

NASA Langley Hypersonic Experimental Aerothermodynamic Capabilities and Recent Contributions

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NASA Langley Research Center



Topic

- LAL Facility Background
- LAL Instrumentation/Techniques
- Types of LAL Ground Testing
 - Flight Program
 - Commercial/DoD Partnership
 - Research and Development
 - Academic Partnership
 - Test Technique Development
 - Facility Calibration Development
- Conclusion

Slides

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11,12

13-15

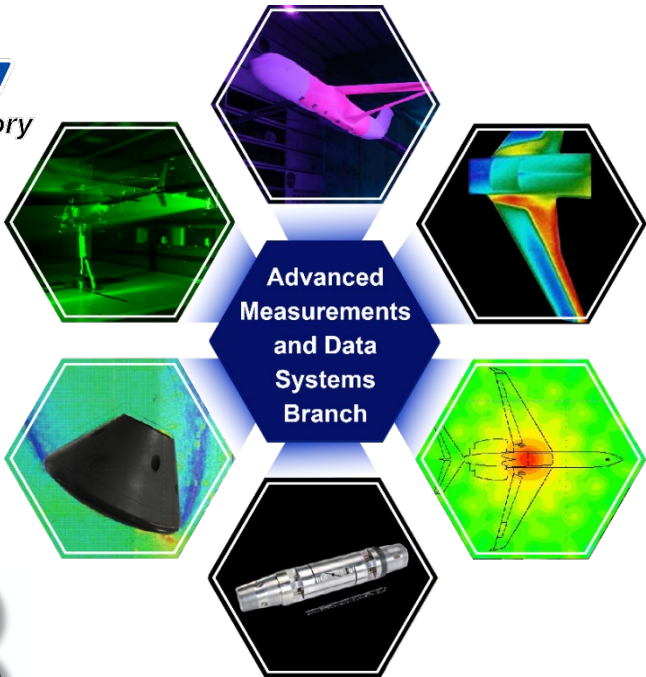
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18, 19

20, 21

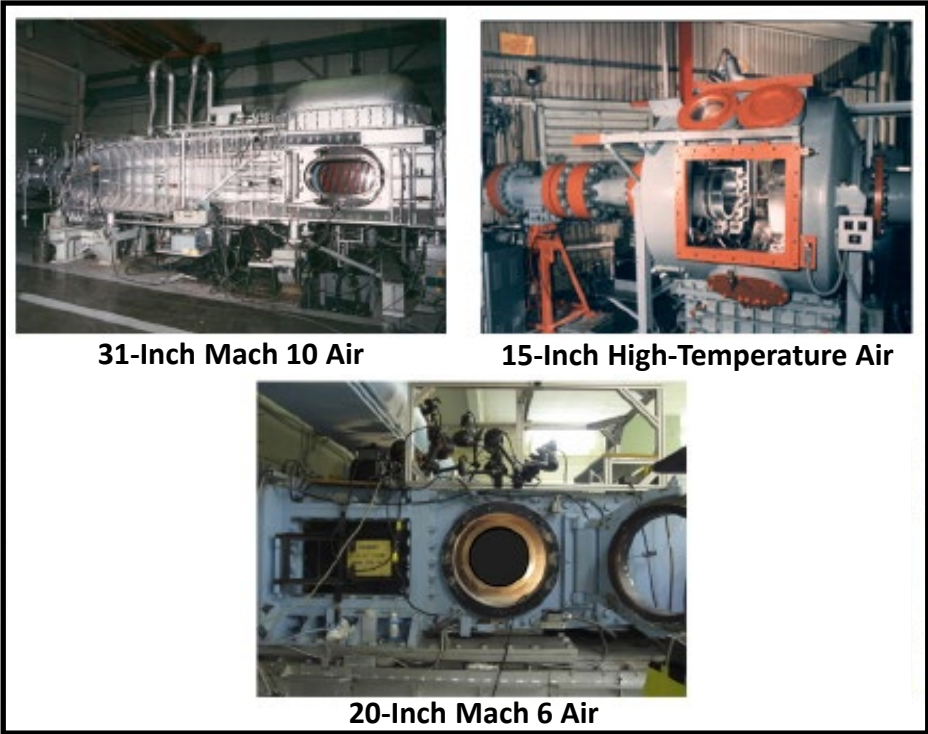
22

Langley Aerothermodynamic Expertise and Facilities

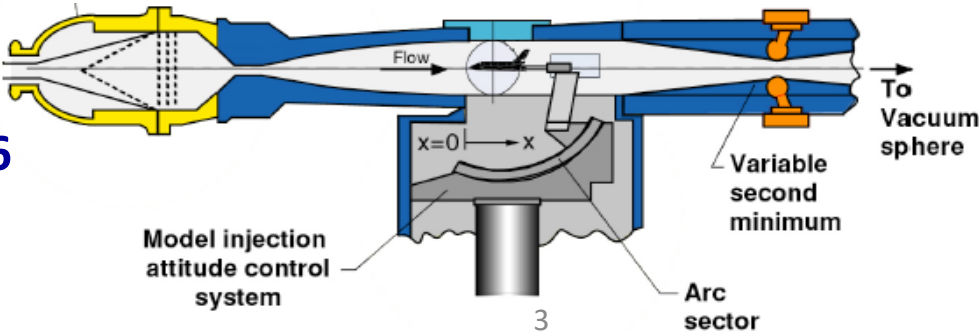


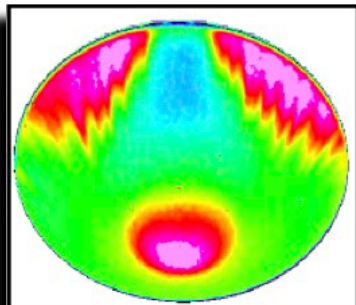
- Operation:**
 - Conventional blow-down wind tunnels
 - Perfect-gas, dry-air facilities provide high flow quality and low-enthalpy test conditions
 - Optical access on three sides for phosphor/IR thermography, PLIF, schlieren, etc.
- Wind Tunnel Features:**
 - 31-inch, Mach 10:**
 - Re: $0.5\text{--}2.1 \times 10^6/\text{ft}$
 - Core Flow: 14" x 14"
 - Max run duration: 2 minutes
 - 20-Inch Mach 6:**
 - Re: $0.5\text{--}8.3 \times 10^6/\text{ft}$
 - Core Flow: 14" x 14"
 - Max run duration: 15 minutes

Experimental Facilities

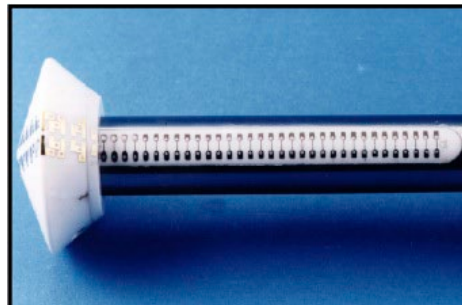


20-Inch Mach 6
Test Section

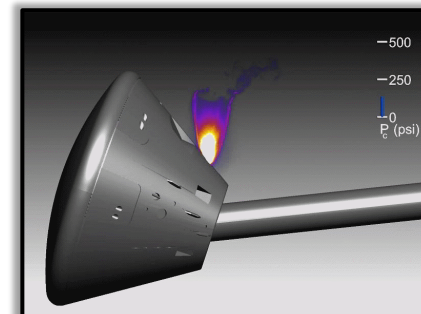




Infrared, phosphor thermography, or temperature-sensitive paint for global heat transfer measurements



Thin-film, thin-skin, or coaxial thermocouple gages for discrete heat transfer measurements



Focused Laser Differential Interferometry (FLDI)
Planar Laser Induced Fluorescence (PLIF)
High-speed photogrammetry



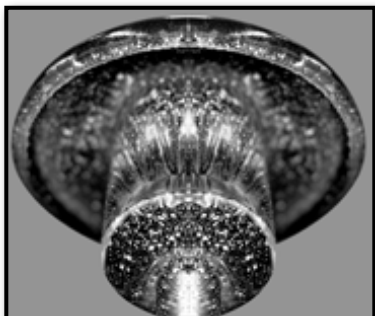
Electronically Scanned Pressure (ESP) measurements



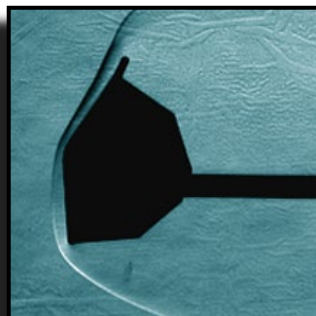
High frequency pressure transducers (Kulites/PCBs):
 $f \leq 1 \text{ MHz}$



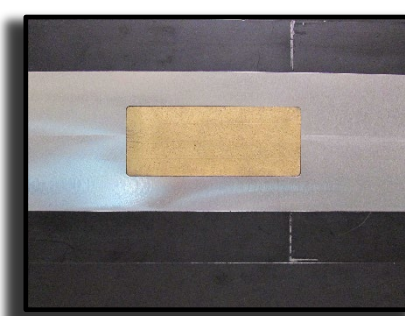
Atomic Layer Thermopile (ALTP),
Hot Wire Anemometry,
Schmidt-Boelter Gauges (discrete heat transfer)



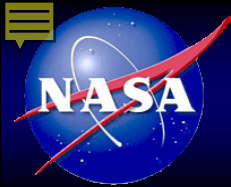
Oil-flow for surface streamline visualization



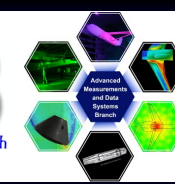
Schlieren (integrated, focusing, background oriented) for flow field visualization



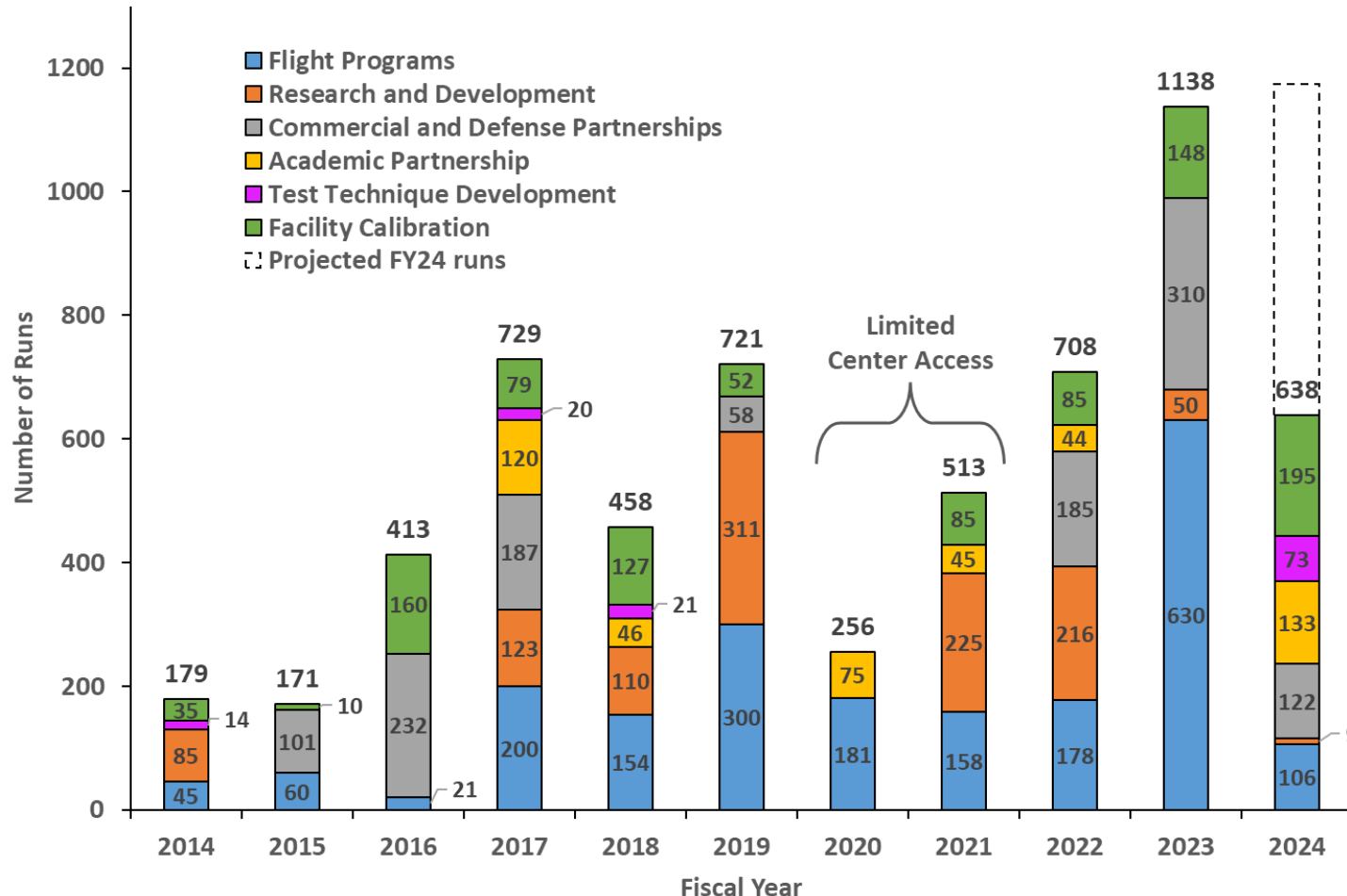
Laser speckle interferometry
Laser-based ultrasound



Decade of LAL 20-Inch Mach 6 Tests



Portfolio of LAL Testing in the 20-Inch Mach 6 Air Tunnel from 2014 to 2024

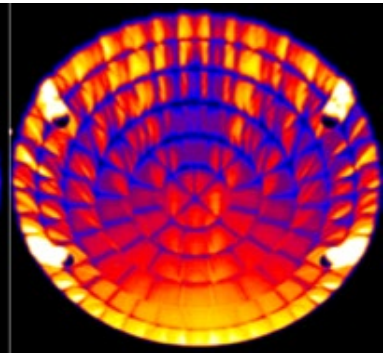
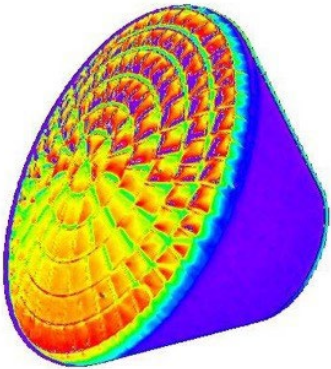
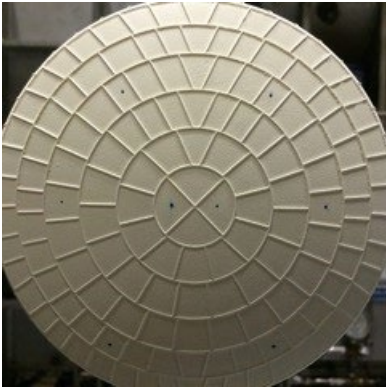


NASA's new funding model (2017) increased demand for:

1. Support for NASA/external flight missions
2. Partnerships with external industry and defense partners
3. Foundational/applied research
4. University collaborations

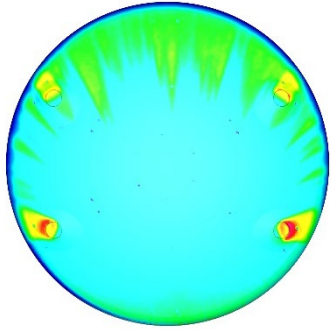
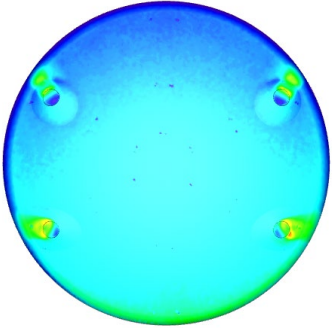
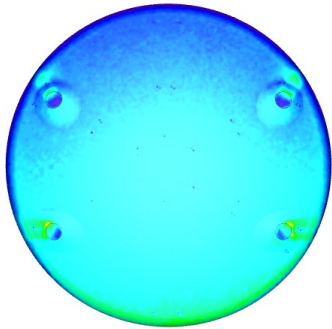


Flight Program Support

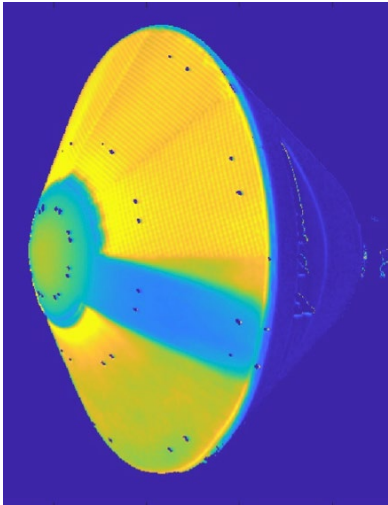
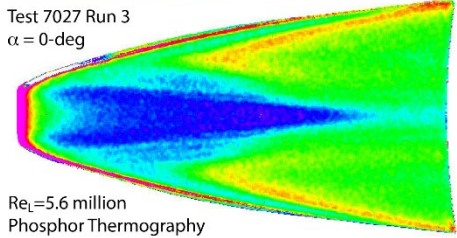
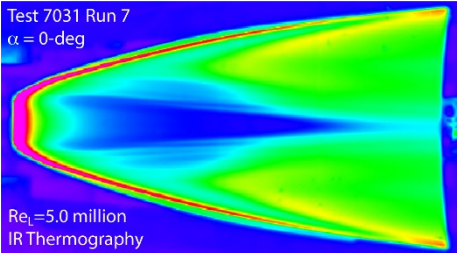


Orion/Multipurpose Crew Vehicle (MPCV)

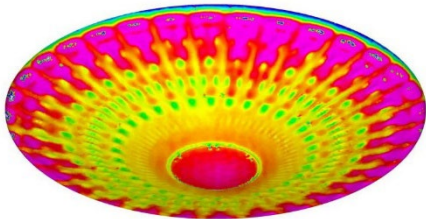
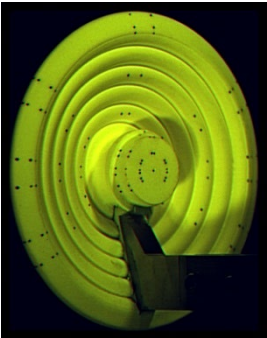
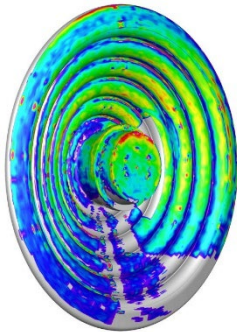
Artemis I



Boundary Layer Transition/Turbulence (BOLT)

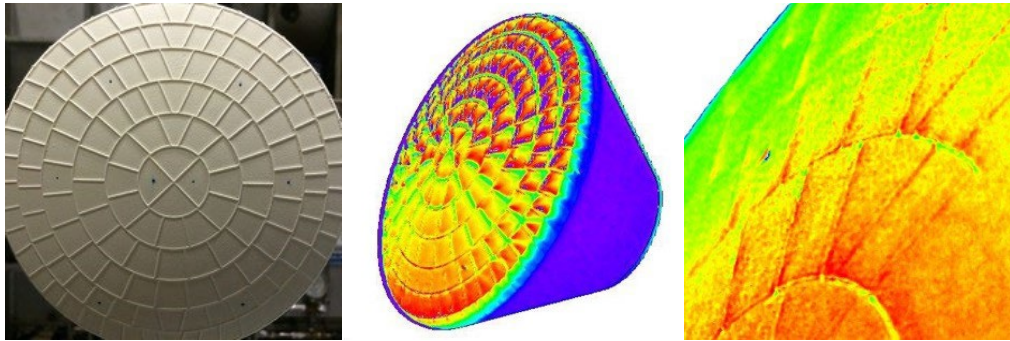


Mars Sample Return – Earth Entry Systems



Low-earth Orbit Flight Test of an Inflatable Decelerator (LOFTID)

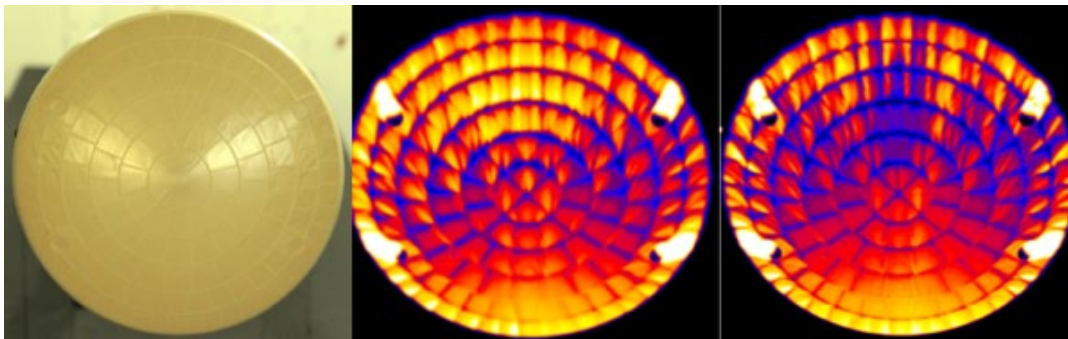
Orion/Artemis I:
Phosphor thermography



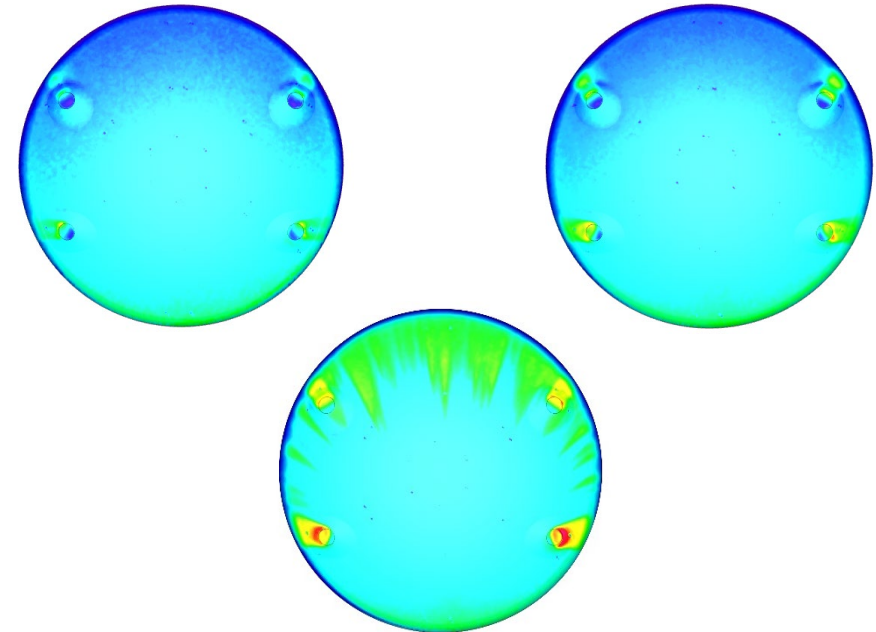
LAL ground tests of Orion Thermal Protection System (TPS) fences and heatshield recession:

- 1) Provided **traceability-to-flight** information to support the Artemis I mission
- 2) **Verified** the block Avcoat RTV fence-induced laminar-to-turbulent **boundary-layer transition assumptions**.

Orion/Artemis I:
IR thermography

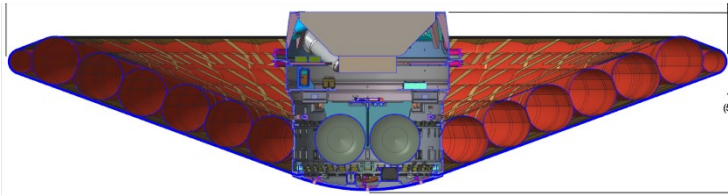


Artemis I
Phosphor Thermography



LAL ground tests provided **aeroheating data** on a wide range of possible char-loss cavity sizes and locations after the **Artemis I flight**, prior to **Artemis II**.

Infrared image of aeroshell after splashdown

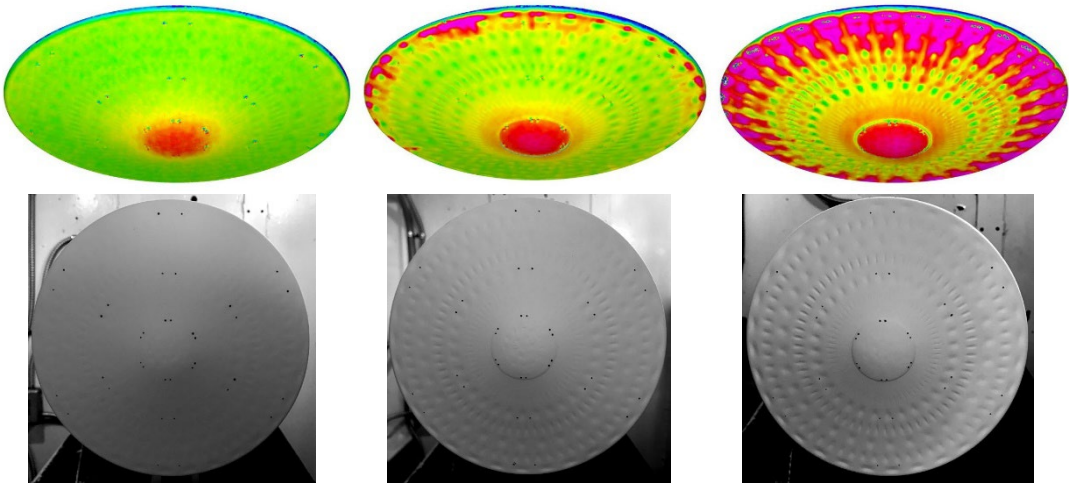


Cross section of aeroshell toroids and payload

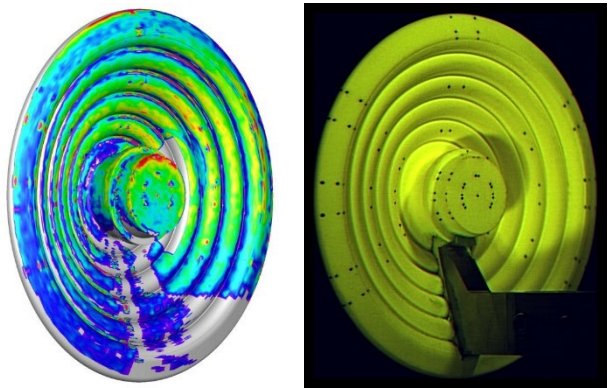
LAL testing demonstrated the:

- 1) **influence of deflections** in the outer mold line of LOFTID’s flexible TPS on boundary-layer transition and convective heating
- 2) heating levels in the **separated, unsteady wake flow** over the back-face of the LOFTID aeroshell.

Flexible TPS scalloping effects on aeroshell heating
(AIAA 2024-1498)



Aeroshell back-face and payload heating



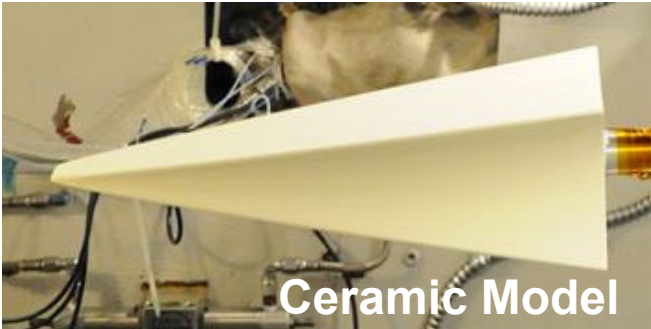
BOLT-2 Launch from Wallops



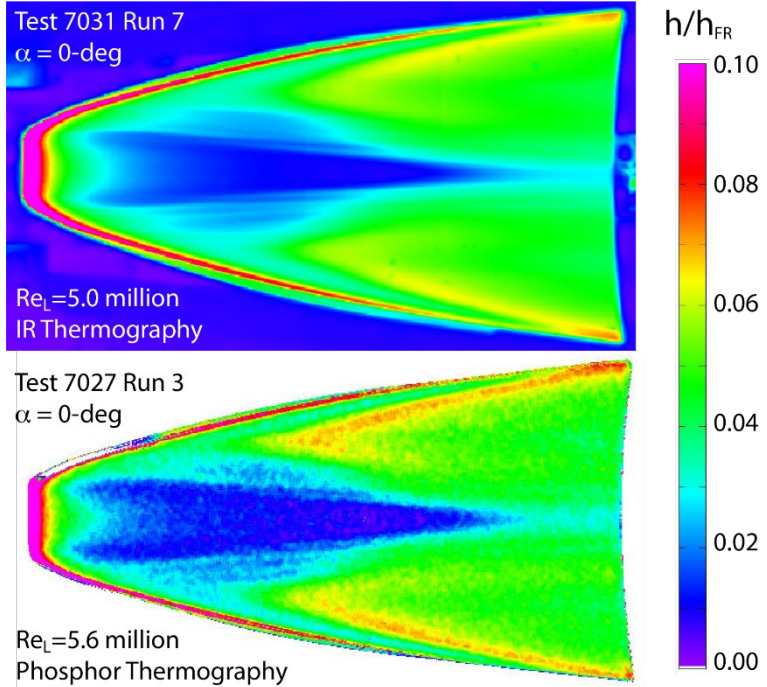
[Photo Source: NASA]



PEEK Model



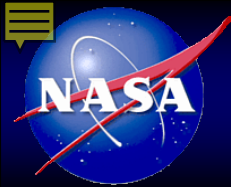
Ceramic Model



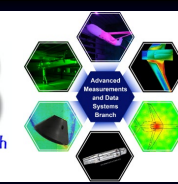
- LAL ground testing of BOLT models with varying scales contributed to:
- Pre-flight screening/analysis:** BOLT-1A (prior to kickoff), BOLT-1A leading edge roughness, BOLT-1A fairing, BOLT-2 (Long-BOLT), BOLT-1B steps
 - Post-flight comparison:** BOLT-2 steps/trips



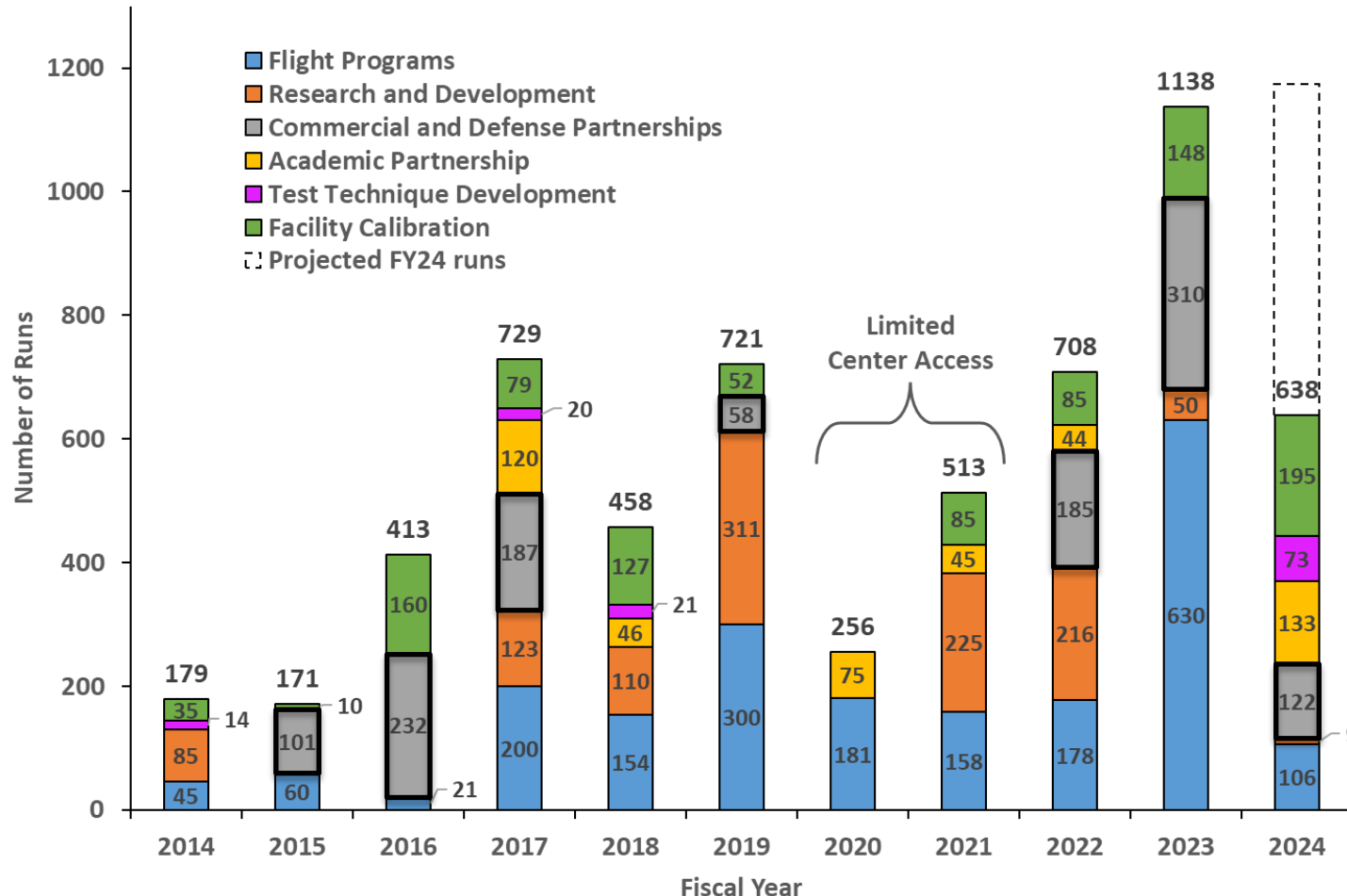
Commercial and Defense Partnerships



Commercial and DoD Partnerships



Portfolio of LAL Testing in the 20-Inch Mach 6 Air Tunnel from 2014 to 2024

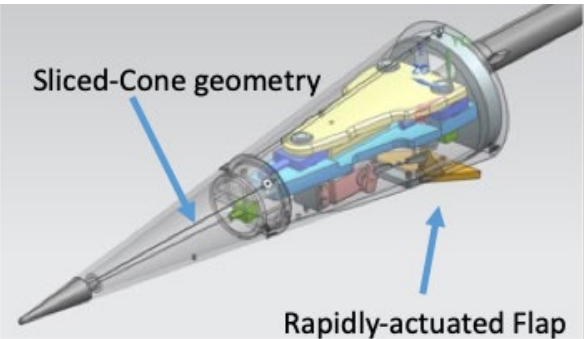
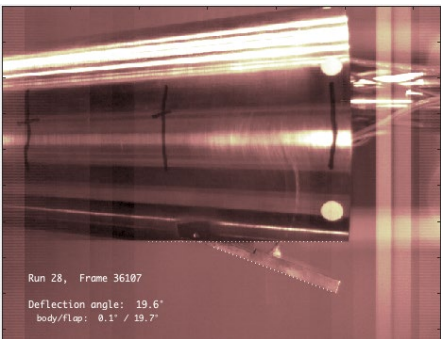


- Percentage of commercial and defense LAL test support over the last ten years: **20%**
- Proprietary, CUI, ITAR, and classified testing can be conducted in the LAL facilities
- A Space Act Agreement is set up to conduct reimbursable work for each individual customer

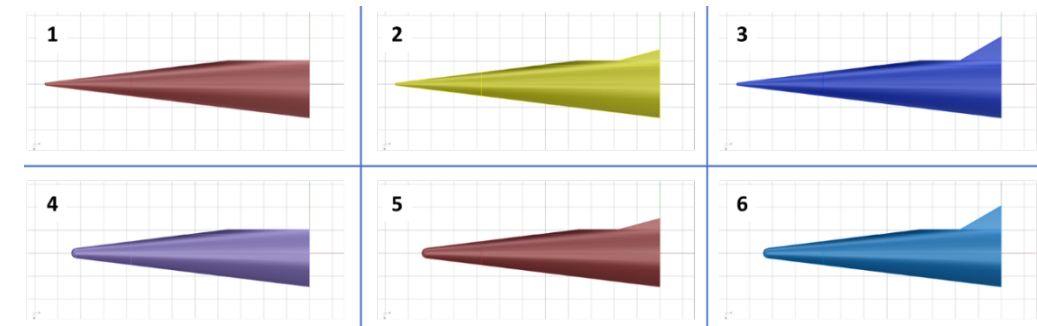
LAL is a **reliable partner for hypersonic commercial and defense testing**, both early in the design phase to generate parametric databases.



Research and Development

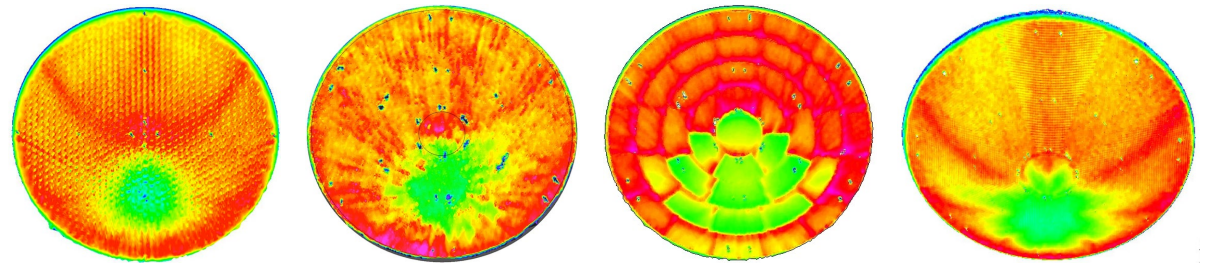


Dynamic Balance Demonstration
(AIAA 2024-2661)

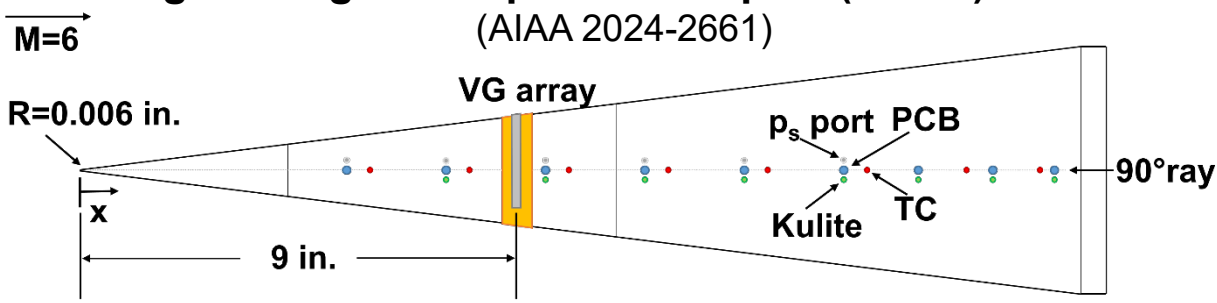


Cone/Slice/Flap Aeroheating/Aerodynamic
Parametric suite of models with varying nose radius, slice definition and flap deflection angle

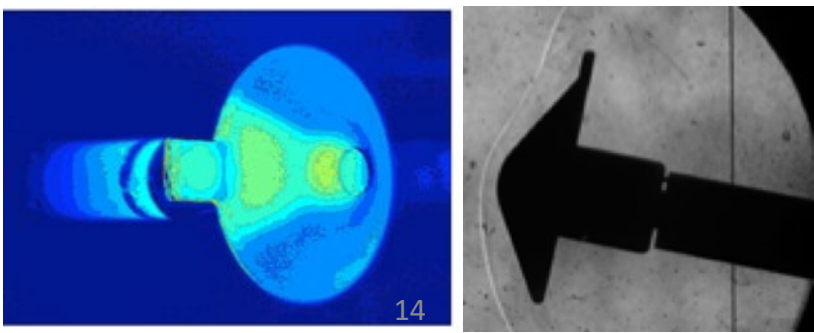
Entry Systems Modeling (ESM) Mission Relevant Roughness
(NASA/TM-2019-220424, TM-2022-0005643, TM-2023-0001707)



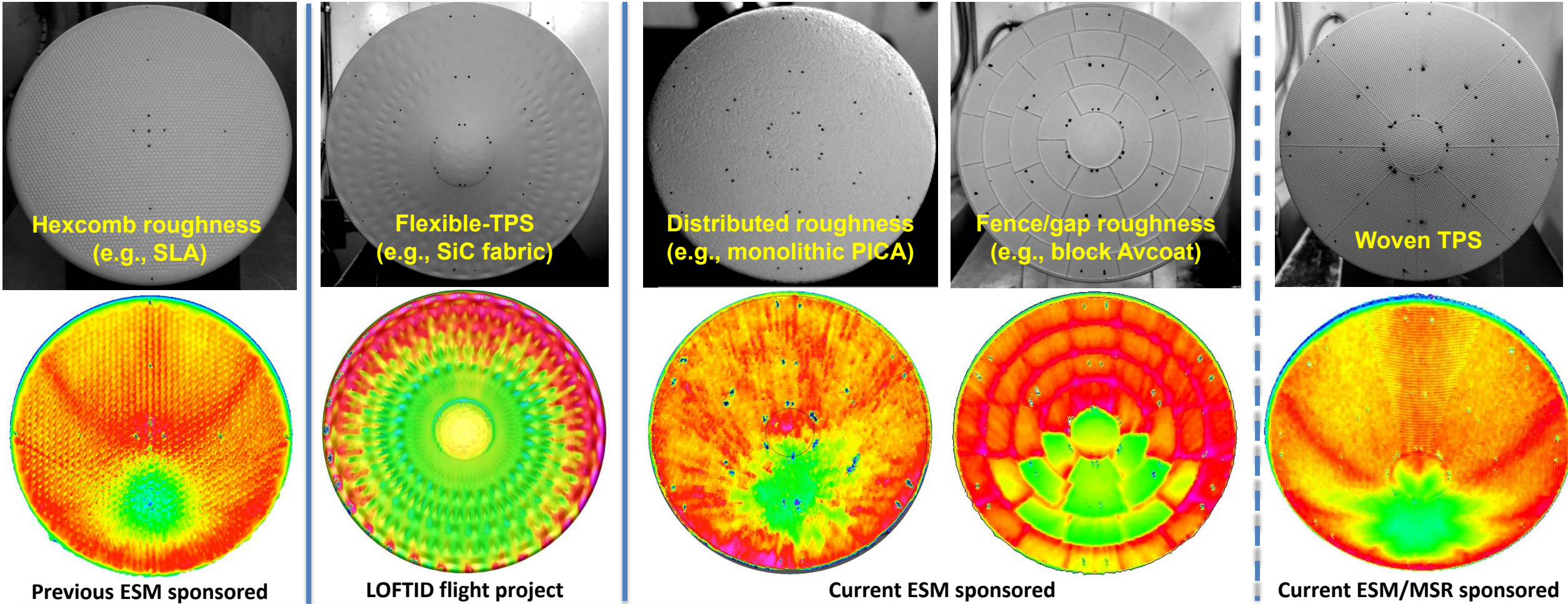
Arnold Engineering Development Complex (AEDC) Tunnel 9 Cone
(AIAA 2024-2661)



Aerodynamic Trim Tabs on Decelerator Aeroshells
(AIAA 2013-2809 and 2013-2308)

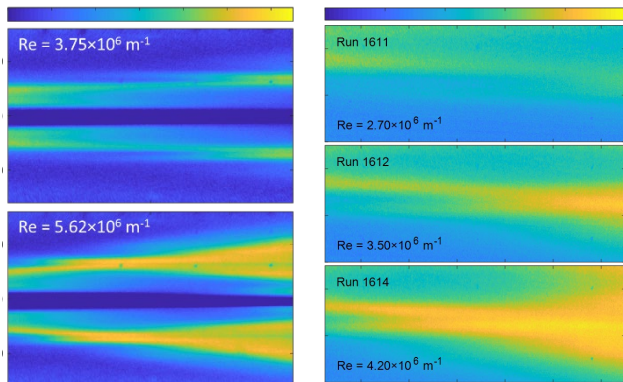


Parametric test campaigns were conducted on “Mission-Relevant Roughness” models, surface roughness features that are **directly traceable to actual thermal protection systems employed on NASA missions.**

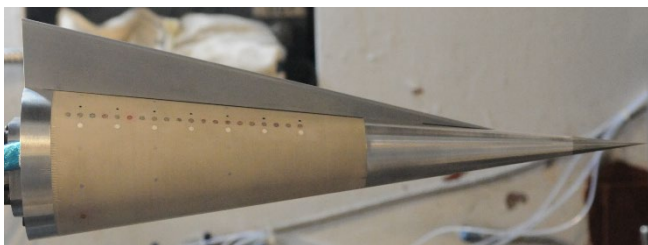




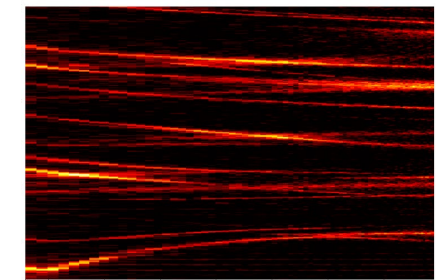
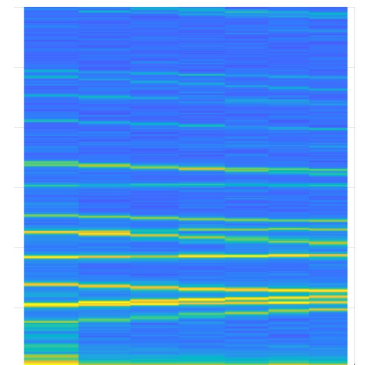
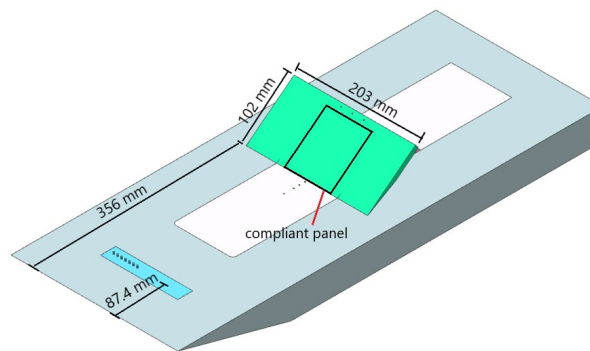
Academic Partnerships



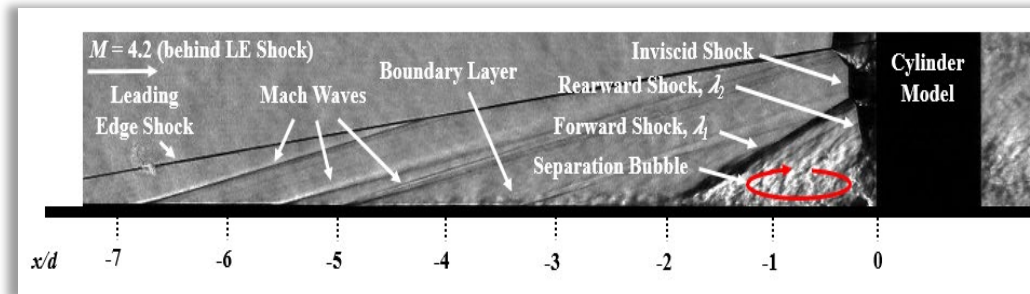
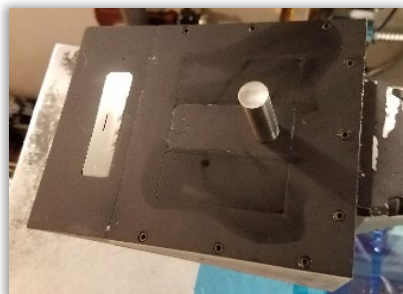
Purdue University:
Cone with Highly-Swept Fin
(AIAA 2022-3857)



LAL capabilities can be mutually beneficial for **research and workforce development.**



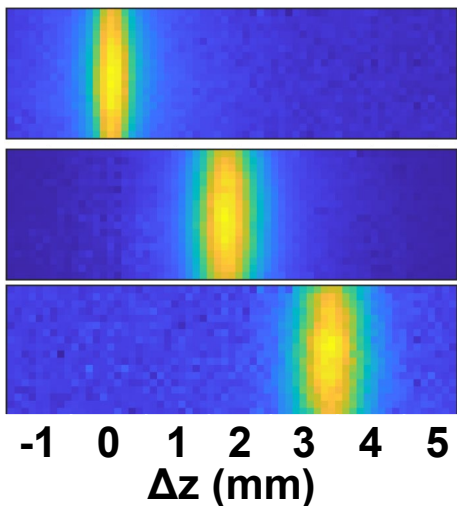
University of Maryland:
Compliant Panel Fluid Thermal Structure Interactions
(AIAA 2023-3851 and 2021-0912)



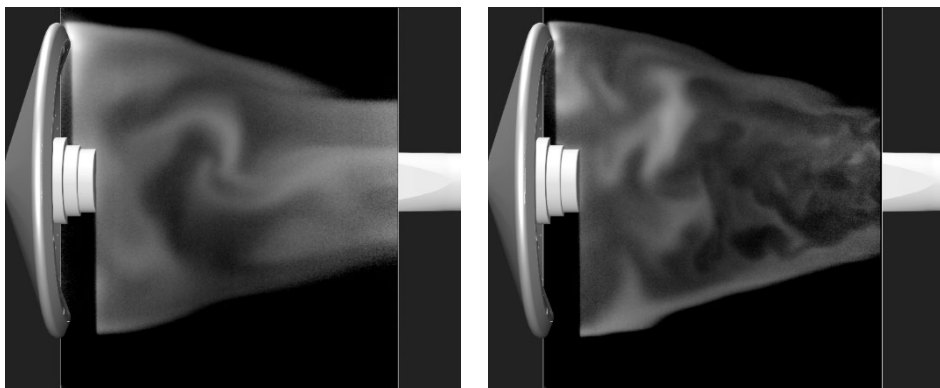
University of Tennessee Space Institute, University of Texas at San Antonio:
Shock-Wave/Boundary-Layer Interactions
(AIAA Journal Vol. 60, No. 5)



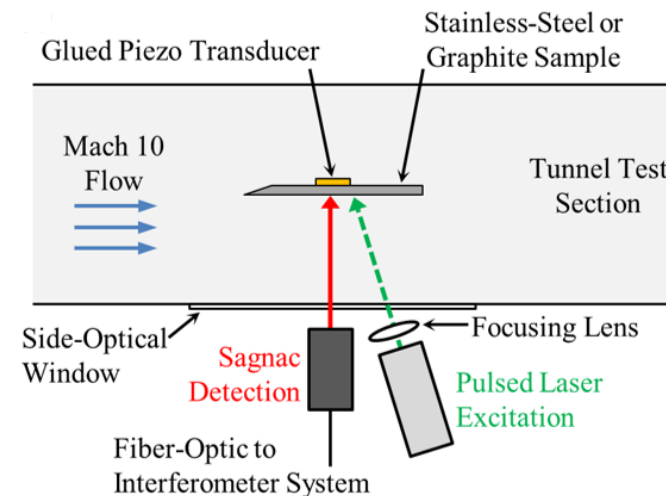
Test Technique Development



Femtosecond Laser Electronic Excitation Tagging Velocimetry
 Calculated velocity from displacement and time interval between images
 (AIAA 2024-2323)



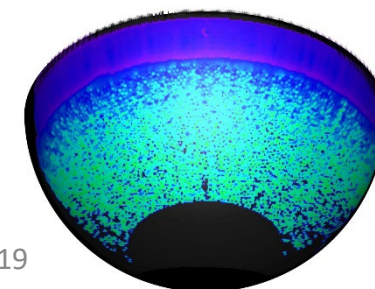
Planar Laser-induced Fluorescence (PLIF)
 (AIAA 2024-1314, 2024-2323, 2022-0897 and 2023-0405)



Lawrence Livermore National Laboratories
 Laser based ultrasonics and
 laser-based speckle interferometry

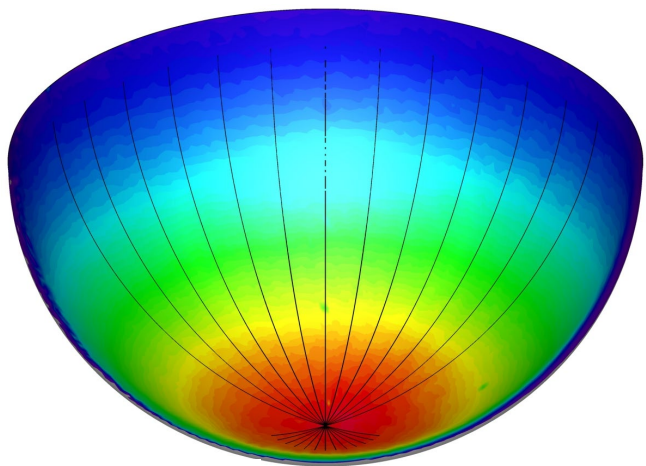
LAL facilities and SME are leveraged to **develop and improve** instrumentation and novel **test techniques**.

Higher Temperature Phosphor System



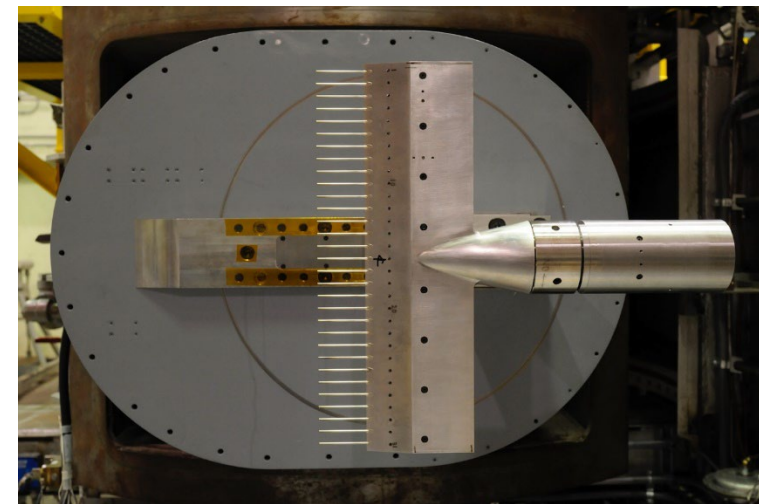
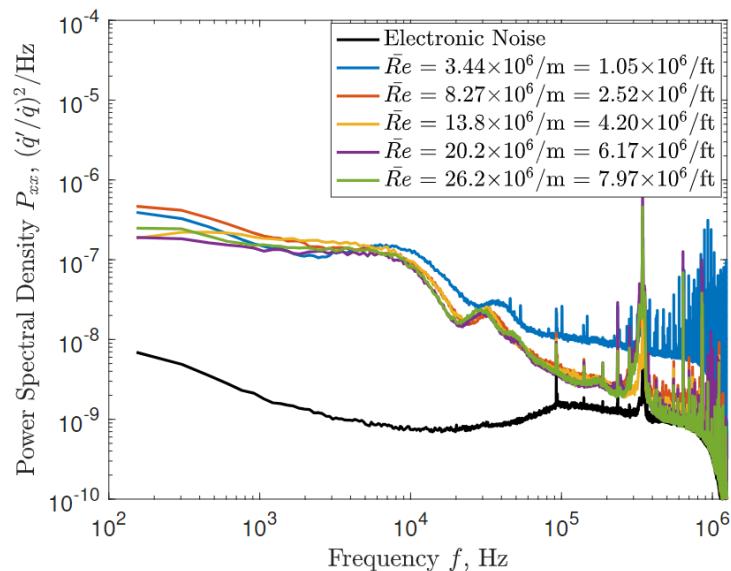


Facility Calibration



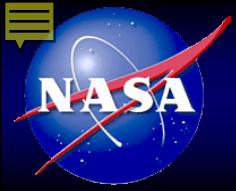
Phosphor Thermography
Check Standard Hemisphere
(AIAA 2016-4322, NASA/TM-20210021999)

Freestream Noise Characterization (AIAA 2018-3073)



Flow Survey Rake
(AIAA 2005-4274)

Periodic **calibrations** and ground tests with **check standard models** are conducted to monitor and maintain the hypersonic flow conditions and data acquisition systems of the LAL facilities.



Conclusion



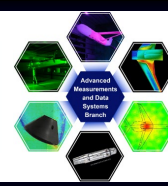
- LAL hypersonic facilities support foundational **research and development** activities, **commercial and defense partnerships**, **academic partnerships**, **test technique development**, **facility calibration** and internal and external **flight programs**.
- Ground test data for flight missions contribute to both **configuration development** and **flight database generation**.
- Hypersonic wind tunnel test campaigns at LaRC also support **CFD benchmarking** and fundamental studies of complex aerothermodynamic phenomena on **slender and blunt** configurations.
- Langley SMEs have decades of experience working on NASA internal programs and collaborating with external entities to solve the difficult challenges of hypersonic flight.
- LAL facilities have a backlog of testing that could carry through Q3 2025; testing priorities are constantly reassessed to accommodate as many tests as possible.

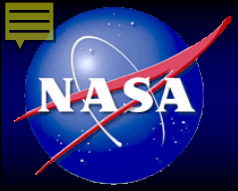
Low-cost, flexible, mid-range LAL facilities are coupled with **deep aerothermal subject matter expertise** to conduct LAL ground tests at NASA Langley Research Center.

Anyone interested in conducting a test in the LAL can contact michelle.mason@nasa.gov or shann.j.rufer@nasa.gov.

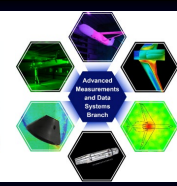


Backup Slides

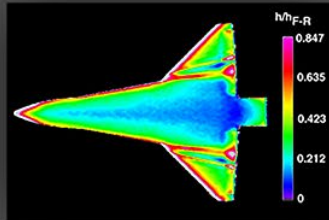




Global Phosphor Thermography



Better



Before

Discrete gauges
150 points/run

After

Global data
150,000 points/run

Impact to a study

Increased amount of
information: **1000x**

Faster

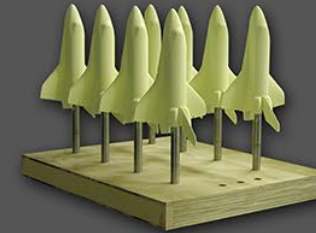


50 weeks to obtain
data on study

5 weeks to obtain
data on study

Time savings: **10x**

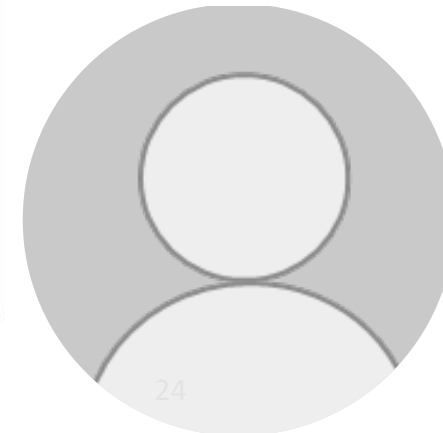
Cheaper

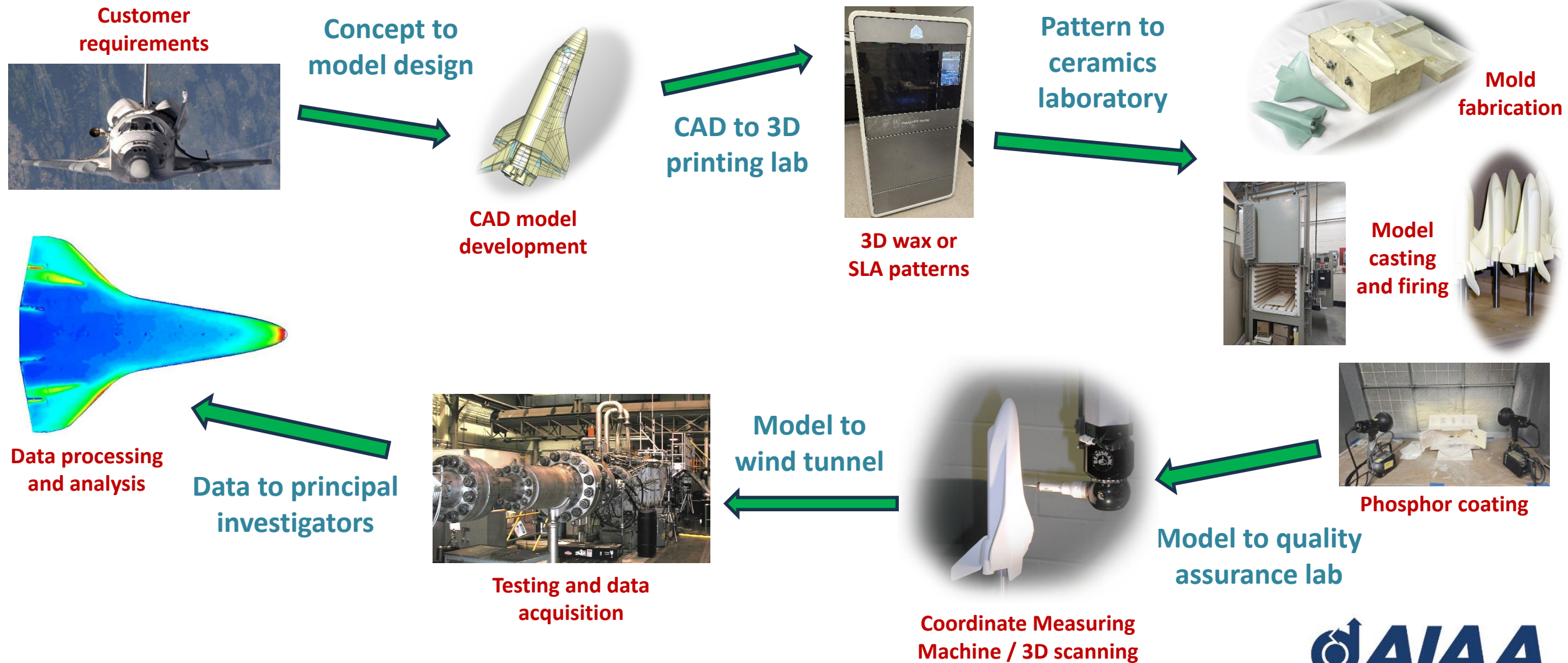


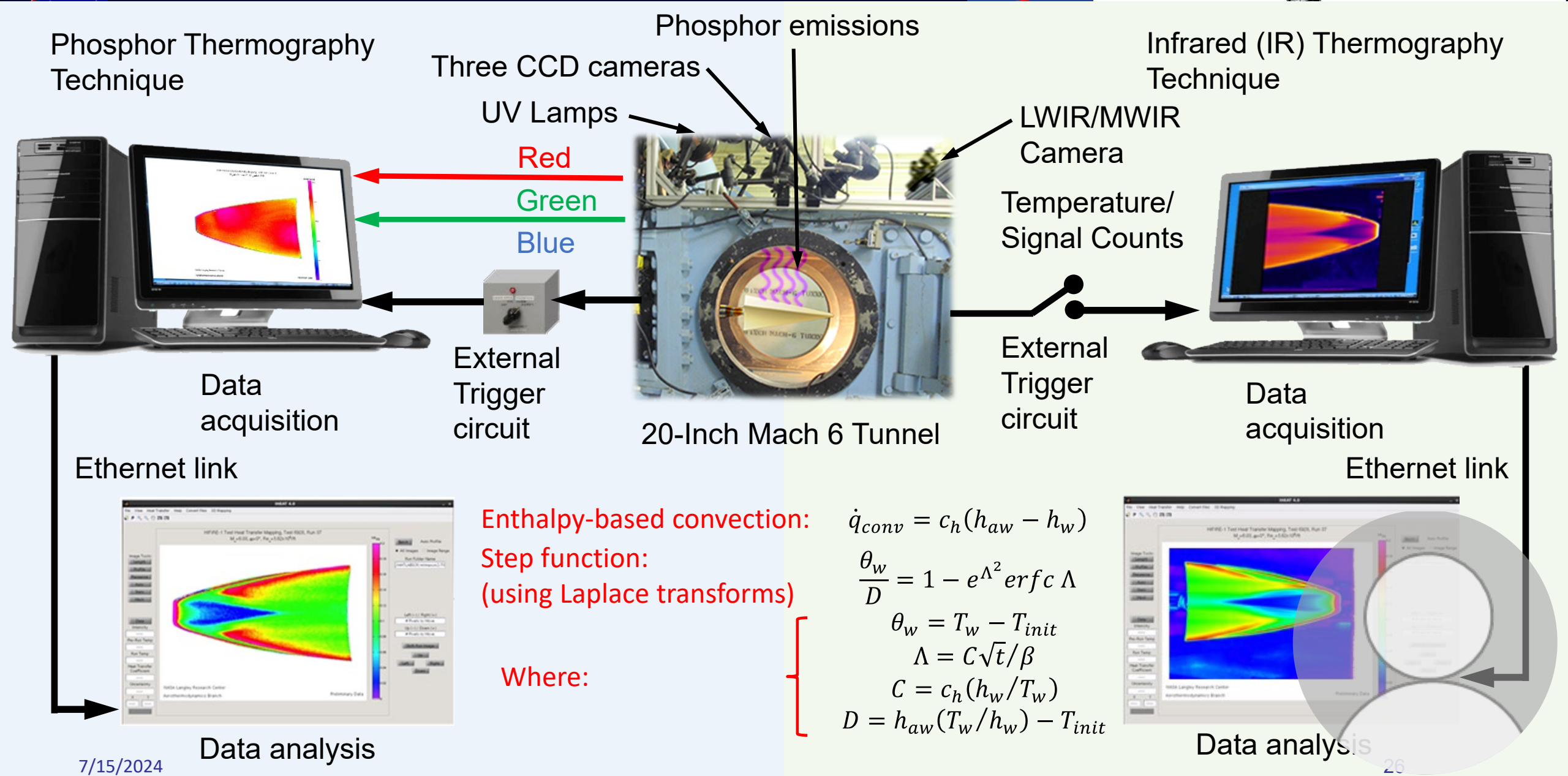
Fabrication cost:
150K (1 model)

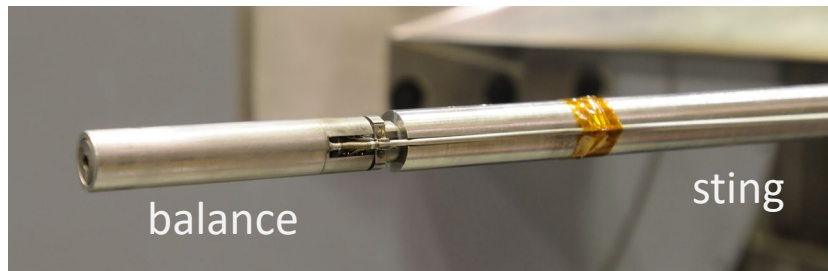
Fabrication cost:
15K (5 models)

Cost reduction: **10x**

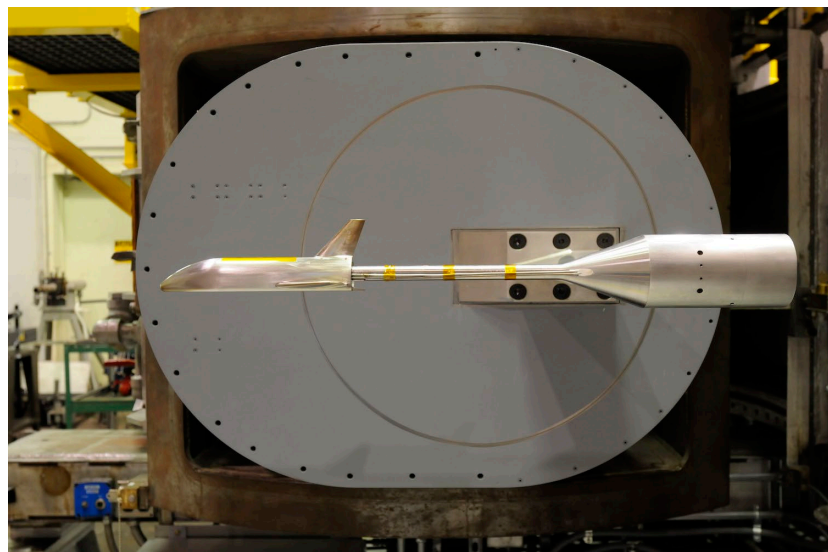






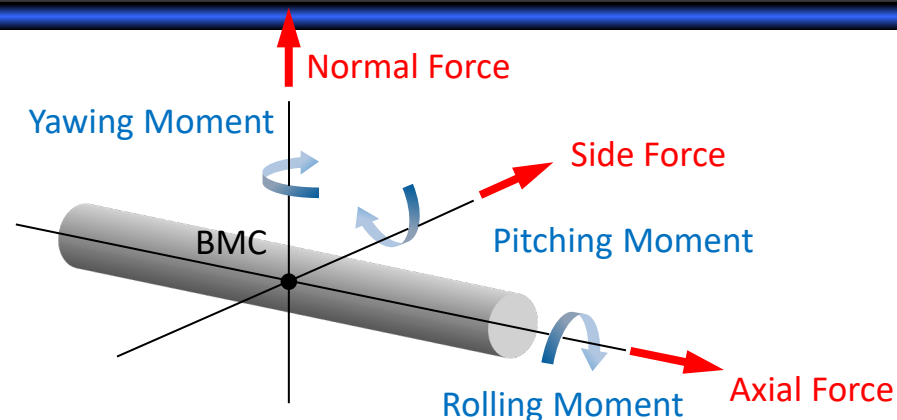


NASA LaRC water-cooled balance mounted on sting



Aerodynamic wind tunnel model mounted to balance in LAL 31-Inch Mach 10 Tunnel

Balance Forces and Moments



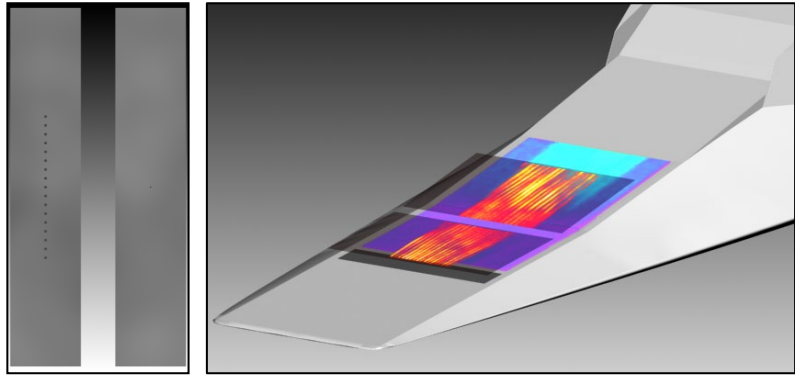
- Model forces and moments are calculated from measured balance loads to account for:
 - Model weight components acting on balance at balance yaw/pitch/roll angles (weight tares)
 - Angle rotations from balance axes to model axes (alignments of balance w.r.t. model)
 - Moment transfers in model coordinate system from balance moment center (BMC) to model moment reference center (MRC or CG)
- Aerodynamic coefficients in the desired aerodynamic axis systems are calculated from model forces and moments, model angles w.r.t. the wind vector, measured or calibrated facility flow conditions, and the model reference dimensions
 - Body axis, stability axis, wind axis
 - Missile axis, aeroballistic axis, vertical axis

$$\begin{bmatrix} C_A \\ C_Y \\ C_N \end{bmatrix}_{BA} = \frac{1}{q_\infty S_{ref}} \begin{bmatrix} AF \\ SF \\ NF \end{bmatrix}_{BA}$$

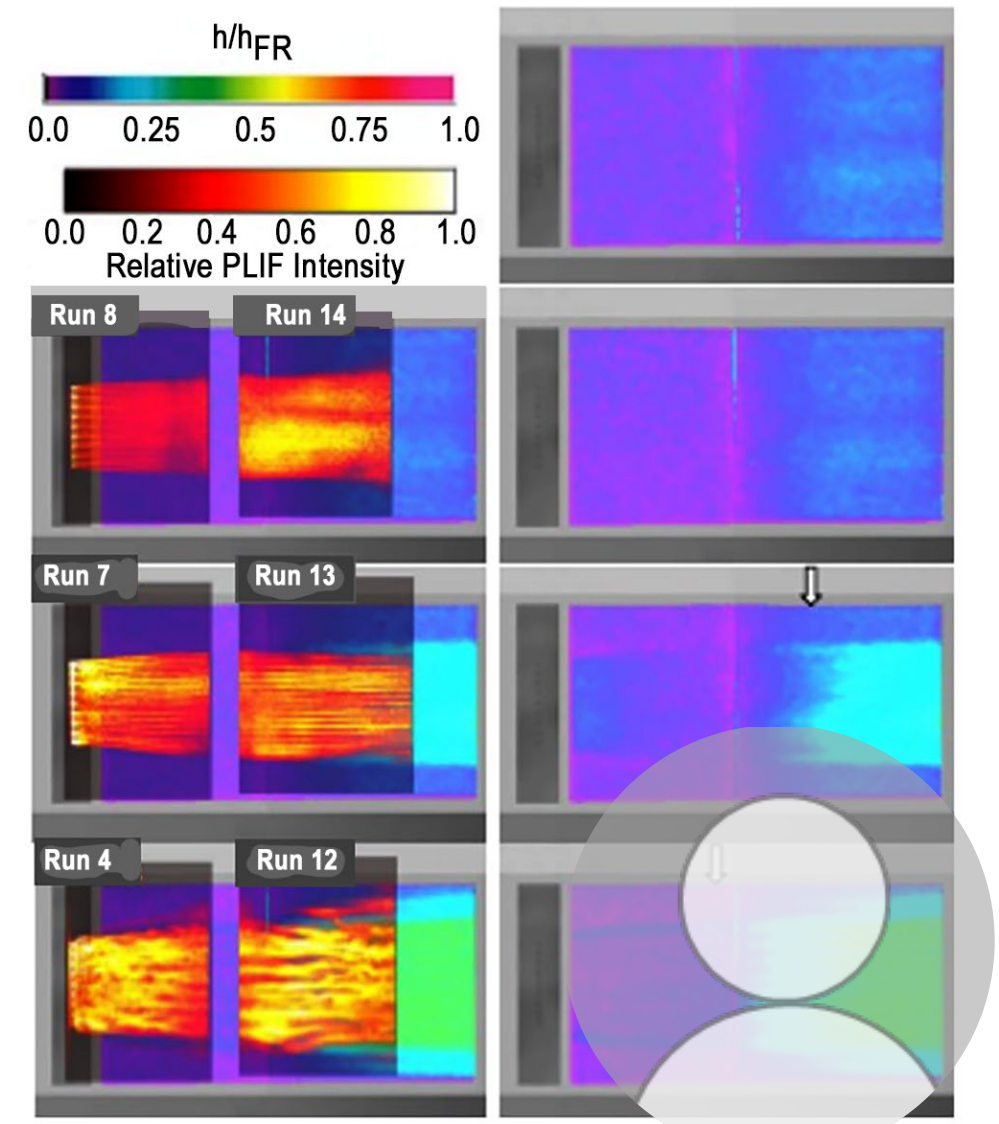
Body-Axis (BA) Force Coefficients

$$\begin{bmatrix} C_l \\ C_m \\ C_n \end{bmatrix}_{BA} = \frac{1}{q_\infty S_{ref}} \begin{bmatrix} RM/b_{ref} \\ PM/l_{ref} \\ YM/b_{ref} \end{bmatrix}_{BA}$$

Body-Axis (BA) Moment Coefficients



- ▶ **Hyper-X study**
 - ▶ Forced boundary layer transition via blowing
 - ▶ Comparison between PLIF images and surface heating measurements
 - ▶ Determination of transition location
 - ▶ Effect of blowing rate
 - ▶ Heating patterns
 - ▶ Flow structures observed in relation to blowing rate
 - ▶ Measurements at multiple off-body locations



- “Mission-Relevant Roughness” means surface roughness features that are directly traceable to actual thermal protection systems employed on NASA missions
- There are many types of ‘roughness’, all of which require different models for transition and heating effects and have different effects on aerothermodynamic environments
 - Compression pads: Relevant to Orion EFT-1, EM-1/2, Genesis (test data from Orion and MSL programs)
 - TPS damage: Relevant to Shuttle (test data from Shuttle RTF program)
 - Distributed “sandgrain”: Relevant to Stardust, Galileo (data from ESM program)
 - Hexcomb: Relevant to Orion EFT-1, Apollo, Viking, Pathfinder (data from ESM program)
 - Blocked TPS: Relevant to Orion EM-1/2, MSL, Mars 2020, Shuttle (data from ESM program)
 - Woven TPS: Relevant to MSR-EES, future missions (data from ESM program and MSR program)
 - Flexible TPS: Relevant to IRVE-II, IRVE-3, LOFTID (data from LOFTID program)

Compression
pad cavity



TPS damage



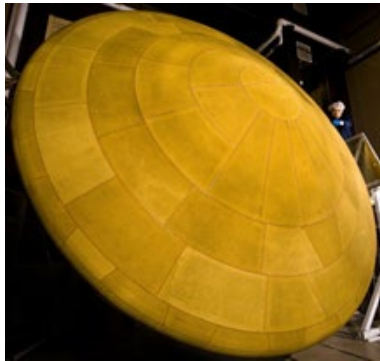
Ablated sandgrain TPS



Ablated
Hexcomb TPS



Block TPS
steps & gaps



Woven TPS



Flexible TPS

