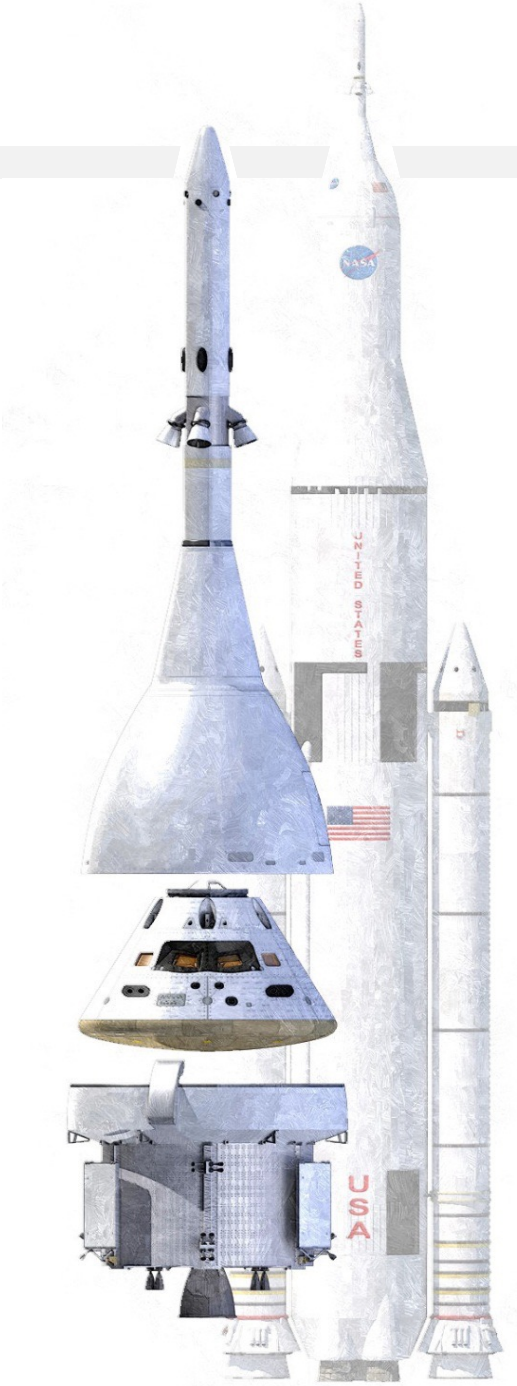


Aerodynamic Modeling for EDL

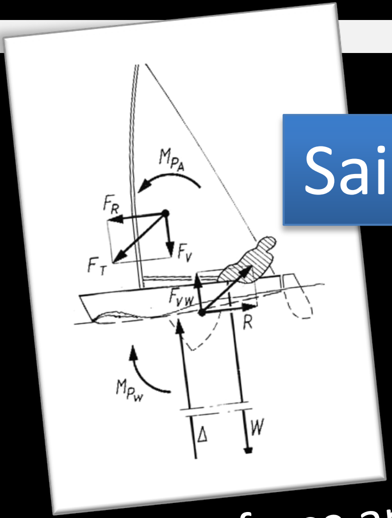
Briefing to Summer Students and the NESC Academy

July 21, 2021

Karen Bibb
Aerothermodynamics Branch, LaRC
Orion Crew Module Aerodatabase Technical Lead

How did I end up studying Aerothermodynamics?

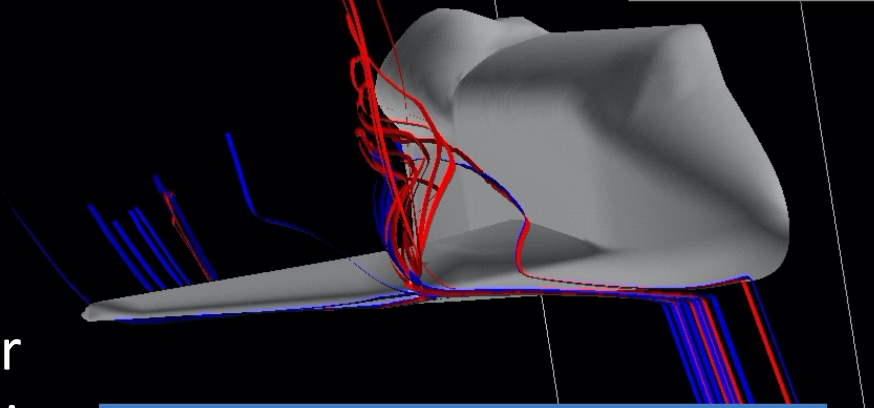
Sailing → Aerodynamics



My first force and moment diagram

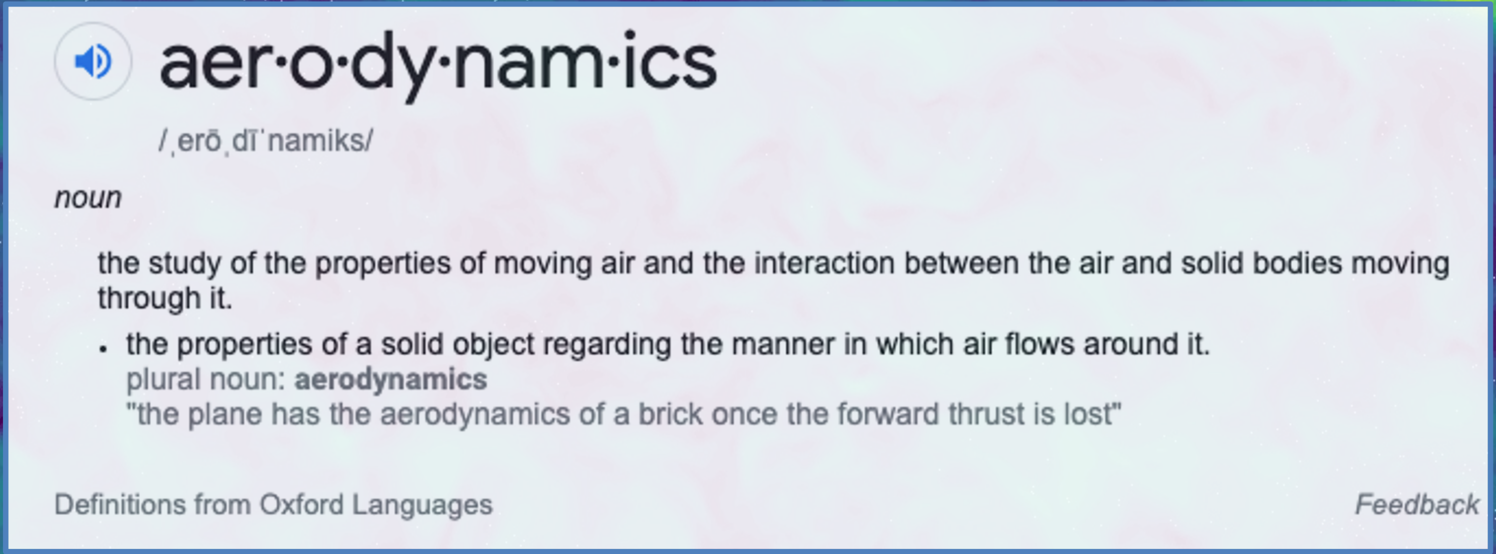
→ Aerospace Engineering
→ Combustion

Sail Aerodynamics for High School Science Fairs



→ Aerothermodynamics

Aerodynamics is…



aer·o·dy·nam·ics

/ˌerōˌdīˈnamiks/

noun

the study of the properties of moving air and the interaction between the air and solid bodies moving through it.

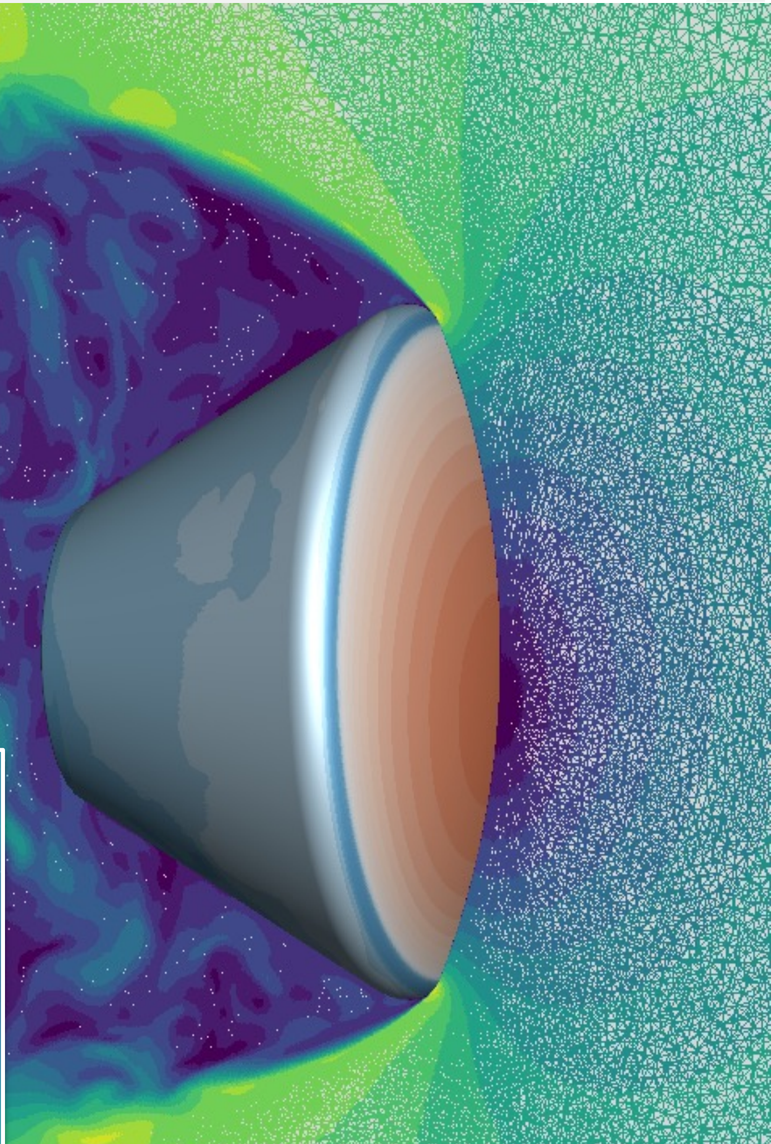
- the properties of a solid object regarding the manner in which air flows around it.
  plural noun: **aerodynamics**
  "the plane has the aerodynamics of a brick once the forward thrust is lost"

Definitions from Oxford Languages

Feedback

What are we covering today?

- How is aerodynamic modeling used in EDL?
- How do we develop aerodynamic predictions?
- How do we communicate aerodynamics to the rest of the EDL disciplines?

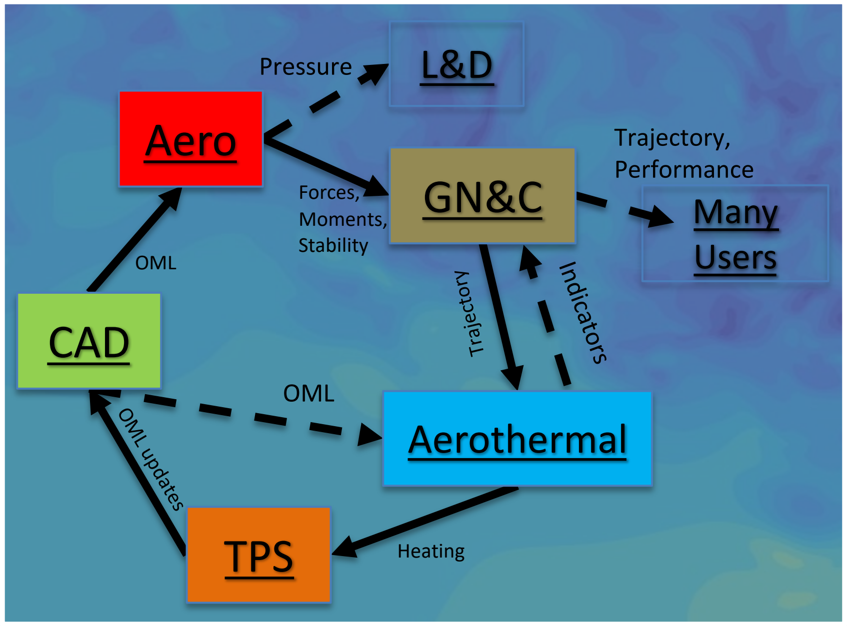


Orion capsule, subsonic, FUN3D DES
Karen Bibb

Aerodynamics in Entry, Descent, and Landing

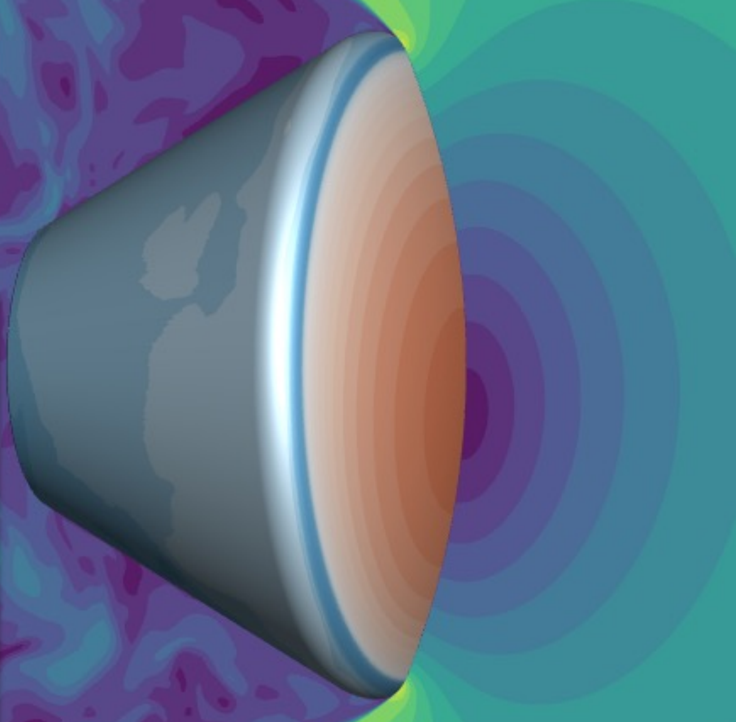
EDL aero is an iterative process

- Start with low fidelity, high uncertainty
- Increase fidelity of analysis, configuration
  - Enable missions
  - Lower uncertainty, risk



Proper characterization of vehicle aerodynamics is critical to EDL

- Large uncertainties / too conservative can keep a design from closing, add to propellant weight, overestimate risk (too many tumbles)
- Not conservative enough leads to vehicle operating outside its design and associated failures.

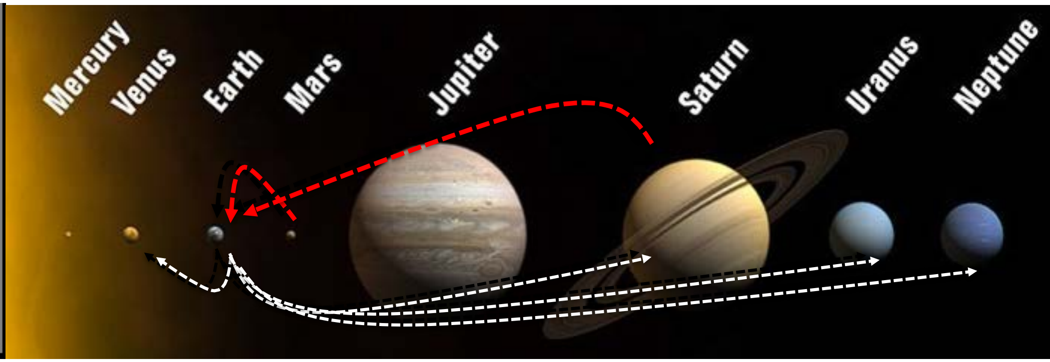


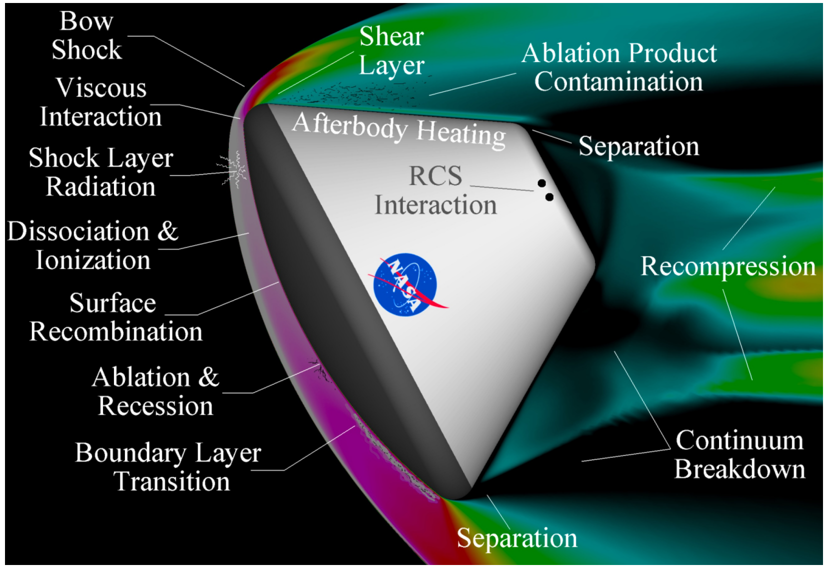
Orion capsule, subsonic, FUN3D DES
Karen Bibb

EDL Aerodynamics

Understand the mission

- Configuration
- Mission phases
- Key parameters for each phase



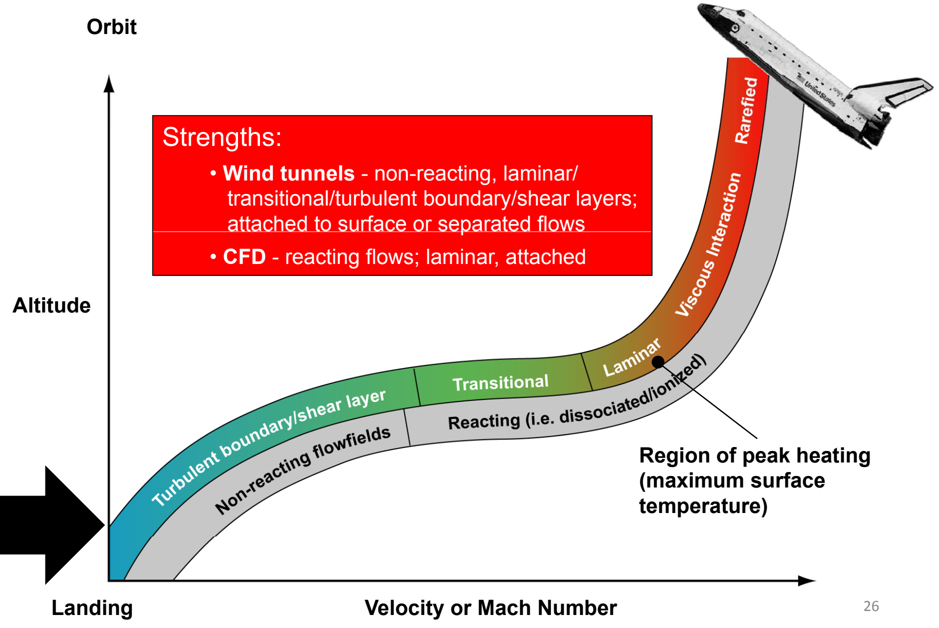


Understand the physics

- Basic important parameters
- Mission-specific complexities

Understand your analysis tools

- Range of applicability
- Accuracy/Uncertainty
- Resource requirements

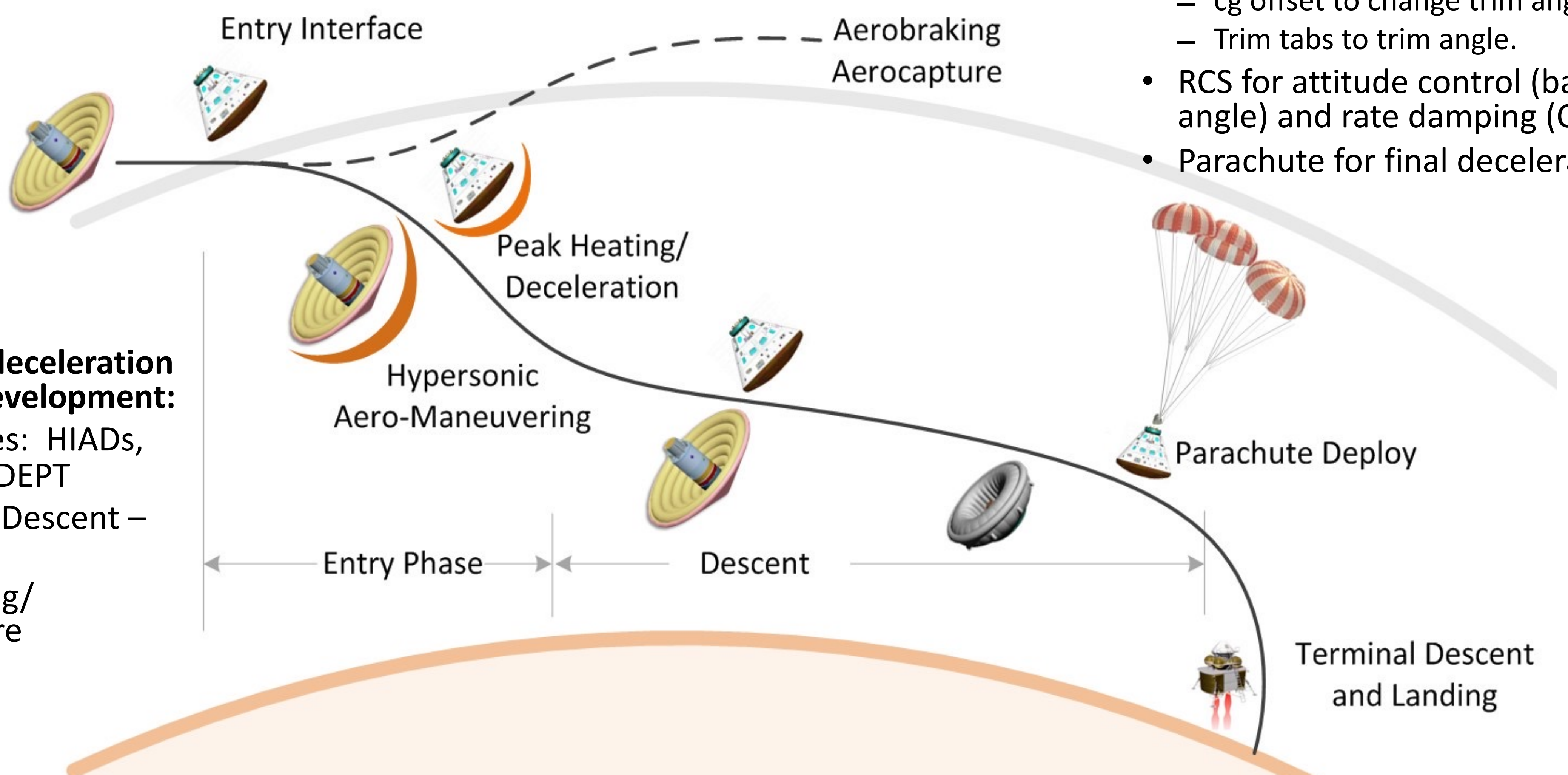


Strengths:

- **Wind tunnels** - non-reacting, laminar/ transitional/turbulent boundary/shear layers; attached to surface or separated flows
- **CFD** - reacting flows; laminar, attached

Missions

Basic capsule entry:
- Aerodynamic deceleration (C_D)
- L/D for range control
  - cg offset to change trim angle
  - Trim tabs to trim angle.
- RCS for attitude control (bank angle) and rate damping (Cmq)
- Parachute for final deceleration



Augmented deceleration systems in development:
- Deployables: HIADs, ballutes, ADEPT
- Propulsive Descent – SRP
- Aerobraking/ Aerocapture

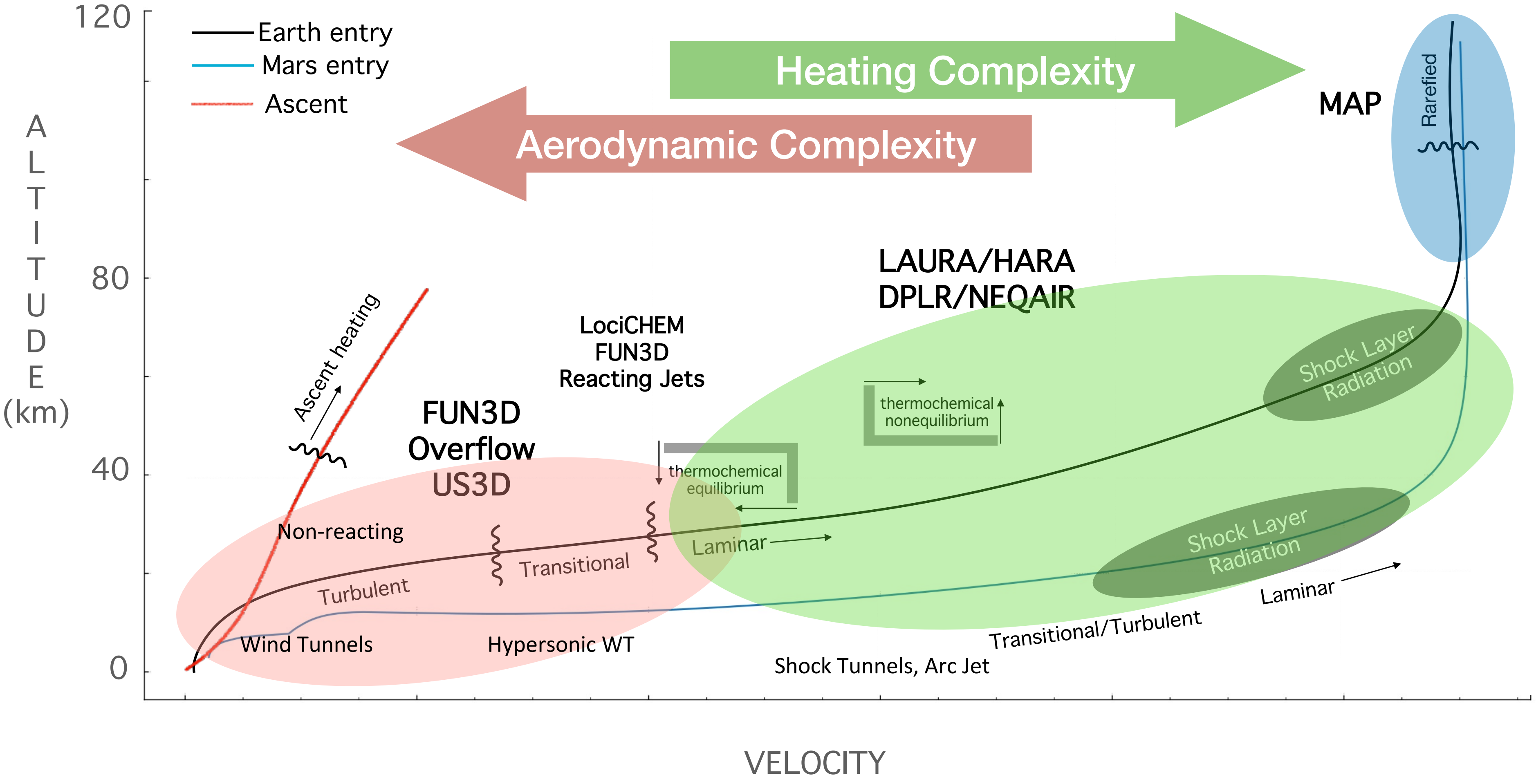
Entry Physics and Tools

Understand the physics

- Rarefied
- Hypersonic
- Supersonic
- Transonic
- Subsonic

Understand your analysis tools

- Computational
- Ground Based
- Flight



Entry Physics and Tools

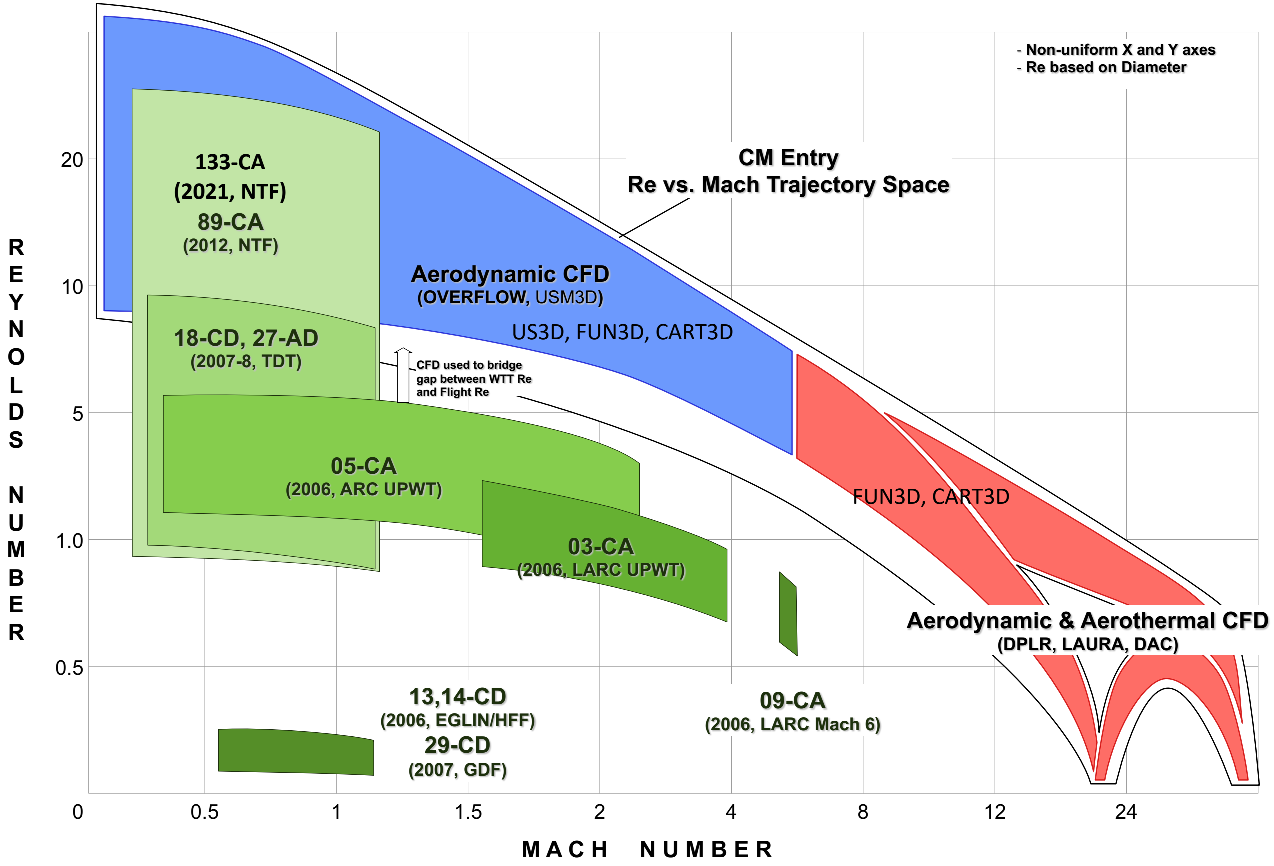
Understand the physics

- Basic important parameters
  - Drag, particularly subsonic
  - L/D, trim angle
  - Dynamic stability (particularly under chutes)
- Mission-specific complexities
  - Orion: Large range of trajectories possible, abort and entry conditions differ
  - LOFTID: HIAD flexible structure
- Accuracy/Uncertainty
  - Subsonic drag is very difficult. Need WT for baseline

Understand your analysis tools

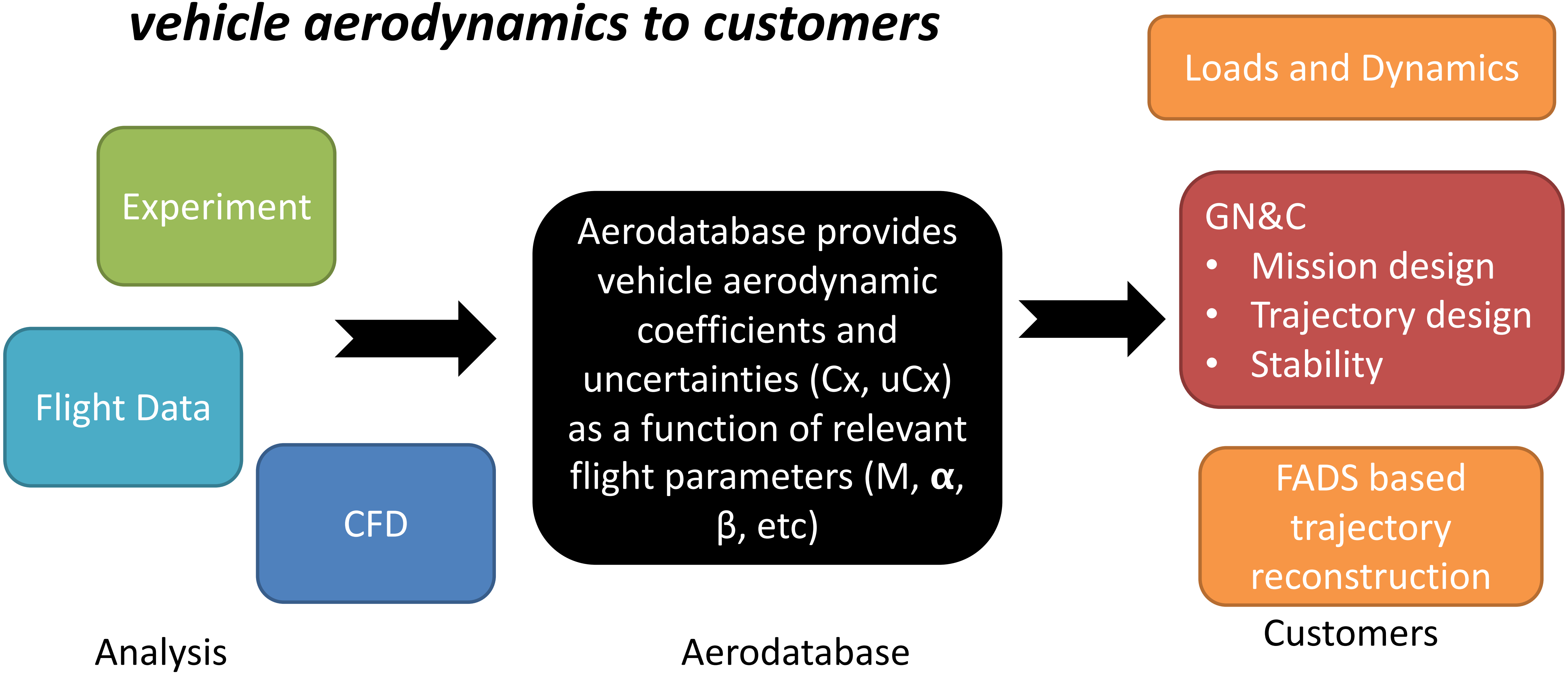
- Flight can validate database, but too limited in range to fully develop database
- Flight Reynolds number testing for subsonic is necessary
- Overflow is the (Orion) workhorse for M<8
  - Difficult to match experiment for subsonic drag
  - DES has been too expensive in the past; we are closer to using it on a larger scale
  - Beginning to use unstructured tools (FUN3D, US3D)
- Aerothermal CFD is sufficient for M>6
  - CART3D for increments

Data Sources and Mission Space
Orion Crew Module Database



Analysis to Customers - Aerodatabase

The aerodatabase is how we communicate vehicle aerodynamics to customers



Experiment

Flight Data

CFD

Analysis

Aerodatabase provides vehicle aerodynamic coefficients and uncertainties (Cx, uCx) as a function of relevant flight parameters (M, **α**, β, etc)

Aerodatabase

Loads and Dynamics

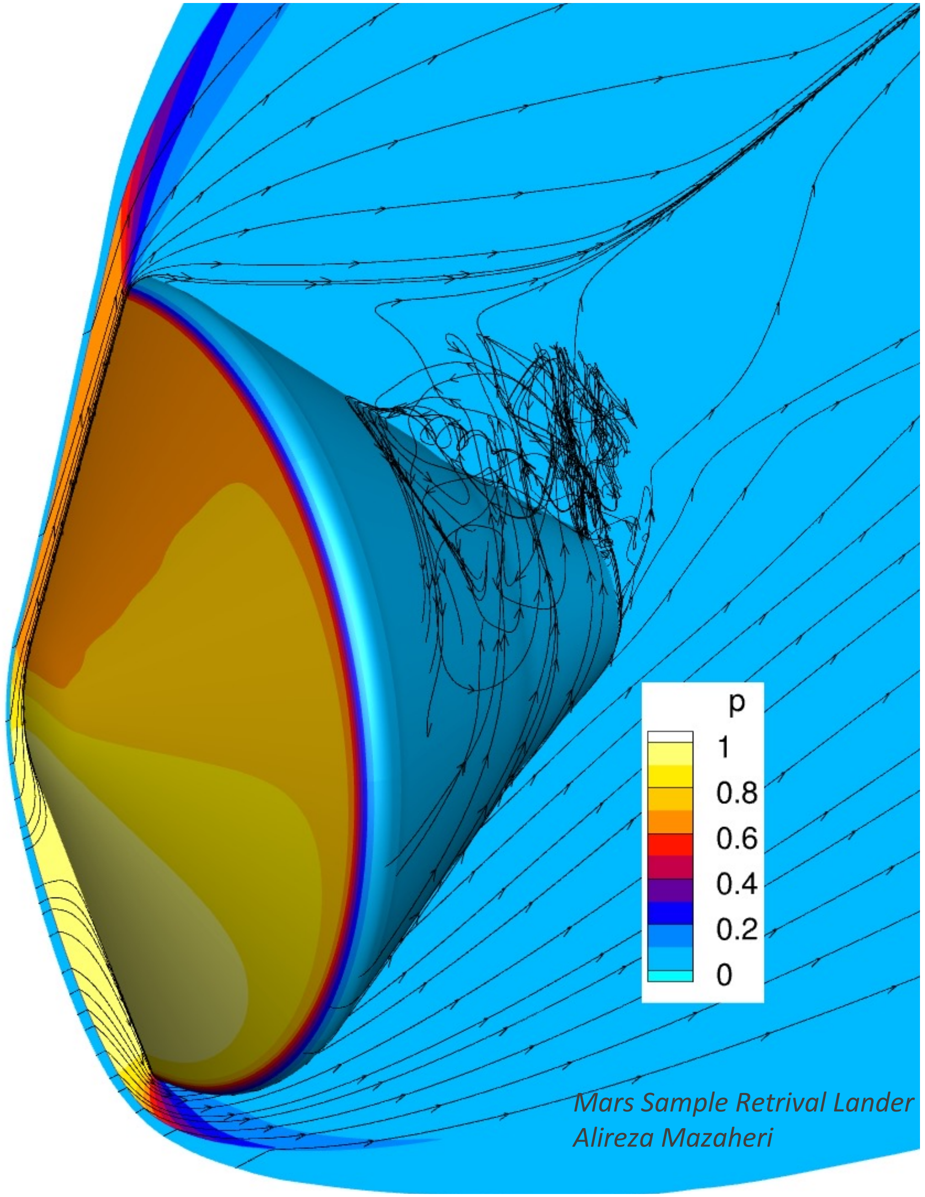
GN&C
- Mission design
- Trajectory design
- Stability

FADS based trajectory reconstruction

Customers

Static, dynamic, rarefied, hypersonic, supersonic, transonic, subsonic

BASIC CAPSULE AERO



Mars Sample Retrival Lander
Alireza Mazaheri

Default Mission – Earth Entry

Rarefied

- Drag and trim angle needed to get proper entry interface conditions

Hypersonic

- Trim angle gradually changes as post-shock conditions change
- Capsules are typically close to neutrally stable to slightly stable
  - RCS used to damp any oscillations

Supersonic

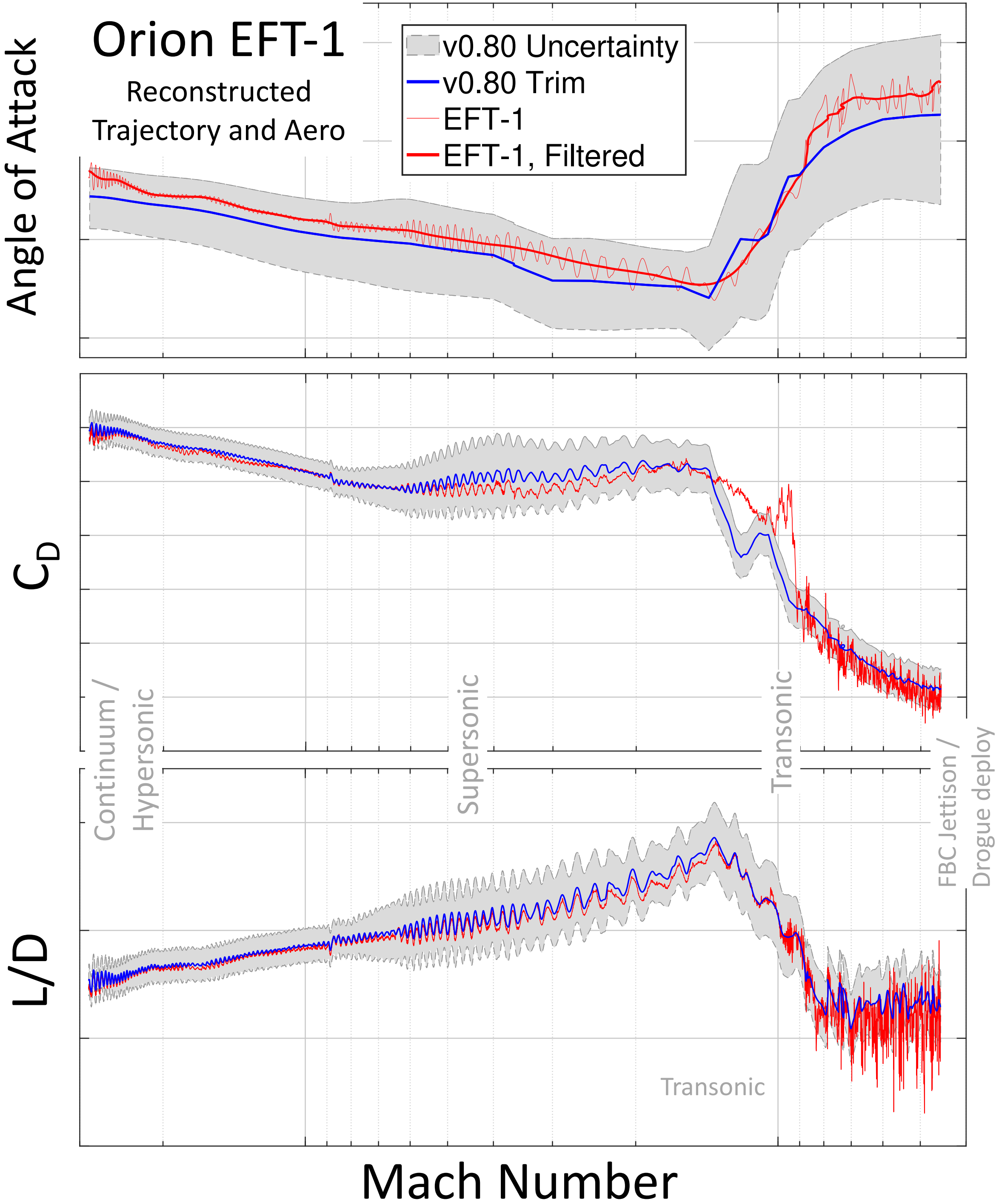
- Non-reacting
- Backshell aero becomes important

Transonic

- Steep drag drop, just need to fly through here

Subsonic

- Wake flow, shoulder separation critical
- Dynamic aero more important



Orion EFT-1 trajectory / aero reconstruction
Karen Bibb

Rarefied

Physics

- Stochastic model of individual particles and their physics
- Probabilistic approach where simple models use cross sections determined from experiments or analytic results
- Considers translation, rotation, vibration, and electronic energy as separate modes of energy and can include chemistry and quasi-neutral ionization

Aero QOI

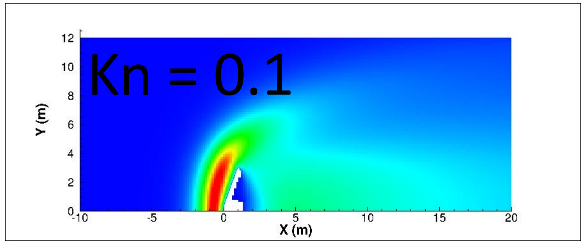
- Drag, trim angle

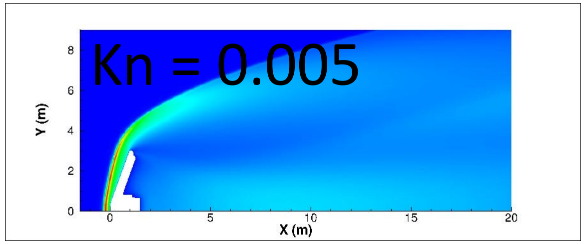
Analysis Tools

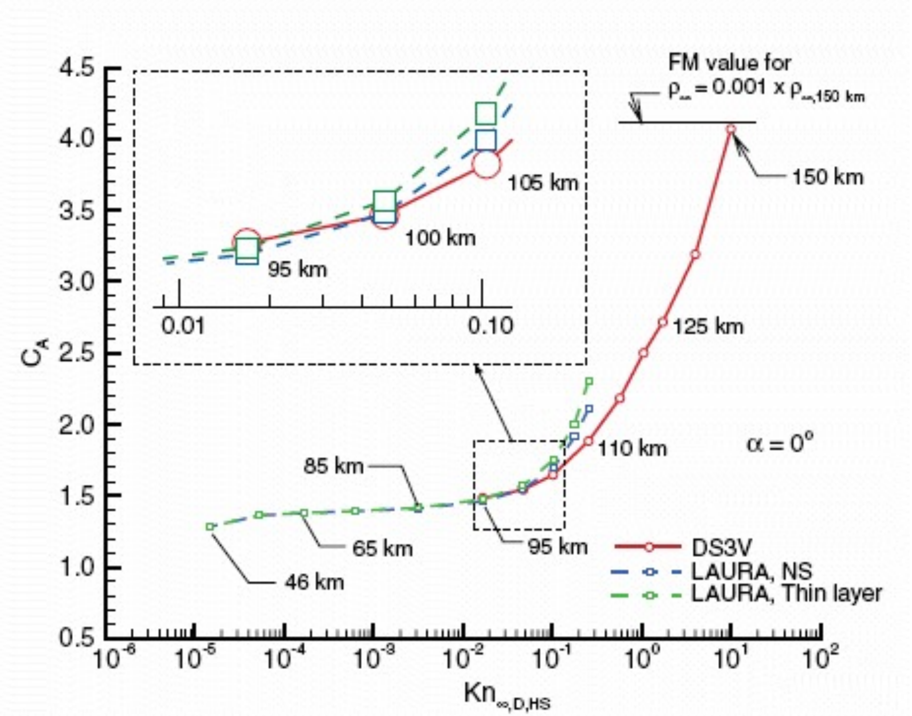
- Free molecular
  - DACFree
- DSMC
  - MAP, DAC

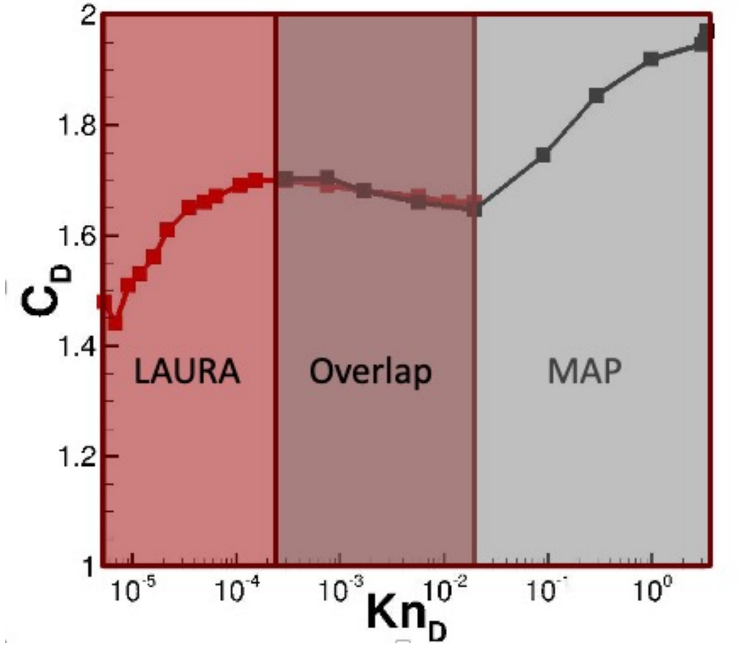
Analysis challenges

- Time accurate DSMC
- Coupling with CFD









Program: Inflatable Re-entry Vehicle Experiment (IRVE) II – flight-test to demonstrate various aspects of inflatable technology.

Issue: Evaluate aerodynamic characteristics of vehicle in low-velocity, rarefied trajectory. Existing aerodynamic databases for similar configurations was not appropriate for IRVE conditions, especially at deployment from launch vehicle

Approach: Perform free molecular and DSMC simulations, overlapping the CFD database at lower altitudes.

Impact: A very strong dependency on velocity was demonstrated. IRVE shown to be statically stable in free-molecular regime but exhibited multiple stable trim points through most of the transitional regime.

courtesy of Derek Liechty

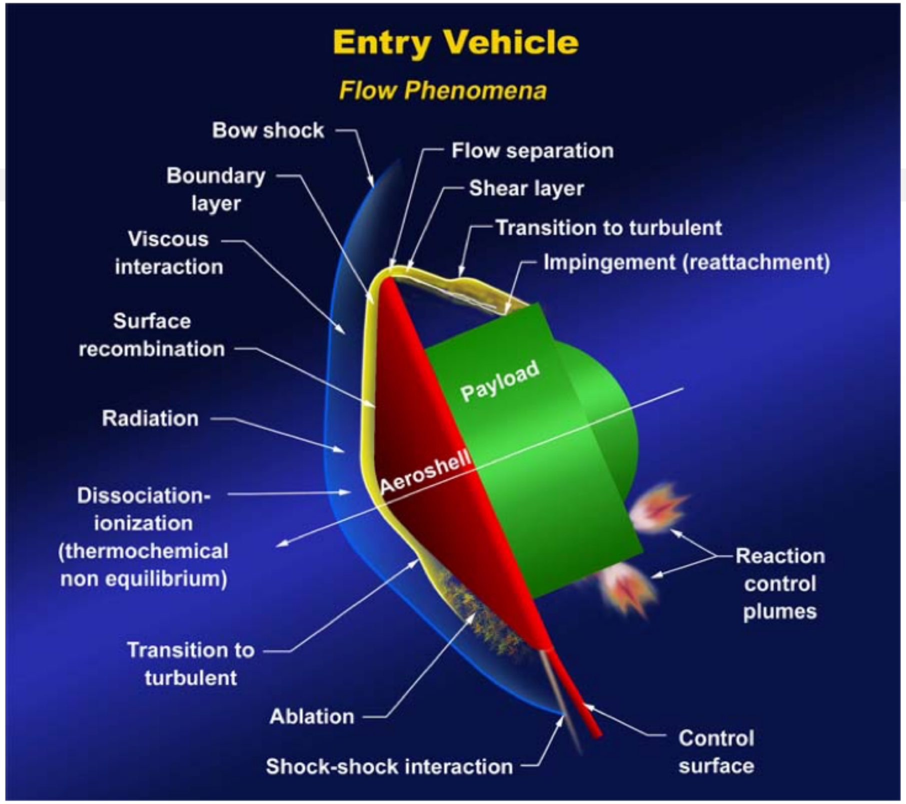
Hypersonic aero

Physics

- Reacting flow, bow shock dominated.
  - Highest speeds are in thermal non-equilibrium
  - Lower speeds are in thermal equilibrium but still not calorically perfect
- Aero is dominated by heatshield pressure
  - Turbulent wake not important. Often aero developed is forebody only
- Trim angle gradually changes with chemistry
  - Changes in post-shock pressure and shock shape
  - STS-1 pitch-up anomaly
- Capsules are typically close to neutrally stable to slightly stable.
  - RCS used to damp any oscillations

Aero QOI

- L/D, trim angle. L/D@M=25, CD



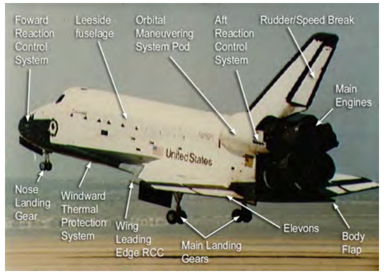
Analysis Tools

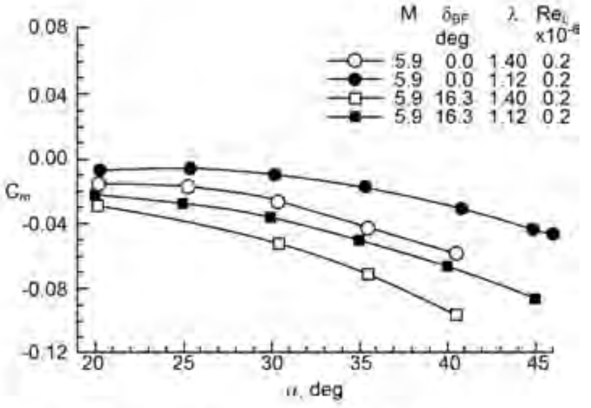
- Newtonian
- Inviscid CFD – CART3D (equilibrium air only)
- **Reacting gas** RANS CFD – LAURA, DPLR, FUN3D, US3D
  - Choice of chemistry model is speed dependent
  - Aero typically piggy-backs on aeroheating work
- WT: LAL (Langley, Mach 6, Mach 10)
  - AEDC, others rarely used for aero

Analysis challenges

- Wake flow, RCS JI
- Unstructured meshes for complex configurations
  - heating is an open problem

STS-1 Landing:





Comparison of pitching moment, air vs. CF_4

Brauckmann, et al., JSR 32.5, 1995, pp 758-764

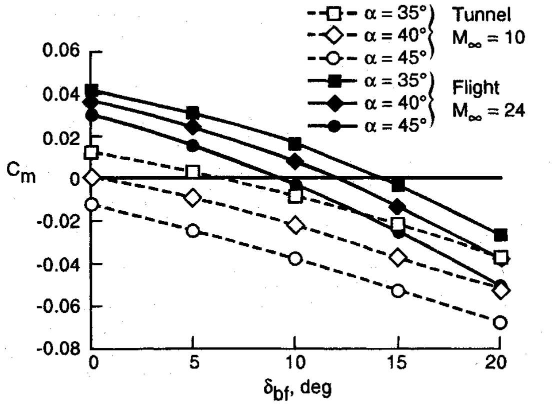


Fig. 11 **Comparison of computed pitching moment based on STS-2 entry interface *CG* location and modified Orbiter lower surface properties.**

Weilmeunster, et al., JSR 31.3, 1994, pp 355-366

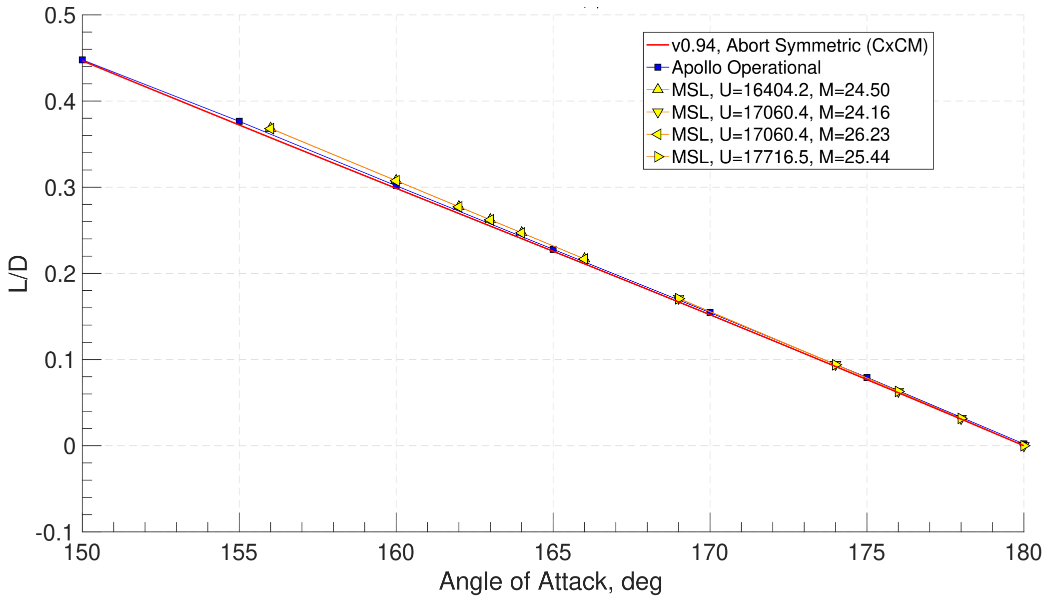
Hypersonic L/D

Physics

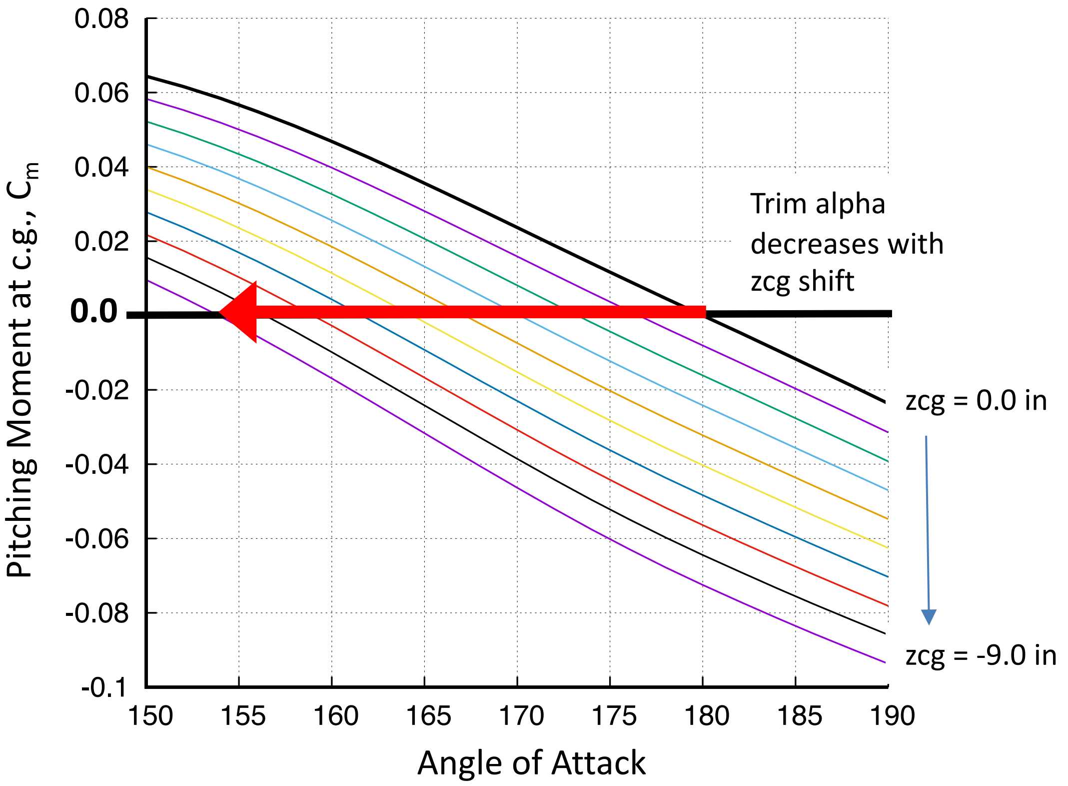
- L/D curve is similar for most capsule shapes
- Target L/D (typically at M=25) is determined by trim angle
- Trim angle (C_m=0) is determined by vehicle pitching moment and zcg location
- Augmented OML shapes can shift C_m (and L/D) curve (trim tabs)

Aero QOI

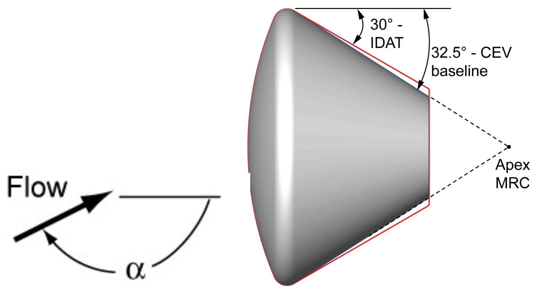
- L/D, trim angle. L/D@M=25, CD



Trim Angle Change with Shift in z-cg



Trim alpha decreases with zcg shift



Supersonic

Physics

- Non-reacting.
    - Mars has strong temperature dependence in ratio of specific heat that must be modeled
- Backshell can have attached flow, higher pressures
- Generally turbulent forebody flow
- Capsules begin to be dynamically unstable
    - RCS used to damp any oscillations
    - More of an issue for Mars

Aero QOI

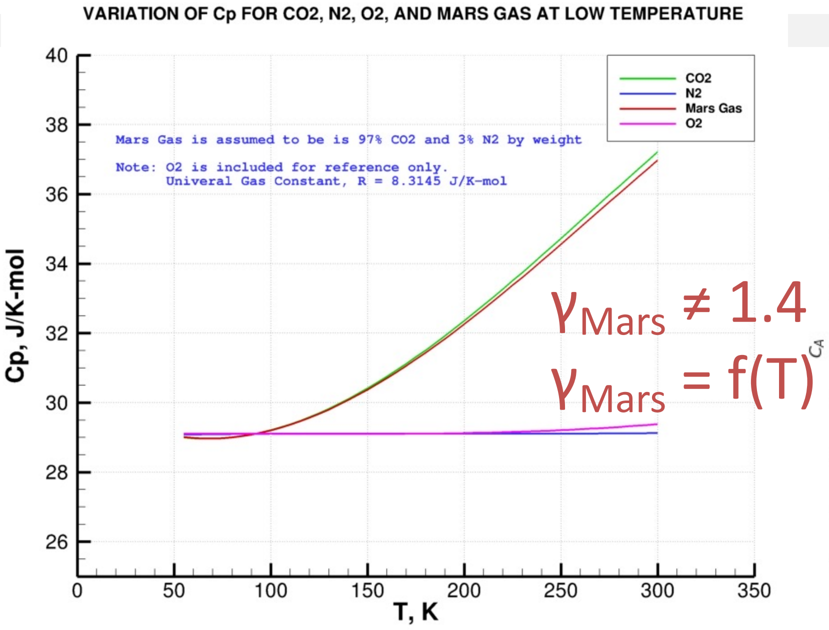
- L/D, trim angle, drag, Cmq

Analysis Tools

- RANS, DES – Overflow, FUN3D, US3D
    - Appropriate γ_{Mars} must be modeled
- Inviscid – CART3D for increments (Orion)
- WT - LAL (Langley, Mach 6, Mach 10)
- WT – Langley UPWT
- Ballistic range for dynamics

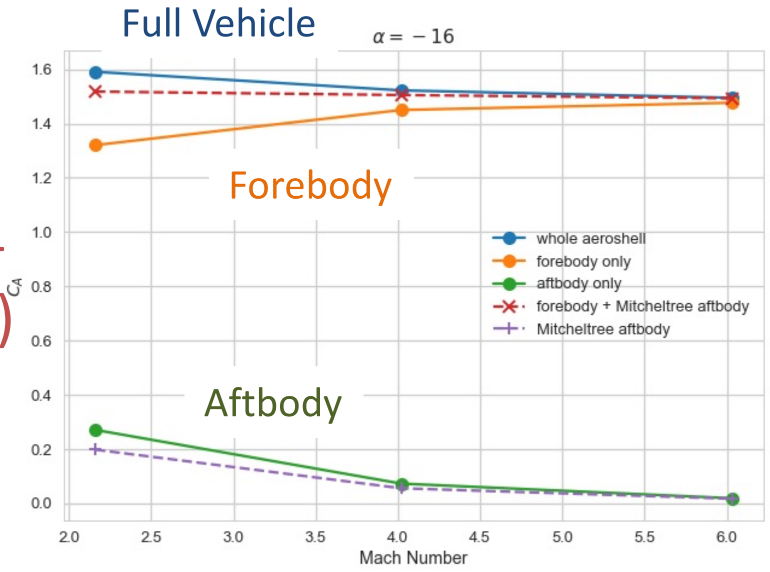
Analysis challenges

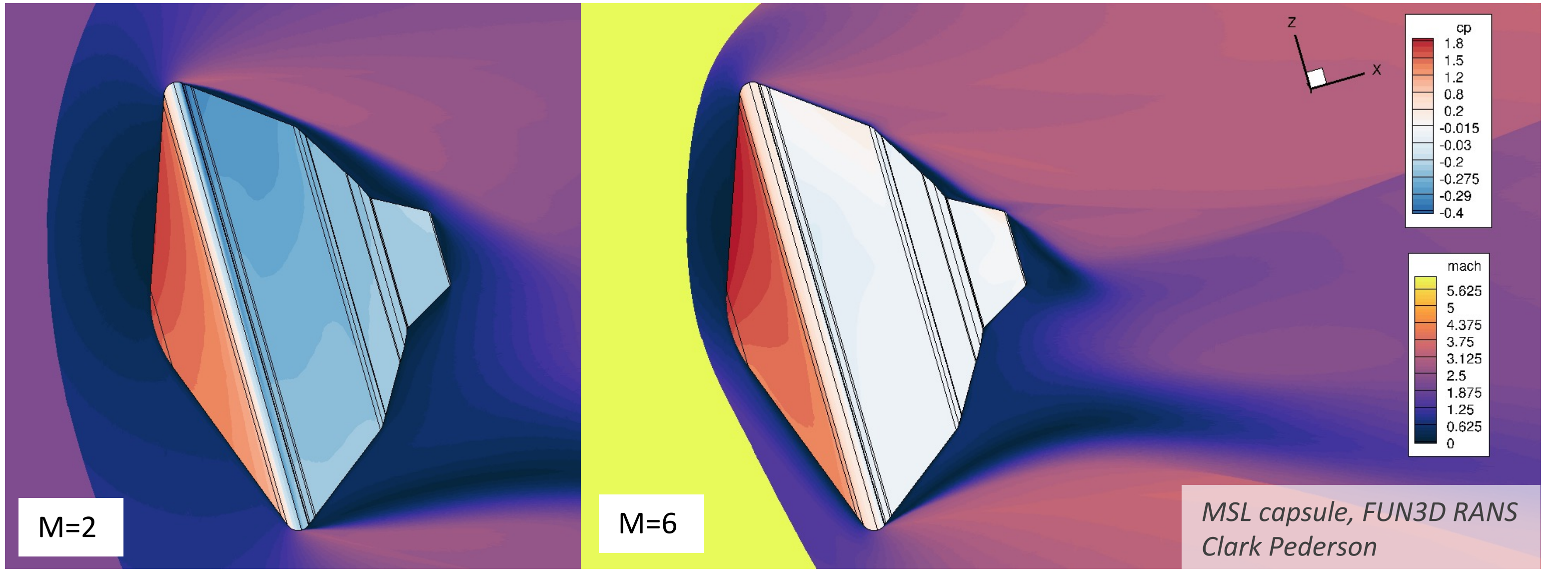
- Wake flow



$\gamma_{Mars} \neq 1.4$

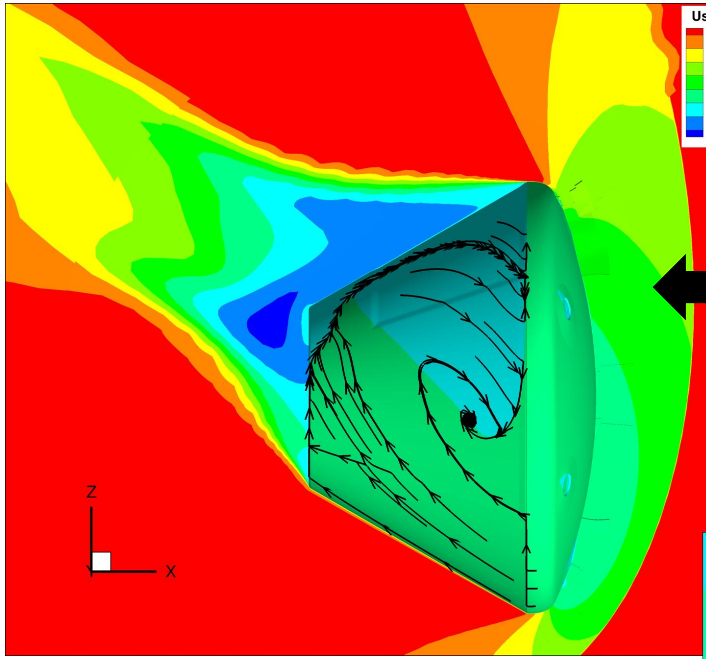
$\gamma_{Mars} = f(T)$





MSL capsule, FUN3D RANS
Clark Pederson

Wake Physics: Supersonic-Transonic-Subsonic

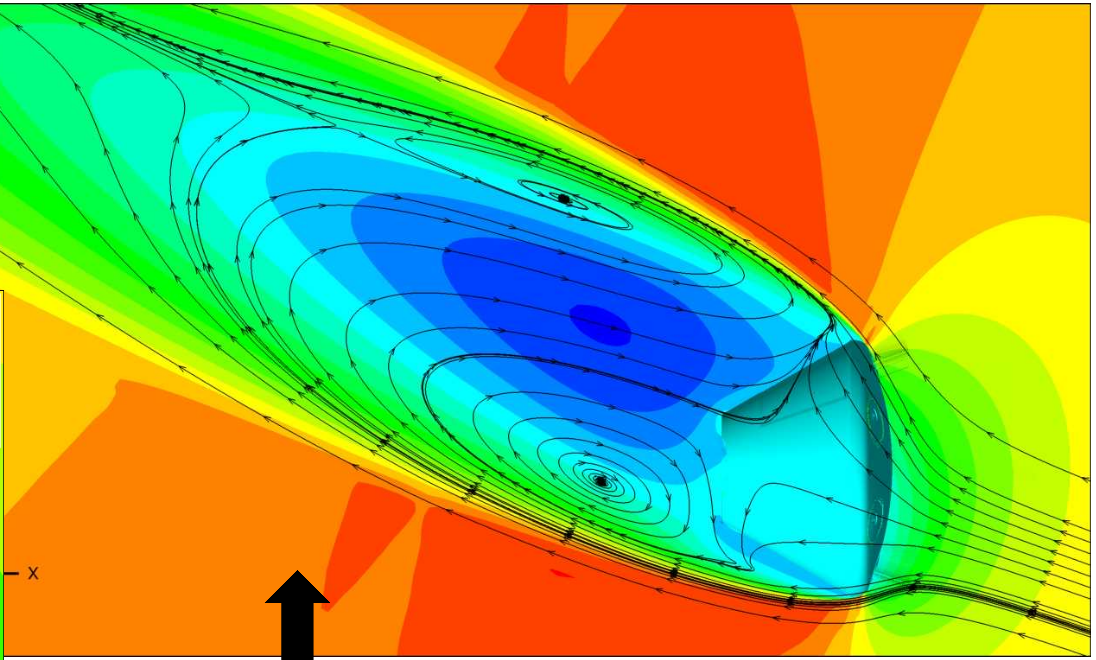


Supersonic

- Separation: shoulder and backshell. Attached on windside
- Compact wake
- CFD accuracy

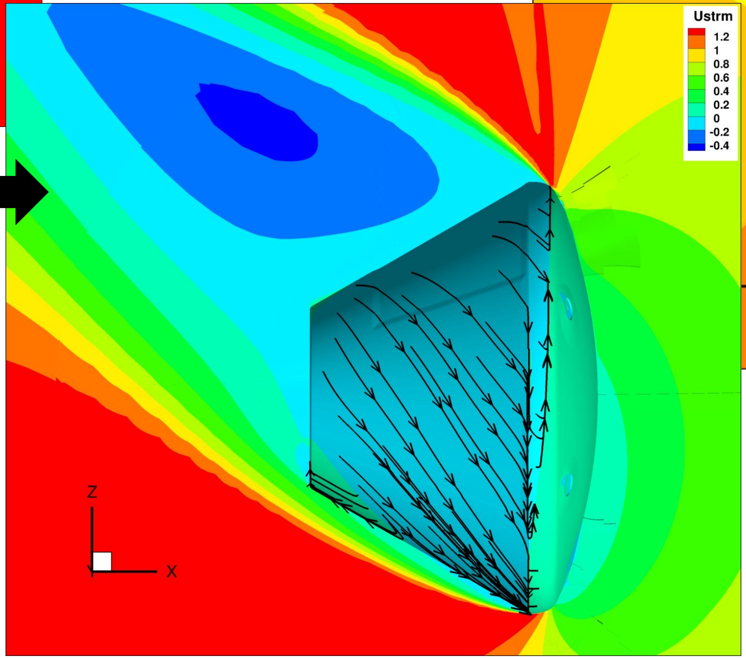
Changing throughout

- Inviscid aero
- Trim angle
- Dominant turbulence physics
- CFD accuracy



Transonic

- Separation: shoulder with possible reattachment and backshell
- Longer, shifted wake



Subsonic

- Separation at shoulder
- Strouhall shedding
- Long wake at M=0.9
- Shorter wake by M=0.3

Orion capsule, Overflow RANS
Robert Childs

Transonic

Physics

- Steep drop in drag and trim angle change through Mach 1 that is difficult to capture with analysis or in database

Aero QOI

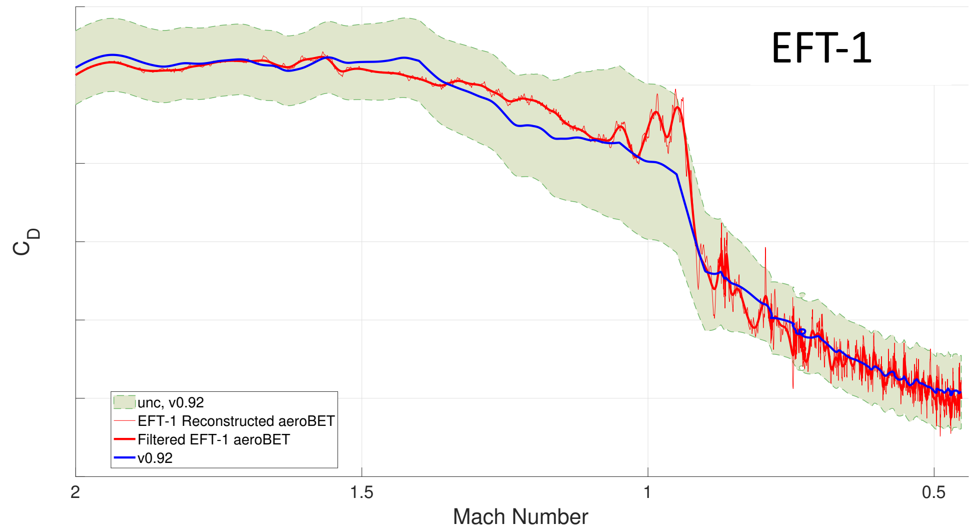
- Vehicle just needs to get through this region
  - Larger uncertainties are ok
  - Typically aerodatabase is ‘smeared’ in this region
- L/D, trim angle, drag, Cmq

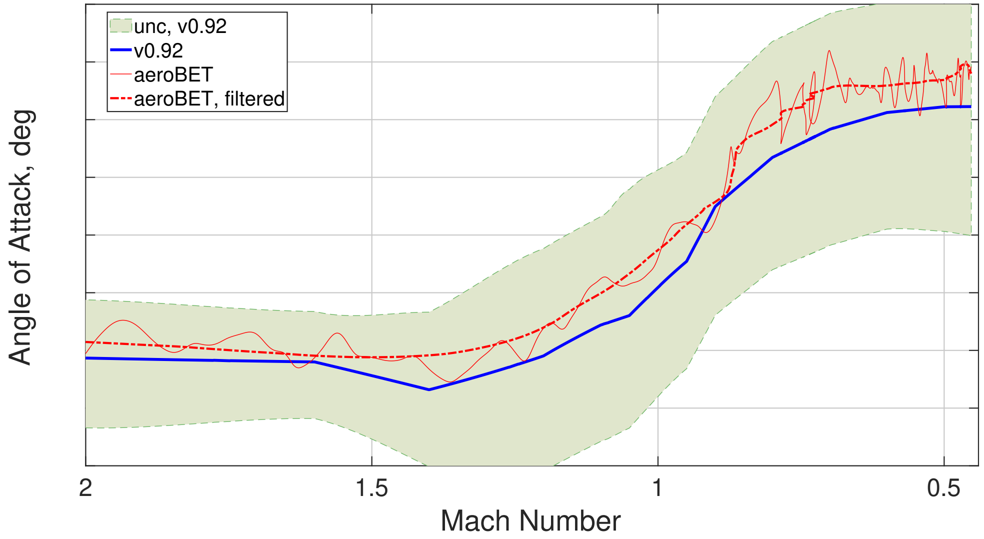
Analysis Tools

- CFD: RANS, DES – Overflow, FUN3D, US3D
- WT: Ames UPWT

Analysis challenges

- Turbulence modeling
  - Wake flow
  - Shoulder separation
- Capturing steep drag change





Orion EFT-1 trajectory / aero reconstruction
Karen Bibb

Subsonic

Physics

- Drag has strong Re dependency for lower Re
  - Surface roughness can change drag significantly
- Backshell can have attached flow, higher pressures
- Generally turbulent forebody flow
- Capsules are dynamically unstable
  - RCS used to damp any oscillations

Aero QOI

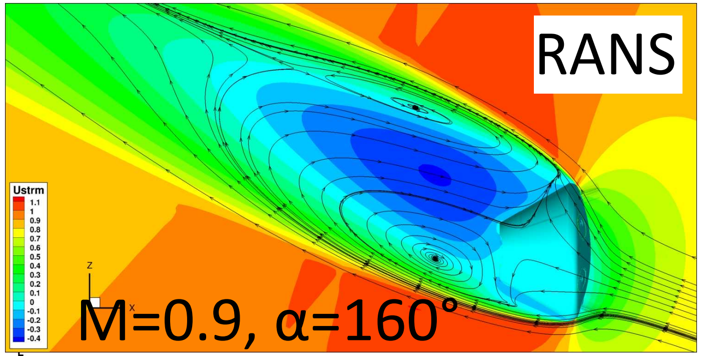
- Drag, Cmq, trim angle

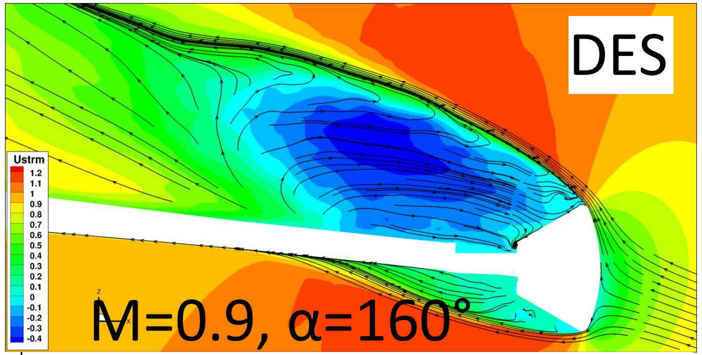
Analysis Tools

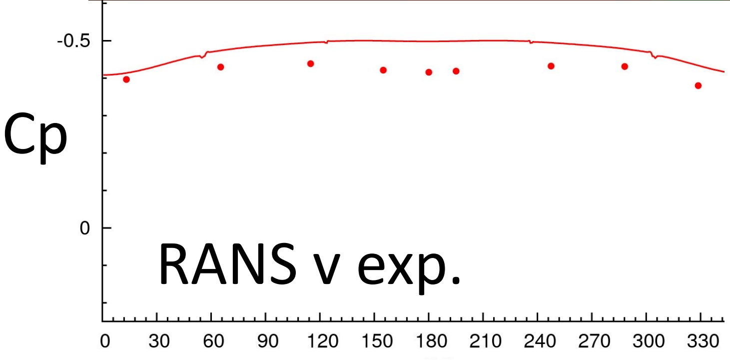
- CFD: RANS, DES – Overflow, FUN3D, US3D
- WT Static aero: Langley NTF (flight Re), Ames UPWT
- WT Dynamic aero: Langley TDT, spin tunnel,
- Flight: Ballistic range, parachute drop testing

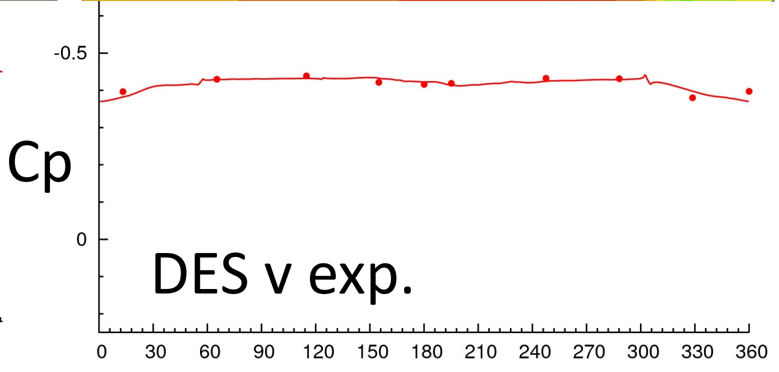
Analysis challenges

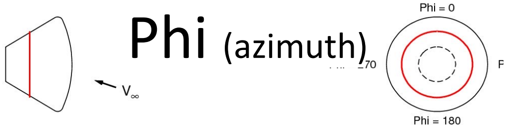
- Surface roughness
- Shoulder separation point is key to drag accuracy
- Re dependencies
- RANS predicts excessive reversed-flow approaching backshell; causes elevated Cp on upper backshell
- DES CFD is becoming the requirement, with significant resource challenges
  - Open question: Can we ‘tune’ RANS to provide DES-like aero while maintaining computational throughput of RANS?

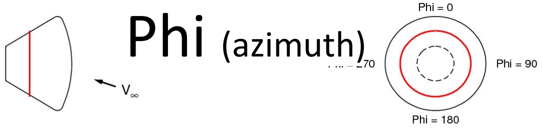












Orion capsule, Overflow RANS
Robert Childs

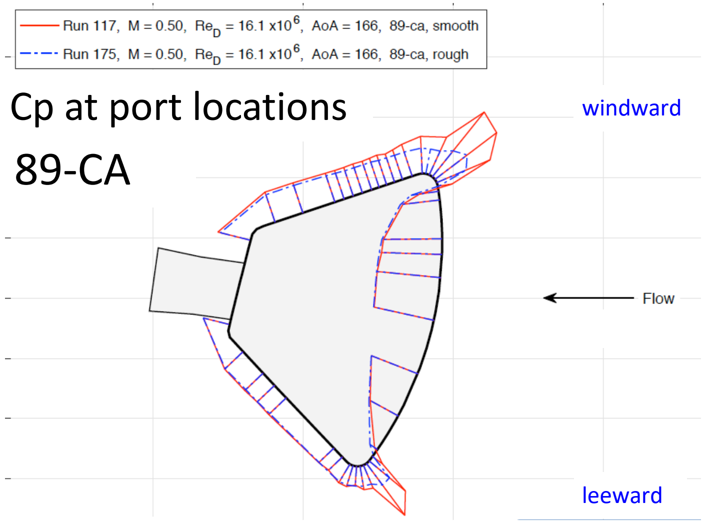
Subsonic – Drag Prediction

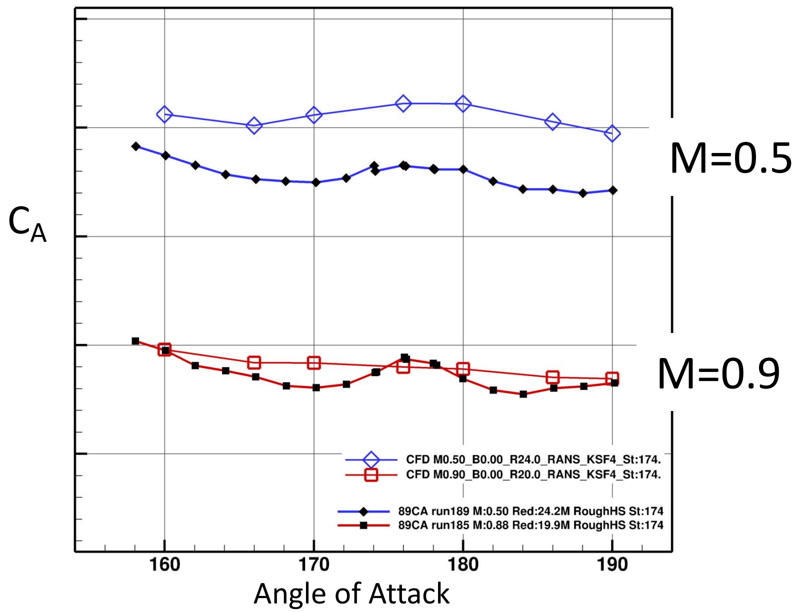
Physics

- State of boundary layer (laminar, transitional, turbulent) is Reynolds number and roughness dependent
  - BL state drives shoulder separation location, magnitude of suction spike, and therefore drag
  - Flight Re typically yield fully turbulent flow
  - Re effects diminish with increasing Mach
- Surface roughness:
  - Increases drag at flight Re
  - Reduces Re effects at lower Re by ensuring fully turbulent flow

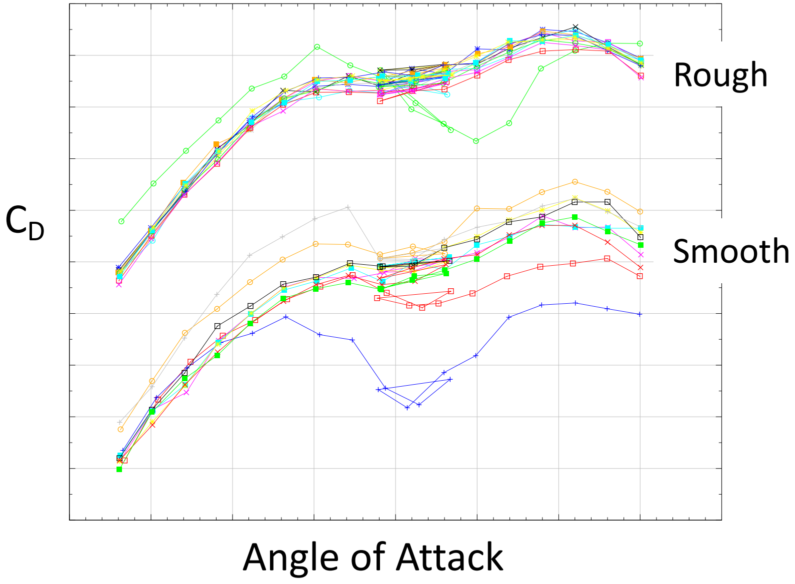
CFD modeling challenges

- CFD doesn't capture transition well without empiricism
  - 'Free transition' an active area of research
  - Flight Re flows are still difficult
- Selecting 'best' turbulence model requires data
  - Compressibility corrections
- Surface roughness with Knopp roughness model
  - Must be empirically set





89-CA: Smooth and Rough



Drag Trends

- Drag increases with Mach number
- Drag increases with surface roughness
- Re effects reduced for flight Re
  - Smooth HS has large variation for ReD < 10

Orion test 89-CA and CFD comparisons
Robert Childs, Greg Brauckmann, Karen Bibb, Orion CAP team

Subsonic – Drag Prediction

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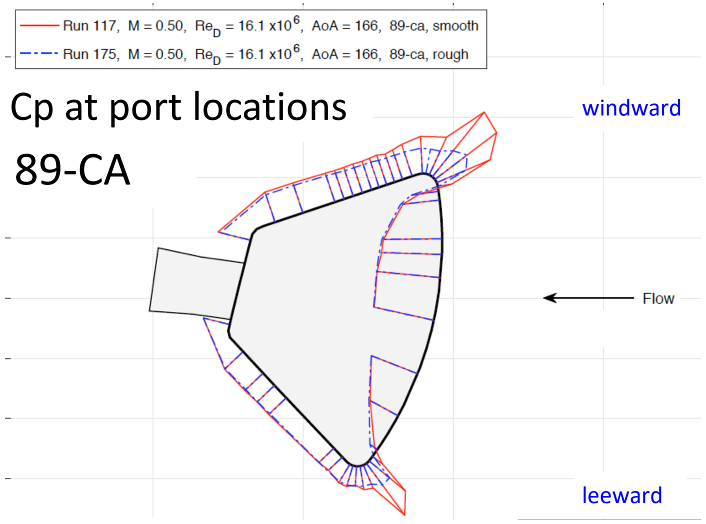
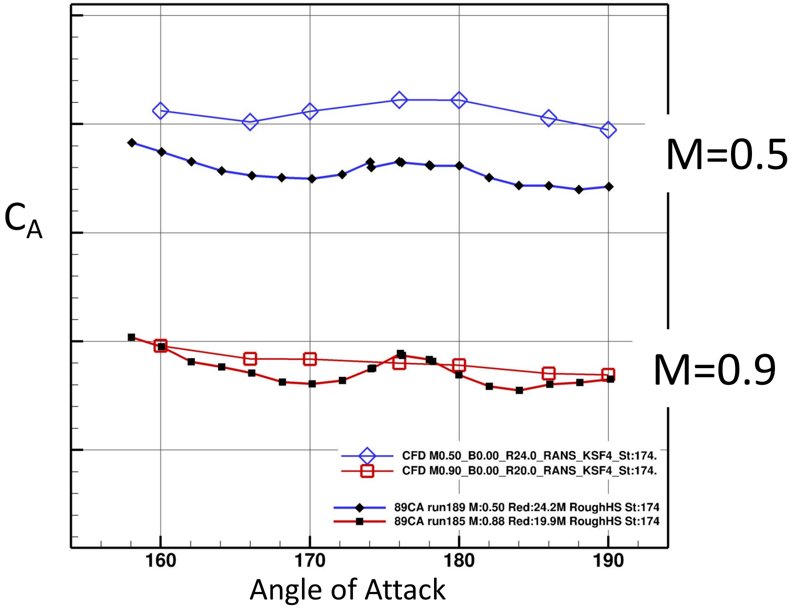
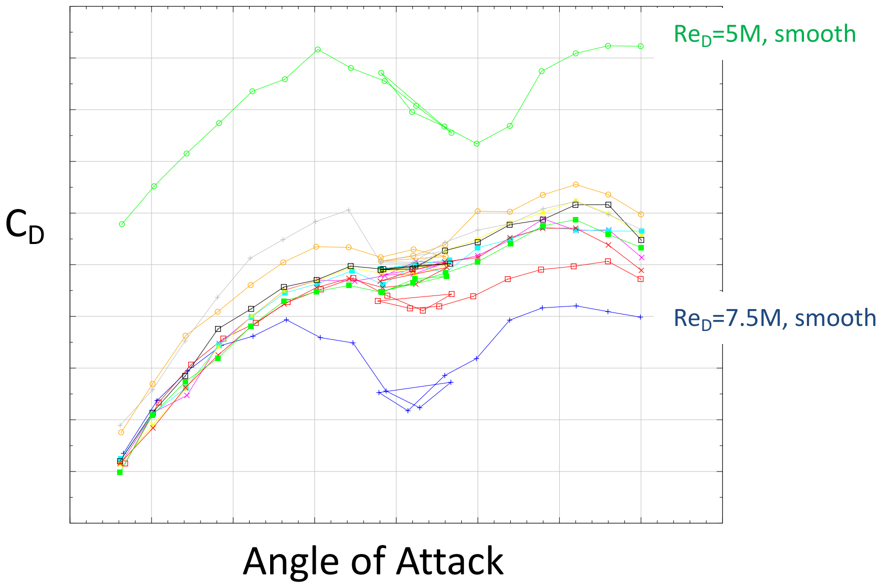
- Surface roughness with Knopp roughness model
  - Must be empirically set





89-CA: Smooth Only



Drag Trends

- Drag increases with Mach number
- Drag increases with surface roughness
- Re effects reduced for flight Re
  - Smooth HS has large variation for ReD < 10

Orion test 89-CA and CFD comparisons
Robert Childs, Greg Brauckmann, Karen Bibb, Orion CAP team

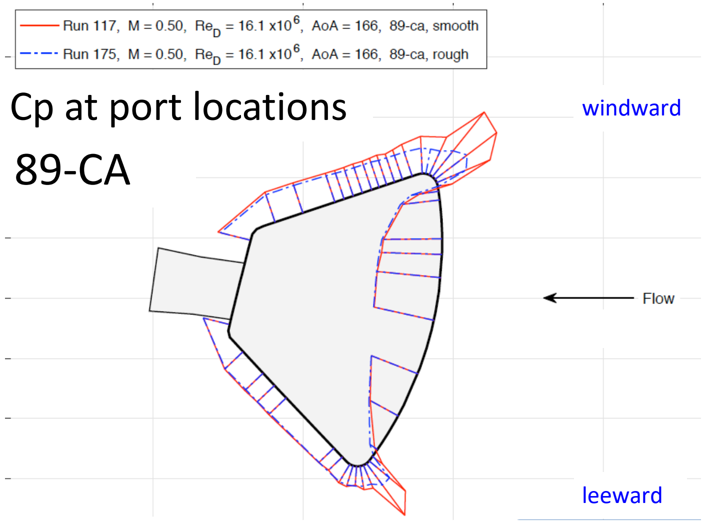
Subsonic – Drag Prediction

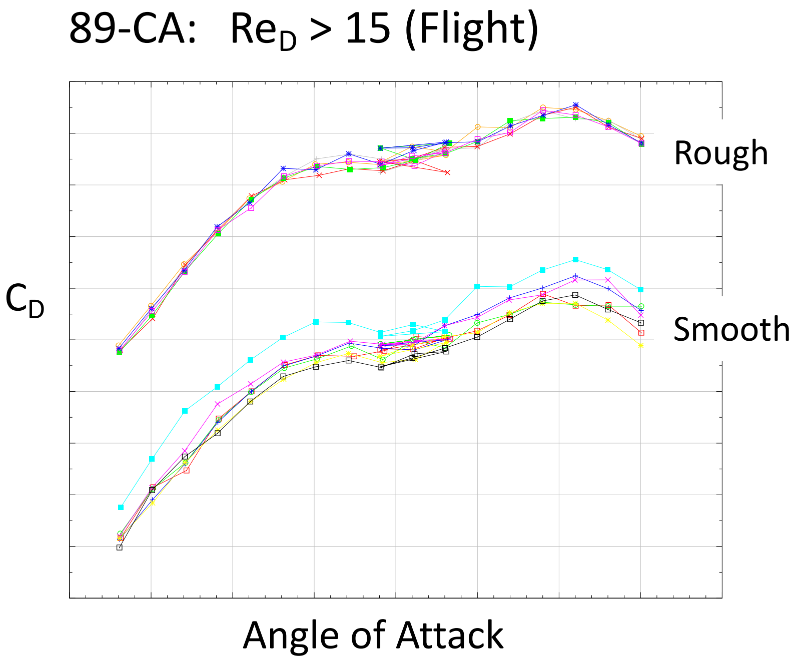
Physics

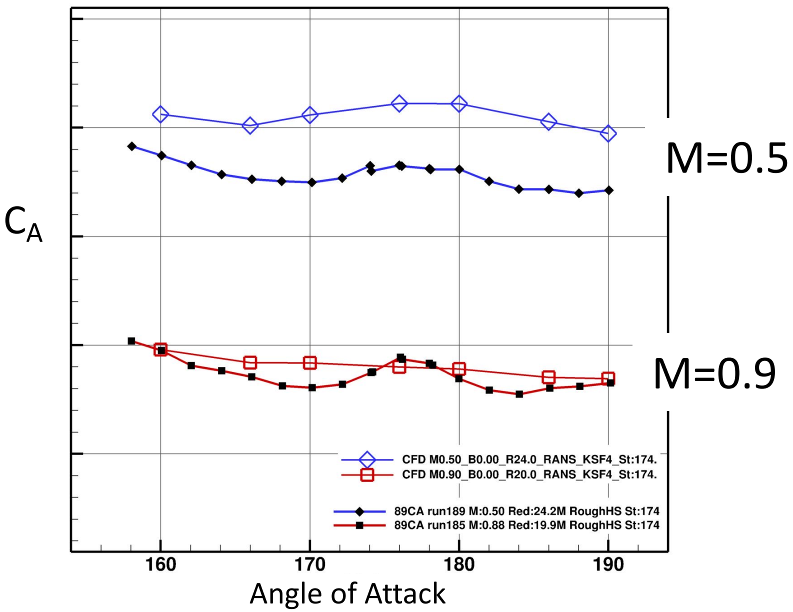
- State of boundary layer (laminar, transitional, turbulent) is Reynolds number and roughness dependent
  - BL state drives shoulder separation location, magnitude of suction spike, and therefore drag
  - Flight Re typically yield fully turbulent flow
  - Re effects diminish with increasing Mach
- Surface roughness:
  - Increases drag at flight Re
  - Reduces Re effects at lower Re by ensuring fully turbulent flow

CFD modeling challenges

- CFD doesn't capture transition well without empiricism
  - 'Free transition' an active area of research
  - Flight Re flows are still difficult
- Selecting 'best' turbulence model requires data
  - Compressibility corrections
- Surface roughness with Knopp roughness model
  - Must be empirically set







Drag Trends

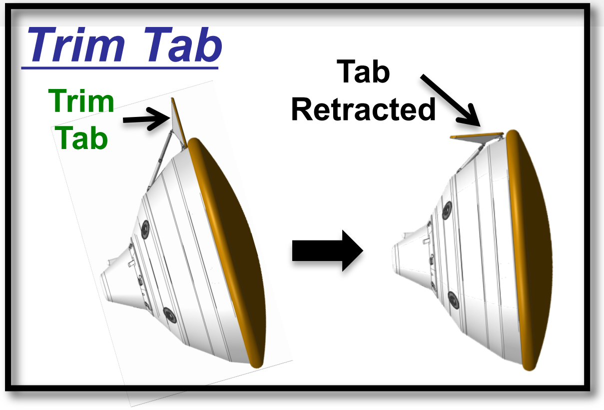
- Drag increases with Mach number
- Drag increases with surface roughness
- Re effects reduced for flight Re
  - Smooth HS has large variation for ReD < 10

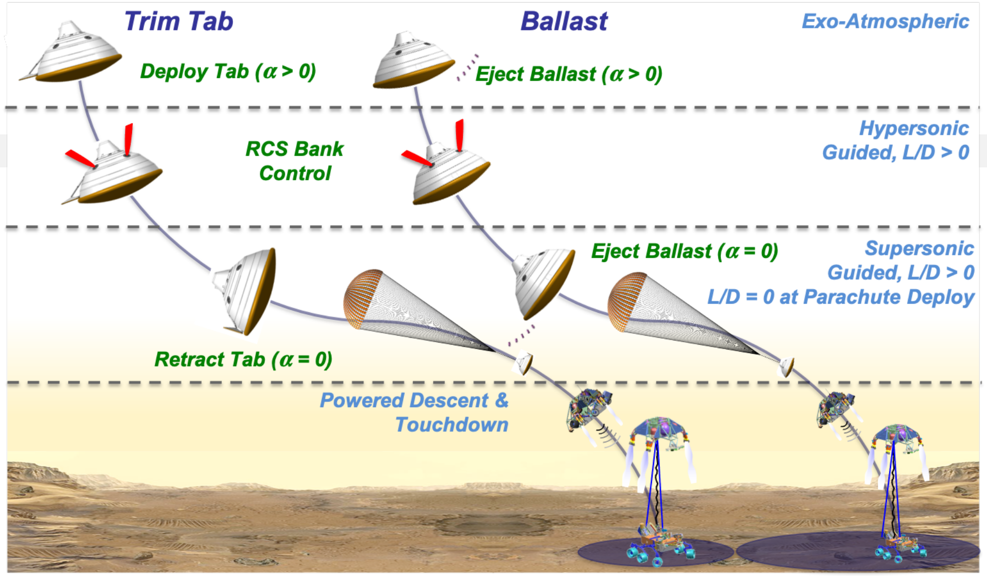
Orion test 89-CA and CFD comparisons
Robert Childs, Greg Brauckmann, Karen Bibb, Orion CAP team

More complex designs, analyses

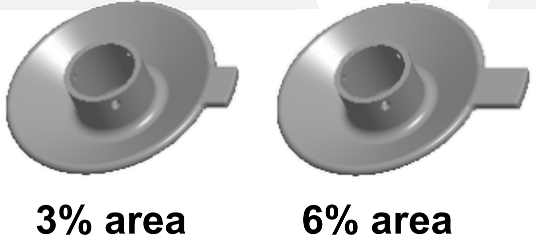
BEYOND THE BASICS

L/D – trim tabs

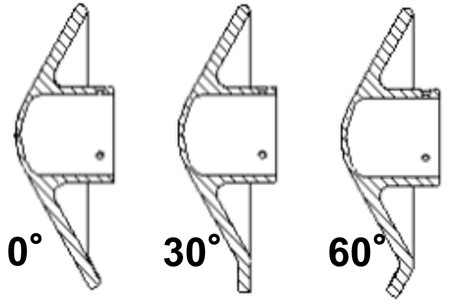




Tab Area



Tab Cant Angle Example



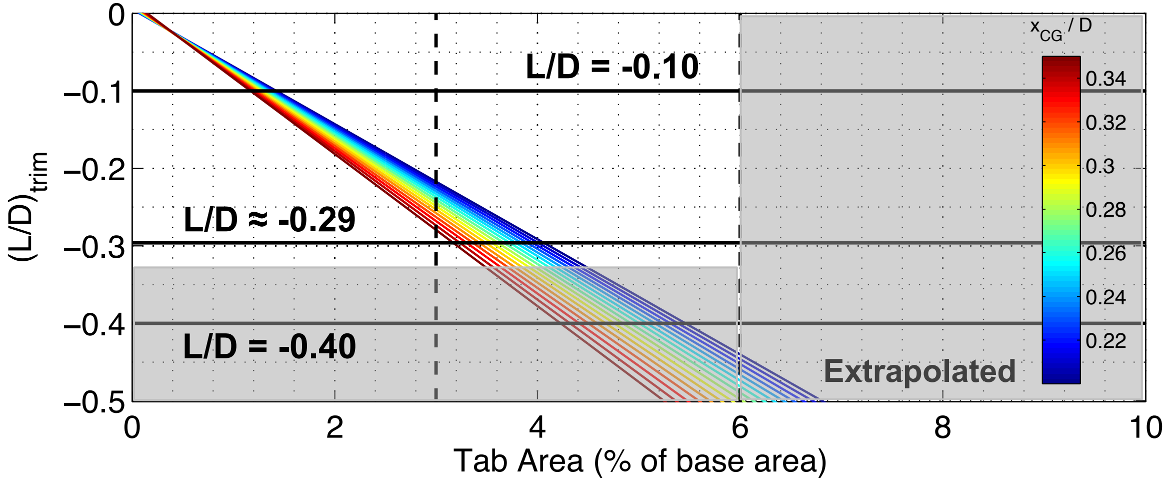
Physics

- Aerodynamic control surfaces capable of trimming the vehicle to a non-zero angle of attack without requiring a radial CG offset
- Potentially low-mass devices, as compared to ballast or CG movement
  - ➢ MSL Ballast System (300 kg + structure) > 1 MER (174 kg)
- Deployable surfaces enable Direct Force Control
  - ➢ Ability to modulate L/D and ballistic coefficient

Analysis challenges

- Separation, expansion, shock-boundary layer interaction in thermally imperfect gas
- Structural, thermal design and operational robustness

70° Sphere-cone, M_∞ = 4.5, 20° tab cant



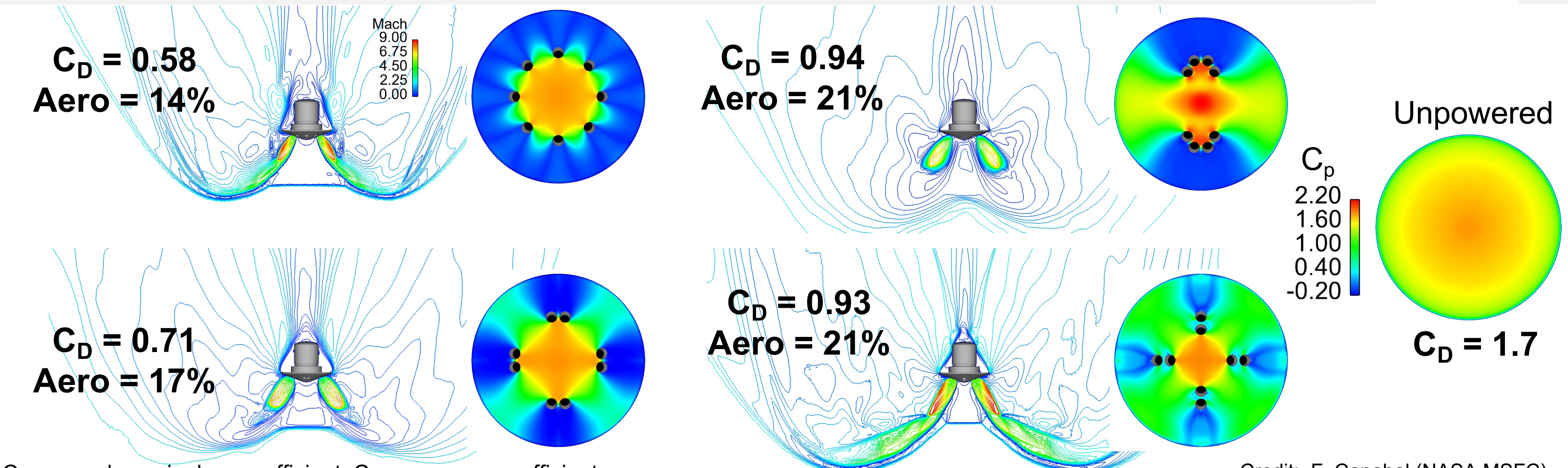
courtesy of Ashley Korzun

More Drag: Retropropulsion

Propulsive descent and landing are enabling for high-mass EDL at Mars

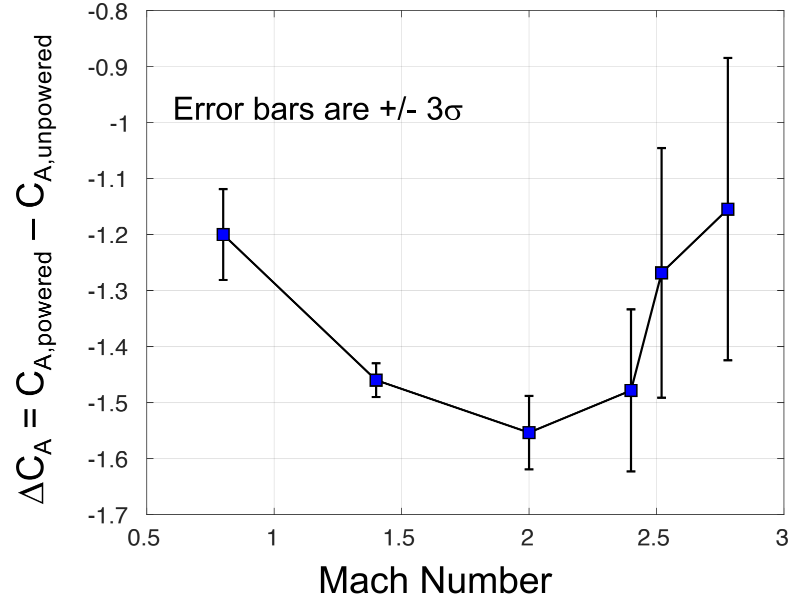
- Engineering analysis for trajectory trade studies assumes

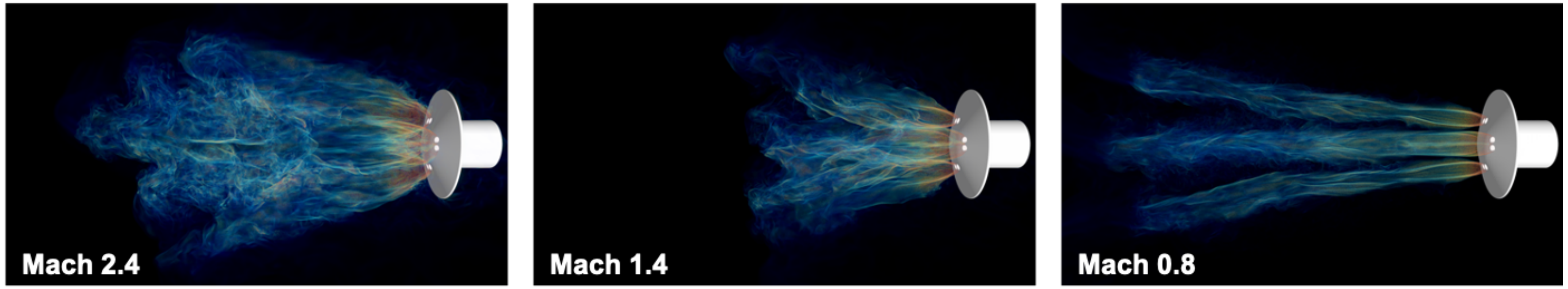
  total drag == engine thrust
- Analysis shows that vehicle contribution to CD can be significant
  - Engine configuration and operating conditions can have significant effects on vehicle aerodynamics
  - Aerodynamic contributions decrease as the vehicle decelerates



C_D = aerodynamic drag coefficient, C_p = pressure coefficient

Credit: F. Canabal (NASA MSFC)





Analysis challenges:

- Large resource requirements to resolve small scales
  - Time accuracy, fine meshes, adaptive meshes
- Chemistry and turbulence models in CFD codes are not well validated for these types of flows

Ashley Korzun will have a whole talk on this topic

courtesy of Ashley Korzun

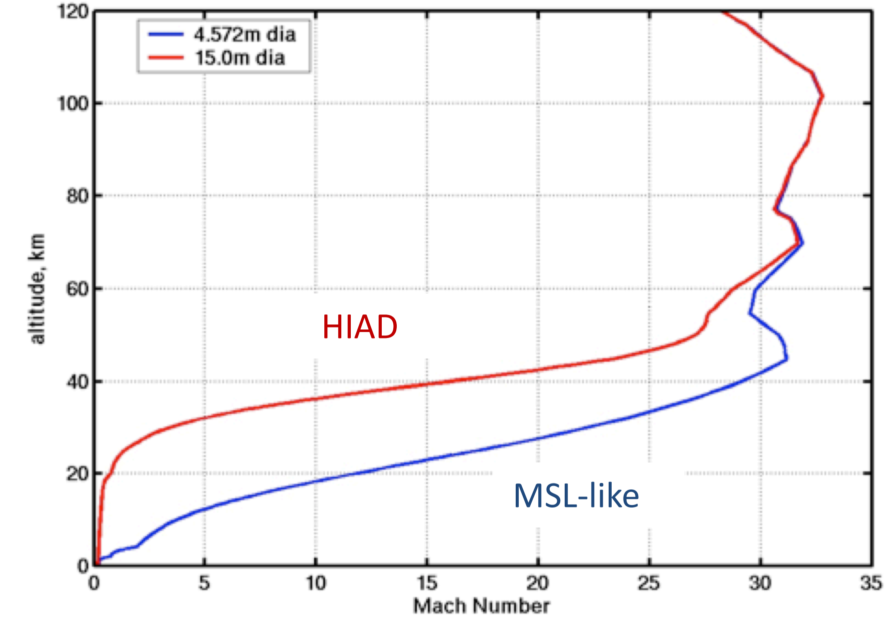
More drag: Flexible structures

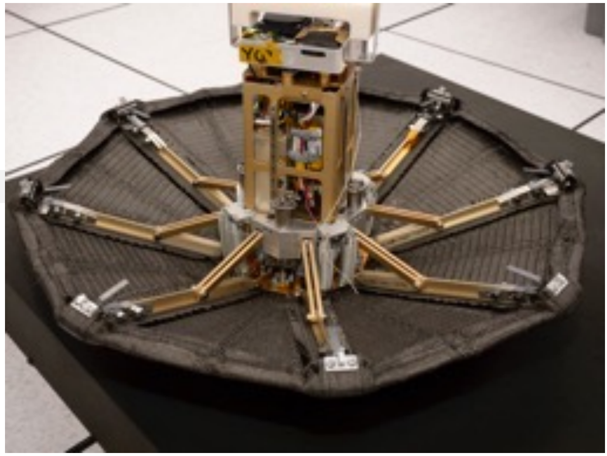
Deployable structures designed to increase drag and extend landing timeline

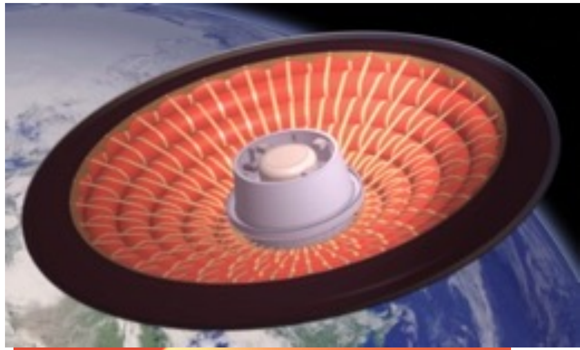
- Inflatables (HIADS, SIADS) – IRVE, LOFTID
- ‘umbrella’ – ADEPT

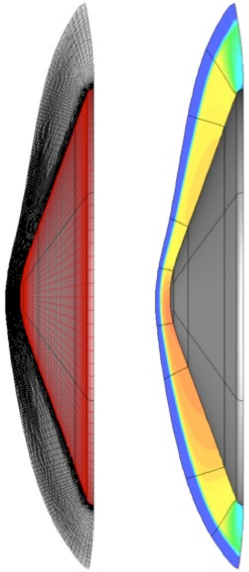
Analysis challenges:

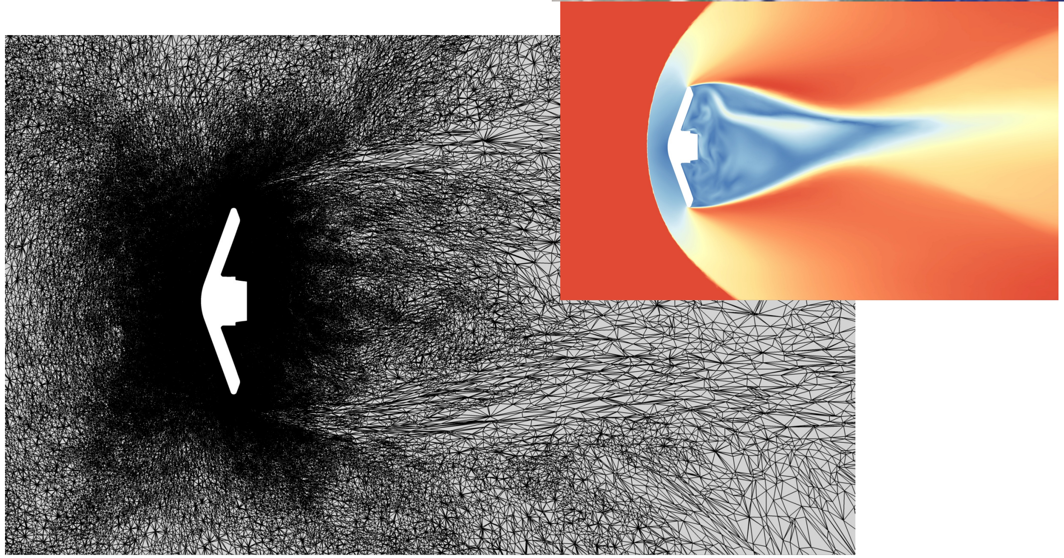
- How do we handle the flexible structures?
- Resolving wake flows with structured grids required advances in grid topology coupled with hypersonic bow shock adaptation







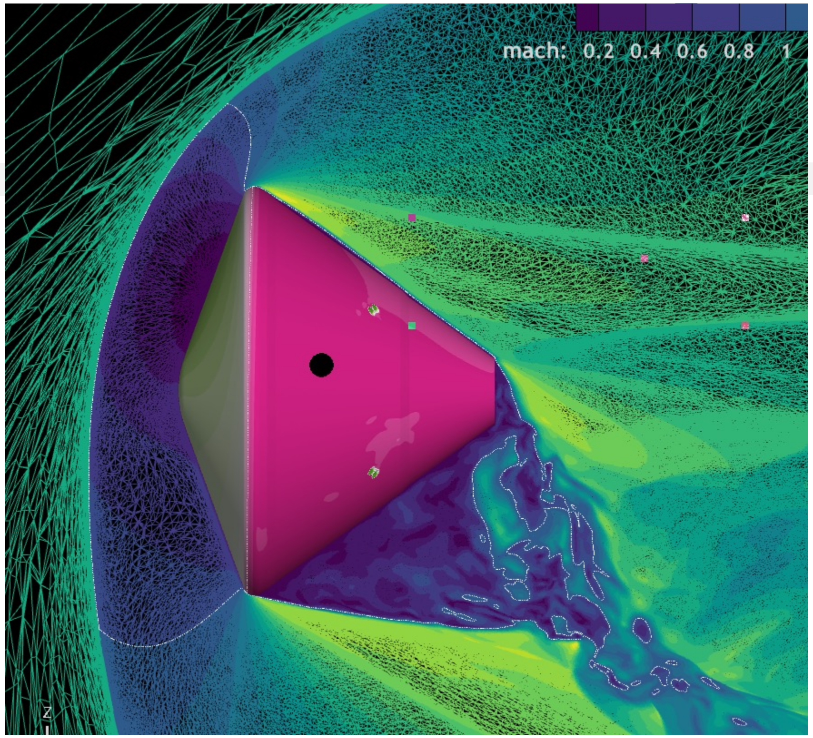




Trajectory compare: Neil Cheatwood

FUN3D CFD: Adam Wise

Control: Jet interactions – RCS

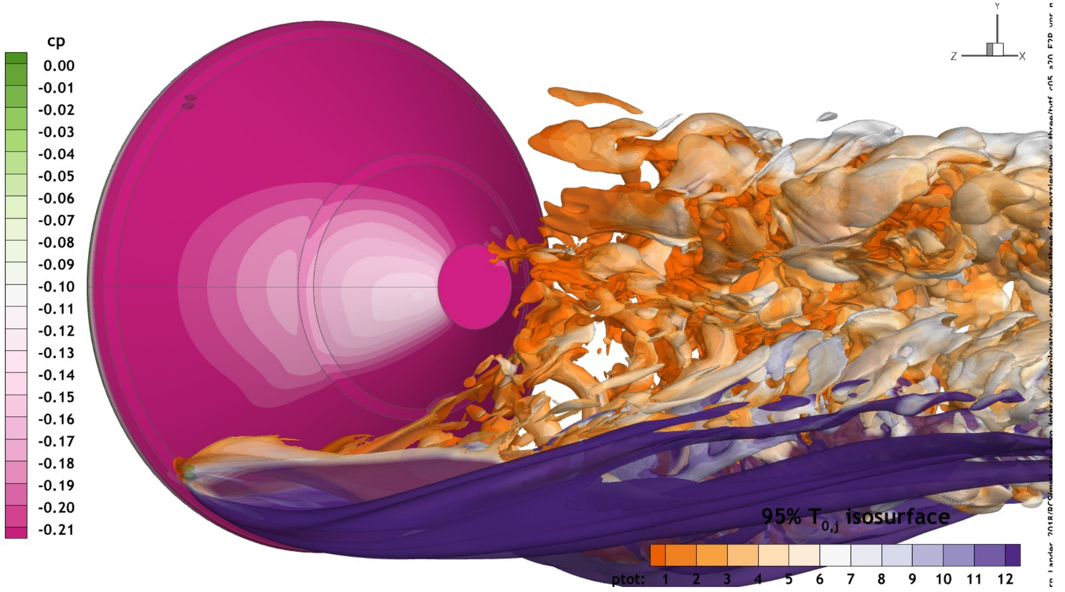


RCS JI is the change in the aeroshell aerodynamics due to presence of the jet.

- Not (typically) an aerodynamic issue hypersonically
- Can be a concern as Mach decreases
- We try to design it away rather than characterize the JI.

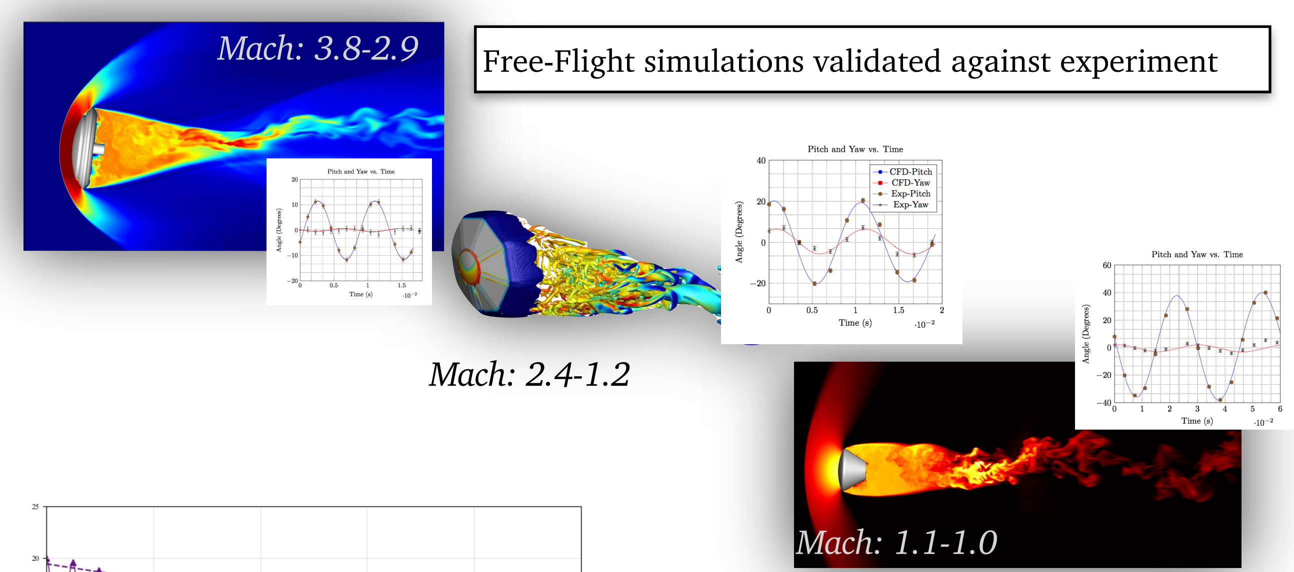
Analysis challenges:

- Separated wake flow needs DES to characterize well. This can matter at lower Mach
- At high Mach, wake can be rarefied (DSMC)
- WT testing is complicated
  - magnitude of interactions can be smaller than balance accuracy
  - Matching reacting plumes in tunnel with inert, cold gases is difficult



Mars SRL, FUN3D DES
Karen Bibb, Bil Kleb

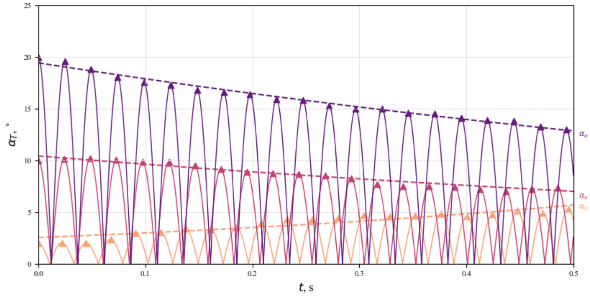
Free Flight CFD Simulation

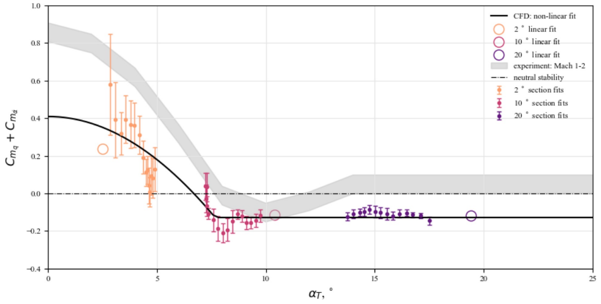


Free-Flight simulations validated against experiment

Free-Flight CFD

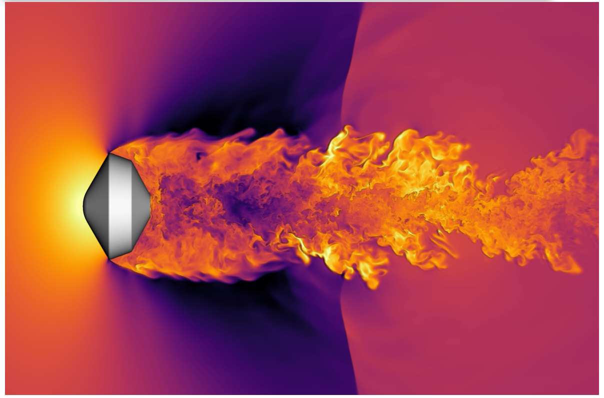
- Dynamic aero-coefficients historically obtained exclusively through ground/flight experimentation
  - Static areo-coefficients can be generated using validated CFD simulations with large databases anchored to experiments
- Moving the computational mesh in response to fluid forces coupled with translation velocity augmentation to discrete equations allows for full 6-DoF simulation of free-flying objects
  - Additional control of individual DoF allows for a range of analysis to be carried out (i.e.: free-to-pitch, forced oscillation, etc)
- Validation of the capability has been carried out for the past 5 years
  - Using various ground test free-flight facilities such as ballistic ranges as well as flight experiments
- The inclusion of an atmosphere model (EarthGRAM) allows for atmospheric flight to be simulated
  - Flight scale simulations can be run to support ground test and ballistic range scale simulations to better understand ground to flight traceability



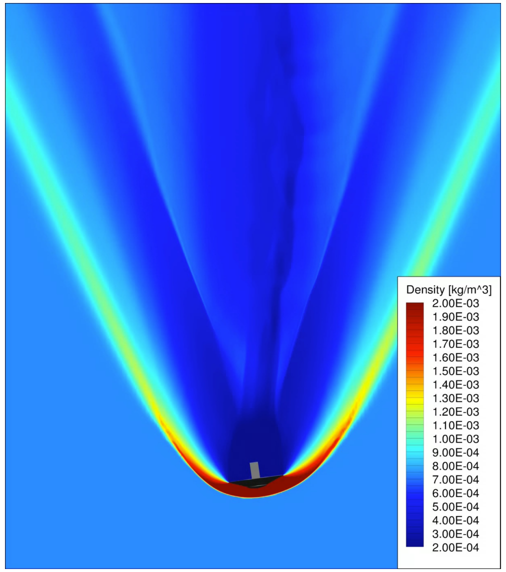


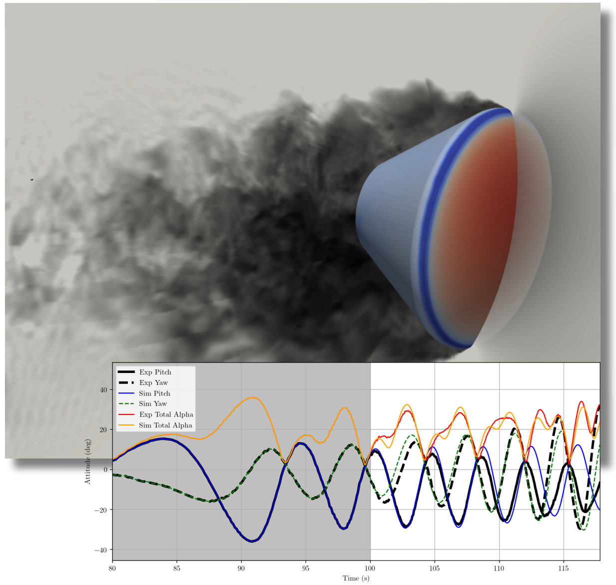
Courtesy of Joe Brock

Obtaining dynamic aero-coefficients exclusively FFCFD



Atmospheric flight simulation with EarthGRAM





Flight Data

- Aerodynamic Reconstruction
  - Accelerometer data to determine aero forces and moments
- FADS – (q,p,$\boldsymbol{\alpha}$,$\boldsymbol{\beta}$) from least squares fit of flight pressures to calibration database
  - Aero responsible for calibration database, Cp (M,$\boldsymbol{\alpha}$,$\boldsymbol{\beta}$), uCp (M,$\boldsymbol{\alpha}$,$\boldsymbol{\beta}$)
- Motion matching – determine database UFs that best match flight to database
  - Trajectory simulations
  - Parameter ID methods
- Pressure measurement comparisons
  - Flight data can help us improve our CFD tools and understand the physics better

Summary for Analysis Methodologies

Ground-based testing

- Not a perfect analogy for flight, imperfect measurements
- Re limitations, high enthalpy limitations
- Very useful for CFD validation
- Most important for dynamics and subsonic capsule aero.

CFD / DSMC

- Models don’t fully simulate reality, but we have very good characterization of the models.
- Separated flows, chemistry modeling, ablation are all challenging.
  - Turbulence effects are primary limitation
- Primary tool for hypersonic/rarefied

Flight

- VERY limited knowledge of the perfect simulation.
- Primary use is aerodynamic database validation, not database development
- Critical to collect as much data as possible from every flight / flight test

Synthesizing all of the aerodynamic data to be use by our customers

AERODATABASE

Aerodatabase Basics

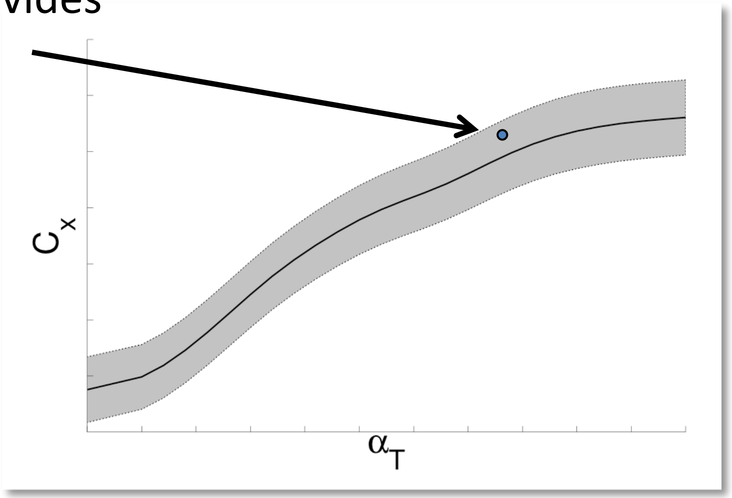
Aerodatabase Development

- Formulation
  - Nominal, uncertainties, dispersions
- Response surface development
  - Independent parameters, coverage
  - Single source, blending
  - Simple interpolation, ML methods
- Provide database to customers
  - API (Orion, MSL)
  - Models that customers implement (SLS)

Aerodatabase Usage

- Trajectory development
  - Nominal, dispersed
  - Stressing trajectories
- Aerodynamic loads

Database provides ***dispersed*** aerodynamic coefficients



Uncertainty factor provided by user. For uniform distribution, between ±1

$$C_x\big|_{dispersed} = \underbrace{C_x(M,\alpha_T)}_{} + \overbrace{UF_{C_x}}^{} \underbrace{uC_x(M,\alpha_T)}_{}$$

Nominal coefficient

1-σ uncertainty bound on coefficient

Aerodatabase Formulations – MSL Static

Formulation defines the necessary terms to provide the 6 aero coefficients, dispersed.

- Aerodatabase provides model for each term as a function of independent variables
  - Essentially, a response surface
- Uncertainties are used, with dispersion model, to provide dispersions on nominal coefficients
  - Uncertainties on aero coefficients are decoupled
    - Allows for trajectory studies to understand effect of larger uncertainty for one parameter at a time
  - ‘adders’ for bias and trim angle, ‘multipliers’ for dispersing the slope and static stability
    - Orion uses slope uncertainties only for pitch and yaw
- Dispersions can be defined as normal, uniform, or any other appropriate distribution

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

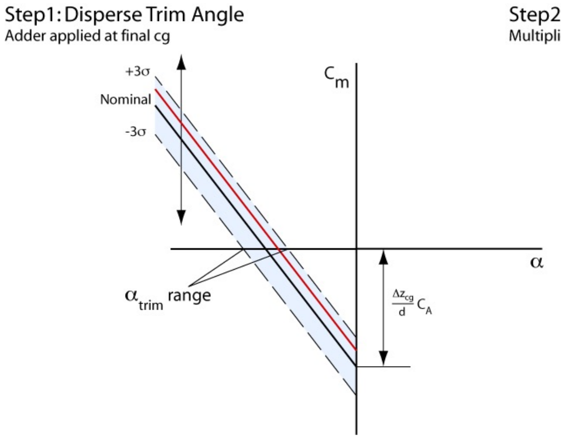
$$C_{N_{Disp}} = \left[C_N(\alpha,\beta)+U^A_{C_N}\right](1+U^M_{C_N})$$

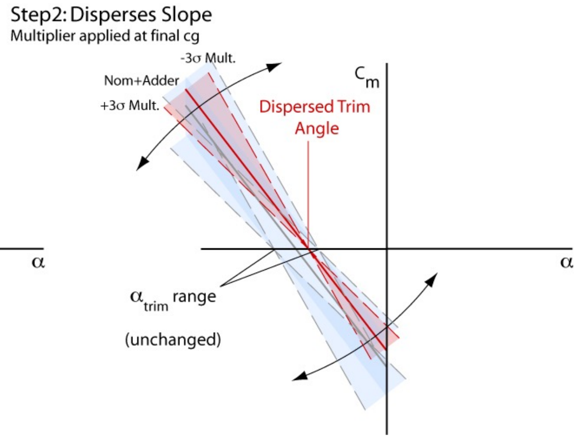
$$C_{Y_{Disp}} = \left[C_Y(\alpha,\beta)+U^A_{C_Y}\right](1+U^M_{C_N})$$

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

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

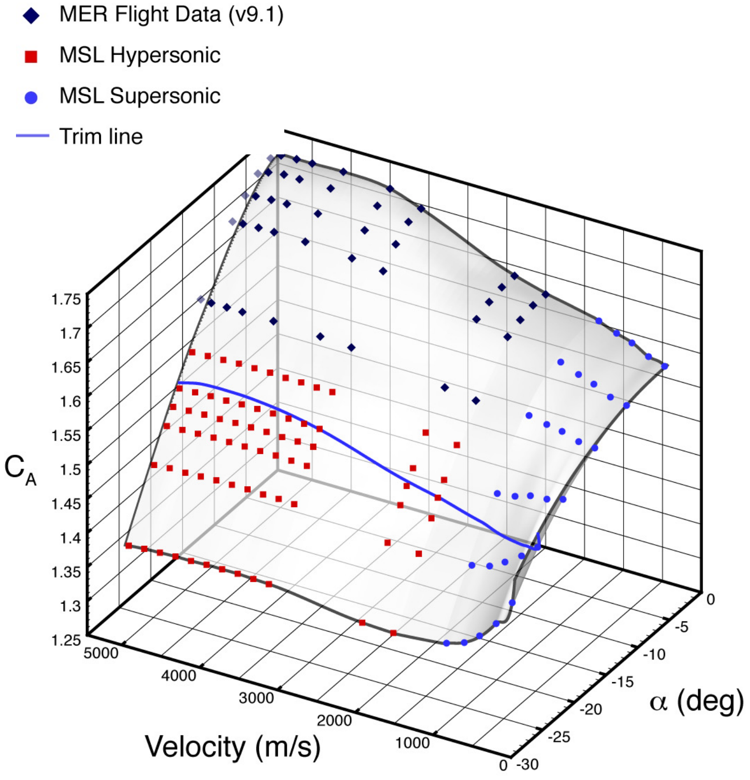
$$C_{l_{Disp}}\Big|_{cg} = \frac{\Delta y}{d}C_N(\alpha,\beta) - \frac{\Delta z}{d}C_Y(\alpha,\beta) + U^A_{C_l}$$


Step1: Disperse Trim Angle
Adder applied at final cg


Step2: Disperses Slope
Multiplier applied at final cg

Courtesy of Mark Schoenenberger

Response Surface Development

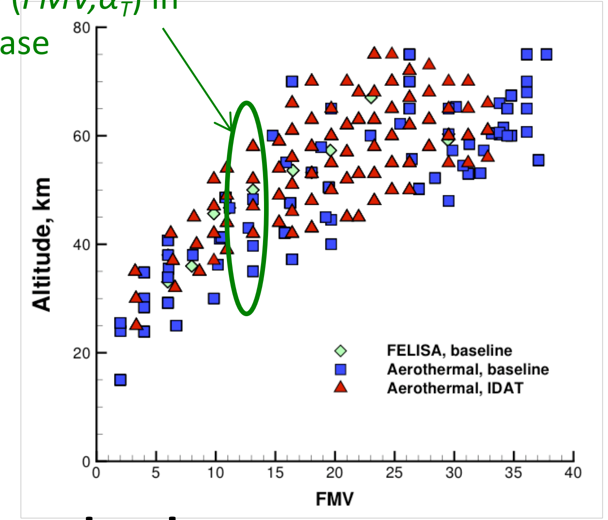


MSL Aerodatabase

C_A, Data and Database

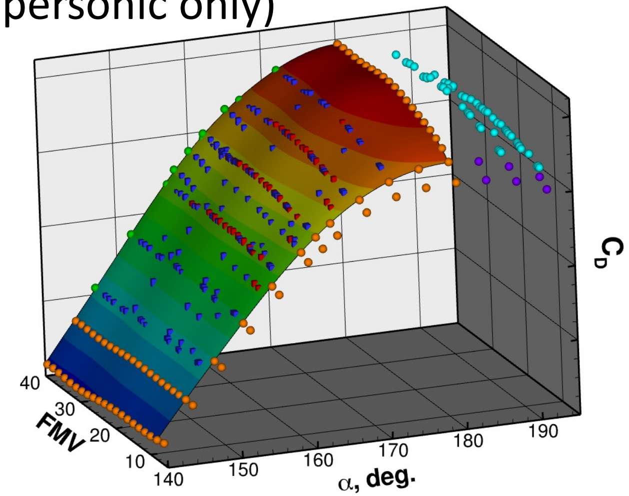
Data sources must be combined into single model

- MSL typically uses single data source for nominal
  - Database uses biparabolic interpolation to provide $C_x(V,\alpha)$
- Orion combines multiple sources using different approaches in different speed regimes
  - Database uses linear interpolation of a final table of data to provide $C_x(FMV,\alpha,\beta)$
- Machine learning and higher order modeling are active research topics


Single (FMV,α_T) in database

Orion Aerodatabase

C_D, Data and Database (hypersonic only)



Courtesy of Mark Schoenenberger

Bibb, et al., AIAA 2011-3506

Uncertainty Development – MSL

Uncertainty model development strategies vary more than the nominal aero analysis

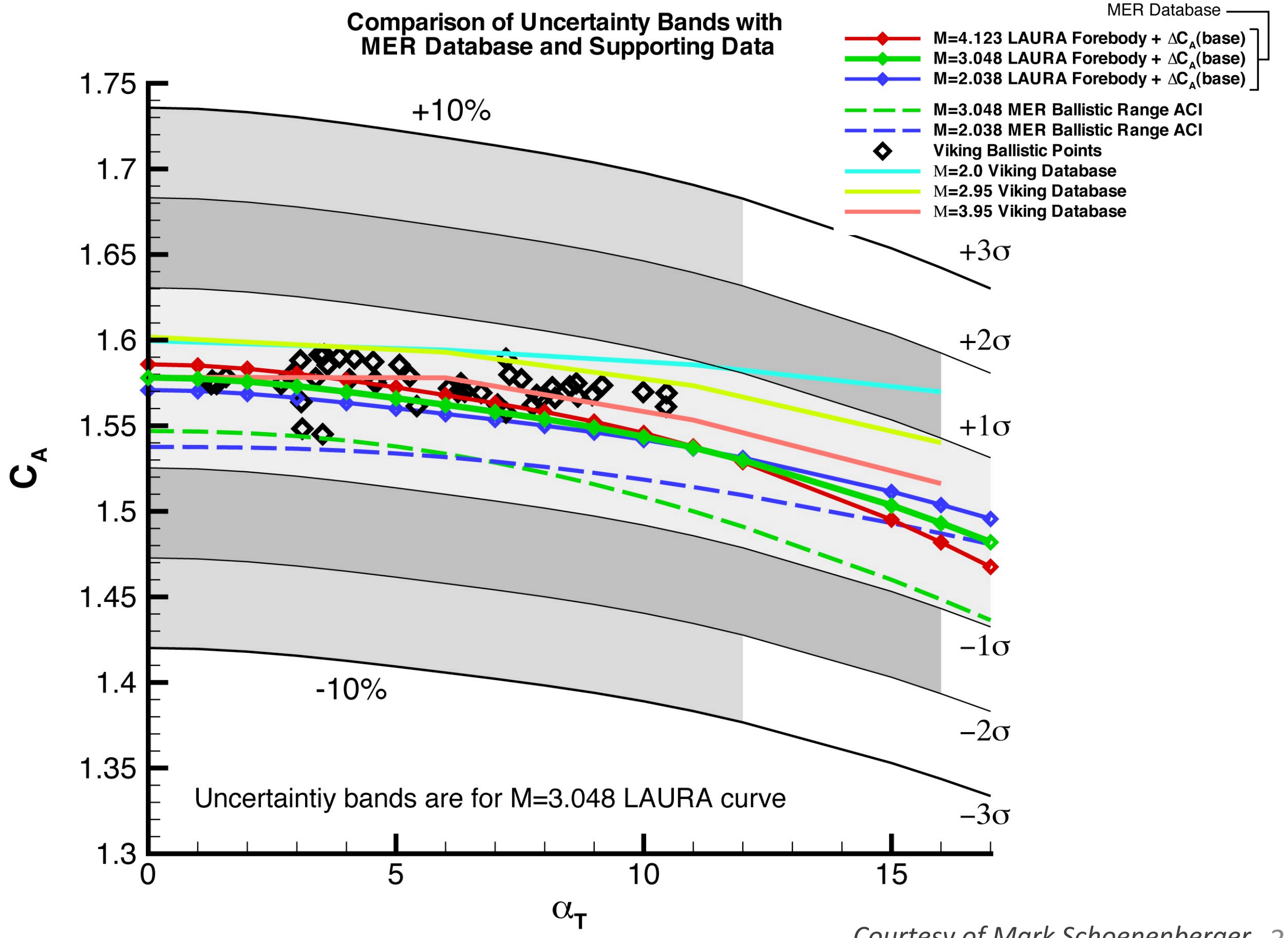
MSL uncertainties are set based on heritage ranges, and numerous analyses performed to support (and adjust) those ranges

- Uncertainties that produced adverse performance in simulation were assessed in more detail to better inform the model implementation and uncertainty levels.
  - persistent roll torque
  - hypersonic pitching moment
- Sensitivity studies for specific phenomena (ablation, deformation, gas chemistry, etc.) run with trajectory sims

MSL Aerodatabase

C_A, uncertainties and additional data sources

$uC_A = \pm 3\% \ C_A$



Courtesy of Mark Schoenenberger

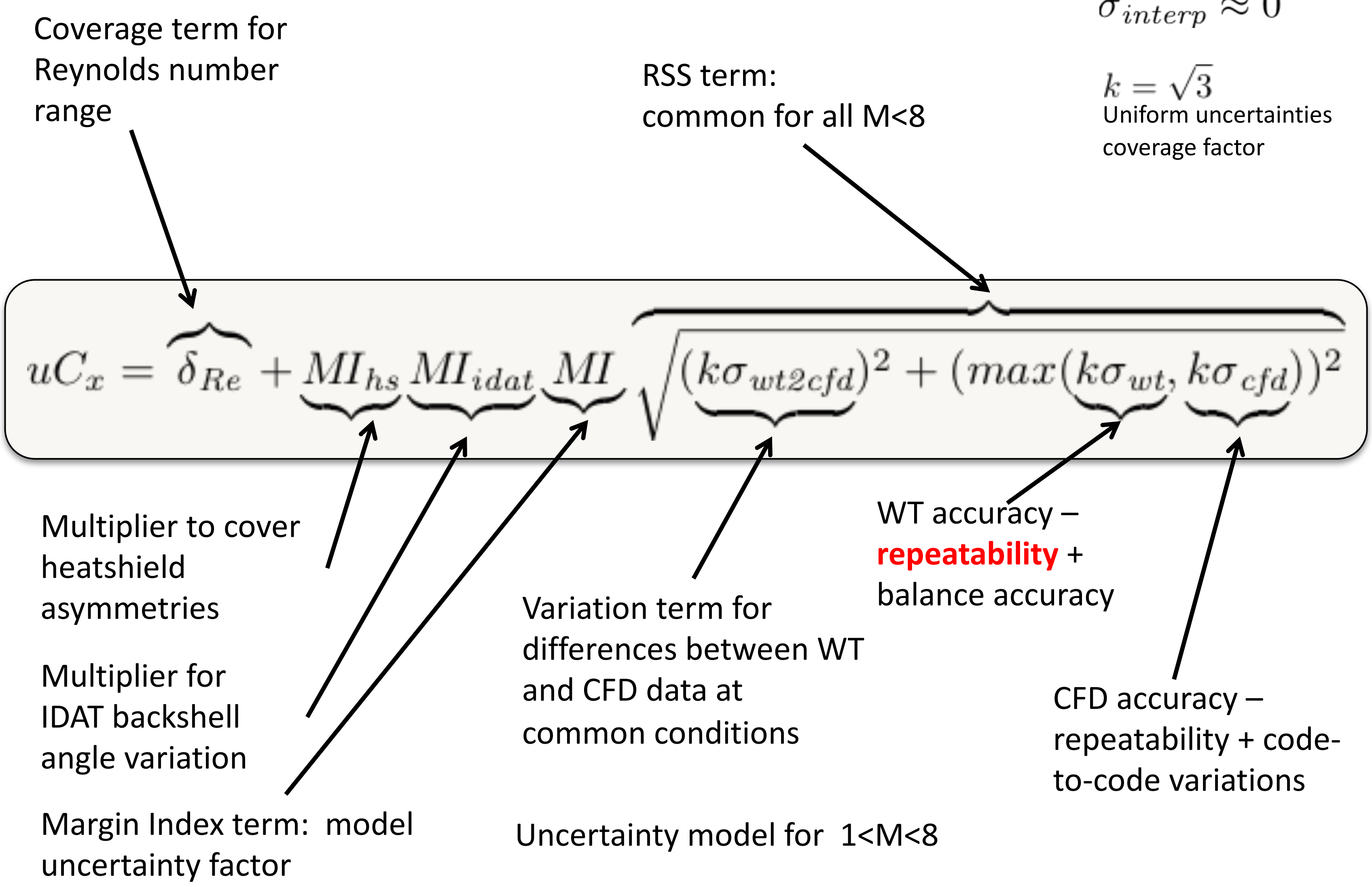
Uncertainty Development – Orion

Orion: individual contributors to error are combined

- Each analysis has associated uncertainties
- Database model has additional uncertainties
- Not shown, we always have a ‘flight’ term that covers how well our models are expected to simulate flight

Based in statistical process control theory

- Variational terms are RSS’d
- Coverage terms are added
- Multipliers used for poorly quantified terms



$\sigma_{interp} \approx 0$

$k = \sqrt{3}$

Uniform uncertainties coverage factor

Coverage term for Reynolds number range

RSS term: common for all M<8

$$uC_x = \overbrace{\delta_{Re}}^{} + \underbrace{MI_{hs}}_{}\,\underbrace{MI_{idat}}_{}\,\underbrace{MI}_{}\,\overbrace{\sqrt{\underbrace{(k\sigma_{wt2cfd})^2}_{} + (max(\underbrace{k\sigma_{wt},}_{}\,\underbrace{k\sigma_{cfd}}_{}))^2}}^{}$$

Multiplier to cover heatshield asymmetries

Multiplier for IDAT backshell angle variation

Margin Index term: model uncertainty factor

Variation term for differences between WT and CFD data at common conditions

WT accuracy – **repeatability** + balance accuracy

CFD accuracy – repeatability + code-to-code variations

Uncertainty model for 1<M<8

Bibb, et al., AIAA 2011-3507

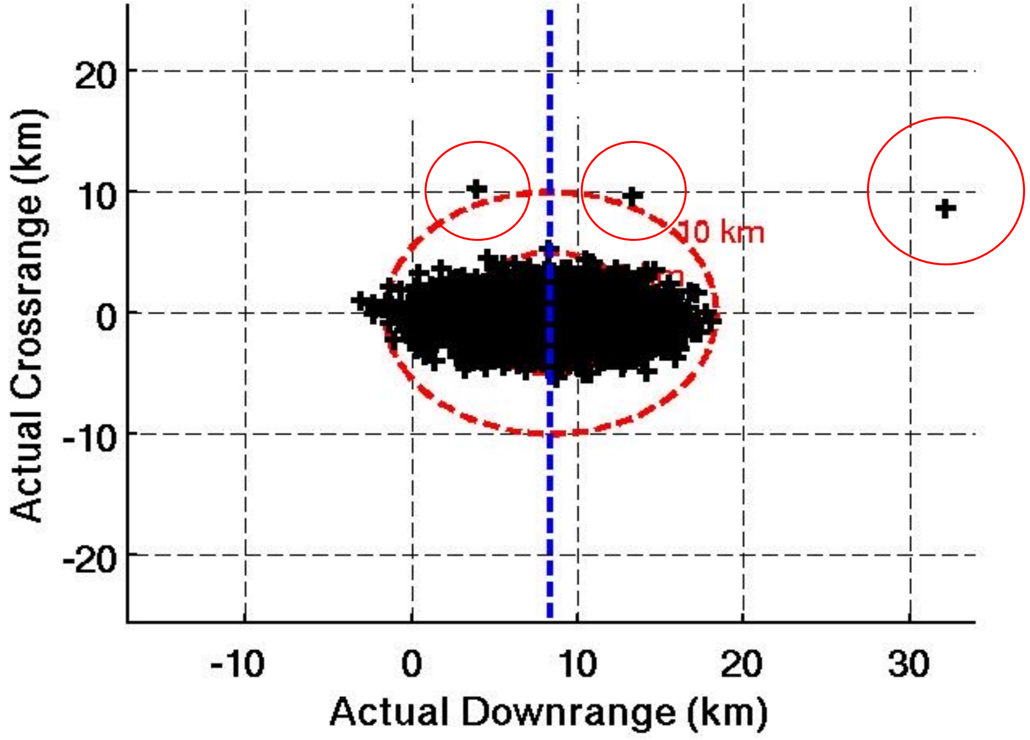
Trajectories and Aerodatabases

GNC uses the aerodatabase with dispersions when running Monte Carlo trajectory simulations

- Trajectory provides state (M, α, β, etc) and uncertainty factors
  - UFs drawn based on (aero) specified distributions
- Aerodatabase returns the 6-DOF dispersed aero coefficients

GNC looks at numerous metrics to understand overall performance and limits

- Outliers in main sims are analyzed in detail
- Sensitivity studies for specific phenomena used to stress the system and understand limits



MSL Trajectory Sim

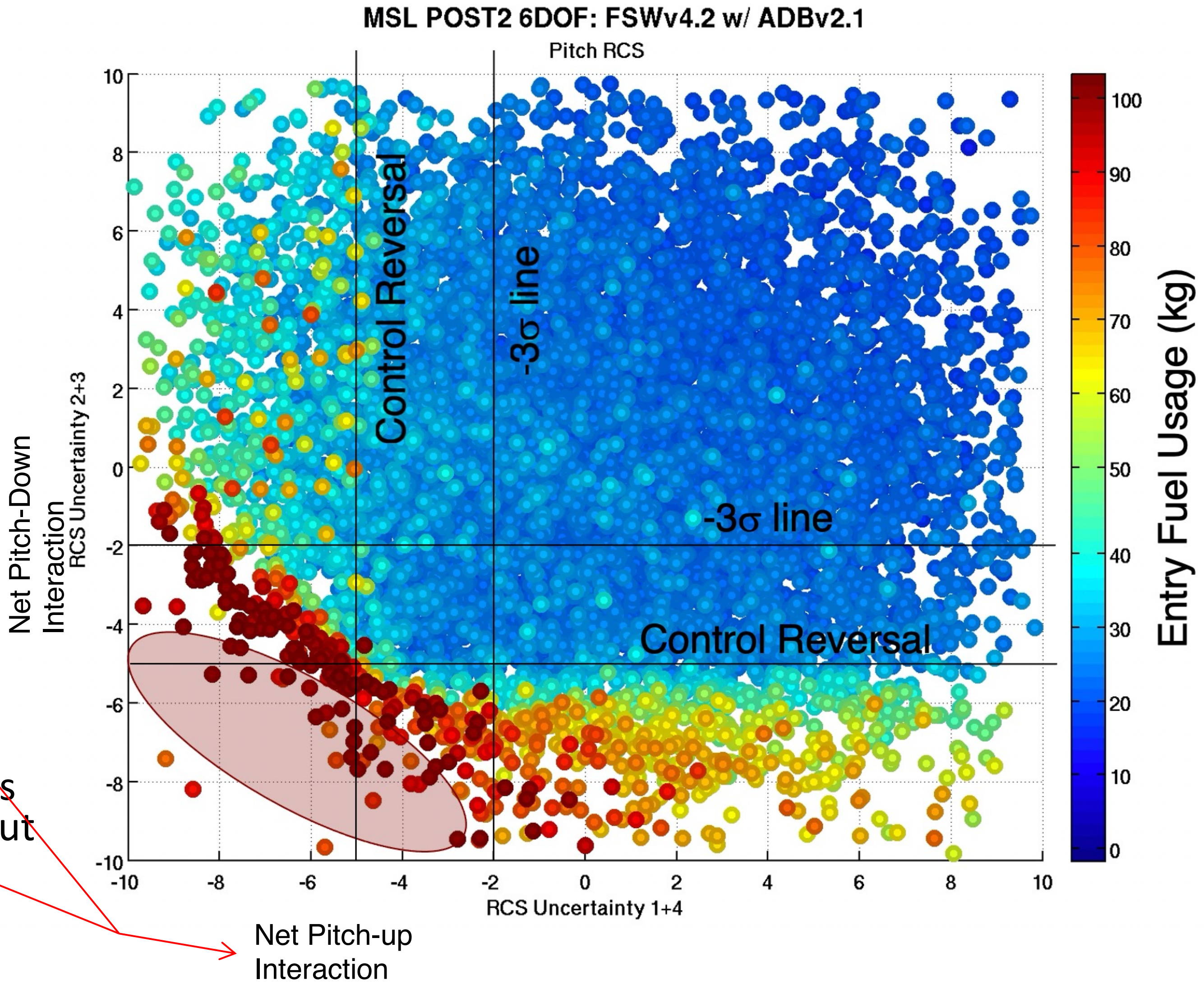
- Outliers determined to come from large roll uncertainty, generating a persistent roll-torque
- Additional analysis showed that a 3σ roll-torque was ~2x conservative modelling.

Courtesy of Mark Schoenenberger

Example: Pitch-Axis Monte Carlo

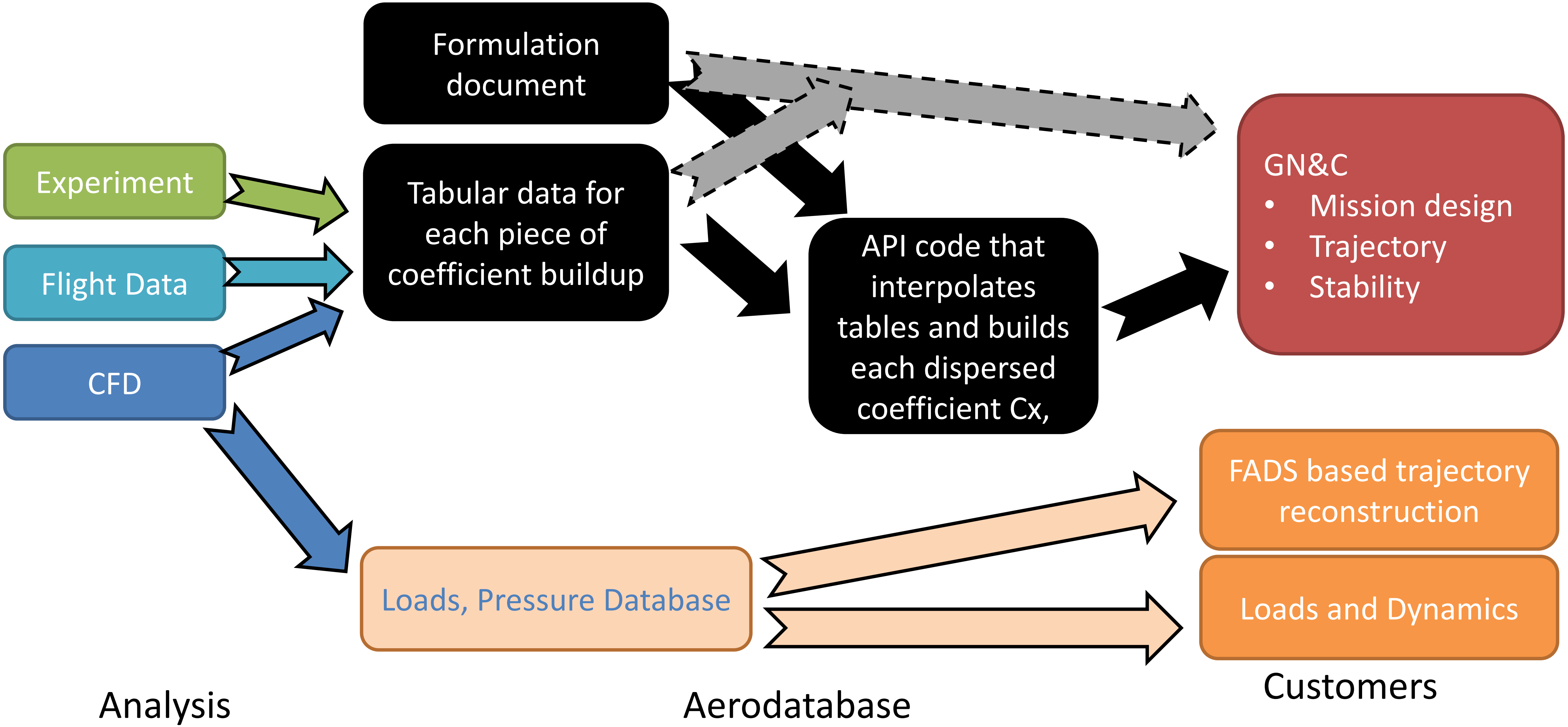
- Stress testing Monte Carlos increased the magnitudes of the aero/RCS interaction variables to well past the +-1.0 values (corresponding to +-3s) about roll, pitch and yaw axes separately
- The controller is robust to interactions up to reversal for these cases.

$$\mathbf{A}_{o,pitch} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ w_{q,1}R_{q,1} & w_{q,2}R_{q,2} & w_{q,3}R_{q,3} & w_{q,4}R_{q,4} \\ 0 & 0 & 0 & 0 \end{bmatrix}$$



- ○ Fuel usage is plotted against the sum of the interactions which together combine to produce an interaction about a principal axis
- ○ Plots show where the "cliffs" occur for principle interactions. "Strong signal" indicates that cross-interactions are small.

Aerodatabase Sausage-making



Experiment

Flight Data

CFD

Formulation document

Tabular data for each piece of coefficient buildup

API code that interpolates tables and builds each dispersed coefficient Cx,

Loads, Pressure Database

GN&C
- Mission design
- Trajectory
- Stability

FADS based trajectory reconstruction

Loads and Dynamics

Analysis

Aerodatabase

Customers

Example Aerodatabase - LOFTID

MAP DSMC

- atmospheric interface to rarefied/continuum overlap (Kn ~ 0.1 to 0.001)

LAURA RANS (reacting gas)

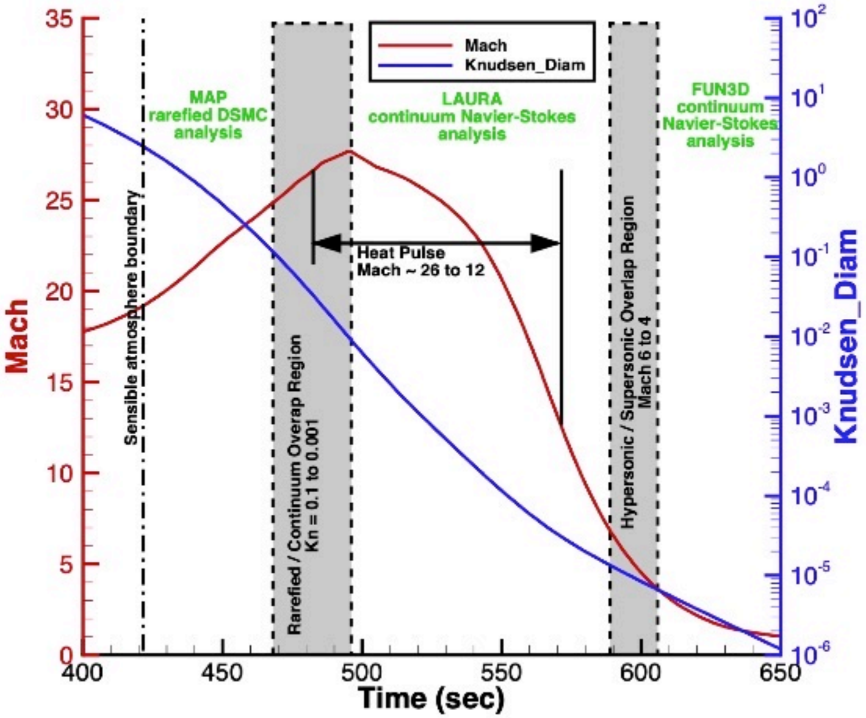
- from rarefied / continuum overlap to hyper / super sonic overlap (M ~ 4 to 6)

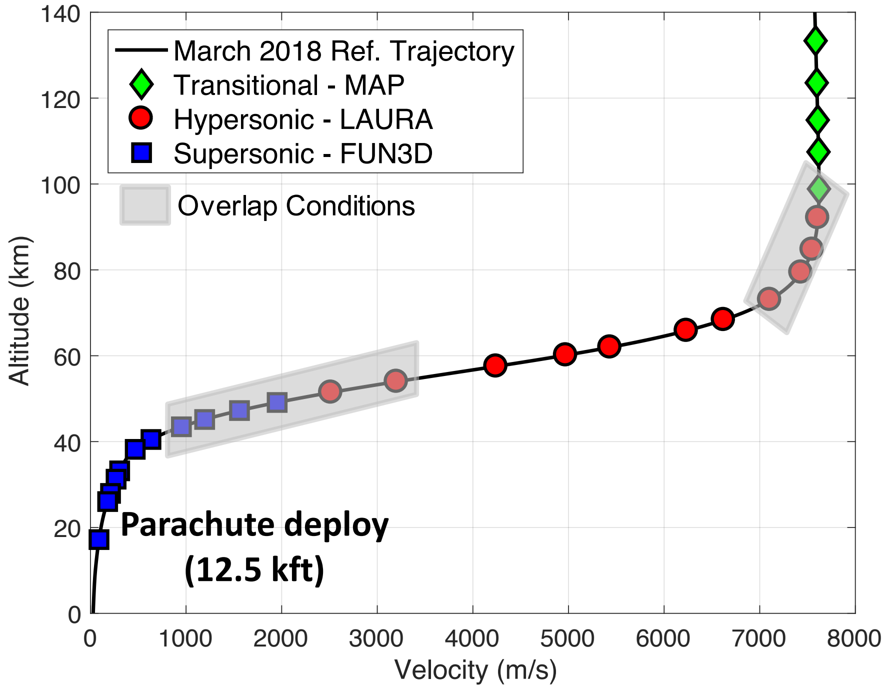
FUN3D RANS (perfect-gas)

- hyper / supersonic overlap down to subsonic

Experimental data

- Help define uncertainty bounds (wake) and heating augmentation factors (scalloping), as well as dynamic stability data





	Flight Regime	Range	Input Parameters	Source
Non-continuum	Free-Molecular	Kn > 3.018, 0° ≤ α_T ≤ 180°	α_T	DAC
	Transitional	0.00572 ≤ Kn ≤ 3.018, 0° ≤ α_T ≤ 8°	α_T, Kn	MAP
Continuum	Hypersonic	M_∞ ≥ 7.88 and Kn < 0.00572, 0° ≤ α_T ≤ 8°	α_T, M_∞	LAURA
	Supersonic	0.7 ≤ M_∞ < 6.0, 0° ≤ α_T ≤ 20°	α_T, M_∞	FUN3D
	Mid-Subsonic	0.3 < M_∞ ≤ 0.65, 0° ≤ α_T ≤ 20°	α_T, M_∞	IRVE-3 BR
	Low-Subsonic	M_∞ ≤ 0.3, 0° ≤ α_T ≤ 70°	α_T	Moonrise WT

courtesy of Adam Wise, Ashley Korzun

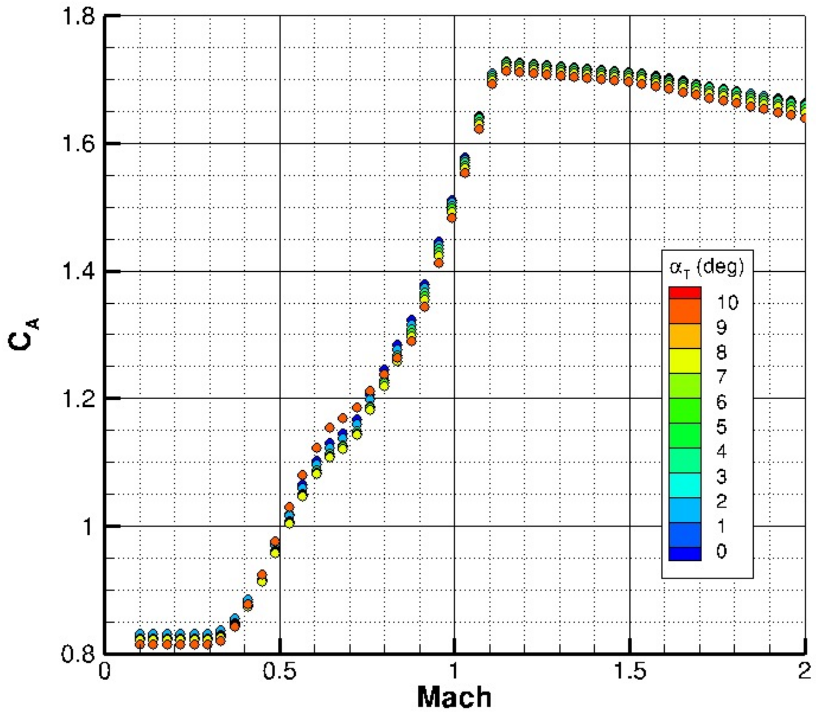
Example Aerodatabase - LOFTID

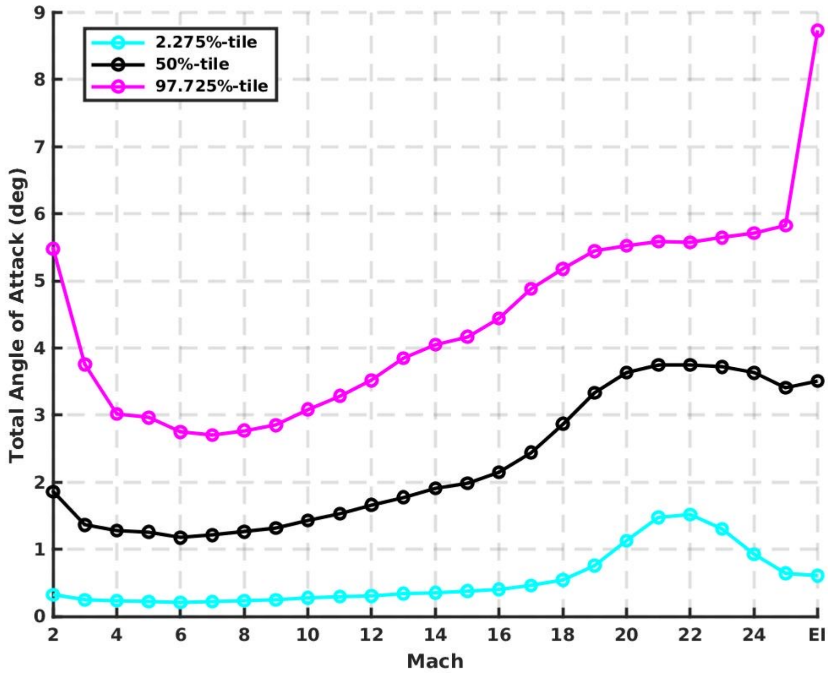
Database implementation
- F90 subroutine
- Database tables hardcoded

Database interpolation
- Continuum data sets linearly blended between breakpoints
- Bi-parabolic interpolation for table look-up for conditions above Mach 6.1
- Linear interpolation used for table look-up for conditions below Mach 6.1

Uncertainties
- Based on IRVE-3, rigid vehicle implementation
- All static aero uncertainties uncorrelated
- Normal distribution used to disperse static aero, except C_{ll}
- Uniform distribution used to disperse C_{mq}, C_{nr}, and C_{ll}

Flight Regime		C_A	C_Y	C_N	C_{ll}	C_m	C_n
Free-Molecular / Transitional	Kn > 1000	±5%	±0.01, ±20%	±0.01, ±20%	$\pm1.24\times10^{-6}$	±0.005, ±20%	±0.005, ±20%
Hypersonic	M > 10	±3%	±0.01, ±20%	±0.01, ±20%	$\pm1.24\times10^{-6}$	±0.003, ±20%	±0.003, ±20%
Supersonic	M < 5	±10%	±0.01, ±20%	±0.01, ±20%	$\pm1.24\times10^{-6}$	±0.005, ±20%	±0.005, ±20%

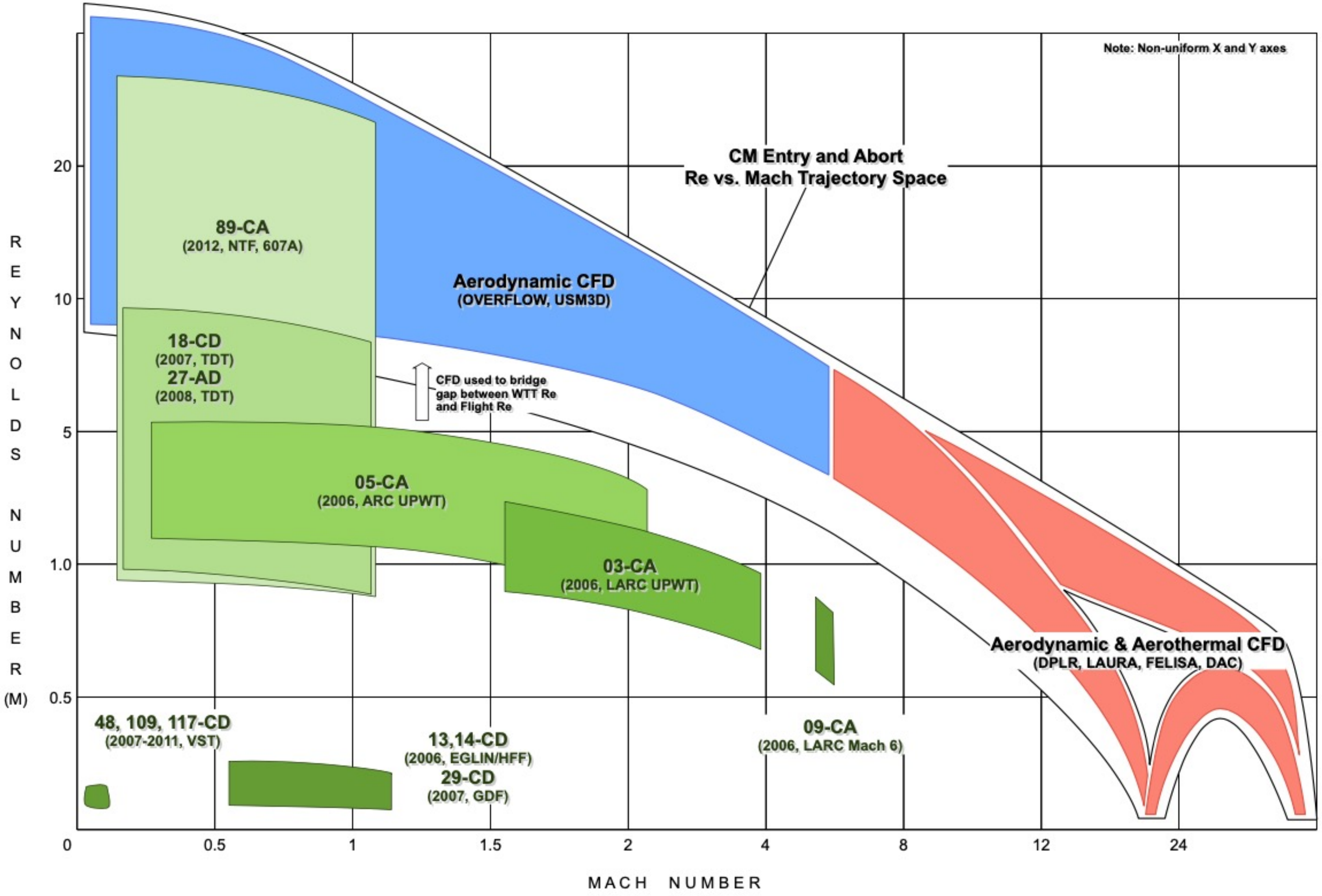




courtesy of Adam Wise, Ashley Korzun

Example Aerodatabase - Orion

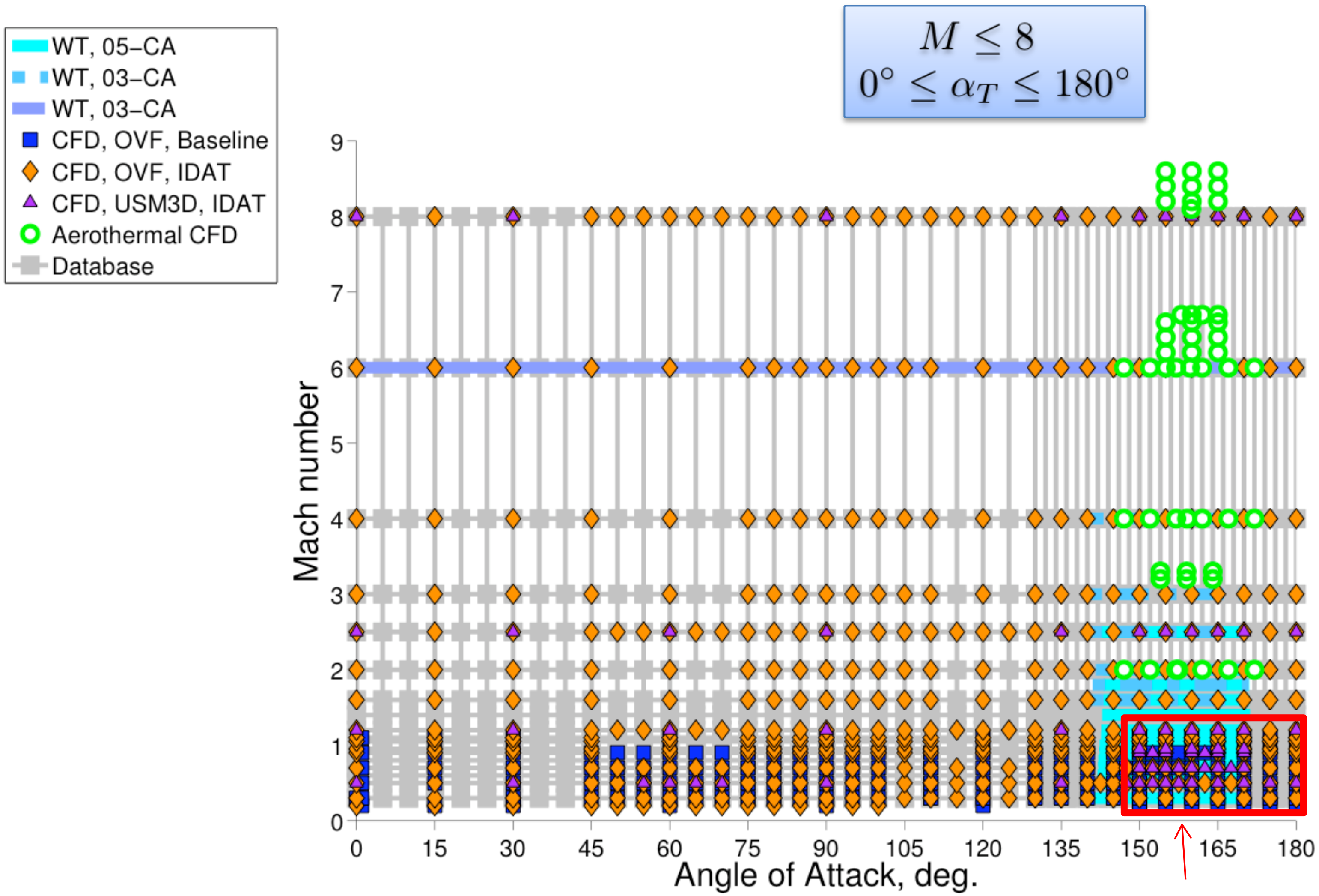
- Orion aerodatabase covers wide range of possible missions, trajectories
  - Guided, ballistic entry
  - Aborts – low Reynolds number
- Aerodatabase API
  - written in C
  - Linearly interpolates database tables
    - Over 200 tables currently
  - Matlab wrapper
  - Python-based development tool



Example Aerodatabase - Orion

- **Primary CFD Set, OVERFLOW**
  - IDAT geometry, 30º backshell
  - 0.3 ≤ M ≤ 8.0, Flight Re_D only
- **Secondary CFD sets, for uncertainties**
  - 0.2 ≤ M ≤ 1.1, WT and Flight Re_D baseline 32.5º backshell, OVERFLOW
  - USM3D, selected Mach numbers, IDAT
- **Aerothermal CFD Set**
  - LAURA, DPLR – viscous, reacting gas air chemistry, laminar and turbulent
  - M > 2, 147º ≤ α ≤ 170º only
  - Baseline and IDAT geometries

- **05-CA, Ames Unitary Plan WT**
  - 0.3 ≤ M ≤ 2.5, 140º ≤ α ≤ 170º
  - Max $Re_D = 5.3 \times 10^6$, 7% model
- **03-CA, Langley Unitary Plan WT**
  - 1.6 ≤ M ≤ 4.0, 140º ≤ α ≤ 170º
  - Max $Re_D = 1.5 \times 10^6$, 3% model
- **09-CA, Langley Aerothermal Lab, Mach 6**
  - M=6.0, 0º ≤ α ≤ 180º



$M \leq 8$

$0^\circ \leq \alpha_T \leq 180^\circ$

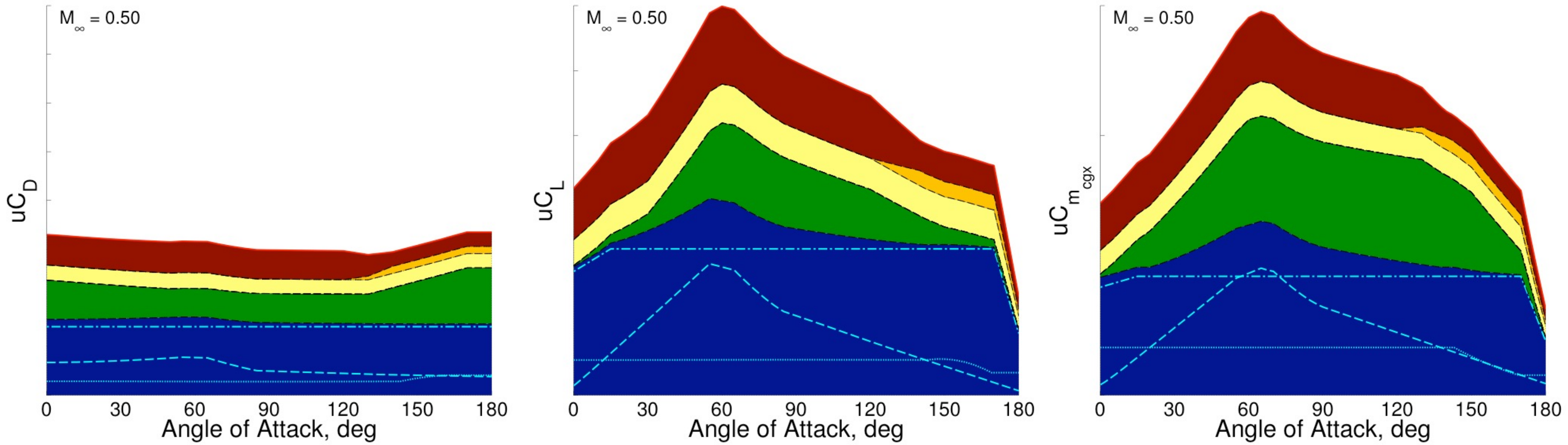
WT dominant region

Bibb, et al., AIAA 2011-3507

Example Aerodatabase - Orion

Buildup plots show relative importance of the uncertainty terms.

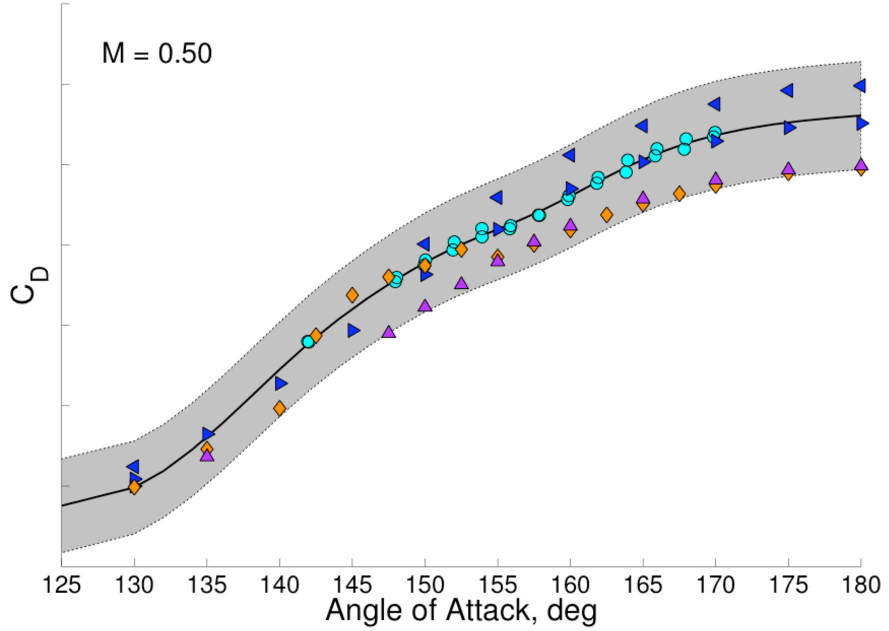
- For M = 0.5
  - RSS term dominated by WT-to-CFD term
  - Reynolds number coverage term also large
  - IDAT coverage is noticeable
  - CFD variations around 60º lead to high error.

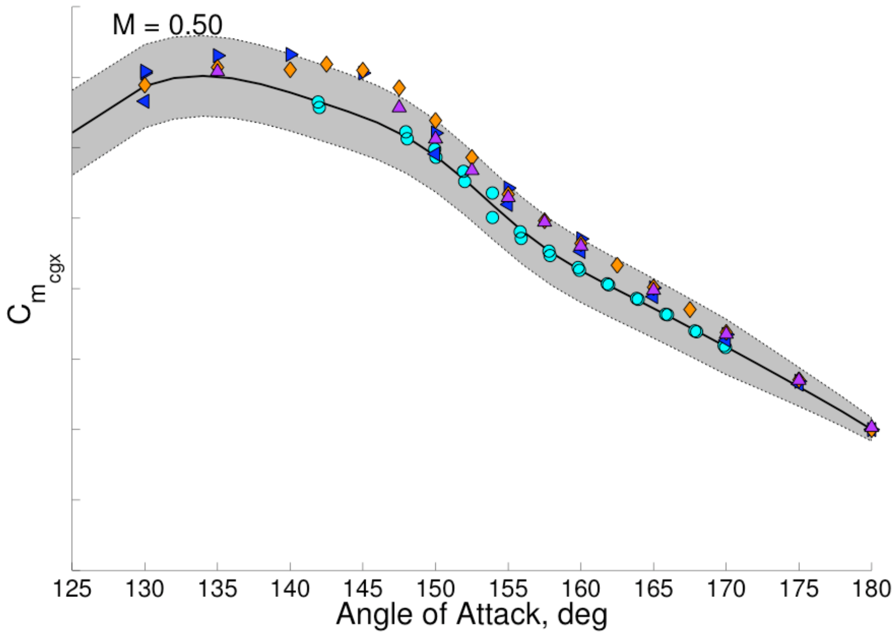


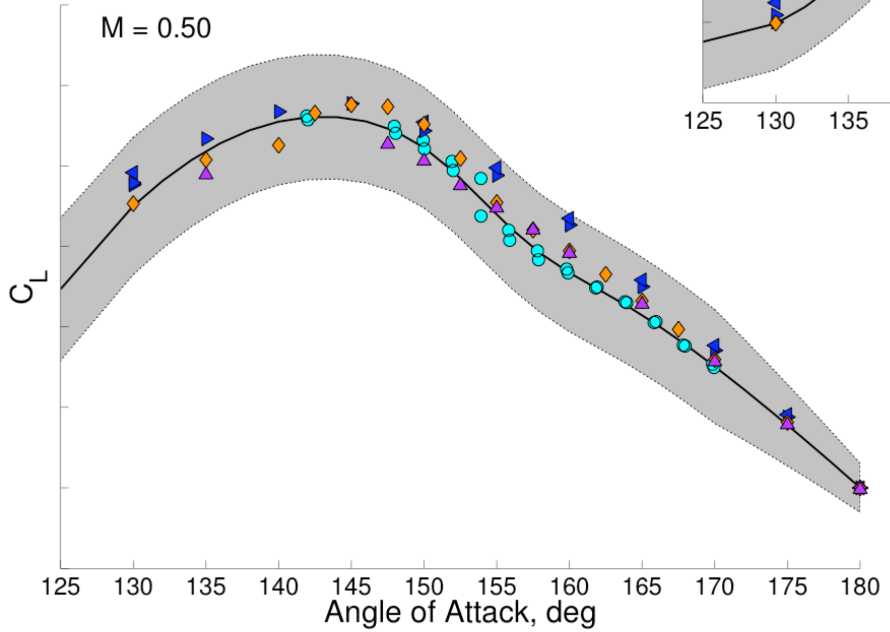
Bibb, et al., AIAA 2011-3507

Example Aerodatabase - Orion

- **Typical plots to visualize database**
- **Uncertainties cover most data, even though CFD not used in trim region**
- **Decrease in uC_L, uC_m near α = 180º evident**





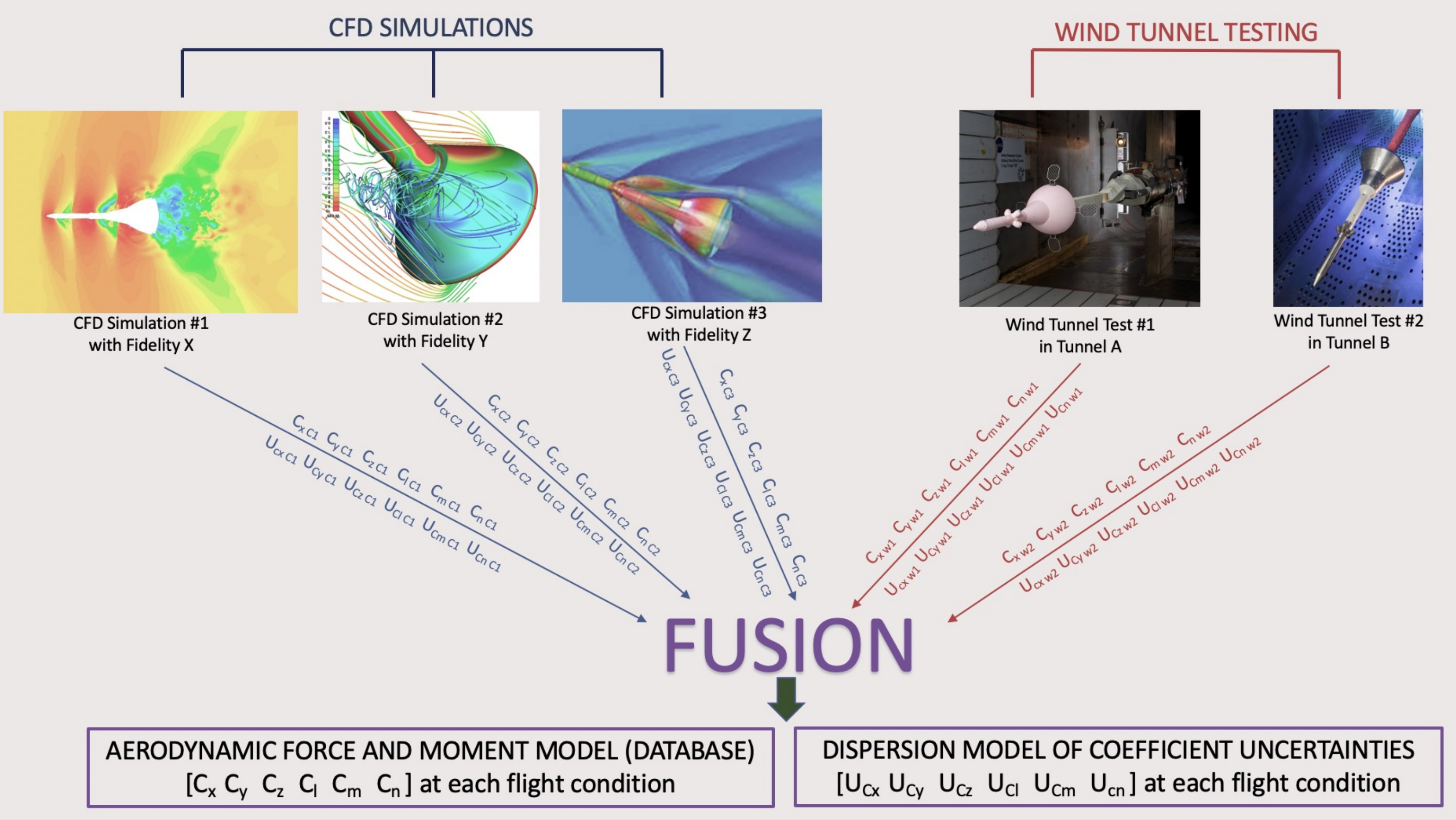


Bibb, et al., AIAA 2011-3507

Research Topics – Machine Learning

- Machine learning / data fusion techniques offer improvements in how we blend datasets and propagate uncertainties.
- Aerofusion team is using MSL and Orion data to explore various methodologies
- Orion is expecting to use techniques for at least some of an upcoming database release.

The AEROFUSION team was selected to look at leveraging and extending data science advances to modernize the aerodynamic model data fusion process for the Mars EDL application- specifically large payload and manned missions that require novel aero shells.



CFD SIMULATIONS

WIND TUNNEL TESTING

CFD Simulation #1
with Fidelity X

CFD Simulation #2
with Fidelity Y

CFD Simulation #3
with Fidelity Z

Wind Tunnel Test #1
in Tunnel A

Wind Tunnel Test #2
in Tunnel B

$C_{x\,C1}$ $C_{y\,C1}$ $C_{z\,C1}$ $C_{l\,C1}$ $C_{m\,C1}$ $C_{n\,C1}$
$U_{Cx\,C1}$ $U_{Cy\,C1}$ $U_{Cz\,C1}$ $U_{Cl\,C1}$ $U_{Cm\,C1}$ $U_{Cn\,C1}$

$C_{x\,C2}$ $C_{y\,C2}$ $C_{z\,C2}$ $C_{l\,C2}$ $C_{m\,C2}$ $C_{n\,C2}$
$U_{Cx\,C2}$ $U_{Cy\,C2}$ $U_{Cz\,C2}$ $U_{Cl\,C2}$ $U_{Cm\,C2}$ $U_{Cn\,C2}$

$C_{x\,C3}$ $C_{y\,C3}$ $C_{z\,C3}$ $C_{l\,C3}$ $C_{m\,C3}$ $C_{n\,C3}$
$U_{Cx\,C3}$ $U_{Cy\,C3}$ $U_{Cz\,C3}$ $U_{Cl\,C3}$ $U_{Cm\,C3}$ $U_{Cn\,C3}$

$C_{x\,w1}$ $C_{y\,w1}$ $C_{z\,w1}$ $C_{l\,w1}$ $C_{m\,w1}$ $C_{n\,w1}$
$U_{Cx\,w1}$ $U_{Cy\,w1}$ $U_{Cz\,w1}$ $U_{Cl\,w1}$ $U_{Cm\,w1}$ $U_{Cn\,w1}$

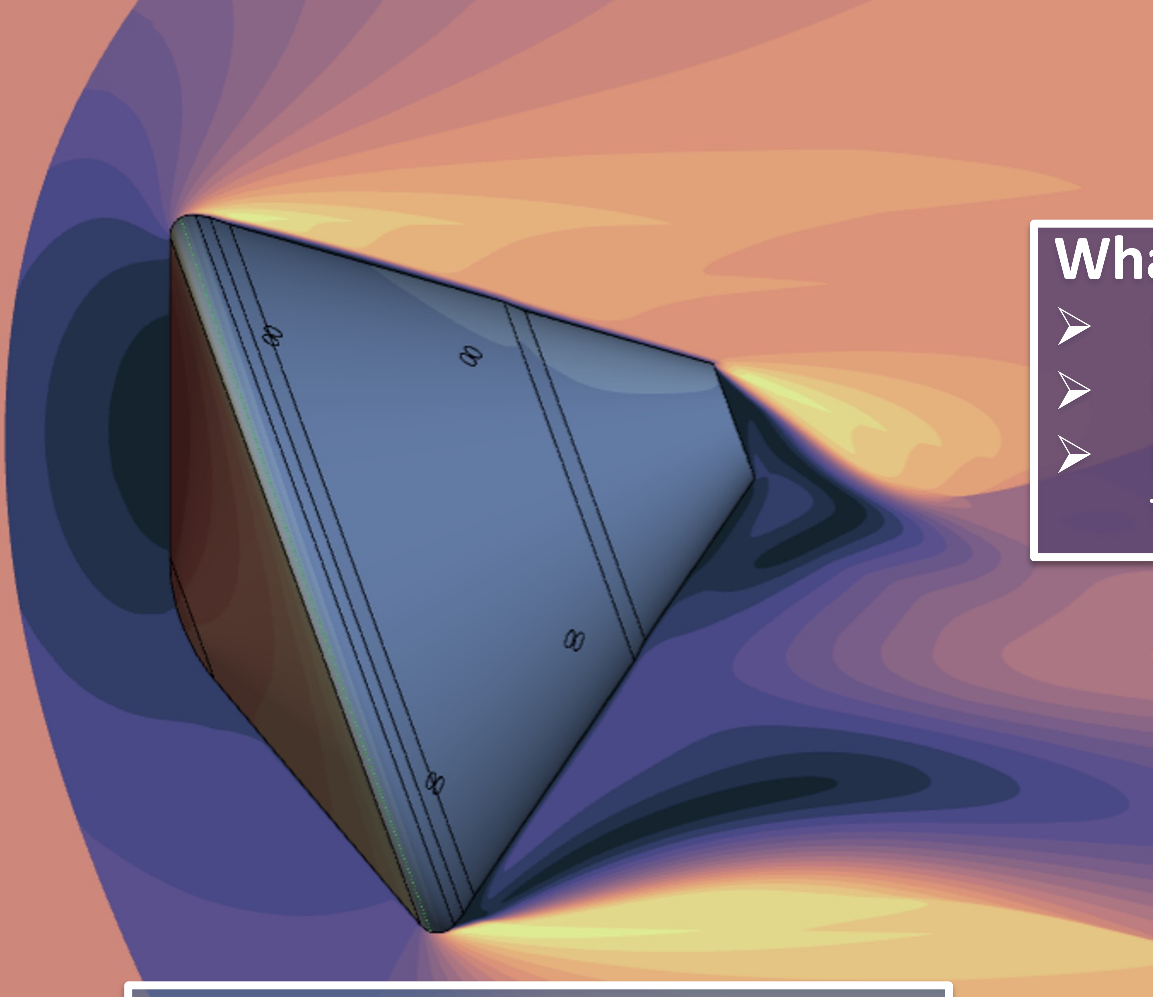
$C_{x\,w2}$ $C_{y\,w2}$ $C_{z\,w2}$ $C_{l\,w2}$ $C_{m\,w2}$ $C_{n\,w2}$
$U_{Cx\,w2}$ $U_{Cy\,w2}$ $U_{Cz\,w2}$ $U_{Cl\,w2}$ $U_{Cm\,w2}$ $U_{Cn\,w2}$

FUSION

AERODYNAMIC FORCE AND MOMENT MODEL (DATABASE)
[C_x C_y C_z C_l C_m C_n] at each flight condition

DISPERSION MODEL OF COEFFICIENT UNCERTAINTIES
[U_{Cx} U_{Cy} U_{Cz} U_{Cl} U_{Cm} U_{Cn}] at each flight condition

courtesy of Mary Stringer, Steve Snyder, TJ Wignall



What we covered today

- ➢ How is aerodynamic modeling used in EDL?
- ➢ How do we develop aerodynamic predictions?
- ➢ How do we communicate aerodynamics to the rest of the EDL disciplines?

Analysis Challenges

- **Improved physics (chemistry, turbulence) in CFD**
- **Computational expense**
- **Decreased uncertainties**

⇒

Rewards

- **Higher precision landings**
- **Larger landed mass.**
- **Missions we couldn't do before**

Collaborators

- Ashley Korzun – LaRC AEFSB, EDL, SRP, FUN3D CFD
- Adam Wise – LaRC AB, LAURA and FUN3D
- Tuan Troung – JSC EG3, Orion Aerosciences (aero)
- Mark Schoenenberger – LaRC AEFSB, Mars aero guru
- Robert Childs – Ames, Capsule aero CFD and turbulence modeling
- Greg Brauckman – LaRC AB, Experimental Aero, Orion testing, STS-1 testing
- Bruce Owens – LaRC, Dynamic aero testing (TDT, spin tunnel)
- Joe Brock – Ames, freeflight CFD with US3D
- Adam Amar – JSC EG3, Orion Aerosciences (aerothermal)
- Derek Liechty – LaRC AB, DSMC
- Clark Pederson – LaRC AB, MSL, turbulence
- Vic Lessard – LaRC AB, Orion aerothermal, LAURA and FUN3D CFD
- Alireza Mazaheri – LaRC AB,
- Bill Wood – LaRC AB, LAURA and FUN3D CFD, SRP
- Bil Kleb – LaRC AB, Computational aerothermal ST and FUN3D S2S guru
- Neil Cheatwood – LaRC AEFSB, EDL, LOFTID
- Francisco Canabal – MSFC, SRP

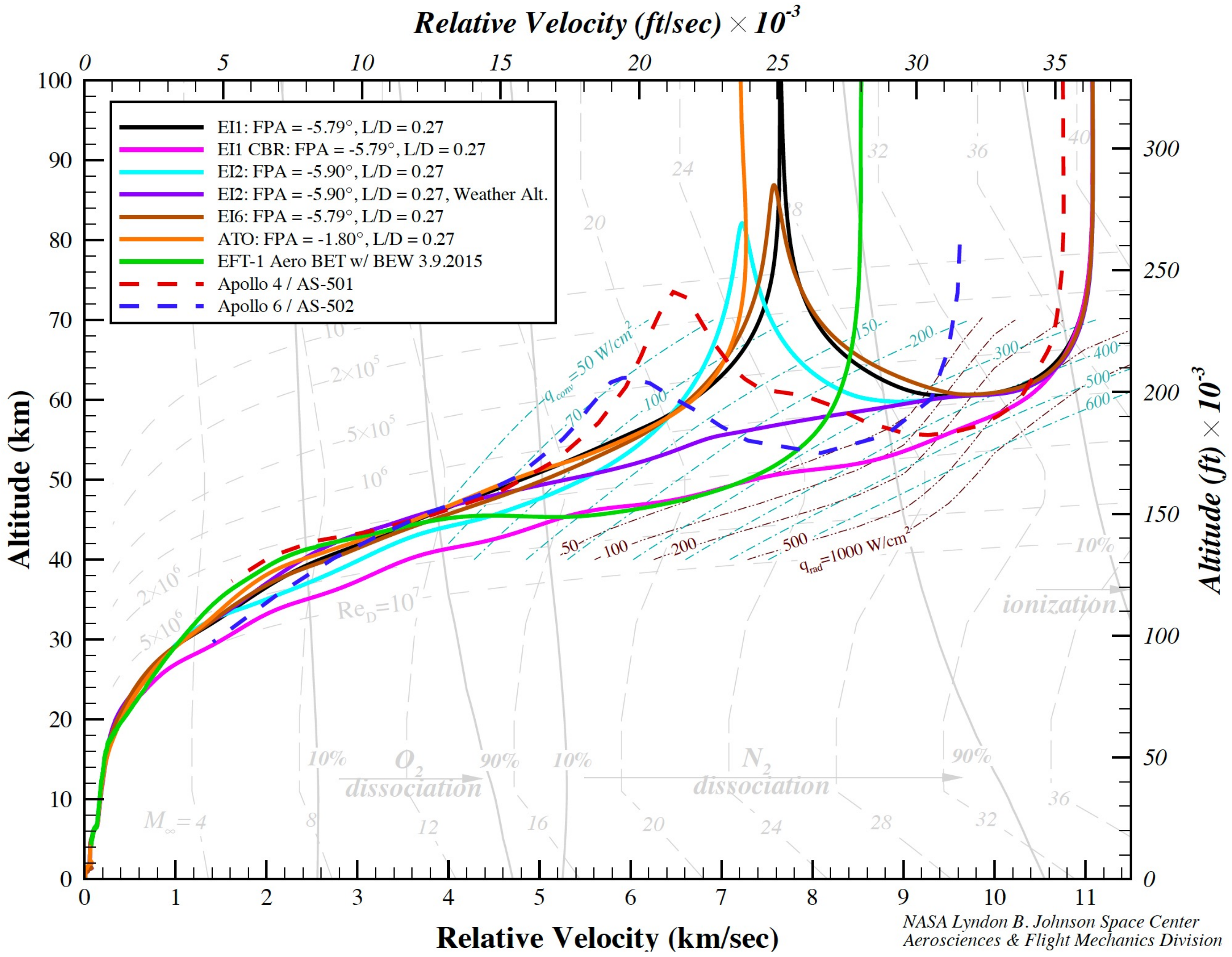

EXPLORE
MOON to MARS

BACKUP

Acronyms

- ADEPT – Adaptable, Deployable Entry and Placement Technology
- CFD – Computational Fluid Dynamics
- DES – Detached Eddy Simulation
- ESM – Entry Systems Modeling
- FADS – Flush Air Data System
- HIAD – Hypersonic Inflatable Aerodynamic Decelerator
- JI – Jet Interaction
- LOFTID – LEO Flight Test of an Inflatable Decelerator
- RCS – Reaction Control System
- SRP – Supersonic Retropropulsion
- TPS – Thermal Protection System
- WT – Wind Tunnel

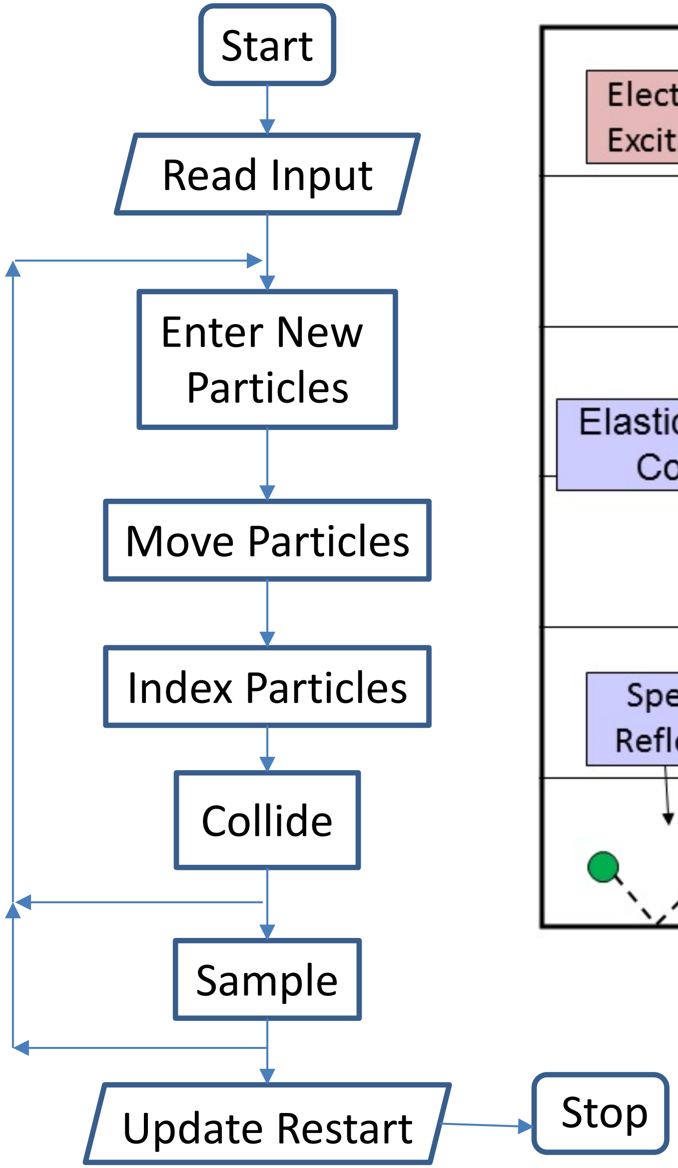
Entry profiles for Orion

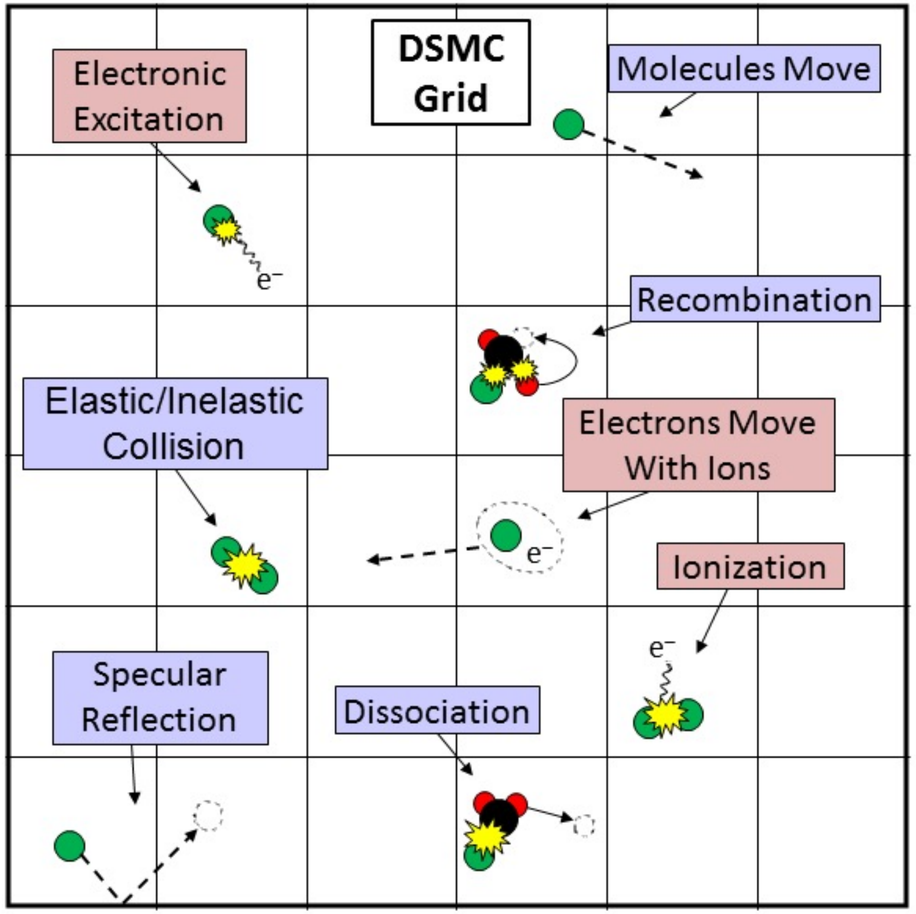


NASA Lyndon B. Johnson Space Center
Aerosciences & Flight Mechanics Division

What is DSMC?

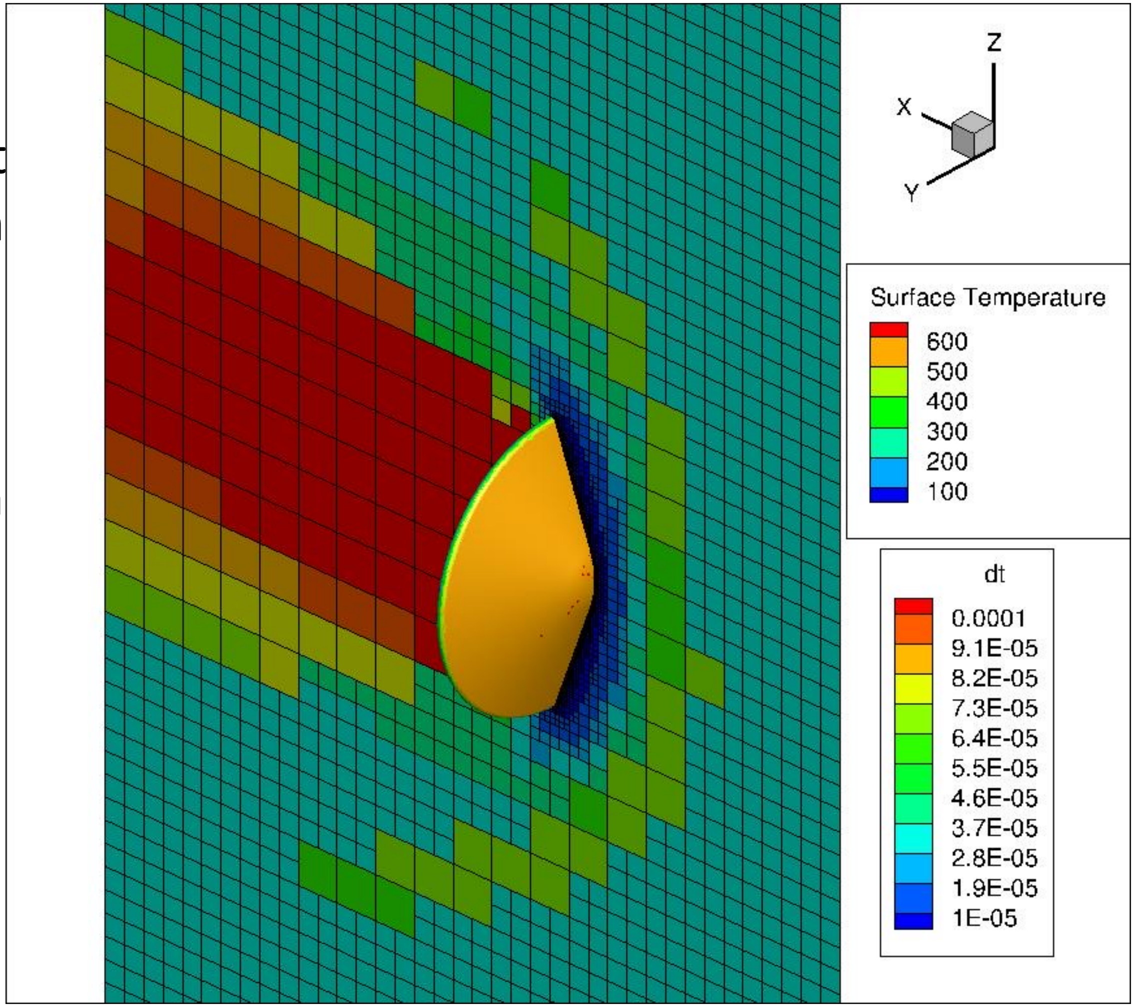
- Direct Simulation Monte Carlo
  - Developed by Dr. Graeme Bird in the '60s
  - Stochastic model of individual simulated particles and their physics
    - Each DSMC 'particle' represents many real particles
  - Probabilistic approach
    - Simplified models use cross sections determined from experiments or analytic results





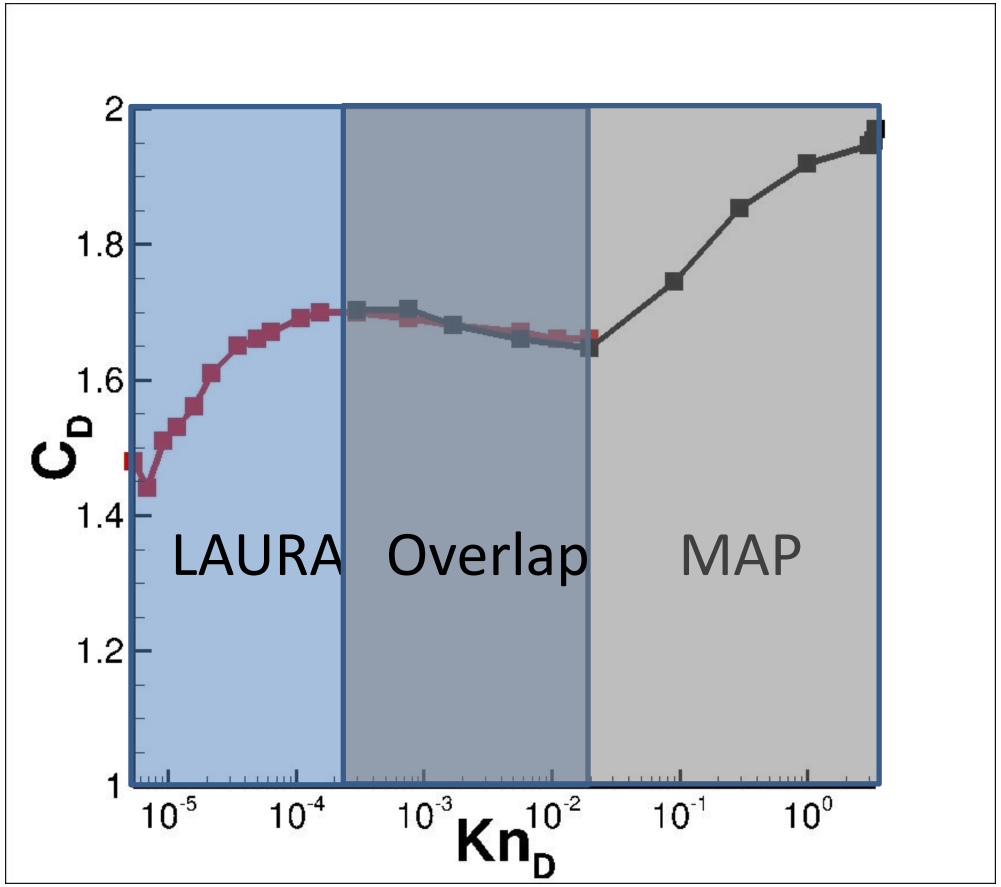
MAP: Multiphysics Algorithm with Particles

- MAP is a 0D/2D/Axi/3D adaptive Cartesian implementation
- Dynamic adaptation
  - Flow field grid – fraction of the local mean free pat
  - Time step – local mean collision time or transit tim
  - Surface temperature – radiative equilibrium
- Grid
  - Morton Octree Cartesian grid for the flow field
  - Unstructured triangular surface grid separate from flow field
- Gas model
  - Internal degrees of freedom – rotational, vibrational, electronic
  - Chemistry – gas phase and surface
  - Charge neutral ionization



CFD Team Tools: Blurring the Lines

- Continually pushing to overlap CFD and DSMC
  - Updating particle properties to reproduce CFD curve fits
    - Earth – 5- and 11-species (neutral/ionized)
    - Mars and Venus – 18-species (ionized)
    - Titan – 13- and 19-species (neutral/ionized)
  - Inclusion of same physics
    - DSMC didn't generally include electronic energy and ionization
    - Radiation
  - Hybrid DSMC/CFD
    - One-way coupling is easy… Two-way not so much!
    - To get valid solutions in all parts of the flow field, we will have to come up with a two-way coupled solution



Uncertainty Development – Orion

Orion: individual contributers to error are combined

- Each analysis has associated uncertainties
- Database model has additional uncertainties
- Not shown, we always have a ‘flight’ term that covers how well our models are expected to simulate flight

Based in statistical process control theory

- Variational terms are RSS’d
- Coverage terms are added
- Multipliers used for poorly quantified terms

Coverage term for laminar-turbulent variations

Coverage term for air chemistry effects

Coverage term for heatshield asymmetries, from companion paper

Coverage term for altitude variations

$$uC_x = \overbrace{\delta_{alt}} + \overbrace{\delta_{ltp}} + \overbrace{\delta_{chem}} + \overbrace{\delta_{hs}} + \underbrace{MI_{idat}}\,\underbrace{MI}\,\underbrace{\sqrt{(k\sigma_{wt2cfd})^2 + (max(k\sigma_{wt}, k\sigma_{cfd}))^2}}$$

Multiplier for IDAT backshell angle variation

Margin Index term: model uncertainty factor

RSS term:
common for all M<8

$\sigma_{interp} \approx 0$

Uncertainty model for 1<M<8

Bibb, et al., AIAA 2011-3506

Uncertainty Development

Uncertainty model development strategies vary more than the nominal aero analysis

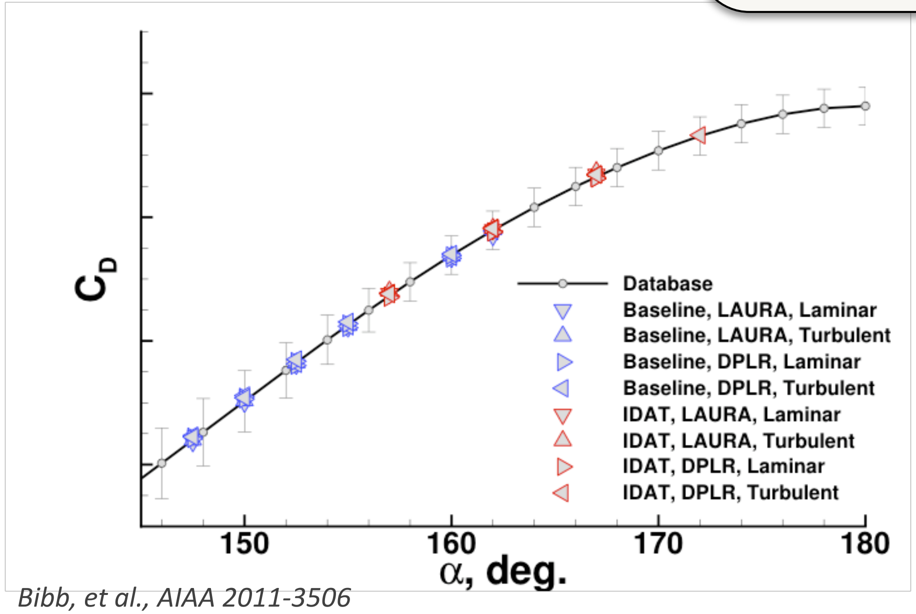
- For Orion, individual contributers to error are combined
  - Based in statistical process control

$$uC_x = \overbrace{\delta_{hs}}^{\text{Heatshield asymmetry term}} + \overbrace{MI}^{\text{Margin Index term: model uncertainty factor}} \overbrace{\sqrt{\underbrace{(k\sigma_{grid})^2}_{\text{CFD accuracy term}} + \underbrace{(k\sigma_{ltp})^2}_{\text{Laminar-turbulent pair (ltp) variation}} + \underbrace{(k\sigma_{ks})^2}_{\text{Combined altitude and code-to-code variation}}}}^{\text{RSS term}}$$

$$k = \sqrt{3}$$

Coverage term for uniform distribution

$$k\sigma_{ks} \approx \sqrt{(k\sigma_{alt})^2 + (k\sigma_{c2c})^2}$$



Bibb, et al., AIAA 2011-3506