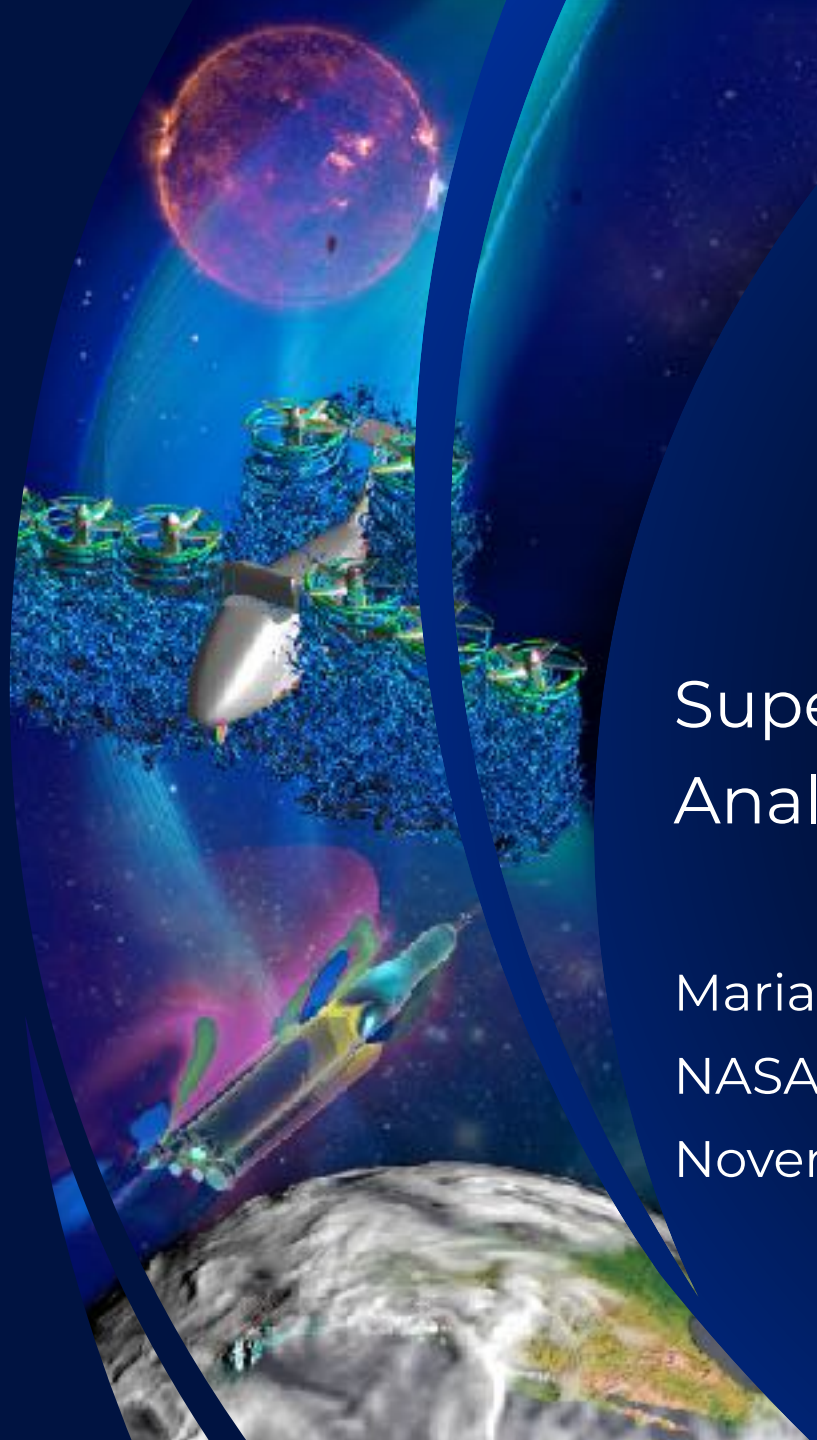


National Aeronautics and Space Administration

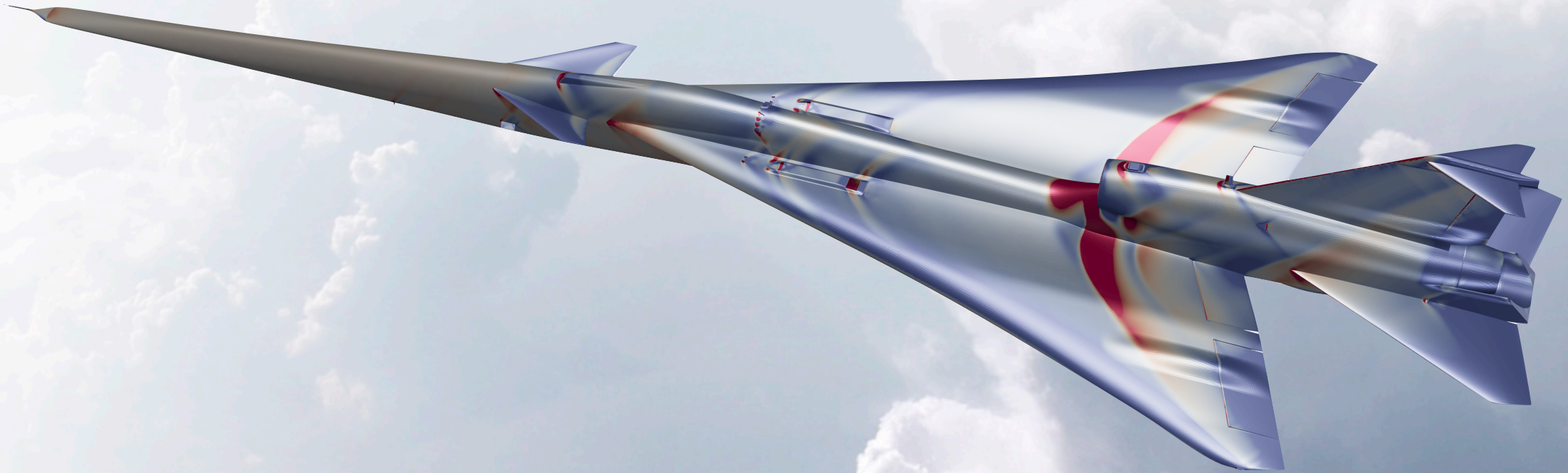
Supercomputing in Supersonics
Analyzing Noise Predictions from High-Speed Aircraft

Marian Nemec
NASA Ames Research Center
November 18-22, 2024

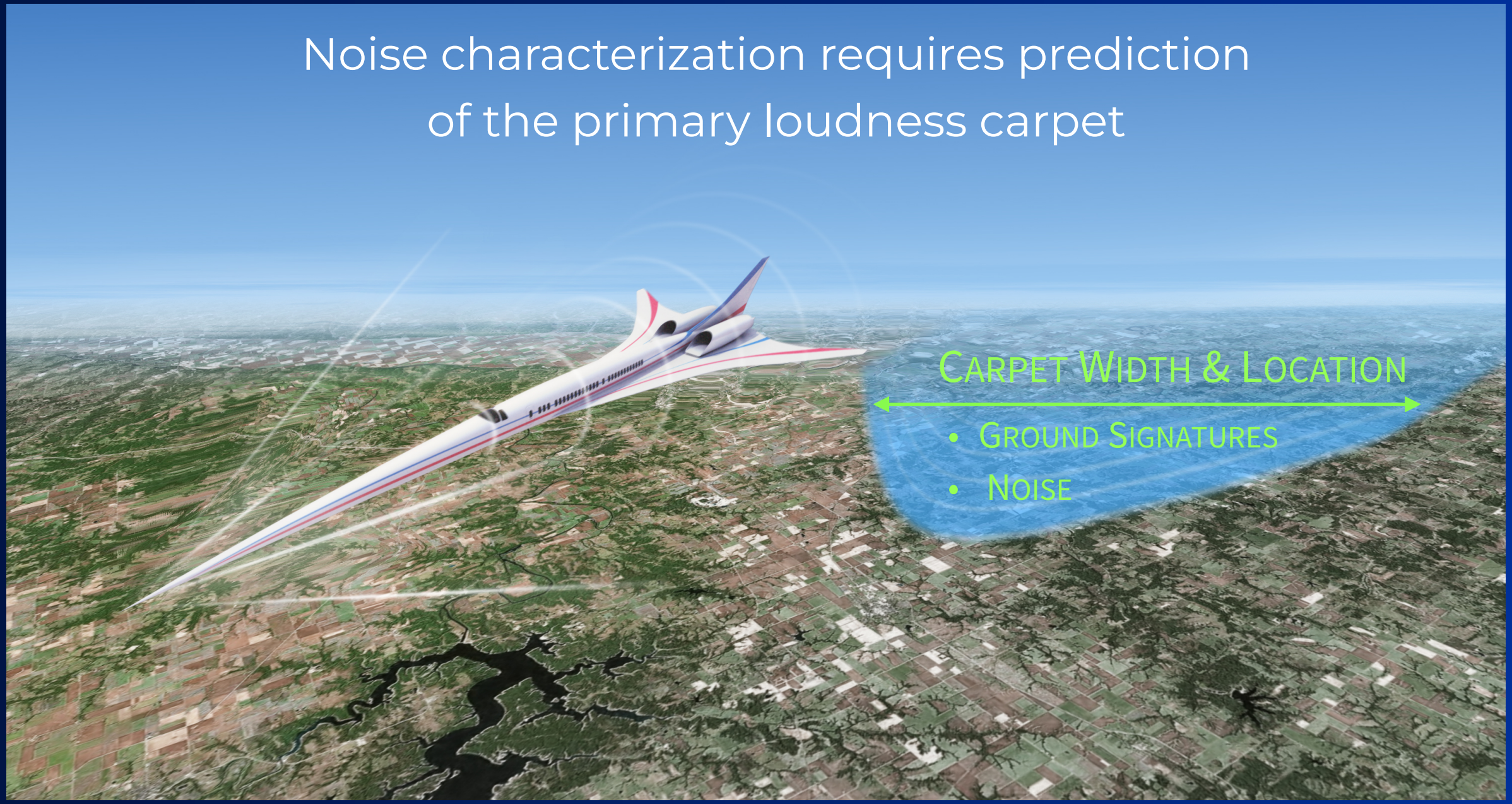
QUESST

NASA @ SC24

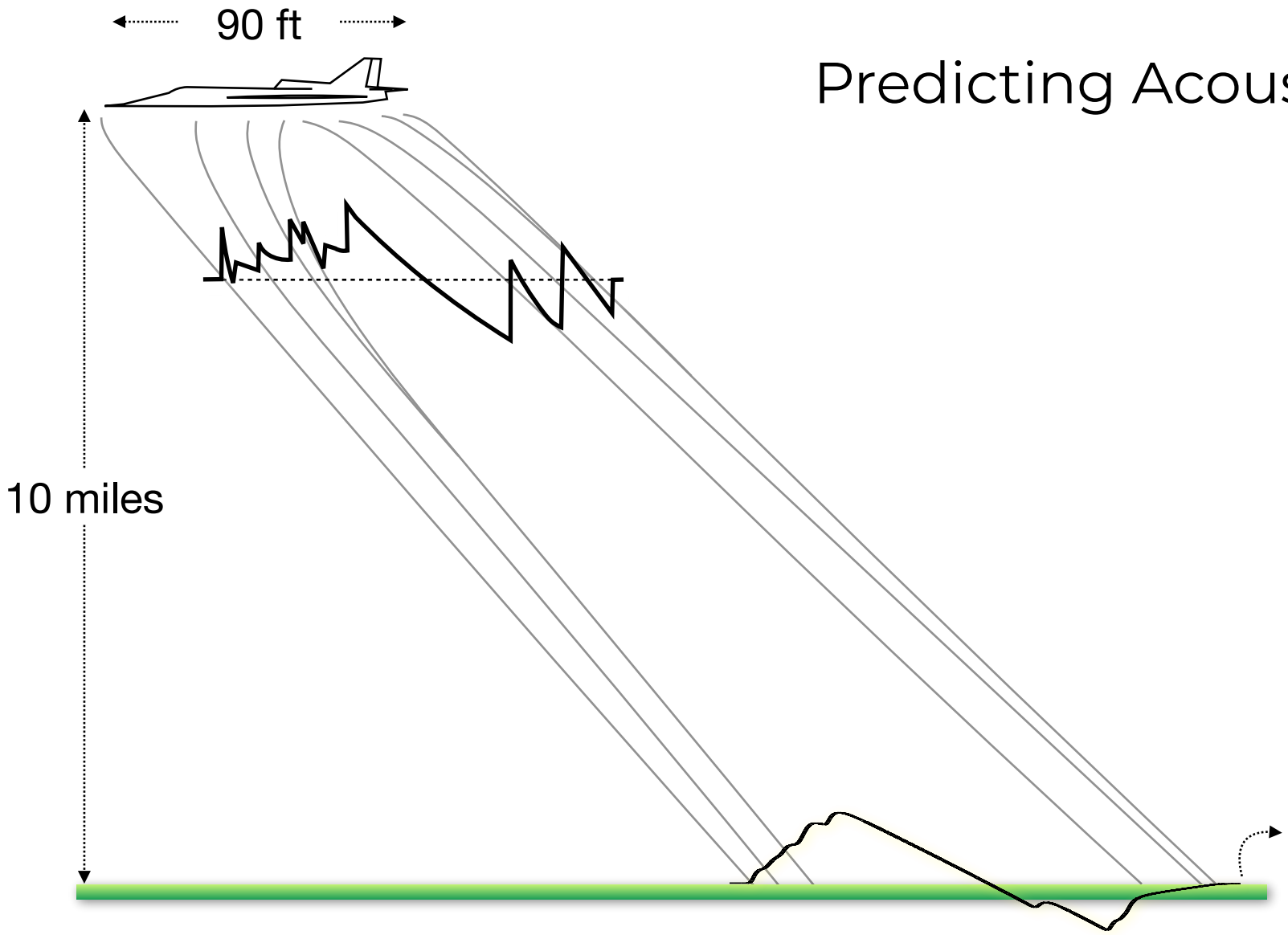
Goal is to quantify uncertainty in the noise reaching ground from supersonic aircraft at cruise conditions



Noise characterization requires prediction of the primary loudness carpet

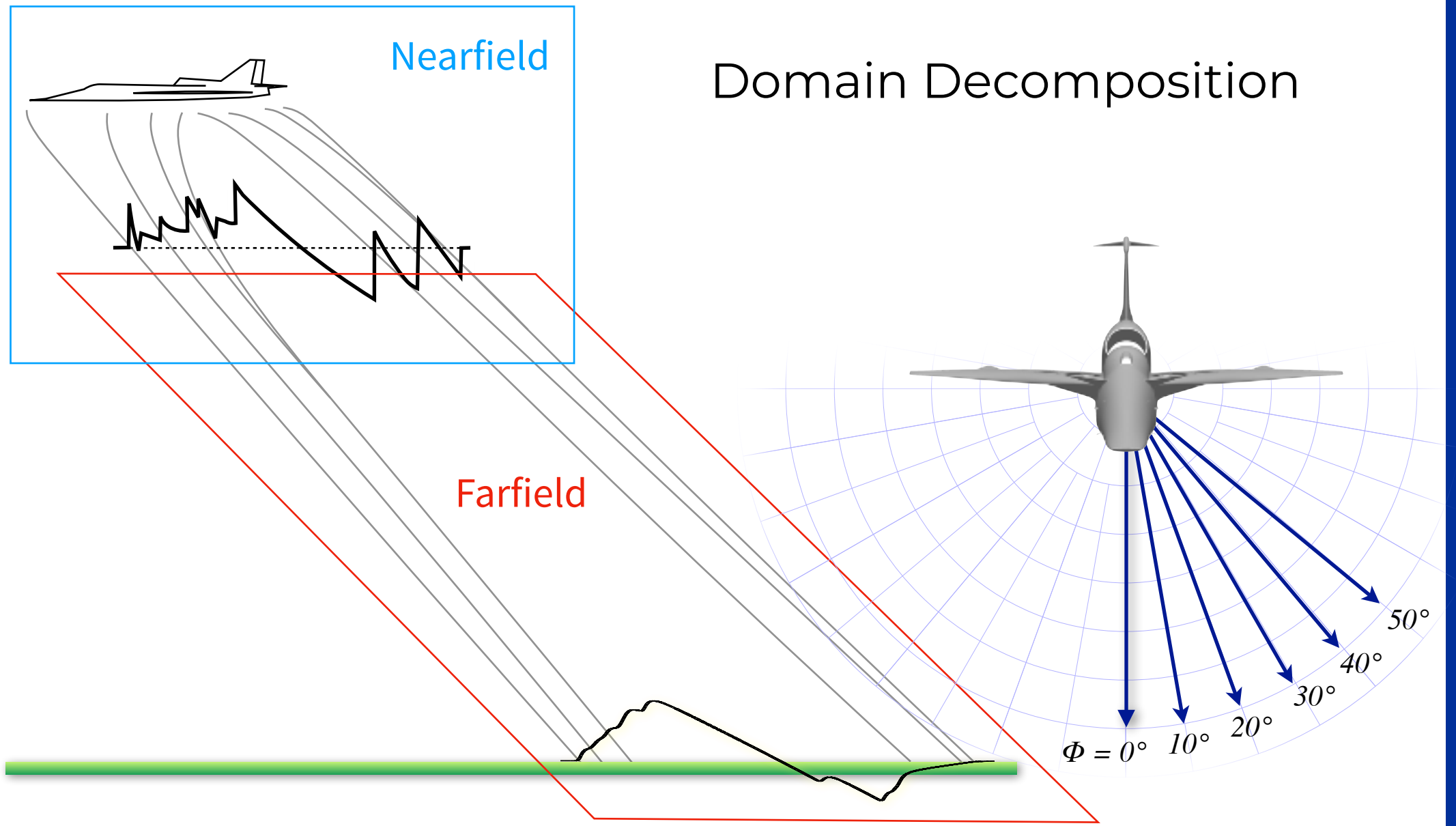


Predicting Acoustic Signatures



Noise Analysis
PL, SEL, ISBAP (dB)

Domain Decomposition




X-59


NASA
X-59
N859NA
BEFORE FLIGHT

Approach: Non-Intrusive Implementtion

QUEST

Sources of Uncertainty

QUESTPrep

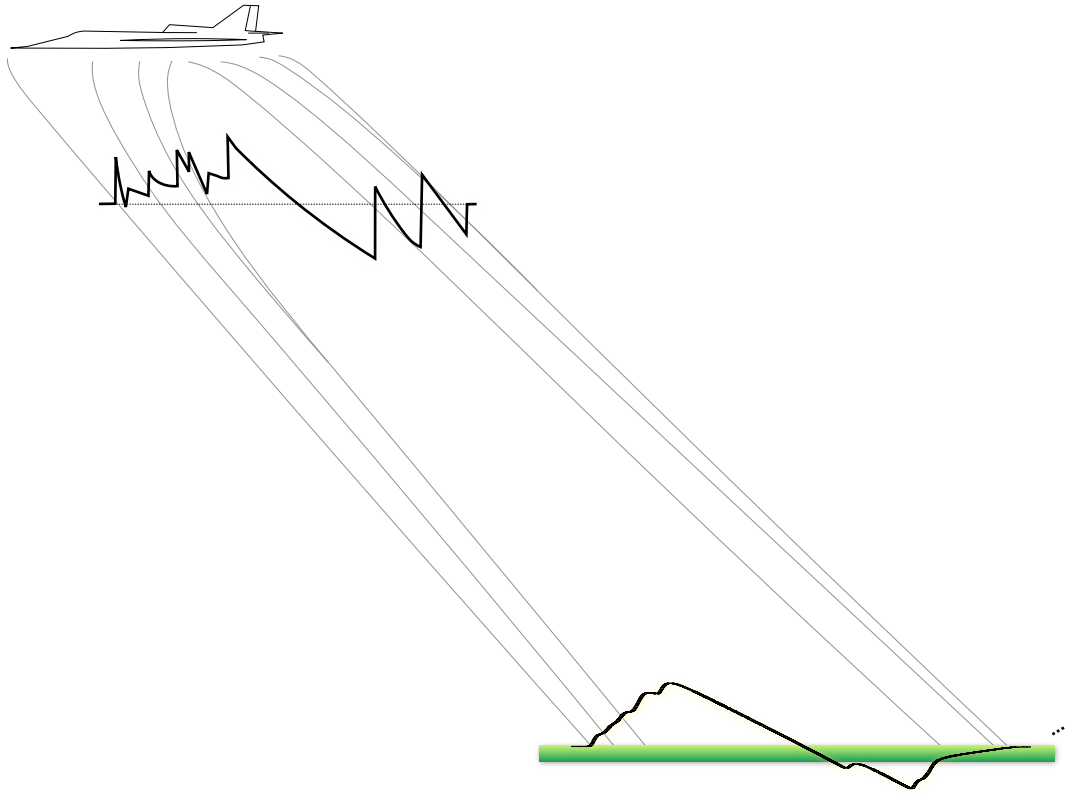
Database

Realizations

QUESTPost

Statistics

Acoustic Signature Simulation

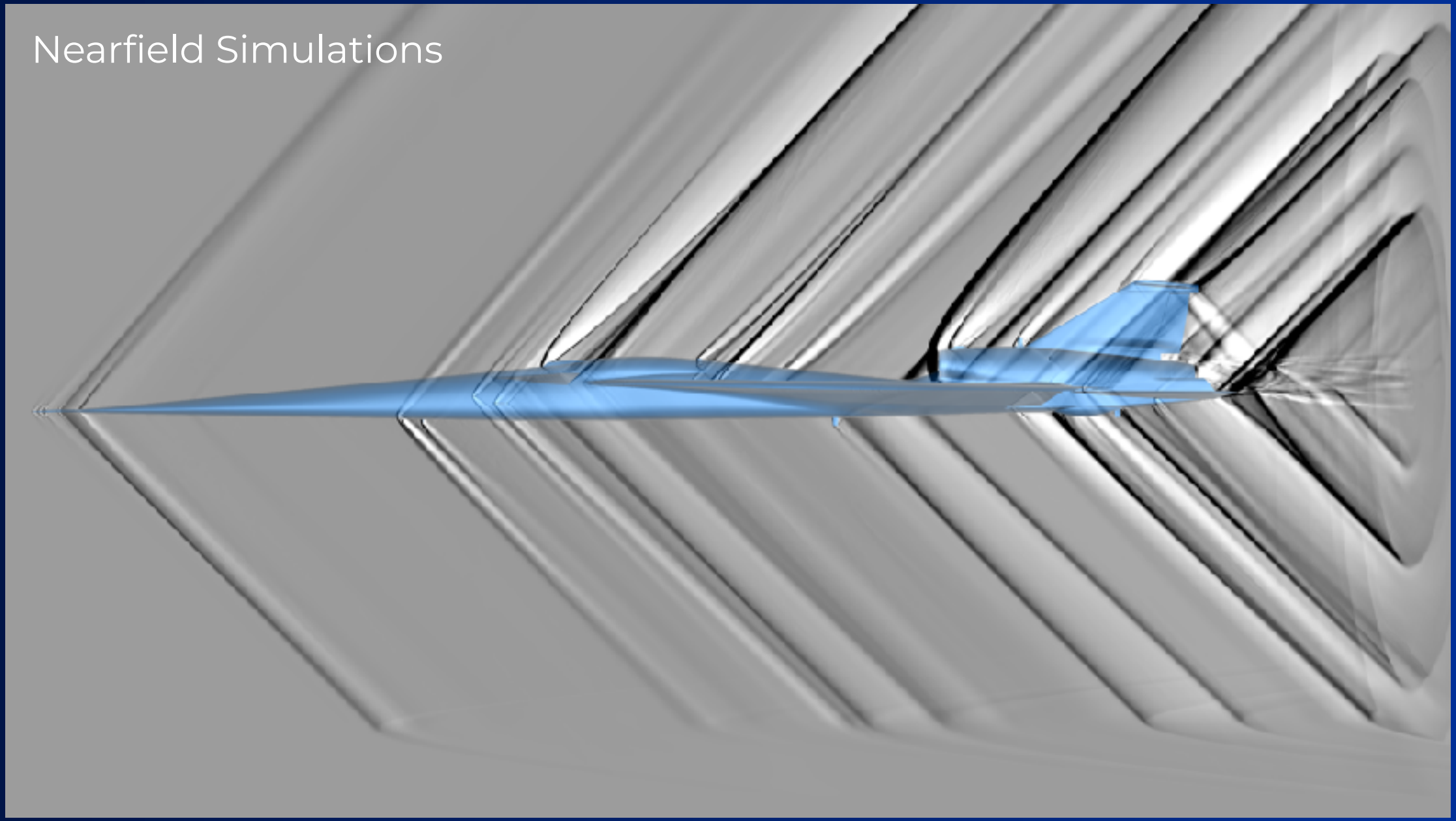


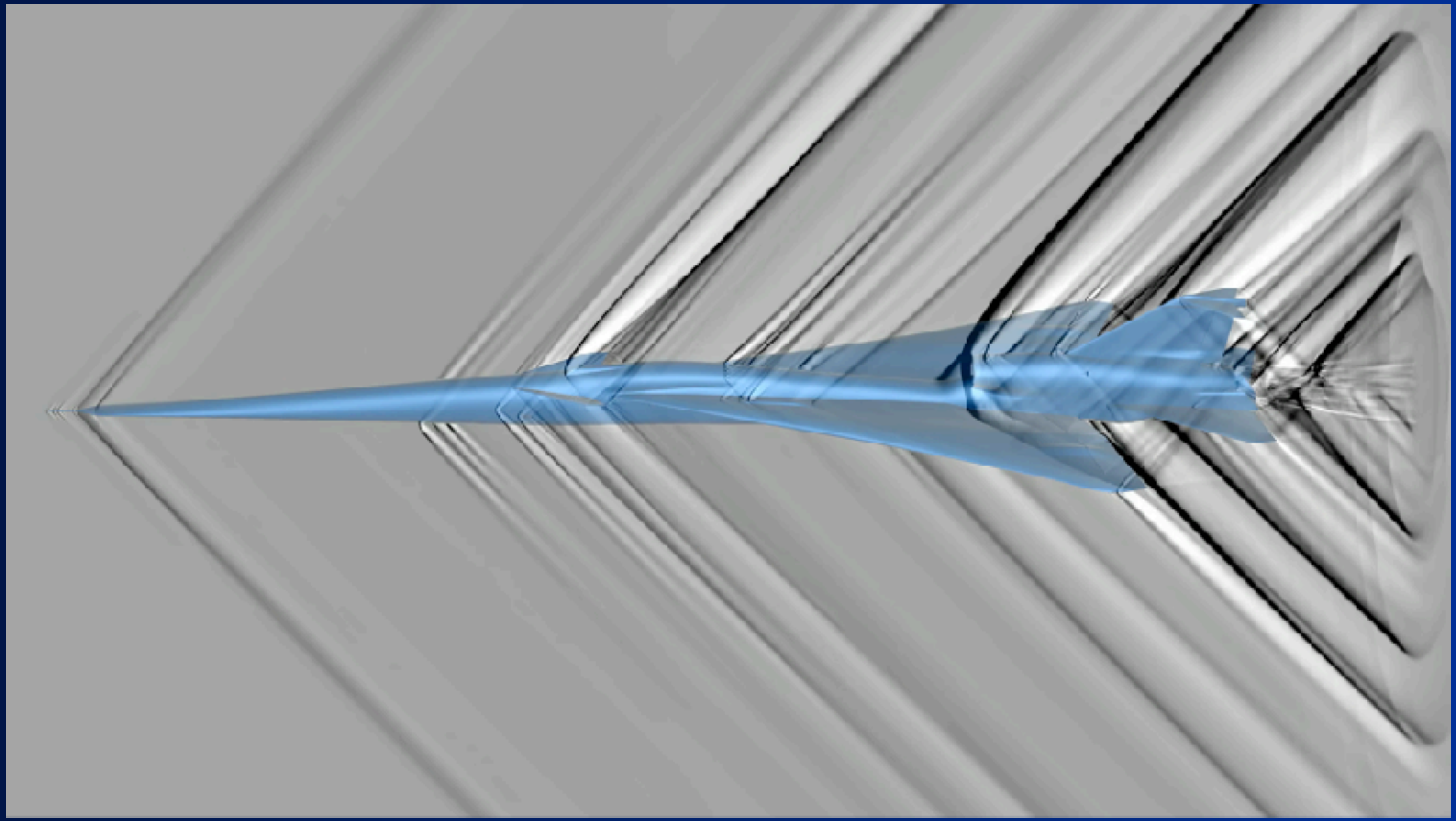
Noise Analysis

PL, ISBAP (dB)

Realizations, e.g. noise metric $J_H(\xi_1),\ J_H(\xi_2),\ \ldots,\ J_H(\xi_N)$

Nearfield Simulations





X-59 & Quesst Mission

Overcoming the barrier to overland supersonic flight

- Civil supersonic flight operations are prohibited over many parts of the world
  - Flight in excess of Mach 1 over land is prohibited in US and Canada
- NASA mission to support development of an en route noise standard
- X-59 is a supersonic-acoustic-signature-generator with characteristics representative of a commercial supersonic transport
- 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
  - New standard must be accepted internationally (ICAO, FAA, EASA, TCCA)

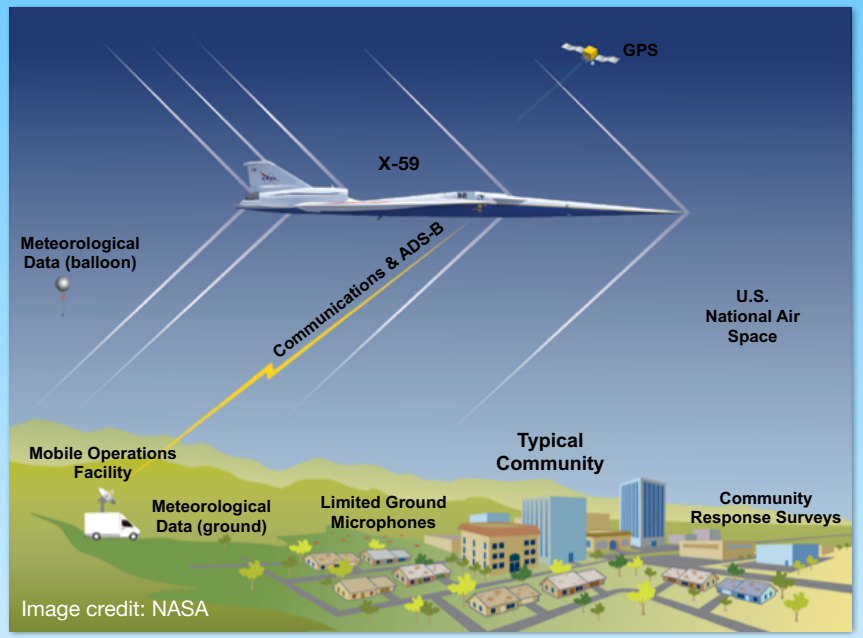


Image credit: NASA


June 19, 2023

Image credit: Lockheed Martin / Garry Tice

Objectives

Toward En Route Noise Certification by Simulation

Simulation Accuracy & Automation

- Improve design confidence
  - Determine level of discretization error in outputs of interest
- Reduce level of CFD expertise
  - Eliminate the need to handcraft a mesh for every simulation
  - Adaptive mesh refinement

Uncertainty Quantification

- Characterize effect of input uncertainties on low-boom outputs
  - Determine mean, standard deviation and probability density function
- Estimate model-form error
- Determine probability of mission success

Aerodynamic Shape Optimization

- Reduce cost by systematically increasing depth of refinement as designs improve
- Reliable analysis and robust designs

Nearfield Solver: Cart3D

$$\mathbf{R}_N(\mathbf{Q}_N) = 0$$

Flow Solver

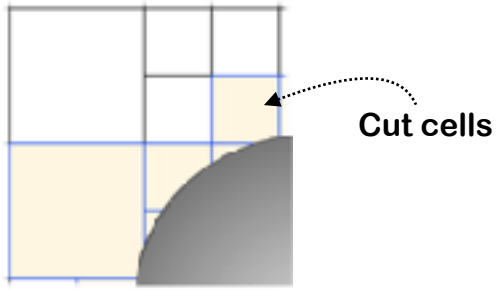
- Inviscid flow (steady Euler equations)
- 2nd-order upwind method
  - van Leer flux, Barth-Jespersen Limiter
- RK-5, Multigrid acceleration
- Domain decomposition: OpenMP & MPI

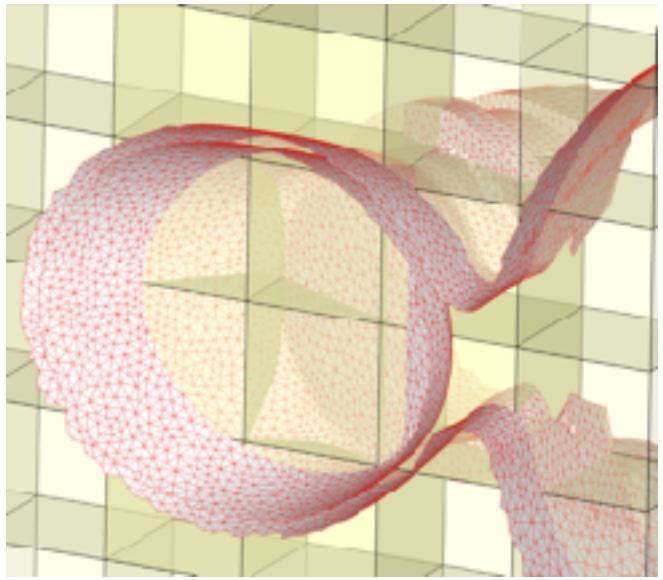
Automatic Meshing

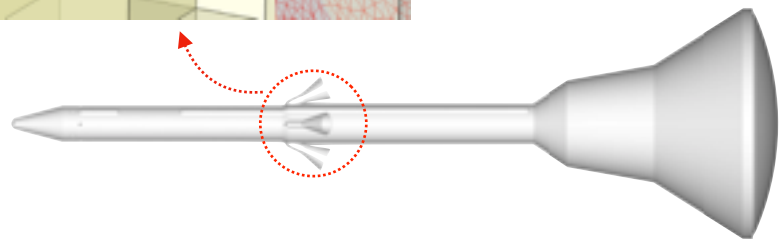
- Multilevel Cartesian mesh with embedded boundaries

Output-Driven Mesh Adaptation

- Method of adjoint-weighted residuals
- Mesh is refined in locations with highest impact on pressure signatures







✓Complex geometry
✓Automation
✓*h*-refinement

Nearfield Solver: Cart3D

$$\mathbf{R}_N(\mathbf{Q}_N) = 0$$

Flow Solver

- Inviscid flow (steady Euler equations)
- 2nd-order upwind method
  - van Leer flux, Barth-Jespersen Limiter
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Automatic Meshing

- Multilevel Cartesian mesh with embedded boundaries

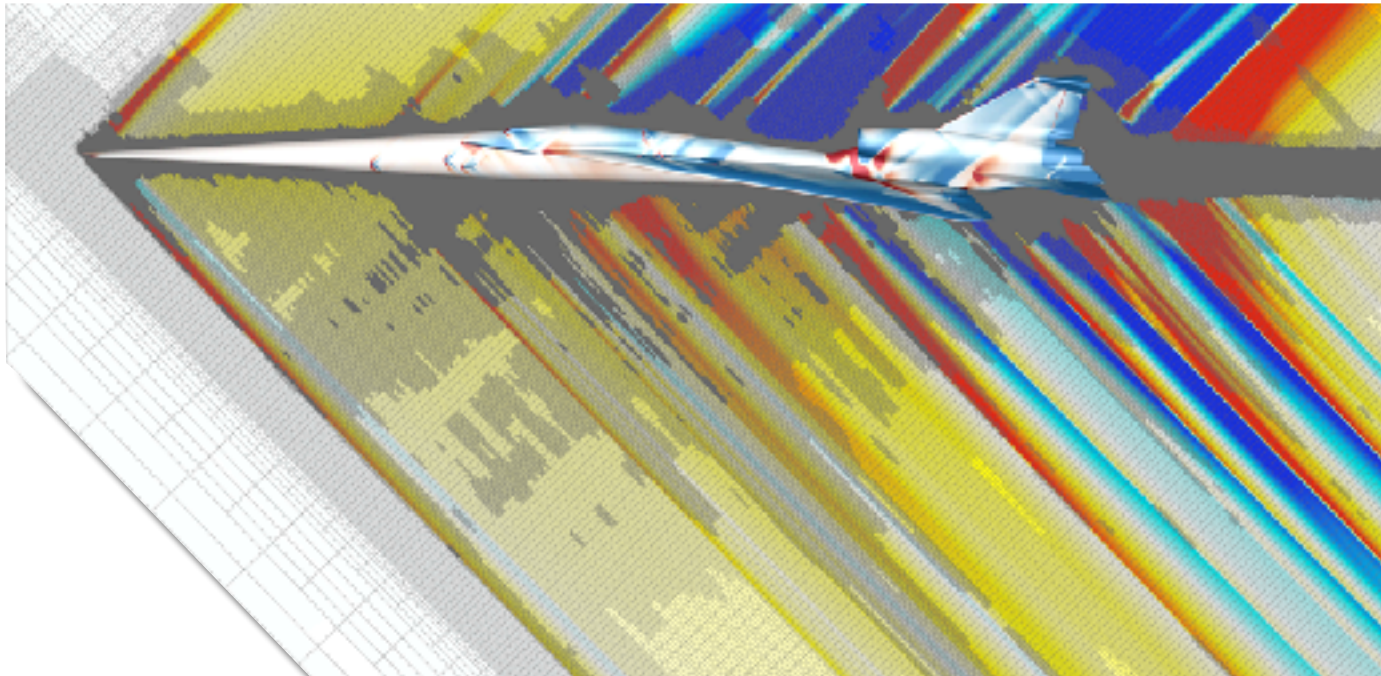
Output-Driven Mesh Adaptation

- Method of adjoint-weighted residuals
- Mesh is refined in locations with highest impact on pressure signatures

Every nearfield simulation includes

- Mesh refinement study to demonstrate mesh convergence
- Reliable bound on remaining discretization error

Credibility, Efficiency & User-Independent Results



Nearfield Solver: Cart3D

$\frac{h}{L} = 1$
$(\approx 30m)$

$\frac{h}{L} = 2$
$(\approx 60m)$

$\frac{h}{L} = 3$
$(\approx 90m)$

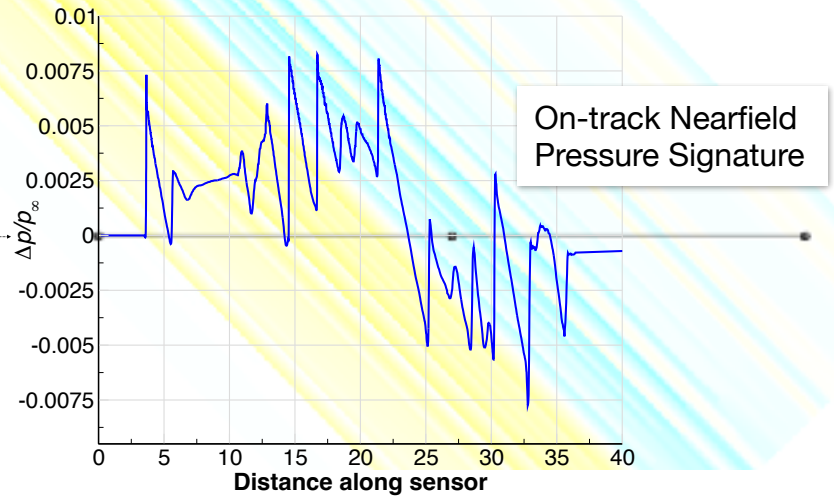
Coefficient of pressure on mid-plane
- White: freestream
- Yellow-Red: above freestream
- Blue: below freestream

Mach number = 1.4
Angle of Attack = 2.05°

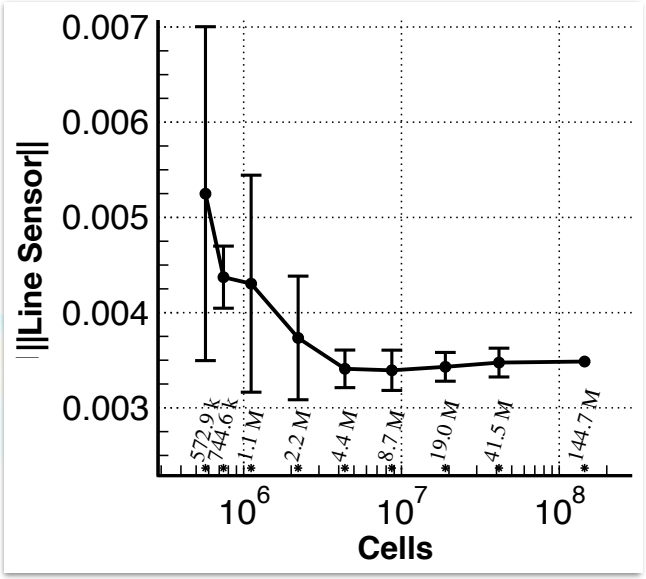
Every nearfield simulation includes

- Mesh refinement study to demonstrate mesh convergence
- Reliable bound on remaining discretization error

Credibility, Efficiency & User-Independent Results



On-track Nearfield Pressure Signature



Farfield Solver: sBOOM

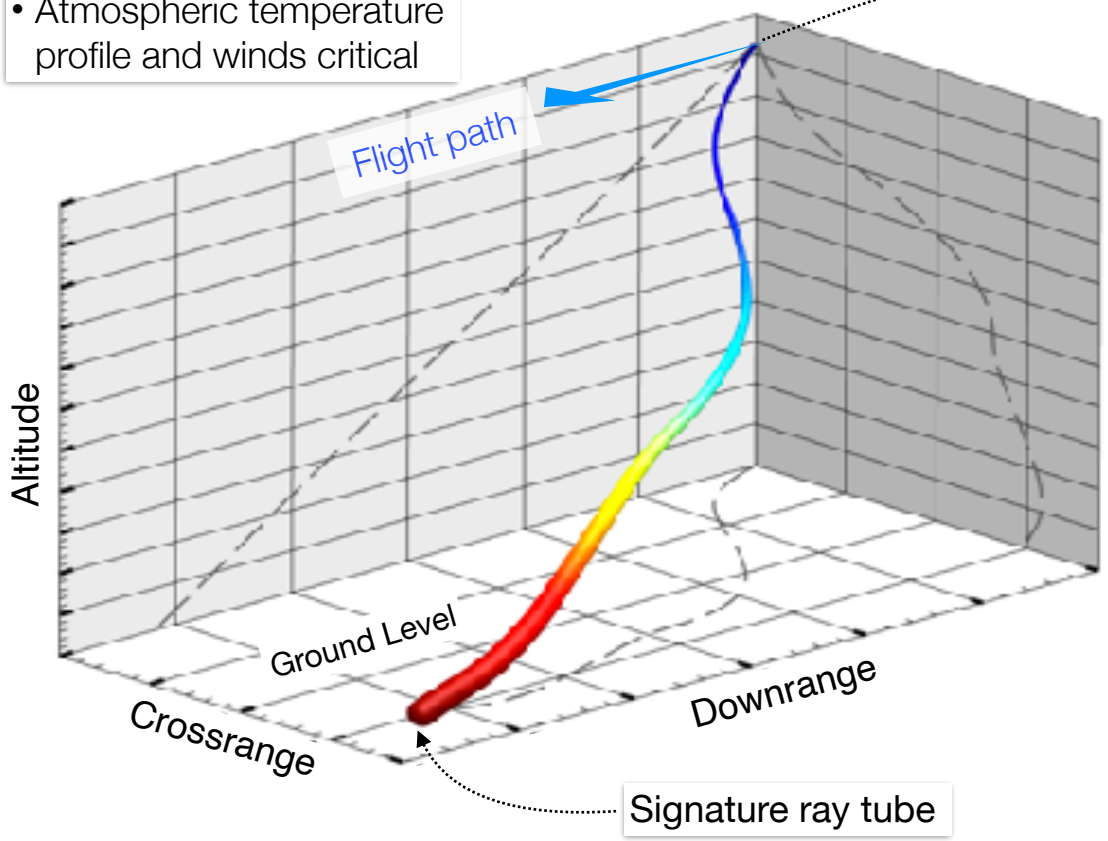
Ray tracing coupled with augmented Burgers' equation

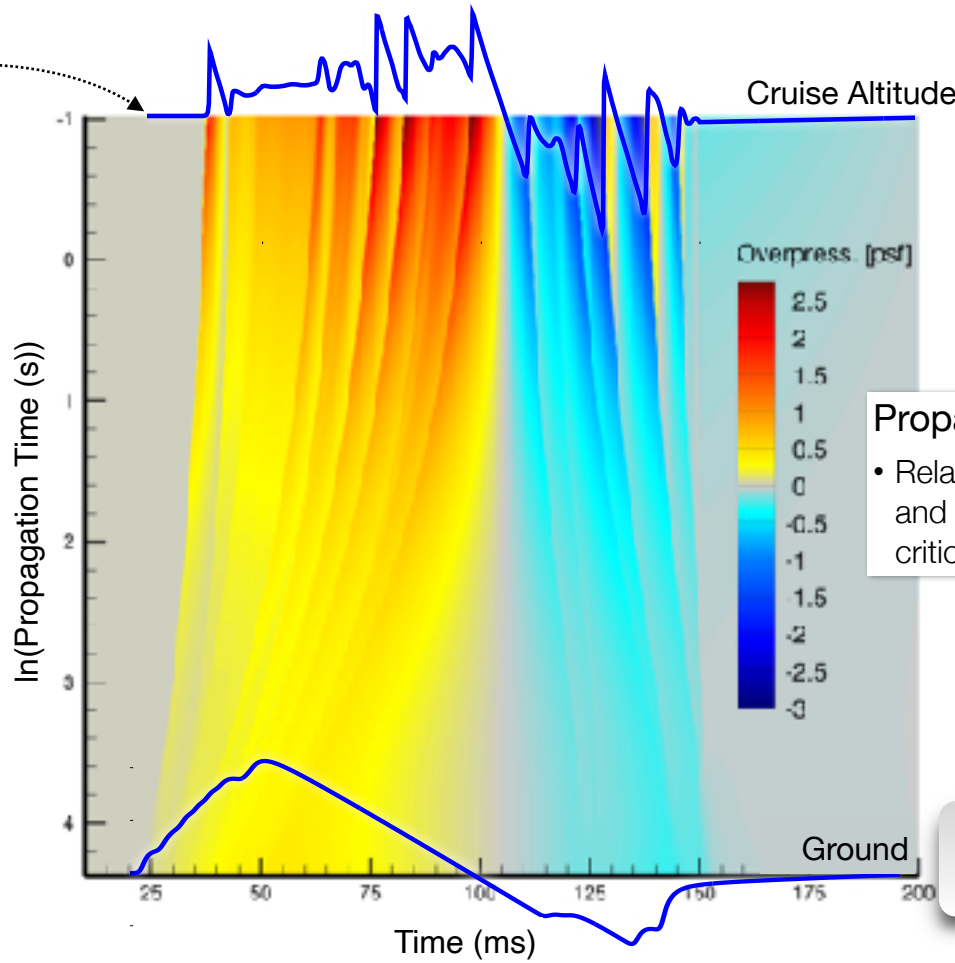
$$\mathbf{R}_F(\mathbf{Q}_N, \mathbf{Q}_F) = 0$$

- Includes nonlinearity, thermoviscous absorption and relaxation
- 2nd-order finite volumes: Godunov's flux, van Leer Limiter, RK2, uniform mesh

Ray tracing

- Atmospheric temperature profile and winds critical





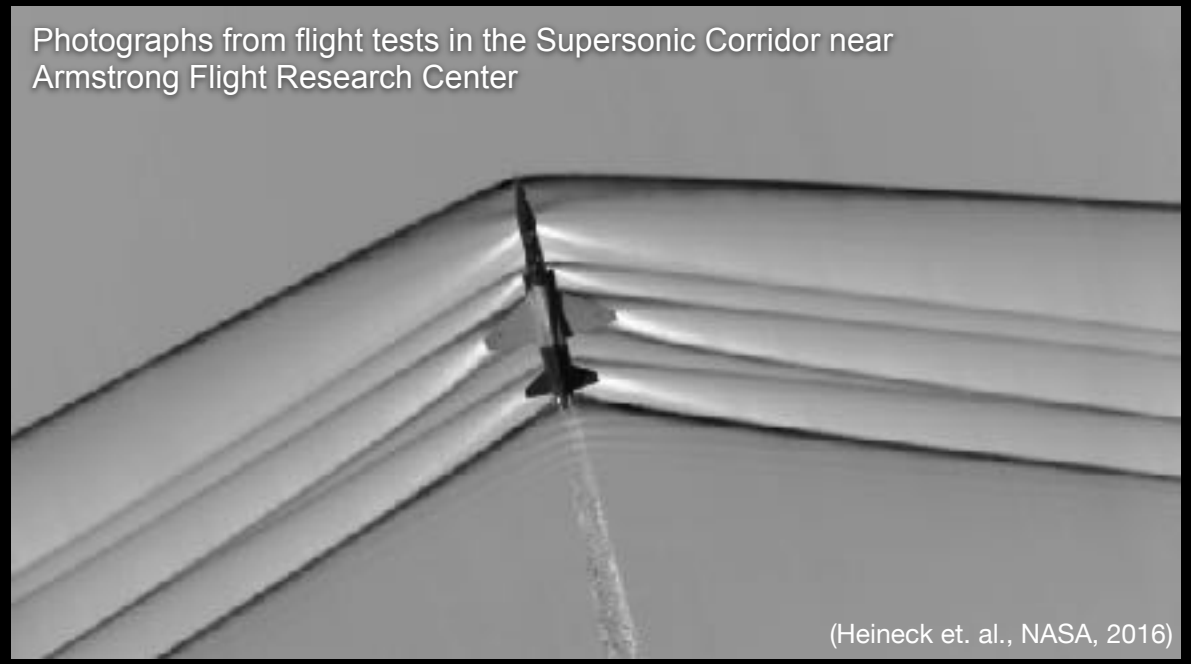
Propagation

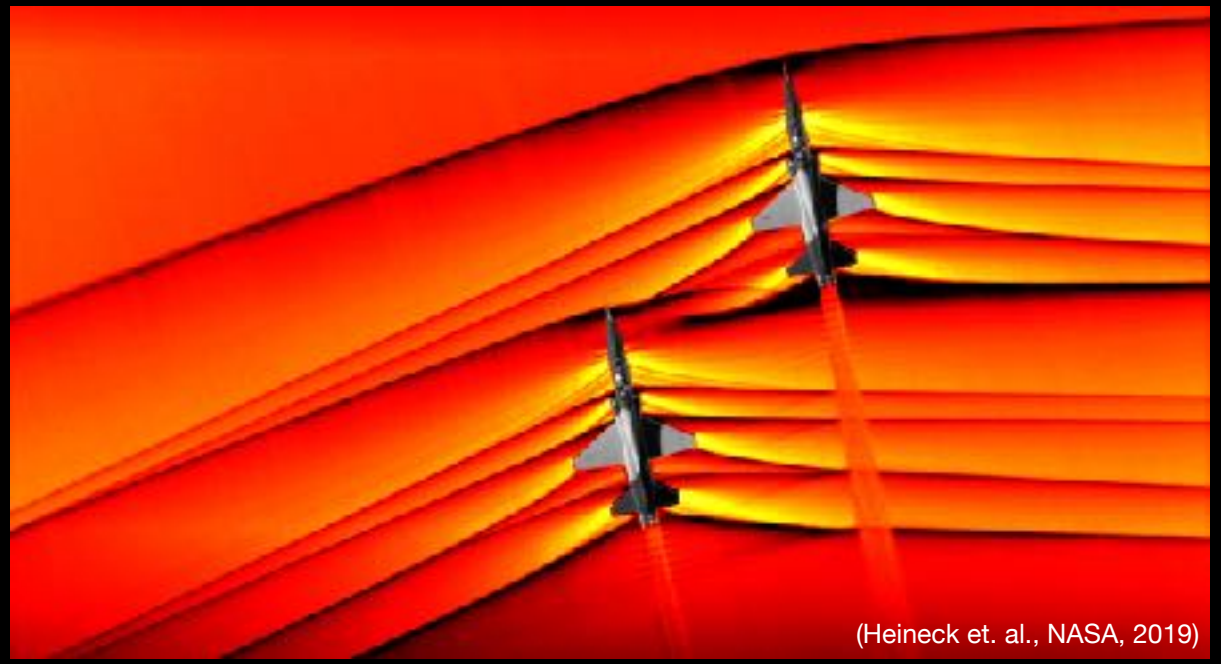
- Relative humidity and temperature critical

Noise Analysis
PL, ISBAP (dB)

Nearfield

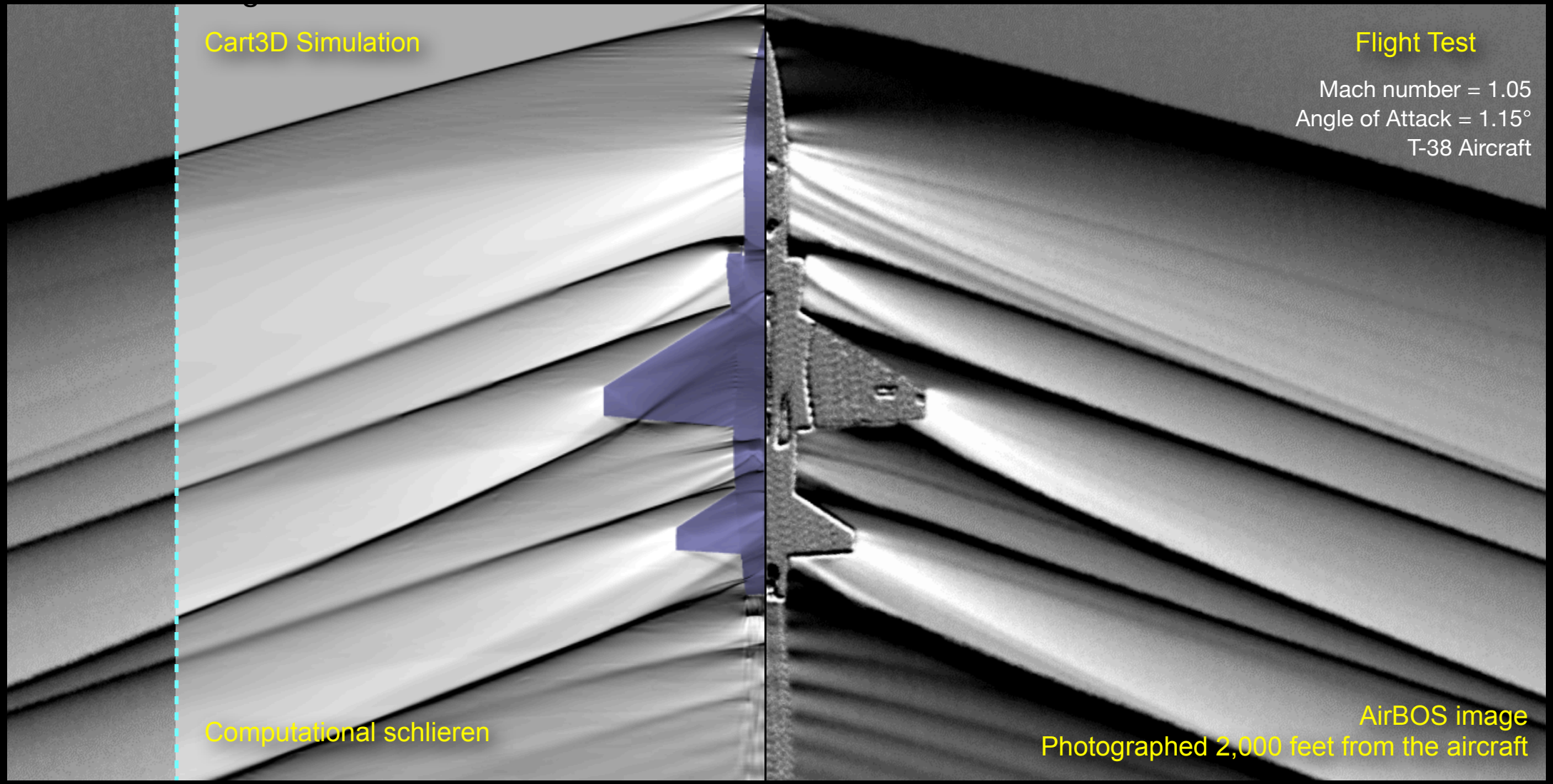
Schlieren Flow Visualization



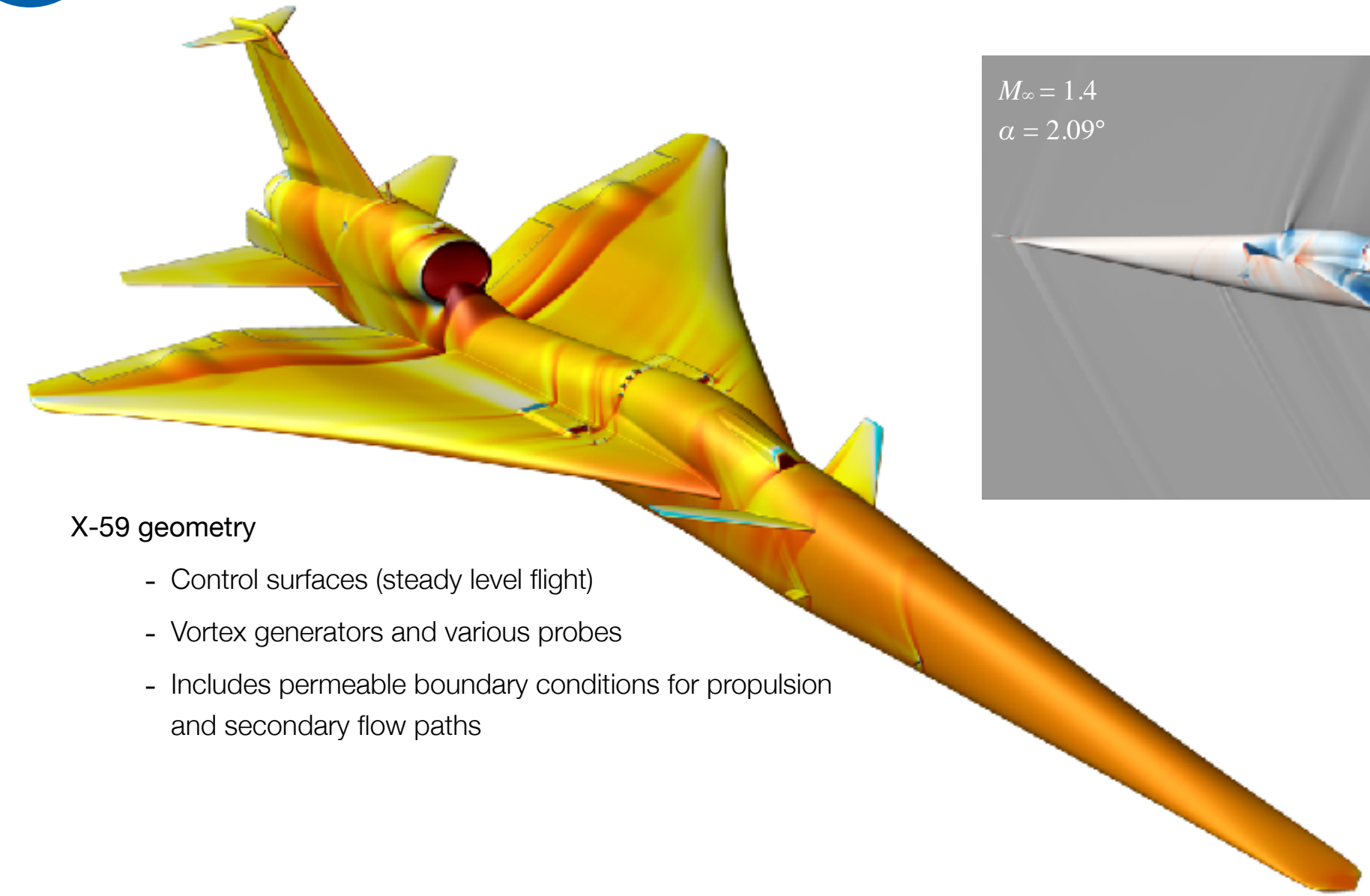


- Schlieren photographs are a well-established experimental technique
  - Visualization of density gradients, excellent for shocks
- New capability in Air-to-Air Background Oriented Schlieren (AirBOS) imaging
  - Allows schlieren imagery of aircraft in flight
  - Emerging technique for validating simulations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

Flight-Matching Computation

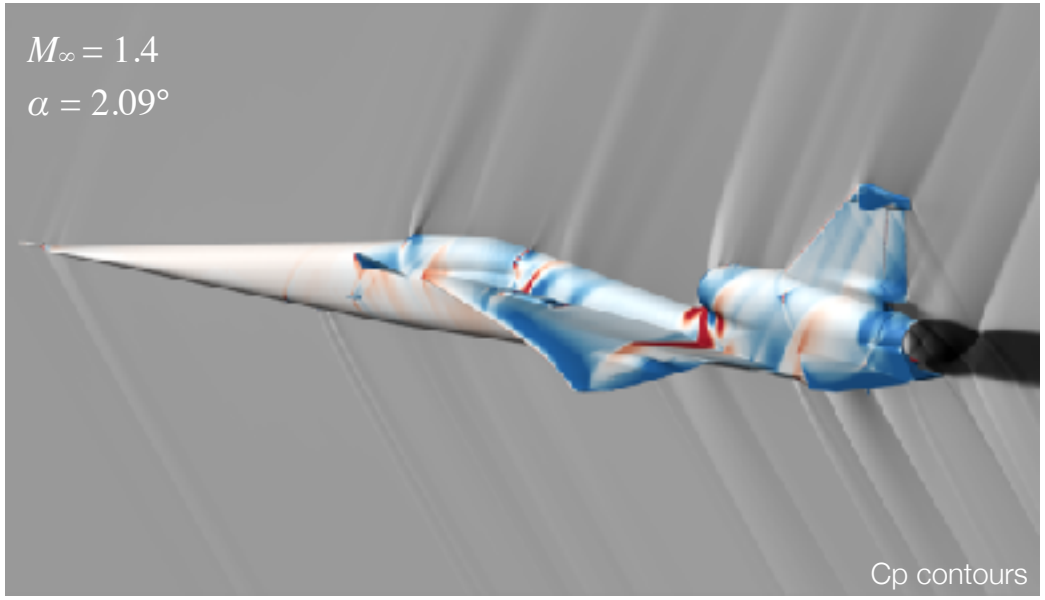


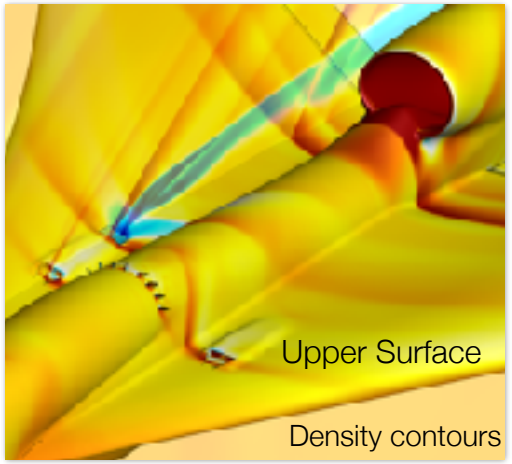
X-59 Loudness Analysis



X-59 geometry

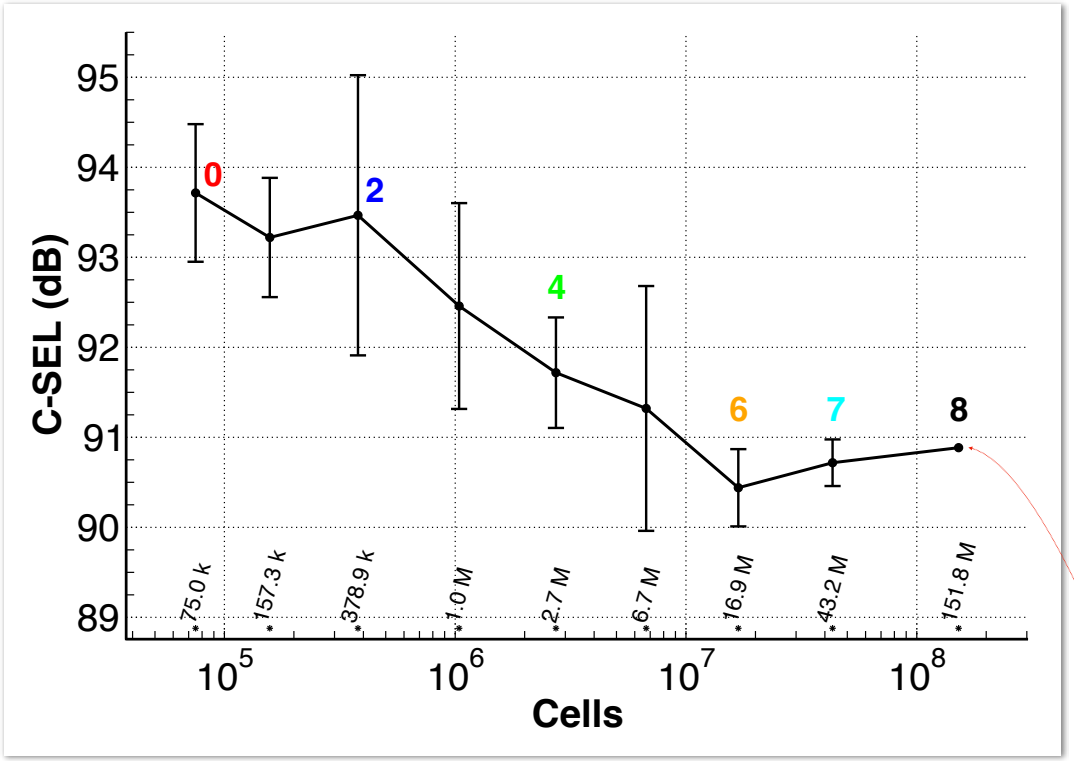
- Control surfaces (steady level flight)
- Vortex generators and various probes
- Includes permeable boundary conditions for propulsion and secondary flow paths

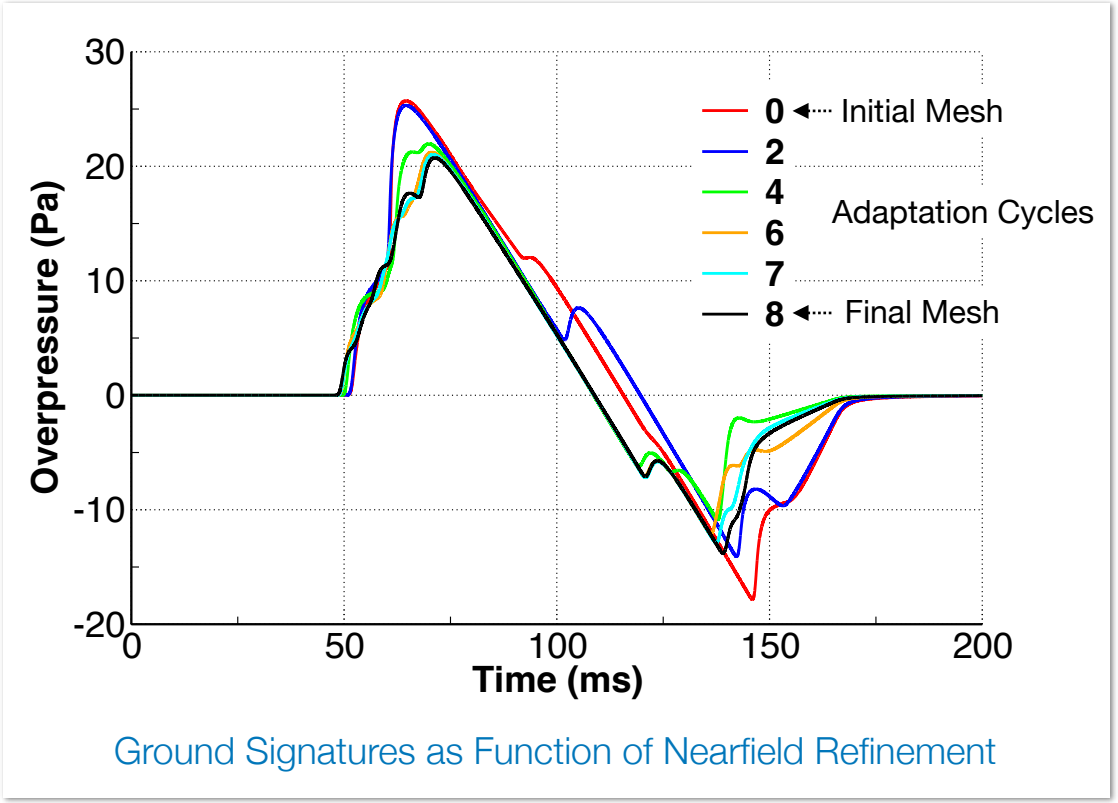




X-59 Loudness Analysis

- Coupled nearfield-farfield simulation
- Altitude 53,200 ft, standard atmosphere, no wind
- Quantity of Interest: C-SEL noise metric

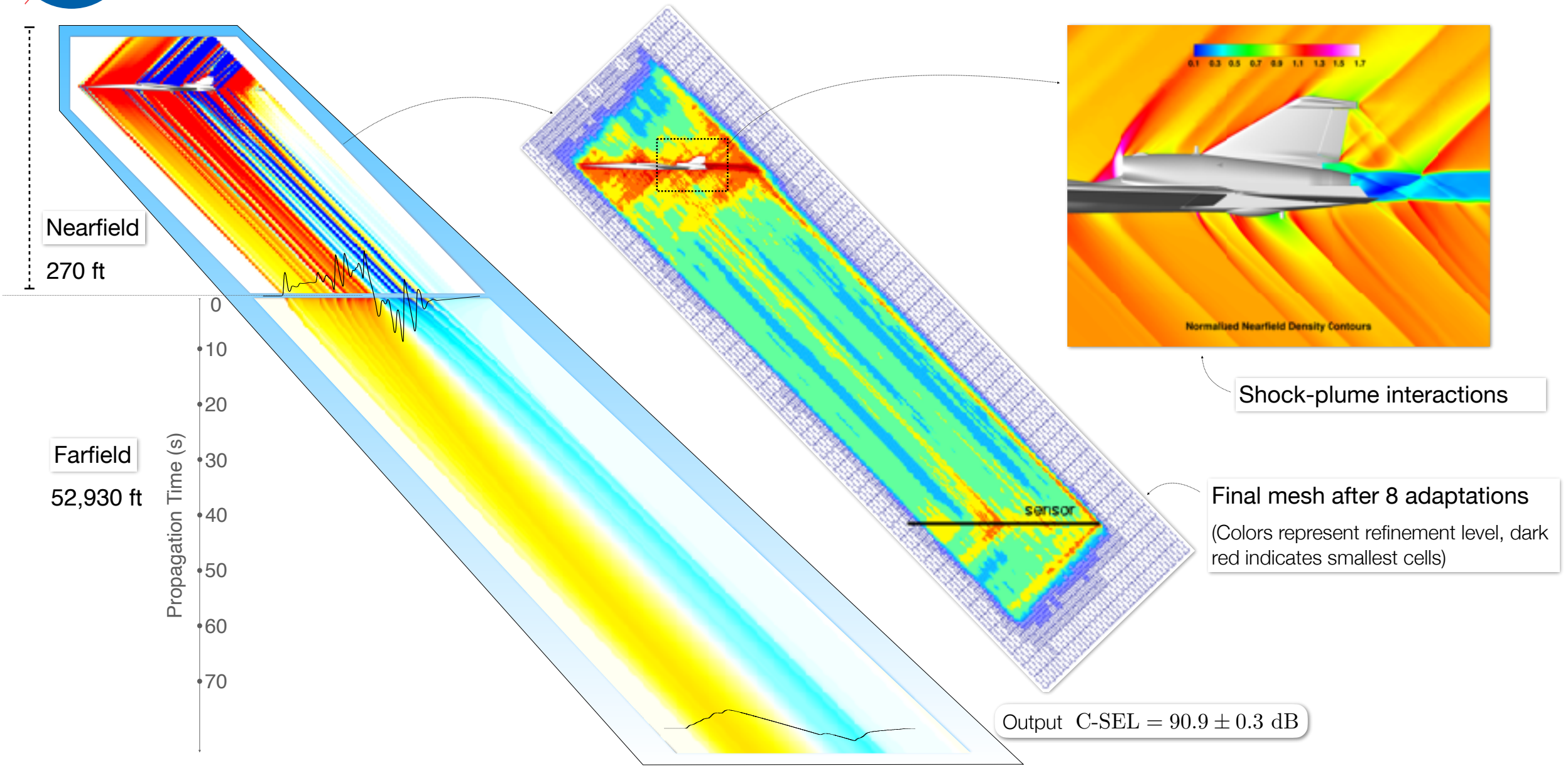




Ground Signatures as Function of Nearfield Refinement

Simulation predicts C-SEL noise level of 90.9 dB on the ground with discretization error level of ±0.3 dB

X-59 Loudness Analysis



Shock-plume interactions

Final mesh after 8 adaptations

(Colors represent refinement level, dark red indicates smallest cells)

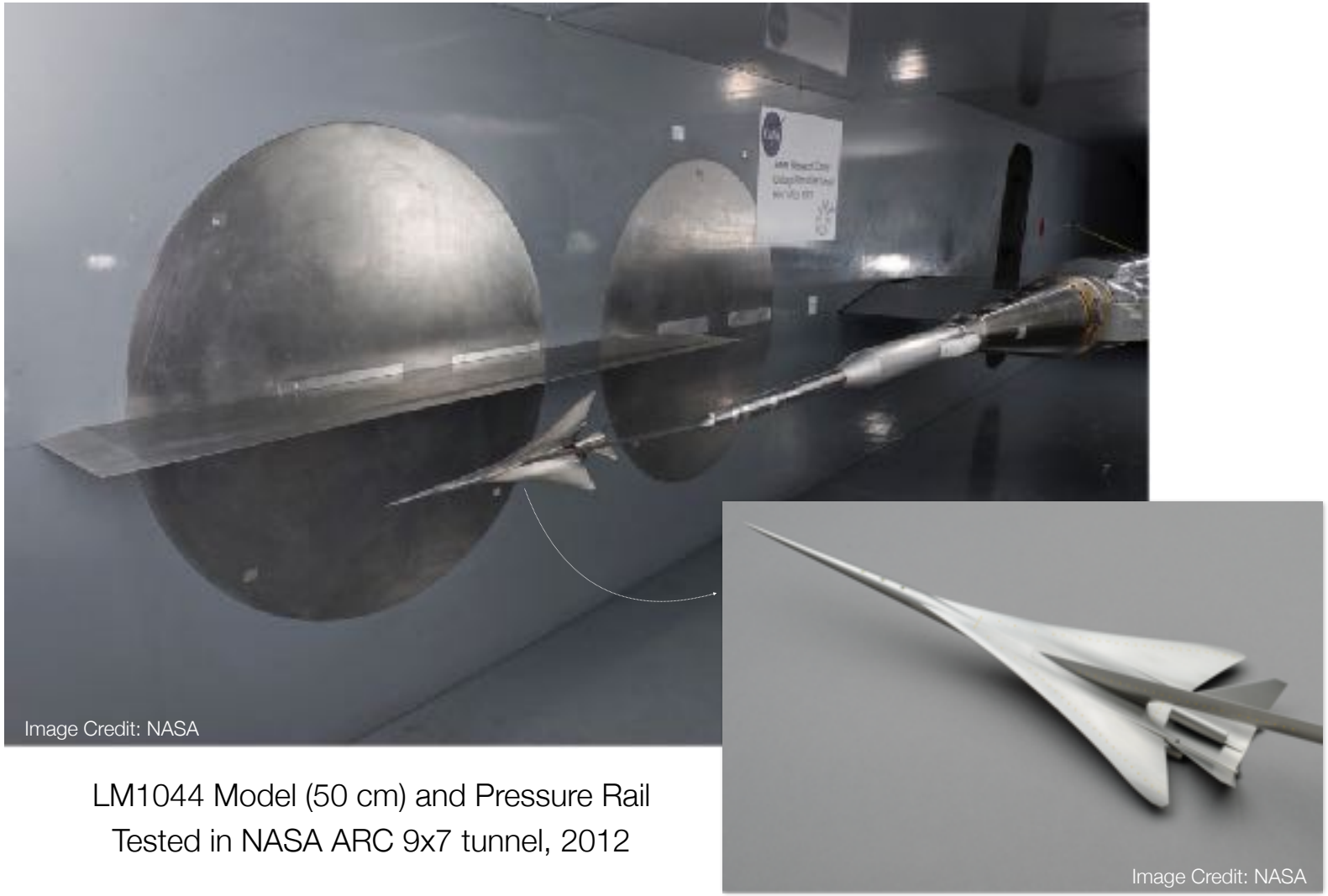
Output $\text{C-SEL} = 90.9 \pm 0.3$ dB

Prediction of Nearfield Signatures

Comparing Predictions with Wind Tunnel Measurements

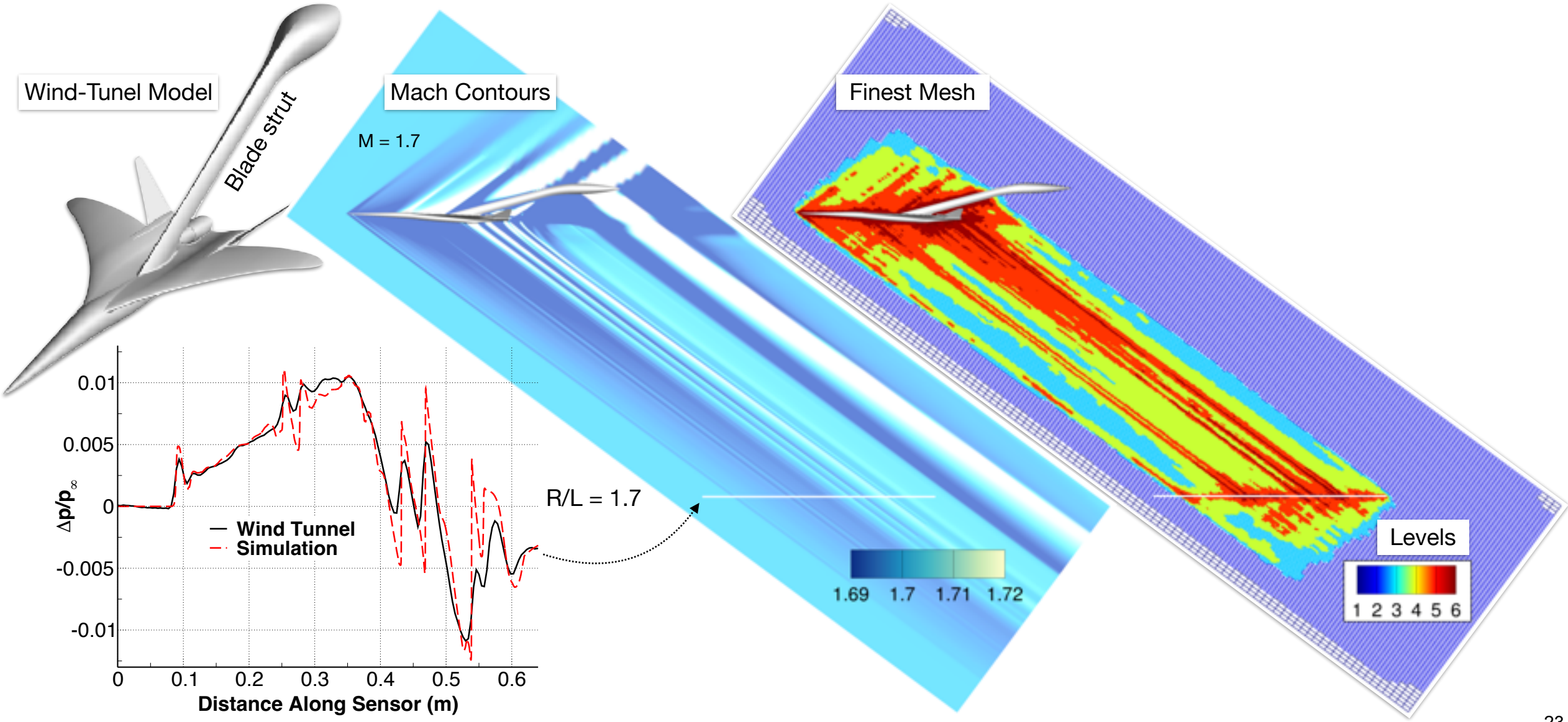


Early supersonic model: XB-70, 2.5 cm,
NASA LaRC 4x4 tunnel, 1963



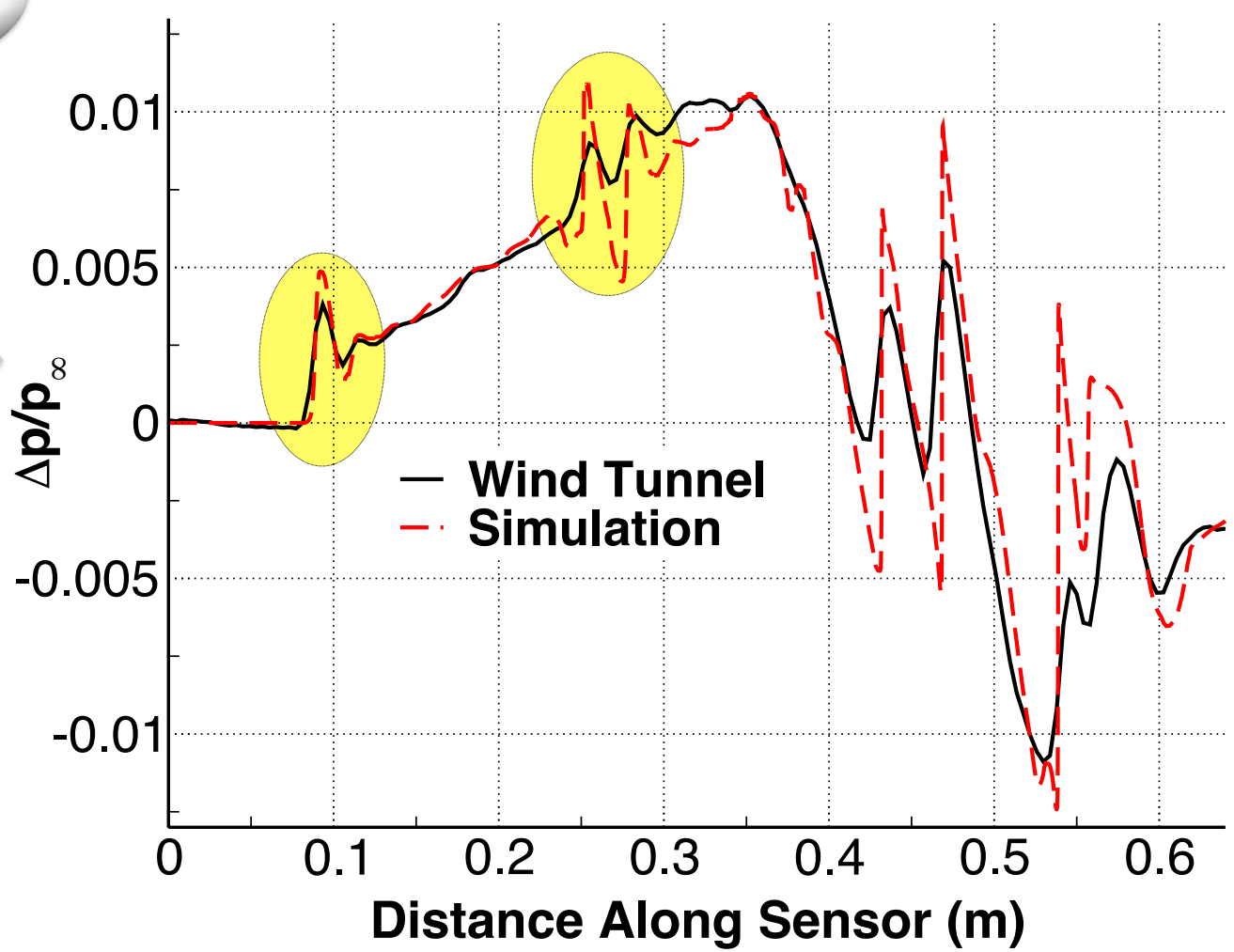
LM1044 Model (50 cm) and Pressure Rail
Tested in NASA ARC 9x7 tunnel, 2012

Prediction of Nearfield Signatures



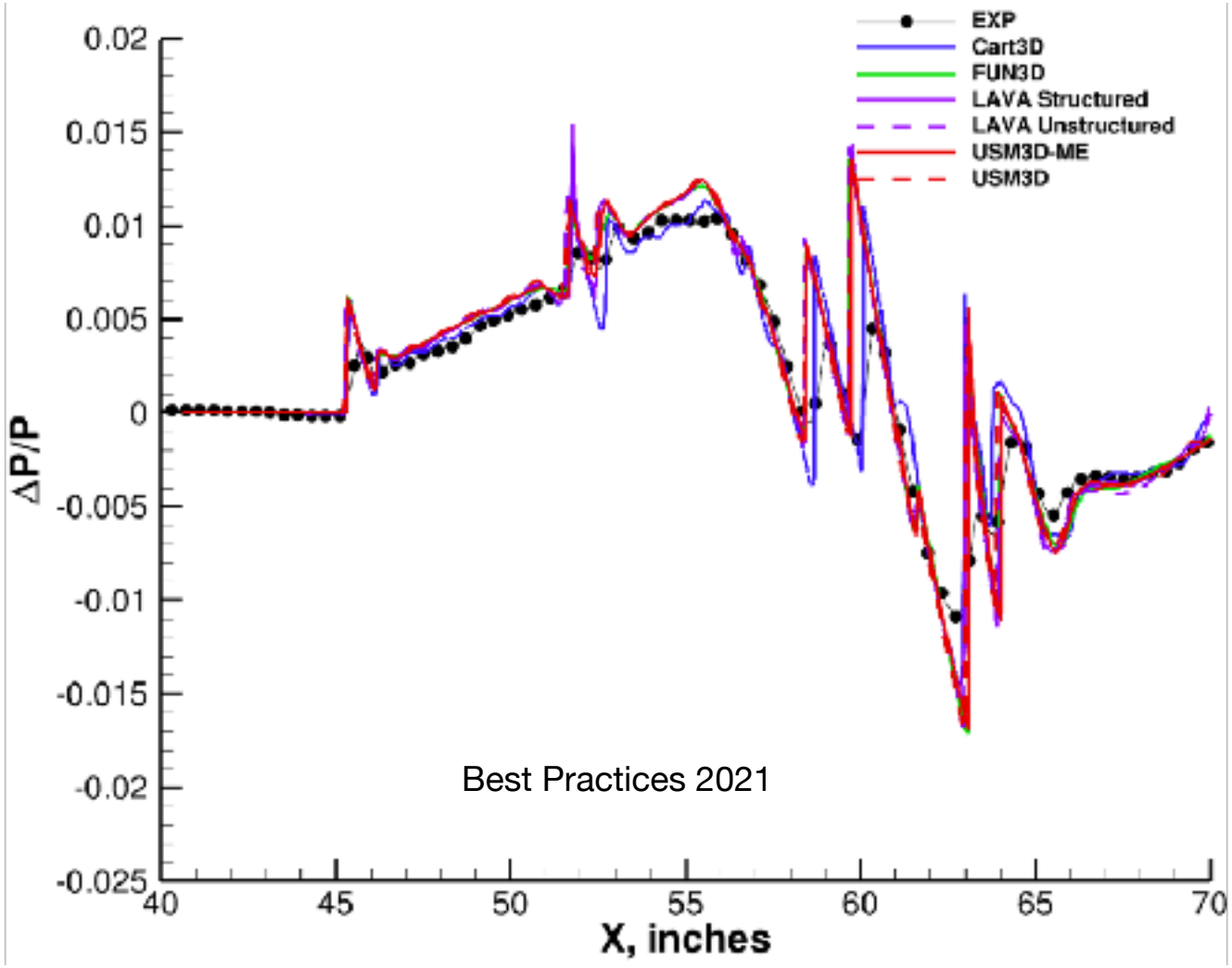
Prediction of Nearfield Signatures





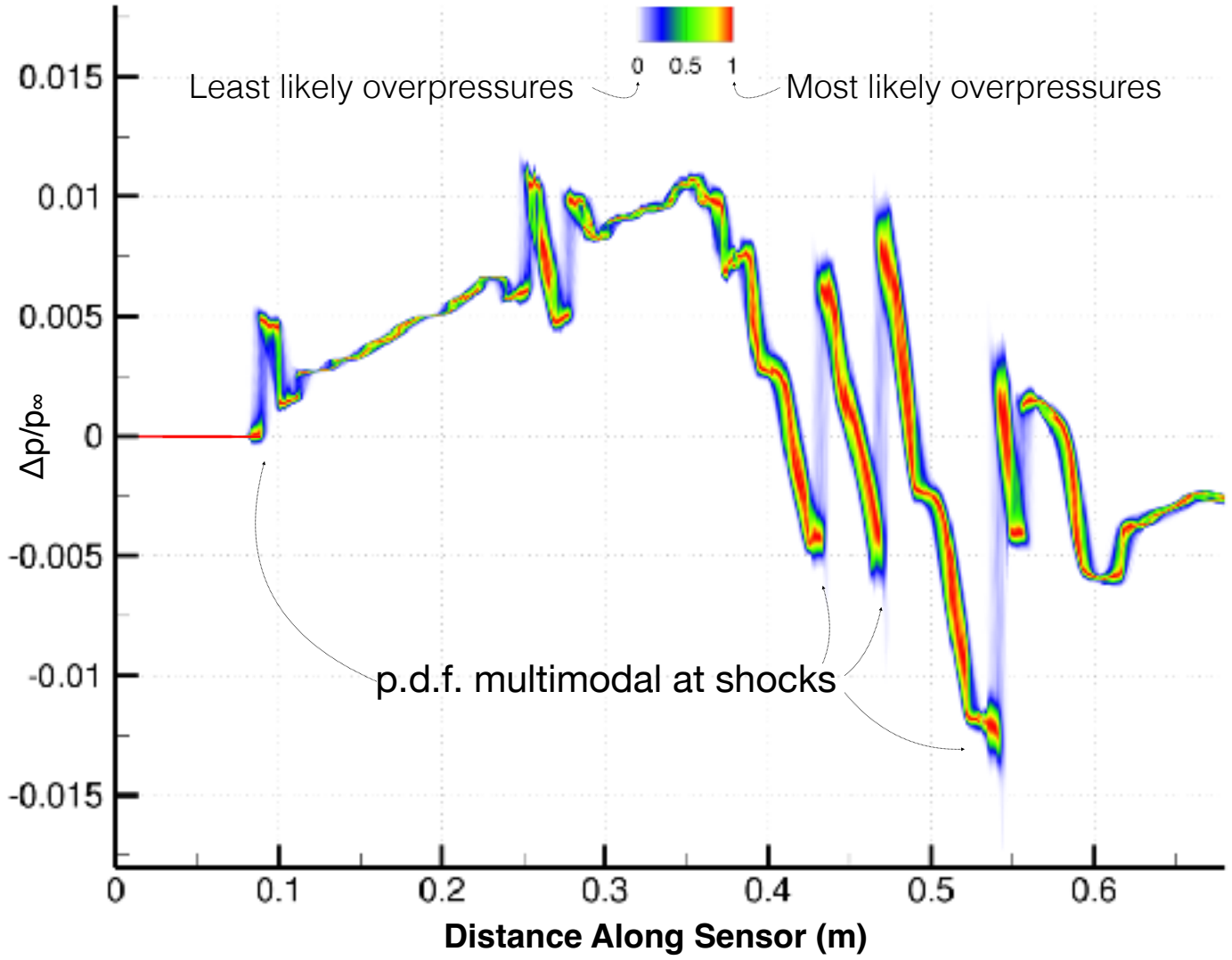
- Comparison of wind tunnel measurements to deterministic simulation reveals significant discrepancies starting at the leading shock, through the rooftop and the recovery region
- Predicted signature misses shock amplitude and rise time

Nearfield Signature UQ



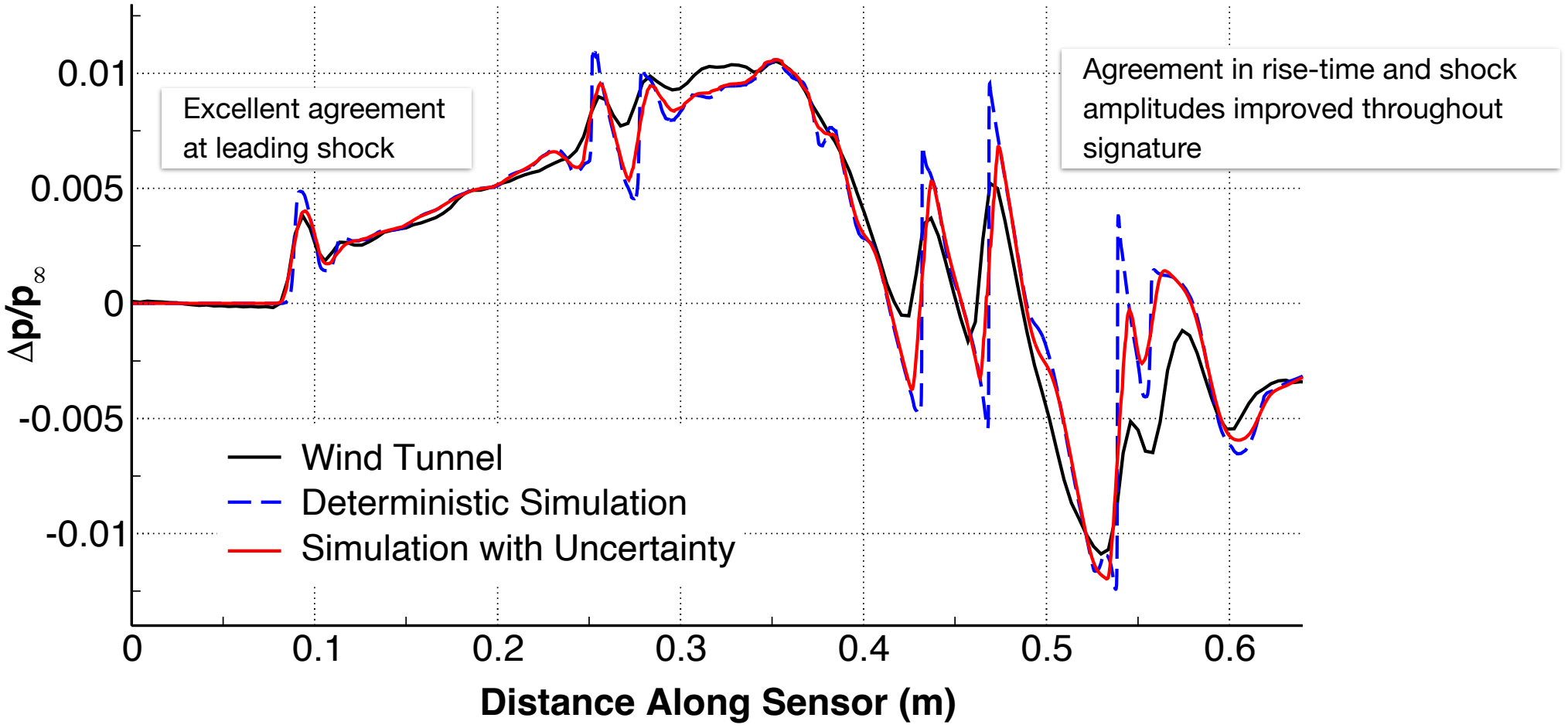
- Consistent predictions between codes
- Higher modeling fidelity does not significantly improve agreement with measurements
- All predicted signatures miss shock amplitude and rise time

Signature Probability Density Function



- p.d.f. provides complete characterization of uncertainty
- computed from the same database (81 realizations) as moment statistics

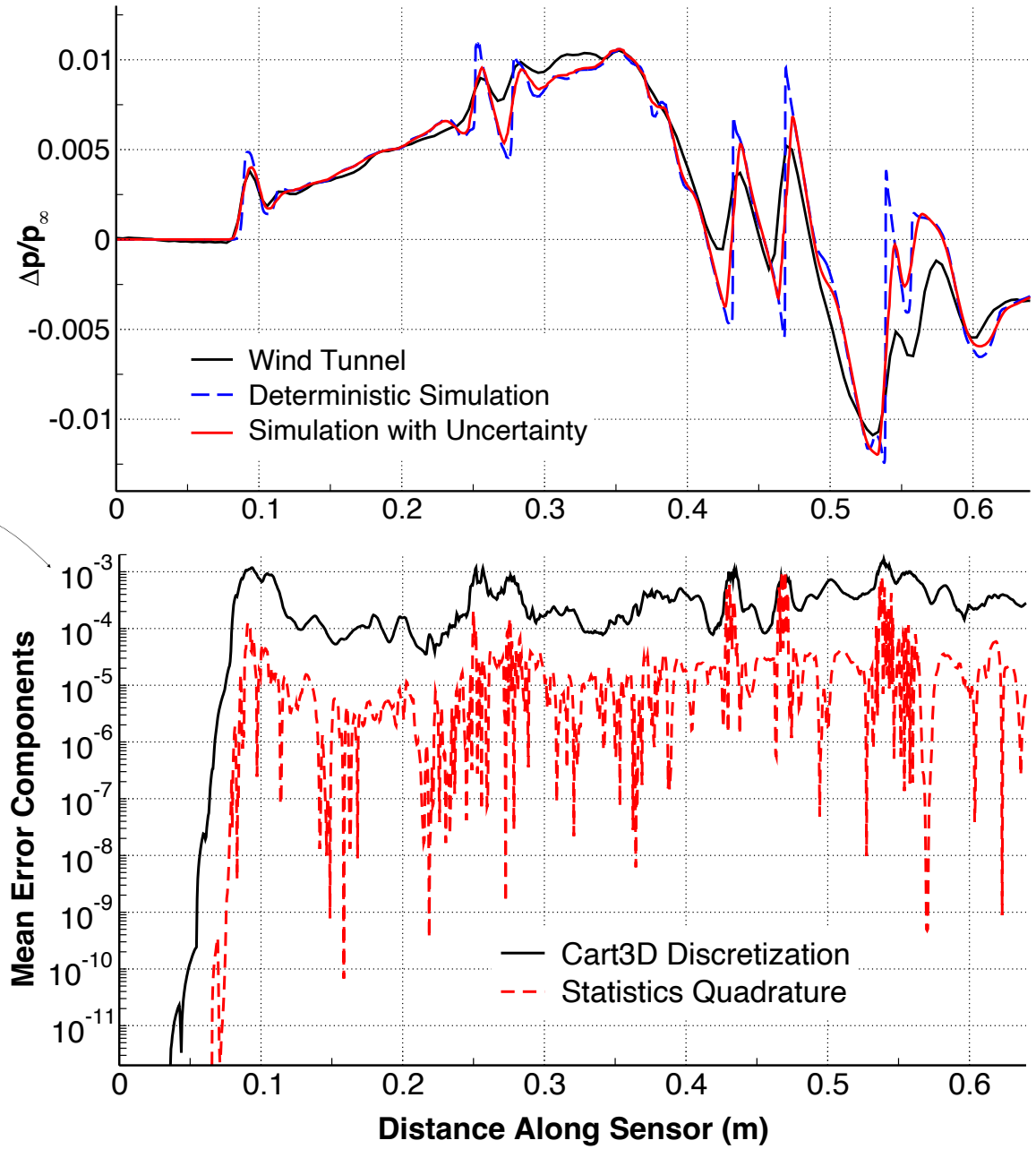
Comparison of Mean Signatures



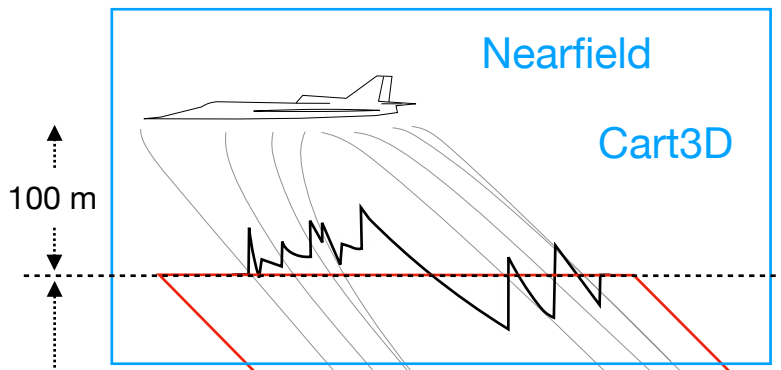
Error Assessment

Error Decomposition for Mean Signature

- Error distributions peak at shocks
- Discretization error from Cart3D simulations is approximately order-of-magnitude larger than error from statistics quadrature
  - Reducing CFD discretization error (increasing mesh refinement) is more important than increasing the number of quadrature points
  - Control of numerical errors critical for bounding model-form error

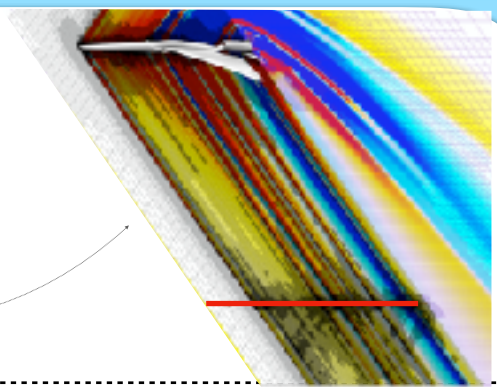


Approach: Nearfield-Farfield Decomposition

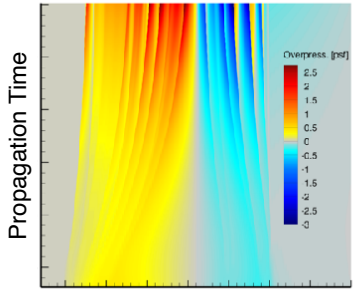


3D effects important

- Aircraft shape
- Inlets, ducts, engine plumes
- Steady, 3D CFD

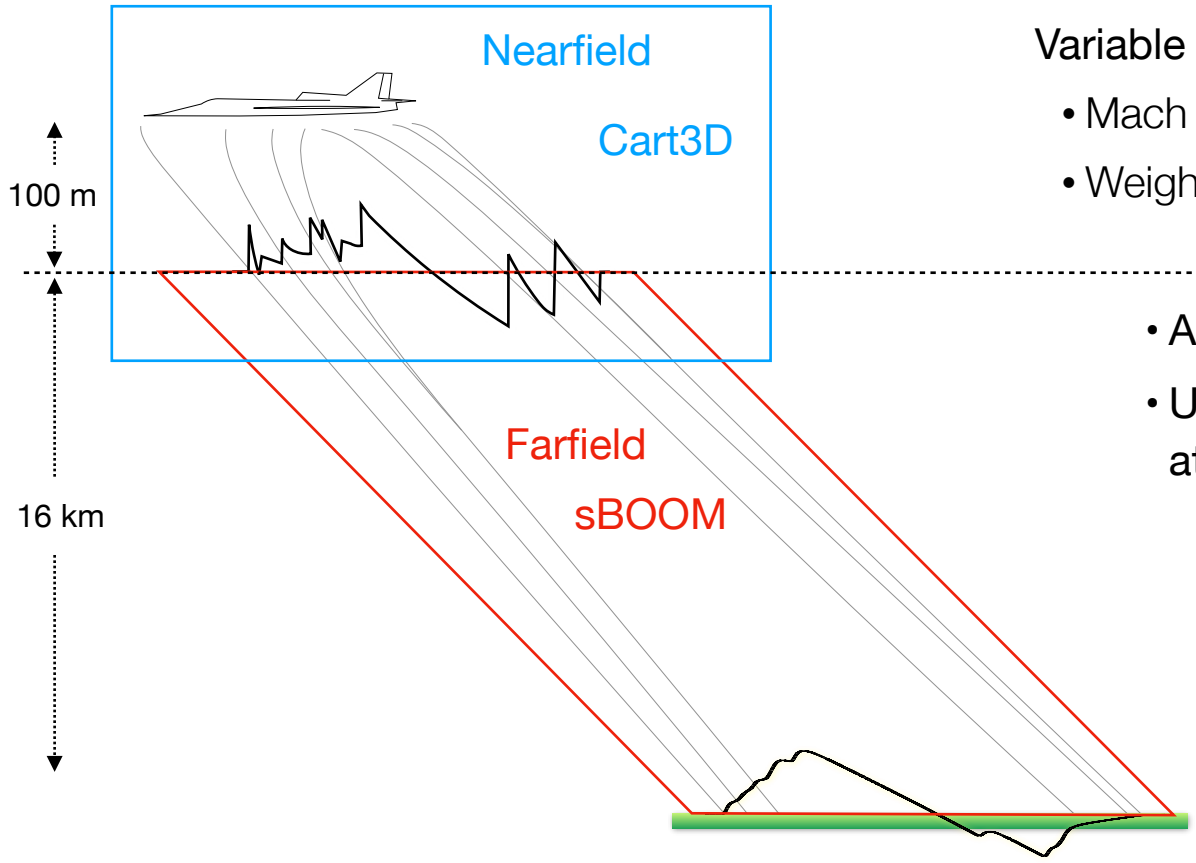


- Stratification
- Absorption
- Winds
- Geometric acoustics
- Augmented Burgers' equation



Noise Analysis
PL, ISBAP (dB)

Sources of Uncertainty



Variable flight conditions

- Mach Number
- Weight

- Altitude
- Uncertain state of atmosphere
  - Temperature
  - Relative Humidity
  - Wind

Atmospheric Observations

Current focus is on variability in atmospheric profiles at Edwards AFB

- Location for X-59 acoustic validation flights

Database of atmospheric profiles from European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5)

- Selected observations from 2003 to 2022
- Selected August at 18:00 UTC (10 am PT)

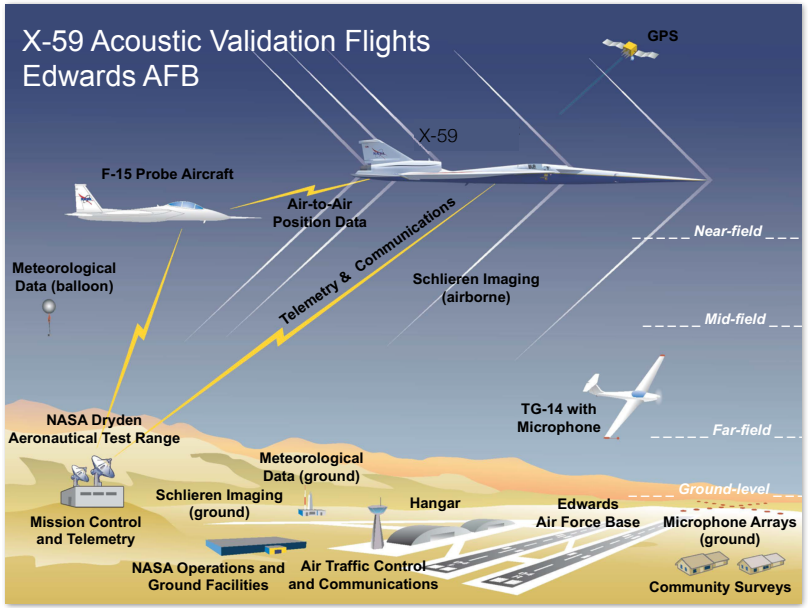
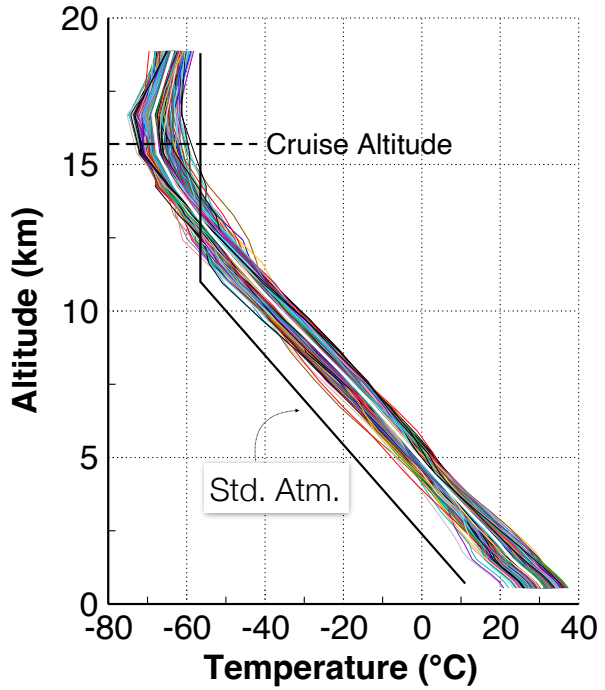
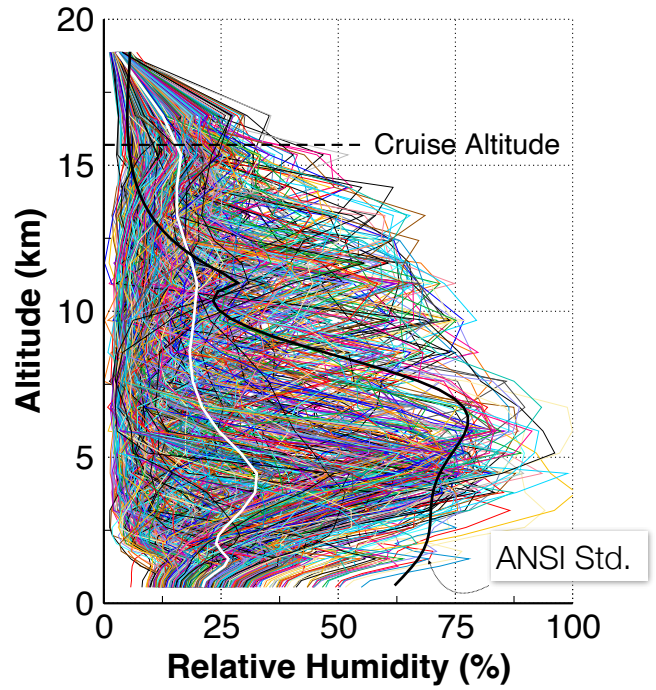


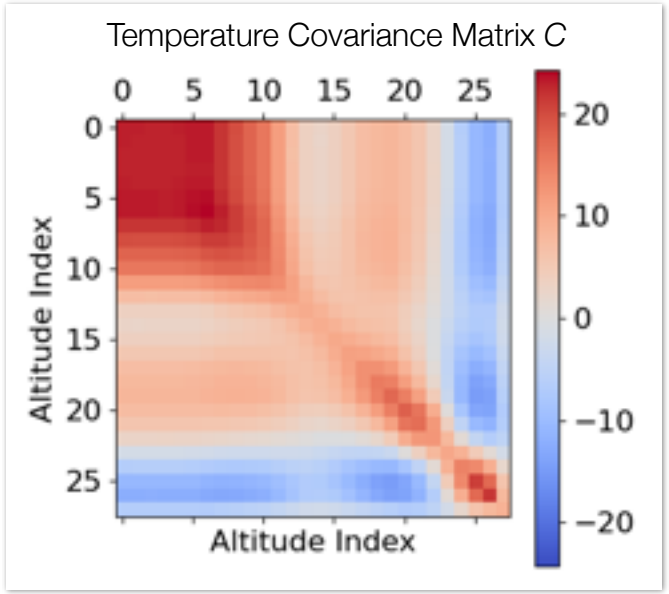
Image Credit: NASA

Edwards AFB
18:00 UTC (10 am PT)
ERA5 Dataset 2003 - 2022
620 profiles





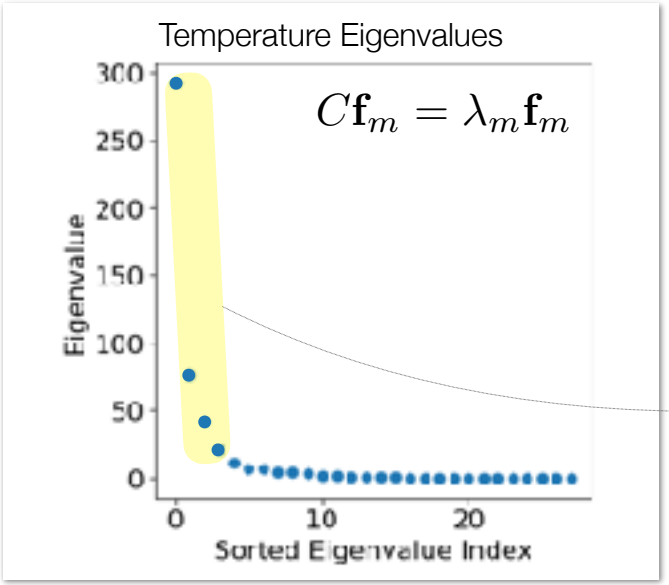
Parameterization of Atmospheric Profiles



Observed Temperature Profiles

Challenge is to accurately and efficiently model stochastic fluctuations in the atmosphere

- Atmospheric profiles are correlated fields → we need independent random variables
- Karhunen-Loeve expansion is used to model uncertainty in atmospheric data
- Main idea is to use the covariance of the observed data to anchor the parameterization
  - Diagonalize discrete covariance matrix
  - Select largest eigenvalues to model fluctuations in atmospheric properties

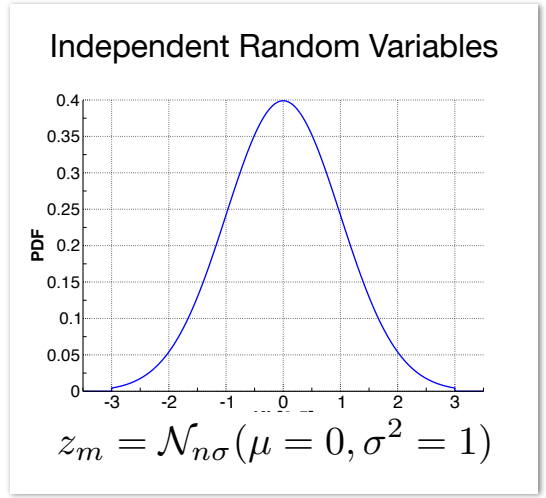


M largest eigenvalues of covariance matrix *C*

Discrete random-process temperature profile

$$\mathbf{T}(\xi) = \bar{\mathbf{T}} + \sum_{m=1}^{M} z_m(\xi)\sqrt{\lambda_m}\mathbf{f}_m$$

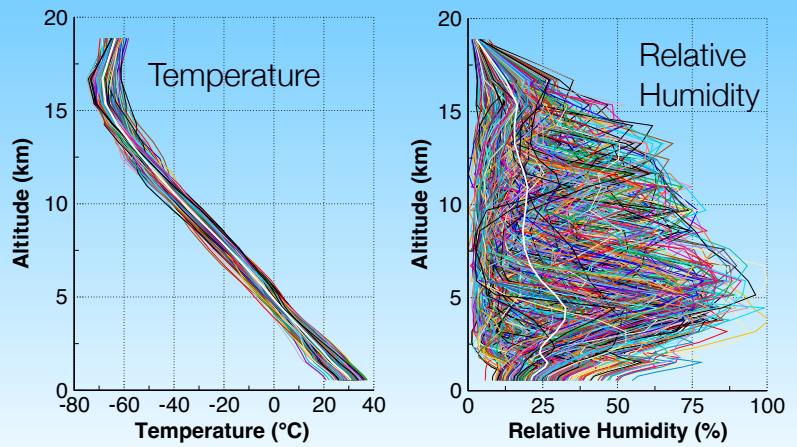
Mean from observed data



Temperature and Dew-Point Temperature System

Edwards AFB ERA5 Data

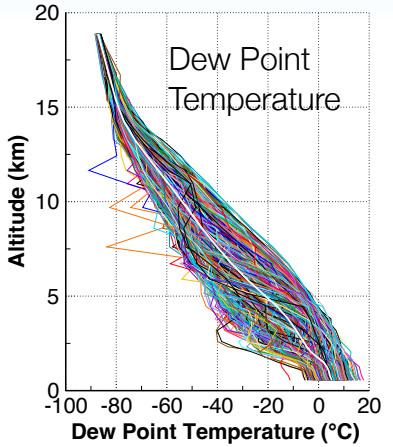
18:00 UTC (10 am PT), August, 2003-2022



Relative Humidity to Dew Point Temperature Transformation

$$\mathbf{T}_{\mathrm{dp}} = f(\mathbf{T}, \mathbf{RH})$$

$$\mathbf{w} = \begin{bmatrix} \mathbf{T} \\ \mathbf{T}_{\mathrm{dp}} \end{bmatrix}$$



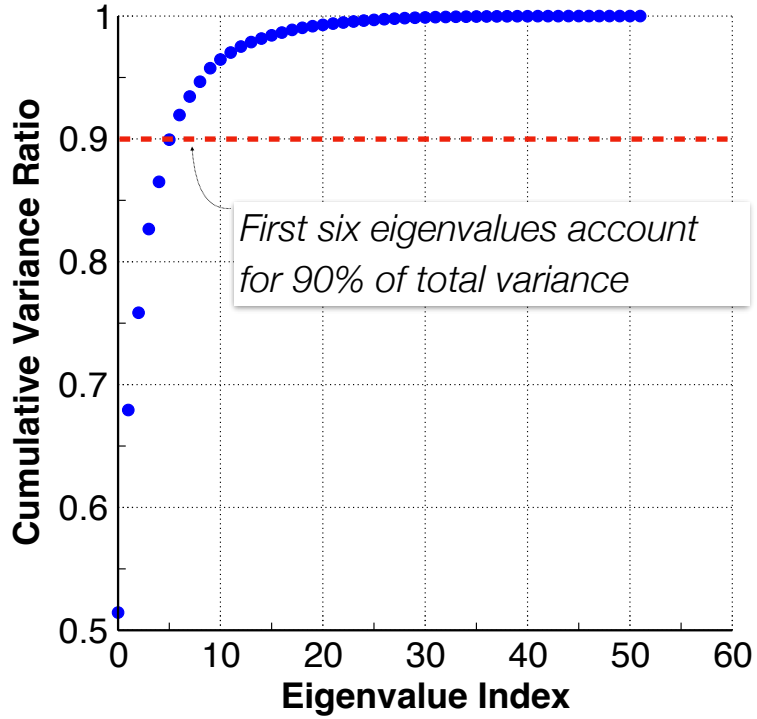
1. Determine how many terms of the KL expansion are required

$$\widetilde{\mathbf{w}}_k = \boldsymbol{\mu}(\mathbf{w}) + \sum_{i=1}^{M} \xi_i(\omega)\sqrt{\lambda_i}\boldsymbol{\phi}_i$$

Choose $m < M$ such that Cumulative Variance Ratio

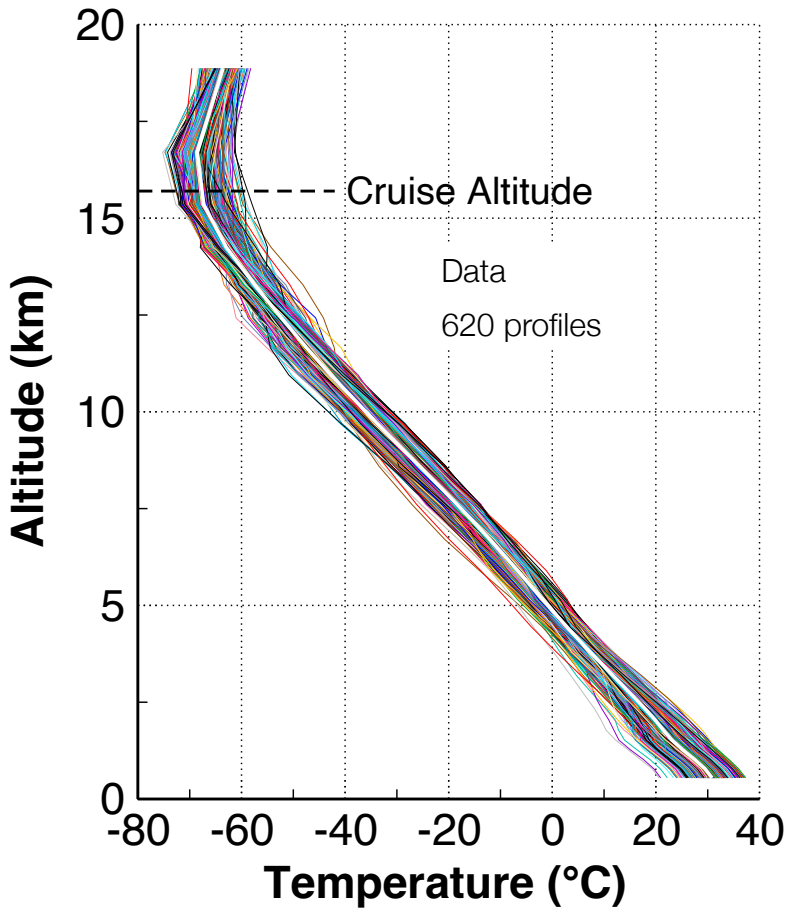
$$V_{\mathrm{CR}} = \frac{\sum_{i=1}^{m} \lambda_i}{\sum_{i=1}^{M} \lambda_i}$$

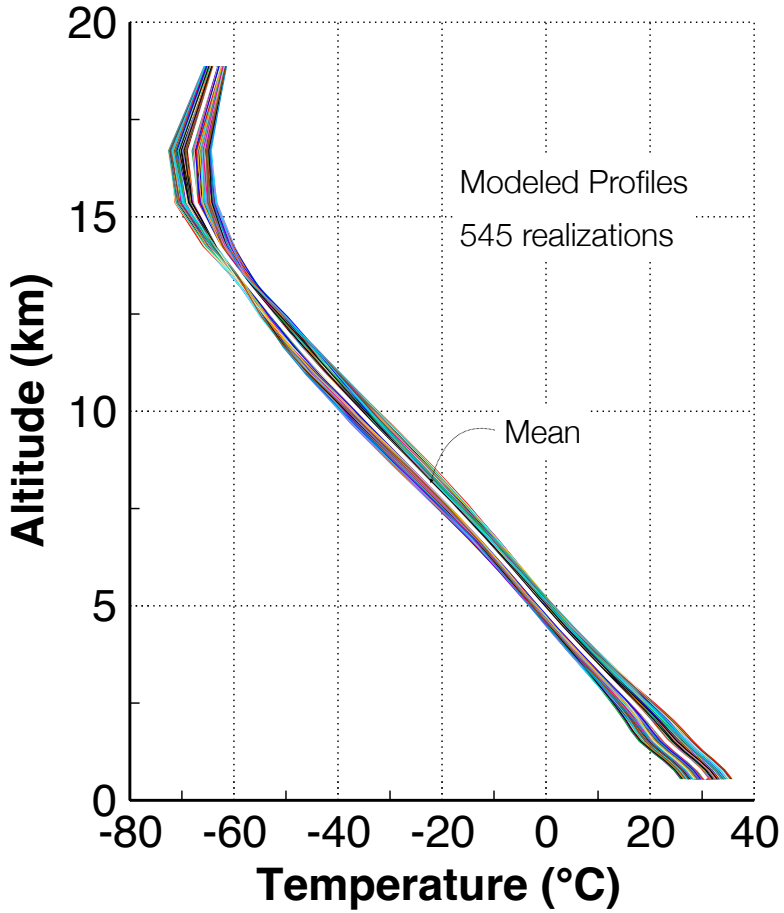
exceeds desired threshold



2. Check fidelity of the truncated **KL*m*** expansion

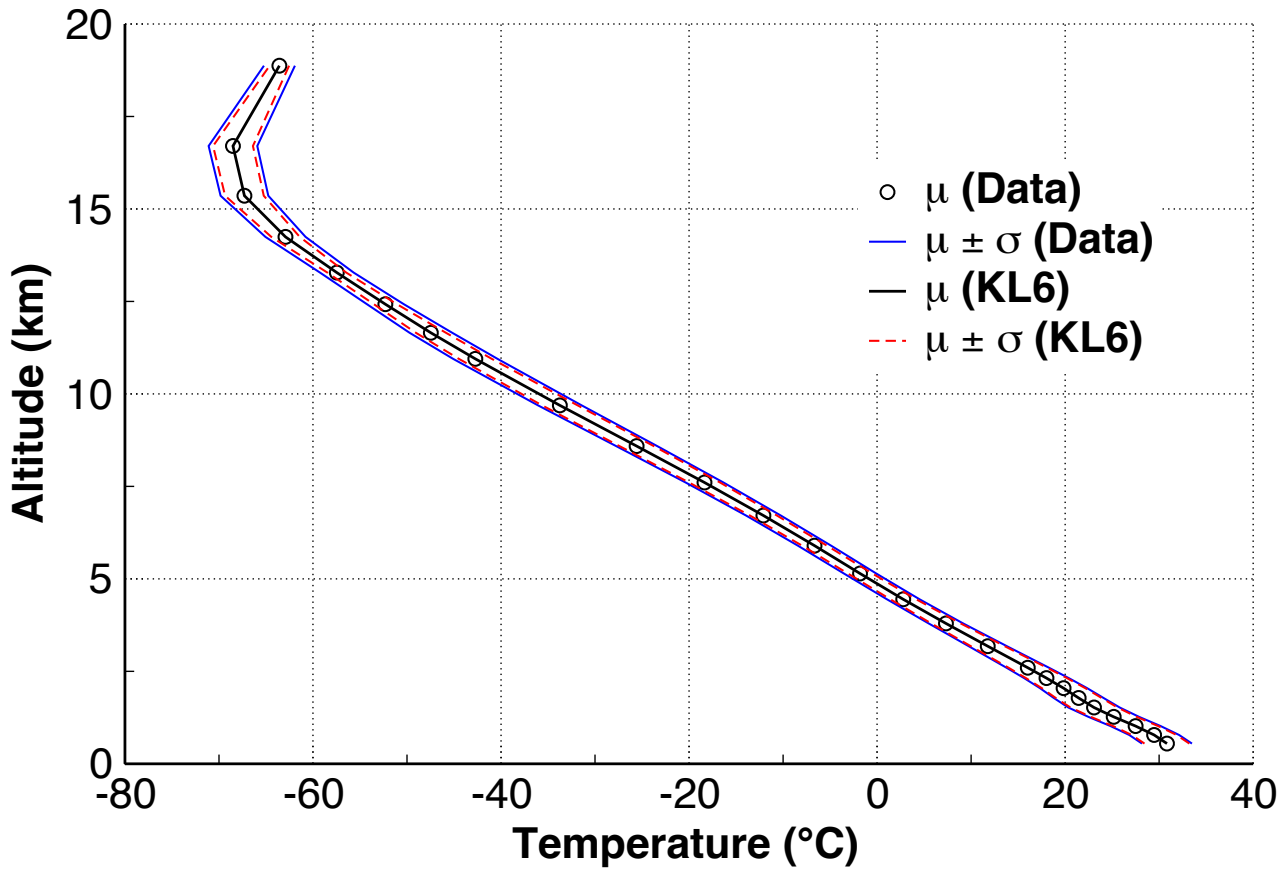
Observed and Modeled Temperature Profiles





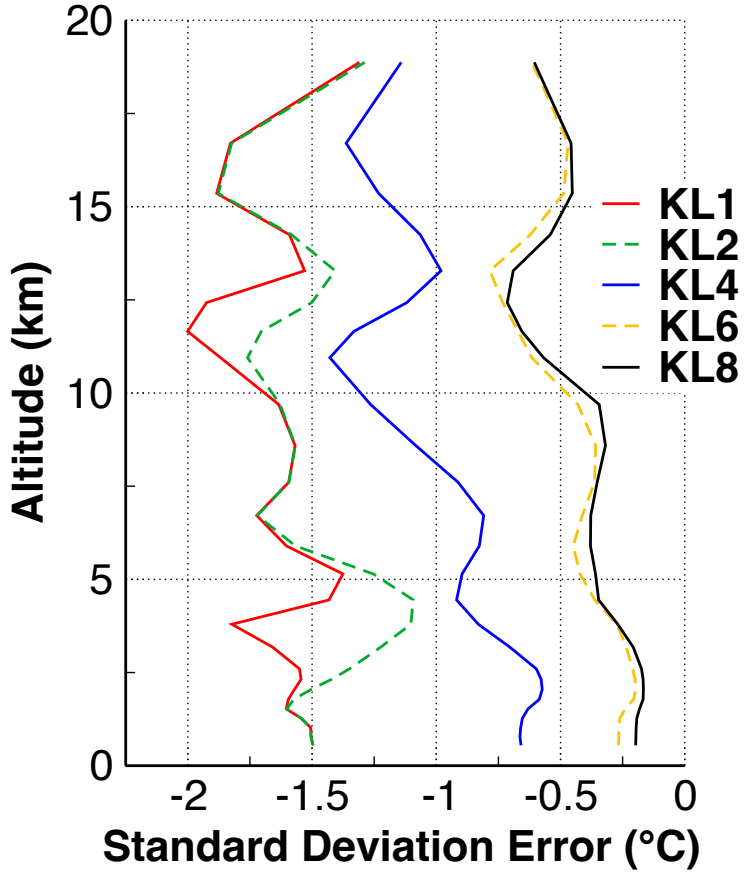
- KL6 expansion
- Good agreement between modeled and measured profiles
  - Infrequent outliers not sampled well
  - Excellent agreement near the mean

Errors in Temperature Statistics



Mean profiles agree exactly (by construction)

KL6 standard deviation errors are small

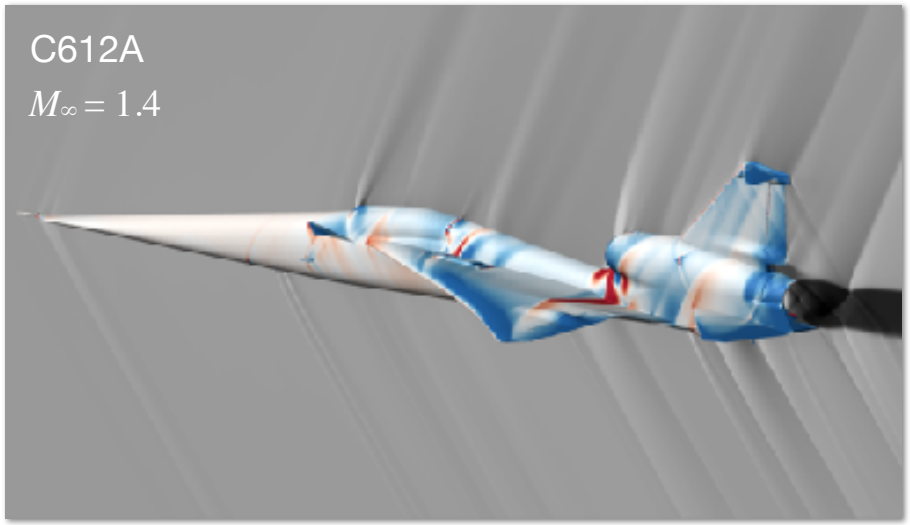


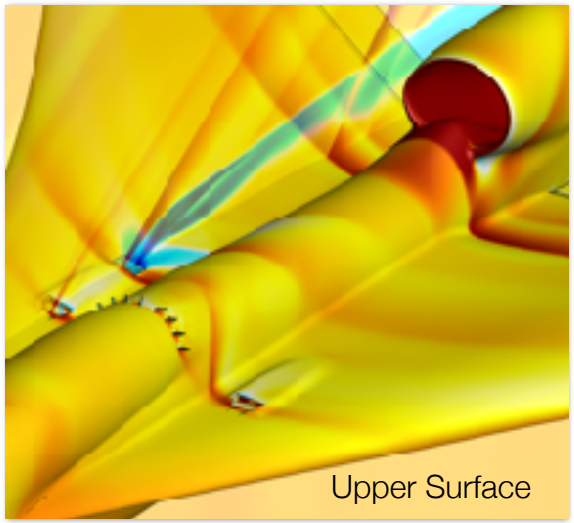
Error in standard deviation decreases as number of terms is increased

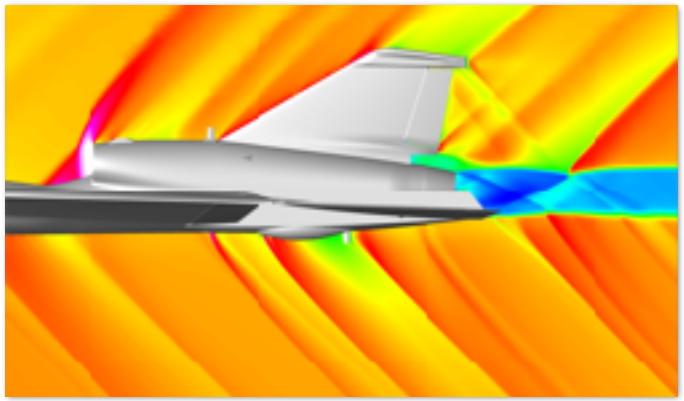
Propagation through Uncertain Atmosphere

Characterize uncertainty in ground signature and loudness due to uncertainty in the atmosphere

- KL6 parameterization of T and RH profiles
  - 6 independent random variables
- Assume flights at Edwards AFB in August, around 10 am PT

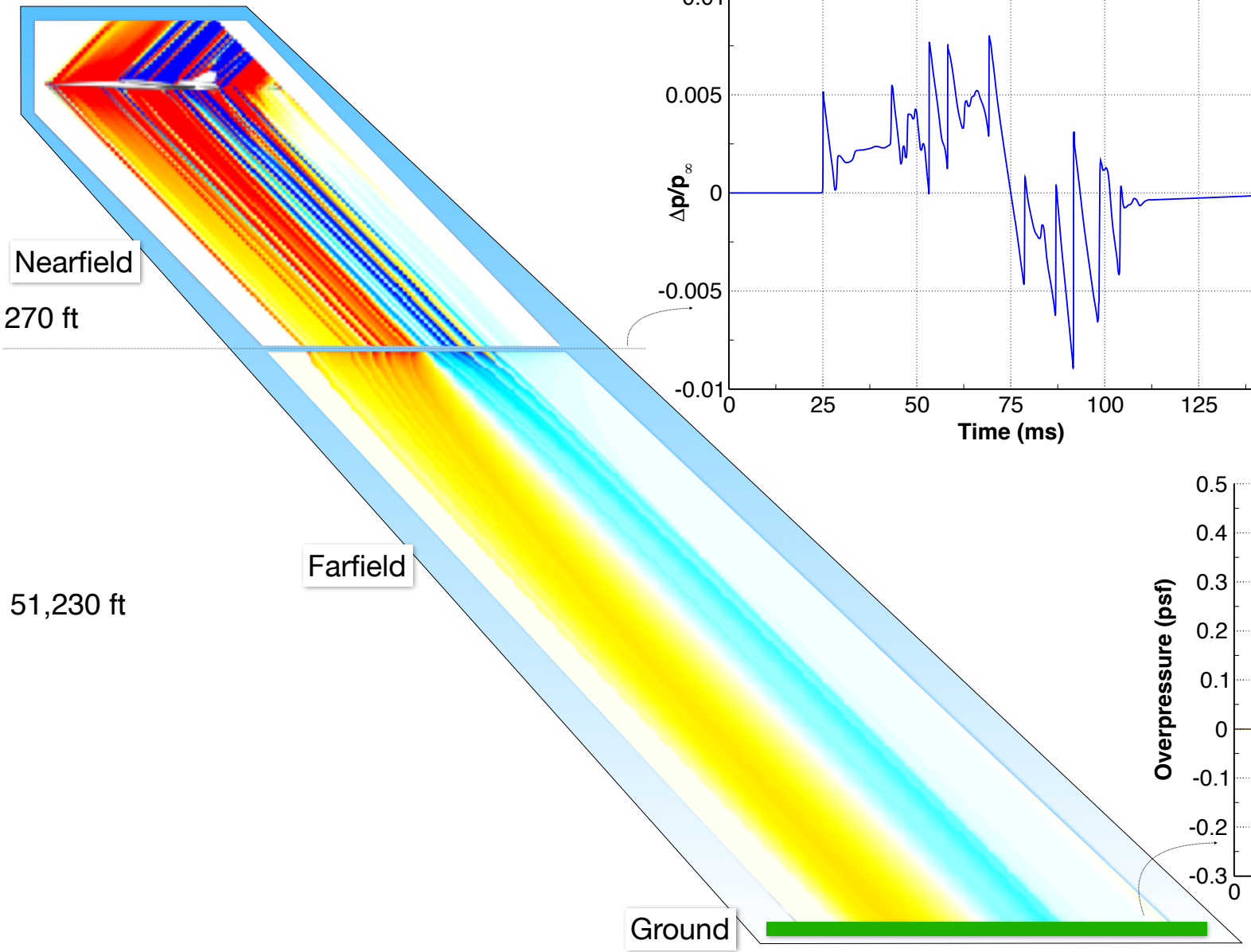




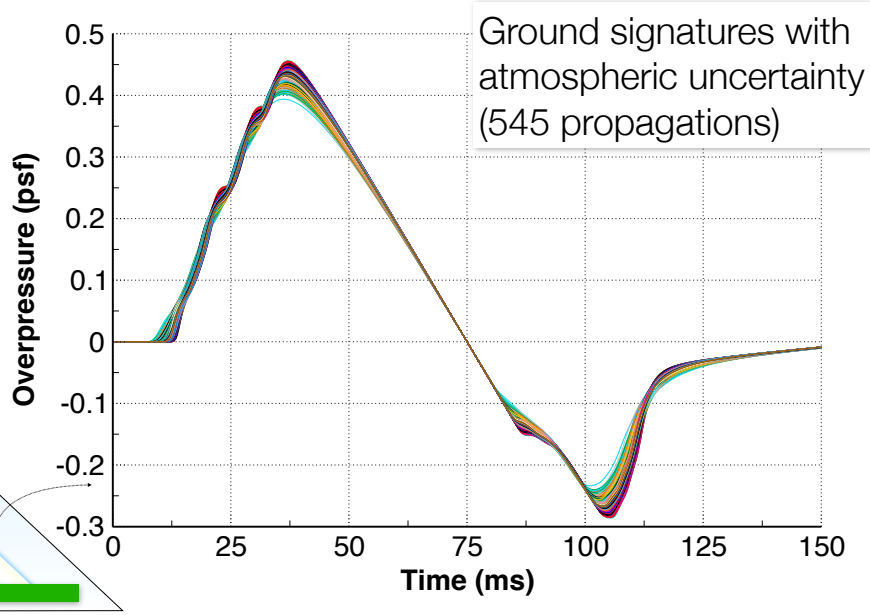


Engine and Plume Region

Propagation through Uncertain Atmosphere



Nearfield signature at nominal Mach number (1.4) and angle of attack (2.09°)

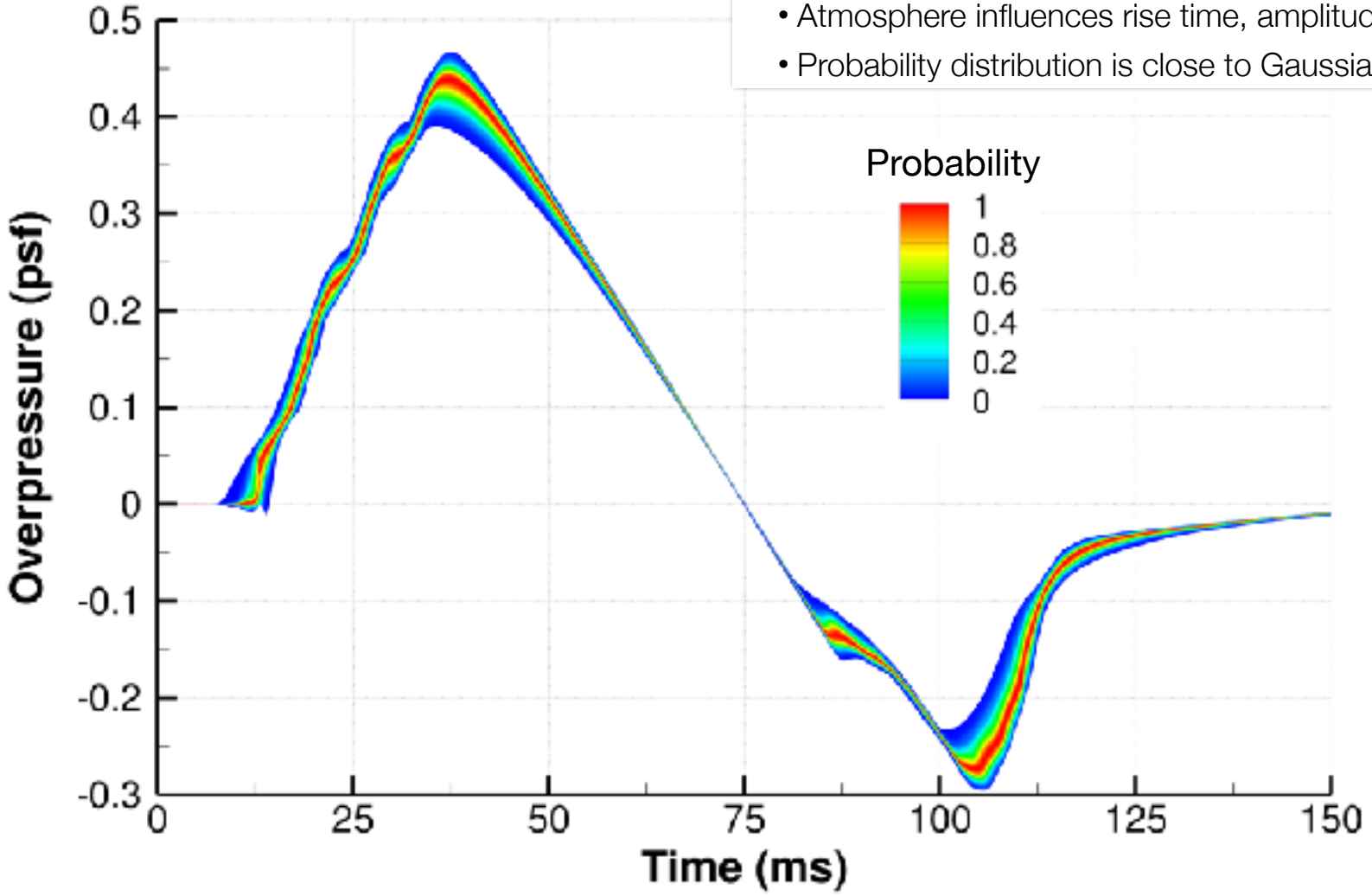


Ground signatures with atmospheric uncertainty (545 propagations)

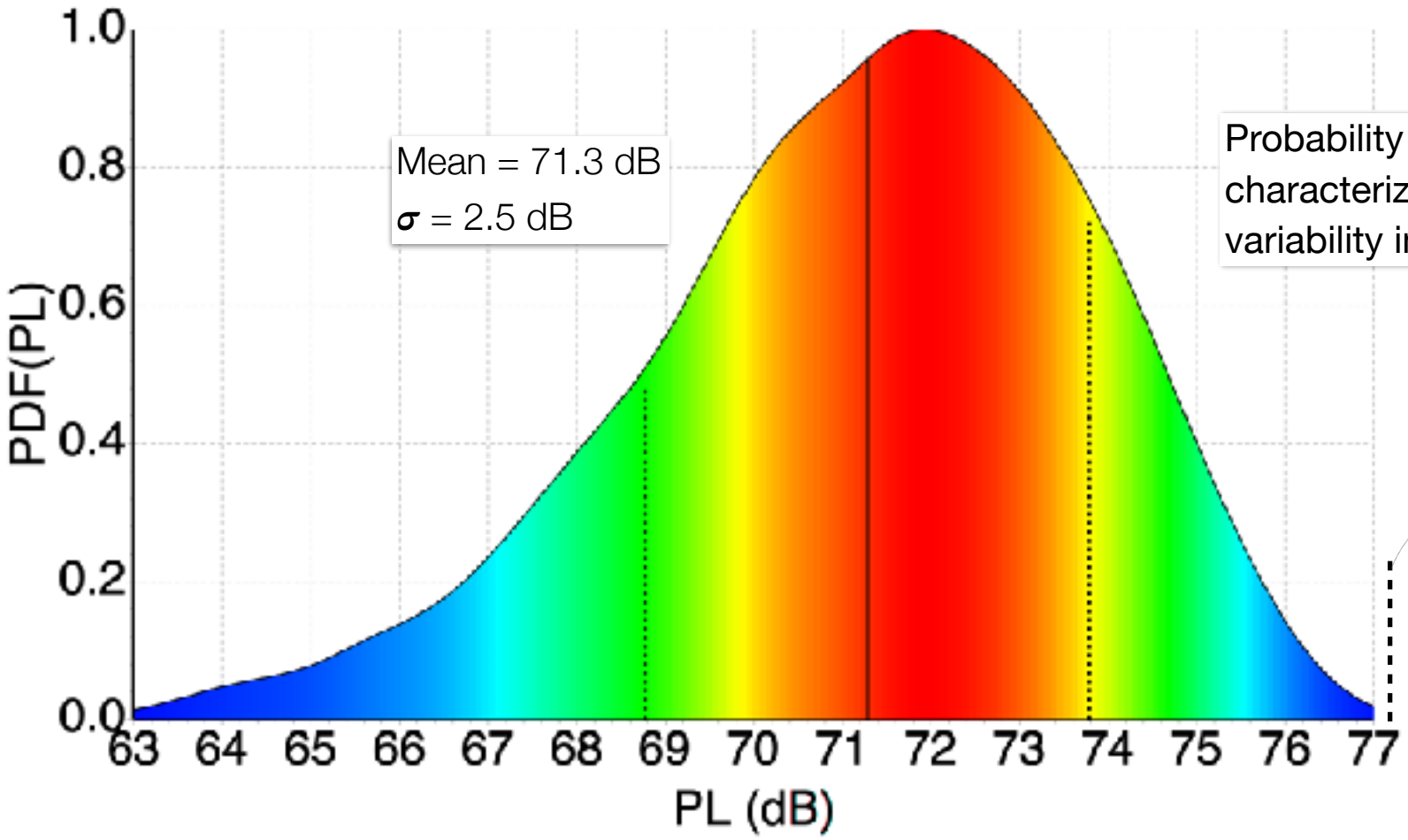
Ground Signature Probability Density

Uncertain T and RH profiles

- Atmosphere influences rise time, amplitude and signal duration
- Probability distribution is close to Gaussian



Perceived Loudness Probability Density



Mean = 71.3 dB

σ = 2.5 dB

Probability density function fully characterizes the uncertainty in PL due to variability in T and RH atmospheric profiles

PL in Std. Atm.

77.3 dB

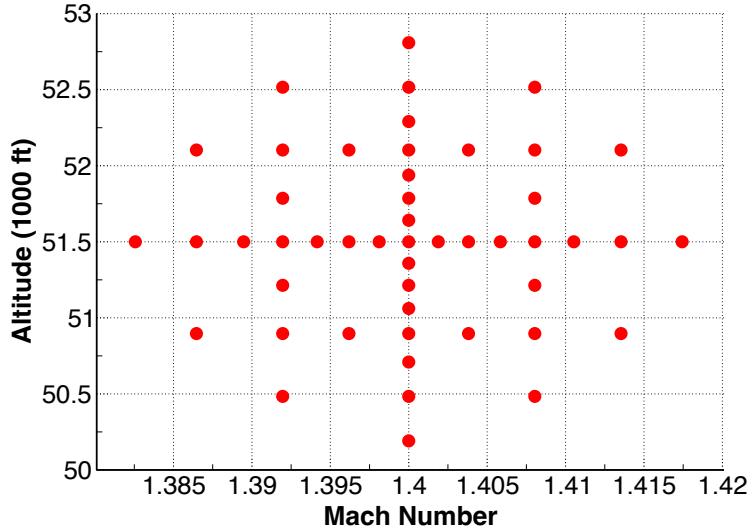
Loudness obtained from propagation through standard atmosphere are highly unlikely at Edwards

Uncertain Operating Conditions and Atmosphere

Characterize uncertainty in ground signature and loudness due to uncertainty in the atmosphere, and variability in cruise Mach number and altitude

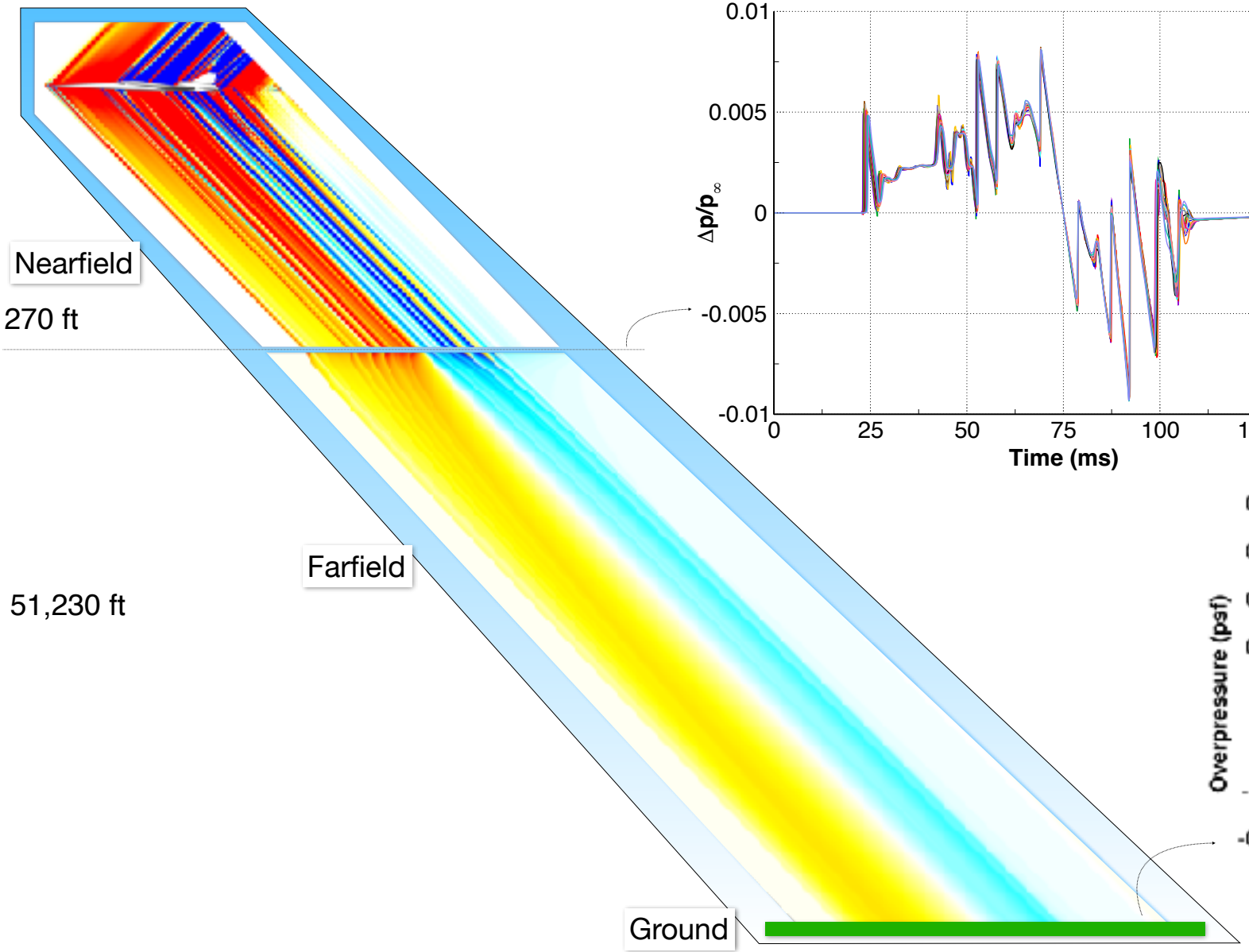
- 8 independent random variables
  - Assume normal distributions for Mach number (M_∞) and altitude (A_c)
  - Reuse KL6 parameterization of T and RH profiles
  - Assume flights at Edwards AFB in August, around 10 am PT

$A_c = \mathcal{N}_{3\sigma}(\mu = 51.5, \sigma = 0.5)$



$M_\infty = \mathcal{N}_{3\sigma}(\mu = 1.4, \sigma = 0.0066)$

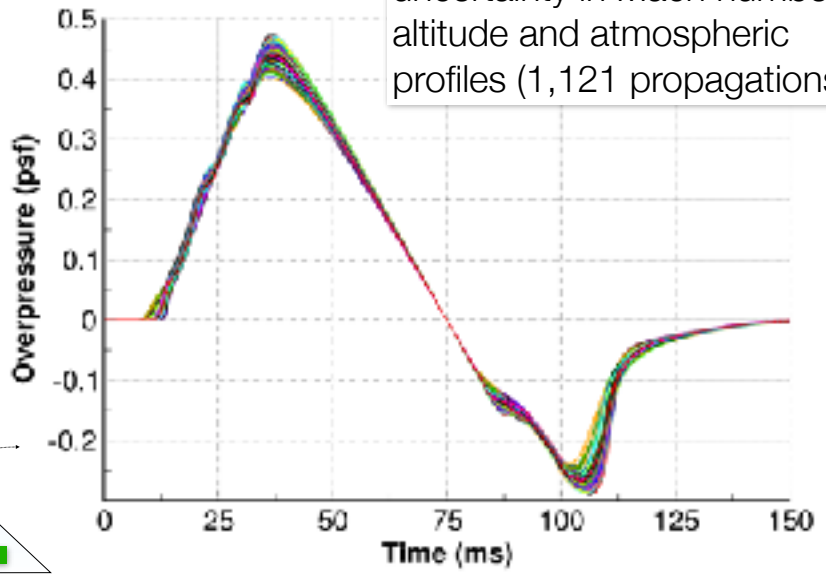
Uncertain Operating Conditions and Atmosphere



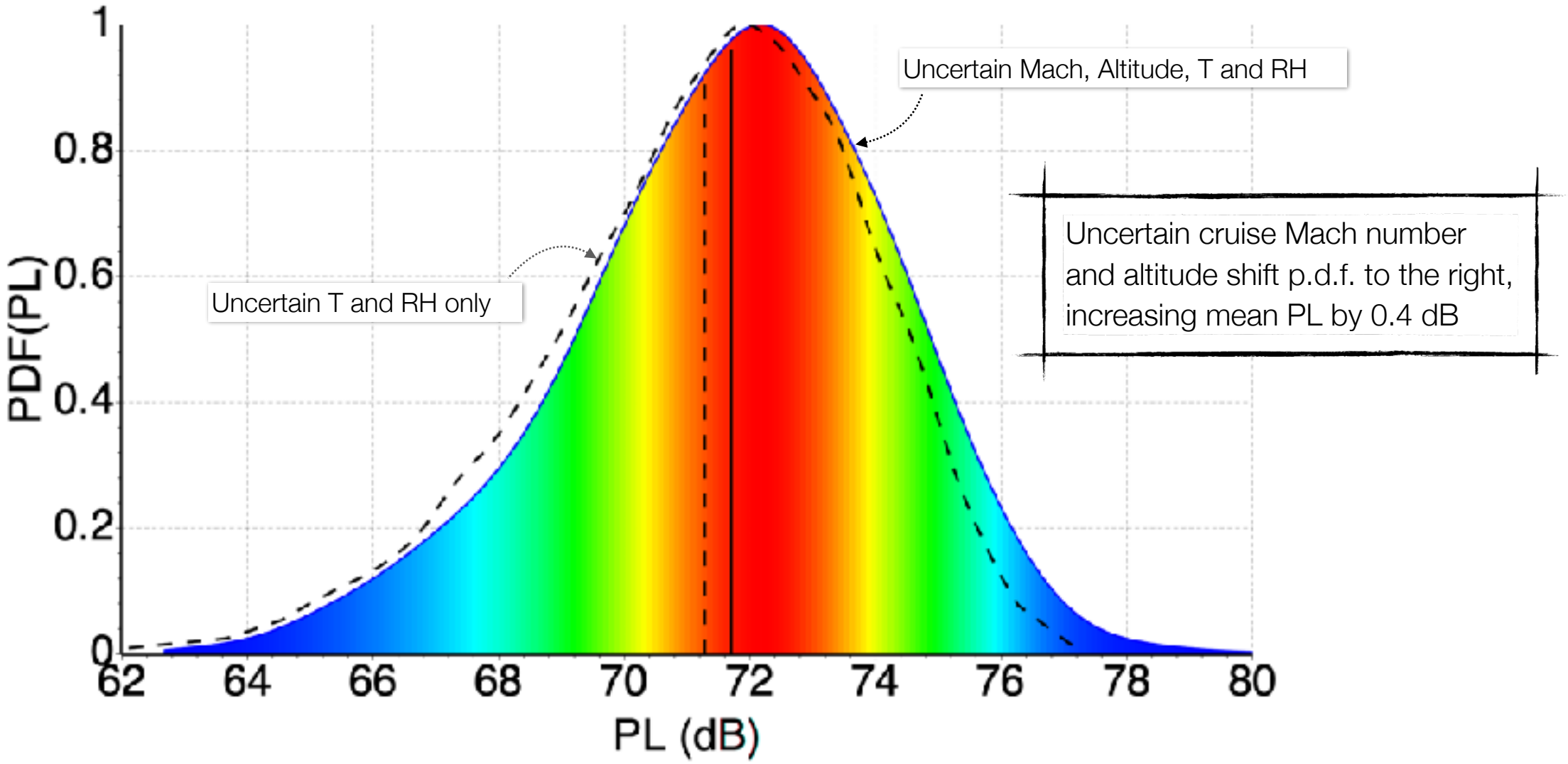
Nearfield signatures due to uncertainty in Mach number (15 solutions)

"Overnight" turnaround on small clusters frequently achieved in practice

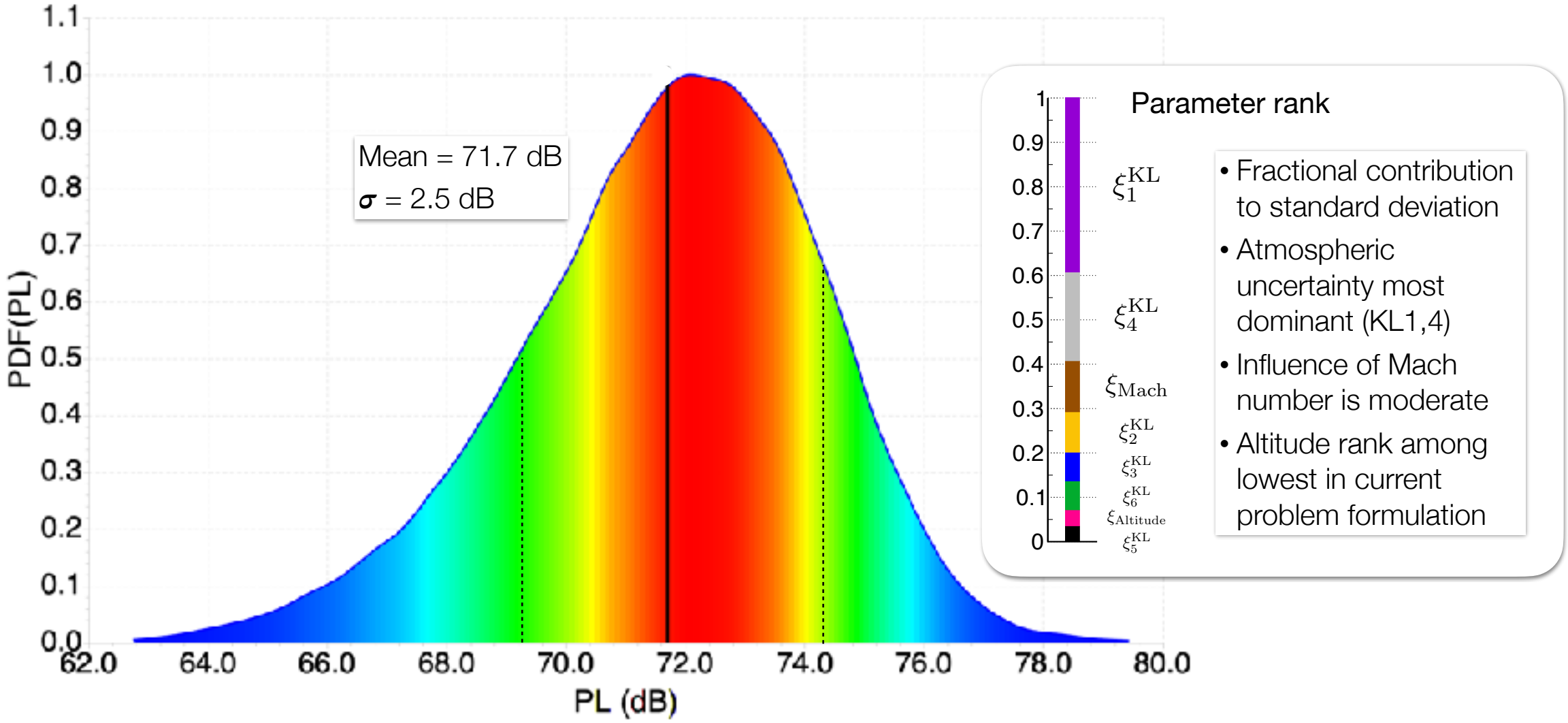
Ground signatures due to uncertainty in Mach number, altitude and atmospheric profiles (1,121 propagations)



Influence of Operating Conditions on PL



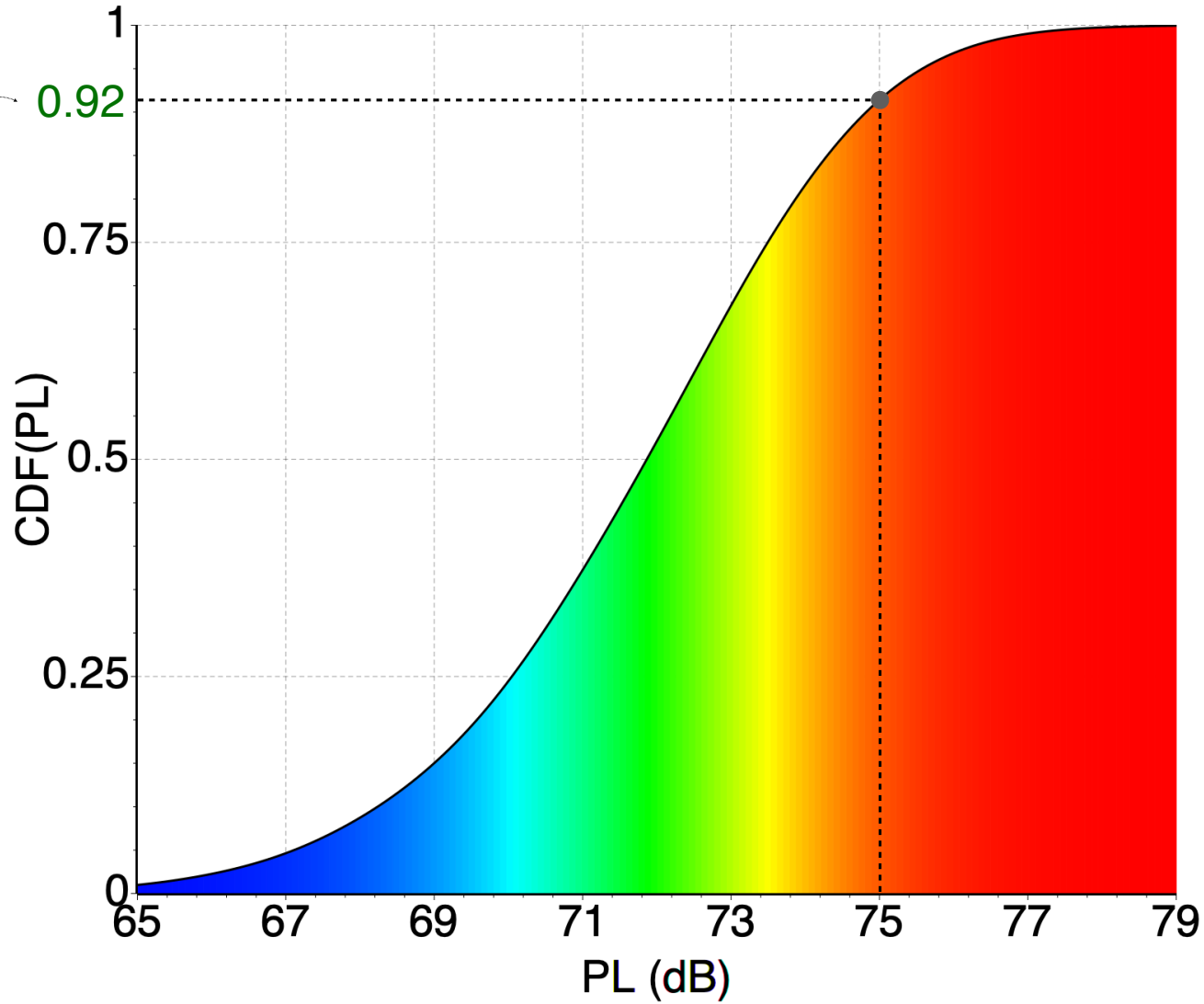
Ranking of Uncertain Inputs



- Fractional contribution to standard deviation
- Atmospheric uncertainty most dominant (KL1,4)
- Influence of Mach number is moderate
- Altitude rank among lowest in current problem formulation

Cumulative Distribution Function for PL

- 92% chance of success
  - Probability of exceeding 75 PL dB at Edwards AFB for flights in August at 18:00 UTC due to uncertainty in cruise Mach number, altitude and atmospheric conditions is 8%
- Estimate neglects variability in aircraft mass and trim, and atmospheric turbulence



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
  - Fast turn-around critical (4 hours per case)
  - Each case fits on 1-4 nodes, but may need 10,000 nodes to fill databases efficiently



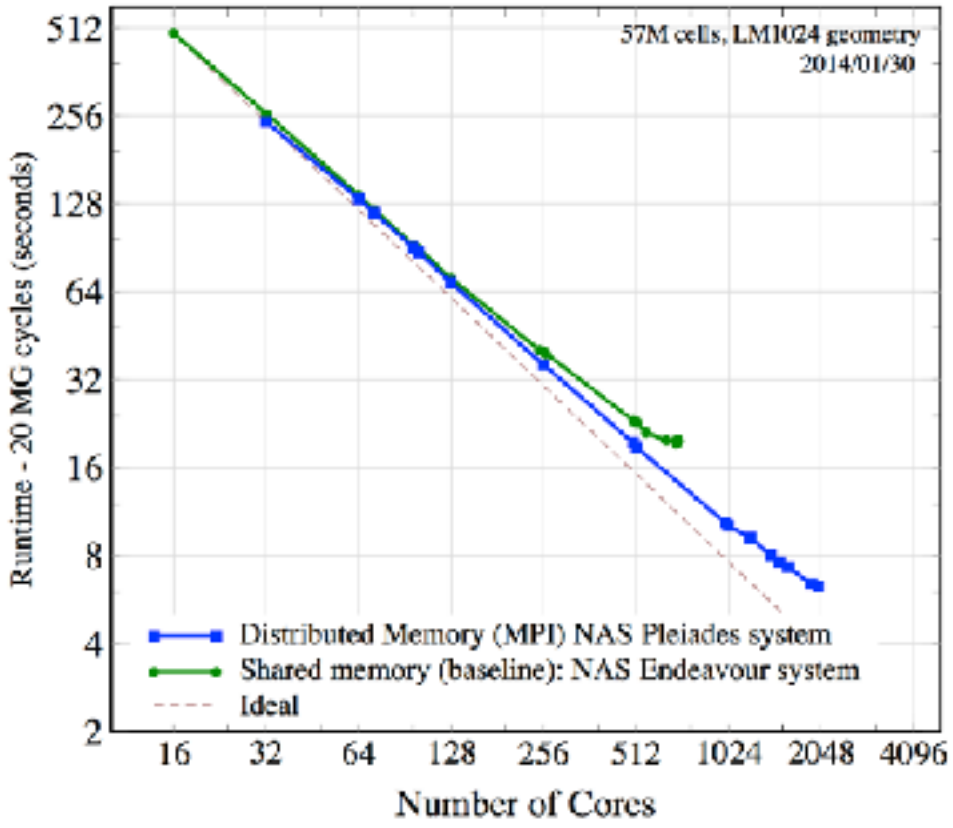


Electra	Endeavour	Aitken	Cabeus
- Skylake	- Cascade Lake, NUMAlink 8	- Cascade Lake, - Rome	- CasLake V100 - Rome A100

Parallel Performance

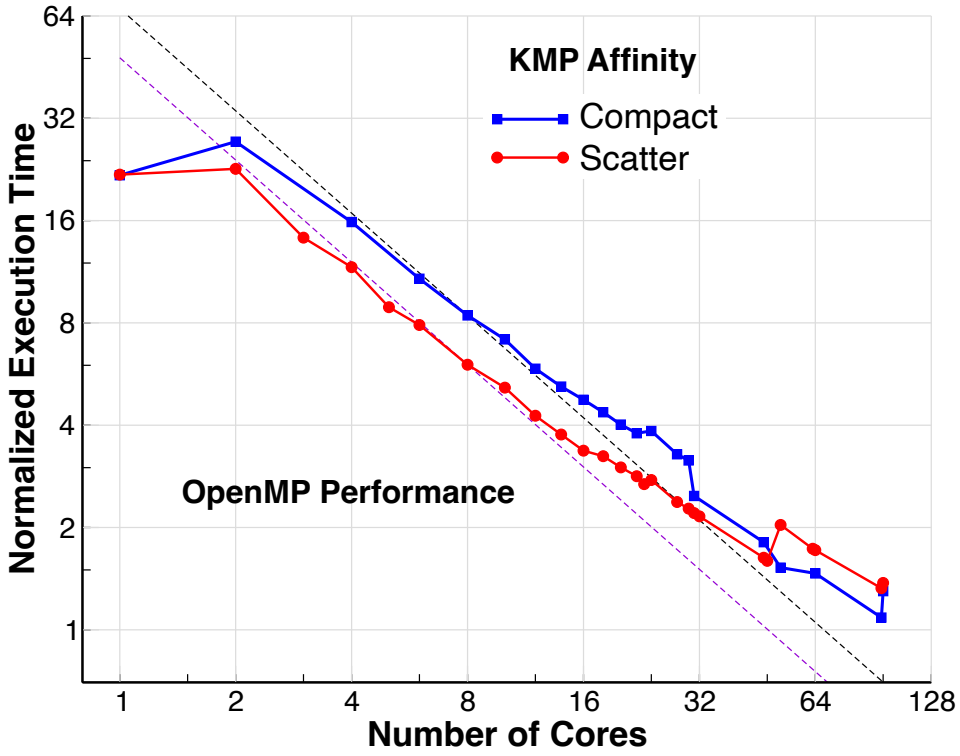
Excellent scalability through use of domain decomposition based on space-filling curves

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

Acknowledgements

- NASA’s High-End Computing Program through the NASA Advanced Supercomputing (NAS) Division at Ames Research Center
  - SciCon in-house performance monitoring and debug tools
- NASA's ARMD Commercial Supersonic Technology Project
- NASA’s Transformational Tools and Technologies Project









National Aeronautics and
Space Administration

Questions?

marian.nemec@nasa.gov

https://www.nasa.gov/aeronautics/supersonic-flight