From Wind Tunnels to Flight Vehicles:

Visualization and quantitative measurements supporting NASA's space program



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OSA Optical Sensor and Sensing Congress:
Laser Applications to Chemical, Security and Environmental Analysis

Combustion and Flow Diagnostics I

24 June 2020

2 – 4 PM PDT

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Outline

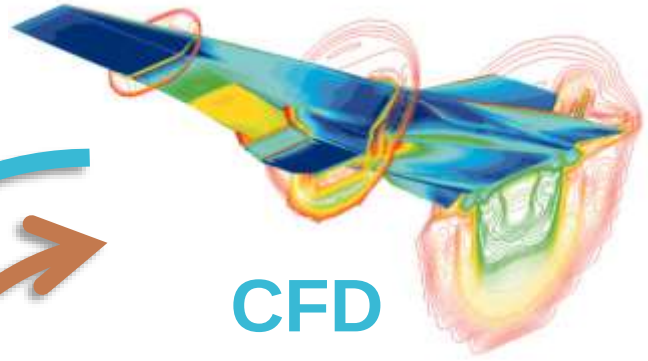
- Computation, Ground Test, Flight Test
- Planar Laser-Induced Fluorescence (PLIF)
- Scientifically Calibrated In-Flight Imagery (SCIFLI)





- Space Shuttle C
- Orion Crew Cap
- Space Launch S

Vehicle Design and Testing



CFD

Dryden Flight Research Center ED97 43968-01
HYPER-X AT MACH 7: This computational fluid dynamic (CFD) image is of the Hyper-X vehicle at the Mach 7 test condition with the engine operating.



Ground Testing



Flight Testing

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/Gallery/Photo/index.html
NASA Photo: EC04-0092-32 Date: March 27, 2004 Photo By: Jim Ross

A modified Pegasus rocket ignites moments after release from the B-52B, beginning the acceleration of the X-43A over the Pacific Ocean on March 27, 2004.

Credit: NASA/Langley Research Center



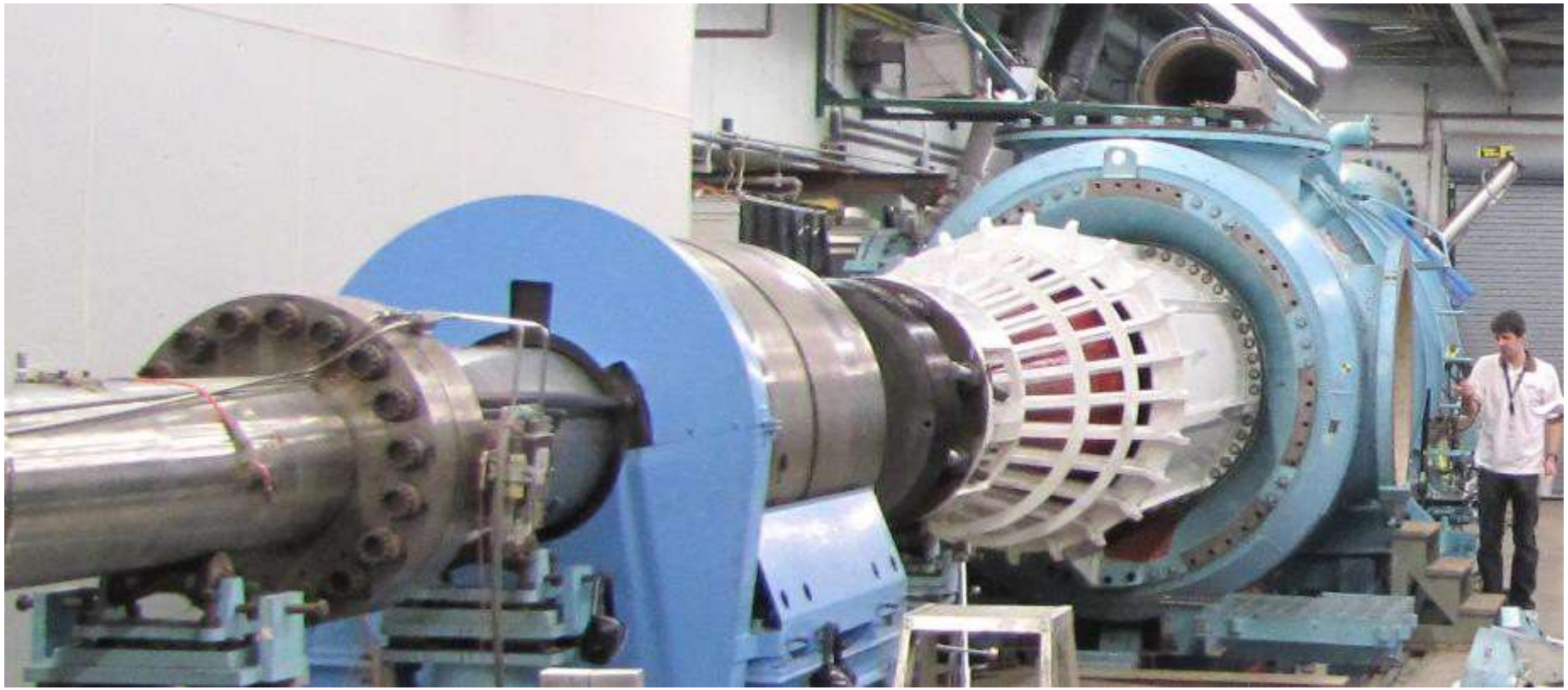
Ground Testing

Facilities

Measurement Techniques

Calspan University of Buffalo Research Center (CUBRC)

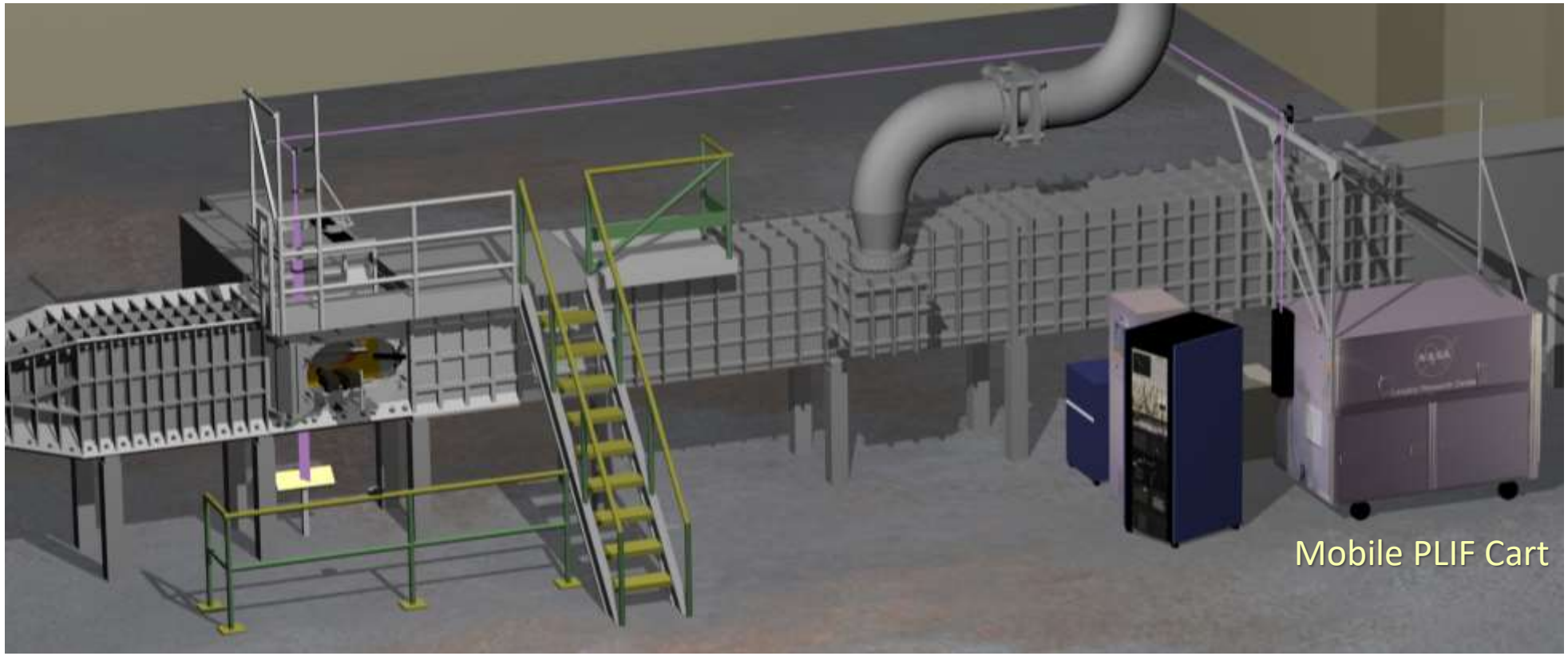
LENS 1 Hypersonic Shock Tunnel



- Mach 6-20, scramjet, entry vehicle, launch vehicle, hypersonic testing
- Large scale, short run duration (tens of ms), 1 or 2 runs per day, tunnel moves, remote operation

NASA Langley Research Center

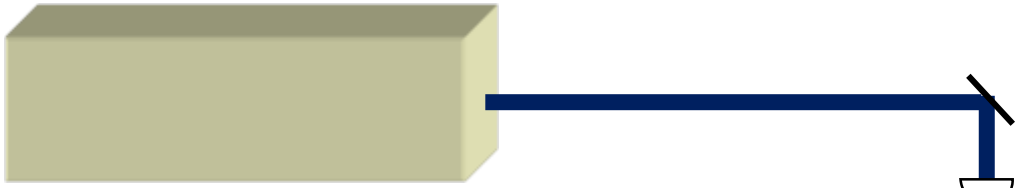
31-Inch Mach 10 Tunnel



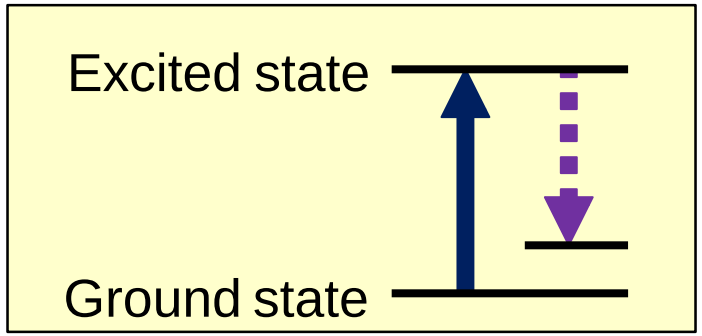
- Mach 10 blowdown facility: 1-2 min.
- Optical access on top, bottom, 1 side
- Model injected into flow from far side

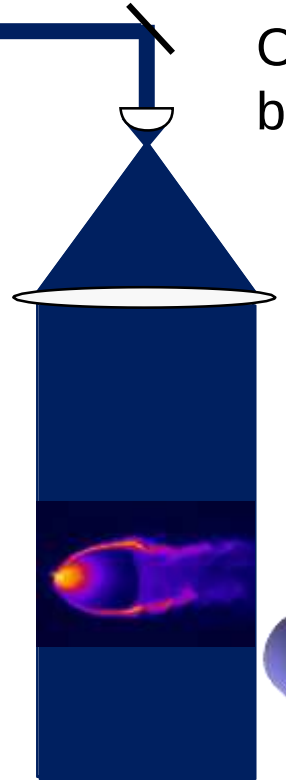
Test conditions:
T_o = 1800°R (1000 K)
P_o = 350 – 1350 psia (2.4 – 9.4 MPa)
Re = 0.5 – 2 million/ft

Planar Laser-Induced Fluorescence (PLIF)



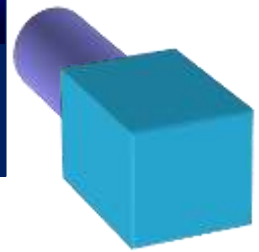
Optics expand laser beam into planar sheet





Laser excites molecular resonance

Excited molecules fluoresce



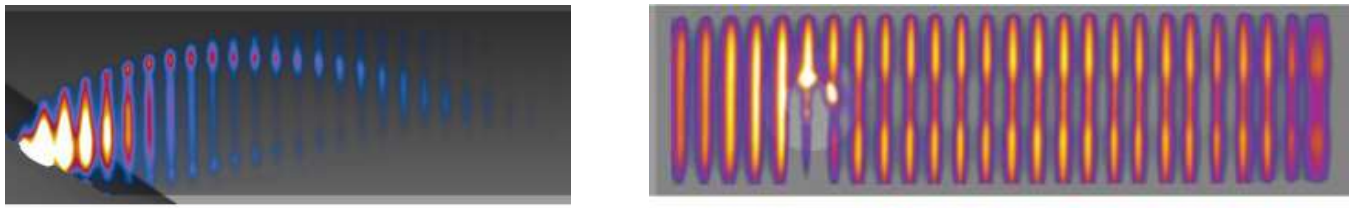
Sensor detects fluorescence

$$\mathbf{LIF \sim n_{NO\ (or\ OH)}}$$

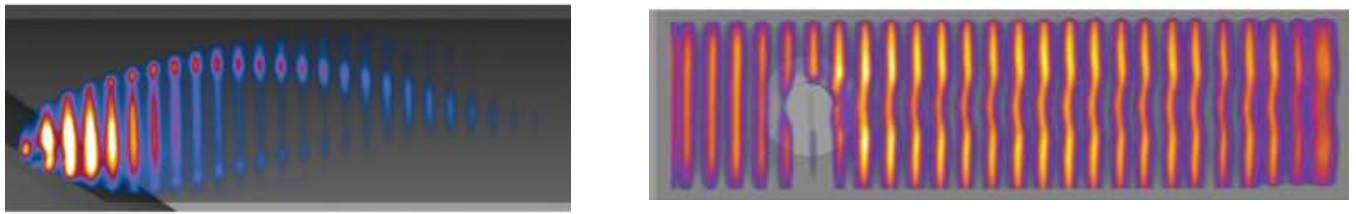
n: Number of molecules
NO: Nitric oxide
OH: Hydroxyl radical

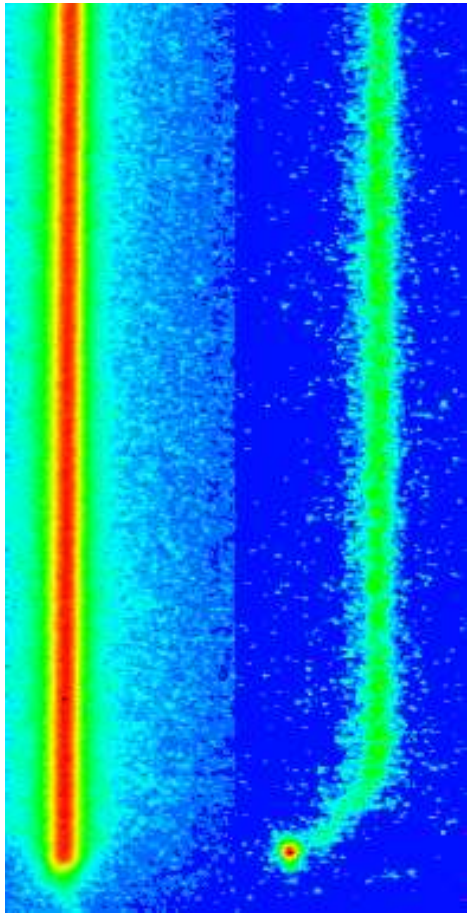
NO PLIF Molecular Tagging Velocimetry

- Flow tagging of NO molecules
  - One laser pulse
  - Two images separated by ~500 ns using same CCD camera
- In 1999 at Australian National University, demonstrated along 1 line (Uncertainty ~100 m/s)
- NASA 2000's: extended to 25 lines (Single shot uncertainty ~30 m/s)
- Applied to: Shuttle, Orion, Mars Science Laboratory capsule…
- Closely related to VENOM technique (Bowersox, North & students)
  - Multi laser techniques



Bathel AIAA Journal Vol. 49 No. 9 https://doi.org/10.2514/1.J050722





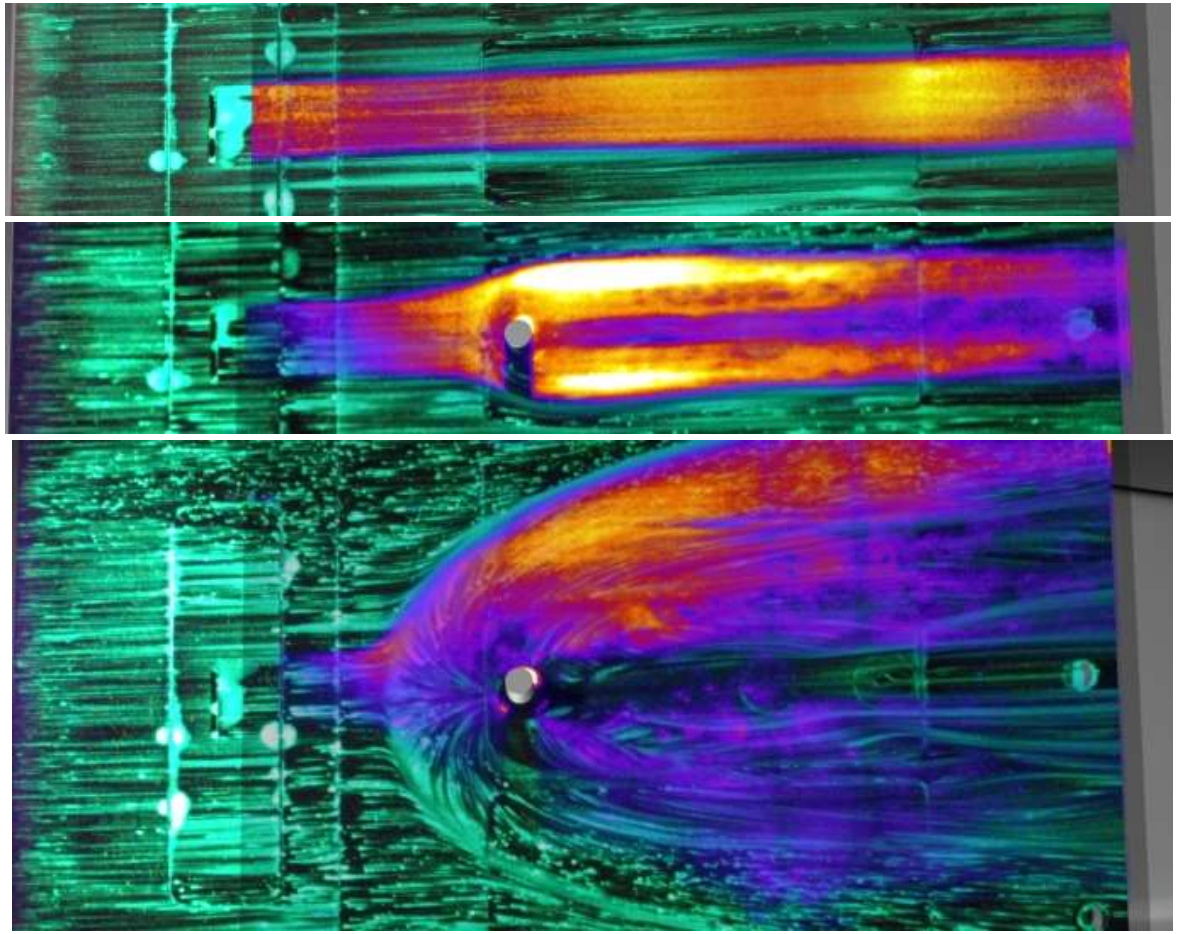
0 ns 500 ns

NO PLIF Velocimetry in a Mach 7 laminar boundary layer at ANU

Danehy AIAA Journal Vol. 41 No. 2 https://doi.org/10.2514/2.1939

Other Relevant Measurement Techniques

- Phosphor Thermography
- Oil Flow
- Schlieren
- Temperature Sensitive Paint (TSP)
- Pressure Sensitive Paint (PSP)
- MHz PLIF
- Infrared (IR, MWIR, LWIR, SWIR) Thermography
- Hyperspectral imaging
- FLEET (Femtosecond Laser Electronic Excitation and Tagging)

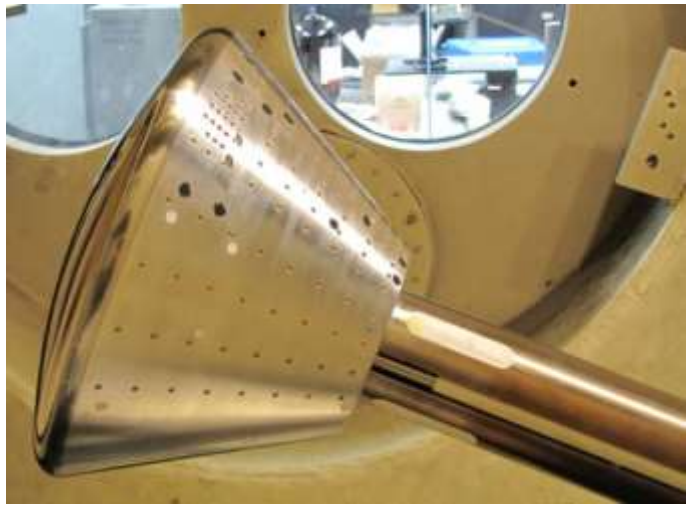


Bathel AIAA-2013-0042 https://doi.org/10.2514/6.2013-42

Mobile PLIF Measurement Cart

- Mobile measurement systems
  - Test in lab;
  - Get set up quickly and get out
  - 1-2 week tests
- Automated operation
  - Acquire thousands of measurements if possible
  - Remote operation
- Hardened hardware
  - Cooled / Heated, SSD, Robust construction
- Prefer simple methods
  - Fewer lasers the better
  - Fewer laser beams the better





Setup and model for Orion Crew Module Backshell Aeroheating Testing in CUBRC, Buffalo NY

Combs et al. J. of Spacecraft and Rockets (2015): Vol.52: 243-252 https://doi.org/10.2514/1.A32946



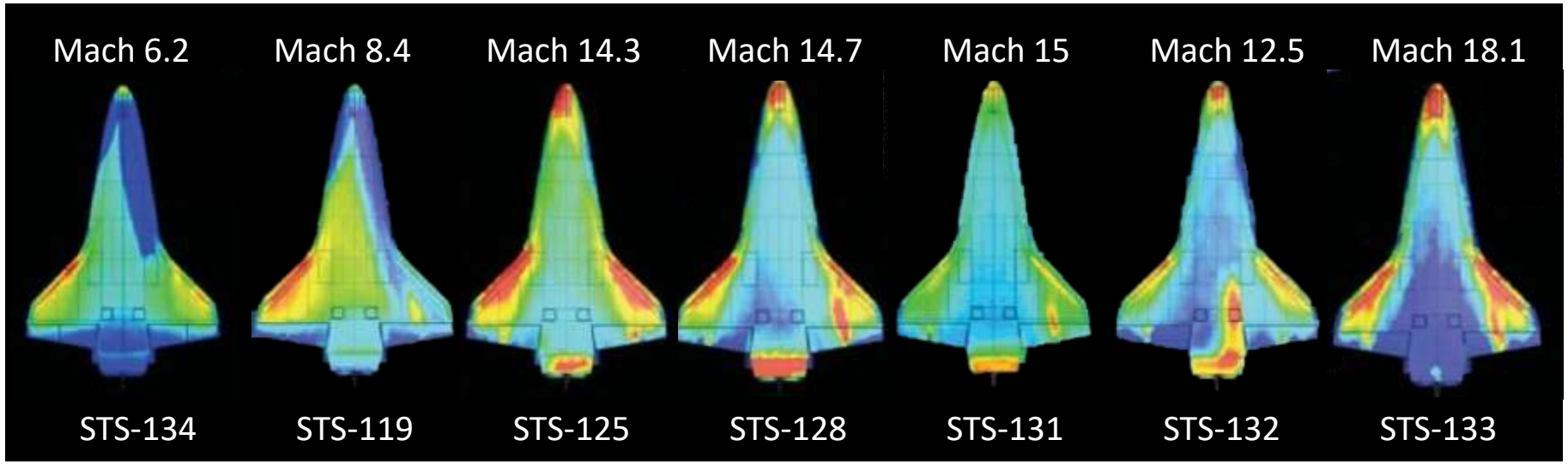
Flight Measurements

Measurement Platforms

Mission Operations

Scientifically Calibrated In-Flight Imagery

- The SCIFLI Team provides *quantitative measurements in engineering units derived from calibrated imagery data*. The data are most often obtained from airborne platforms, but have also been acquired from land and ship based assets.
- SCIFLI evolved from HYTHIRM, a project which thermally mapped the Orbiter heatshield during Space Shuttle reentries ranging from Mach 6 to Mach 18.
- We are currently working missions for the Commercial Crew Program/SpaceX, the Orion Program, the Space Launch System (SLS) Program, and the Hayabusa 2 JAXA asteroid sample return mission, in addition to developing a NASA-owned imaging platform.



Platforms for Flight Data Capture

Airborne

- WB-57 (NASA JSC)
- Gulfstream III (NASA LaRC, JSC, AFRC)
- P-3 Orion (Navy)
- Global Hawk (NASA AFRC)
- DC-8 (NASA AFRC)
- HU-25 (NASA LaRC)








Ground-Based

- Mobile Aerospace Reconnaissance Systems (MARS)
- Telescience Research and Technology Support (TRaTS, NASA KSC)
- Haleakala Observatory (Air Force Maui Optical and Supercomputing Observatory – AMOS)





Seaborne

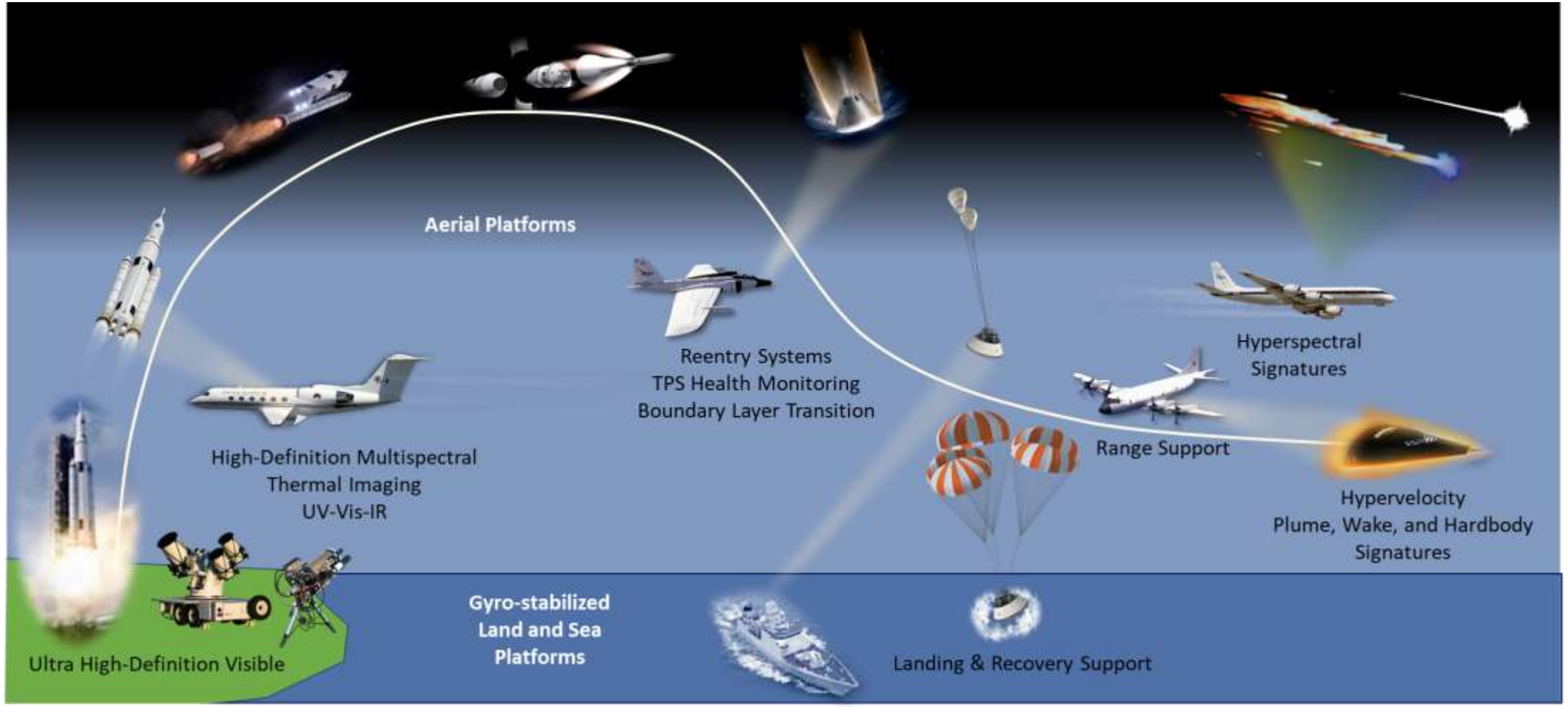
- MARS housed in gyrostabilized system
- TRaTS onboard recovery vessel





Launch, Reentry, Parachute Deployment

Highly Customizable Mission Architectures For Critical Data Capture



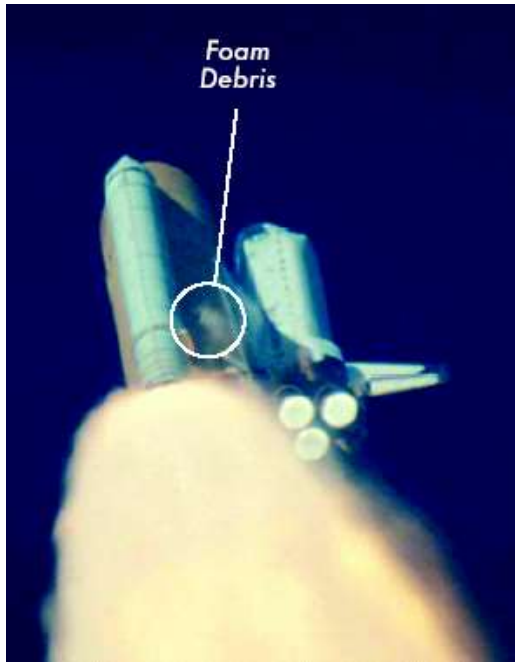


Space Shuttle Orbiter

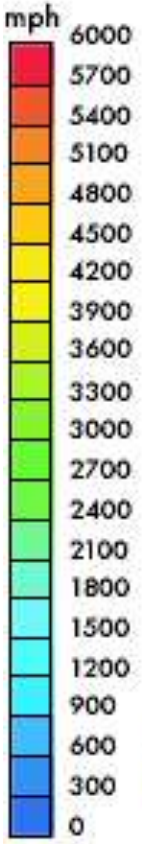
Thermal Protection System

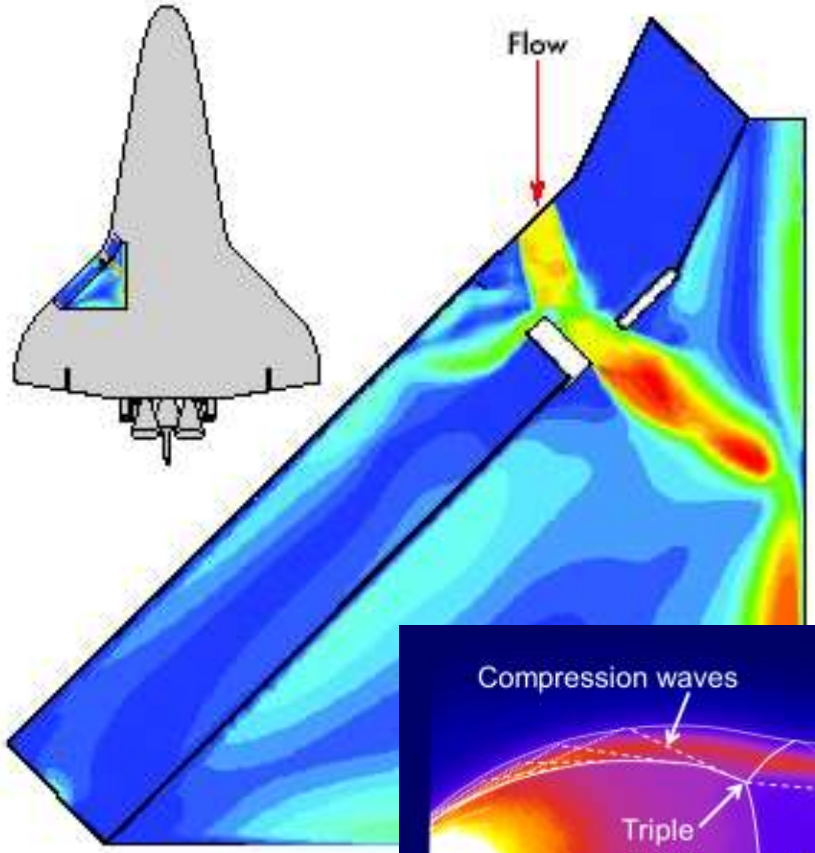
Hypersonic Boundary Layer Transition

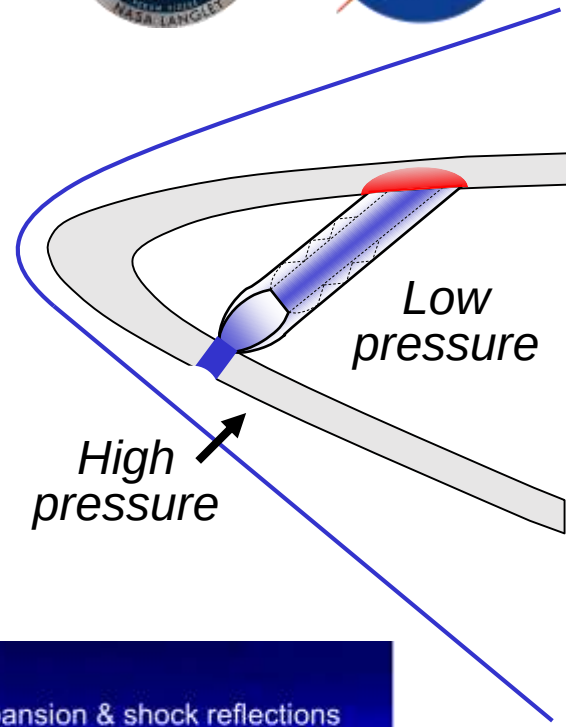
Space Shuttle Return to Flight

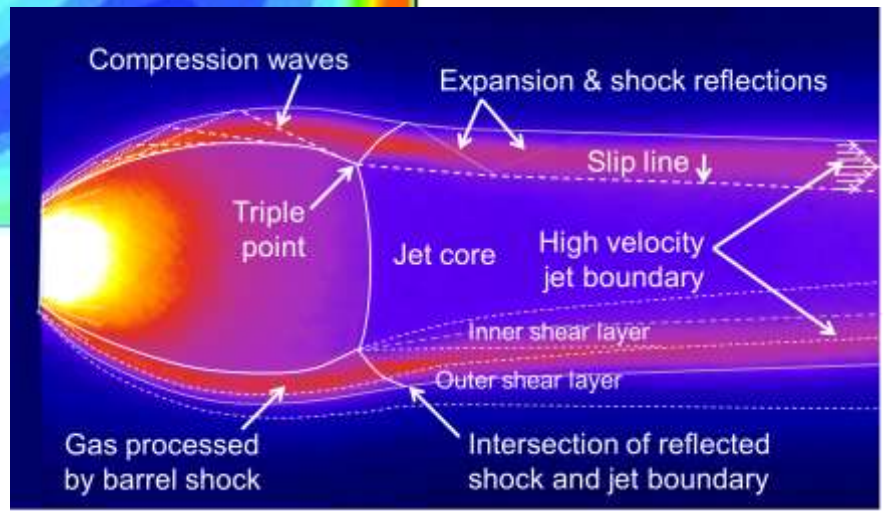








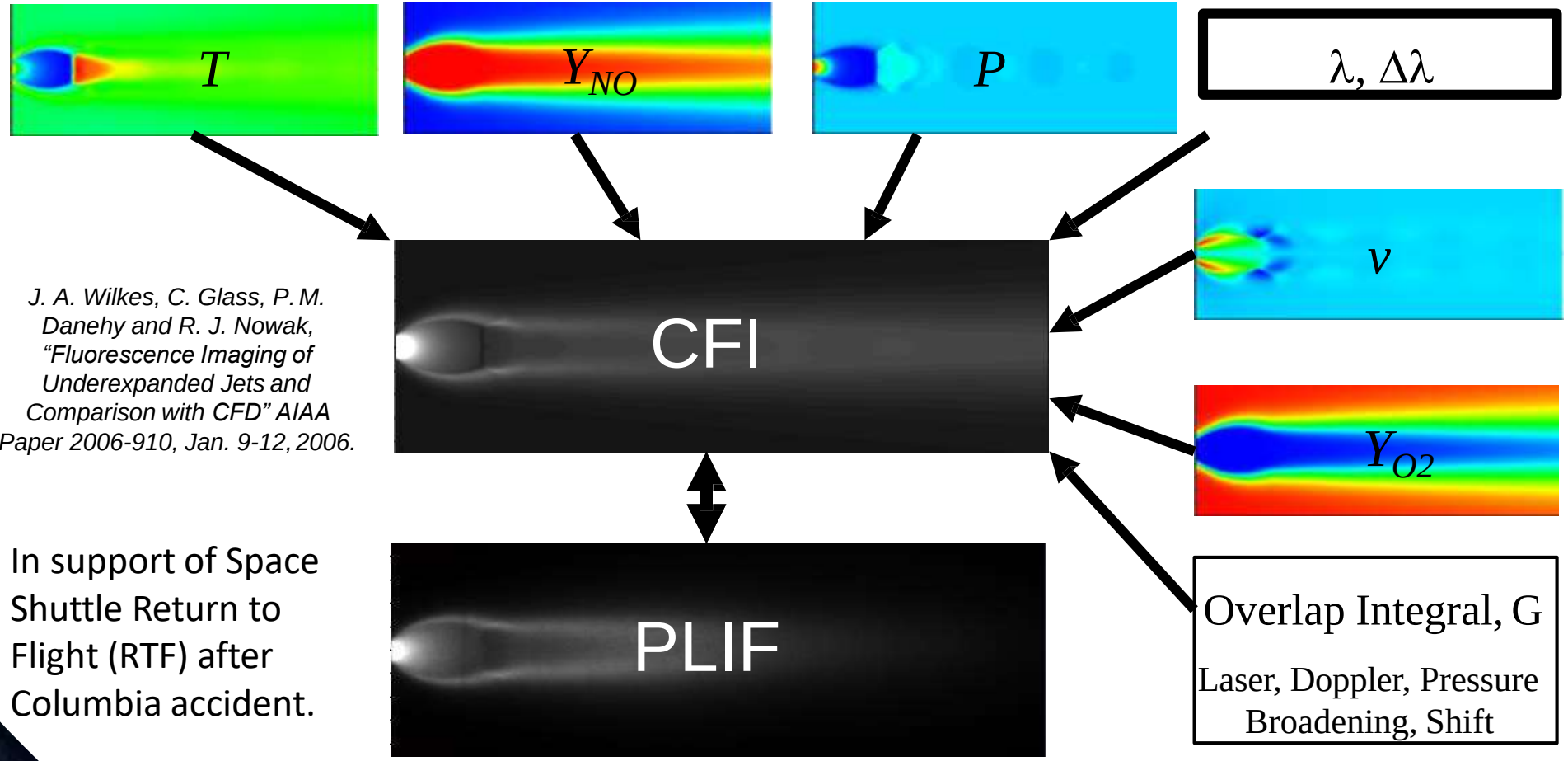




Figures publicly available from NASA: STS-115 mission summary and CAIB (Columbia Accident Investigation Board) report

Computational Flow Imaging (CFI)

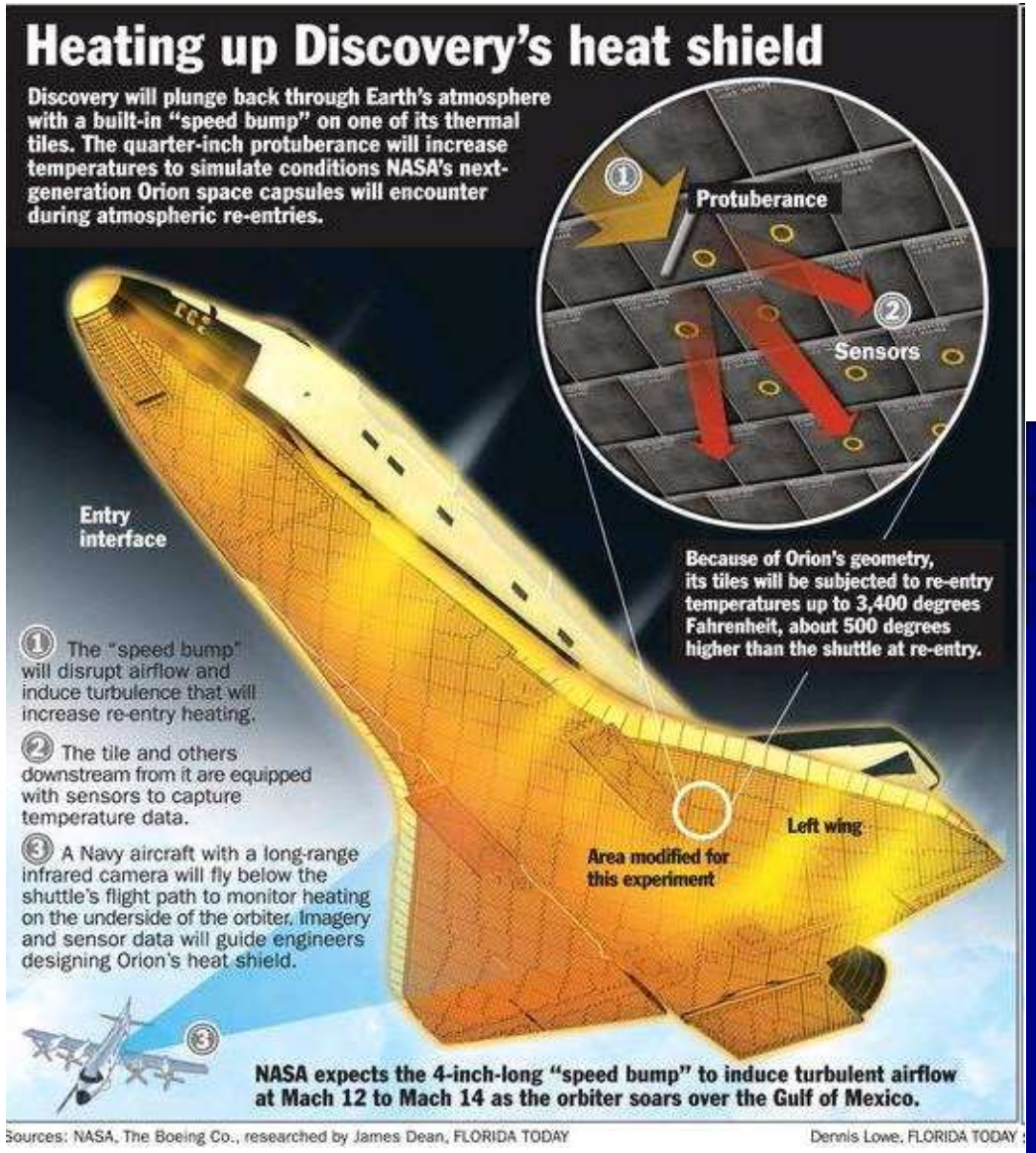
- Enables more direct comparison between PLIF and CFD
- Compute PLIF Images based on CFD and spectroscopic data (broadening, shift, quenching)



J. A. Wilkes, C. Glass, P. M. Danehy and R. J. Nowak, "Fluorescence Imaging of Underexpanded Jets and Comparison with CFD" AIAA Paper 2006-910, Jan. 9-12, 2006.

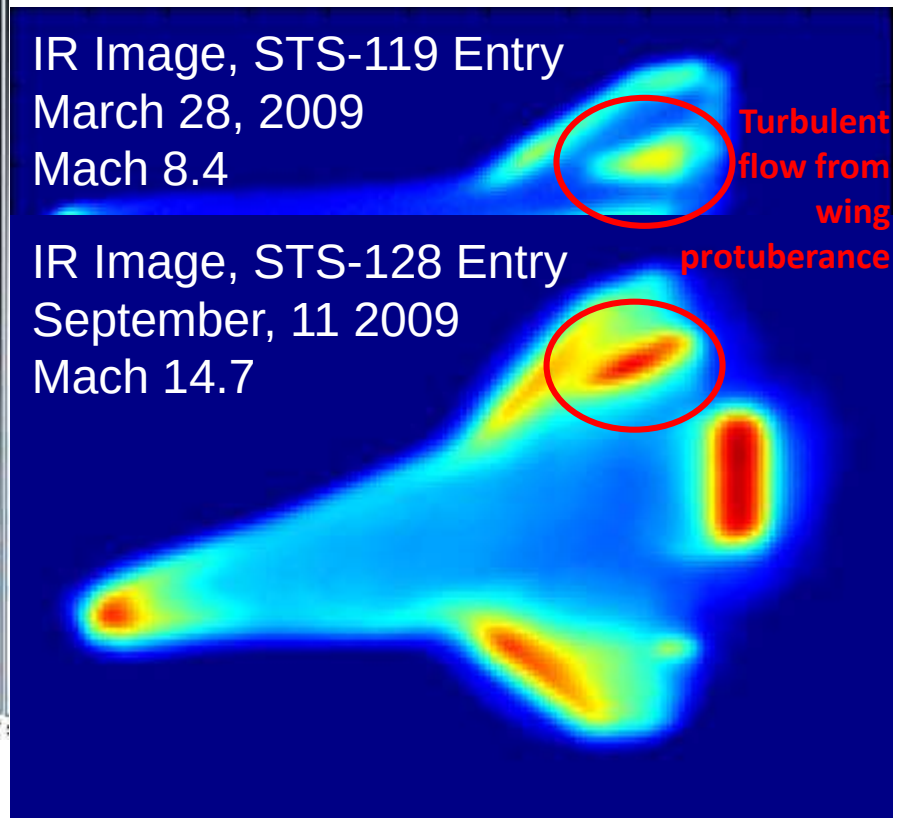
In support of Space Shuttle Return to Flight (RTF) after Columbia accident.

Boundary Layer Transition Flight Experiment



HYpersonic THermodynamic InfraRed Measurements
HYTHIRM
NASA Langley Research Center

HYTHIRM: Remote, quantitative, global heating



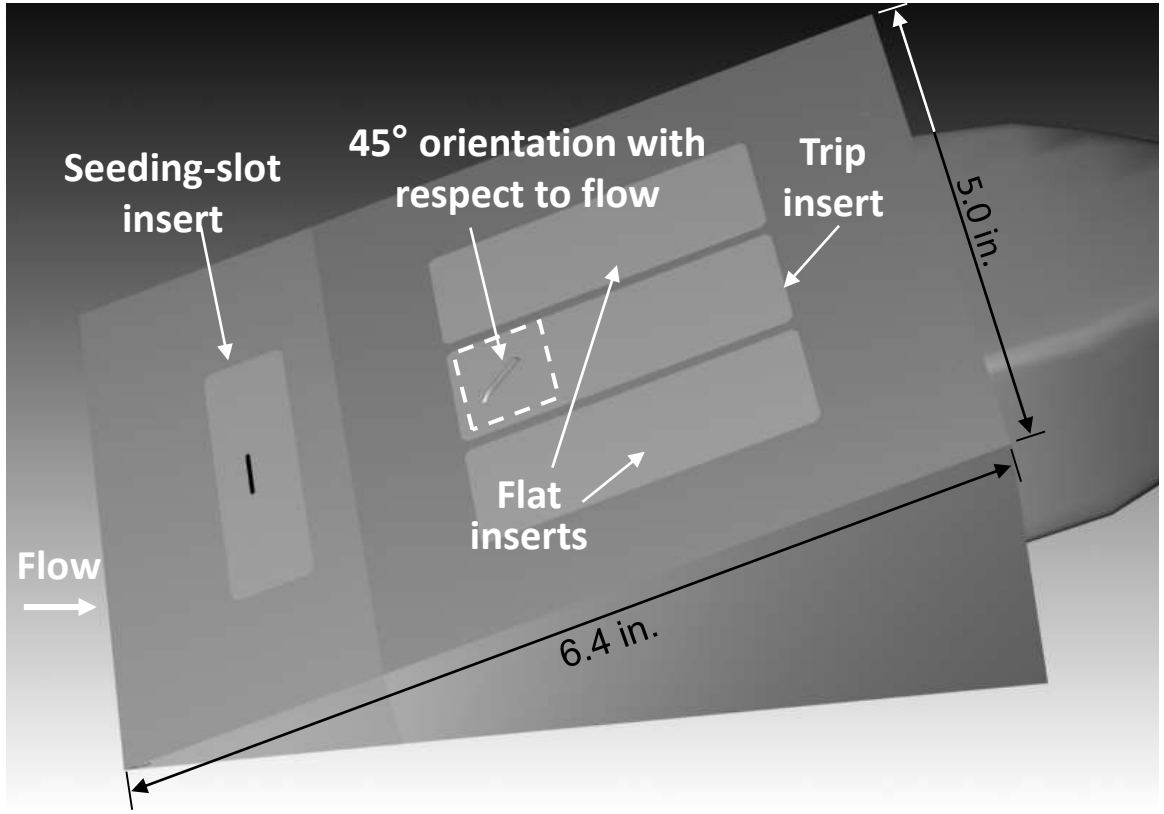
Model and Protuberances

20° full angle wedge model

Top surface: 20° wrt oncoming flow (M_e ~4)

Interchangeable inserts for NO seeding and trips

DTO Trip manufactured with Stereo Lithography



BLT-DTO



1 mm tall, ~10.3 mm wide

Rectangular Fence

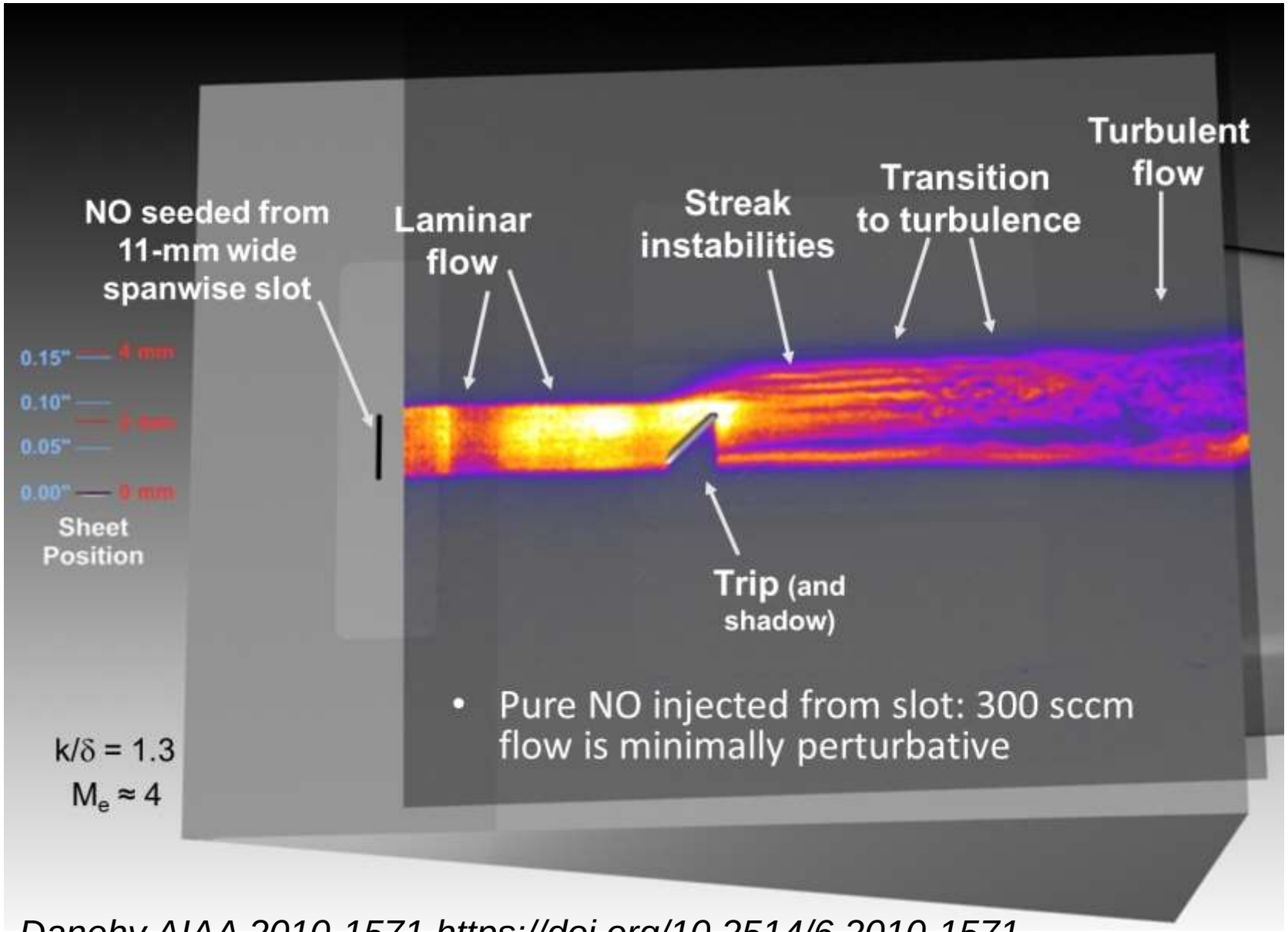


1 mm tall, 8.35 mm wide

BLT: Boundary Layer Transition
DTO: Detailed Test Objective

Danehy AIAA 2010-1571 https://doi.org/10.2514/6.2010-1571

Flow over Shuttle DTO Trip at High-Re



Nitric oxide PLIF measurements of boundary layer at various heights

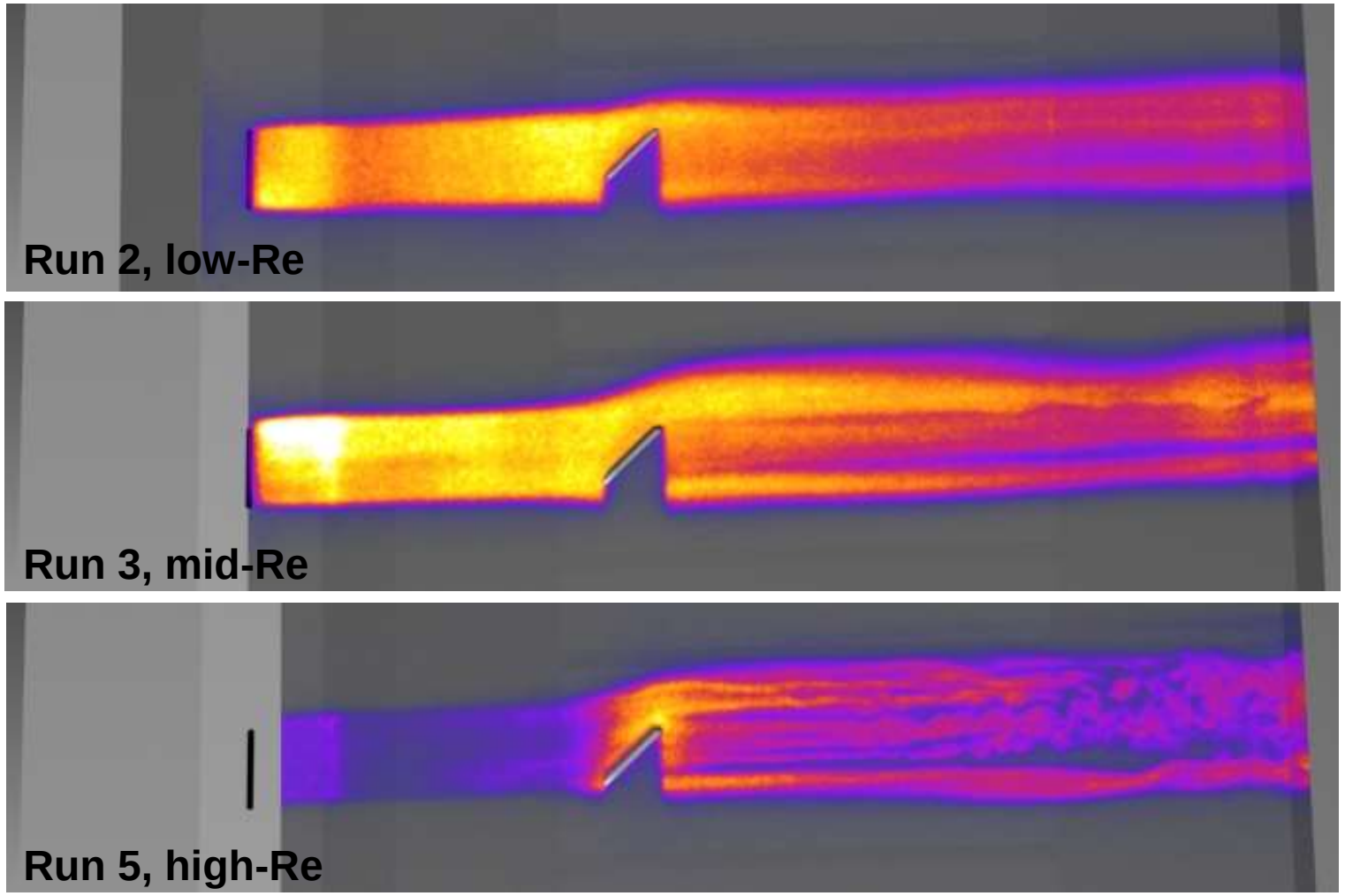
NASA Langley 31-Inch Mach 10 Tunnel

DTO: Detailed Test Objective

NO: Nitric Oxide

Danehy AIAA 2010-1571 https://doi.org/10.2514/6.2010-1571

Shuttle DTO Trip: Reynolds-Number Sweep



All images obtained about 0.5 mm above surface

Flow appears mostly steady and laminar at low-Re condition.

Flow unsteadiness occurs at mid-Re condition.

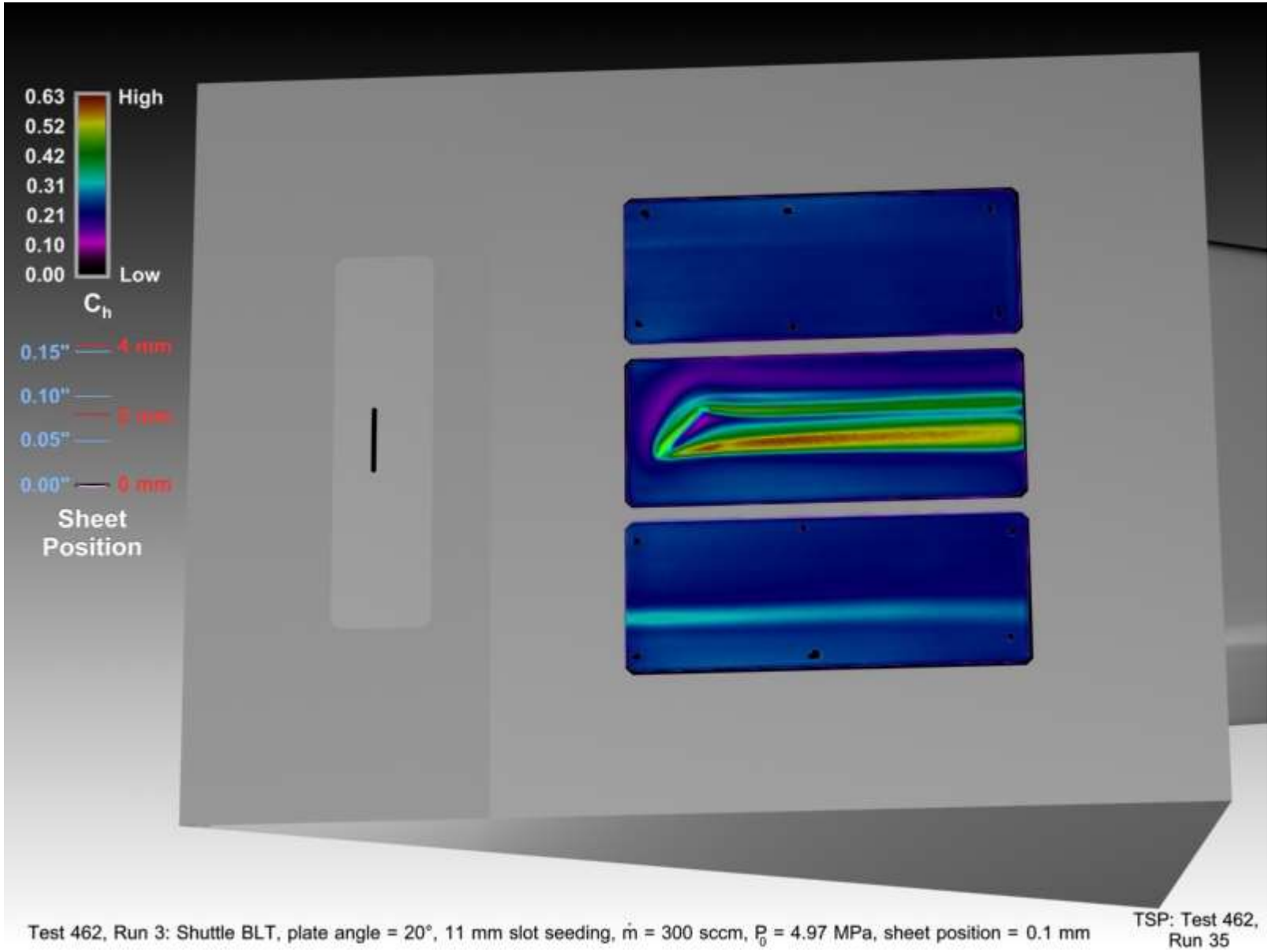
Transition is much closer to trip for high-Re condition.

NASA LaRC 31-Inch Mach 10 Tunnel

k: trip height
δ: boundary layer thickness

Danehy AIAA 2010-1571 https://doi.org/10.2514/6.2010-1571

Temperature Sensitive Paint (TSP)



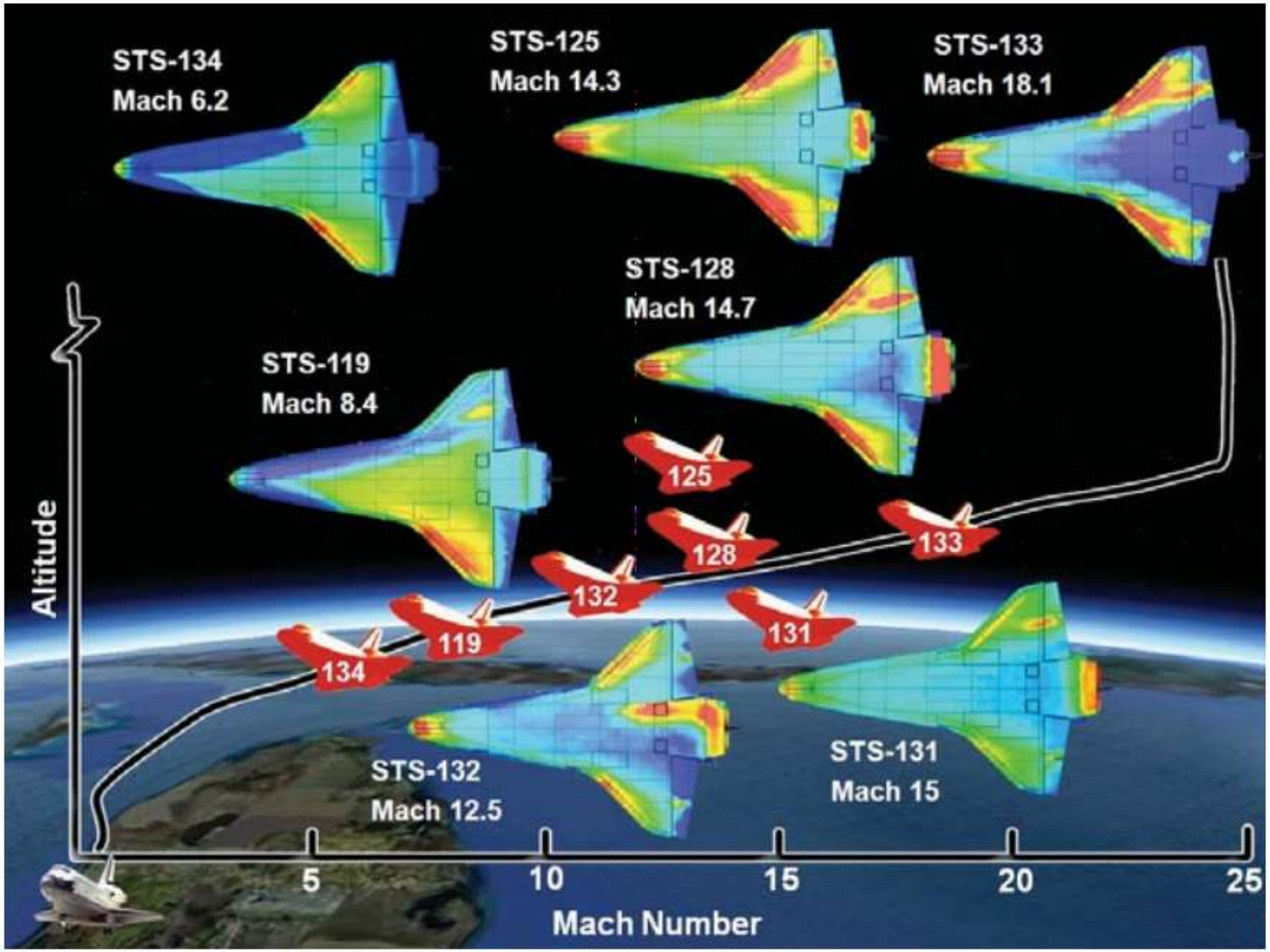
TSP measurements of surface temperature at various Reynolds numbers

NASA Langley 31-Inch Mach 10 Tunnel

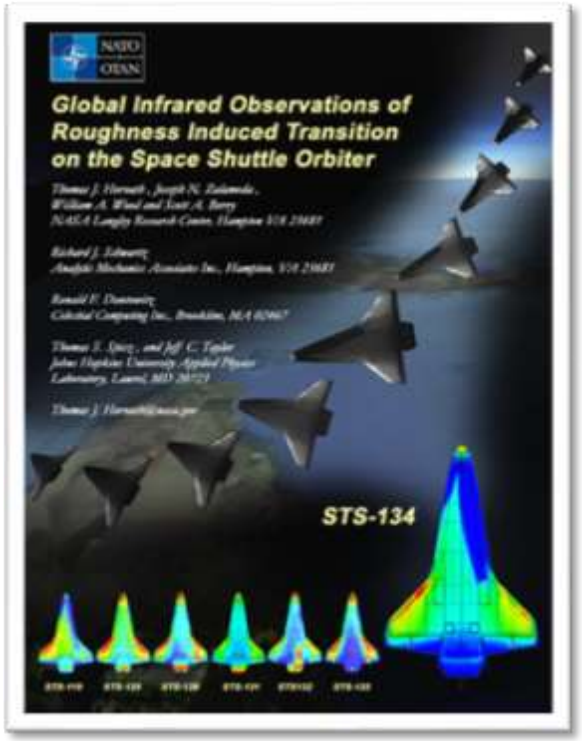
BLT: Boundary Layer Transition

Danehy AIAA 2010-1571 https://doi.org/10.2514/6.2010-1571

7 Space Shuttle Program Observations



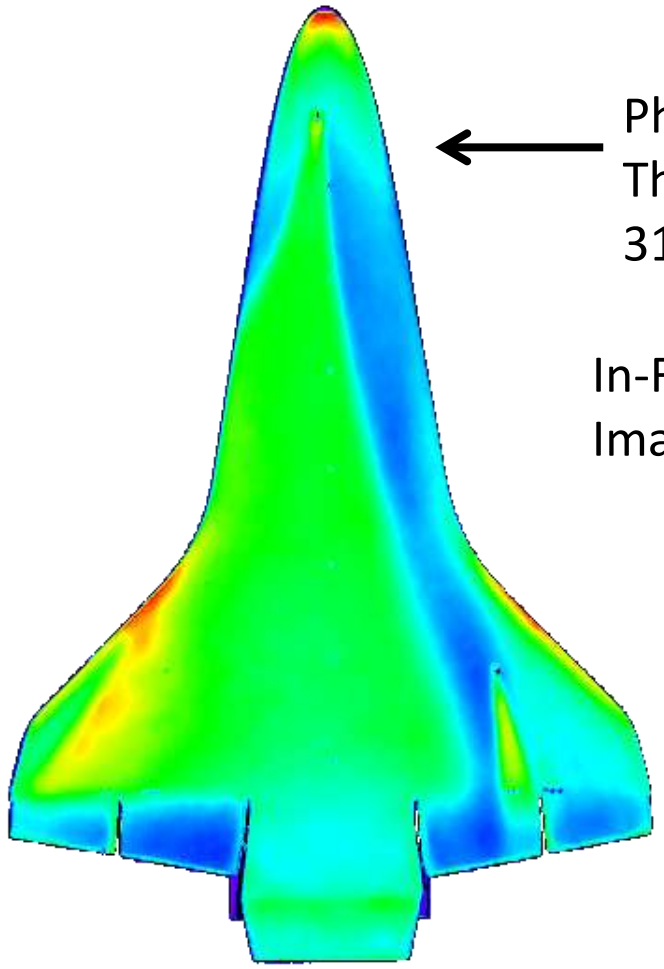
Thermally mapped Orbiter heatshield with and without DTO at Mach numbers from 18.1 down to 6.2



https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120007110.pdf

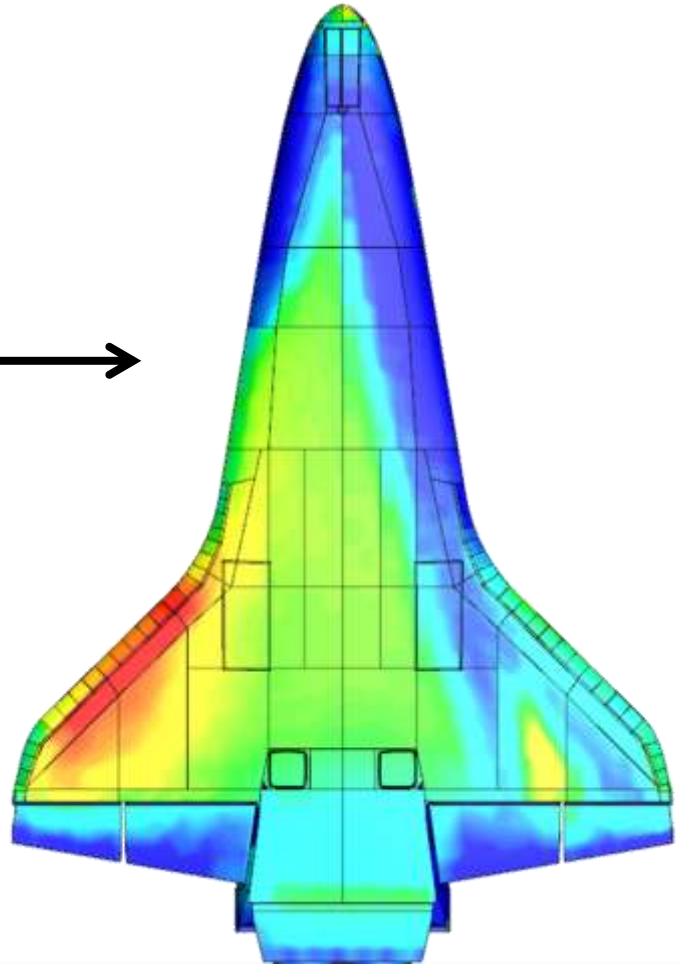
Ground-to-Flight Validation

Data provided the connection between ground testing, flight…

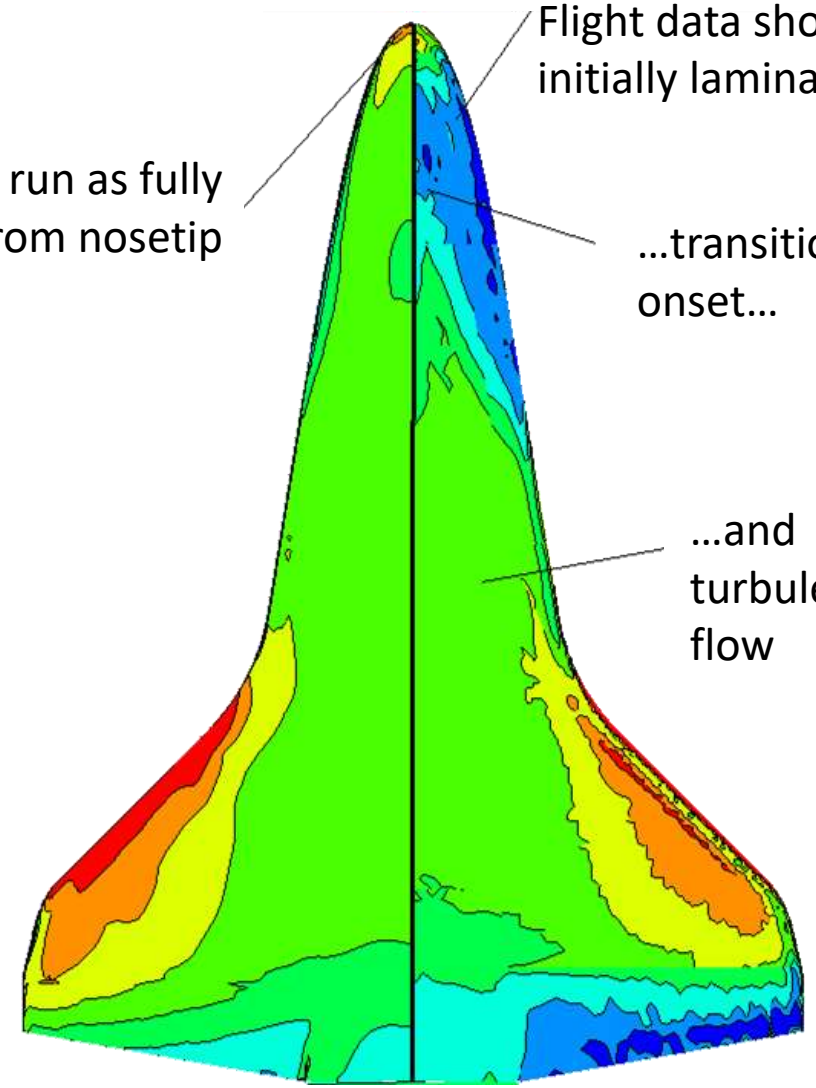


Phosphor Thermography in 31-Inch Mach 10

In-Flight Thermal Imagery of STS-119

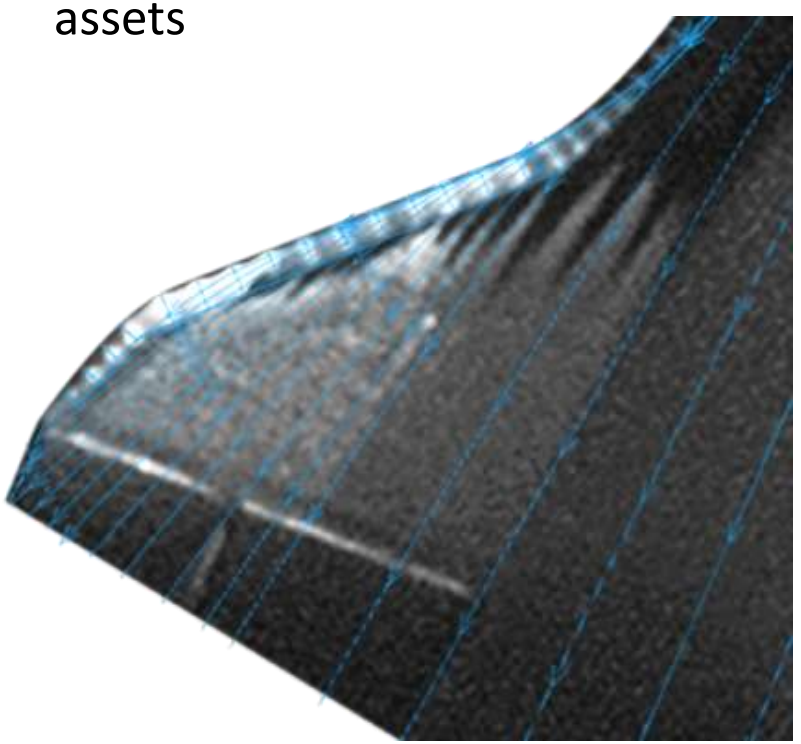


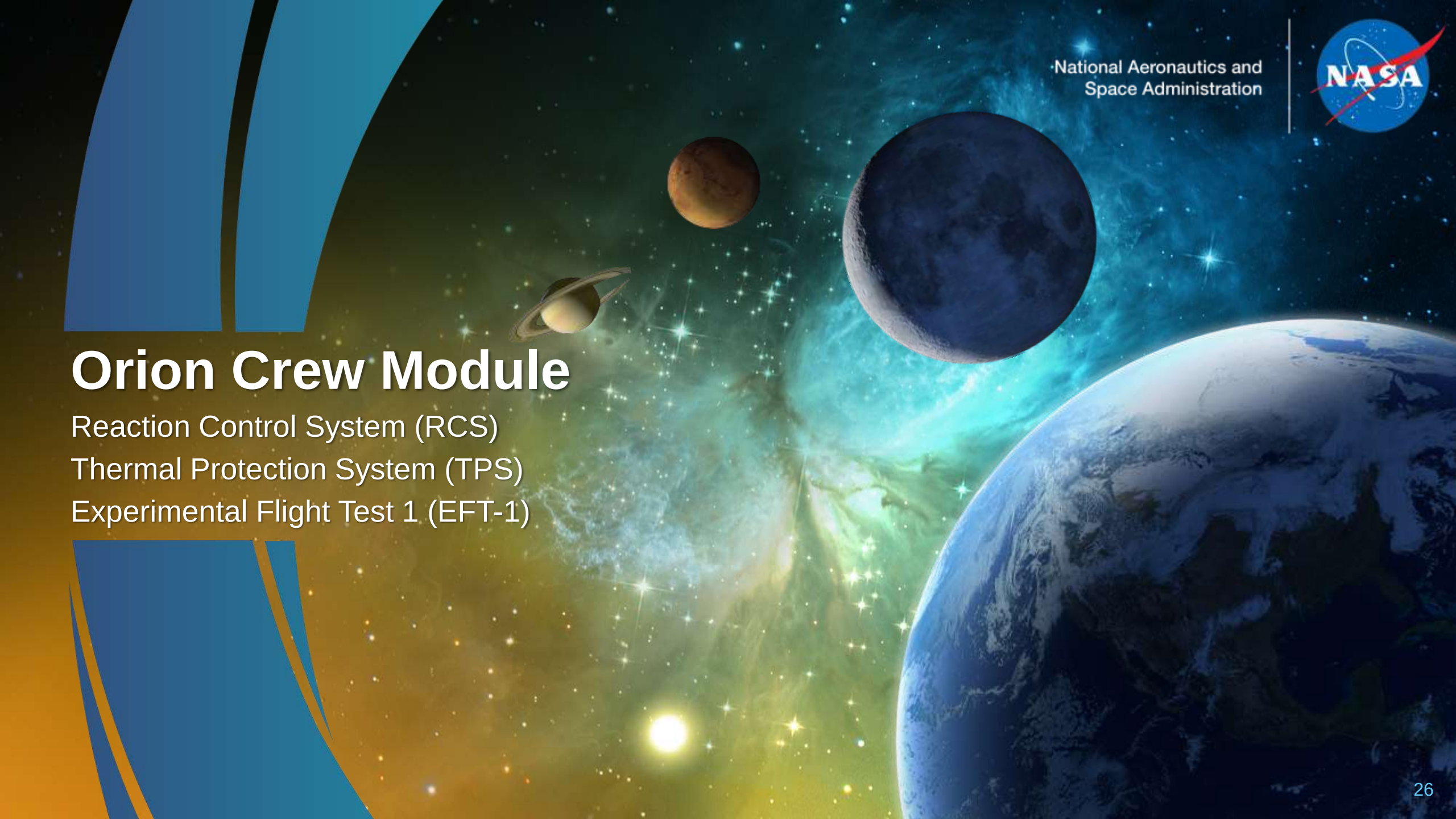
CFD-to-Flight Validation



…and computational analysis

Natural boundary layer transition observed by MARS ground-based assets





Orion Crew Module

Reaction Control System (RCS)

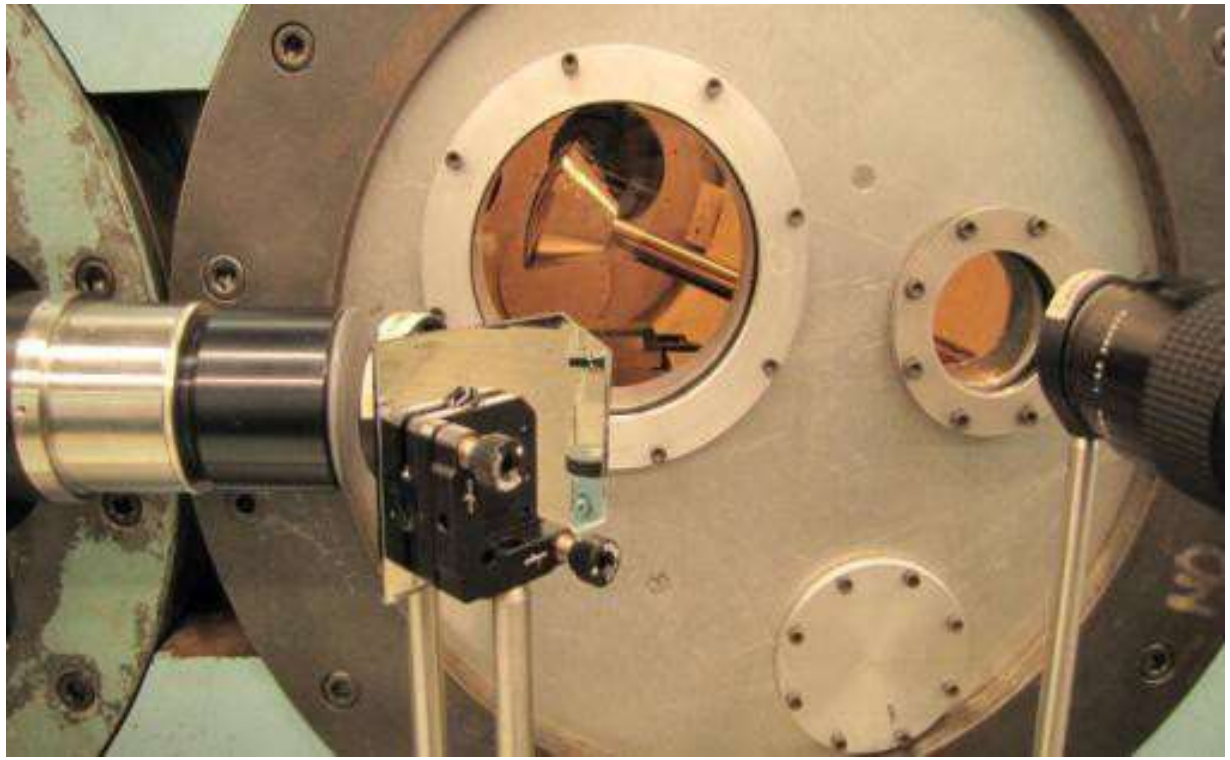
Thermal Protection System (TPS)

Experimental Flight Test 1 (EFT-1)

OH PLIF Imaging in CUBRC Lens-1 Facility

- Optics direct laser sheet directed into flow
- Imaged by cameras





Combs et al. J. of Spacecraft and Rockets (2015): Vol.52: 243-252 https://doi.org/10.2514/1.A32946

Orion Backshell Testing at CUBRC

- Short duration shock tunnel testing (LENS-1) at Mach 8
- Primary goal: Determine backshell heating environment with gauges
- Visualize shear layer, Reaction Control System (RCS) Jets with 1% NO



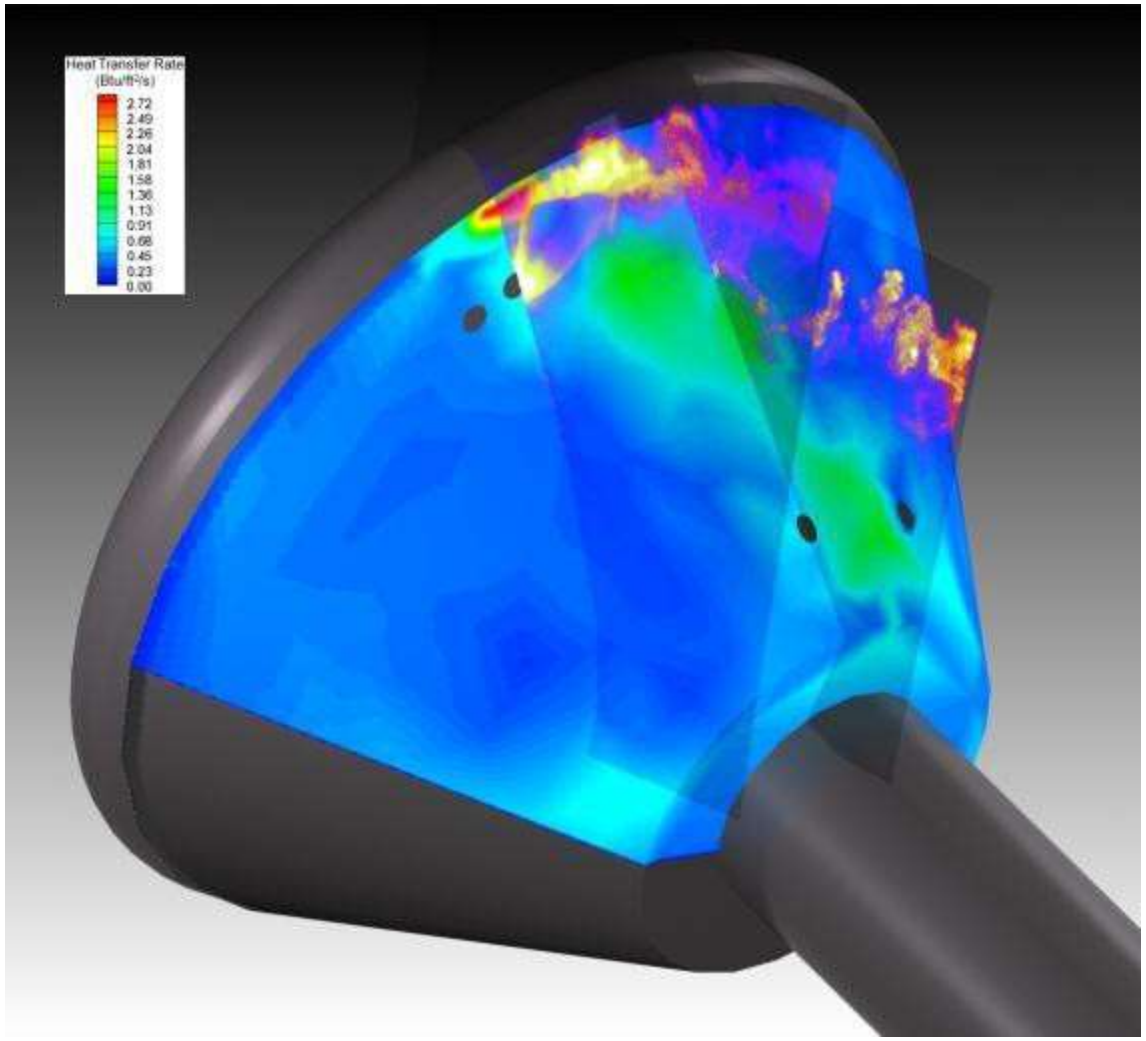


Schlieren didn't show jets

Combs et al. J. of Spacecraft and Rockets (2015): Vol.52, Issue 1: 243-252 https://doi.org/10.2514/1.A32946

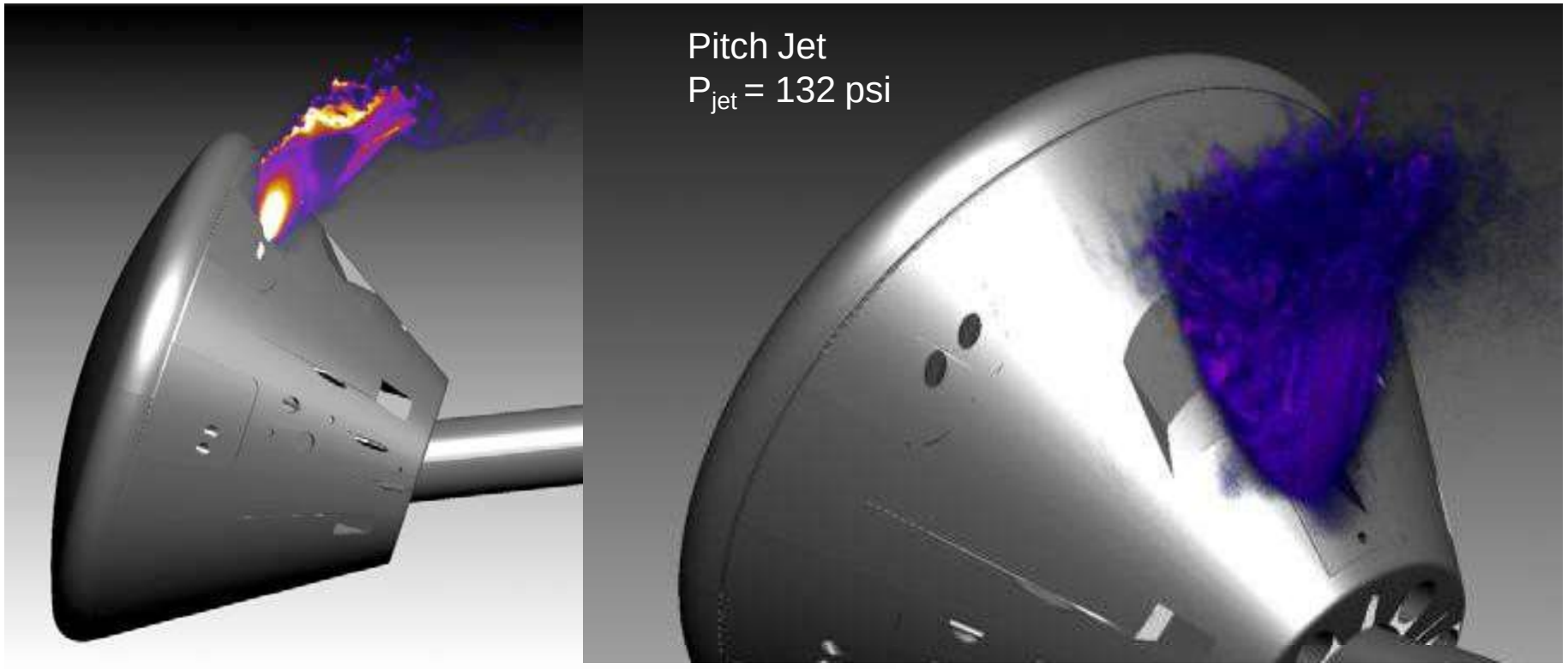
PLIF helps interpret conventional data

- Composite of two PLIF images taken at different image planes plus heating map generated by discrete gauges
- Clear that roll jet fluid is not heating the model
- Possibly a horseshoe vortex wrapping around roll jet structure is heating surface
- Separation shock may be cause of high heating near capsule lip



Combs et al. J. of Spacecraft and Rockets (2015): Vol.52: 243-252

Volumetric Imaging of RCS Jets

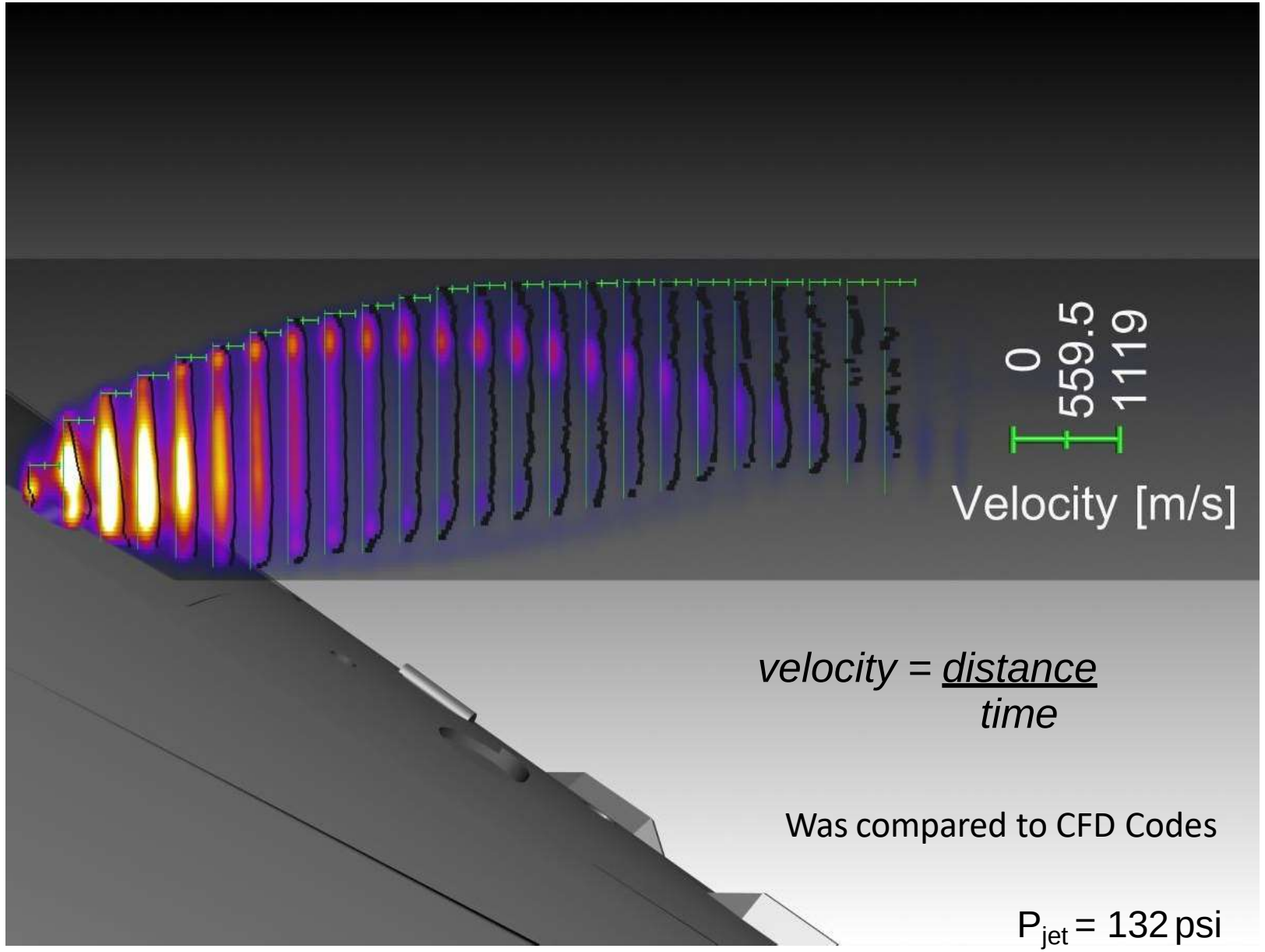


- 1 minute runs in NASA Langley's 31" Mach 10 facility
- Single shot images of NO-seeded RCS jet fluid; scan laser sheet
- Multiple images displayed simultaneously to show 3D trajectory of jet

RCS: Reaction Control System **NO:** Nitric oxide

J. A. Inman, P. M. Danehy, et al. AIAA Journal Vol. 47, No. 4, April (2009)

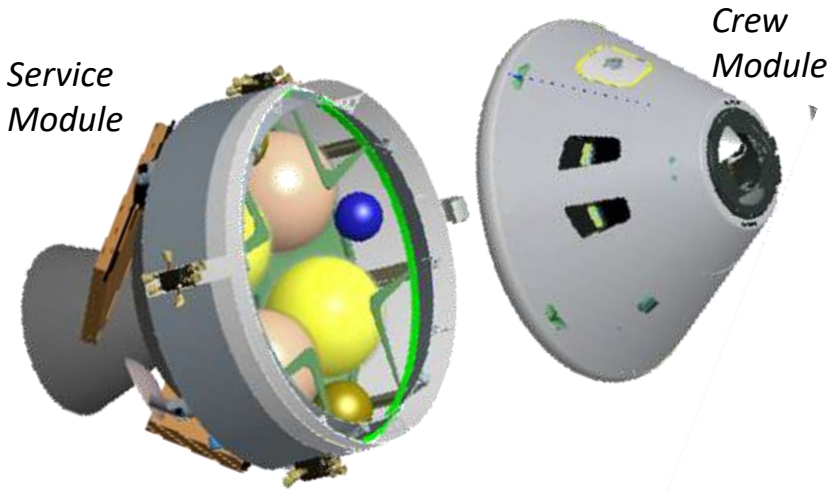
Orion Yaw RCS Jet Velocimetry

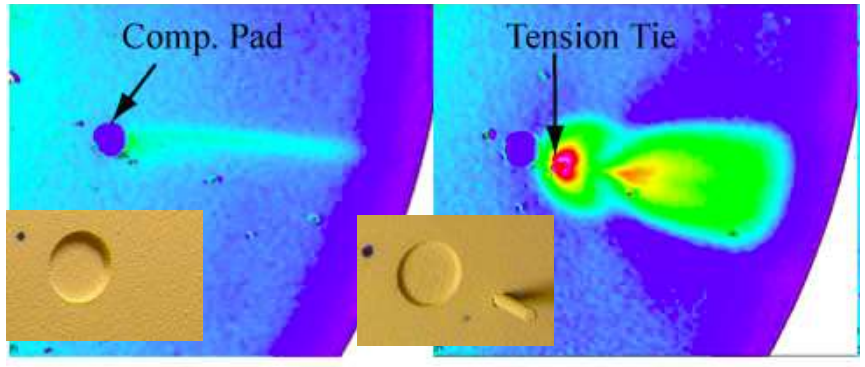


Velocity profiles obtained at two dozen locations downstream of nozzle exit

RCS: Reaction Control System

Compression Pads / Tension Ties

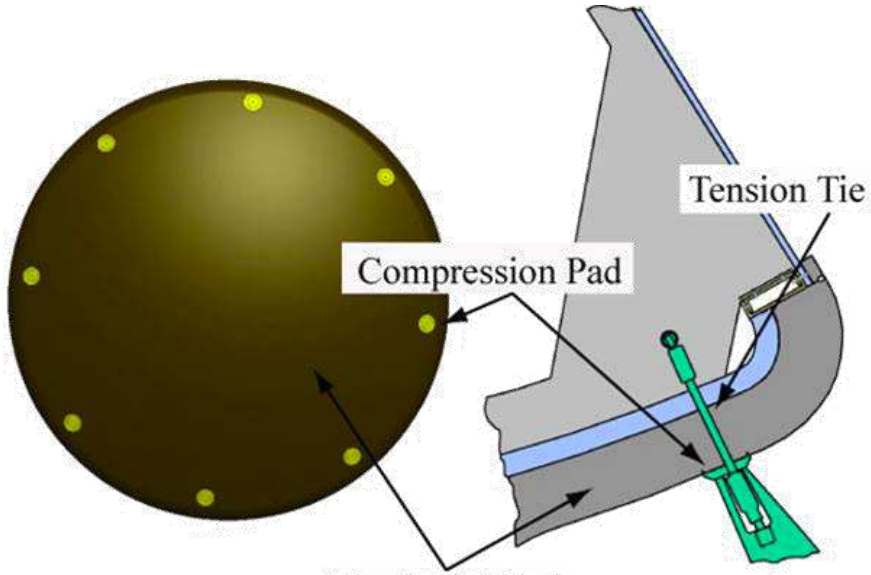




3x higher heating downstream of tension tie

Many researchers using cylinders in fundamental trip studies (Schneider, Mahesh, Choudhari, Goldstein and co-workers)

Cause augmented surface heating



Forebody Heat Shield

Liechty, AIAA-2008-1240

Cylindrical Trip, Side View: AoA Sweep

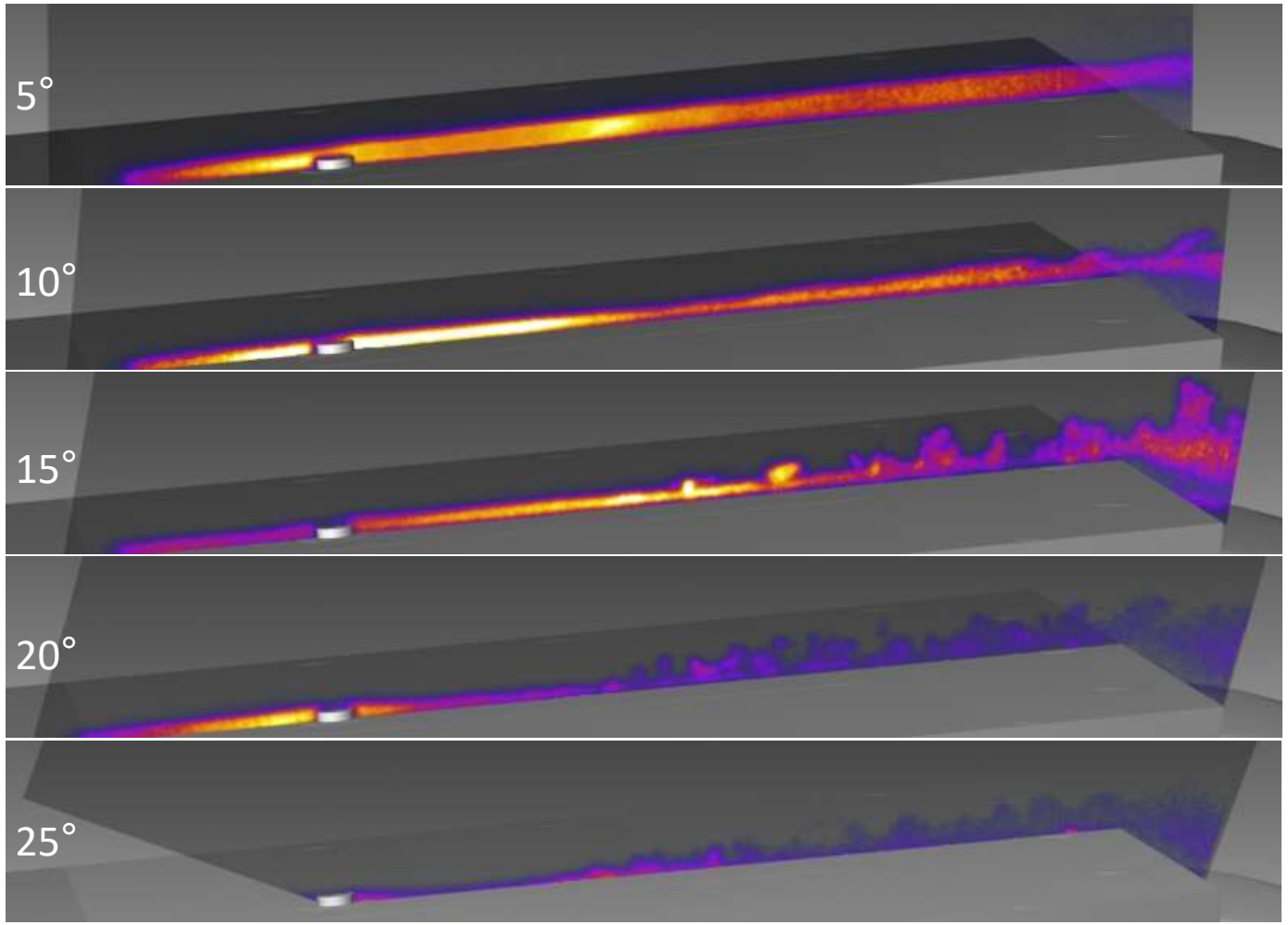


Plate Angle =

M_2 = 8.2

M_2 = 6.6

M_2 = 5.2

M_2 = 4.2

M_2 = 3.4

oblique shock calculation

Nitric oxide PLIF measurements of flow behind cylindrical trips at various AoAs

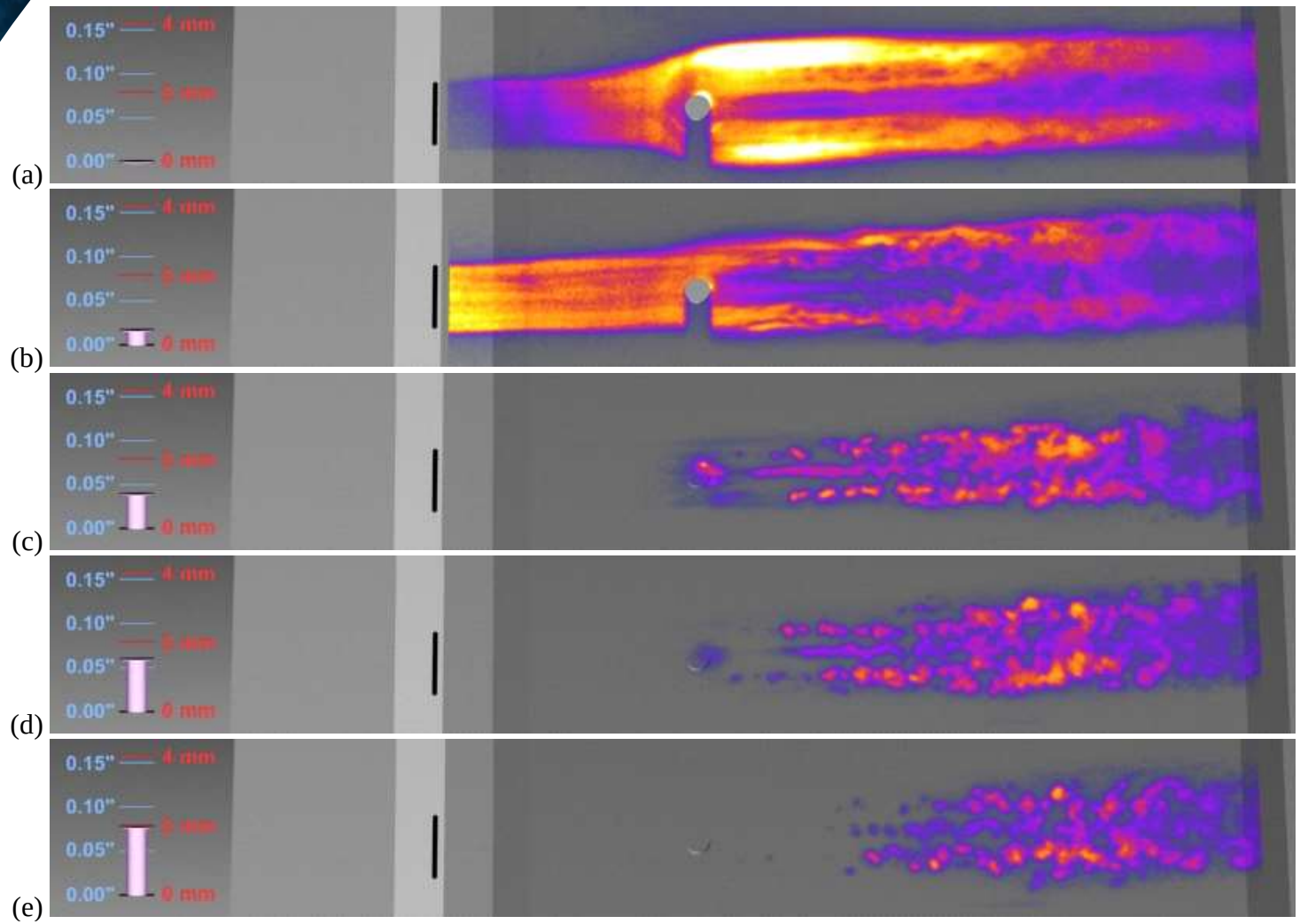
NASA Langley 31-Inch Mach 10 Tunnel

AoA: Angle of Attack
NO: Nitric Oxide

1 mm tall trip, High-Re
Steeper angle, much more unsteady

Bathel AIAA-2013-0042 https://doi.org/10.2514/6.2013-42

Cylindrical Trip, Plan View: High-Re



NO PLIF measurements of flow behind cylindrical trips at various heights above the surface

NASA Langley 31-Inch Mach 10 Tunnel

NO: Nitric Oxide
k: trip height
δ: boundary layer thickness

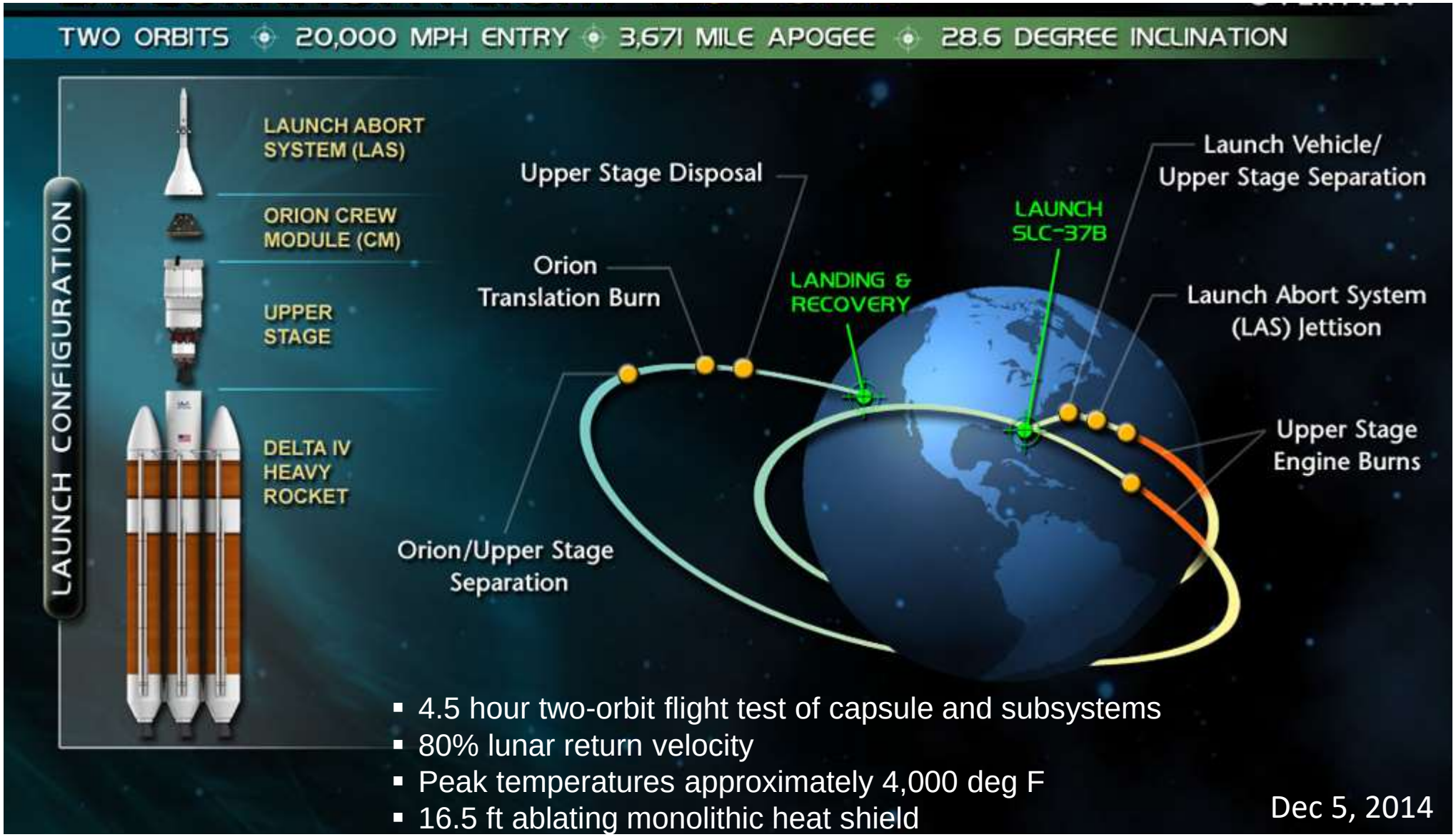
Periodic/irregular flow structures move forward to trip

Plate Angle = 20°
high-Re
$k/\delta = 1.4$

$M_e \approx 4$
$Re_k \approx 5600$

Bathel AIAA-2013-0042 https://doi.org/10.2514/6.2013-42

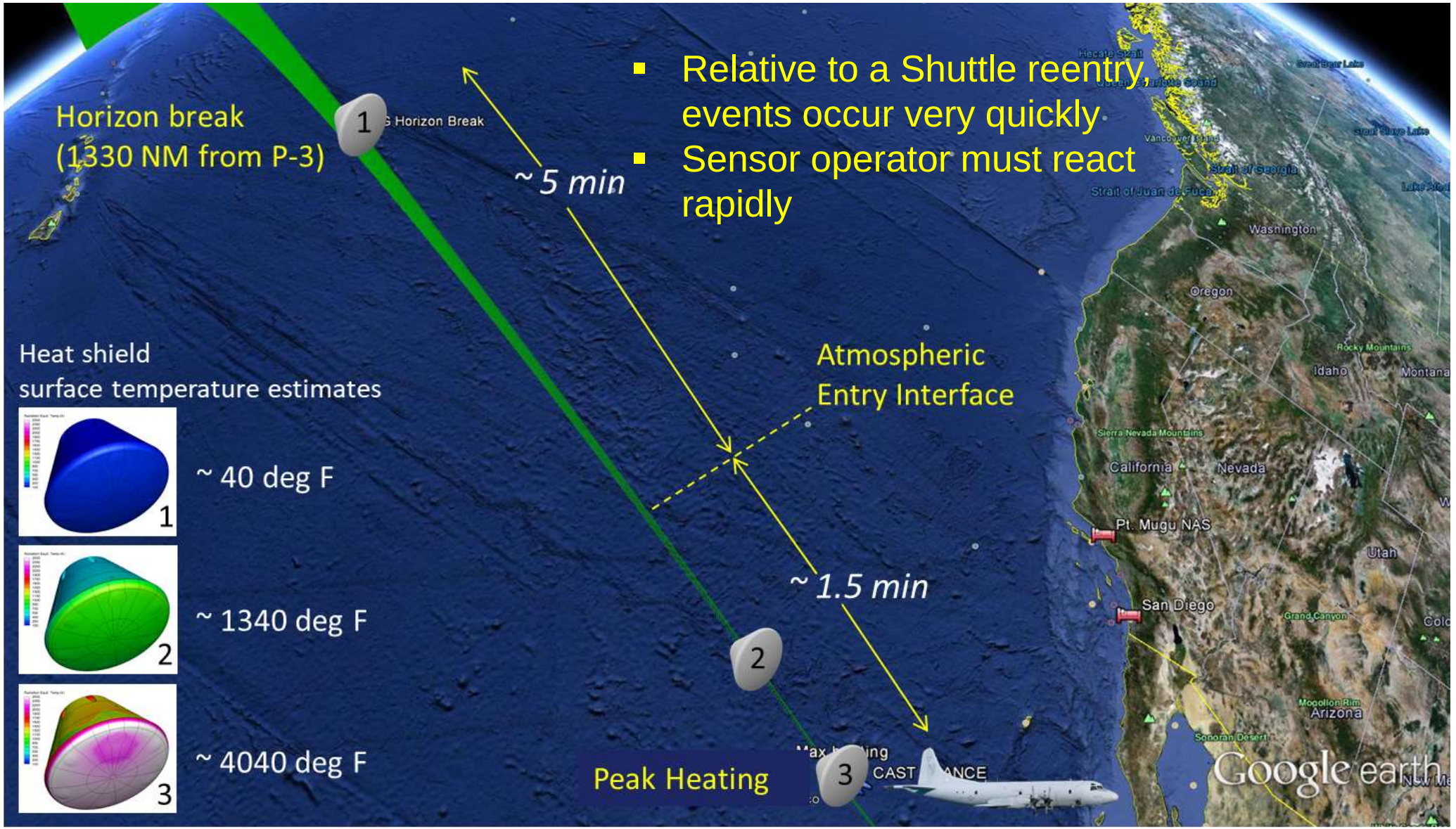
Exploration Flight Test 1 (EFT-1)



- 4.5 hour two-orbit flight test of capsule and subsystems
- 80% lunar return velocity
- Peak temperatures approximately 4,000 deg F
- 16.5 ft ablating monolithic heat shield

Dec 5, 2014

Exploration Flight Test 1 (EFT-1)



- Relative to a Shuttle reentry events occur very quickly
- Sensor operator must react rapidly

Exploration Flight Test 1 (EFT-1)

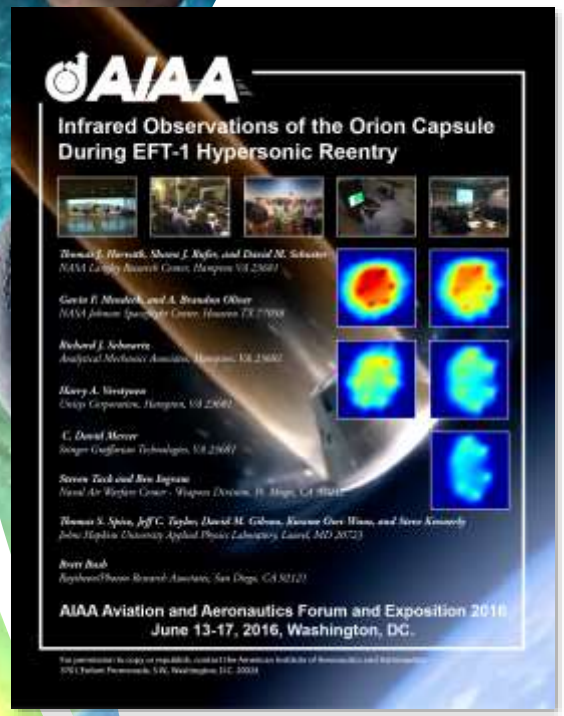
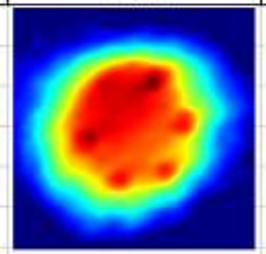
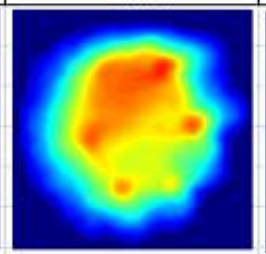
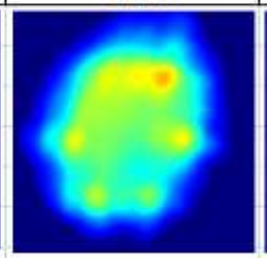
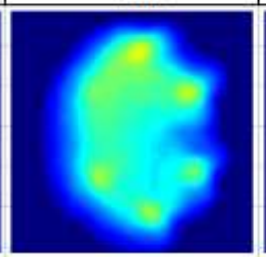
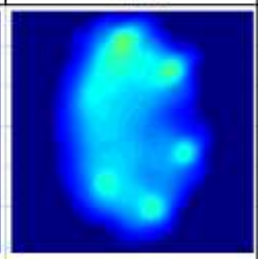
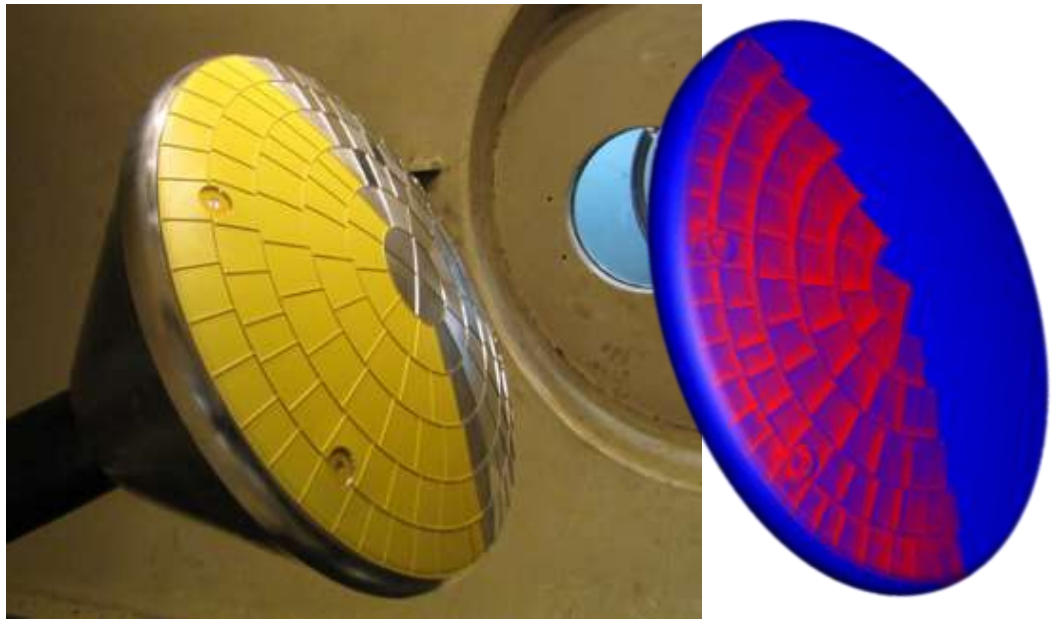


Image Frame Number:	7848	8028	8251	8474	8632
Image Frame Time Reference (GMT):	16:21:29.9917	16:21:35.9798	16:21:43.3983	16:21:50.8271	16:21:56.0939
Mach number:	9.91	9.33	8.66	8.04	7.63
Target Range (nmi):	65.1	57.2	49.2	43.3	40.6
Target elevation (deg):	15.4	17.4	20.2	22.7	24.1
Raw Image Pixel Footprint (inches):	17.1	15.0	12.9	11.4	10.7
Capsule apparent pitch (angle of attack;deg):	-19.1	-19.1	-19.2	-19.4	-19.4
Capsule "up" (reference to z-axis; deg):	18	18	18	-7	-9
Capsule bank angle (deg):	30.39	22.21	27.85	38.48	46.46
Angle of l.o.s. to heatshield normal(deg):	11.5	33.5	36.0	44.0	53.0
Peak temperature (deg F):	1940	1843	1760	1718	1643
Minimum temperature (deg F):	~1720	~1630	~1520	~1480	~1400
Temperature (deg F):						

Data shows augmented heating near compression pads

Orion Reentry Peak Heating

- New heatshield design—segmented ablator.
- Shuttle embedded thermocouples exhibited anomalous behavior and delivered unreliable, discrete surface temperature results
- SCIFLI advocating for peak heating thermal observation

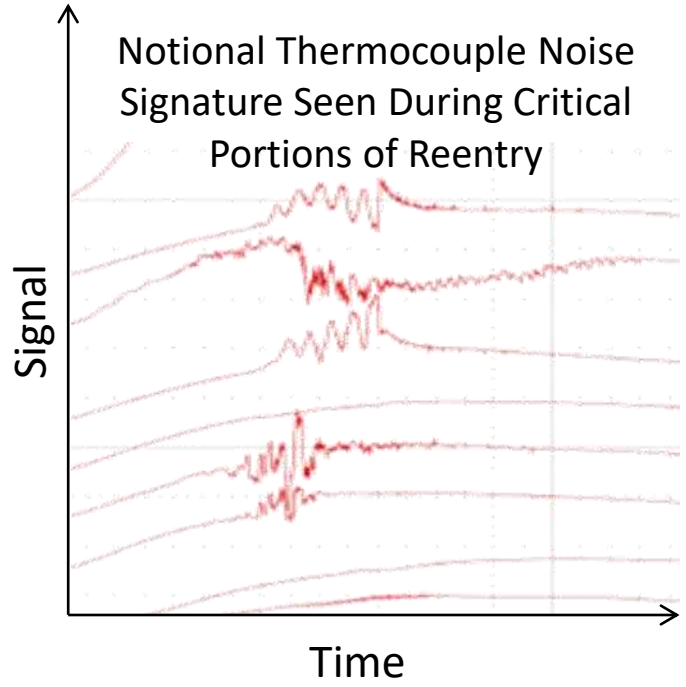


Testing representative block-TPS layouts in
20-Inch Mach 6 with global phosphor thermography

https://www.nasa.gov/centers/ames/images/content/671692main_MarsScienceLabHeatshield017a%5B2%5D.jpeg

Approximate reentry Mach numbers:

- Shuttle: 25
- EFT-1: 28
- Apollo: 36
- **Artemis 1: 40**



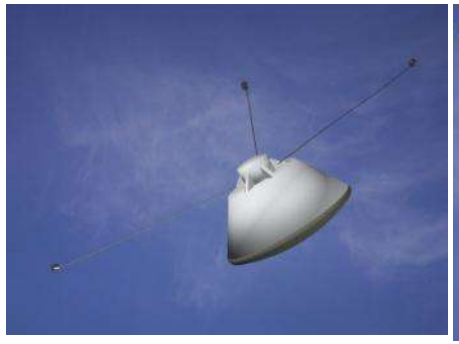
Behavior has been observed on:

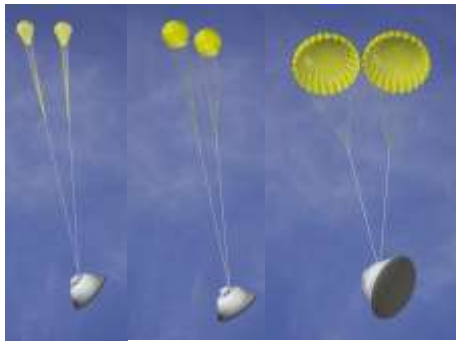
- Shuttle Orbiter
- Dragon Capsule
- Orion Capsule

Orion Parachute Deployment

SCIFLI tasked with observation of Forward Bay Cover (FBC) deployment, parachute deployment sequence, and splashdown









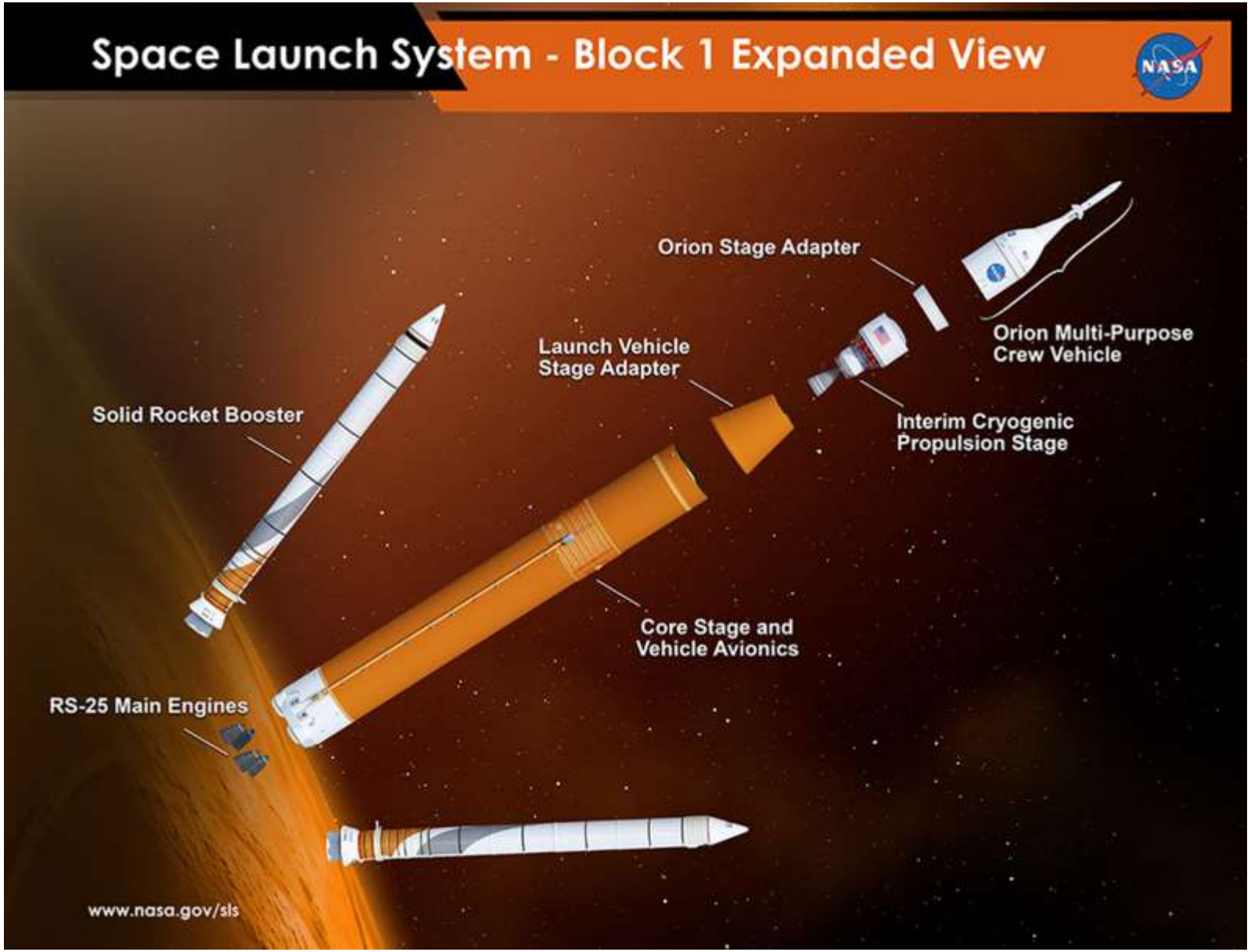


Space Launch System (SLS)

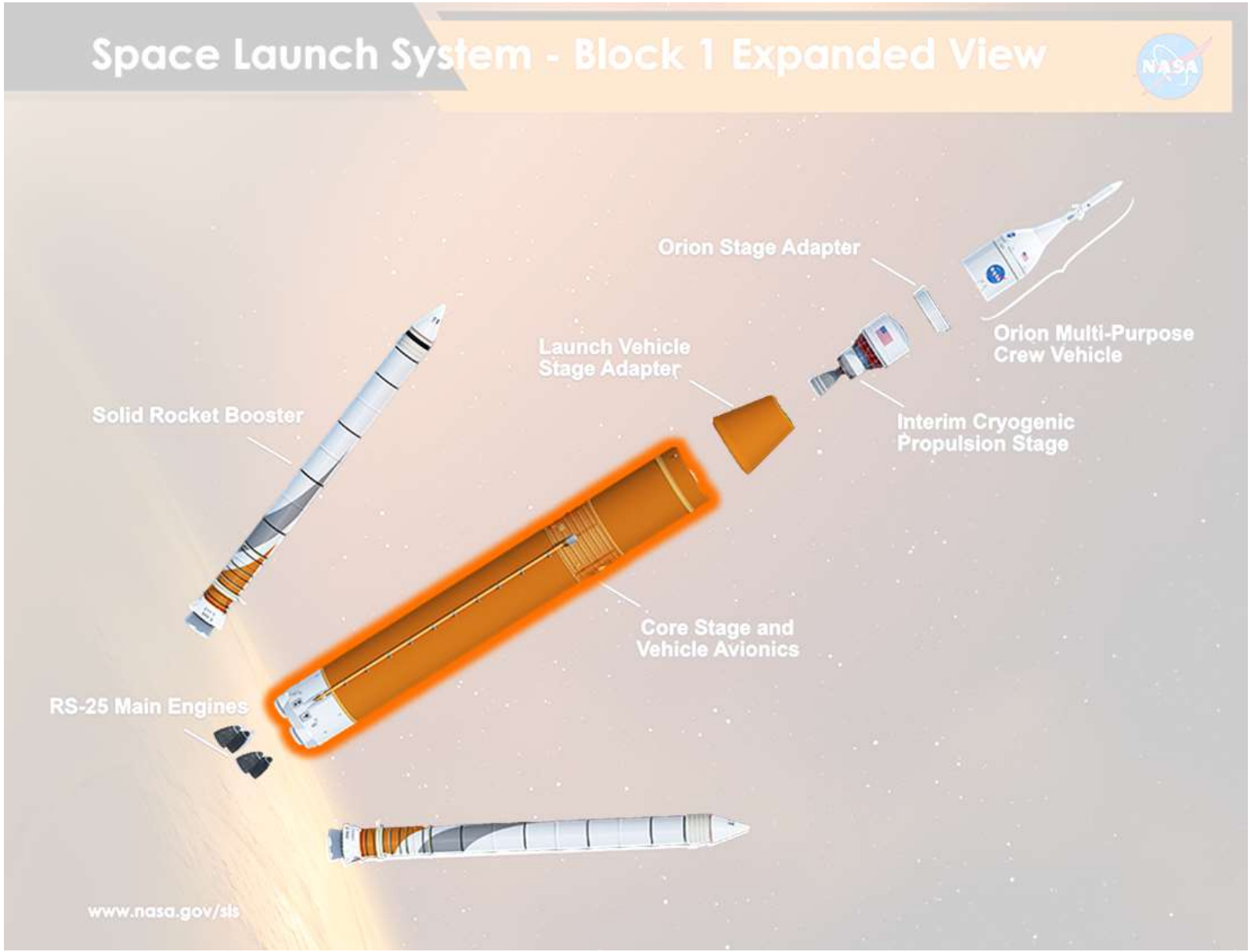
Base Heating of Rocket Core Stage

Artemis I Launch

Artemis 1: SLS Block 1



SLS Block 1 Core Stage



OH PLIF Visualization and Thermometry for NASA Space Launch System (SLS) Base Flow Heating

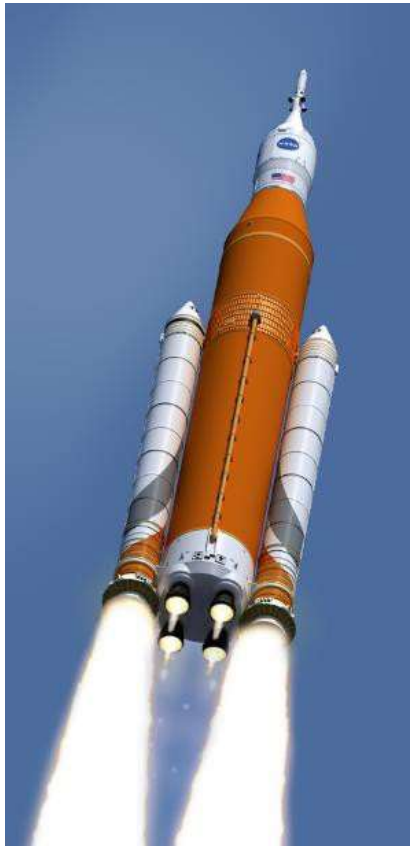
Optical Diagnostic Imaging of Multi-Rocket Plume-Induced Base Flow Environments

Manish Mehta[1] and Darrell E. Gaddy[2]
NASA Marshall Space Flight Center, Huntsville, Alabama, 35812

Paul M. Danehy[3], and Jennifer A. Inman[4]
NASA Langley Research Center, Hampton, Virginia, 23666

and

Ron Parker[5] and Aaron T. Dufrene[6]
CUBRC Inc., Buffalo, New York, 14225



Measurements at CUBRC in Buffalo
Using NASA Mobile PLIF system

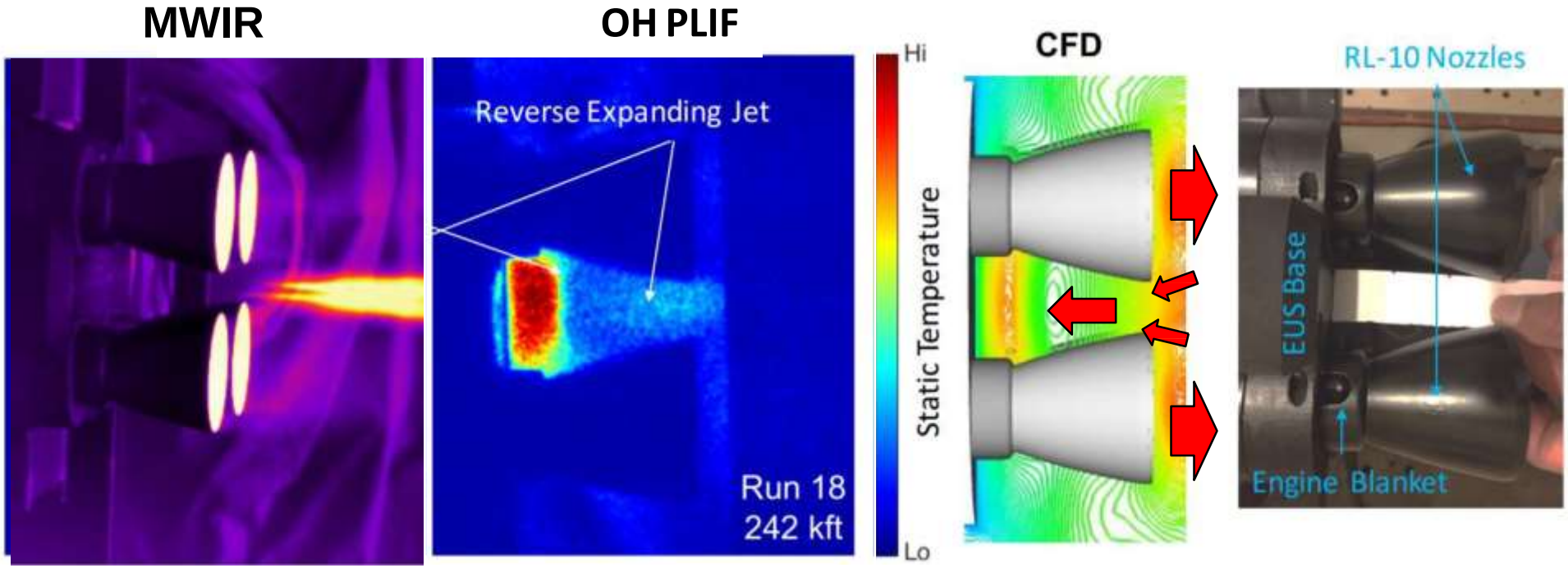
AIAA AVIATION Forum
5-9 June 2017, Denver, Colorado
47th AIAA Fluid Dynamics Conference

Ross Burns, Paul Danehy, Jennifer Inman, Manish Mehta, Darrell Gaddy, Ron Parker, Aaron Dufrene, Joshua Weisberger "Quantitative, Multi-Line, OH-PLIF thermometry to examine base heating in the space launch system core and EUS stages," *Joint Army Navy NASA Air Force (JANNAF) 36th Exhaust Plume and Signatures (EPSS) Meeting*, 4-8 December 2017, Newport News, VA.

JANNAF Conference, Newport News, Dec 2018

OH PLIF Visualization and Thermometry for NASA Space Launch System (SLS) Plume Induced Base Heating

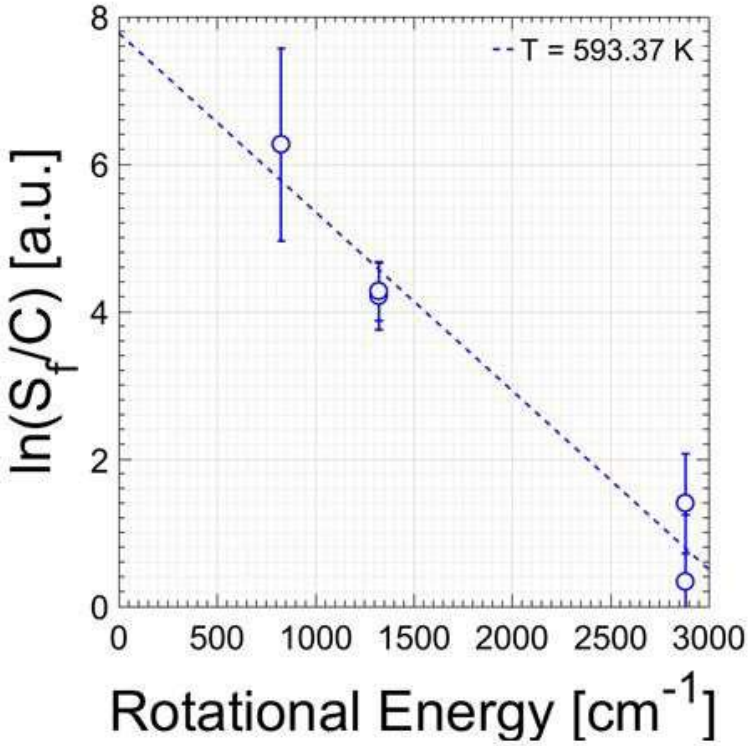
- At high altitudes, flow leaving engines impinges on base
- Prior to PLIF: no direct experimental evidence of shock formation
- Wind tunnel tests: Use OH Planar Laser-Induced Fluorescence (PLIF)
  - Naturally-occurring OH present in plume and plume-induced base flow
- OH PLIF flow visualization clearly showed stagnation shock.
  - Neither Schlieren nor IR showed base flow structures
- Position of shock agreed with CFD, increasing confidence in CFD.

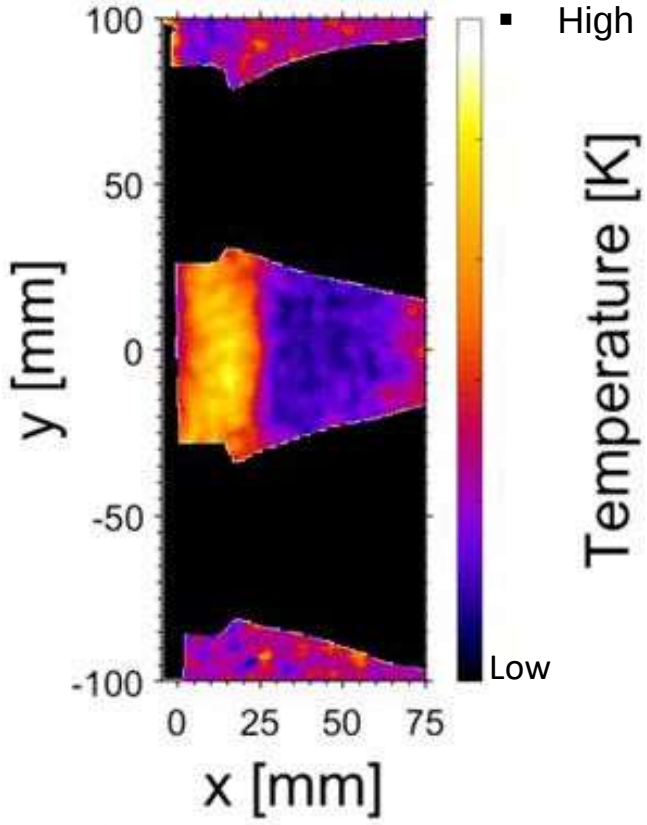


Mehta AIAA 2017-3465 https://doi.org/10.2514/6.2017-3465

OH PLIF Thermometry of SLS Base Flow

- Probe different ground state transitions: measure rotational temperature

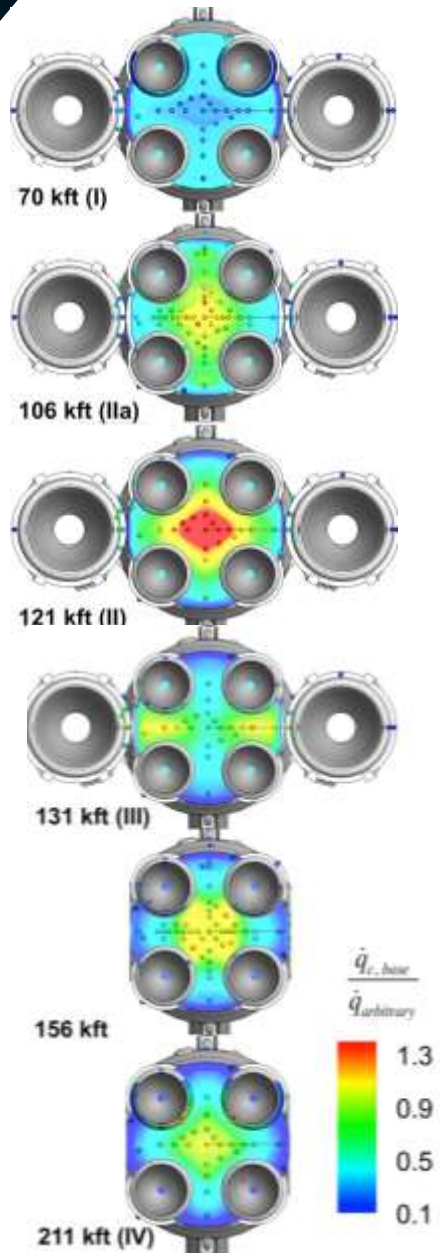




- "Recovery temperature" measurement is needed to determine flight-scaled convective heat transfer coefficient
- Quantity critical in determining flight-scaled heat transfer rates
  - Previously used a few thermocouples protruding into flow: 50-80% uncertainty
  - Using PLIF for the first time, measured with uncertainty of 10-30% with only 5 images
- Used to design base thermal protection system (TPS) thickness

Mehta AIAA 2017-3465 https://doi.org/10.2514/6.2017-3465

SLS Core Stage Base Heating



- Baseflow physics expected to be significantly different than Evolved Expendable Launch Vehicles (EELV, i.e. Delta IV and Atlas V) and Shuttle
- Experimental test data at CUBRC indicated higher base heating than predicted by CFD
- Flight data needed for validation and accurate assessment of thermal margins
  - Limited thermocouple instrumentation
  - Infrared imagery to complement onboard instrumentation
- Spectral and radiance modeling study showed feasibility of thermal observation
- SCIFLI tasked with making thermal measurements of base region

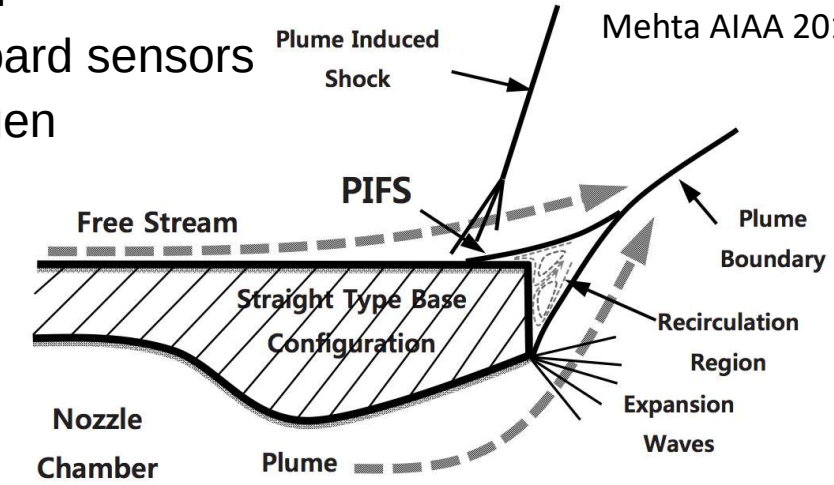
Mehta AIAA 2016-0547

Plume-Induced Flow Separation (PIFS)

- Seen on Saturn V – “dirty” kerosene flames are visible*
- Infrared imaging to look for PIFS on SLS – invisible
- PIFS is a complex flow phenomenon and is strongly affected by nozzle-to-freestream pressure ratio and base shape
- PIFS-induced aerodynamic forces affect longitudinal stability
- Localized surface heating increases near the flow separation point and plume induced shock can occur
- Flight data needed for validation of design models and the accurate assessment of thermal margins
  - Limited thermocouple instrumentation
  - Infrared imagery to complement onboard sensors
  - Better suited to visualize LOX/Hydrogen
- SCIFLI tasked with observing SLS ascent



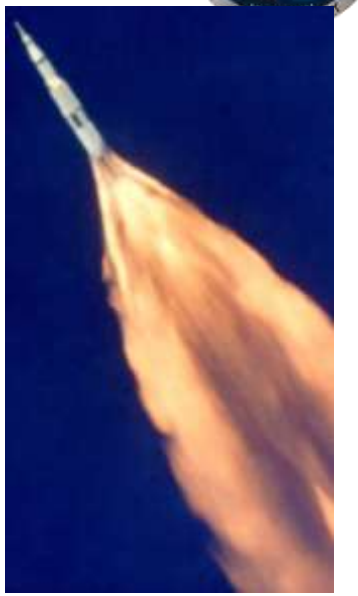
Mehta AIAA 2011-711



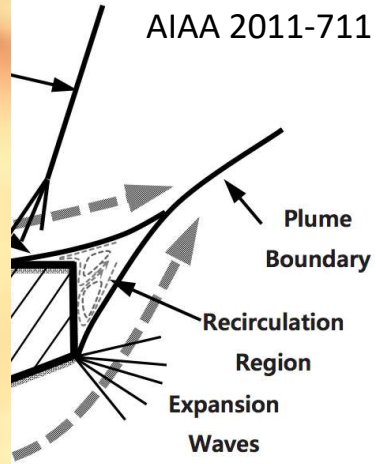
*The Airborne Lightweight Optical Tracking System (ALOTS) was used to observe the flow separation location on the Saturn V AS-506 (Apollo 11) vehicle in flight. The uncertainty of flight PIFS data was estimated at least ±10 percent.



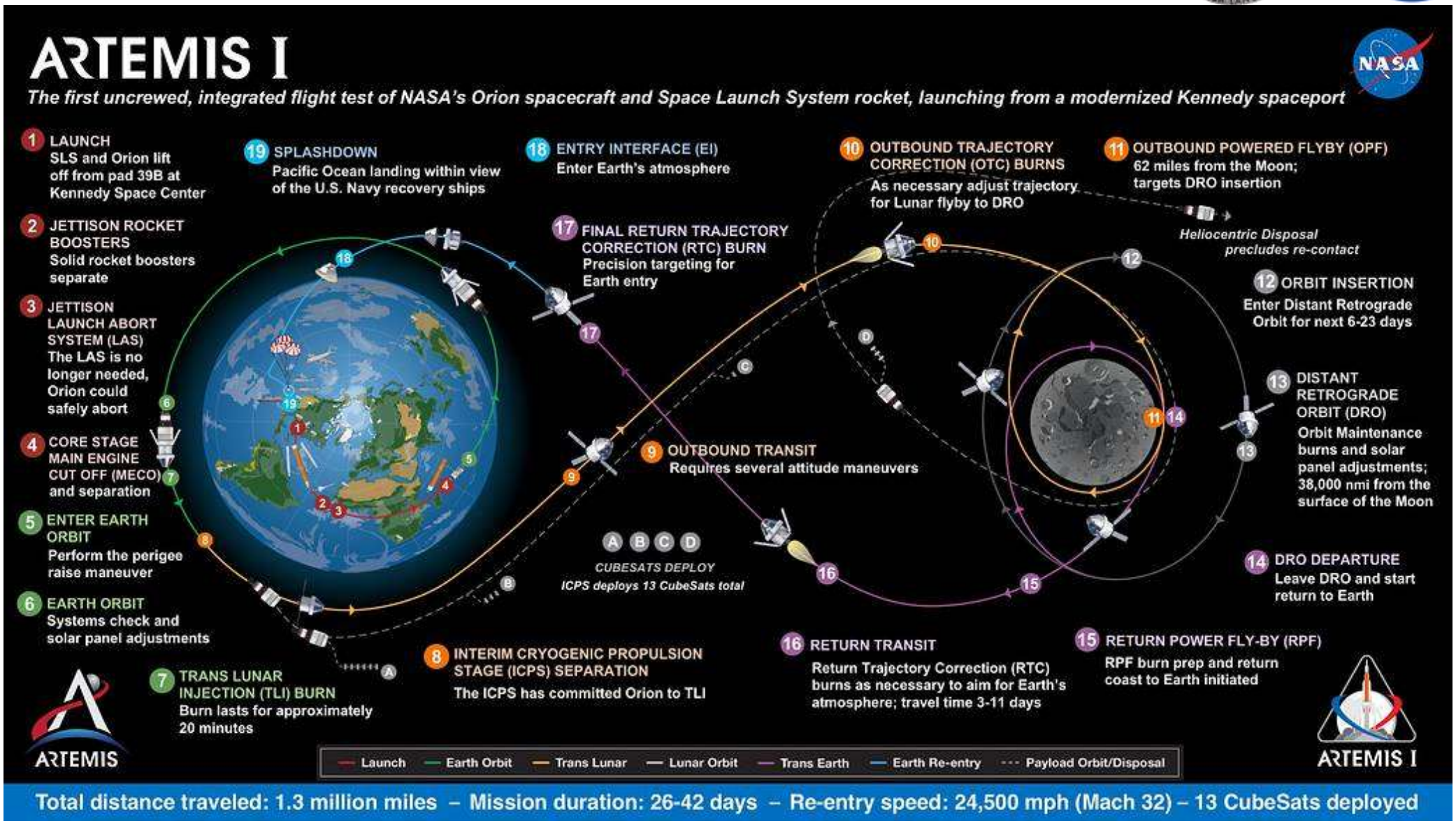




AIAA 2011-711



SLS Launch and Orion Parachutes



Acknowledgments



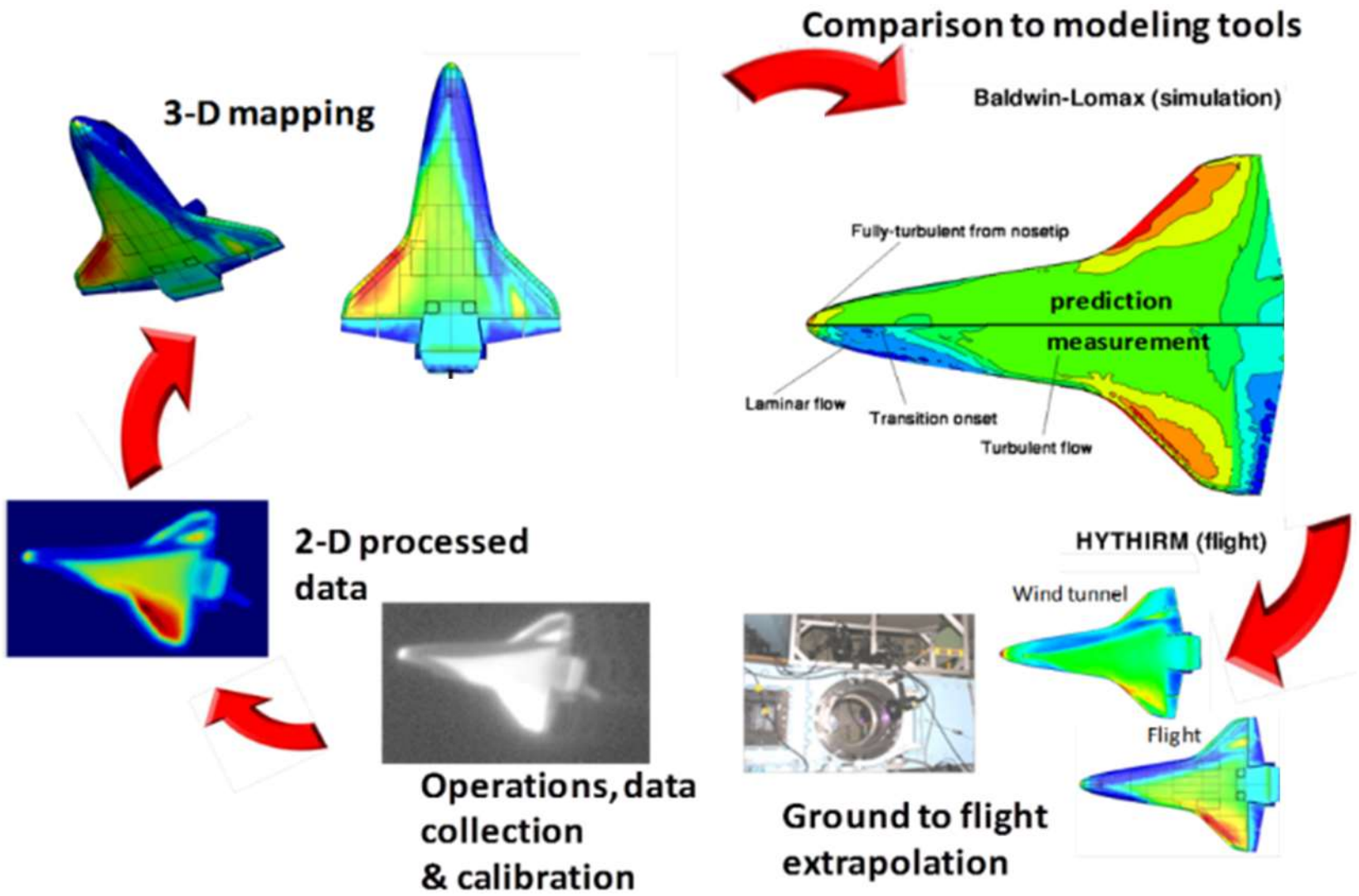


OSA Optical Sensor and Sensing Congress: Laser Applications to Chemical, Security and Environmental Analysis

Back Up

Flight-Truth Datasets Close the Loop

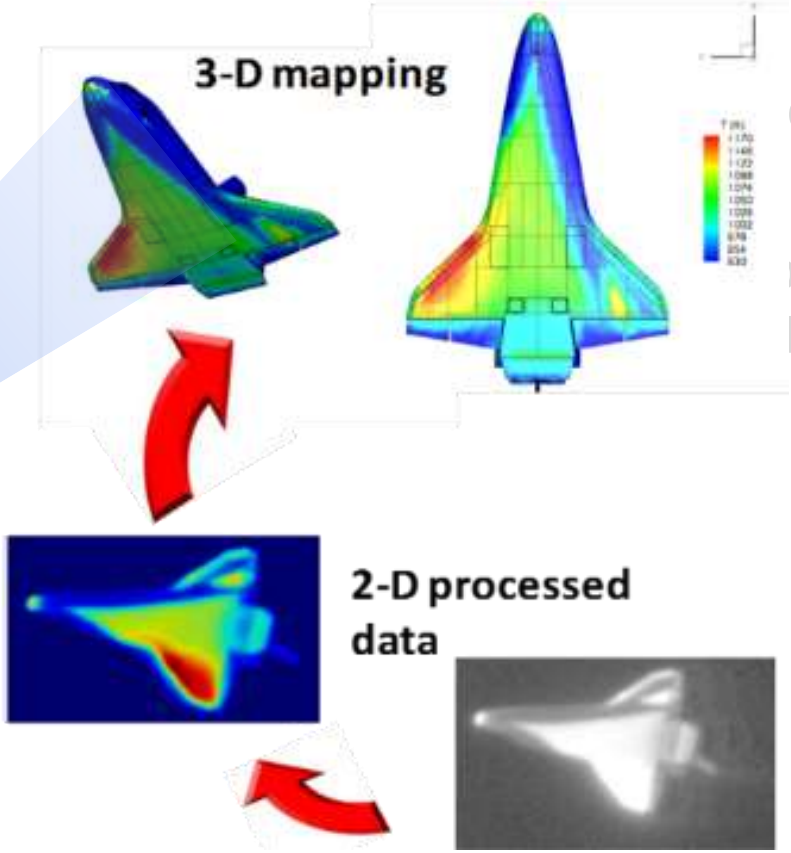
Validate wind tunnel tests and analytical models



Introduction

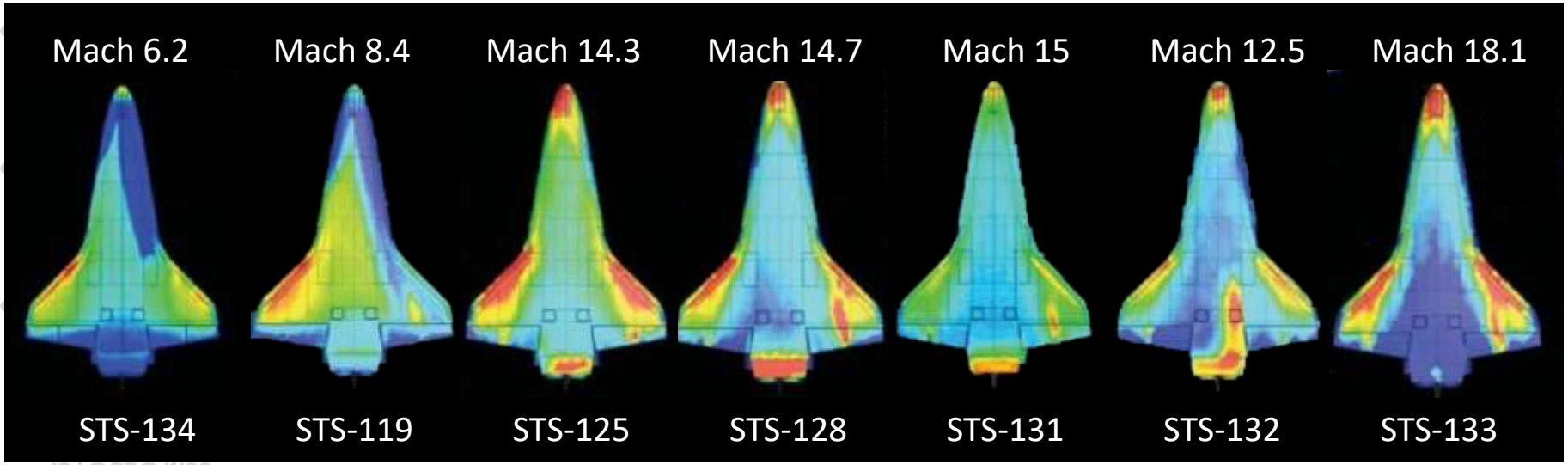
- The SCIFLI Team provides *quantitative measurements in engineering units derived from calibrated imagery data*. The data are most often obtained from airborne platforms, but have also been acquired from land and ship based assets.
- SCIFLI evolved from HYTHIRM, a pro ce Shuttle reentries ranging from Mach 6
- More recently, we have deployed for A)- propulsion imaging missions as well a L).
- The SCIFLI team is collaborating with capabi es on high altitude, long endu
- We are ntly working ssions for Program/S ion Program, (SLS) n to develop platform.





- The SCIFLI Team pr… *…ts in engineering units derived from ca…* …are most often obtained from airborn… …n acquired from land and ship based assets.

- SCIFLI evolved from HYTHIRM, a project which imaged numerous Space Shuttle reentries ranging from Mach 6 to Mach 18.



platform.

Partners

NASA

Langley Research Center

- Aerothermodynamics Branch
- Advanced Measurement and Data Systems Branch
- Space Technology and Exploration Directorate
- Direct-funded contractors
- Aeronautics Research Mission Directorate Project Office
- Gulfstream III aircraft

Johnson Space Center/Ellington Field

- Spaceflight Meteorology Group
- Image Science & Analysis Group
- WB-57 High-Altitude Research / Airborne Science Program
- Flight Operations Division, Gulfstream III Aircraft

Kennedy Space Center

- Telescience Research and Technology Support

Armstrong Flight Research Center

- Gulfstream III
- DC-8
- Global Hawk

Ames Research Center

Commercial

Analytical Mechanics Associates (AMA)

MARS Scientific (Mobile Aerospace Reconnaissance Systems)

Torch Technologies

Opto-Knowledge Systems, Inc. (OKSI)

Academia

Johns Hopkins Applied Physics Laboratory (APL)

Department of Defense

Naval Air Systems Command (NAVAIR)

Air Test and Evaluation Squadron 30 (VX-30) and Cast Glance

45th Space Wing, USAF Space Command

Non-Profit

Southern Research Institute (DYNAMITE sensor package)

Customers

Johnson Space Center

Orion Program: EM-1 Reentry, Forward Bay Cover Deployment, Parachute Deployment Sequence, Splashdown

Commercial Crew Program (CCP): SpaceX Dragon 2 Parachute Drop Tests

Space Shuttle Program

SpaceX / COTS / Boeing / CCP

C1: Commercial Orbital Transportation Services (COTS) Demo Flight 1 of Dragon Capsule

C2+: COTS Demo Flight 2

CRS-3: Commercial Resupply Services

ORBCOMM 1: Supersonic Retropropulsion (SRP)

CRS-4

NASA Headquarters

NASA Engineering and Safety Center (NESC)

Max Launch Abort System (MLAS)

Marshall Space Flight Center

Space Launch System

Plume-Induced Flow Separation

Core Stage Base Heating

Langley Research Center

Orion Program

Exploration Flight Test 1 (EFT-1)

Artemis 1

Core Stage Reentry and Breakup

Kennedy Space Center

Commercial Crew Program

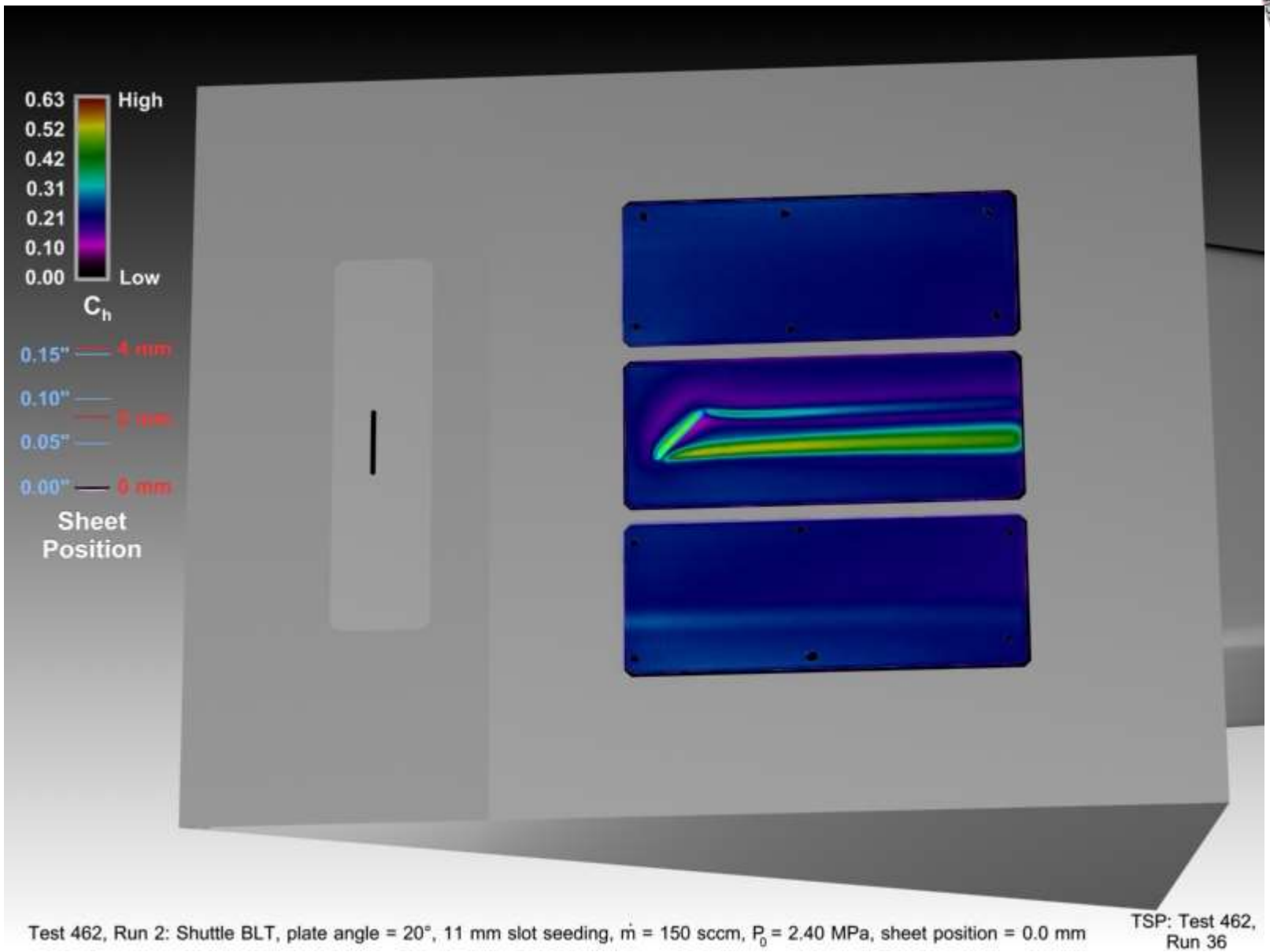
SpaceX Dragon 2 Parachute Drop Tests

Wallops Flight Facilty

Max Launch Abort System (MLAS)

KinetX

TSP Heating: Low Re



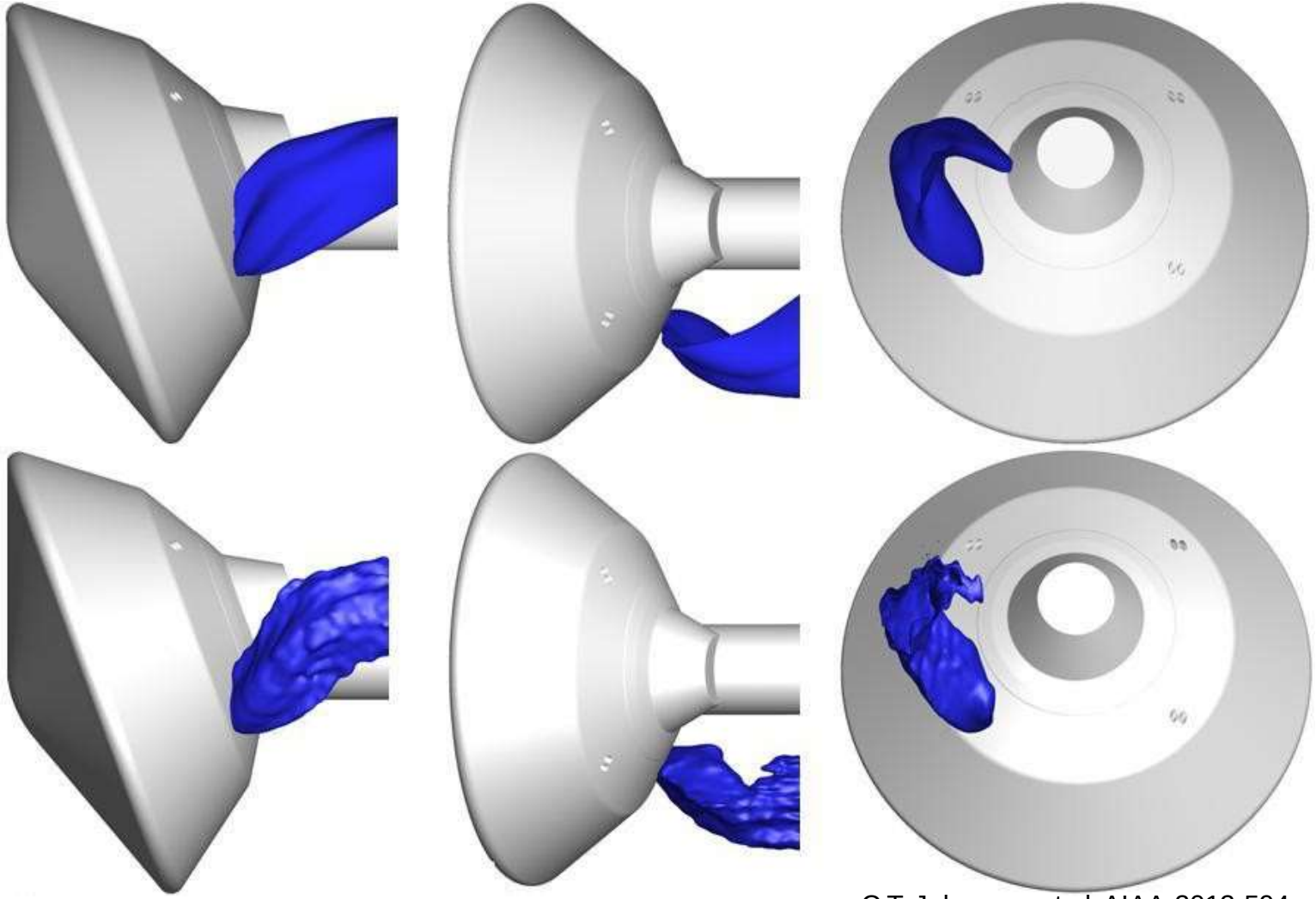
Danehy AIAA 2010-1571 https://doi.org/10.2514/6.2010-1571

MSL NO PLIF vs CFD (CFI), Mach 10

- Mars Science Lab (MSL) vehicle delivered Curiosity:
  - Do we understand RCS jet wake flow and interactions? Predict?

OVERFLOW (CFI Model)

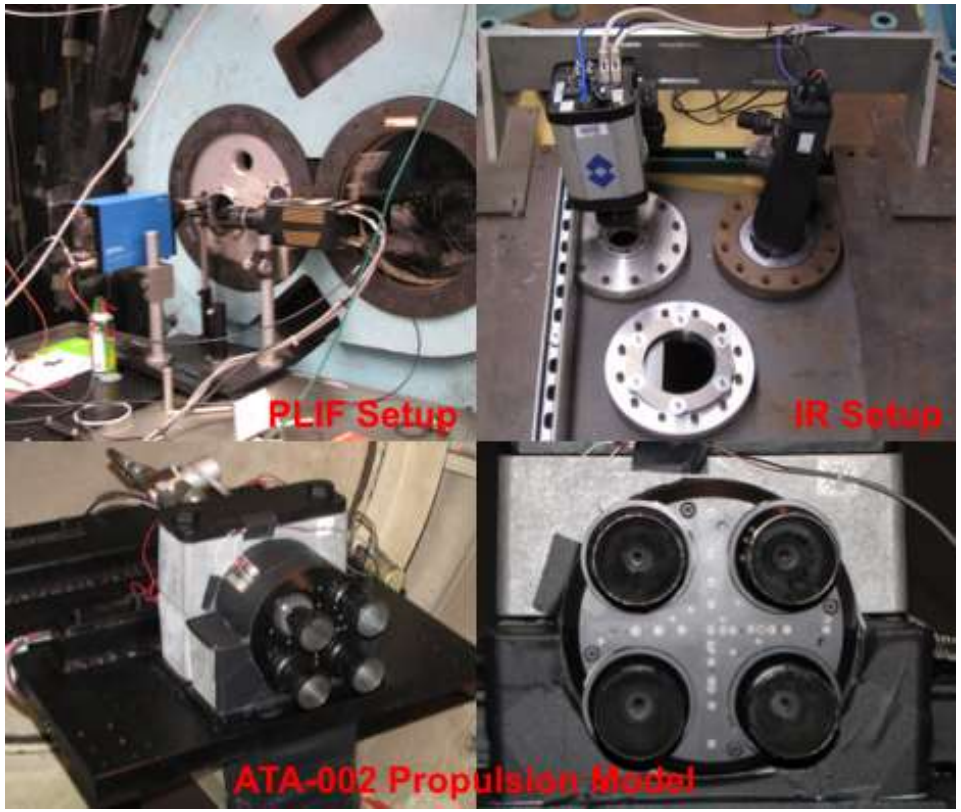
NO PLIF (with smoothing)



C.T. Johansen et al. AIAA-2012-594

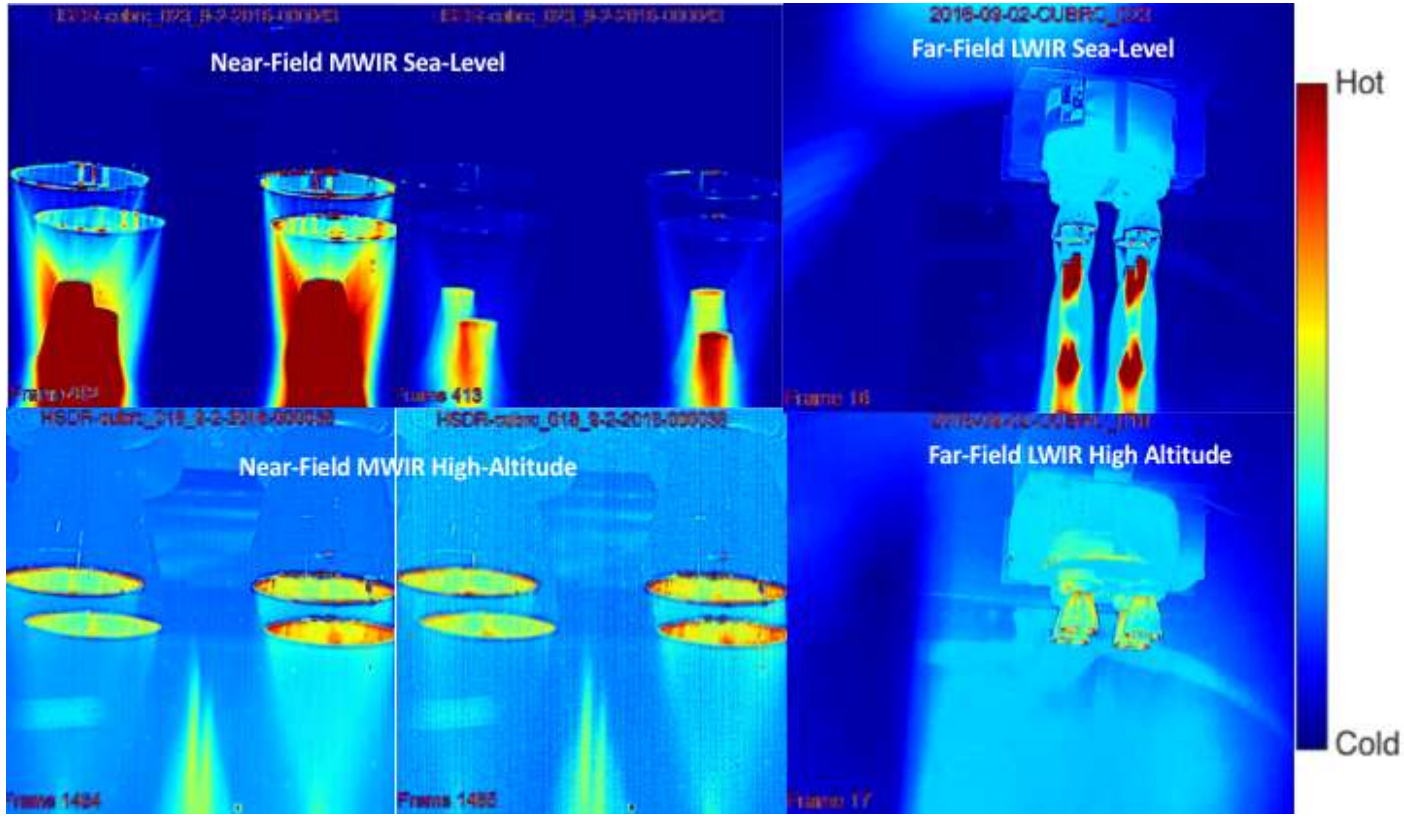
Optical Diagnostics for Plume-Induced Environments

Project Manager(s):
Dr. Manish Mehta/Aerosciences Branch (EV33)



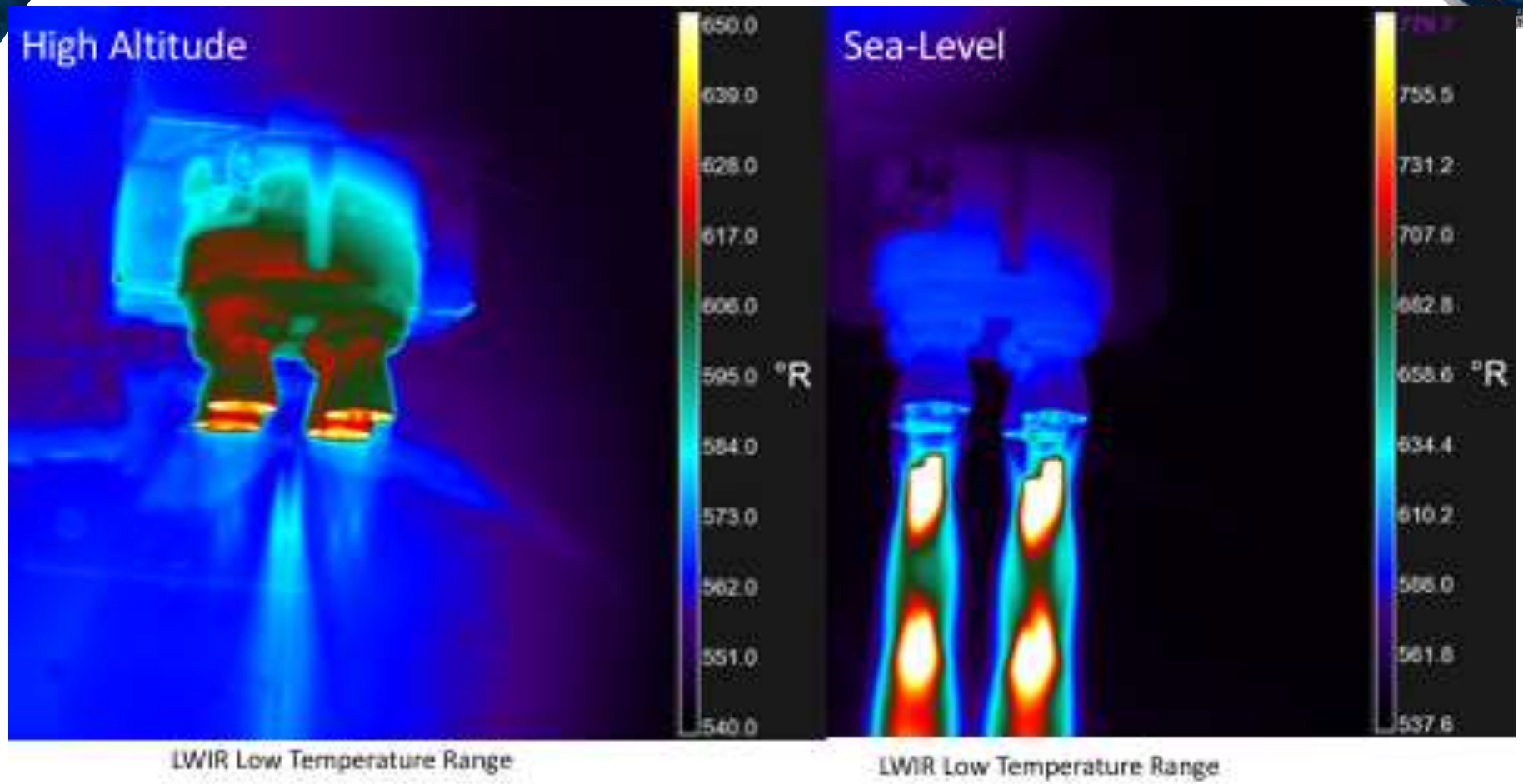
Determine the feasibility of various novel non-intrusive optical diagnostics to capture complex launch vehicle rocket plume-induced base flow physics in a ground test facility. Such diagnostic imaging will provide confirmation on shock tunnel test technique and computational modeling validation. Hydroxyl radical – planar laser induced fluorescence (OH-PLIF) and carbon-dioxide seeded infrared (IR) imaging and tunable diode laser absorption spectroscopy (TDLAS) were the optical diagnostics proposed to visualize base flows of the 2% Space Launch System (SLS) hot-fire propulsion model at various altitudes. NASA has proposed to use a 9 million pound thrust SLS vehicle with multiple rocket engines and solid rocket motors for humans to explore deep space. As a result, base heating rates and drag will be considerably higher than current launch vehicles and the flow physics needs to be understood for efficient design of the thermal protection system (TPS). These diagnostics were developed and tested in collaboration with NASA Marshall Space Flight Center, NASA Langley Research Center and CUBRC Inc.

Optical Diagnostics for Plume-Induced Environments



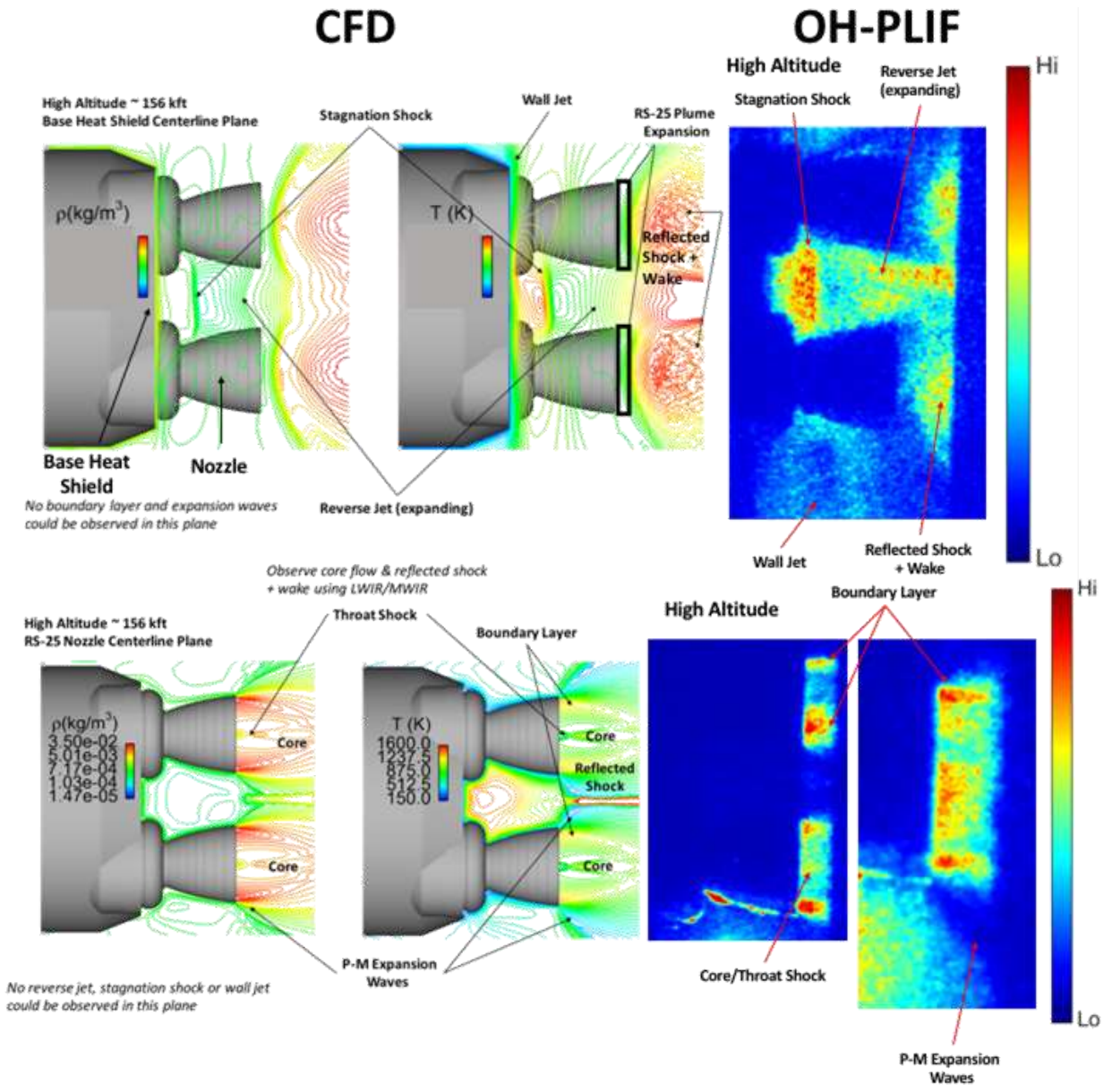
IR imaging captured rocket plume flow structures. Near-field MWIR low temperature range and high temperature range post-processed images at sea-level (top-left); far-field LWIR low temperature range post-processed image at sea-level; near-field MWIR low temperature and medium temperature range images at high altitude (bottom-left); far-field LWIR low temperature range at high altitude

Optical Diagnostics for Plume-Induced Environments

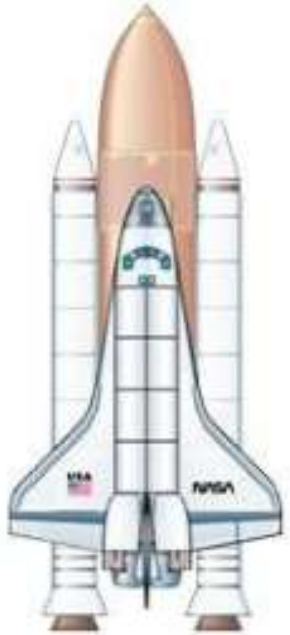


LWIR imaging captured launch vehicle test model base and nozzle surface wall temperatures at high altitude (left) and sea-level (right) conditions

Optical Diagnostics for Plume-Induced Environments



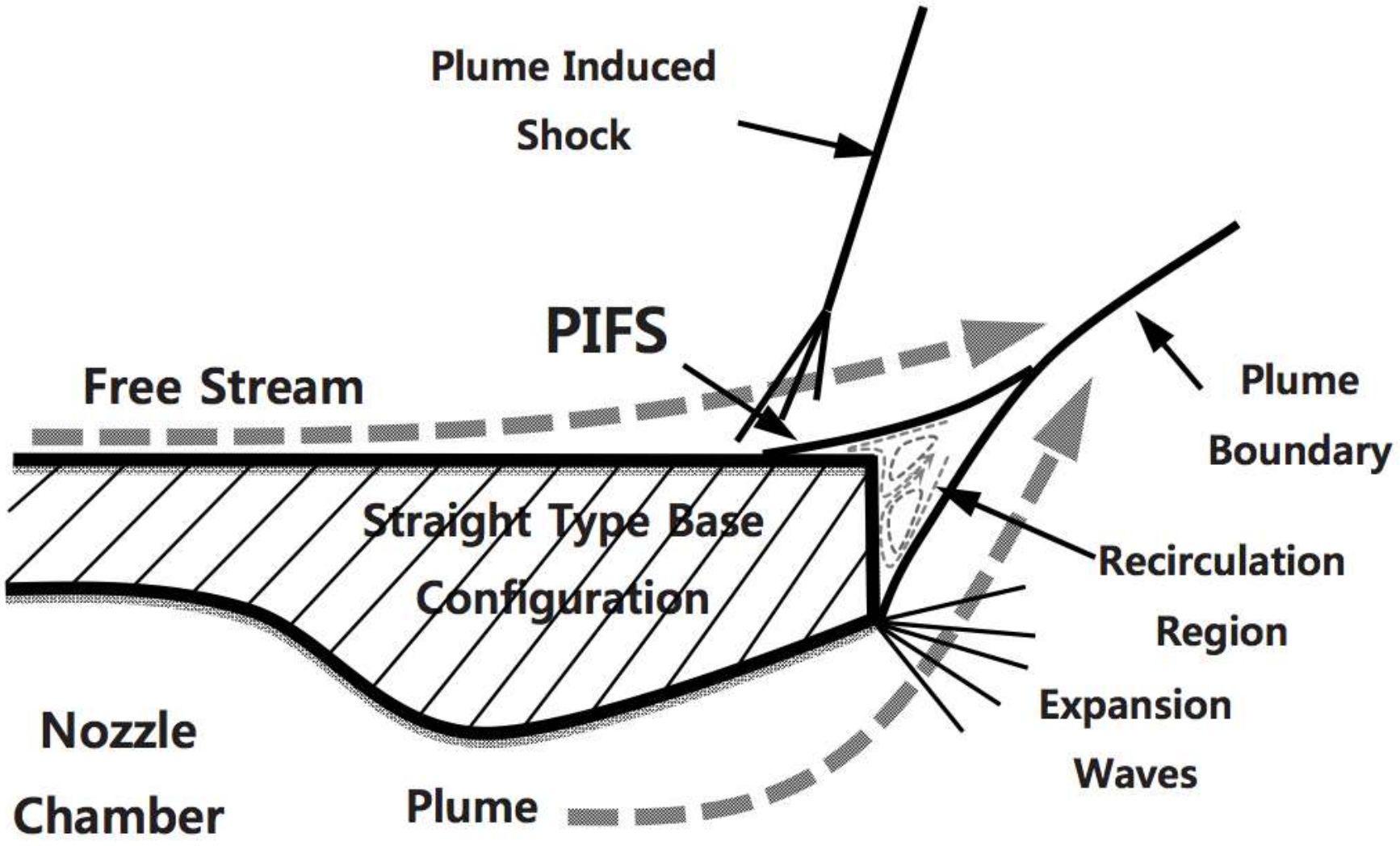
Solid Rocket Booster Separation







- Space Shuttle design – SRBs extended below main engines
- SLS design – SRBs are even with core stage
- CFD shows potential for re-contact after SRB separation
- SCIFLI tasked with imaging SRB separation


Plume Induced
Shock
PIFS
Free Stream
Plume
Boundary
Straight Type Base
Configuration
Recirculation
Region
Expansion
Waves
Nozzle
Chamber
Plume

Electro-Optical Imagers

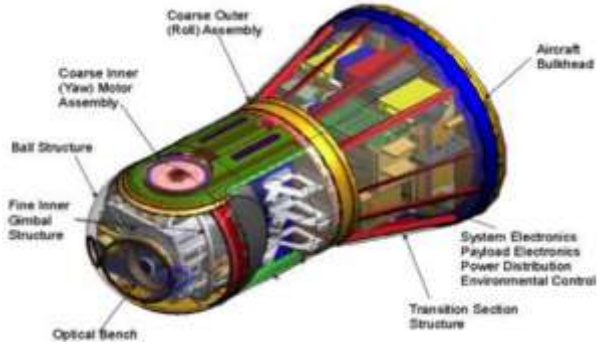
MARS (Mobile Aerospace Reconnaissance System)

- Ground-based or gyrostabilized Kineto Tracking Mount (KTM) for ground or ship-based telescopic surveillance of aerospace vehicles
- Visible, Infrared, Spectrographic, Hyperspectral



DyNAMITE (Day Night Airborne Motion Imagery for Terrestrial Environments)

- Full motion gimbal mounted sensor package in nosecone of WB-57 at JSC/Ellington
- MWIR and Visible



TRaTS (Telescience Research and Technology Support)

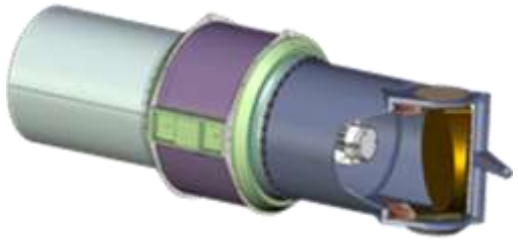
- Ground-based or sea-based gyrostabilized system (GSS) tracker

SAMI (SCIFLI Airborne Multispectral Imager)

- Sensor package to be installed on NASA Langley aircraft (e.g. G-III)

Cast Glance

- Gyro-stabilized gimbaled mirror and 7-inch telescope plus computer aided pointing system, mounted in P-3 Orion aircraft at Pt. Magu, CA
- Visible, NIR, SWIR, MWIR



HAARTS (High-fidelity Automated Airborne Reconfigurable Tracking System)