



The NASA Ames Aerothermodynamics Branch
(Code TSA)

Jeffrey Hill
Branch Chief

Overview

- **Mission**: Provide integrated modeling, simulation, and test capabilities in the areas of aerothermodynamics, shock layer radiation, and entry system design.
  - We define and validate the aerothermal environments used to design planetary entry systems.
- **Capabilities**:
  - CFD simulation for entry vehicles at hypersonic velocities.
    - Arc jet facility flow modeling and characterization.
  - Modeling and testing of shock layer kinetics and radiation.
  - Development of flow-field diagnostic techniques.
  - Aero- and Aerothermal testing via ballistic ranges.
- **Pedigree:**
  - TSA has roots dating back to founding of Ames in 1940s.
  - Models, tools developed in TSA are foundational in our field.

Branch Staff

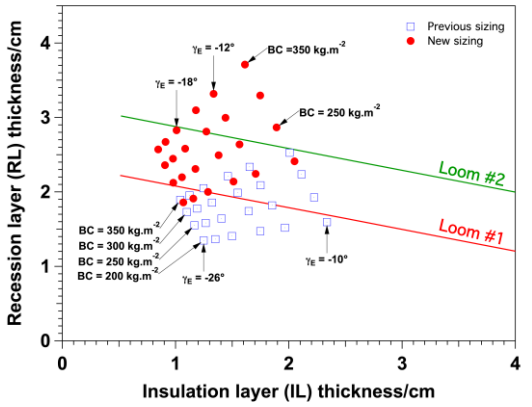


- Branch Staff: 8 civil servants, 14 contractors, 2 post docs, 1 research associate.
- NASA Awards for Exceptional Achievement (3), Engineering Achievement (5), Scientific Achievement (1), Early Career Achievement (1), Outstanding Leadership (1) & Public Service (3).
- 10 AIAA Associate Fellows.

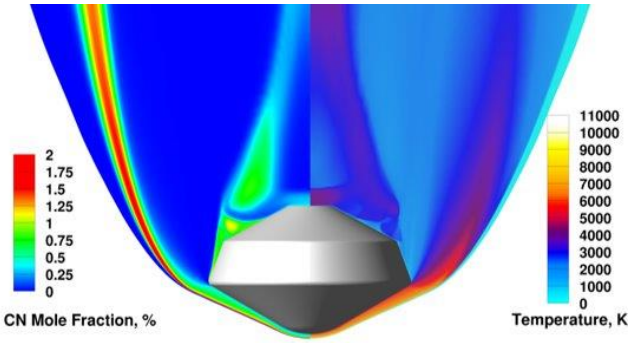
EDL Engineering Design & Test

- TSA provides critical aerothermal engineering leadership and support to NASA's EDL programs.
  - Supply key expertise and work force for Orion, Mars 2020, Dragonfly, MSR, Commercial Crew IV&V, etc.
- Our contributions span the vehicle life cycle from preliminary mission design to post flight analysis.
  - Recent Pre-Phase A: 7 New Frontiers 4 proposals, 2 Decadal Survey Concept studies, MSR formulation.
  - Recent Post-Flight: Orion EFT-1, MSL, M2020.
- We are a preferred partner for aerothermal engineering expertise.
  - Excellent relationships w/ LaRC, JSC, JPL, APL, etc.
  - Reimbursable Space Act Agreements with SpaceX, Blue Origin, Lockheed Martin, Sierra Nevada, etc.

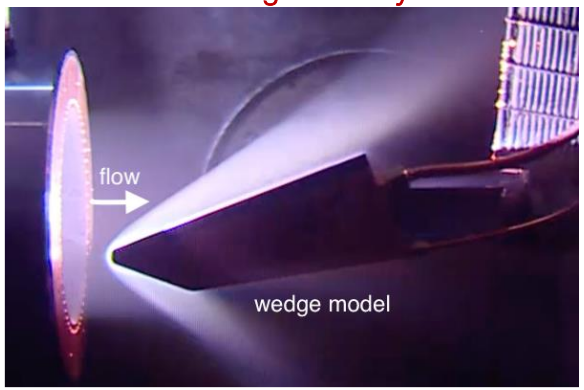
Preliminary Mission Design



Flight Vehicle Environments

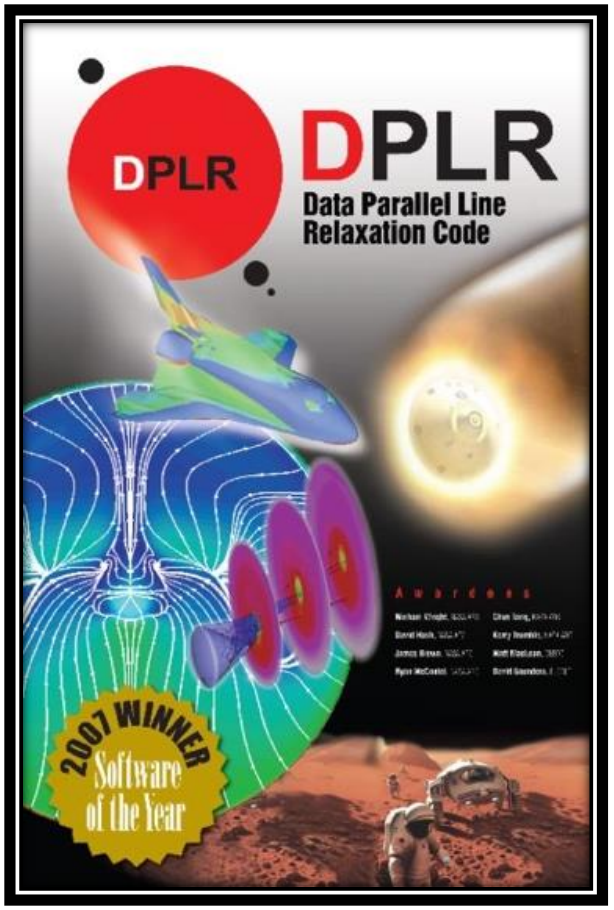


Test Design & Analysis



Aerothermal CFD

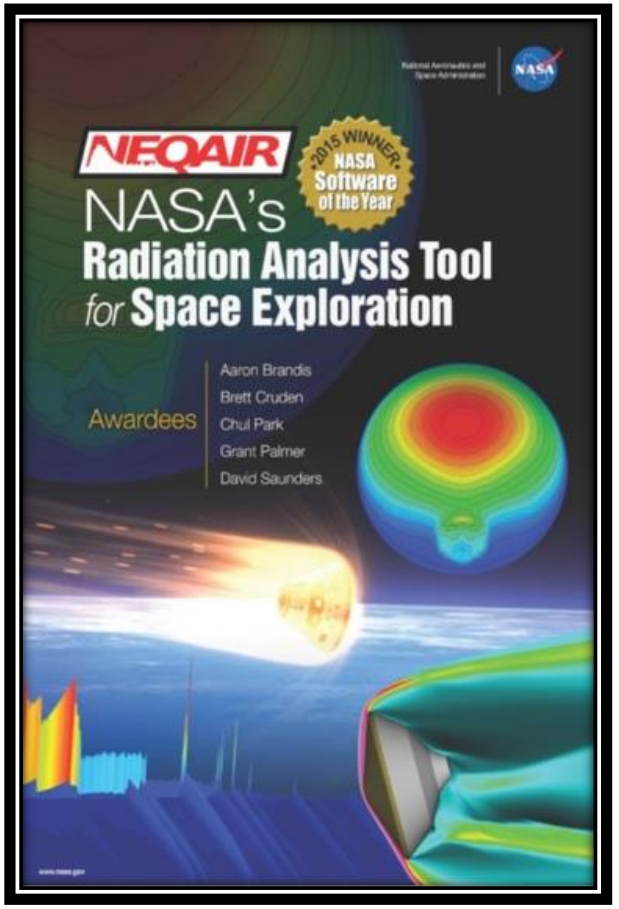
- DPLR is Code TSA's principal tool for aerothermal CFD analysis.
  - MPI parallel, block structured, finite volume code.
  - Simulates multispecies gas mixtures in chemical and thermal non-equilibrium for all planetary atmospheres.
  - Developed by M. Wright, uses 2T thermal non-equilibrium model of C. Park, both TSA Emeritus.
- DPLR (+LAURA from LaRC) is the foundation of NASA's entry system design process.
  - Used on every entry system of the past two decades.
  - Heavily validated against ground and flight test data.
- TSA collaborates with U. of Minnesota to develop US3D, the unstructured successor of DPLR.
  - Both codes in use, slow migration towards US3D.
  - US3D provides new analysis capabilities not possible with DPLR, foundational to current research efforts.



US3D

Shock Layer Radiation

- Non-Equilibrium Air (NEQAIR) is TSA's primary tool for high temperature gas radiation modeling.
  - Line-by-line spectral computation of radiation intensity with solution of 1D transport equation.
  - Boltzmann or QSS models for excited states.
- Enables radiative heat flux prediction for planetary entry systems:
  - Forebody: Tangent-slab approximation, ~hours.
  - Backshell: Full angular integration, ~days.
- Heavily validated against shock tube experiments and relevant flight test data.
- Can be coupled to DPLR to account for radiative cooling of shock layer.
  - Yields significant reduction in radiative and convective heating for high speed, e.g. lunar return, entries.

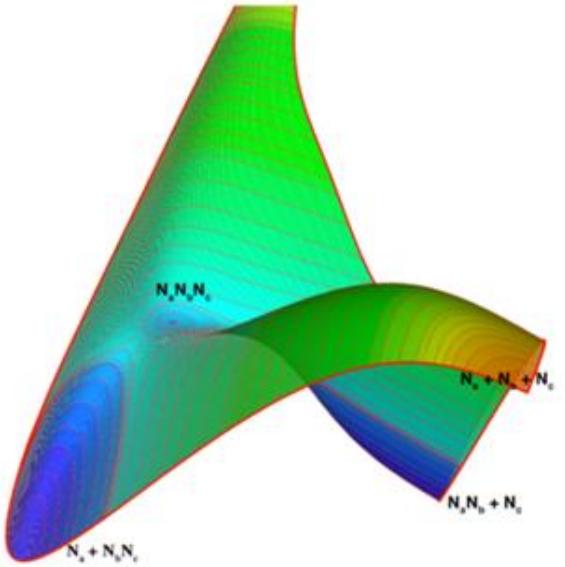


Shock Layer Kinetics

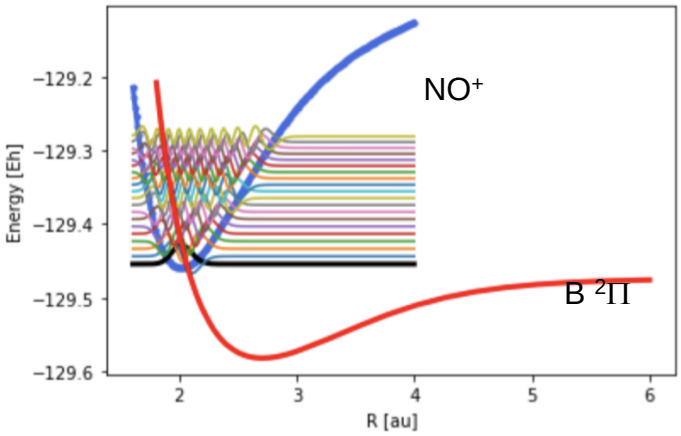
- Planetary entry modeling requires <u>hundreds</u> of parameters describing the non-equilibrium behavior of the gas.

- Historically, many key parameters were inferred from experimental data and have high uncertainties.
  - Models must be valid at high temperature conditions which are difficult to investigate.
  - Hard to construct experiments sensitive to details of the non-equilibrium kinetics.

- TSA contributes to development of non-equilibrium chemistry model using computational chemistry techniques.
  - *Ab initio* potential energy surfaces (PES) for N_3, N_4, and CO_2.
  - Rate coefficients for N_2+N, N_2+N_2, CO+Ar, CO+O.
  - Dipole transition moments for radiative emission.
  - State-specific kinetic models.

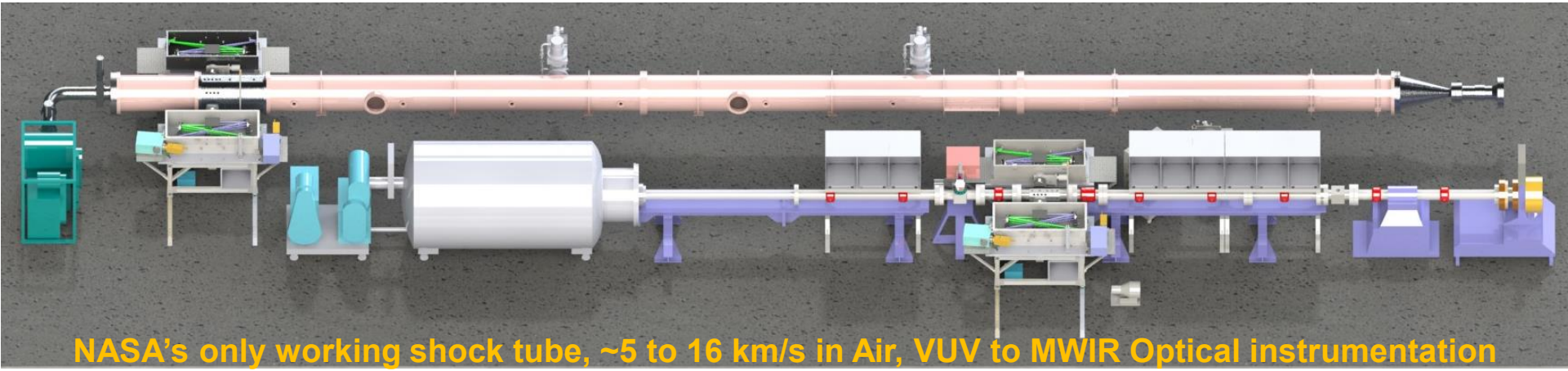


N3 potential energy surface.



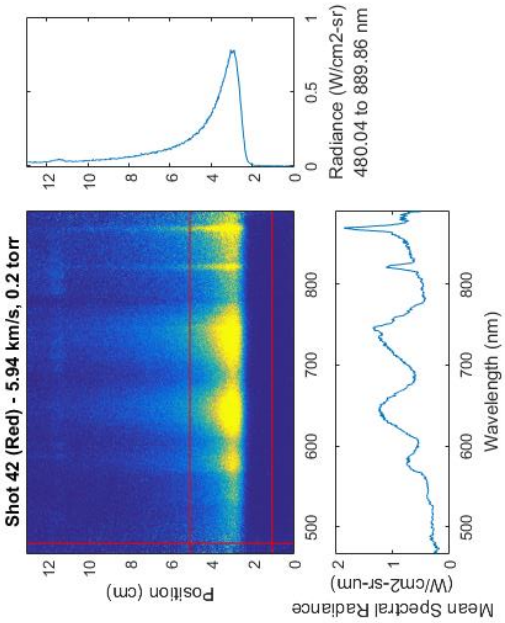
Nuclear dynamics simulation of NO dissociative recombination.

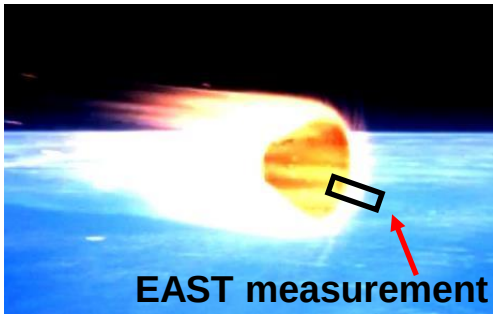
Electric Arc Shock Tube (EAST)

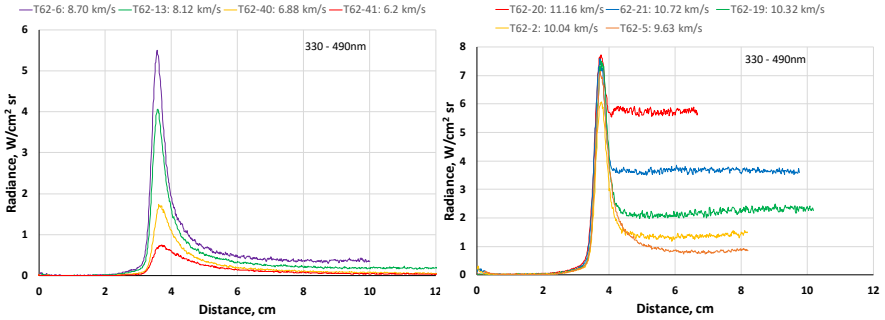


- Shock tube produces conditions analogous to those behind bow shock of hypersonic flight vehicles
- Emission spectroscopy characterizes radiative heating from excited gas, spectral signatures and dissociation processes
- Measurements used to benchmark radiative heating predictions, e.g. using NEQAIR, for flight missions and inform margin policy

Example EAST data





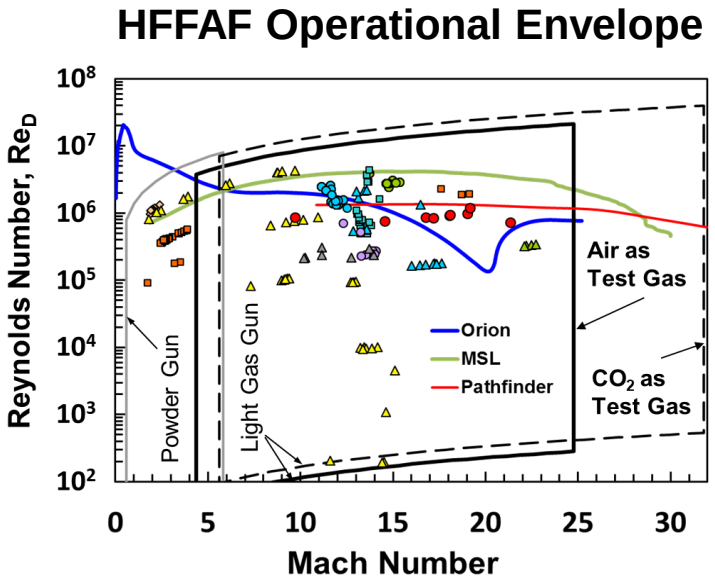


EAST UV data for N_2 from 6.2 to 11.2 km/s

AIAA 2018-3437

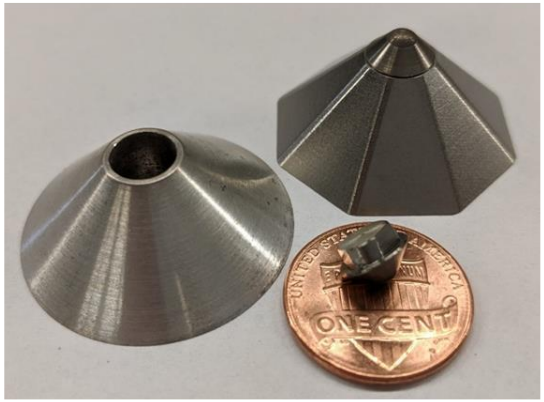
Hypervelocity Free Flight Aerodynamic Facility (HFFAF)





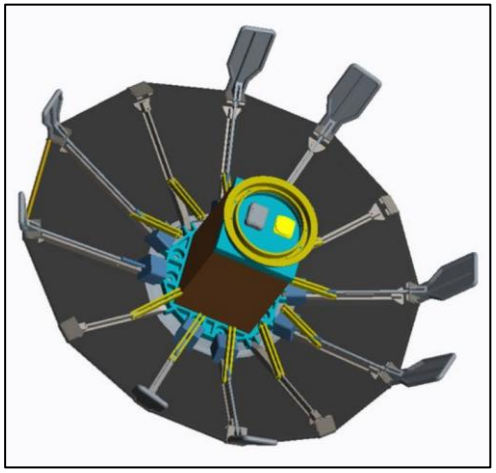
- Free-flight ground test of entry aerodynamics and aerothermodynamics
  - Light Gas Gun launches models through quiescent test gas.
  - Enable observation of vehicle dynamics without model-support interference.
  - Infrared thermal imaging provides global heat transfer maps on vehicle surface.

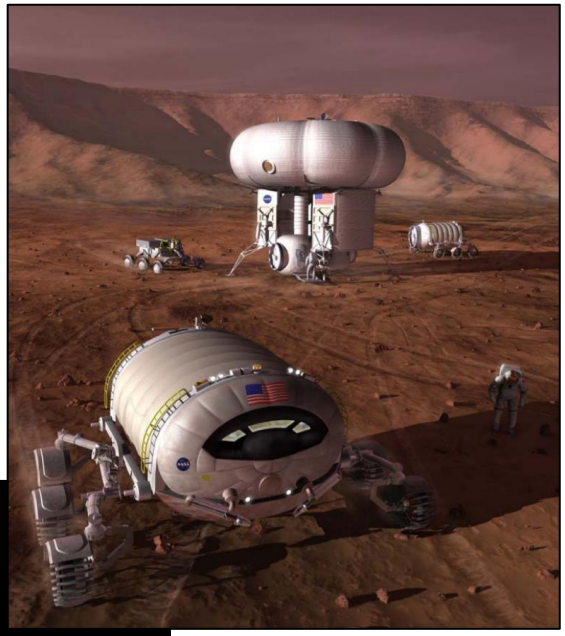
- Operational Envelope
  - Velocity: 0.2 km/s to 8.5 km/s
  - Pressure: $4x10^{-5}$ to 1 bar
  - Test Gas: Air, N_2, CO_2, He/H_2, Ar, etc.
  - Diameter: 8 mm to 38 mm

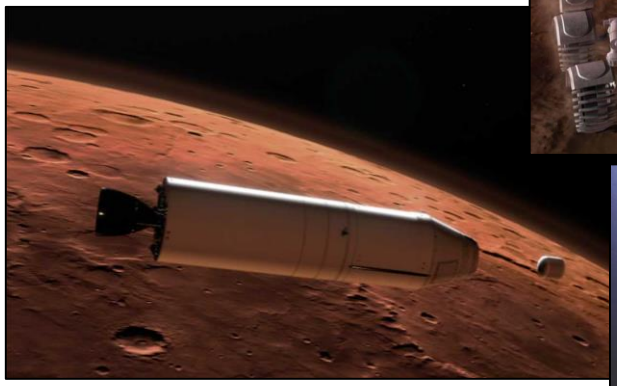


Looking Forward

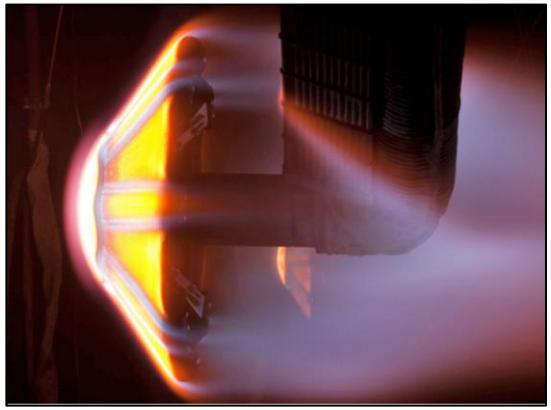
- NASA is already hard at work designing a new generation of space missions.
- These ambitious missions will demand novel entry systems that exceed existing design and analysis capabilities.
- TSA will continue to leverage our rich history and innovative spirit to help solve NASA's entry systems challenges.





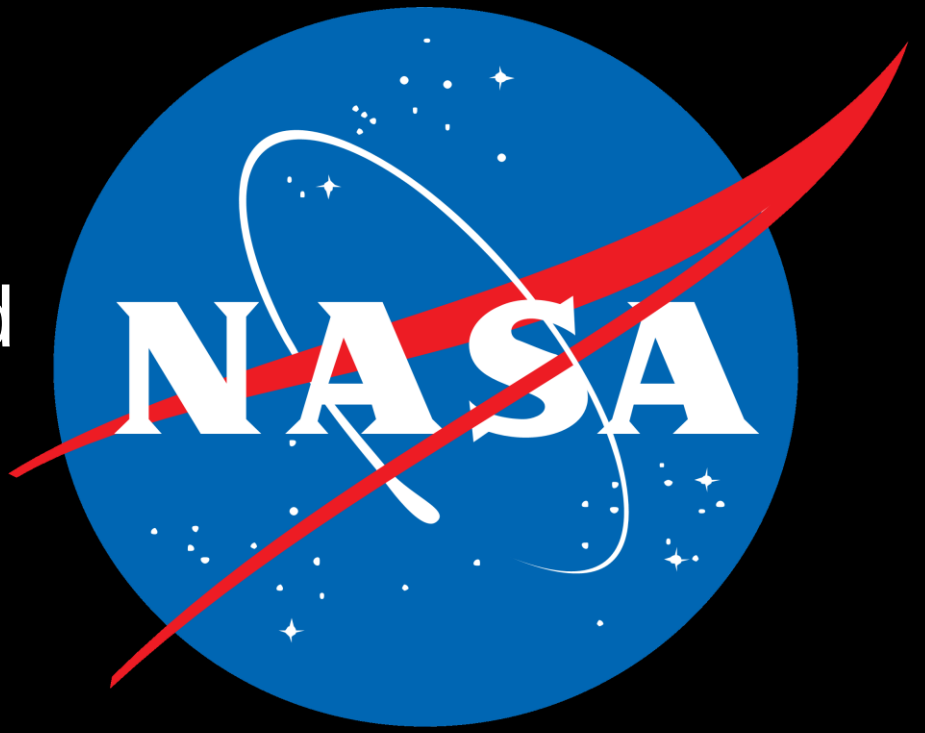






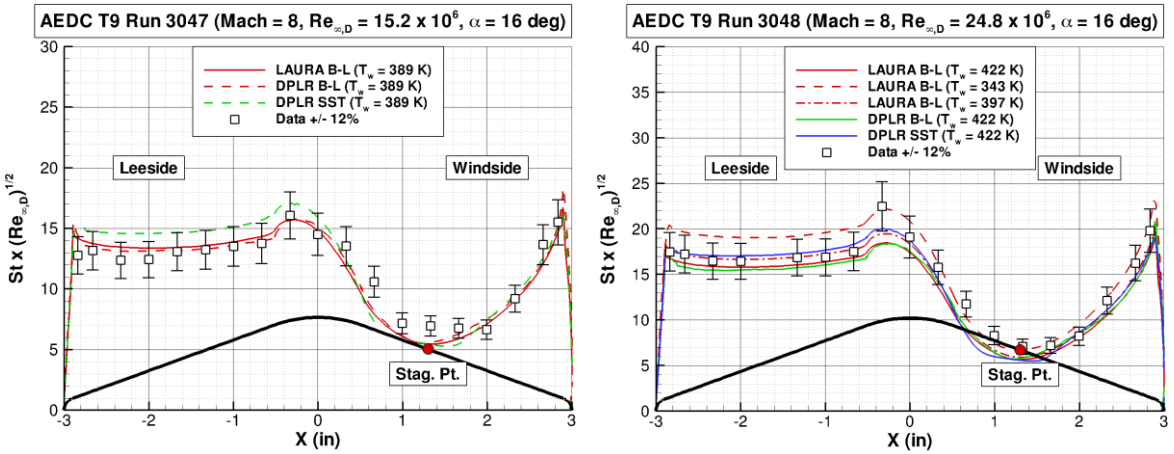
Code TSA is a trusted mission partner enabling NASA's vision to *Go*, *Land*, *Live* and *Explore* beyond Earth.

National Aeronautics and
Space Administration

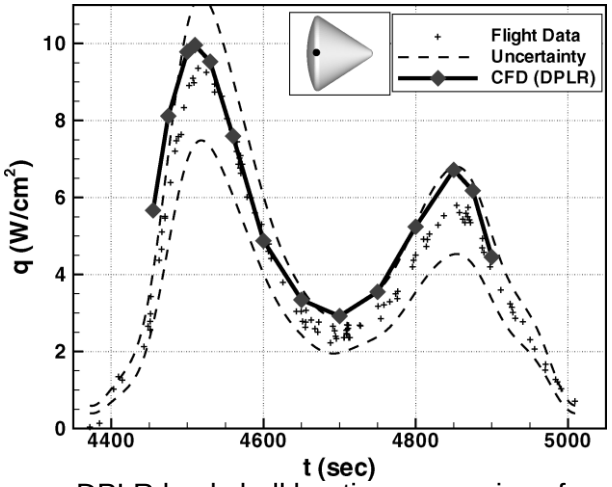


Ames Research Center
Entry Systems and Technology Division

Aerothermal CFD



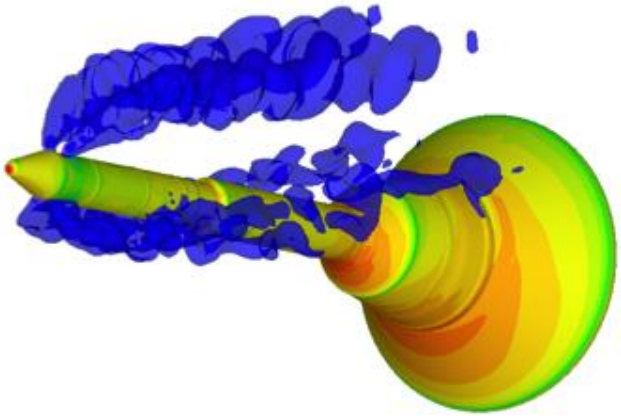
LAURA and DPLR Heat Transfer Compared to AEDC Tunnel 9 Data (AIAA 2009-4075)

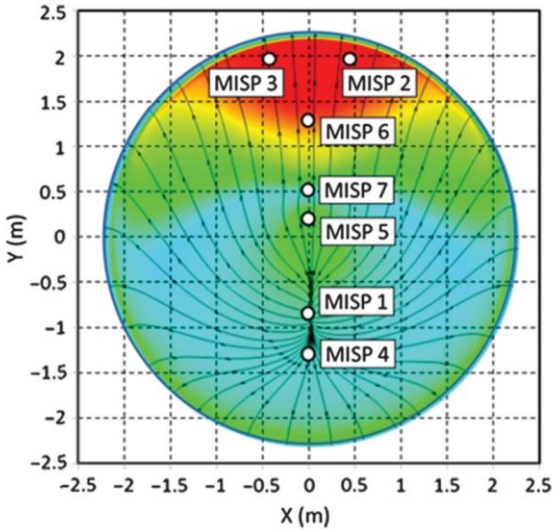


DPLR backshell heating comparison for Apollo AS-202 entry (JTHT Vol 20, No 1)

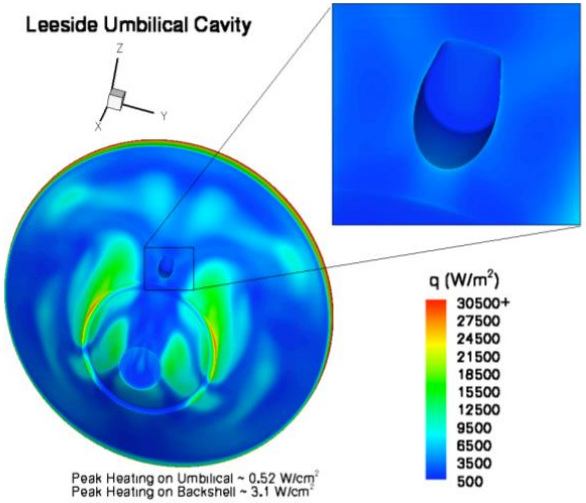
Validation

Application





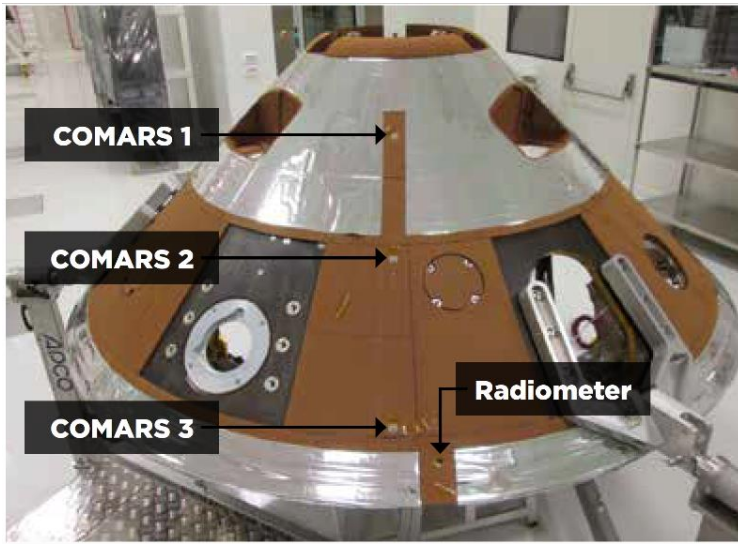
AIAA 2013-2779

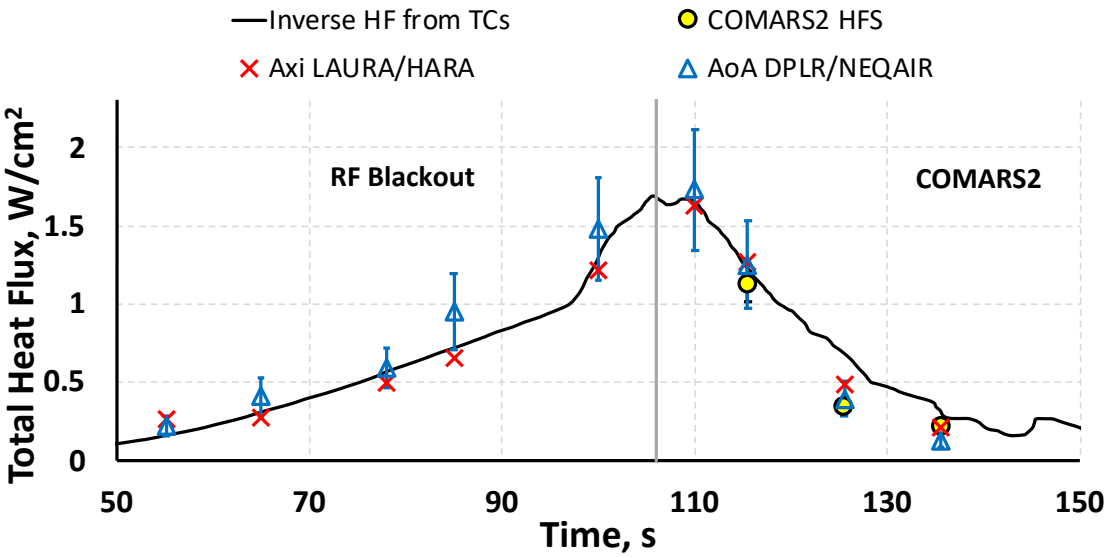


AIAA 2008-1279

Schiaparelli Data Analysis[1]

- Until recently, NASA design practices did not consider radiative heating on the backshell; believed insignificant.
- EXOMARS studies in Europe suggested that MWIR radiation from CO_2 could exceed convective heating.
- Schiaparelli lander was instrumented to measure total & radiative heating on the backshell → first flight measurement of CO_2 radiation.
- Analysis of this data demonstrated that EAST-derived radiation models enable accurate prediction of measured heating.

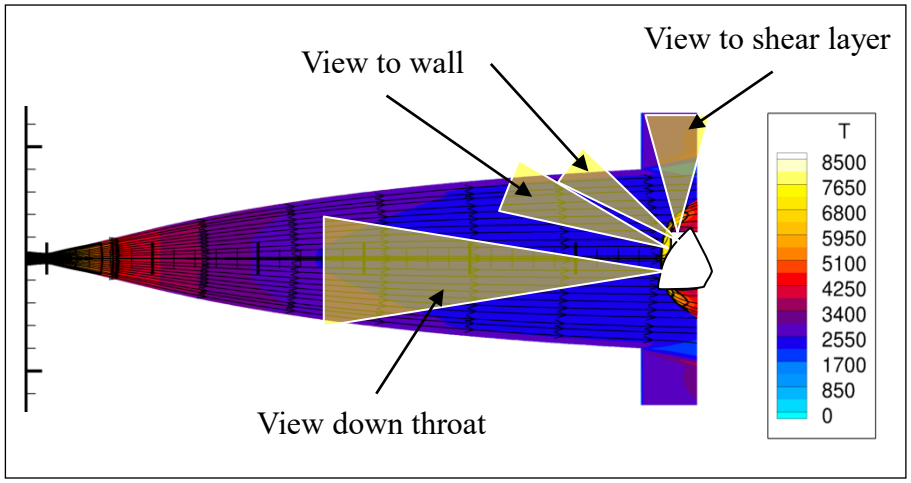


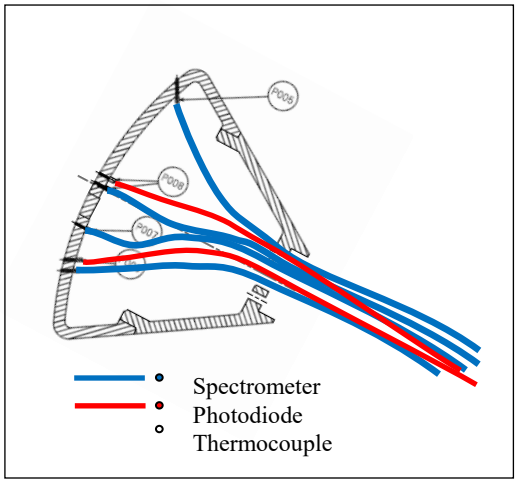


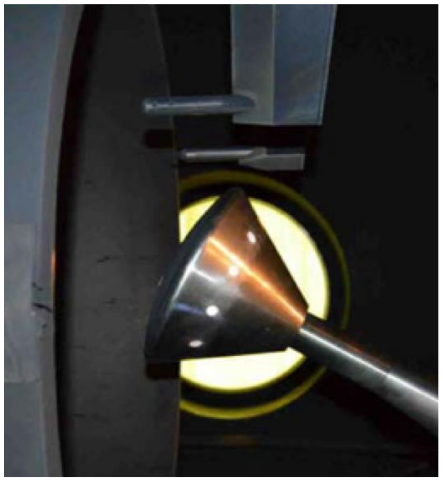
[1] AIAA 2019-3260

HIEST Heating Anomaly[2]

2021 AIAA Best Thermophysics Paper



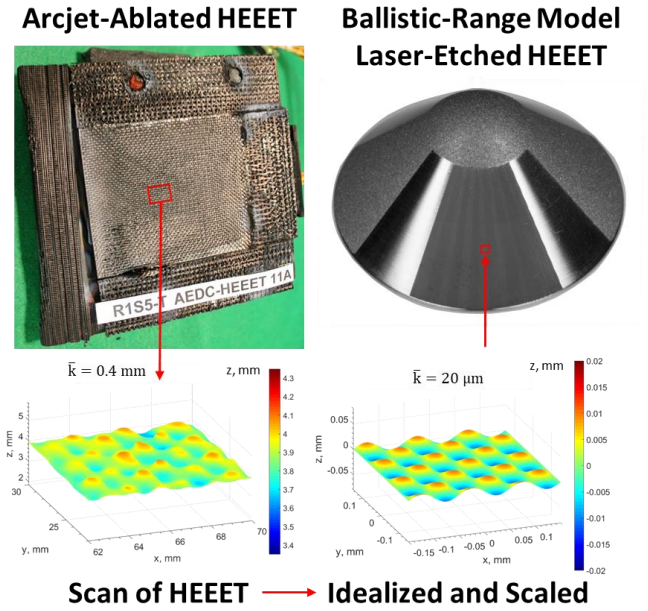


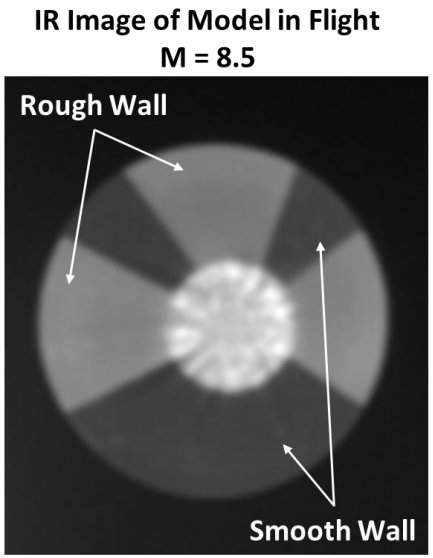


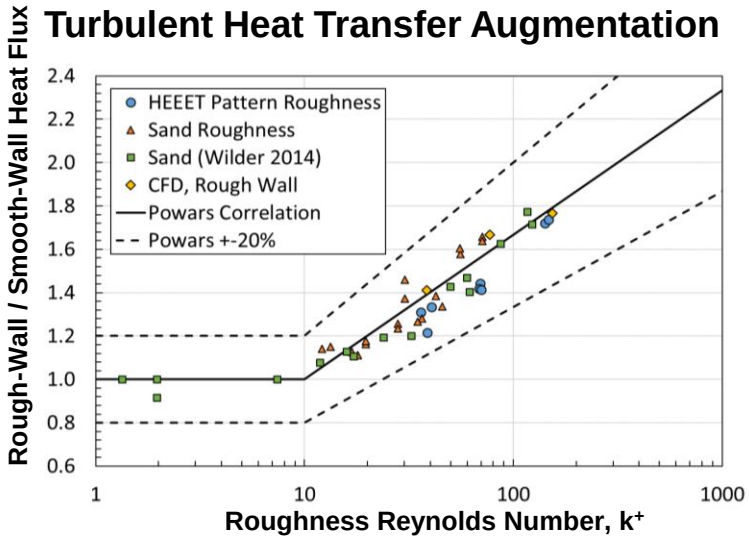
- JAXA HIEST is world's largest high enthalpy reflected shock tunnel.
  - Used to study of vehicle heating at super-orbital conditions.
  - Orion MPCV is using HIEST to investigate heating on 1/40th scale Apollo Capsule.
- Previous test campaigns measured anomalously high heating on the test article, likely from shock layer radiation due to iron impurities.
- Recently, Code TSA lead a test campaign that instrumented the model with multiple fiberoptic spectrometer to positively identify the source of the heating.
- Onset of the anomalous heating was shown to be consistent with establishment of the bow shock, with spectral analysis confirming stainless steel contaminants.

[2] AIAA 2021-0103

Mission Relevant Roughness[3]







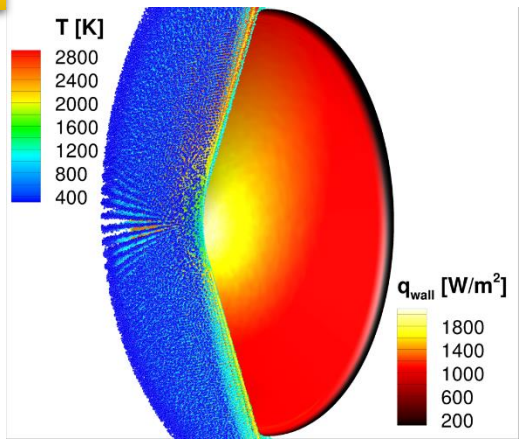
- Current CFD state-of-the-art unable to reliably predict hypersonic turbulent heat transfer for rough surfaces.
- Current design practices apply test-derived augmentation factors to CFD smooth wall heatflux predictions.
- Legacy correlations based on sand grain roughness, but modern woven TPS materials have highly regular, anisotropic surface patterns.
- Work underway to extend correlations to mission-relevant surface roughness.

[3] AIAA 2019-3009

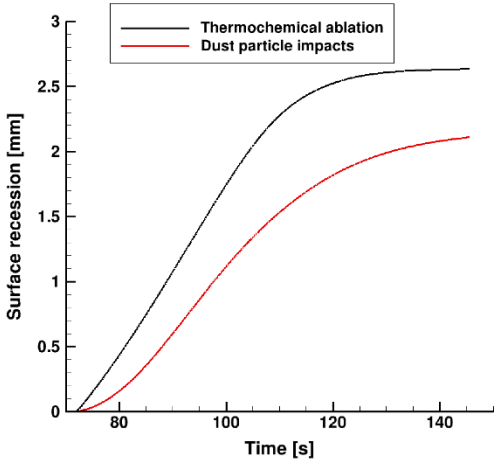
Simulation of Dusty Flows [4]

2020 AIAA Best Thermophysics Paper

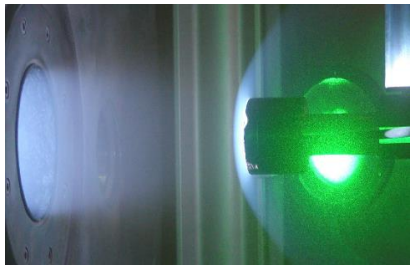
- Spacecraft entering Martian atmosphere face a unique challenge – the presence of dust.
- Heatshield erosion due to particle impacts during a major regional or global dust storm can increase TPS thickness and/or reducing TPS margins.
- Research performed in Code TSA for the ESM project is developing the capability to model dusty flows.
  - DUST, a Lagrangian particle solver, has been developed and coupled with US3D to model particle-fluid interaction.
  - Particle impact surface damage models have been built into the Icarus material response solver.
- Experiments to be performed in the DLR L2K arcjet facility will generate new dust erosion data for enhanced surface damage models.



Dust particles traveling through shock layer, Schiaparelli entry capsule



Heatshield erosion due to thermochemical ablation and dust particle impacts during 2007 global dust storm.



Dust-laden flow in L2K arcjet.

[4] G.E. Palmer, et al., "Modeling Heatshield Erosion due to Dust Particle Impacts for Martian Entries"

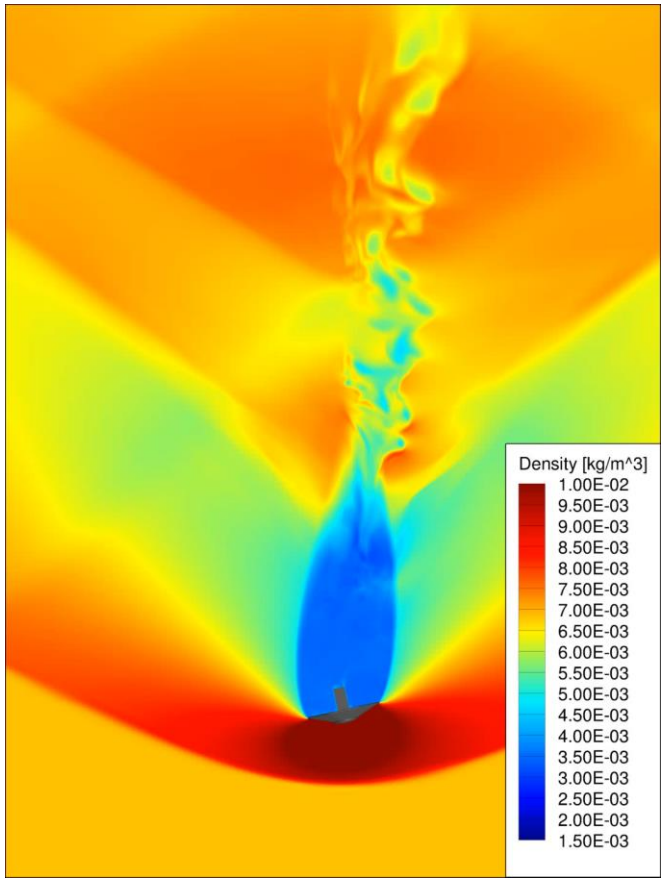
Dynamic Capsule Stability

- To date, assessment of capsule dynamic stability at NASA has relied exclusively on experimental data.
- Code TSA is leading an effort to develop time-accurate simulation tools able to accurately predict the onset and growth of dynamic instability.
- Capsule stability depends on accurate simulation of the massively unsteady wake, which present unique numerical challenges:
  - Requires low-dissipation, high-resolution flux schemes.
  - Requires high-accuracy, efficient time integration schemes.
  - Requires high-quality, high-resolution wake grids.
  - Requires generalized, quality-preserving grid motion strategies.

TSA seeks to break reliance on heritage aeroshell shapes by reducing the expense required to characterize the stability of new designs.



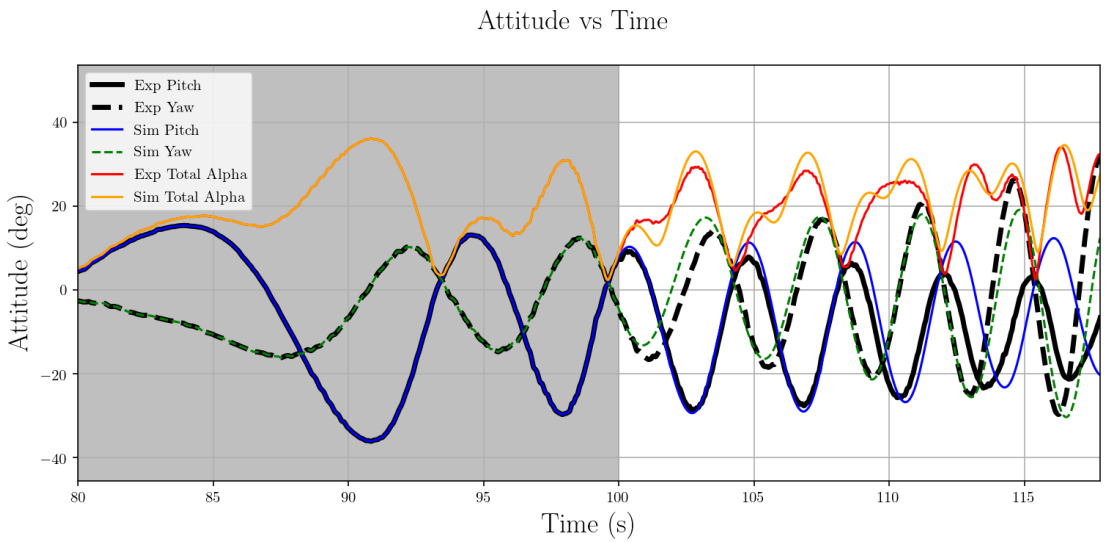
Capsule Dynamic Stability



ADEPT supersonic descent simulation.



AA-2 Launch Abort Test just before capsule separation.



Flight data comparison for AA-2 post-capsule-separation dynamics.