NASA Supersonics Research and the X-59 — How They Will Benefit You!

Presentation at
"Discover NASA with CTSGC"
seminar series — March 14, 2023

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Outline

- Brief history of supersonic flight
- Shock waves and sonic booms
- Sonic boom pressure signatures and loudness
- Tools for studying quiet supersonic flight
  - CFD (Computational Fluid Dynamics)
  - Wind tunnels
  - Flight test
- Quesst Mission
  - X-59 airplane
  - Mission profile
  - Flight simulations
  - Wind tunnel data validations
- Video: Supersonic flight research leading to Quesst

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Initial Supersonic Speed Records

1st airplane to exceed Mach 1:

Bell X-1, October 14, 1947, flown by Chuck Yeager
— Mach 1.06 at 43,000 feet altitude

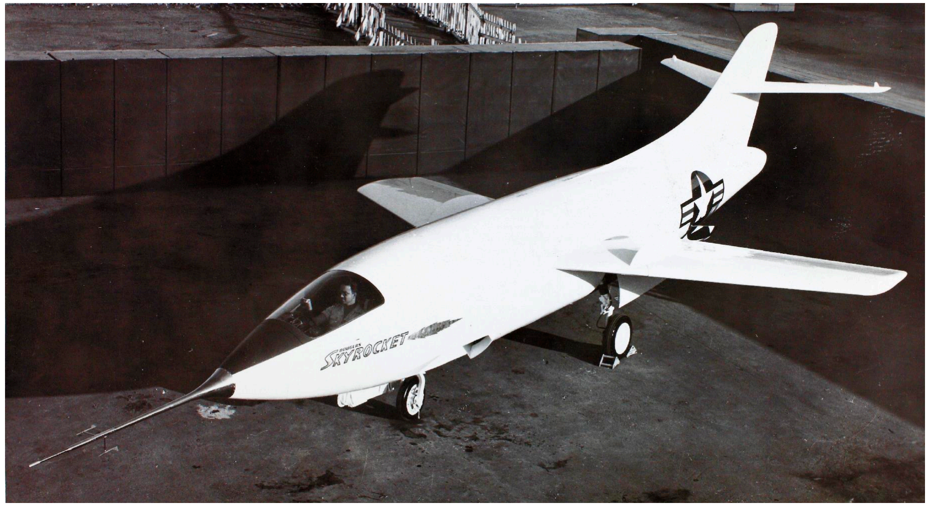
Mach number = $\frac{\text{aircraft speed}}{\text{speed of sound}}$

Speed of sound @ 43,000 ft = 662 mph

Mach 1.06 @ 43,000 ft = 702 mph

1st airplane to exceed Mach 2:

Douglas D-558-II Skyrocket, November 20, 1953, flown by Scott Crossfield — Mach 2.005 at 62,000 feet altitude



1st airplane to exceed Mach 3:

Bell X-2, September 27, 1956, flown by Milburn Apt
— Mach 3.196 at 65,500 feet altitude

A Brief History of Commercial Supersonic Flight

1947 – X-1 breaks the sound barrier

1954 – First SST concept studies

1961 – St. Louis sonic boom study

1962 – Concorde agreement

1963 – US SST announced

1964 – Oklahoma City sonic boom study

1969 – Concorde first flight

1971 – US SST canceled

1973 – US prohibits overland flight

1976 – First commercial Concorde flight

2003 – Concorde retired

Operation Bongo II

- Starting in February 1964, the FAA and U.S. Air Force conducted a study of the effects of sonic booms on the public and on urban structures
- For 6 months, F-101 Voodoos, F-104 Starfighters, F-106 Delta Darts, and B-58 Hustlers flew eight supersonic flights per day over Oklahoma City
- Boom intensities of 1 to 2 psf at ground level were created
- Almost 10,000 complaints of building damage were filed—mostly shattered windows and broken plaster—and there were thousands of personal complaints from individuals
- Negative publicity about the tests led to the the 1971 cancellation of the Boeing 2707 project and to the United States' complete withdrawal from SST design

Commercial Supersonic Transports

**** Supersonic over water only ****

Concorde

- 20 aircraft built, 14 used for commercial service by British Airways and Air France
- 1st flight: 3/2/69
- Cruised at Mach 2 and > 50,000 feet altitude
- Passenger service from 1969 to 2003

Tupolev Tu-144

- 16 aircraft built, 14 used for commercial service by Aeroflot
- 1st flight: 12/31/68
- Cruised at Mach 2 and 52,000 ft altitude
- Passenger service from 1975 to 1978

Concorde Take-Off and High-Altitude Sonic Boom

The Concorde was very loud on take-off *and* so was the boom from high altitude

https://www.youtube.com/watch?v=5MCETiKCLhc

Air Transport Speeds at Subsonic Limits

Aside from the Concorde, commercial air travel has been limited to less than 600 mph

Airplane	Year of introduction	Cruise Mach	Cruise Speed (mph)
Boeing 707	1958	0.82	540
Concorde	1976	2.0	1,320
Boeing 787	2009	0.85	560

Boeing 707

Concorde

Boeing 787

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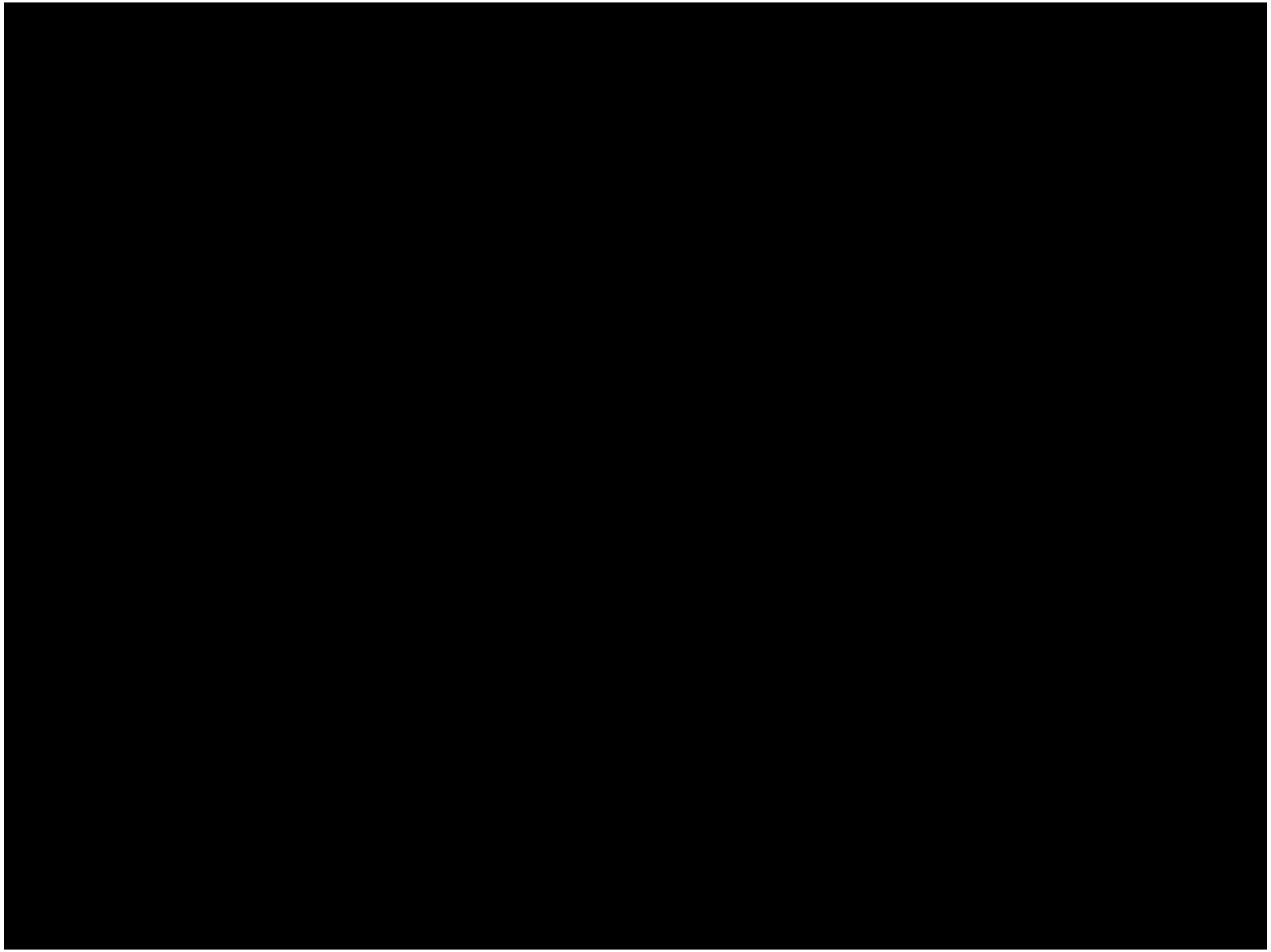
Blue Angels High Speed Passes Video

Three solo passes over San Francisco Bay during Fleet Week

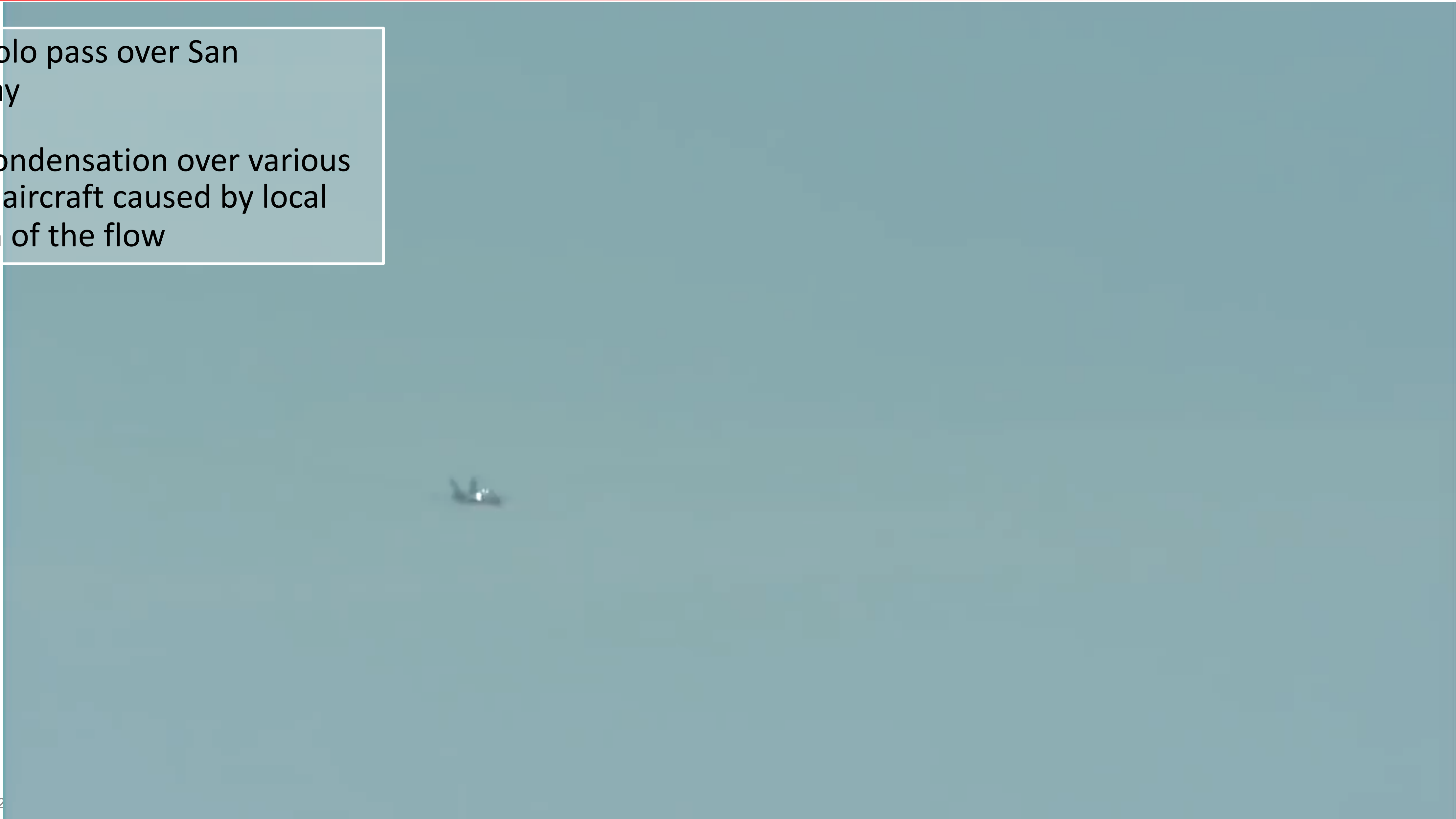


https://www.youtube.com/watch?v=K7rAUu8djZ4

Blue Angels High Speed Pass Video

One more solo pass over San Francisco Bay

Watch for condensation over various parts of the aircraft caused by local acceleration of the flow

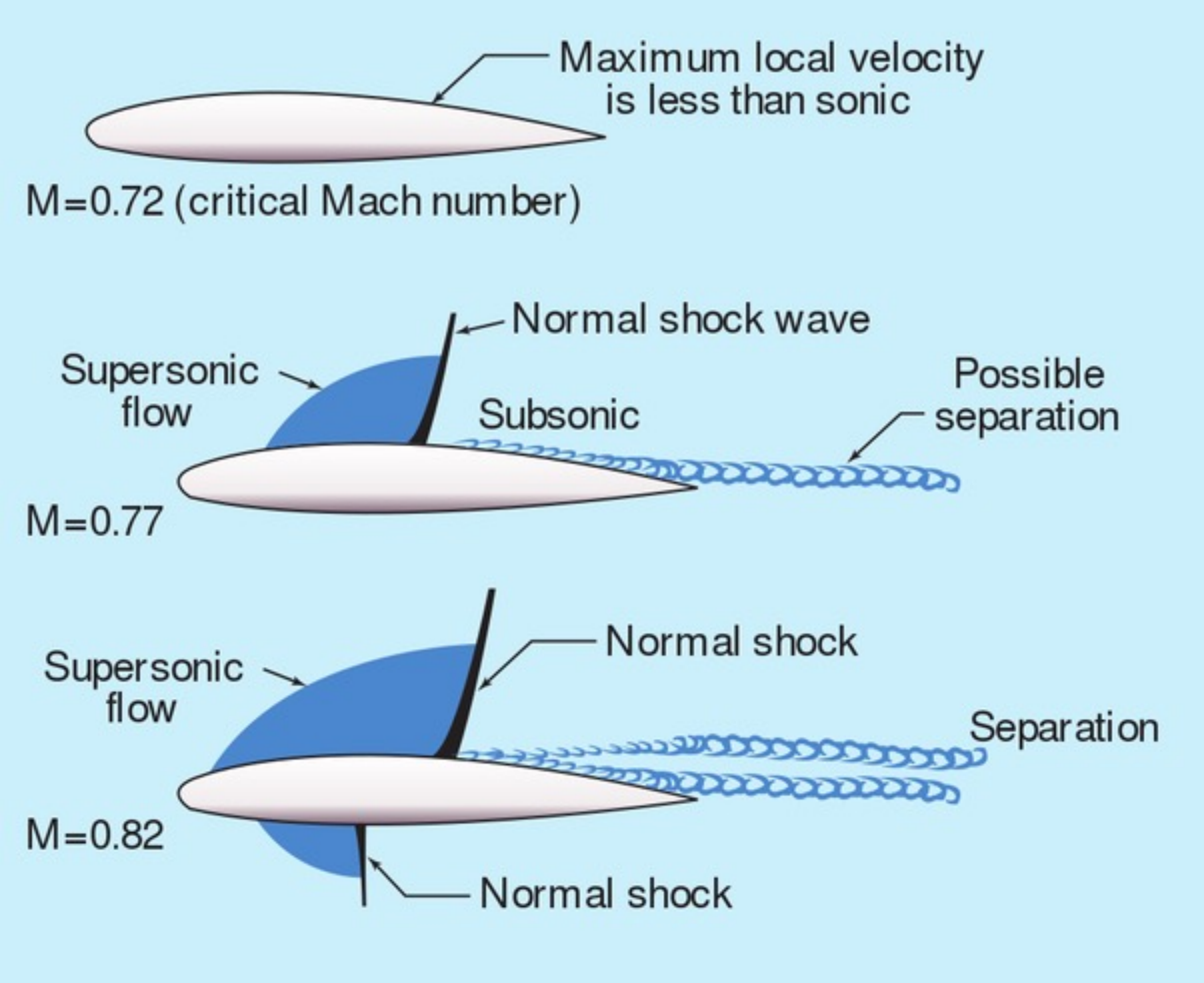


https://www.youtube.com/watch?v=ONx0gSZ9NyM

Blue Angel Shock Waves

Local Supersonic Flow

- Drag increases before reaching Mach 1
- Shock waves form and flow separation occurs
- This defines start of transonic speed regime



What is the Sound Barrier?

NOTHING!!!

- The uninformed media continually promotes the idea that there is a “barrier” that is “broken” when a jet goes supersonic, and that a sonic boom is produced at that moment (and only then) — this is not true!

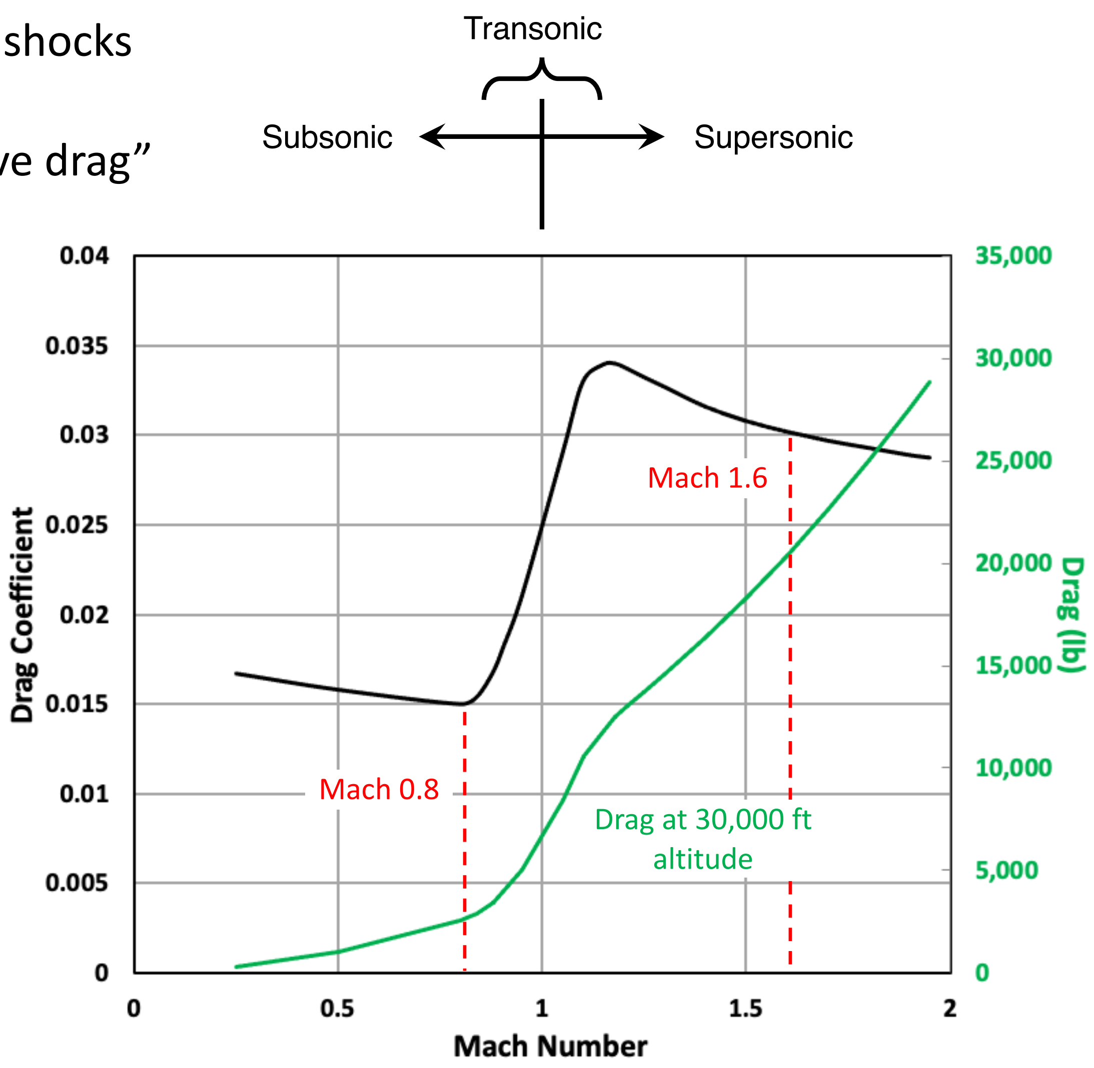
- The aircraft produces shock waves continually while flying at supersonic speeds, and these are heard as a sonic boom

- The boom follows the airplane (just as waves from a boat are continuous), so everyone under or near the flight path of the airplane will hear the boom

- The only barrier to going supersonic is overcoming the high amount of drag

How High is the Drag?

- Aerodynamic drag increases dramatically from subsonic to supersonic speeds
- As incoming air is redirected around an aircraft at supersonic speeds, shocks are created
- The pressure of the air increases across these shocks and causes "wave drag"
- The more the air is redirected, the stronger the shock, and the greater the drag
- Drag *coefficient* increases through transonic speeds, but then lowers at higher supersonic speeds
- Actual drag *force* increases dramatically at high supersonic speeds, but is reduced as altitude is increased

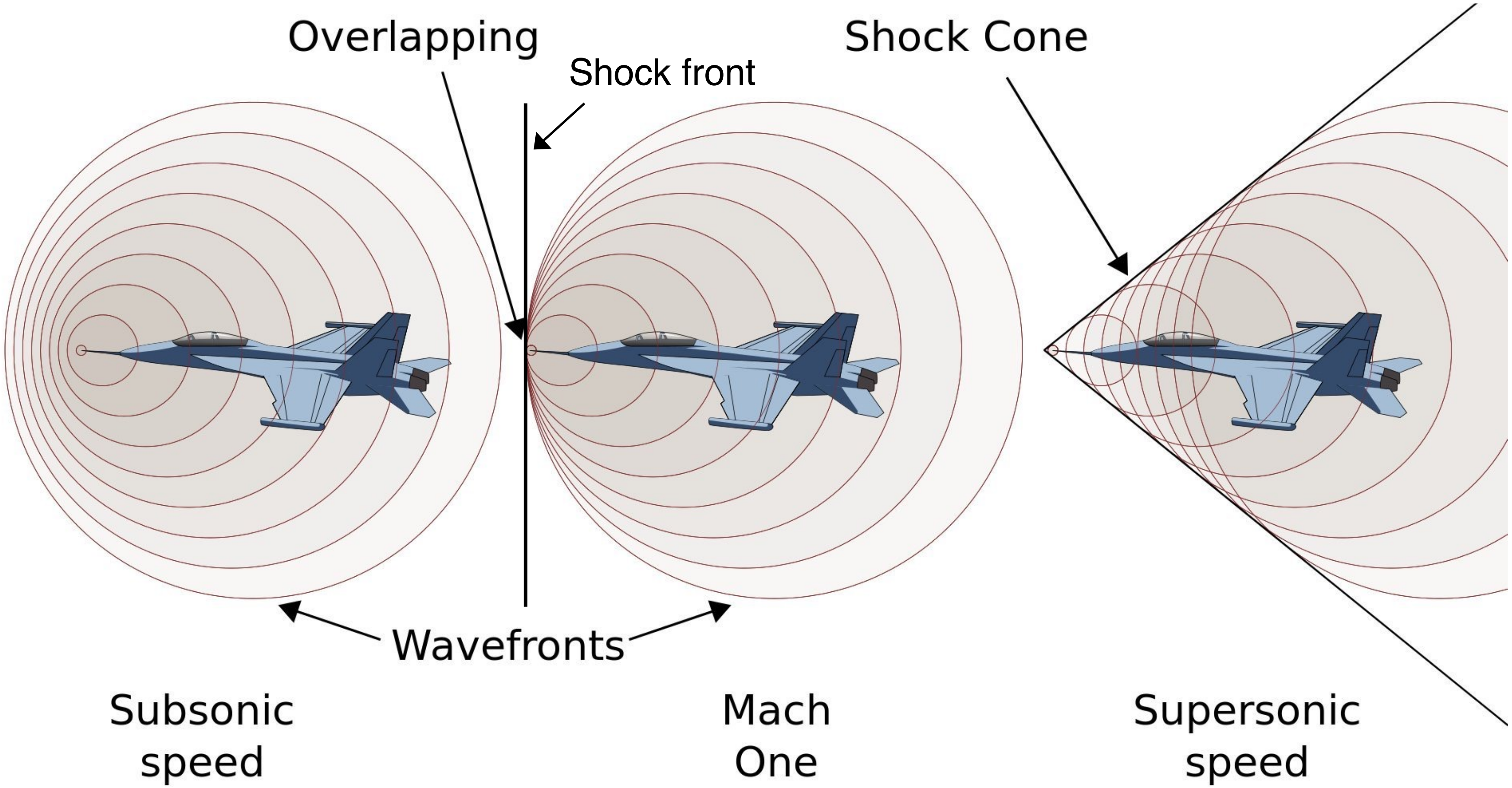


Example: Fighter airplane drag

Wing area (S): 600 sq ft

Mach	Altitude (ft)	Dynamic Pressure (q; psf)	Speed (mph)	$C_D = D/qS$ Drag Coefficient	**Drag (lb)**
0.8	30,000	282	542	0.015	**2,530**
1.6	30,000	1,126	1,084	0.030	**20,400**
1.6	60,000	270	1,059	0.030	**4,900**

What Makes a Sonic Boom?



- Conical shock wave produces sonic boom at ground which moves with the airplane
- Boom is created over *entire* length of supersonic flight, just as a boat wake is continuous

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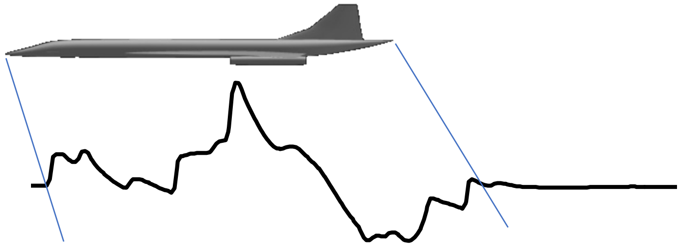
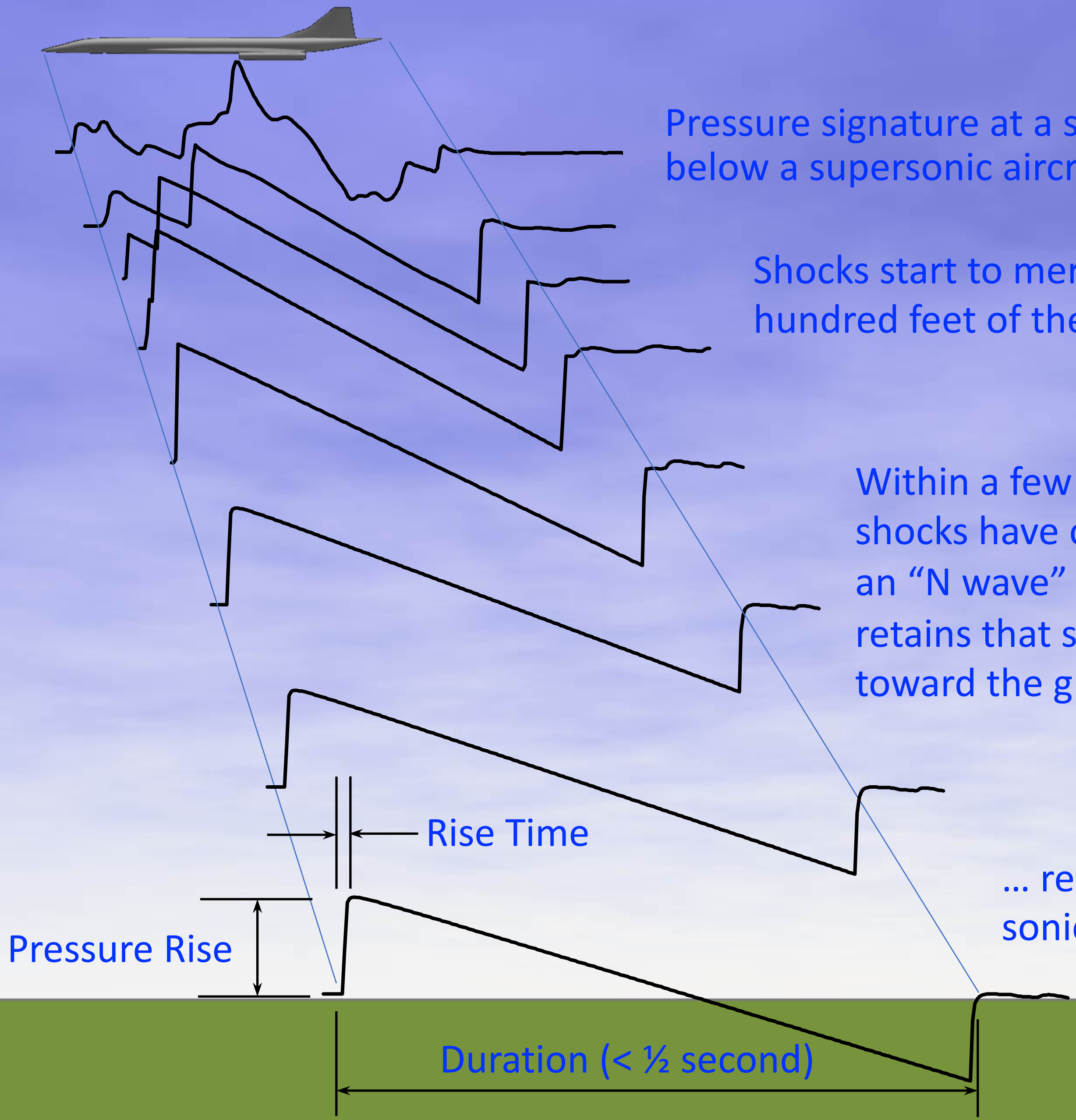


Sonic Boom Basics: N-Wave Sonic Boom



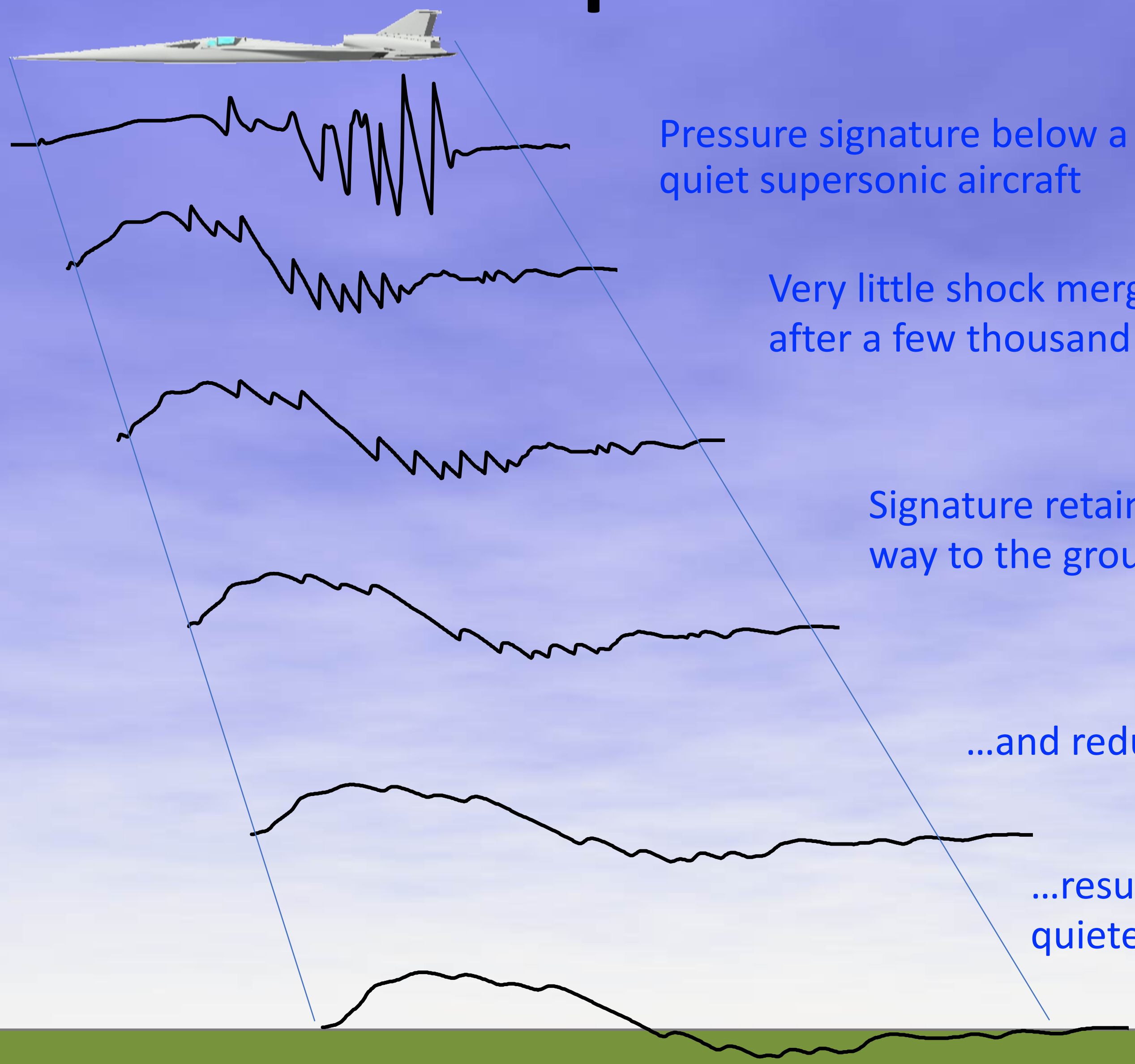
Pressure signature at a short distance below a supersonic aircraft

Shocks start to merge within a few hundred feet of the aircraft

Within a few thousand feet, the shocks have completely merged into an “N wave” and the signature retains that shape as it travels toward the ground …

… resulting in a LOUD sonic boom at the ground

Sonic Boom Basics: Shaped Pressure Signal



Pressure signature below a quiet supersonic aircraft

Very little shock merging after a few thousand feet

Signature retains it shape all the way to the ground…

…and reduces in strength…

…resulting in a significantly quieter sound at the ground

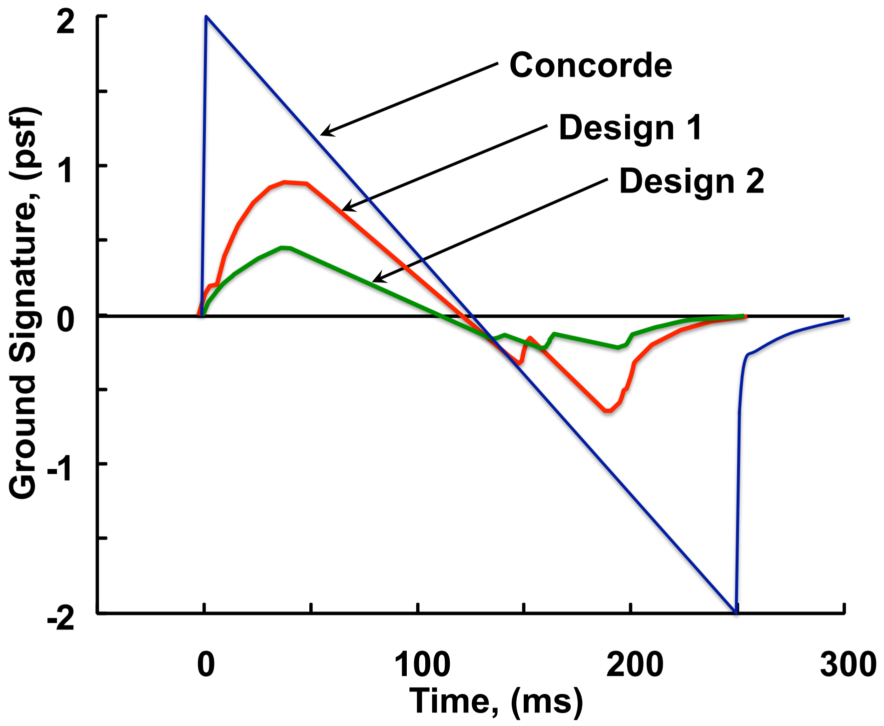
From Boom to Thump: How NASA is Addressing the Quiet Supersonic Design Technical Challenge

Objective

- Develop and validate tools and design approaches to enable the development of supersonic airliners with very little perceived supersonic noise:
  <75 PLdB, or about 30 dB less than Concorde and typical military aircraft

Approach

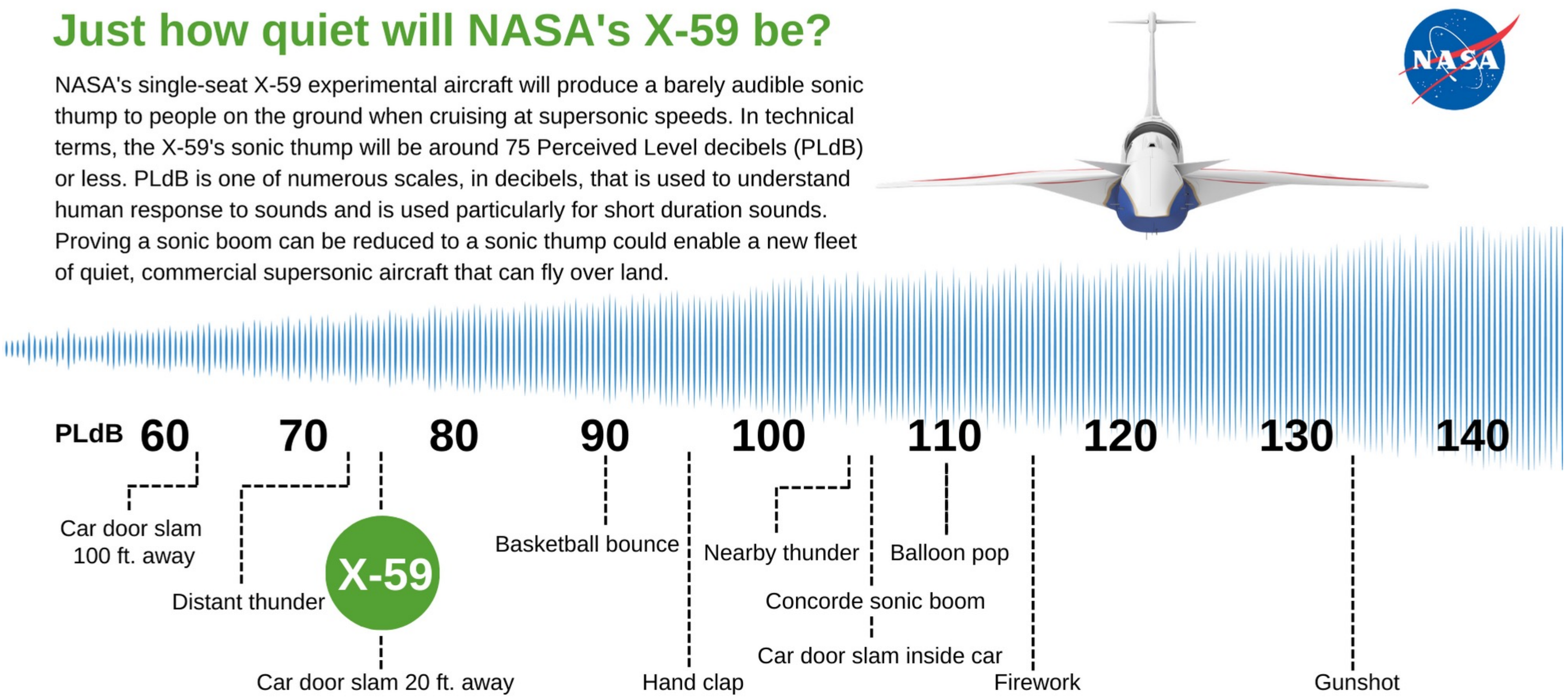
- Build on 40+ years of sonic boom minimization research
- Improve usability, accuracy and speed of high-fidelity analysis tools for inclusion in the design process
- Develop new near-field & ground signature design targets that produce less noise, and allow more flexibility in the design process
- Conduct validation studies in wind tunnels and in flight



Result

- NASA's breakthrough technology development has been validated in wind tunnels, now ready for flight demonstration

Sound Levels from Impulsive Noise Sources



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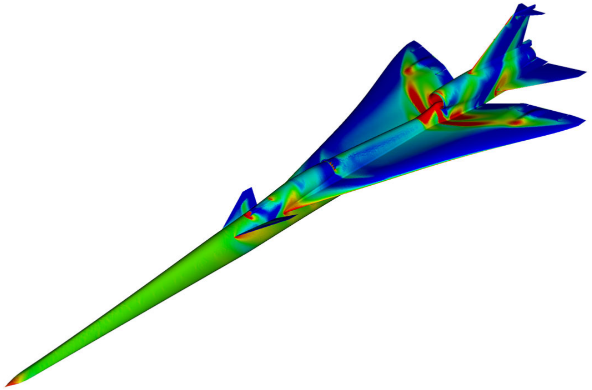


Tools for Studying Quiet Supersonic Flight

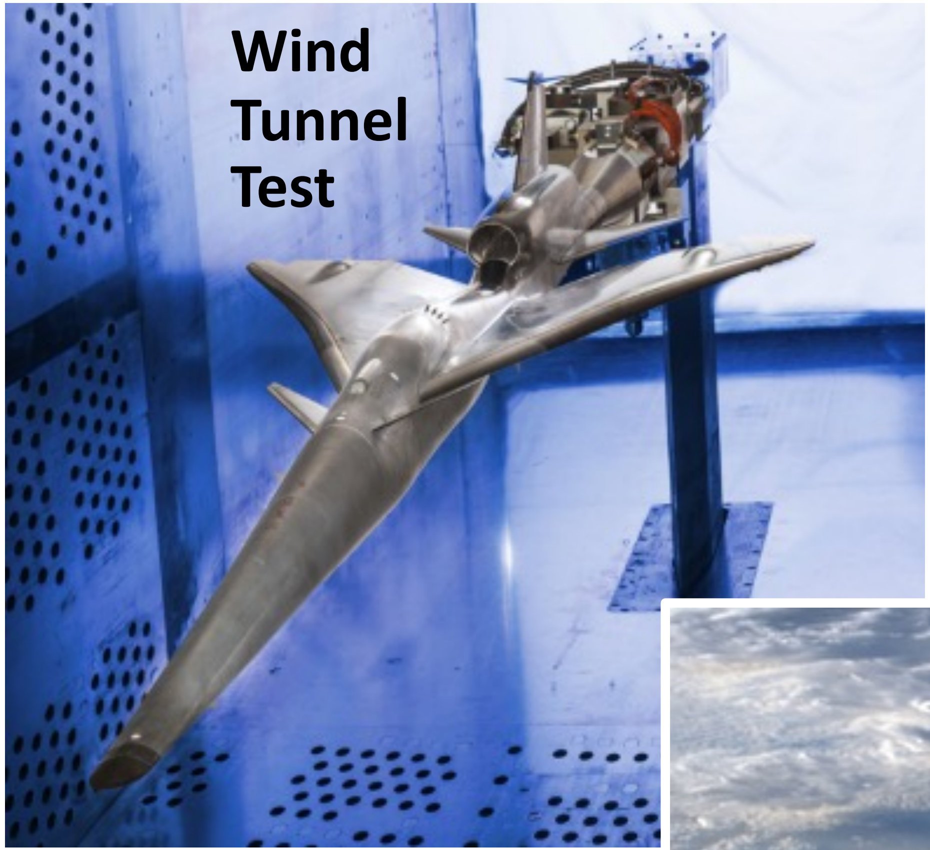


Image Credit: NASA Glenn Research Center

Computer
Simulation

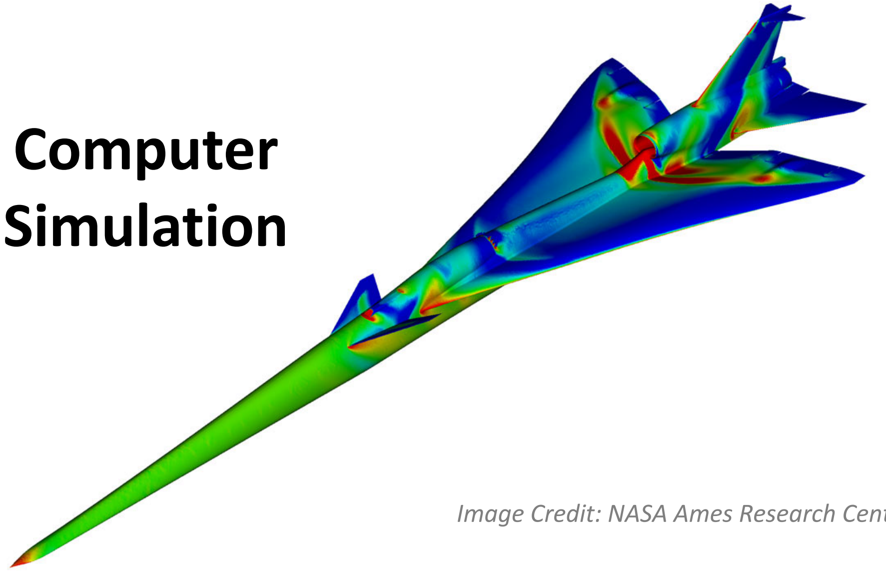


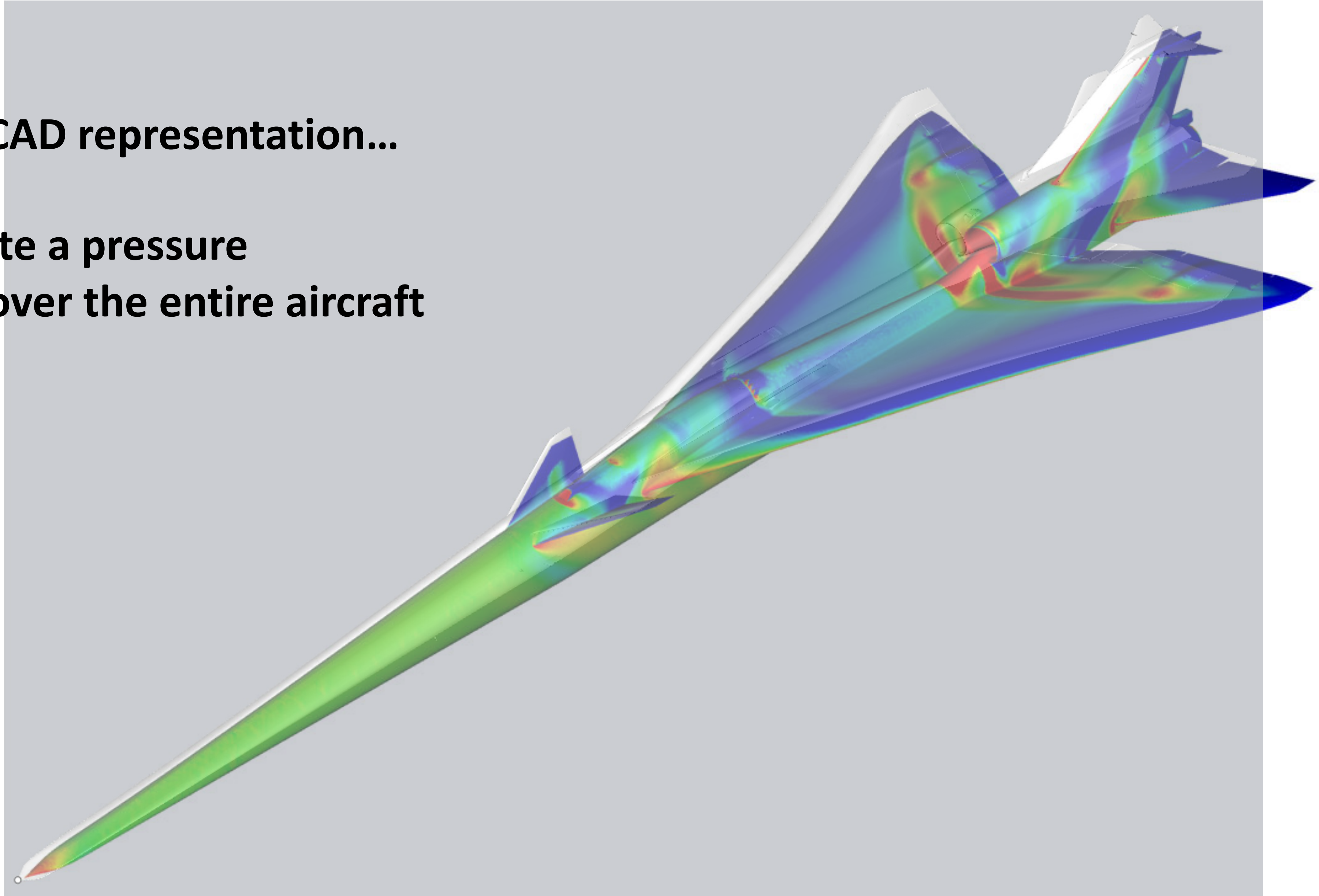
Image Credit: NASA Ames Research Center

Image Credit: Lockheed Martin

Computational Fluid Dynamics (CFD) for Computer Simulation of Aerodynamics and Sonic Boom

Start with a CAD representation…

…and compute a pressure distribution over the entire aircraft



Shock Wave Predictions for X-59

Predictions of surface and flow field pressures by LAVA

- Shock waves (higher pressures) in red
- Expansion waves (lower pressures) in blue

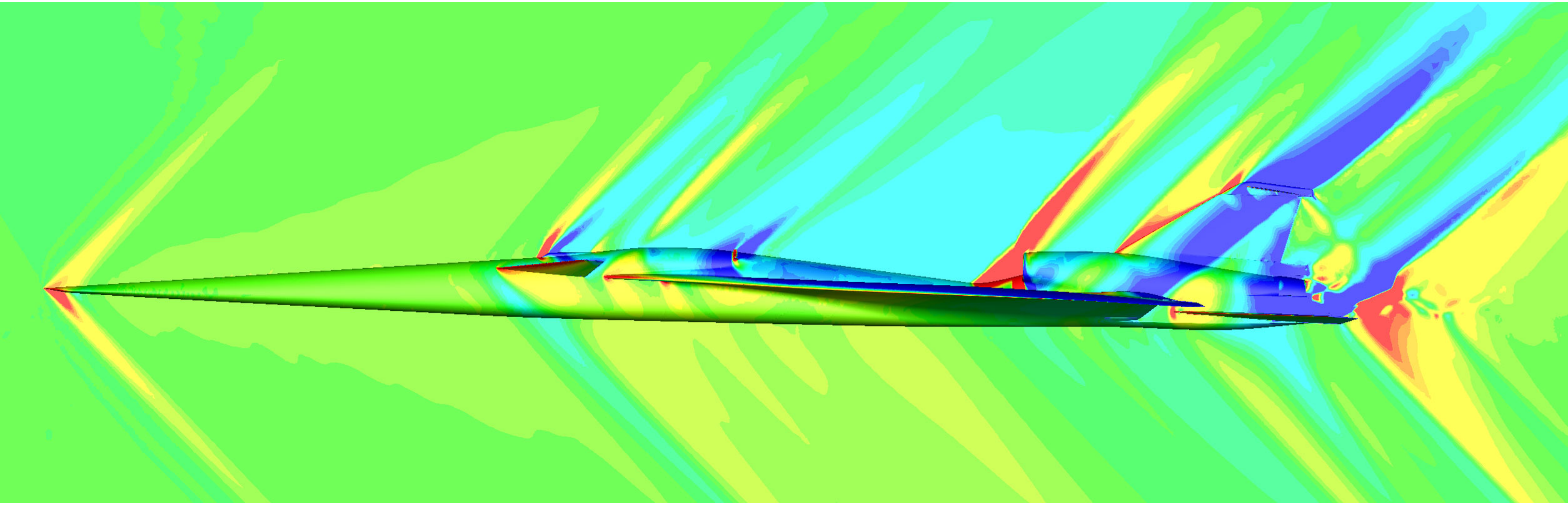
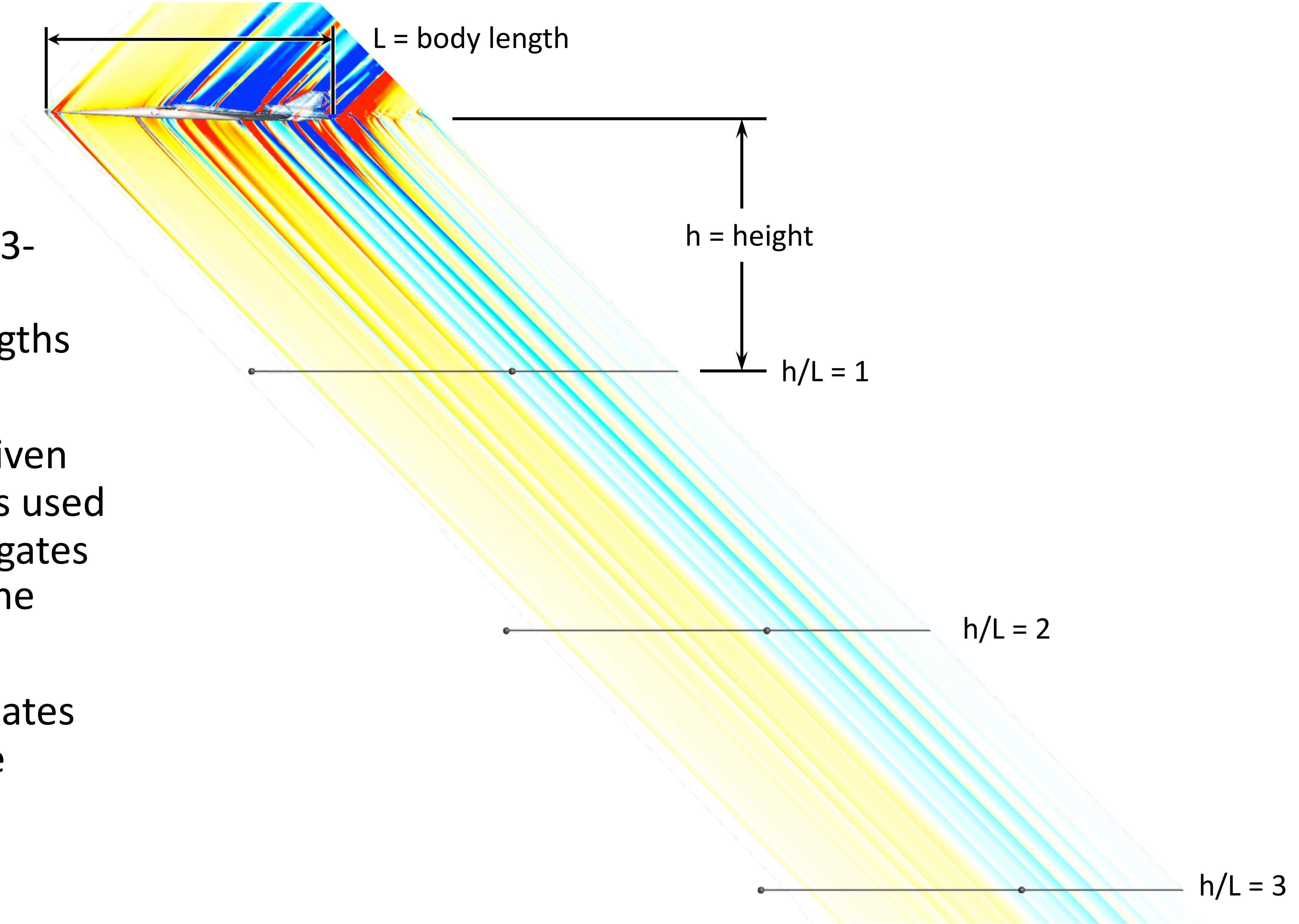


Image Credit: NASA Ames Research Center
https://www.nasa.gov/specials/X59/tools.html

Propagation of Shock Waves Towards Ground

- The Cart3D (Cartesian mesh, 3-dimensional) flow solution is extended to several body lengths away from the airplane
- The pressure signature at a given distance below the airplane is used as input to a code that propagates the signature all the way to the ground
- An acoustics code then calculates the predicted loudness of the signature at ground level



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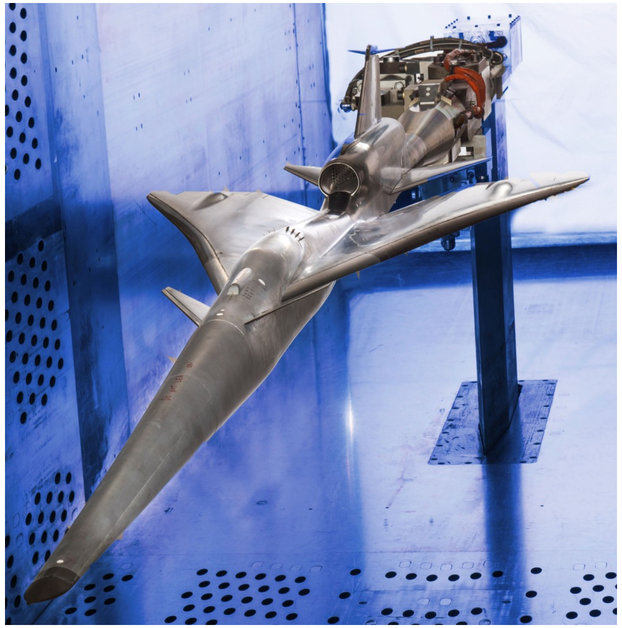
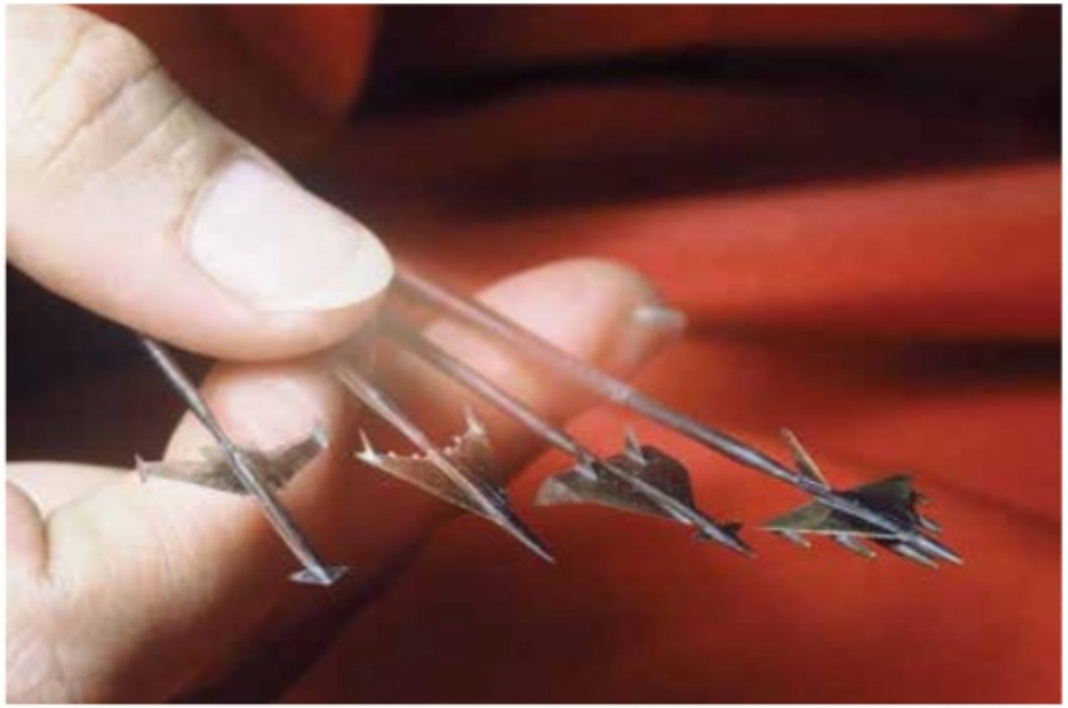


Mid-60's Langley Sonic Boom Tests

- Compared signatures for different model sizes
- Models made of XB-70, B-58, other supersonic concepts
- Tests conducted in Langley Unitary 4x4-ft Supersonic Wind Tunnels



(NASA photo, Courtesy of Harry Carlson)

Figure 9.4. Small sonic boom wind-tunnel models tested in the wind tunnel (ref. 9.1).

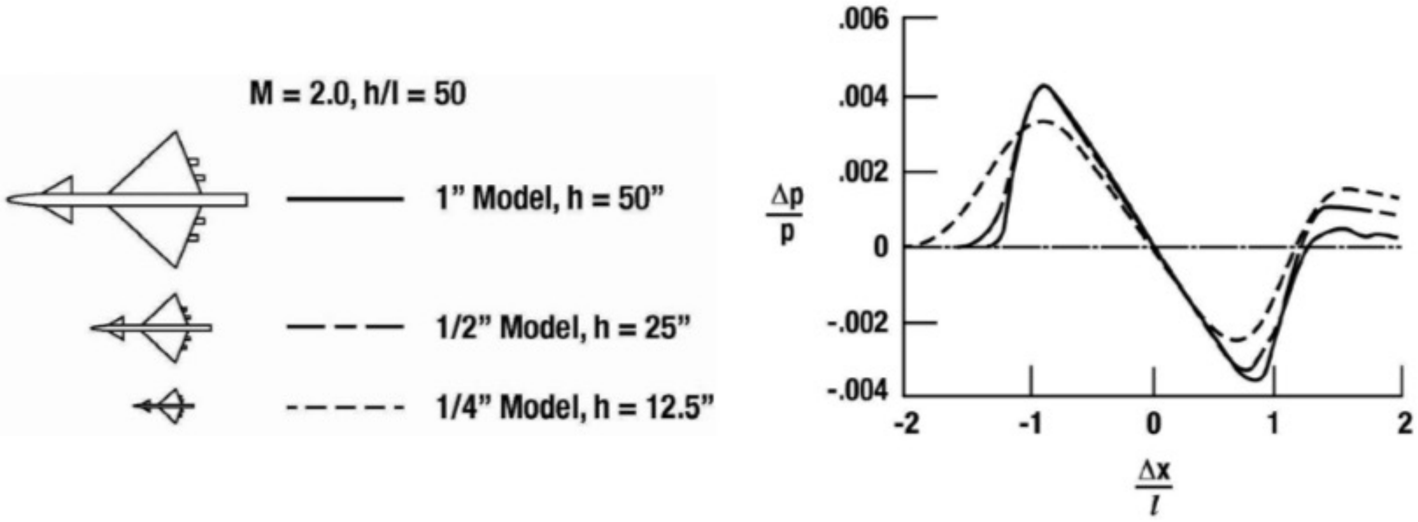
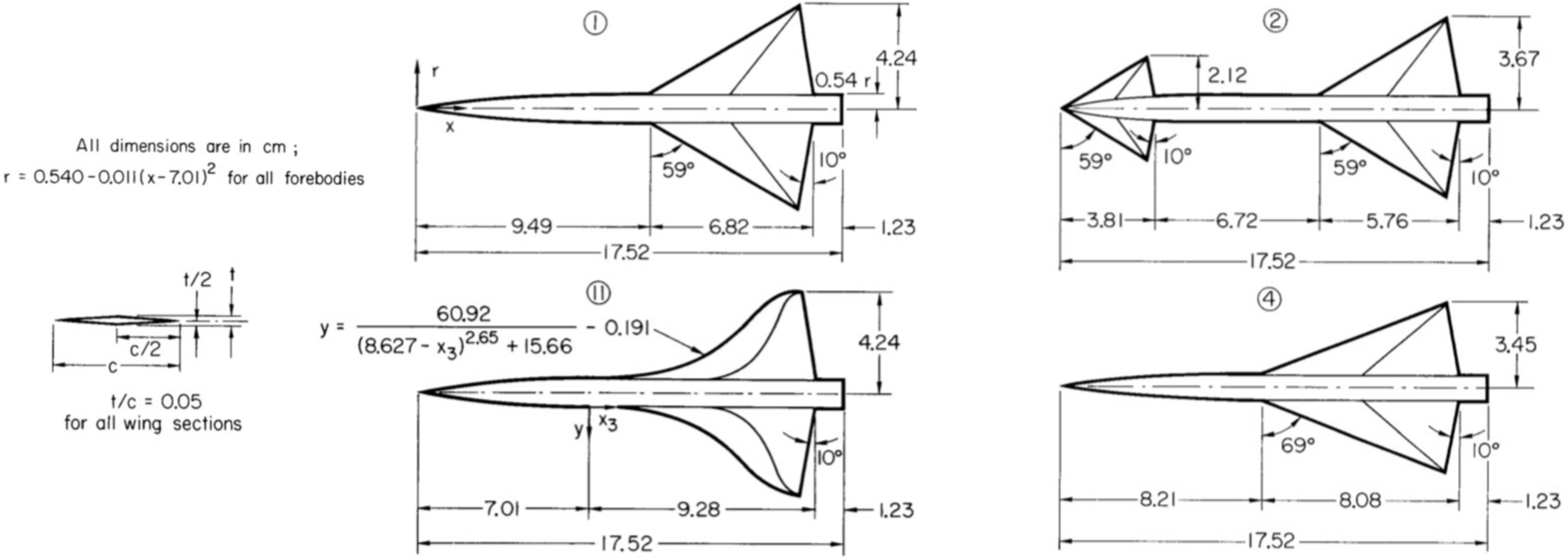


Figure 9.5. Effect of model size on measured signatures (adapted from ref. 9.4).

Maglieri et al, SONIC BOOM: Six Decades of Research, NASA/SP-2014-622, p. 396
Carlson & Morris, Wind Tunnel Sonic Boom Testing Techniques, Journal of Aircraft v. 4, no. 3, May–June 1967

Early 70's Ames Sonic Boom Tests

- Studies of planform effects
- 12 models: delta wings, swept edges, and curved edges
- Mach 1.68, 2.0 (Ames 9x7) and Mach 2.7 (Ames 8x7)

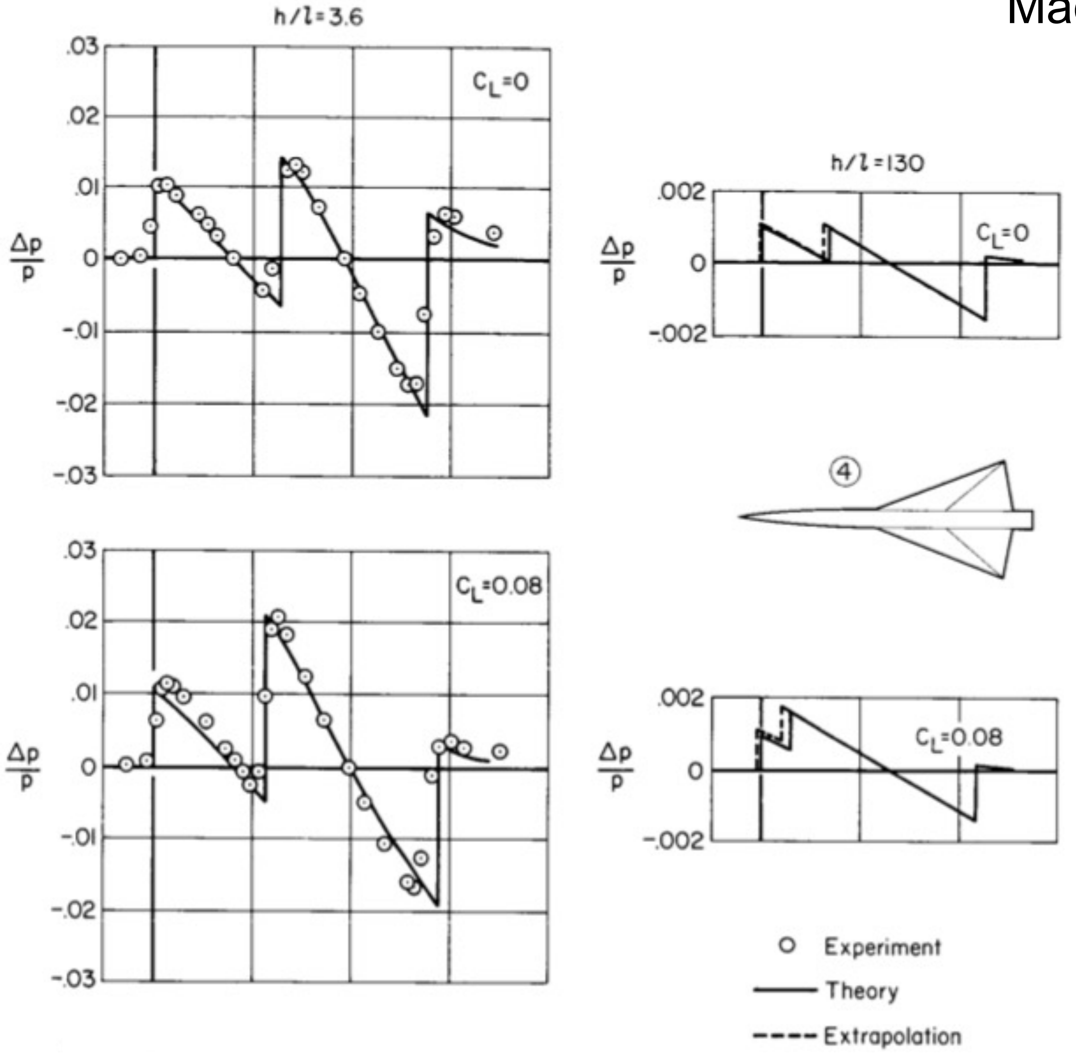


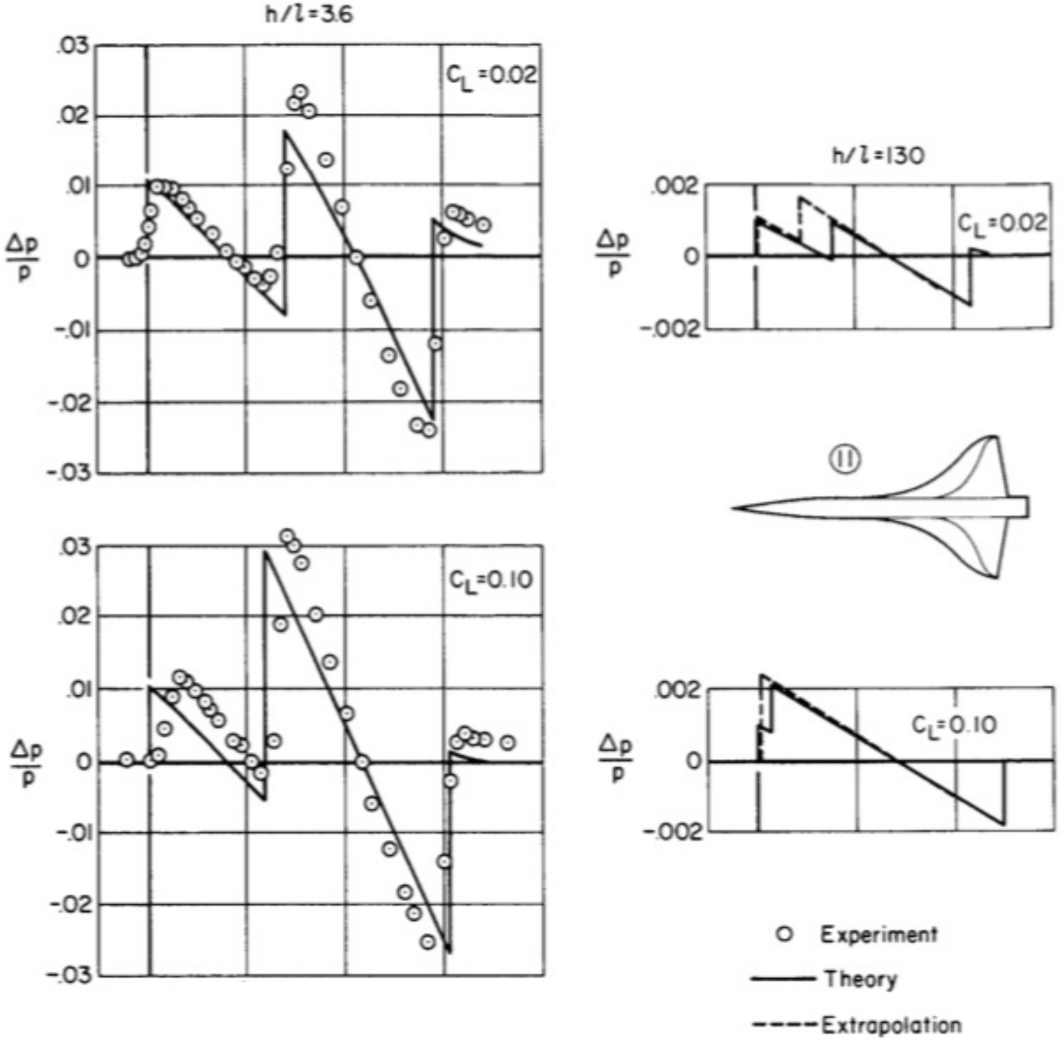
Hunton, Hicks, Mendoza: Some Effects of Wing Planform on Sonic Boom, NASA TN D-7160, January 1973

Early 70's Ames Sonic Boom Tests

Example signatures: comparison of theory and experiment for straight and curved delta wings

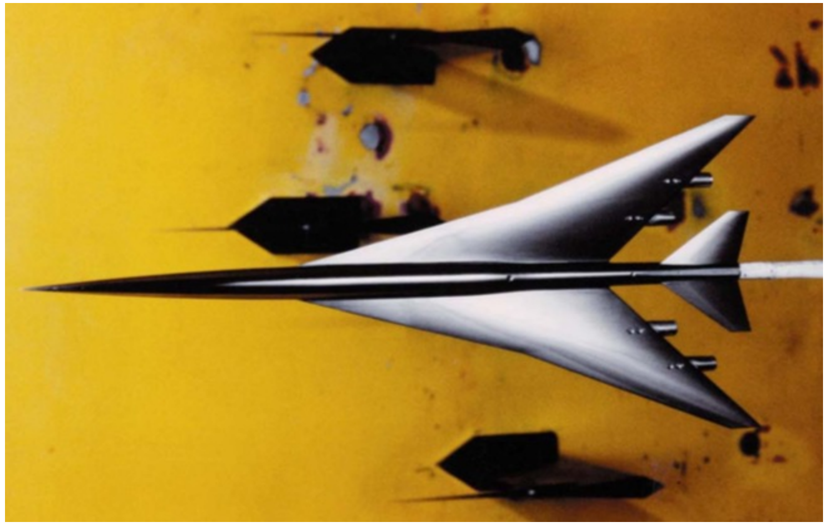
Mach 1.68





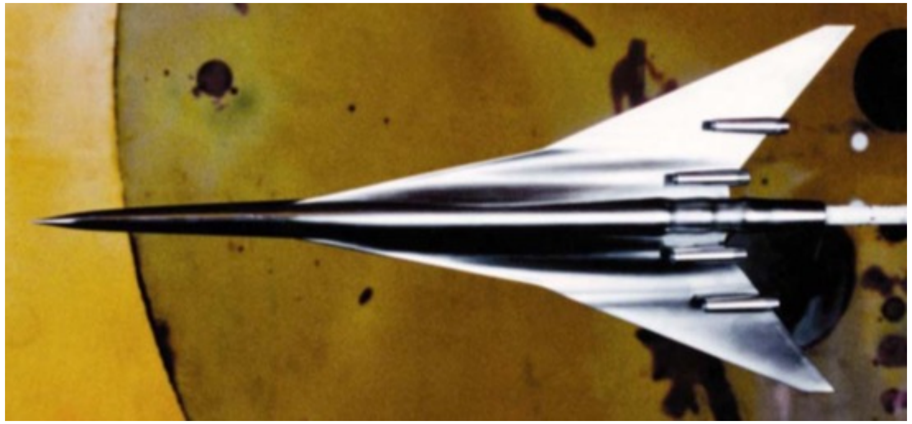
Hunton, Hicks, Mendoza: Some Effects of Wing Planform on Sonic Boom, NASA TN D-7160, January 1973

Early 90's Ames Sonic Boom Tests (9x7-Ft Wind Tunnel)

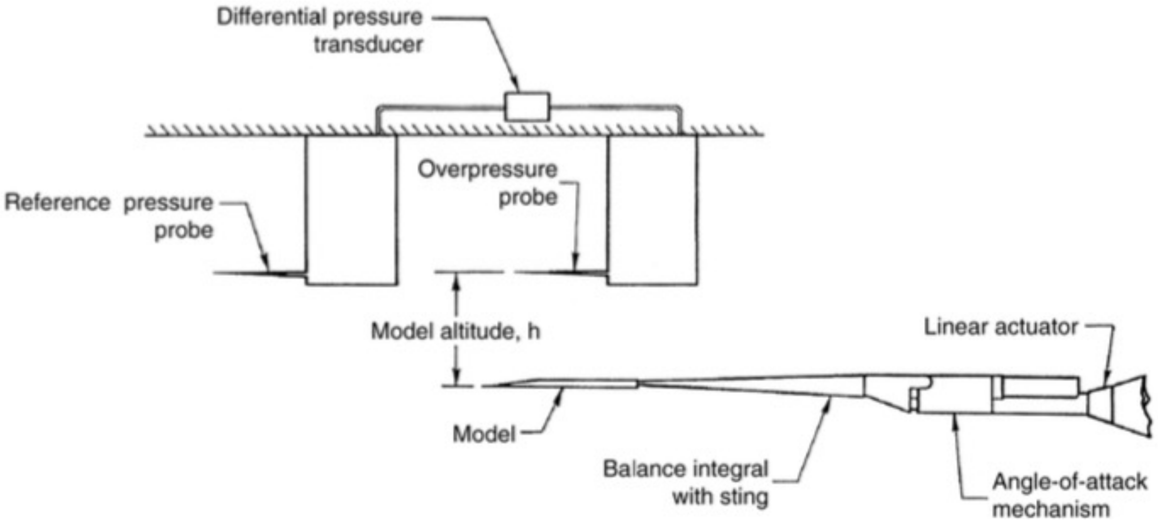


Low-boom wing-tail model

Low-boom wing-canard model



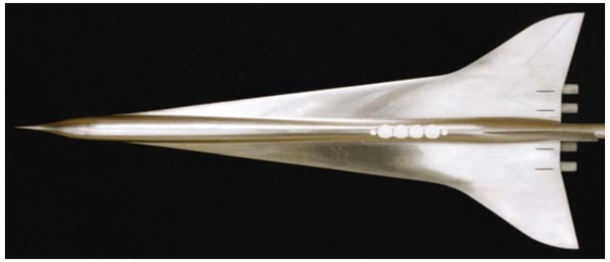
Boeing 1080-911 configuration

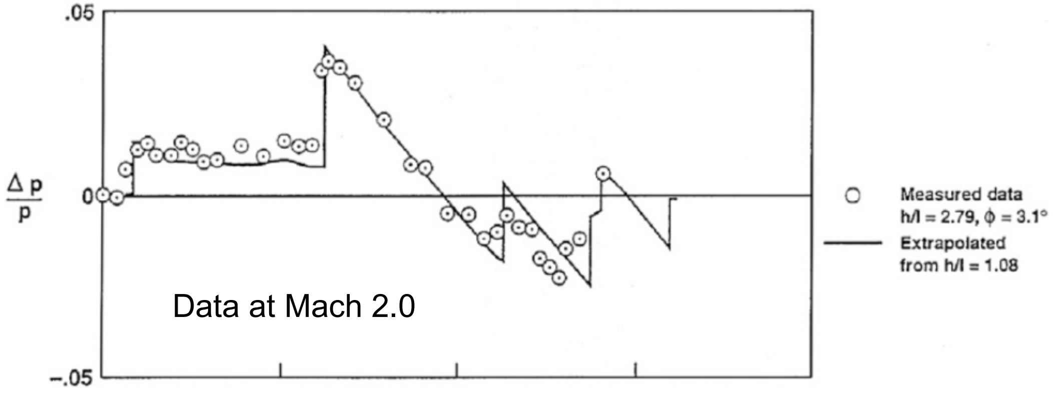


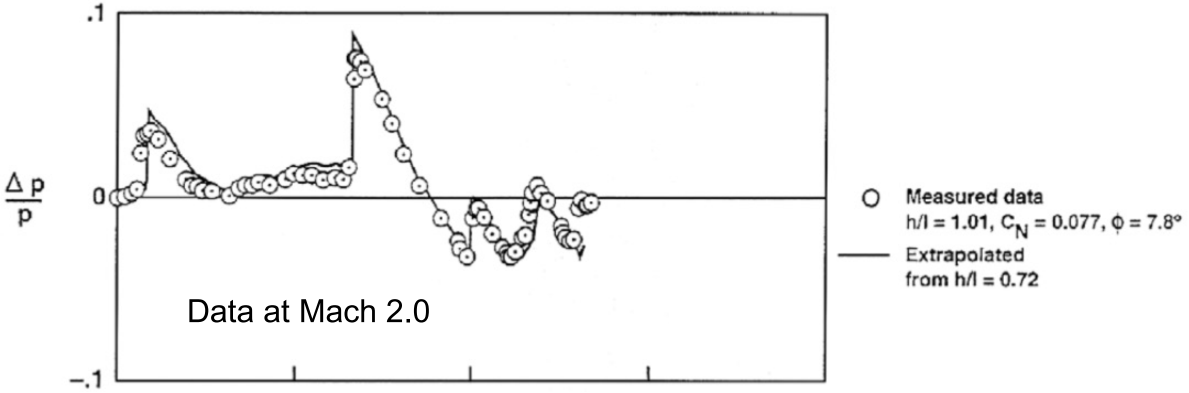
Mendoza, Hicks, Cliff: Wind Tunnel Sonic Boom Tests on Four High-Speed Civil Transport Models at Mach Numbers from 1.68 to 2.4, NASA TM-2008-214561, September 2008

Early 90's Ames Sonic Boom Tests (9x7-Ft Wind Tunnel)

Langley Mach 3 model







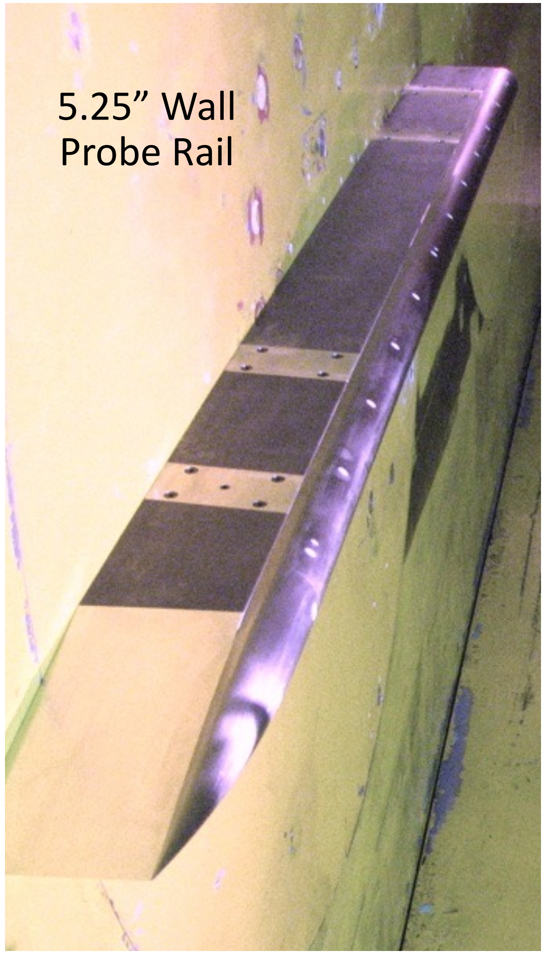
Mendoza, Hicks, Cliff: Wind Tunnel Sonic Boom Investigations of Two Different Models Designed to Generate Shaped Pressure Signatures, NASA TM-2008-214562, September 2008

2008 Sonic Boom Test in Ames 9x7 — Probes and Rails

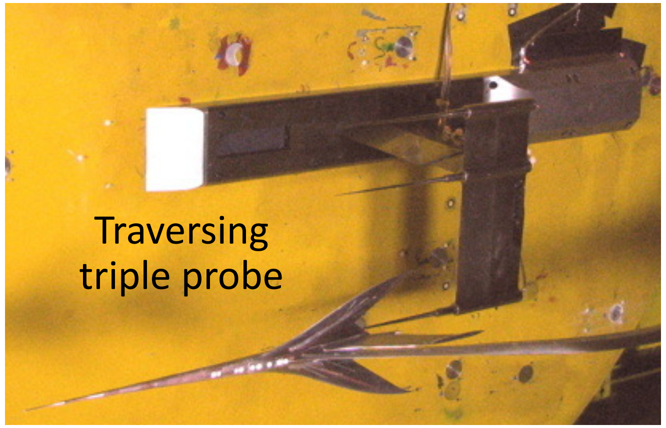
- Evaluated several pressure rails to acquire a line of data at one time instead of moving the model or probes in small increments over many minutes

Ames 2° Conical Probe on 10” Probe Holder

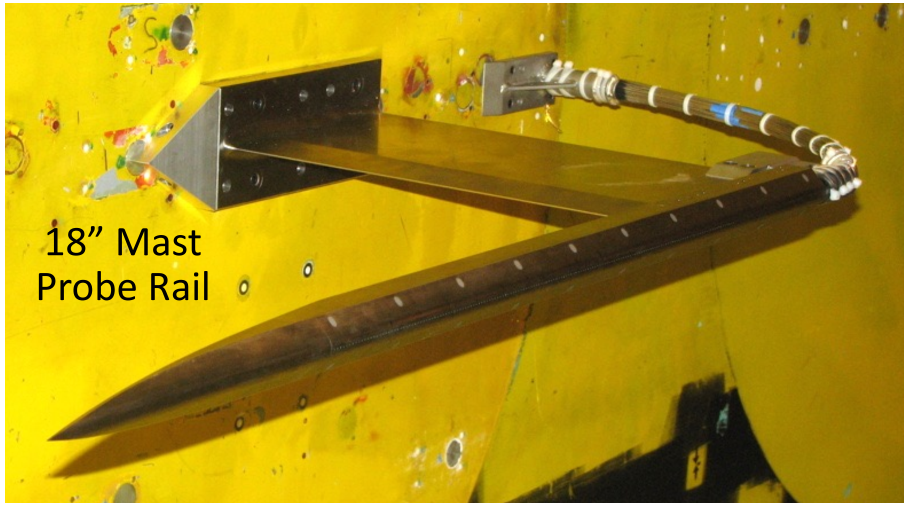
1.25” Wall Probe Rail



5.25” Wall Probe Rail



Traversing triple probe



18” Mast Probe Rail

Durston, Donald A. et al: *Near-Field Sonic Boom Test on Two Low-Boom Configurations Using Multiple Measurement Techniques at NASA Ames*. AIAA 2011-3333, 29th AIAA Applied Aerodynamics Conference, Honolulu HI, June 2011

Lockheed and Boeing Concepts Tested in Wind Tunnels

- **In 2009, NASA contracted Lockheed and Boeing to design future supersonic commercial transports that would have quiet sonic booms**
- **Small-scale wind tunnel models were made of these concepts and were tested in NASA Ames and Glenn supersonic wind tunnels**

Image credit: The Boeing Company
https://www.nasa.gov/aero/centers_tackle_sonic_boom.html

Image credit: Lockheed Martin Corporation
https://www.lockheedmartin.com/en-us/news/features/2016/webt-supersonic-flight-hush-sonic-boom.html

Boeing Low-Boom 0.65%-Scale Model in Ames 9x7-Ft Supersonic Wind Tunnel

<u>SONIC BOOM WIND TUNNEL TESTING 101</u>

- This model is 15.75” long
- Pressure rail on side wall of tunnel has 420 tiny orifices along 66” of its thin edge for measuring pressure distribution below underside of model
- Pressure distribution shows us where shock and expansion waves are below model, such as on ground track under airplane flying overhead
- Computer codes are used to theoretically extrapolate these pressures to ground level, from which we calculate boom loudness

Image Credit: NASA Ames Research Center

Boeing Low-Boom 1.79%-Scale Model in Ames 9x7-Ft Supersonic Wind Tunnel

- Same airplane configuration as model on previous slide, but this model is 2.75 times larger
- Larger model was used primarily for aerodynamic measurements (lift, drag, etc)
- It is not very suitable for sonic boom measurements because it is too long (43”) for the pressure rail (66”-long instrumented length)
- Combination of this model and the small model give us the aerodynamics and sonic boom pressure signature — both are critical for validating airplane design

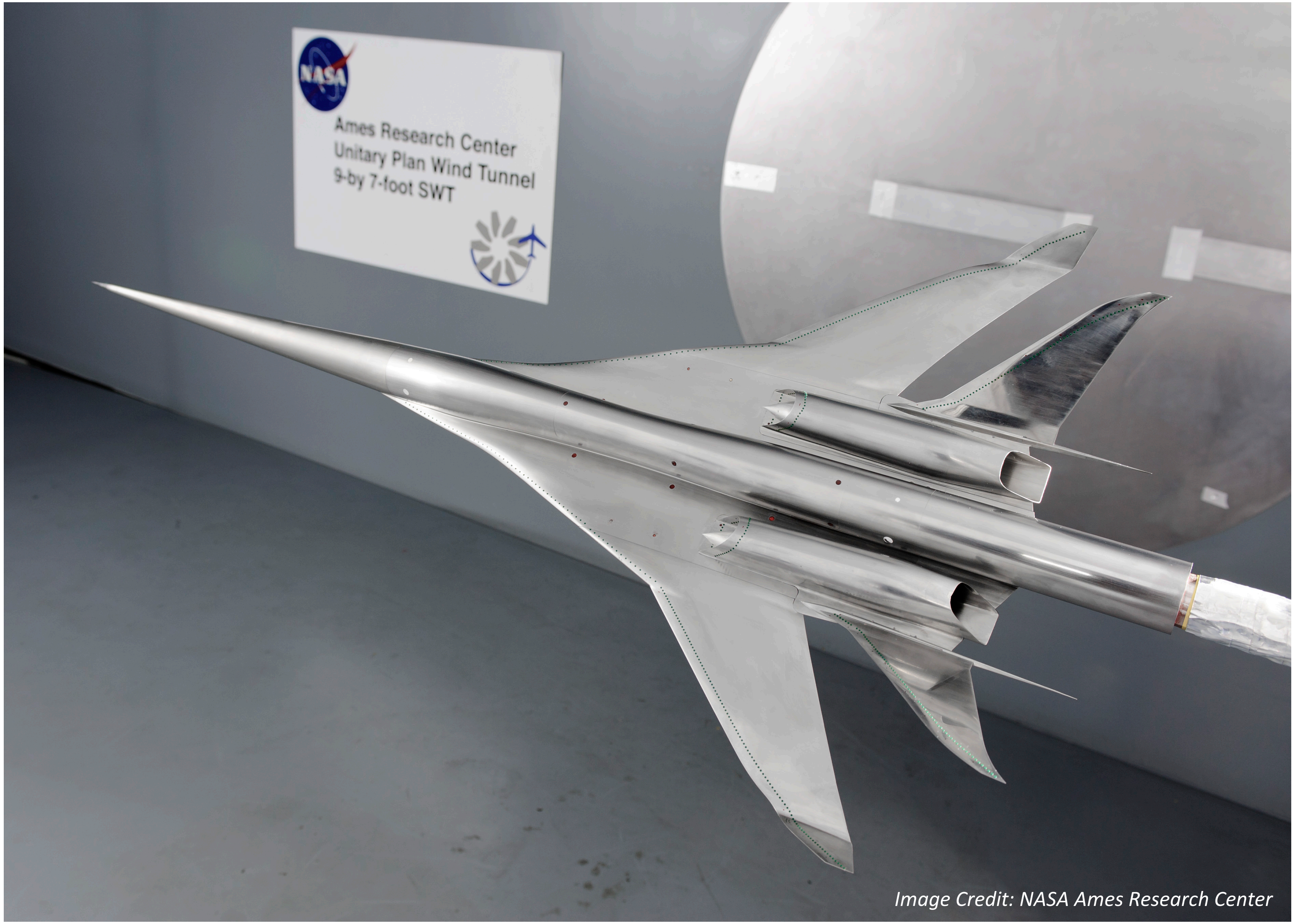


Image Credit: NASA Ames Research Center

Lockheed Low-Boom 0.8%-Scale Model in Ames 9x7-Ft Supersonic Wind Tunnel

- Support hardware in tunnel allows movement of model
  - fore and aft for measuring pressures along length of rail
  - side to side for varying distance from model to rail
- Hundreds of test conditions and model positions and angles are run in a test
- Typical sonic boom test takes about two weeks of running at two shifts per day
- This tunnel is power-hungry—cost of electricity (uses up to 175 MW) + personnel + maintenance costs are almost $3/second!

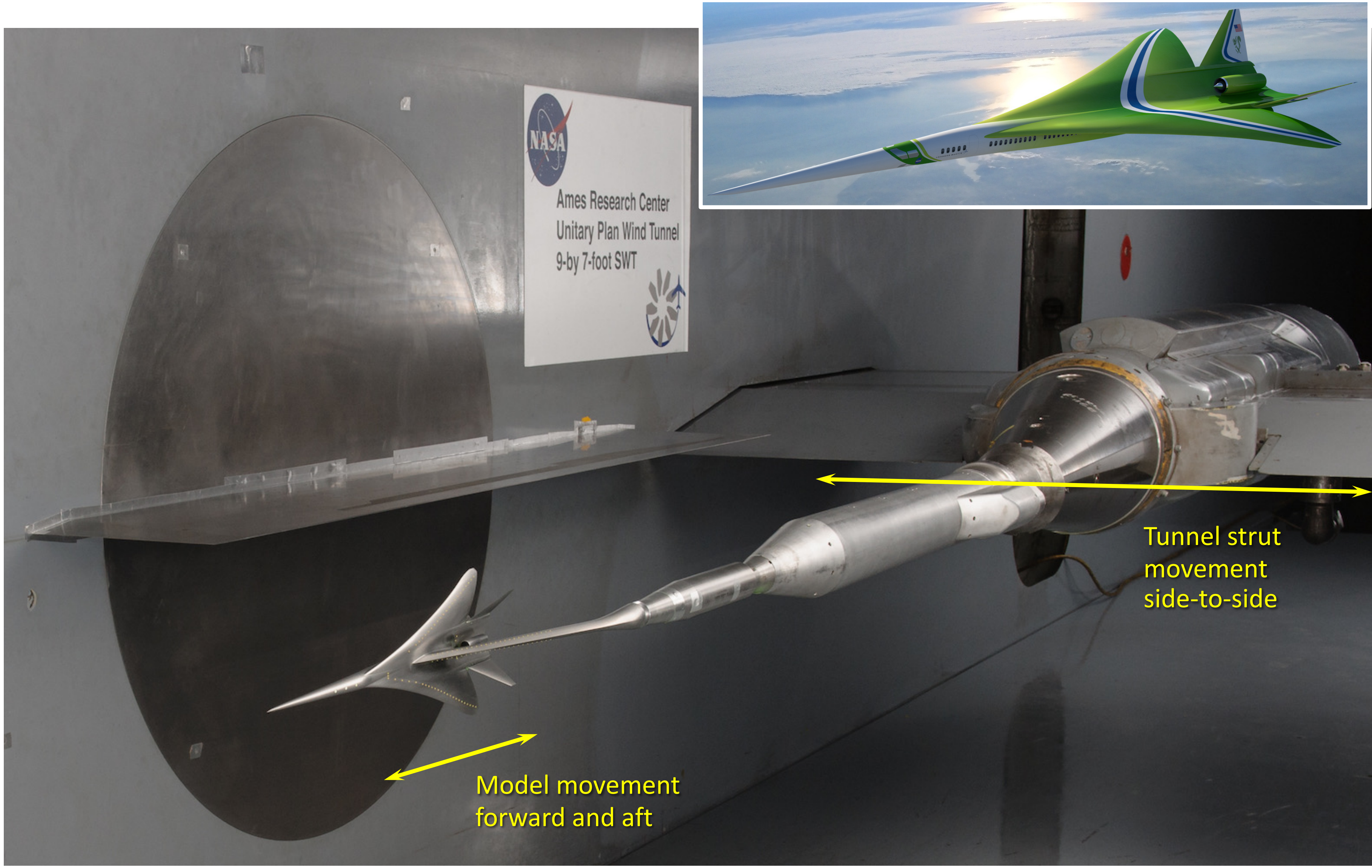


Image Credit: NASA Ames Research Center

Schlieren Image of Boeing 0.65%-Scale Model in Glenn 8x6-Ft Supersonic Wind Tunnel

- Schlieren is German for “streak”
- Bright, columnated light is shone across tunnel through side windows
- Shock and expansion waves show up as density gradients in the flow
- Test condition: Mach 1.8 (about 1200 mph)
- 56.3° shock wave angle from vertical = $\cos^{-1}(1/M)$

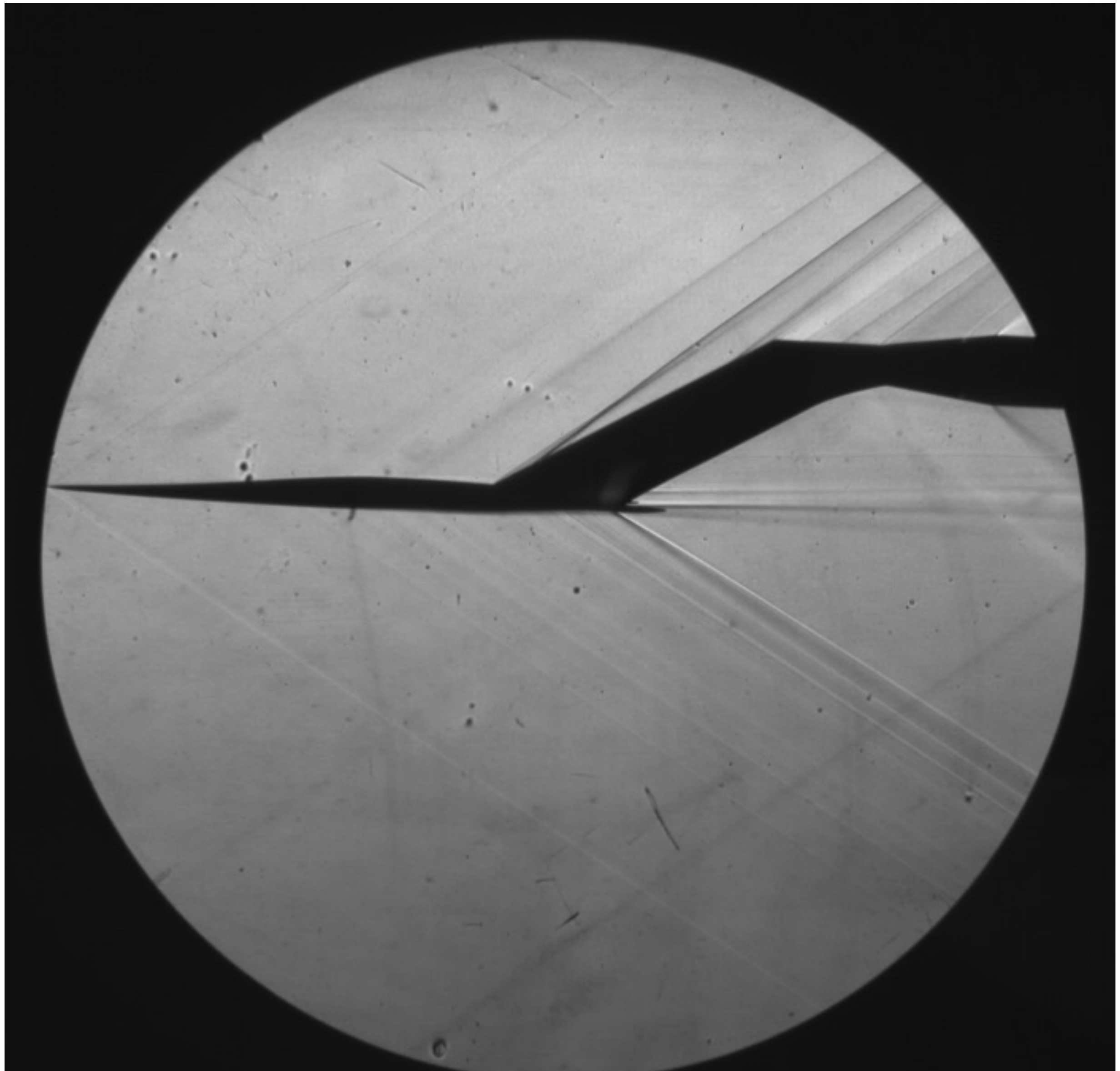


Image Credit: NASA Glenn Research Center

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AirBOS Image of T-38 in Flight

AirBOS:
Air Background-Oriented Schlieren

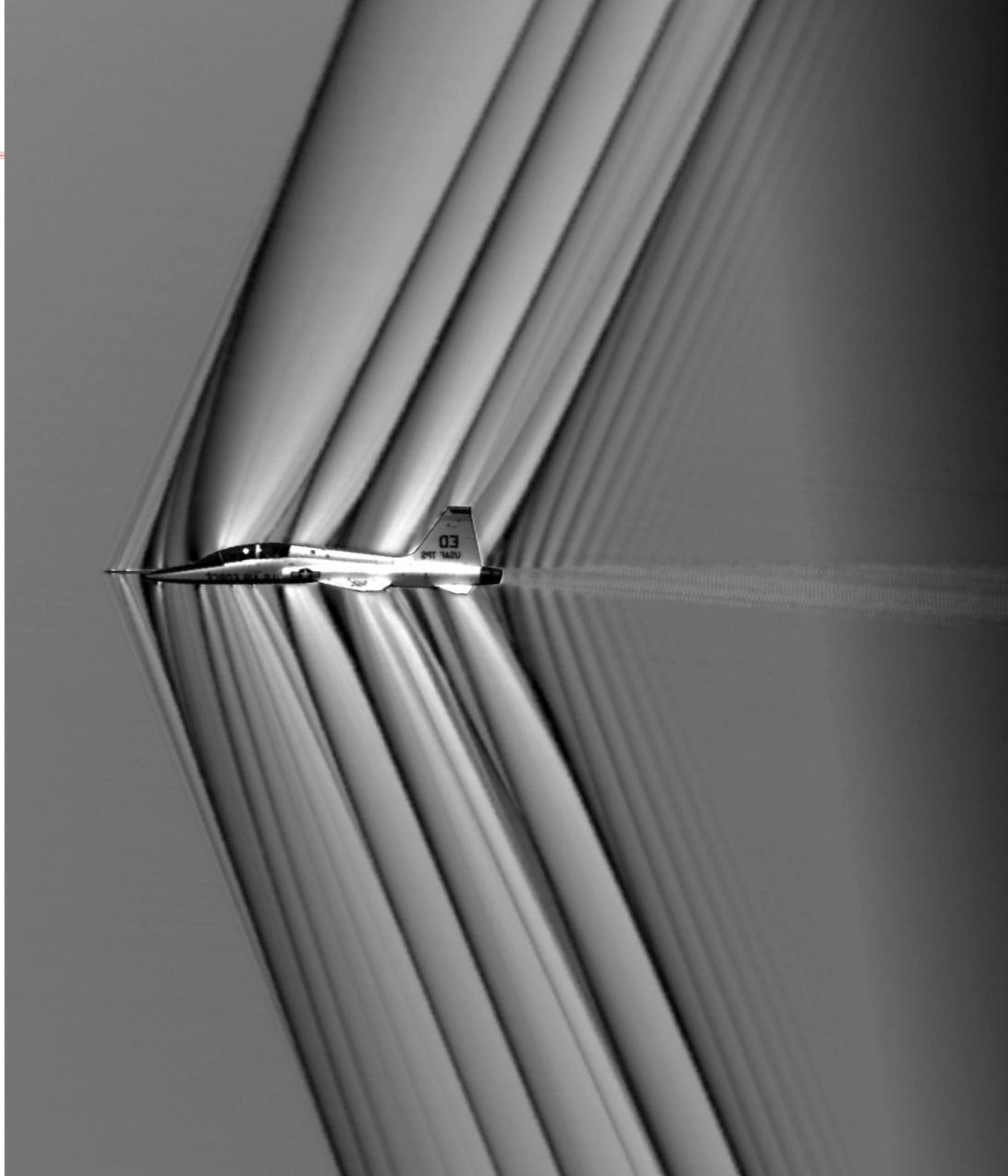
- Target airplane makes supersonic pass below camera airplane (typically the NASA King Air)
- Multiple images taken
- Distortions in viewing background are caused by shock wave density gradients
- Aligning images and processing results gives clean view of flow field without background

Image Credit: NASA Ames Research Center and NASA Armstrong Flight Research Center
https://aviationweek.com/aviation-week-space-technology/2015-09-07

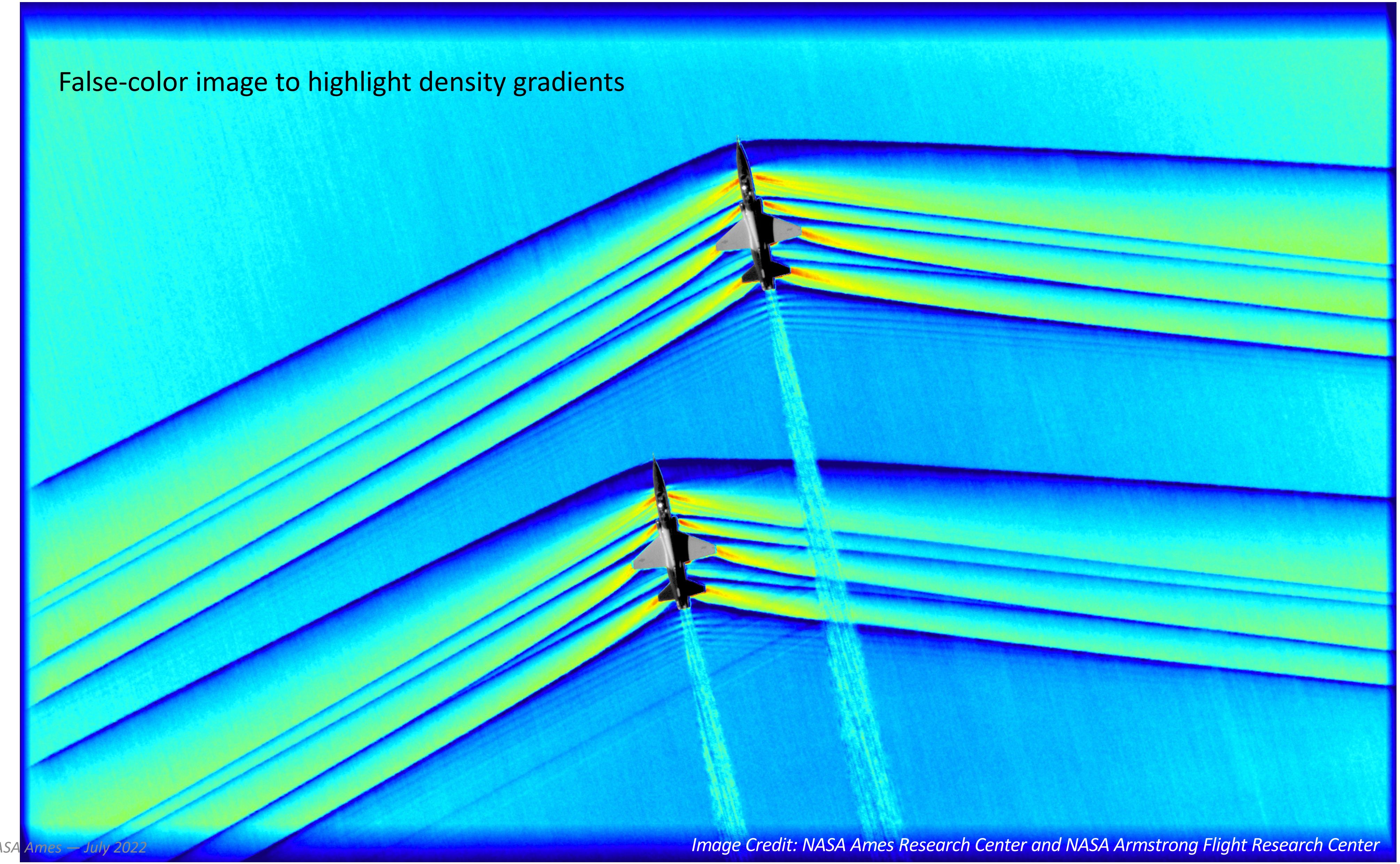
AirBOS Image of T-38 in Flight

- T-38 supersonic jet flying at Mach ~1.08
- Series of high-speed photographic images were processed to reveal the structure of shock and expansion waves above and below the aircraft
- Lots of flow detail visible close to the aircraft, but shocks merge as they get further away

Image Credit: NASA Ames Research Center and NASA Armstrong Flight Research Center
https://www.nasa.gov/centers/armstrong/features/supersonic-shockwave-interaction.html



AirBOS Image of Two T-38s in Formation



BOSCO Image of T-38 in Flight

BOSCO:
Background-Oriented Schlieren
using Celestial Objects

- Target airplane makes supersonic pass between sun and observer
- Observer on ground takes multiple images

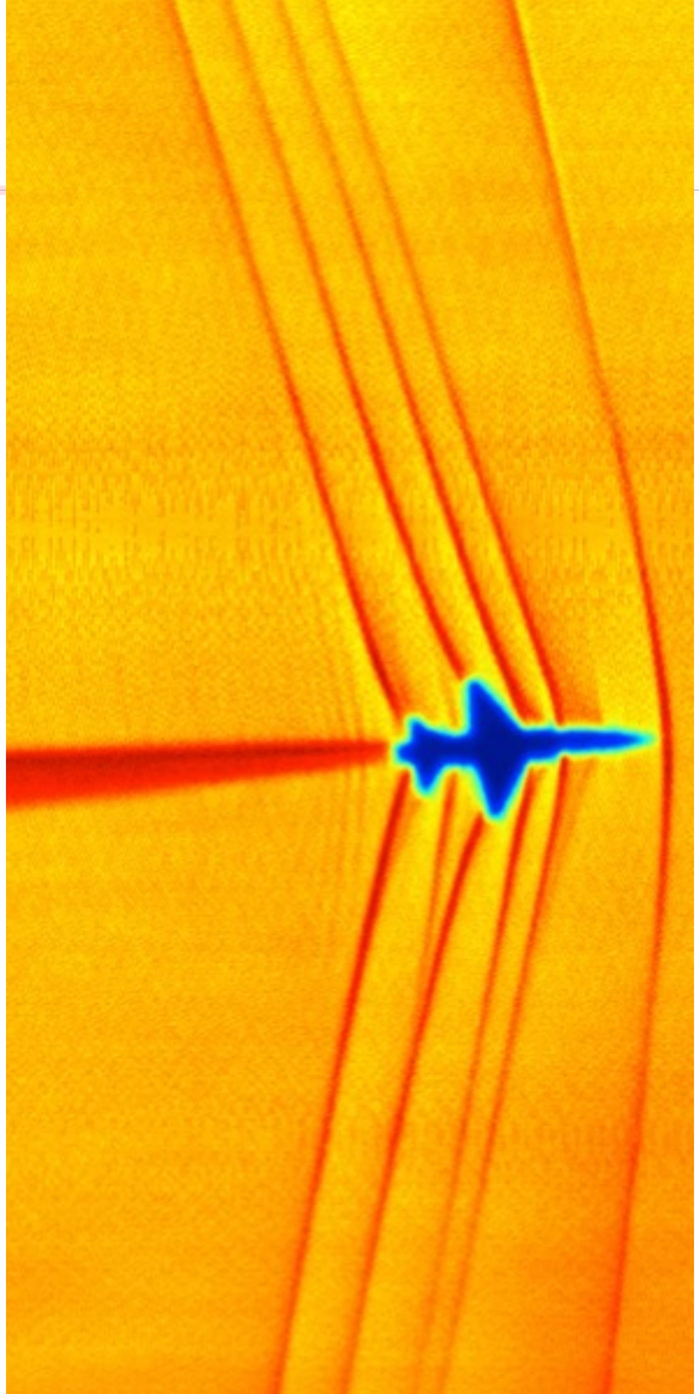


Image Credit: NASA Armstrong Flight Research Center

Outline

- Brief history of supersonic flight
- Shock waves and sonic booms
- Sonic boom pressure signatures and loudness
- Tools for studying quiet supersonic flight
  - CFD (Computational Fluid Dynamics)
  - Wind tunnels
  - Flight test
- Quesst Mission
  - X-59 airplane
  - Mission profile
  - Flight simulations
  - Wind tunnel data validations
- Video: Supersonic flight research leading to Quesst

Quesst Mission

...to demonstrate <u>quiet</u> sonic boom technology

NASA X-59

Image Credit: Lockheed Martin

The inspiration for this design draws heavily from the images captured from 2019's Air-to-Air Background Oriented Schlieren flight series, which recorded images of intersecting shockwaves from supersonic jets.

SHOCKWAVES

The supersonic shockwaves do not merge, enabling the X-59 to produce a quieter sound to people on the ground.

AIRCRAFT

The aircraft represents the X-59, which will be flown over U.S. communities to elicit residents' responses to its sounds.

LAND CRESCENT

The crescent represents land, highlighting the crucial and unique aspect of our mission – commercial supersonic flight **over land**.

HOUSES

The three houses represent the communities of residents who will provide the data that could lead to commercial supersonic flight over land.

Blue and green symbolize the Earth, which is where NASA's Quesst to enable quiet supersonic flight over land is taking place, and where the value of NASA's aeronautics research is experienced by humankind every day.

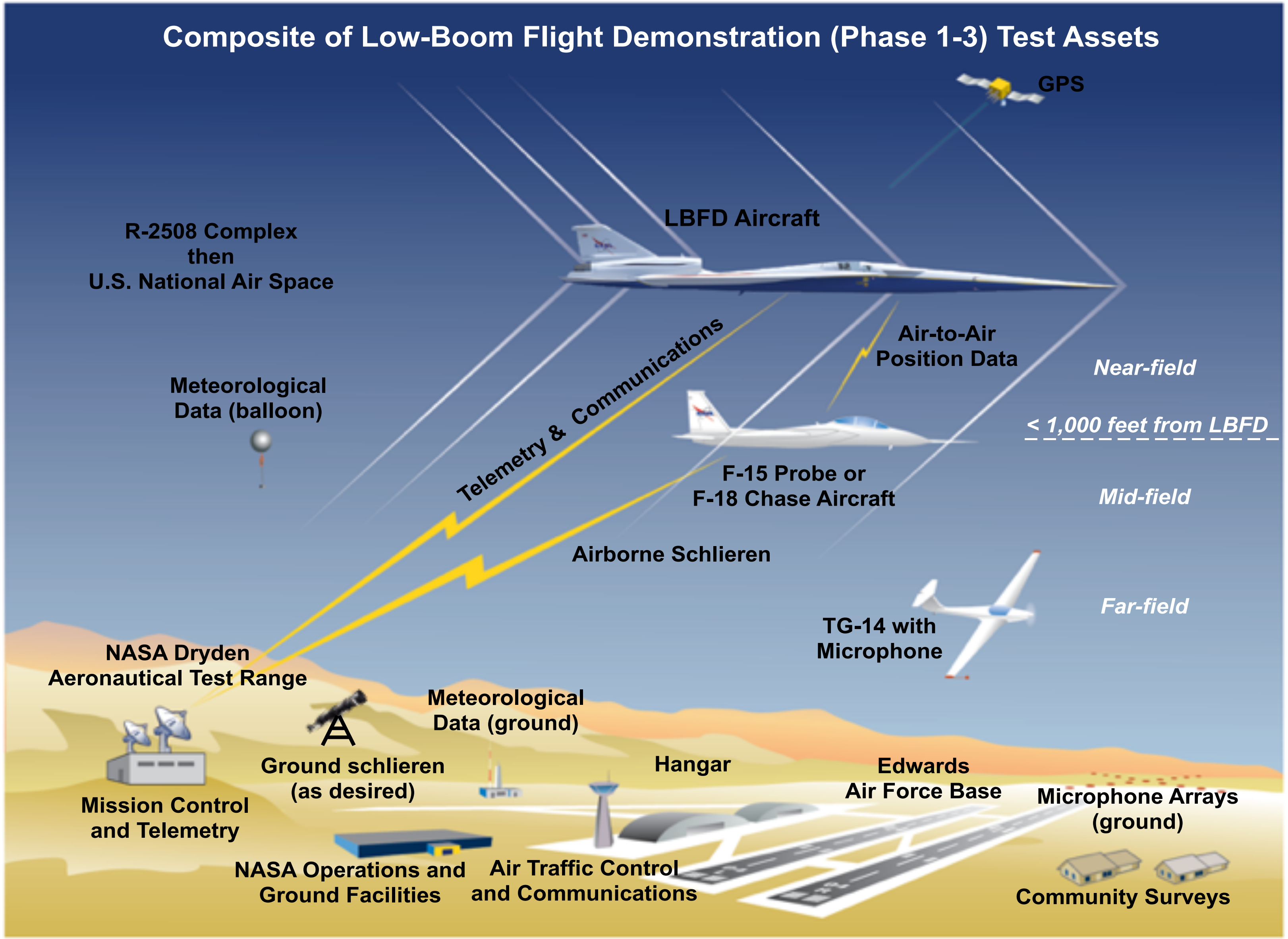
Quesst Mission Goal and Schedule

- *Goal is FAA (Federal Aviation Administration) and ICAO (International Civil Aviation Organization) rule change to allow supersonic flight over land for aircraft that have quiet sonic boom*
- *Opens door for development of a new generation of environmentally-friendly supersonic civil transport aircraft*

- *June 2017: Preliminary Design Review*
- *April 2018: Contract award to Lockheed Martin to build aircraft*
- *2022–2023: First flight, envelope expansion, boom validation testing*
- *2024 & later: Flight tests over populated areas to get community responses*

Image Credit: Lockheed Martin

X-59 Flight Test Concept of Operations



Project Phases

Phase 1 - Aircraft Development

- Detailed Design
- Fabrication, Integration, and Ground Test
- Checkout Flights
- Subsonic Envelope Expansion
- Supersonic Envelope Expansion

Phase 2 – Acoustic Validation

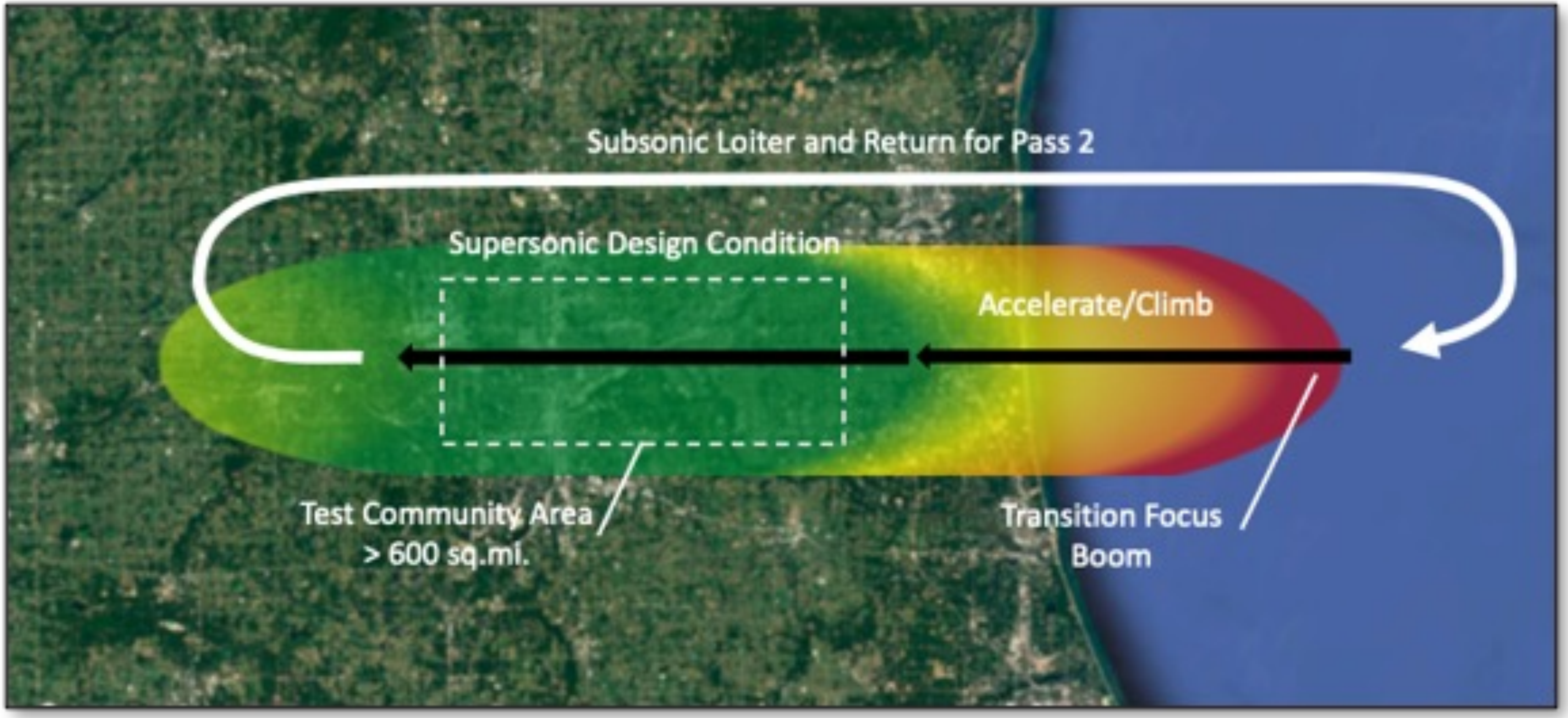
- Aircraft Operations / Facilities
- Research Measurements

Phase 3 – Community Response

- Initial community response overflight study
- Multiple campaigns (4 to 6) over representative communities and weather across the U.S.

Mission Profile for X-59 Flights

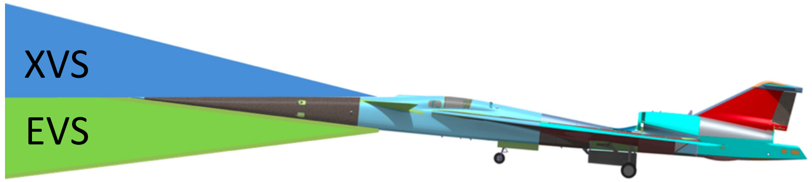
Concept of Operations: Representative Community Response Deployment



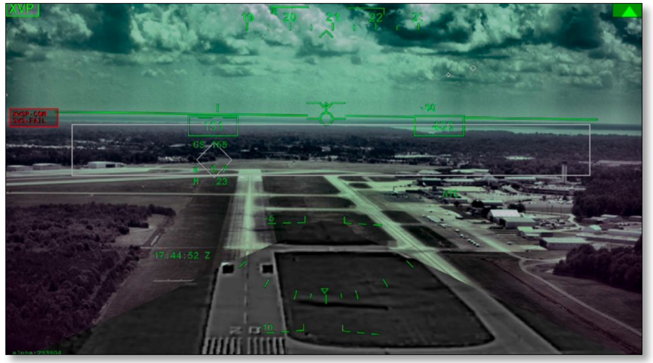
X-59 eXternal Vision System

Concept View of X-59 Cockpit

Camera Viewing Angles



Cameras on Flight Test Aircraft



XVS Image During Flight Test

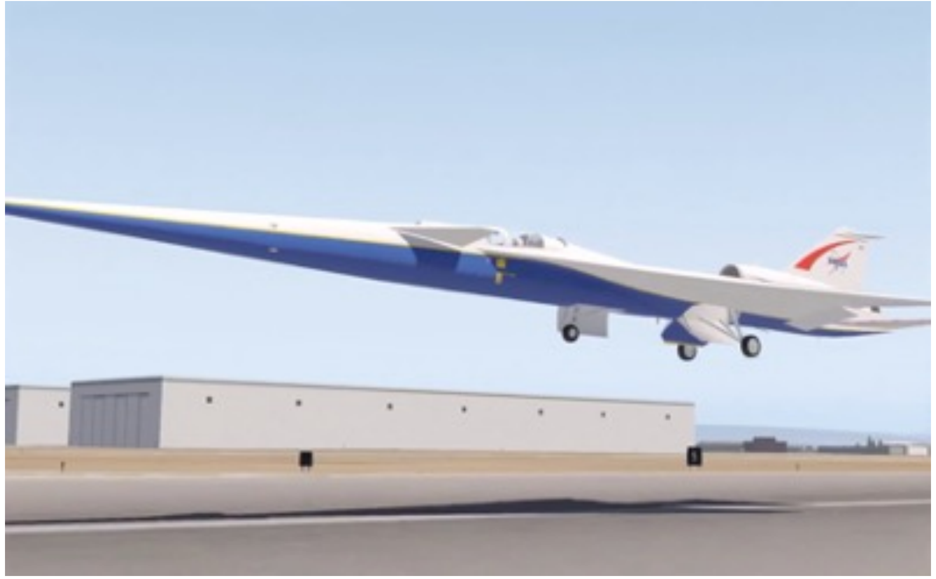
XVS Station in Flight Test Aircraft

Flight Simulator Development

- Aircraft and cockpit simulations validate aircraft designs, systems, and performance – also used for pilot training and flight planning

X-59 Flight Simulator Models Available for Download

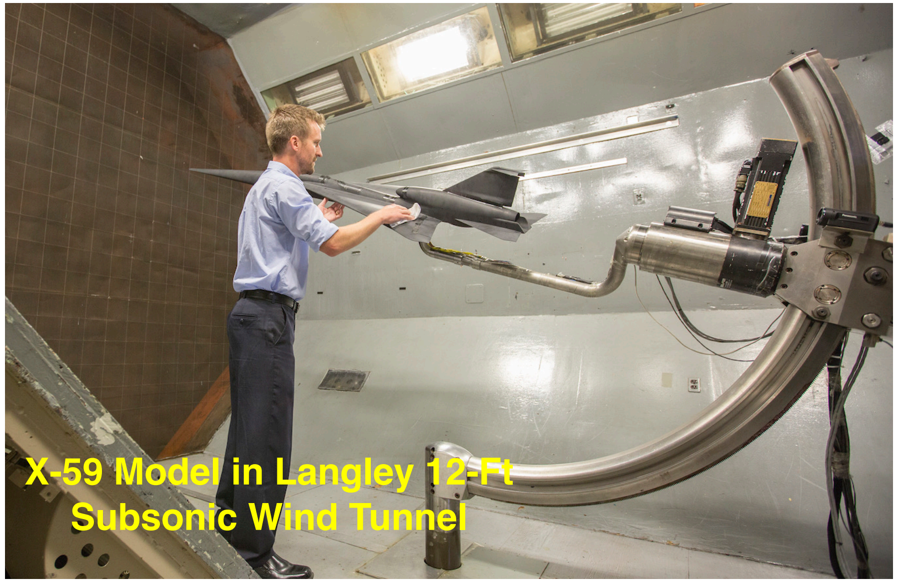
- Undergraduate interns at NASA Ames, Armstrong, and Langley spent the summer of 2019 competing to develop a laptop flight simulator of the X-59
- Simulations were made in X-Plane software
- Students were given airplane geometry, but had to build up the aerodynamics, propulsion, stability and control on their own
- Each team made a promotional video of their configuration
- Simulation models available for download

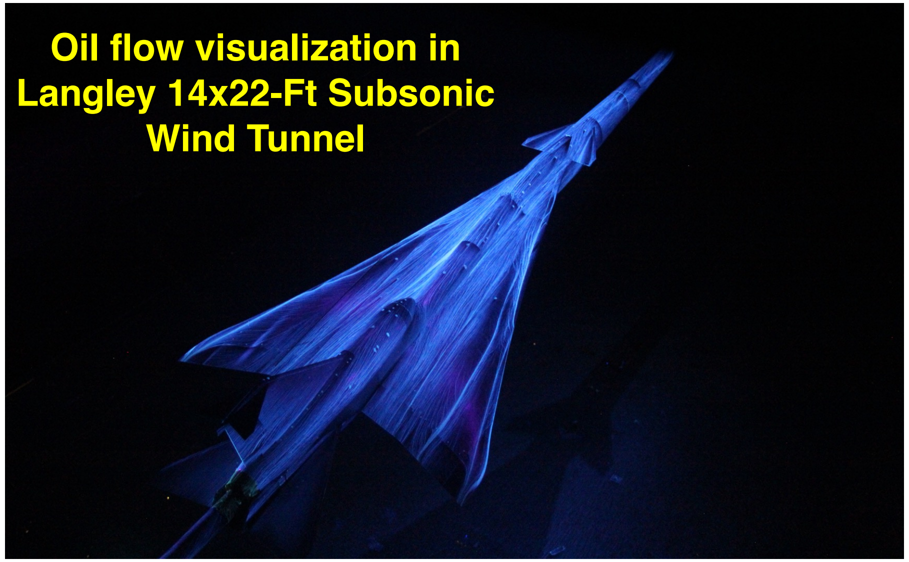


https://www.nasa.gov/feature/langley/instructions-for-downloading-and-flying-all-three-x-59-laptop-flight-simulation-models/

X-59 Wind Tunnel Validations

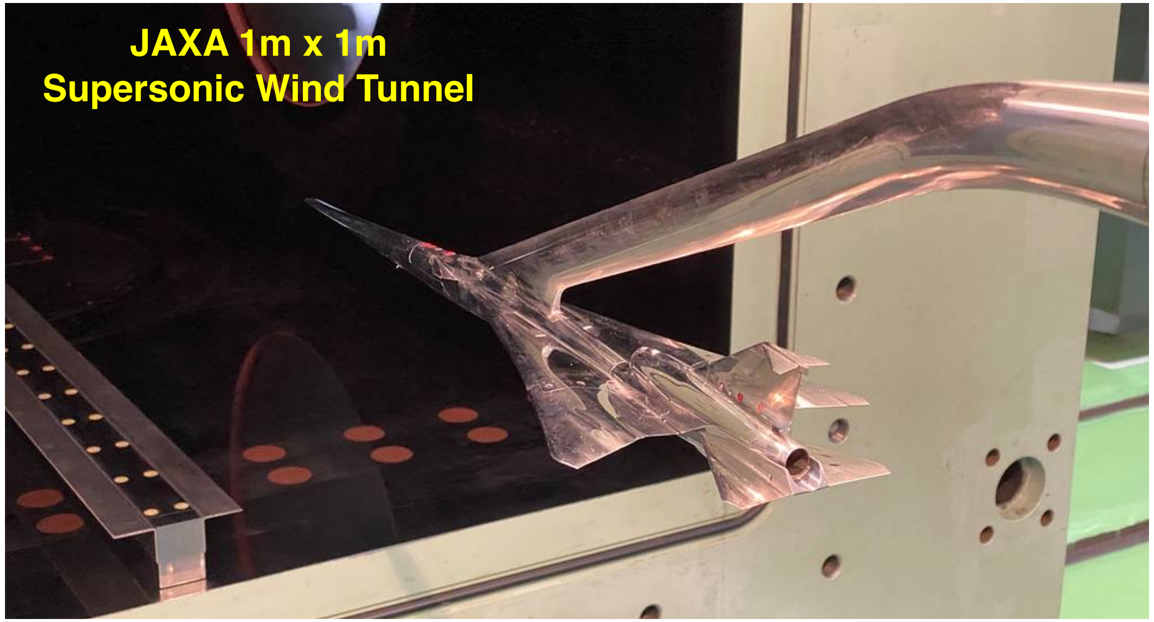
Low- and high-speed aerodynamic and Propulsion/Airframe Interaction (PAI) wind-tunnel tests validate predictions and ensure readiness of the design





X-59 Wind Tunnel Validations

Sonic boom wind-tunnel tests conducted on 1.62%-Scale X-59 model



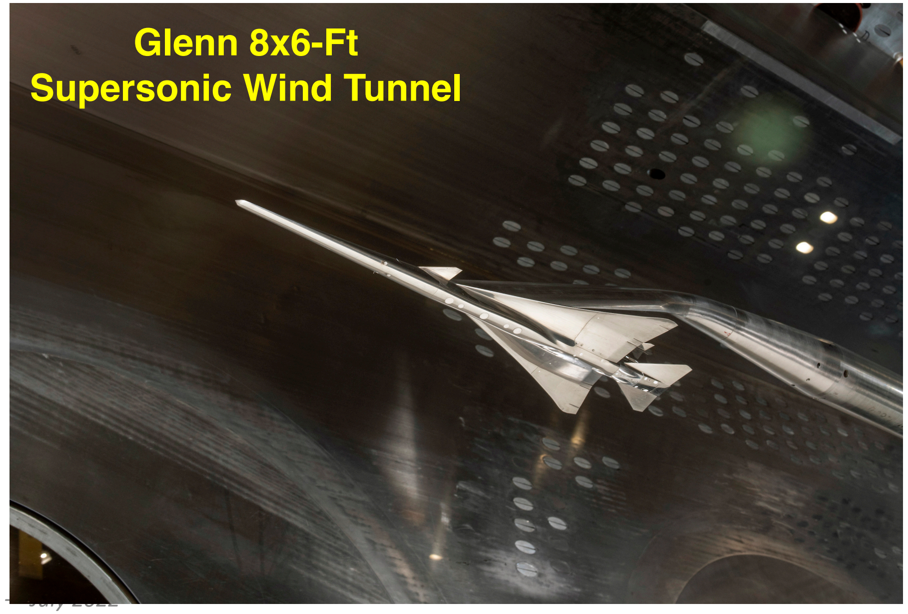


Image Credits: Quentin Schwinn, NASA GRC

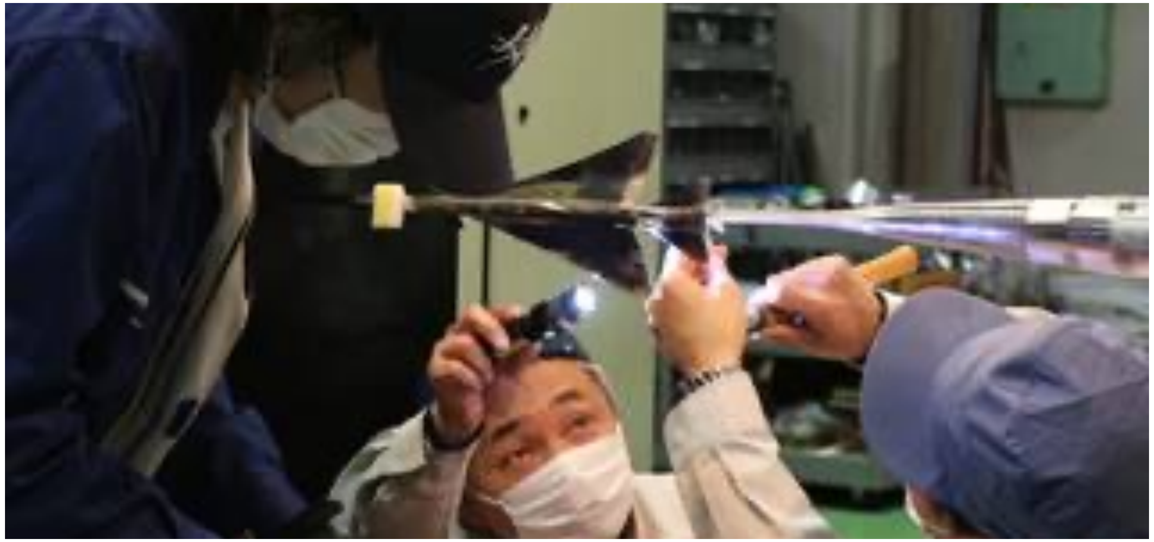
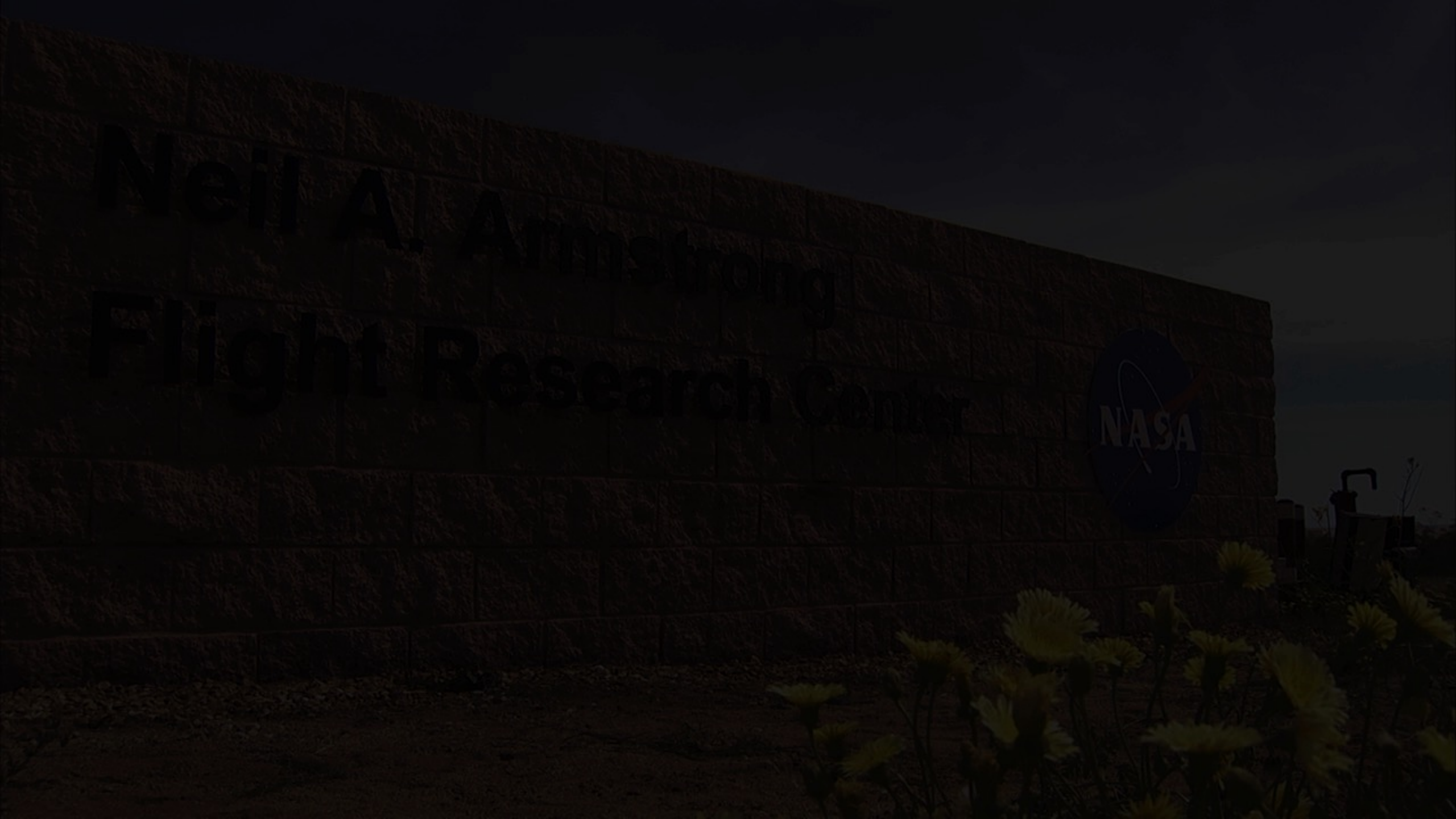


Image Credits: JAXA

X-59 Wind Tunnel Validations

1.62%-scale X-59 sonic boom model in NASA Glenn 8x6-Ft Supersonic Wind Tunnel



Neil A. Armstrong
Flight Research Center
NASA

Any Questions?

Image credit: Lockheed Martin