



Uncertainty Modeling for Mars Ascent Vehicle's Aerodynamic Database Development

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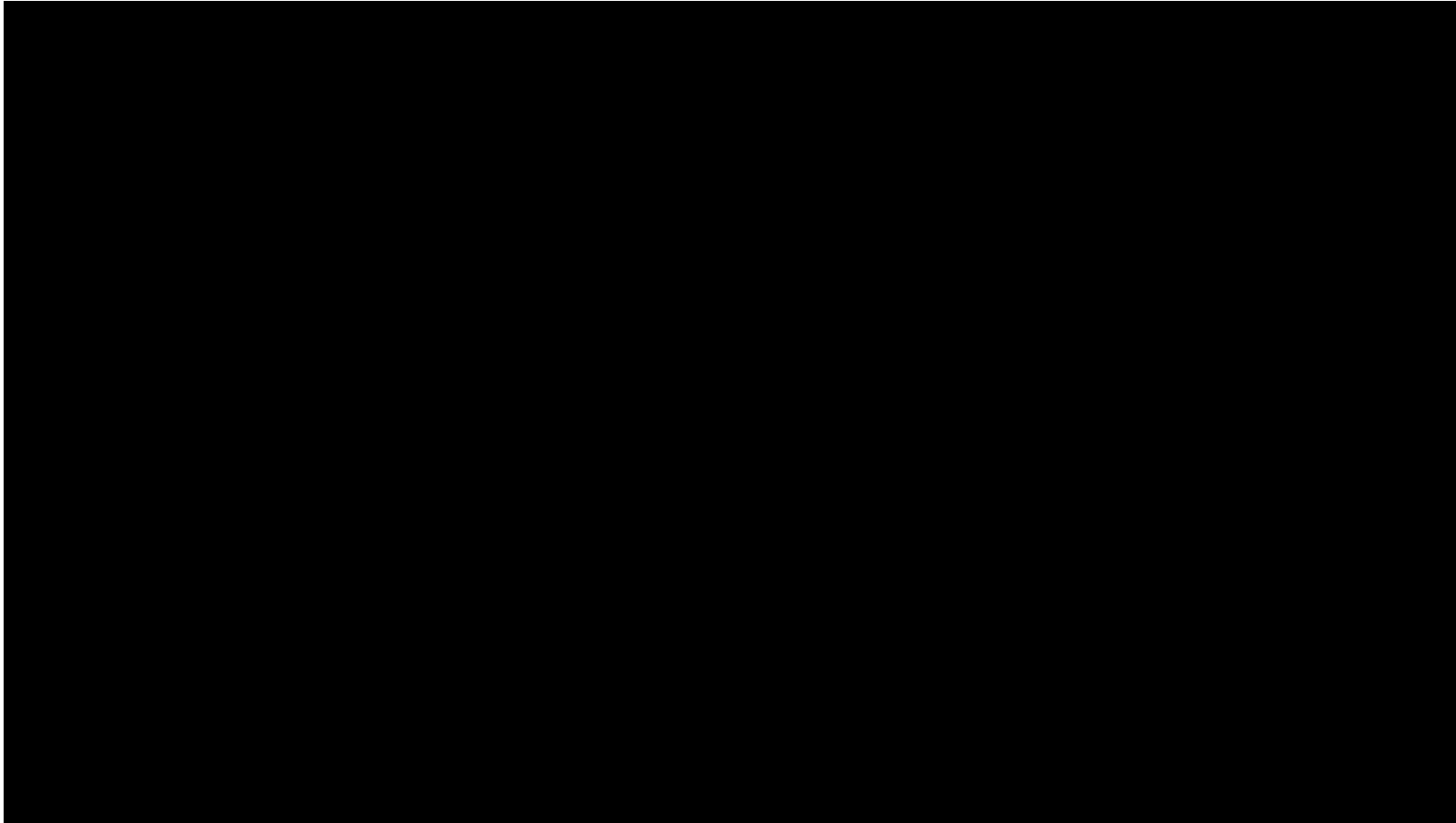
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Orlando, FL, USA

Mars Sample Return Mission

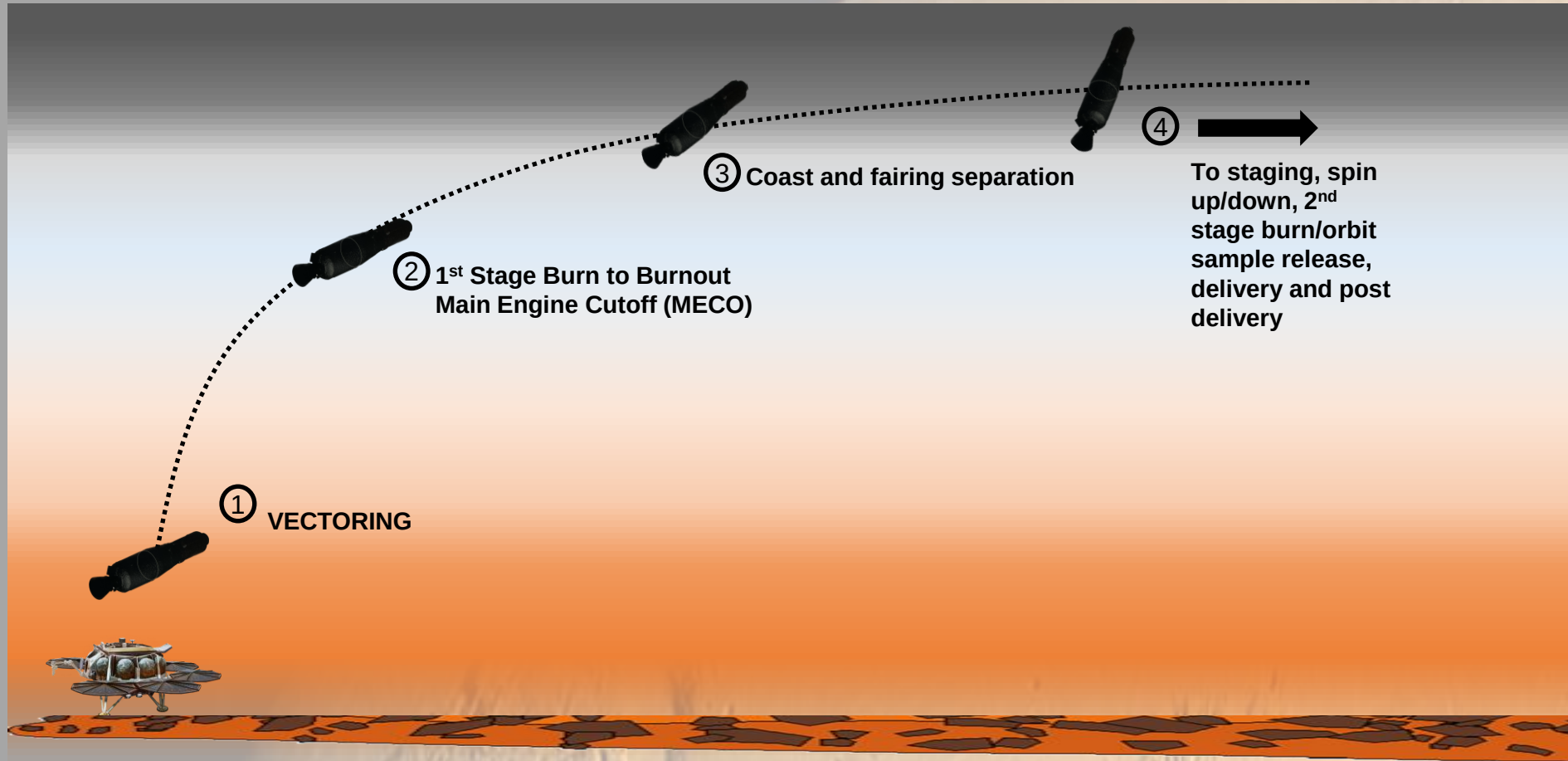
National Aeronautics and Space Administration
Langley Research Center
Mars Ascent Vehicle



Video Link: <https://mars.nasa.gov/msr/multimedia/videos/?v=523>

Mission Operations

National Aeronautics and Space Administration
Langley Research Center
Mars Ascent Vehicle



Mission profile applicable to the aerodynamic database development.

Objectives



- **Develop Mars Ascent Vehicle's (MAV) aerodynamic database ("Aerodatabases") for flight trajectory analysis – POST2 and DSENGS Monte Carlo runs**
- Data obtained from computational tools and wind tunnel experimentation to predict static and dynamic aerodynamic forces and moments for main engine off cases.
- Compare and validate CFD results with 14" Trisonic wind tunnel data to quantify uncertainties on a representative vehicle
- Special focus in the continuum flow regime: Supersonic, transonic and subsonic



Image courtesy of NASA

Launch to Mars: Planned launch in 2028 (on board NASA's Sample Retrieval Lander)

Mars Arrival: 2030

Landing Site: Near the Perseverance rover's landing site in Jezero Crater

Launch from Mars: Early 2030s

Outline

National Aeronautics and Space Administration
Langley Research Center
Mars Ascent Vehicle

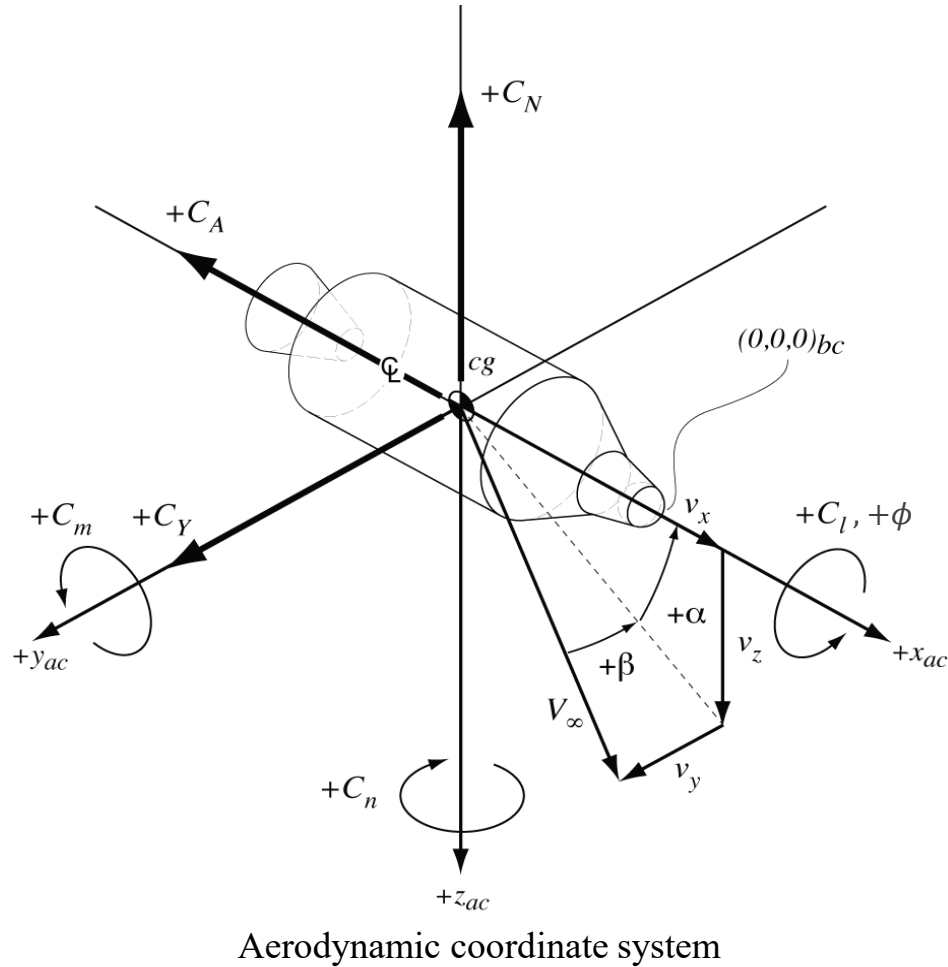


- Objectives
- Mission Operation
- Aerodatabase Architecture
- Static Aerodynamic Data Analysis and Comparison
- Uncertainty Modeling
- Conclusion



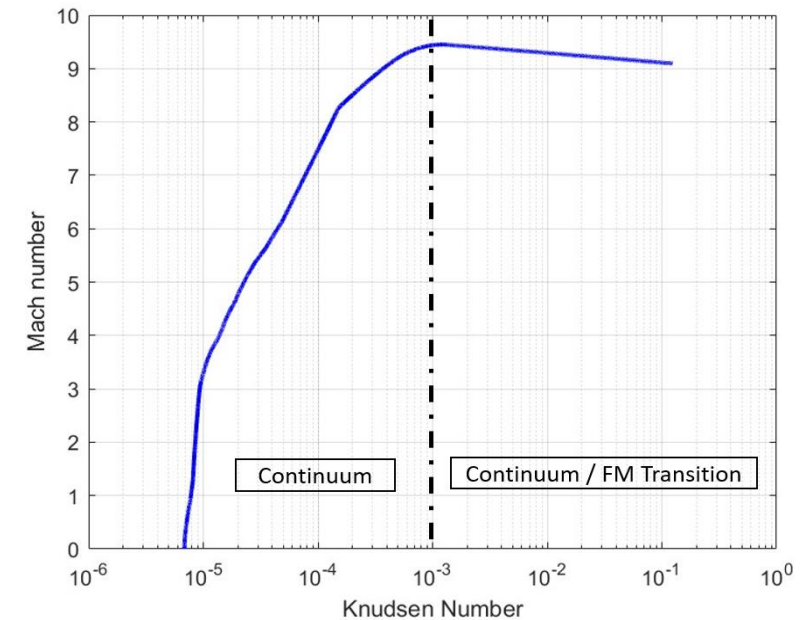
Image courtesy of NASA

Reference Trajectory



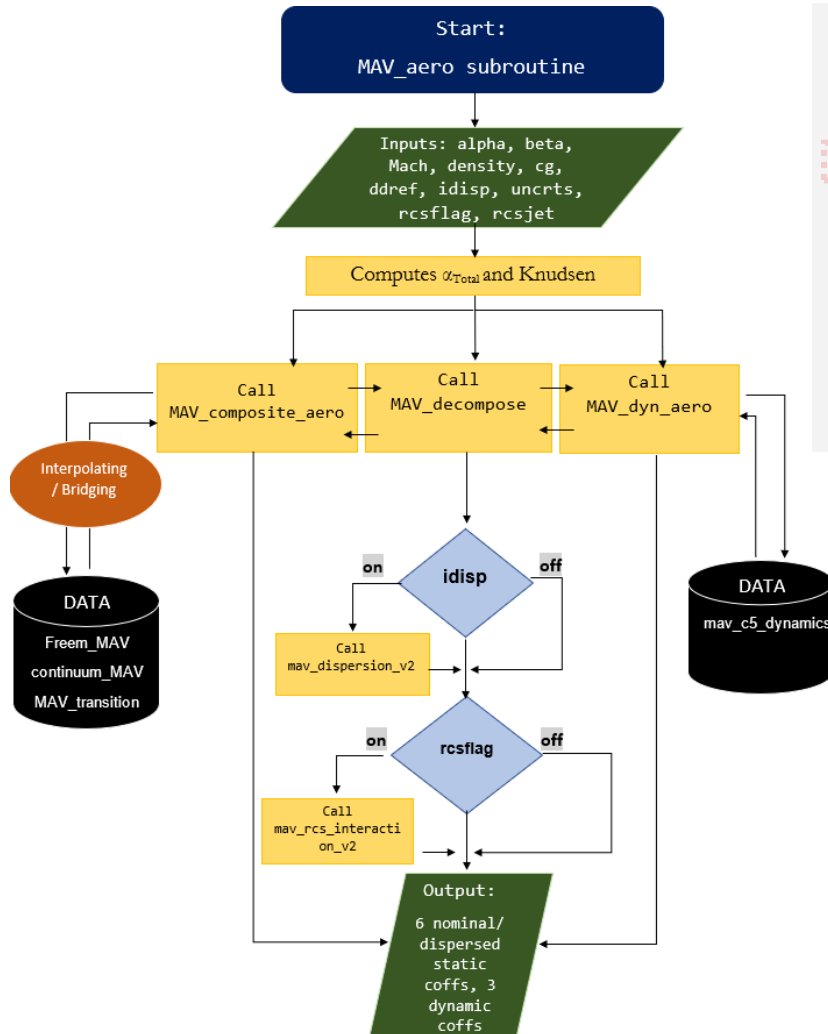
Static aerodynamics in the current aerodatabase

Flight regime	Range covered	Input parameters	Data source
Free Molecular	$Kn \approx 10,000; 0^\circ < \alpha < 30^\circ$	Kn, α, β	MSR_MAV DSMC
Transitional	$0.01 < Kn < 1000; 0^\circ < \alpha < 30^\circ$	Kn, α, β	MSR_MAV DSMC
Hypersonic	$5 < M < 10; Kn < 0.01$	M, α, β	FUN3D
Supersonic	$1.96 < M < 4.99; 0^\circ < \alpha < 20^\circ$	M, α, β	FUN3D + 14" Trisonic WT
Transonic/Subsonic	$0.3 < M < 1.05; 0^\circ < \alpha < 20^\circ$	M, α, β	FUN3D + 14" Trisonic WT



Solid Rocket Motor 1 (SRM1) burnout phase of the trajectory

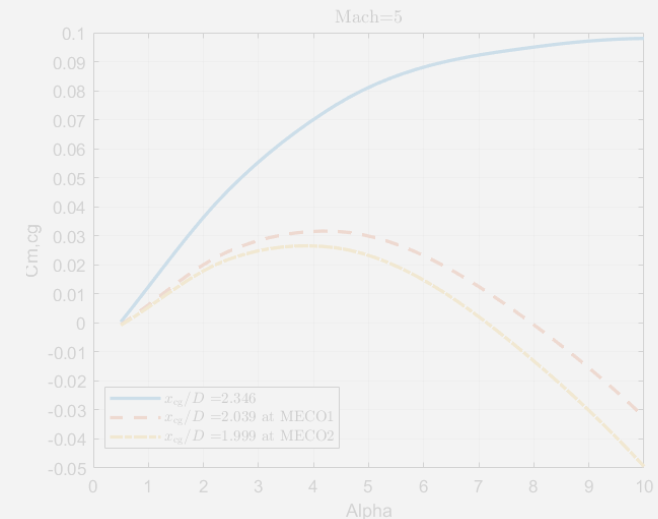
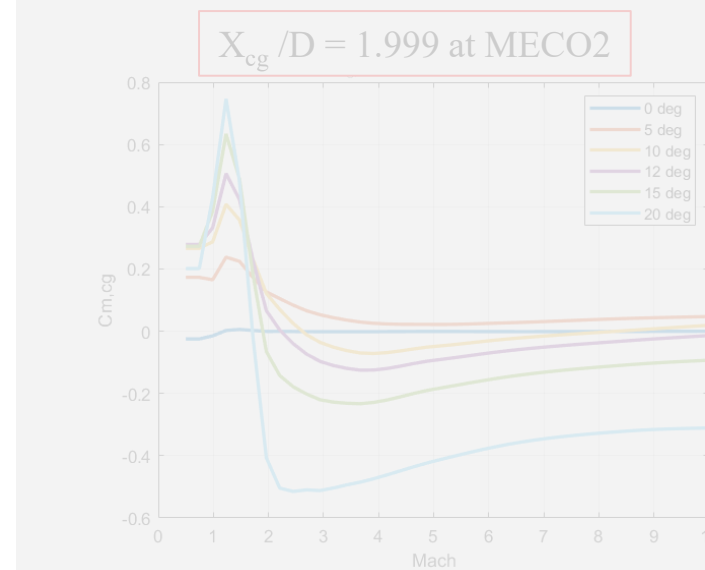
Aerodatabase Architecture



Subroutine	Description
MAV_composite_aero	Static aero C_A , C_N , and C_m in all regimes
decomp_MAV	Decomposes aero to six coefficients using equations
dispersions_MAV_v2	Requires an array of adders and multipliers and returns dispersed aero coefficients
MAV_rcs_interaction_v2	Requires an array of RCS jet on/off and returns the coefficients due to jet interactions
MAV_transition	Tabulates C_A , C_N and C_m for transitional aero conditions from DSMC
MAV_continuum	Tabulates C_A , C_N and C_m for continuum aero conditions from FUN3D
freem_MAV	Tabulates C_A , C_N and C_m for continuum free-molecular conditions
mav_c5_dynamics	Tabulates pitch damp, roll and yaw dynamic coefficients
bridge_MAV	Bridging function between free-molecular aero to hypersonic [12]
parab_MAV	Bi-parabolic function for interpolation for table-look in continuum conditions

$$Kn = \frac{\bar{m}_{wt}}{\sqrt{2}\pi d^2 \rho D_{REF}}$$

$$\text{Subroutine} = \begin{cases} \text{MAV_continuum} & Kn \leq 0.0046 \\ \text{MAV_transition} & 0.0046 < Kn \leq 1000 \\ \text{freem_MAV} & Kn > 1000 \end{cases}$$

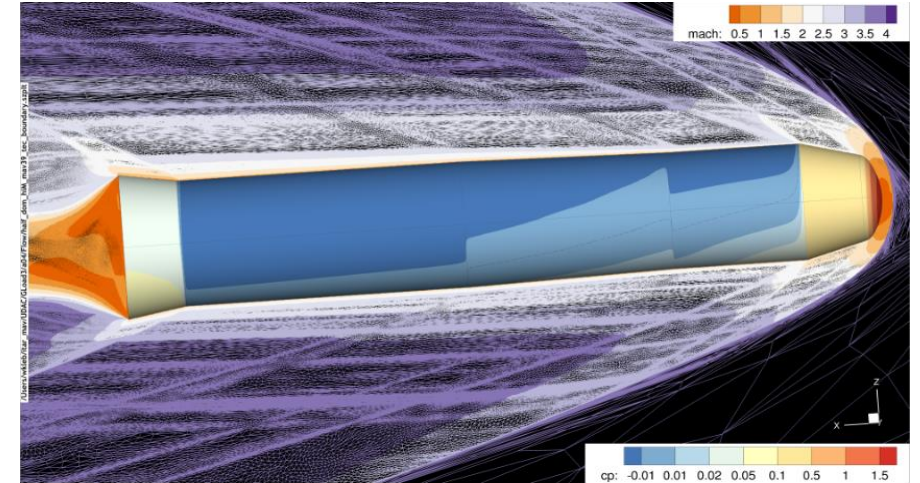


Data Sources



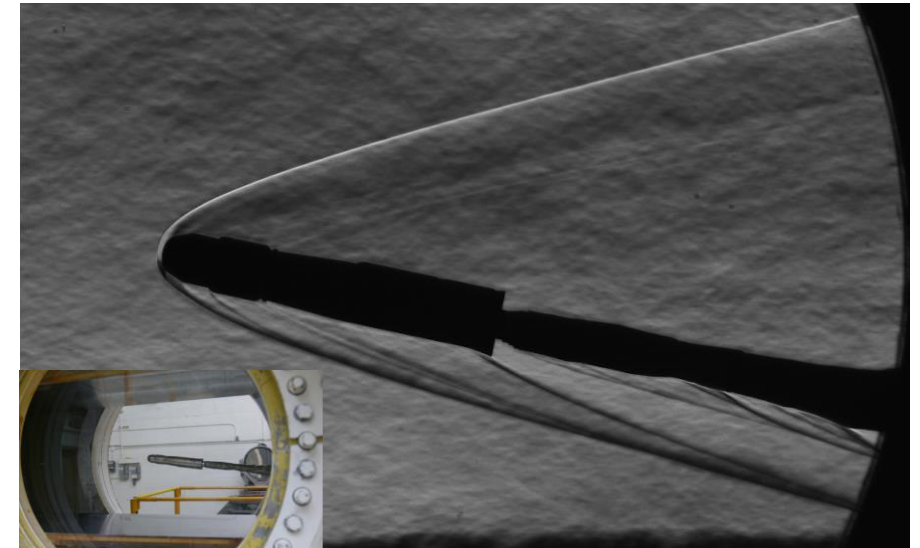
FUN3D –Fully Unstructured Navier Stokes 3D [1]

- Finite volume node-centered discretization.
- Spalart-Allmaras (SA) turbulence model.
- Second order accuracy.
- Gradient-based values use least square/Green-Gauss techniques.
- Sketch-to-Solution process.
- Solution-error-based mesh adaptation technique.
- CFD data (FUN3D) uses all surfaces except for the vehicle base plane.



14 “ Trisonic Wind Tunnel at NASA Marshall Space Flight Center [2]

- 14x14 inch blowdown tunnel from pressure storage to vacuum/atmospheric exhaust.
- Interchangeable test sections for subsonic/transonic ($M=0.2 - 2.5$) and supersonic conditions ($2.55 - 5.00$).
- Controllable diffuser for speed variability. Remote compressor station for air supply.
- Test article made of Inconel alloy 718. Model is 0.0577 scaled.
- WT data has base pressure correction applied to estimate ‘forebody’ surface.



[1] Anderson, W. K., Biedron, R. T., Carlson, J.-R., Derlaga, J. M., Druyor, C. T., Jr., Gnoffo, P. A., Hammond, D. P., Jacobson, K. E., Jones, W. T., Kleb, B., Lee-Rausch, E. M., Nastac, G. C., Nielsen, E. J., Park, M. A., Rumsey, C. L., Thomas, J. L., Thompson, K. B., Walden, A. C., Wang, L., Wood, S. L., and Wood, W. A., “FUN3D Manual: 14.0.2,” NASA TM 2023-0004211, Nov. 2023

[2] Simon, E., “The George C. Marshall Space Flight Center’s 14 by 14-inch Trisonic Wind Tunnel Technical Handbook,” NASA TM X-64624, Nov. 1971

Test Matrix

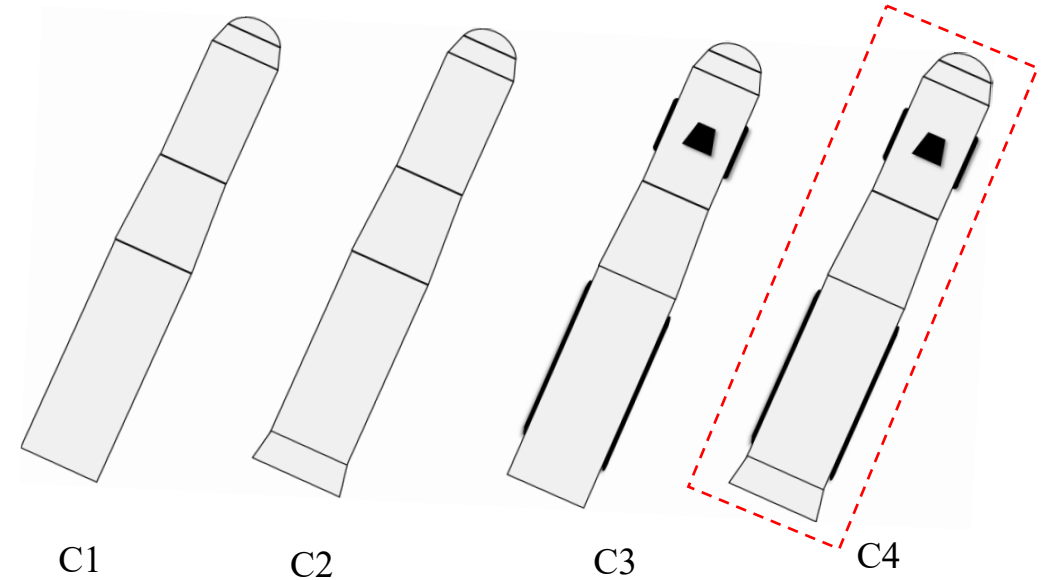


Test Matrix

Methodology	M	α	ϕ
CFD	0.8, 1.05, 1.96, 2.99, and 4.96	-8° to 20°	0° - 180°
Wind Tunnel	0.8, 1.05, 1.96, 2.99, and 4.96	-1.6° to 18°	0° - 180°

Tested configurations

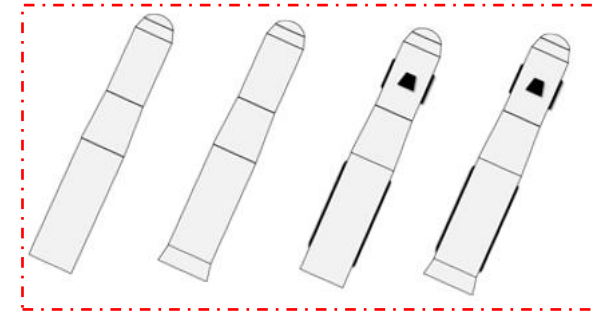
Configuration ID	Description
C1	Smooth with no aft ramp (Baseline)
C2	Smooth with aft ramp
C3	Protuberance with no aft ramp
C4	Protuberance with aft ramp



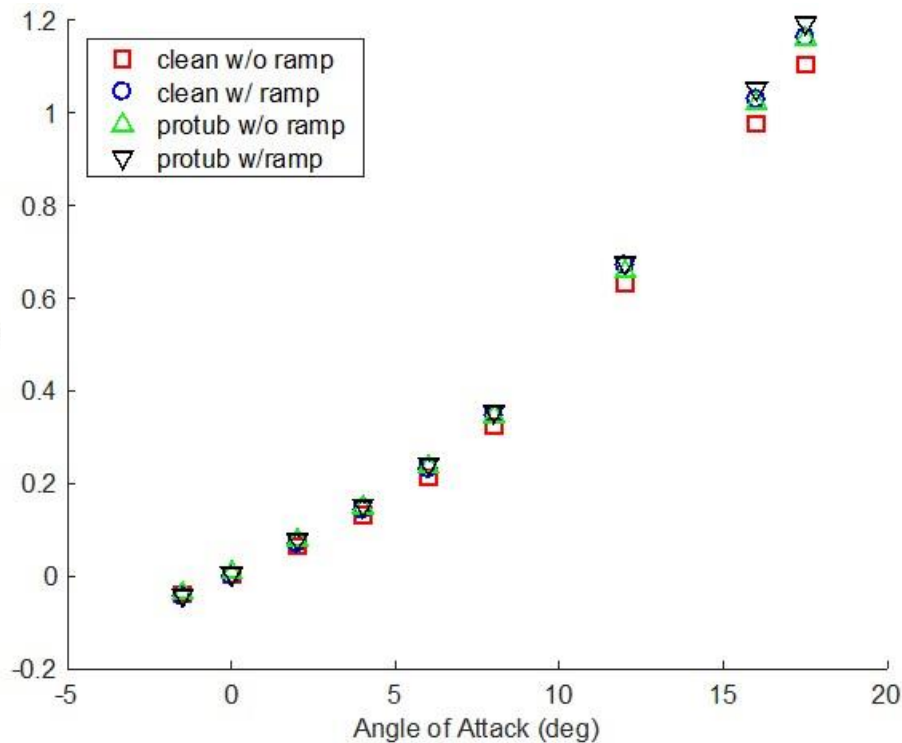
Static Aero Data Analysis



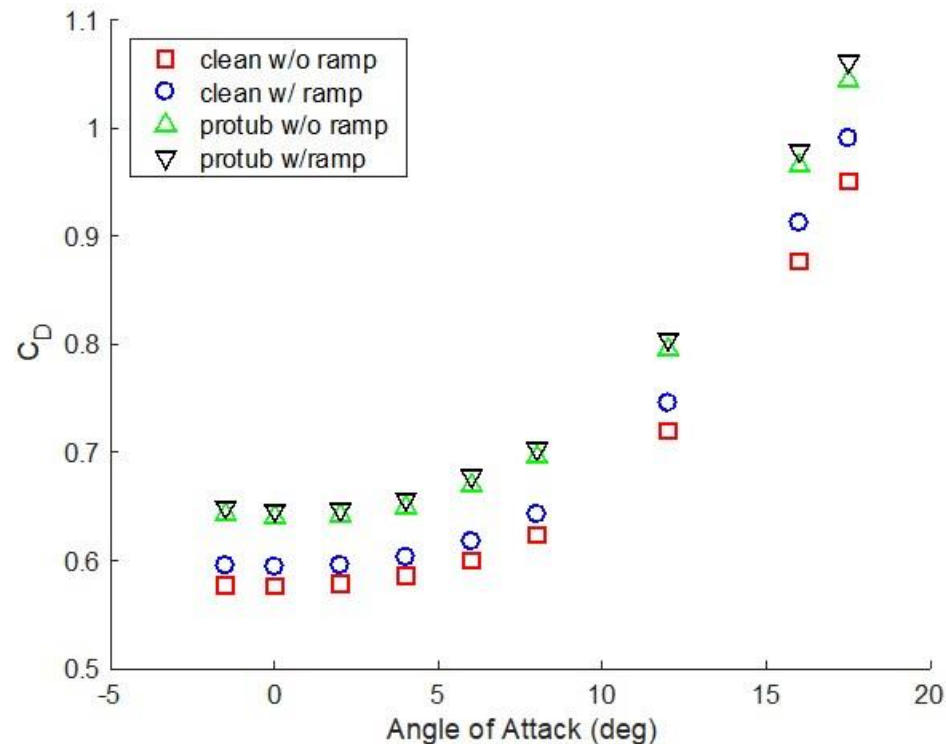
Wind tunnel data: Effects of geometry variations on lift and drag coefficients at Mach = 2.99



Observation: Protuberance effects are greater than ramp effects on drag (consistent supersonically)



$$C_L = -C_A \sin \alpha + C_N \cos \alpha$$

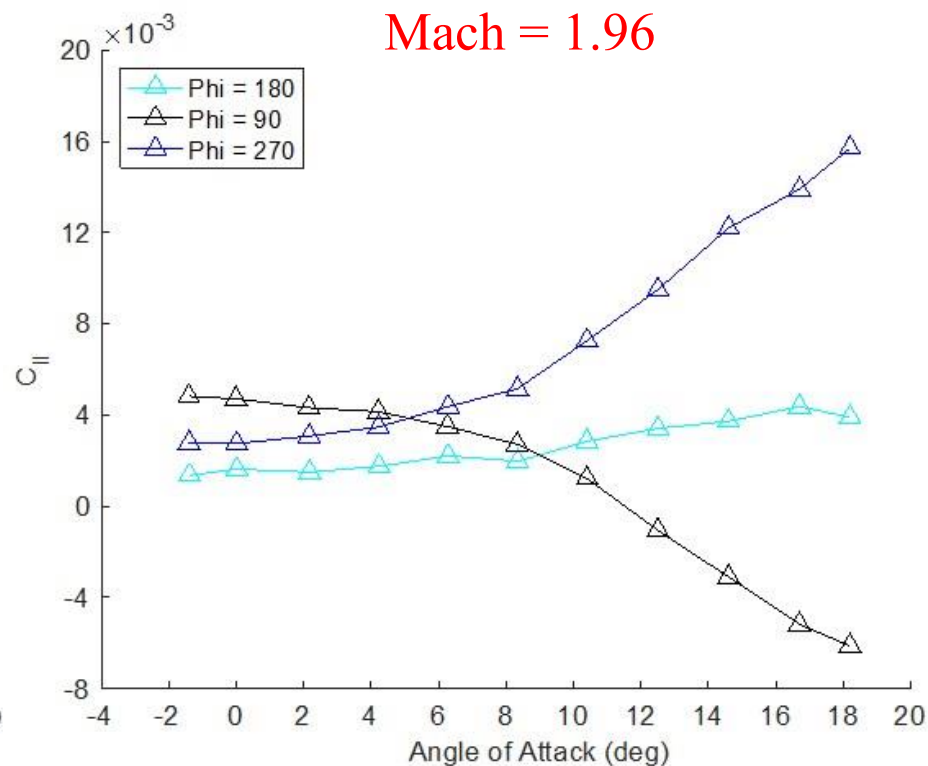
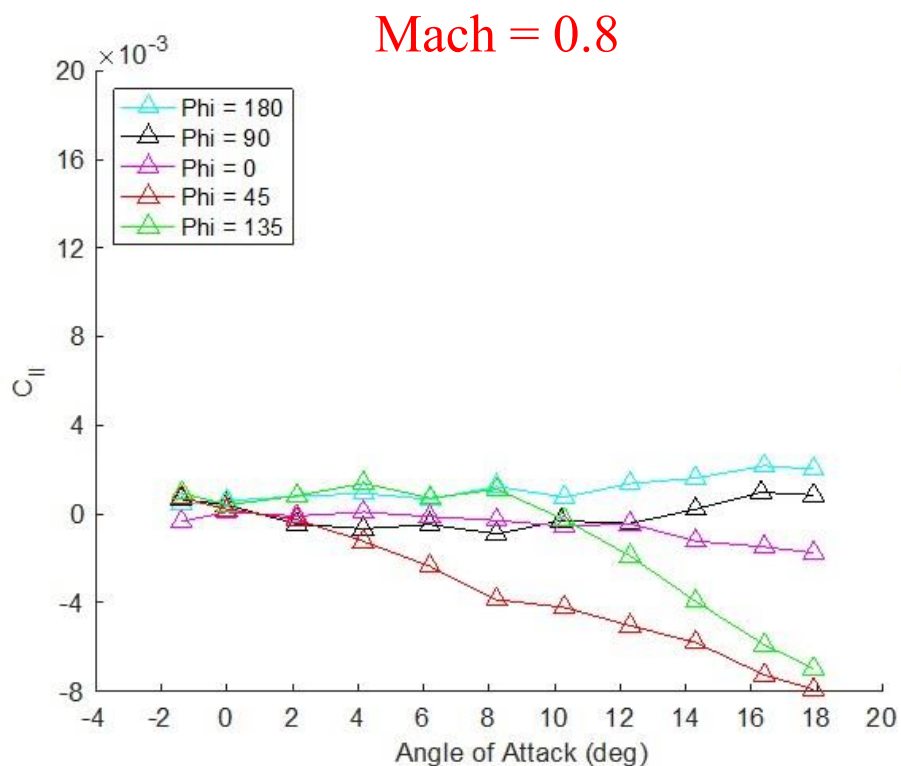
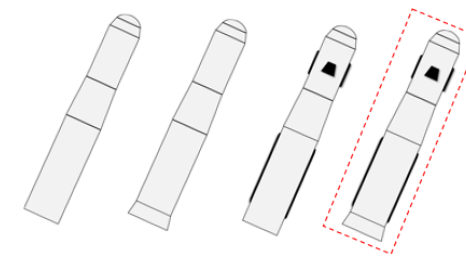


$$C_D = C_A \cos \alpha + C_N \sin \alpha$$

Static Aero Data Analysis



Wind tunnel data: Effects of roll angle ϕ on rolling moment



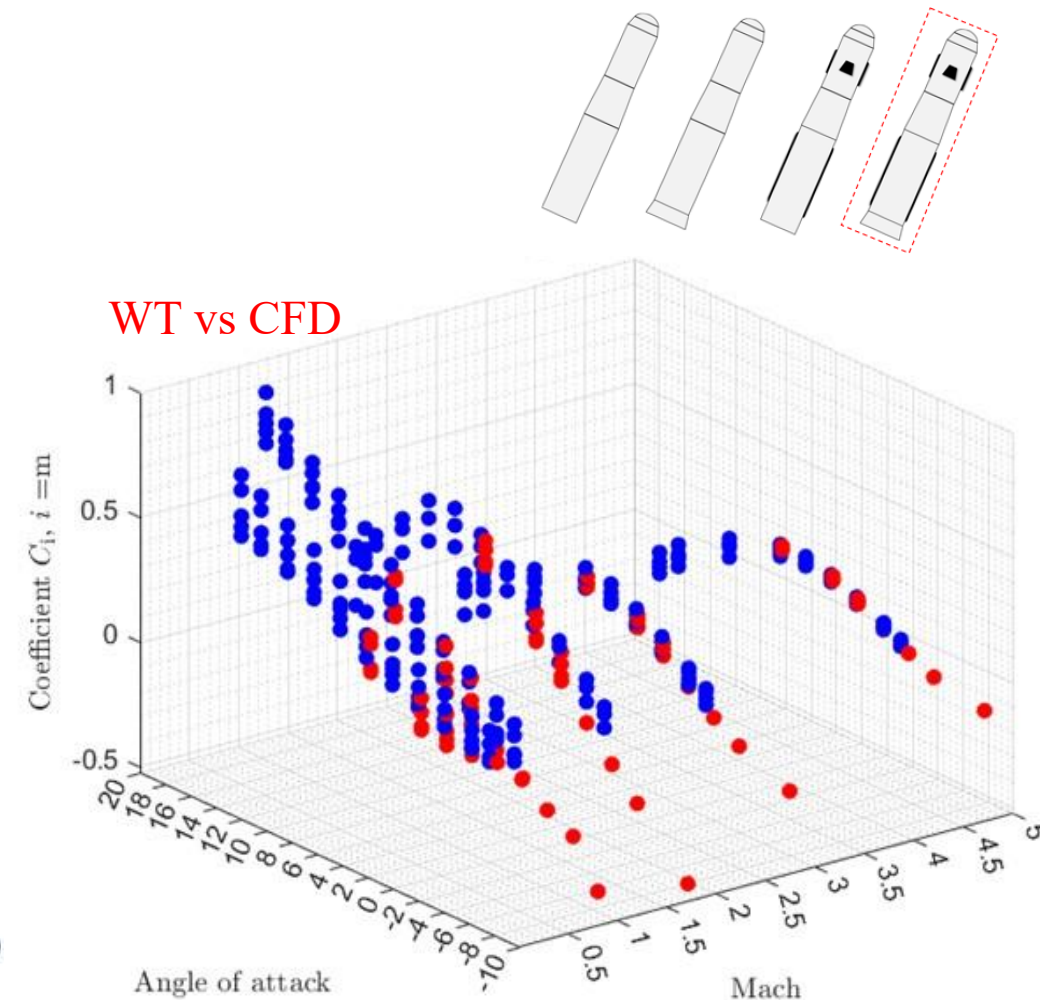
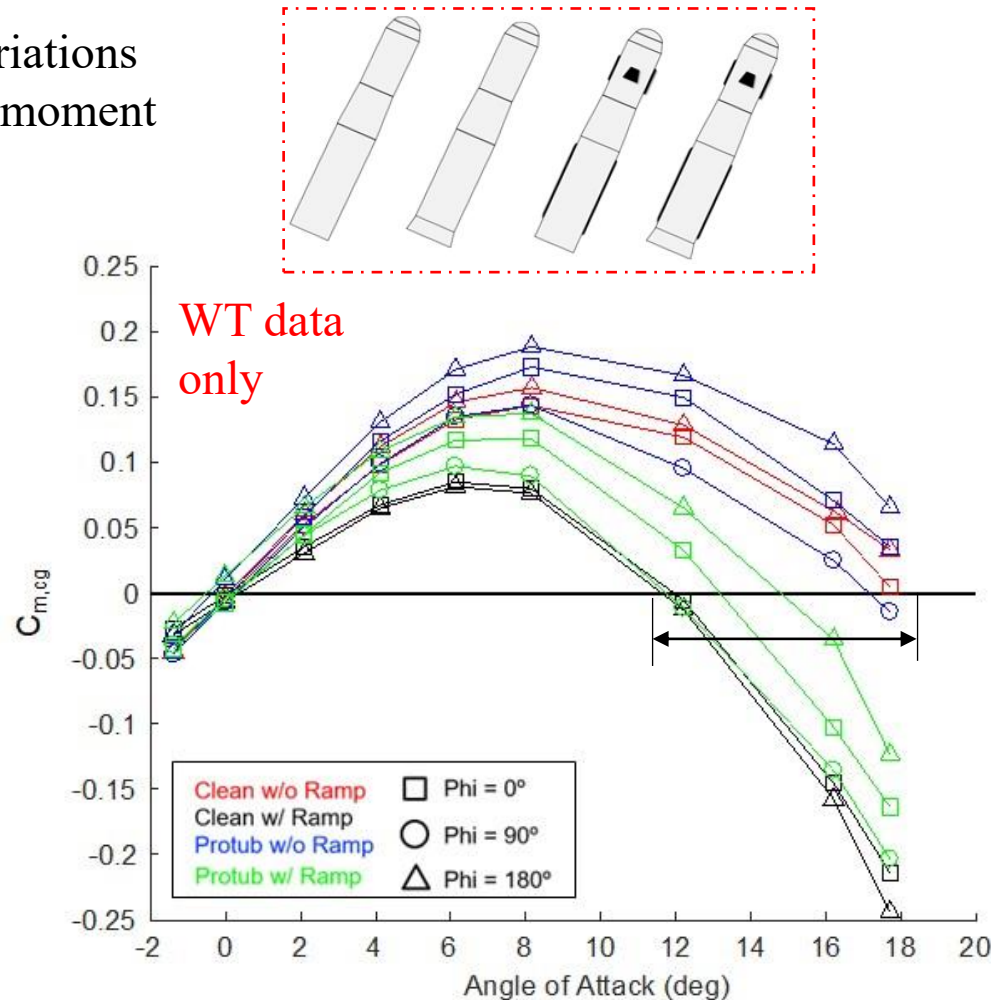
- Rolling moment increases between Mach 0.8 and Mach 1.96
- Rolling moment increases rapidly for $\alpha > 8$ deg, for specific orientations ϕ
- Identification of favorable roll orientation and establishment of uncertainty is important



Static Aero Data Analysis/Comparison

Effects of geometry variations and roll angle on pitch moment coefficient

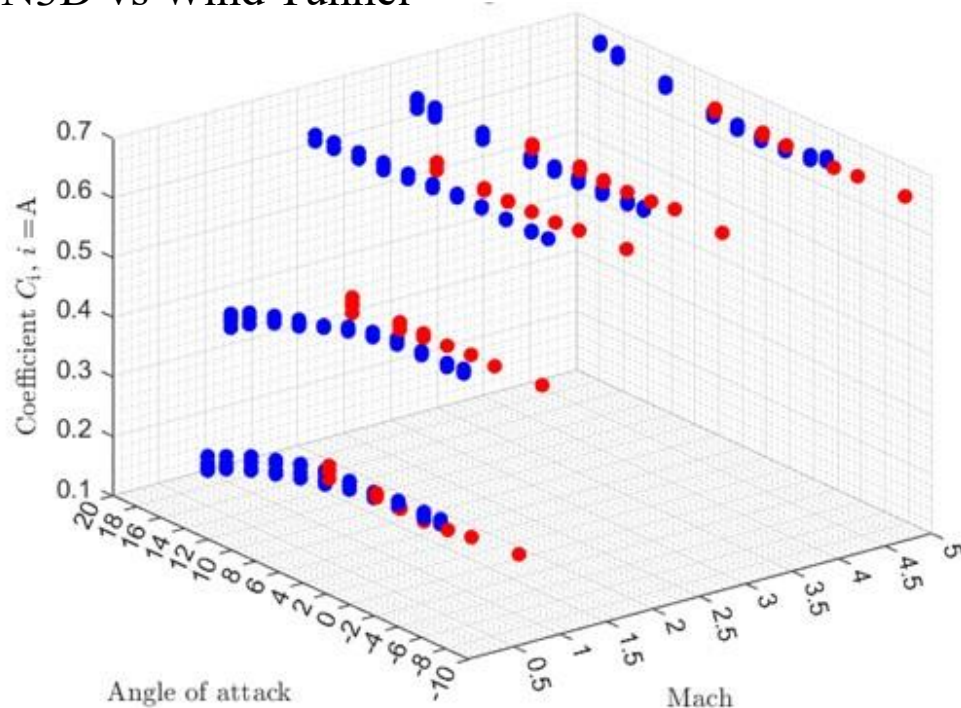
Observation: Two trim points.
Significant effects of varying geometry on trim angle



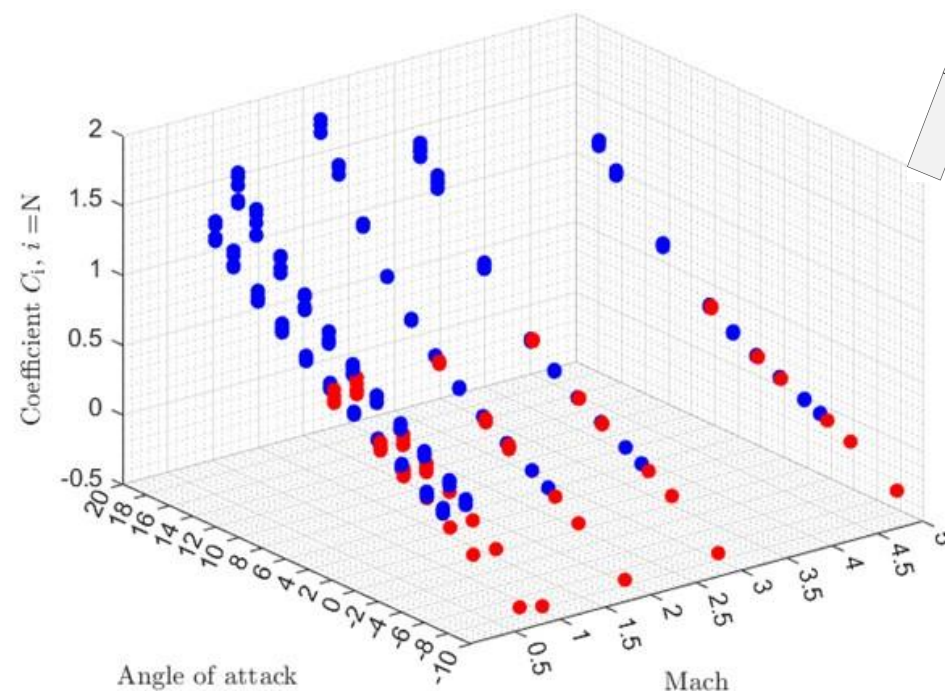
Static Aero Data Comparison



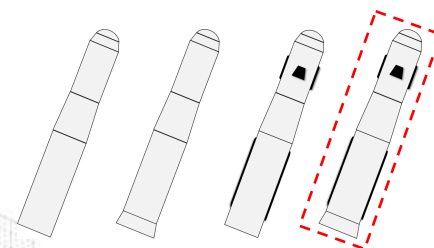
FUN3D vs Wind Tunnel



Axial Force coefficient



Normal force coefficient



● FUN3D
● WT

Observation: High supersonic data tend to match closer to CFD due to the dominance of forebody pressure in the flowfield

Uncertainty Modeling



$$C_{A_{Disp}} = C_A(\alpha, \beta)(1 + U_{C_A}^M)$$

Benefit: Decoupling
of the uncertainties
for 6 static aero

$$C_{N_{Disp}} = [C_N(\alpha, \beta) + U_{C_N}^A] (1 + U_{C_N}^M)$$

$$C_{Y_{Disp}} = [C_Y(\alpha, \beta) + U_{C_Y}^A] (1 + U_{C_Y}^M)$$

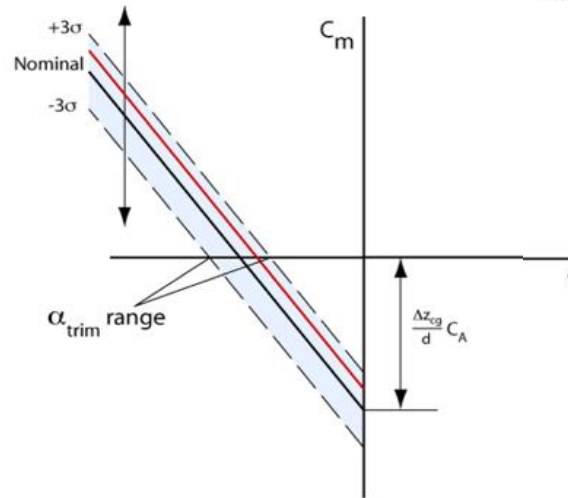
$$C_{m_{Disp}}|_{cg} = \left[C_m(\alpha, \beta)|_{MRP} + \frac{\Delta x}{d} C_N(\alpha, \beta) - \frac{\Delta z}{d} C_A(\alpha, \beta) + U_{C_m}^A \right] (1 + U_{C_m}^M)$$

$$C_{n_{Disp}}|_{cg} = \left[C_n(\alpha, \beta)|_{MRP} + \frac{\Delta x}{d} C_Y(\alpha, \beta) + \frac{\Delta y}{d} C_A(\alpha, \beta) + U_{C_n}^A \right] (1 + U_{C_n}^M)$$

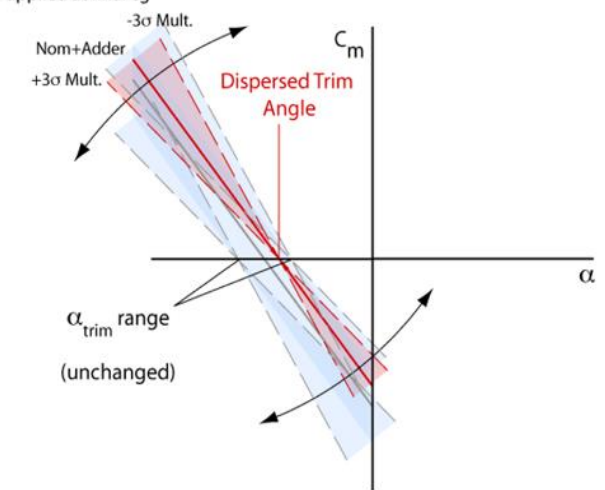
$$C_{l_{Disp}}|_{cg} = \frac{\Delta y}{d} C_N(\alpha, \beta) - \frac{\Delta z}{d} C_Y(\alpha, \beta) + U_{C_l}^A$$

Adders and multipliers disperse intercepts and local slope separately

Step1: Disperse Trim Angle
Adder applied at final cg



Step2: Disperses Slope
Multiplier applied at final cg



➤ Adders, U_C^A result in trim angle shifts

➤ Use data comparison to quantify and refine uncertainties

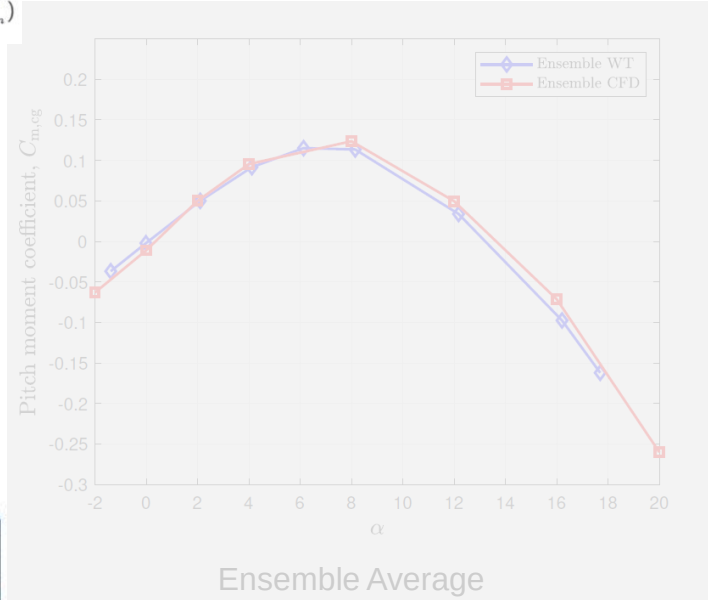
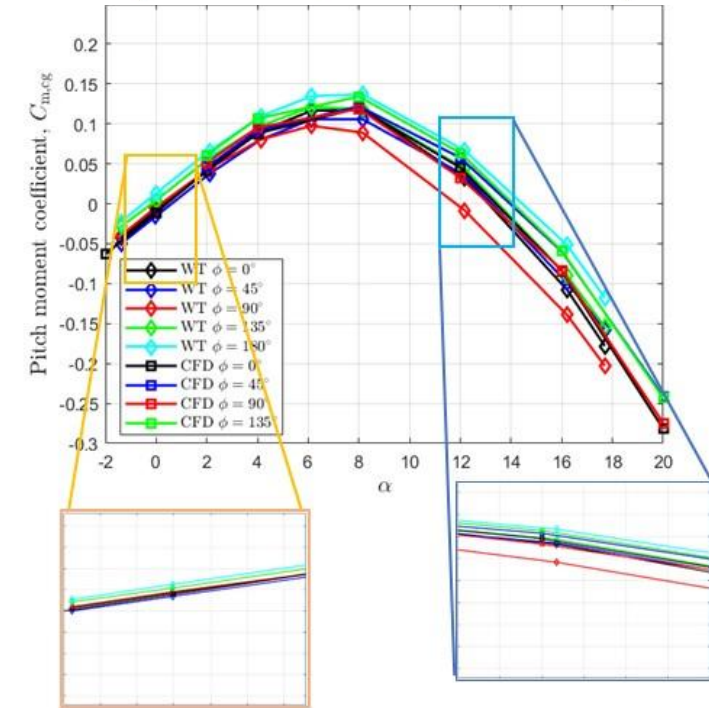
➤ Multipliers: U_C^M result in curve slopes

➤ Uncertainties cover a range of Mach number, roll angle to capture protuberance effects, and some alpha functionality

Uncertainty Modeling



$$C_{m_{Disp}}|_{cg} = \left[C_m(\alpha, \beta)|_{MRP} + \frac{\Delta x}{d} C_N(\alpha, \beta) - \frac{\Delta z}{d} C_A(\alpha, \beta) + U_{C_m}^A \right] (1 + U_{C_m}^M)$$

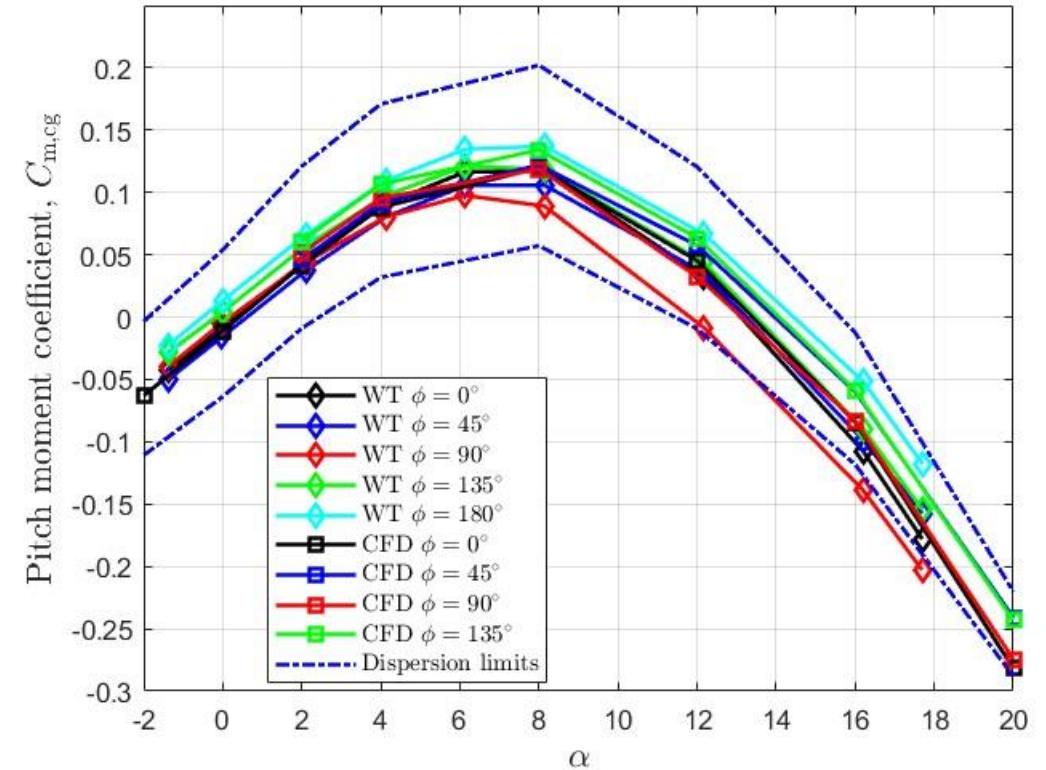
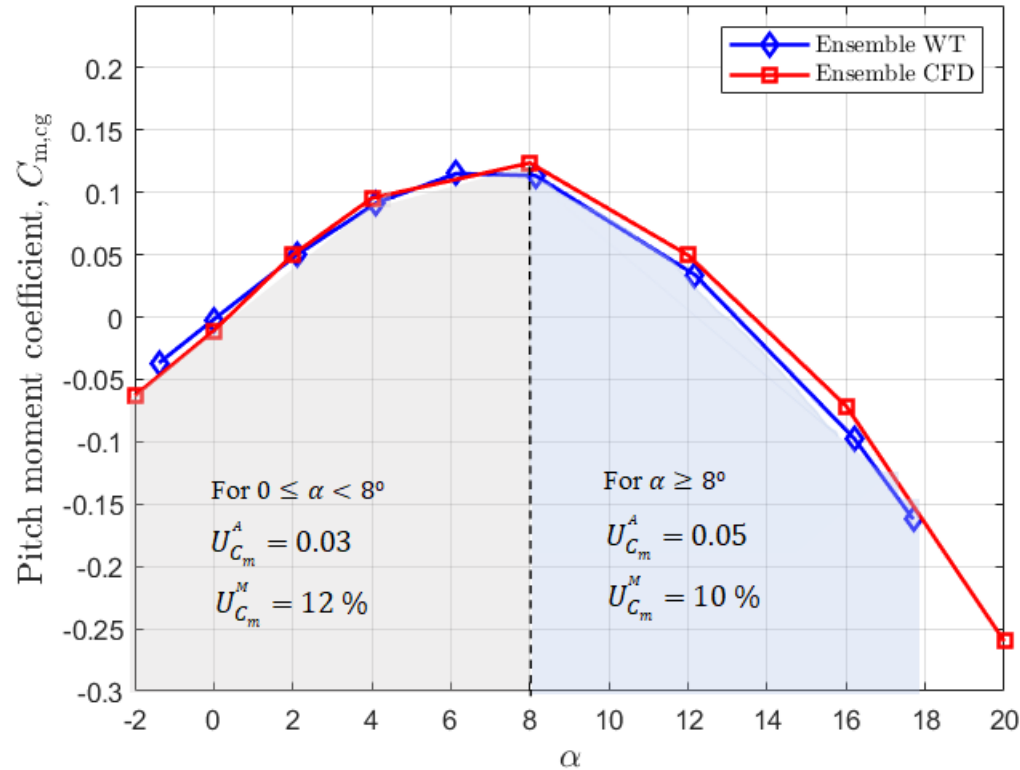


Adder uncertainty, $U_{C_m}^A$, is obtained from 3σ at trim points where $\sigma = \frac{\Sigma(C_{m_i} - \bar{C}_m)^2}{N}$.

These are used to disperse local points of the linear slopes

Multiplier uncertainty, $U_{C_m}^M$, is obtained by matching slopes of linear fitted functions

Uncertainty Modeling



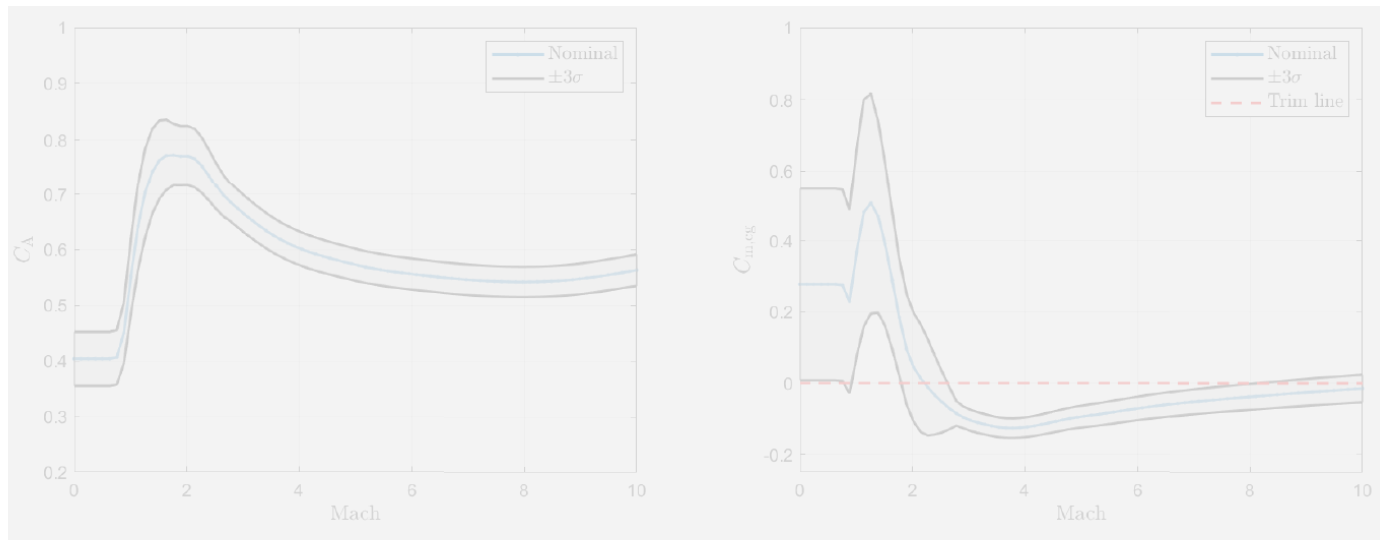
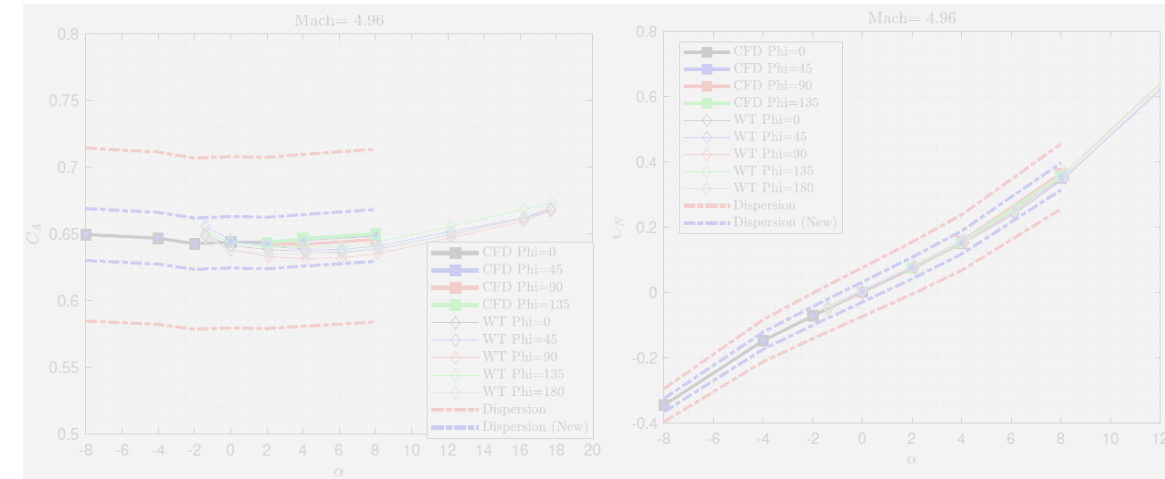
Aerodatabase Input: Monte Carlo simulations for all adders and multipliers (values ranging from -1 to 1)

Uncertainty Modeling



MAVs derived static aerodynamic 3σ uncertainties

Mach	C_A		C_Y		C_N		C_{II}		$C_{m, cg}$		$C_{n, cg}$	
	U^A	U^M	U^A	U^M	U^A	U^M	U^A	U^M	U^A	U^M	U^A	U^M
0.8	N/A $\pm 12\%$		$0.04 \pm 7\%$		$0.10 \pm 7\%$		$0.01 \pm \text{N/A}$		$0.15 \pm 25\%$		$0.15 \pm 3\%$	
1.05	N/A $\pm 12\%$		$0.04 \pm 7\%$		$0.10 \pm 5\%$		$0.01 \pm \text{N/A}$		$0.20 \pm 25\%$		$0.20 \pm 3\%$	
1.96	N/A $\pm 7\%$		$0.03 \pm 7\%$		$0.05 \pm 5\%$		$0.01 \pm \text{N/A}$		$0.15 \pm 15\%$		$0.05 \pm 3\%$	
2.99	N/A $\pm 5\%$		$0.03 \pm 7\%$		$0.05 \pm 5\%$		$0.01 \pm \text{N/A}$		$0.05 \pm 12\%$		$0.05 \pm 3\%$	
4.96	N/A $\pm 3\%$		$0.03 \pm 7\%$		$0.05 \pm 5\%$		$0.01 \pm \text{N/A}$		$0.03 \pm 12\%, \alpha \leq 8^\circ$		$0.03 \pm 3\%$	
									$0.05 \pm 10\%, \alpha > 8^\circ$			



- $\pm 3\sigma$ uncertainties shown with blue dashed lines, based on current (and consistent with Mars flight heritage) $\pm 10\%$ for supersonic C_A [3-4]
- Wind tunnel analysis yield higher fidelity uncertainties.

Conclusion



- Demonstrated an overview of MAV's aerodatabase development
- Observed the effects of vehicle geometry and roll angle on forces and moments
- Provided data comparison between CFD and WT datasets.
- Derived refined adders/multipliers revised based on FUN3D and 14" Trisonic WT data
- Uncertainties are expanded as function of roll angle to capture protuberance effects
- Uncertainties also captured Mach effects and angle of attack effects for unique cases (pitch moment at $M=5$)

Future Work



➤ Compare current uncertainty modeling with other methodologies [5]:

1. Identify possible contributions to the uncertainty model for aerodynamic coefficients
2. Develop individual contributions to the uncertainty model for the aerodynamic coefficients using statistical approaches
3. Combine additive and root sum square (RSS) methods to develop aerodynamic uncertainties

$$k = \sqrt{3}$$

$$M.F = 2$$

The proposed model:

$$uC_i = \Delta_{e2m} + \Delta_{cfg} + \Delta_{\phi} + \Delta_{GS} + M.F \sqrt{(k\sigma_{CFD})^2 + (k\sigma_{WT})^2}$$

$k = \text{confidence level}$
 $M.F = \text{Margin Factor}$

$$uC_i = \Delta_{e2m} + \Delta_{cfg} + \Delta_{\phi} + \Delta_{GS} + M.F \sqrt{\boxed{(k\sigma_{grid})^2 + (k\sigma_{de})^2 + (k\sigma_{fs})^2} + \boxed{(k\sigma_{cal})^2 + (k\sigma_{mb})^2 + (k\sigma_{blkg})^2 + (k\sigma_{rep})^2}}$$