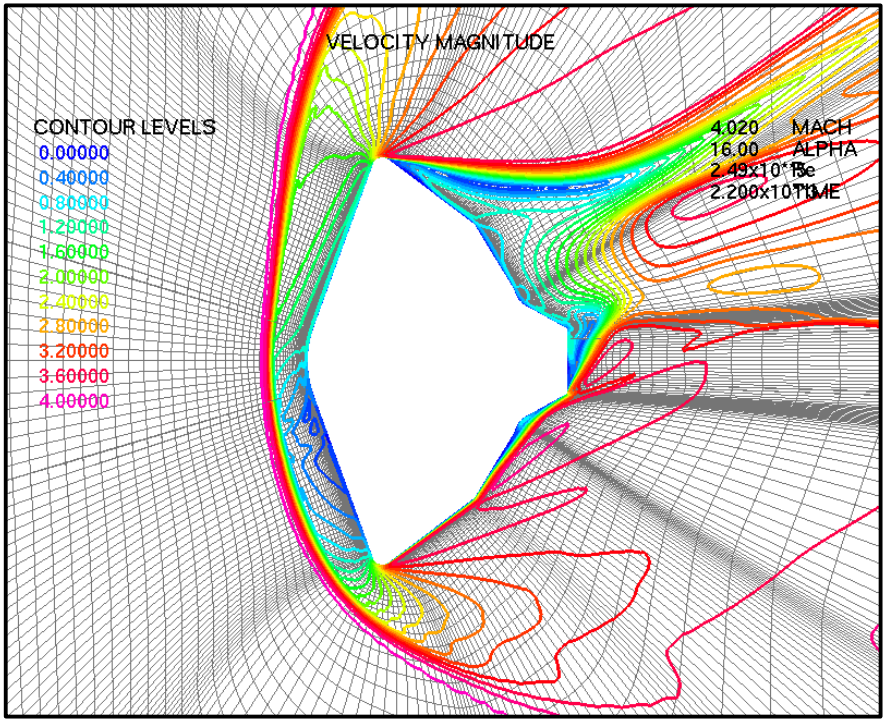


Unadapted

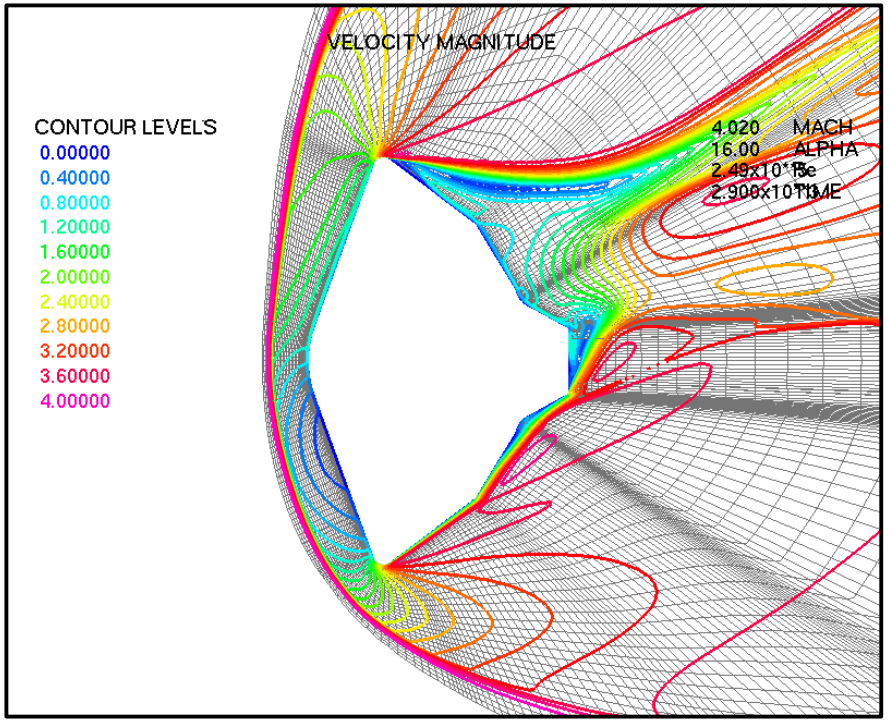


Adapted to bow shock
Mach 4, alpha 16 deg

Major flow-field features are identical, forces are close

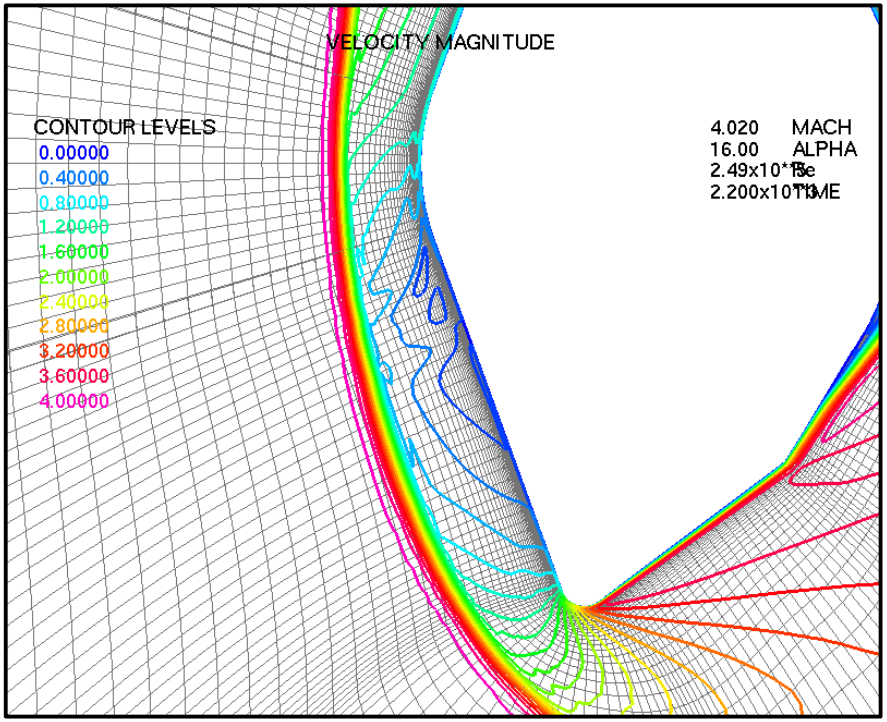


Unadapted

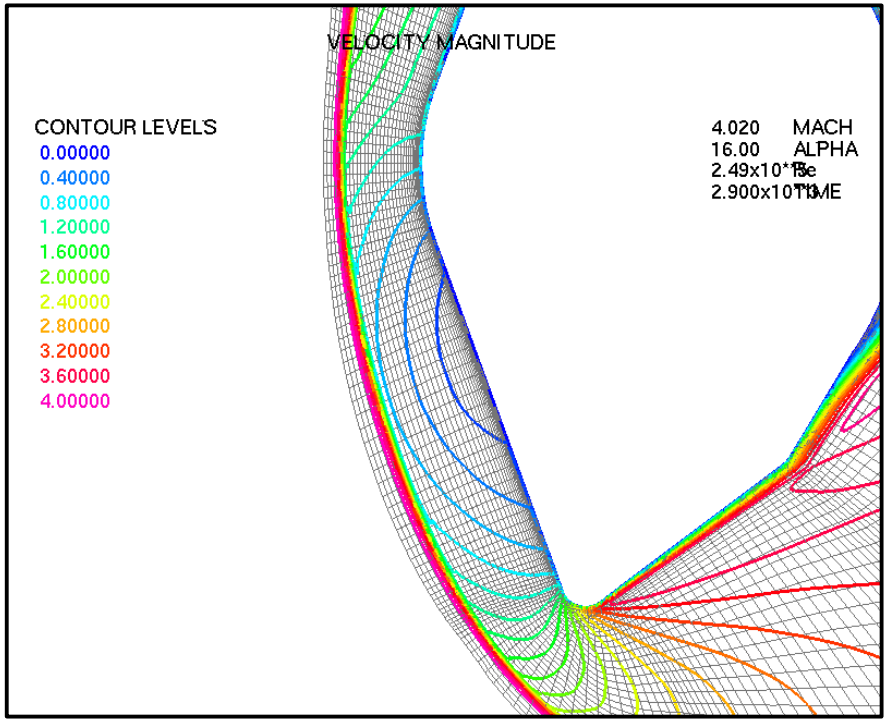


Adapted to bow shock
Mach 4, alpha 16 deg

Much better resolution of post-shock flow



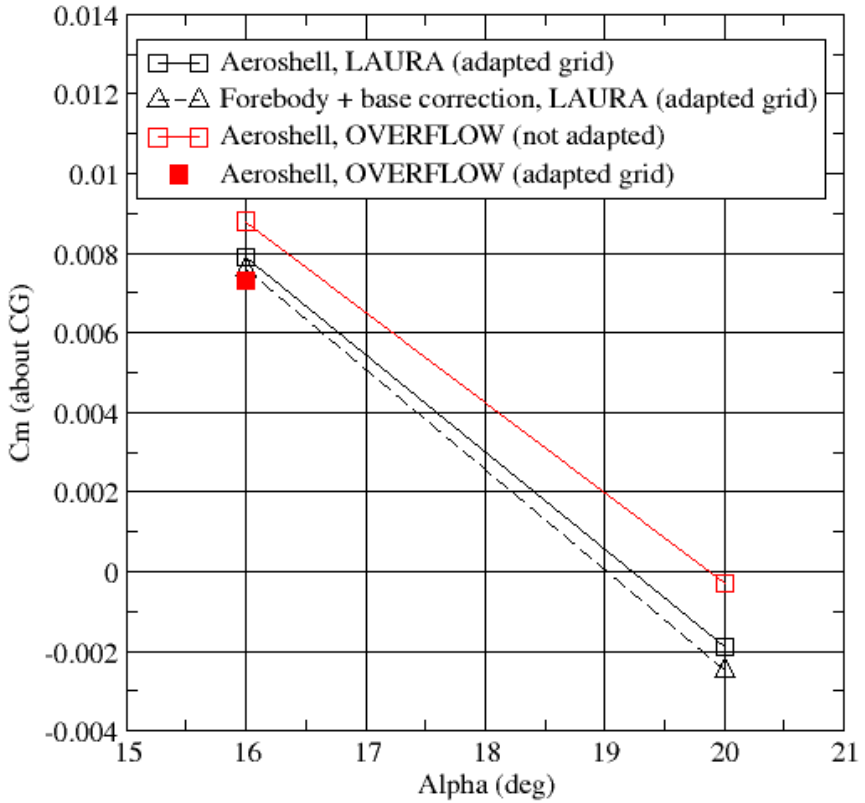
Unadapted

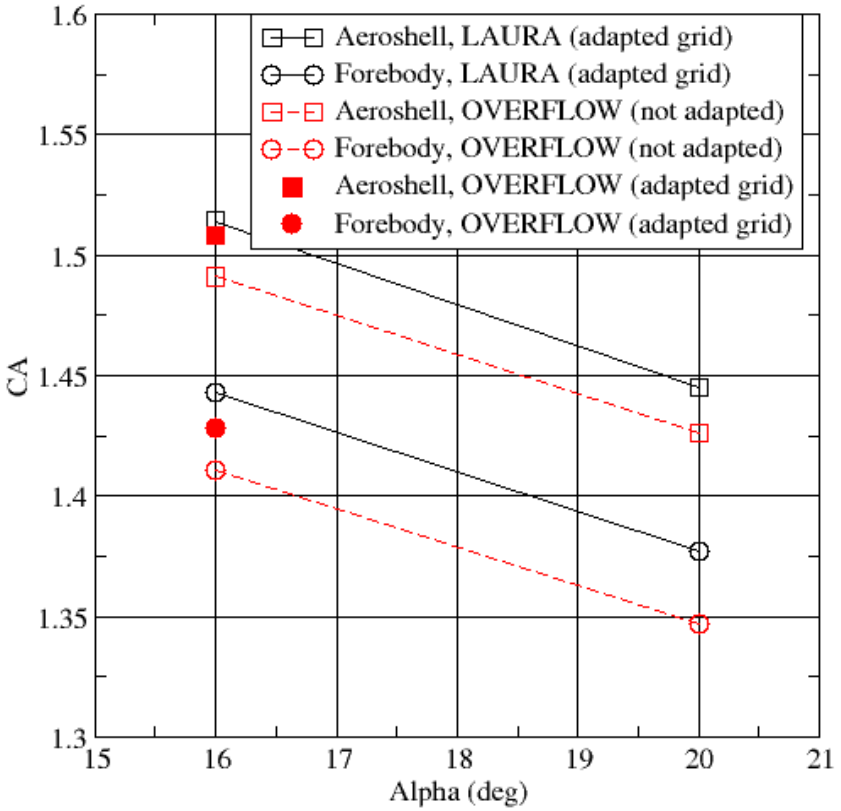


Adapted to bow shock
Mach 4, alpha 16 deg

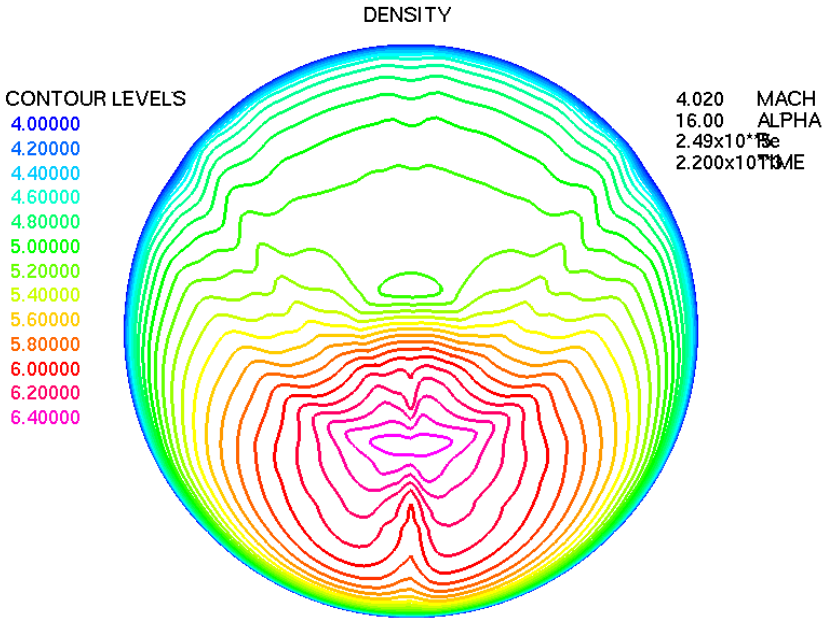
Supersonic Aero Database Calculations

Mach 4, alpha=16 and 20 deg

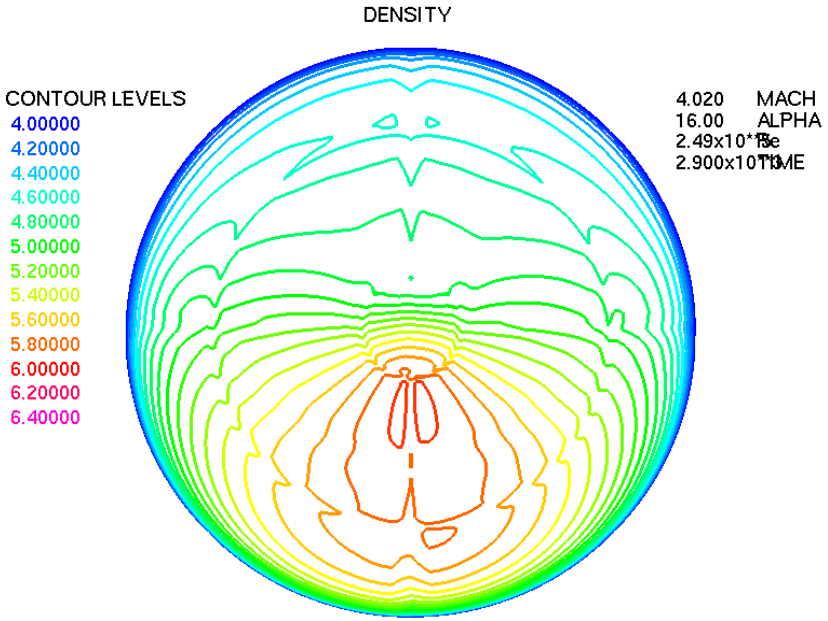




Unadapted grid shows anomalous "feature" in surface density



Adapted grid shows grid-partitioning artifacts due to poor convergence

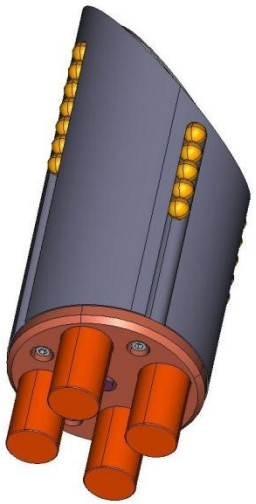


Entry Balance Mass Jettison

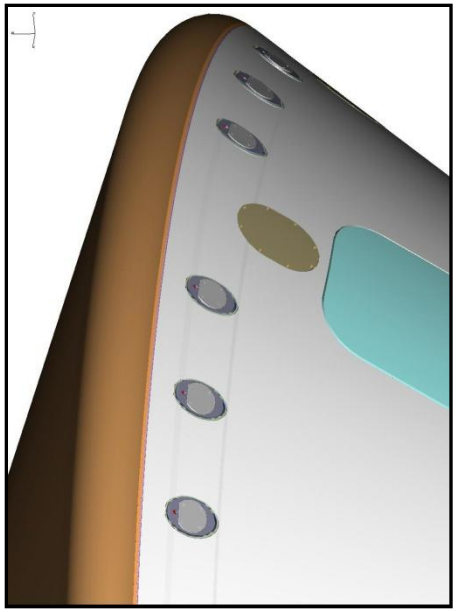
6 tungsten masses (29 kg each) jettisoned before parachute deploy, to shift center-of-gravity to capsule centerline

- Design issues:
  - Do masses separate cleanly?
  - Any aerodynamic effect on capsule?
- Solver issues:
  - Accept unresolved regions around mass-capsule intersection

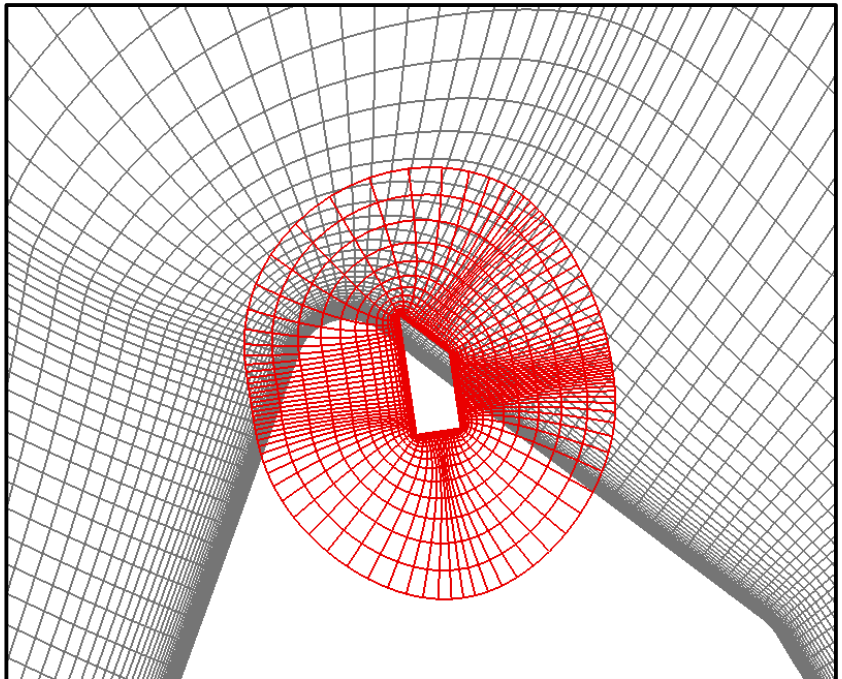
Drawing of EBMD mass



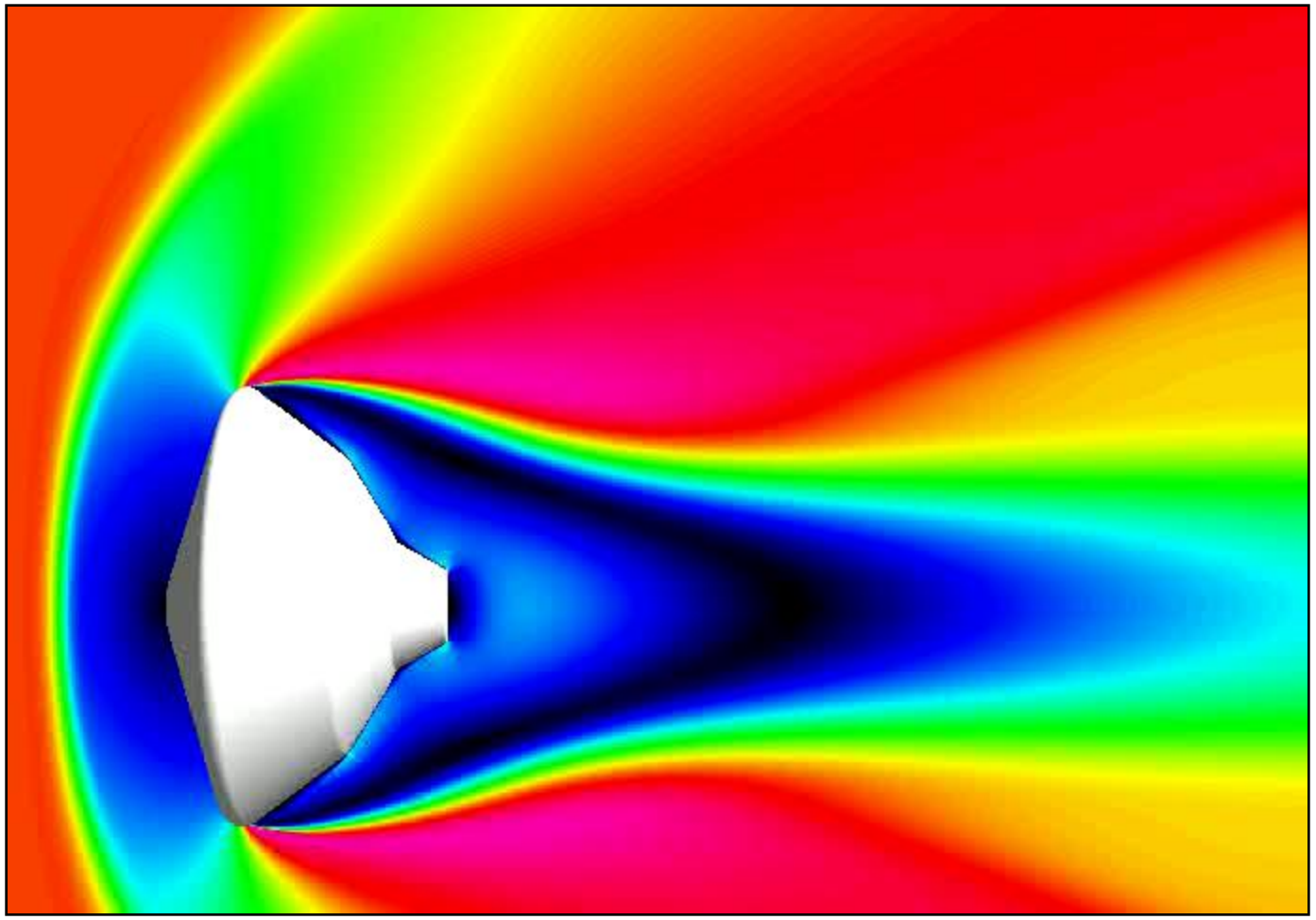
6 jettison locations on capsule



Coarse version of CFD grids



Entry Balance Mass Jettison



Capsule Flowfield Calculations Lessons Learned

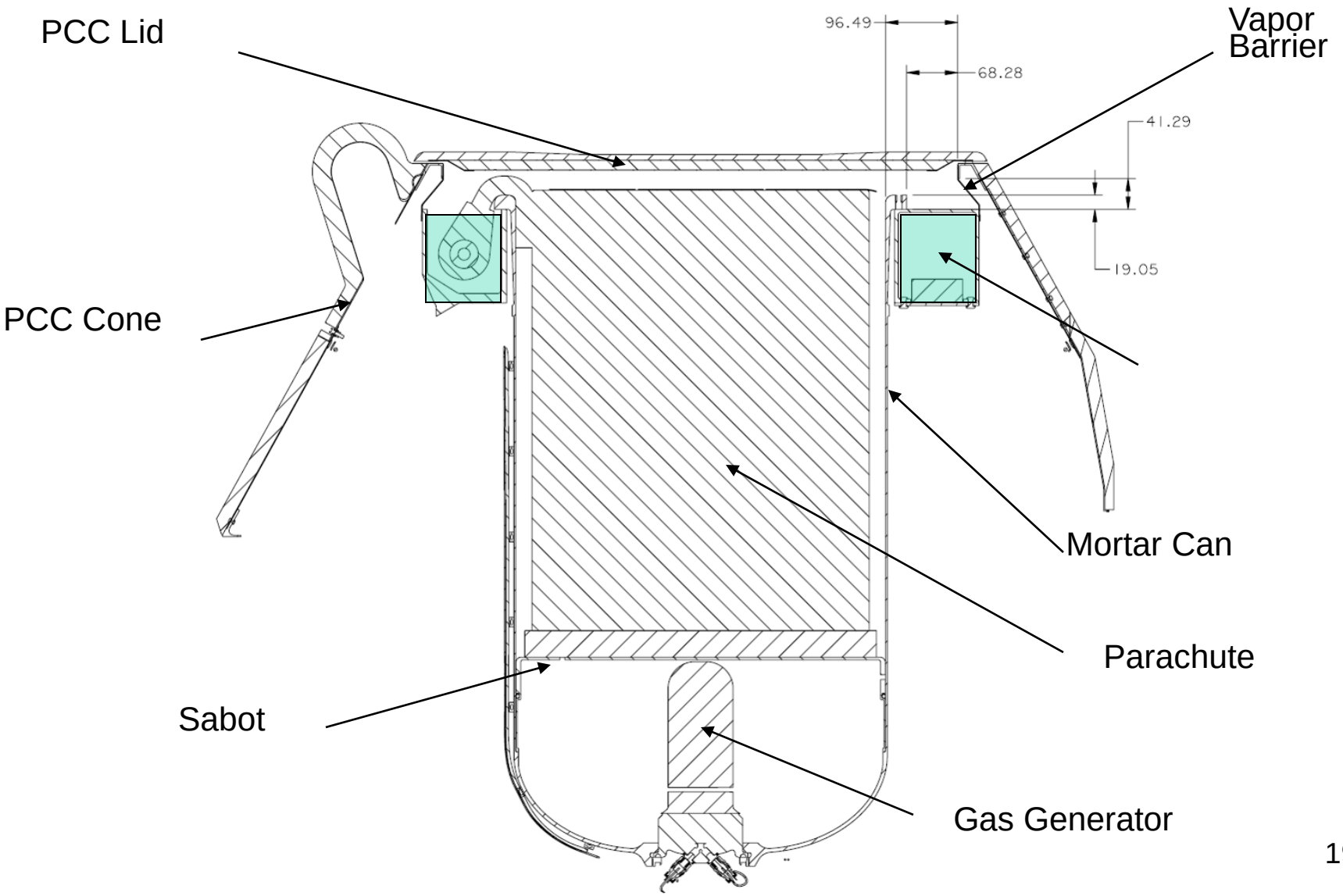
- Database calculations
  - For shocks above Mach 3(ish), watch for effects of non-aligned shocks on downstream flow properties
    - Can be mitigated by central differencing with scalar dissipation, at the expense of shock resolution
  - Be alert for grid boundary convergence issues, especially for
    - Extremely fine viscous clustering
    - Excessive grid splitting due to MPI load-balancing (OVERFLOW)
- Entry balance mass jettison
  - Ignoring resolution of capsule/mass intersection OK in this case
    - Simulation is good enough to answer engineering questions

Parachute Canister Mortar Launch

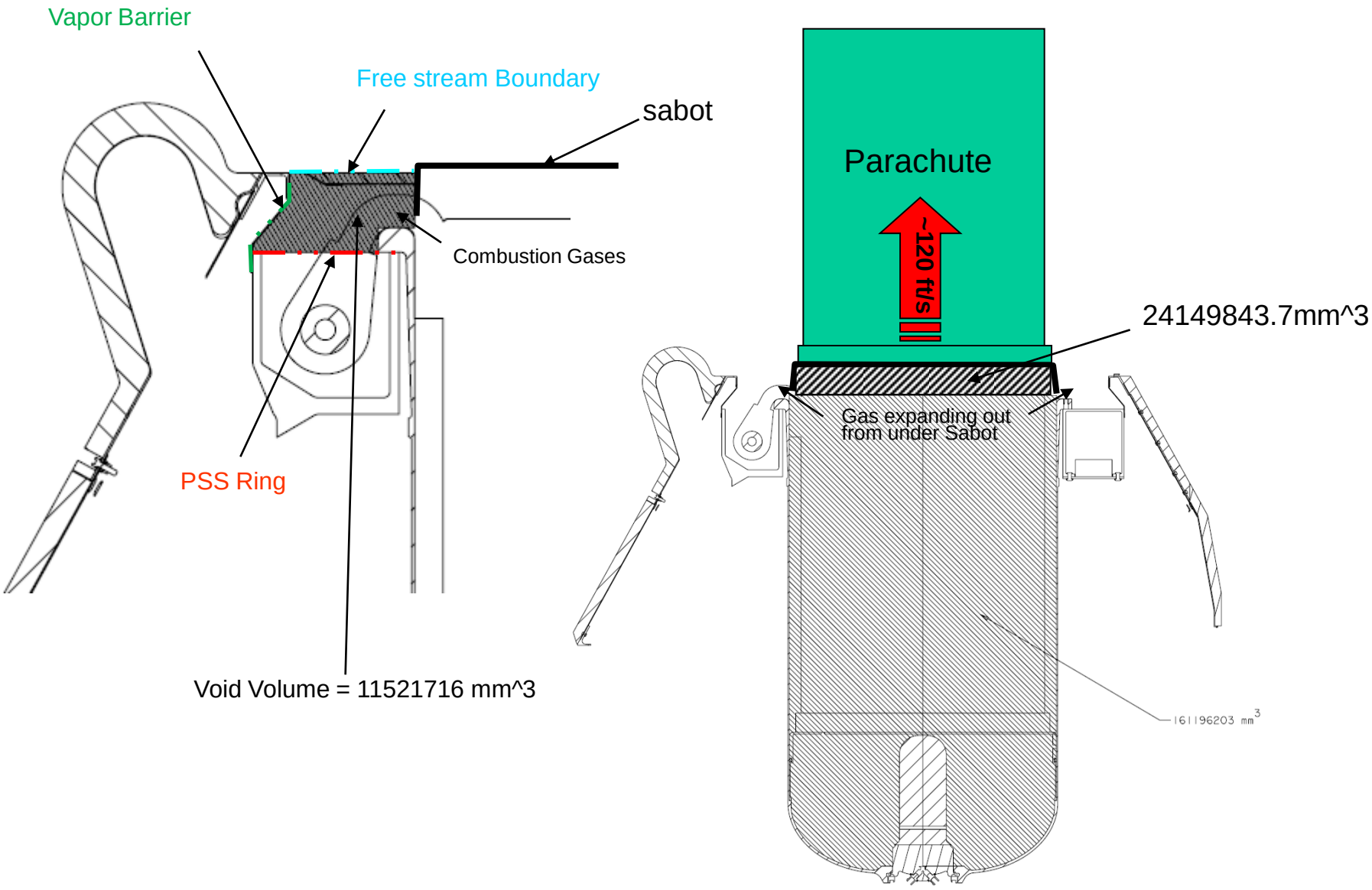
Parachute canister is expelled by mortar fire

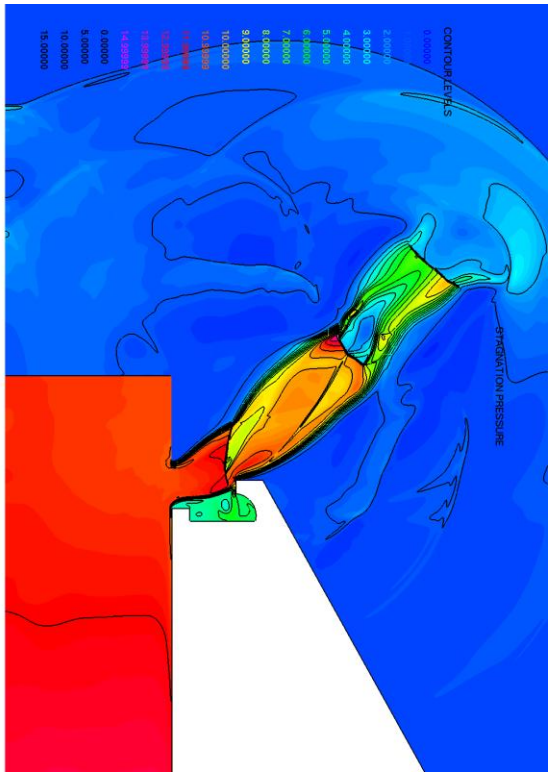
- Calculations with two gases
  - Mars atmosphere (molecular wt=43.5, gamma=1.29)
  - Mortar gas (molecular wt=25.2, gamma=1.23)
- Design issue:
  - What is worst-case pressure load on flexible vapor barrier?
- Solver/grid issues:
  - Sealing small gap
  - Shock capturing
  - Grid adaption

Mortar Launch (t =0s)

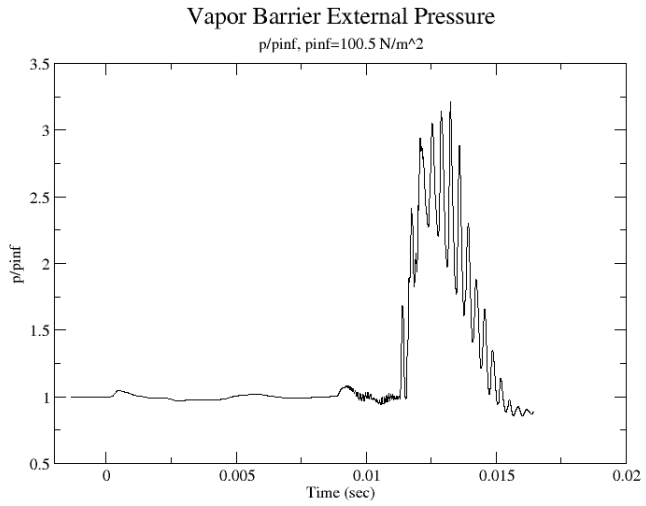


Mortar Launch (t~1.15ms)





Stagnation pressure contours



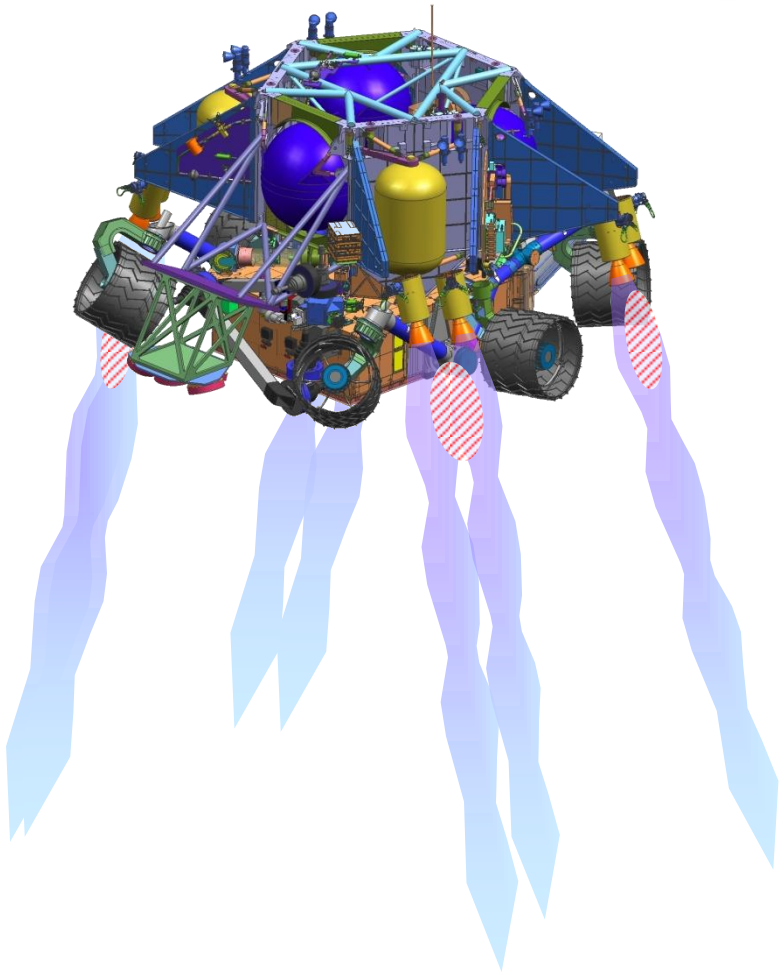
Powered Descent Plume Flowfields*

- Calculations with two gases
  - Mars atmosphere (molecular wt=43.5, gamma=1.33)
  - Main Landing Engine (MLE) plume (molecular wt=13.4, gamma=1.38)
- Design issues:
  - Highly under-expanded plumes (40:1)
  - Interaction of closely-paired plumes and proximity to stowed rover
- Solver issues:
  - Turbulence modeling
  - Shock capturing
  - Downstream boundary condition for oncoming flows

*Similar calculations were performed by Dr. Francisco Canabal (NASA MSFC), using the Loci-Chem CFD code. Information presented here reflects lessons learned from those calculations as well.

Powered Descent Plume Flowfields

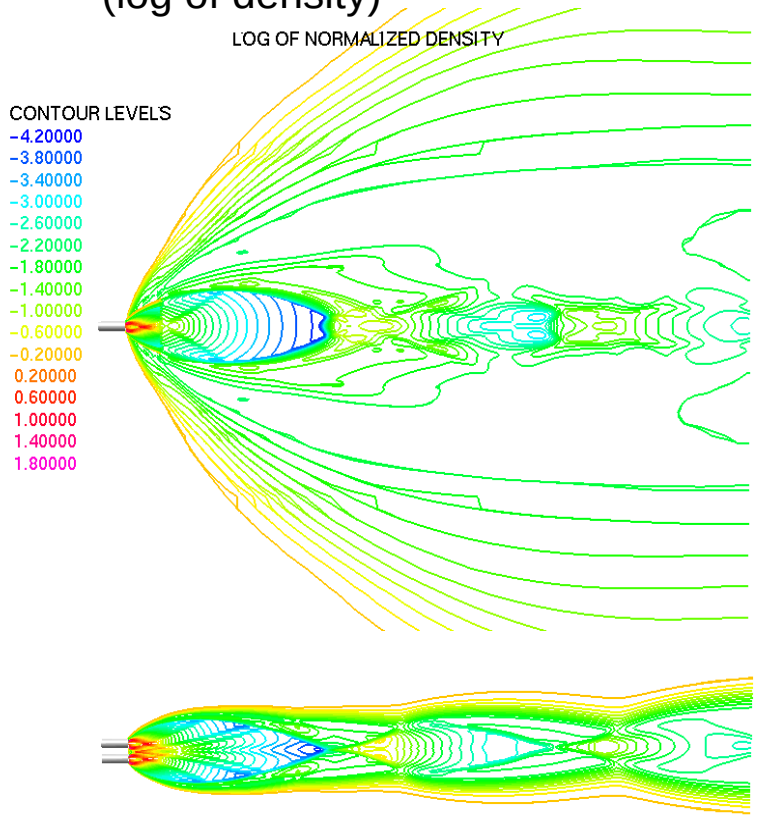
- Rover heating due to plume radiation
- Direct plume impingement on rover

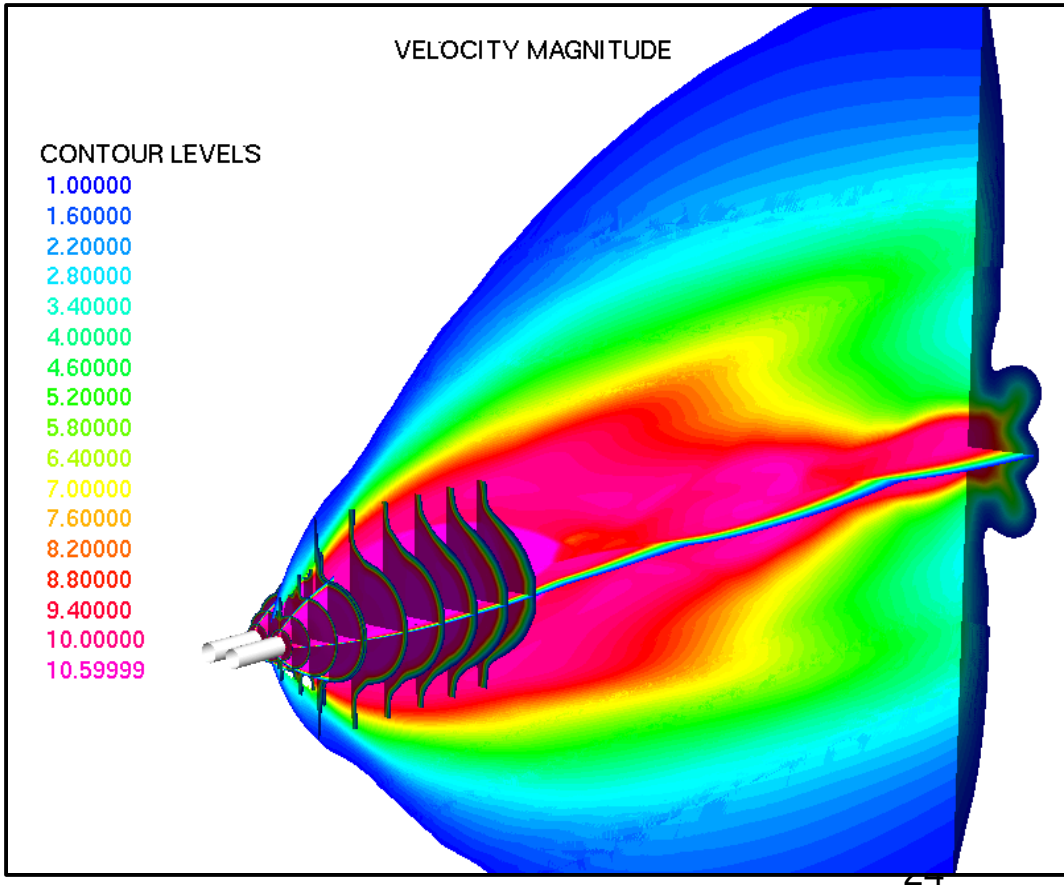


Powered Descent Plume Flowfields

- Plumes are highly underexpanded (40:1 pressure ratio)
- Two-plume simulation shows interaction sheet at intersection plane

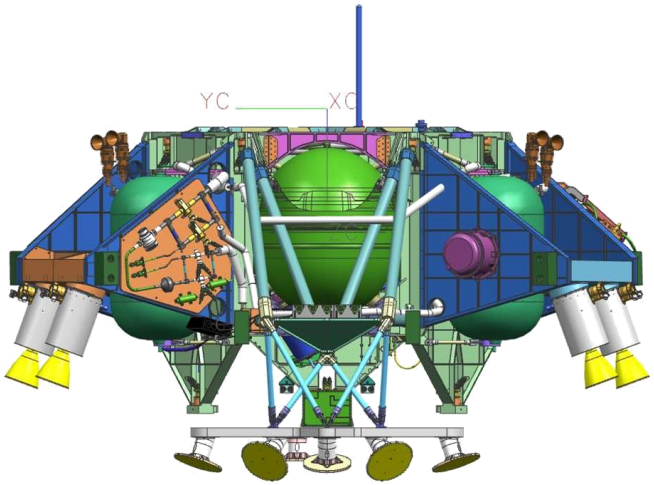
Side and top views
(log of density)

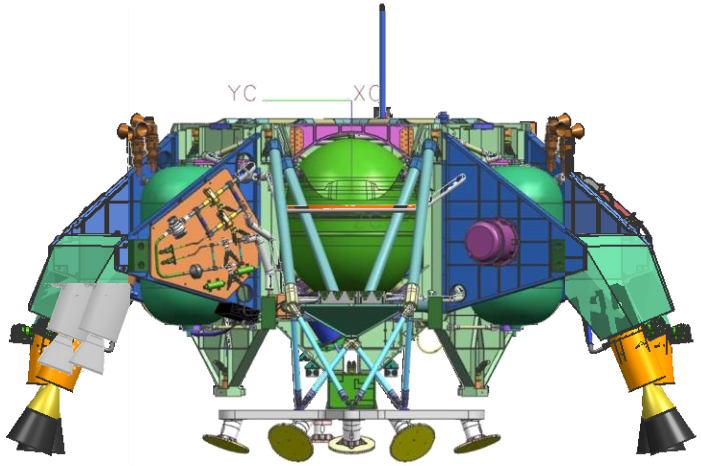




Powered Descent Plume Flowfields

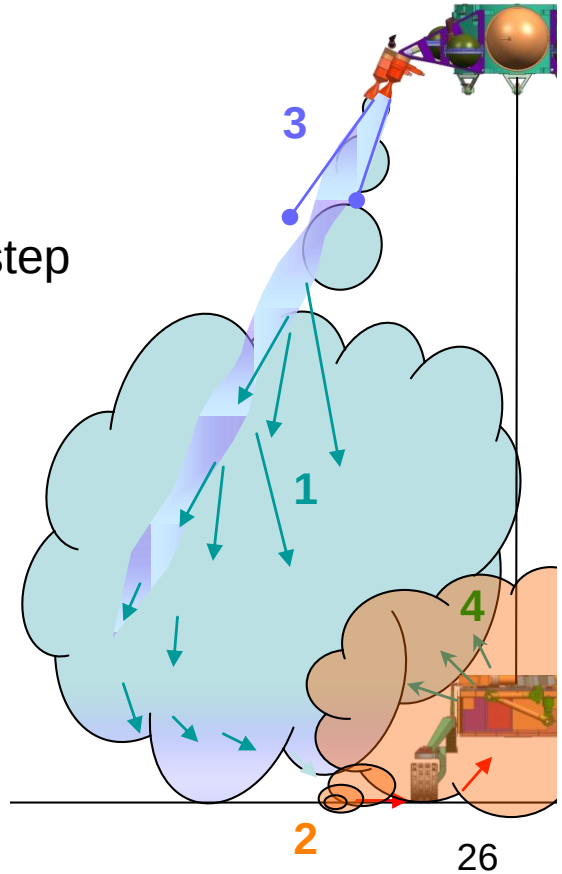
- MLE's moved out and down
- MLE pairs changed from 20/20 deg cant angles to 22.5/5 deg
  - Reduces plume-plume interaction
- All 8 engines fire for initial slowing
- Outboard 4 (22.5 deg cant) fire for final descent and hover





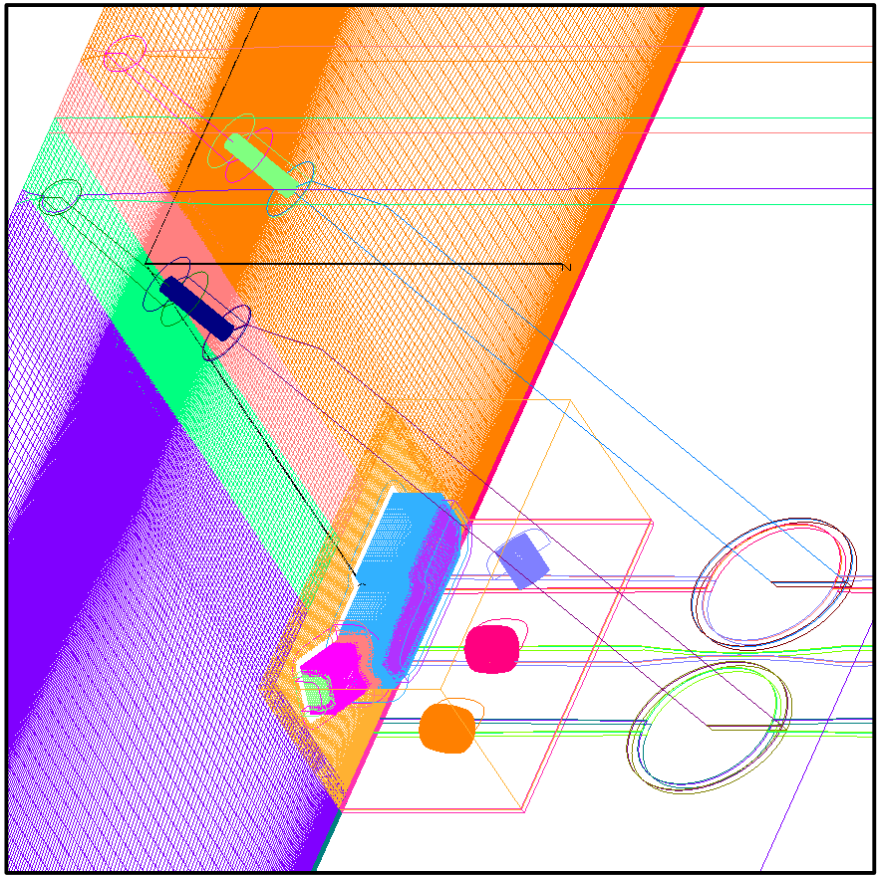
Plumes in Ground Proximity

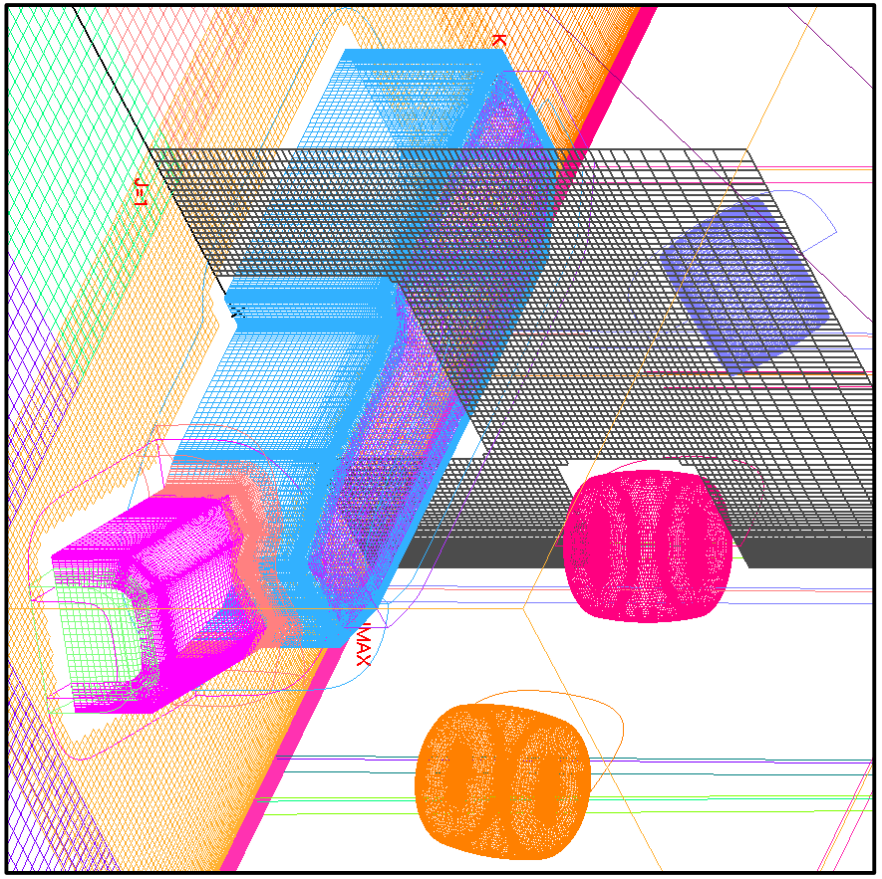
- Design issues:
  - Flowfield in proximity to rover – dust, plume contaminants, heating effect on rover and its instruments
  - Effect of ground slope, shape
- Solver issues:
  - Robustness, time-accuracy and achievable time-step
  - Total physical time simulated, unsteadiness
  - Accuracy and uncertainty



Plumes in Ground Proximity

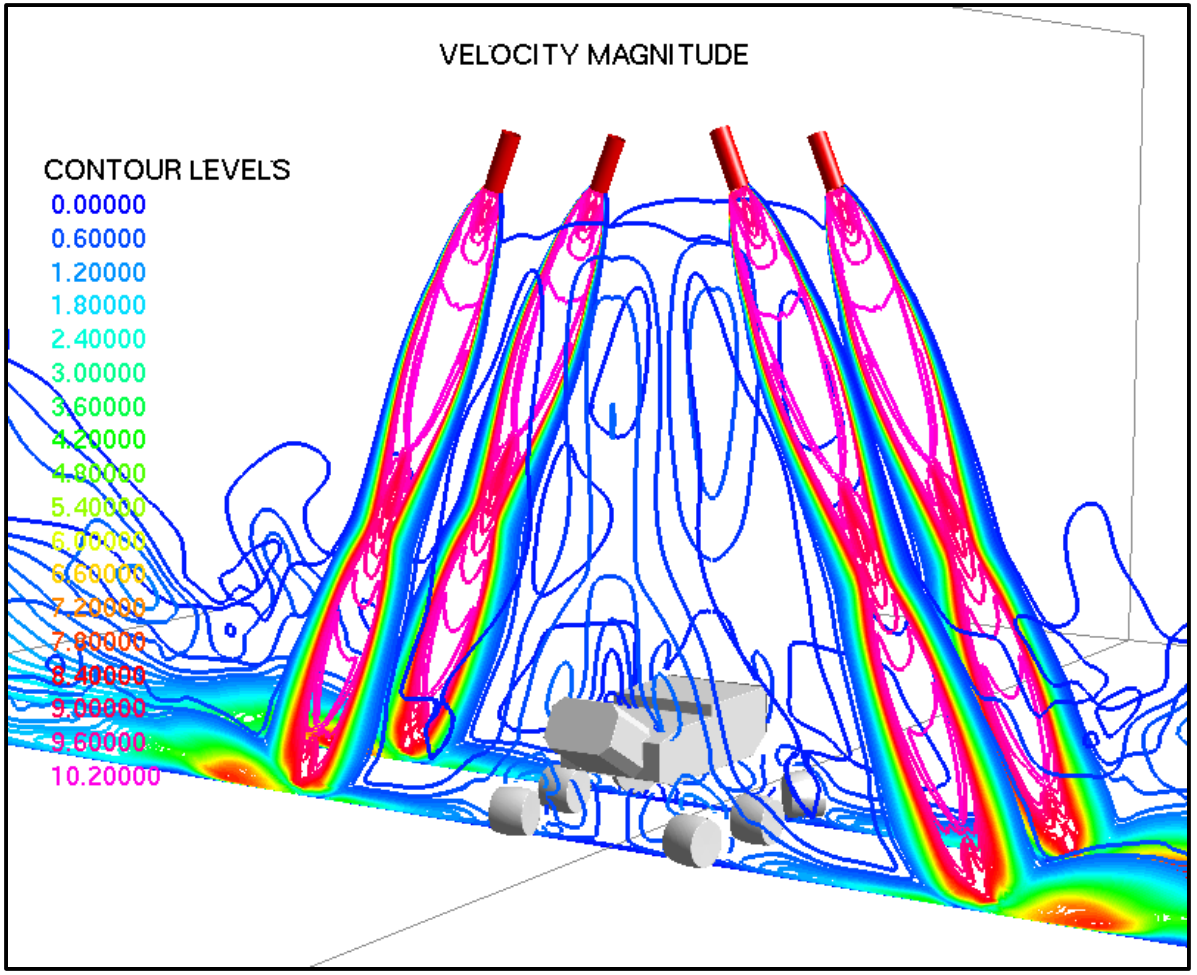
32 million-point grid, ½ symmetry



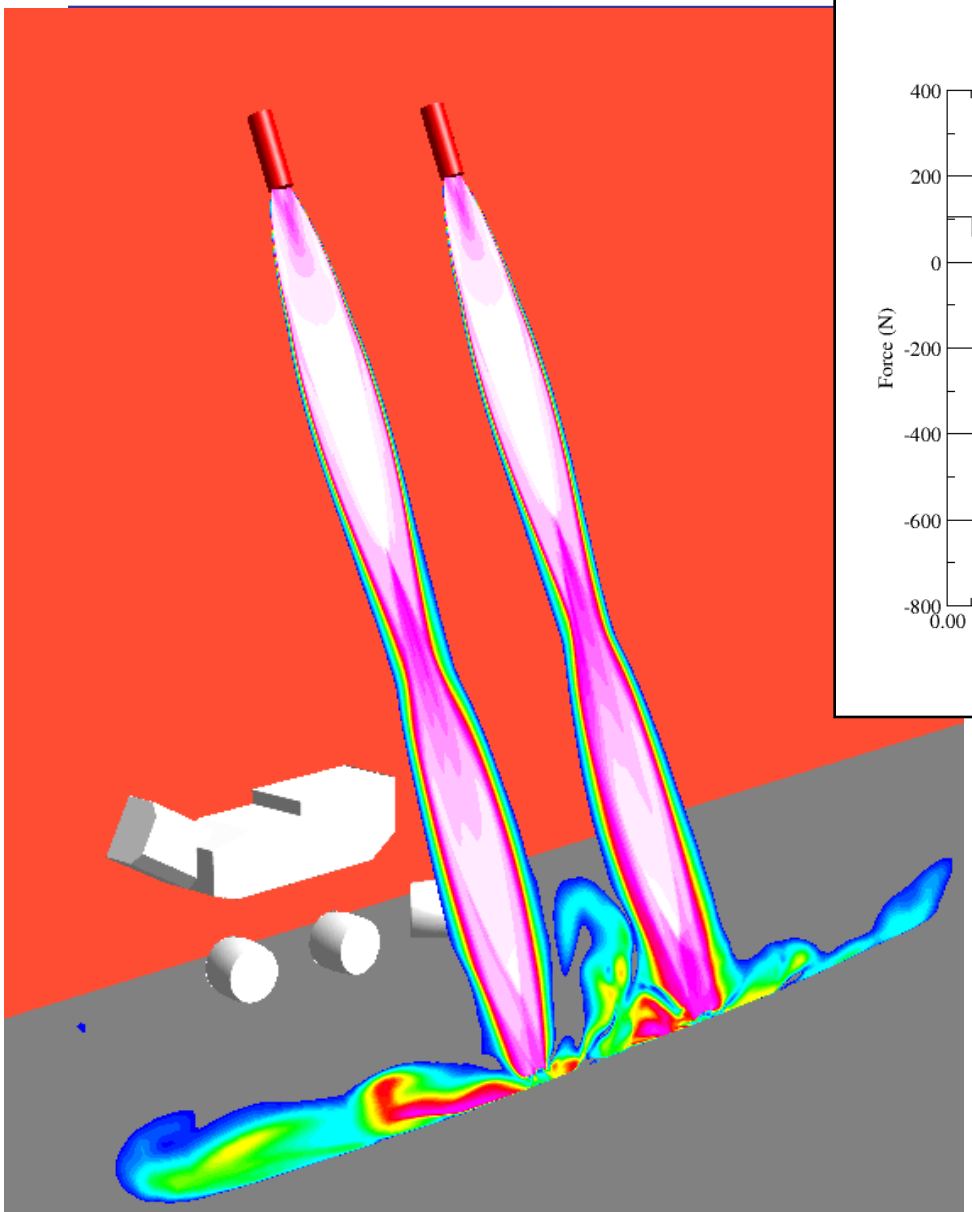


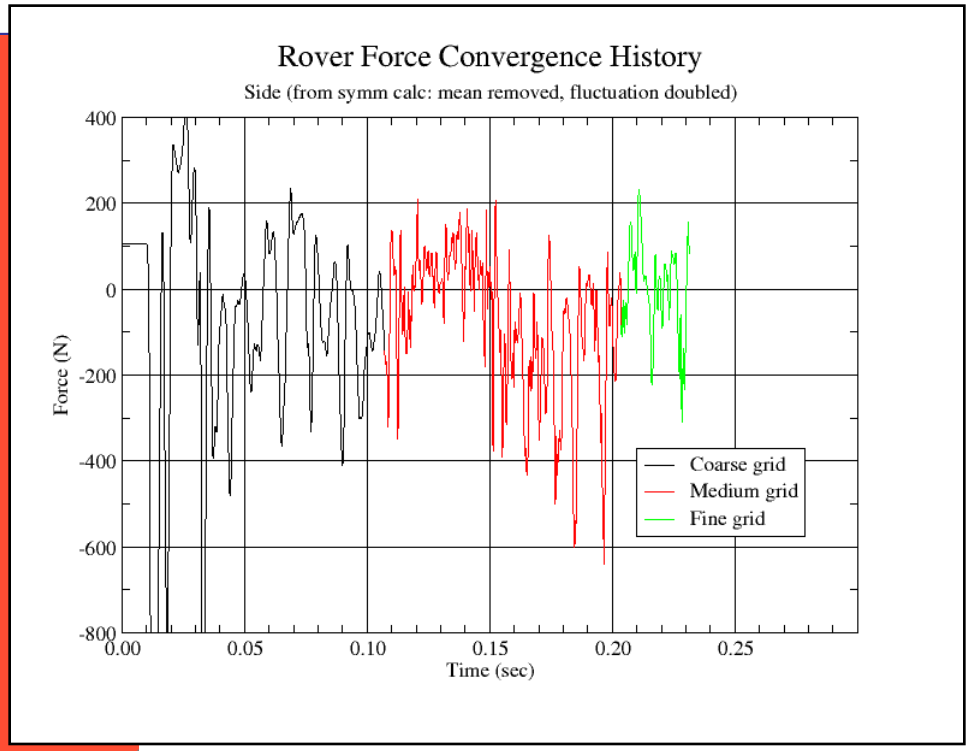
Plumes in Ground Proximity

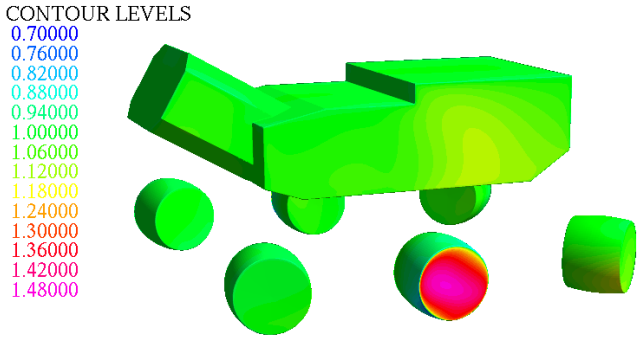
- Dust velocity might be up to 600 m/s (1/3 micron, CD=1)



Plumes in Ground Proximity

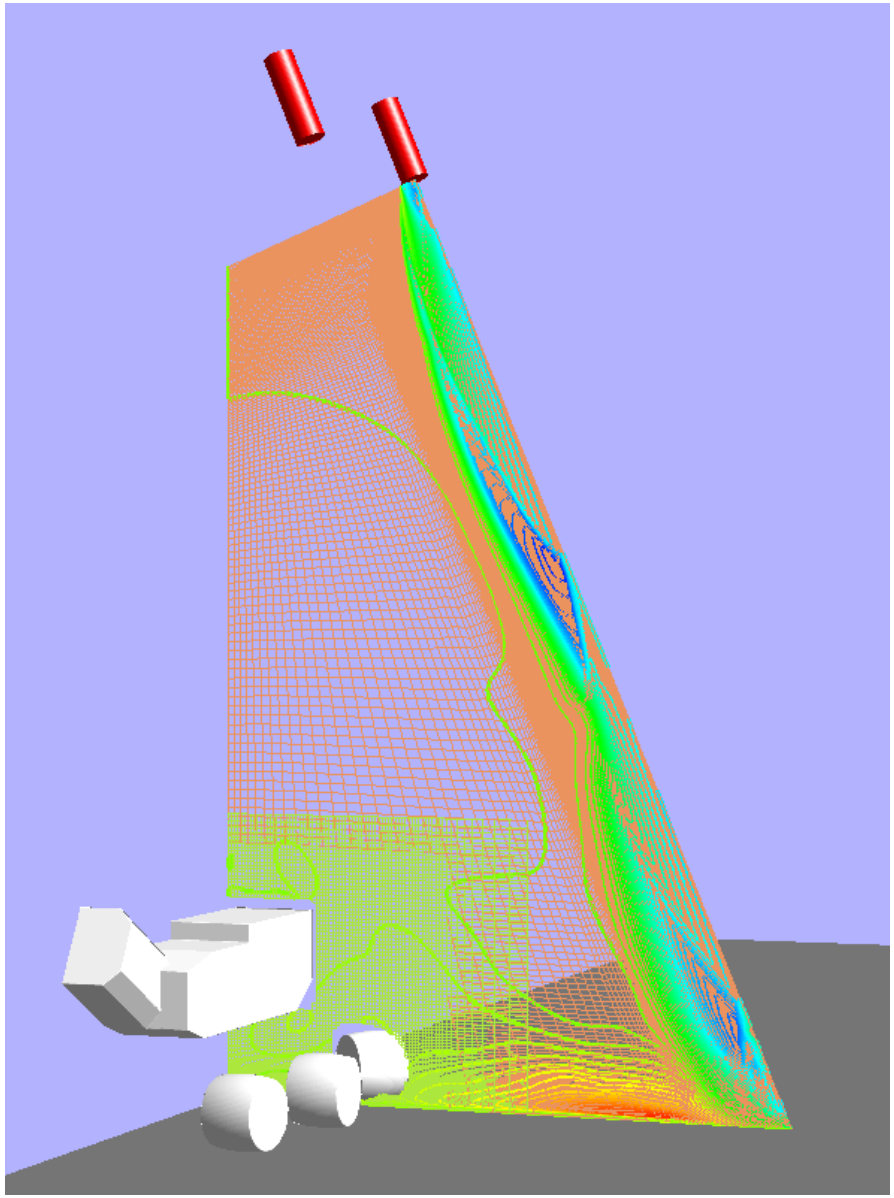


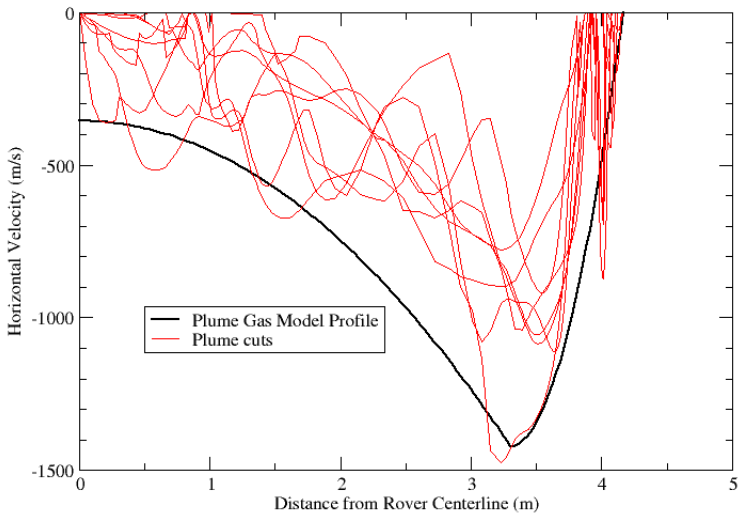


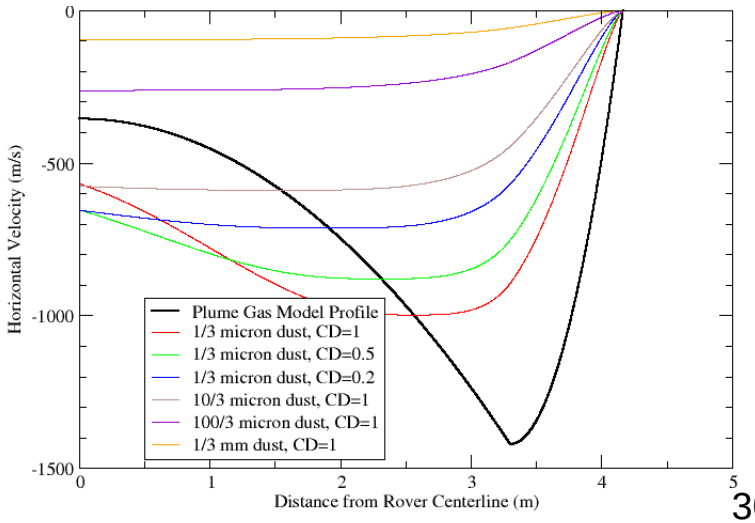


Rover surface pressure

Plumes in Ground Proximity







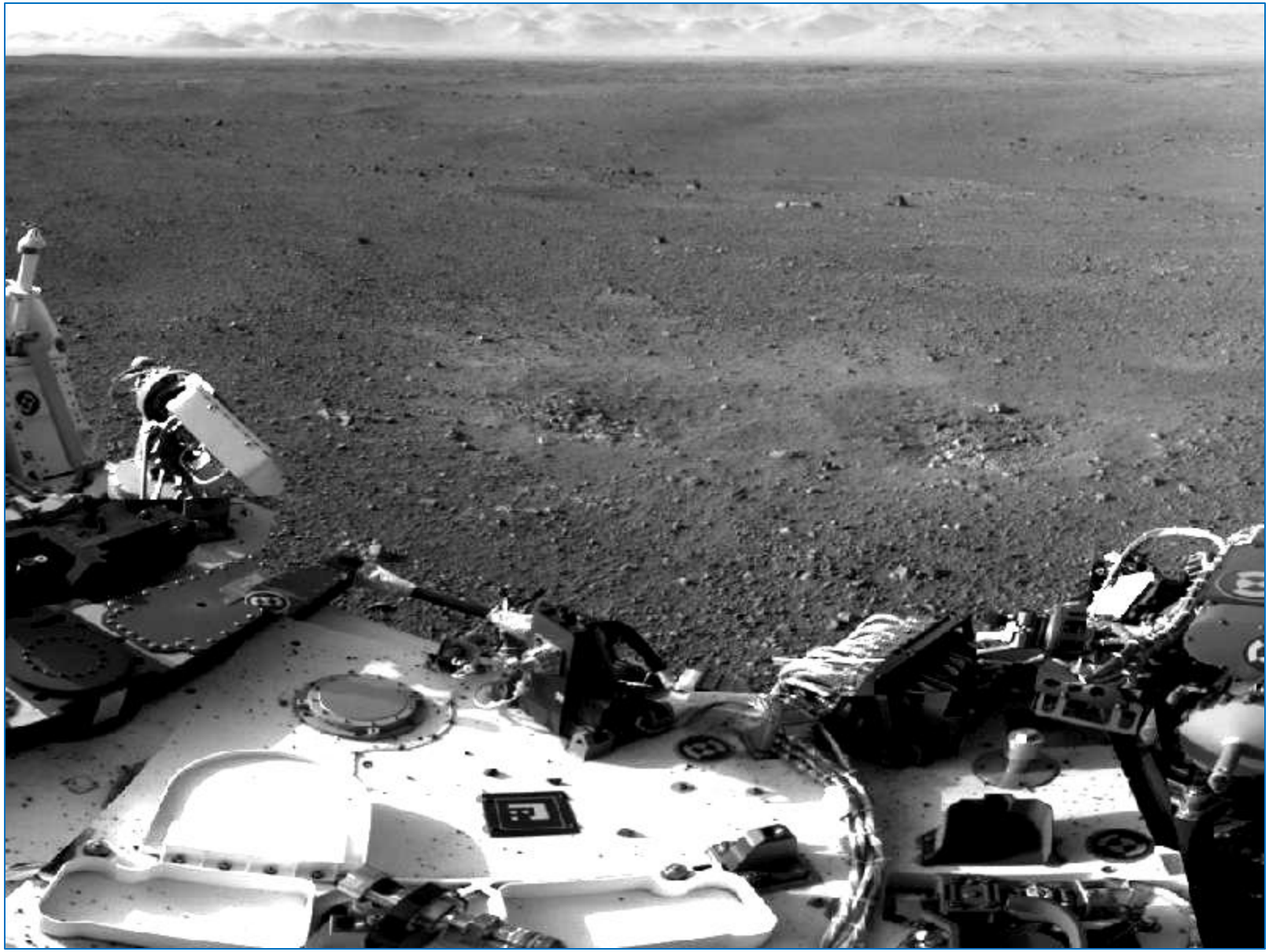


Image shows blast marks from descent rocket engines and debris on Rover deck. (Image credit: NASA/JPL-Caltech)

Descent and Landing Plumes Lessons Learned

- For hover/ground proximity cases, never clearly achieved steady "average" flow-field
  - Plume termination shocks not steady (numerical?)
  - Expense of running fine-grid solution
    - 32Mpts, time-step=1.1.E-5 sec
    - 32 sec/step on 128 CPUs (NAS Columbia SGI Altix)
    - 1 sec real-time would take 33 days of computing
- ...and what was the accuracy again?
  - Grid, turbulence model sensitivity?
  - What engineering questions *can* we answer?

Conclusions

- Missions such as MSL have widely varying applications needing CFD analysis
- Both capsule and plume flowfield computations have unique requirements and concerns
  - Capsule flow simulations fairly routine
  - Plume flowfields still difficult due to stability limitations, unsteadiness, uncertainty
- CFD is still not as easy as we would like for addressing engineering questions!