An Overview of the Space Shuttle Aerothermodynamic Design

Presented
During the
NESC CCDEV TIM
November 2011

By

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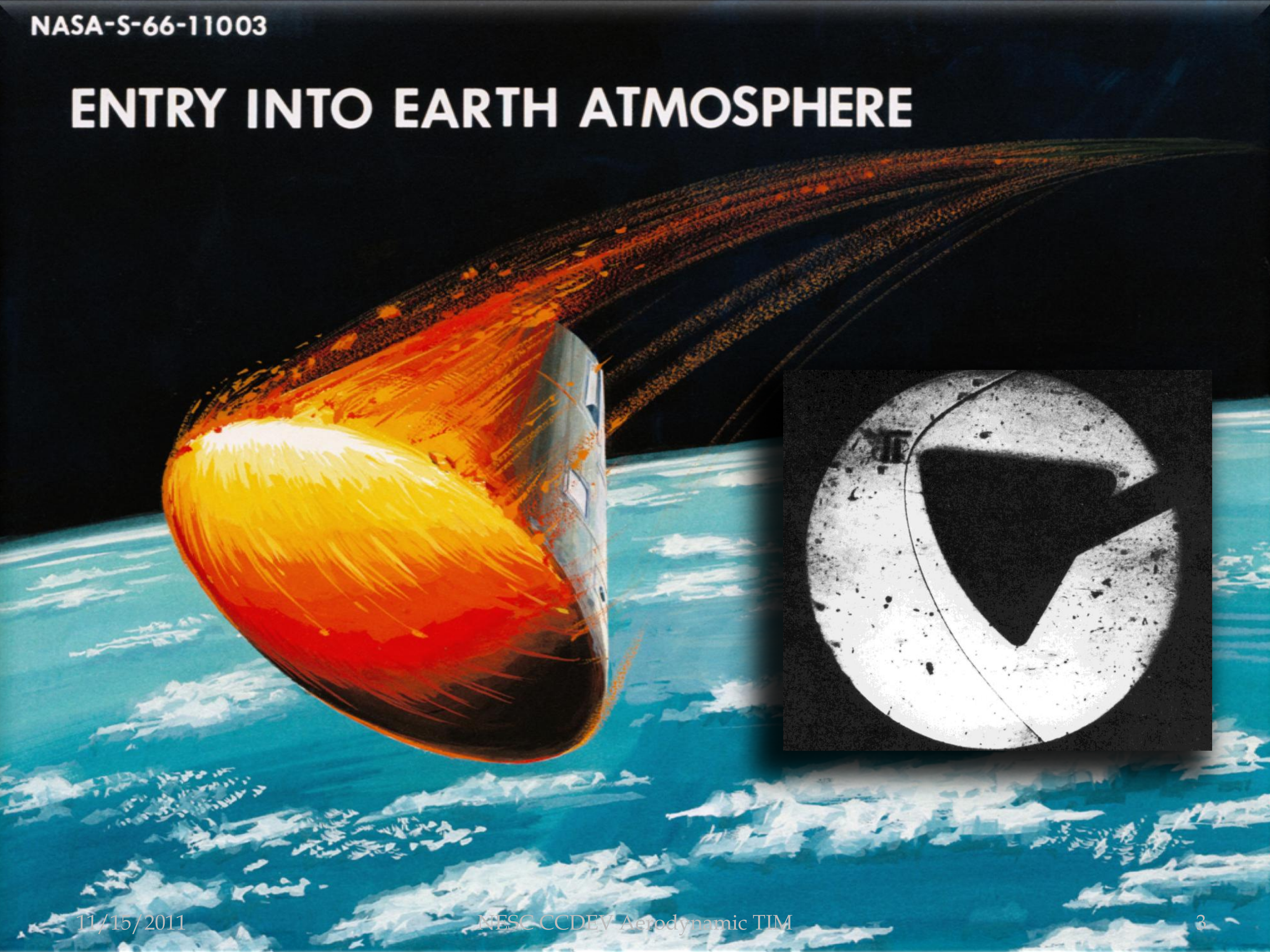
JSC/EG3

Apollo 13
April 11th, 1970

The
Space Shuttle
Aerothermodynamic
Design
began with
Mercury,
Gemini,
&
Apollo

41 years later...


NASA-S-66-11003
ENTRY INTO EARTH ATMOSPHERE

Entry Heating 101

- Radiation Equilibrium Surface Temperature
  - Surface Temperature Reaches an Equilibrium: Heat Rate to the Surface = Heat Radiated from the Surface + Heat Conducted to the Orbiter Structure
  - Tile Material with RCG Coating, Emissivity is 0.8 to 0.85, Conduction is About 1 Percent
- Catalytic Efficiency of the Surface
  - Metal Surfaces act as a Catalyst, Increasing Heat Transfer to the Surface.
  - Tile RCG Coating Has a Low Catalytic Efficiency

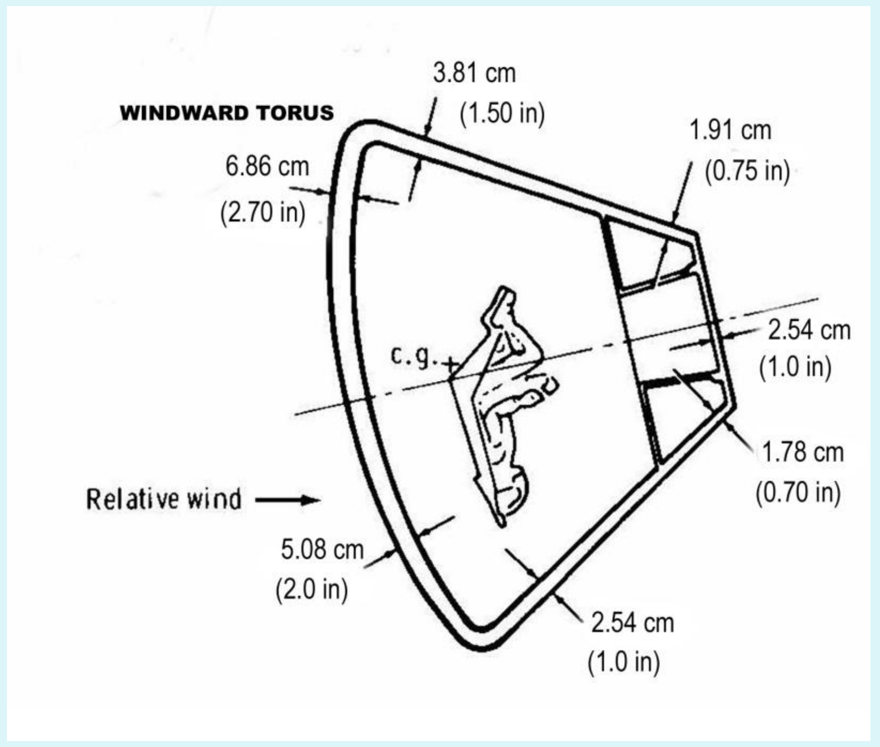
Apollo Heat Shield Design

•Heat Shield Had to be Designed Before the Lunar Trajectories Were Known
- •Heat Rate: 20g Emergency Lunar Return
- •Heat Load: Spacecraft Barely Captured by the Atmosphere

•Compounding of Conservatism from Each Group!

•Ablator used on Lee Side Due to Large Uncertainties

•Factor of 2 Over Design for Operational Missions Except Windward Torus – Structure Reached Design Temperature of 589K (600F)



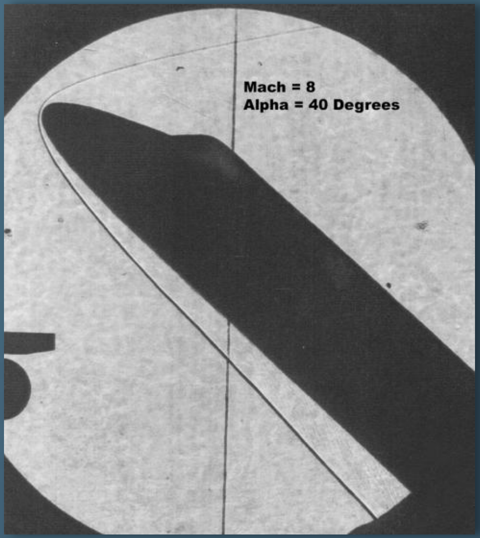
Apollo Boundary Layer Transition

- Apollo Experience
  - Flight Data Agreed with AEDC Tunnel B at Mach 8
  - Operational Flights Were Laminar
    - Based on Ablator Recession Rates
  - Maximum Heat Rate Trajectory Showed Transition to Turbulent Heating

Space Shuttle Thermal Protection System Design Goals

- Efficient, Reusable, Minimum Weight TPS
- Laminar Boundary-Layer During Peak Heating
- Windward Surface Shape Optimized to Maintain Laminar Flow
- Trajectory Designed to Maintain Laminar Conditions
- All Parties Agreed to Minimize Conservatism
  - Design Based on Nominal Trajectory, Nominal Heating Rates, Nominal Material Properties, & Aerodynamic Smooth Surface

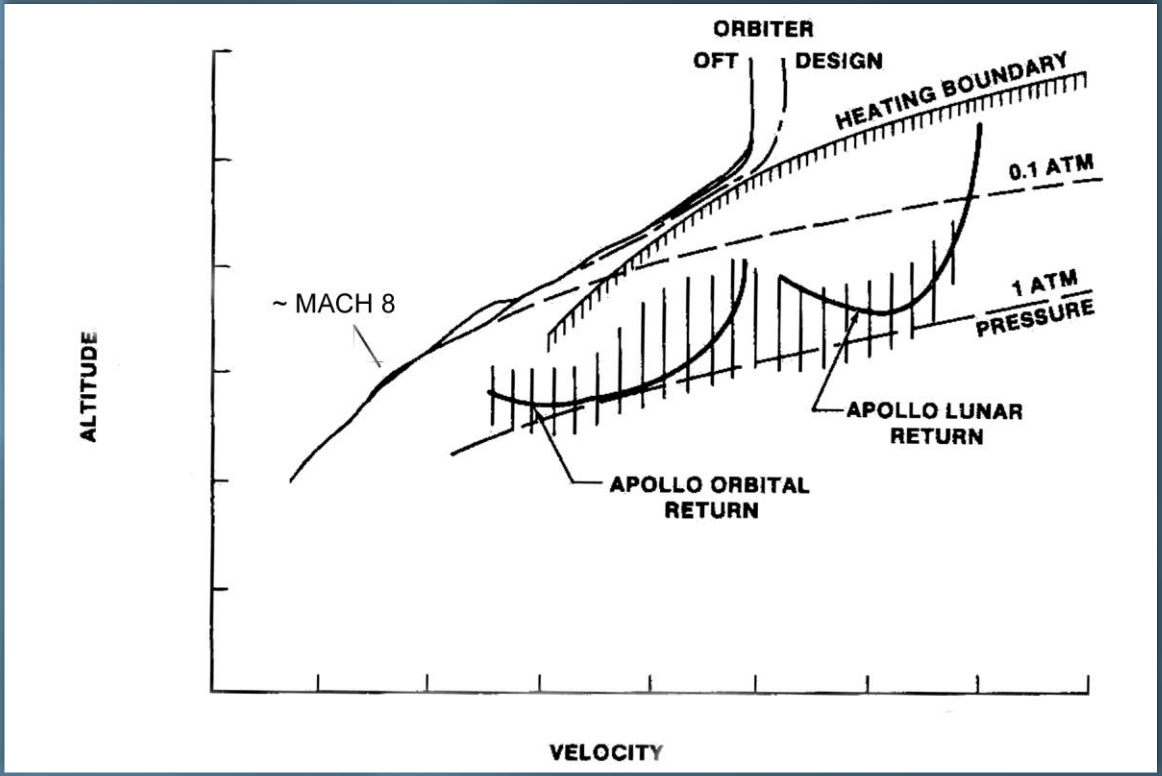
Design Philosophy



- Critical Design Review, 1978
- Polar Orbit – Western Test Range
  - Mission 3b, 25k lbs Payload Retrieval
  - 104 Degree Inclination, 100 NM Altitude
    - Trajectory 14414.14C
- Design for the Polar Orbit Mission
- Fly STS-1 as Conservatively as Possible
- Gradually Increase Entry Conditions During the Orbiter Flight Test (OFT) Program
- Use the OFT Flight Data to Assess the Vehicle Capability

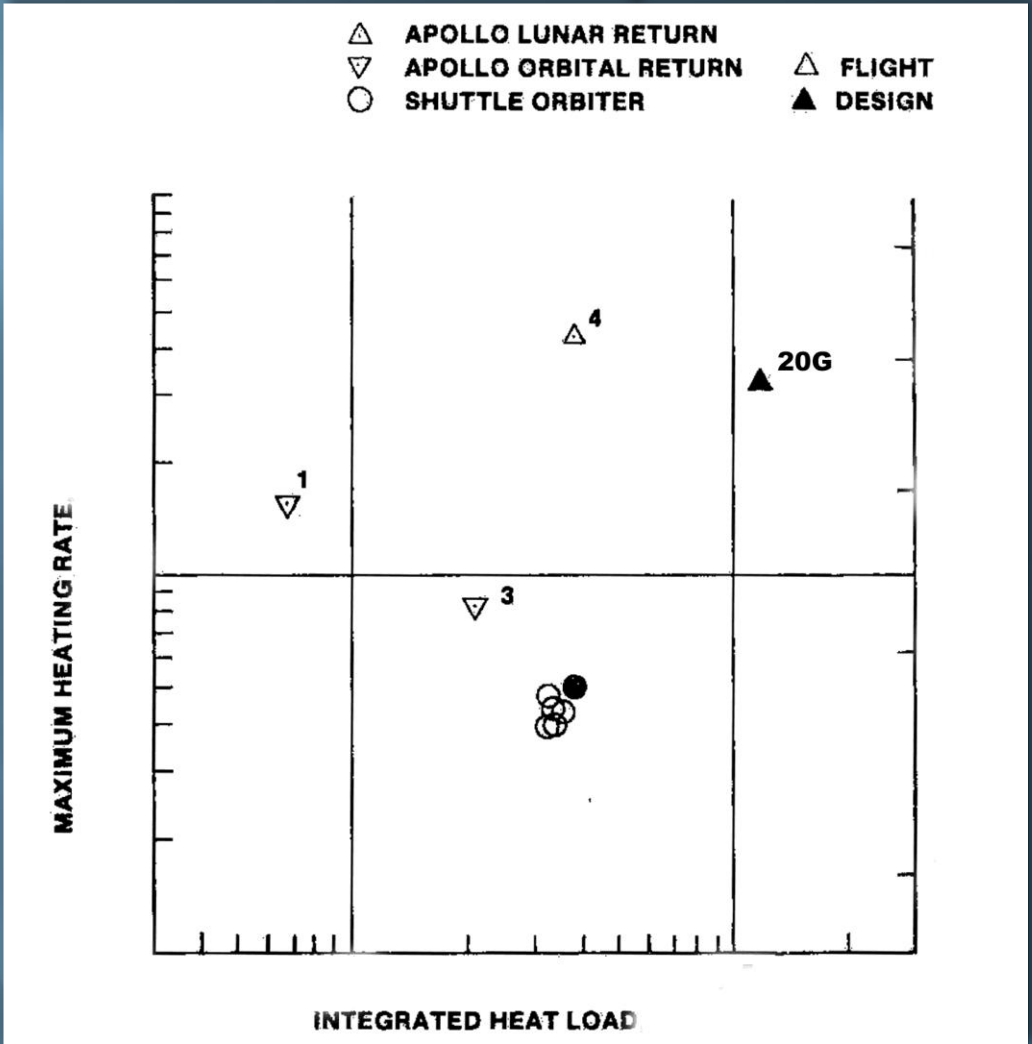
Systems Approach to Entry Design

- Trajectory, Aerothermodynamic Predictions, TPS Materials
- Conservatism from Each Discipline was Combined (RSS) to Produce System Uncertainties



Heat Rate and Heat Load Comparison With Apollo

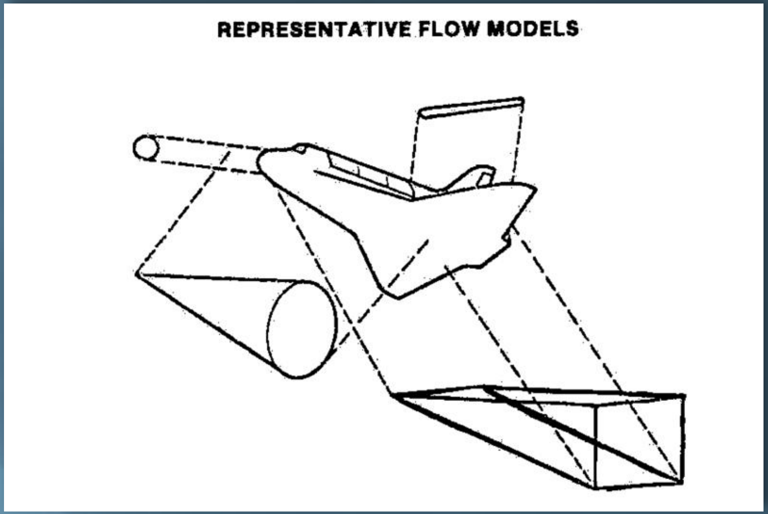
- Apollo Operational Trajectories Were Very Benign Compared to Design
- Orbiter OFT Flights Were Much Closer to Design

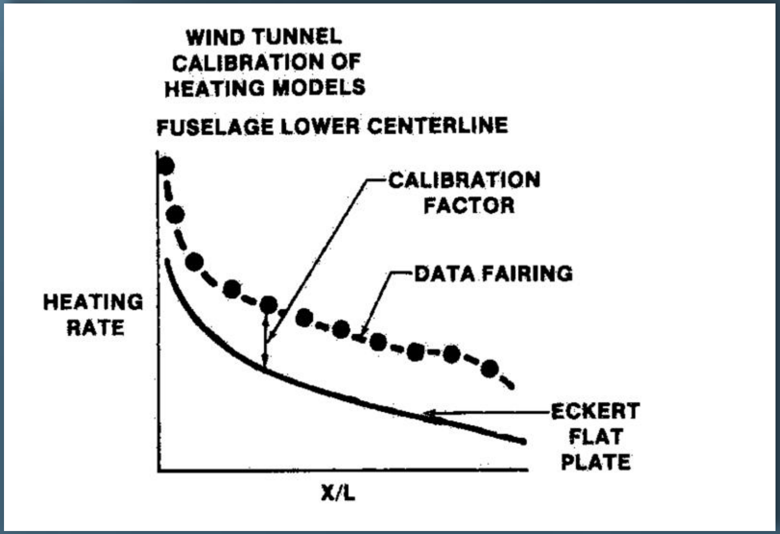


Orbiter Heating Design Approach

❑ Three Levels of Sophistication

- <u>Simplified Heating Model</u> Stagnation Heating to a 1 Ft. Sphere
  - BLT Based on Normal Shock Reynolds Number
  - Used for Trajectory Design
- <u>Design Methodology</u>
- Orbiter Wind Tunnel Data, at Mach 8, Scaled to Flight Conditions Using 2-D Flow Models.
- <u>Benchmark 3-D Flow Field Calculations</u>
  - 4 Flight Conditions
  - Used to Check the Design Methodology Before STS-1





Surface Roughness

- "Design" BLT Approach Used Spherical Roughness Elements from RI Experience with Hemisphere/Cone Data
  - Assumed that Single Roughness Elements Would Trip the Boundary Layer.
- Resulted in Very Smooth Surface Roughness Requirements – Tile to Tile Steps and Gaps
- Contrasted With NASA/JSC Approach
  - Mach 8 Normal Shock Reynolds Number Data Matches Apollo Transition Data & Planned Shuttle Flight Reynolds Number
- JSC Conducted a Unique Surface Roughness Test
  - Random Tile Roughness Plated on Model Surface
  - Resulted In Relaxed Roughness Requirement

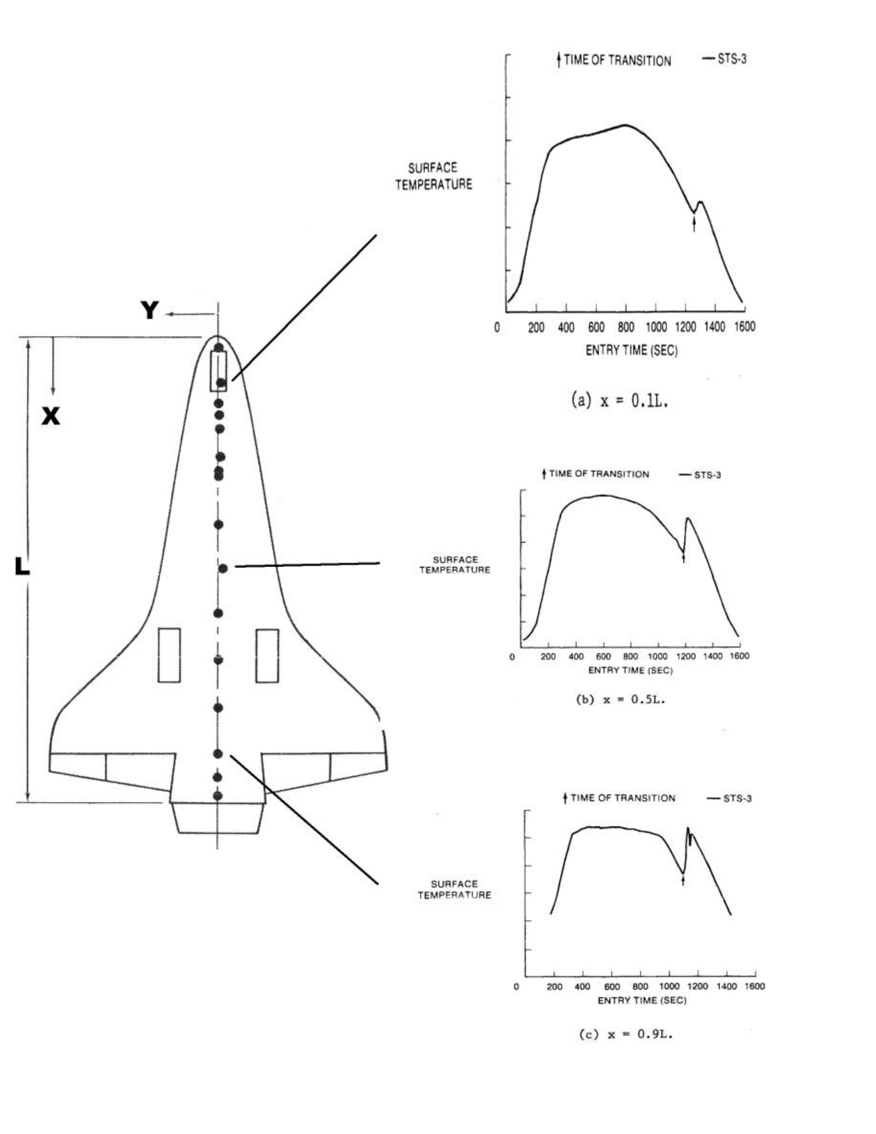
STS-1 Preflight Assessments

- Included Uncertainty and Trajectory Dispersions,
- +3 Sigma Boundary-Layer Transition Data
- NASA "Lost Tile" Analysis
  - Ames Research Center Channel Nozzle Arc Jet Test
  - Johnson Space Center Thermal Analysis
  - Concluded There Was Enough Thermal Conduction to Prevent Local Structural Failure for a Single Lost Tile.

STS-3 Surface Temperature Data

- 96 Locations
  - 3 shown
- Nominal BLT!

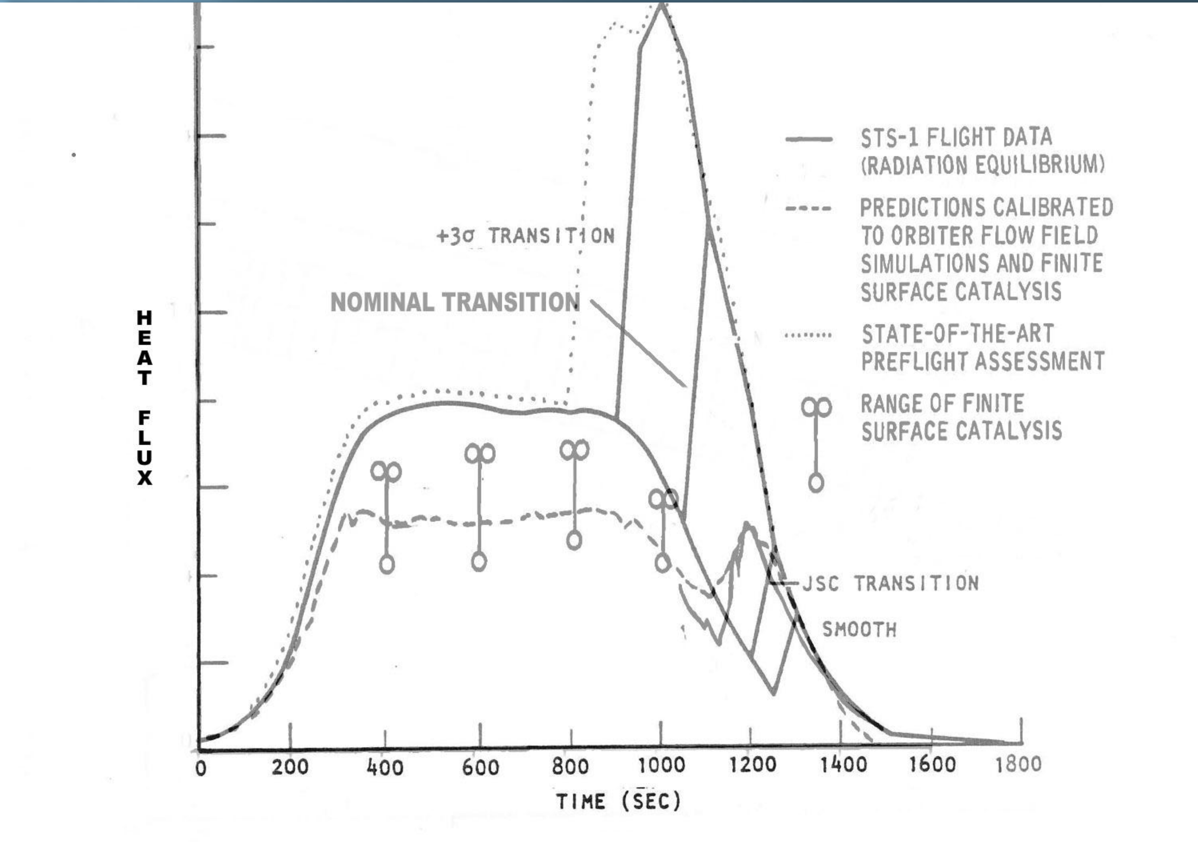
Note: Heating Rate is Proportional to Temp. Raised to the 4th Power



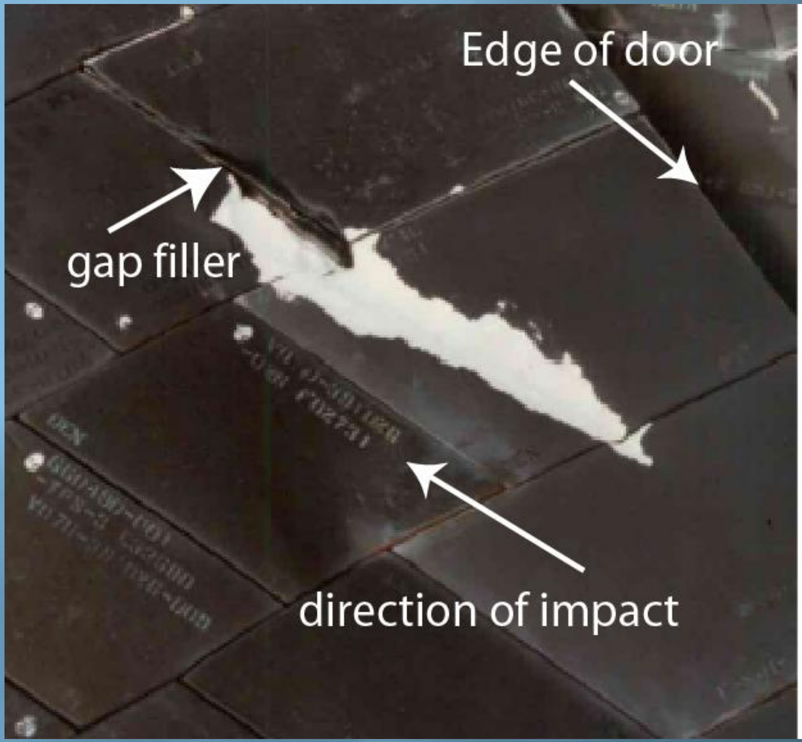
STS-1 Compared to Design

- Design (RI) Used Equilibrium Air – Fully Catalytic Surface Chemistry
- Wind Tunnel Derived Boundary-Layer Transition (BLT)

X/L = 0.4,
Center Line



STS-1 Boundary Layer Transition



Nose Gear Door Gouge

12 in X 1 in X 1 in

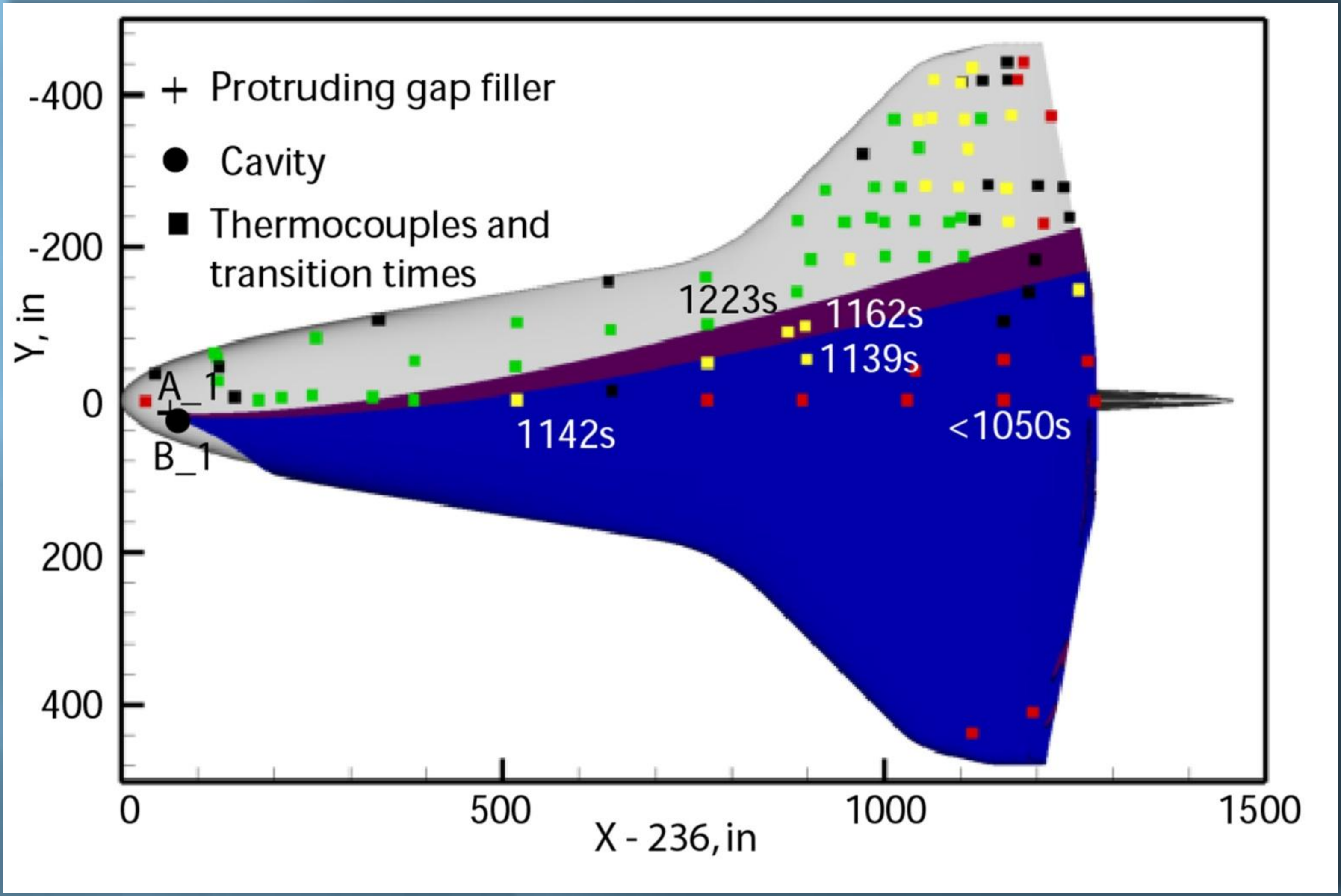
Displaced Gap Filler

Protruding About 0.4 In

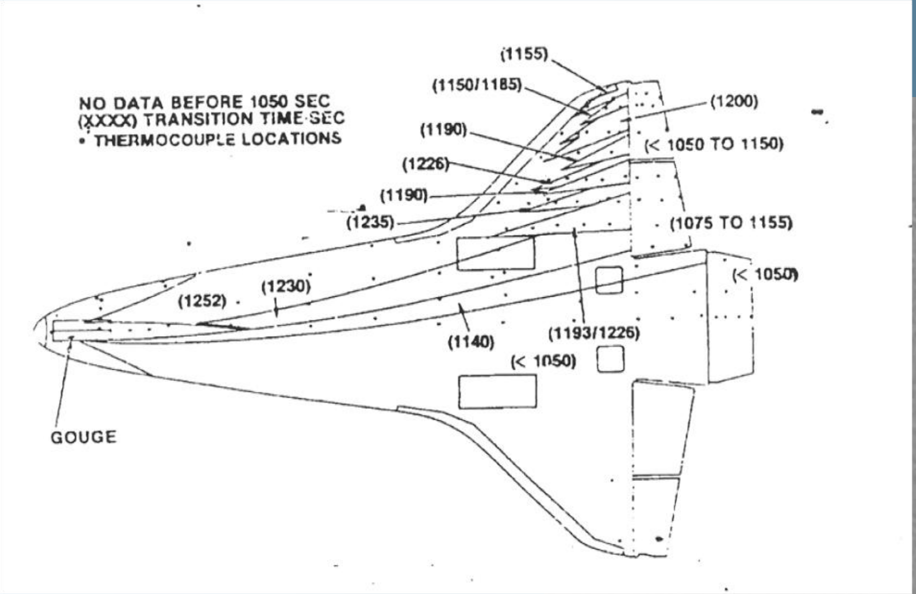
From Ref. 17, by Dr. McGinley, et Al.

STS-1 & BLT Wedge Tool Comparison

- Return to Flight Damage Assessment Tool



HYTHIRM and
MARS* collaboration



STS-1 Transition Map by Harthun, Blumer, & Miller, N84-10150

STS-134 June 1, 2011, Mach 6.2
~ 4 in per pixel from 32 nm (NIR)

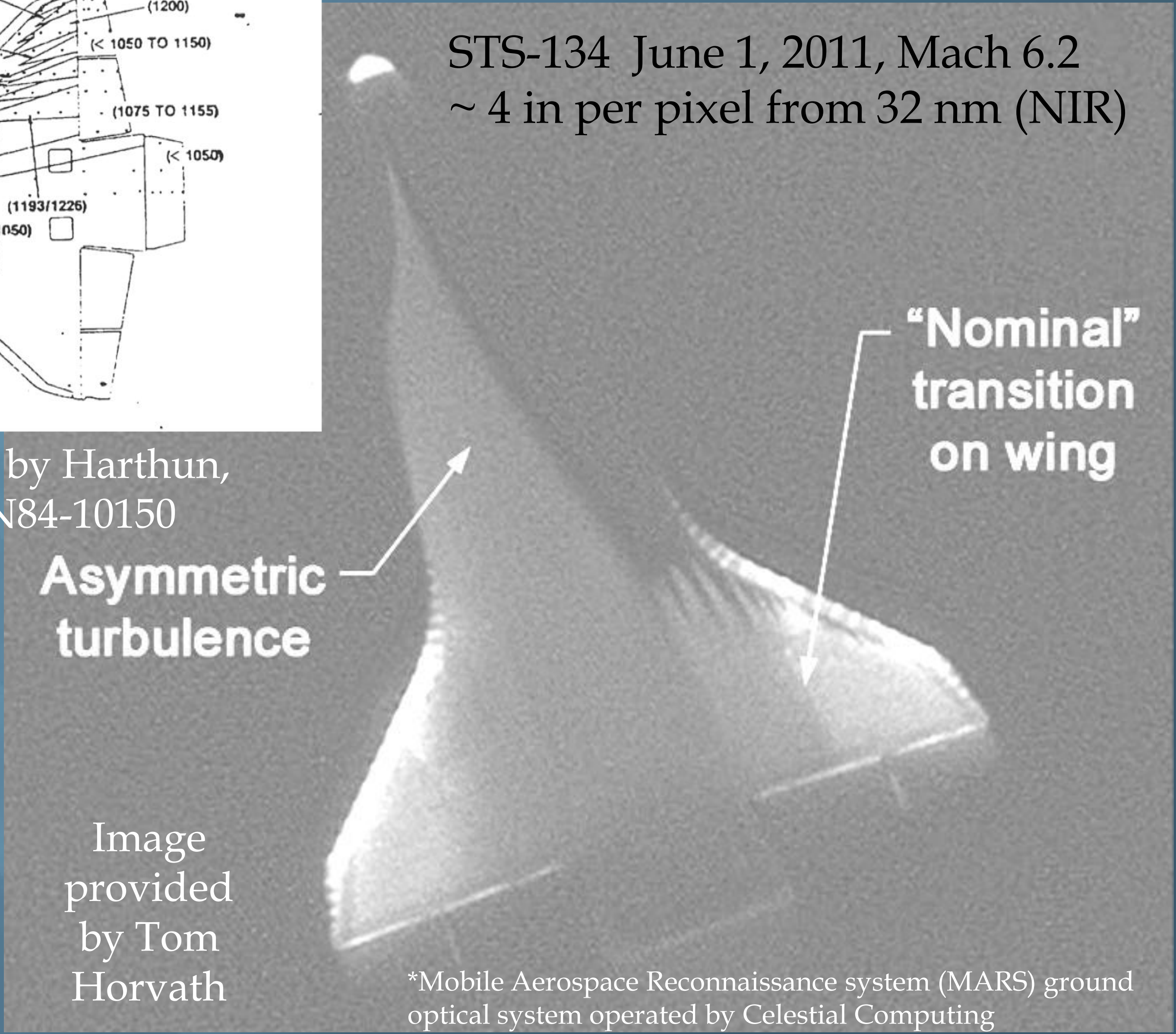
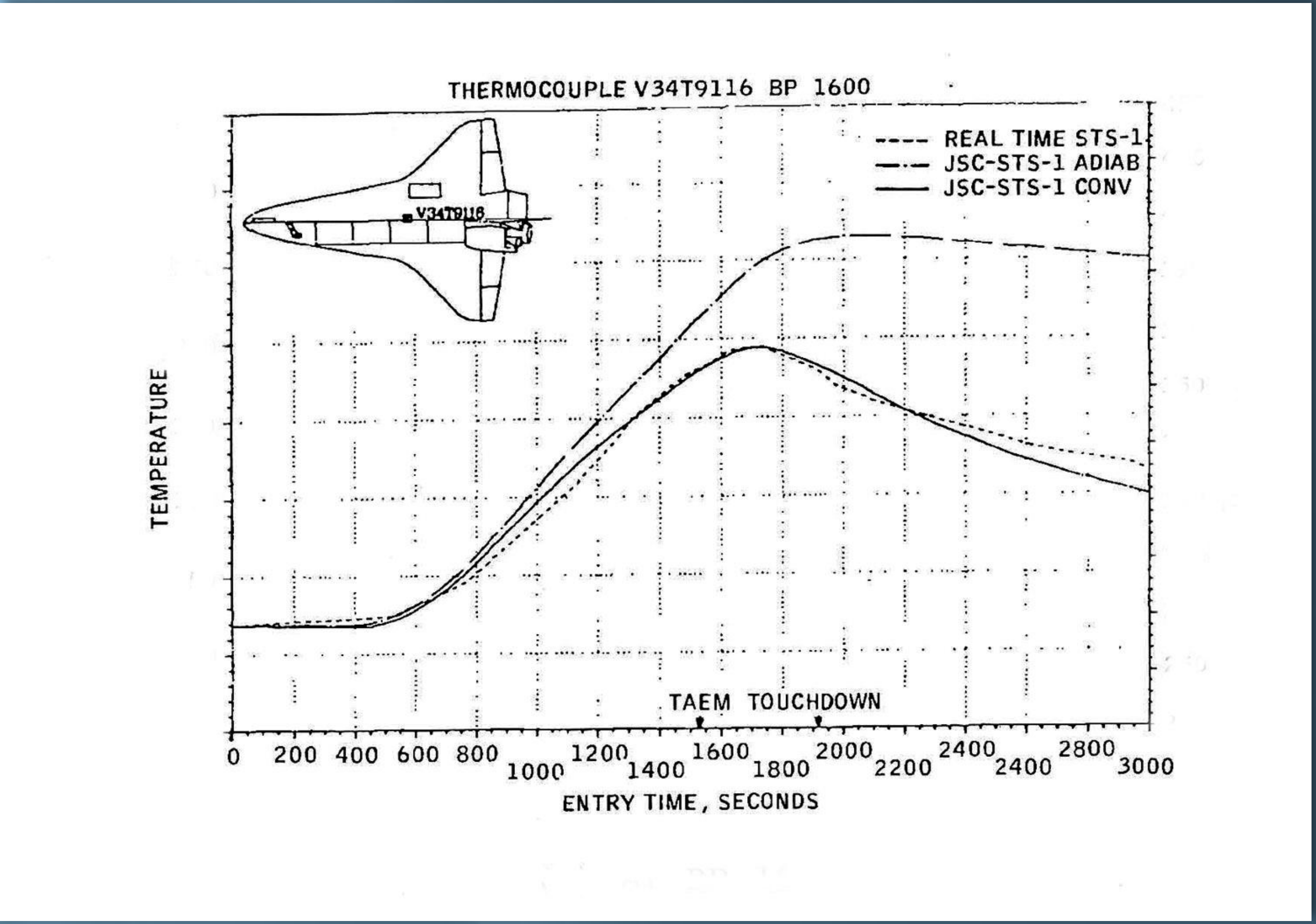


Image provided by Tom Horvath

*Mobile Aerospace Reconnaissance system (MARS) ground optical system operated by Celestial Computing

STS-1 Structural Thermal Response

- Convective Cooling Was Not Anticipated
- Not All Locations Benefit



TPS Tile Acreage Margin

- Windward Surface Structural Temperatures Were Recorded for Each Flight at 20 Locations
- STS-73, Early BLT Due to Protruding Gap Filler
  - About 105F of Margin
- STS-99, 28, 32, 48, 94, 102,
  - About 125F of Margin
- STS-27, Severe Damage During Ascent
  - 707 Tile Damage Sites, 298 Greater Than 1 Sq. In.
  - About 130F Margin (at Measurement Locations)
  - One Missing Tile Over an Antenna Cover
    - Tin Coating Was Hot Enough to Flow
    - Aluminum Was Hot Enough to Change the Anneal State
- OFT Flights
    - STS-1, Asymmetric BLT, About 135F of Margin
    - STS-4 & 5 Were Coolest, About 170F of Margin

TPS Margin Comments

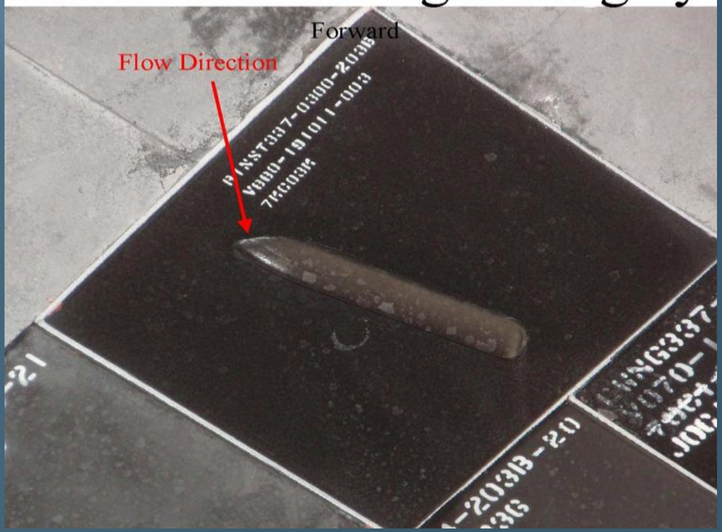
- Considerable Margin Existed in the Acreage Tile System
  - Operational Trajectories Were Slightly More Benign than Design
  - Design Used Conservative Boundary-Layer Transition Models
  - Tile RCG Coating is Almost Non Catalytic
    - Design Assumed Fully Catalytic
  - Convective Cooling is a Significant Effect in Most Locations – Not Anticipated During Design
- Note: Protruding Gap Fillers, Causing Early BLT Was Not Considered During Design
  - However, BLT Model Used For Design Had Similar Heating Effects, Without the Asymmetry

Boundary-Layer Transition DTO

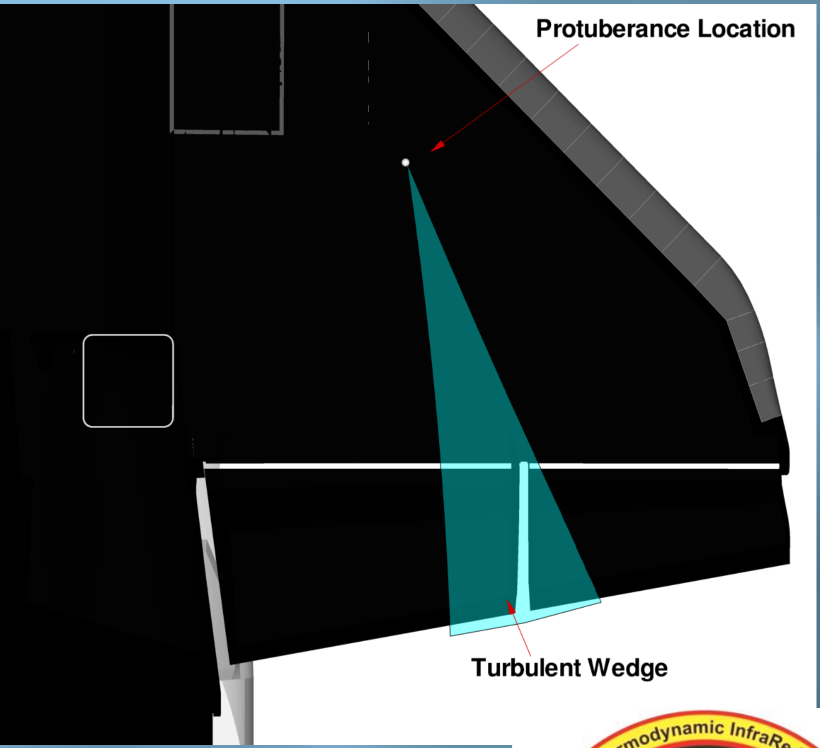
- Motivated by the Two Protruding Gap Fillers During STS-114
- Designed to Obtain BLT Data With a Known Protuberance Height
- Flown 5 Times With 3 Different Protuberance Heights; 6.35 mm (0.25 in), 8.9 mm (0.35 in), 12.7 mm (0.5 in)
  - Data Agreed Well With Predictions of Transition Onset Time
  - Data Showed the Temperature Predictions Were Very Conservative – And Still Under Investigation

8.9 mm (0.35 in)
Protuberance

STS-131 Post Flight Imagery

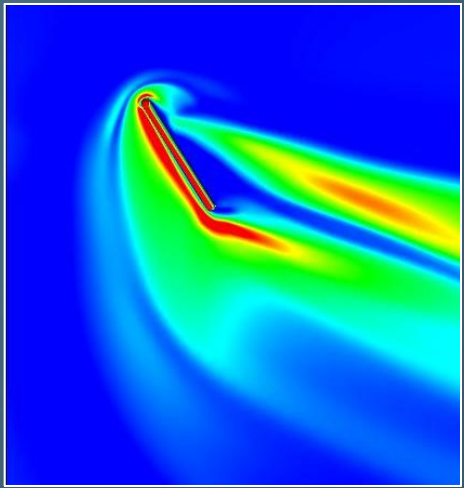


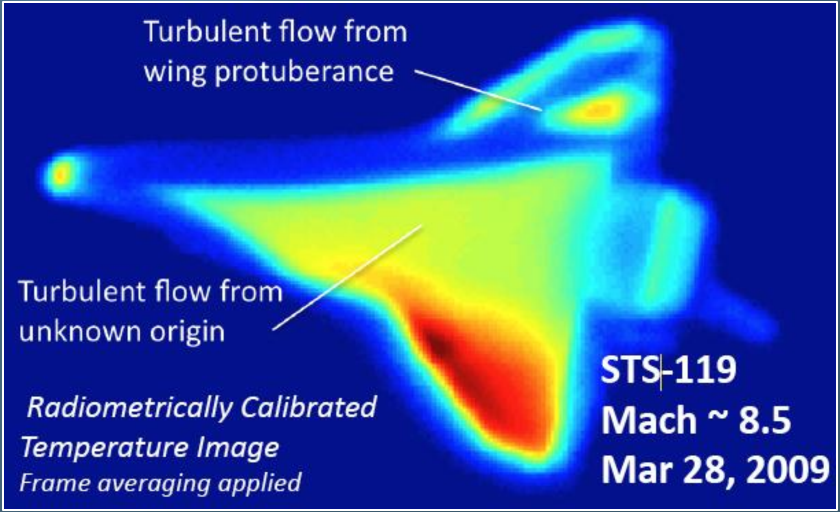
Boundary Layer Transition Flight Experiment



Modified Tile

CFD prediction





Space Shuttle Program Issues Motivated Development of Analysis Capability

- STS-1 Hypersonic Pitching Moment
  - LAURA CFD Code by Dr. Peter Gnoffo
- Orbiter On Orbit Plume Impingement
  - Direct Simulation Monte Carlo Methods for Rarefied Flows – DAC Code by Jay LeBeau
- Launch Vehicle Transonic Aerodynamic Issues
  - Chimera Grid Scheme, F3D CFD Code by Dr. Joe Steger
  - OVERFLOW CFD code by Dr. Pieter Buning
- TPS Damage Assessment Tools for Flight Support
  - Hypersonic Flow Field Codes: LAURA, DPLR

Lessons Learned

- Minimize Conservatism with a Systems Approach
- Test and Analyze the Flight Geometry
- Take Advantage of Internal Cooling When Appropriate
- Design for Laminar Peak Heating
  - Geometry, Trajectory, Surface Roughness
- Use Reasonable BLT Estimates
  - Wind Tunnel Data at Full Scale Reynolds Number ?
- Tile Designs Require Robust Gap Filler Installations
  - Developed After STS-114

Acknowledgements

- Dr. Robert Ried/JSC - Retired
- Ms. Dottie Lee/JSC - Retired
- Mr. Brian Anderson/JSC
- Dr. Chuck Campbell/JSC
- Mr. Gerald LeBeau/JSC
- Mr. Steve Derry/JSC
- Mr. Reynaldo Gomez/JSC
- Dr. Georgi Ushev/Boeing
- Dr. Catherine McGinley/LaRC
- Dr. Tom Horvath/LaRC

LEGACY
"That Which is Left to Future Generations"

- Thirty Years of Experience with the First Reusable Thermal Protection System
- Hypersonic Data - National Asset
  - Orbiter Flight Test (OFT) Data
  - Boundary Layer Transition DTO
  - HYTHIRM
  - Orbiter Vehicle Surface Geometry Scans for Future CFD Analysis
- Incredible Improvement in Analysis Capability
  - Motivated by Space Shuttle Issues
  - 10 Orders of Magnitude improvement in Computing Capability During the 30+ Years!
    - Transonic Ascent Issues, Entry Issues, Debris Damage Assessment, Internal Flows
  - Computational Fluid Dynamics
    - LAURA, OVERFLOW, DPLR, codes
  - Direct Simulation Monte Carlo methods
    - DAC Code for Rarefied Flows
- Personnel with 30+ Years of Experience

BACKUP

Sept 27, 2011

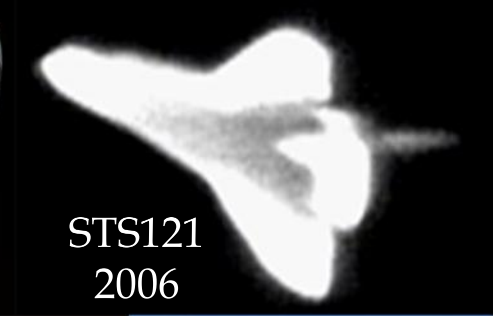
Aeronautics Research Mission Directorate

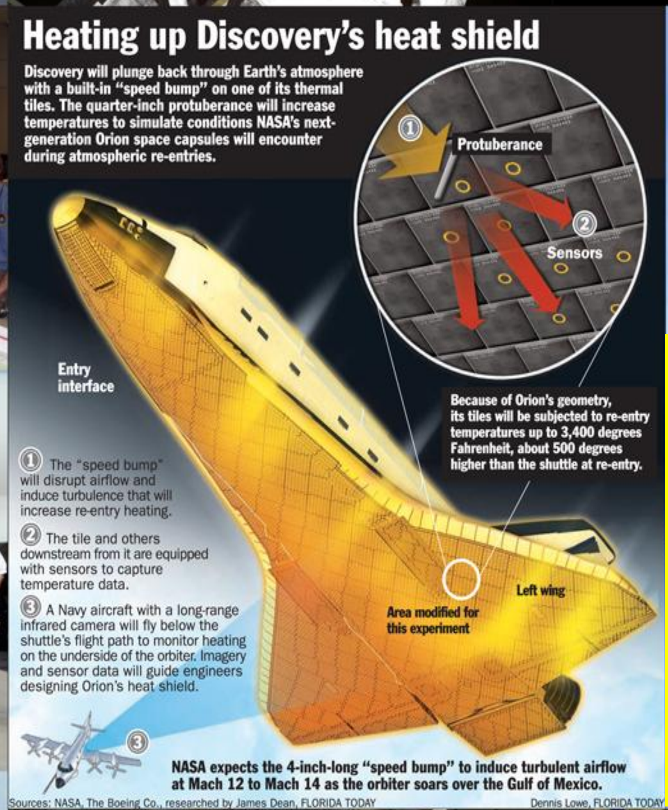
HYTHIRM SLIDES FOR FRED MARTIN AIAA 2011 SPACE CONFERENCE – SHUTTLE LEGACY SESSION

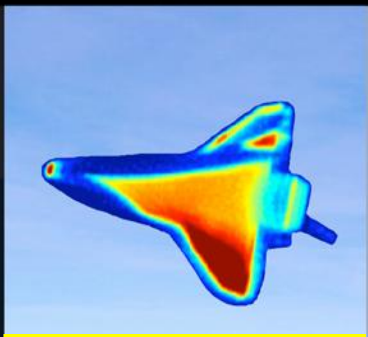
Hypersonic Thermodynamic Infrared Measurements

Thomas Horvath/LaRC

Jay Grinstead/ARC

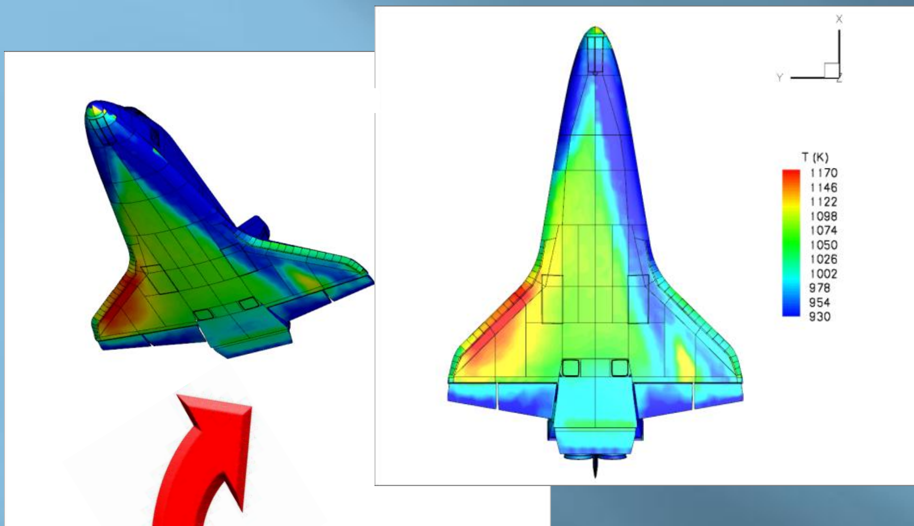




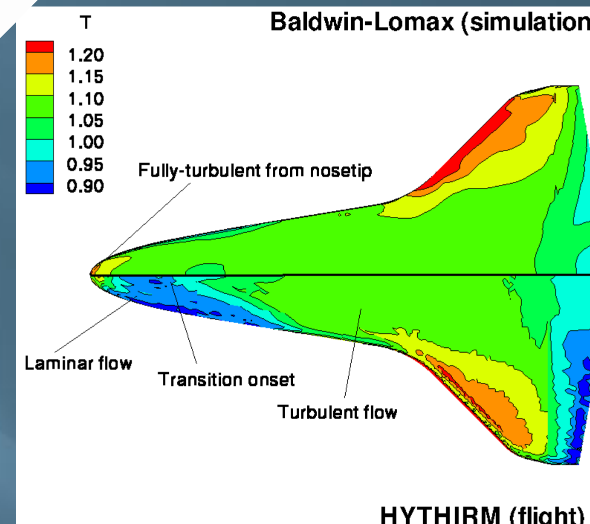


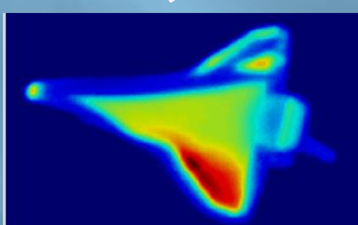
Success Criteria:
To obtain spatially resolved infrared imagery that will provide a quantified surface temperature map of the Shuttle during hypersonic re-entry

An Emerging Thermal Assessment Capability



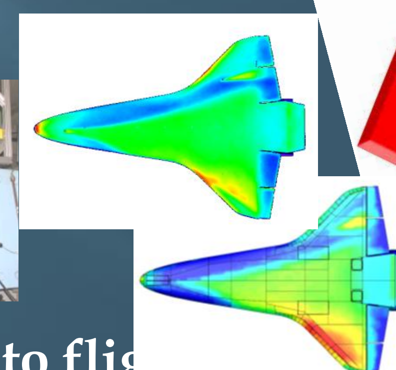
Comparison to Modeling Tools





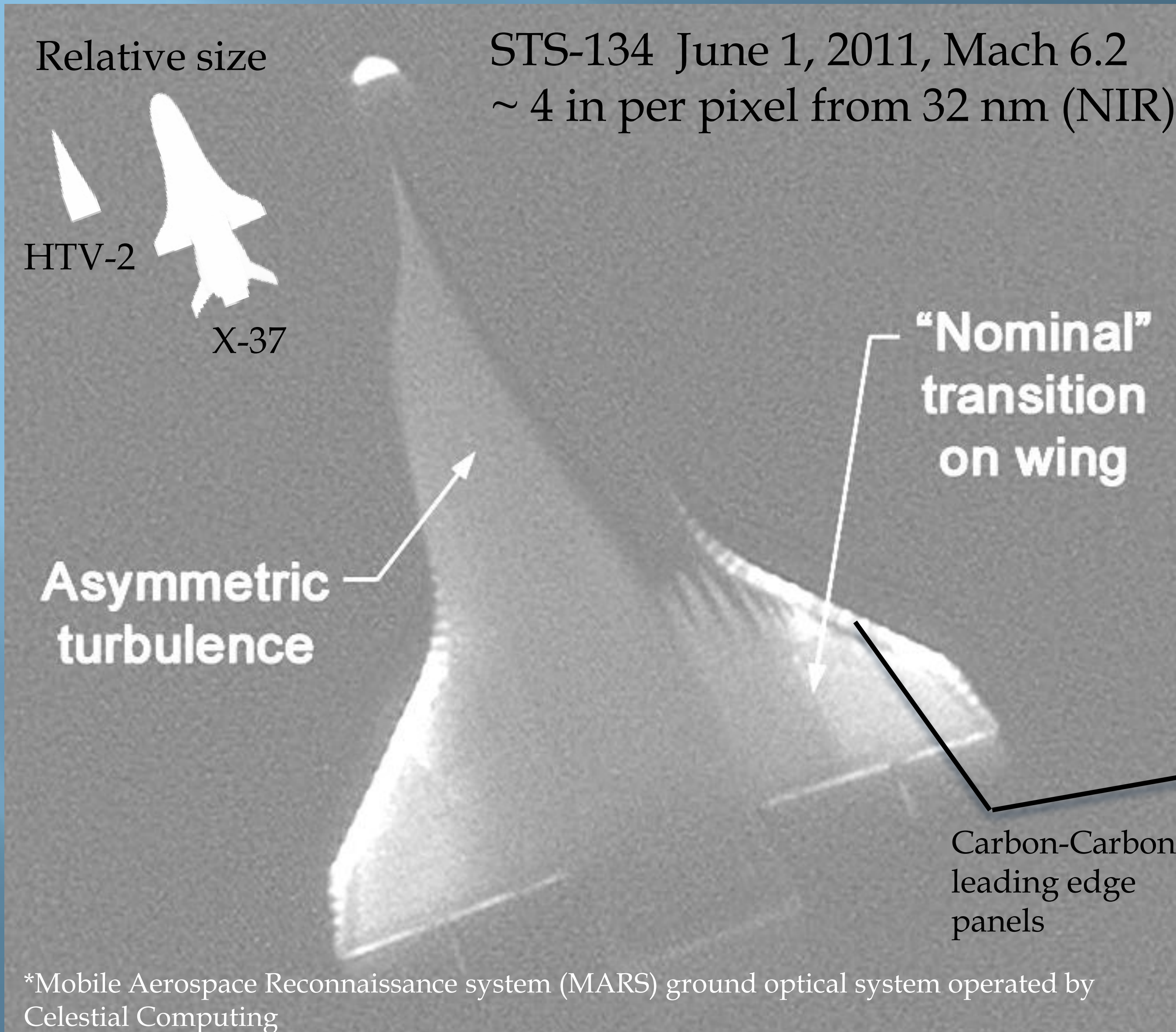
2-D processed data

Operations, Data Collection & Calibration



Ground to flight extrapolation

Spatial Resolution is a Necessity



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HYTHIRM and MARS* collaboration

On-orbit photo of Shuttle

The Orbiter is a LARGE target!