

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

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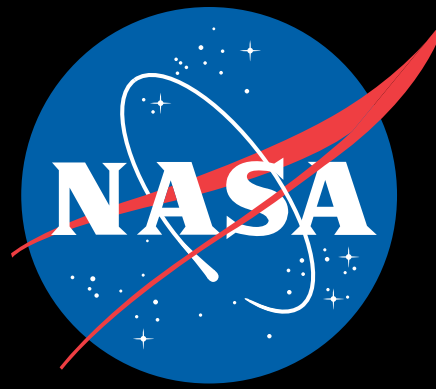
NASA Ames

Wade Spurlock

Science & Technology Corp

Computational Aerosciences Branch
NASA Advanced Supercomputing Division
Ames Research Center

Motivation

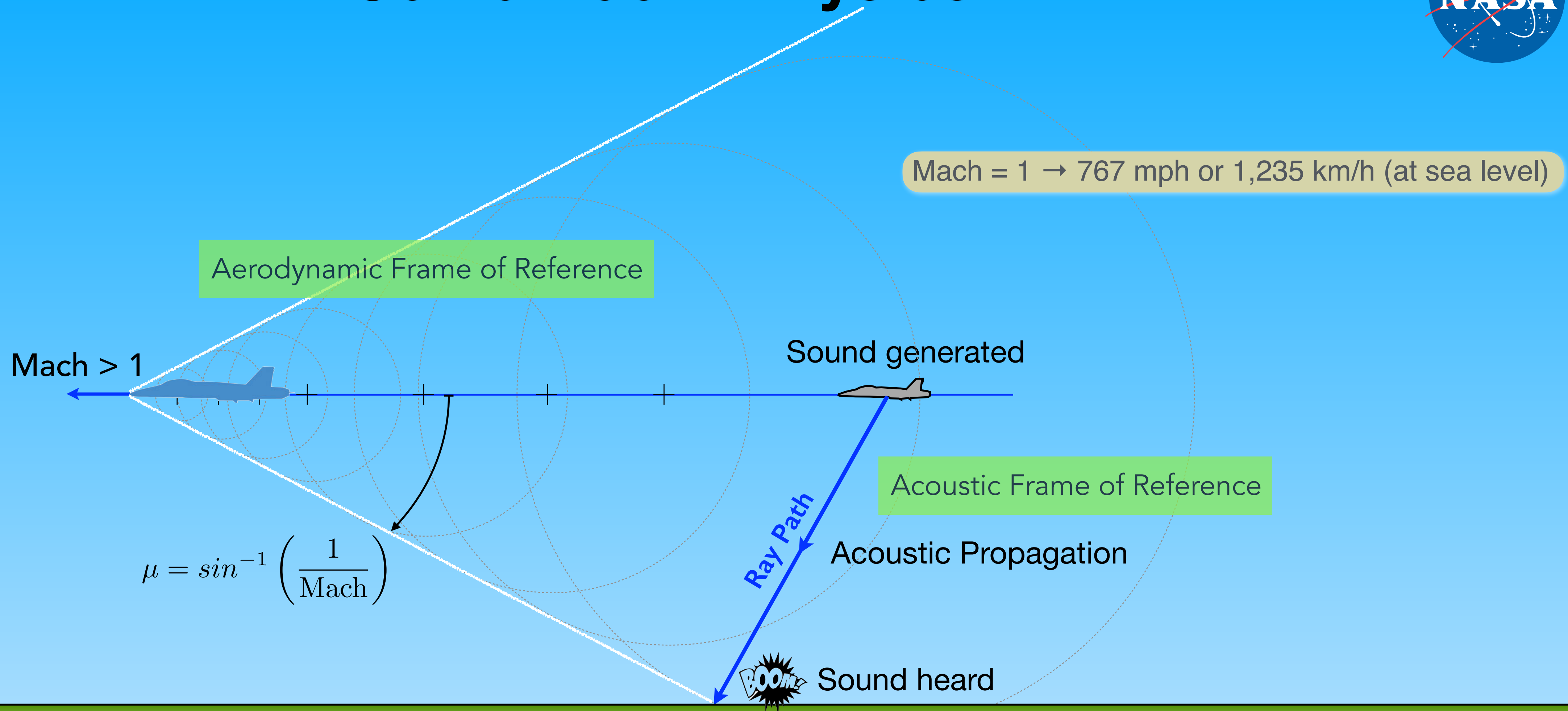


Overcoming the Barrier to Overland Supersonic Flight

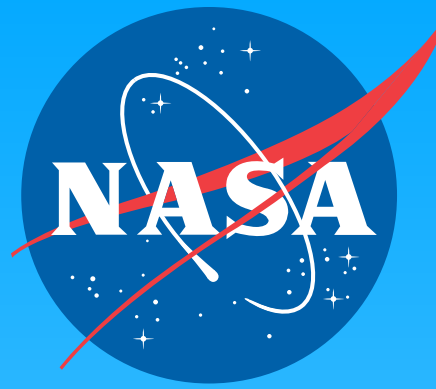
- Vision for Commercial Supersonic Flight is a future where fast air travel is available to a broad spectrum of the traveling public
- Biggest challenge is sonic boom
 - Civil supersonic flight operations are prohibited over many parts of the world
 - Currently, U.S. law prohibits flight in excess of 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



Sonic Boom Physics



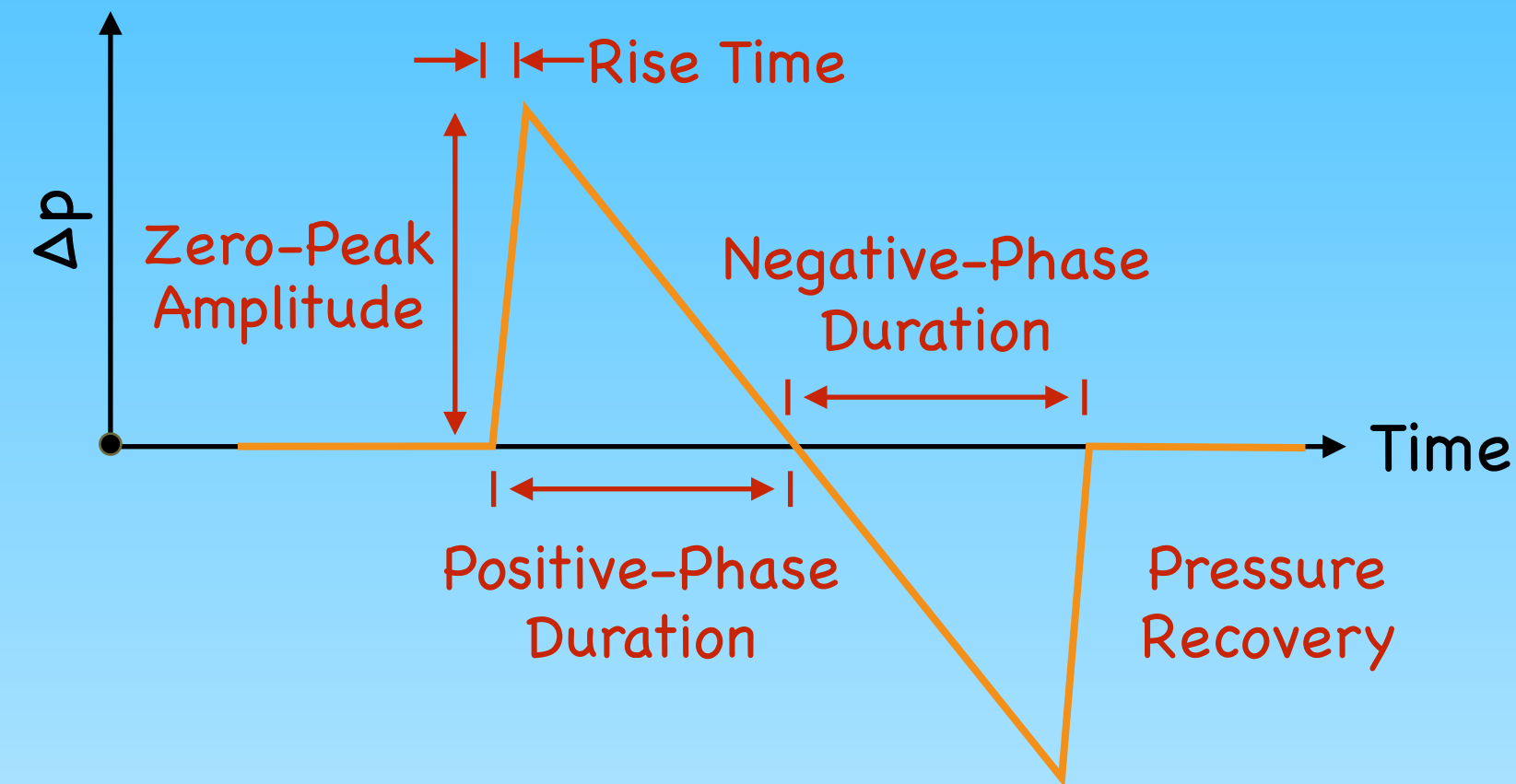
- Goals
- Simulation-based analysis must reliably predict ground noise
 - Simulation-based design must reliably determine aircraft shape to minimize ground noise



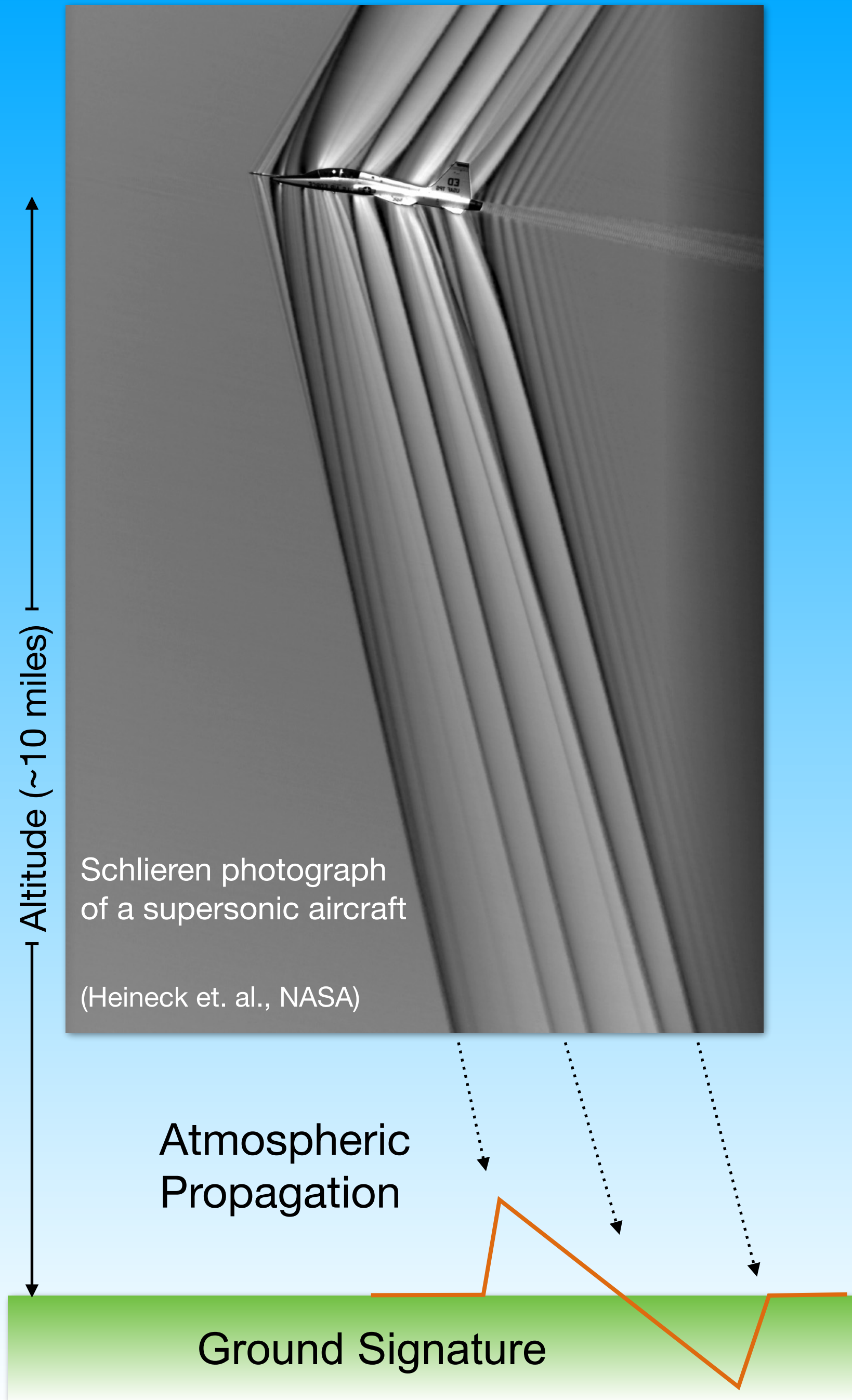
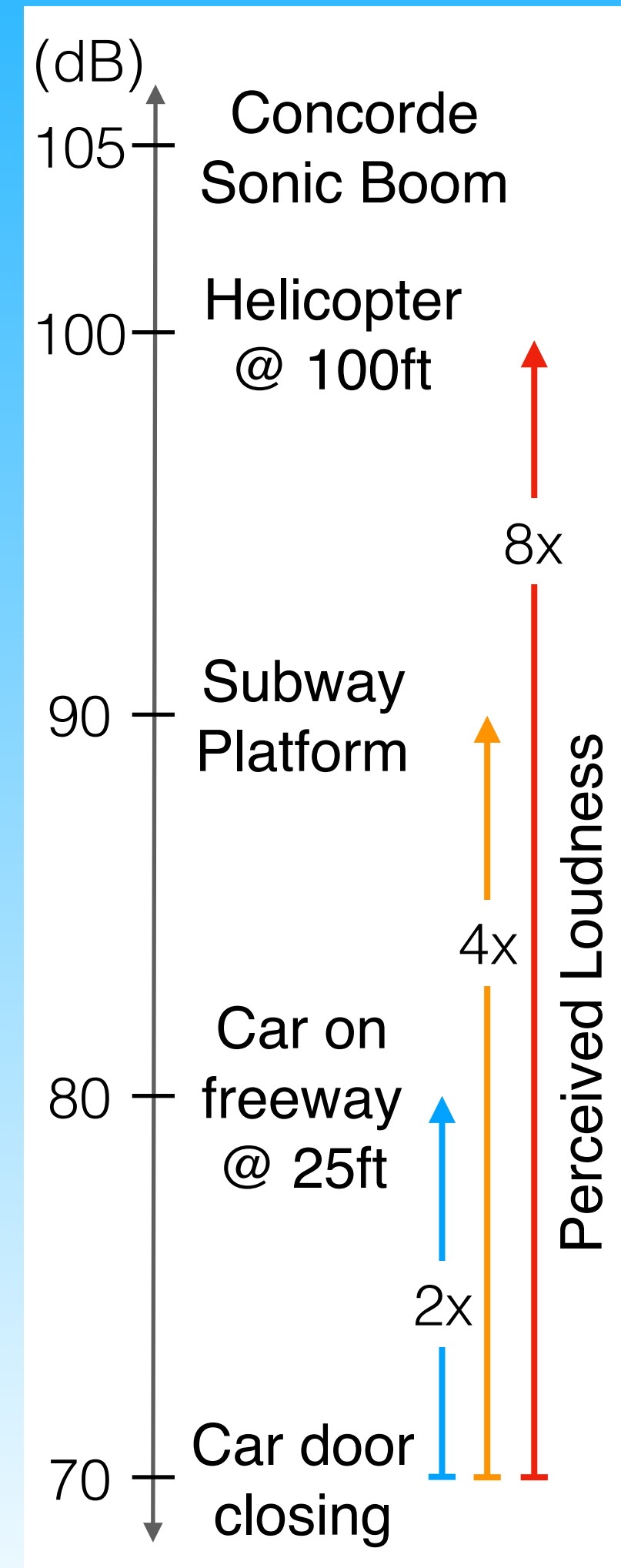
Sonic Boom Noise

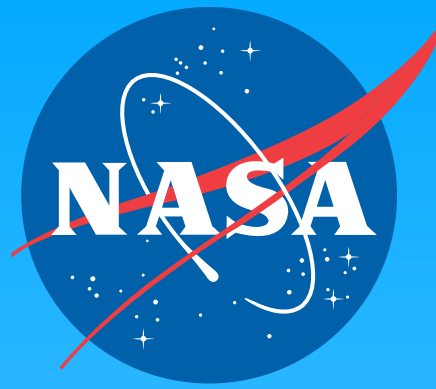
Boom sound characteristics are a function of the ground pressure signature

- 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

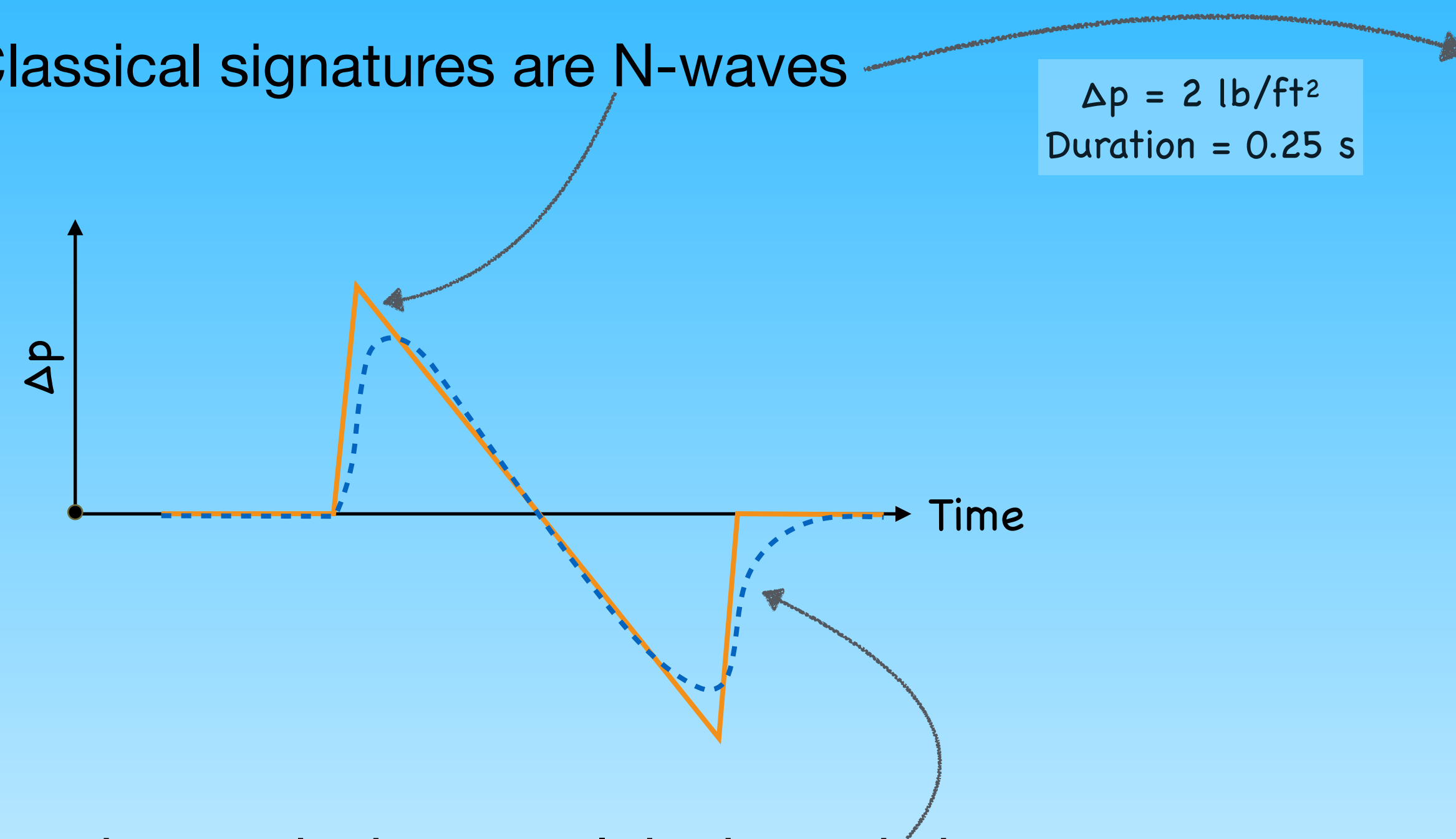




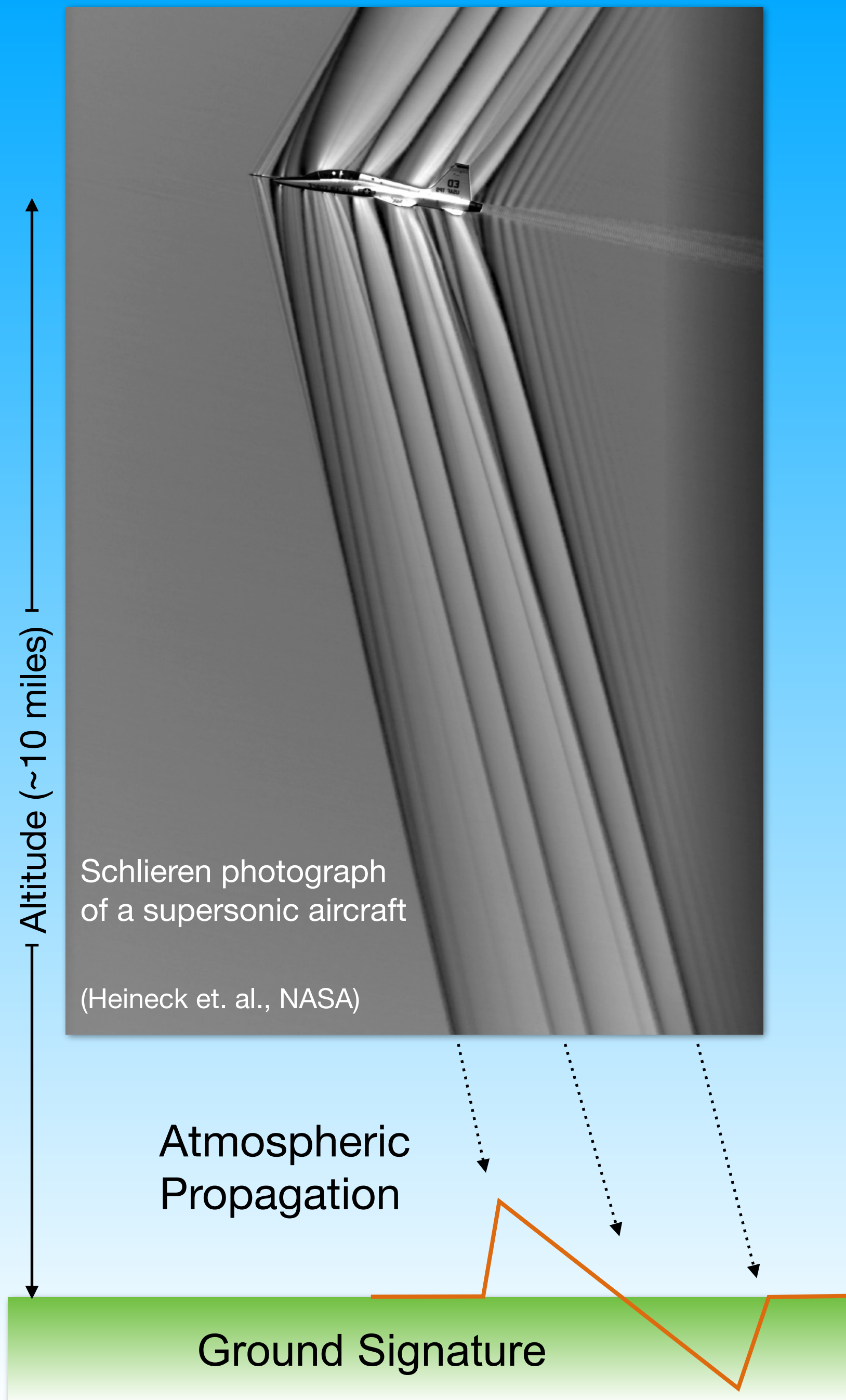
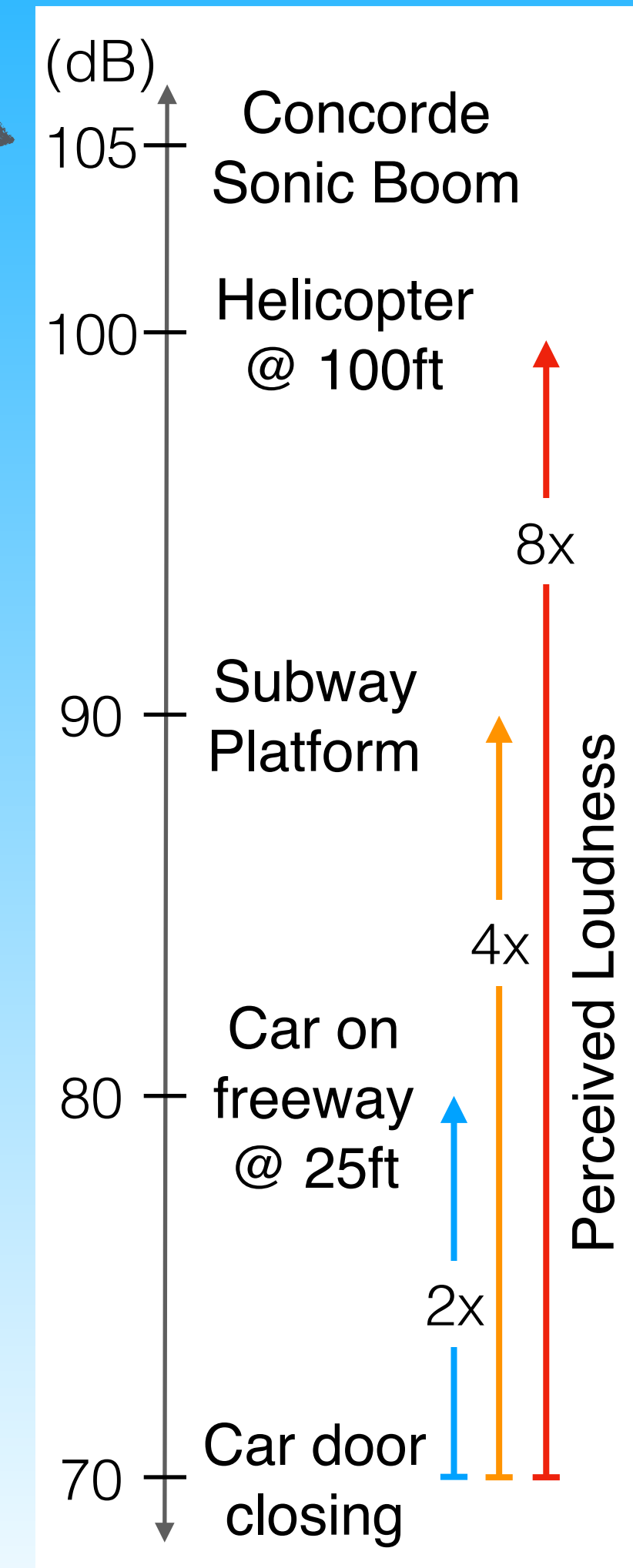
Sonic Boom Noise

Boom sound characteristics are a function of the ground pressure signature

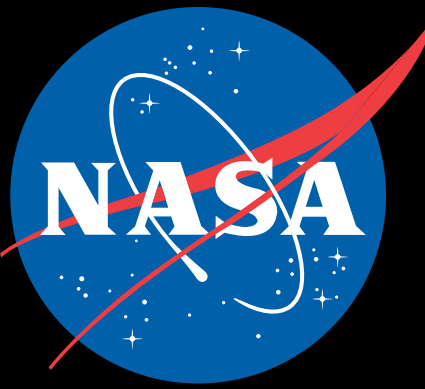
- Classical signatures are N-waves



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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

Atmospheric conditions
(wind, temperature, humidity)

Aircraft shape and
operating conditions

BOOM CARPET

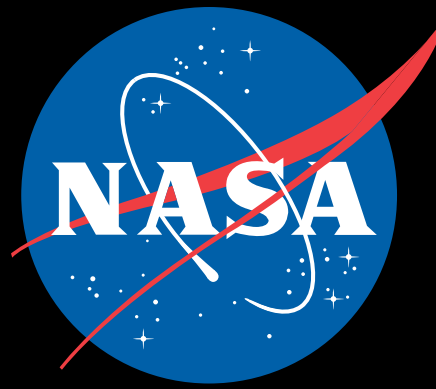
Local terrain

Additional factors

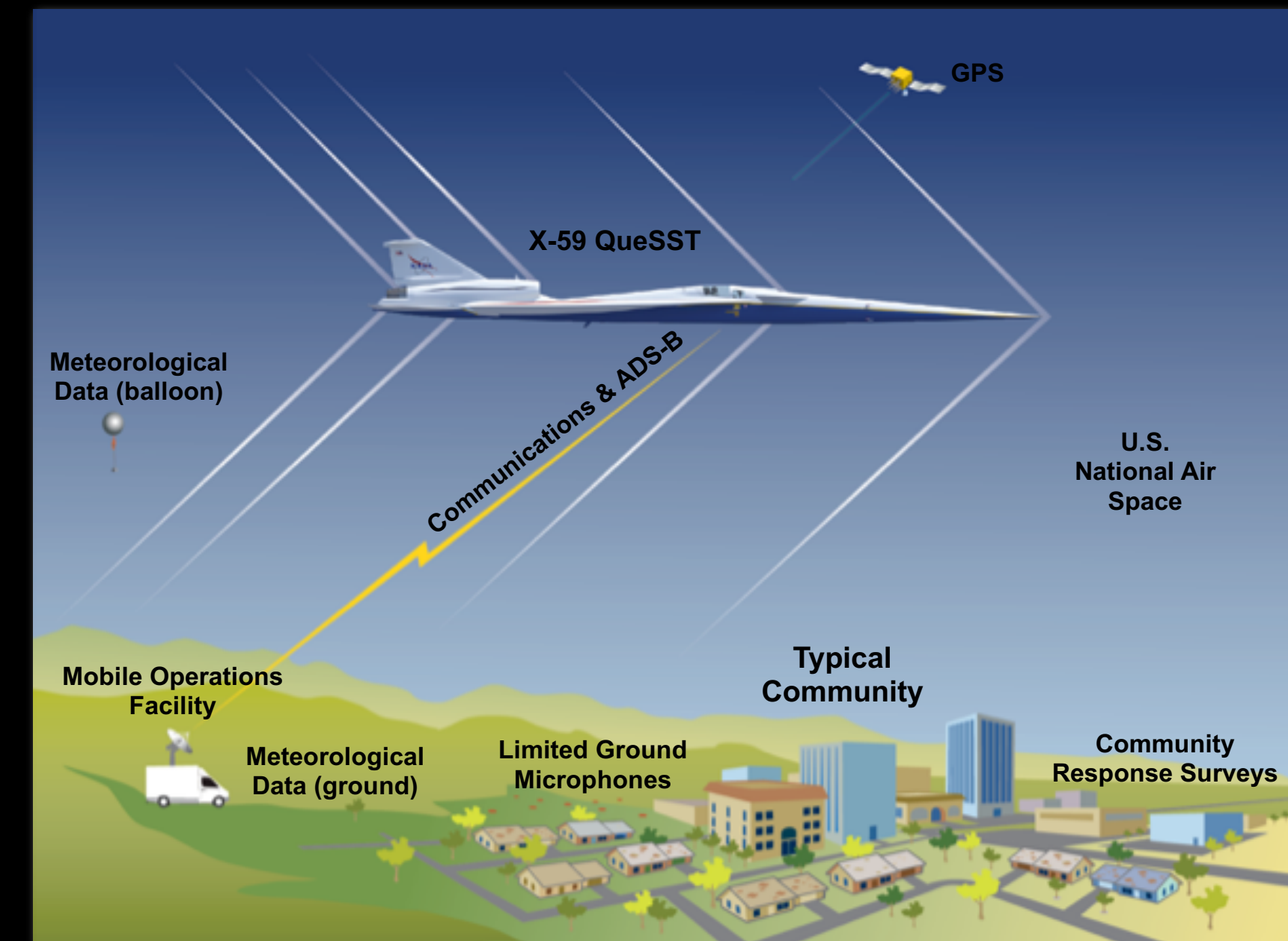
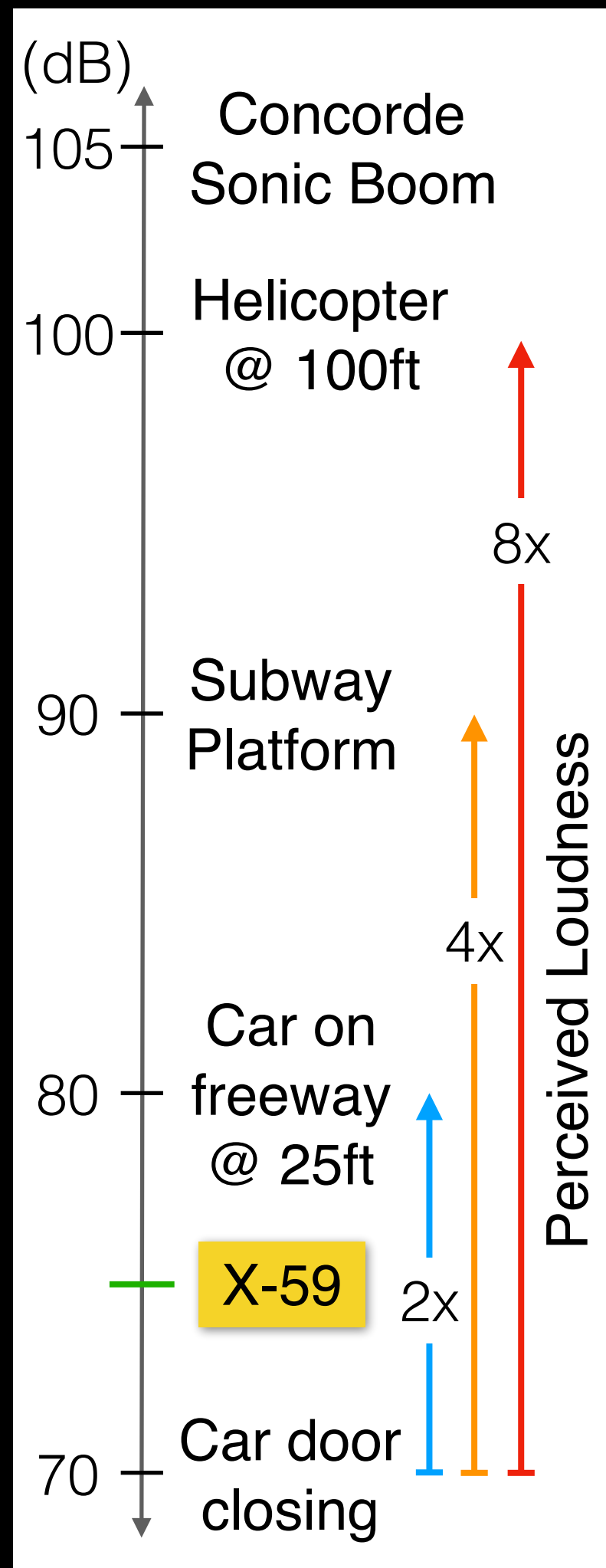
- Aircraft acceleration and maneuvers, focus booms
- Secondary boom carpets

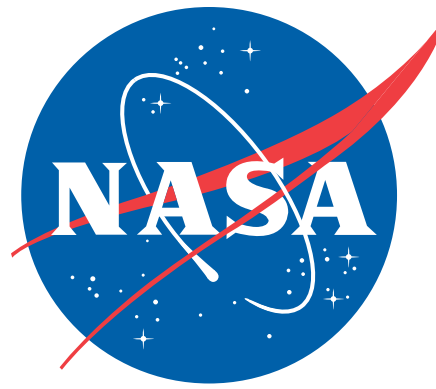


Low-Boom Flight Demonstration



- 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

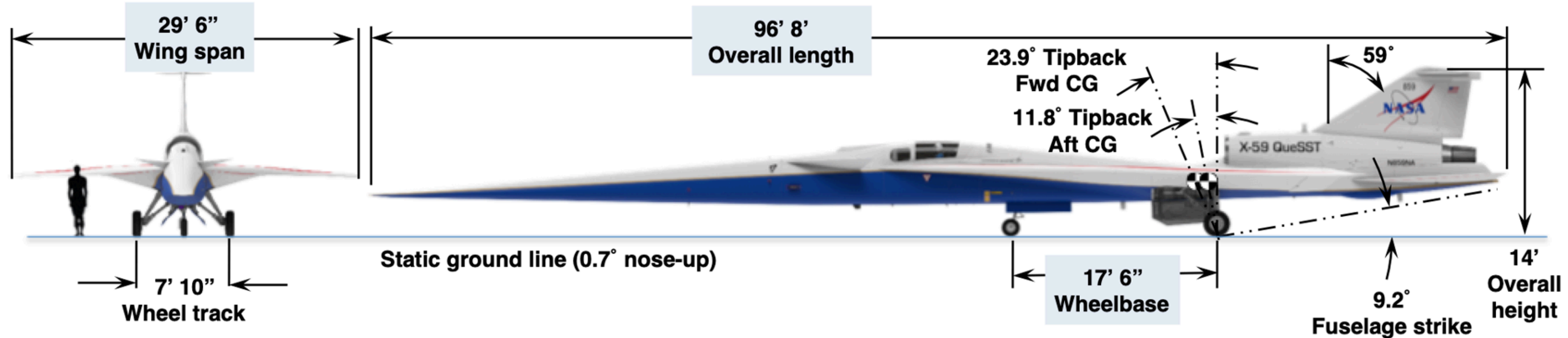
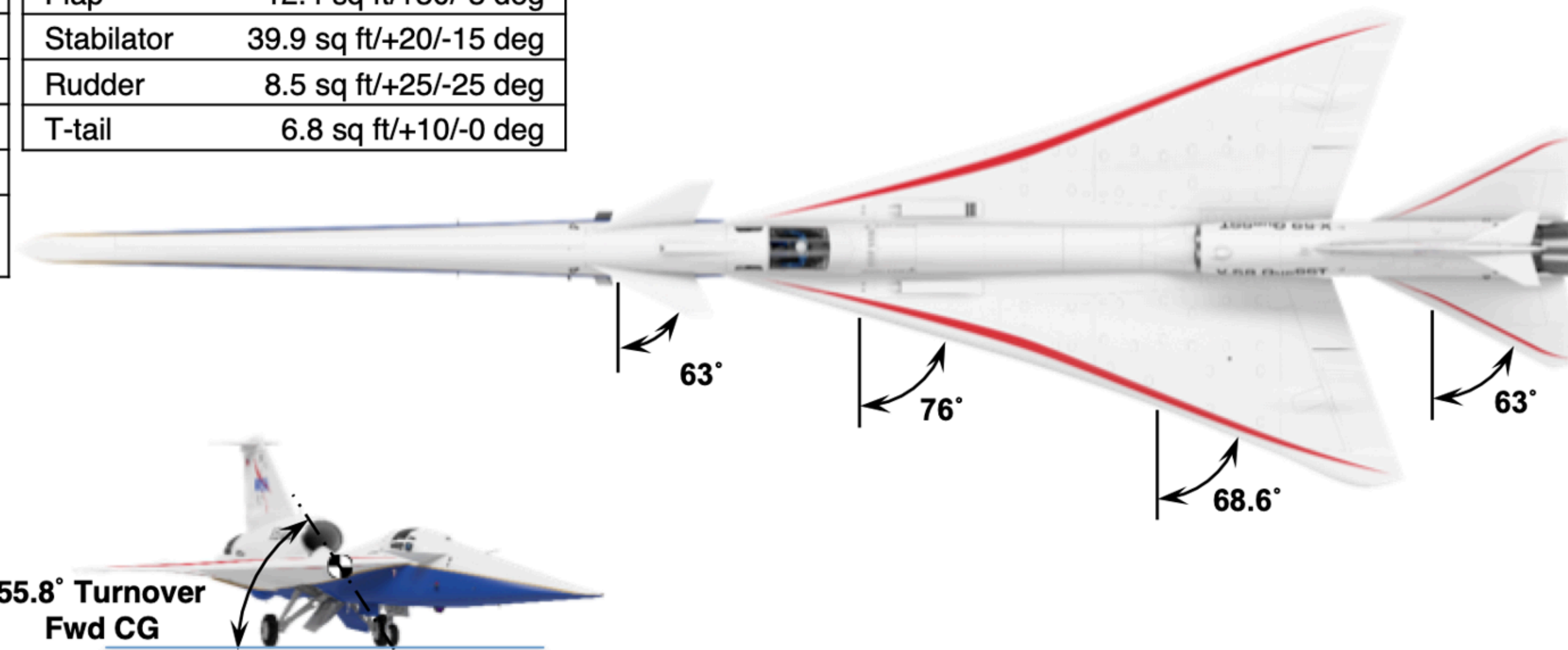




X-59 Aircraft

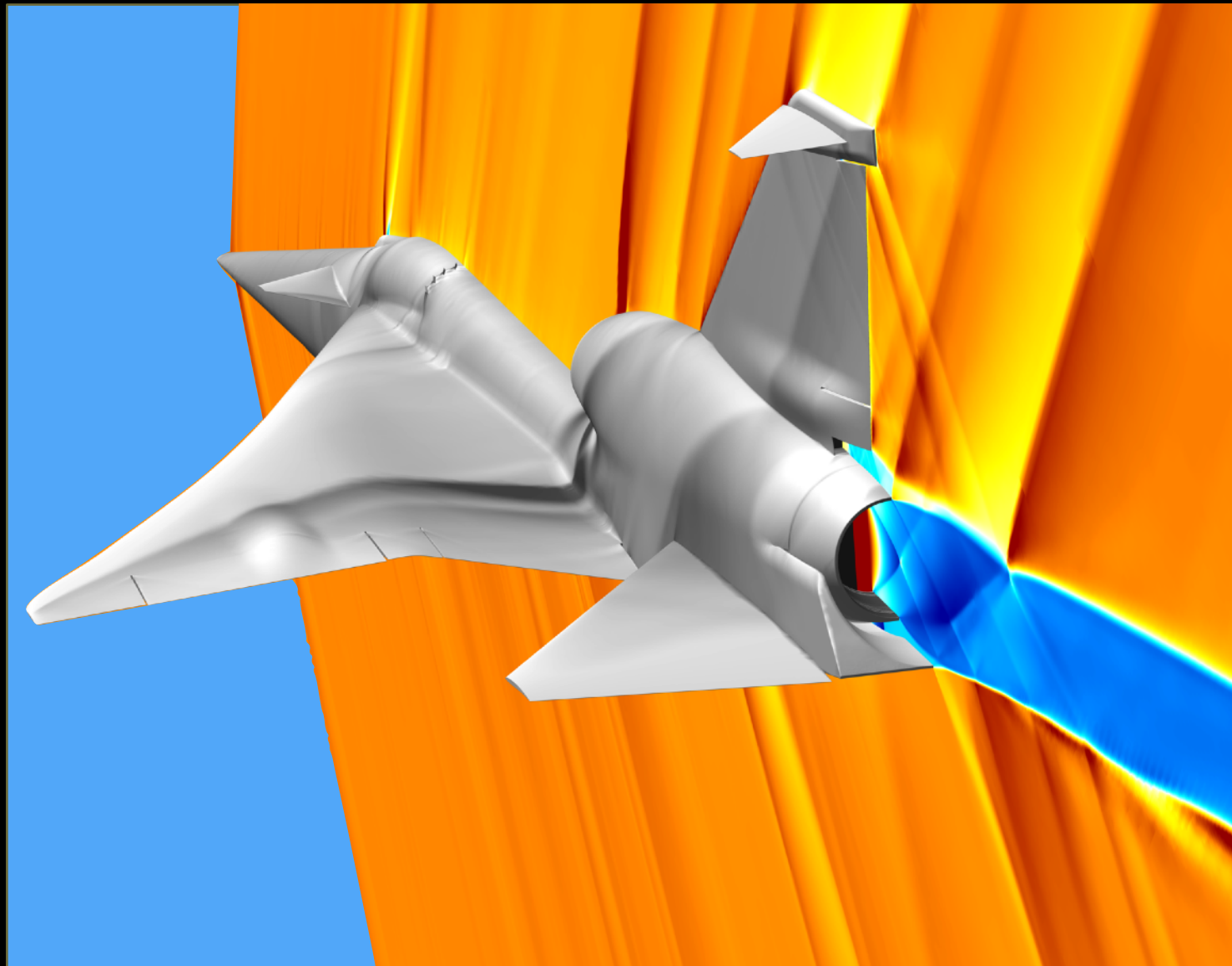
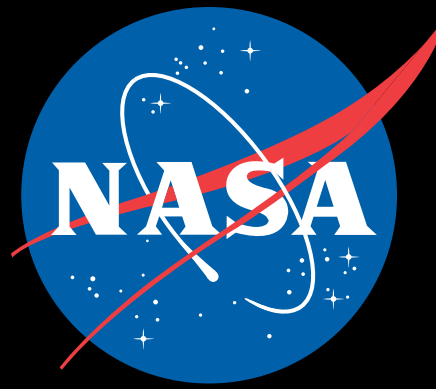
Configuration C612	
MDGW	24,300 lbs
Fuel (Std Day)	7,500 lbs
Payload	600 lbs
Design Mach	1.4
Loudness	<75 PLdB
Engine	1xF414-GE-100
Landing Gear	F-16 Blk25 NLG F-16 Blk25 MLG

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

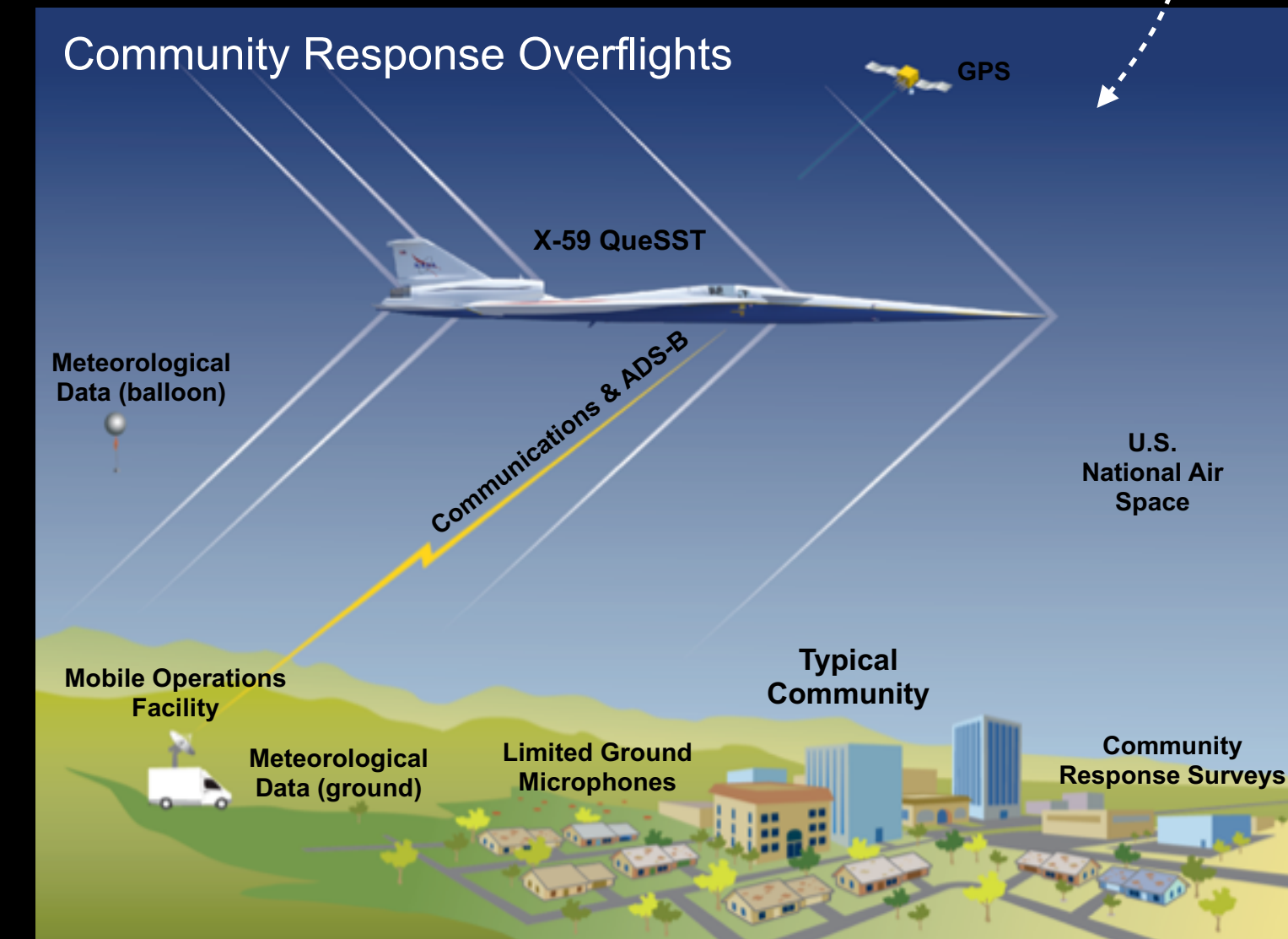
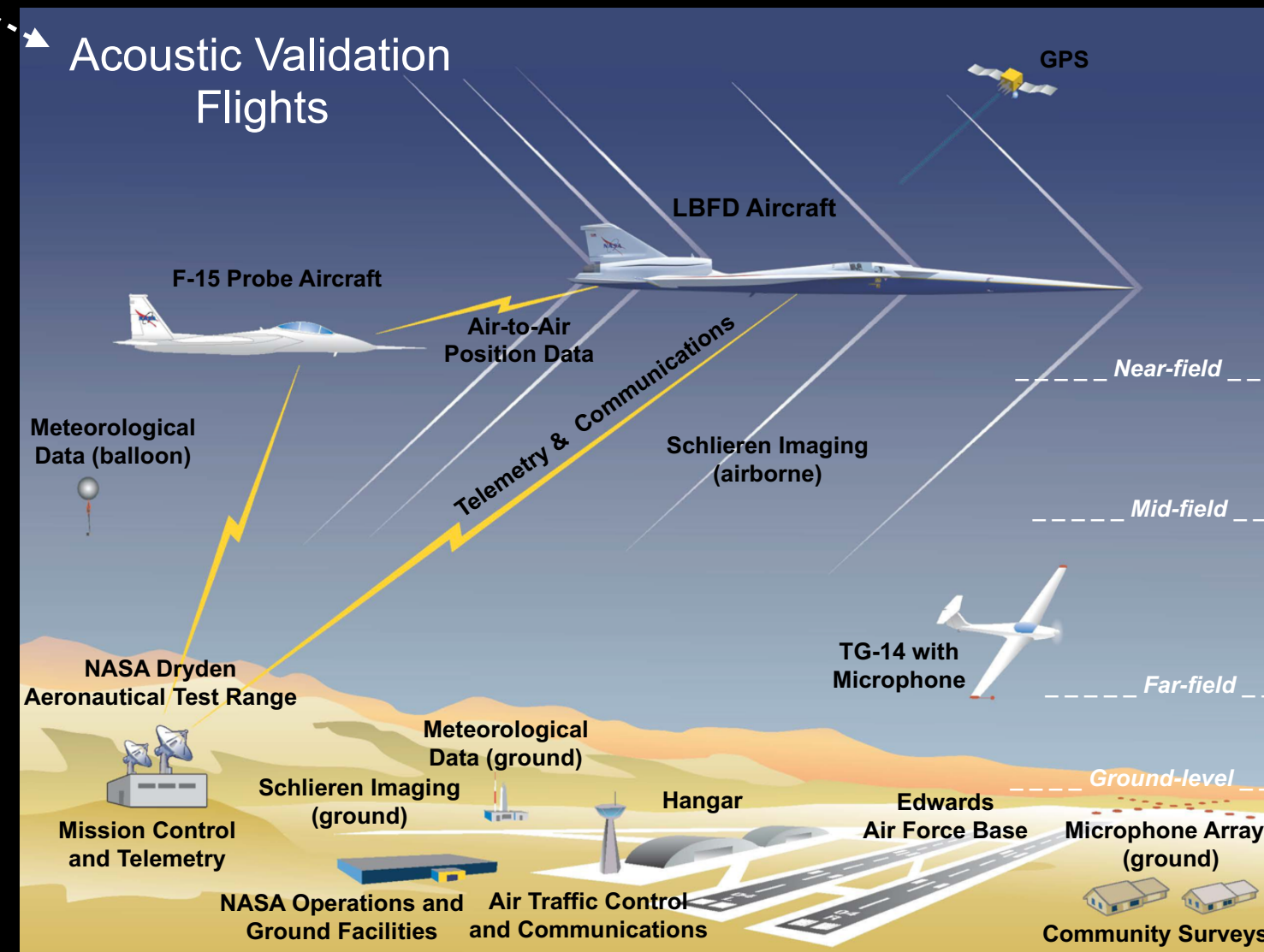




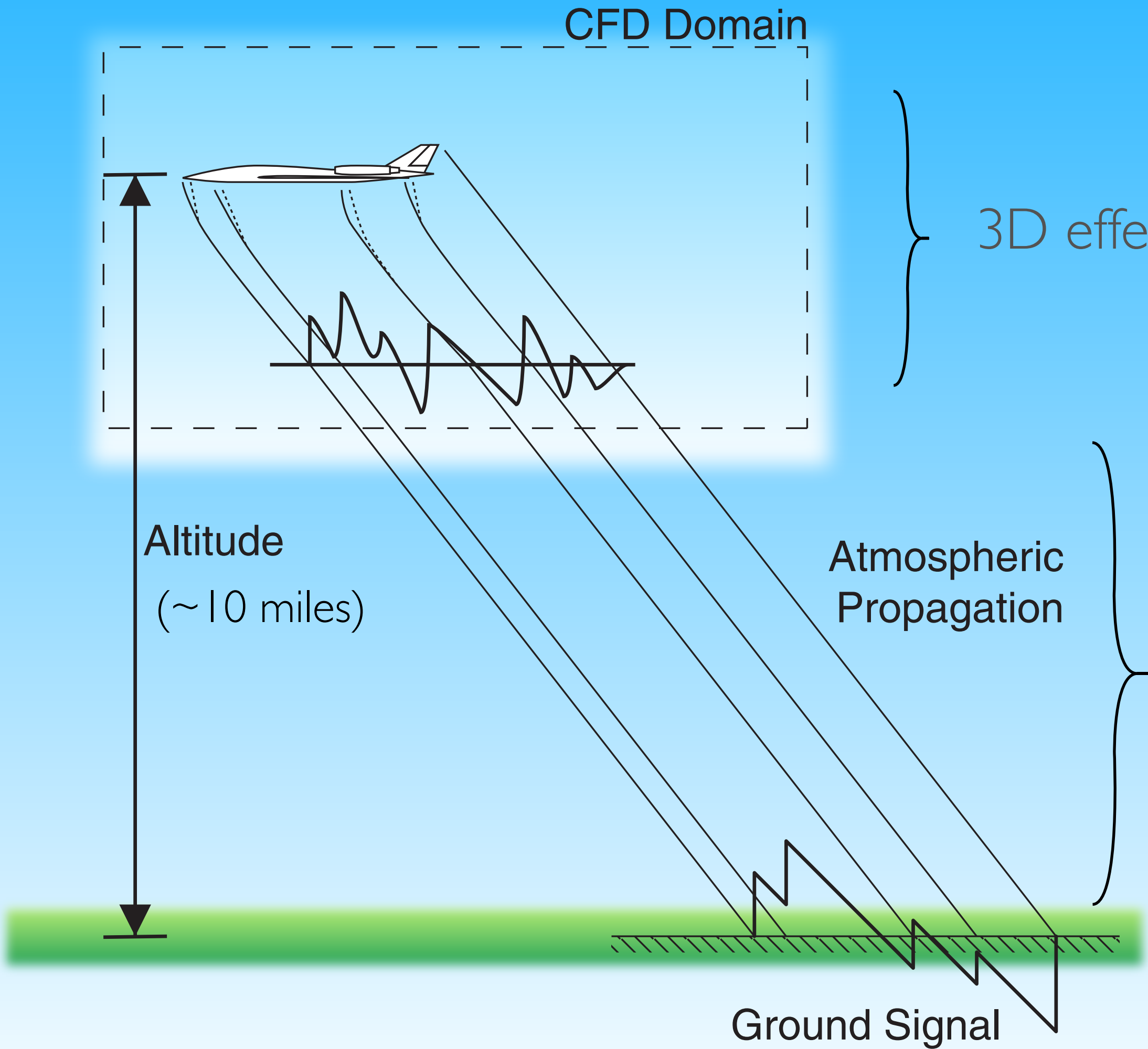
Role of High-Fidelity Simulations and HPC



- 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

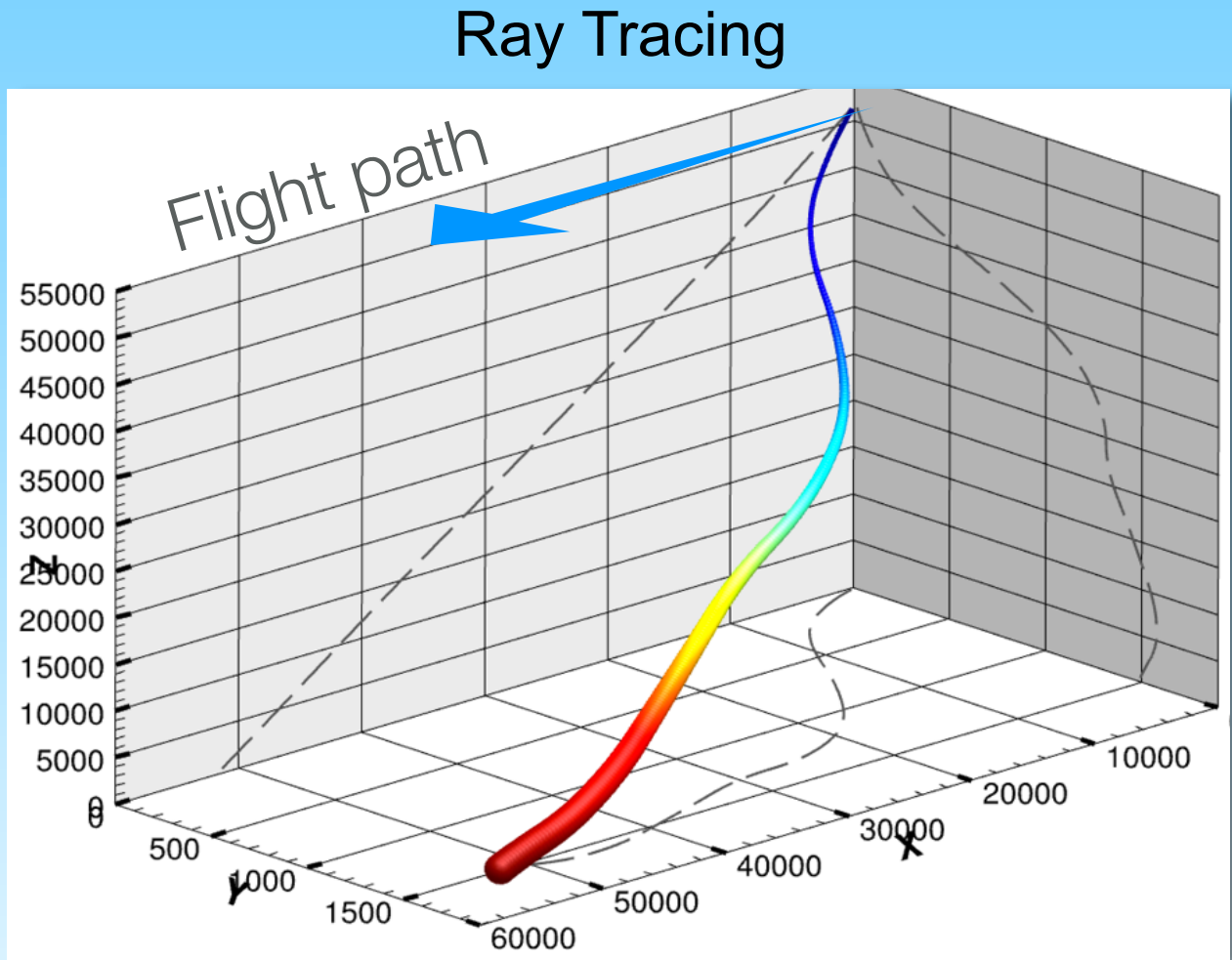


Nearfield

3D effects (aircraft shape and plume)
Use CFD

Propagation

Atmospheric variability
Absorption
Use Ray Tracing and quasi-1D PDE



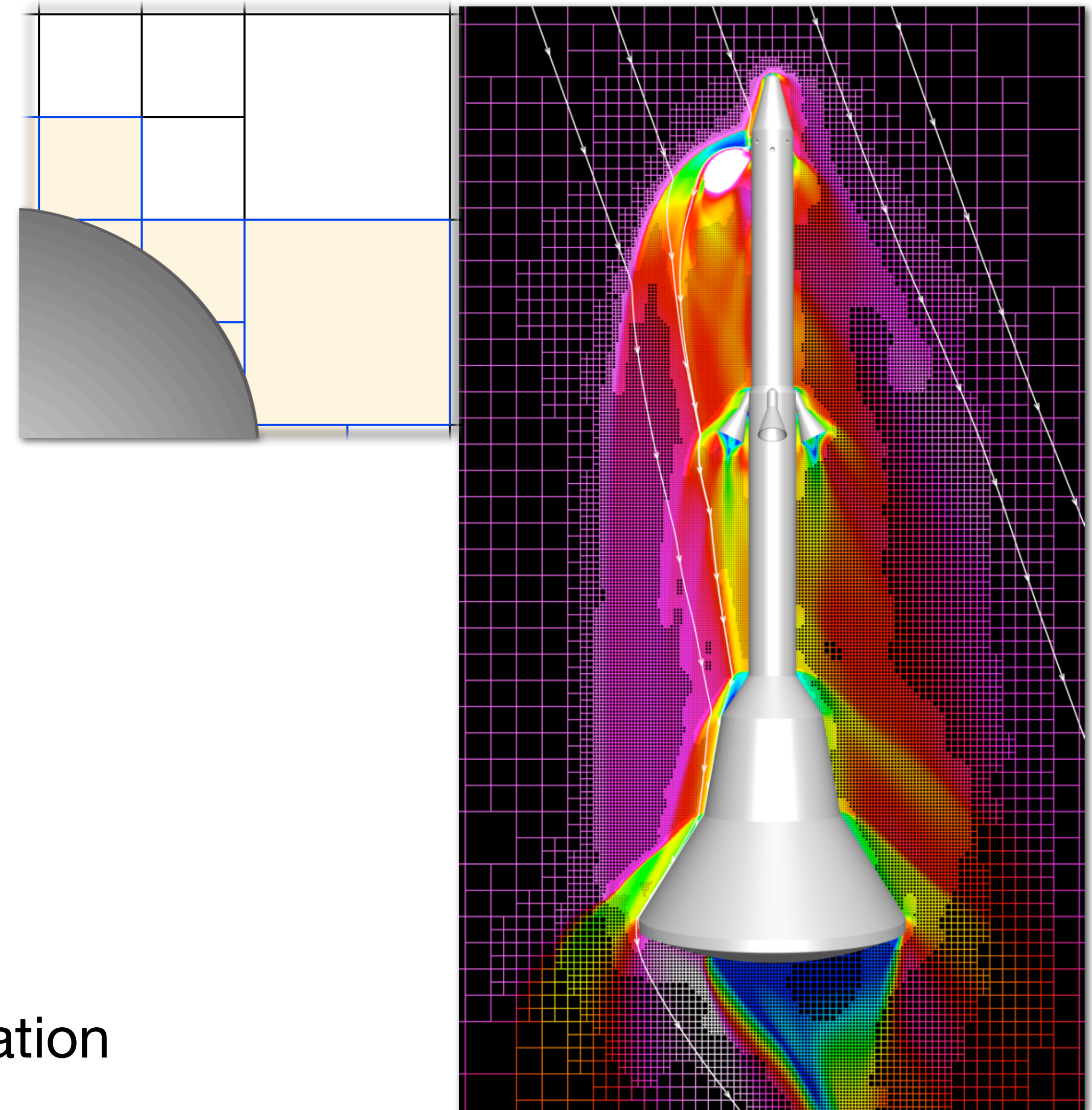
Core Solver: Cart3D

Meshing

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

Flow Solver

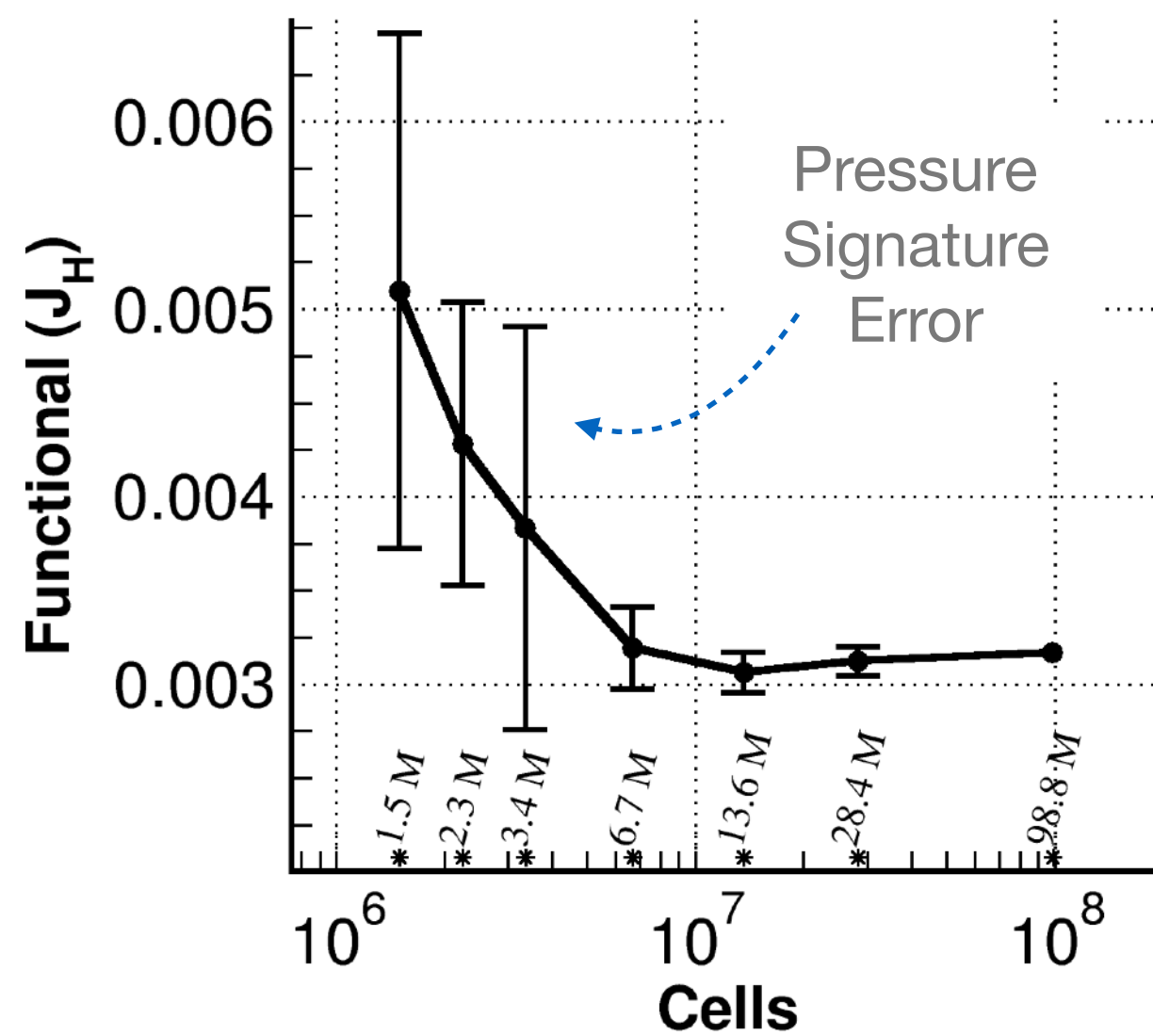
- Inviscid flow assumption (Euler equations)
- Second-order spatial and temporal discretization
 - Fully conservative finite-volume method
 - Dual time-stepping for unsteady flows
- Calorically perfect and equilibrium gas models
- Runge-Kutta time marching with multigrid acceleration



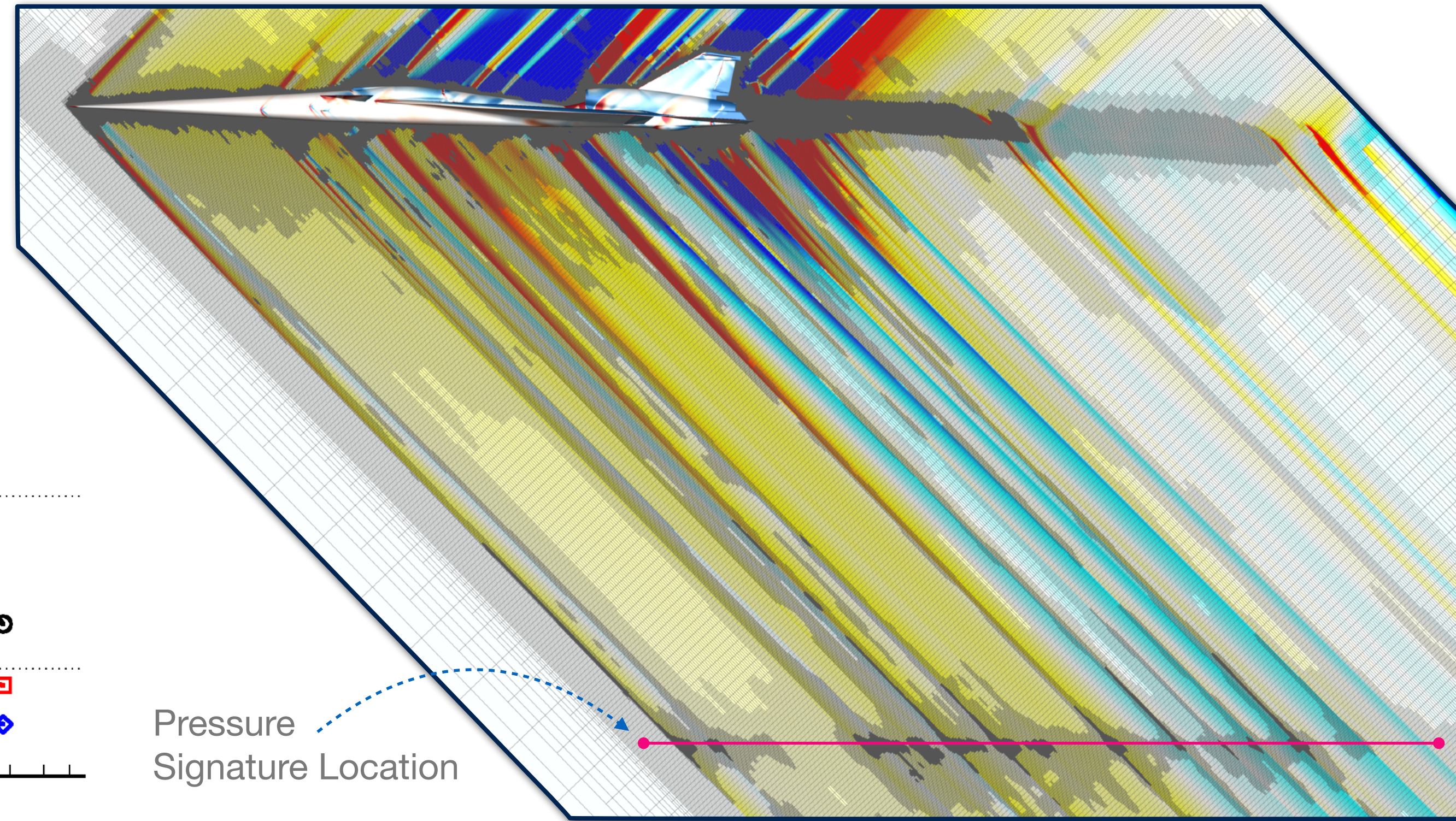
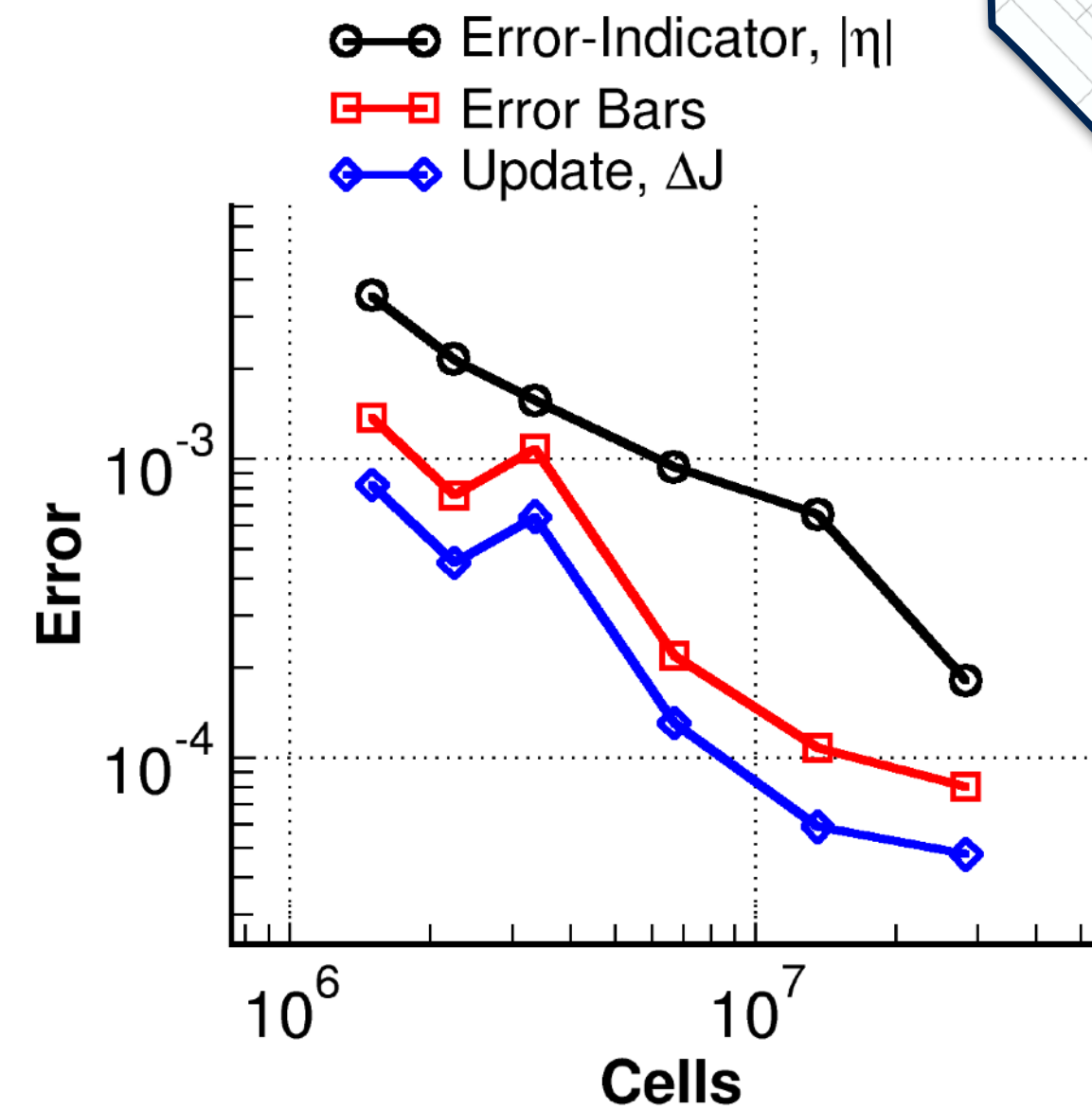
Core Solver: Cart3D

Error Estimation and Goal-Oriented Mesh Adaptation

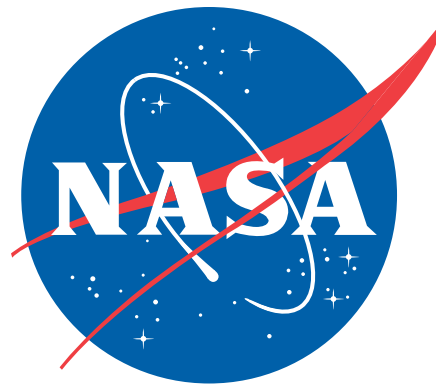
- Mesh automatically refined in locations with most impact on user selected outputs (pressure signatures, lift, drag, moments, ...)
- Method of adjoint weighted residuals
- Used for every simulation



Adaptation Convergence History



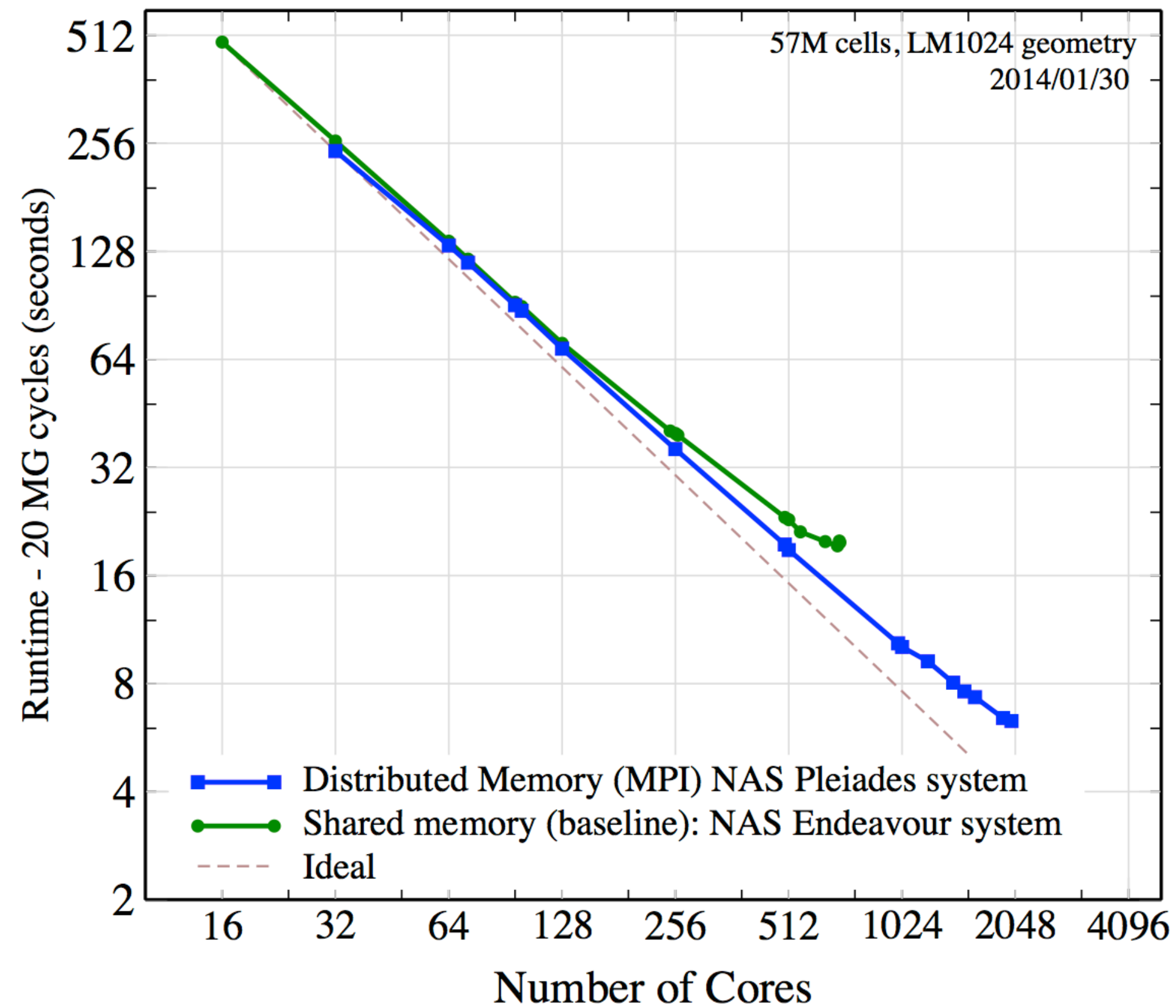
Near-body region of adapted mesh around LBFD aircraft for pressure sensor output (C_p contours)



Parallel Performance

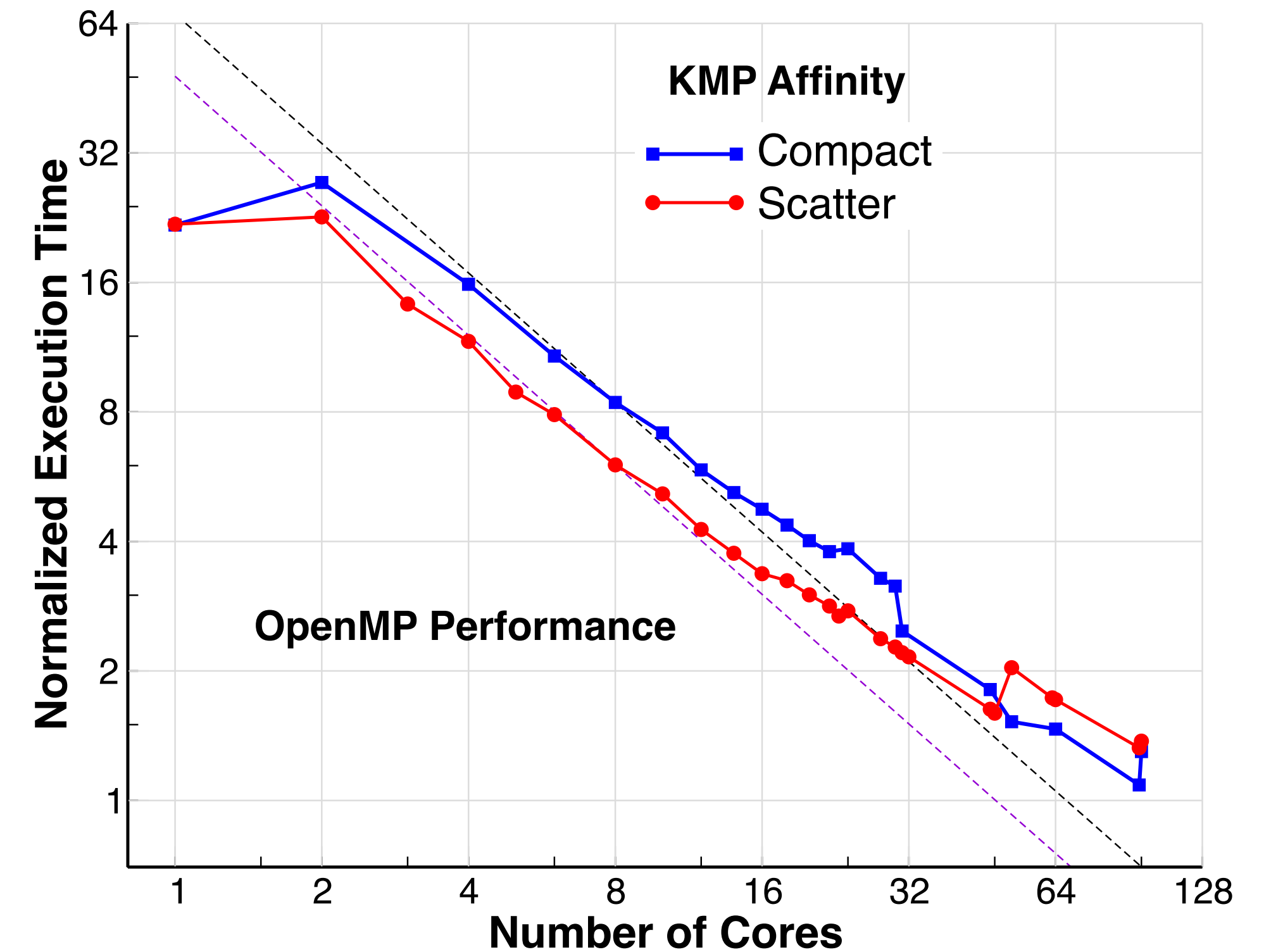
Excellent scalability through use of domain decomposition based on space-filling curves

HECC Supercomputing Systems



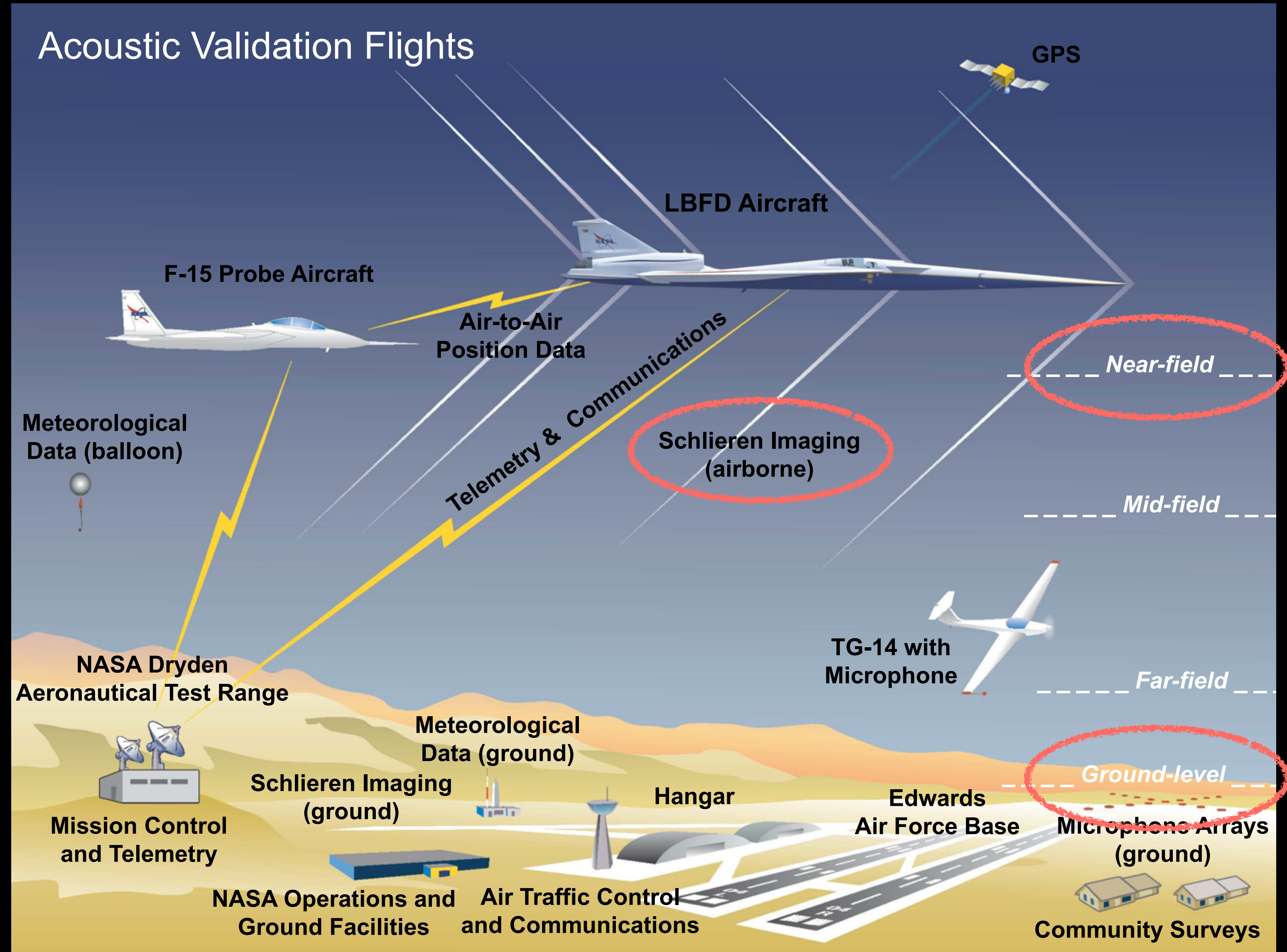
OpenMP and MPI fully supported

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

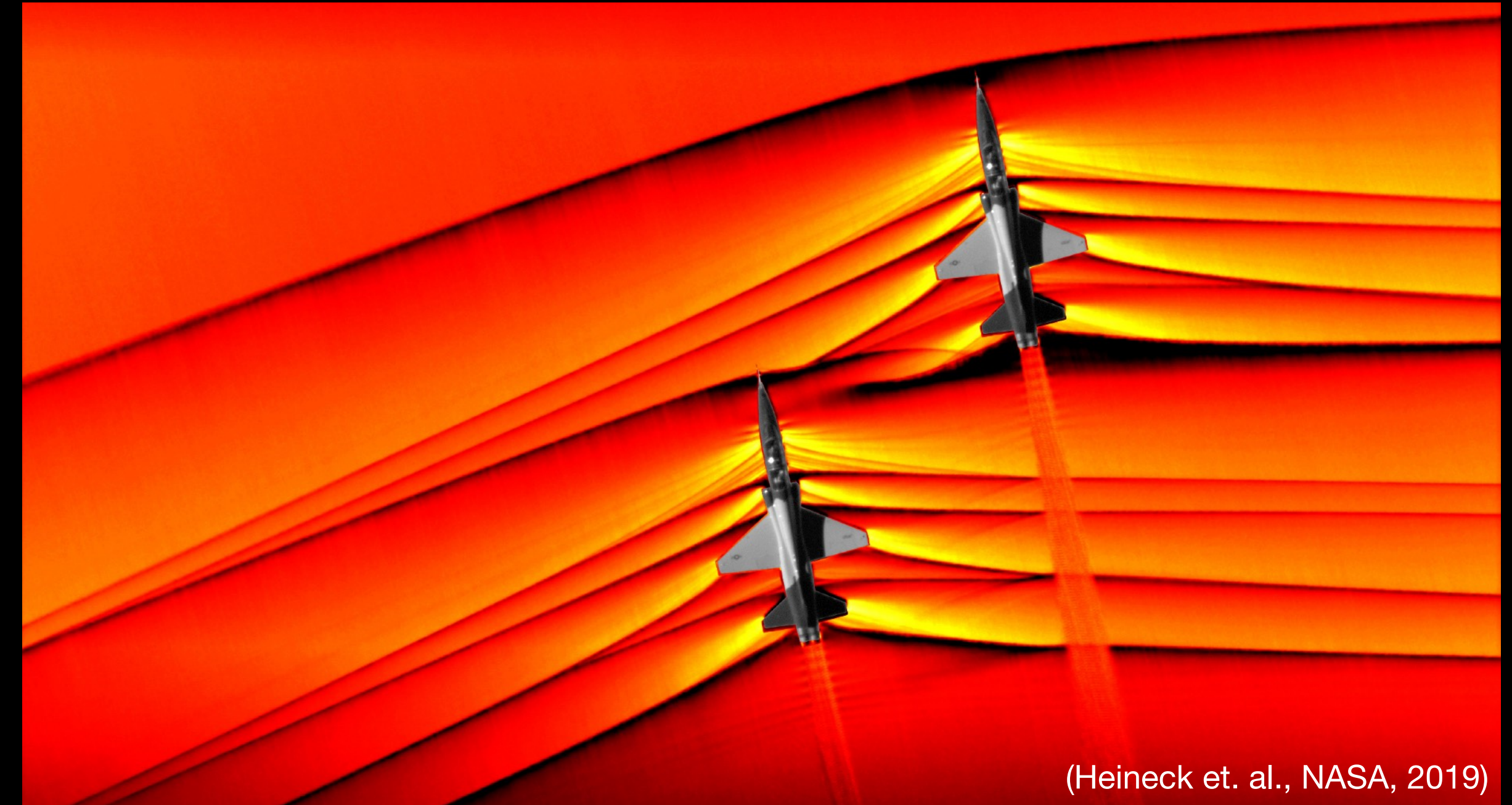
Nearfield

Schlieren Flow Visualization

Photographs from flight tests in the Supersonic Corridor near Armstrong Flight Research Center



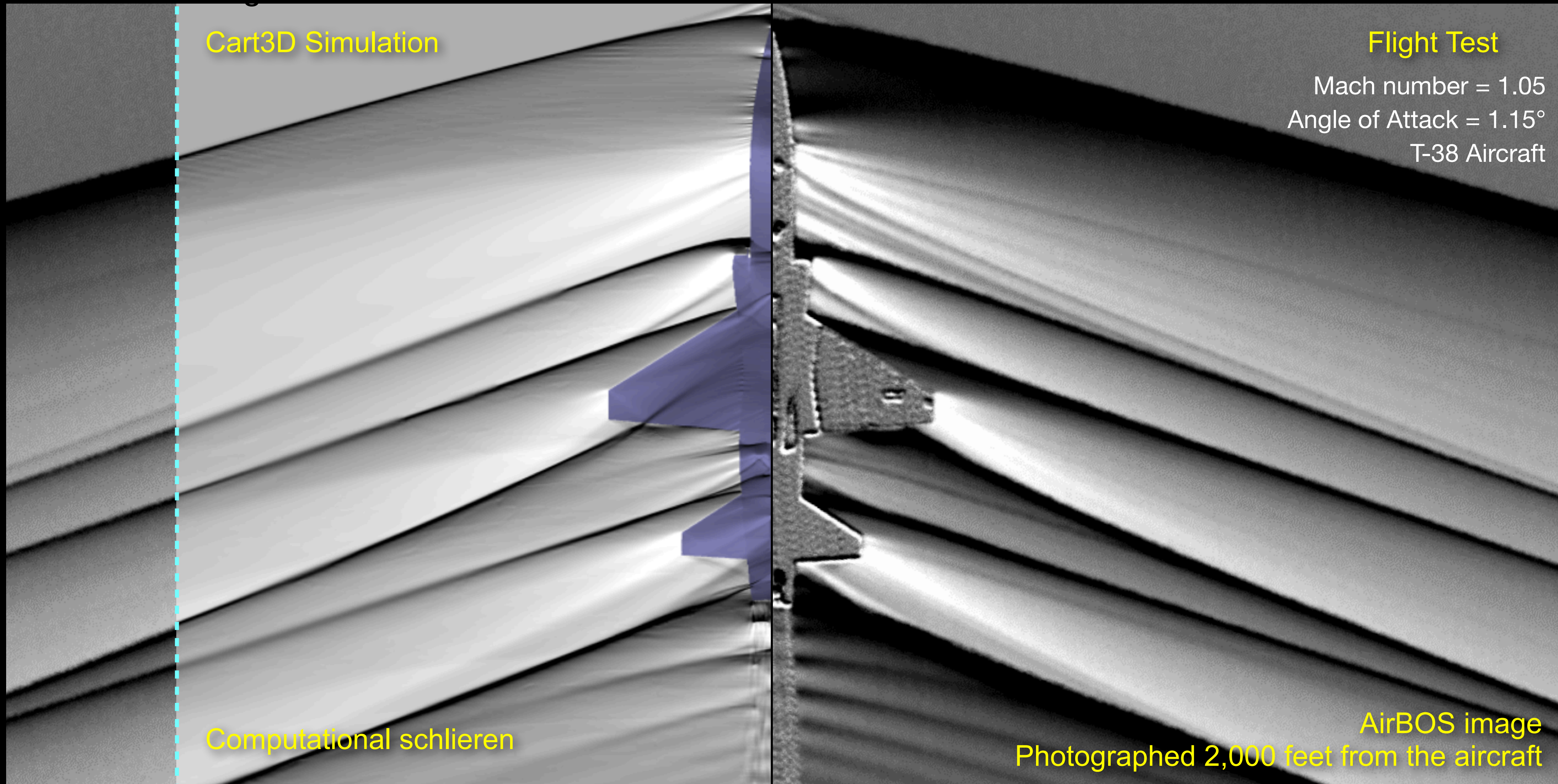
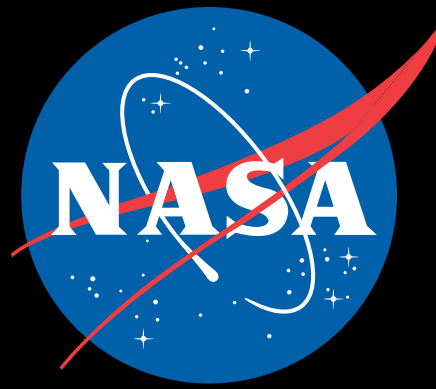
(Heineck et. al., NASA, 2016)



(Heineck et. al., NASA, 2019)

- 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



Cart3D Simulation

Flight Test

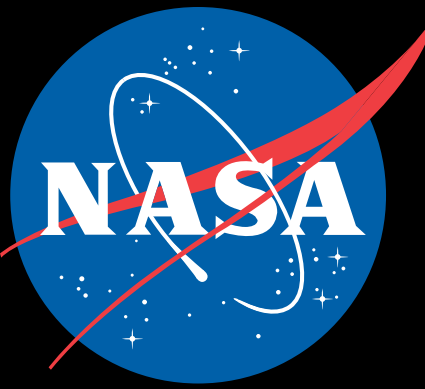
Mach number = 1.05
Angle of Attack = 1.15°
T-38 Aircraft

Computational schlieren

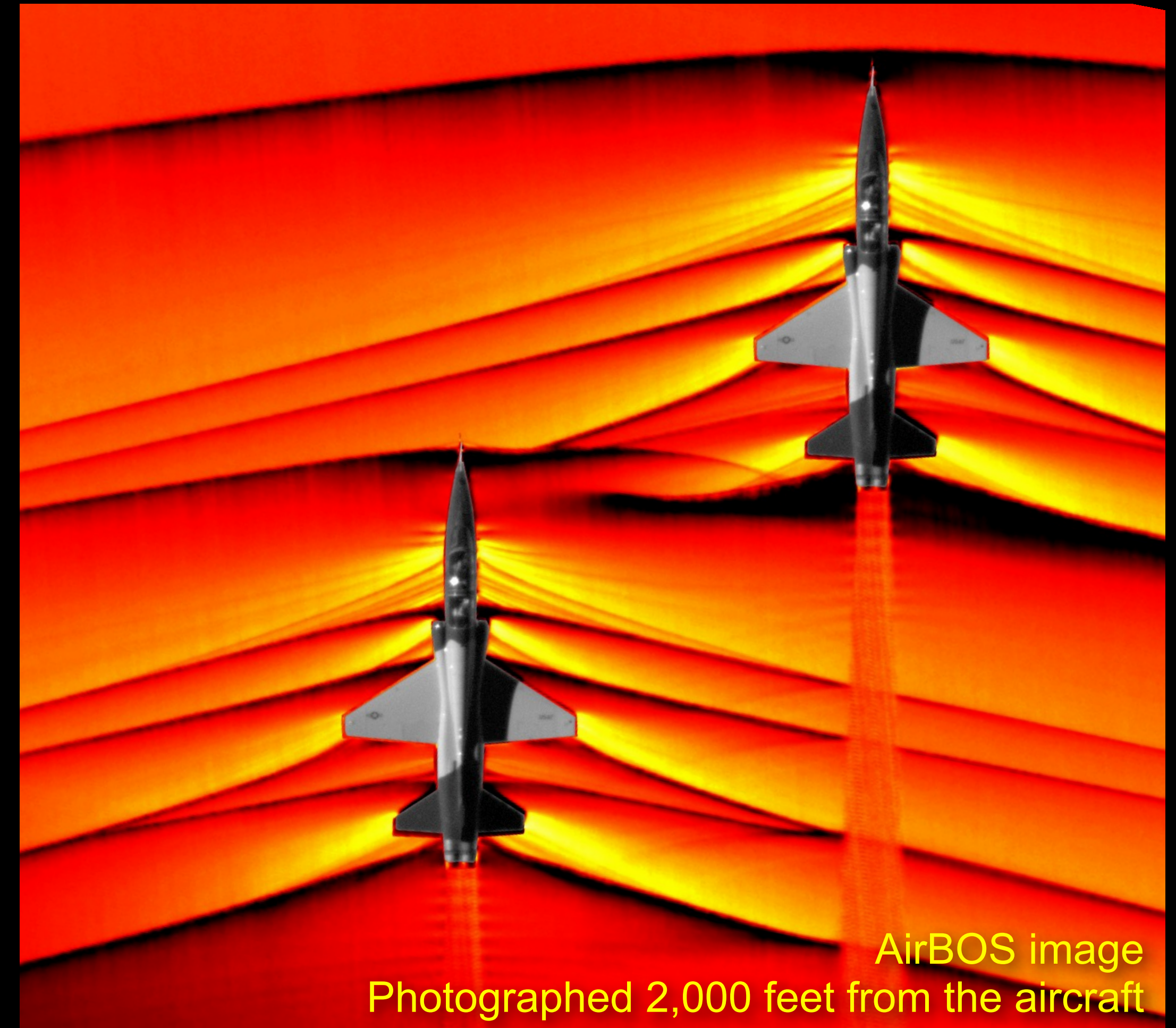
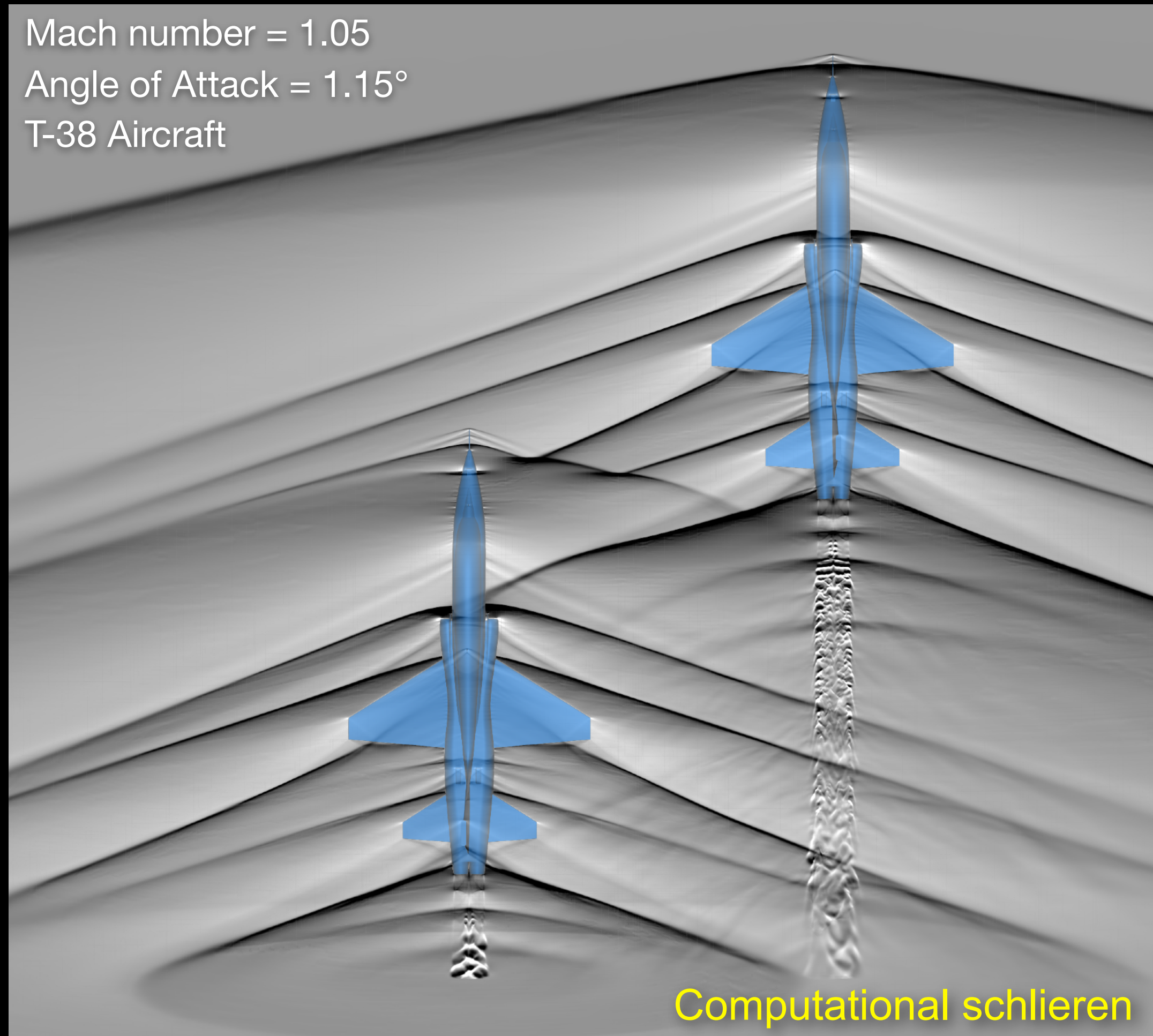
AirBOS image
Photographed 2,000 feet from the aircraft

Shock-Shock Interactions

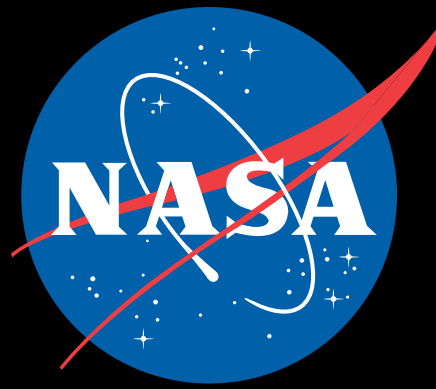
Supersonic Formation Flight



Mach number = 1.05
Angle of Attack = 1.15°
T-38 Aircraft

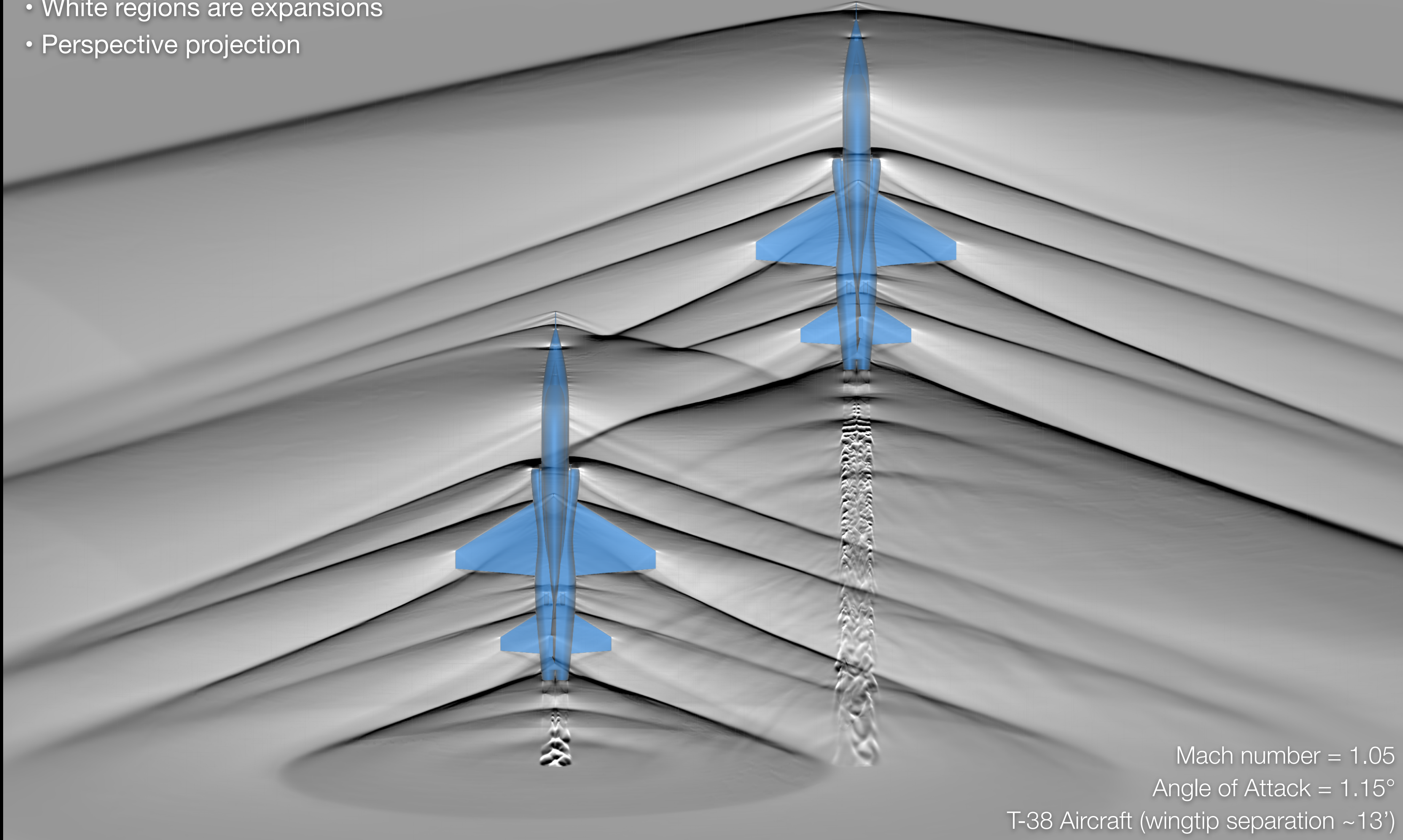


Preliminary work toward flight-matching simulations and future acoustic validation flights



Computational schlieren

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

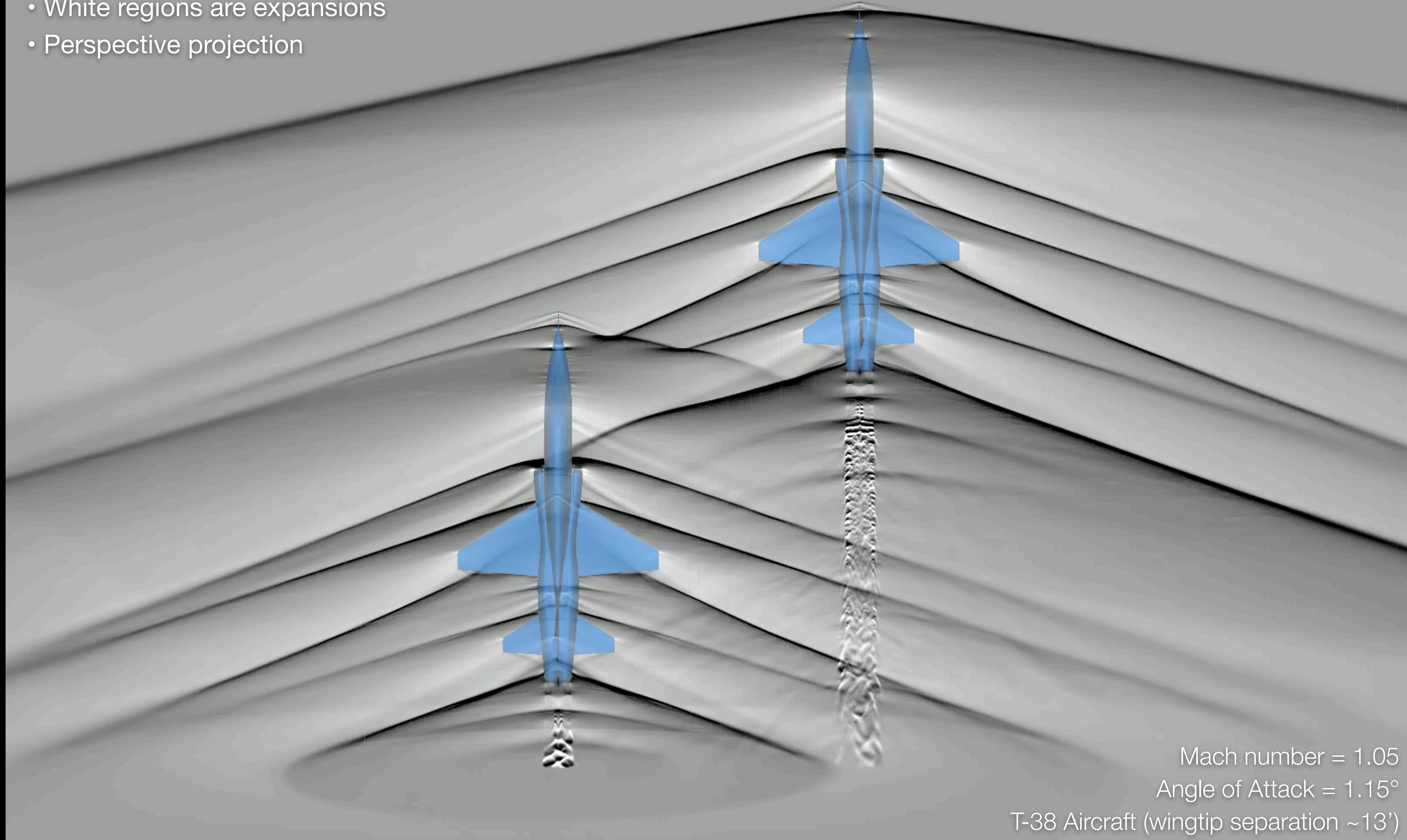


Mach number = 1.05
Angle of Attack = 1.15°

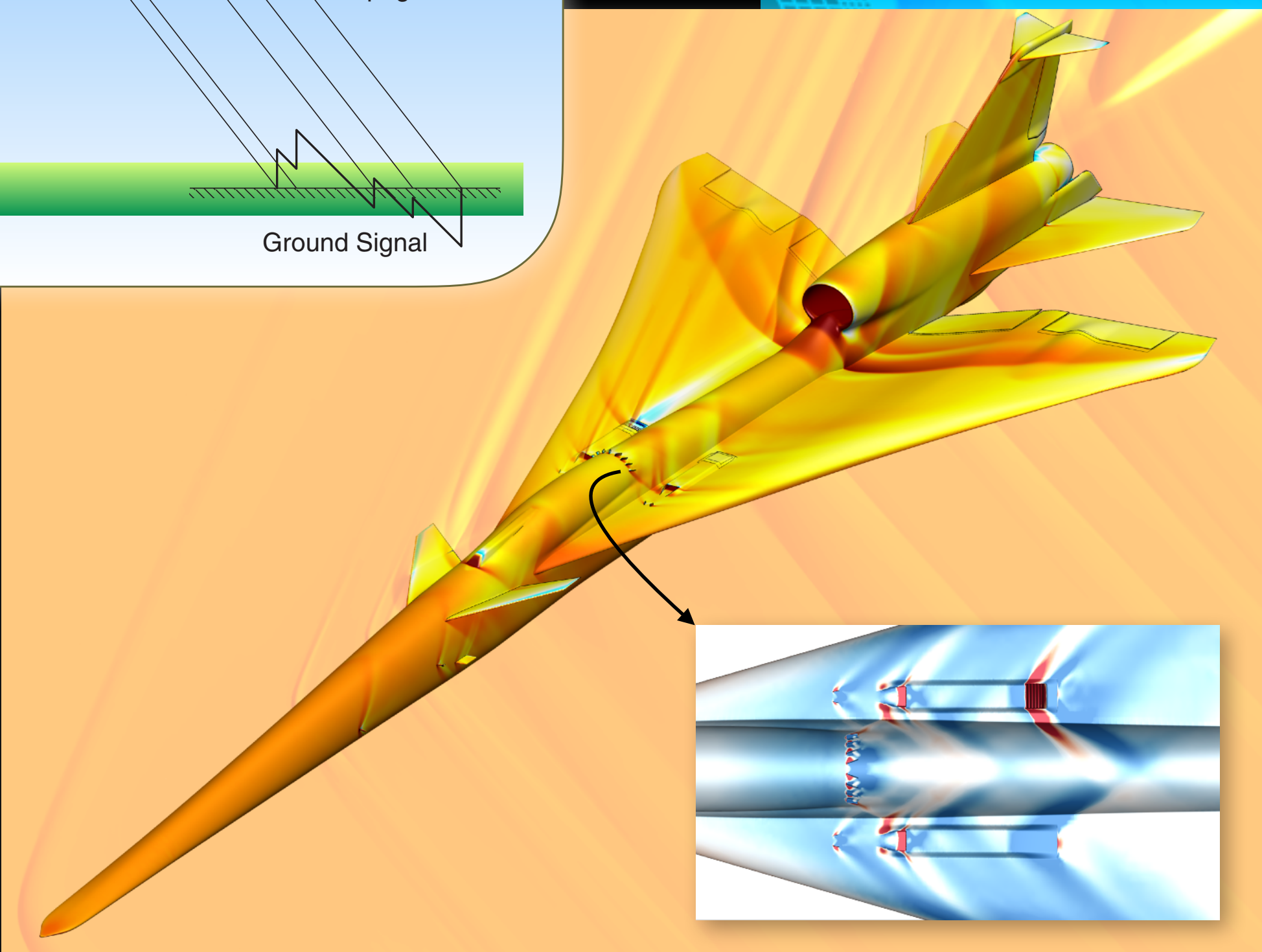
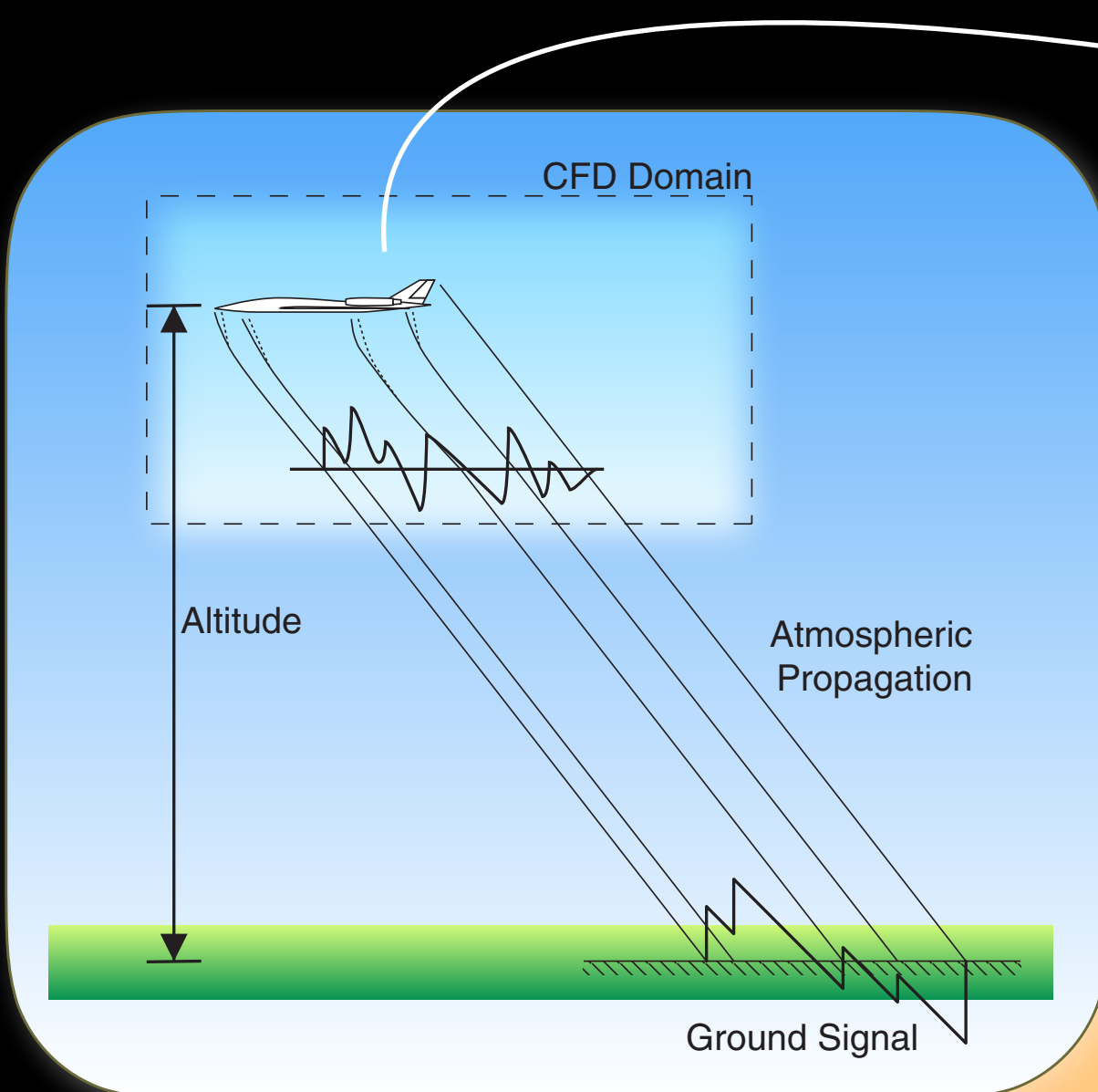
T-38 Aircraft (wingtip separation ~13')

Computational schlieren

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

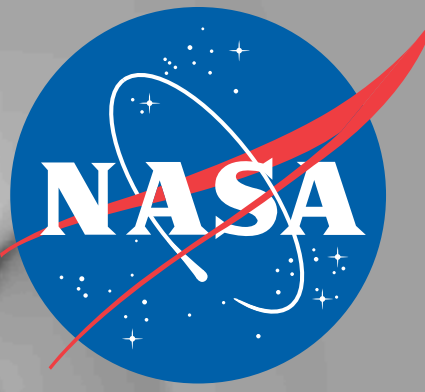


X-59 Nearfield Predictions



Challenging simulations:

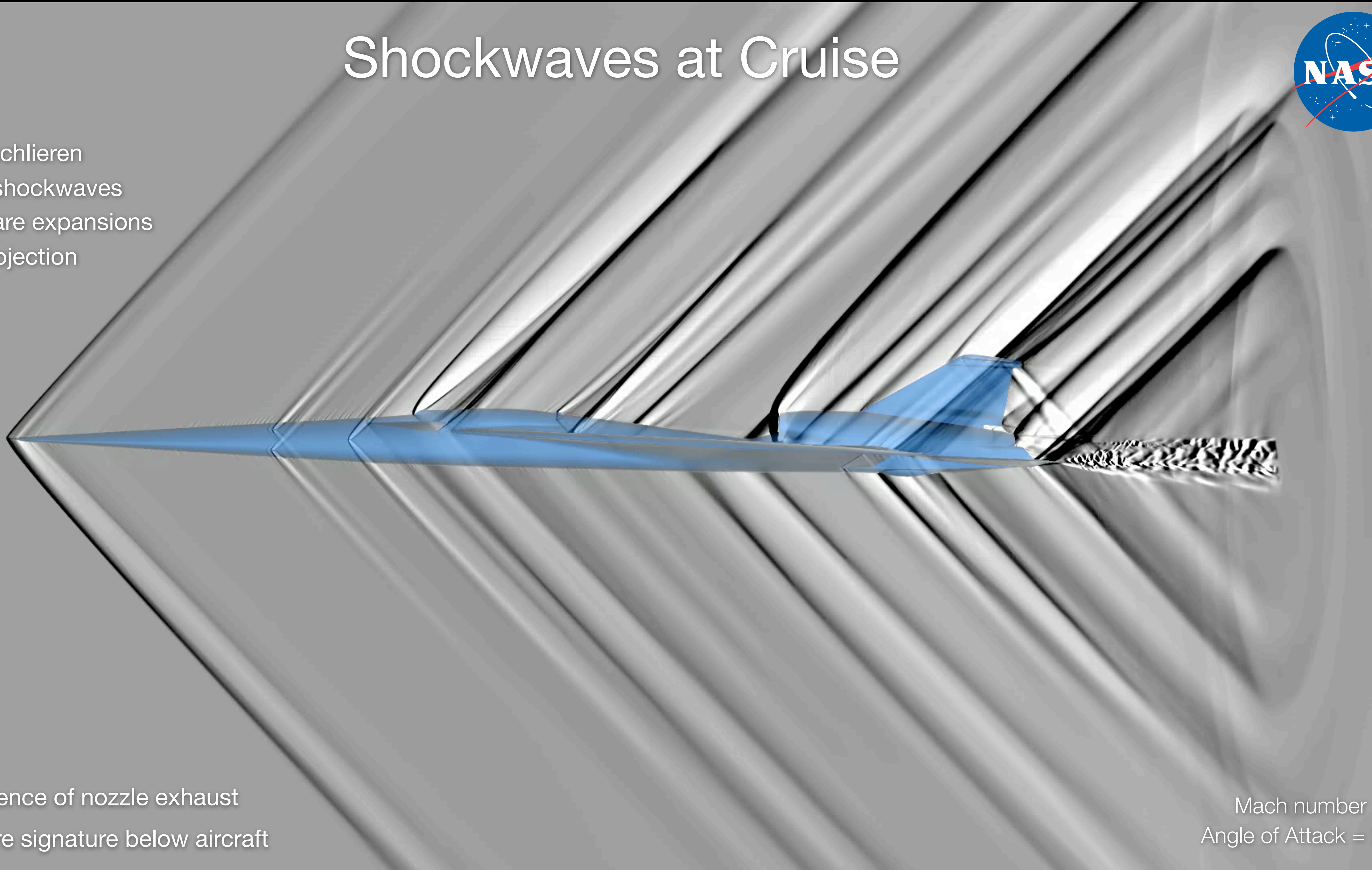
- Fine geometric detail (probes, vortex generators, flaps, ailerons, stabilator, t-tail, ...)
- Many secondary-air systems, in addition to the main engine
- Requires accurate prediction of a *complex system of shockwaves* far from the aircraft in addition to standard aerodynamic performance coefficients



Shockwaves at Cruise

Computational schlieren

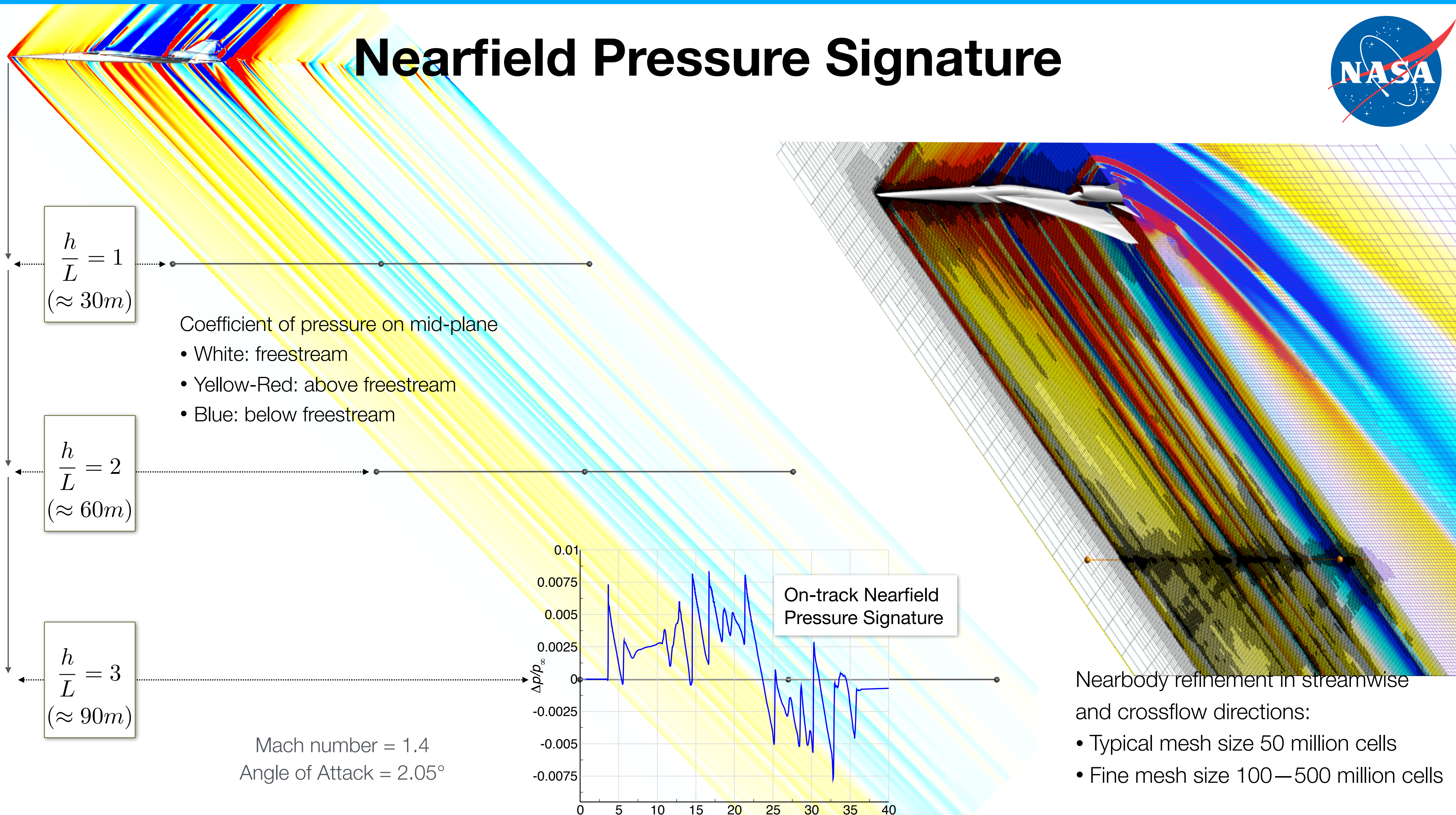
- Dark lines are shockwaves
- White regions are expansions
- Perspective projection



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

Mach number = 1.4
Angle of Attack = 2.05°

Nearfield Pressure Signature



$$\frac{h}{L} = 1$$

($\approx 30m$)

Coefficient of pressure on mid-plane

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

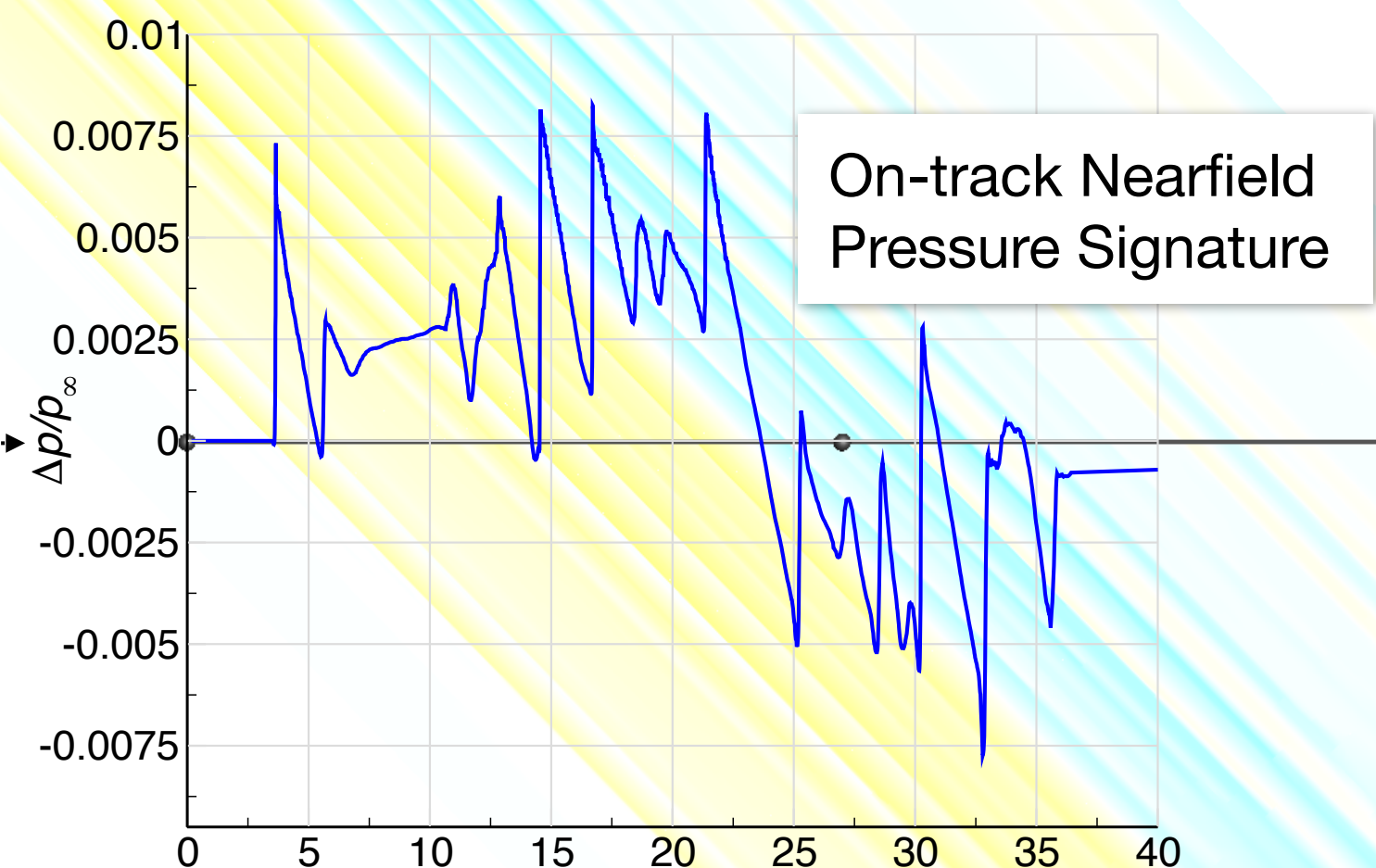
$$\frac{h}{L} = 2$$

($\approx 60m$)

$$\frac{h}{L} = 3$$

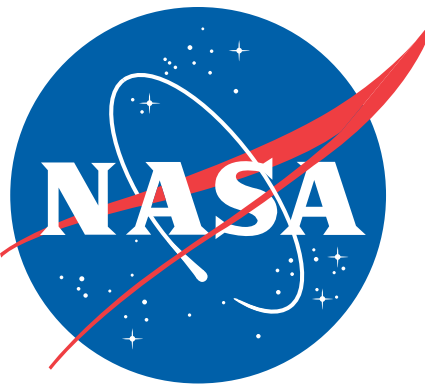
($\approx 90m$)

Mach number = 1.4
Angle of Attack = 2.05°

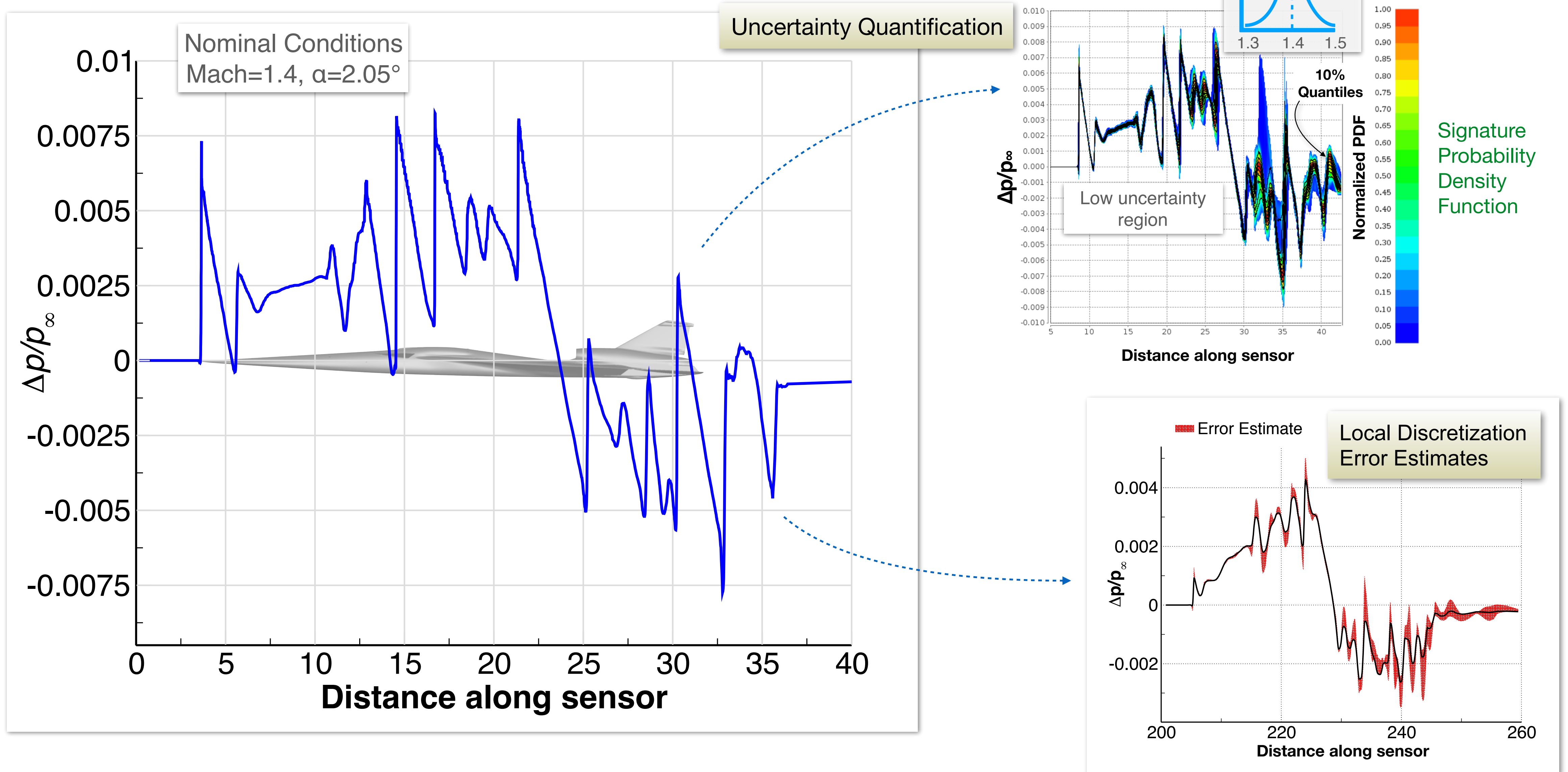


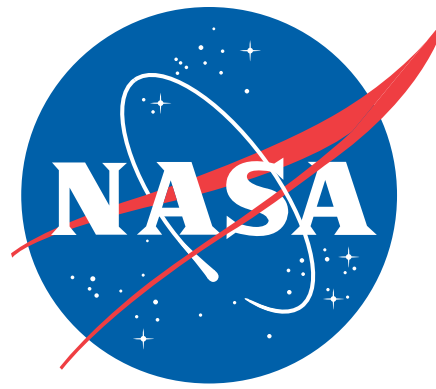
Nearbody refinement in streamwise and crossflow directions:

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

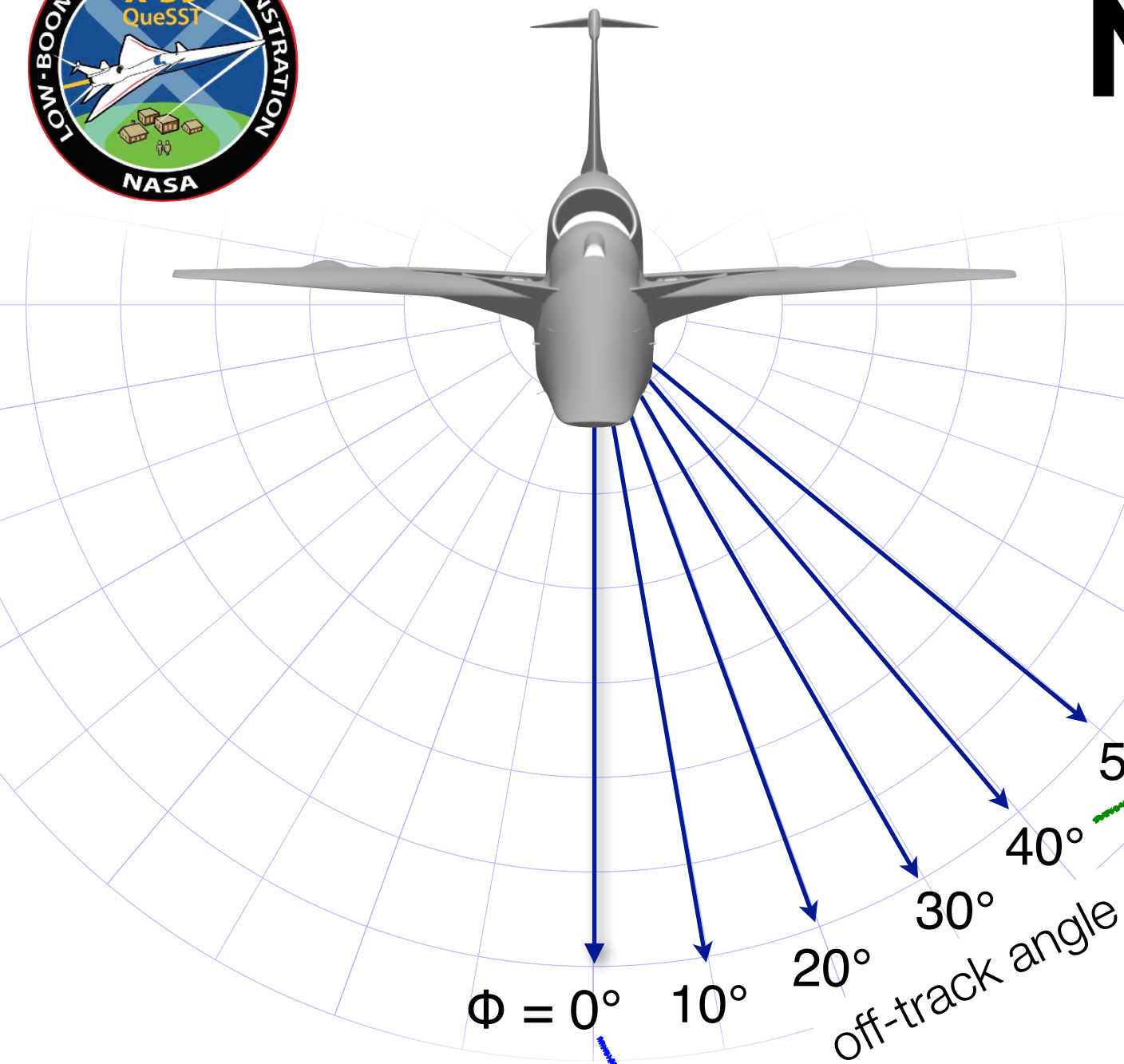


Nearfield Pressure Signature

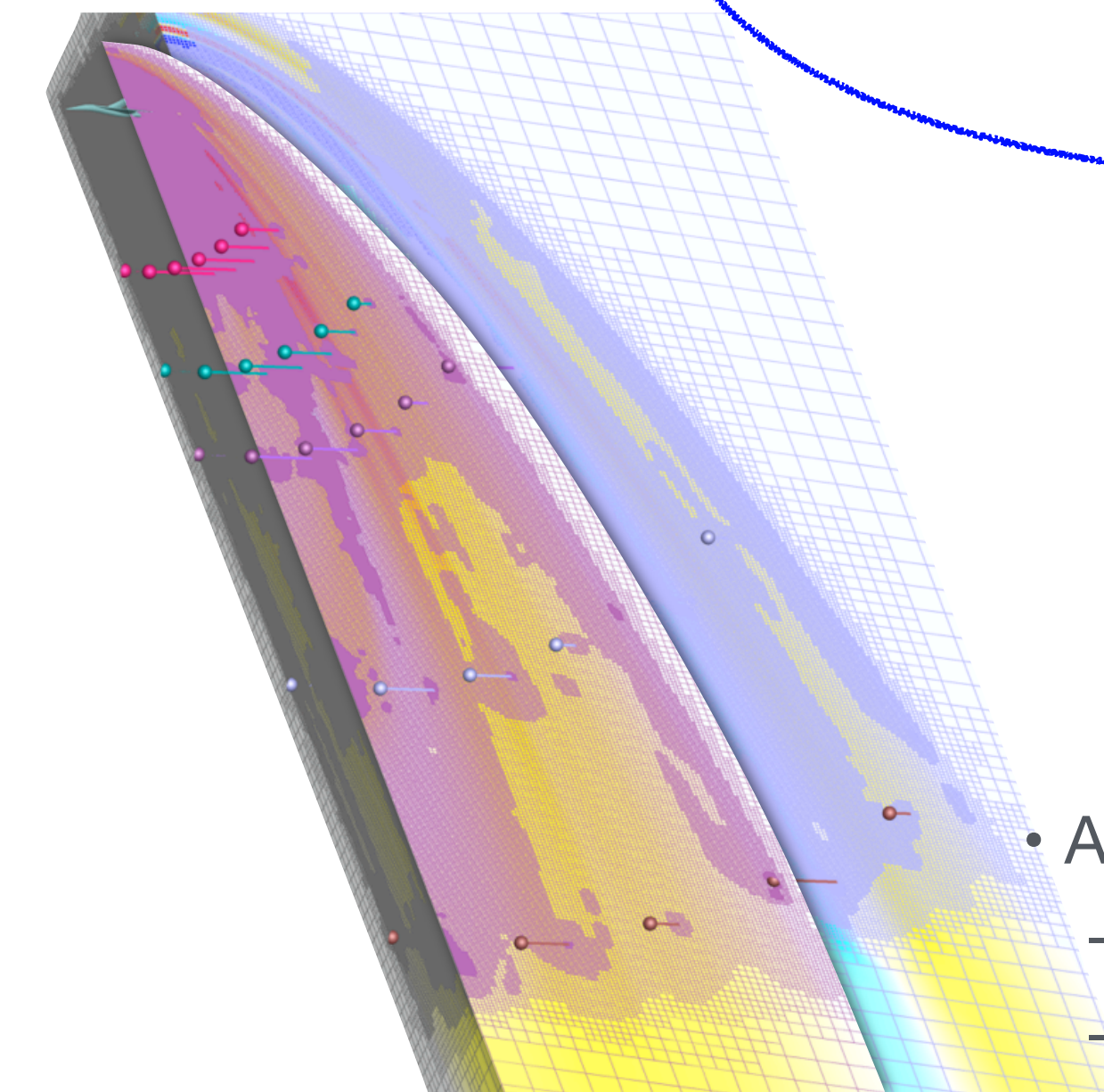
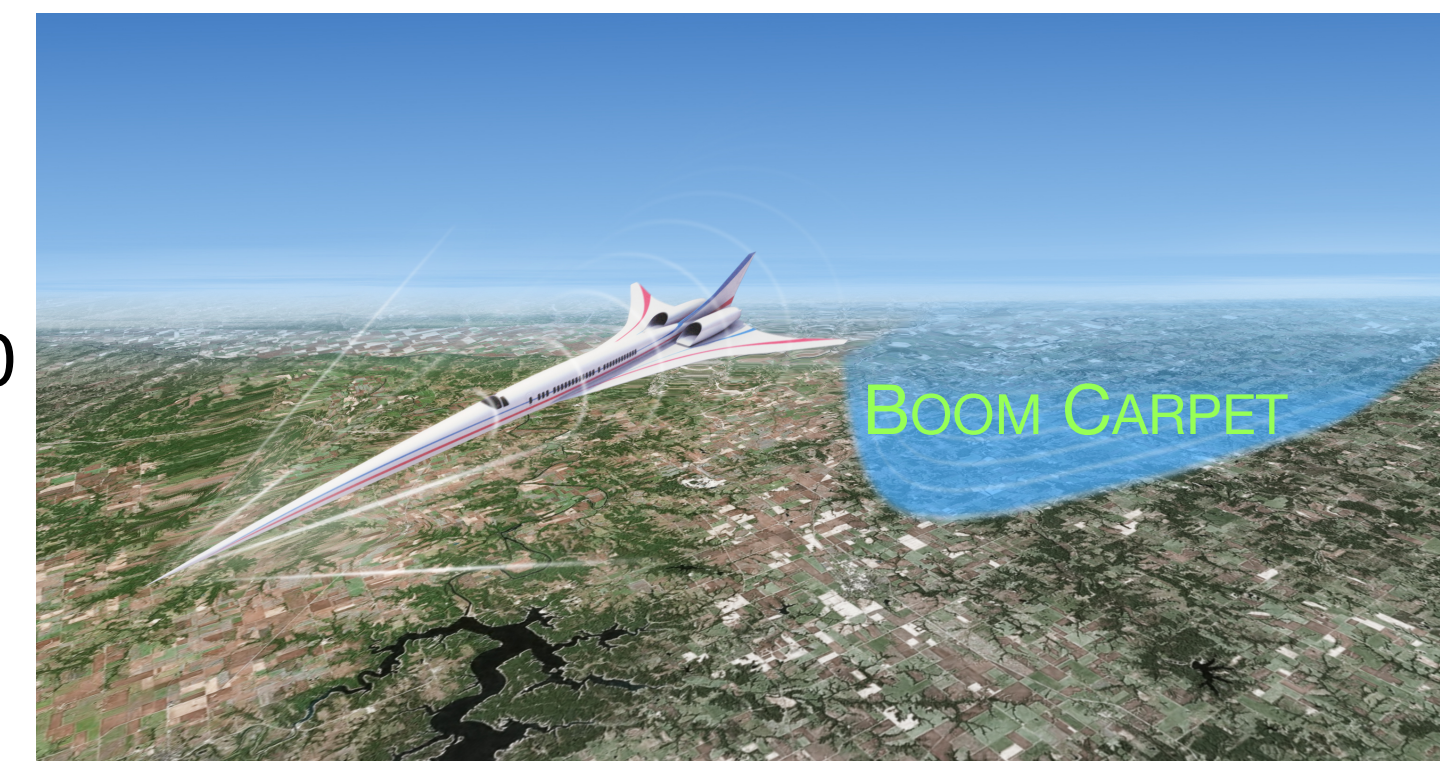
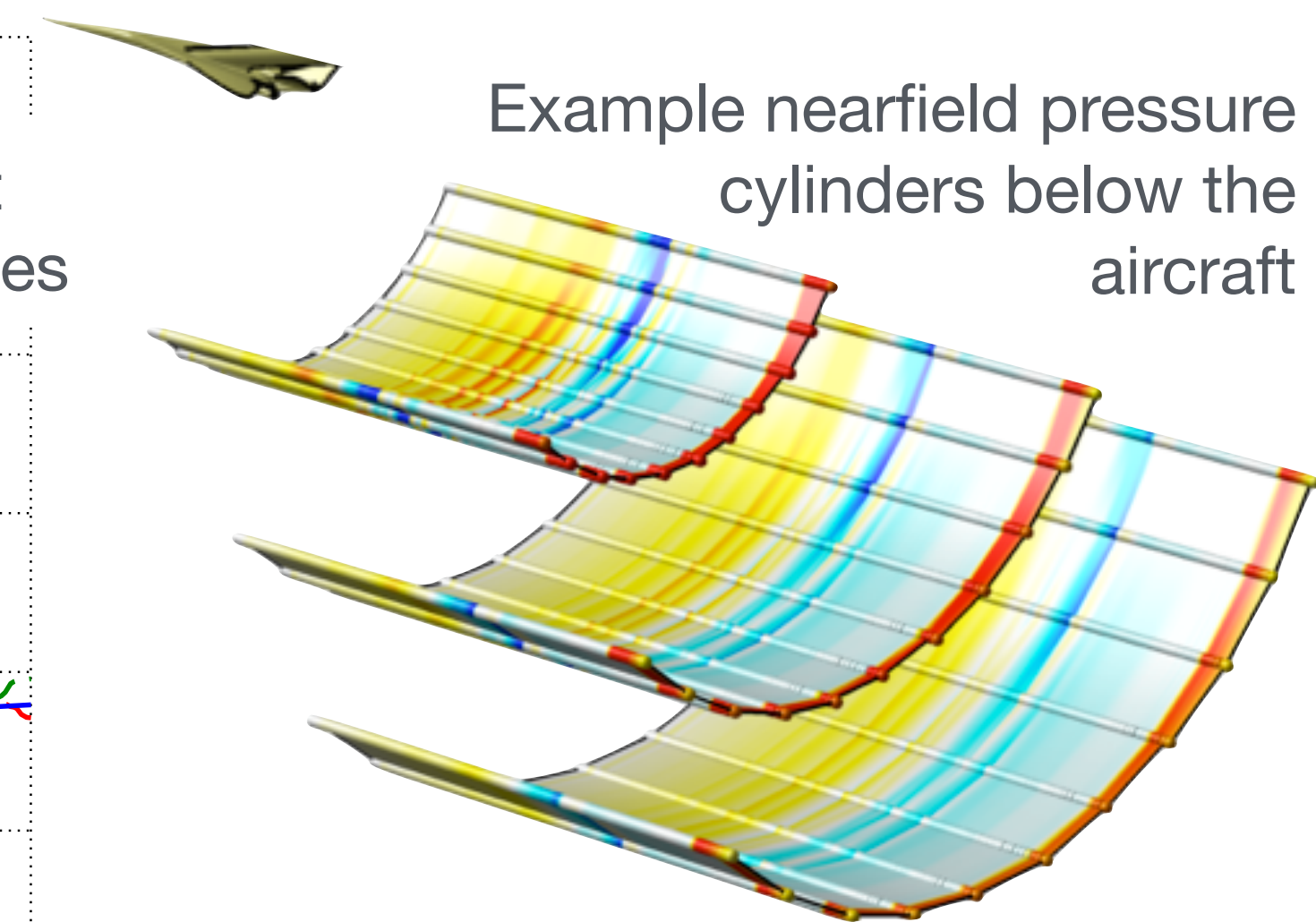
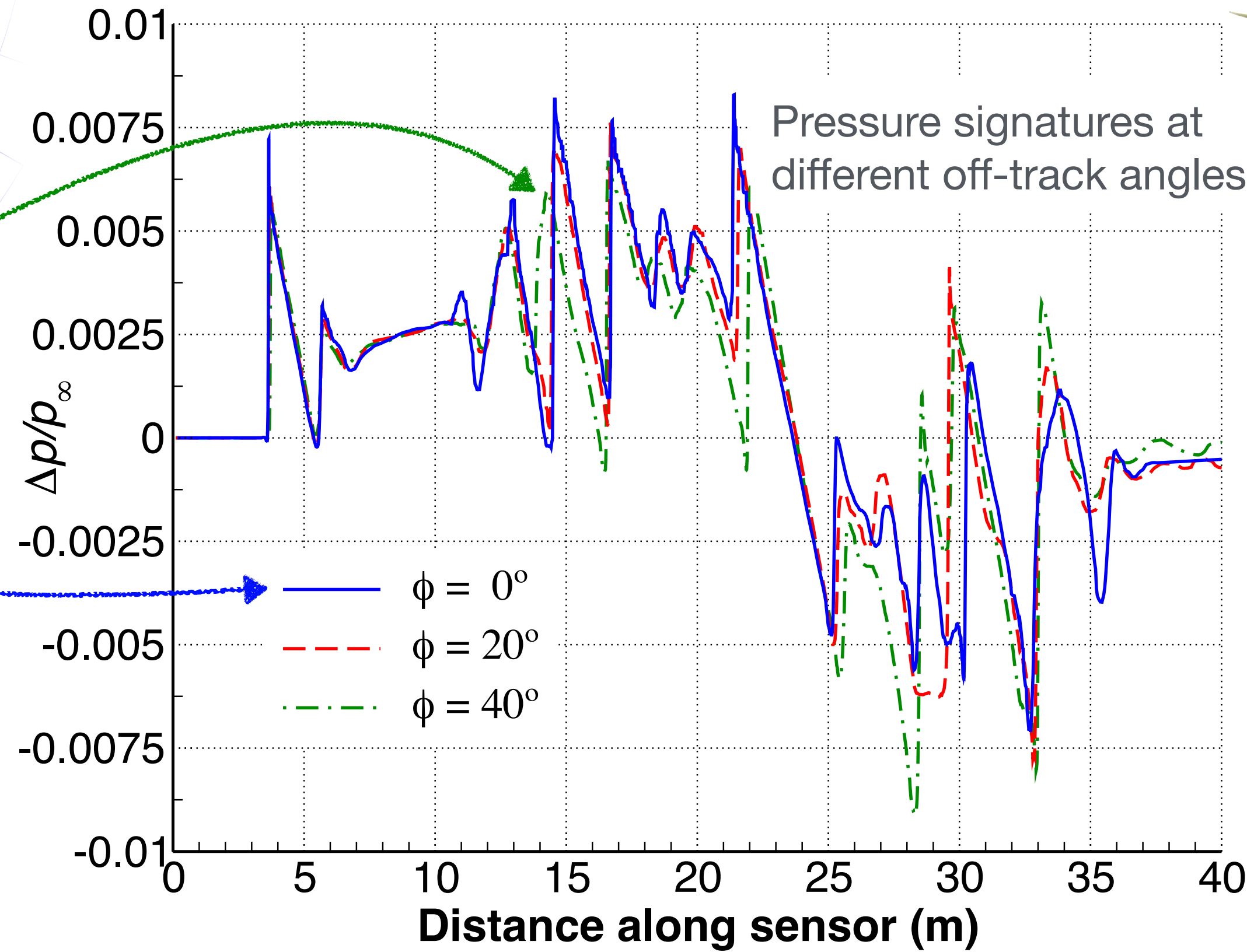




Nearfield Pressure Cylinders



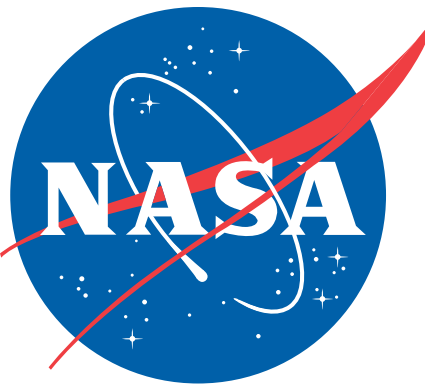
- Recall that goal is to compute the boom carpet on the ground
 - This requires computation of the nearfield pressure cylinder, not just the on-track signature



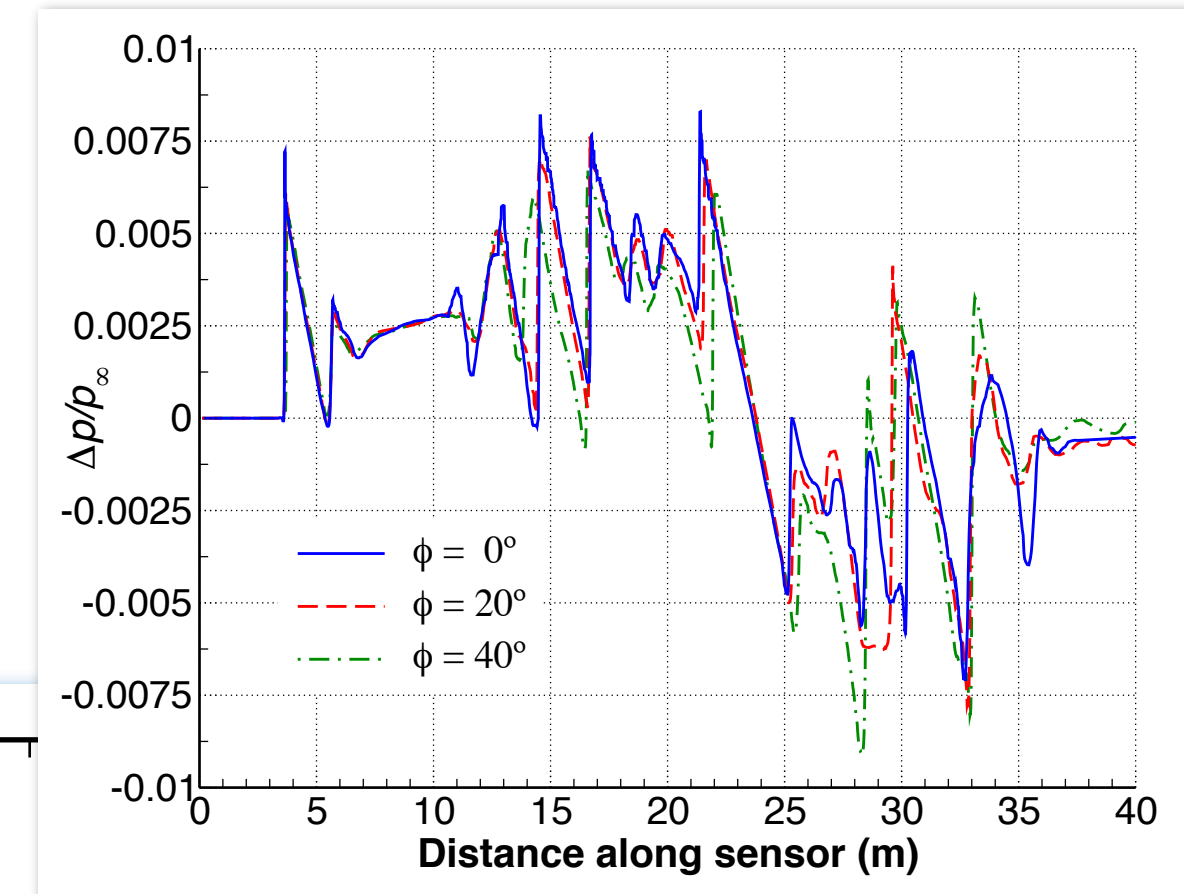
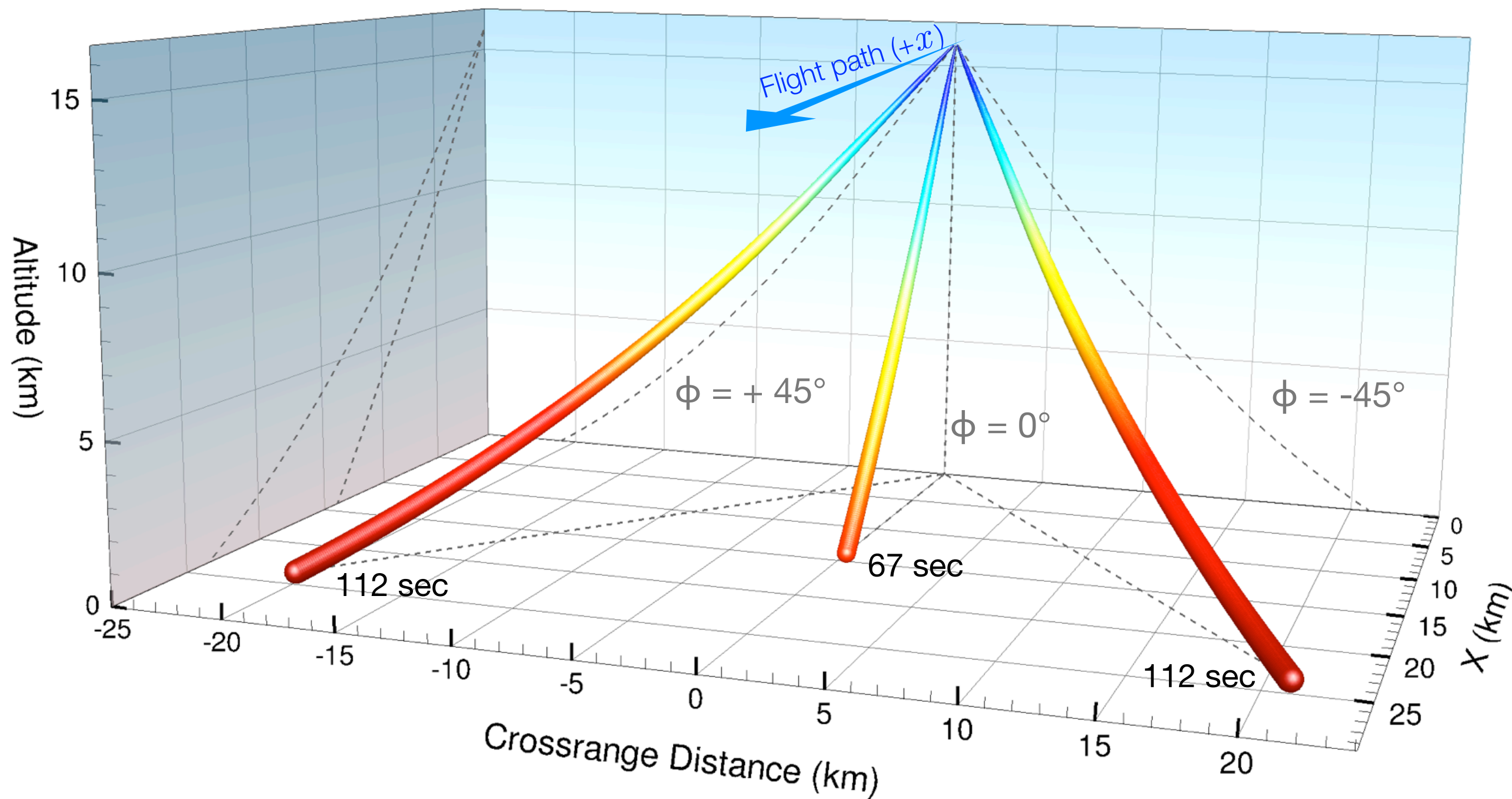
- Adaptively refined mesh for many sensor locations
 - In practice, we take full advantage of mesh alignment
 - Separate into several cases with sensors at similar off-track angles



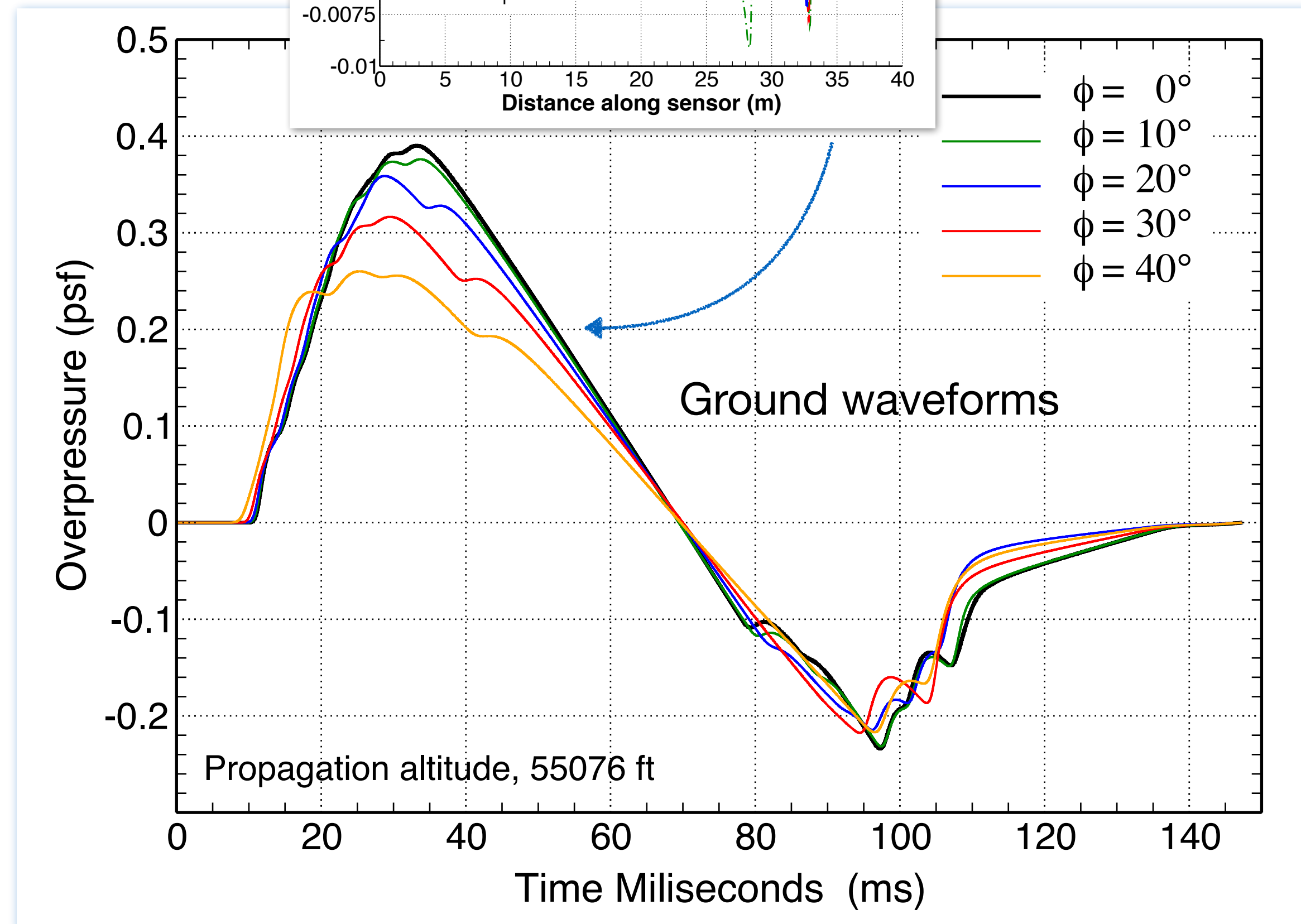
Atmospheric Propagation and Ground Signatures

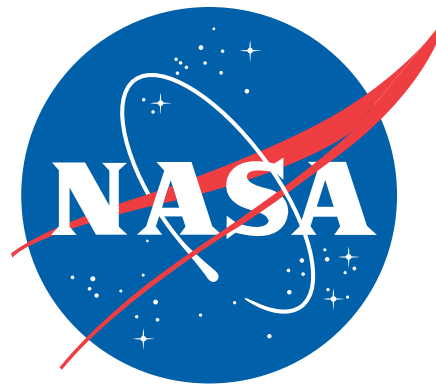


- Propagate nearfield signature through atmosphere to ground
- Numerical analysis via sBOOM:
 1. Ray tracing (path and arrival time)
 2. Quasi-1D propagation (signature morphology)
 - Includes relaxation losses, stratification, spreading and non-linear propagation



Nearfield signatures

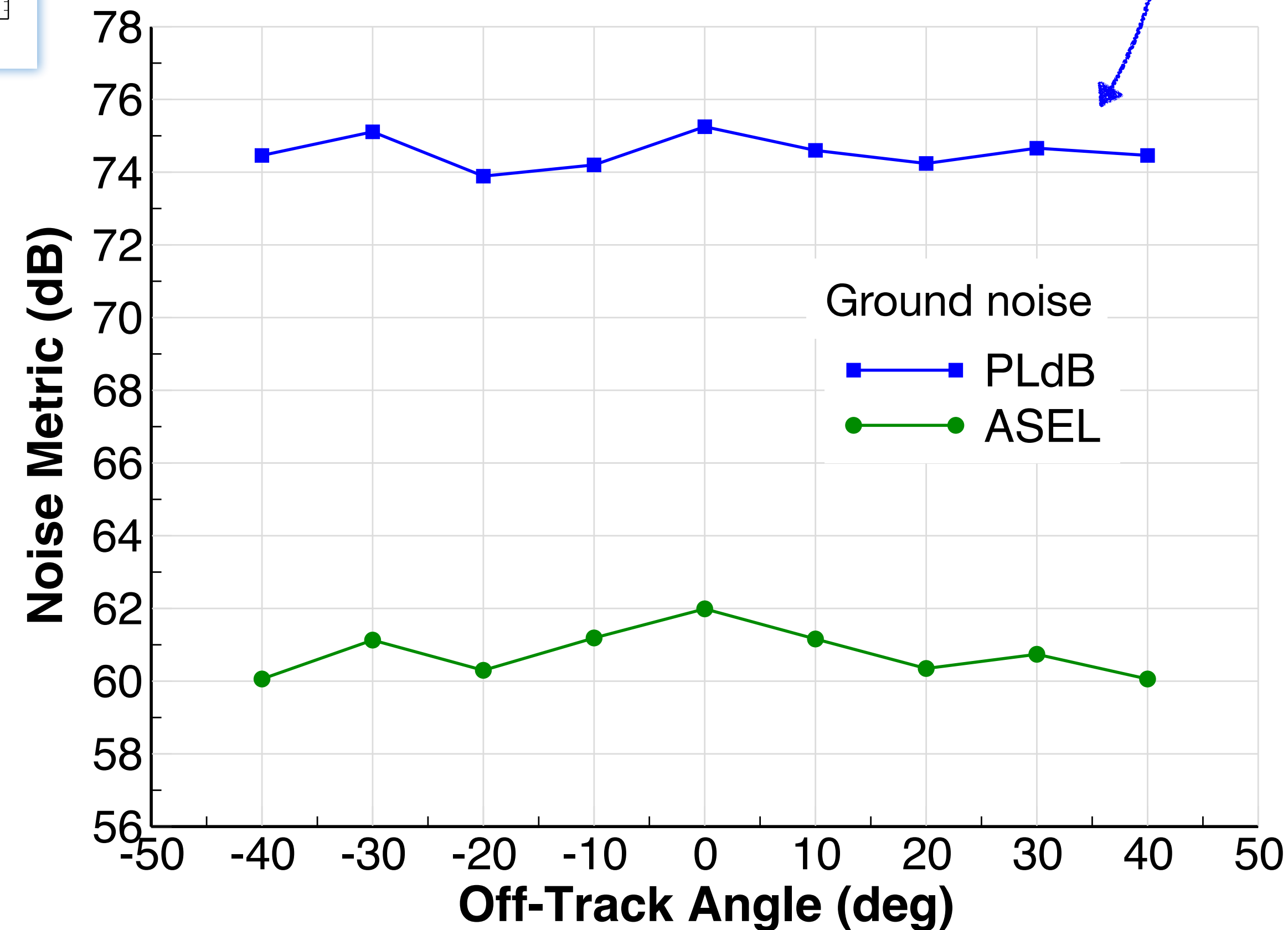
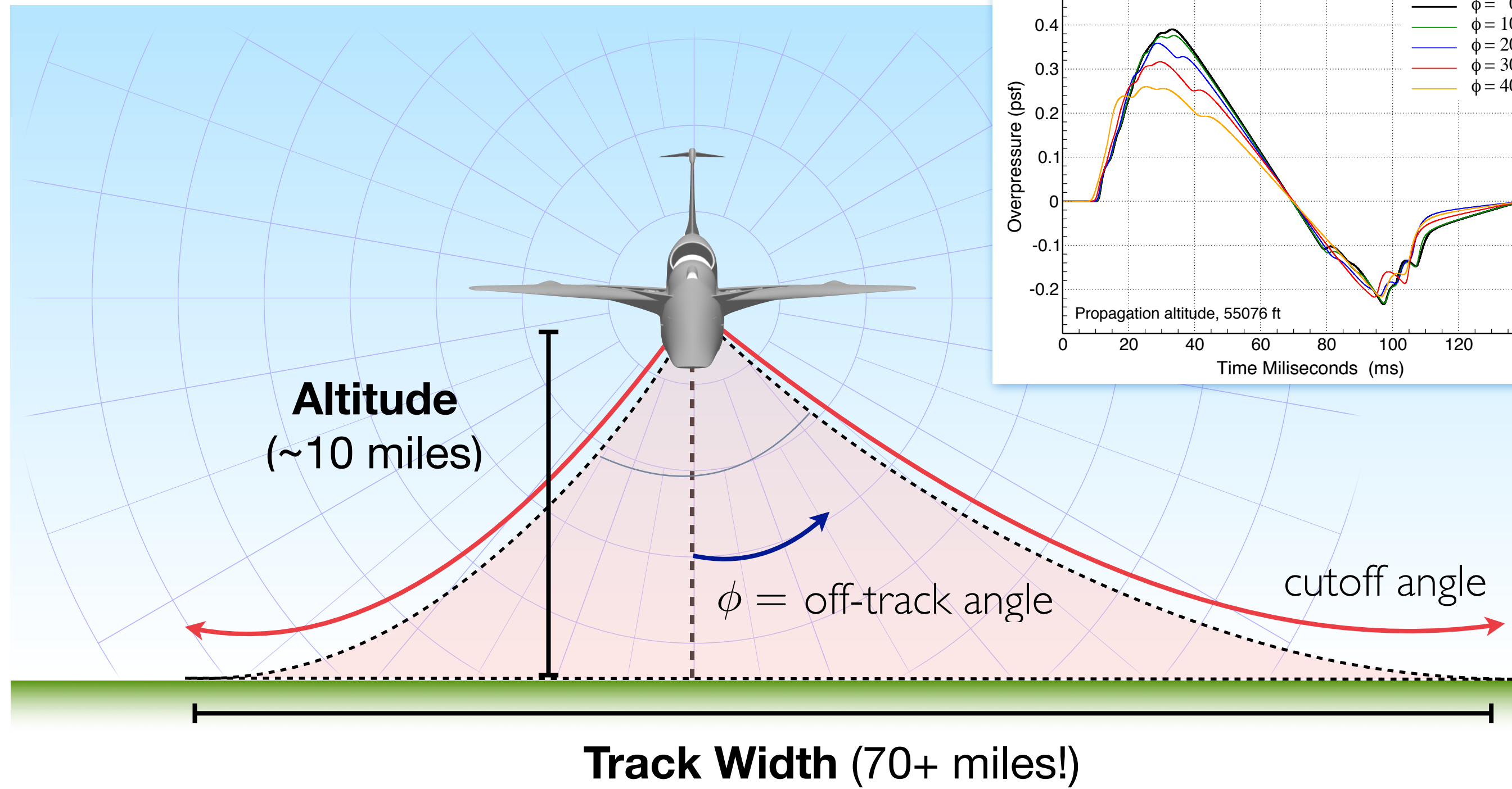
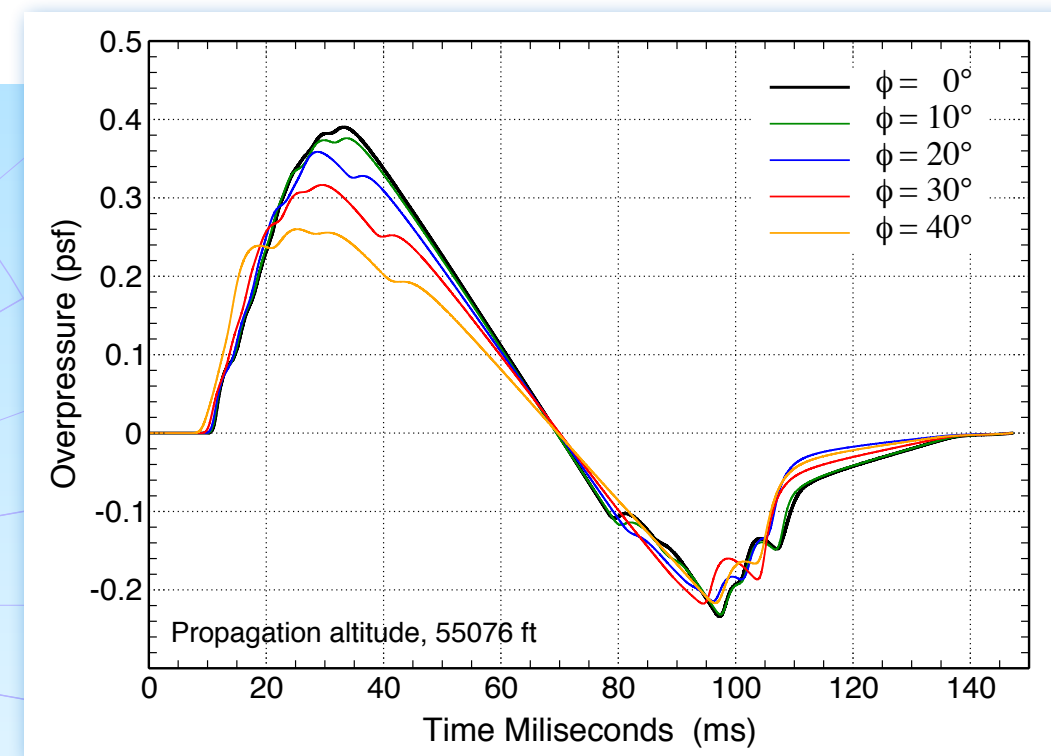




Sonic Boom Carpet

Noise target is **75 PLdB**

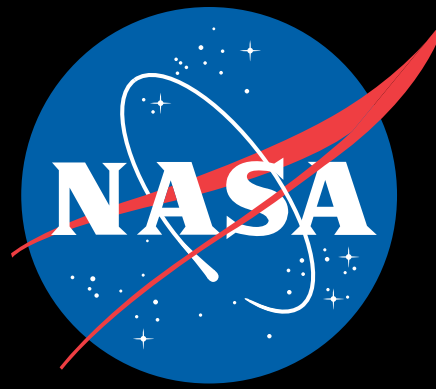
- Current design is **quieter** than target over the full carpet
- Holds for most atmospheric conditions



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

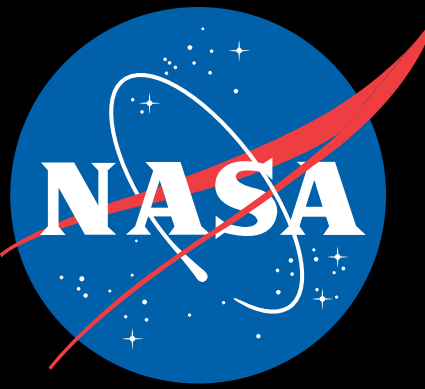
Electra

- 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

