Building Aerodynamic Databases for the Space Launch System

Jamie Meeroff, Stuart Rogers, Derek Dalle, Guy Schauerhamer, Joshua Diaz, Aaron Burkhead

Computational Aerosciences Branch
NASA Ames Research Center

SuperComputing 2022 Dallas, TX

SLS Aerodynamic Databases

NASA's Artemis Missions

Orion

Space Launch System

Exploration Ground Systems

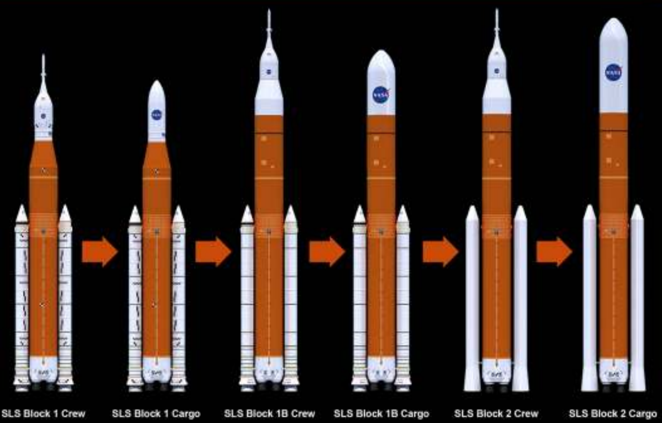
Gateway

Human Landing System

Artemis Base Camp

The Space Launch System

	SLS Block 1 Crew	SLS Block 1 Cargo	SLS Block 1B Crew	SLS Block 1B Cargo	SLS Block 2 Crew	SLS Block 2 Cargo
Payload to TLI/Moon	> 26 t (57k lbs)	> 26 t (57k lbs)	34–37 t (74k–81k lbs)	37–40 t (81k–88k lbs)	> 45 t (99k lbs)	> 45 t (99k lbs)
Payload Volume	N/A**	9,030 ft³ (256m³)	10,100 ft³ (286m³)**	18,970 ft³ (537 m³)	10,100 ft³ (286m³)**	34,910 ft³ (988 m³)
Maximum Thrust	8.8M lbs	8.8M lbs	8.8M lbs	8.8M lbs	11.9M lbs	11.9M lbs

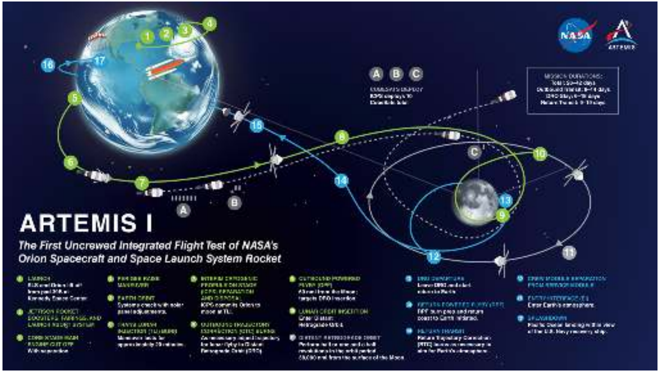


Trans-Lunar Injection (TLI) is a propulsive maneuver used to set a spacecraft on a trajectory that will cause it to arrive at the Moon. A spacecraft performs **TLI** to begin a lunar transfer from a low circular parking orbit around Earth.

The numbers depicted here indicate the mass capability at the Trans-Lunar Injection point.

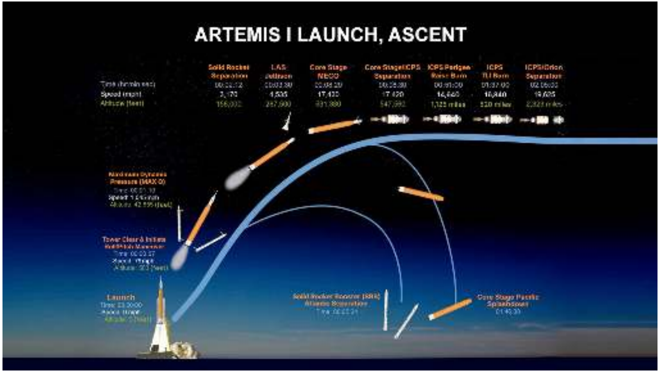
** Not including Orion/Service Module volume

Artemis Aerodynamics



Aerodynamics matter during the initial and final phases of a typical Artemis mission

Artemis Aerodynamics



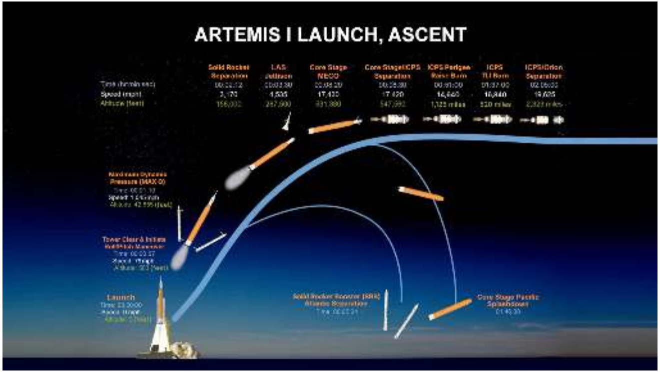
Liftoff and Transition

Aerodynamics matter during the initial and final phases of a typical Artemis mission

Artemis Aerodynamics

Ascent

Liftoff and Transition



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Launch Abort

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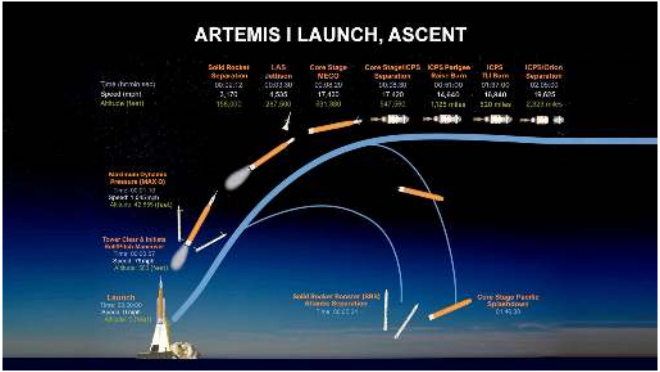

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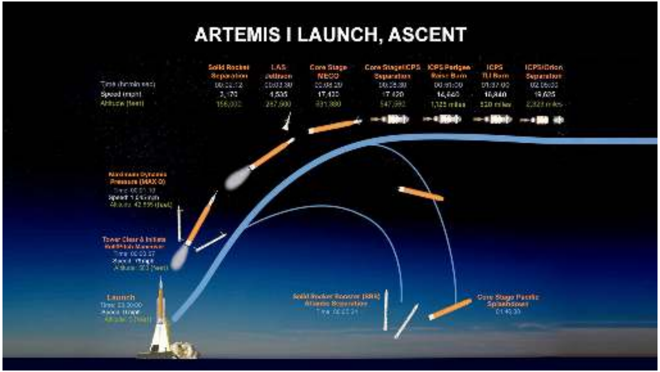
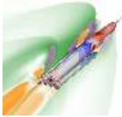


Booster Separation



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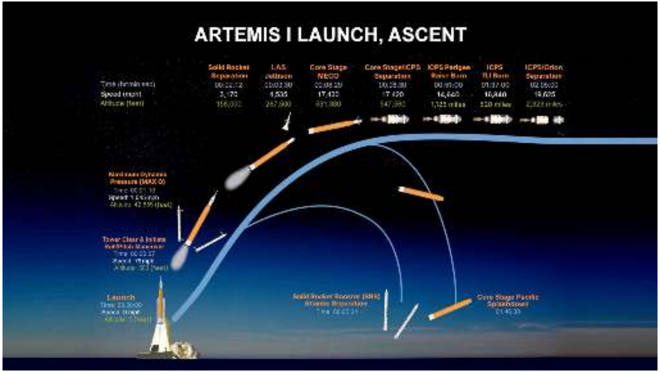

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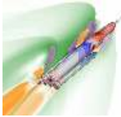


Panel Separation

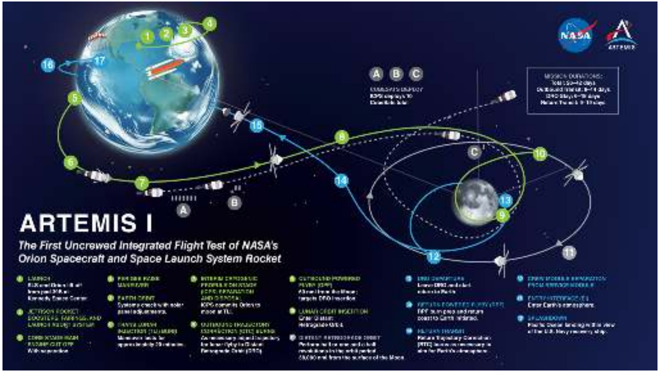
Aerodynamics matter during the initial and final phases of a typical Artemis mission

Artemis Aerodynamics

Launch Abort

Ascent

Liftoff and Transition



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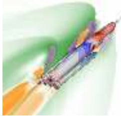


Panel Separation

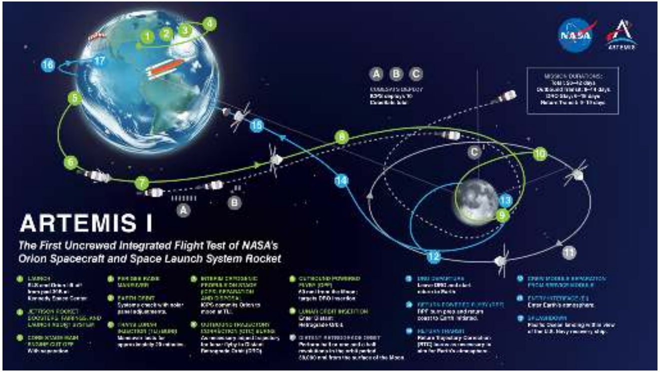
Reentry

Artemis Aerodynamics

Launch Abort

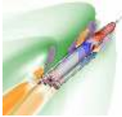
Ascent

Liftoff and Transition



Each phase of flight makes extensive use of NASA's HPC resources for analysis

Booster Separation



Panel Separation

Reentry

Ascent

- The "ascent" phase begins after the vehicle clears tower and ends after booster separation
- Aerodynamics are a major driver in this phase of flight - transonics and max q
- Methodology: Computational Fluid Dynamics (RANS) and wind tunnel experiments (validation and UQ)
- Different requirements from different "customers":
  - Surface pressures for crush loads(venting)
  - Protuberance loads for external partners

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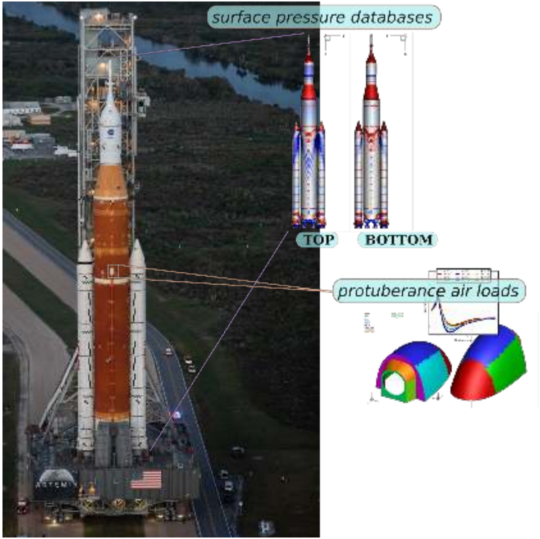

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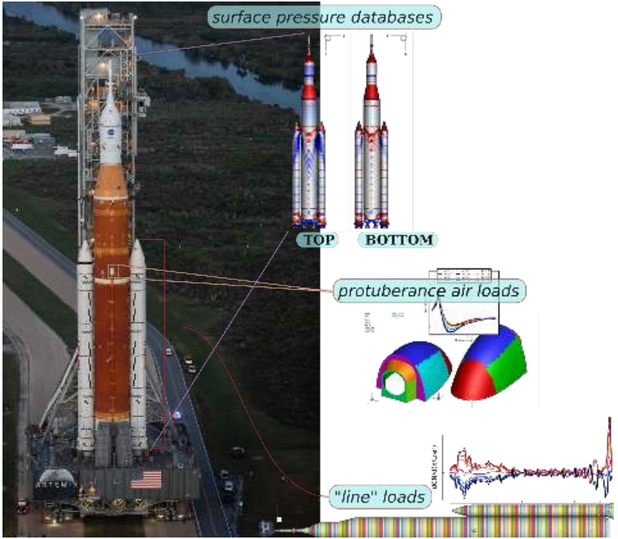

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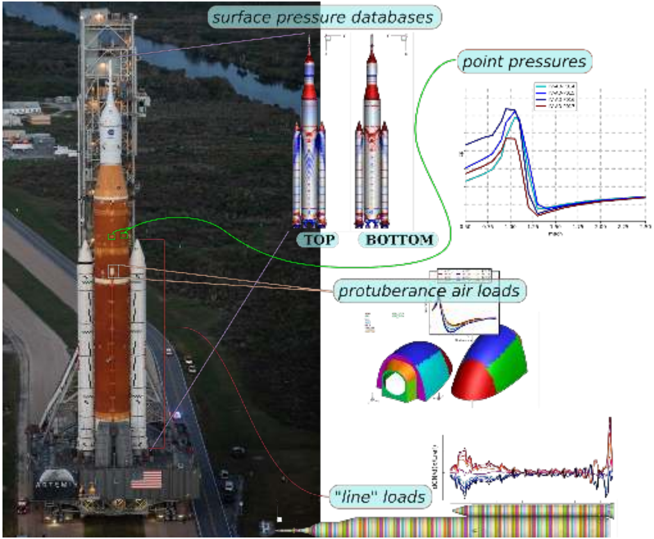

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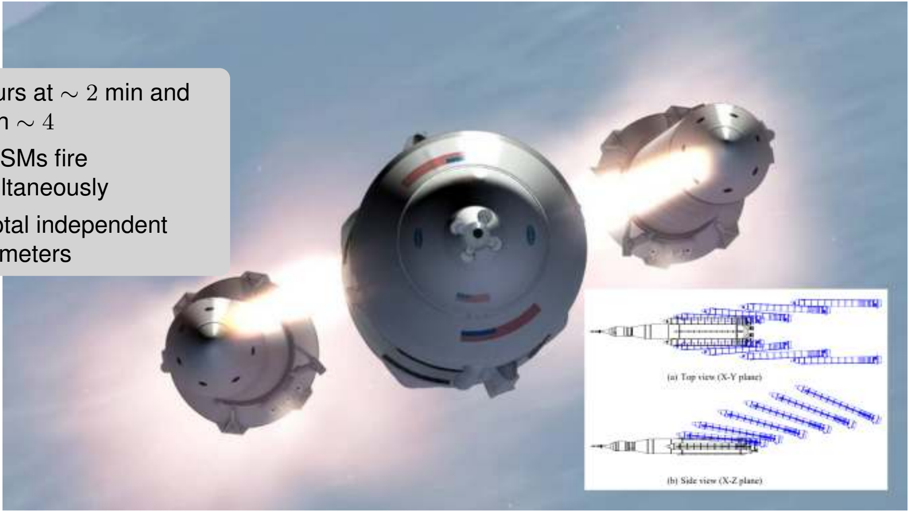
Booster Separation

- Occurs at ~ 2 min and Mach ~ 4
- 16 BSMs fire simultaneously
- 33 total independent parameters



Booster Separation is Incredibly Complex

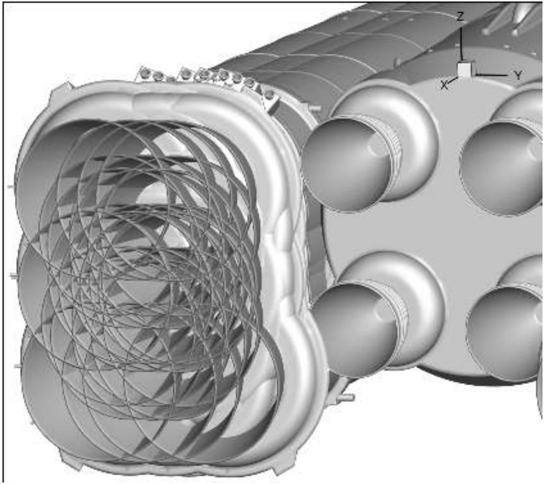
8-dimensional run matrix:

Variable	Description
dx	SRB axial translation
dy	SRB outward translation
dz	SRB vertical translation
dpsi	SRB yaw (rel. to core)
dtheta	SRB pitch
alpha	CORE angle of attack
beta	CORE sideslip angle
CTBSM	BSM thrust coefficient

Other variables held constant:

Variable	Description
dphi	SRB roll
mach	CORE Mach number
CTCSE	CORE engine thrust
CTSRB	SRB thrust

Full run matrix: $\mathcal{O}$(10k) cases

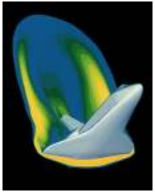


All SRB positions simulated at dx=6 ft in Artemis I database

How are Databases Built?

Shuttle Era

- Experimental (wind tunnel) data
  - Small scale models
  - Relatively costly and time consuming
  - Limited data access
- Engineering methods (back of envelope)
  - Fast and cheap
  - Only applicable in narrow range
- Computational methods in infancy



Present

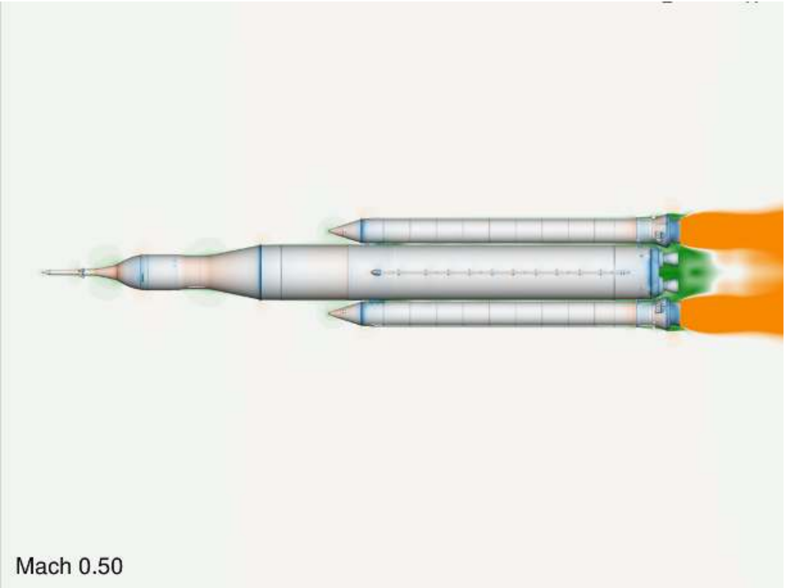
- Wind tunnel data still critical
- Computational methods (CFD) much more mature
  - Full data access
  - Able to simulate conditions wind tunnel can not
  - Limited by resources and availability
- Use both where applicable

Computational Resources Used (c. 2017)

- Over 71 million core hours
- Over 500 terabytes of storage used

- Block 1 Crew Ascent
  - 3000+ cases
  - 36 million core hours
- Block 1B Crew Ascent & Booster Separation
  - $\sim$1,300 + $\sim$3000 cases
  - 25 million core hours
- Block 1B Cargo Ascent Database
  - $\sim$1,300 cases
  - 5 million core hours

Sample Results - Ascent



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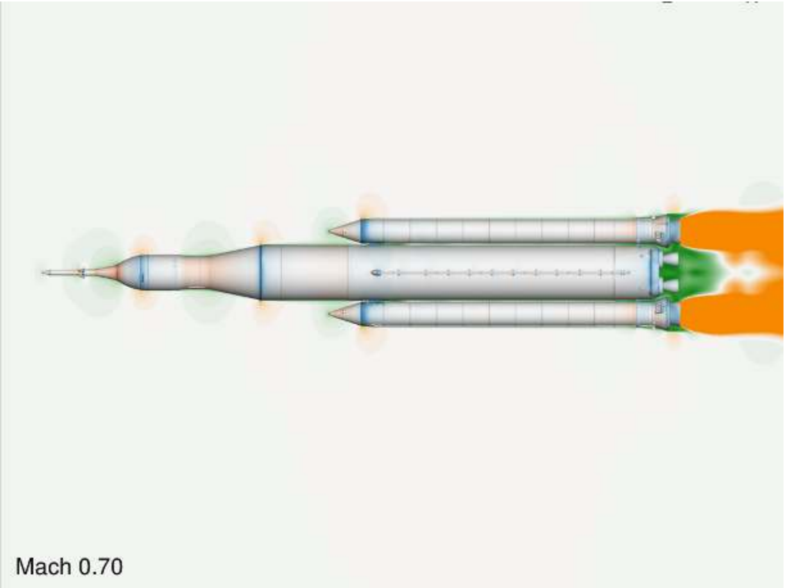

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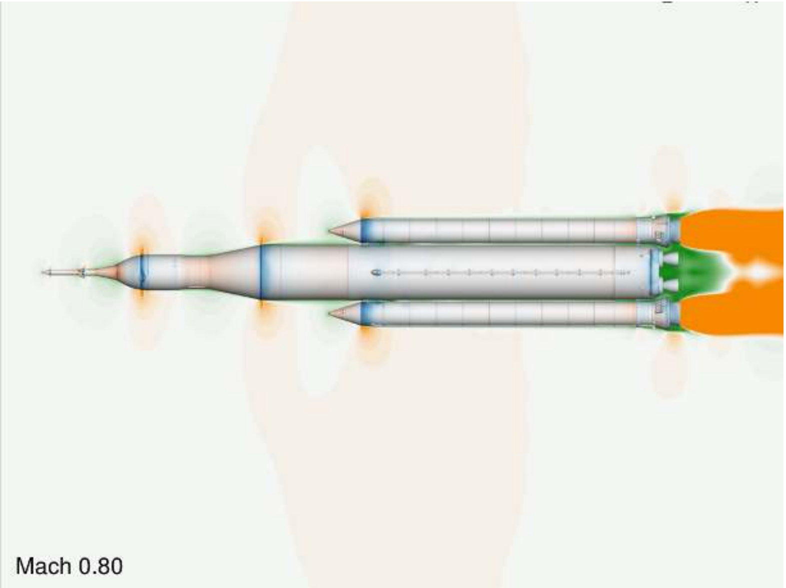

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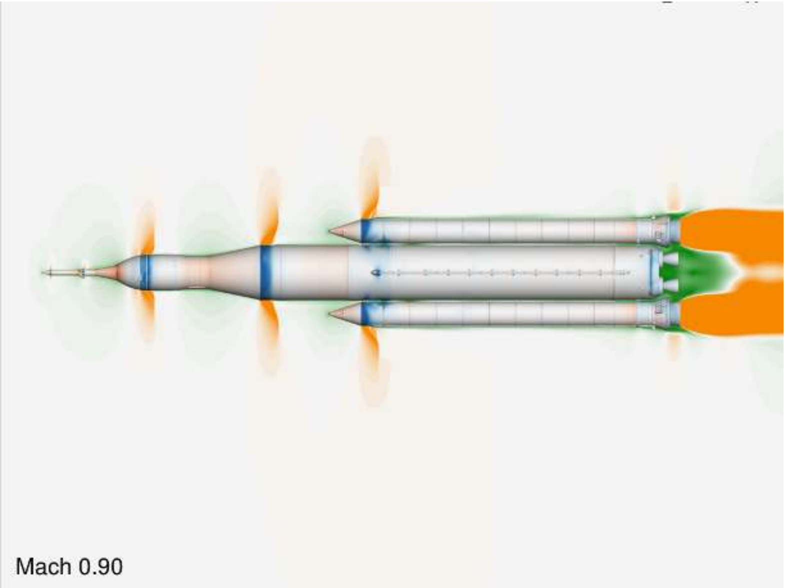

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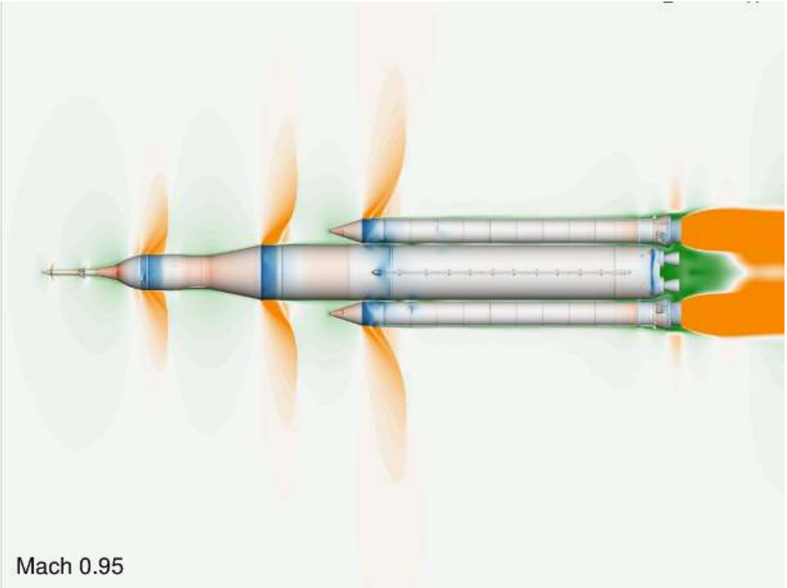

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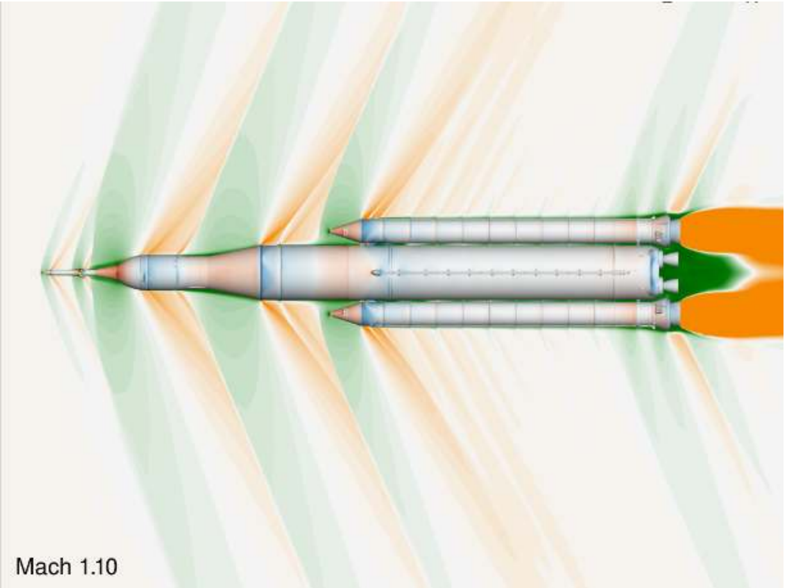

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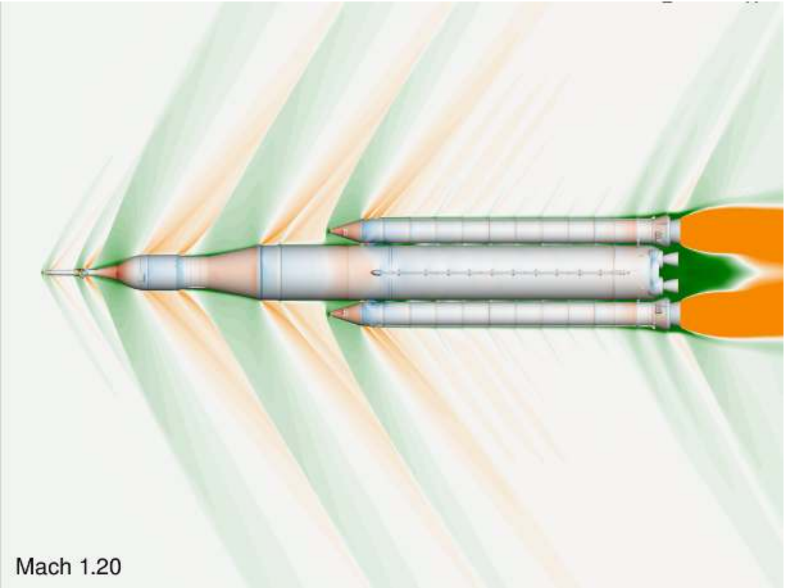

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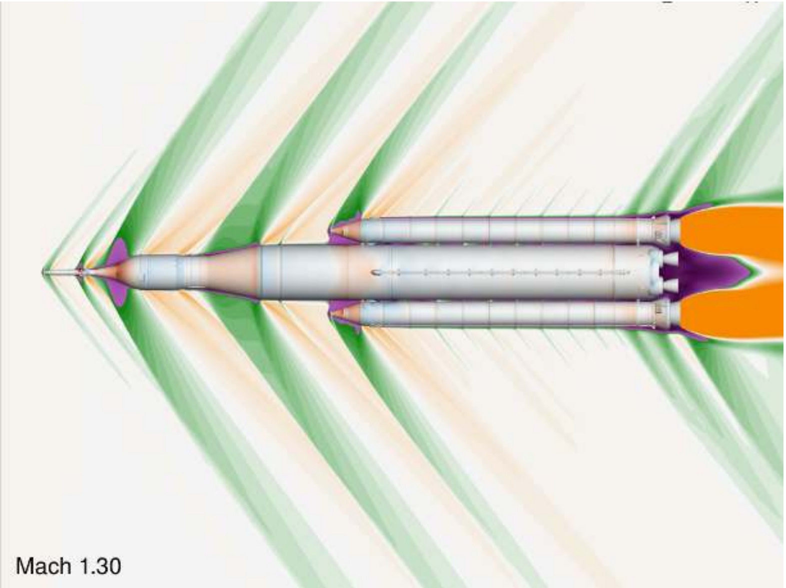

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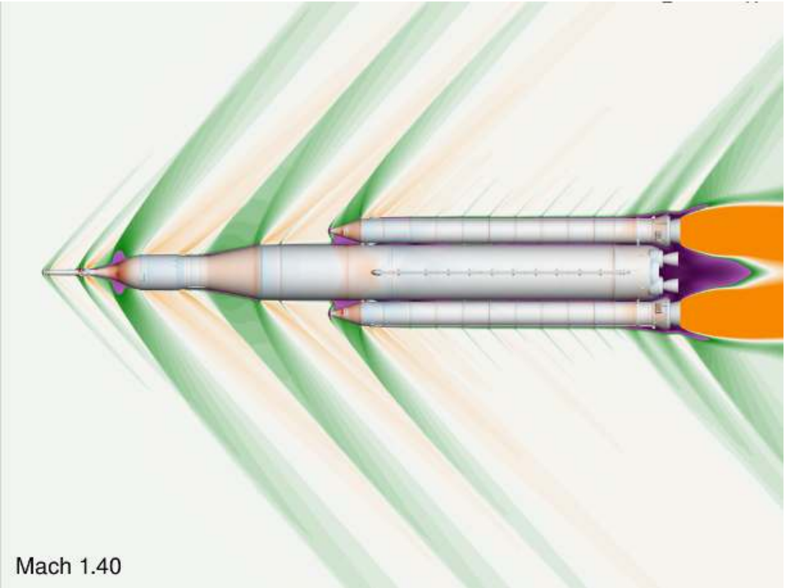

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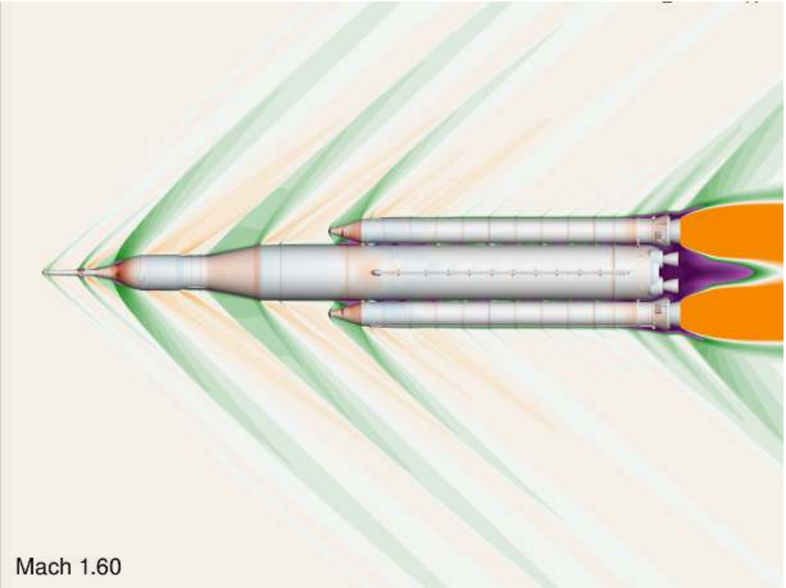

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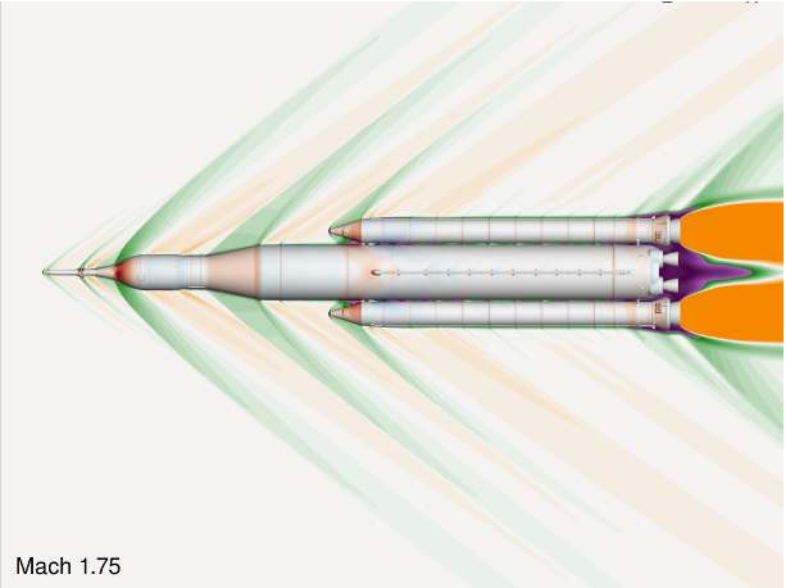

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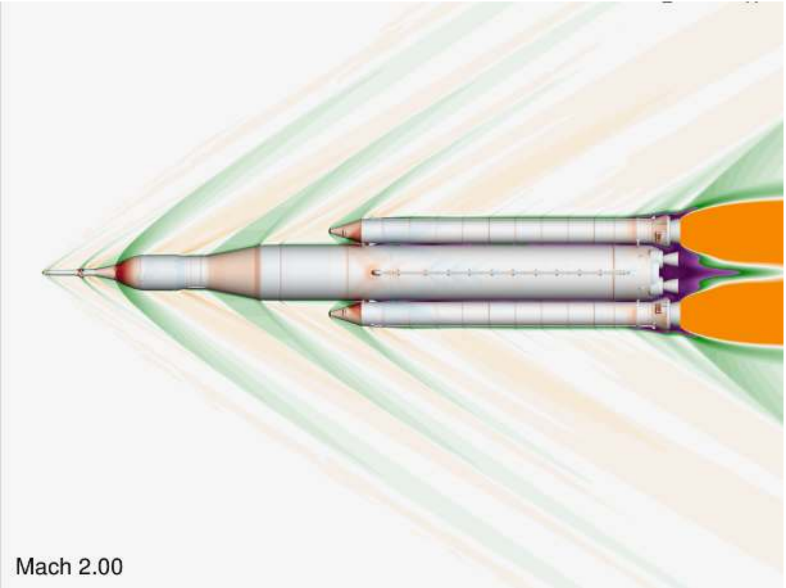

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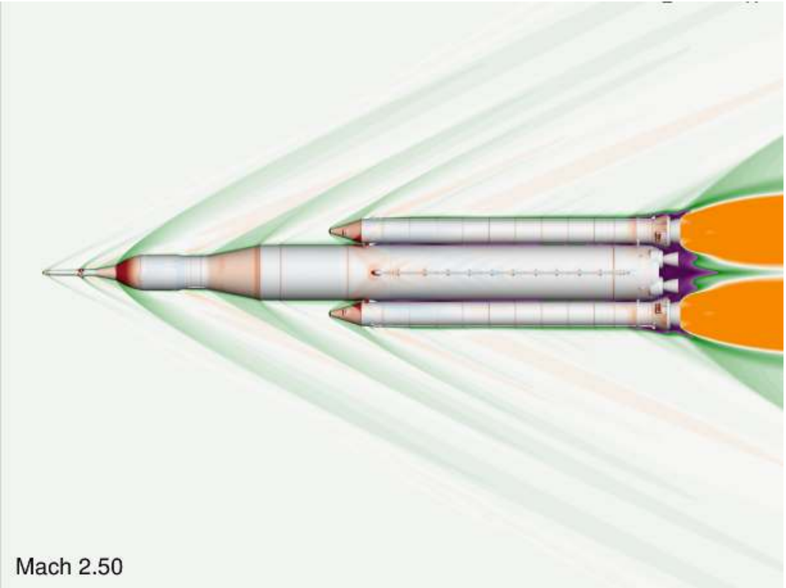

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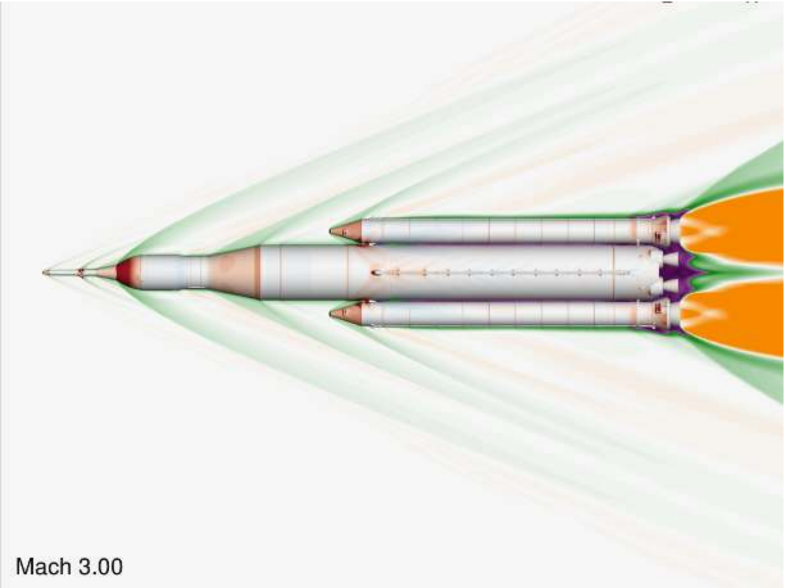

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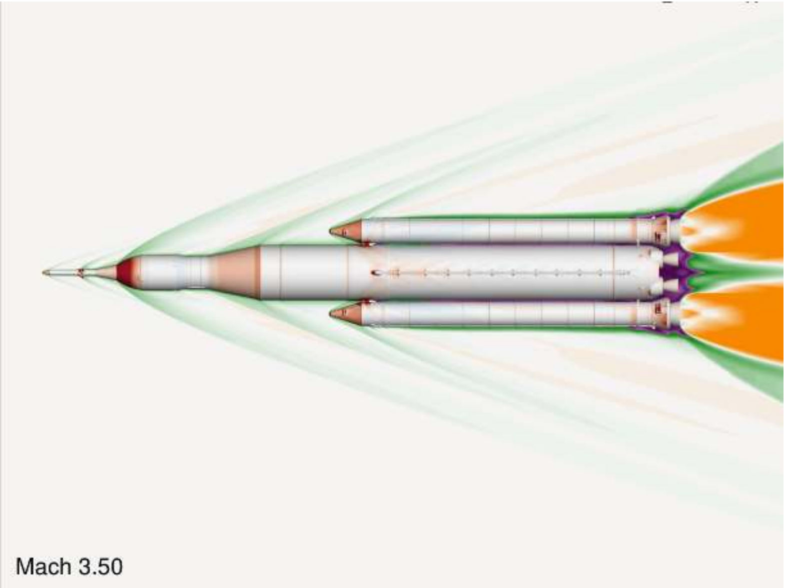

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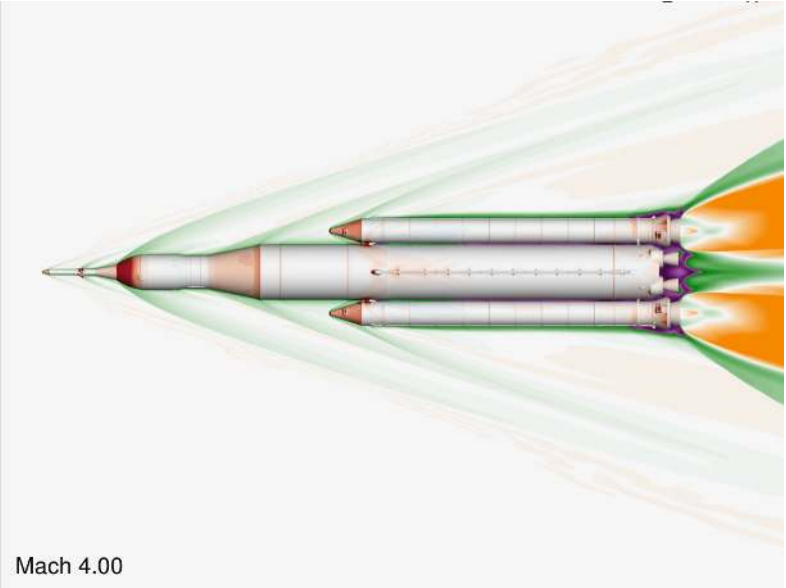

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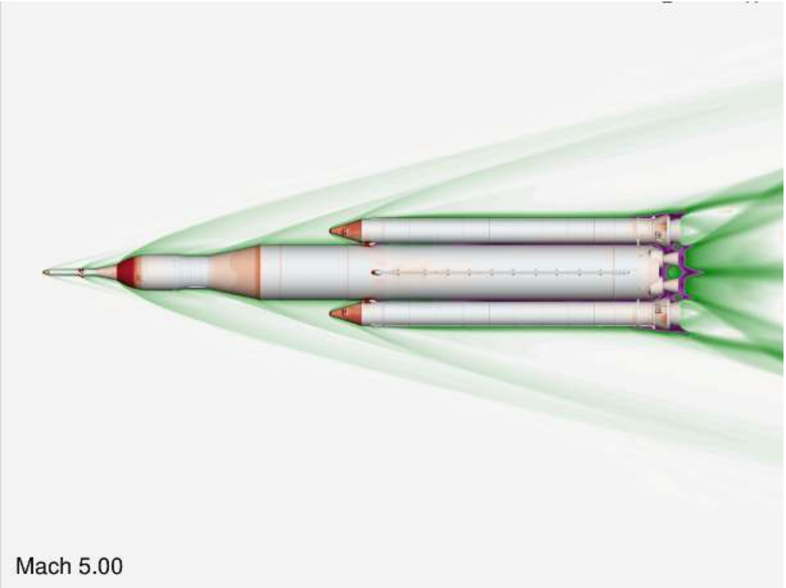
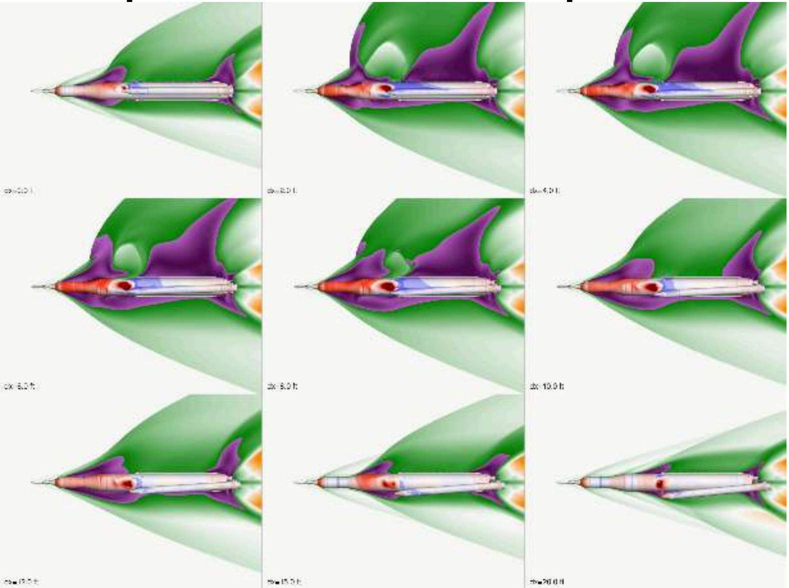
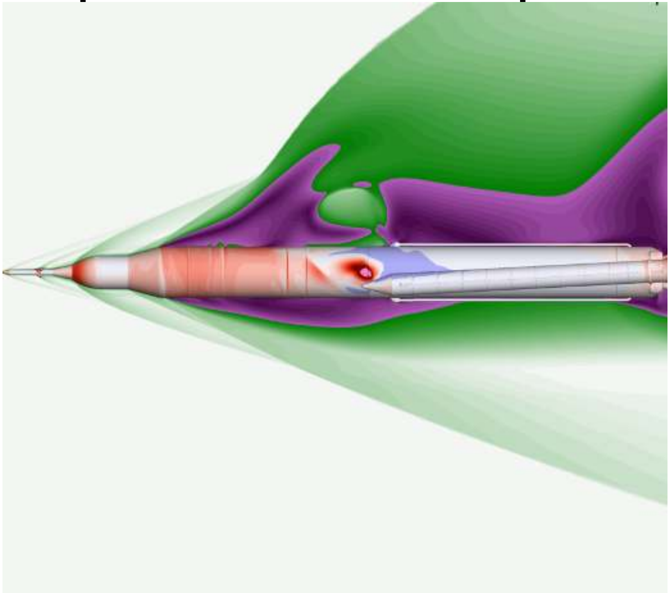


Sample Results - Booster Separation



Sample Results - Booster Separation



1. Cut plane through $y{=}0$

Color scheme:

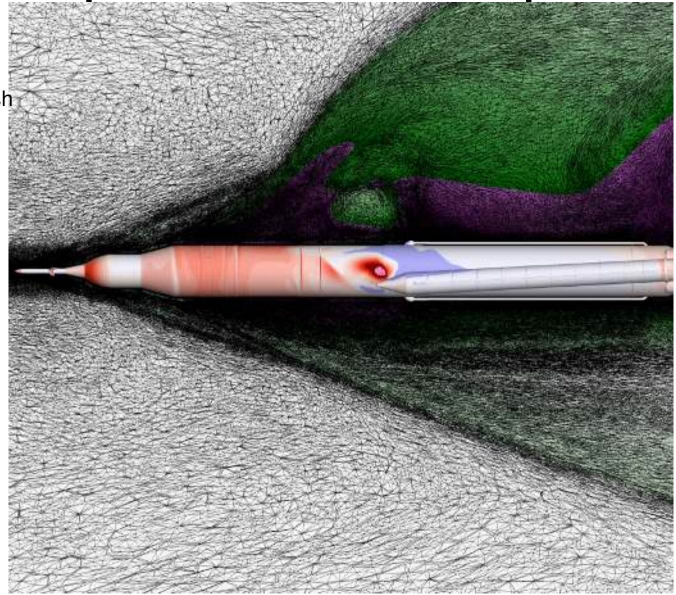
blue: negative $C_p < 0$
red: positive C_p
pink: very high C_p
purple: $M \leq 1.0$
green: $1 < M < M_\infty$
orange: $M > M_\infty$

Variable	*Value*
dx	6.0 ft
dy	$\approx$2 ft
dz	≈ -7 ft
dps	$\approx 0^\circ$
dth	$\approx -3^\circ$
alpha	$\approx 2^\circ$
beta	$\approx -2^\circ$

Sample Results - Booster Separation

2. $y=0$ cut plane with mesh

Color scheme:
blue: negative $C_p < 0$
red: positive C_p
pink: very high C_p
purple: $M \leq 1.0$
green: $1 < M < M_\infty$
orange: $M > M_\infty$



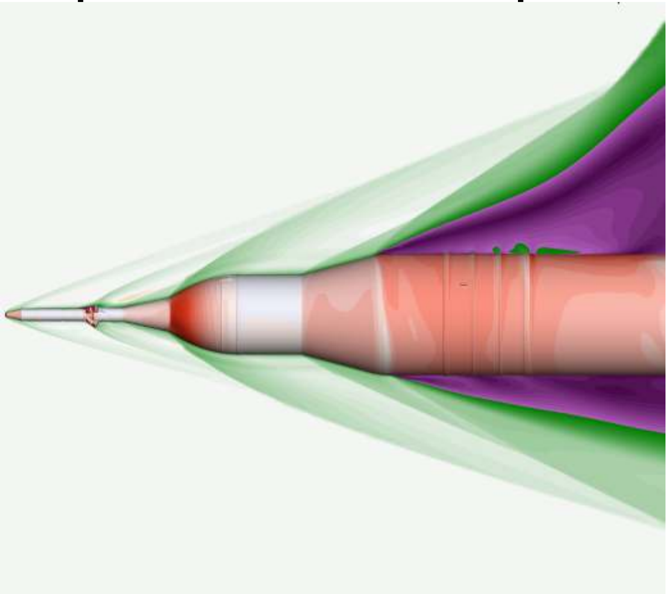
Variable	*Value*
dx	6.0 ft
dy	≈2 ft
dz	≈−7 ft
dps	≈0°
dth	≈−3°
alpha	≈2°
beta	≈−2°

Sample Results - Booster Separation

3. $y=0$ cut plane zoom-in

Color scheme:
blue: negative $C_p < 0$
red: positive C_p
pink: very high C_p
purple: $M \leq 1.0$
green: $1 < M < M_\infty$
orange: $M > M_\infty$

Variable	*Value*
dx	6.0 ft
dy	≈2 ft
dz	≈−7 ft
dps	≈0°
dth	≈−3°
alpha	≈2°
beta	≈−2°



Sample Results - Booster Separation

4. $z = 0$ cut plane

Color scheme:
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pink: very high C_p
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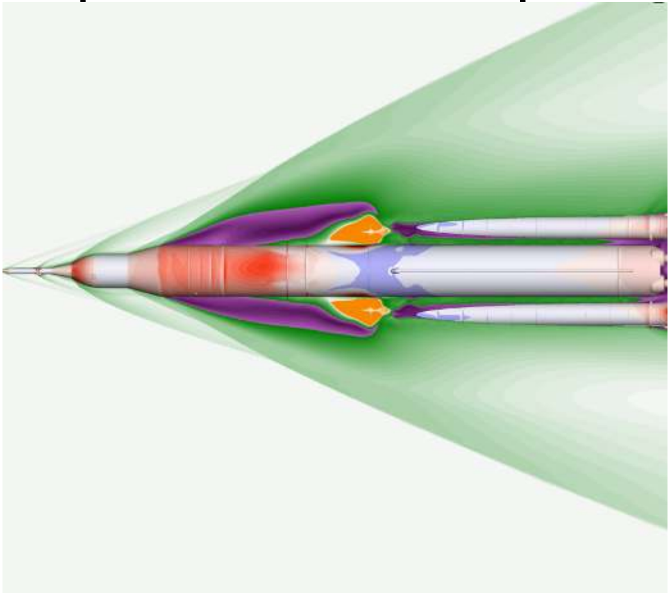
green: $1 < M < M_\infty$
orange: $M > M_\infty$



Variable	*Value*
dx	6.0 ft
dy	≈2 ft
dz	≈−7 ft
dps	≈0°
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alpha	≈2°
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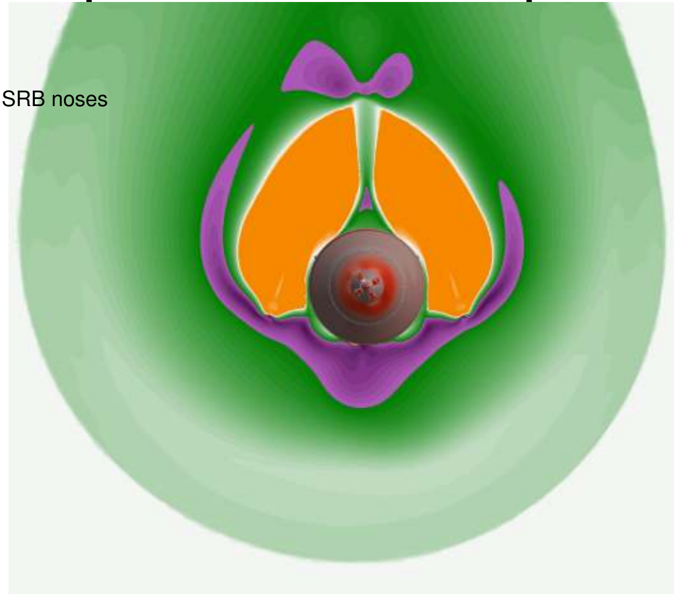
Sample Results - Booster Separation



5. Constant-x cut through SRB noses

Color scheme:

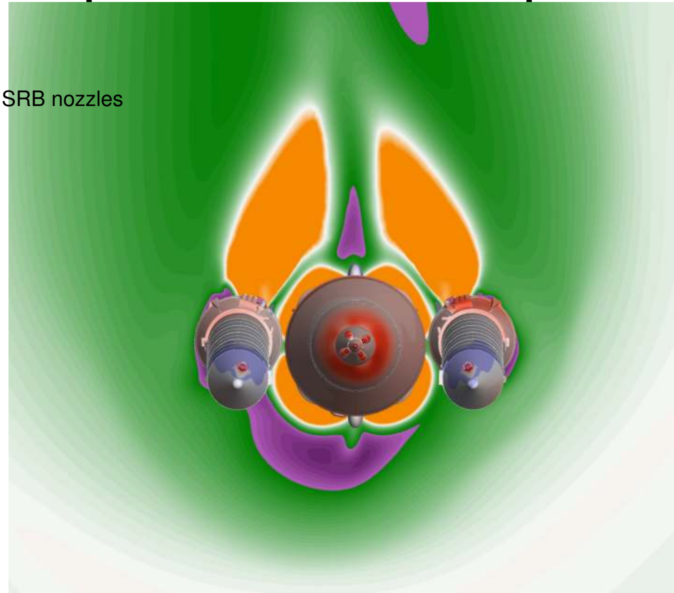
blue: negative $C_p < 0$
red: positive C_p
pink: very high C_p
purple: $M \leq 1.0$
green: $1 < M < M_\infty$
orange: $M > M_\infty$

Variable	***Value***
dx	6.0 ft
dy	$\approx$2 ft
dz	≈ -7 ft
dps	$\approx 0^\circ$
dth	$\approx -3^\circ$
alpha	$\approx 2^\circ$
beta	$\approx -2^\circ$

Sample Results - Booster Separation

6. Constant-x cut through SRB nozzles

Color scheme:
blue: negative $C_p < 0$
red: positive C_p
pink: very high C_p
purple: $M \leq 1.0$
green: $1 < M < M_\infty$
orange: $M > M_\infty$

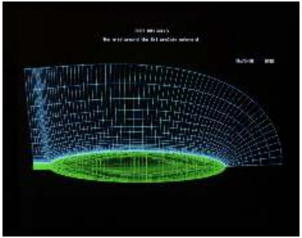


Variable	*Value*
dx	6.0 ft
dy	≈2 ft
dz	≈−7 ft
dps	≈0°
dth	≈−3°
alpha	≈2°
beta	≈−2°

HPC Impact

HPC Impact #1: Resources

A brief history of the NASA Advanced Supercomputing Division...



Navier (1985)
1.95 gigaflops

HPC Impact #1: Resources

A brief history of the NASA Advanced Supercomputing Division...

Columbia - 2004
63-86 teraflops

HPC Impact #1: Resources

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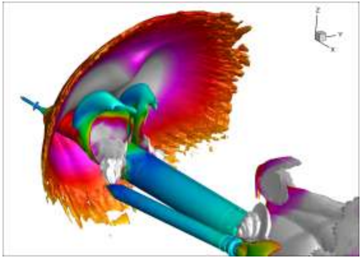

Pleiades - 2008
2008 - 0.49 petaflops
2022 - 5.95 petaflops

HPC Impact #1: Resources

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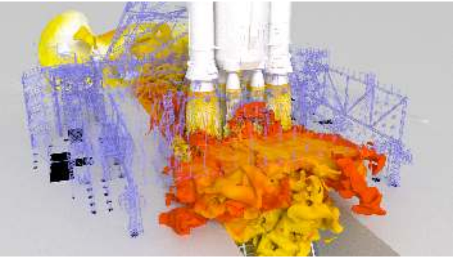


Modular - 2016/2019
Electra - 5.44 petaflops
Aitken - 9.07 petaflops

Resources lead to more robust CFD solvers

FUN3D

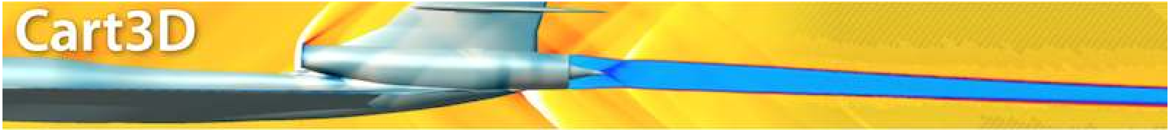
Fully Unstructured Navier-Stokes

https://fun3d.larc.nasa.gov

OVERFLOW 2

https://overflow.larc.nasa.gov/

And many more . . .

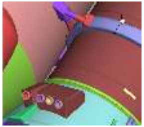


https://www.nas.nasa.gov/publications/software/docs/cart3d/

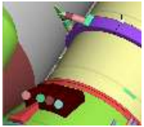
Resources lead to better Meshing

Space Shuttle, c. 2006

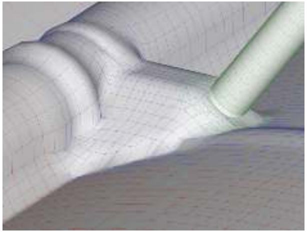
Artemis I, c. 2014



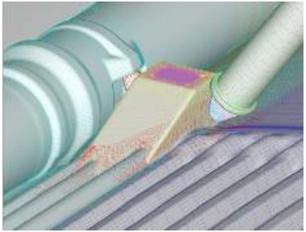
Artemis I, c. 2017



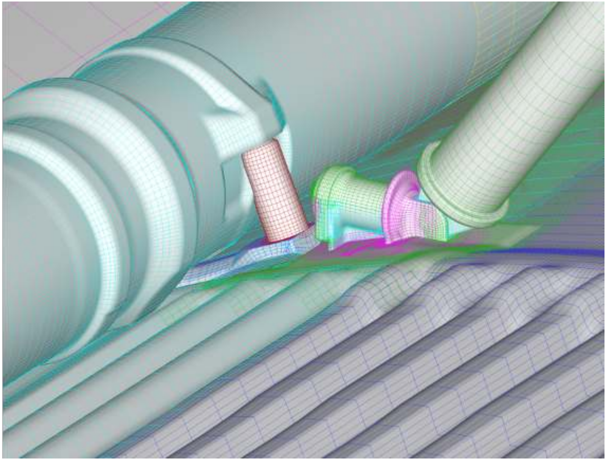
Artemis I, c. 2022



1990s



c. 2003

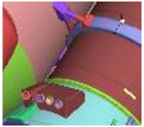


c. 2006

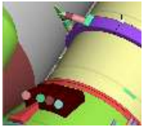
Resources lead to better Meshing

Space Shuttle, c. 2006

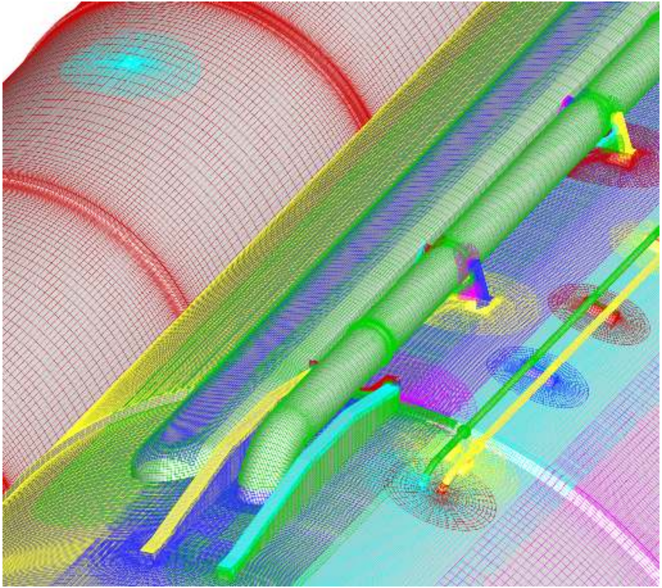
Artemis I, c. 2014



Artemis I, c. 2017



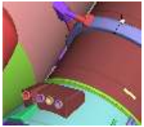
Artemis I, c. 2022



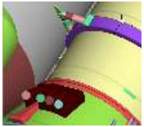
Resources lead to better Meshing

Space Shuttle, c. 2006

Artemis I, c. 2014

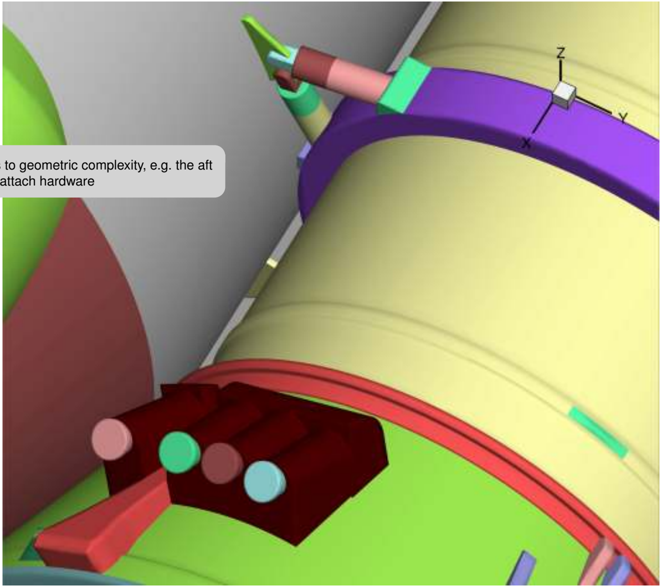


Artemis I, c. 2017



Artemis I, c. 2022

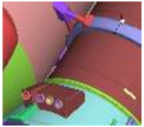
Further increases to geometric complexity, e.g. the aft BSM pod and aft attach hardware



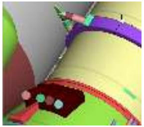
Resources lead to better Meshing

Space Shuttle, c. 2006

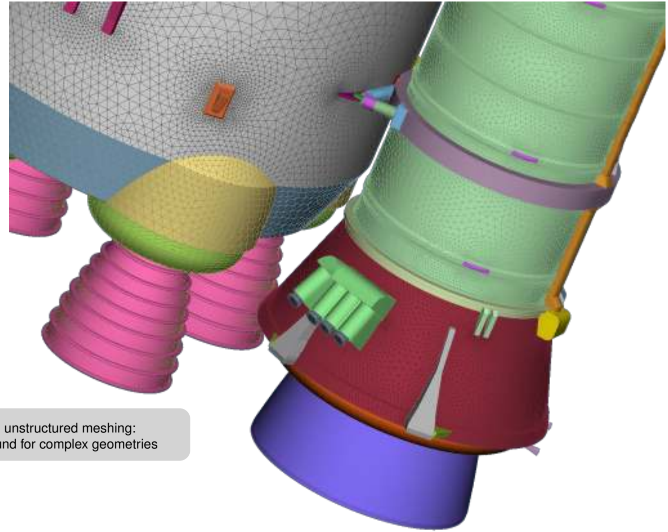
Artemis I, c. 2014



Artemis I, c. 2017



Artemis I, c. 2022

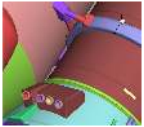


Introduced unstructured meshing:
faster turnaround for complex geometries

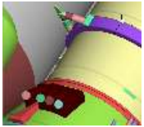
Resources lead to better Meshing

Space Shuttle, c. 2006

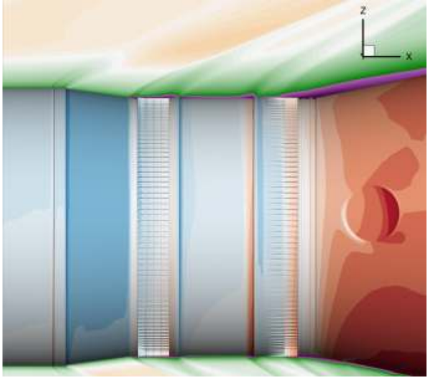
Artemis I, c. 2014



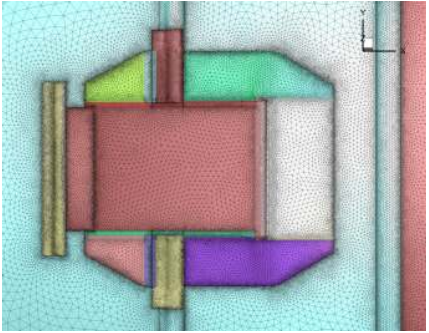
Artemis I, c. 2017



Artemis I, c. 2022



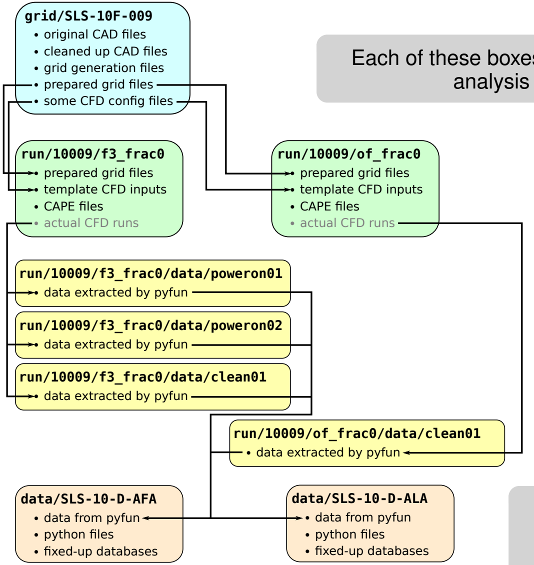
ICPS Orthogrid



Orion Umbilical Cover

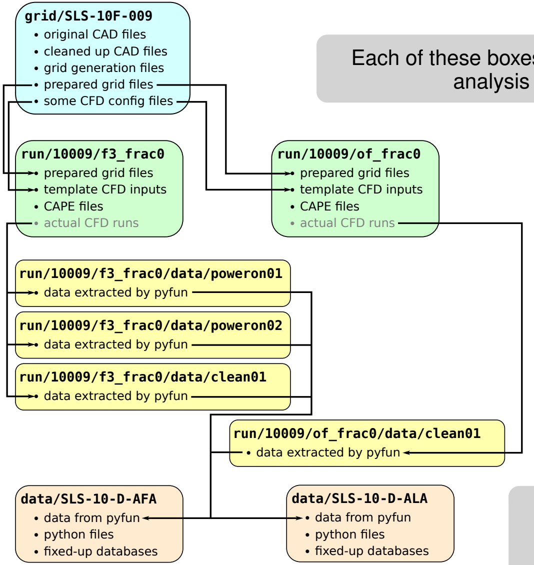
HPC Impact #2: CFD as Software Development

Each of these boxes is a `git` repository used in our analysis of one Artemis I task



Key aspect: use code and/or command line to generate inputs for each CFD case; no clicking to copy files manually!

HPC Impact #2: CFD as Software Development



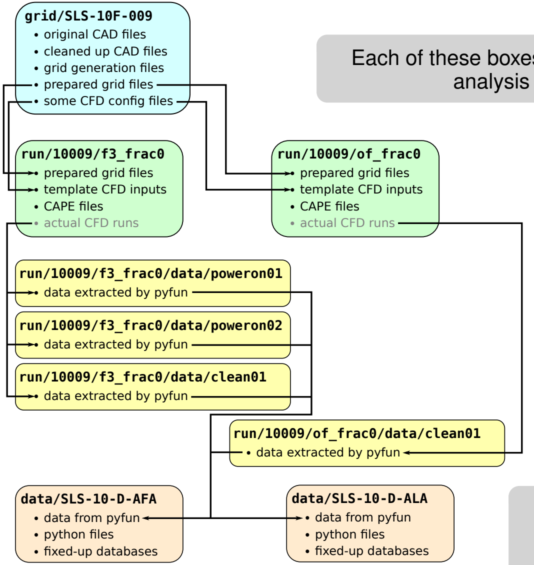
Each of these boxes is a `git` repository used in our analysis of one Artemis I task

Using version control software like this has certain implications:

- No spreadsheets, rich-text word docs, etc.
- Everything that changes w/ time should be text
- Can be a challenge for new team members to learn

Key aspect: use code and/or command line to generate inputs for each CFD case; no clicking to copy files manually!

HPC Impact #2: CFD as Software Development



Each of these boxes is a `git` repository used in our analysis of one Artemis I task

Using version control software like this has certain implications:

- No spreadsheets, rich-text word docs, etc.
- Everything that changes w/ time should be text
- Can be a challenge for new team members to learn
- Avoid having one HUGE repo where all the work is done
- This requires some planning

Key aspect: use code and/or command line to generate inputs for each CFD case; no clicking to copy files manually!

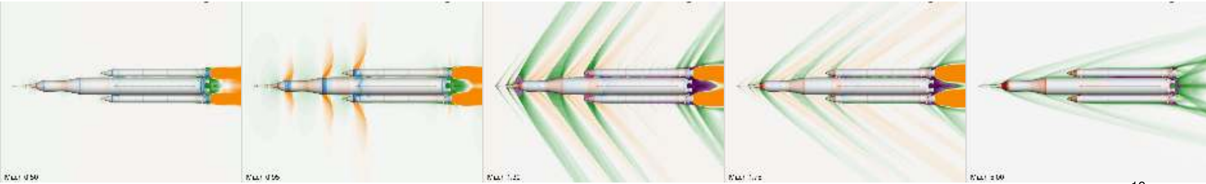
CAPE

Use a single tool to set up, run, backup, and extract data from each case

Running

Example: set up and submit 10 OVERFLOW jobs at Mach 1.75

```
$ pyover --re m1.75 -n 10
```



CAPE

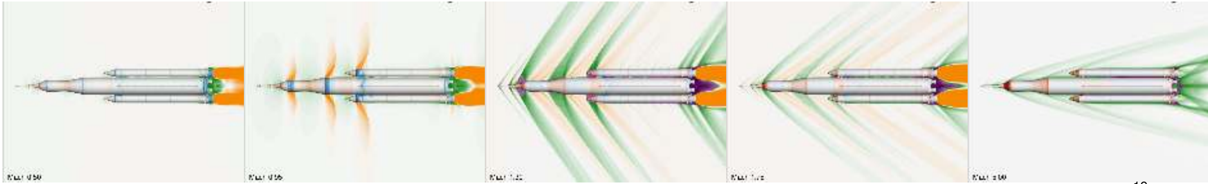
Use a single tool to set up, run, backup, and extract data from each case

Checking status

Example: Check status of FUN3D jobs at Mach 1.75

```
$ pyfun --re m1.75 -c
Case Config/Run Directory     Status  Iterations  Que CPU Time
---- ----------------------- ------- ----------- --- --------
81   poweron/m1.75a0.0r000.0 RUNNING 4237/5000   R    11273.7
82   poweron/m1.75a4.0r000.0 QUEUE   3000/4000   Q     2633.1
83   poweron/m1.75a4.0r090.0 PASS    5000/5000   .    10743.3

PASS=1, RUNNING=1, QUEUE=1,
```



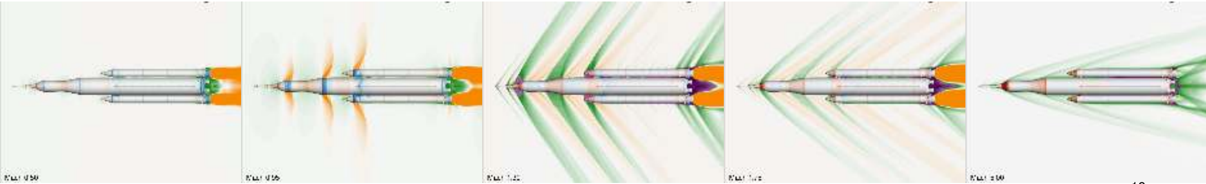
CAPE

Use a single tool to set up, run, backup, and extract data from each case

Generate report

Example: generate LaTeX report for cases 79 and 402

```
$ pycart -I 79,402 --report
```



CAPE

Use a single tool to set up, run, backup, and extract data from each case

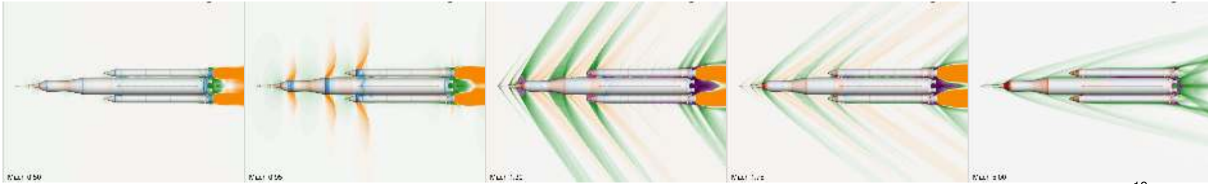
Generate report

Example: generate LaTeX report for cases 79 and 402

```
$ pycart -I 79,402 --report
```

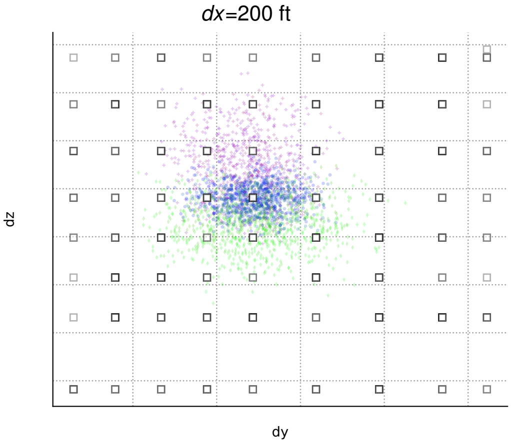
Tool is open source:

`https://github.com/nasa/cape.git`



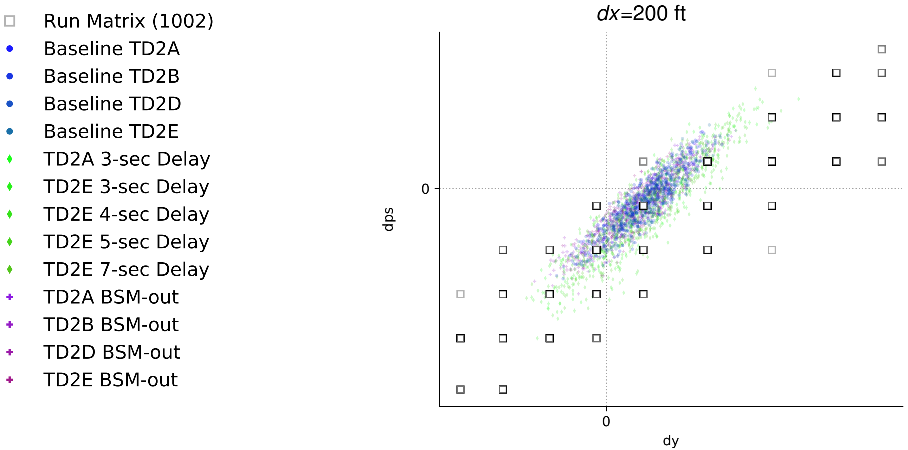
HPC Impact #3: Data Science

- Run Matrix (1002)
- Baseline TD2A
- Baseline TD2B
- Baseline TD2D
- Baseline TD2E
- TD2A 3-sec Delay
- TD2E 3-sec Delay
- TD2E 4-sec Delay
- TD2E 5-sec Delay
- TD2E 7-sec Delay
- TD2A BSM-out
- TD2B BSM-out
- TD2D BSM-out
- TD2E BSM-out



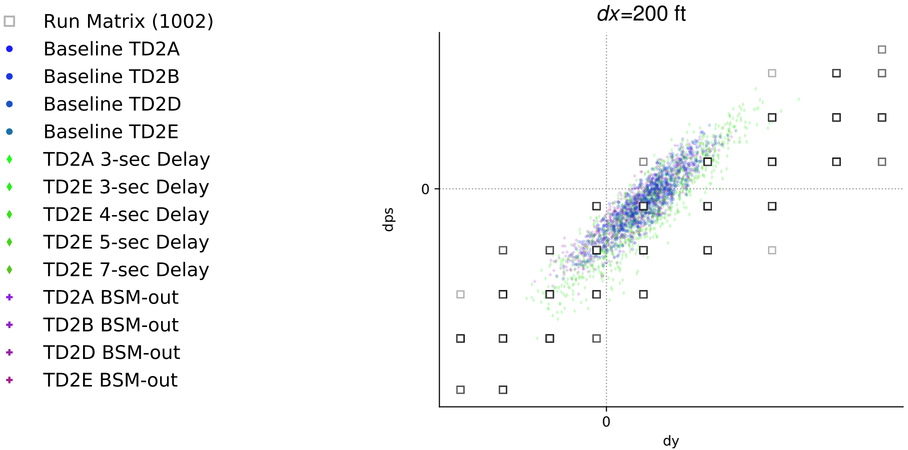
Usually sufficient to use square matrices

HPC Impact #3: Data Science



Sometimes a square matrix leads to spurious results

HPC Impact #3: Data Science



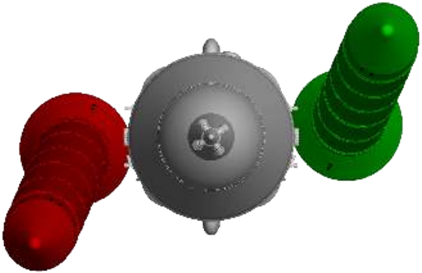
Solution: Use machine learning concepts to create correlated matrices

Summary

- Hundreds of millions of CPU hours have been dedicated to the study of SLS aerodynamics
- HPC is integral to the success of any Artemis mission
- Reduces the reliance on costly and time consuming physical tests
- Helps agency realize goal of safe and reliable missions

Where do we go from here?

- Future SLS missions - Block 2
- More machine learning - convergence
- Ever evolving/more robust methods



Acknowledgments

- Previous members of the NASA ARC/TNA SLS CFD Team
- Other current and former members of the SLS Aero Task Team
- NASA Advanced Supercomputing facilities
- SLS Program; this work is part of the SLS Aero Task Team
- Exploration Systems Development Mission Directorate (ESDMD)
- NASA Engineering & Safety Center (NESC) for discussions and reviews