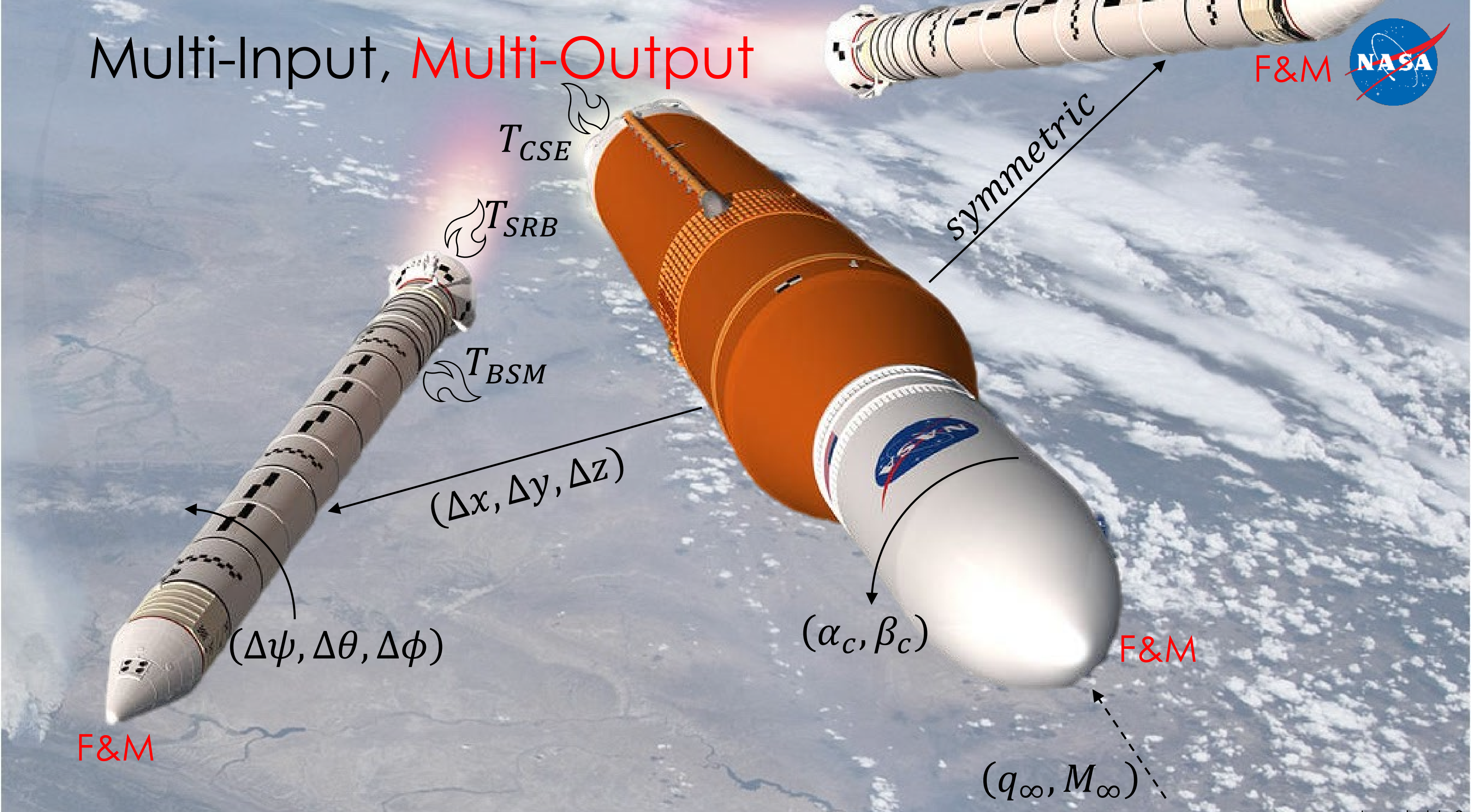
Development of Aerodynamic Loads Databases for the Space Launch System Booster Separation Event

Michael Lee, Derek Dalle,
Michael Sanders, Carole Addona

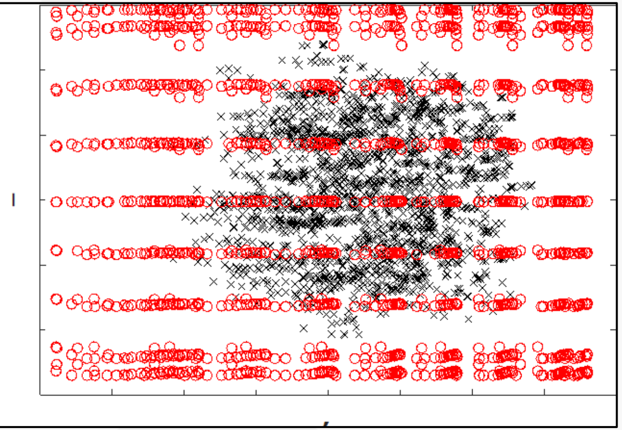
2024 AIAA SciTech Forum

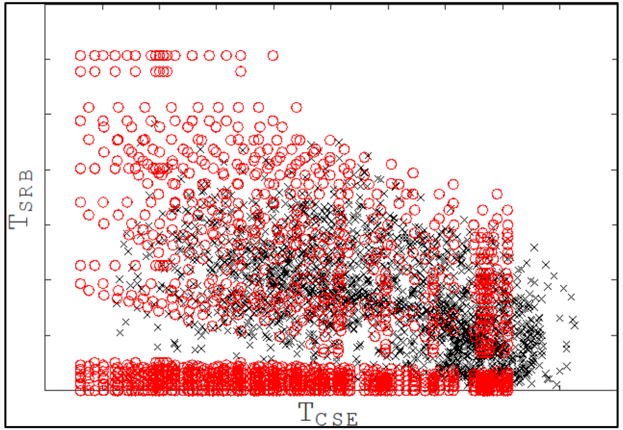
Multi-Input, Multi-Output

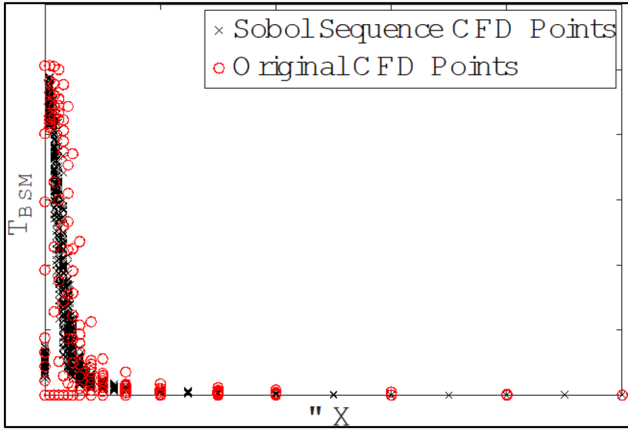


SLS Booster Separation Aero Database

- Captures freestream, motor plume, and shock envelope effects
- Spans and informs broad separation trajectory window







Data Pipeline

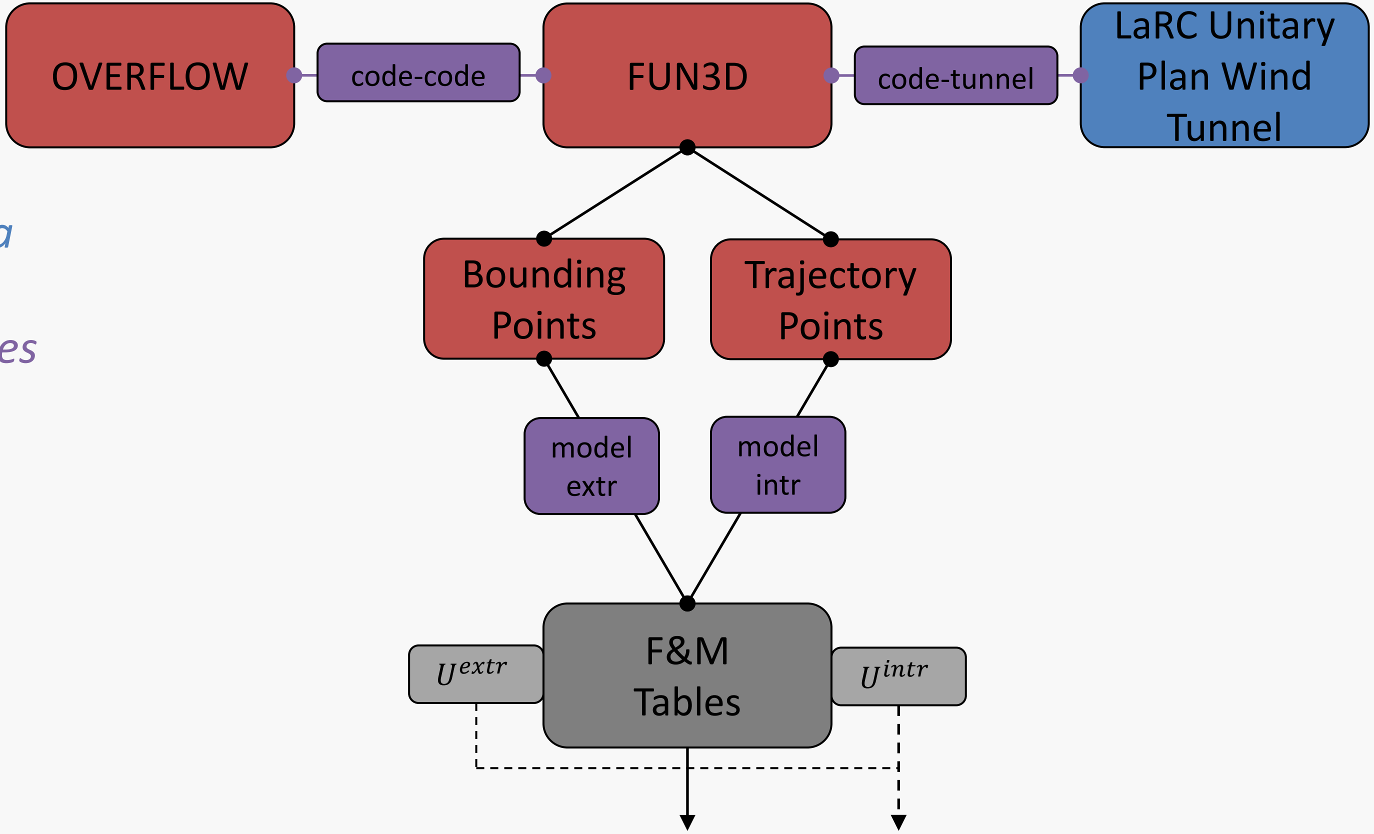
Tunnel Data

CFD Data

Uncertainties

Delivered Loads

Trajectory Simulations

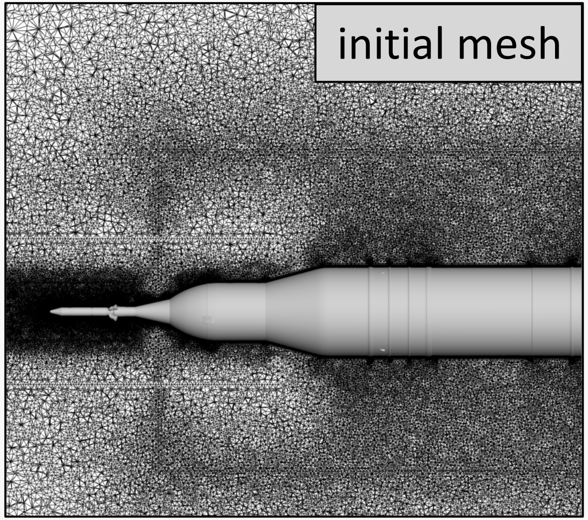


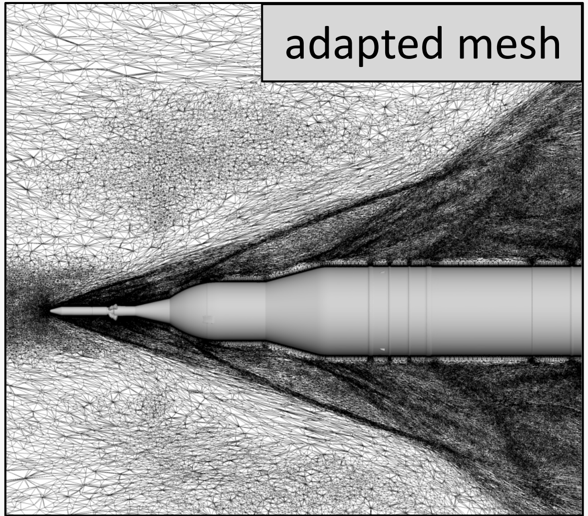
$$C_Y^{RSRB}(\vec{p}, \epsilon) = C_{Y,nom}^{RSRB}(\vec{p}) + \epsilon U C_Y^{RSRB}(\vec{p})$$

Nominal Data Pipeline

FUN3D Simulations

- Thousands of simulated points
- Steady RANS-SA
  - Asymptotic or limit cycle iteration convergence
- Perfect gas everywhere
  - Engine temperature not matched
  - Engine thrust matched via freestream ratios of pressure and temperature
  - Engine mass flow matched
- Off-body mesh adaptation based on Mach number

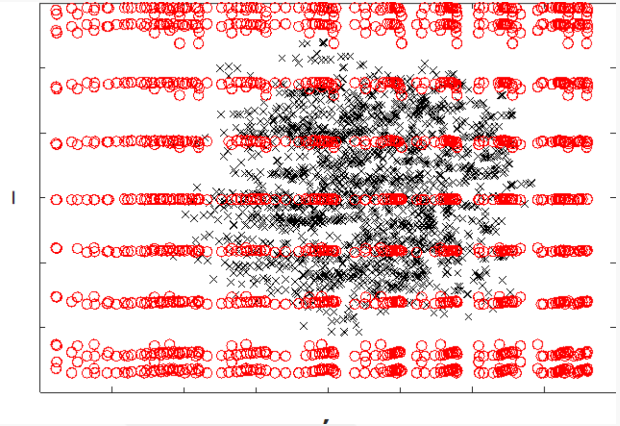


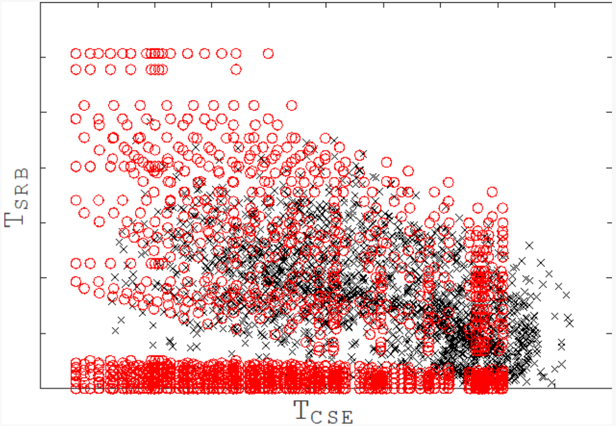


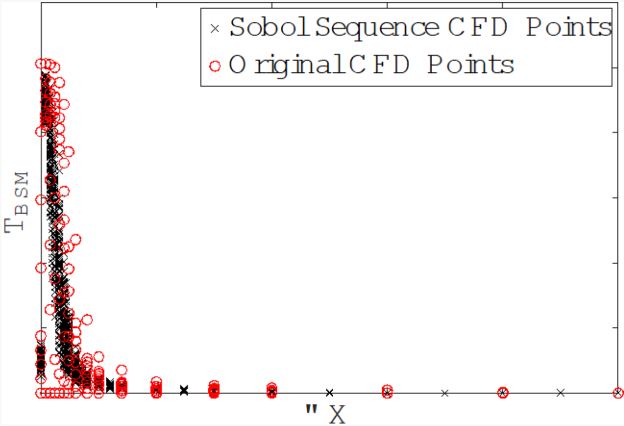
13D Run Matrix Organization

- Original bounding run matrix sought to capture entire viable separation envelope

- Secondary Sobol sequence to more densely fill simulated trajectory window







Data Table Interpolation

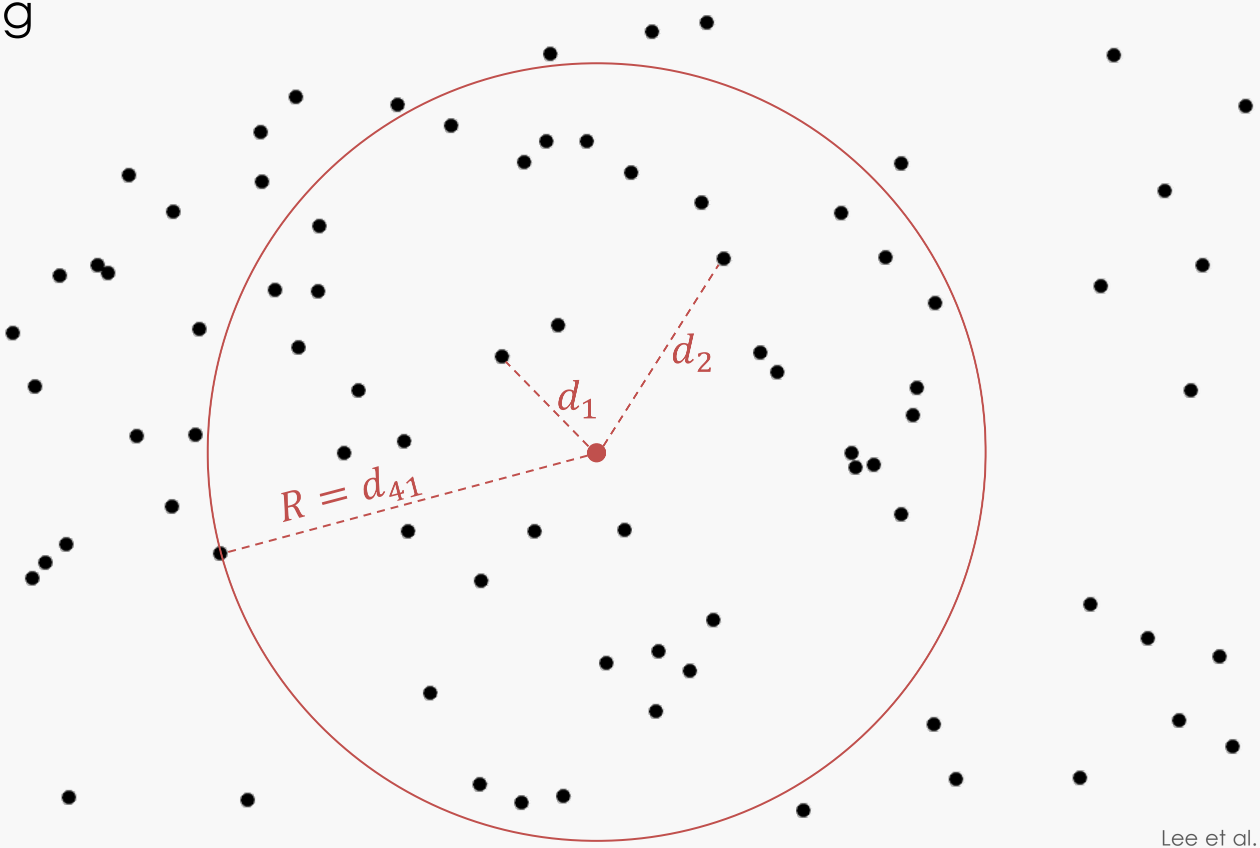
Inverse Distance Weighting
with an R-sphere

$$v_q = \frac{\sum wv}{\sum w}$$

$$w_n = \left(\frac{\max 0, R - d_n}{R d_n}\right)^2$$

$$d_n = \left|\frac{p_q - p_n}{D_{ref}}\right|$$

D_{ref}: per-unit norm.



Data Space Dimension Reduction

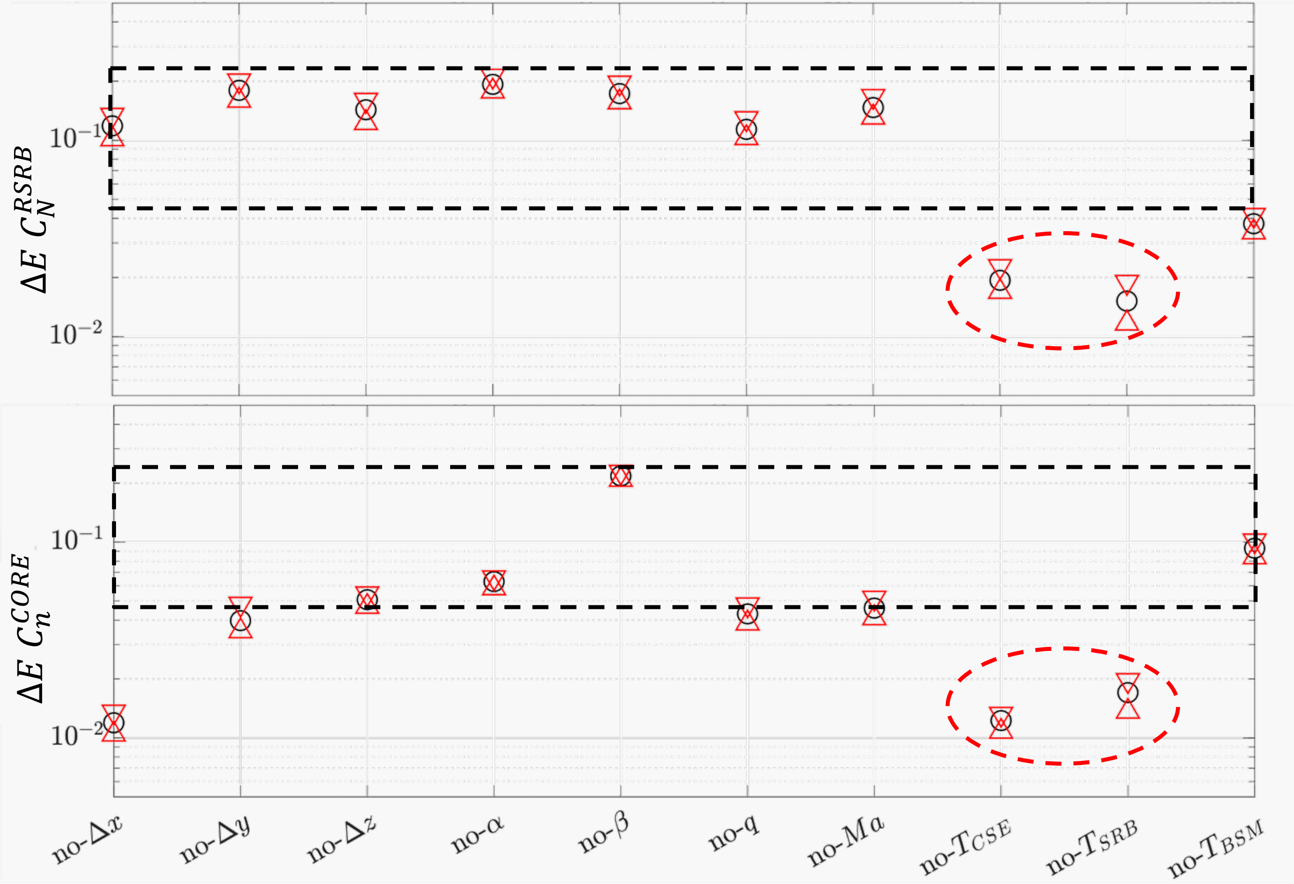
- Are the F&M outputs sensitive to all thirteen parameter inputs?

- 50 different times:
  1. Randomly assign 75% of CFD points as P_{train} and 25% as P_{test}
     - 75%-25% split done separately at each principal ΔX
  2. Interpolate from P_{train} in 13D and find $E_{ALL}(\Delta X) = rms\left|P_{all}^{ITP} - P_{all}^{CFD}\right|$
  3. Interpolate from P_{train} in 12D and find $E_{LOO}(\Delta X) = rms\left|P_{all}^{ITP} - P_{all}^{CFD}\right|$
     - Flatten each dimension once, except Euler angles

- Observe min/mean/max trends in $\Delta\mathrm{E}(\Delta X) = |E_{ALL} - E_{LOO}|$

Data Space Dimension Reduction

Order-of-magnitude sensitivity comparison



thrusts T_{CSE}, T_{BSM} disregarded in data tables

Uncertainty Pipeline and Trajectory Simulations

Uncertainty Model

- Uncertainty captures differences between FUN3D and:
  - Alternative simulated plume physics
    - Multispecies plumes modeled with OVERFLOW
  - Physical full-configuration flow physics
    - LaRC UPWT test with air jet BSMs
  - Interpolated physics
    - Point dropout analysis in interior/exterior space

- Additive uncertainty model

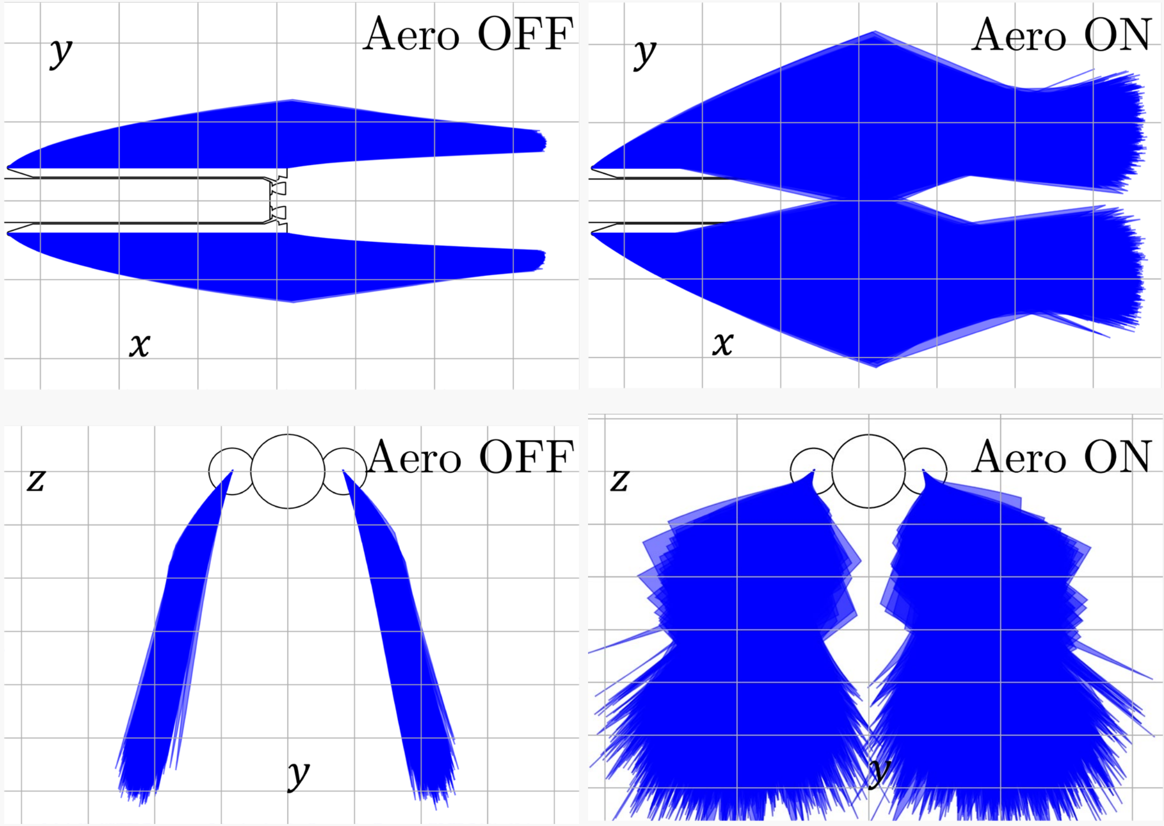
$$U_{tot}^{intr}$$

$$U_{tot}^{extr}$$

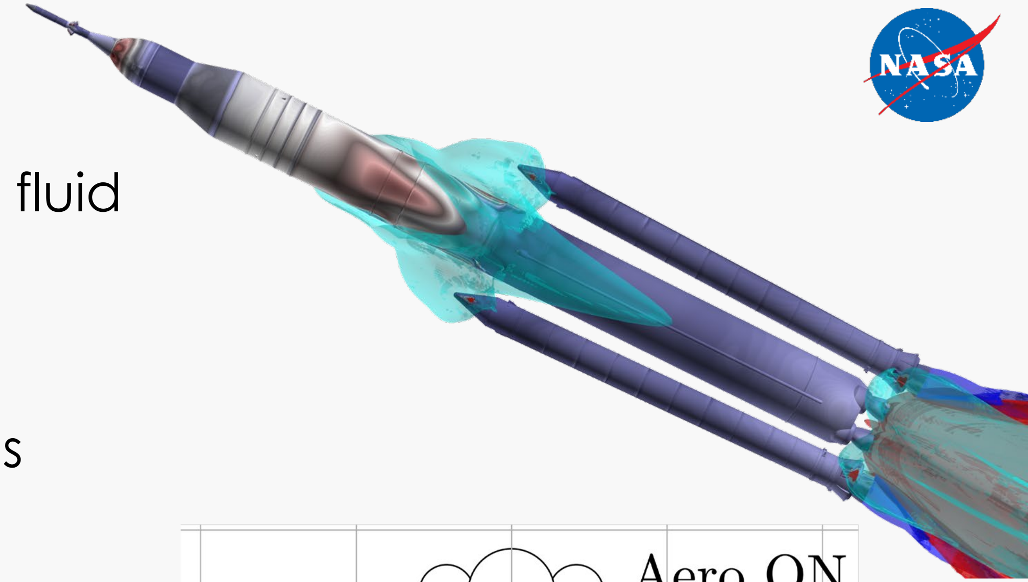
photo: NASA

Trajectory Simulations: CLVTOPS

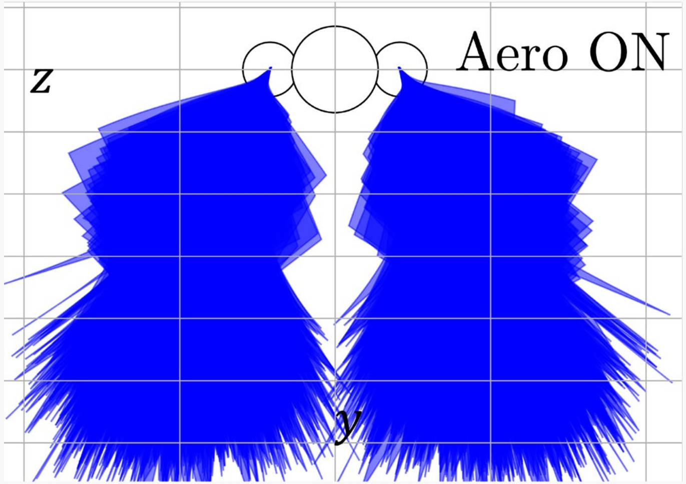
- Developed for multibody dynamic simulations
- Integrates aero database with many others
- Monte Carlo dispersions of separation trajectories



Summary



- Very complicated multibody fluid dynamics problem
- Critical for SLS launch missions
- Aerodynamic F&M database
  - Captures relevant trajectory space
  - Accounts for myriad uncertainties
  - Informs trajectory simulations and ultimate mission efficacy



National Aeronautics and Space Administration

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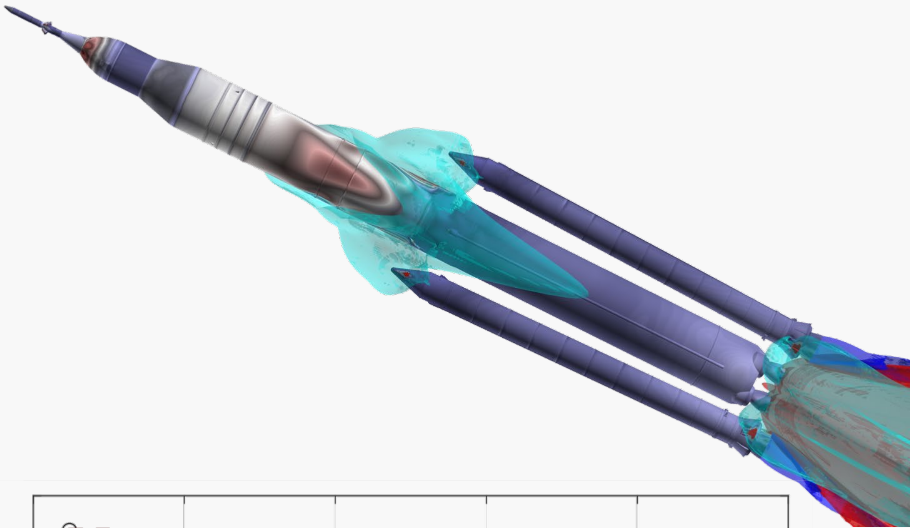
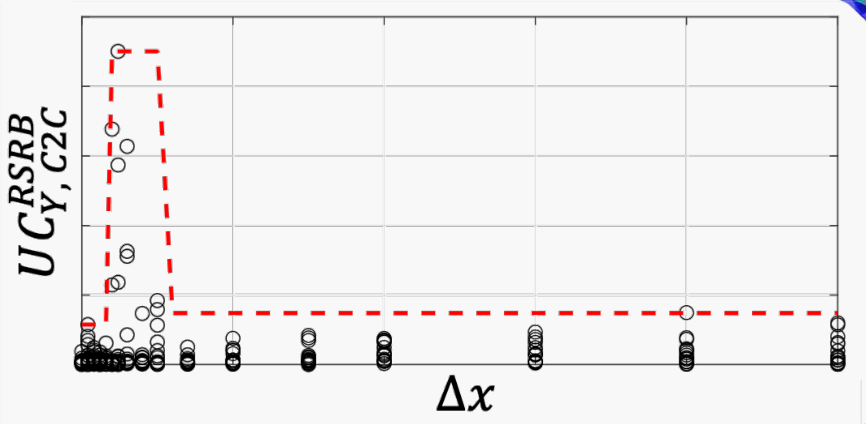
Code-to-code Uncertainty

- Compare FUN3D to OVERFLOW
- Key OVERFLOW differences
  - Overset surface mesh
  - Overset structured volume mesh
  - Multispecies engine plumes
- 99.7 percentile of F&M comparisons
  - Function of Δx
  - Dominated by few cases



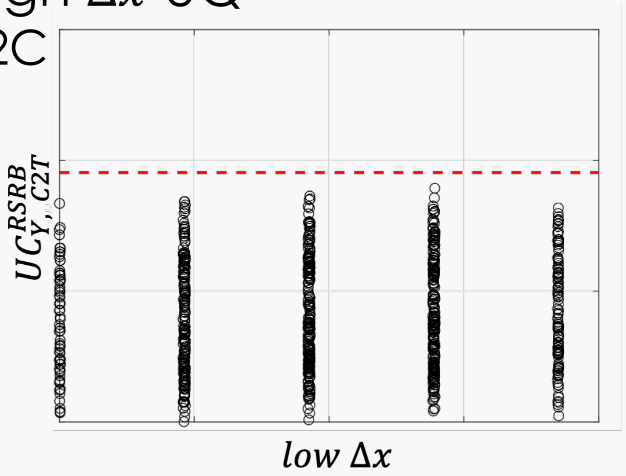


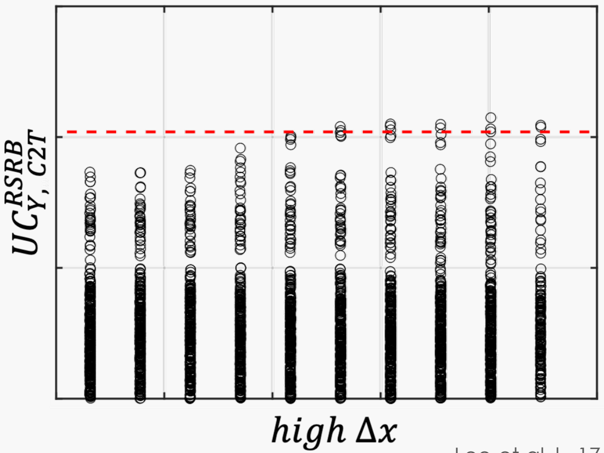
Code-to-tunnel Uncertainty

- Langley Unitary Plan Wind Tunnel test 1891 (2014)
  - Boosters mounted on separate stings
  - BSMs represented as air jets
  - CSE/SRB engines not active

photo: NASA

- BSM-on/off for low/high Δx UQ
  - More points than C2C
  - 99.7 percentile bounds





Model Uncertainty

- Identical 50-trial 25%-dropout procedure
  - 99.7 percentile bound on test point interpolations
  - $U_{mod} \leftarrow$ mean of 50 trials

- Calculated separately for exterior (bounding) points and interior (Sobol sequence) points
  - Generally, $U_{mod}^{exterior} > U_{mod}^{interior}$
  - Unnecessary penalty on interior (more relevant) data space

Model Uncertainty