

Method for System-Level Multidisciplinary Uncertainty Analysis of Low-Boom Flight Vehicles

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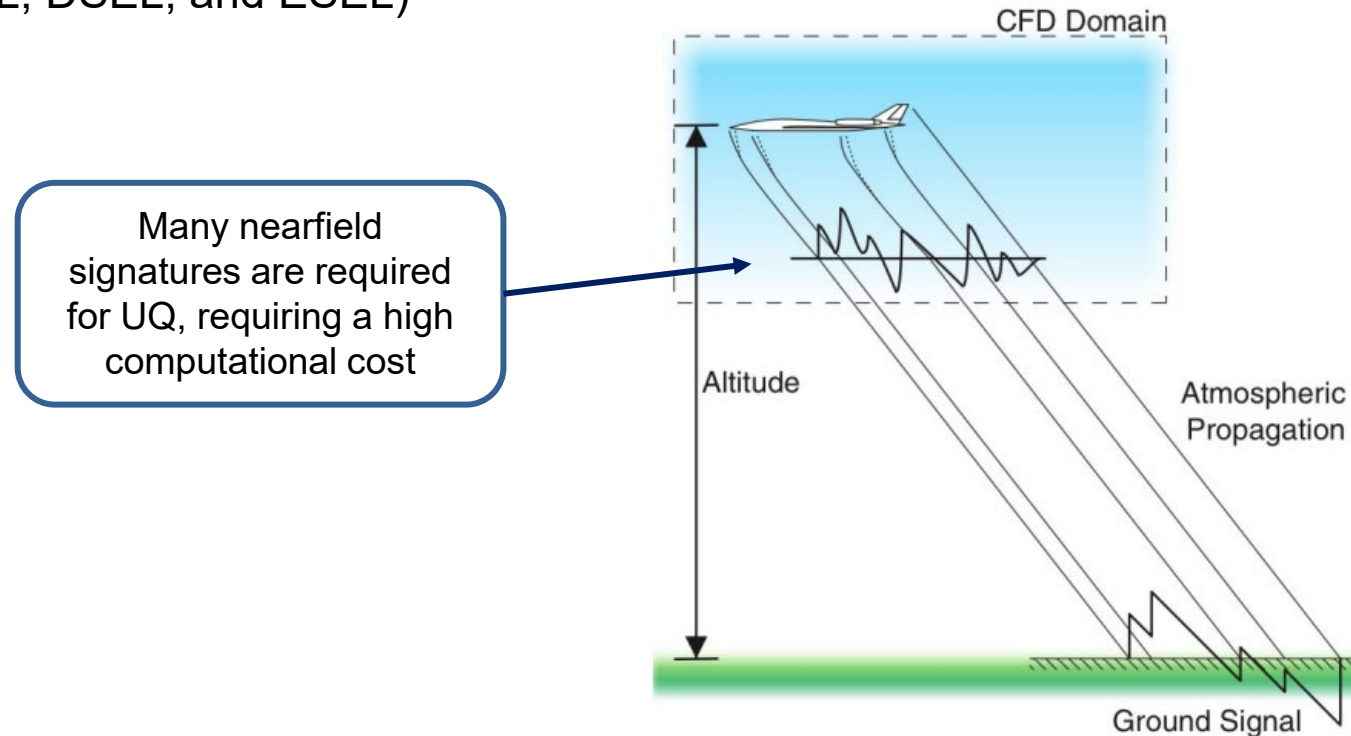


Innovation in Commercial High-Speed Aircraft

- NASA Aeronautics Strategic Thrust: Innovation in Commercial High-Speed Aircraft
 - Enable the establishment of an acceptable sonic boom level by developing tools and survey techniques to create a sonic boom community response database
 - Enable vehicle designs that achieve the acceptable sonic boom level
- Commercial Supersonic Technologies (CST) project, Uncertainty Quantification (UQ)
 - Enable evaluation of the sonic boom loudness uncertainty for low-boom supersonic vehicle concepts
- Previous uncertainty quantification (UQ) and design studies indicate that the sonic boom loudness on the ground can be sensitive to off-design flight conditions
 - UQ helps to ensure that designs meet certification requirements at all flight conditions
 - **System-level multidisciplinary analysis (MDA)** is performed to obtain accurate uncertainty intervals and sensitivity values at a lower computational cost

Sonic Boom Loudness Prediction

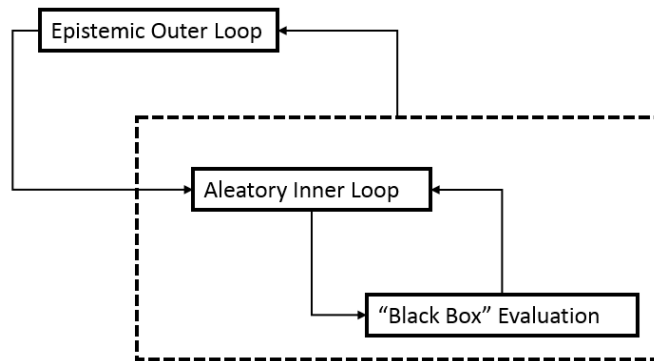
- Sonic boom loudness metrics are computed using this procedure:
 1. Generate a nearfield pressure signature by extracting pressure along a line in a CFD flow solution
 2. Propagate that signature through the atmosphere to the ground by using a software that solves an augmented Burger's equation
 3. Calculate loudness metrics based on the frequency content of the final ground signal. Different frequency weightings are considered: Perceived Loudness (PLdB) and B-, D-, and E-weighted sound exposure levels (BSEL, DSEL, and ESEL)



Uncertainty Quantification Methods

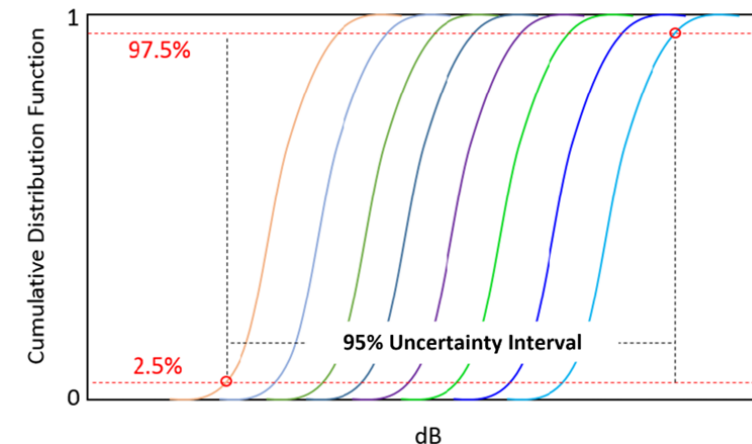
- Polynomial Chaos Expansions (PCEs) are surrogate models based on spectral representation of uncertainty
 - Analytical expressions for response mean, standard deviation, and Sobol indices (global nonlinear sensitivity parameters) are available based on the PCE structure and fit coefficients
- Uncertainty Quantification is performed using NASA's UQPCE software
 - UQPCE utilizes PCEs to model the uncertainty space, generate uncertainty intervals, and calculate sensitivity metrics
 - Aleatory and epistemic uncertain parameters are handled in two separate loops and combined via a "P-Box" approach

Second-Order Probability Architecture



Each iteration of the epistemic outer loop represents one sample of the epistemic uncertain variables

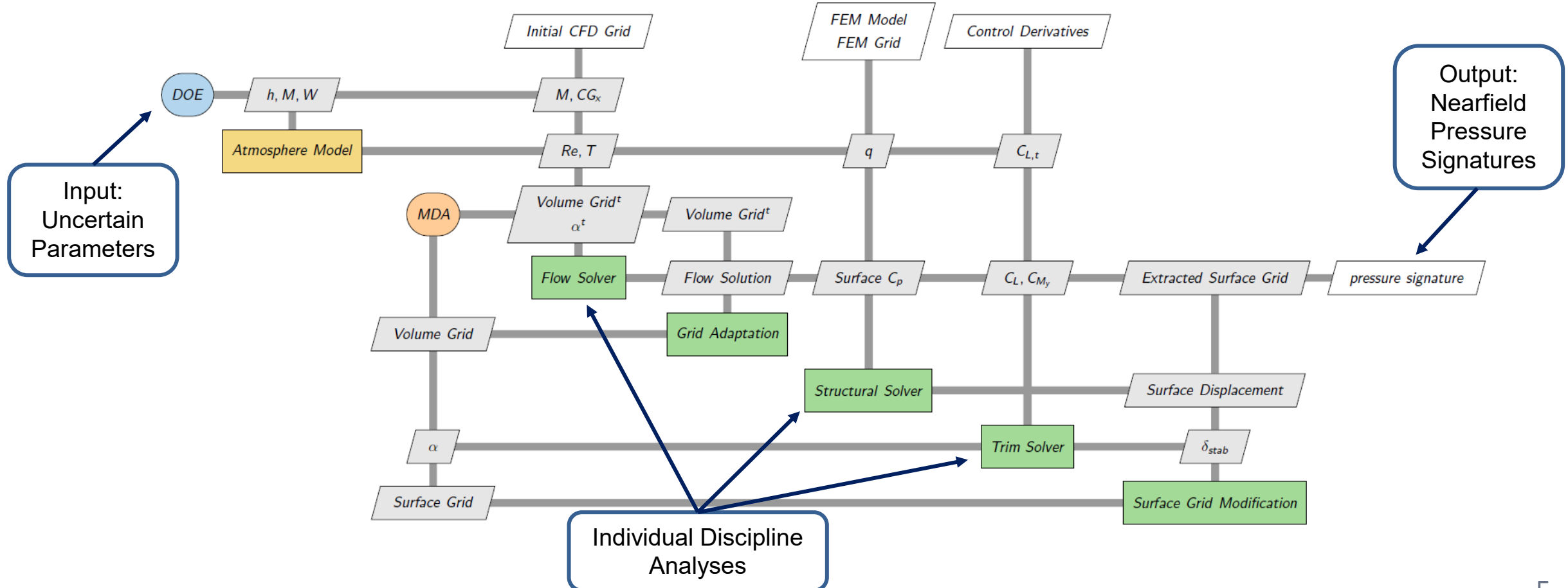
P-Box Plot



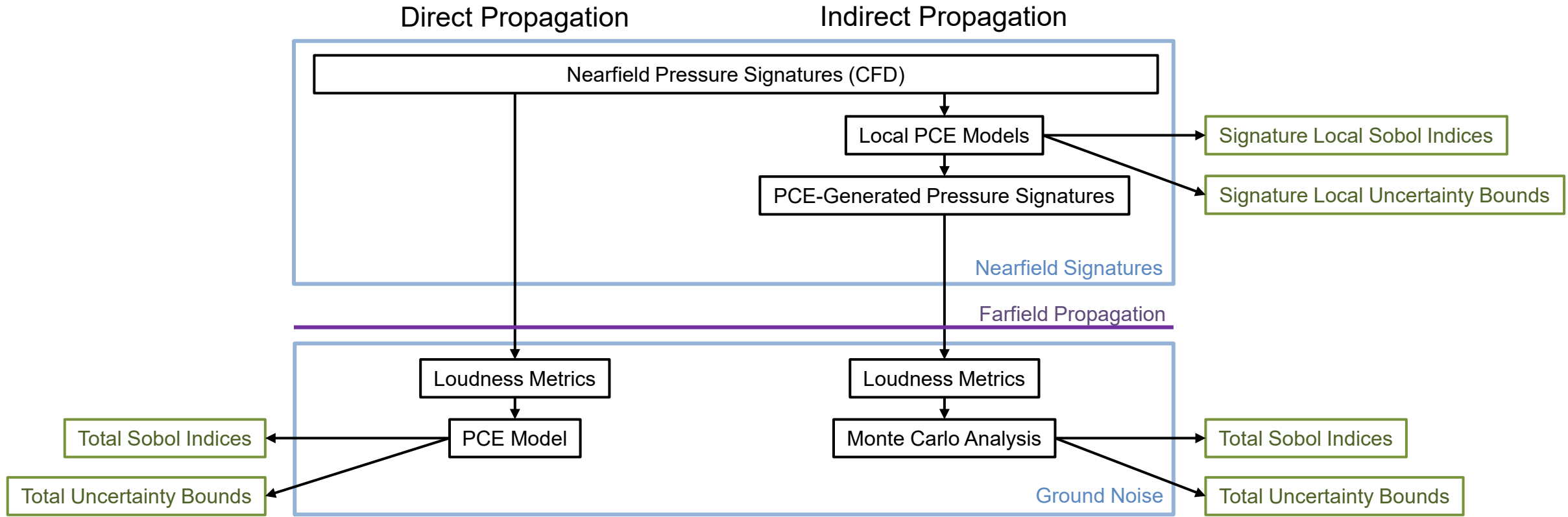
Each CDF shown here is generated within an aleatory inner loop, and represents one iteration of the epistemic outer loop

Near-Field MDA Framework Architecture

- An MDA framework is used to **generate nearfield pressure signatures** of the trimmed aircraft at various points in the uncertainty space
- Signature generation for UQ is a multidisciplinary problem, utilizing several different codes to solve disciplinary subproblems and capture the effects of interactions between them
- Fixed-point iteration is used to solve the overall problem; sample pressure signatures are extracted from the flow solution once select quantities from the various subproblems have converged

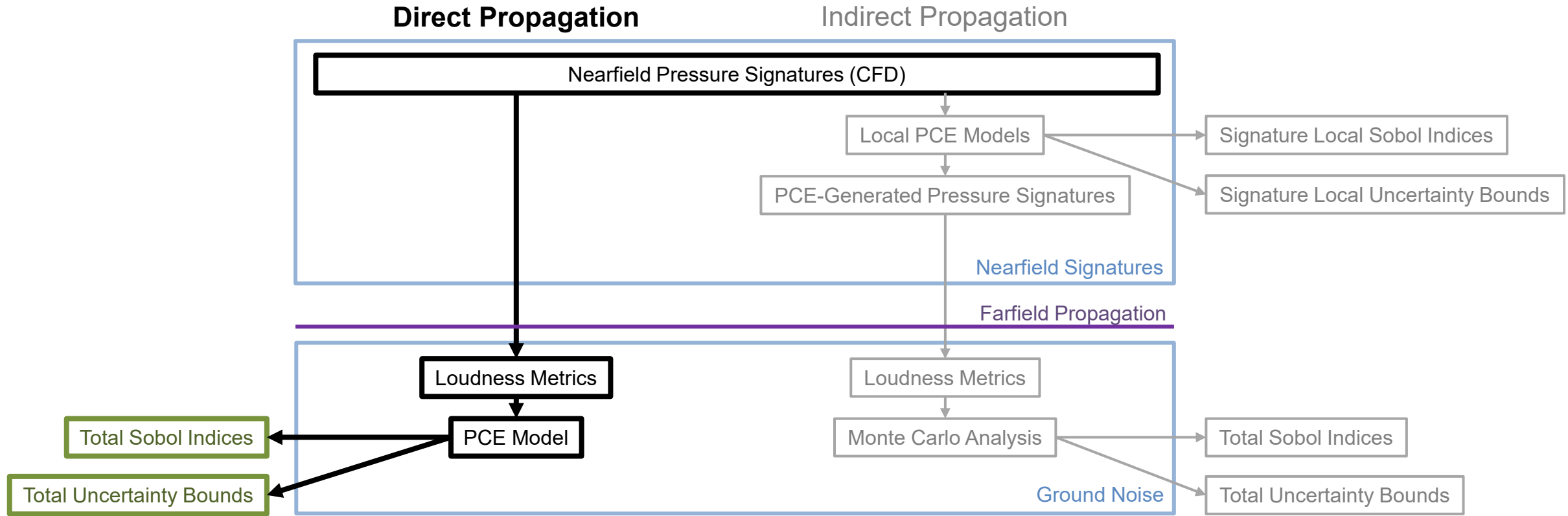


Propagation UQ Methods



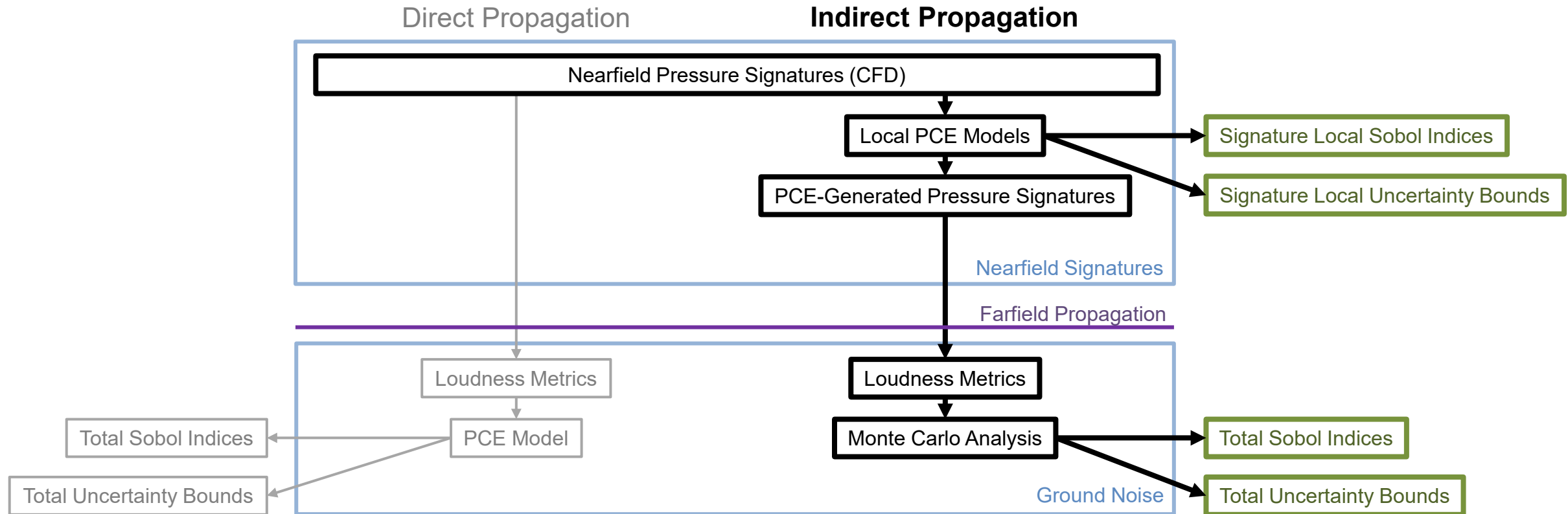
- Two UQ methods are used for this milestone to handle the interface between nearfield and farfield: **direct propagation** and **indirect propagation**

Propagation UQ Methods, Direct Propagation



- CFD pressure signatures are directly propagated to the ground to obtain loudness metrics
- Nearfield and propagation uncertain parameters are coupled, and UQ results are obtained for both sets of parameters at once
- Requires more CFD samples than indirect propagation

Propagation UQ Methods, Indirect Propagation

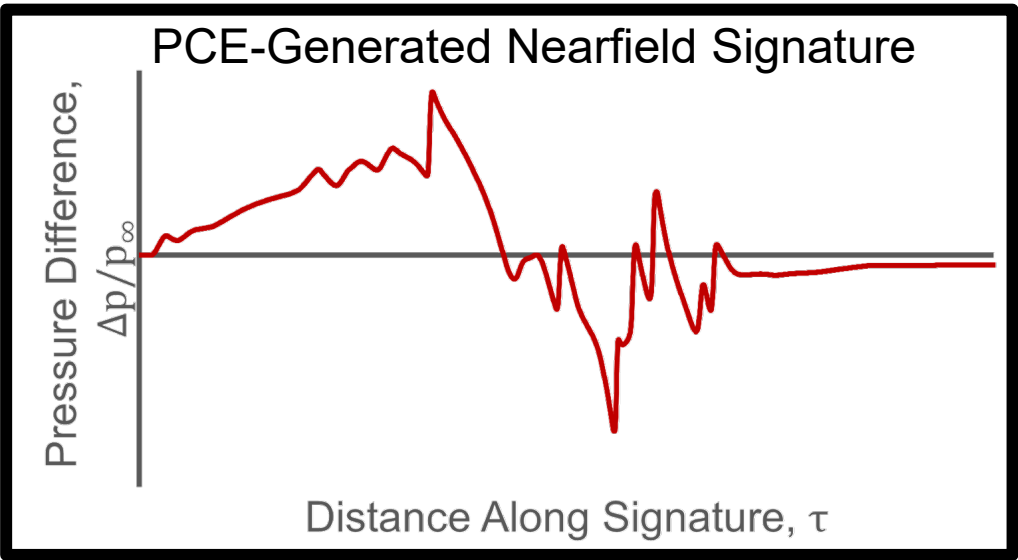
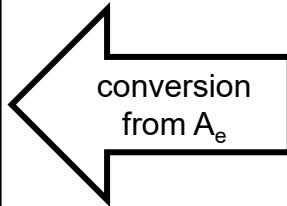
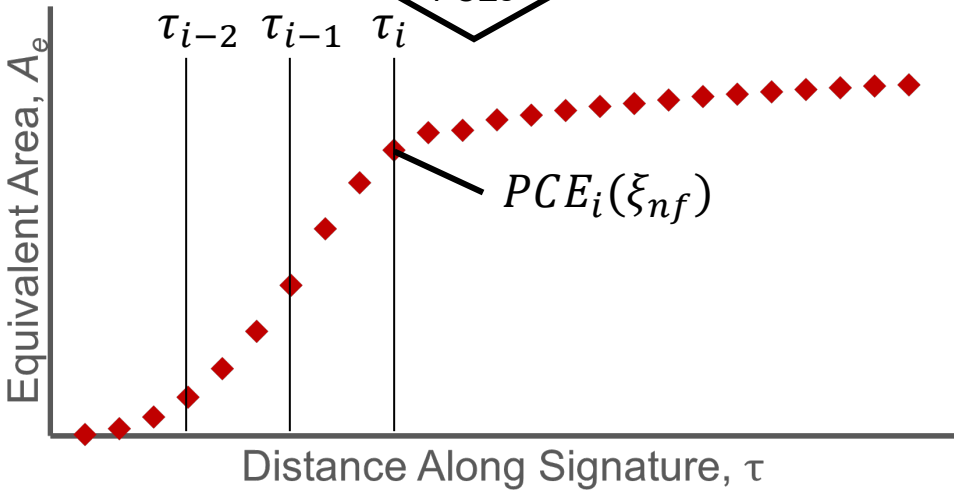
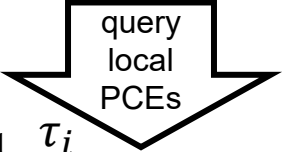
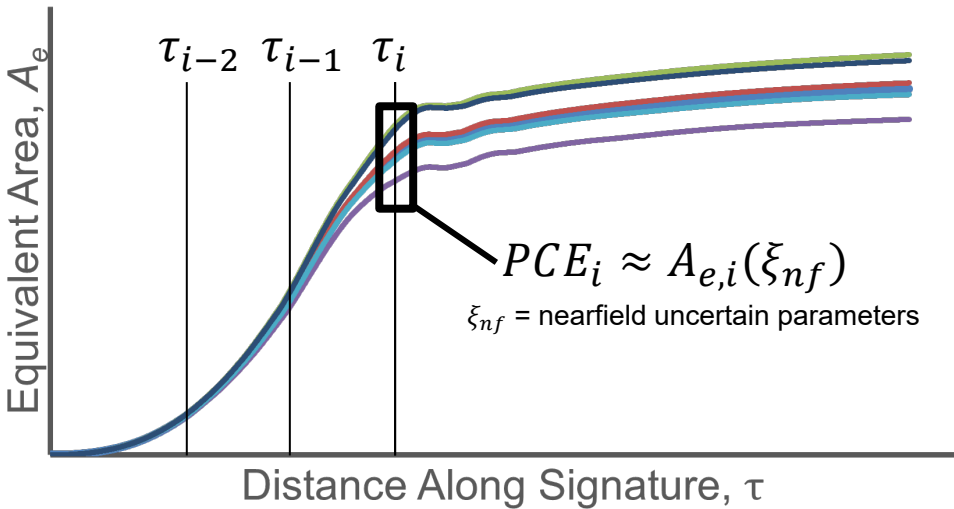
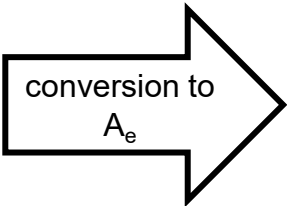
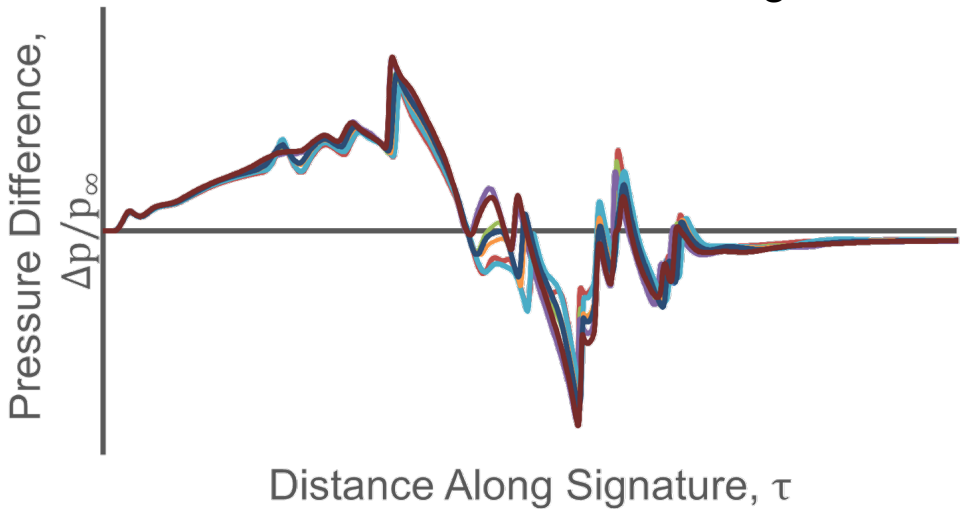


- CFD pressure signatures are used build local PCE models at discrete locations along the signatures
- A large set of PCE-generated signatures can be generated at low cost for Monte Carlo analysis
- Nearfield and propagation uncertain parameters are coupled as part of the model fitting process

Indirect Propagation Method



Collection of CFD Nearfield Signatures



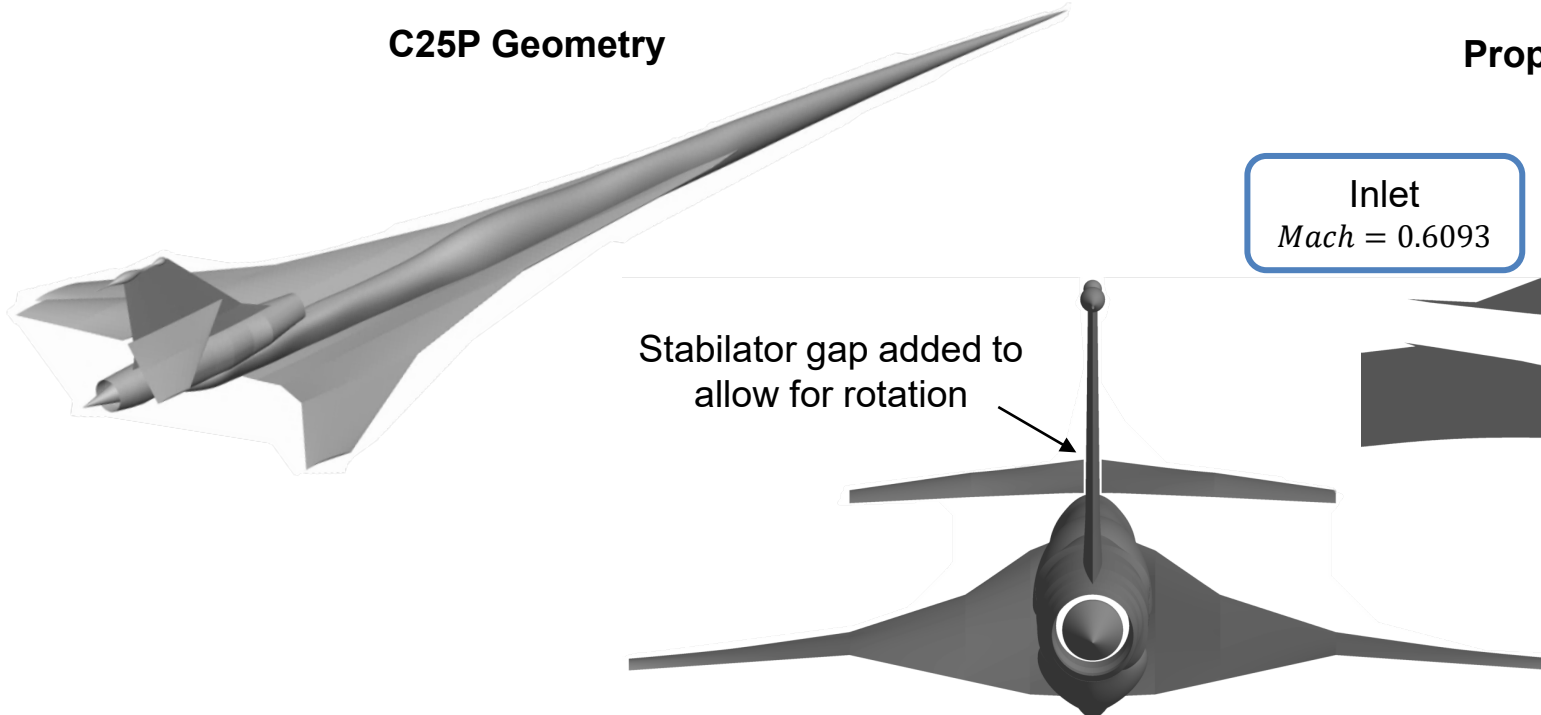
Case Study, NASA C25P

- NASA Concept 25 with Engine Boundary Conditions (C25P)
 - Low-boom demonstrator-sized concept with propulsive boundary conditions
 - Featured in the 2nd AIAA Sonic Boom Prediction Workshop
 - Grid deformation during aeroelastic analysis is relatively robust for this geometry
 - CFD cases include plume effects from propulsion
 - PCBoom used as sonic boom propagation code

Baseline Flight Conditions

Mach	1.60
Angle of Attack (deg)	3.375
Altitude (ft)	51,706
Weight (lbf)	21,000

C25P Geometry



Propulsive Boundary Conditions

Inlet
 $Mach = 0.6093$

Plenum
 $total\ press.\ ratio = 14.540$
 $total\ temp.\ ratio = 7.8722$

Uncertain Parameter Definitions

- Uncertain parameters can be categorized as either **nearfield** or **propagation** variables
- Some variables (*) are used in both phases of analysis
 - For direct propagation, these are linked and hold the same value in both phases
 - For indirect propagation, the values are linked via the local PCE model fits
- Perturbations are based on a standard atmosphere with no wind

Uncertain Input Parameters, Nearfield

Input	Type	Distribution	Definition	Units
Mach Number*	Epistemic	Interval	[1.58, 1.62]	-
Altitude*	Epistemic	Interval	[50,407.5, 52,992.5]	ft
Weight	Epistemic	Interval	[19,950, 22,050]	lbf

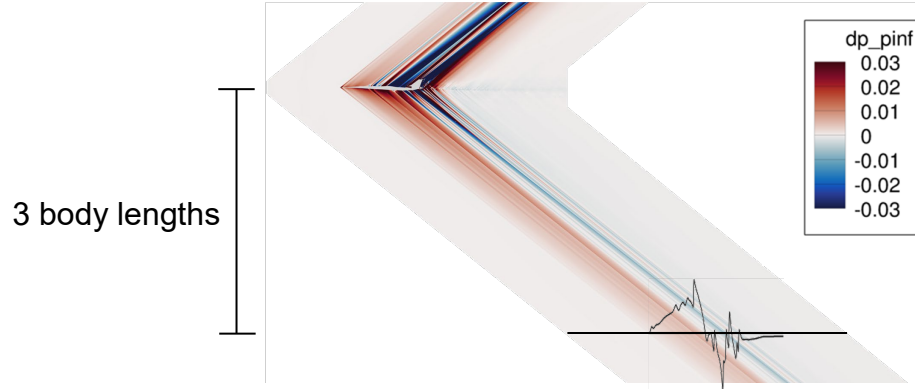
Uncertain Input Parameters, Propagation

Input	Type	Distribution	Definition	Units
Mach Number*	Epistemic	Interval	[1.58, 1.62]	-
Altitude*	Epistemic	Interval	[50,407.5, 52,992.5]	ft
Ground Altitude	Epistemic	Interval	[600, 1400]	ft
X-Wind Perturbation	Aleatory	Normal	N(0, 4)	ft/s
Y-Wind Perturbation	Aleatory	Normal	N(0, 4)	ft/s
Temperature Perturbation	Aleatory	Normal	N(0, 3)	°F
Humidity Factor	Aleatory	Normal	N(1.0, 0.05)	-

MDA Components

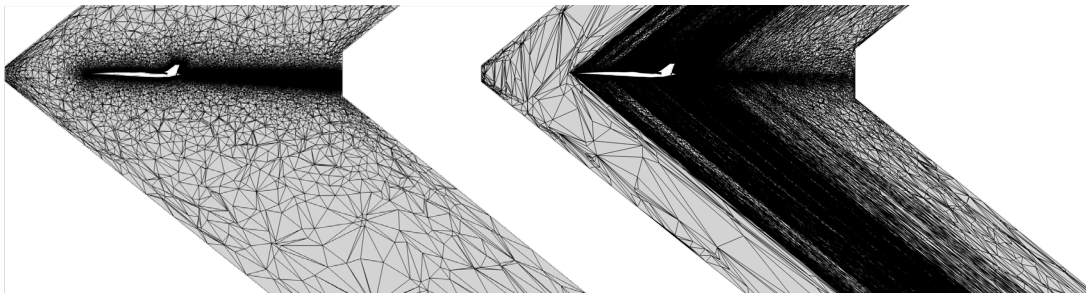


Flow solutions are computed using FUN3D, a 2nd order accurate node-based RANS solver developed by NASA



Pressure signatures are extracted at a radius of 3 body lengths, directly underneath the aircraft model

FUN3D feature-based **grid adaptation** resolves the pressure signatures



MDA Iteration 1

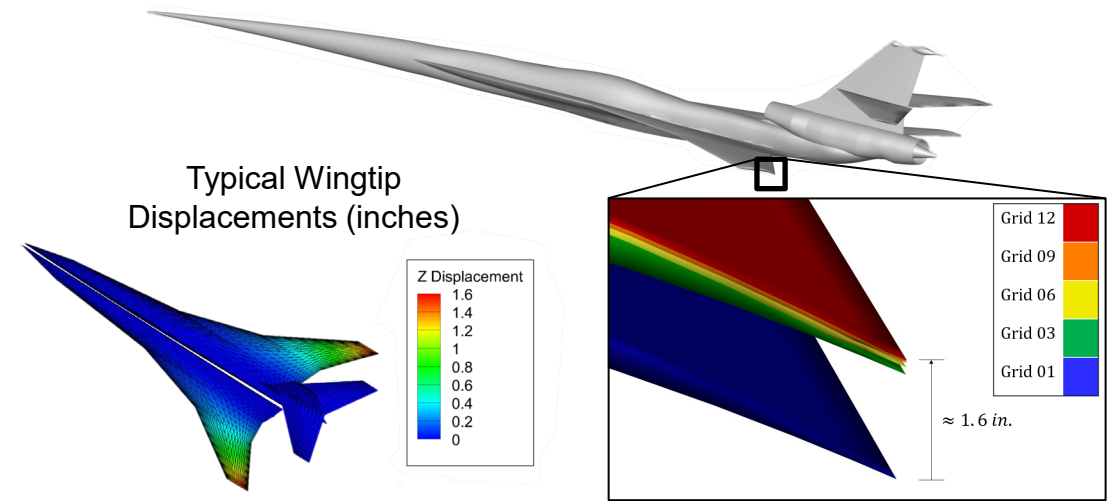
MDA Iteration 12

Trim is achieved by solving a linear system once per MDA iteration:

$$\begin{bmatrix} \frac{\partial C_L}{\partial \alpha} & \frac{\partial C_L}{\partial \delta_{stab}} \\ \frac{\partial C_{M_y}}{\partial \alpha} & \frac{\partial C_{M_y}}{\partial \delta_{stab}} \end{bmatrix} \begin{bmatrix} \Delta \alpha \\ \Delta \delta_{stab} \end{bmatrix} = \begin{bmatrix} -(C_L - C_{L,target}) \\ -(C_{M_y} - C_{M_y,target}) \end{bmatrix}$$

Control derivative estimates are obtained beforehand from the baseline run

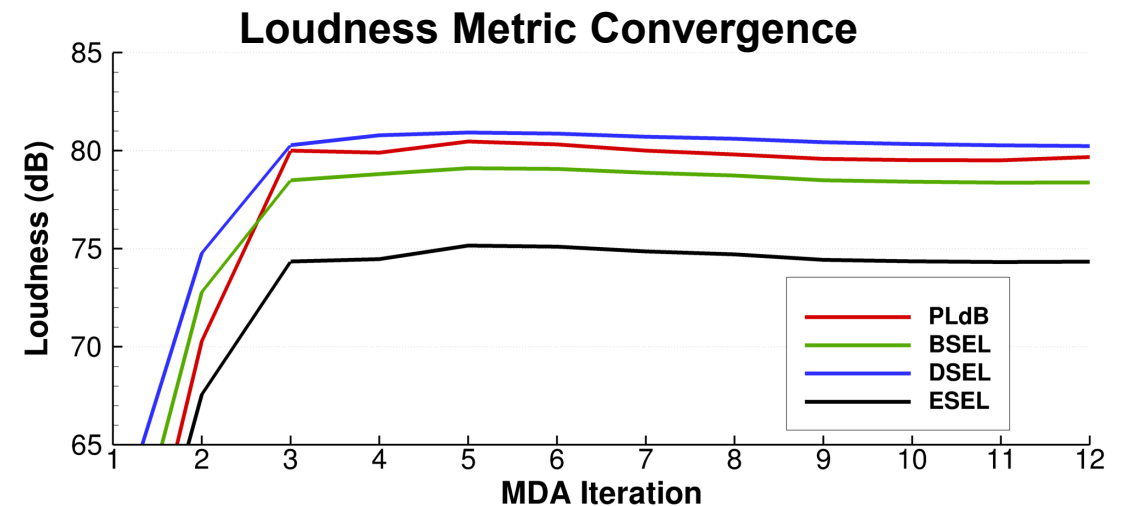
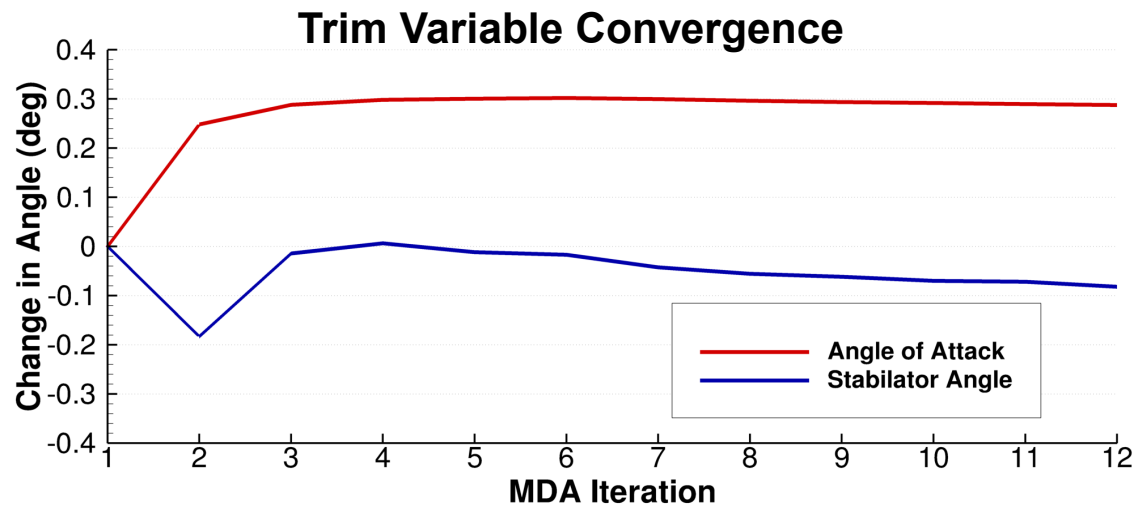
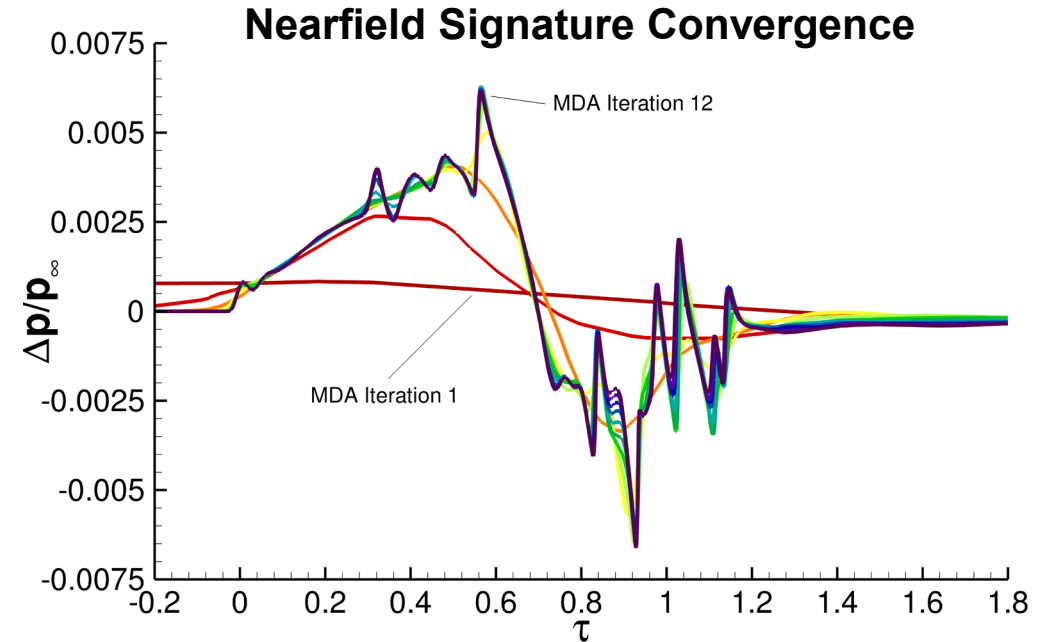
Structural deformations are computed using NASTRAN, and loads are transferred via the MELD transfer scheme within FUNtoFEM



Typical Wingtip Displacements (inches)

MDA Convergence

- 12 MDA iterations are executed to converge the nearfield signature shape
 - Peaks converge quickly, before iteration 12
 - Some features still lack resolution, but their effects on the loudness metrics are small
- Angle of attack converges to within 0.01° , stabilator deflection angle to within 0.025°
- BSEL, DSEL, and ESEL metrics converge to within 0.1 dB
- PLdB converges less reliably, to within 0.4 dB



UQ Results, Direct Propagation

- Results from **90** MDA executions were included in the PCE model
- Backwards Elimination was used to eliminate unnecessary terms in the PCE model

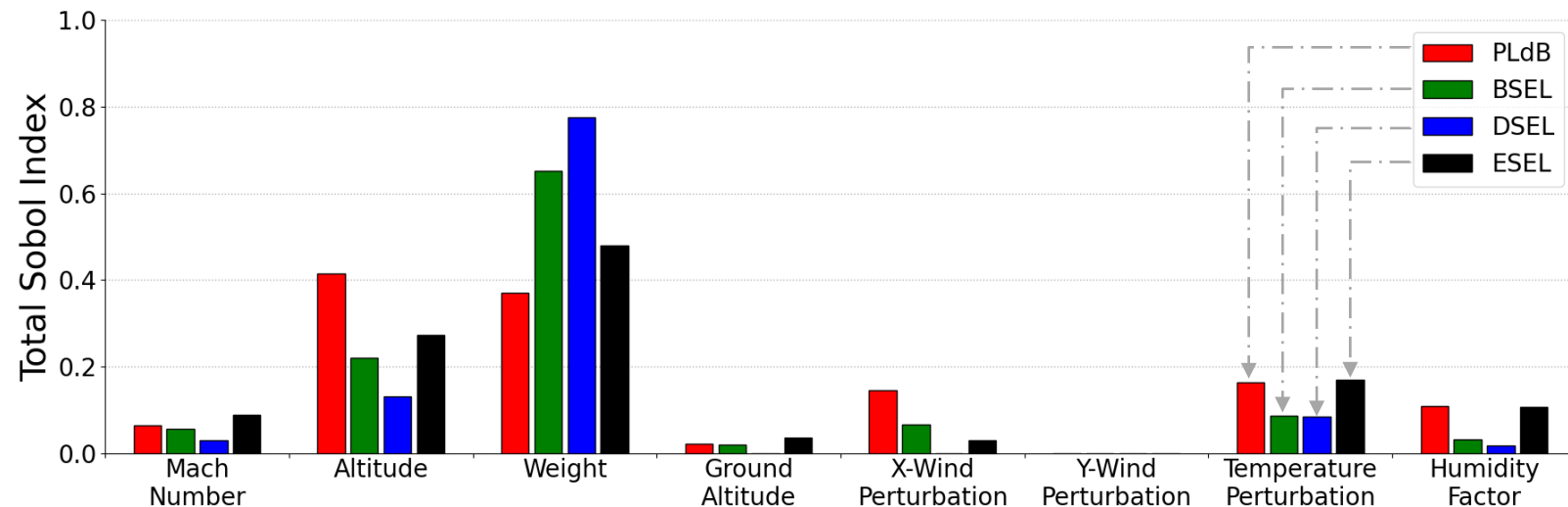
Sobol Indices are generated for the loudness metric responses

- Weight and altitude uncertainties account for most of the global uncertainty for all loudness metrics
- These parameters determine the target lift coefficient, and therefore the trim state of the model

Model Fit Statistics

Method	PLdB	BSEL	DSEL	ESEL
PCE R ²	0.858	0.947	0.982	0.862
Mean Model Error (dB)	0.20	0.10	0.05	0.14
Mean Verification Error (dB)	0.31	0.15	0.06	0.17
Max Verification Error (dB)	0.57	0.31	0.12	0.33

Total Sobol Index:
the portion of system variance attributed to one uncertain parameter and its interactions



UQ Results, Indirect Propagation

- Nearfield signatures from **21** MDA executions are included
- 3,600 local PCE models are built on nearfield signature samples
- Monte Carlo analysis is performed to obtain UQ metrics

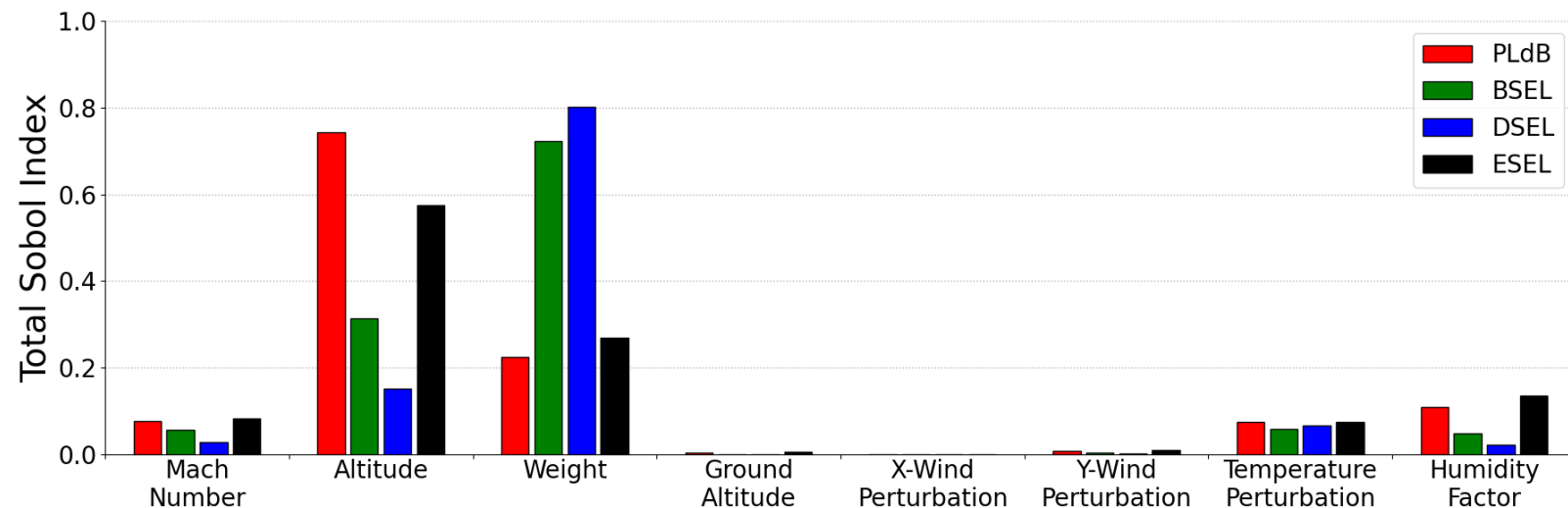
Sobol Indices are generated for the loudness metric responses

- Weight and altitude uncertainties account for most of the global uncertainty for all loudness metrics
- Contributions from ground altitude and wind perturbation uncertainties are negligible

Model Fit Statistics

Method	PLdB	BSEL	DSEL	ESEL
PCE R ²	0.948	0.966	0.983	0.958
Mean Model Error (dB)	0.13	0.09	0.04	0.09
Mean Verification Error (dB)	0.19	0.12	0.05	0.14
Max Verification Error (dB)	0.55	0.37	0.17	0.43

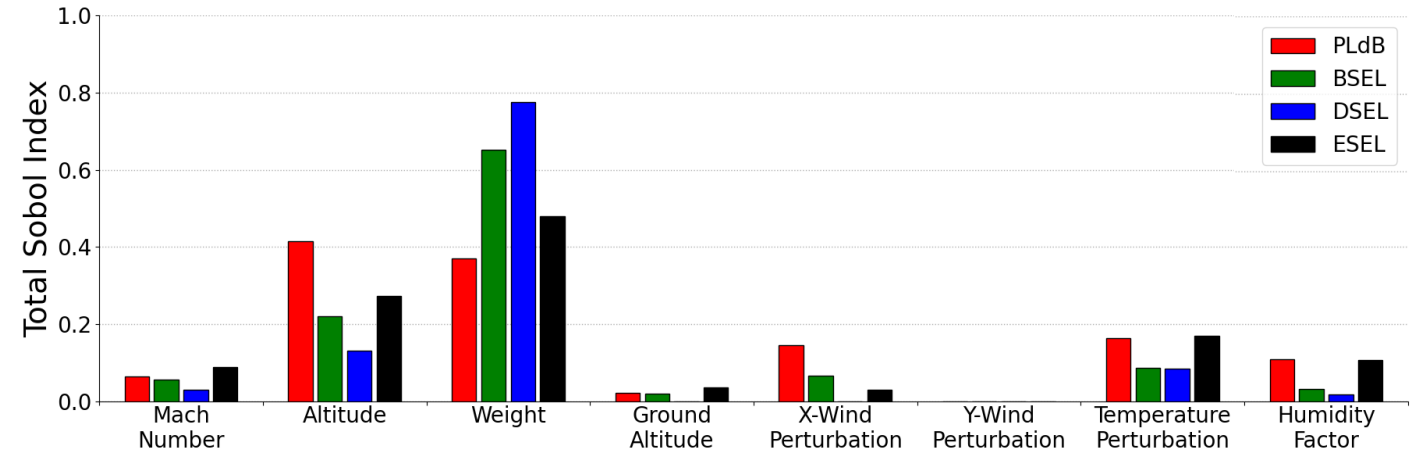
Total Sobol Index:
the portion of system variance attributed to one uncertain parameter and its interactions



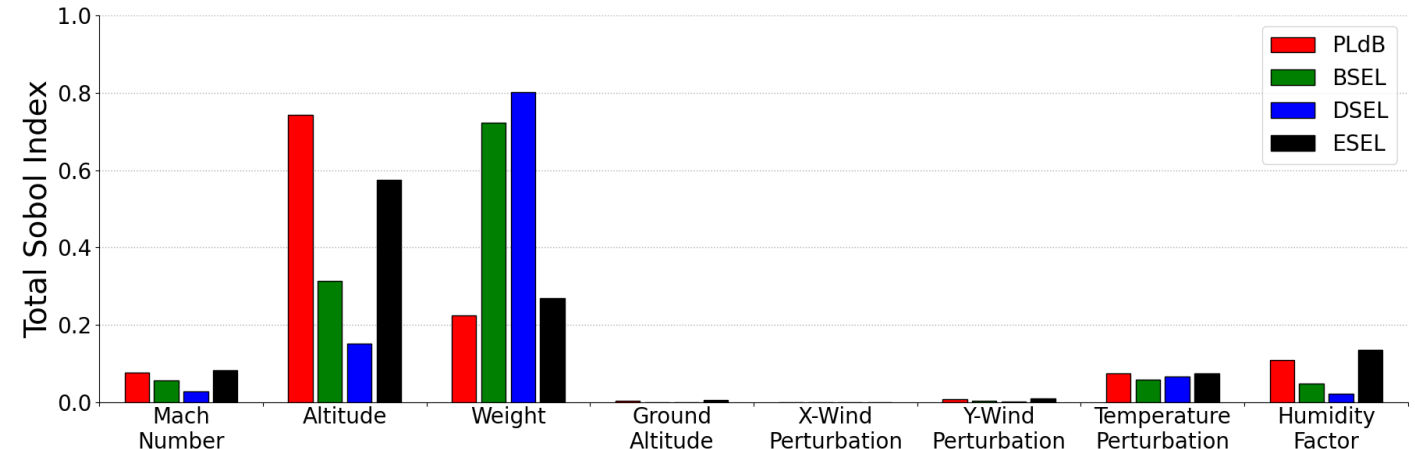
UQ Results, Total Sobol Indices Compared

- Generally, good agreement in the trends in Sobol indices between the direct and indirect propagation methods
- Sobol indices of BSEL and DSEL metrics show good agreement across all uncertain parameters
- PLdB and ESEL show weaker agreement, likely due to error in PCE models due to remaining grid error or higher order effects

Direct Propagation



Indirect Propagation

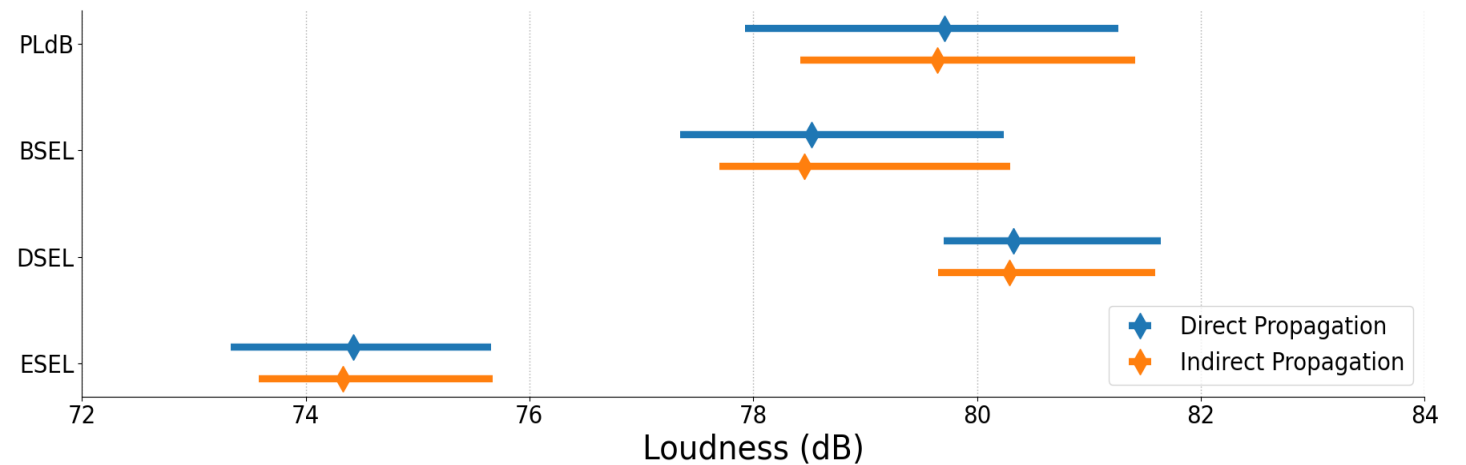


UQ Results, Uncertainty Intervals

- 95% uncertainty intervals are calculated
- Good agreement between indirect and direct methods
- Indirect method has slightly lower mean value estimates, which is in line with the average loudness metric discrepancies in the local PCE verification cases

95% Uncertainty Intervals

Method	Direct Propagation	Indirect Propagation
PLdB	[77.93, 81.26]	[78.42, 81.41]
BSEL	[77.35, 80.24]	[77.70, 80.30]
DSEL	[79.70, 81.64]	[79.65, 81.59]
ESEL	[73.33, 75.66]	[73.58, 75.67]



Computational Cost

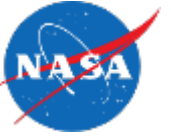
- For this study, indirect propagation required approximately 30% of the computational expense of direct propagation
- The cost advantage of indirect propagation grows with:
 - increased cost of each MDA execution
 - decreased number of nearfield uncertain parameters
 - increased number of propagation uncertain parameters
- PCE model fitting has negligible computational cost, but intermediate signature processing requires some time to implement

	Direct Propagation	Indirect Propagation
MDA Executions	90	21
Monte Carlo Executions	-	36,000,000
MDA Wall Time (hrs)	1047	244
Monte Carlo Wall Time (hrs)	-	60
Total Wall Time (hrs)	1047	304

(All computations were performed in parallel on 400 CPU cores)

- Summary
 - Demonstrated a system-level MDA framework for low-boom uncertainty quantification
 - Compared performance and cost of direct and indirect propagation methods
 - Local PCE models built on equivalent area can accurately model nearfield uncertainties
 - Indirect propagation can save computational cost and produce comparable results to direct propagation
- Next Steps
 - Extend the MDA framework to include propulsion model
 - Move towards robust design of low-boom aircraft shapes, using UQPCE to calculate uncertainty-based objectives or constraints
 - Utilize OpenMDAO to organize the MDA and handle derivative information

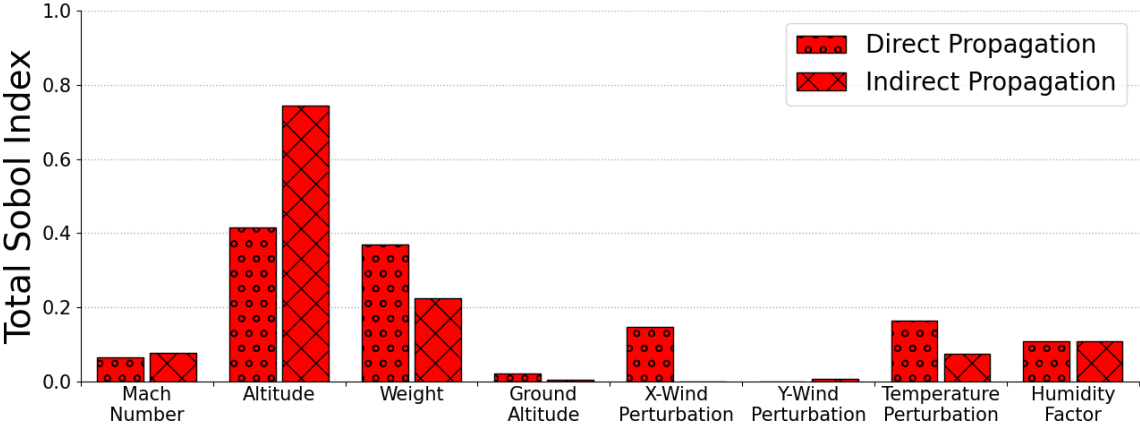
Questions



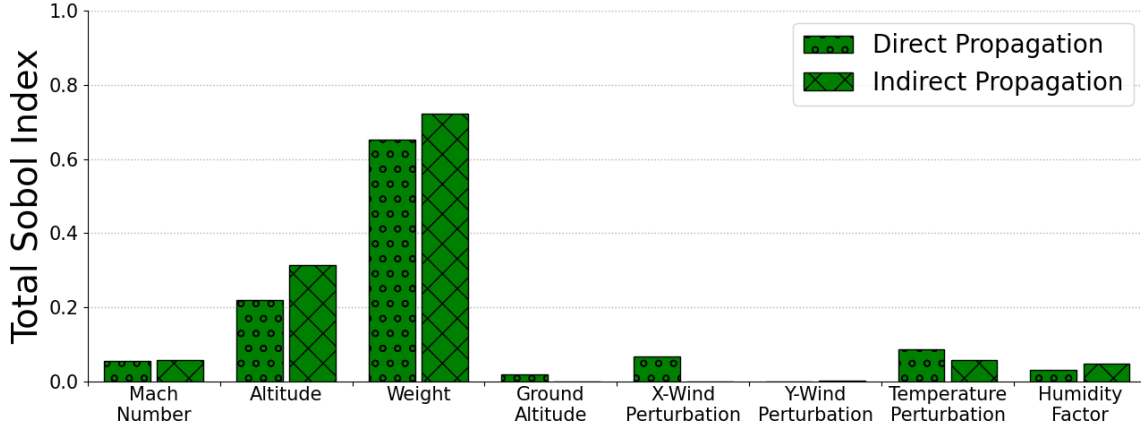
UQ Results, Total Sobol Index Comparison



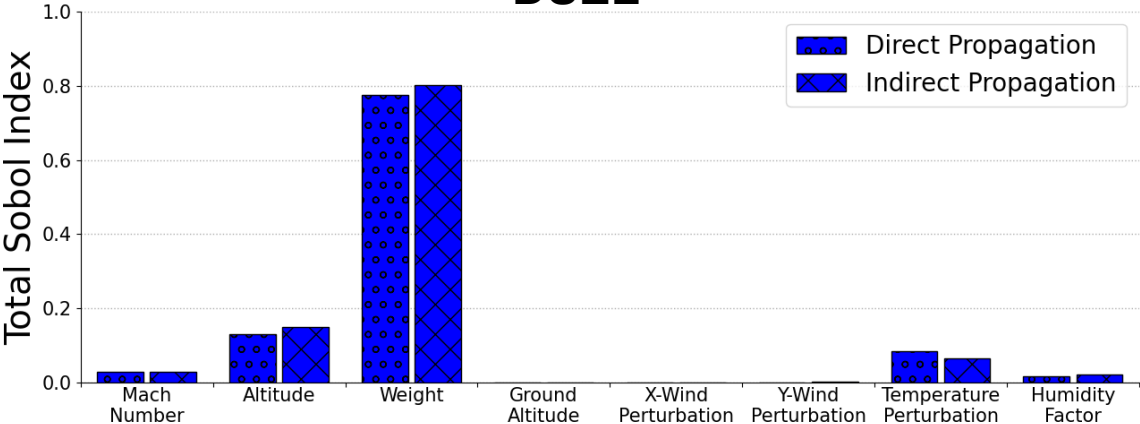
PLdB



BSEL



DSEL



ESEL

