



Development of the BOLT II Roughness Experiment for Flight

Scott A. Berry

NASA Langley Research Center

Michael T. Semper

U.S. Air Force Academy

Andrew K. Riha, C. Daniel Mullen, and Helen L. Reed

Texas A&M University

Aaron T. Dufrene

CUBRC Inc.

Hermann F. Fasel

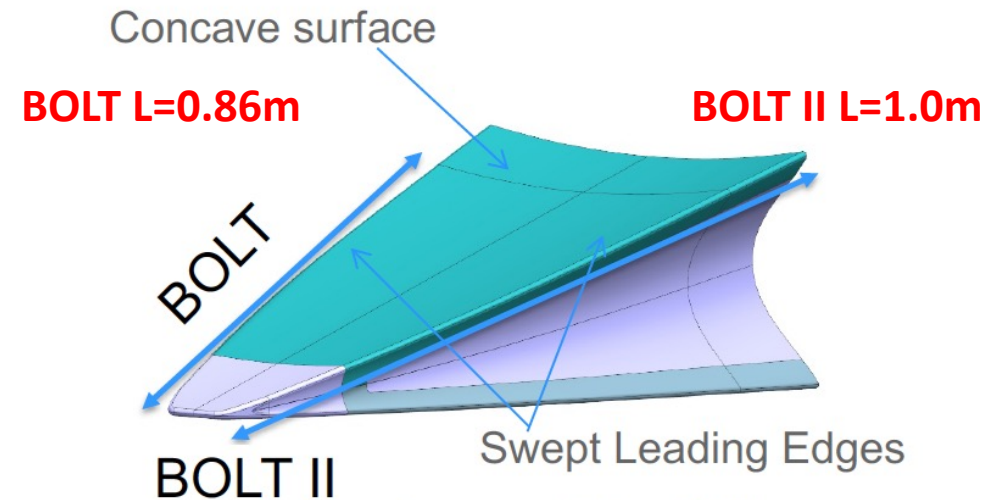
University of Arizona

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Brief Introduction

- The Air Force Office of Scientific Research (AFOSR) primary sponsor of the BOLT (for Boundary Layer Transition) project as continuation of previous HIFiRE flights (1 & 5 previously dedicated to Hyp BoLT)
 - Using sounding rockets as cost effective flight research tool
 - Study hypersonic BoLT on increasingly complex geometries
 - BOLT shape includes concave surfaces and swept leading edges
- Two missions, two flights:
 - BOLT
 - Johns Hopkins University Applied Physics Laboratory as lead
 - Focus on transition onset measurements
 - Flew June 2021 from Esrange Sweden (data under review)
 - BOLT II
 - Texas A&M and CUBRC provide primary leadership
 - Focus on turbulence measurements
 - Scheduled to fly from NASA Wallops in April 2022
 - Flight named in memory of Mike Holden
- NASA's support to both BOLT missions provided through the Hypersonic Technologies Project (HTP)

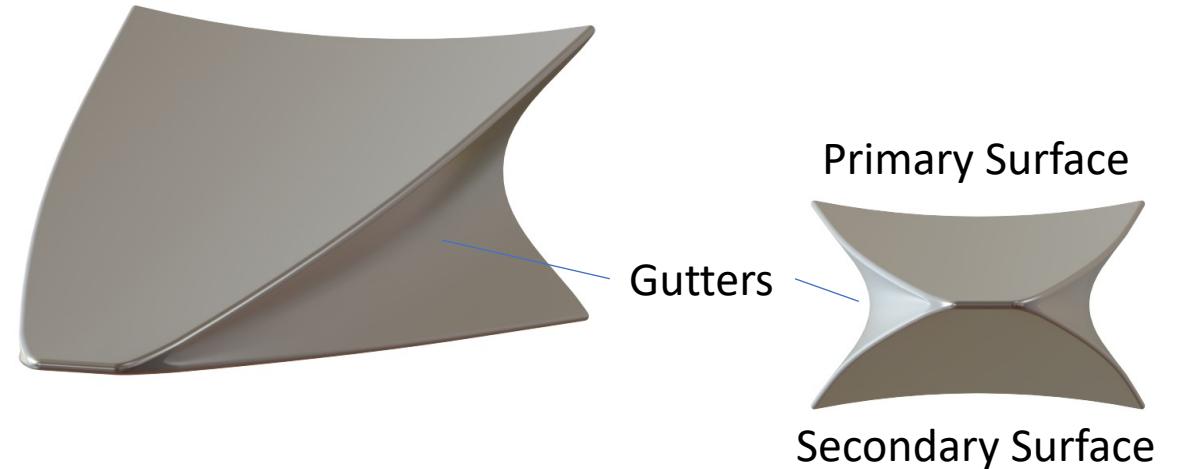


Bowersox, Dufrene 2020

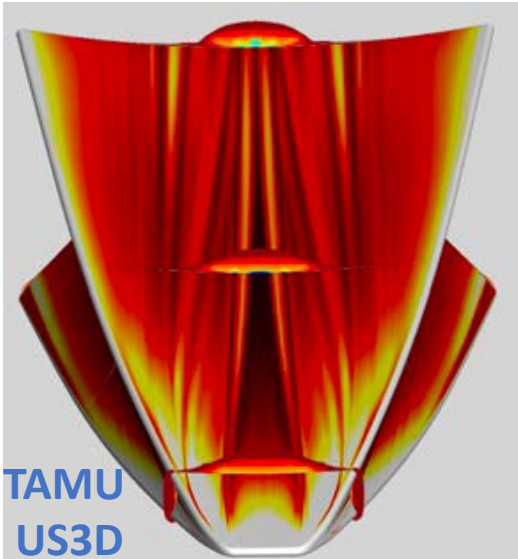


BOLT II Roughness Experiment

- BOLT geometry provides two independent surfaces
 - Primary side for smooth wall transition & turbulence
 - Secondary side for investigation of roughness effects
- BOLT roughness side designed to study step effects
- BOLT II roughness side designed to investigate discrete tripping



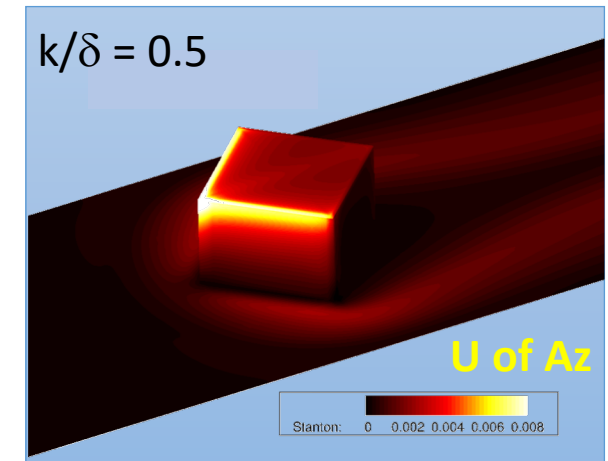
BOLT Basic State



- BOLT geometry provides varying boundary layer profile
 - ✓ Thick, “stable” center region
 - ✓ Thin outer sections with various instability modes

The basic research objective of Side B roughness experiment is to improve knowledge regarding forced boundary layer transition and turbulence on a complex hypersonic vehicle

The goal, however, is to provide flight data of discrete roughness effects, to compare against possible correlations



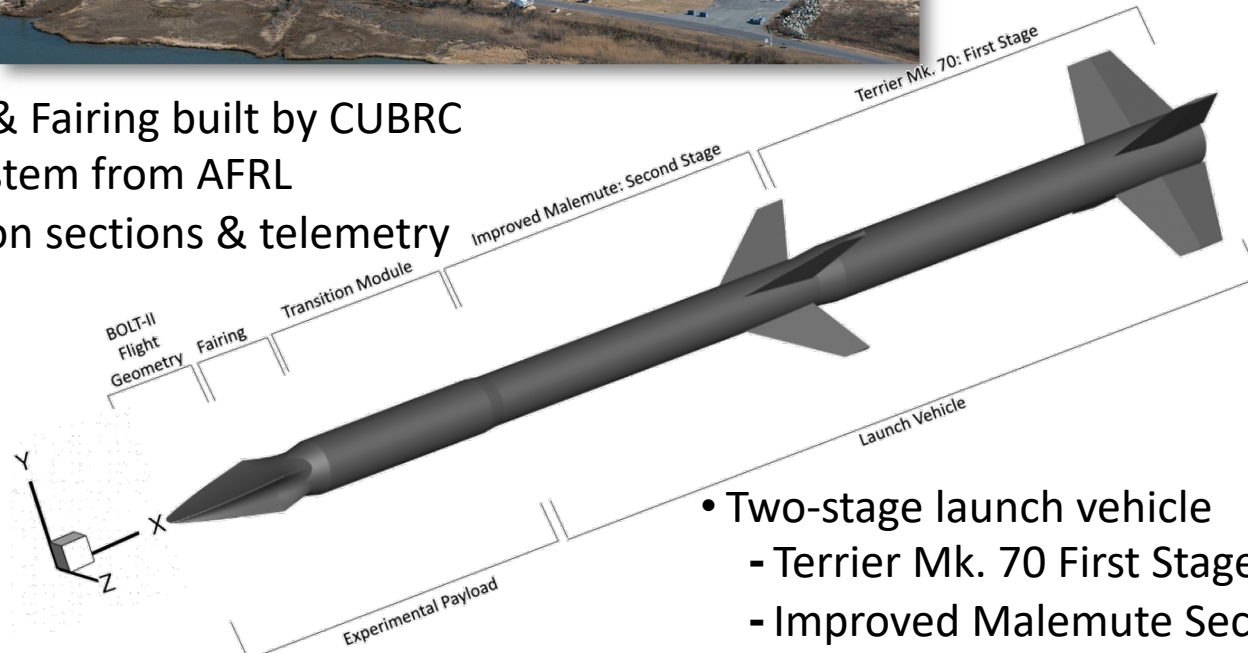
Preliminary computations of heating from “pizza box” trip

BOLT II Flight Analysis

Flight from Wallops Flight Facility on Eastern Shore of Virginia



- BOLT II & Fairing built by CUBRC
- DAQ System from AFRL
- Transition sections & telemetry by WFF

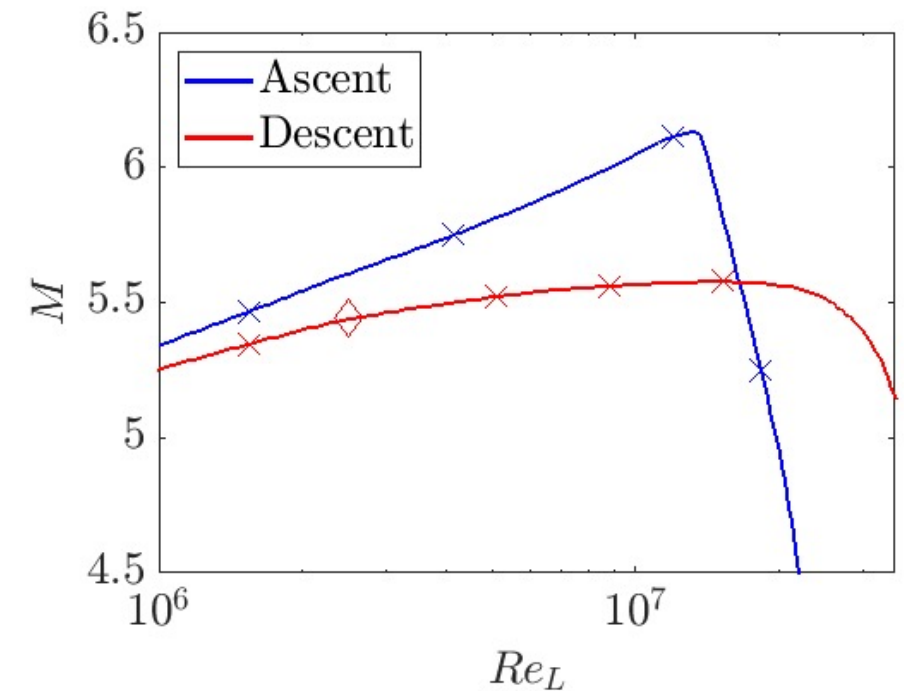


- Two-stage launch vehicle
 - Terrier Mk. 70 First Stage
 - Improved Malemute Second Stage

Spin stabilized with requirement for 5 Hz roll rate or less

Angle of attack & yaw desired to be less than $\pm 2^\circ$, although $\pm 5^\circ$ is acceptable

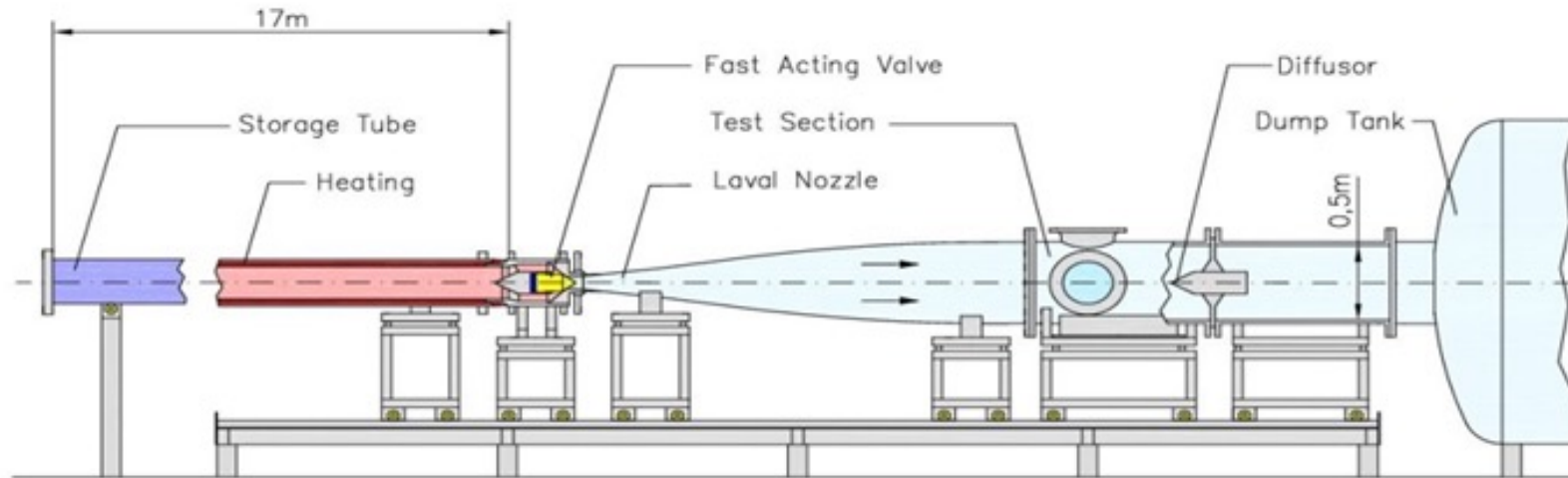
Experimental test windows shown below
X Trajectory points used for present analysis
◇ Trajectory point used to size trips



Tripping Study at USAFA M6LT

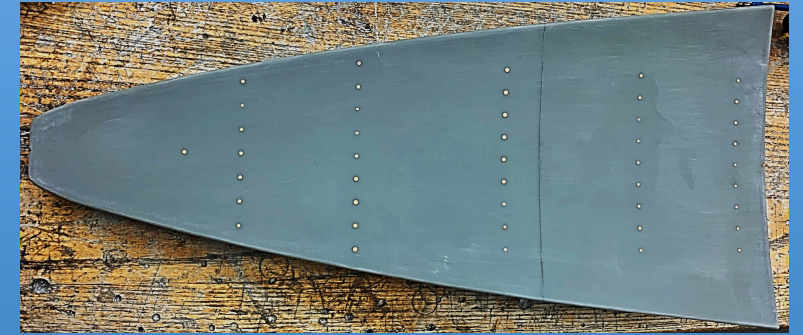
USAFA Mach 6 Ludwieg Tube

- 500mm (19.5") diameter test section
- Conventional tunnel (2-3% freestream pressure fluctuations)
- Unit Reynolds numbers from 2.5 to 30 million/m (0.8 - 9.1 million/ft)
- Test duration: 100 – 150 milliseconds
- Turnaround time: 5 – 10 minutes

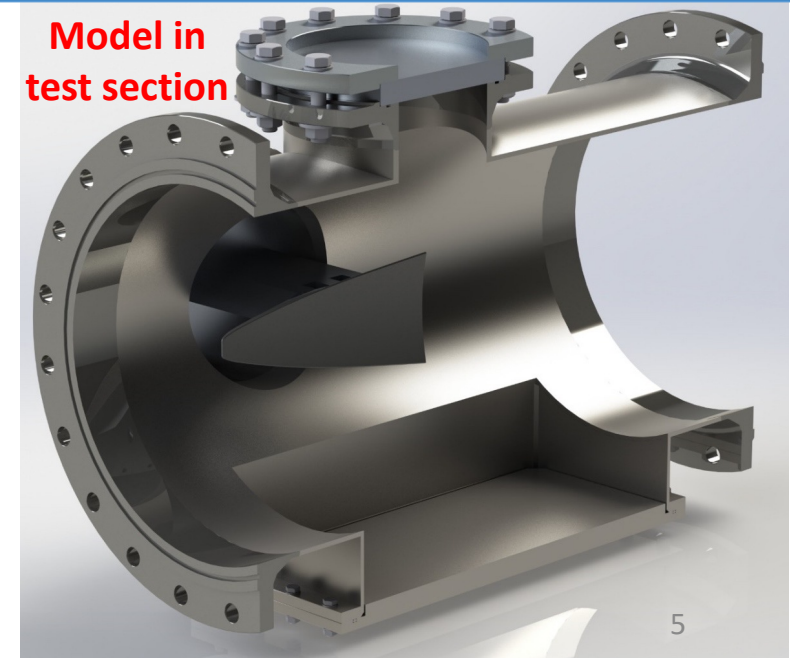


Model Details

- SLA printed (Accura Xtreme resin) and UV cured
- 33%-scale flight vehicle, one side only
 - 330 x 156 x 50 mm (LxWxH)

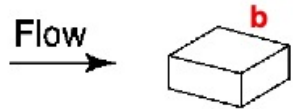


Model in test section

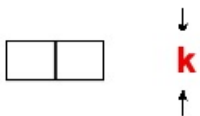


Initial Trip Sizing & Results

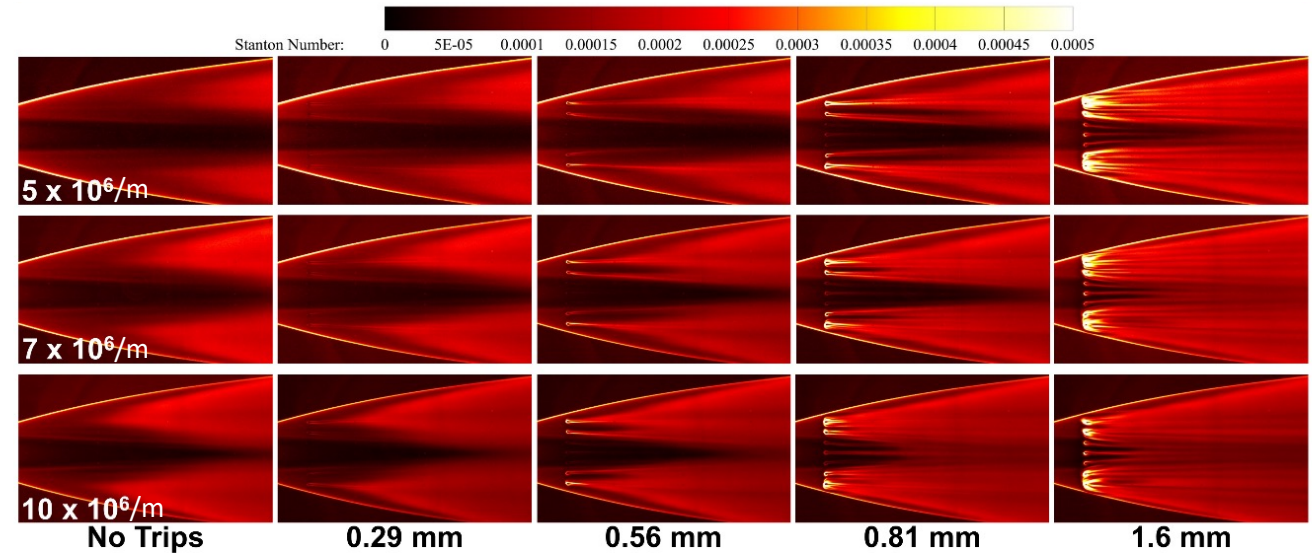
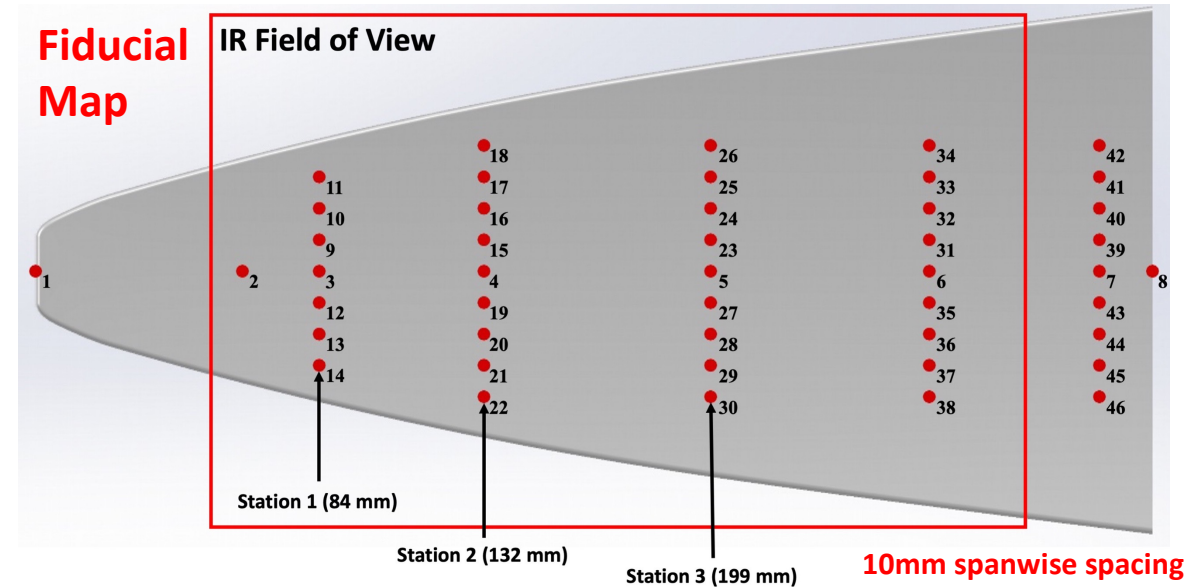
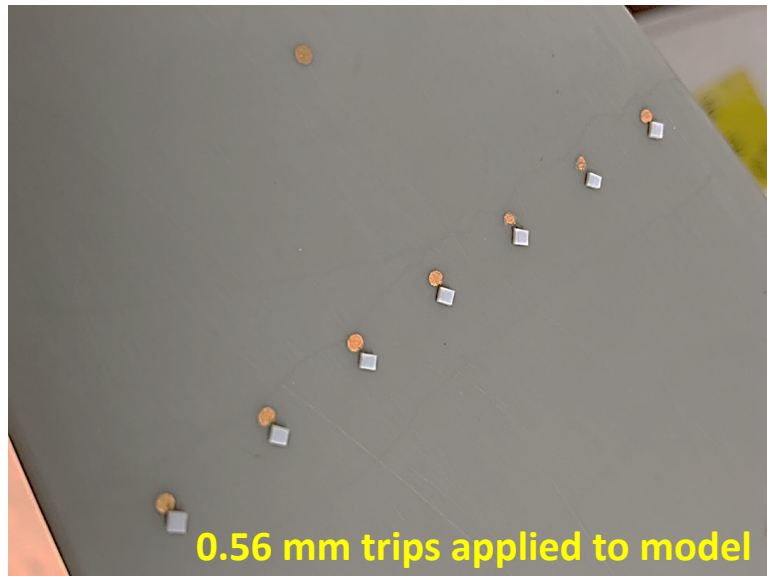
- Pizza box trip geometry (diamonds)
- Two types of trips used
 - Self-adhesive Teflon PTFE tape applied directly to model
 - SLA printed trips glued to model
- Various aspect ratios tested, $b =$
 - 0.5 mm, 1.0 mm, 1.3 mm, and 2.5 mm square
- Teflon PTFE tape heights, $k =$
 - 0.29 mm, 0.56 mm, 0.81 mm, and 1.6 mm
- SLA printed trip heights
 - 2.5 mm and 3.7 mm



Oblique View



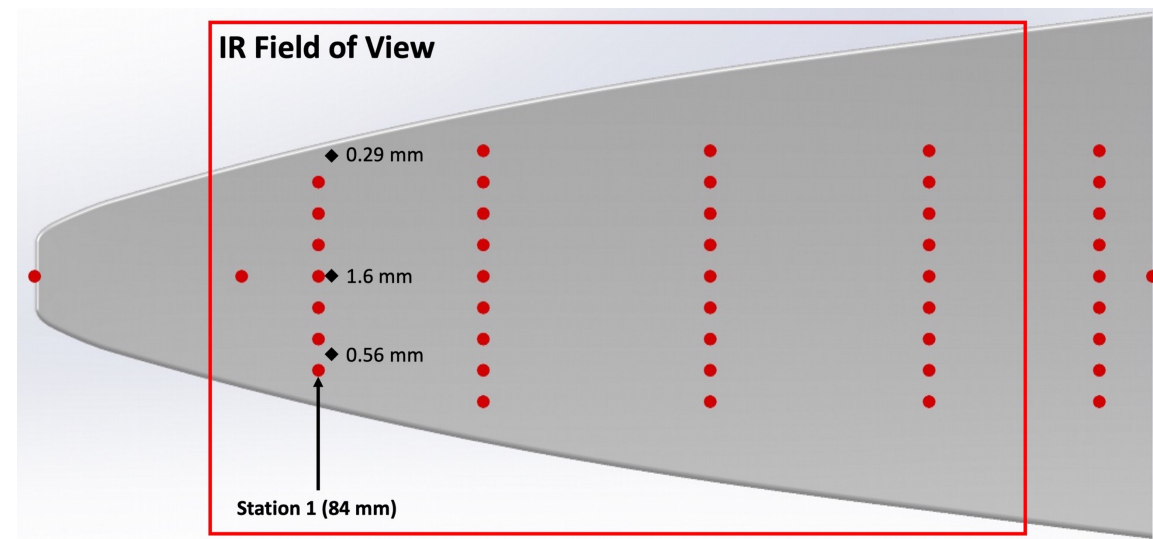
Side View



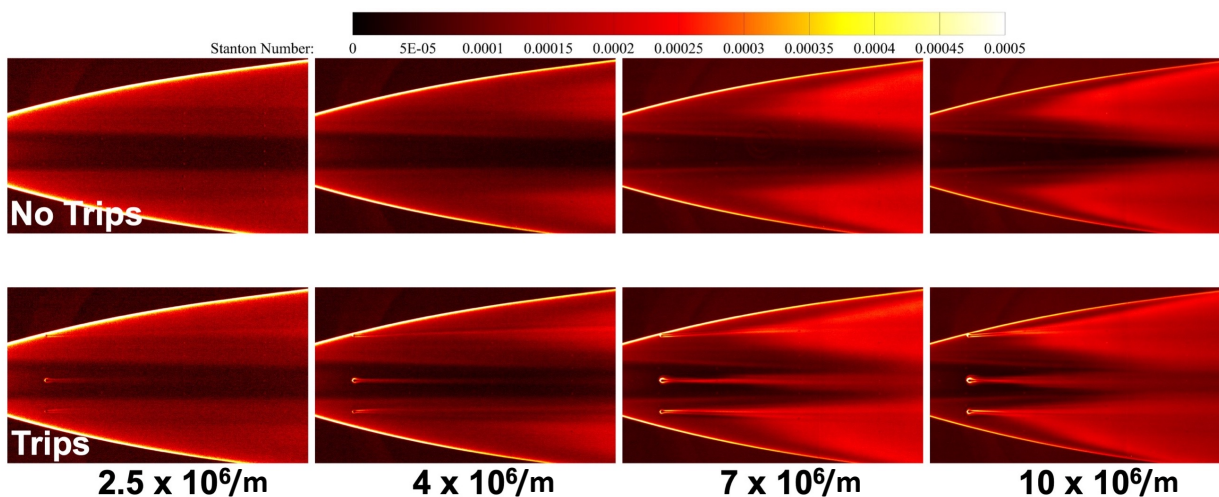


Initial Flight Tripping Concept & Results

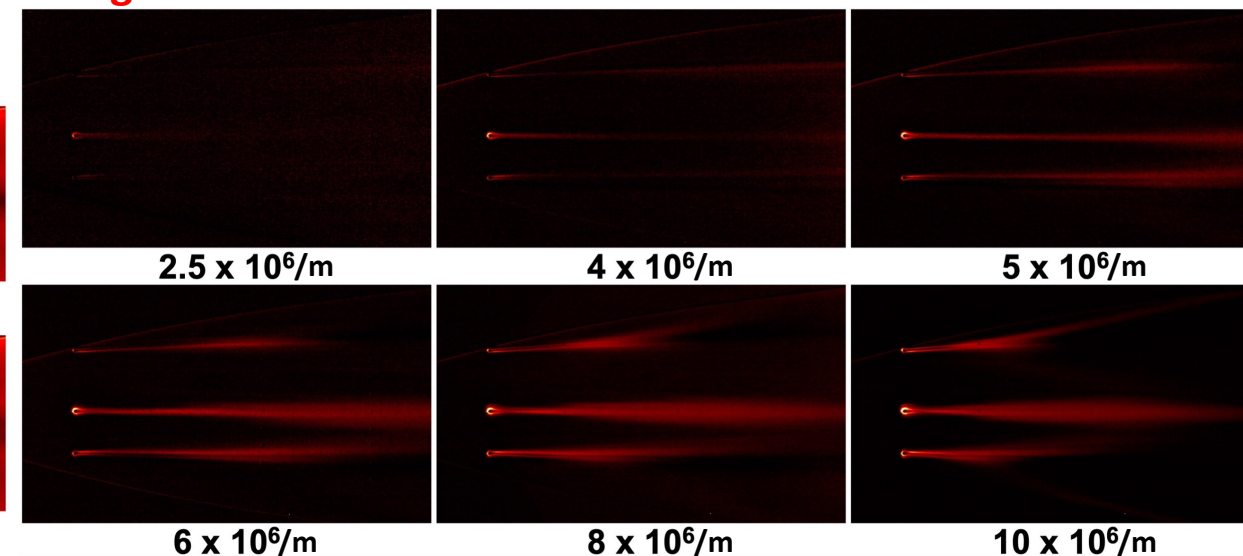
- Based on previous results, selected 3 spanwise Station 1 locations and heights to simultaneously transition
- Selected locations and heights shown to right
- Re range, with and without trips, shown below
 - Noted difficulty with determining onset across the span due to natural lobes that appear with increasing Re
- Implemented “background subtraction” process for easier identification on transition onset, shown lower right



Baseline Heating



Background Subtracted





Computations of WT & Flight Cases

Simulation Details

- All solutions were smooth surface and laminar
- Boundary layer based on 99.5% total enthalpy
- Two solvers used to expedite cases
 - DPLR solutions
 - ~ 60 million cell grid
 - 3rd-order MUSCL Steger-Warming convective fluxes
 - 2nd-order central viscous fluxes
 - US3D solutions
 - ~60 million cell grid
 - 2nd-order Modified Steger-Warming convective fluxes
 - Central deferred-correction viscous fluxes
- Verification analysis completed to ensure grid converged and consistent results

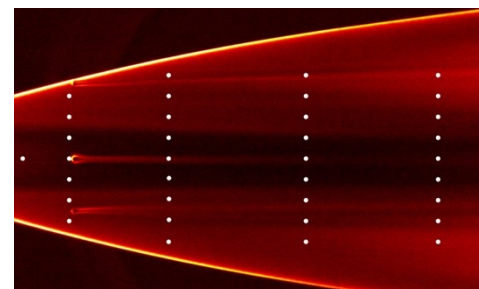
Wind Tunnel Cases

Case	Mach	Unit Reynolds [1/m x 10 ⁶]	CFD Solver
Wind Tunnel 1	5.9	2.5	DPLR
Wind Tunnel 2	5.9	4.0	DPLR
Wind Tunnel 3	5.9	10.0	DPLR

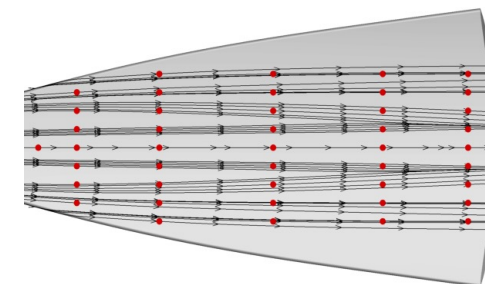
Flight Cases

Case	Mach	Unit Reynolds [1/m x 10 ⁶]	CFD Solver
Ascent 1 (A1)	5.3	18.21	US3D
Ascent 2 (A2)	6.1	11.93	US3D
Ascent 3 (A3)	5.8	4.13	US3D
Ascent 4 (A4)	5.5	1.55	DPLR
Descent 1 (D1)	5.3	1.54	DPLR
Descent 2 (D2)	5.5	5.09	DPLR
Descent 3 (D3)	5.6	8.82	DPLR
Descent 4 (D4)	5.6	15.26	US3D

Comparison of wind tunnel streaks behind trips to inviscid streamlines calculated at same condition



IR image superimposed with fiducial marks

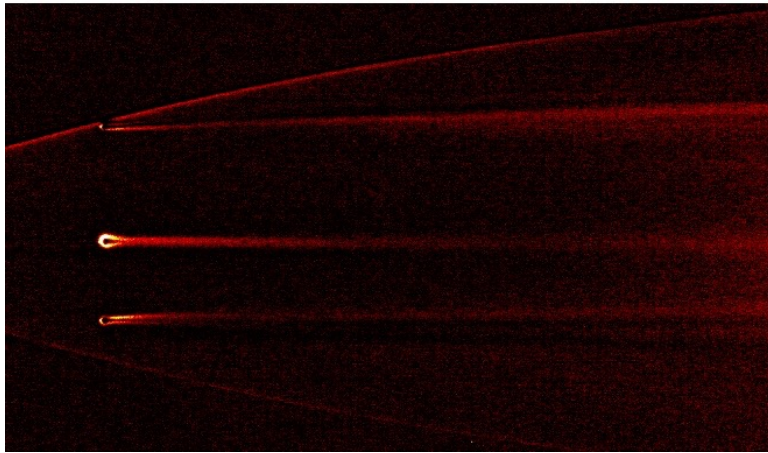


Boundary-layer edge streamlines

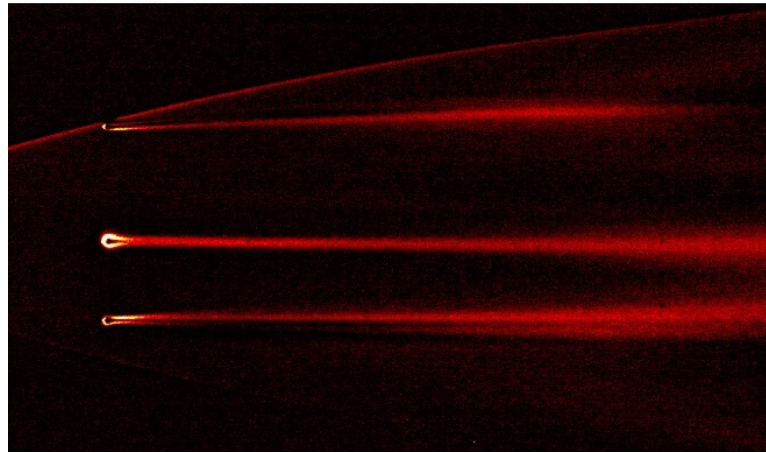
Examination of Trip Correlations



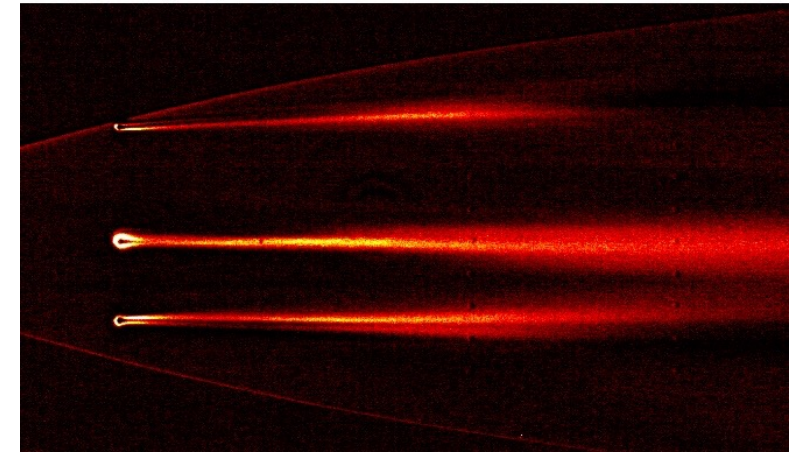
Background subtraction used to better visualize wedge behavior



$4 \times 10^6/\text{m}$



$5 \times 10^6/\text{m}$



$6 \times 10^6/\text{m}$

Incipient trips between 4 & 5 million/m? BL properties below scaled from WT cases at $Re = 5$ million/m

0.062" Trip on CL

$\delta = 0.084'' \rightarrow k/\delta = 0.74$

$\delta^* = 0.046'' \rightarrow k/\delta^* = 1.35$

$\theta = 0.009'' \rightarrow k/\theta = 6.89$

$Re_\theta = 179$

$Me = 2.55$

Upper 0.0115" Trip @ LE

$\delta = 0.014'' \rightarrow k/\delta = 0.82$

$\delta^* = 0.009'' \rightarrow k/\delta^* = 1.23$

$\theta = 0.0012'' \rightarrow k/\theta = 9.58$

$Re_\theta = 62.4$

$Me = 3.32$

Lower 0.022" Trip @ 13.5

$\delta = 0.033'' \rightarrow k/\delta = 0.67$

$\delta^* = 0.020'' \rightarrow k/\delta^* = 1.1$

$\theta = 0.0030'' \rightarrow k/\theta = 7.33$

$Re_\theta = 118.3$

$Me = 3.15$

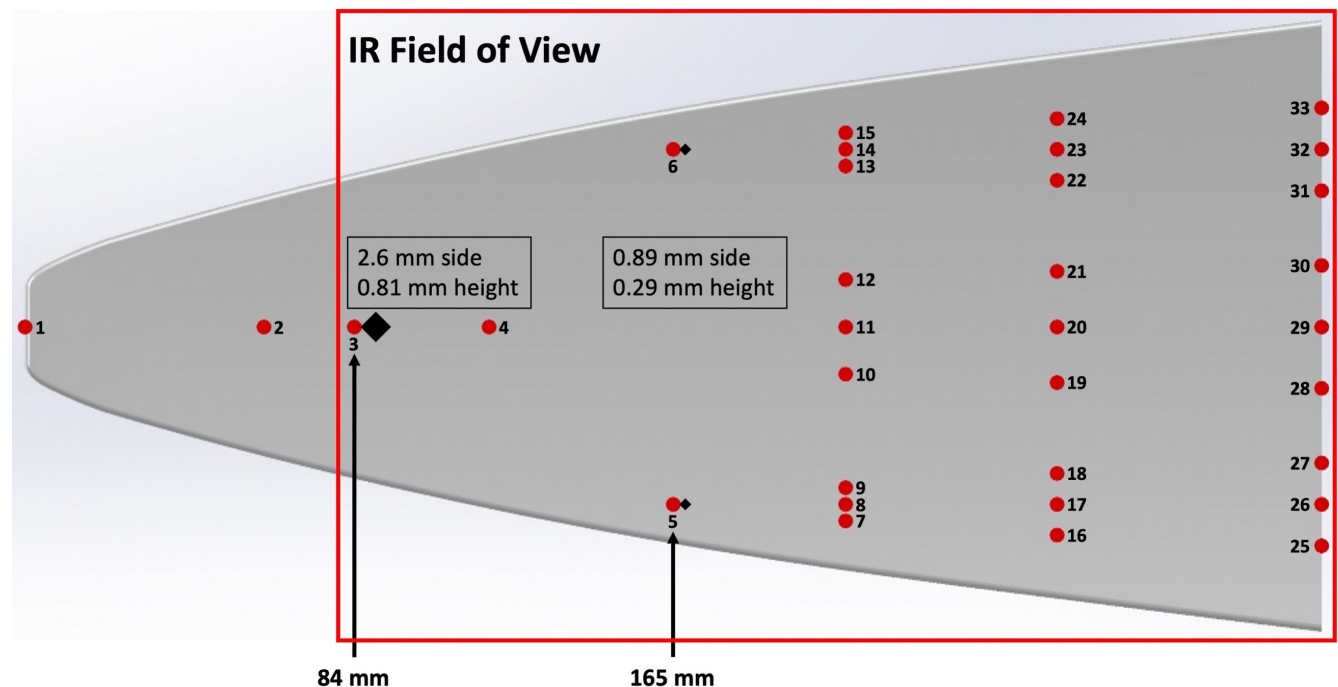
Thus, k/δ of 0.7 selected as simple approach to scale incipient trips to flight

FYI, Hyper-X also used k/δ of 0.7 to successfully size trips for Mach 7 flight (JSR 47.6 2010)

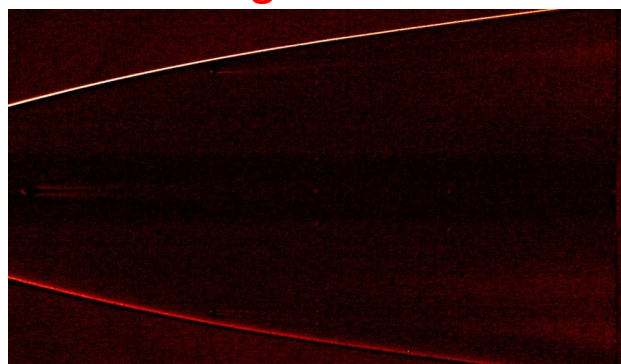


Final Flight Tripping Concept & Results

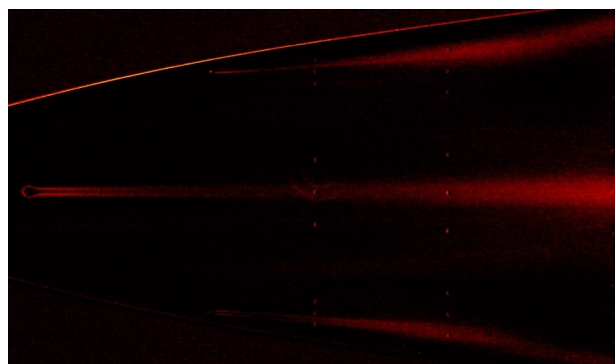
- During a follow up entry in USAFA M6LT, final flight trips were investigated
- Final locations and heights shown to right
 - Flight sensor budget for roughness side allowed for three independent trips
 - Trips near leading edge pushed back and out to further separate the sensors groupings
- Sample “background subtraction” results shown below



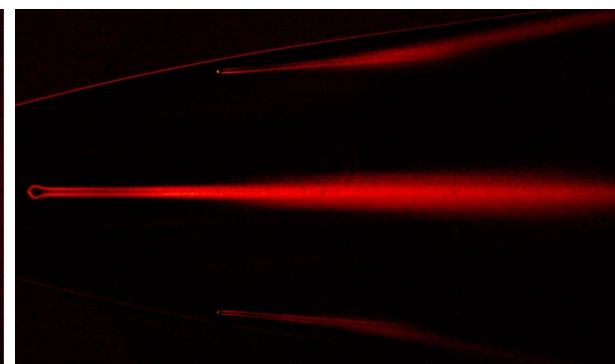
Select Background Subtracted Results



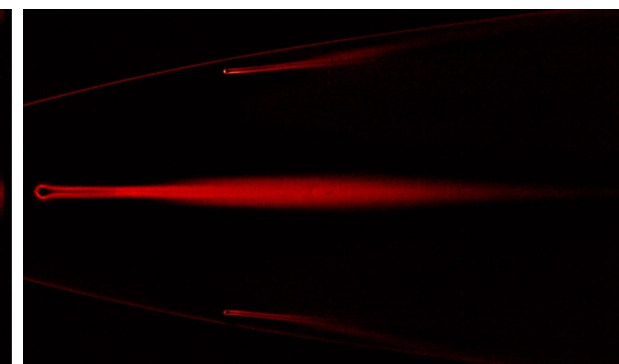
$2.5 \times 10^6/\text{m}$



$5 \times 10^6/\text{m}$



$7 \times 10^6/\text{m}$



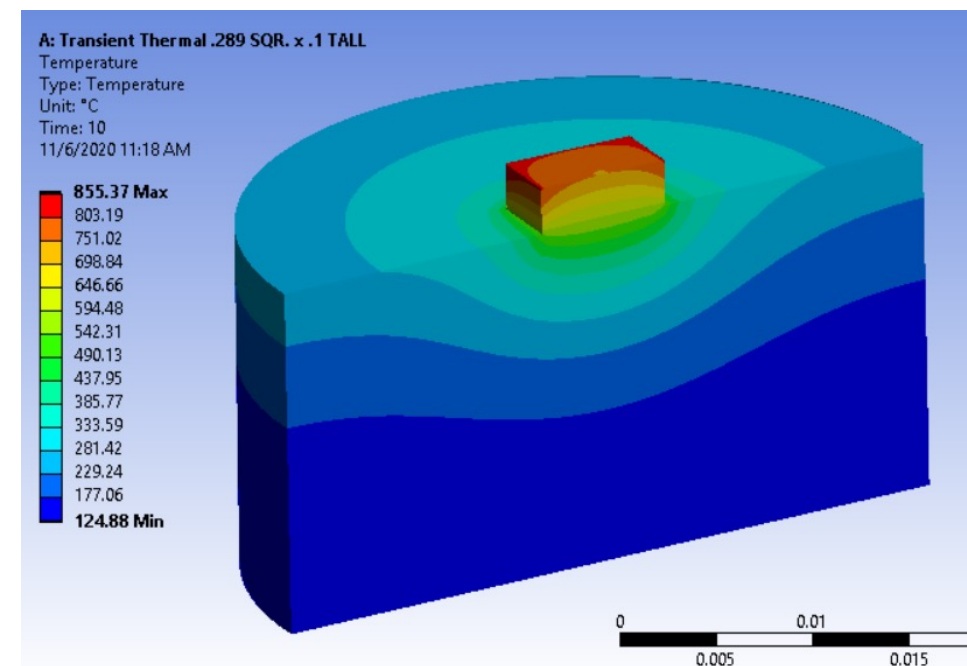
$10 \times 10^6/\text{m}$



Structural-Thermal Analysis of Final Trips

- Finite element analysis of an integral trip design conducted to ensure trip integrity throughout flight
- Smooth-wall fully turbulent convective heating solutions for a BOLT flight used as baseline
- 20% augmentation added to account for different trajectory
- Based on independent computations of heating around pizza box trips for various aspect ratio trips (see table to right), a conservative 10x augmentation was applied to all 5 faces of the pizza box based on b/k of 3
- Integral trips conduct heat locally into the body during flight, but effect is localized (see image to right)
- Worst case predicted temperature at trip corners less than 1600°F, which is much less than melting point of SS410 (2800°F)
 - Oxidation effects start at about 1300°F
 - Scaling/spalling effects start above 1800°F

b/k	k/d	Stanton Number Ratio to smooth wall value
3	0.75	8.9
2	0.75	10.3
1.41	0.75	11.8
0.75	0.75	13.7



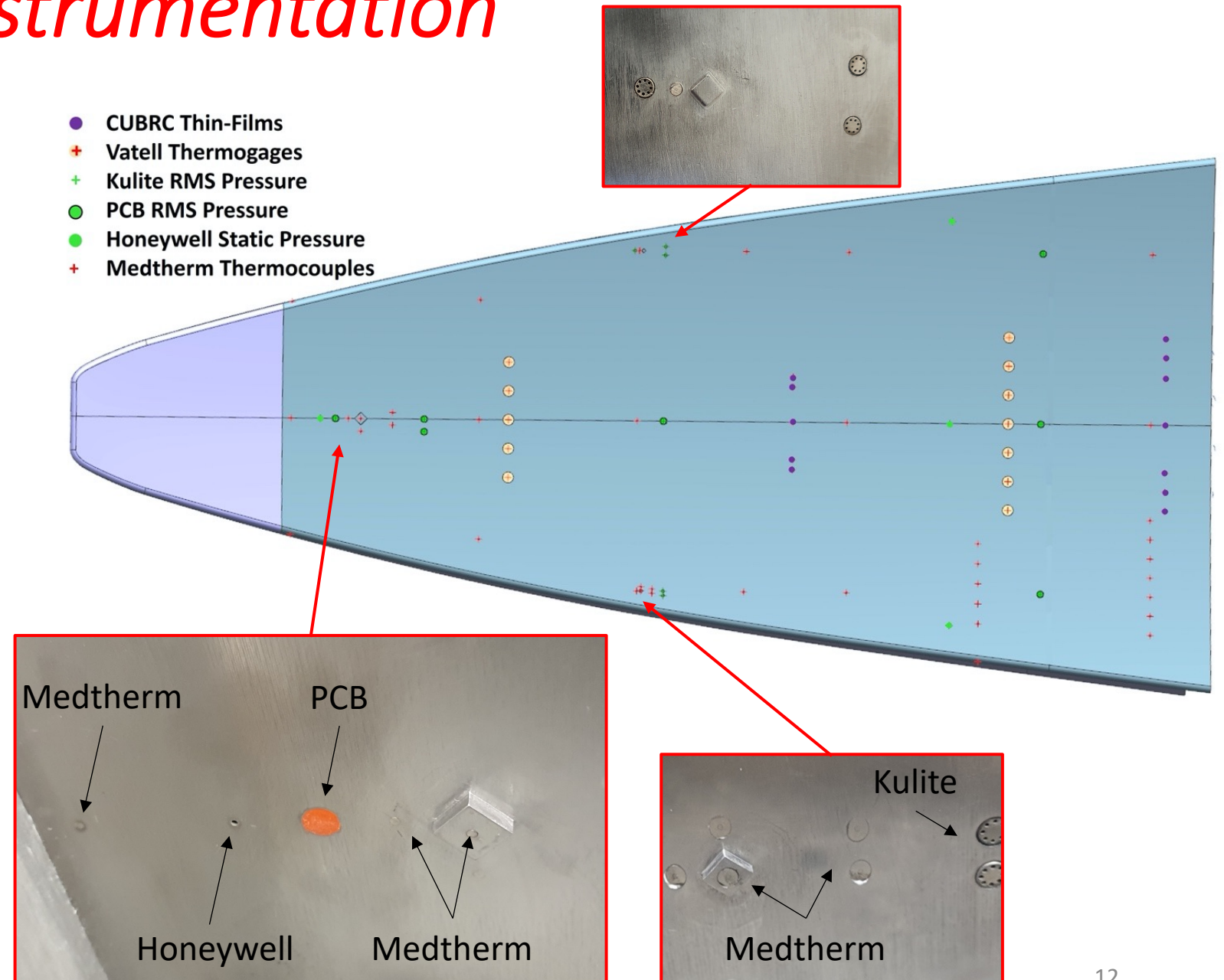
Final Trips & Instrumentation

Roughness side sensor budget
38 thermocouples (Medtherms)
16 pressure sensors
 4 Honeywell for FADS
 7 PCB high-frequency
 5 Kulite high-frequency
12 Vatel heat-flux gages
12 CUBRC thin-film gages

Three independent sensor groupings

- Axial arrays to pick up transition onset and progression
- Spanwise arrays to identify wedge development and movement
- Local sensors to assist post flight computations of flow around trips

CL Trip $k = 2.252$ mm & $b = 7.875$ mm
LE Trips $k = 0.903$ mm & $b = 2.709$ mm





Summary

- Review provided of decisions made in development of the BOLT II roughness experiment for flight
- Combined experimental and computational effort taken to develop the roughness experimental plans for flight of BOLT II
- Wind tunnel testing completed at US Air Force Academy Mach 6 Ludwig Tube
- Computational solutions provided at wind tunnel and flight conditions to allow examination of correlations and eventual scaling to flight
- A true correlation was not found, but a simple scaling based on $k/\delta = 0.7$ was used based on the present results and past guidance from the Hyper-X program
- Three trip locations were selected based primarily on the number of available instrumentations to dedicate to the roughness experiment, arranged to provide axial movement of transition as well as lateral spreading of turbulence
- Finite element analysis completed to ensure trip integrity throughout flight