National Aeronautics and Space Administration

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SPACE LAUNCH SYSTEM

11 JAN 2019

Comparison of SLS Sectional Loads from Pressure-Sensitive Paint and CFD

AIAA SciTech Forum 2019

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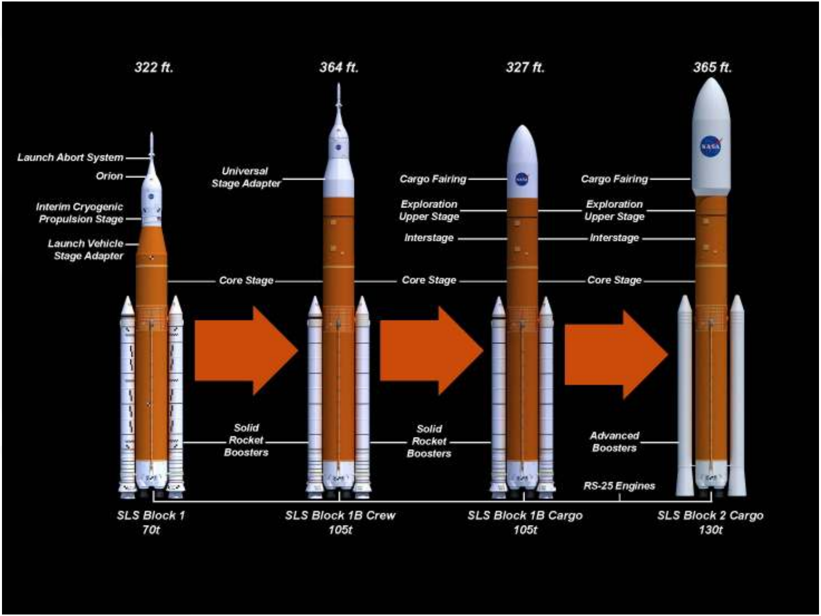


Image Credit: NASA/MSFC

Image Credit: NASA

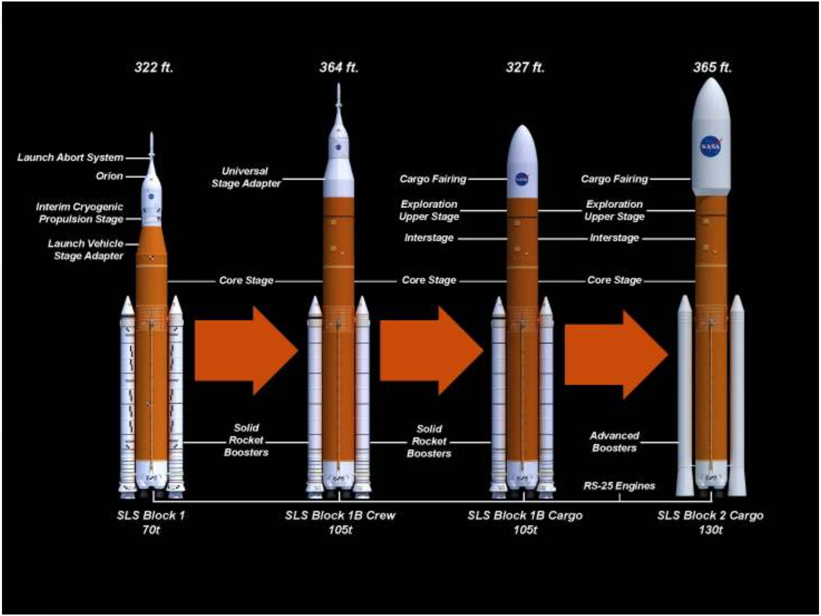


Image Credit: NASA/MSFC

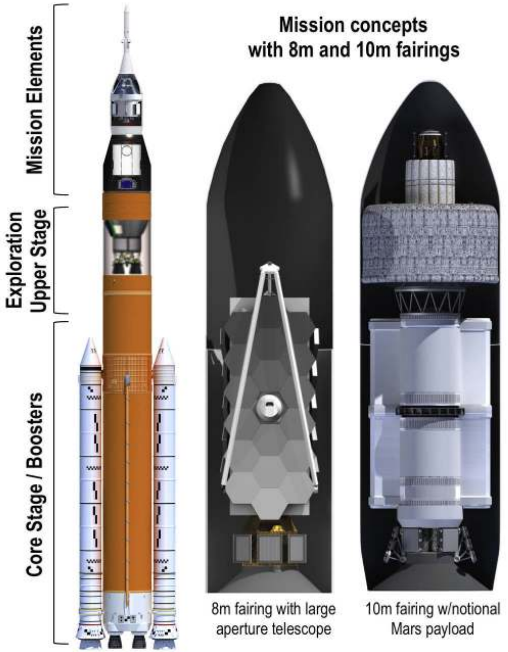


Image Credit: NASA/MSFC

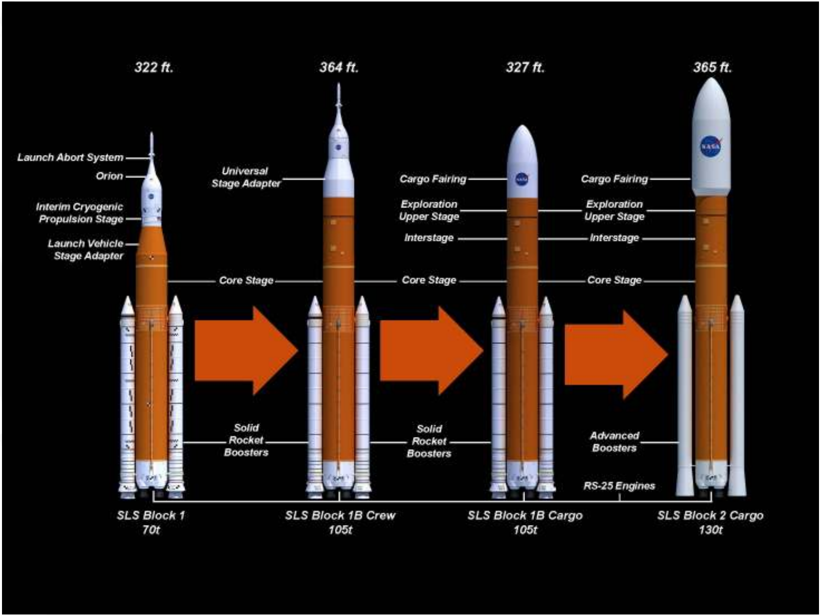
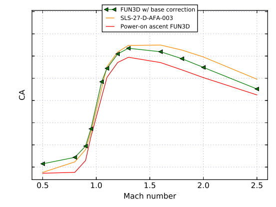


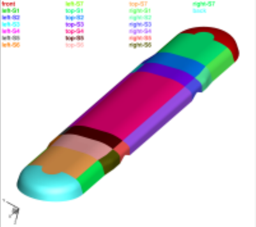
Image Credit: NASA/MSFC

Introduction: Aerodynamic Databases

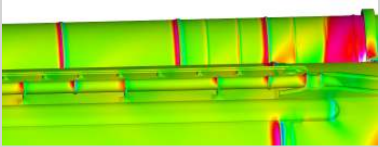
Ascent Forces and Moments



Protuberance Air Loads



Surface Pressures

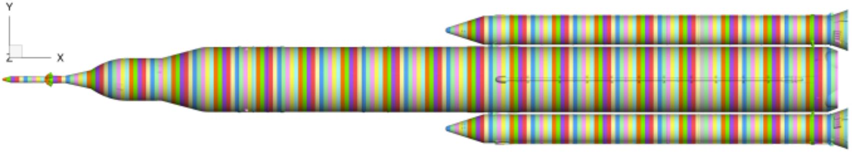


Line Loads

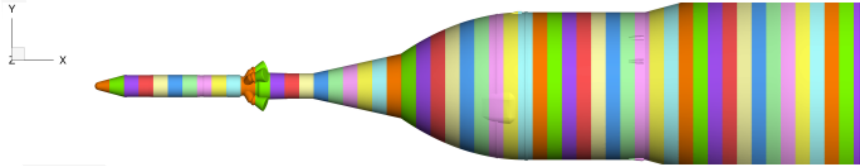
- Additional databases for other portions of flight (i.e. liftoff and transition)
- Most databases are a combination of wind tunnel data and CFD simulations

Sectional Loads (Line Loads)

Sectional Loads/Line Loads



Sectional load slices for SLS Block 1B Crew configuration



Sectional load slices on forward portion of SLS Block 1B

- Line loads are a tool to evaluate the impact of aero loads on vehicle structures by dividing vehicle into a number of fixed width slices
- Calculate the load on each slice, normalized by slice width
- Valid for long/skinny vehicles, like a rocket

Sectional Load Calculation

Line loads for a section i typically take the form of:

$$C_{N,i} = \int_{\hat{x}_i}^{\hat{x}_{i+1}} \int C_N(\hat{x}, s)\, \mathrm{d}s\, \mathrm{d}\hat{x}$$

Where $\hat{x}$ is a non-dimensionalized axial coordinate and s is a parametric variable along the vehicle edge

In practice, these line loads are divided by slice length to provide a universal value:

$$\hat{C}_{N,i} = \frac{1}{\hat{x}_{i+1} - \hat{x}_i} \int_{\hat{x}_i}^{\hat{x}_{i+1}} \int C_N(\hat{x}, s)\, \mathrm{d}s\, \mathrm{d}\hat{x}$$

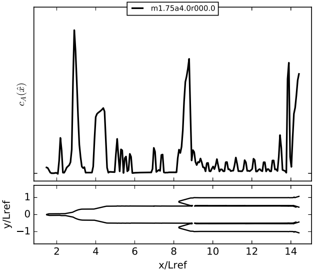
discretized value for the derivative of C_N with respect to $\hat{x}$, i.e. $dCN/d(x/L_{ref})$

The TRILOAD* routine from the CGT package (NASA Ames) is used to calculated the final profiles

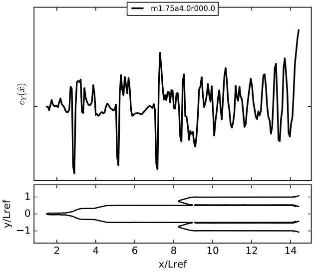
* Pandya, S. and Chan, W. M., Computation of Sectional Loads from Surface Triangulation and Flow Data, AIAA Paper 2011-3680

Example of a Sectional Load

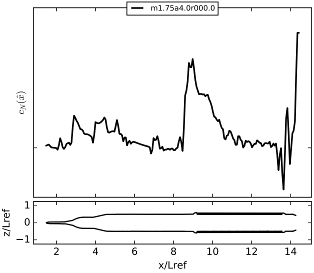
- Deliver three force components (no moments)
- Profiles are a function of axial distance along the rocket
- For SLS, we use 200 slices and deliver line loads on the core, left booster, and right booster all separately
- Delivered database based on **Flight** CFD, wind tunnel runs used as "sanity check"



Axial loads: $c_A(x/L_{ref}) = c_A(\hat{x})$



Lateral loads: $c_Y(\hat{x})$



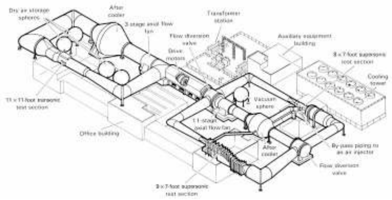
Normal loads: $c_N(\hat{x})$

Experimental Setup

Experimental Setup

NASA Ames UPWT

- Tests completed in 11x11-foot and 9x7-foot test sections
- Three configurations tested: Block 1 Crew, Block 1B Crew, Block 1B Cargo
- Tested at 1.3% scale



From: Baals, D. D. and Corliss, W., Wind Tunnels of NASA, Tech. Rep. NASA-SP-440

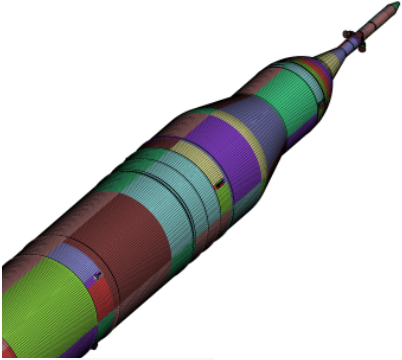
Pressure-Sensitive Paint

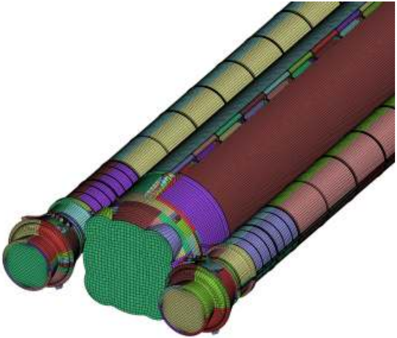
- Steady PSP collected for all three configurations in 11-foot test section (Mach 0.2 to 1.4)
- No viscous contributions
- Light source: 40 x 400 nm LEDs
- Image collection: 8 cameras around plenum

Image Credit: NASA/ARC/Dominic Hart

PSP Surface Representation

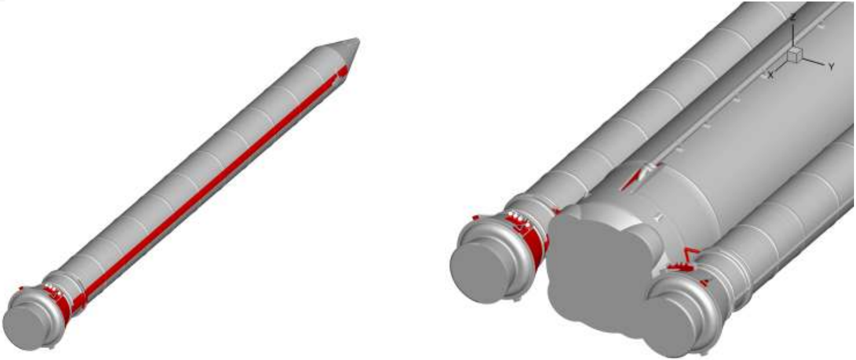
- Format: Plot3D, multiple zone, no I-blanks
- Structured patches - user determined
- Resolution limited by image reduction process - coarse protuberances





PSP Optical Access

- PSP requires clear optical path to produce accurate data
- Difficult to get optical access to regions under pressurization lines and between booster and core (among others)
- These regions are considered to have $C_P = 0$



Areas in red show regions with no optical access

PSP Sectional Load Extraction

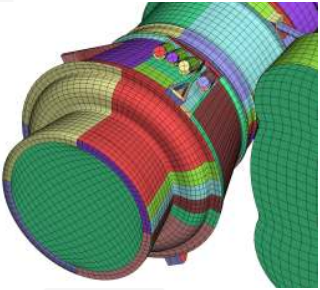
Post-processed surface C_P on Plot3D mesh

Split Cells $\rightarrow$

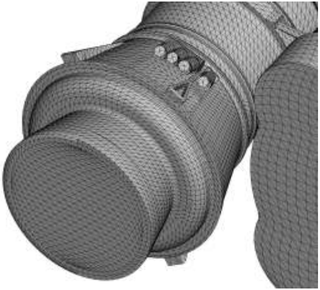
Surface C_P on triangulated mesh

TRILOAD $\rightarrow$

Sectional load profile



$\Rightarrow$

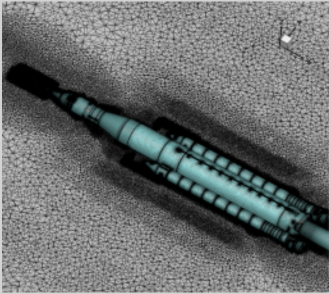


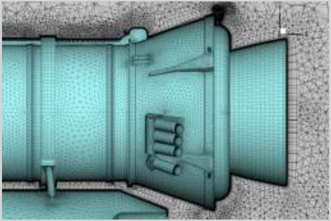
CFD Setup

Flow Solver

- FUN3D - 3D unstructured (mixed-element) flow solver developed at NASA LaRC*
- Run in RANS or uRANS (whenever RANS solution was not steady) mode using Spalart-Allmaras turbulence model
- 2 feature-based adaptations during every run
- 2250 FUN3D simulations run - only a subset is comparable to PSP

CFD Mesh

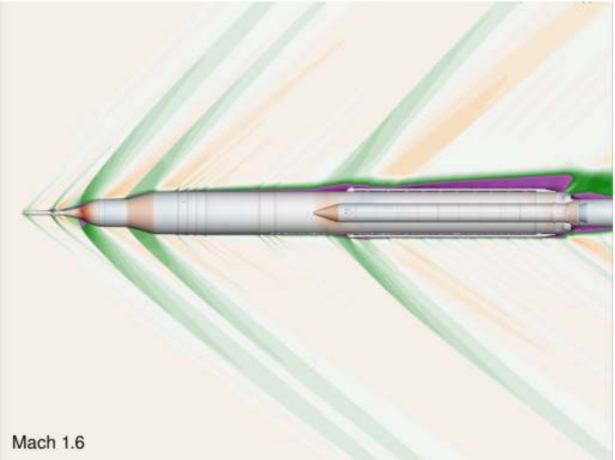




*Biedron, R. T., et al., FUN3D Manual: 13.1, Tech. Rep. TM-2017-219580

Sample CFD Solution

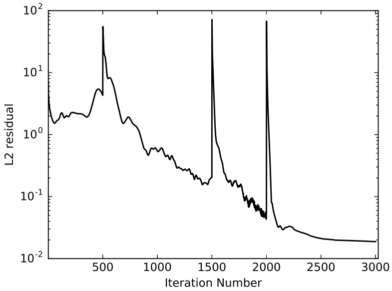
Converged CFD Solution, Block 1B Crew, Mach 1.6 and $\alpha_t = 4^\circ$

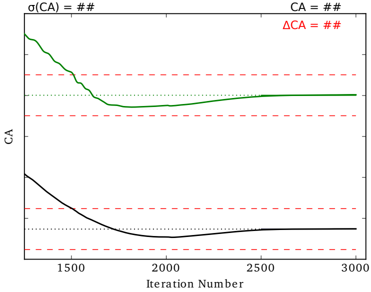


Flow field is colored by Mach number, surface is shaded by C_p

Sample CFD Solution

Converged CFD Solution, Block 1B Crew, Mach 1.6 and $\alpha_t = 4^\circ$





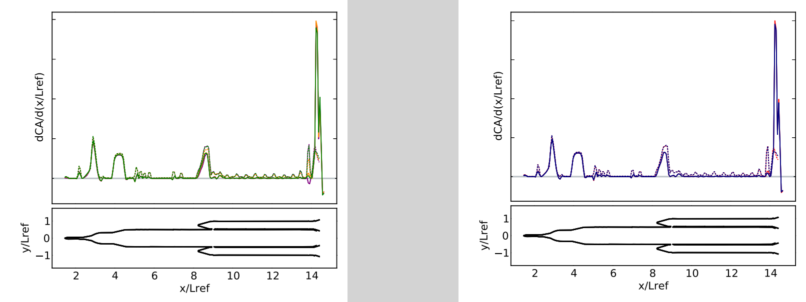
L_2 norm has converged a few magnitudes and bulk forces are stable

Sectional Load Comparisons

Sectional Load Comparisons

- Comparisons made at three Mach numbers: 0.95, 1.10, and 1.30
- All at $\alpha_t = 4.0°$ and five different roll angles (missile axis CS)

Block 1B Crew *STACK/CA* at Mach 1.30

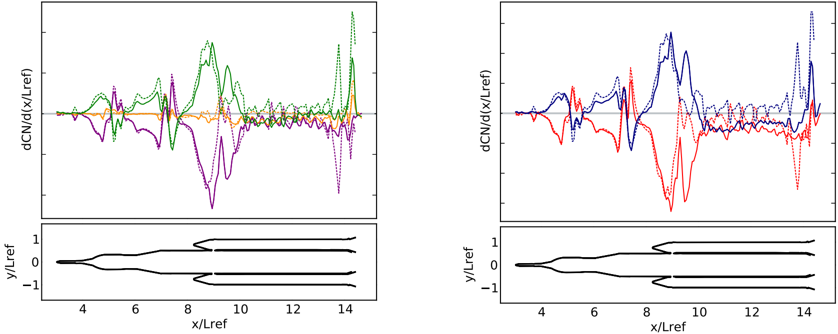


Solid lines = PSP
Dashed lines = CFD

α_t = 4°, φ = 180° (α = -4°, β = 0°)
α_t = 4°, φ = 90° (α = 0°, β = 4°)
α_t = 4°, φ = 360° (α = 4°, β = 0°)
α_t = 4°, φ = 45° (α = 2.8°, β = 2.8°)
α_t = 4°, φ = 225° (α = -2.8°, β = -2.8°)

Block 1 Crew

STACK/*CN* at Mach 0.95

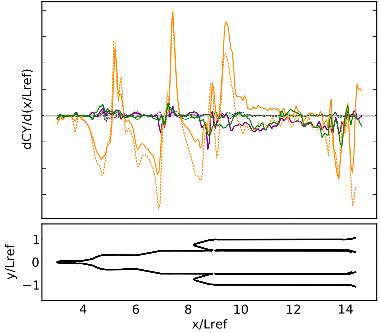


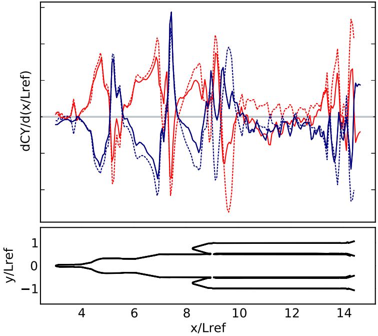
- Good matching except at attach hardware and between booster and core

Solid lines = PSP
Dashed lines = CFD

α_t = 4°, φ = 180° (α = -4°, β = 0°)
α_t = 4°, φ = 90° (α = 0°, β = 4°)
α_t = 4°, φ = 360° (α = 4°, β = 0°)
α_t = 4°, φ = 45° (α = 2.8°, β = 2.8°)
α_t = 4°, φ = 225° (α = -2.8°, β = -2.8°)

STACK/CY at Mach 0.95





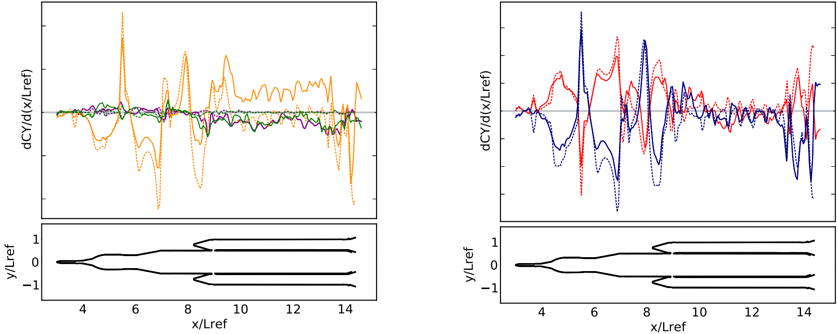
- Trends match, but more differences - larger projected area in Y

Solid lines = PSP
Dashed lines = CFD

- α_t = 4°, φ = 180° (α = -4°, β = 0°)
- α_t = 4°, φ = 90° (α = 0°, β = 4°)
- α_t = 4°, φ = 360° (α = 4°, β = 0°)
- α_t = 4°, φ = 45° (α = 2.8°, β = 2.8°)
- α_t = 4°, φ = 225° (α = -2.8°, β = -2.8°)

Block 1 Crew

STACK/*CY* at Mach 1.10



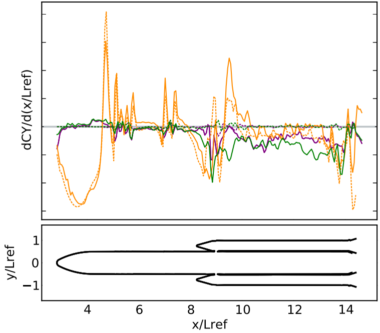
- Large differences between booster and core at $\phi = 90^\circ$ due to shielding

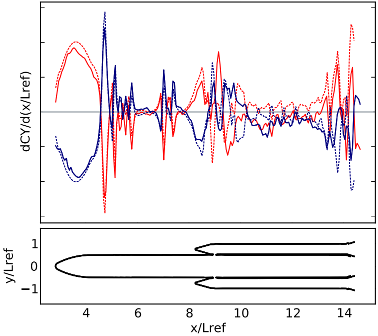
Solid lines = PSP
Dashed lines = CFD

α_t = 4°, φ = 180° (α = -4°, β = 0°)
α_t = 4°, φ = 90° (α = 0°, β = 4°)
α_t = 4°, φ = 360° (α = 4°, β = 0°)
α_t = 4°, φ = 45° (α = 2.8°, β = 2.8°)
α_t = 4°, φ = 225° (α = -2.8°, β = -2.8°)

Block 1B Cargo

STACK/*CY* at Mach 0.95





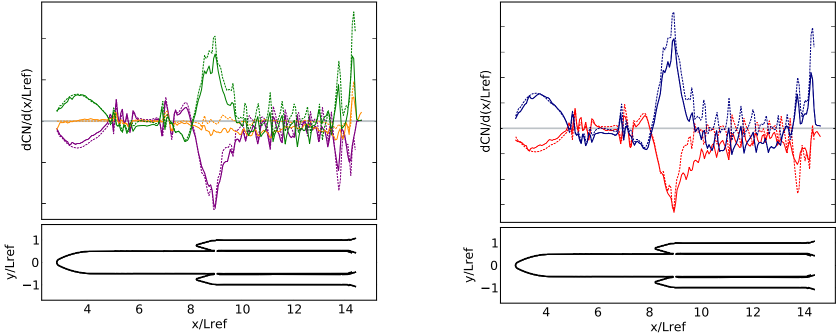
- Divergence starts at FWD attach and continues downstream

Solid lines = PSP
Dashed lines = CFD

- α_t = 4°, φ = 180° (α = -4°, β = 0°)
- α_t = 4°, φ = 90° (α = 0°, β = 4°)
- α_t = 4°, φ = 360° (α = 4°, β = 0°)
- α_t = 4°, φ = 45° (α = 2.8°, β = 2.8°)
- α_t = 4°, φ = 225° (α = -2.8°, β = -2.8°)

Block 1B Cargo

STACK/*CN* at Mach 1.10

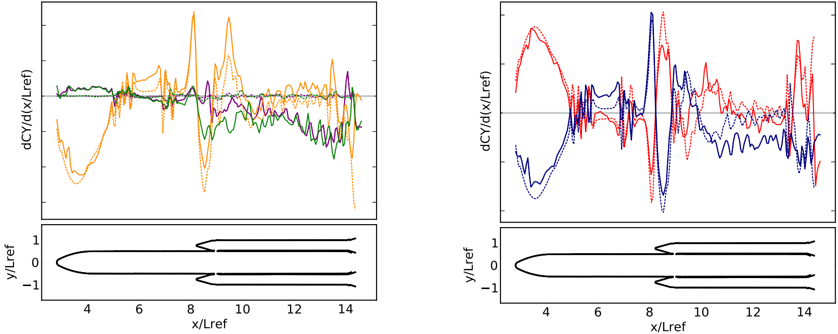


- Very good agreement in normal force at this condition

Solid lines = PSP
Dashed lines = CFD

α_t = 4°, φ = 180° (α = -4°, β = 0°)
α_t = 4°, φ = 90° (α = 0°, β = 4°)
α_t = 4°, φ = 360° (α = 4°, β = 0°)
α_t = 4°, φ = 45° (α = 2.8°, β = 2.8°)
α_t = 4°, φ = 225° (α = -2.8°, β = -2.8°)

STACK/*CY* at Mach 1.30



- Still poor agreement between booster and core, symmetry lacking

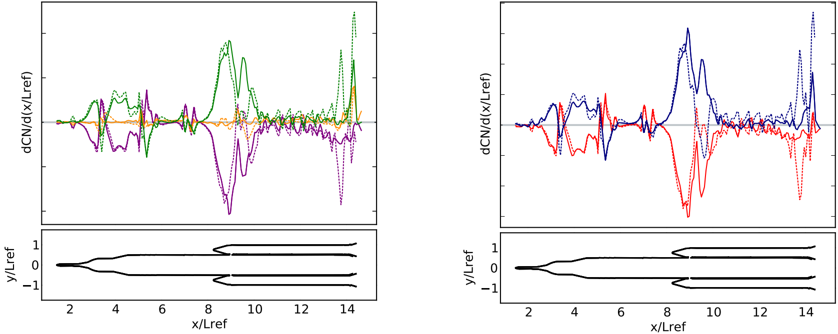
Solid lines = PSP
Dashed lines = CFD

- α_t = 4°, φ = 180° (α = -4°, β = 0°)
- α_t = 4°, φ = 90° (α = 0°, β = 4°)
- α_t = 4°, φ = 360° (α = 4°, β = 0°)
- α_t = 4°, φ = 45° (α = 2.8°, β = 2.8°)
- α_t = 4°, φ = 225° (α = -2.8°, β = -2.8°)

Block 1B Crew

Block 1B Crew

STACK/*CN* at Mach 0.95



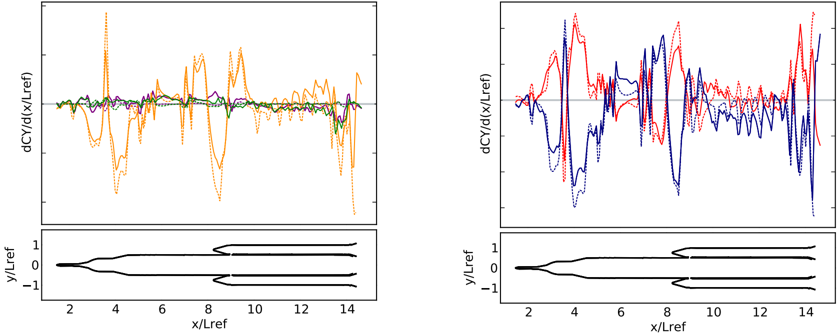
- Good agreement except at attach points

Solid lines = PSP
Dashed lines = CFD

α_t = 4°, φ = 180° (α = -4°, β = 0°)
α_t = 4°, φ = 90° (α = 0°, β = 4°)
α_t = 4°, φ = 360° (α = 4°, β = 0°)
α_t = 4°, φ = 45° (α = 2.8°, β = 2.8°)
α_t = 4°, φ = 225° (α = -2.8°, β = -2.8°)

Block 1B Crew

STACK/*CY* at Mach 1.10



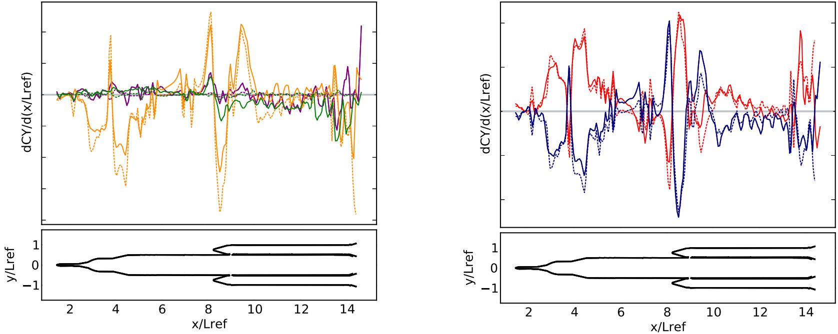
- Offset between booster and core seen for Block 1 Crew no longer present

Solid lines = PSP
Dashed lines = CFD

- α_t = 4°, φ = 180° (α = -4°, β = 0°)
- α_t = 4°, φ = 90° (α = 0°, β = 4°)
- α_t = 4°, φ = 360° (α = 4°, β = 0°)
- α_t = 4°, φ = 45° (α = 2.8°, β = 2.8°)
- α_t = 4°, φ = 225° (α = -2.8°, β = -2.8°)

Block 1B Crew

STACK/*CY* at Mach 1.30



- Trends match well, peaks at different magnitudes

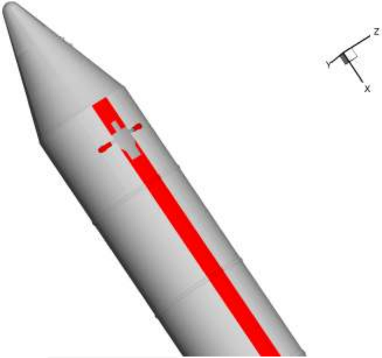
Solid lines = PSP
Dashed lines = CFD

- α_t = 4°, φ = 180° (α = -4°, β = 0°)
- α_t = 4°, φ = 90° (α = 0°, β = 4°)
- α_t = 4°, φ = 360° (α = 4°, β = 0°)
- α_t = 4°, φ = 45° (α = 2.8°, β = 2.8°)
- α_t = 4°, φ = 225° (α = -2.8°, β = -2.8°)

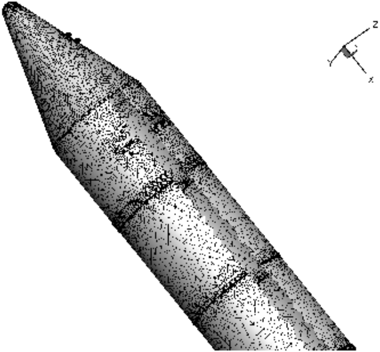
Effects of Optical Shielding

Accounting for Optical Shielding

- Line loads calculated by zeroing out areas of no or little optical access
- These areas are sometimes regions of volatile loading (fwd/aft attach)
- **Solution: remove cells from shielded areas in final CFD solution**



PSP Surface with Shielded Regions in Red

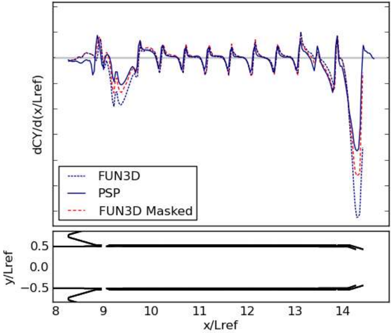


Masked CFD Surface Mesh

Accounting for Optical Shielding

- Line loads calculated by zeroing out areas of no or little optical access
- These areas are sometimes regions of volatile loading (fwd/aft attach)
- **Solution: remove cells from shielded areas in final CFD solution**

C_p on RSRB after Masking



RSRB/CY Line Loads

Mach $= 1.05$, $\alpha_t = 8^\circ$, $\phi = 0^\circ$

Summary

- Sectional loads for three different configurations of SLS were extracted from PSP data and compared to those from CFD simulations
- Relatively good agreement can be seen between the two data sources
  - C_A and C_N - good
  - C_Y - worse, but still favorable [optical effects amplified]
- Areas of poor agreement often correspond to areas of poor optical access (i.e. attach hardware)
- Favorable comparisons with PSP sectional loads gives more credence for using CFD for database delivery
  - Sectional load databases currently come from CFD at flight conditions
  - CFD solutions from WT simulations used as sanity check for those at flight conditions

Future Work

- Extend masking for all sectional loads
- Continue to improve PSP grid resolution and optical access
- Database buildup and uncertainty quantification

Acknowledgments

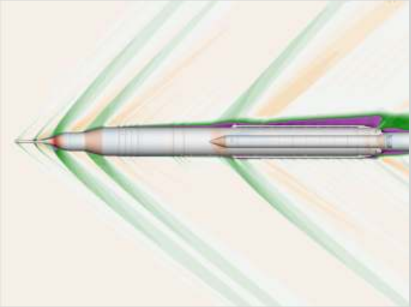
- SLS Program; this work is part of the SLS Aero Task Team
- Patrick Shea and team for organizing wind tunnel test efforts
- Other members of the NASA ARC/TNA SLS CFD Team:
  - Jeff Onufer
  - Tom Pulliam
  - and many previous members
- NASA Advanced Supercomputing facilities
- NASA Ames UPWT

Backup Slides

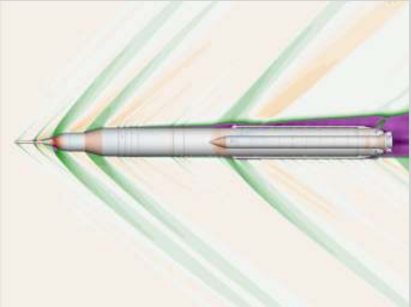
Wind Tunnel vs. Flight CFD

Block 1B Crew, Mach 1.6 and $\alpha_t = 4^\circ$

Wind Tunnel



Flight



Flow field is colored by Mach number, surface is shaded by C_p

Salient differences: Reynolds number and plume-on effects