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

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EXPLORATION MISSION-2
Crewed Hybrid Free Return Trajectory, demonstrating crewed flight and spacecraft systems performance beyond Low Earth Orbit (LEO)

- Crew Module (CM) / Service Module (SM) separation
- Entry and Landing
- Crew and Orion Capsule Recovery
- Crew Module Separation
- Perigee Raise Maneuver (PRM) by Interim Cryogenic Propulsion Stage (ICPS) into 100x975 nmi orbit
- Trans-Lunar Outbound: 4 days with Outbound Trajectory Corrections (OTC) by Orion Aux Engines
- Trans-Earth Return: 4 days Return Trajectory Corrections (RTC) by Orion Aux Engines
- ICPS Disposal to Heliocentric orbit
- Apogee Raise Burn to High Earth Orbit with 24 hour period for Systems Checkout followed by ICPS separation from Orion
- Orion Trans-Lunar Injection (TLI) by Orion Orbital Maneuvering System (OMS)

SLS Configuration (Block 1) with Human Rated ICPS | 22x975 nmi (40.7x1806 km) insertion orbit | 28.5 deg inclination
4 astronauts | Total distance traveled: 1,090,320 km – Mission duration: 9 Days – Re-entry speed: 24,500 mph (Mach 32)

Image Credit: NASA
Introduction: Aerodynamic Databases

Ascent Forces and Moments

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

Protuberance Air Loads

Surface Pressures

Line Loads

www.nasa.gov/sls
Sectional Loads
(Line Loads)
Line loads are a tool to evaluate the impact of aero loads on vehicle structures by dividing the 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.
Line loads for a section $i$ typically take the form of:

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

Where $\tilde{x}$ 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:

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

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

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

• 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: $c_A \left( \frac{x}{L_{ref}} \right) = c_A (\hat{x})$

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

**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
Post-processed surface $C_P$ on Plot3D mesh.

Split Cells $\rightarrow$

Surface $C_P$ on triangulated mesh.

$TRILOAD$ $\rightarrow$

Sectional load profile.
CFD Setup
• **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

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

Block 1B Crew STACK/CA at Mach 1.30

Sectional Load Comparisons

- Solid lines = PSP
- Dashed lines = CFD

$\alpha_t = 4^\circ$, $\varphi = 180^\circ$ ($\alpha = -4^\circ$, $\beta = 0^\circ$)
$\alpha_t = 4^\circ$, $\varphi = 90^\circ$ ($\alpha = 0^\circ$, $\beta = 4^\circ$)
$\alpha_t = 4^\circ$, $\varphi = 360^\circ$ ($\alpha = 4^\circ$, $\beta = 0^\circ$)
$\alpha_t = 4^\circ$, $\varphi = 45^\circ$ ($\alpha = 2.8^\circ$, $\beta = 2.8^\circ$)
$\alpha_t = 4^\circ$, $\varphi = 225^\circ$ ($\alpha = -2.8^\circ$, $\beta = -2.8^\circ$)
Block 1 Crew
• Good matching except at attach hardware and between booster and core

- Solid lines = PSP
- Dashed lines = CFD

- \( \alpha_t = 4°, \varphi = 180° \) (\( \alpha = -4°, \beta = 0° \))
- \( \alpha_t = 4°, \varphi = 90° \) (\( \alpha = 0°, \beta = 4° \))
- \( \alpha_t = 4°, \varphi = 360° \) (\( \alpha = 4°, \beta = 0° \))
- \( \alpha_t = 4°, \varphi = 45° \) (\( \alpha = 2.8°, \beta = 2.8° \))
- \( \alpha_t = 4°, \varphi = 225° \) (\( \alpha = -2.8°, \beta = -2.8° \))
• Trends match, but more differences - larger projected area in $Y$

- Solid lines = PSP
- Dashed lines = CFD

- $\alpha_t = 4^\circ$, $\varphi = 180^\circ$ ($\alpha = -4^\circ$, $\beta = 0^\circ$)
- $\alpha_t = 4^\circ$, $\varphi = 90^\circ$ ($\alpha = 0^\circ$, $\beta = 4^\circ$)
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- $\alpha_t = 4^\circ$, $\varphi = 225^\circ$ ($\alpha = -2.8^\circ$, $\beta = -2.8^\circ$)
• Large differences between booster and core at $\phi = 90^\circ$ due to shielding

- Solid lines = PSP
- Dashed lines = CFD

- $\alpha_t = 4^\circ, \phi = 180^\circ (\alpha = -4^\circ, \beta = 0^\circ)$
- $\alpha_t = 4^\circ, \phi = 90^\circ (\alpha = 0^\circ, \beta = 4^\circ)$
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- $\alpha_t = 4^\circ, \phi = 225^\circ (\alpha = -2.8^\circ, \beta = -2.8^\circ)$
Block 1B Cargo
**STACK/CY at Mach 0.95**

- Divergence starts at FWD attach and continues downstream

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- **Solid lines** = PSP
- **Dashed lines** = CFD

- $\alpha_t = 4^\circ$, $\varphi = 180^\circ$ ($\alpha = -4^\circ$, $\beta = 0^\circ$)
- $\alpha_t = 4^\circ$, $\varphi = 90^\circ$ ($\alpha = 0^\circ$, $\beta = 4^\circ$)
- $\alpha_t = 4^\circ$, $\varphi = 360^\circ$ ($\alpha = 4^\circ$, $\beta = 0^\circ$)
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- $\alpha_t = 4^\circ$, $\varphi = 225^\circ$ ($\alpha = -2.8^\circ$, $\beta = -2.8^\circ$)
• Very good agreement in normal force at this condition

Solid lines = PSP
Dashed lines = CFD

\( \alpha_t = 4^\circ, \varphi = 180^\circ (\alpha = -4^\circ, \beta = 0^\circ) \)
\( \alpha_t = 4^\circ, \varphi = 90^\circ (\alpha = 0^\circ, \beta = 4^\circ) \)
\( \alpha_t = 4^\circ, \varphi = 360^\circ (\alpha = 4^\circ, \beta = 0^\circ) \)
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\( \alpha_t = 4^\circ, \varphi = 225^\circ (\alpha = -2.8^\circ, \beta = -2.8^\circ) \)
Still poor agreement between booster and core, symmetry lacking

- Solid lines = PSP
- Dashed lines = CFD

- $\alpha = 4^\circ$, $\phi = 180^\circ$ ($\alpha = -4^\circ$, $\beta = 0^\circ$)
- $\alpha = 4^\circ$, $\phi = 90^\circ$ ($\alpha = 0^\circ$, $\beta = 4^\circ$)
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- $\alpha = 4^\circ$, $\phi = 225^\circ$ ($\alpha = -2.8^\circ$, $\beta = -2.8^\circ$)
Block 1B Crew
• Good agreement except at attach points

- Solid lines = PSP
- Dashed lines = CFD

- \( \alpha_t = 4^\circ, \varphi = 180^\circ \) (\( \alpha = -4^\circ, \beta = 0^\circ \))
- \( \alpha_t = 4^\circ, \varphi = 90^\circ \) (\( \alpha = 0^\circ, \beta = 4^\circ \))
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- \( \alpha_t = 4^\circ, \varphi = 45^\circ \) (\( \alpha = 2.8^\circ, \beta = 2.8^\circ \))
- \( \alpha_t = 4^\circ, \varphi = 225^\circ \) (\( \alpha = -2.8^\circ, \beta = -2.8^\circ \))
• Offset between booster and core seen for Block 1 Crew no longer present

Solid lines = PSP
Dashed lines = CFD

- \( \alpha_t = 4^\circ, \phi = 180^\circ \) (\( \alpha = -4^\circ, \beta = 0^\circ \))
- \( \alpha_t = 4^\circ, \phi = 90^\circ \) (\( \alpha = 0^\circ, \beta = 4^\circ \))
- \( \alpha_t = 4^\circ, \phi = 360^\circ \) (\( \alpha = 4^\circ, \beta = 0^\circ \))
- \( \alpha_t = 4^\circ, \phi = 45^\circ \) (\( \alpha = 2.8^\circ, \beta = 2.8^\circ \))
- \( \alpha_t = 4^\circ, \phi = 225^\circ \) (\( \alpha = -2.8^\circ, \beta = -2.8^\circ \))
• Trends match well, peaks at different magnitudes

- Solid lines = PSP
- Dashed lines = CFD

\[ \frac{dC}{d(x/L_{ref})} \]

- \( \alpha_t = 4°, \varphi = 180° \) (\( \alpha = -4°, \beta = 0° \))
- \( \alpha_t = 4°, \varphi = 90° \) (\( \alpha = 0°, \beta = 4° \))
- \( \alpha_t = 4°, \varphi = 360° \) (\( \alpha = 4°, \beta = 0° \))
- \( \alpha_t = 4°, \varphi = 45° \) (\( \alpha = 2.8°, \beta = 2.8° \))
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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

\[ \text{Mach} = 1.05, \alpha_t = 8^\circ, \phi = 0^\circ \]

RSRB/CY Line Loads
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
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  - Tom Pulliam
  - and many previous members
- NASA Advanced Supercomputing facilities
- NASA Ames UPWT
Block 1B Crew, Mach 1.6 and $\alpha_t = 4^\circ$

Flow field is colored by Mach number, surface is shaded by $C_P$

Salient differences: Reynolds number and plume-on effects