National Aeronautics and Space Administration

Minimizing Sonic Boom Through Simulation-Based Design: The X-59 Airplane

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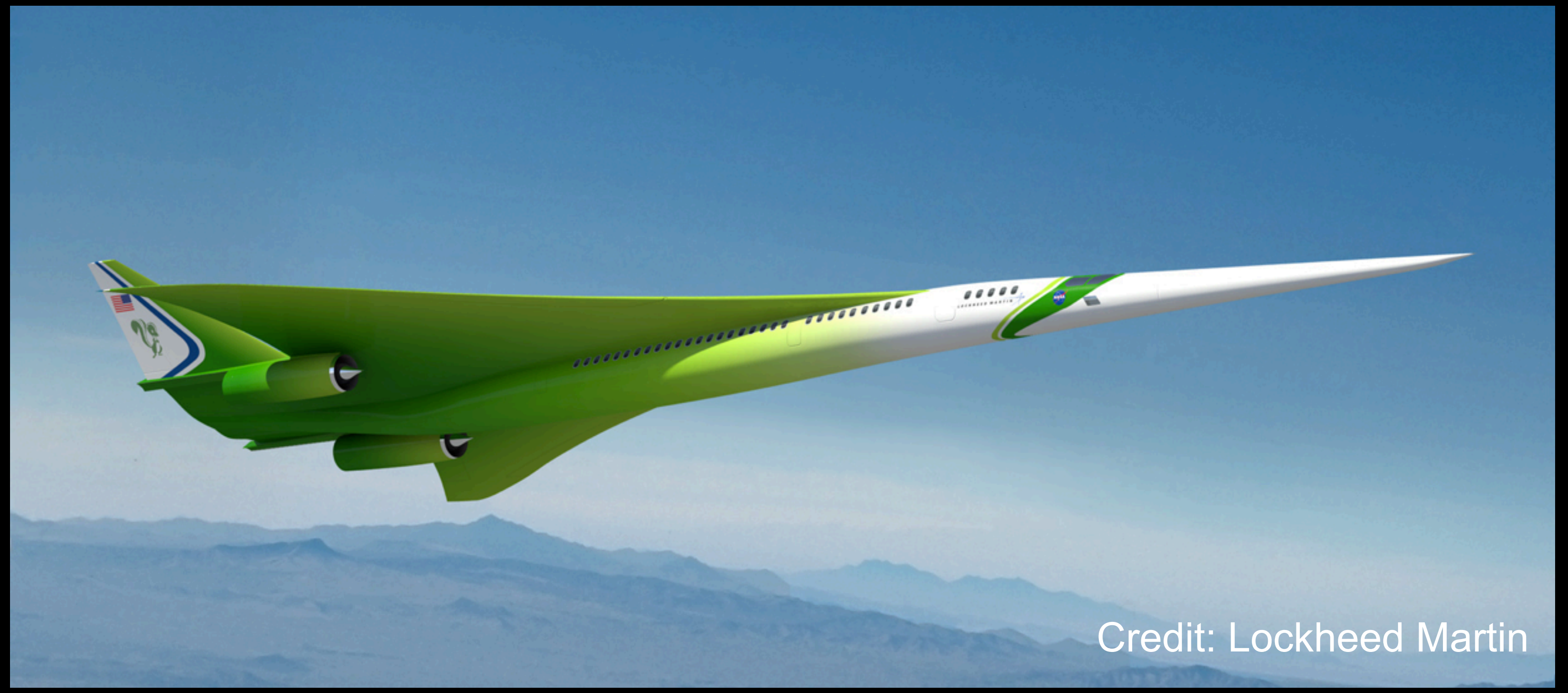
SC19, Denver, CO
Nov 17-22, 2019

Motivation

Overcoming the Barrier to Overland Supersonic Flight

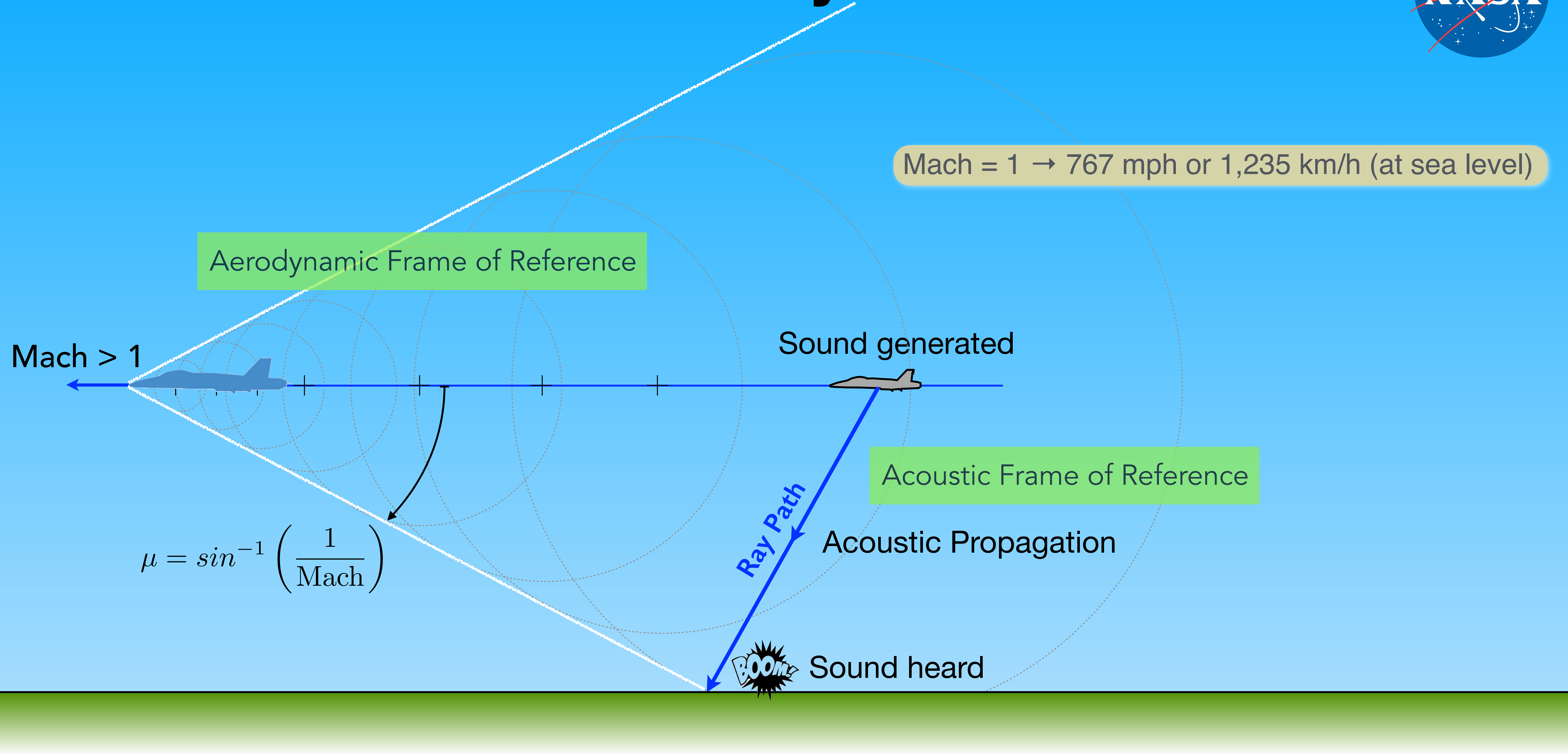
- Vision for Commercial Supersonic Flight is a future where fast air travel is available to a broad spectrum of the traveling public
- Biggest challenge is sonic boom
  - Civil supersonic flight operations are prohibited over many parts of the world
  - Currently, U.S. law prohibits flight in excess of Mach 1 overland
- Supersonic En-Route Noise standard is required
  - Must be accepted internationally (ICAO, FAA, EASA, TCCA)
- Additional barriers include airport noise, high-altitude emissions, efficiency, and many more

www.nasa.gov



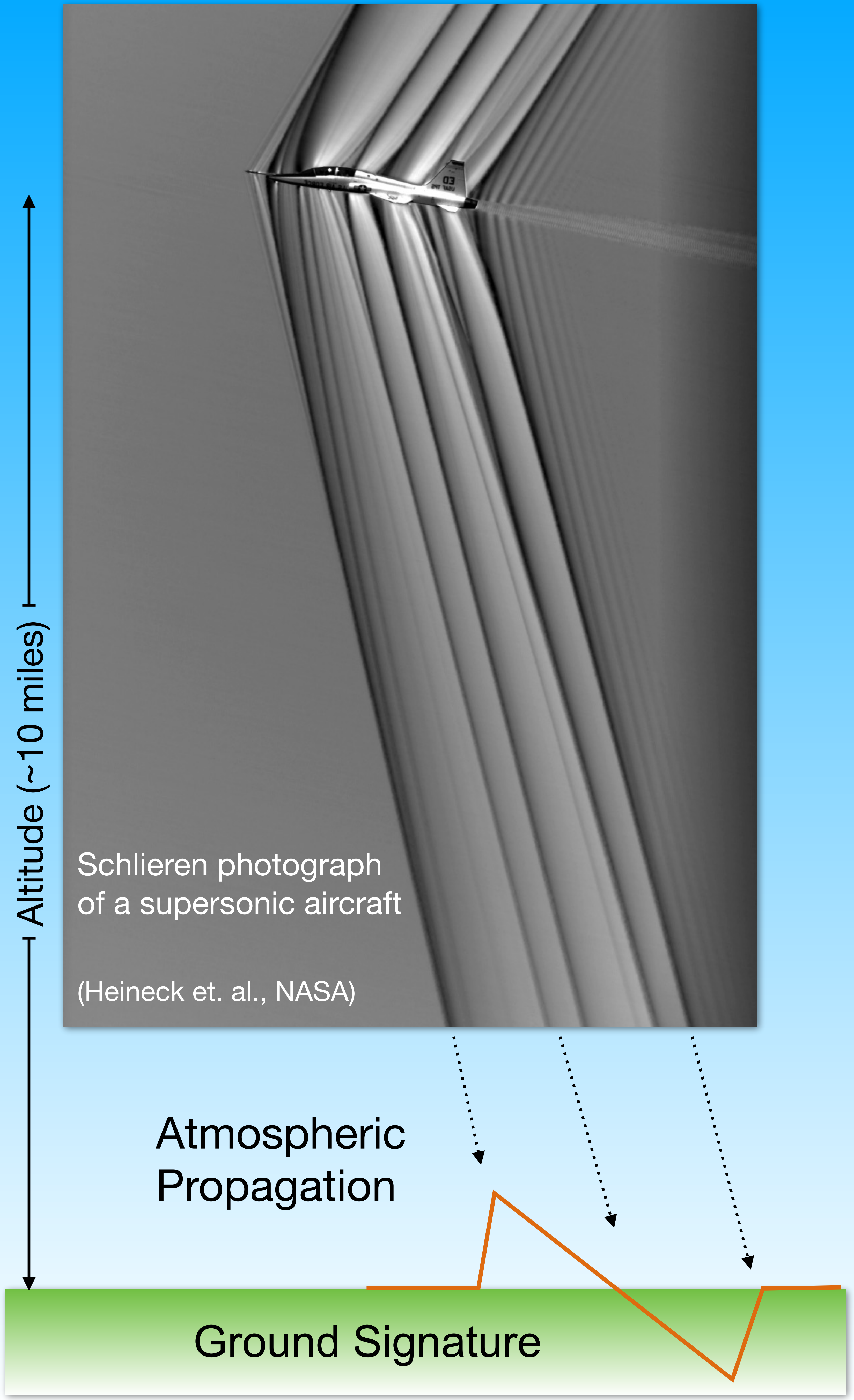
Credit: Lockheed Martin

Sonic Boom Physics



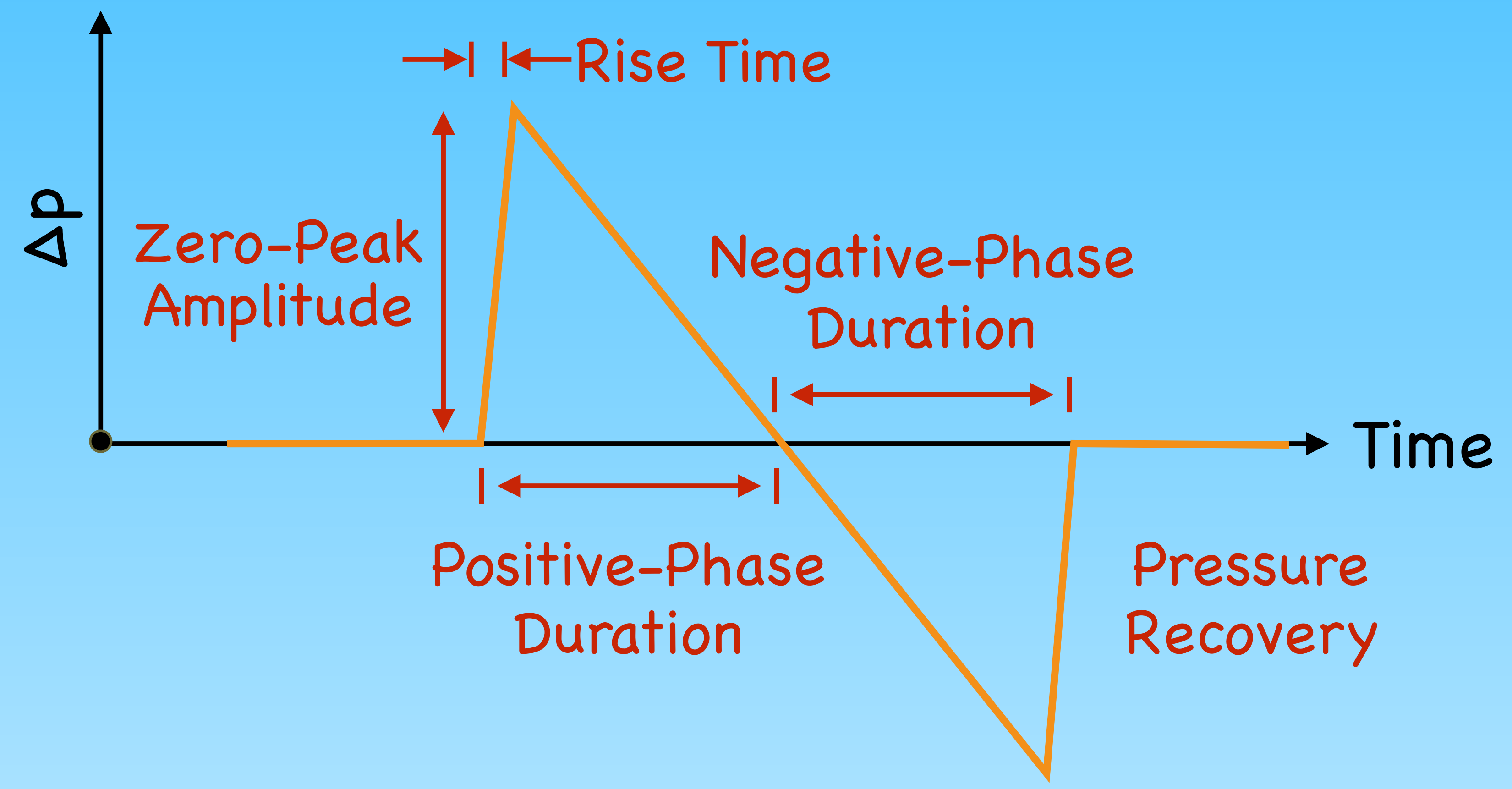
Goals
- Simulation-based analysis must reliably predict ground noise
- Simulation-based design must reliably determine aircraft shape to minimize ground noise

Sonic Boom Noise

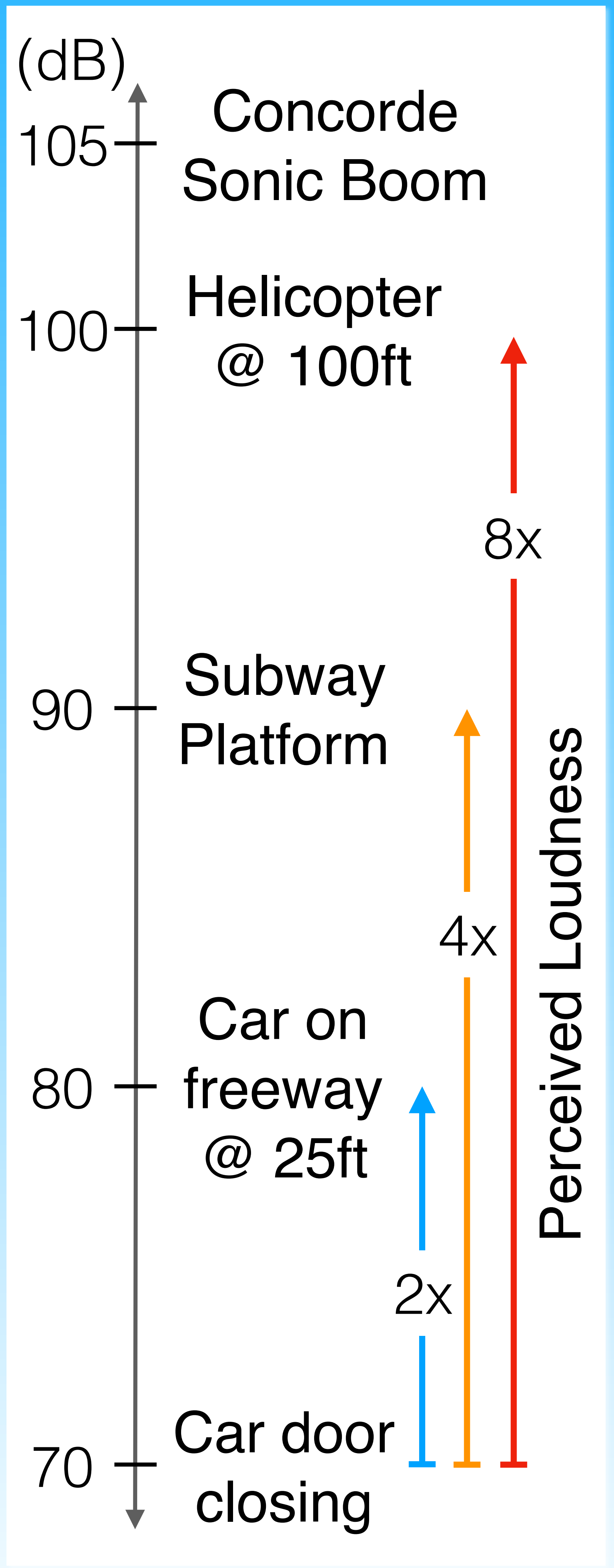


Boom sound characteristics are a function of the ground pressure signature

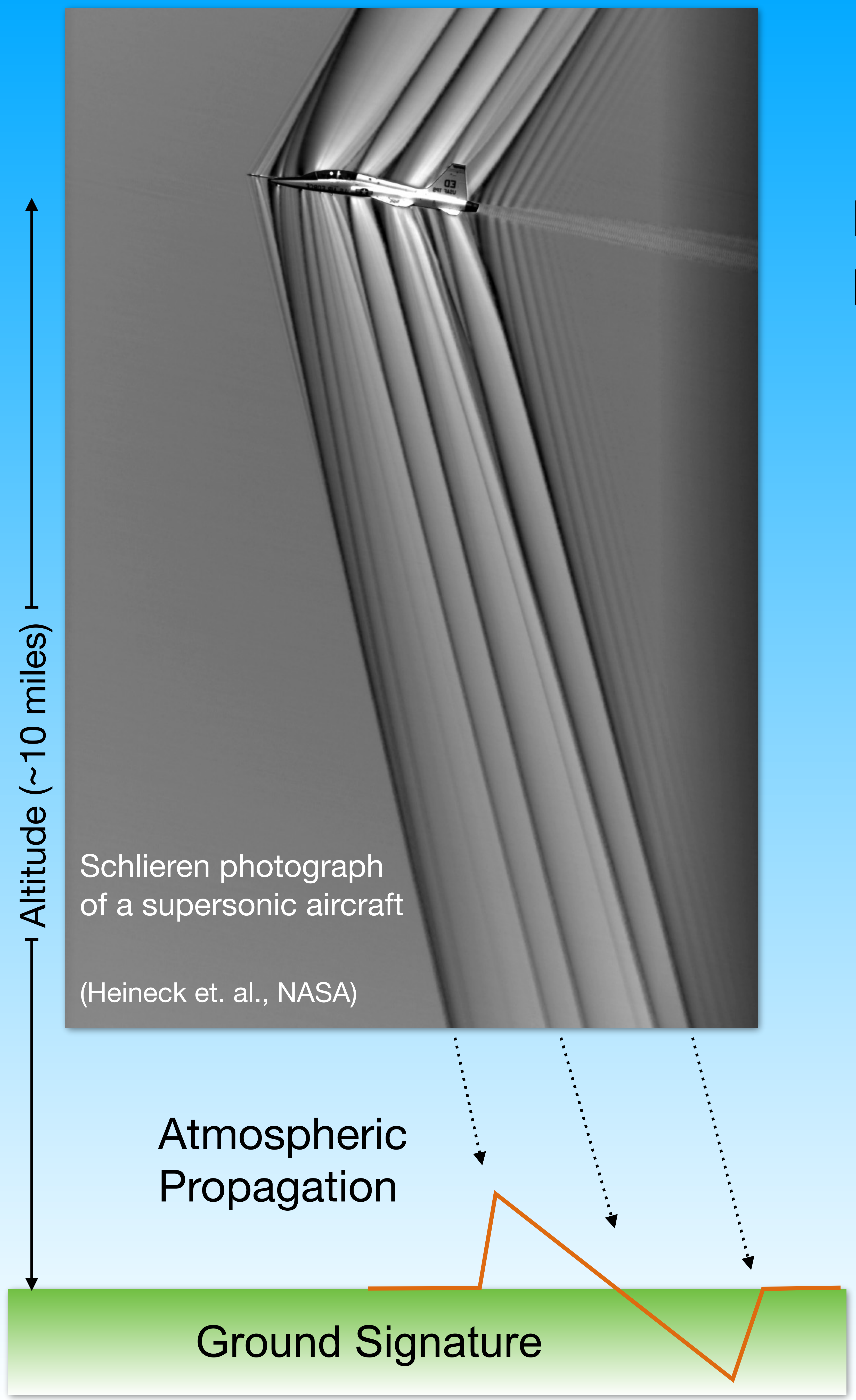
- Classical signatures are N-waves



- Low-boom designs exploit shaped signatures
  - Strategy is to increase rise time, decrease amplitude, increase duration and smooth recovery
  - Requires designing aircraft with nearfield signatures that do not coalesce into N-waves



Sonic Boom Noise



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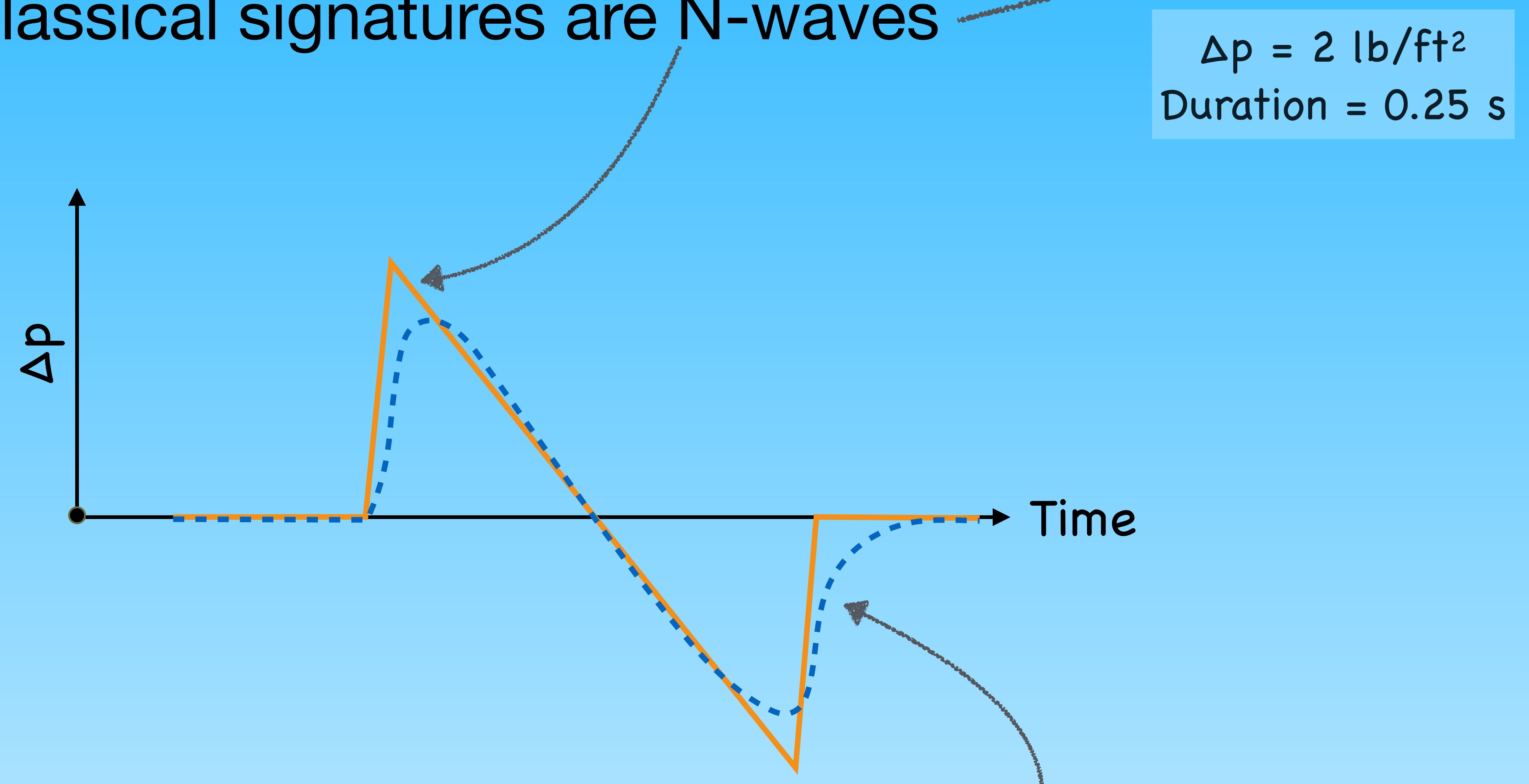

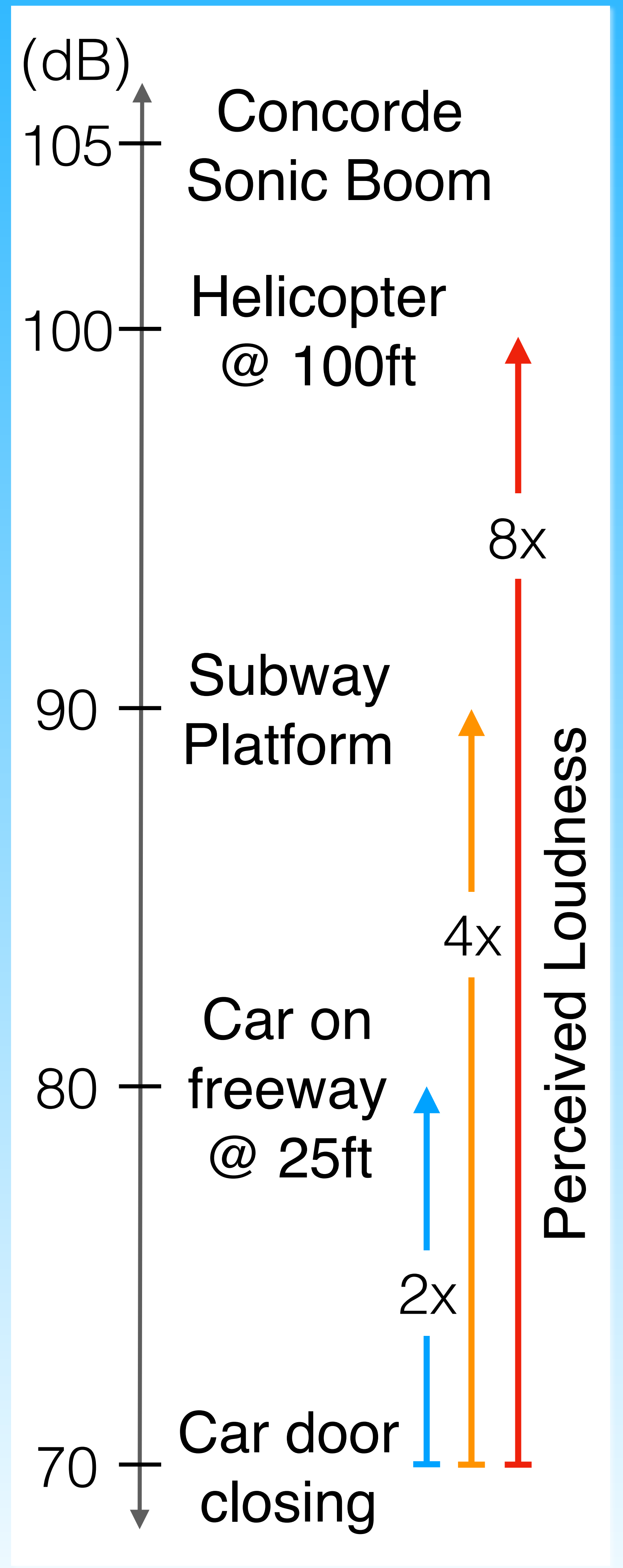

- Low-boom designs exploit shaped signatures
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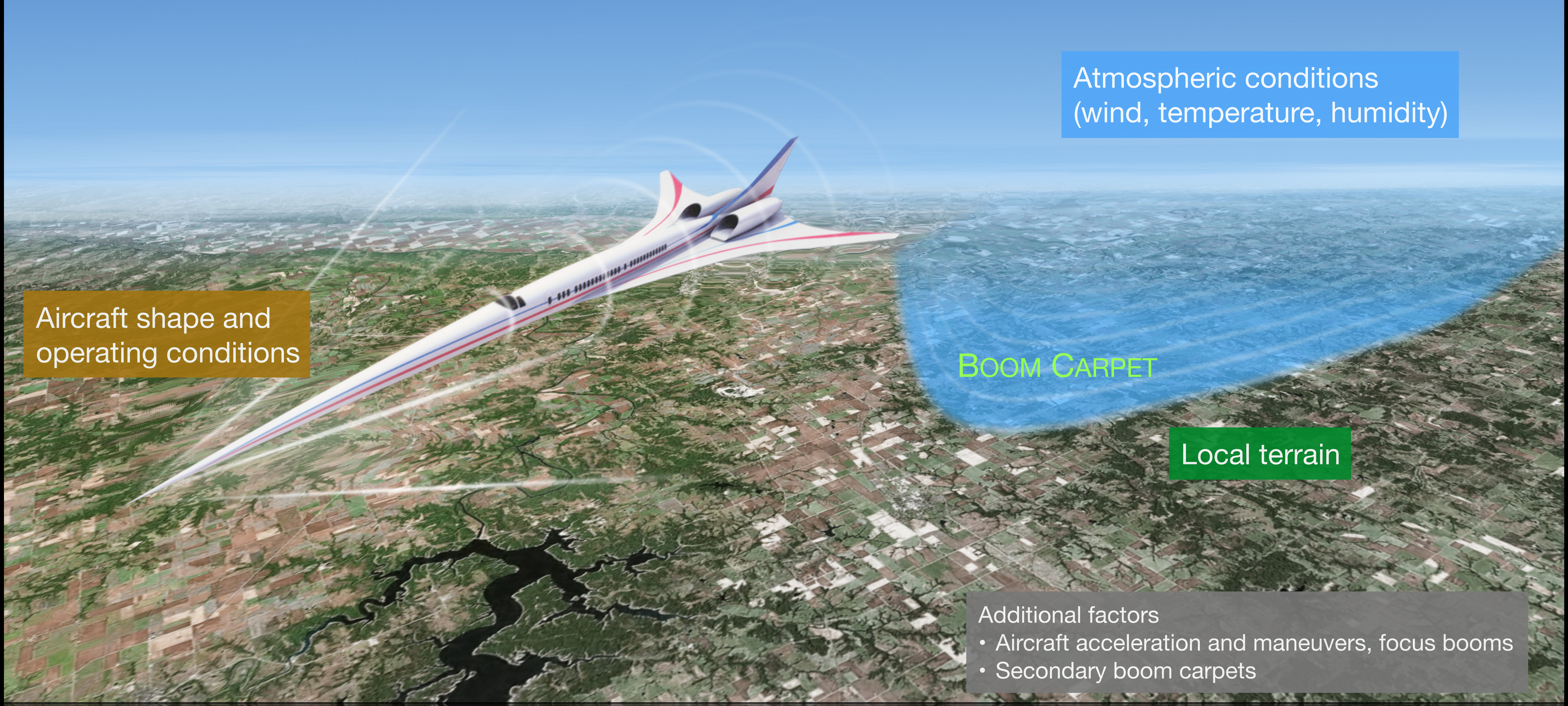
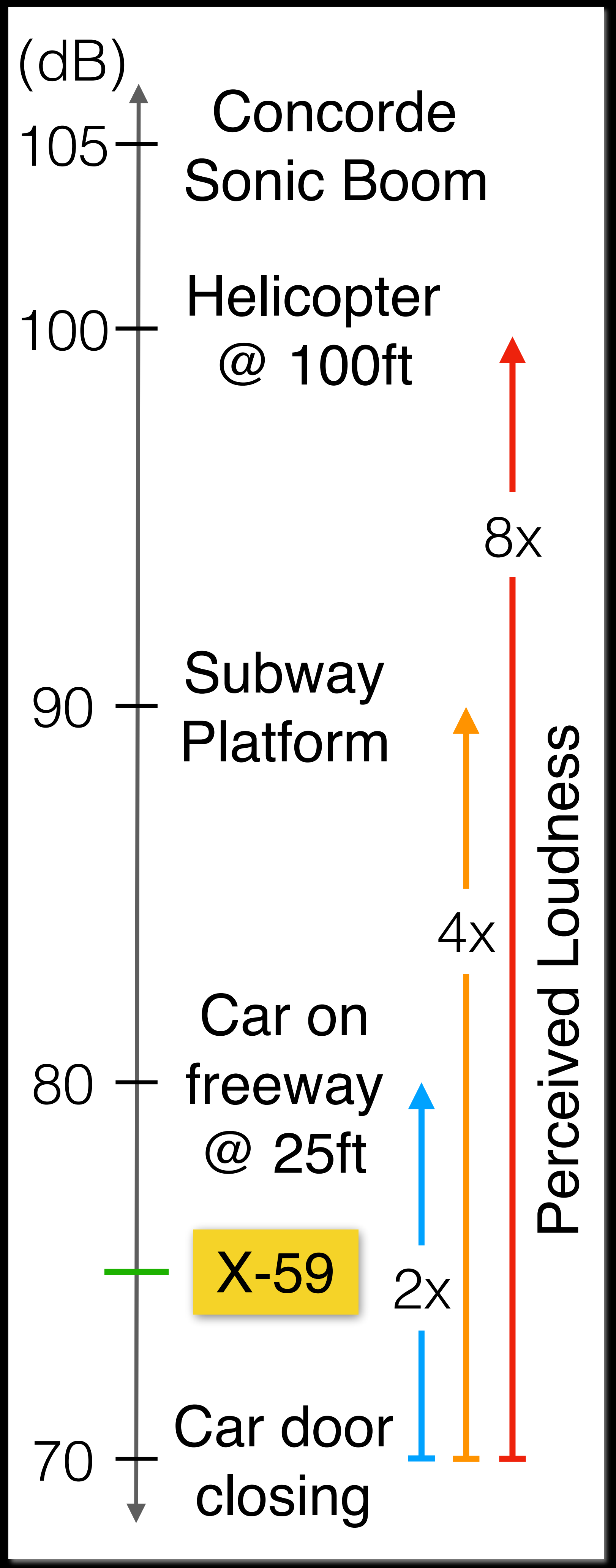
Sonic Boom Footprint

Sonic boom characterization requires prediction of the primary boom carpet

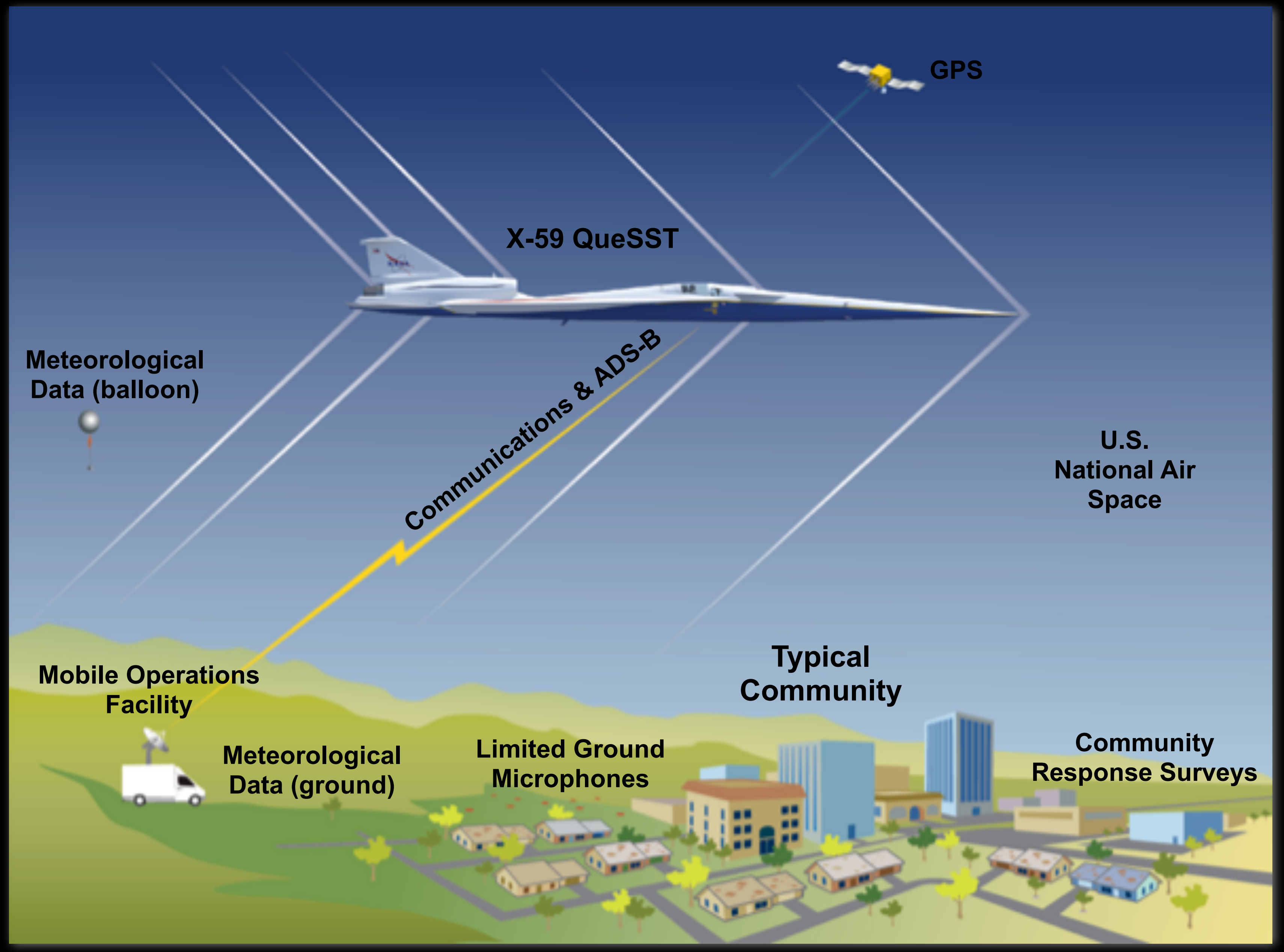
- Influenced by several factors, some with significant uncertainties



Low-Boom Flight Demonstration



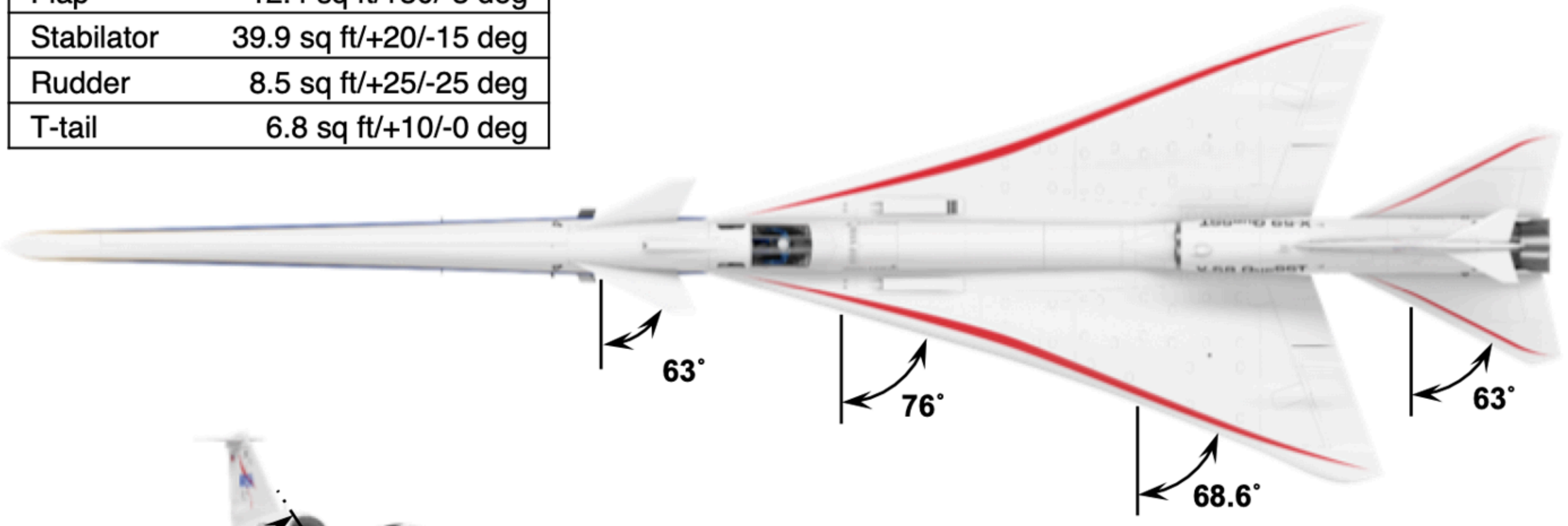
- NASA mission to support development of an En-Route noise standard
  - Aircraft is a supersonic-acoustic-signature-generator with characteristics representative of a commercial supersonic transport
- Design Mach number is 1.4
- Design sonic boom sound level is 75 PLdB (Perceived Level)
  - Roughly a factor of eight quieter than the boom generated by Concorde
  - Near ambient noise level of a city
  - Similar to a rumble from a distant thunderstorm
- Goal is to perform multiple overflights of representative communities and climate across the US to collect noise response data
- Deliver community response data to ICAO

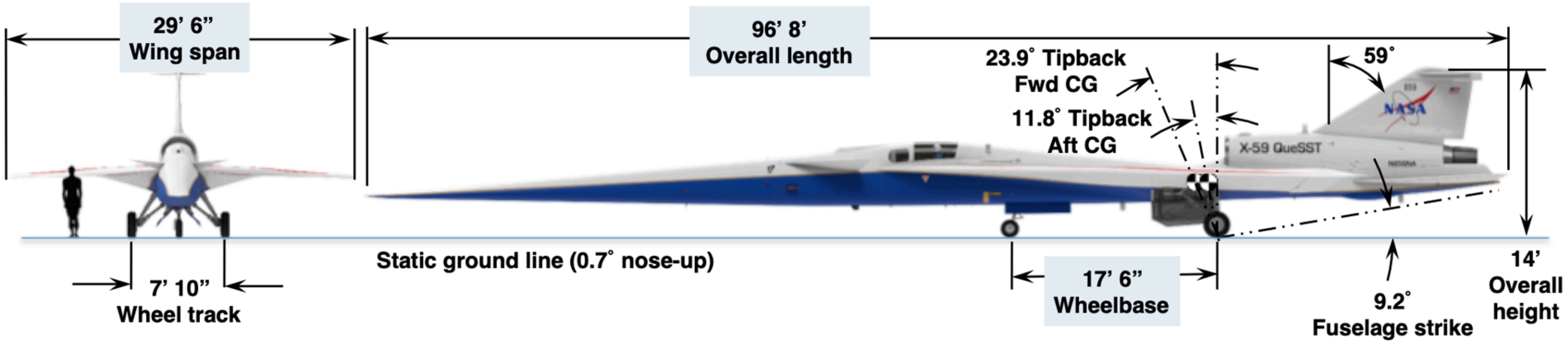


X-59 Aircraft

Configuration C612	
MDGW	24,300 lbs
Fuel (Std Day)	7,500 lbs
Payload	600 lbs
Design Mach	1.4
Loudness	<75 PLdB
Engine	1xF414-GE-100
Landing Gear	F-16 Blk25 NLG F-16 Blk25 MLG

Control Surfaces	
Aileron	12.9 sq ft/+35/-25 deg
Flap	12.4 sq ft/+30/-3 deg
Stabilator	39.9 sq ft/+20/-15 deg
Rudder	8.5 sq ft/+25/-25 deg
T-tail	6.8 sq ft/+10/-0 deg

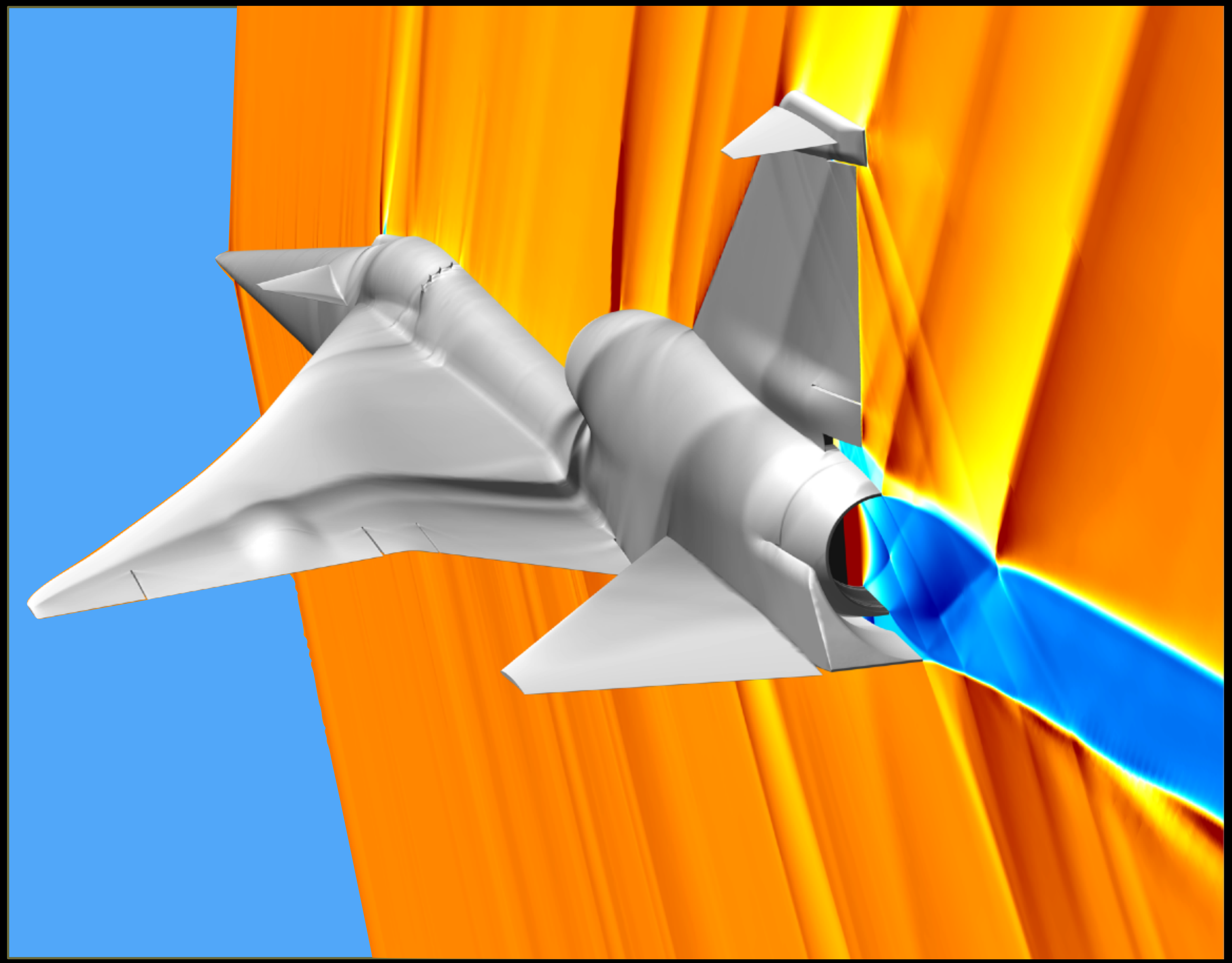


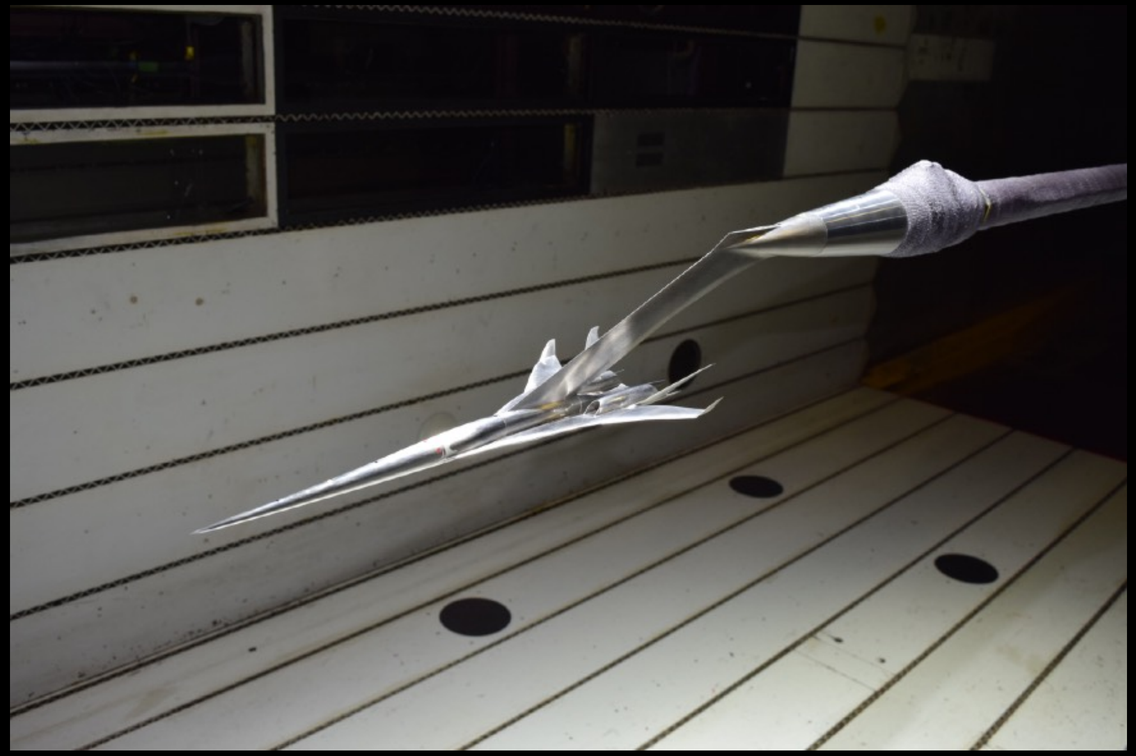


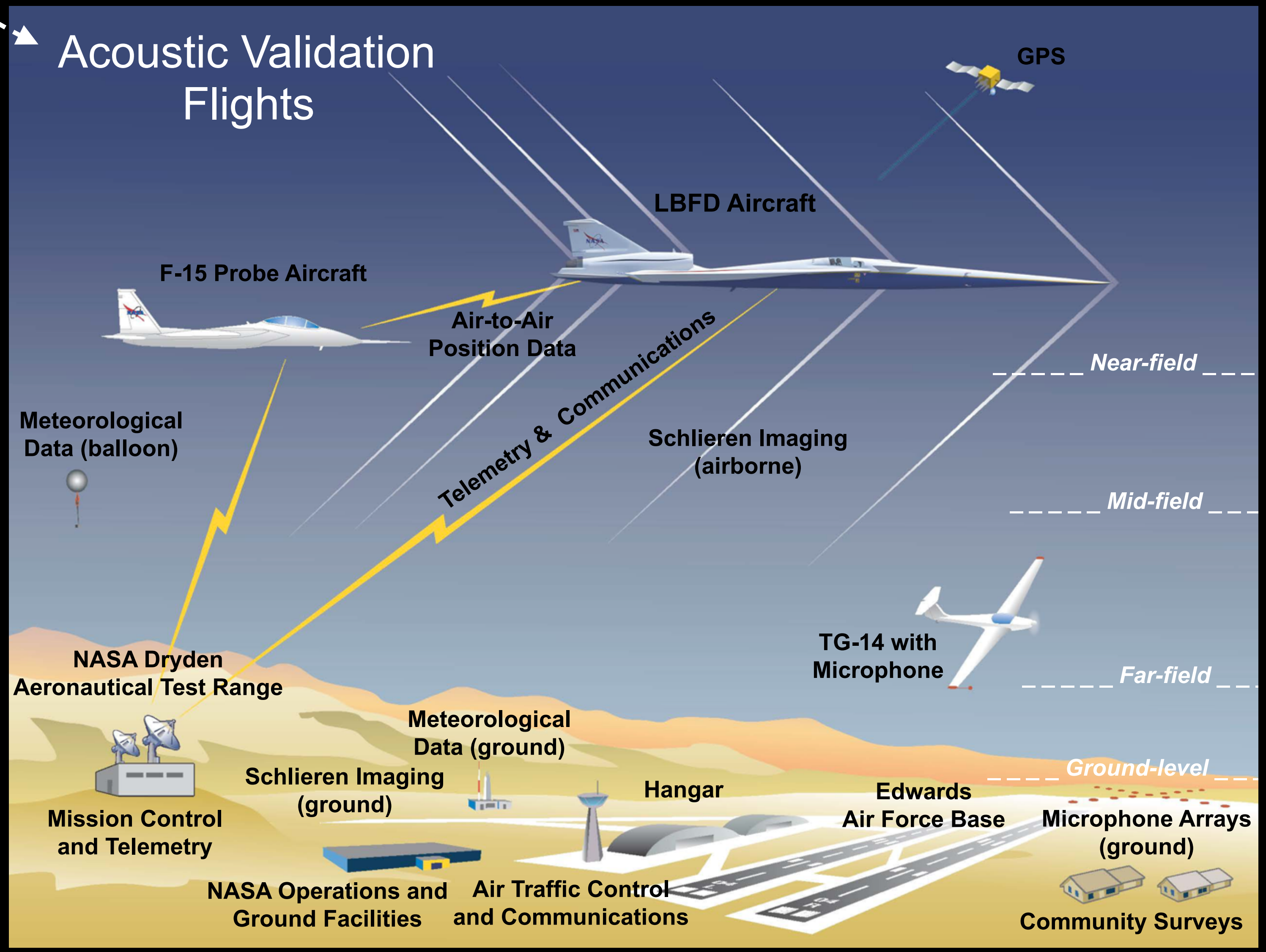
www.nasa.gov/aero/x-59-quesst-overview

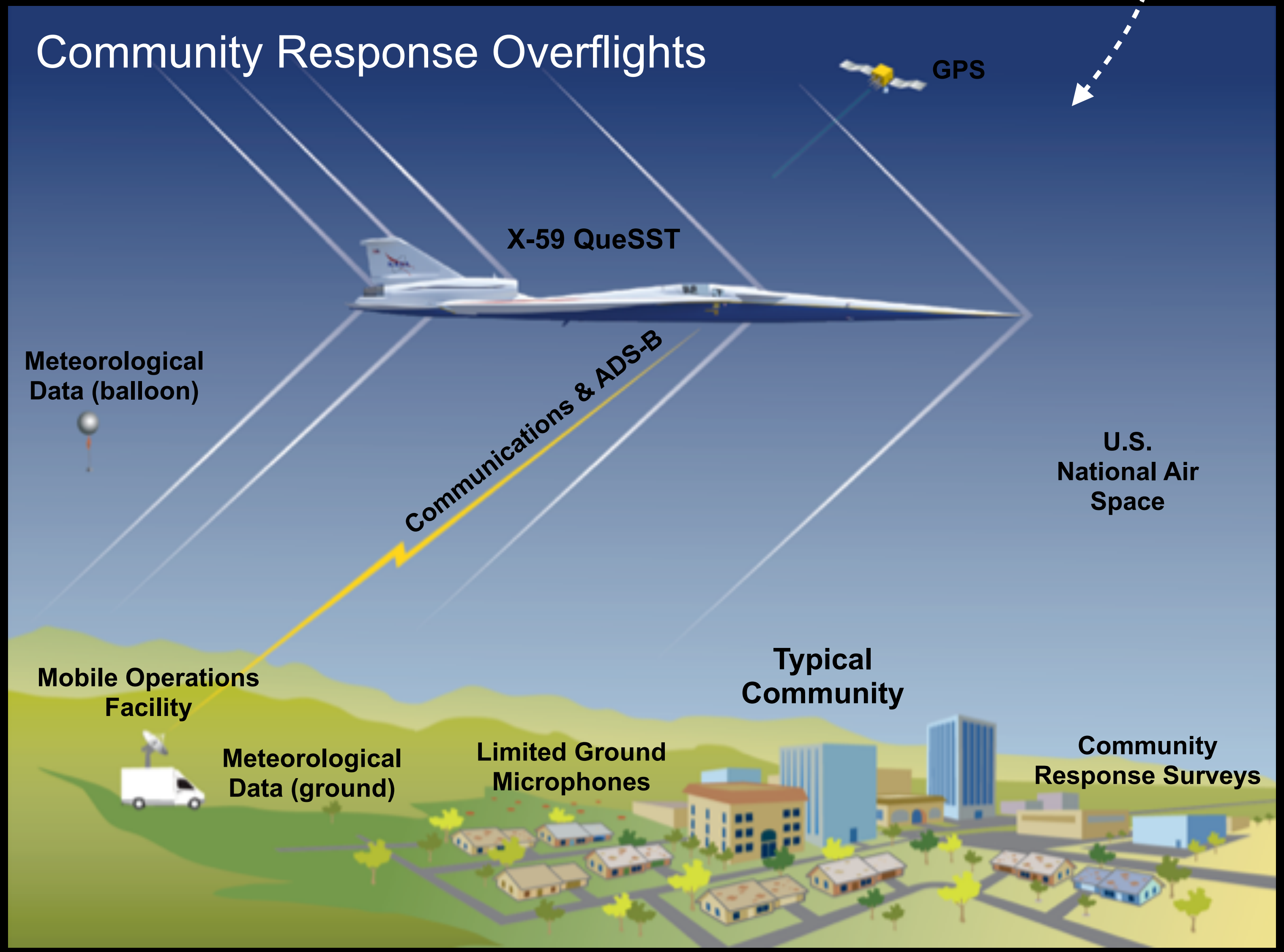
Role of High-Fidelity Simulations and HPC

- High-fidelity CFD simulations are a major contributor to X-59
  - All aspects of aerodynamic design and acoustic analysis
  - Wind-tunnel hardware verification and test support
  - Uncertainty quantification
- Ongoing pre-test analysis to support acoustic validation flights
- Near-real-time prediction capability for community test planning
- Suite of new prediction tools for certification of supersonic aircraft

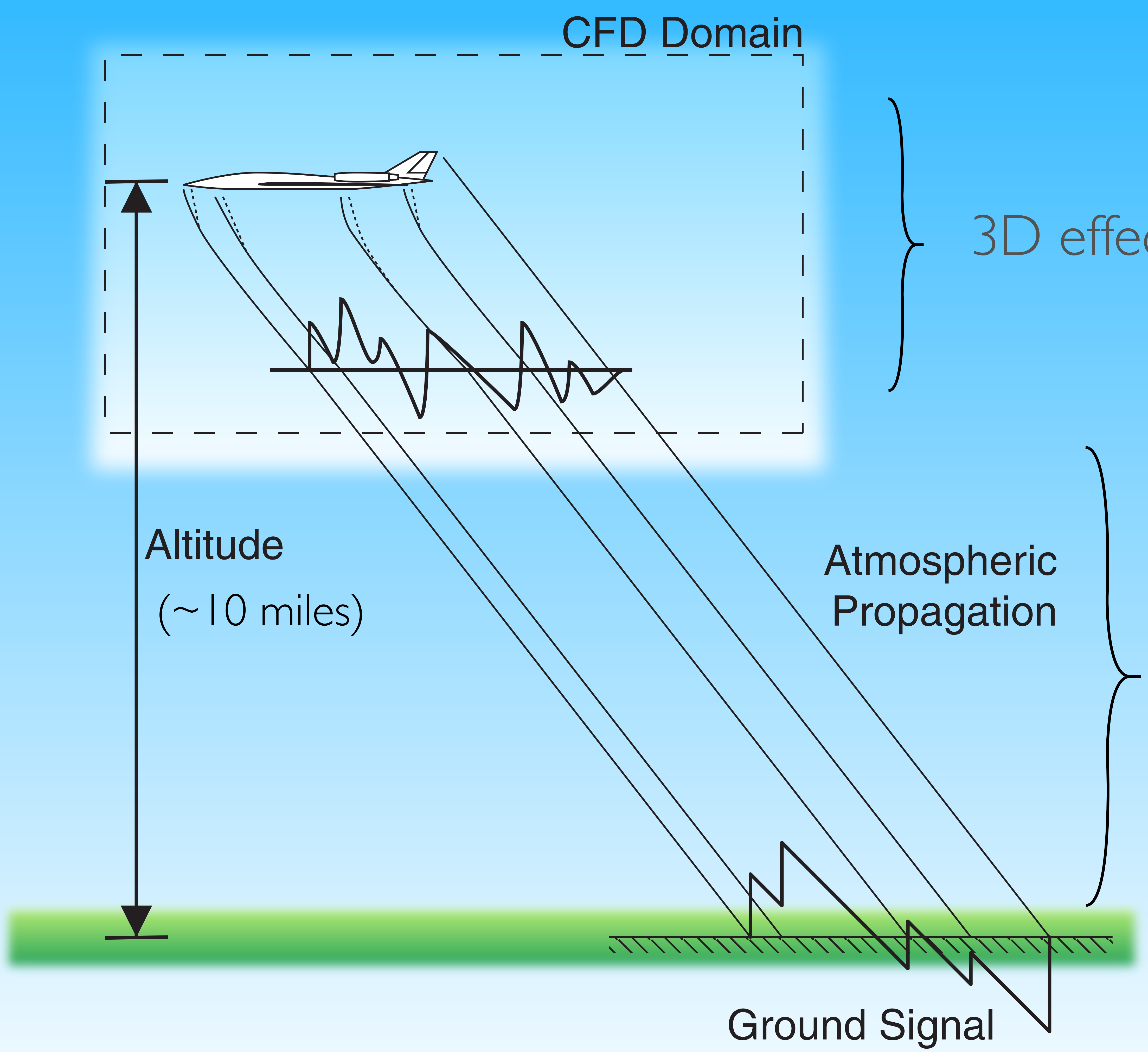








Sonic Boom Analysis



Nearfield

3D effects (aircraft shape and plume)

Use CFD

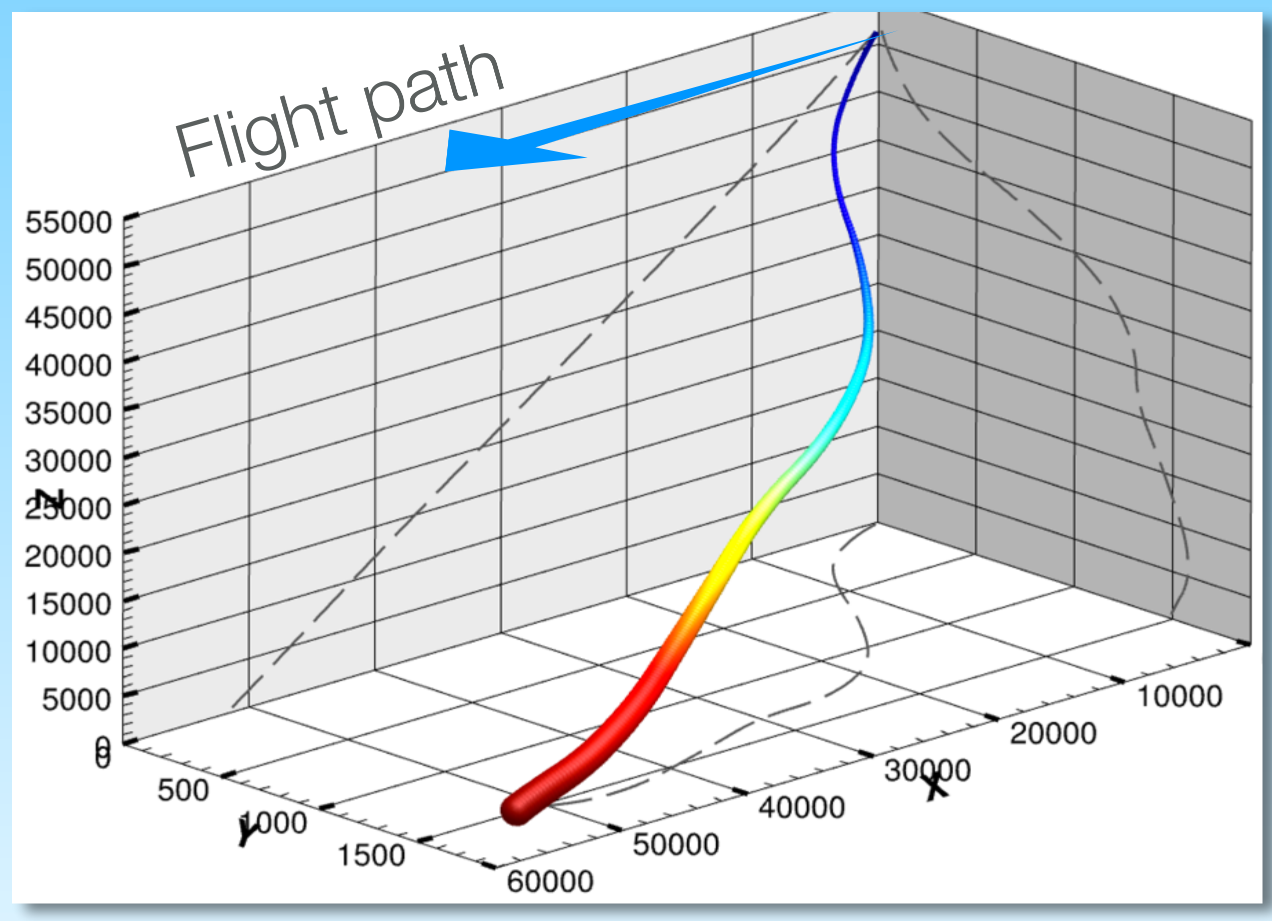
Propagation

Atmospheric variability

Absorption

Use Ray Tracing and quasi-1D PDE

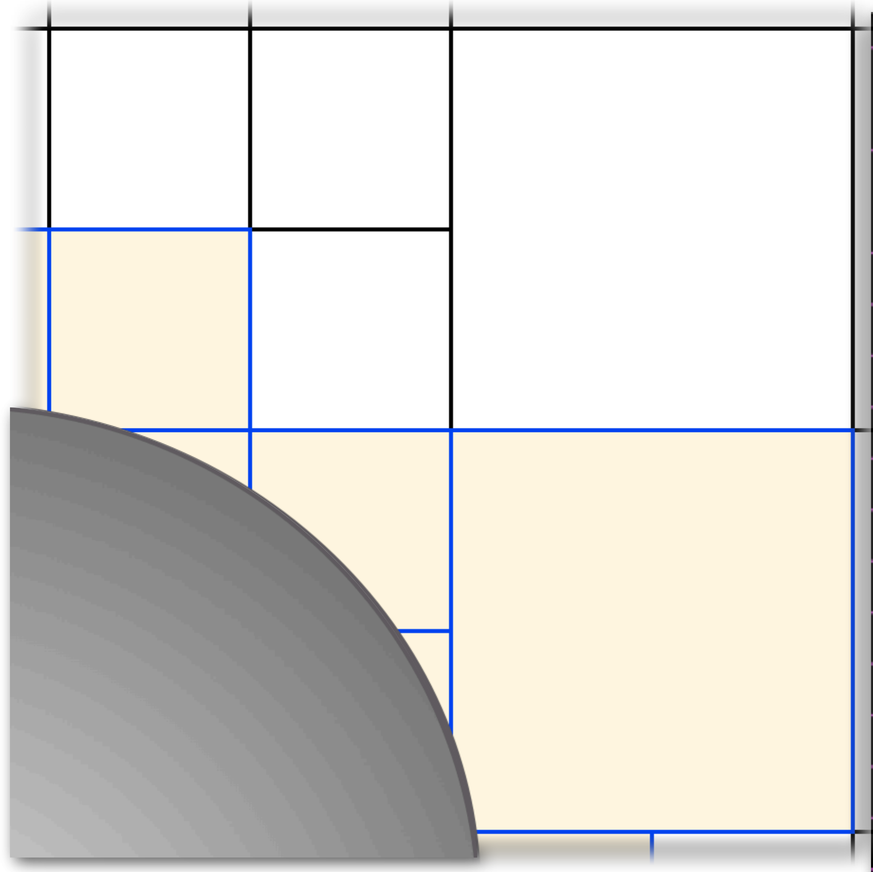
Ray Tracing

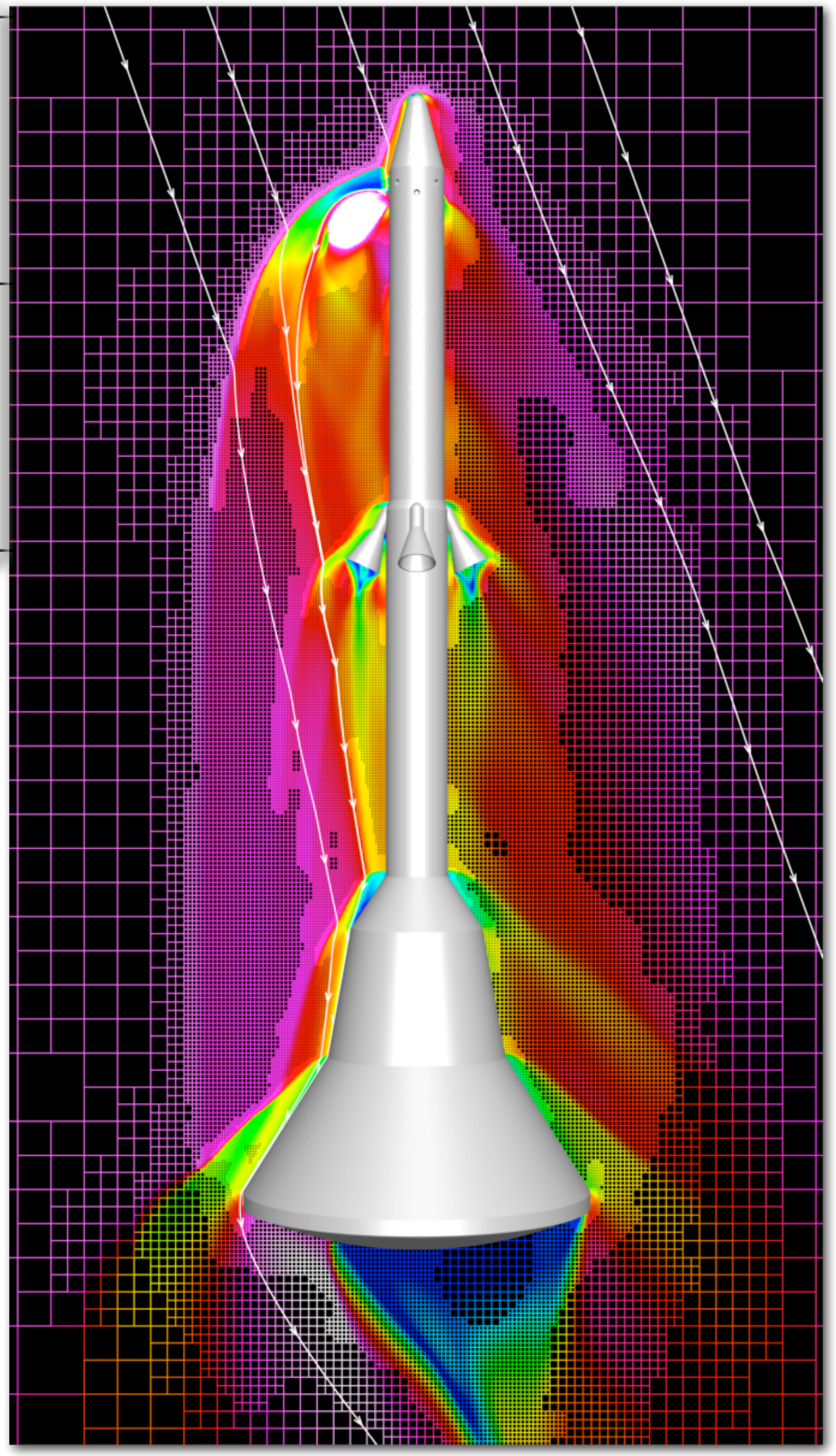


Core Solver: Cart3D

Meshing

- Multilevel embedded-boundary Cartesian mesh
  - Cut-cells at boundary
  - Handles arbitrarily complex vehicle shapes





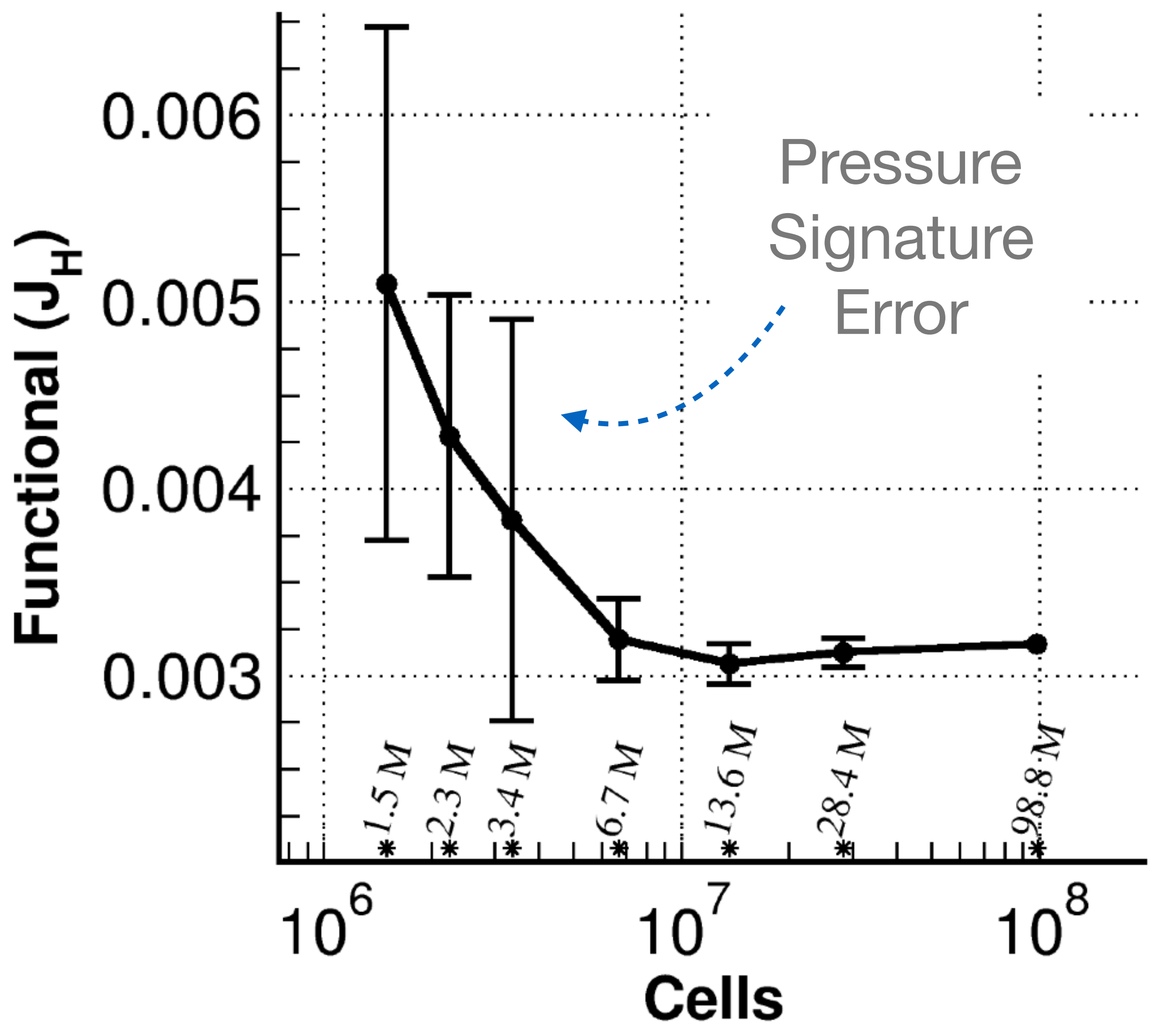
Flow Solver

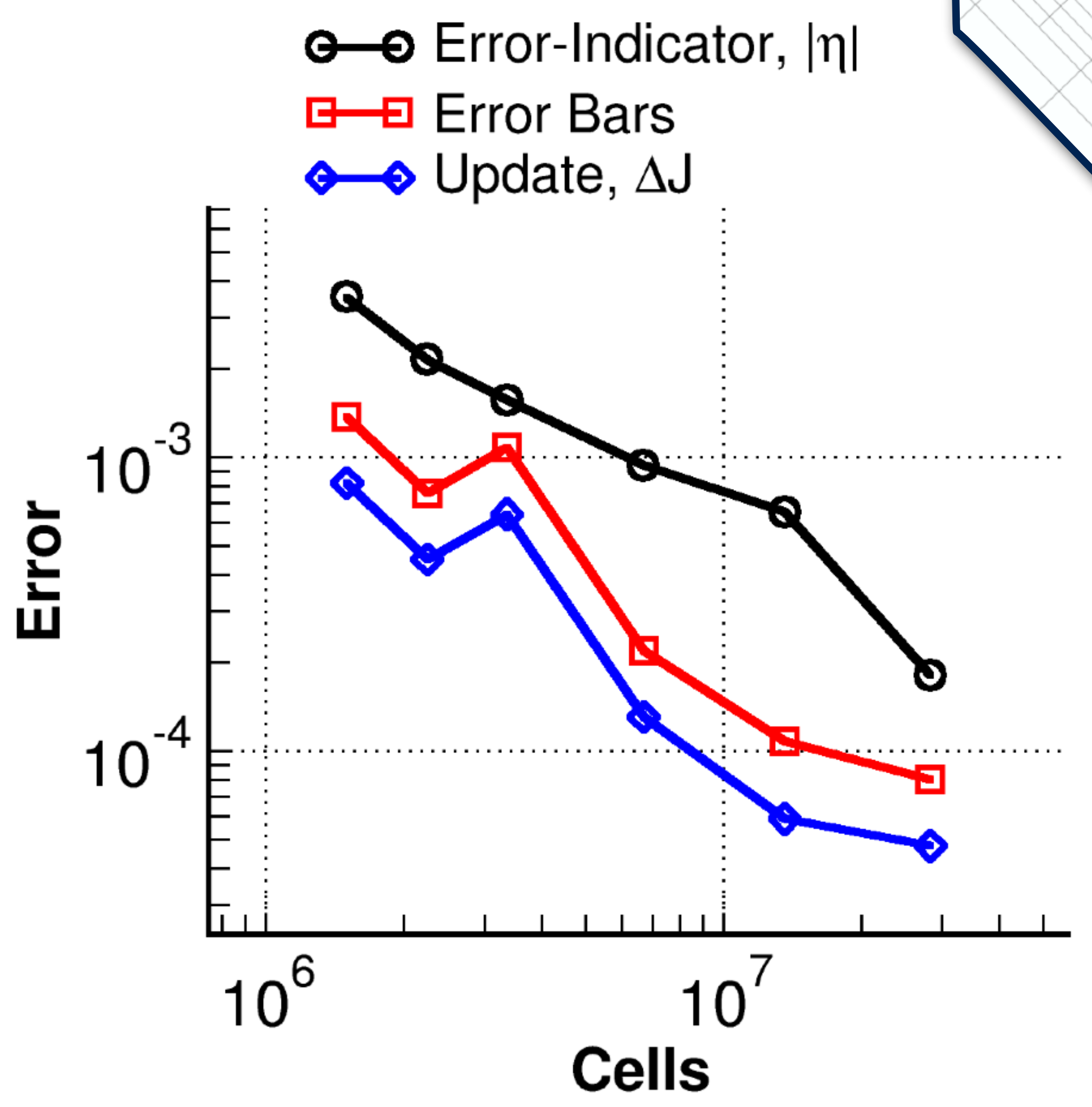
- Inviscid flow assumption (Euler equations)
- Second-order spatial and temporal discretization
  - Fully conservative finite-volume method
  - Dual time-stepping for unsteady flows
- Calorically perfect and equilibrium gas models
- Runge-Kutta time marching with multigrid acceleration

Core Solver: Cart3D

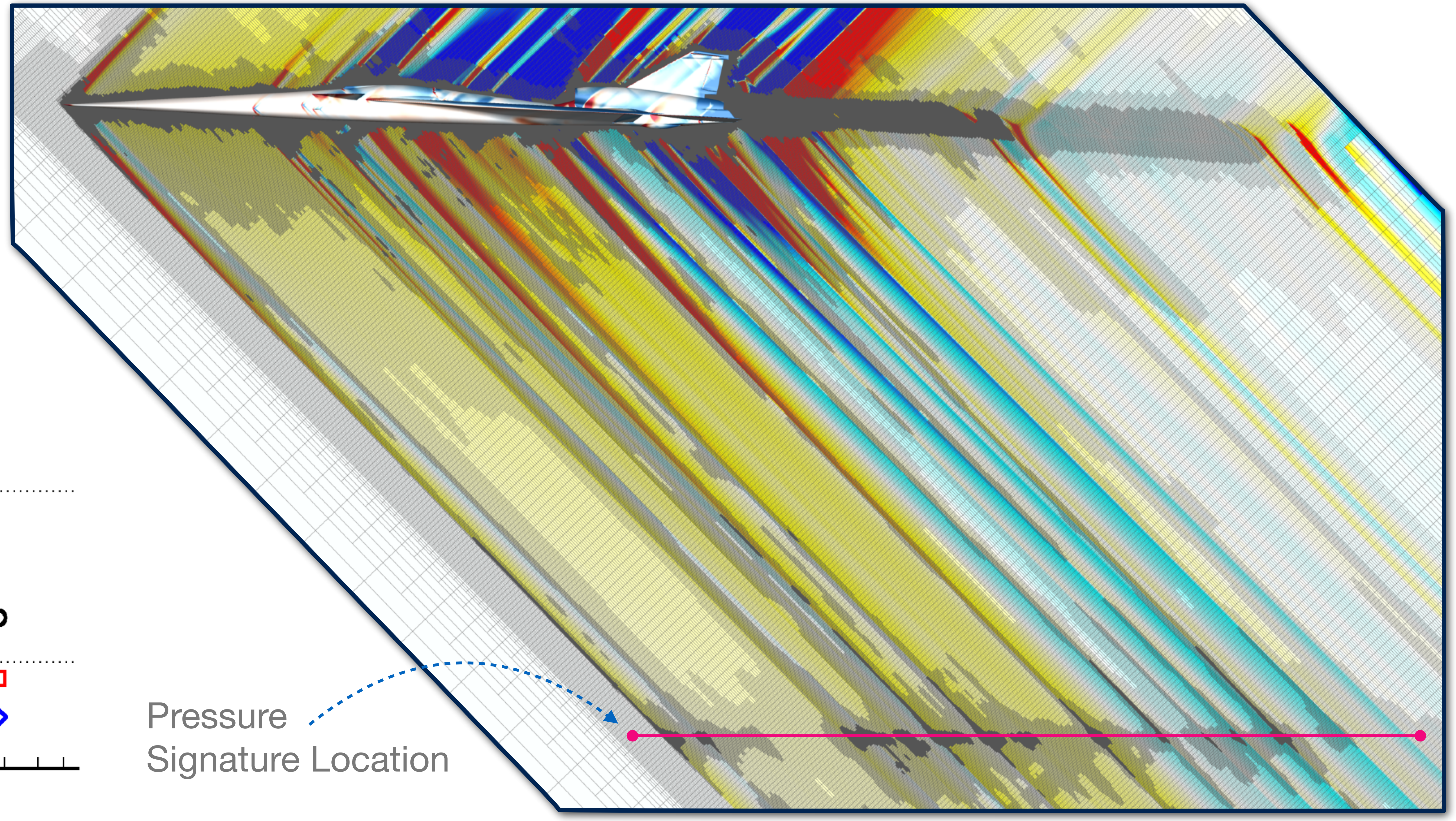
Error Estimation and Goal-Oriented Mesh Adaptation

- Mesh automatically refined in locations with most impact on user selected outputs (pressure signatures, lift, drag, moments, ...)
  - Method of adjoint weighted residuals
  - Used for every simulation





Adaptation Convergence History

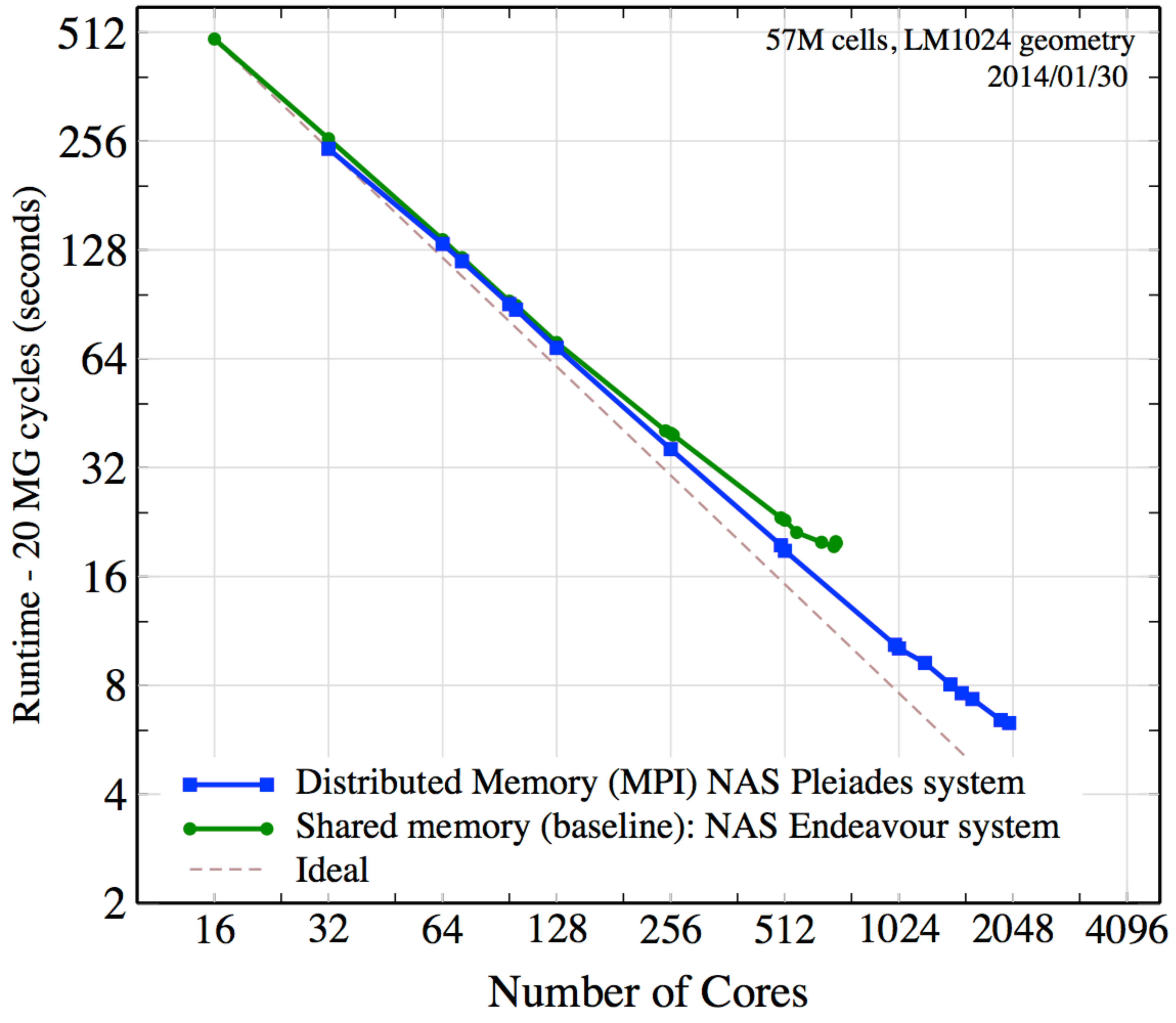


Near-body region of adapted mesh around LBFD aircraft for pressure sensor output (C_p contours)

Parallel Performance

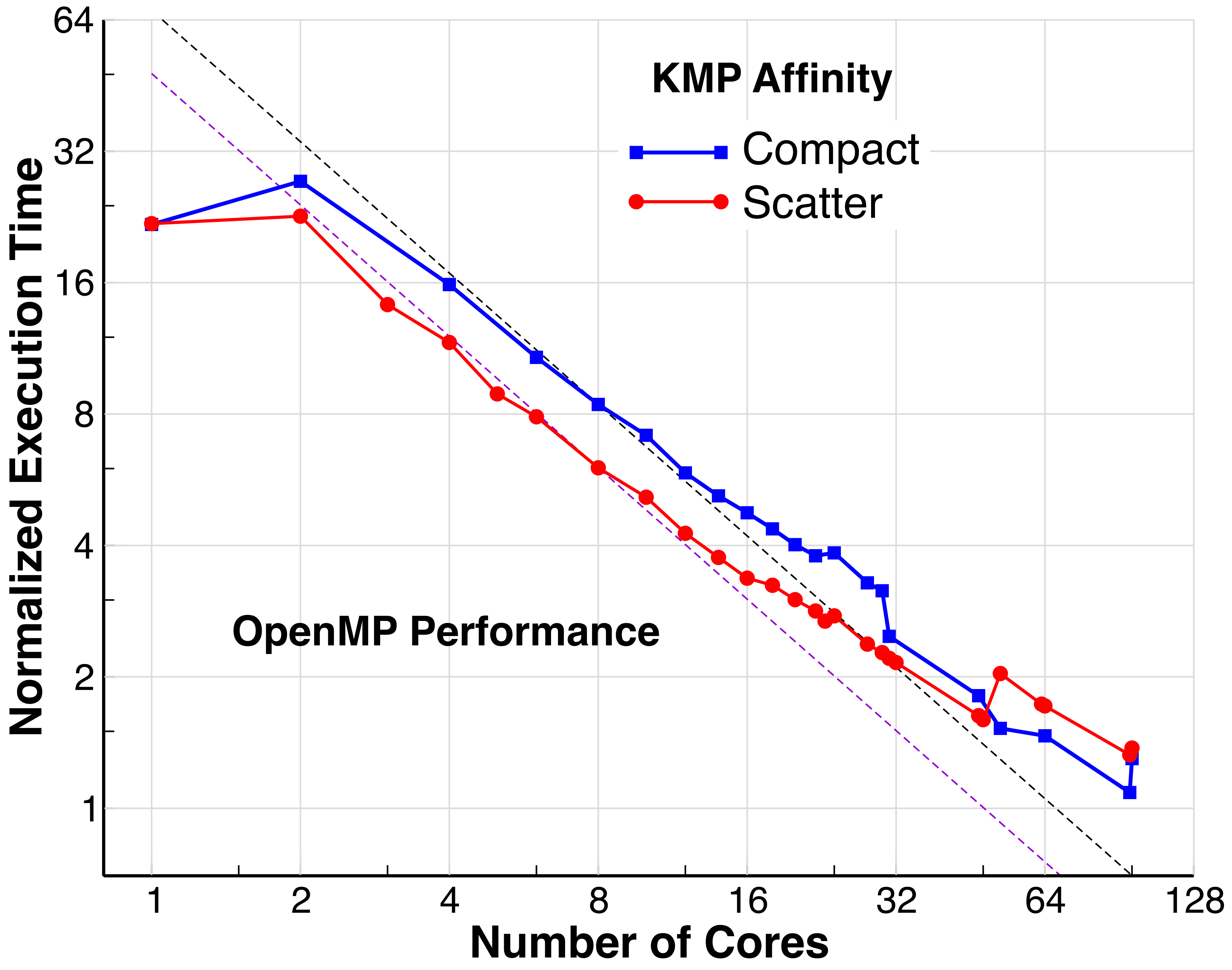
Excellent scalability through use of domain decomposition based on space-filling curves

HECC Supercomputing Systems



OpenMP and MPI fully supported

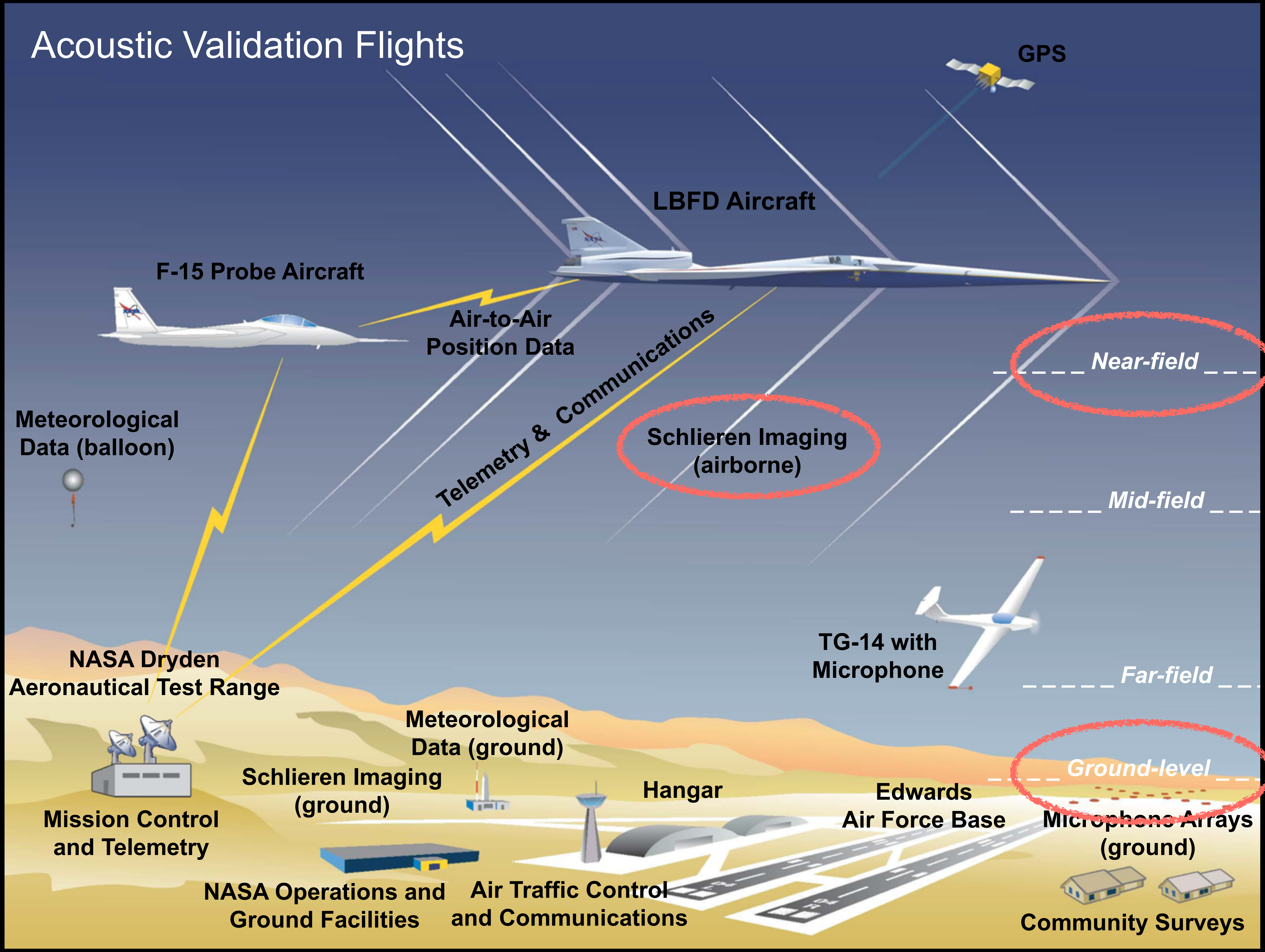
Cascade Lake Engineering Workstation



- Intel(R) Xeon(R) Gold 6252 CPU
- 2 sockets, 24 physical cores per socket
- Hyper-Threading and TurboBoost ON
- icc, version 19.0.4.243

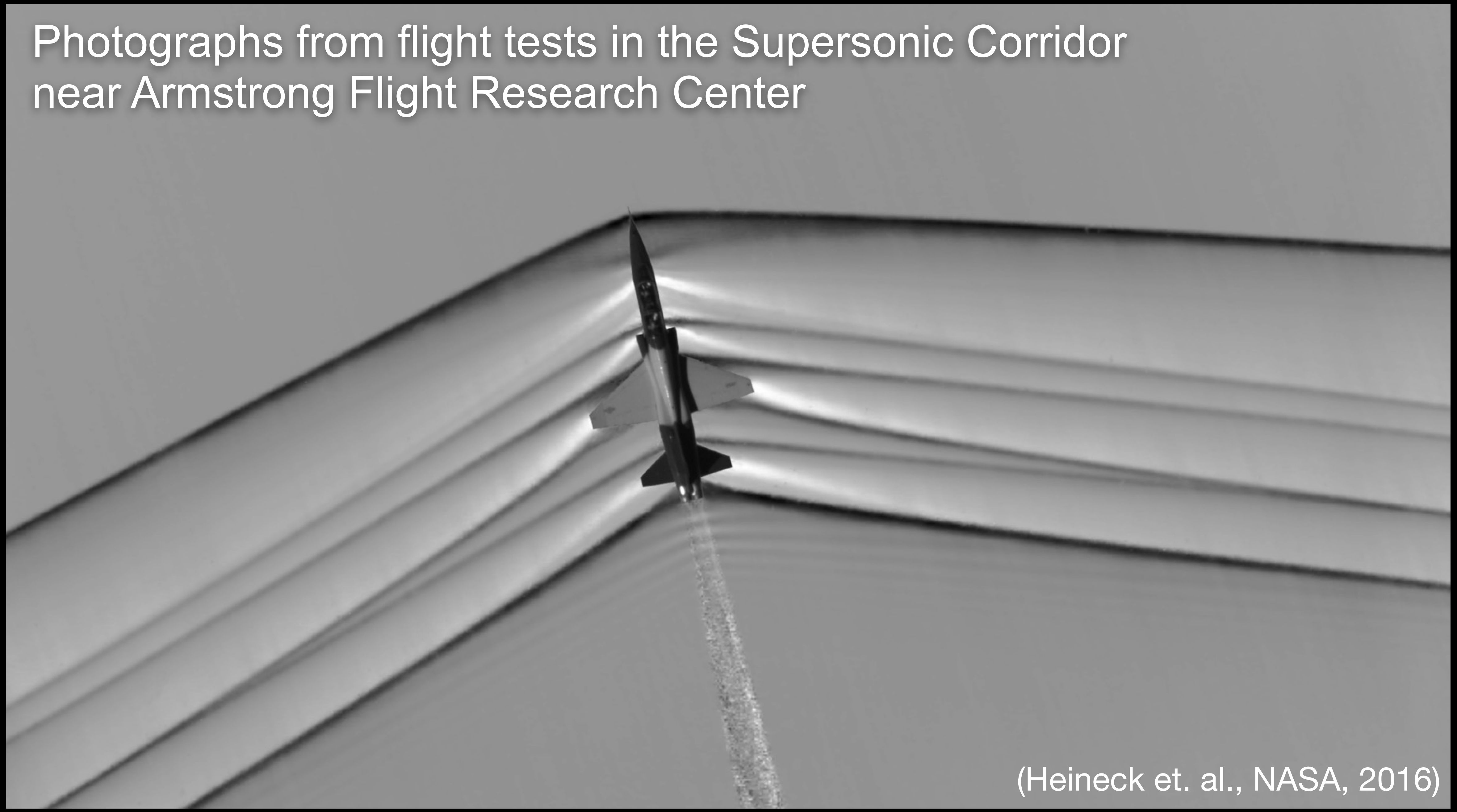
Example Results

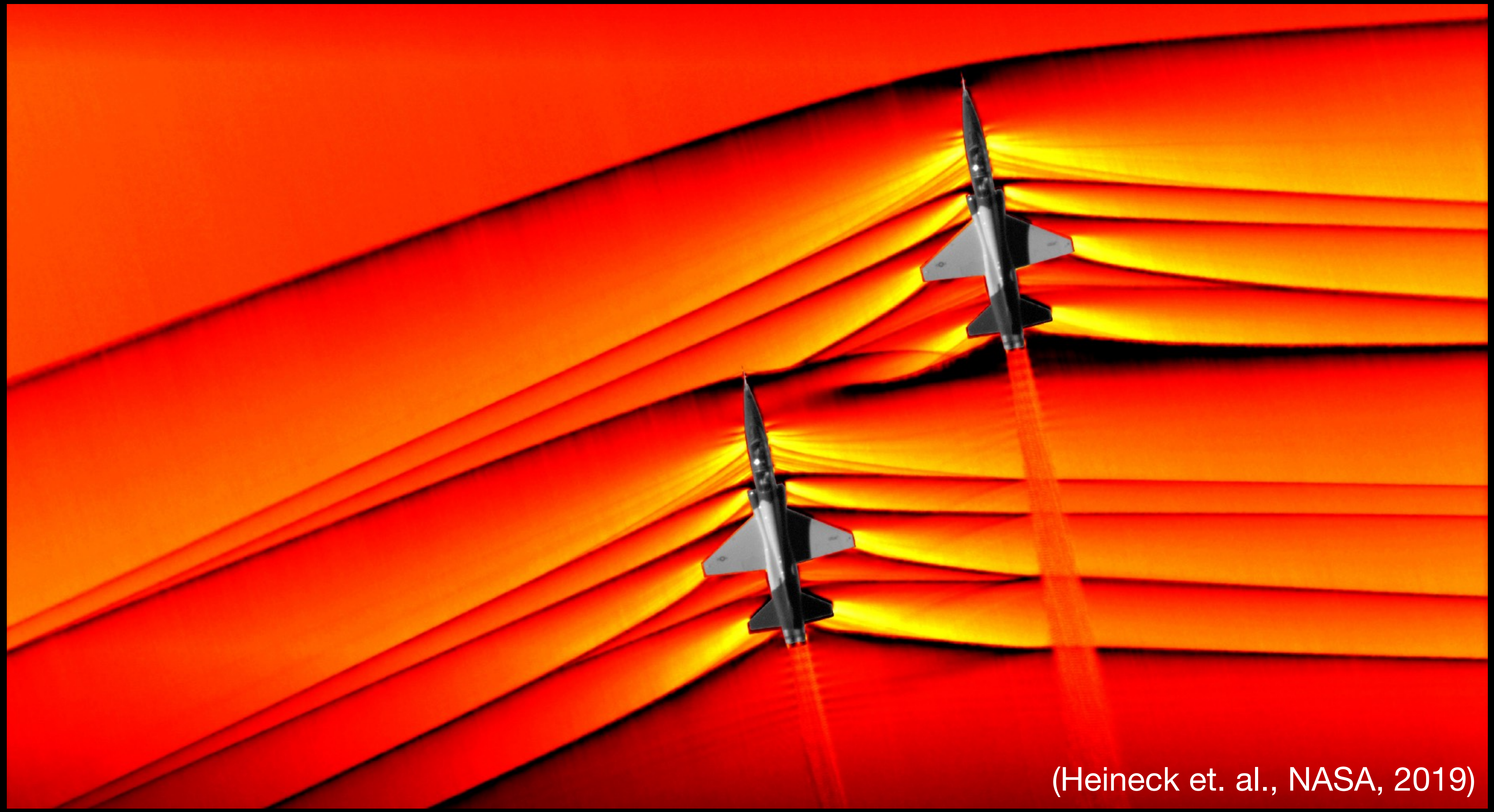
1. Nearfield Flow Solutions
2. Nearfield Signatures
3. Ground Signatures
4. Ground Noise Level



Nearfield

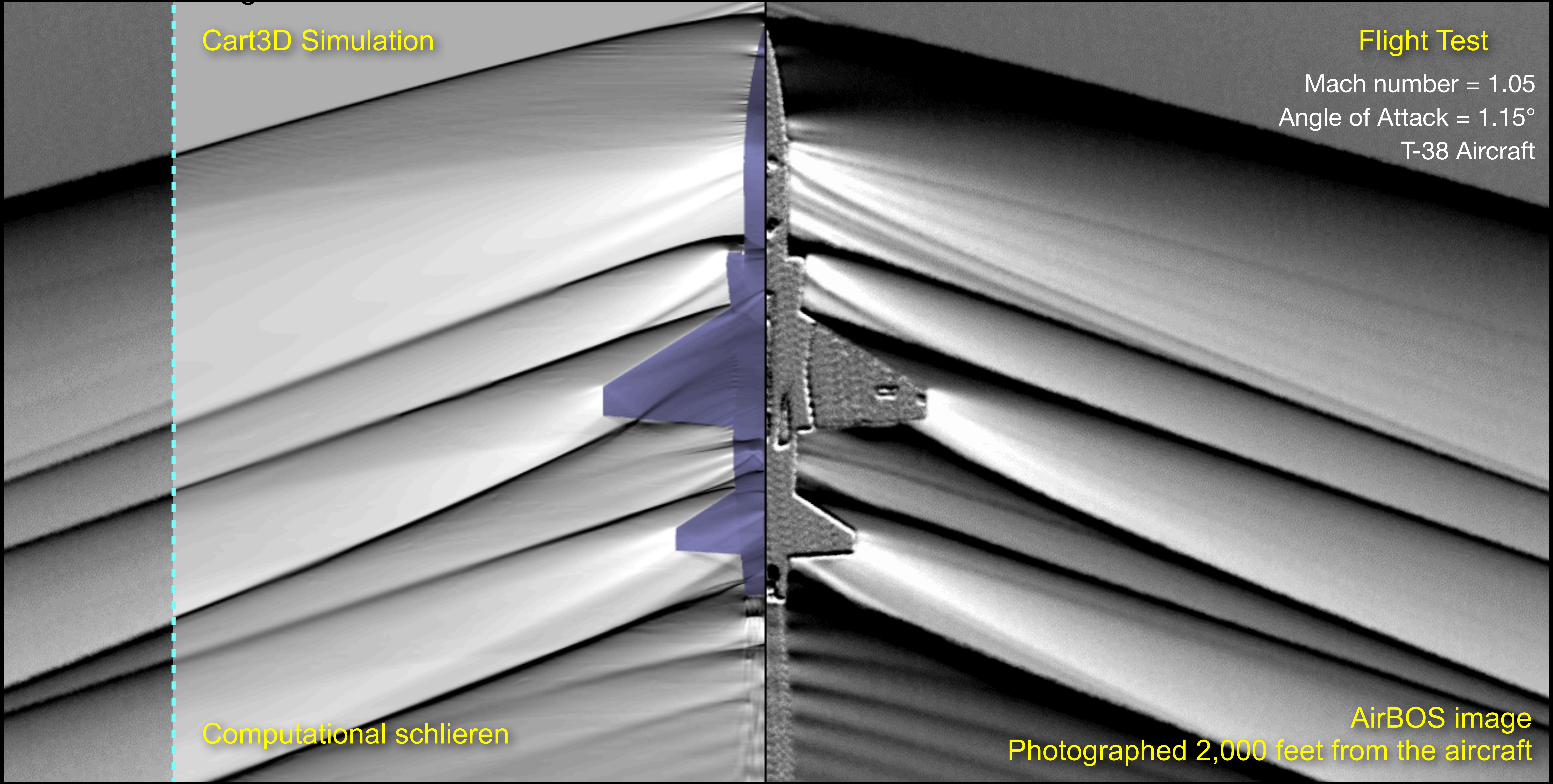
Schlieren Flow Visualization





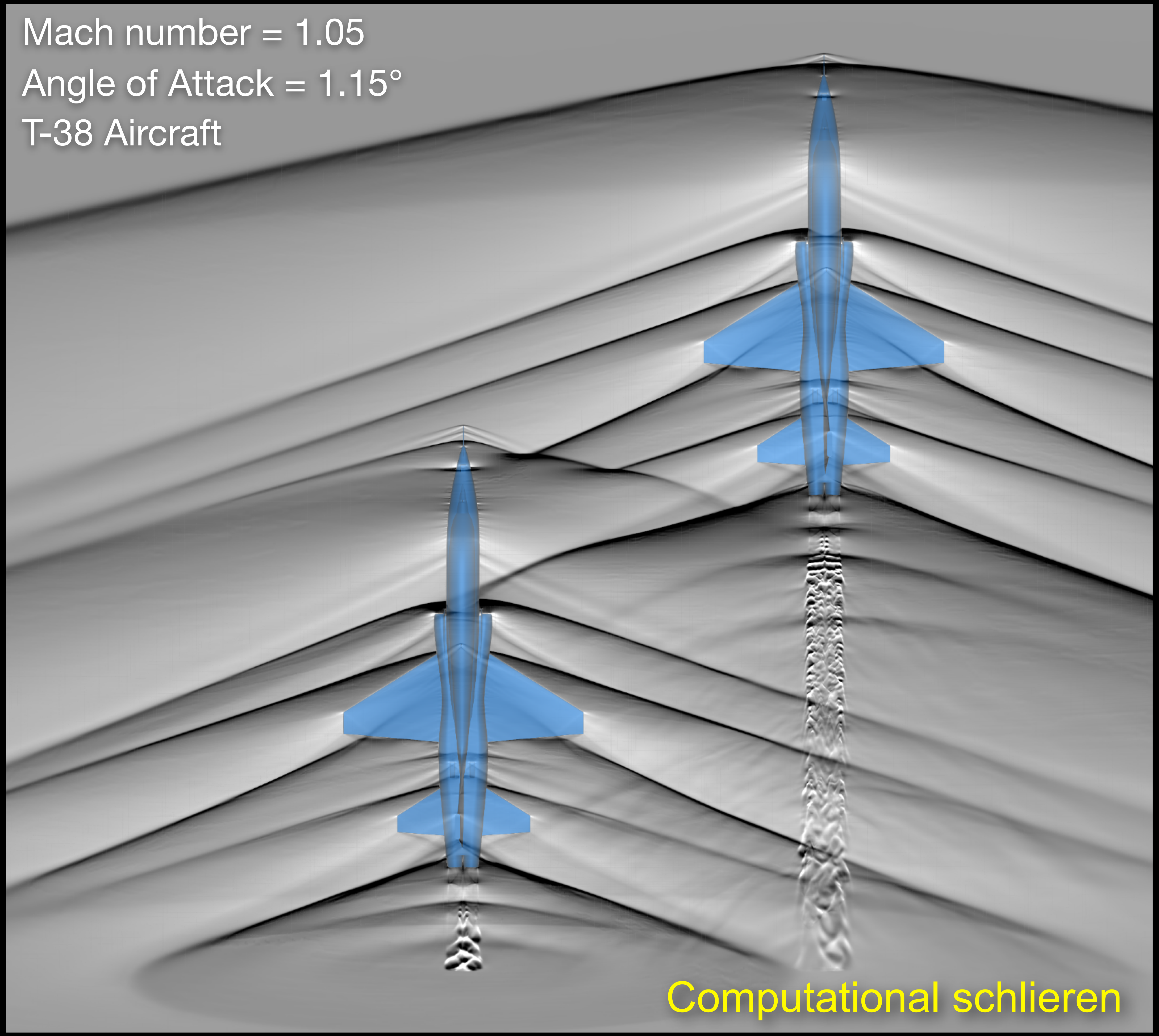
- Schlieren photographs are a well-established experimental technique
  - Visualization of density gradients, excellent for shocks
- New capability in Air-to-Air Background Oriented Schlieren (AirBOS) imaging
  - Allows schlieren imagery of aircraft in flight
  - Emerging technique for validating simulations through comparison with computational schlierens

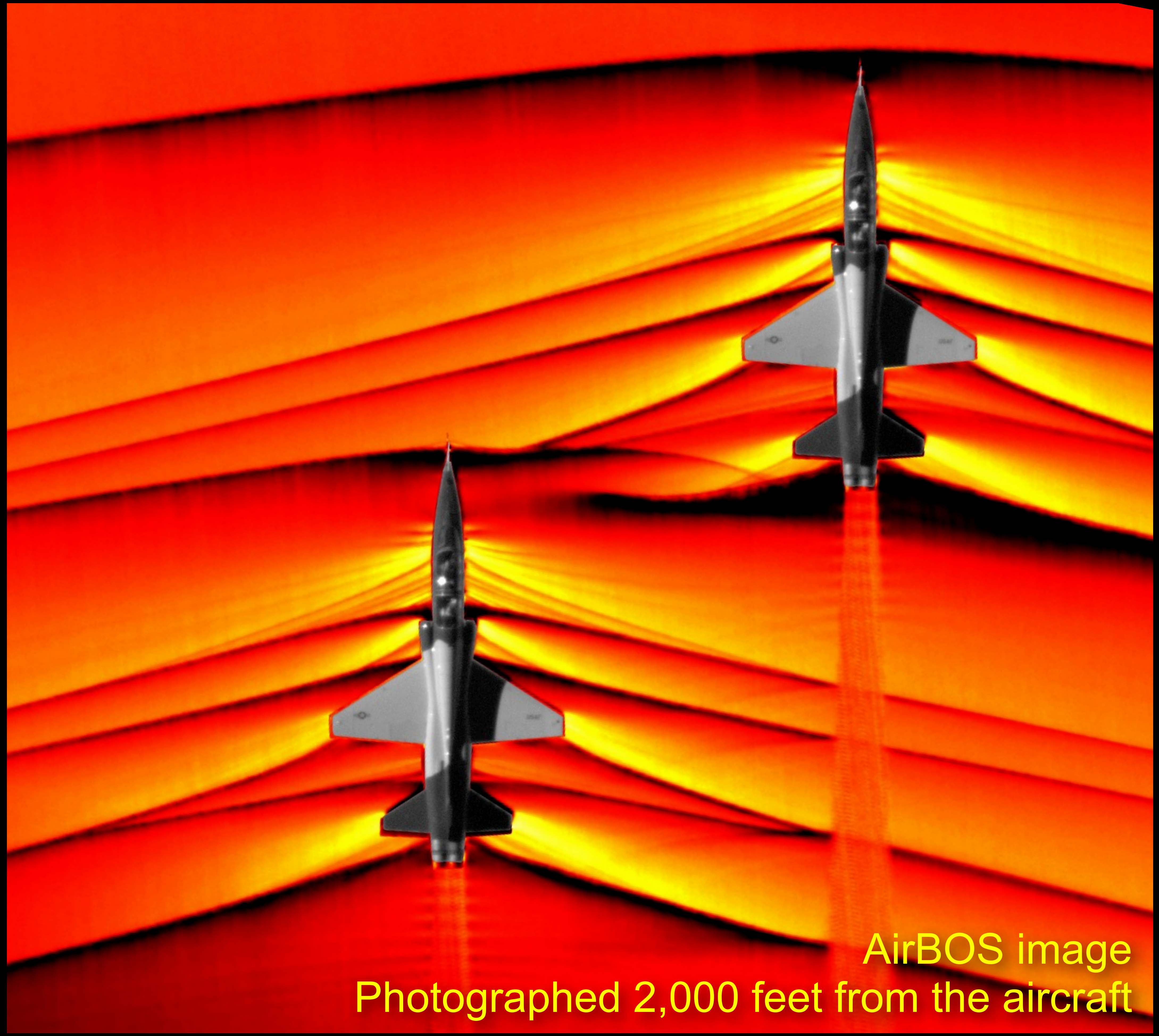
Flight-Matching Computation



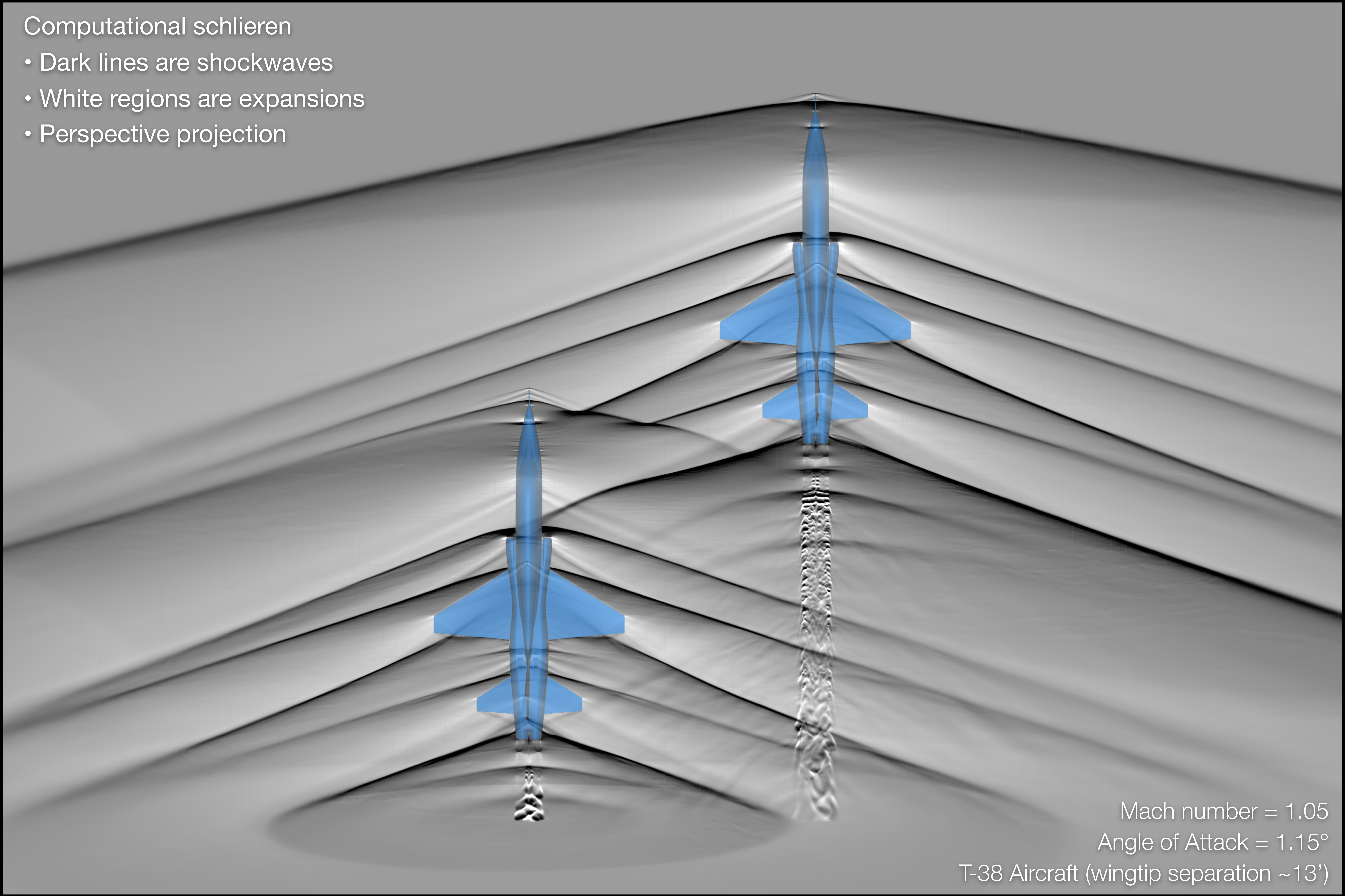
Shock-Shock Interactions

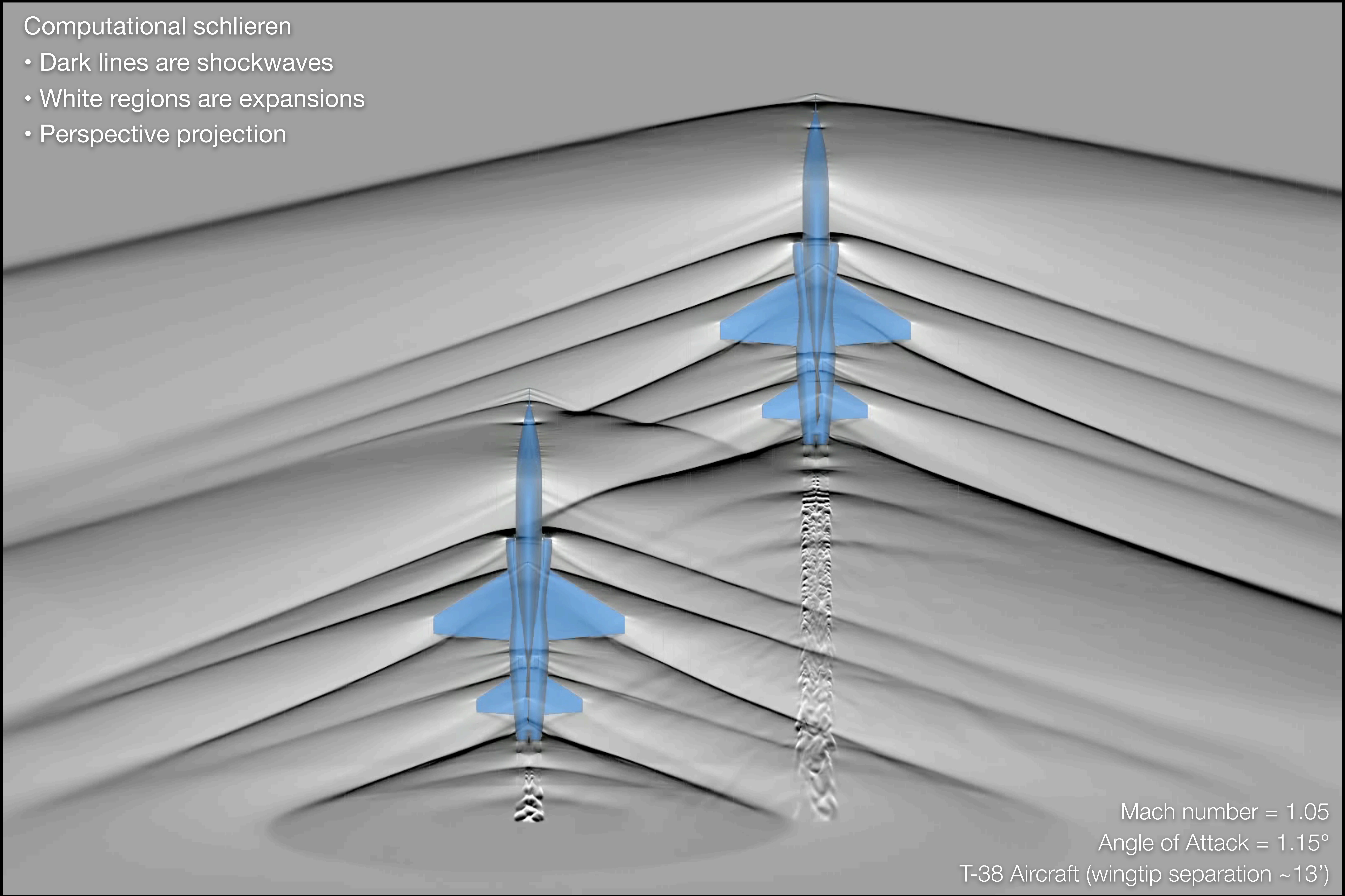
Supersonic Formation Flight





Preliminary work toward flight-matching simulations and future acoustic validation flights


Computational schlieren
• Dark lines are shockwaves
• White regions are expansions
• Perspective projection
Mach number = 1.05
Angle of Attack = 1.15°
T-38 Aircraft (wingtip separation ~13')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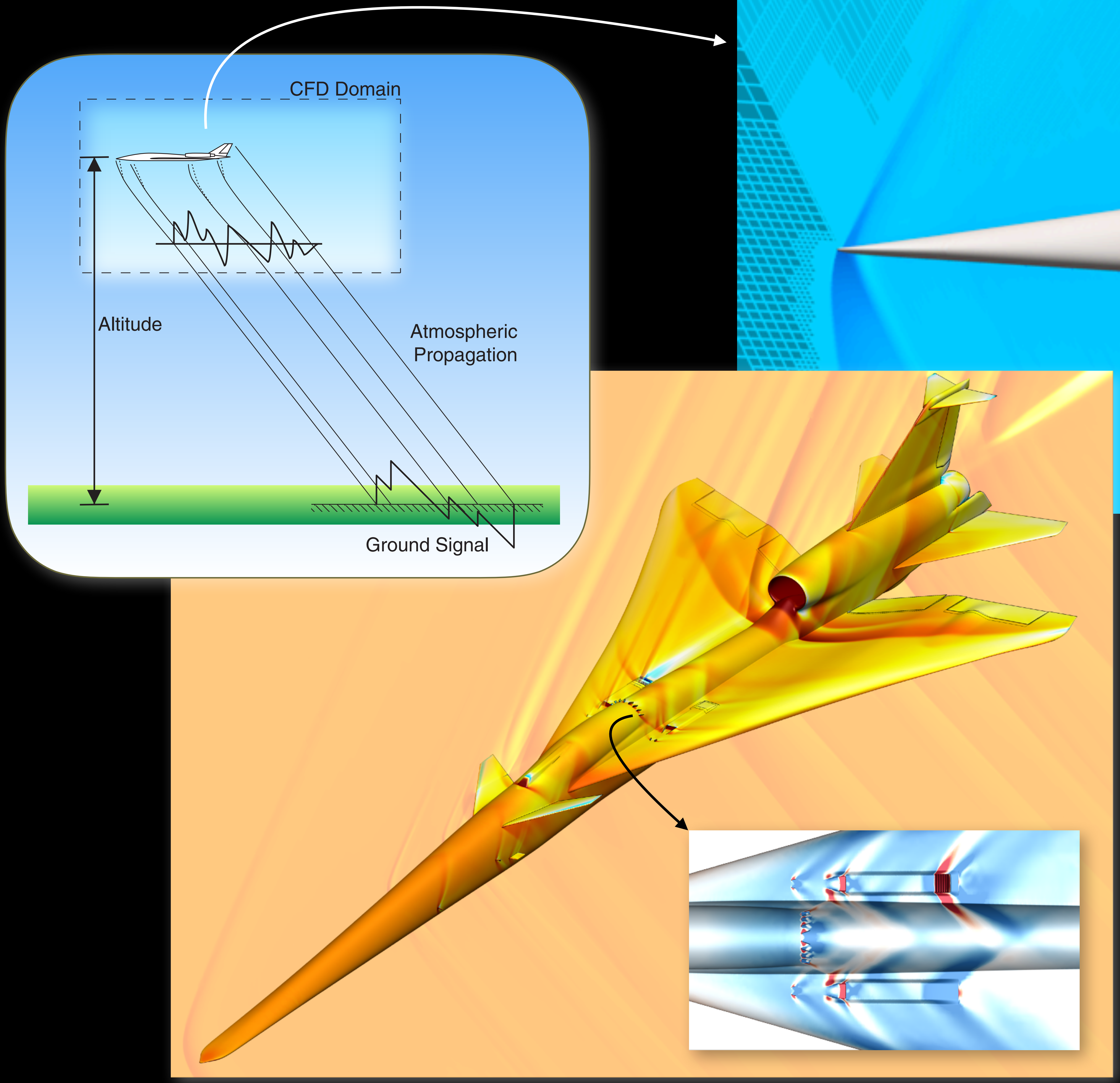
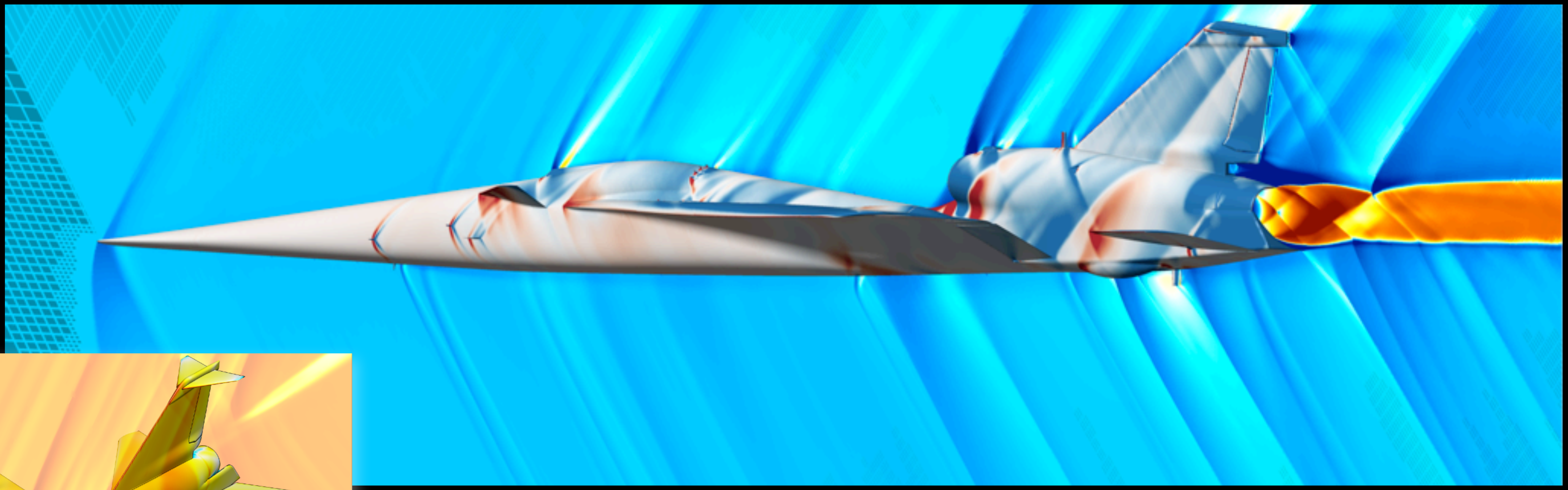
X-59 Nearfield Predictions





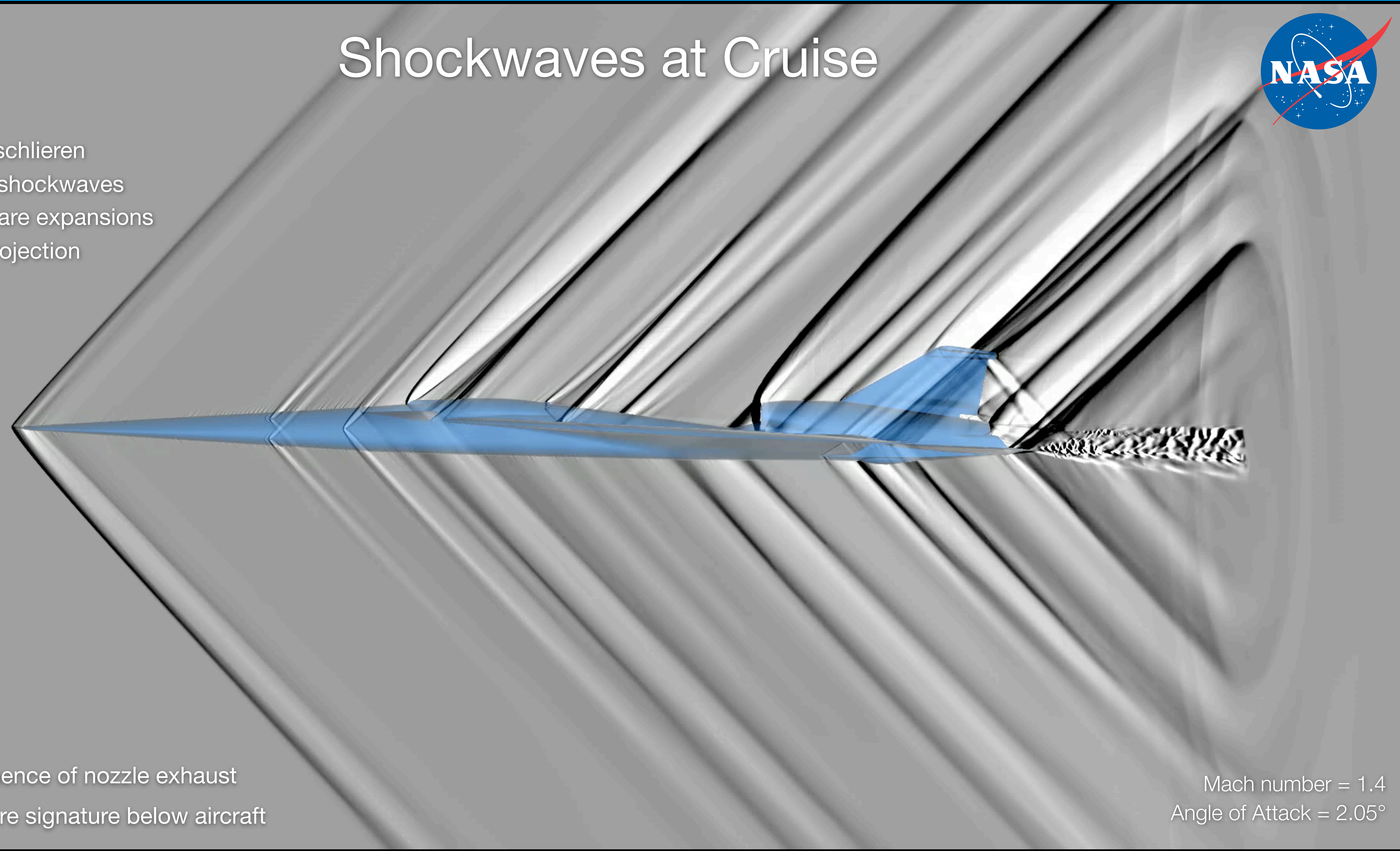
Challenging simulations:

- Fine geometric detail (probes, vortex generators, flaps, ailerons, stabilator, t-tail, …)
- Many secondary-air systems, in addition to the main engine
- Requires accurate prediction of a ***complex system of shockwaves*** far from the aircraft in addition to standard aerodynamic performance coefficients

Shockwaves at Cruise

Computational schlieren

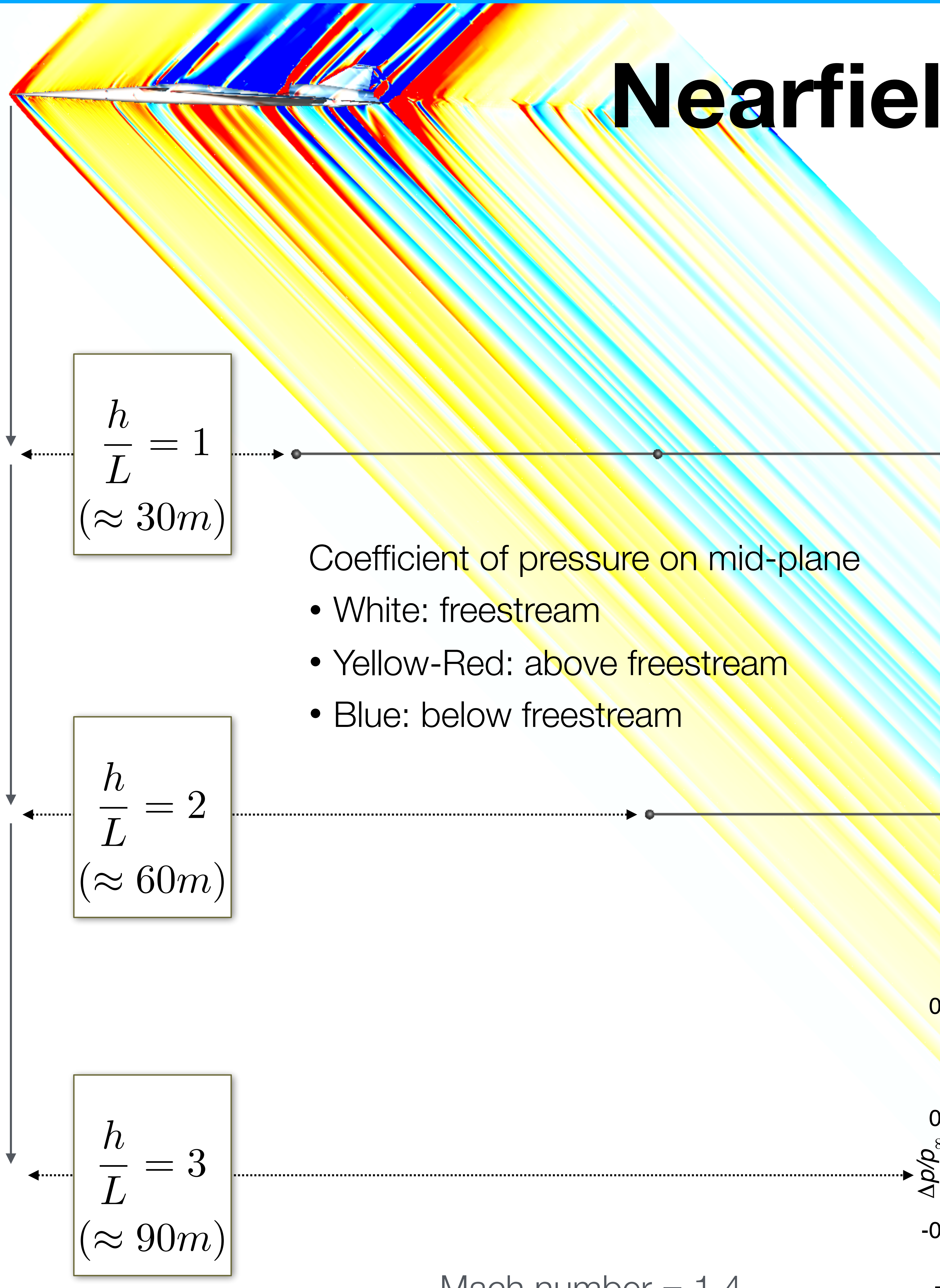
- Dark lines are shockwaves
- White regions are expansions
- Perspective projection



- Significant influence of nozzle exhaust
- Shaped pressure signature below aircraft

Mach number = 1.4
Angle of Attack = 2.05°

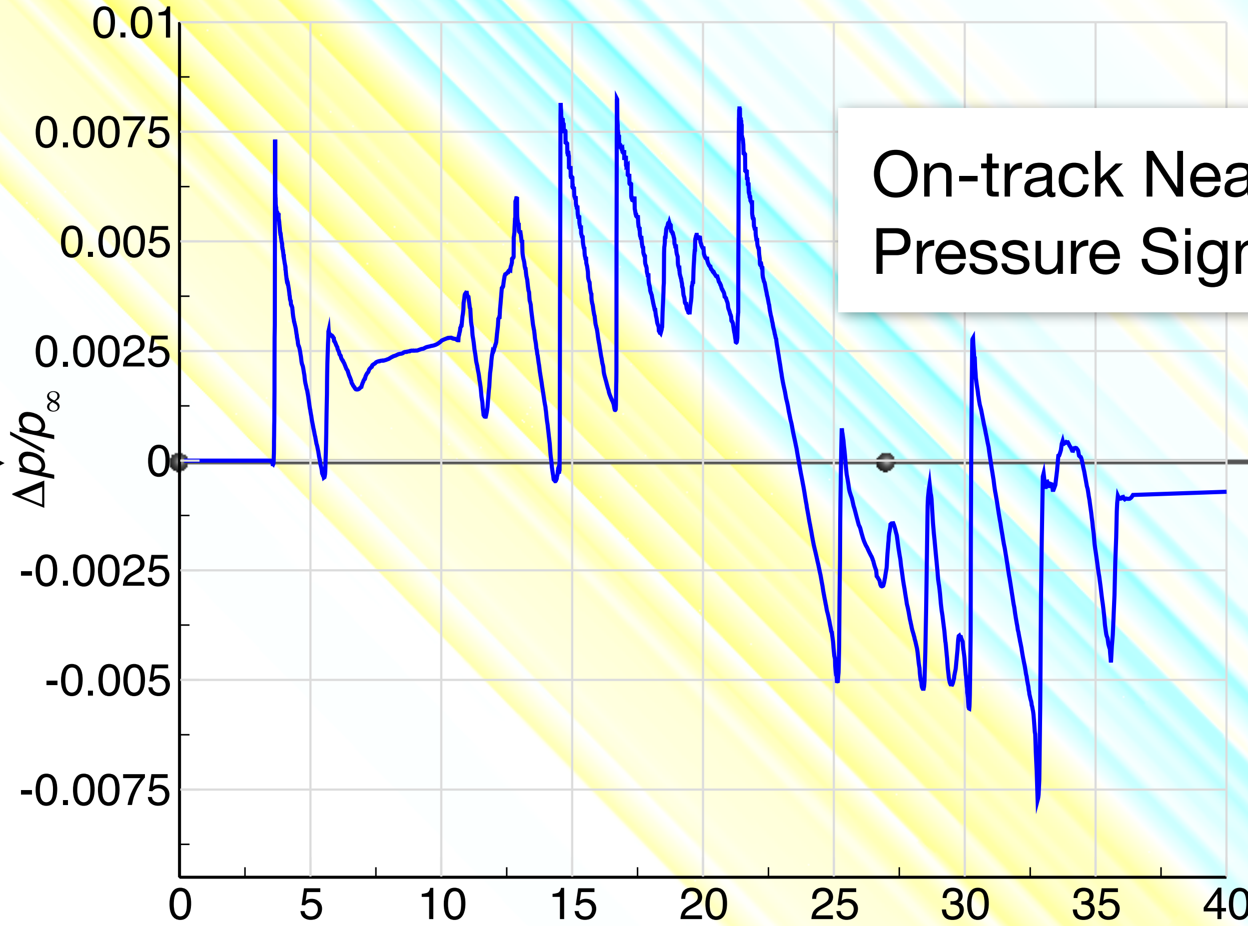
Nearfield Pressure Signature



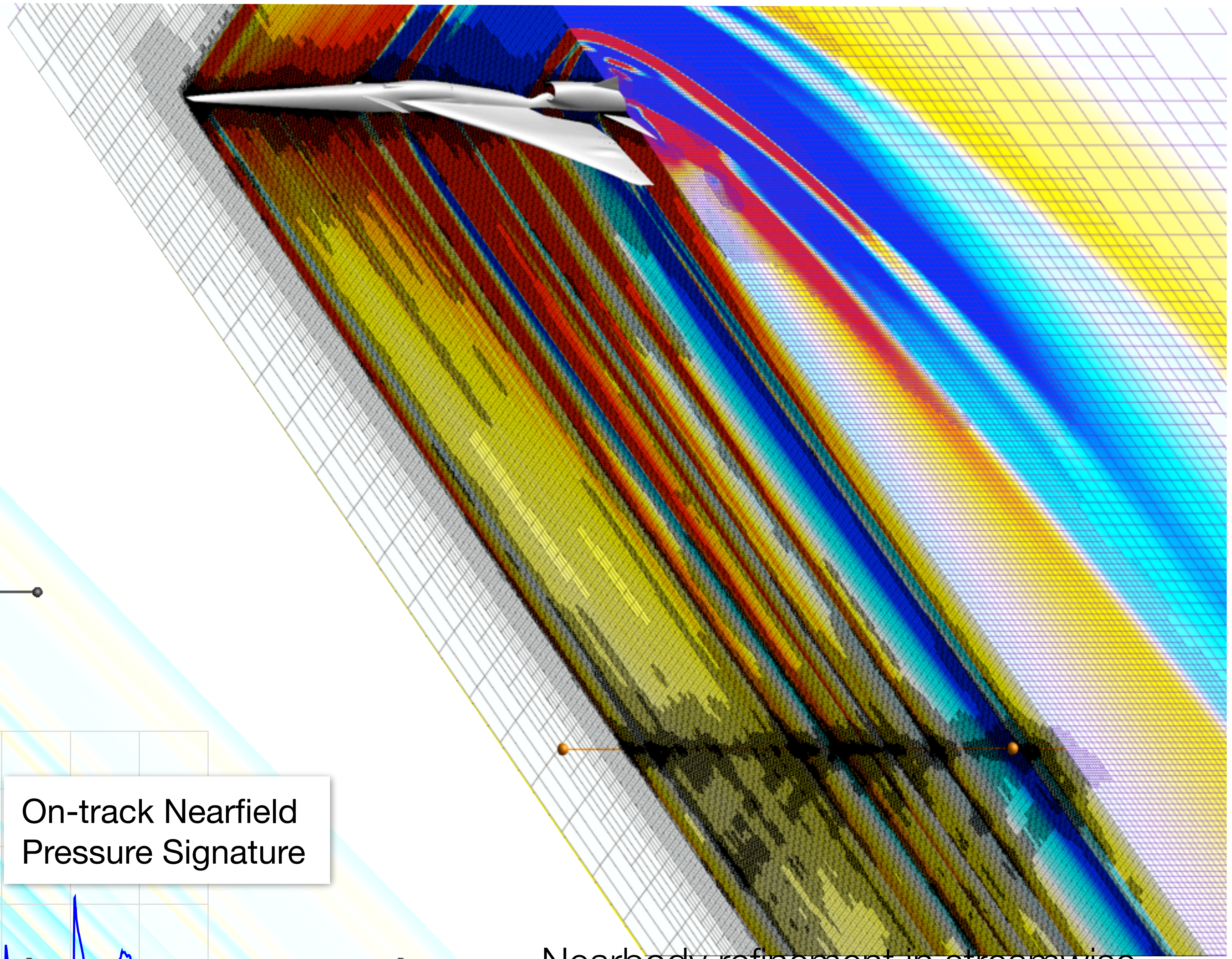
Coefficient of pressure on mid-plane

- White: freestream
- Yellow-Red: above freestream
- Blue: below freestream

Mach number = 1.4
Angle of Attack = 2.05°



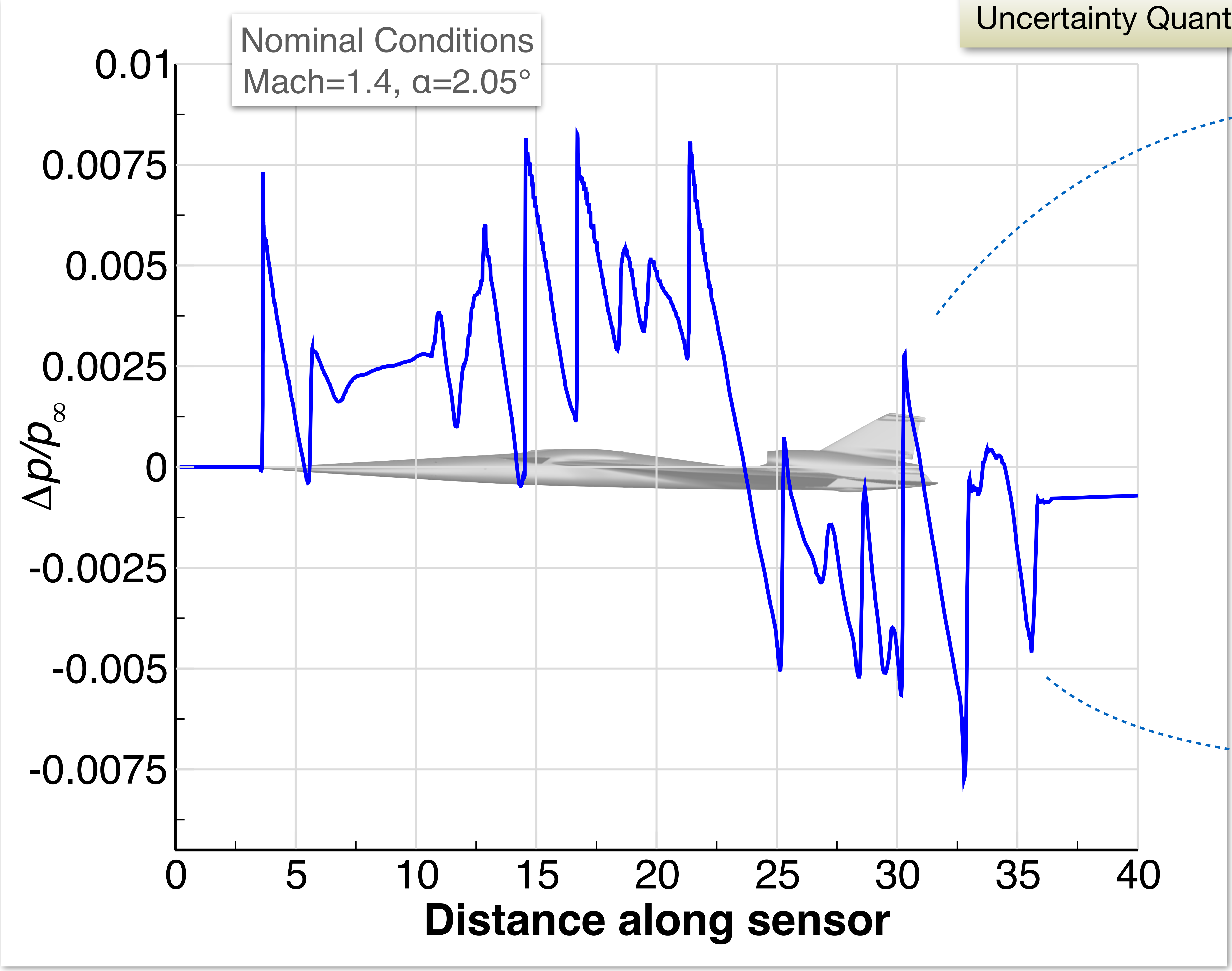
On-track Nearfield Pressure Signature



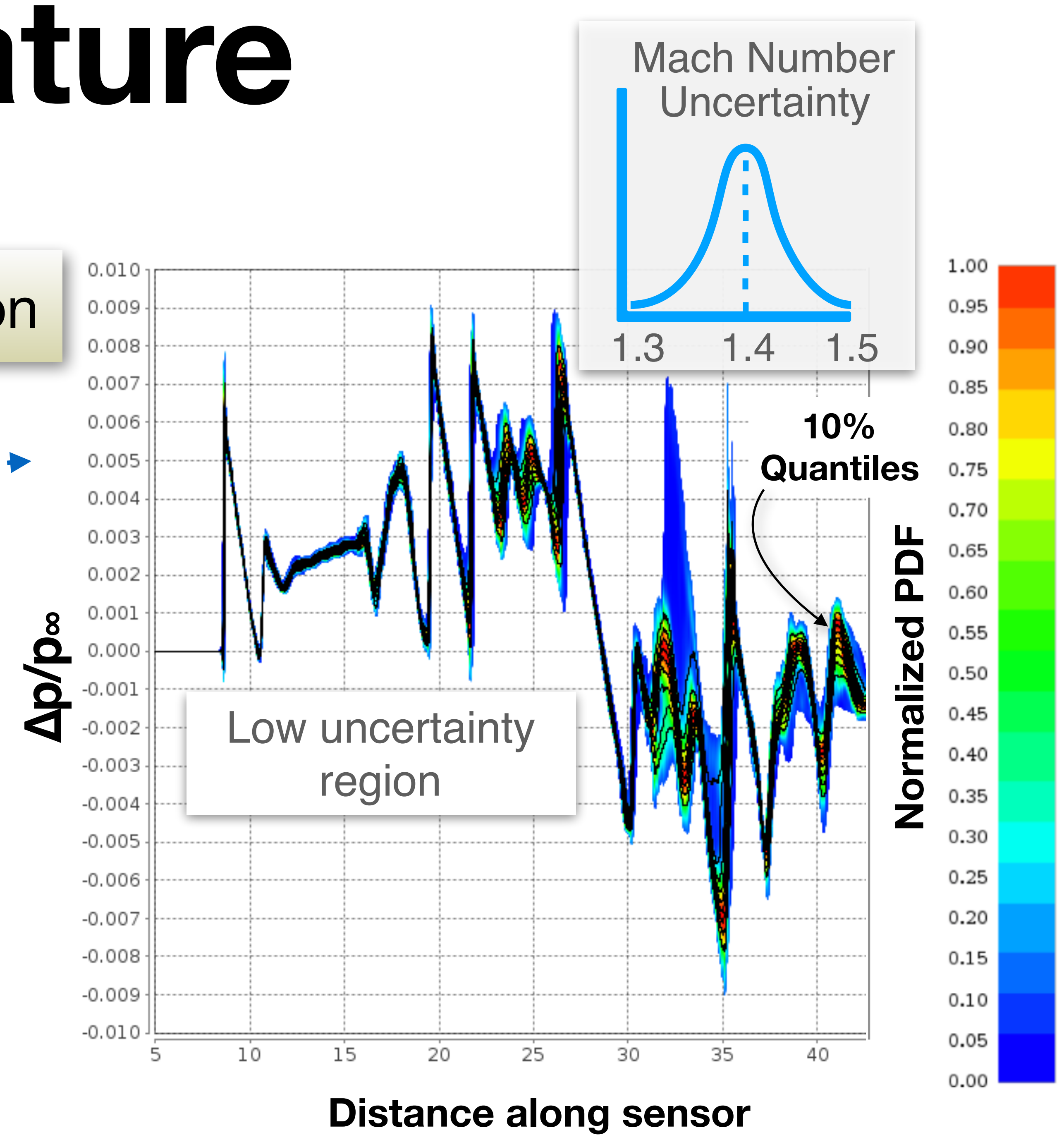
Nearbody refinement in streamwise and crossflow directions:

- Typical mesh size 50 million cells
- Fine mesh size 100—500 million cells

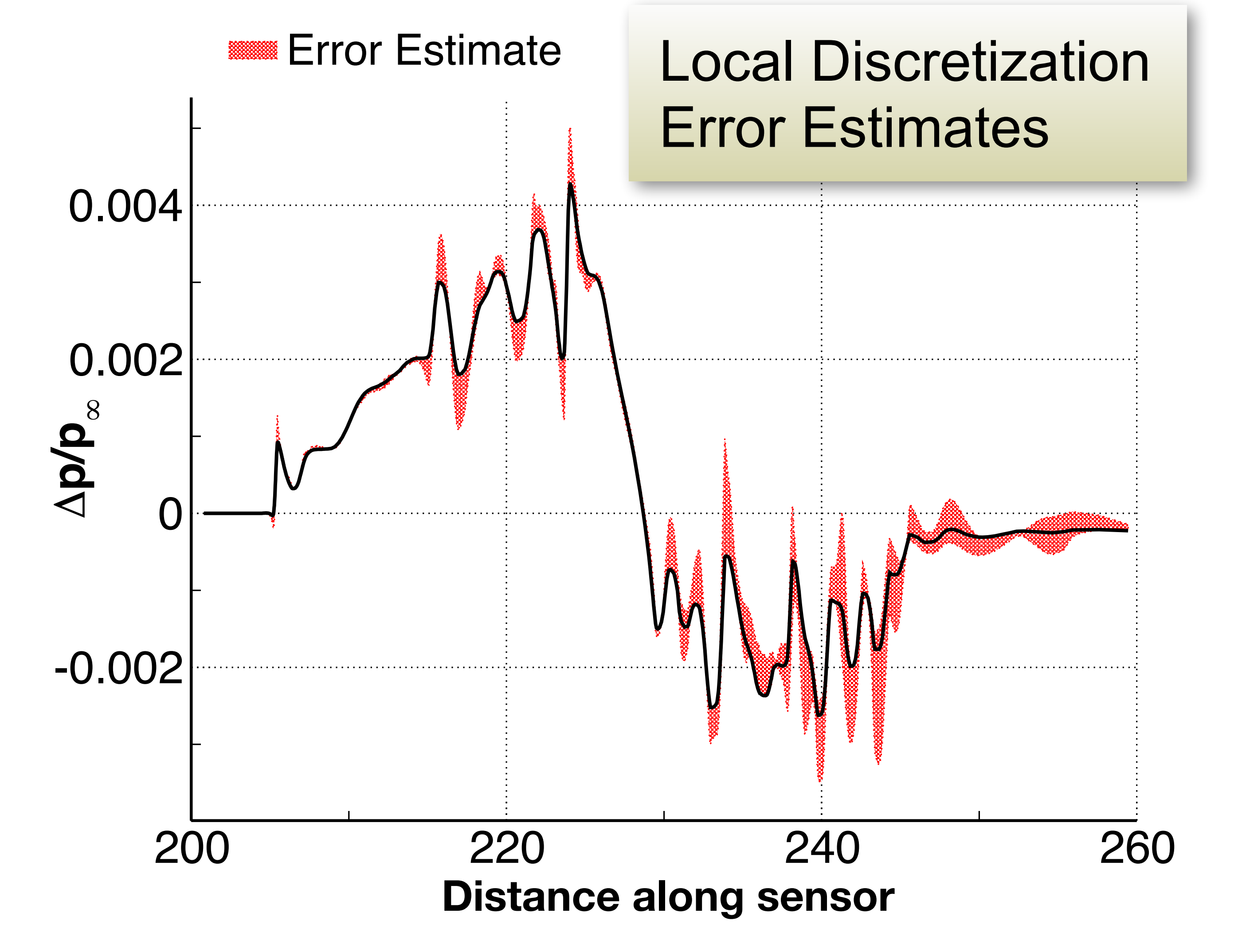
Nearfield Pressure Signature



Uncertainty Quantification

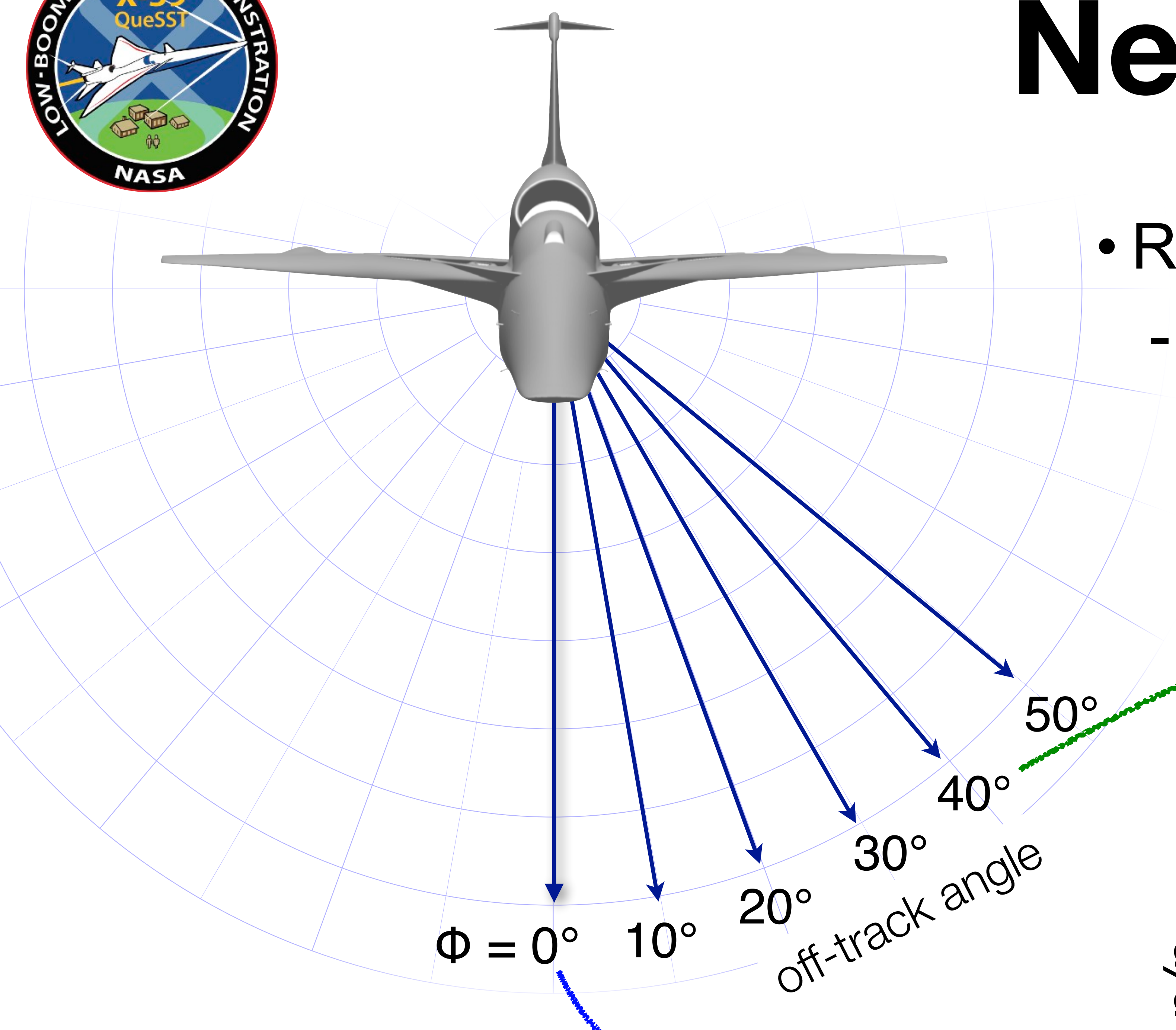


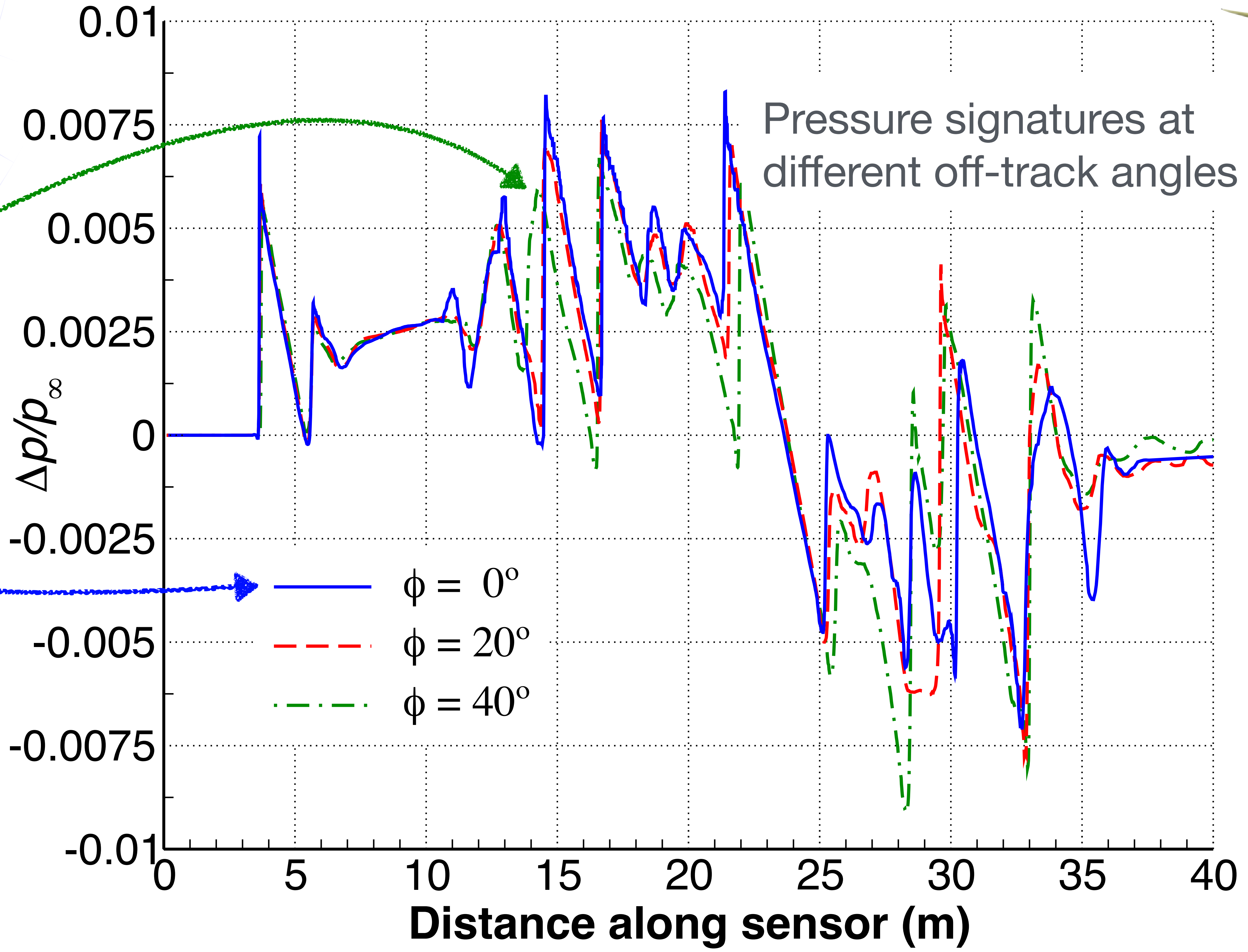
Local Discretization Error Estimates

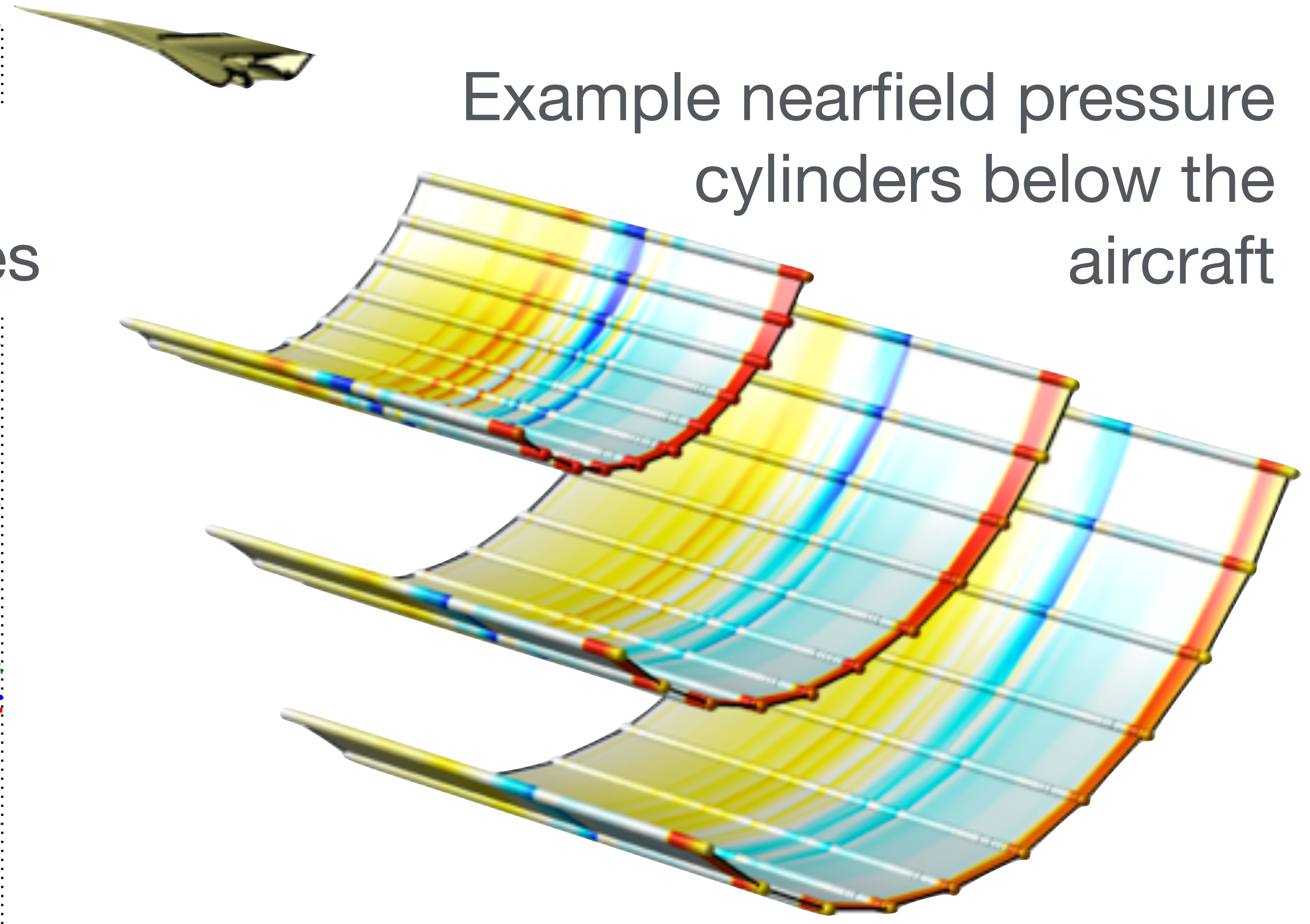


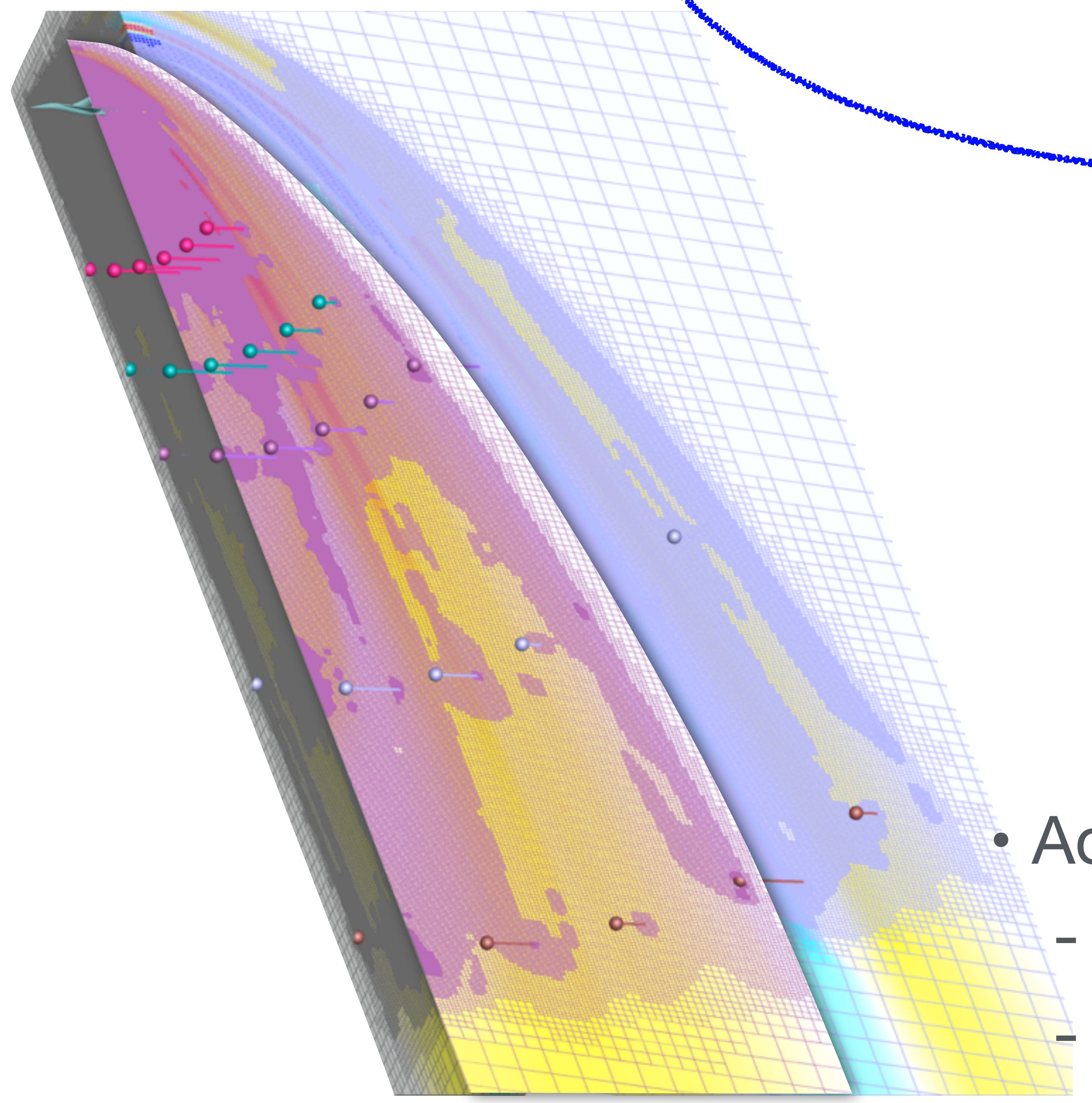
Nearfield Pressure Cylinders

- Recall that goal is to compute the boom carpet on the ground
  - This requires computation of the nearfield pressure cylinder, not just the on-track signature

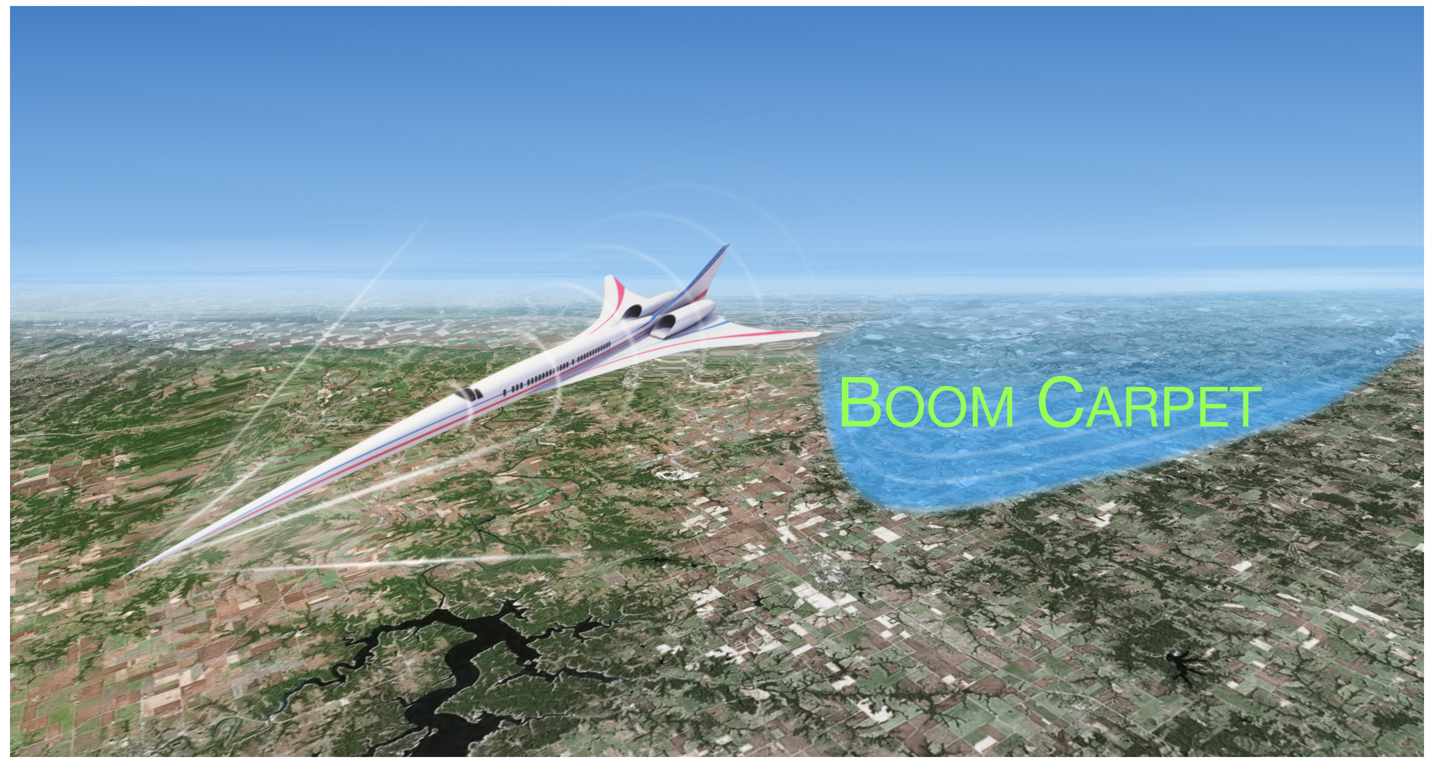






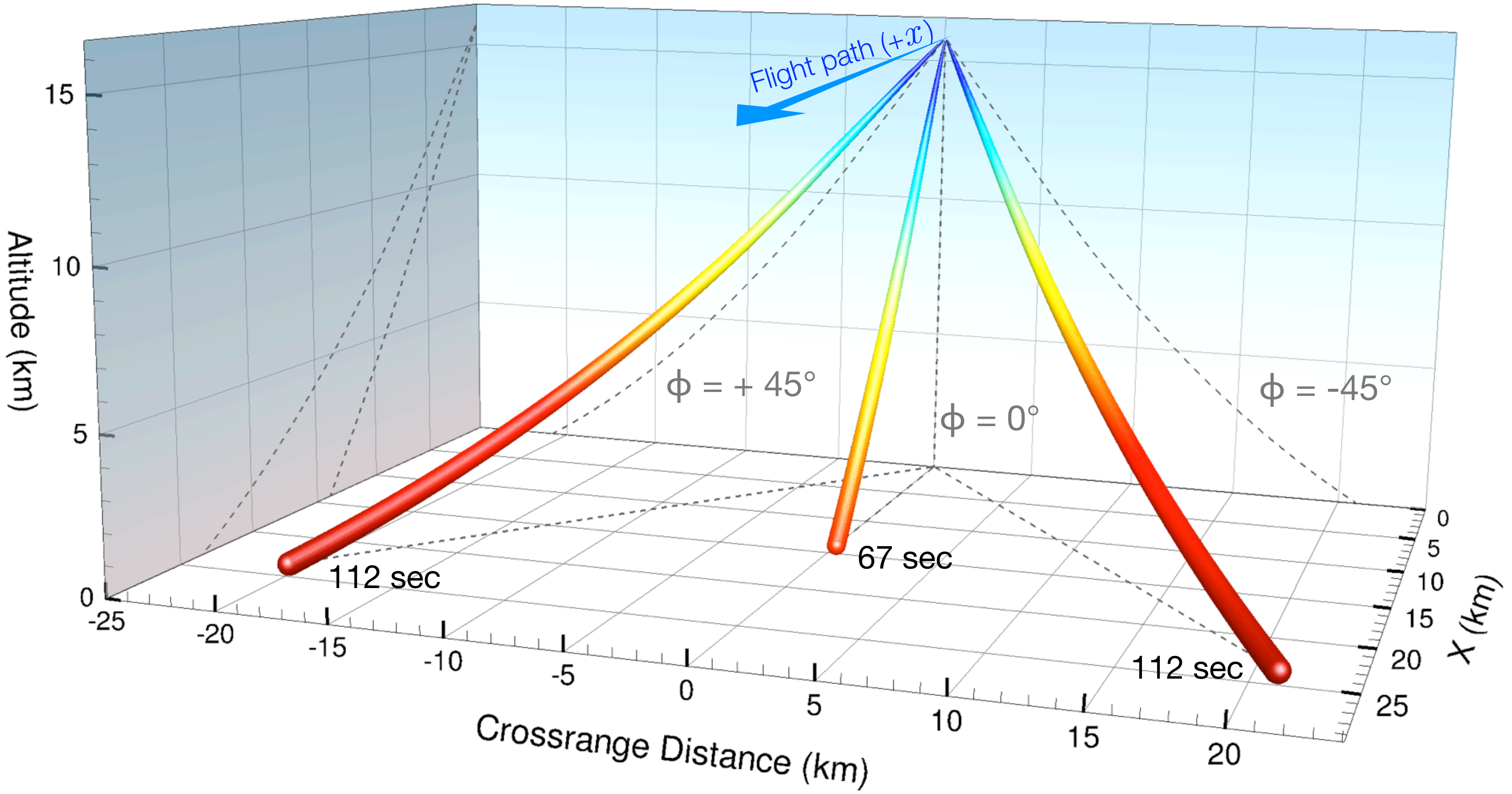


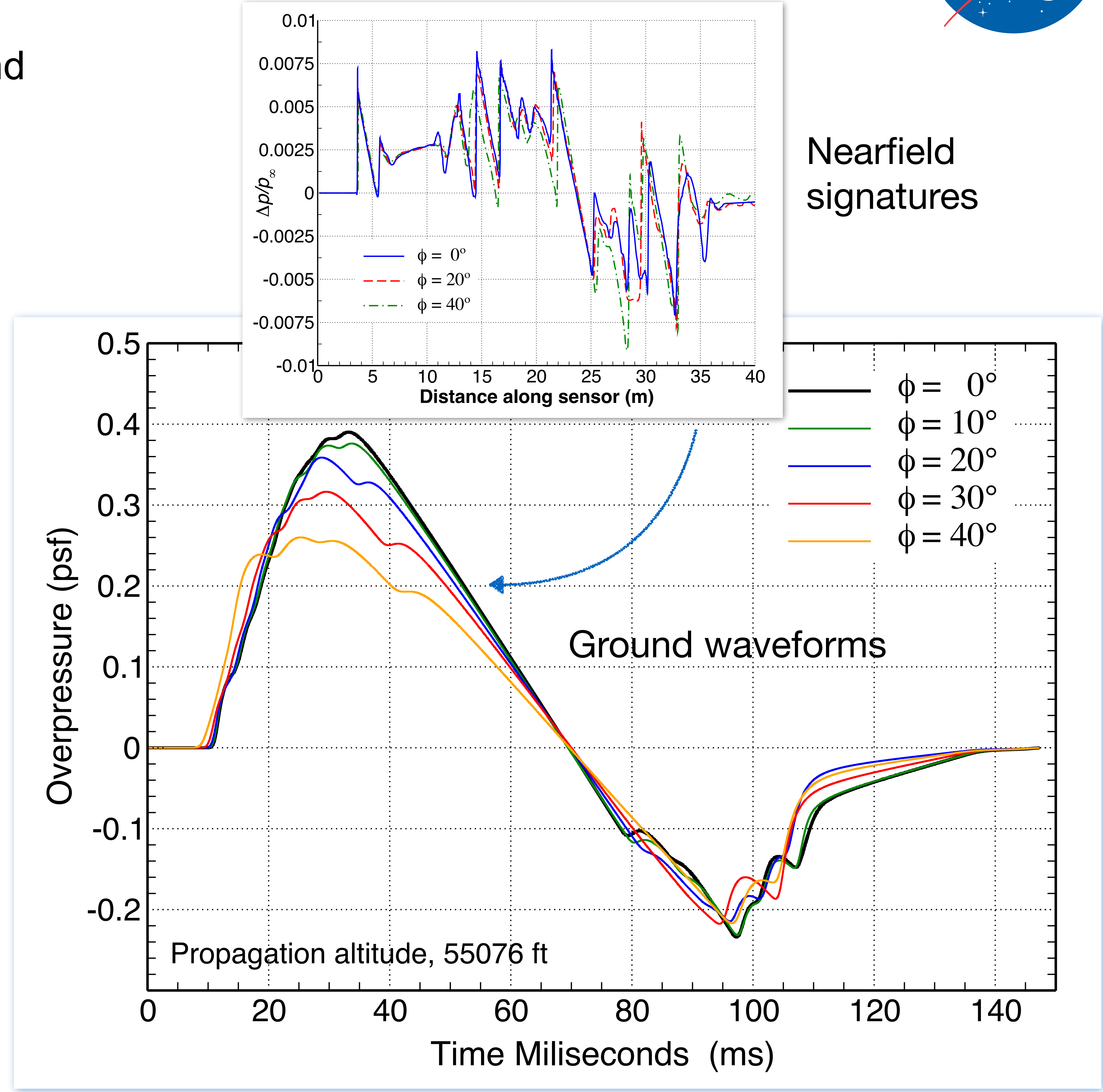
- Adaptively refined mesh for many sensor locations
  - In practice, we take full advantage of mesh alignment
  - Separate into several cases with sensors at similar off-track angles



Atmospheric Propagation and Ground Signatures

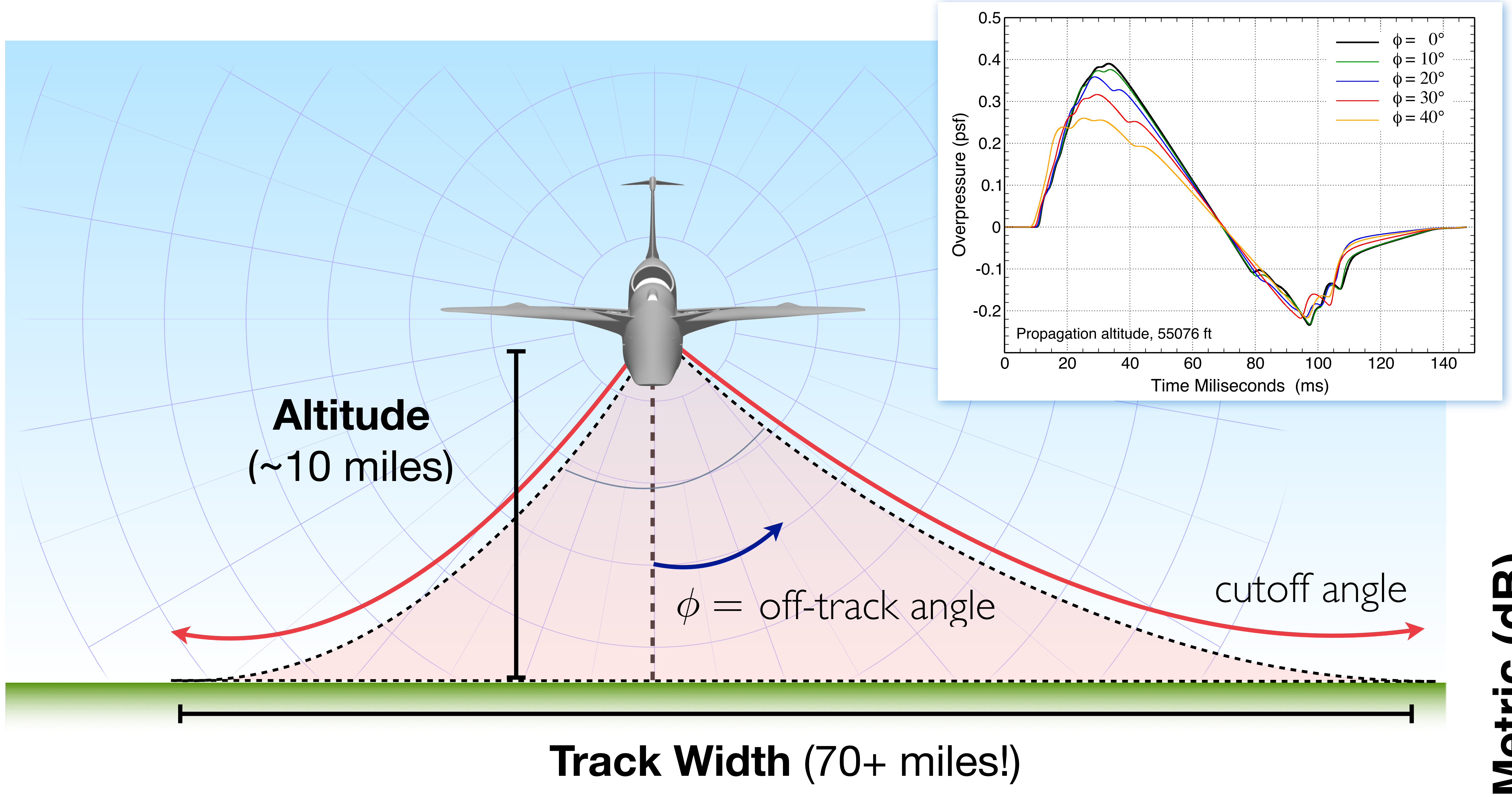
- Propagate nearfield signature through atmosphere to ground
- Numerical analysis via sBOOM:
  1. Ray tracing (path and arrival time)
  2. Quasi-1D propagation (signature morphology)
     - Includes relaxation loses, stratification, spreading and non-linear propagation





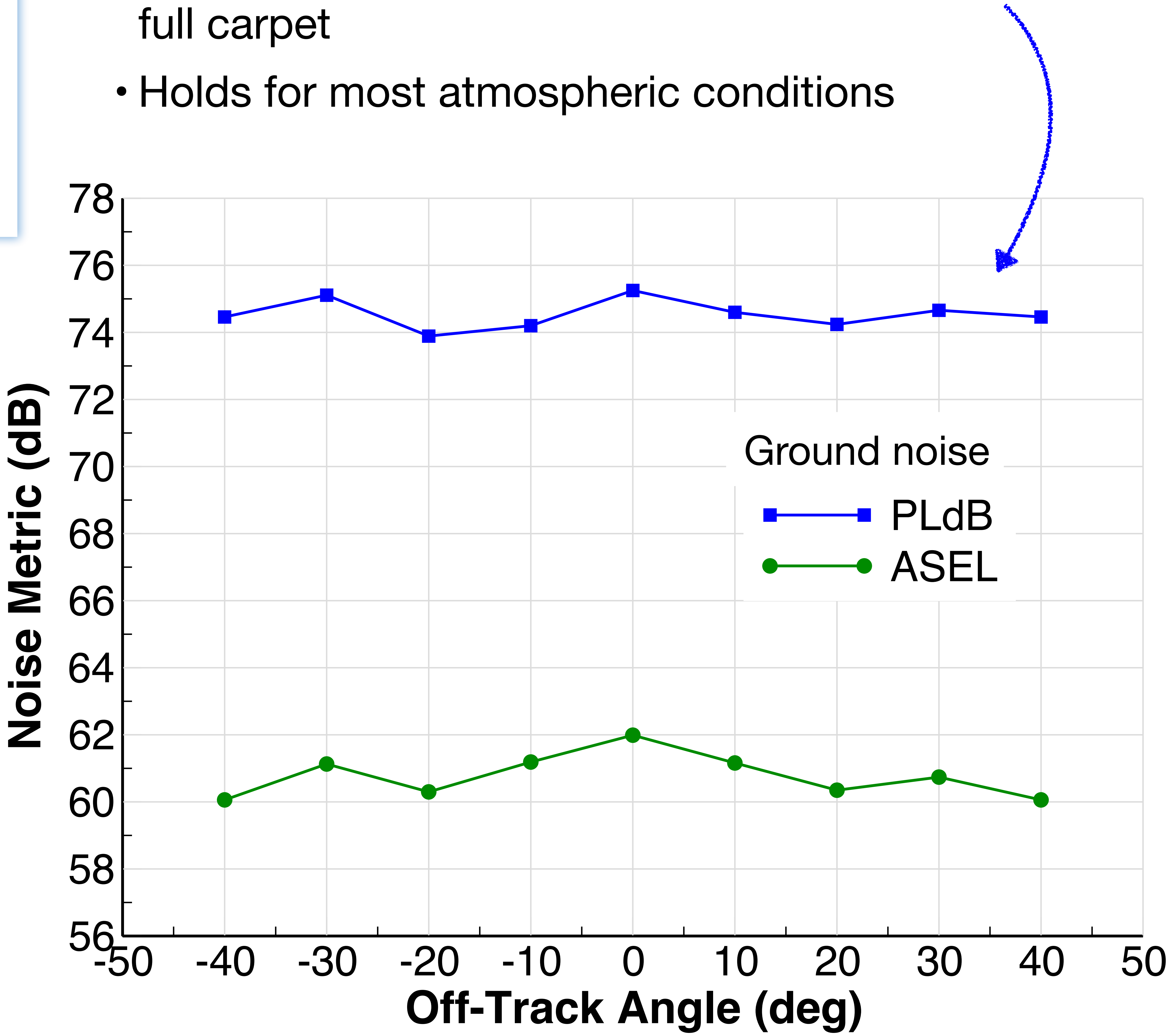
Nearfield signatures

Sonic Boom Carpet



Noise target is **75** PLdB

- Current design is **quieter** than target over the full carpet
- Holds for most atmospheric conditions



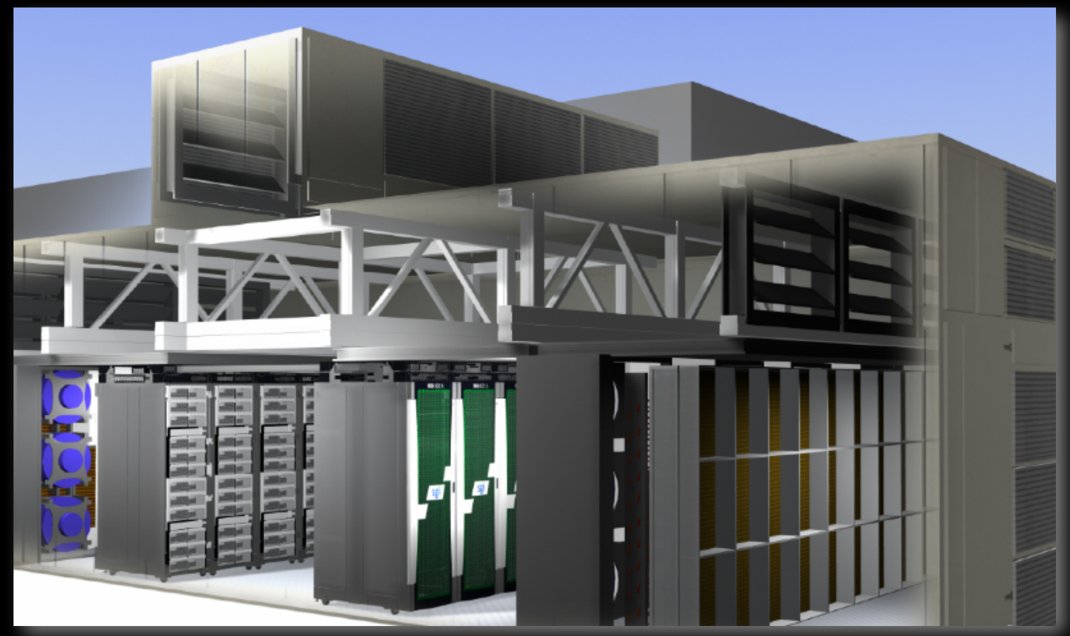
Convert ground waveform to level of noise for each off-track angle up to cutoff

- Perceived level (PLdB) is the primary metric
- ASEL, BSEL & CSEL also used

Importance of High-End Computing

Challenges of simulating low-boom aircraft

- Propagation of weak shocks over several aircraft lengths
  - Difficult to reap benefits of advanced higher-order schemes
  - Highly susceptible to attenuation by discretization error
- Wide range of scales: complex flow & aircraft geometry
  - Large grids even with adaptive mesh refinement
- Many engineering cases
  - Operating conditions, flaps, ailerons, stabilator, T-tail, engine settings
  - Fast turn-around critical (4—8 hours per case)
  - Each case fits on 1—4 nodes, but may need several 100 nodes to fill databases efficiently



Endeavour
- Sandy Bridge

Pleiades
- Broadwell

Electra
- Skylake

Aitken
- Cascade Lake

Acknowledgements

- NASA High-End Computing (HEC) Program through the NASA Advanced Supercomputing (NAS) Division
  - SciCon in-house performance monitoring and debug tools
- NASA's ARMD Commercial Supersonic Technology and LBFD/X-59 Projects