CFD 2030 Grand Challenge: CFD-in-the-Loop Monte Carlo Simulation for Space Vehicle Design

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CFD2030 Grand Challenge Problems for Numerical Simulation in Aerospace Engineering
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Outline

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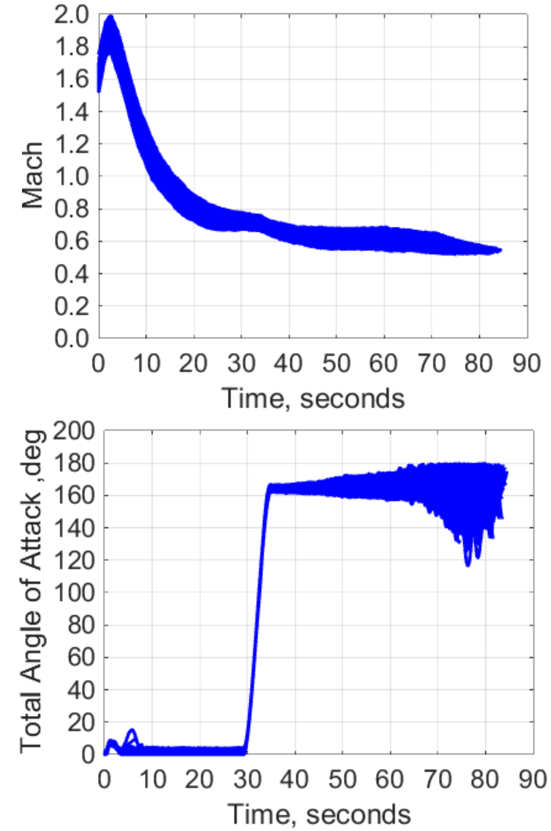
- Conclusion

Space Vehicle Design Challenges

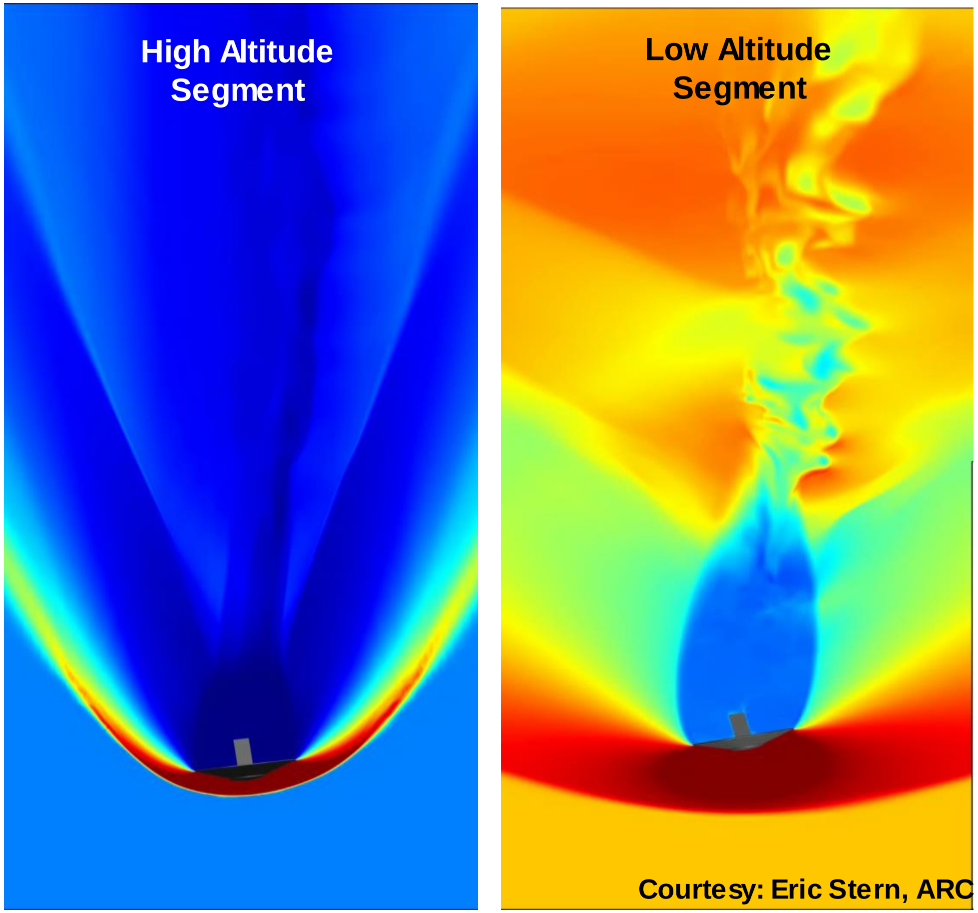
- **Space vehicle flight qualification is substantially different from that of aircraft.**
  - **Little to no flight demonstration/test, often in environments with high degrees of uncertainty.**
  - **Monte Carlo (MC) flight simulation and probabilistic methods used to evaluate design.**
  - **Aerosciences databases required to fuel MC simulations.**
    - **Large aerosciences parameter matrices involving dozens of independent variables with uncertainties.**
    - **Data developed from ground tests, empirical and analytical data, CFD, past flight performance data and engineering judgment.**
    - **Can require years to develop.**
- **Space Vehicles usually fly preset trajectories with little opportunity for placarding.**
  - **Fly through the complete range of flow conditions from low subsonic to hypersonic.**
  - **Fly a narrow trajectory corridor, but require broad parameter matrices to cover off-nominal performance cases.**
  - **Transient and acceleration effects can be important.**
    - **Not accurately represented in the present database approach.**
- **Replacing the aerodynamic database with a direct CFD simulation has substantial advantages.**
  - **Designers have early access to MC simulation without waiting for aerosciences database development.**
  - **Aerosciences unsteady and transient effects more accurately represented in the simulation.**
  - **Design changes can be more readily evaluated.**
  - **If desired, a trajectory-focused database can be extracted from the simulations conducted to date.**

Monte Carlo Flight Simulation (Approximately 1000 Simulations on a Notional Space Vehicle Design)



CFD-in-the-Loop Flight Simulation

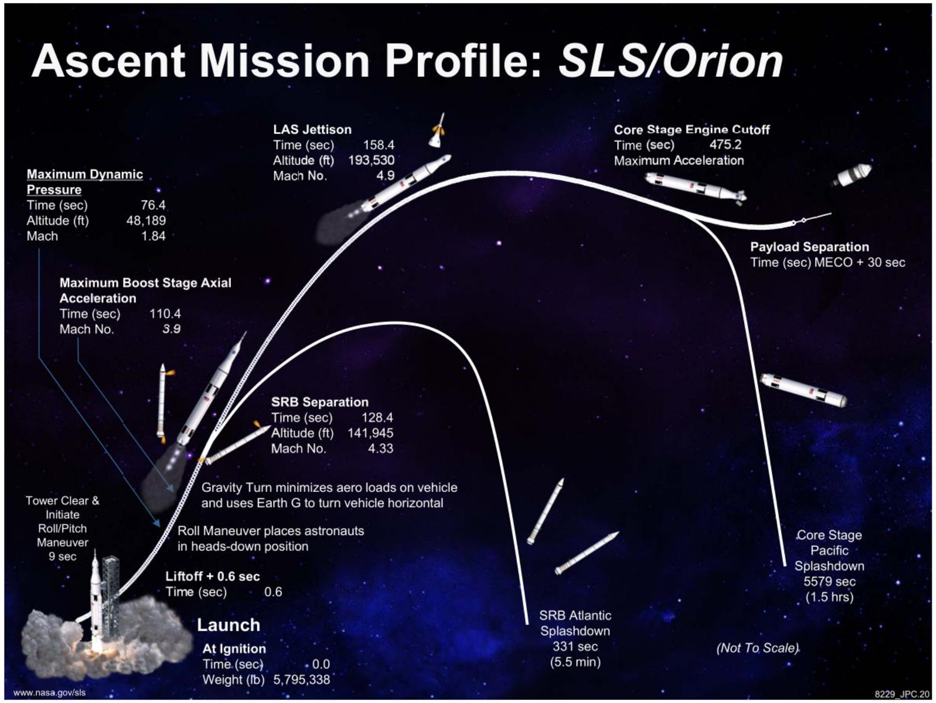
NASA/ESM 6-DOF Coupled CFD Entry Simulation



- **Credible efforts toward 6-DOF coupled CFD Simulation through DoD's CREATE-AV and NASA Entry Systems Modeling projects.**

Space Applications of Interest
Ascent

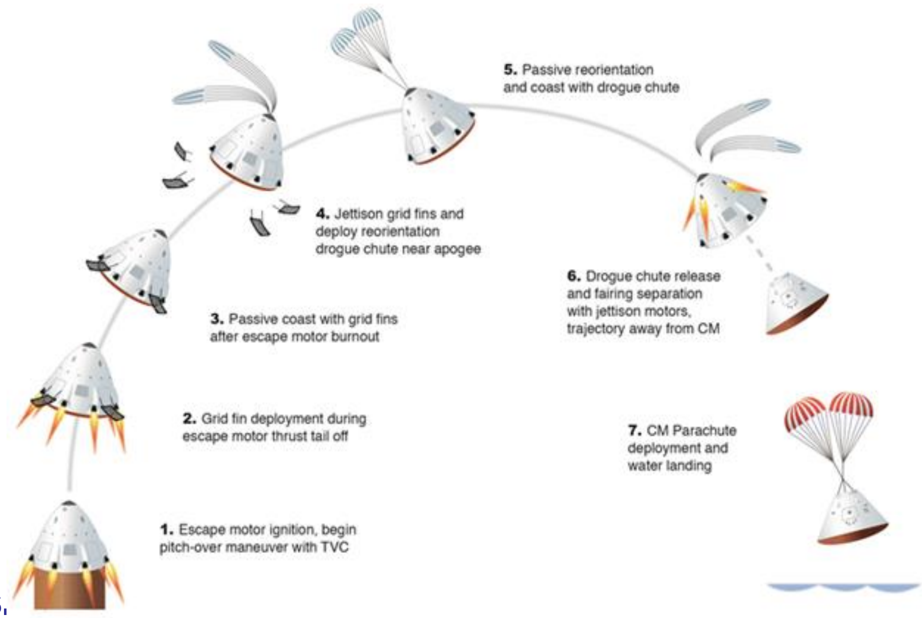
- **Ascent flight phase spans the entire flow regime from stationary on the pad to hypersonic flight in rarefied atmosphere.**
- **Pad operations involve ground wind simulations and complex ground support geometries.**
  - **Vehicle oriented “90°” to the flow.**
  - **Engine ignition transients can be particularly important to the design and simulation.**
- **Liftoff transition involves rapid acceleration and transition from 90° to 0° total angle of attack.**
  - **Combination of vehicle pitch and roll maneuvering.**



- **Acceleration through transonic speed regime can involve strong buffet and aeroacoustic effects.**
  - **Potentially harmful to the vehicle structure, flight systems, and crew.**
- **Vehicle staging and separation events.**
  - **Complex multi-body and plume vehicle interactions.**
- **High altitude flight in non-continuum flow.**

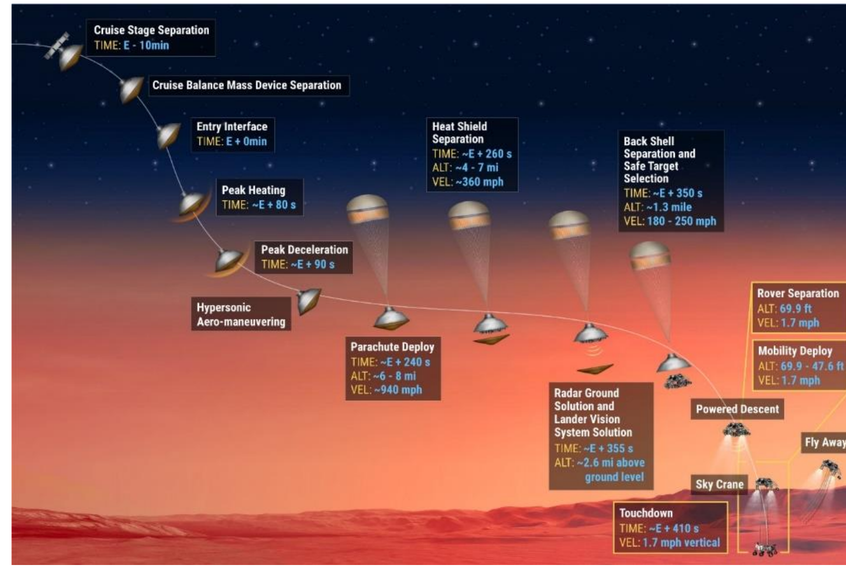
Space Applications of Interest
Abort

- **Abort systems are used for crew rescue in the event of a catastrophic failure.**
  - **Most provide full abort coverage from stationary on the launch pad, along the complete ascent trajectory, to orbit insertion.**
- **Two primary concepts in use today:**
  - **Tractor systems as used on Mercury, Apollo, Soyuz, and Orion.**
  - **Pusher Systems as employed on most commercial crew launch systems.**



- **Launch abort vehicles must be maneuverable and most require stable flight from 0° to 180° total angle of attack.**
  - **Control is afforded by both propulsive and mechanical systems and can be passive or active.**
- **Staging and separation events required for most abort scenarios.**
- **Parachutes and/or propulsive systems required to land the payload.**
- **Aero/Plume, Plume/Plume, and Plume/Vehicle interactions can be important and difficult to predict.**
  - **Vehicles routinely fly through their own plumes.**

Space Applications of Interest
Entry Descent and Landing

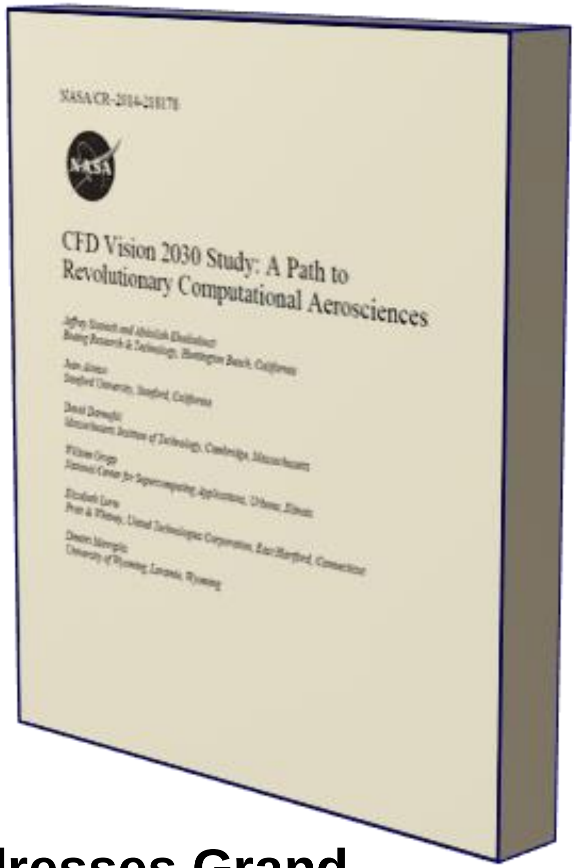


- **Entry systems reverse the ascent process transitioning from hypersonic flight to landing.**
- **Atmospheric heating at hypersonic conditions is of primary concern.**
  - **Entry interface typically occurs in rarefied atmospheres requiring non-continuum flow simulations.**
  - **Chemical reactions and shock radiation effects can be important to the analysis.**
- **Vehicle control is usually provided through a propulsive reaction control system.**
  - **Aero/plume interactions can have a large impact on control authority.**
- **A variety of vehicle decelerator concepts can be employed.**
  - **Hypersonic inflatable and mechanically deployed heatshields, supersonic and subsonic parachutes, retro propulsion and vehicle maneuvering.**
- **Staging, separation, and mass redistribution events.**
- **Plume/surface interaction important to terrain navigation and landing.**

CFD Vision 2030 Gaps and Impediments

- **CFD Vision 2030 Study identified five primary gaps and impediments:**

  1. **Effective Utilization of High Performance Computing (HPC)**
  2. **Unsteady Turbulent Flow Simulation Including Transition and Separation**
  3. **Autonomous and Reliable CFD Simulation**
  4. **Knowledge Extraction and Visualization**
  5. **Multidisciplinary/Multiphysics Simulations and Frameworks**

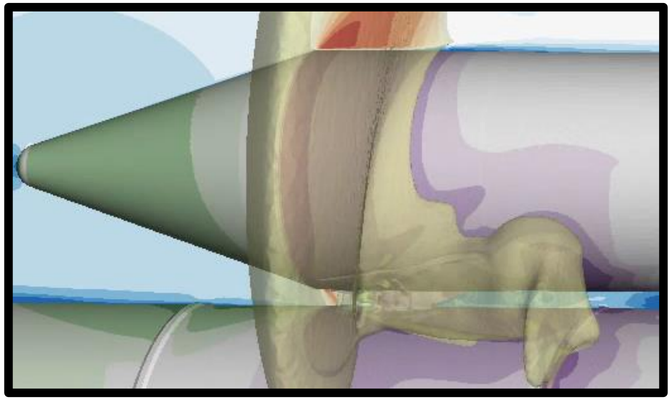


- **CFD-in-the-Loop Monte Carlo Analysis addresses Grand Challenge Problem 4: Probabilistic Analysis of a Powered Space Access System.**
  - **Gaps and impediments 1, 2, 3, and 5 present the greatest roadblocks to meeting the challenge.**

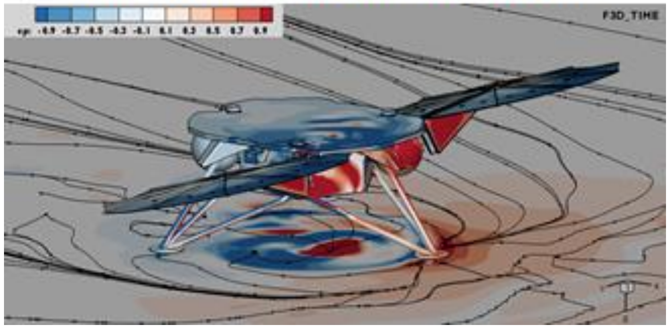
Challenging Space Vehicle Flow Physics

- Space vehicle aerosciences encompasses majority of critical flow phenomena addressed in the CFD Vision 2030 Study.
- Unsteady flows due to smooth body and shock induced separation.
  - Launch vehicle and spacecraft ground winds.
  - Transonic buffet and aeroacoustics.
  - Bluff body entry systems.
- Aero/plume, plume/plume, and plume/surface interactions.
  - Chemistry and flow structure resolution are often critical.
  - RCS firing into separated wakes problematic for entry systems.
- Transient analysis is a "must have" for most space vehicle simulations.
  - Accelerating and maneuvering flight, staging and component separations, naturally occurring flow unsteadiness, geometries not optimized for aero.
- Require strong focus on development of accurate and efficient unsteady CFD techniques that are competitive with current steady flow simulations.
  - Physics complexity pushing space vehicle aerosciences community more often to Detached Eddy Simulation and Hybrid Reynolds Averaged Navier-Stokes/Large Eddy Simulation capability.

Launch Vehicle Buffet



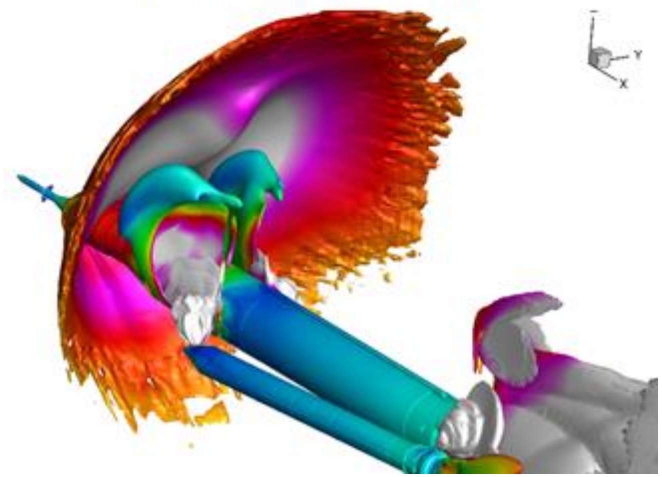
Mars INSIGHT Ground Wind Loads



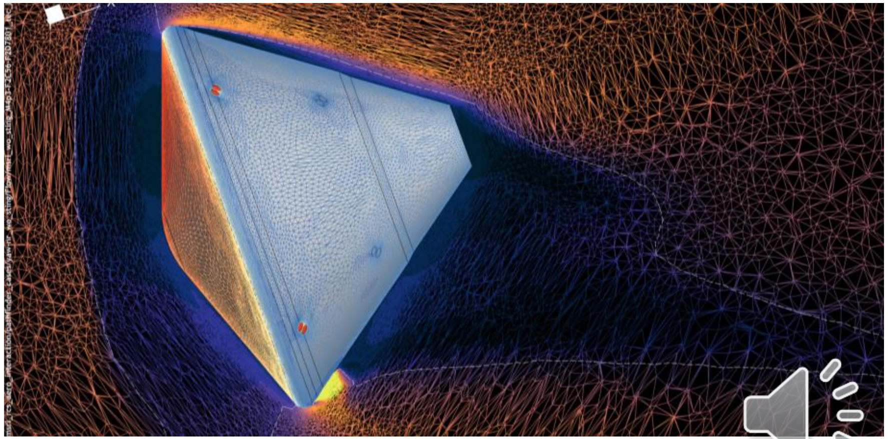
Geometry Modeling, Grid Generation, and Automation

- **Efficient geometry modeling, grid generation, and automation critical to solving the grand challenge.**
  - **MC simulation requires accurate modeling, both geometry and physics, of a vehicle maneuvering arbitrarily and unpredictably as it responds to dispersed flight condition uncertainties.**
- **MC simulations can require 1000's of simulations.**
  - **User must be removed from the geometry modeling and grid generation process as much as possible.**
- **Flow physics can evolve rapidly during a given trajectory simulation requiring robust automatic mesh refinement techniques.**
  - **Adaptation to a specified accuracy metric likely required to manage simulation cost.**

SLS Booster Separation



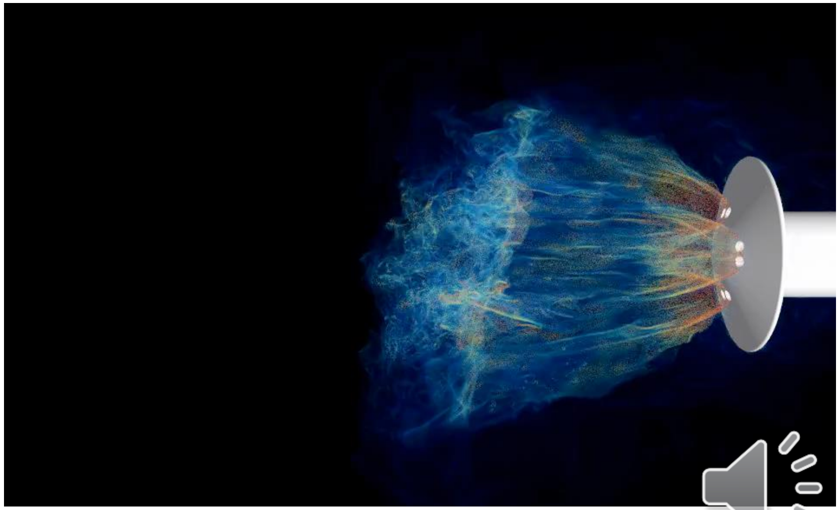
Entry System Adaptive Mesh Refinement



HPC Considerations

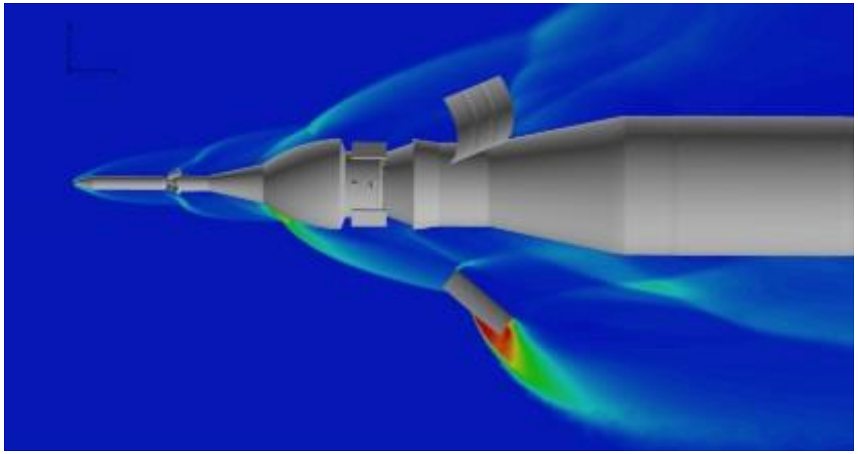
- **Typical MC flight simulation for design purposes requires 3000 or more independent flight simulations dispersing up to 100 design parameters.**
  - **Simulations employing table lookup aerodynamic databases can be performed on desktop workstations and small computing clusters.**
  - **Adding CFD-in-the-loop moves the simulation off the desktop.**
- **Tuning efficiency of a single CFD-in-the-loop flight simulation is pacing item for this challenge.**
  - **Multiple simulations required for MC analysis is embarrassingly parallel.**
- **Near term progress may require development and implementation of novel Model Order Reduction and/or Machine Learning techniques.**
- **Access to emerging HPC hardware, CFD tool adaptation, and algorithm development are enabling.**
  - **Problem is increasingly a computer science problem over a flow physics problem.**

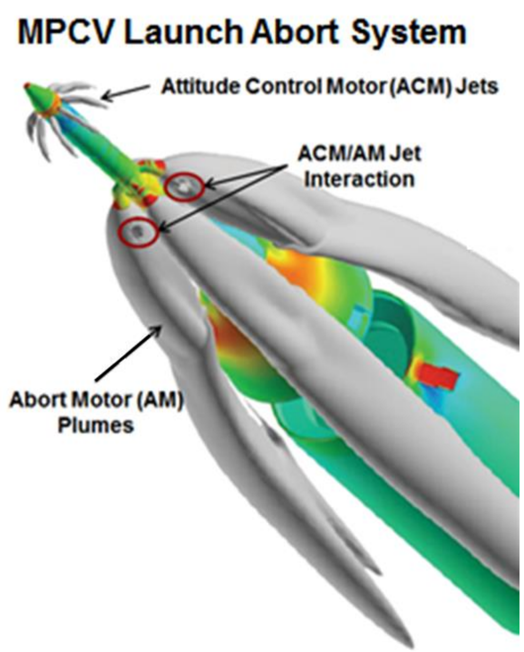
Supersonic Retropropulsion Simulation on Summit



Multidisciplinary/Multiphysics Simulation Challenges

- **Aero/plume interaction, chemically reacting flows, fluid/structure interaction are a few multidisciplinary and multiphysics problems important to space vehicle aerosciences.**
- **Efficient CFD-in-the-loop MC simulation presents a different set of challenges.**
  - **6-DOF flight simulation for vehicle design is highly developed and diverse in available tools.**
  - **Not likely that the comprehensive capability of these tools could be built directly into the CFD solver.**
- **Frameworks effectively coupling the CFD and simulation tools will allow the integration of CFD capability tailored to a given problem.**
  - **Dichotomy of computing platforms required for CFD code and simulators could prove to be a challenge for developers and users alike.**

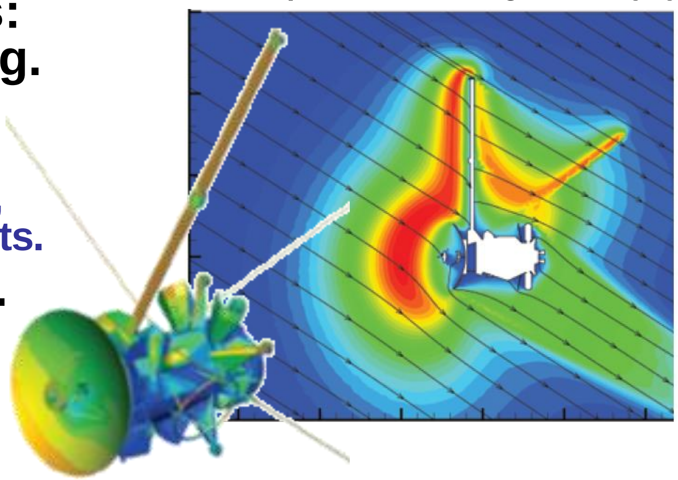




Conclusion

- **Detailed Aerosciences analysis is required in two primary flight phases for space vehicles: Ascent/Abort and Entry Descent and Landing.**
  - **Vehicles not optimized for aerodynamics.**
  - **Prediction of unsteady flows, plume/surface/ aerodynamic interaction, shock effects, heating, and vehicle flight stability are prime requirements.**
- **Designers regularly deal with unsteady flow.**
  - **Steady CFD implementation can be clumsy and prone to large variation.**
  - **Community increasingly turning to DES and HR-LES for select cases.**

Direct Simulation Monte Carlo Analysis of Cassini Spacecraft during Titan Flyby



- **CFD-in-the-loop MC simulation has potential to significantly reduce design development time and lessen the cost and schedule impact of vehicle design changes and/or block upgrades**
- **Challenges to realizing this capability are significant and well-aligned with the goals proposed in the CFD Vision 2030 Study.**
- **The grand challenge is partially scalable and could be initially demonstrated on only a segment of a flight simulation.**
  - **EDL may be a good choice for demonstrating capability; several initial efforts in free-flight CFD EDL analysis are underway.**
- **Model Order Reduction and Machine Learning techniques may be required for near-term implementation of CFD tools capable of simulating space vehicle flows of interest.**