

5...4...3...2...1...

SPACE LAUNCH SYSTEM

AIAA HRS Lunch and Learn
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Data Fusion Techniques for
SLS Aerodynamics Analysis

Outline

- **Introduction and Background**
- **The Wind Tunnel - Adjusted Reduced Order Model (WAROM)**
- **Conclusions and Future Applications**

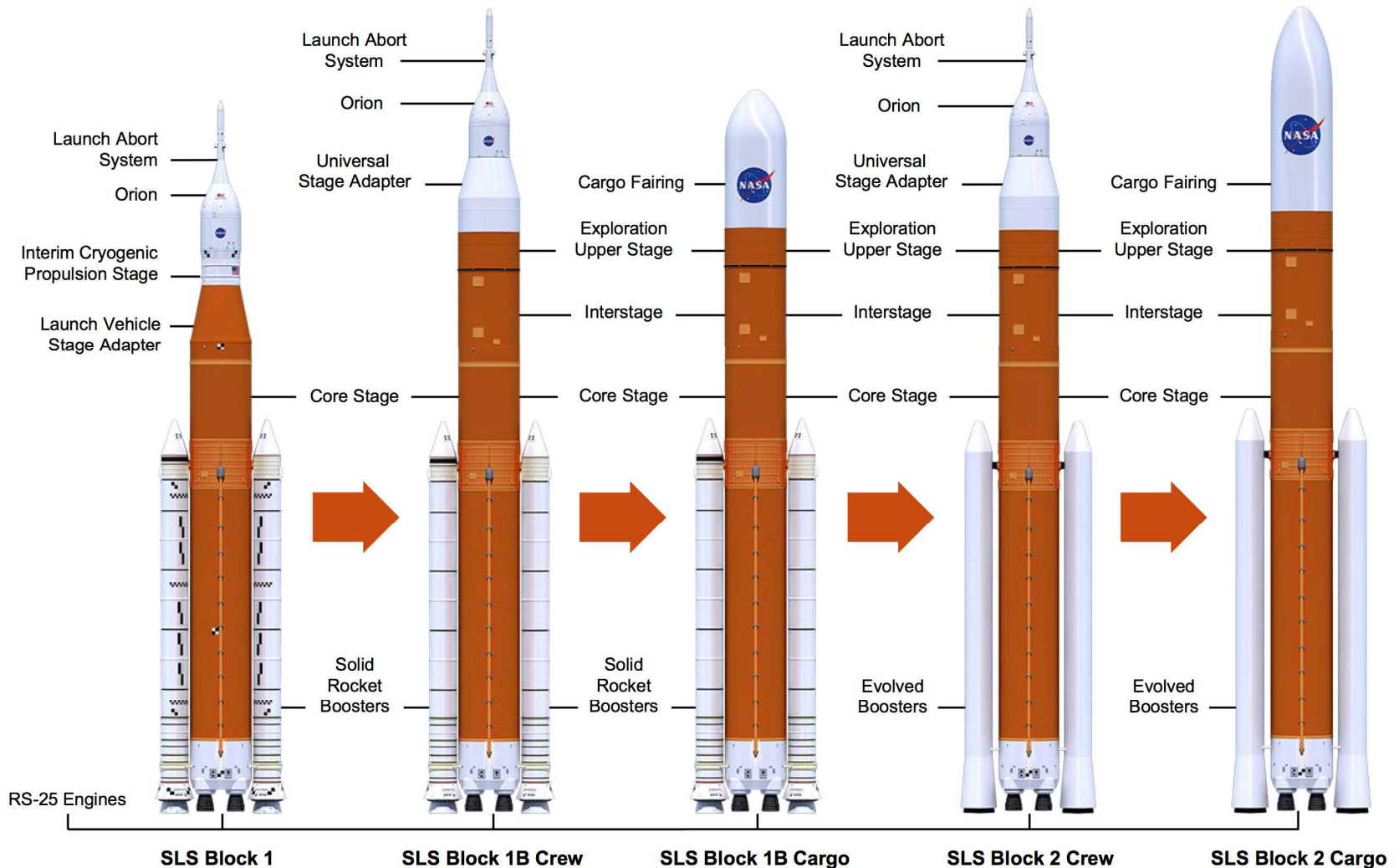


Background



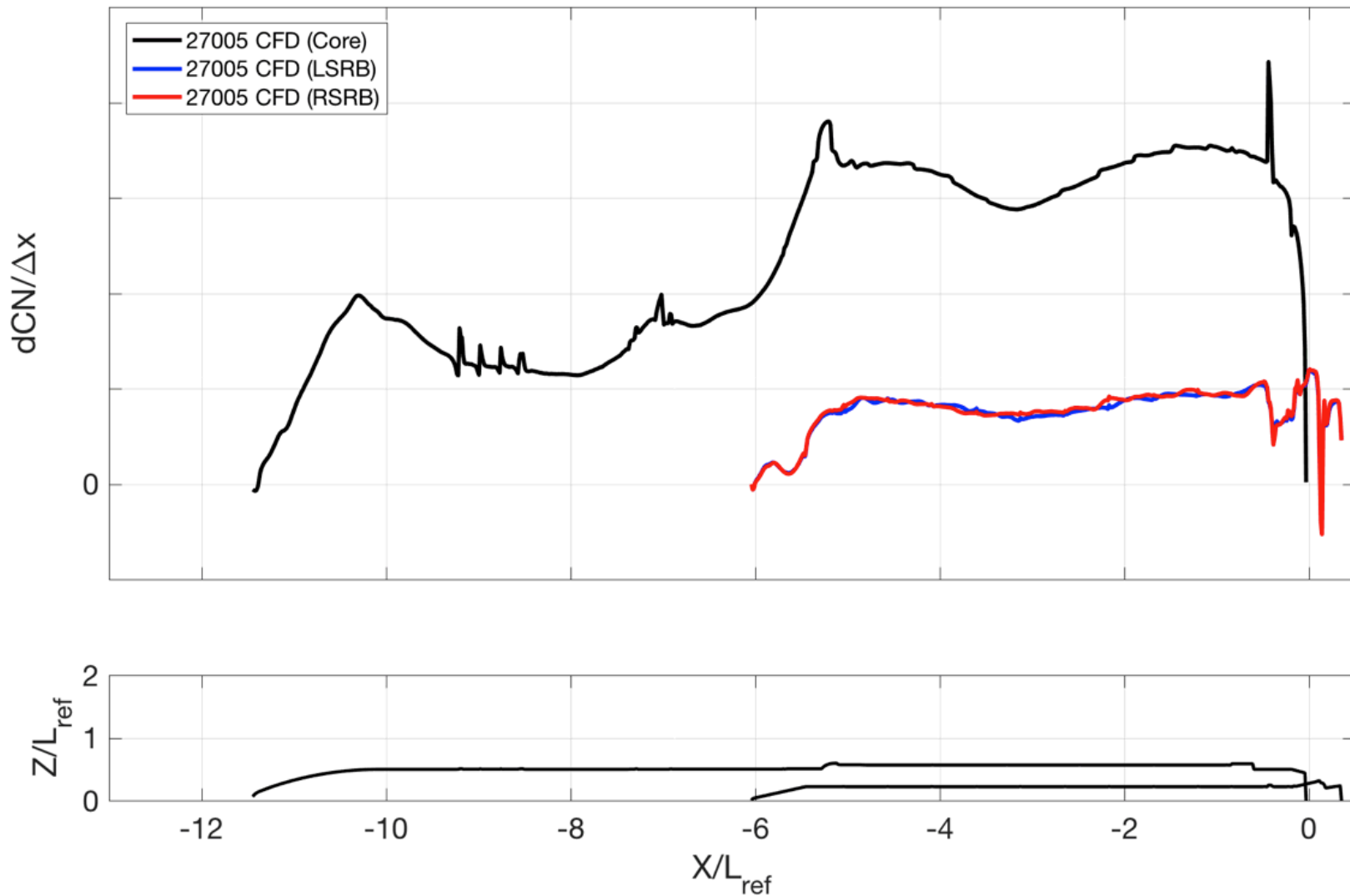
Space Launch System Overview

- **Heavy-lift launch vehicle designed to expand NASA's mission capabilities**
 - Flexible system designed to meet a variety of crew and cargo mission needs



What is a line load?

SLS-27005 LO/T Normal Force Line loads (Missile Axis) at $\alpha_T=90^\circ$, $\phi_A=0^\circ$



Representative Liftoff Lineloads Problem

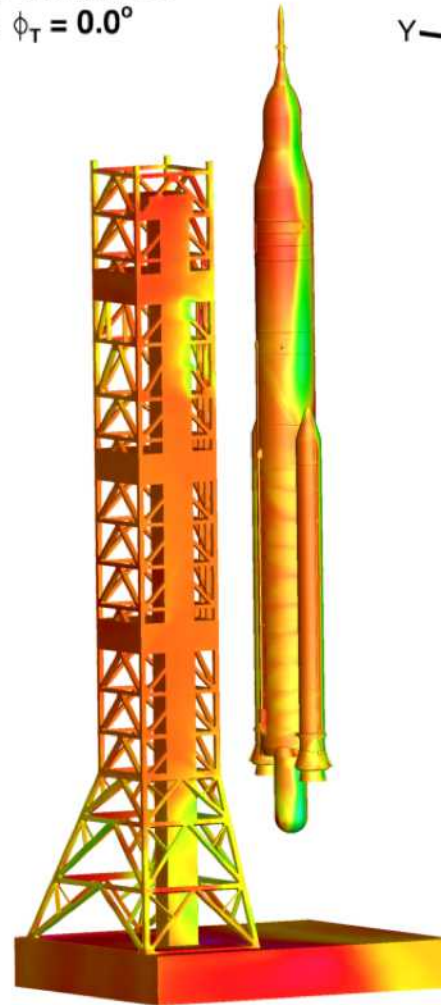
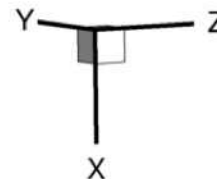
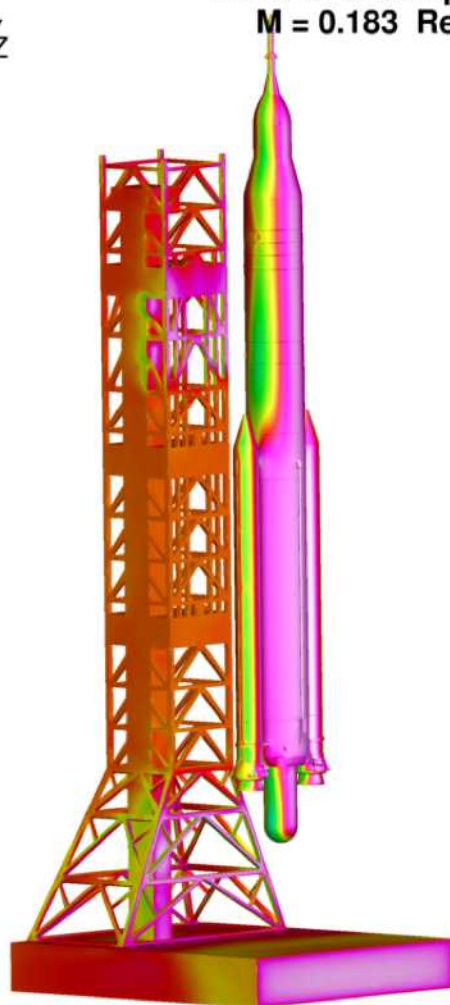
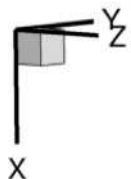
- Provide axial force, normal force, and side force lineloads for the SLS core, port SRB, and starboard SRB during Liftoff and Transition for the following conditions:
 - $\alpha_p = 0^\circ$ to 90° by 5°
 - $\phi_p = 0^\circ$ to 345° by 15°
- Aerodynamic influence of the launch tower is required as an increment (tower-on / tower-off)
- End Use: Loads & Dynamics, GNC Tower/Nozzle Clearance

SLS Block 1B Crew with Launch Tower

SLS-28005.W/Tower open gap : TimeAveraged Pressure Coefficient

Kestrel Grid: open Tower: hel27.t36p SA+DDES

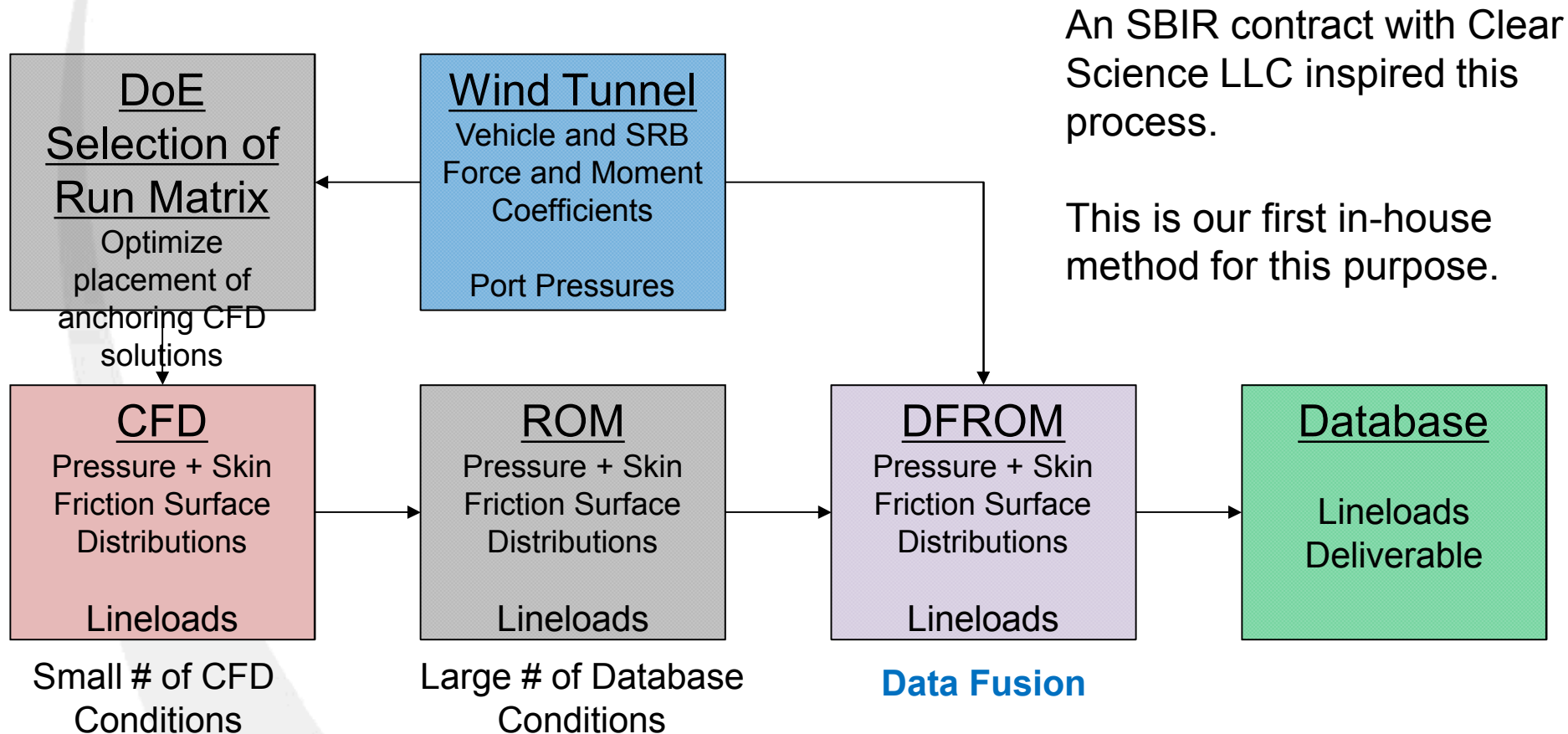
$M = 0.183$ $Re_D = 615000.0$ $h/l = 0.2$ $\phi_T = 0.0^\circ$



The Challenge

- End-user requires accurate sectional force coefficients, for both free-flight and in tower effect, for over 500 combinations of total angle-of-attack, roll angle, and height off the launch pad
- **Each individual CFD solution requires:**
 - grids on the order of 1.6 to 3.0 *billion* grid points
 - 480 to 3000 processors, depending on condition / CPU architecture
 - 3 to 9 days on Pleiades cluster, depending on same
 - careful post-processing and validation against wind-tunnel data
- **Wind tunnel provides the needed real measurement for validation, but cannot provide line loads**
- **A CFD matrix that includes all required points would be impossible, given time and resource requirements**
- **How can we use data fusion to make the best use of both wind tunnel and CFD, leveraging their respective areas of strength?**

Overview of Database Development Process



The DFROM allows a relatively small number of CFD solutions to be extended into a higher-resolution database, corrected by measured wind tunnel data.



Reduced Order Modeling



ROM Development: What is it?

- **A Reduced Order Model (ROM) is defined as a mathematical model, derived from a sequence of high fidelity observations or simulations, that preserves the essential physics and predictive capability of the original data set, but can be interrogated at a much lower computational cost**
- **Key characteristics**
 - much cheaper to interrogate at a condition than CFD
 - No significant loss of accuracy relative to the CFD
 - Can be interrogated at conditions other than those conditions used in construction of the ROM
 - A separate ROM is created for each component: Core, LSRB, RSRB

ROM Development: Objective

- Create a Reduced Order Model (ROM) that allows for approximating lineloads throughout the flight domain

$$\textit{Lineloads} = f(\alpha_P, \phi_P)$$

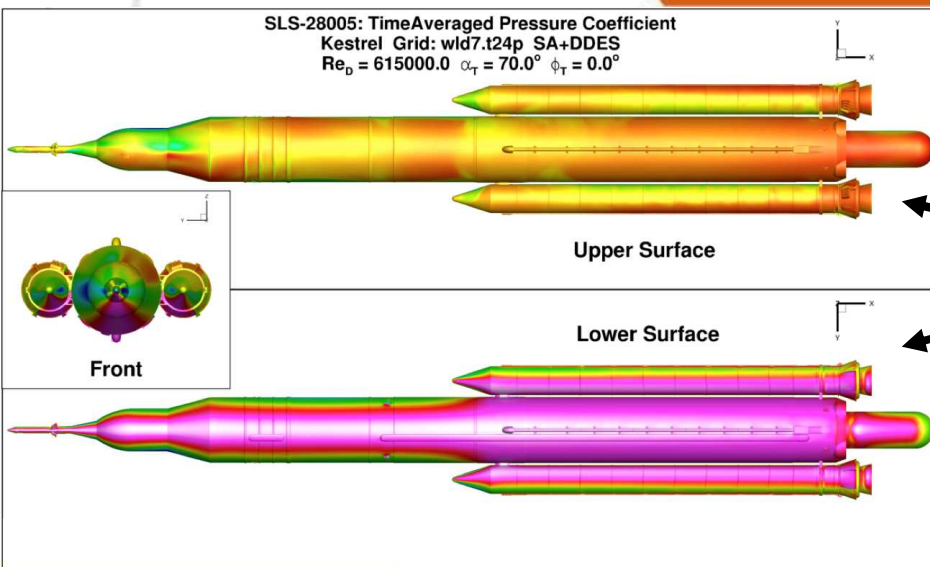
- Anchor the ROM results by equating the integrated force and moment values from the ROM with the experimentally derived values from the wind tunnel force and moment database
 - Assimilation of CFD based ROM with wind tunnel data
 - Data Fused ROM (DFROM)

$$\textit{Lineloads} = f(\alpha_P, \phi_P, F_{F\&M})$$

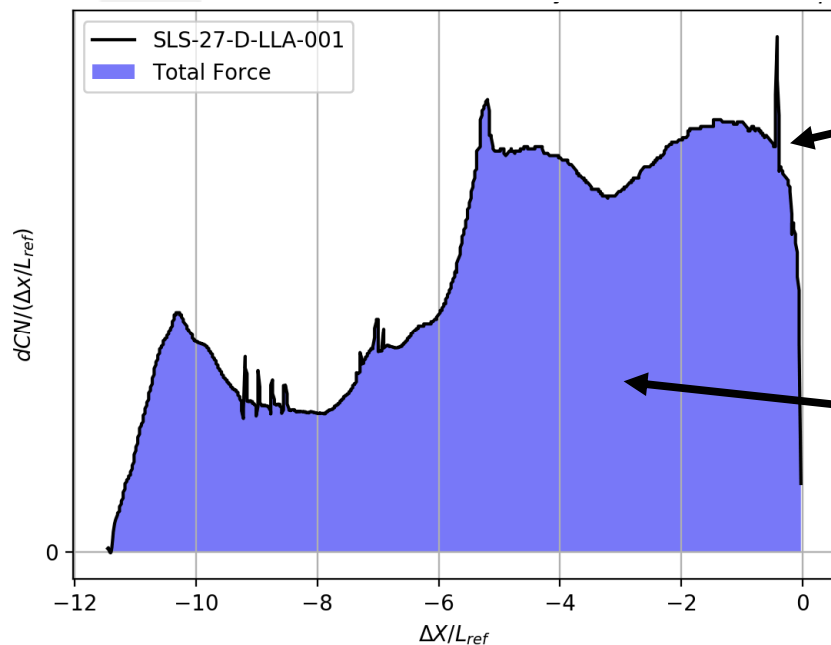
Basic Steps to Create the ROM/FMROM

- 1. Principal Component Analysis (PCA) is performed on a set of CFD solutions, using the covariance between surfaces of pressure and skin friction to find the underlying modes that represent the total information.**
- 2. The eigenvalues of the covariance matrix provide the relative importance of each of the associated modes, allowing transformation in to Principal Component space.**
- 3. The pressure and skin friction surfaces at any point in the desired database can be constructed from a linear combination of principal component surfaces**
- 4. The surfaces can be adjusted such that, when integrated spatially, the cumulative forces and moments match those observed in wind tunnel**
 - This is the data fusion/assimilation that turns the ROM into a DFROM

Conceptual Description of Data Fusion Process



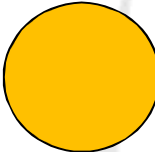
Adjust the principal components of
the pressure and skin friction
surfaces...



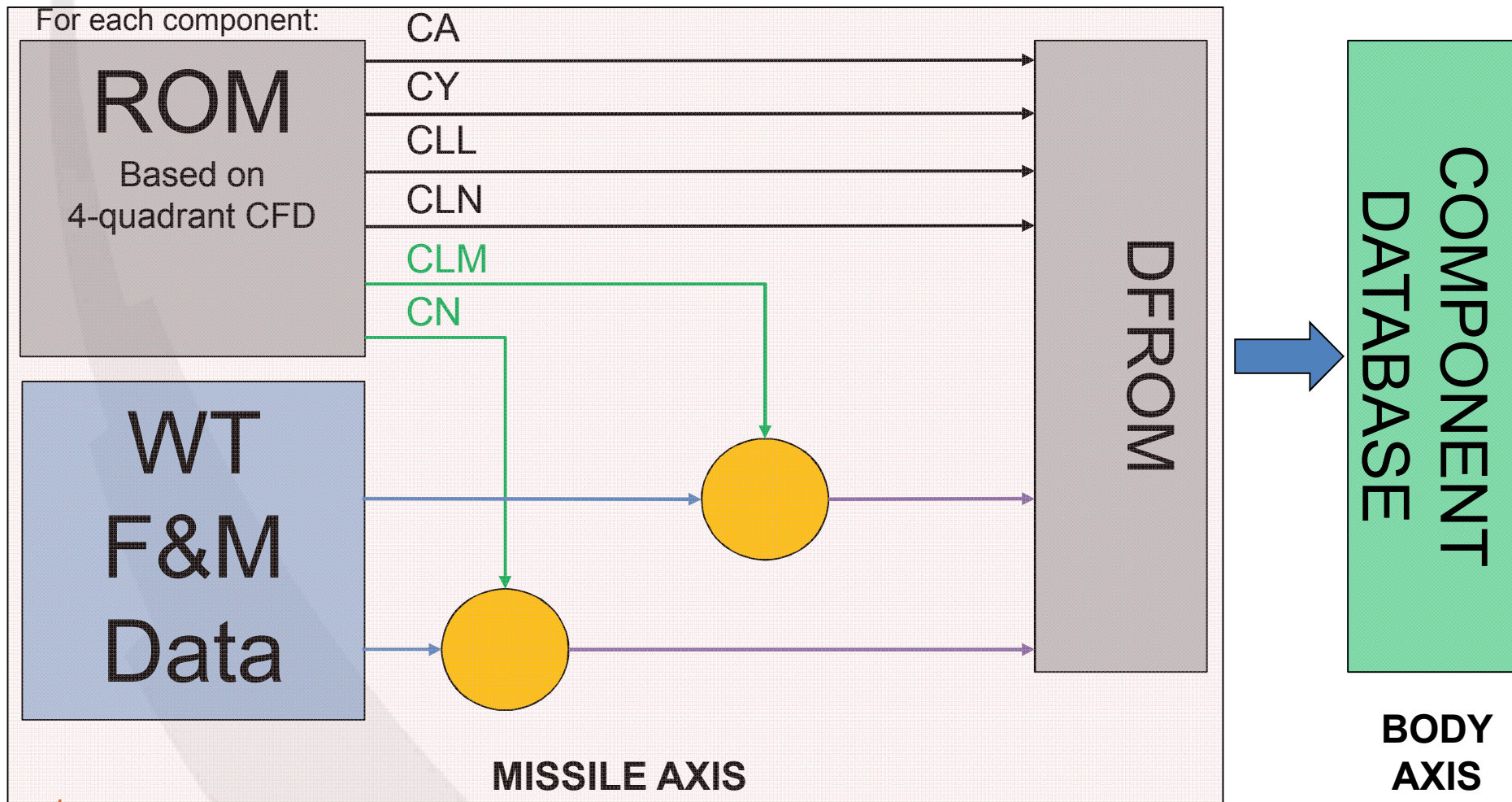
... in a way that minimizes the
deviation of the CFD lineload ...

... such that the integrated value of
the lineload matches the value
measured in wind tunnel testing.

Flowchart of DFROM Adjustment

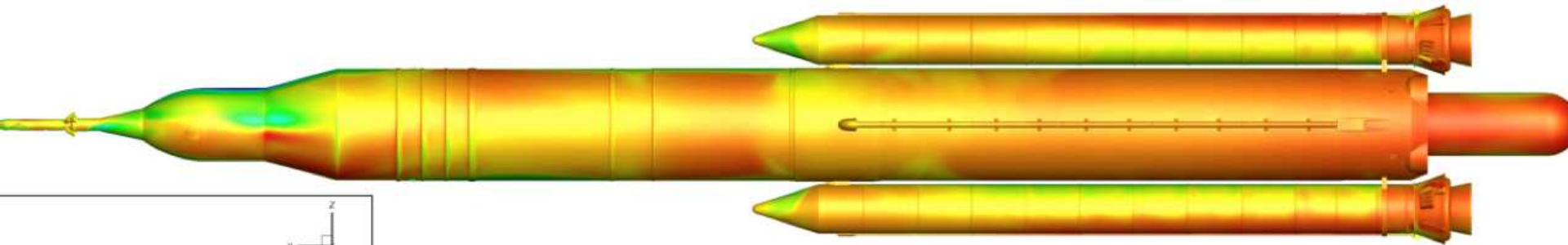
 = adjust ROM surfaces such that cumulative line loads match wind tunnel force and moments

CY & CLN are affected indirectly when transformed to body axis

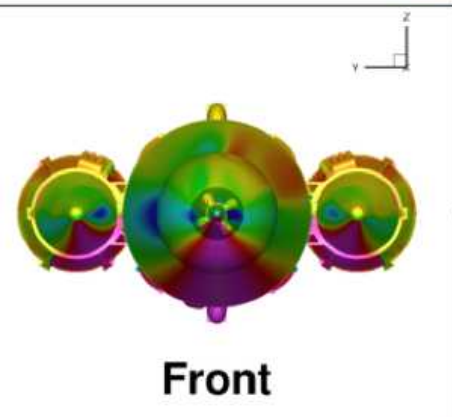


CFD Pressure Contours

SLS-28005: TimeAveraged Pressure Coefficient
Kestrel Grid: wld7.t24p SA+DDES
 $Re_D = 615000.0$ $\alpha_T = 70.0^\circ$ $\phi_T = 0.0^\circ$

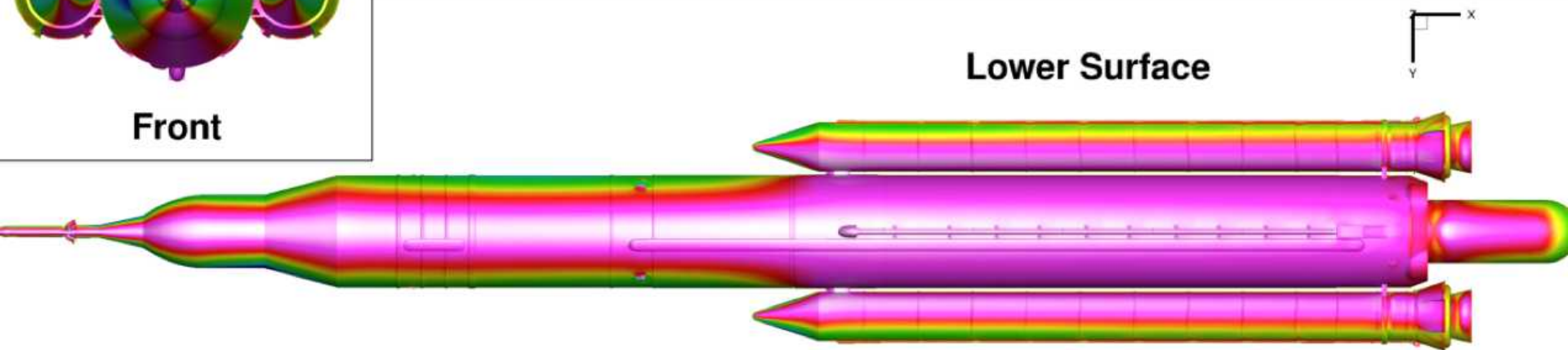


Upper Surface



Front

Lower Surface

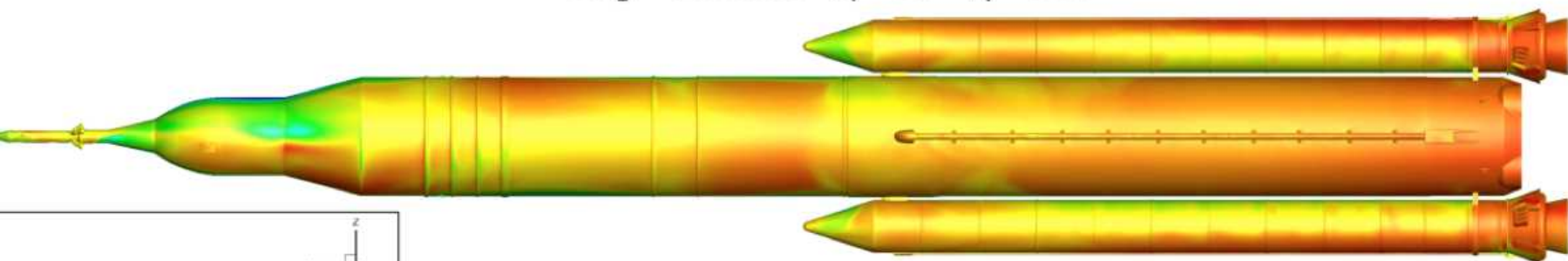


DFROM Pressure Contours

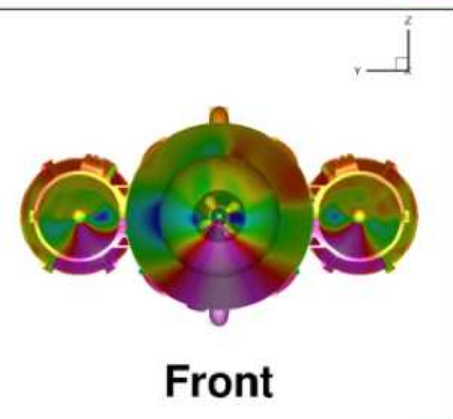
romwtld7.rom_70_000: TimeAveraged Pressure Coefficient

KPBROM Grid: wld7.t24p PB-ROM

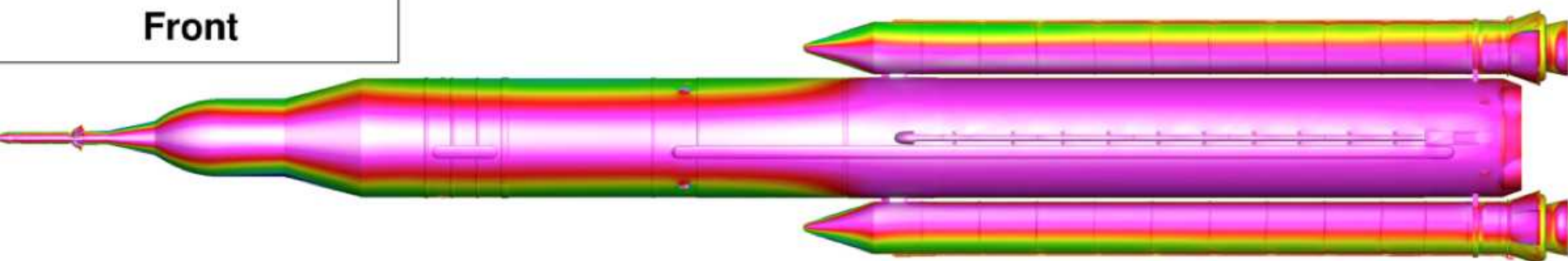
$Re_D = 615000.0$ $\alpha_T = 70^\circ$ $\phi_T = 000^\circ$



Upper Surface



Front

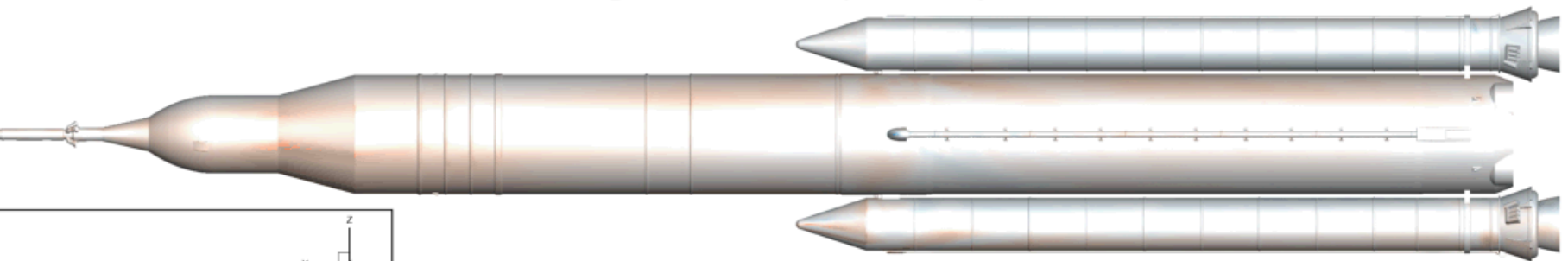


Lower Surface

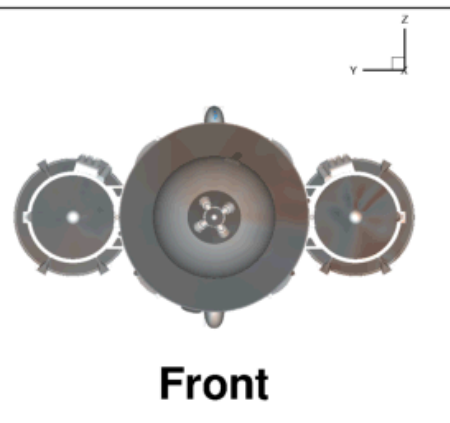
romwtld7.rom_70_000: TimeAveraged Pressure Coefficient

KPBROM Grid: wld7.t24p diff

$Re_D = 615000.0$ $\alpha_T = 70^\circ$ $\phi_T = 000^\circ$

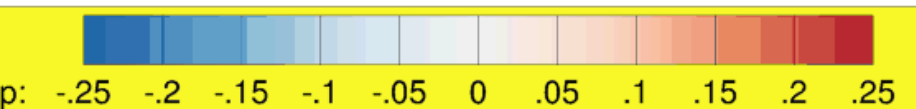
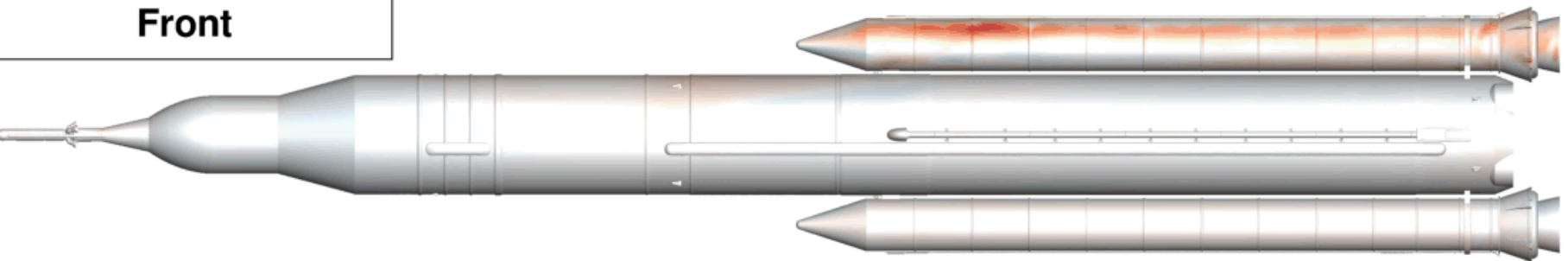


Upper Surface



Front

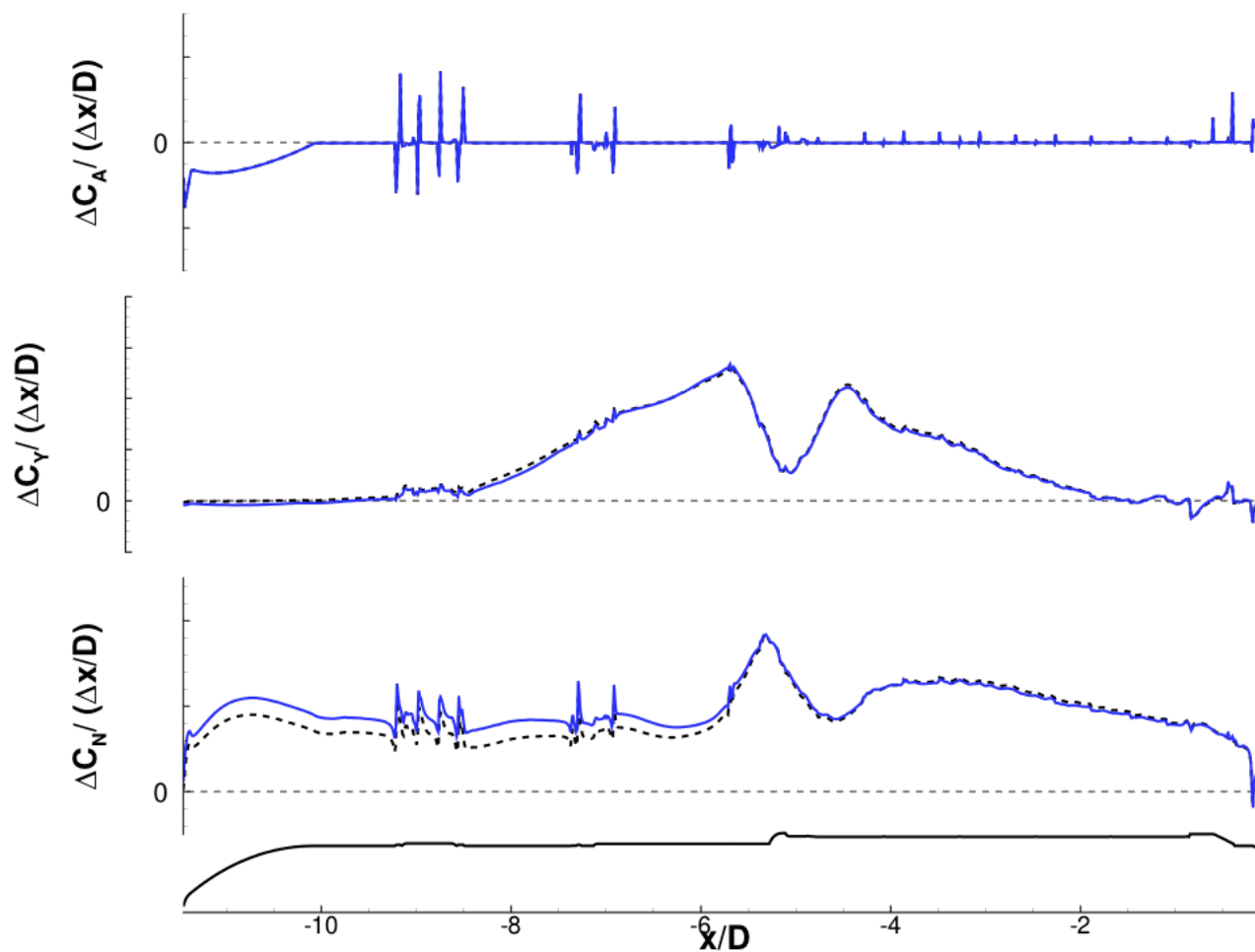
Lower Surface



Lineloads Adjustment

Section Forces
Axis: Missile Part: core
 $\alpha_p = 55^\circ$ $\phi_p = 210^\circ$

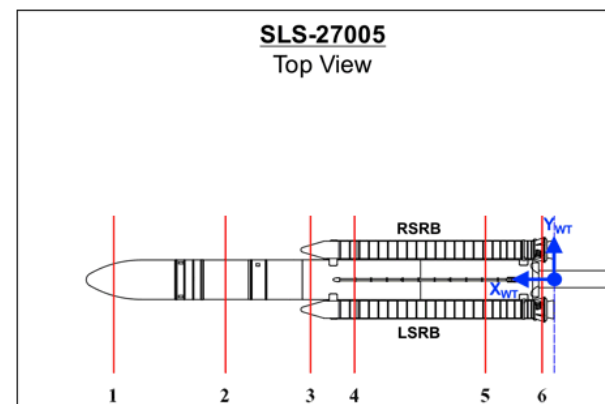
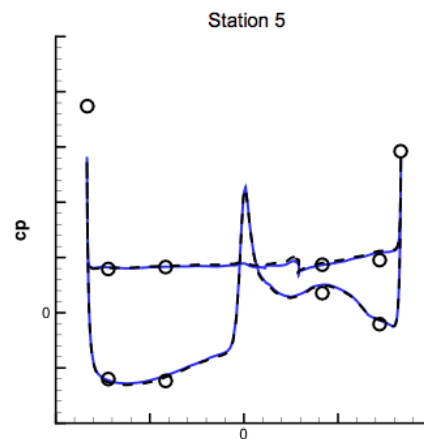
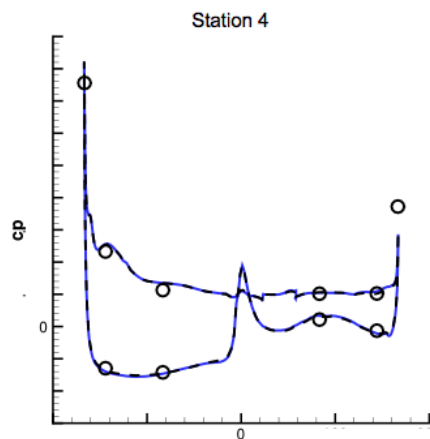
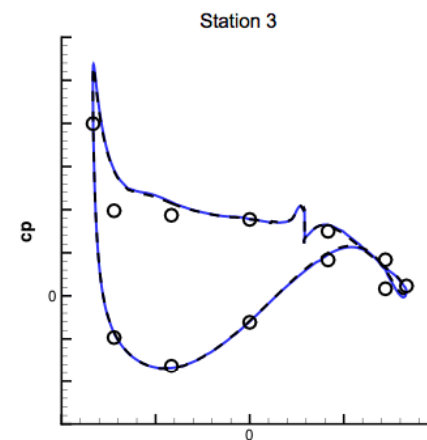
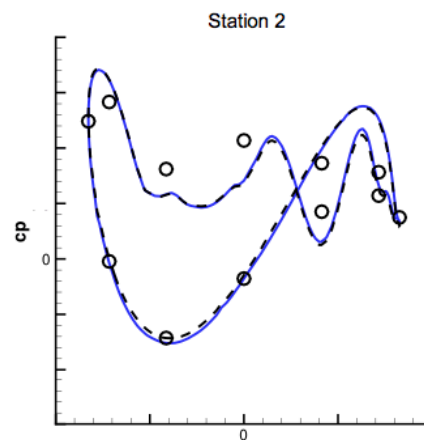
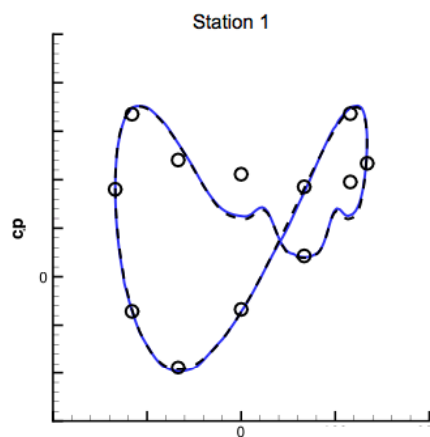
— Lineload A
— Missile ROM
— Zero Line



Lineloads Adjustment

Line Cp Plots
Part: core
 $\alpha_p = 55^\circ$ $\phi_p = 210^\circ$

— DFROM
 - - ROM
 ○ WT

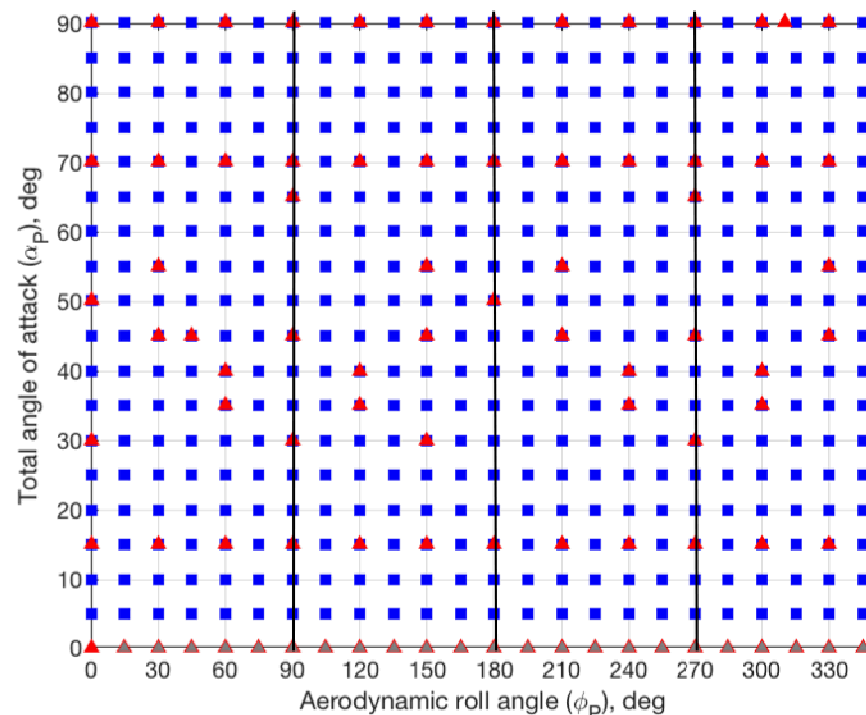
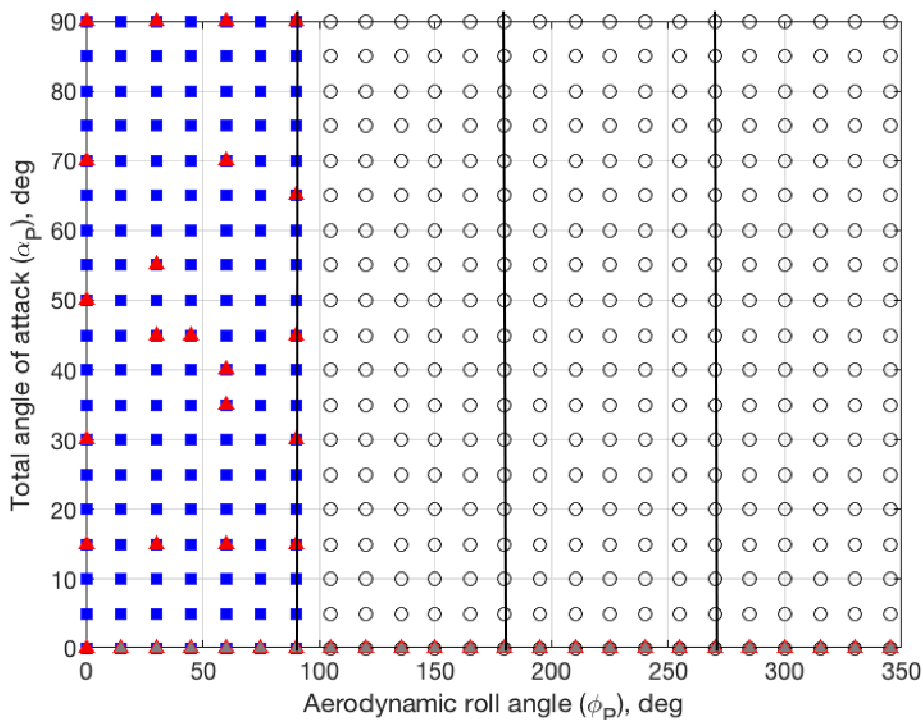
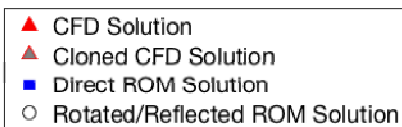


Example CFD and ROM Breakpoints

SLS-28-D-LLA-002

Expanded CFD
Matrix

SLS-27-D-LLA-001





Conclusions and Future Applications



Conclusions

- **The DFROM allows a large solution space to be analyzed based on a relatively sparse matrix of CFD**
 - This is a significant advantage for applications for which CFD is highly complex + expensive
 - The DFROM approach likely saved on the order of **10M CPU hours** versus taking a CFD-only approach for this problem
- **The DFROM makes use of both wind tunnel and CFD where they are most useful for this problem**
 - CFD: generating line loads from surface solutions
 - Wind Tunnel: providing real data for validation of CFD for highly complex geometry and conditions, and an anchor for the ROM to ground it in real measurement
- **The DFROM provides in-house capability that was previously available only as a black-box through a contractor**
 - Our methods are available to NASA/LaRC for V&V, and further research and development

Potential Future Applications

- **Adjusting ROMs currently used for flutter and aeroacoustics with experimental data, extending into time-dependent phenomena**
- **Applying to other SLS configurations and flight regimes (such as ascent, booster separation, etc)**
- **Applying to other complex vehicles, including aviation**
- **Extending to include flight data in addition to wind tunnel and CFD data**
- **Other applications with complex CFD requirements or deliverables much larger in scope than single-source capability**