X-38 "First Flight" Aerodynamic Lessons Learned

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Briefing Outline

"You cannot be Certain about Uncertainty "

- X-38 Project Overview
- X-38 Aerodynamic Phases – OML Configuration(s) Evolution (X-24A / Rev. 3.1 / Rev 8.3)
- V-131/2 (X-24A/X-23) Development & Flight Testing
- V-131R/V-201 (ELV Ascent / 7 crew) Development & Flight Test 1
- V-131R FF1 Anomaly Resolution & Recertification
- Comments on Lessons Learned

X-38 Mission Vision Goals

- X-38 is a CRV Prototype + Technology Demonstrator
  - *“Prove human-capable vehicles can be designed/ built/ operated for an order of magnitude less”*
- CRV Requirements
- Concept → Lifting Body Entry Vehicle + Parachute Landing
  - X-23/X-24A Derived Shape + GPADS Pararoil
    - Both Significantly Modified since beginning of program
- Other Elements
  - COTS Utilization – Maximize use of Off the Shelf Technology
  - Concurrent Engineering Approach – Reduces Cost
    - Build a little / Test a little / Fix a little
    - Use ground/flight test experience to refine designs and define requirements
    - Subsystem hardware is ahead of high fidelity design analysis
  - Predominantly Civil Servants doing Engineering (2 to 1)
  - Extensive European Involvement
    - Key Elements (Nose Cap / Body Flaps / Rudders / Landing Gear, etc.)
    - Aerodynamic and Aerothermodynamic Databases

CRV Mission/X-38 Vehicle Overview

LOW COST, HIGH-TECH SPACE RESCUE

<u>It's Mission</u>

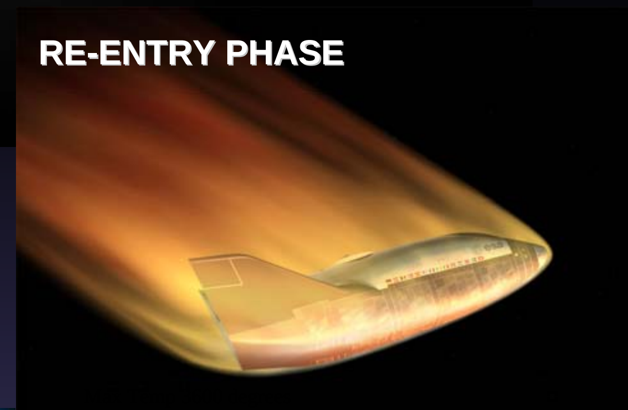
Return full station crew complement (7) to Earth as a result of:

- **Medical Emergency**
- **Station Evacuation**
- **Shuttle Unavailable**

<u>X-38 Specifications</u>

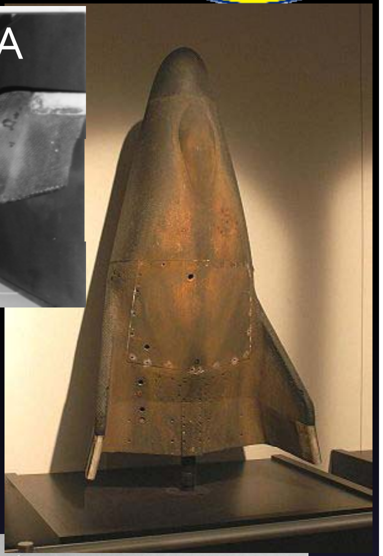
- **Crew Return Vehicle (CRV) Prototype**
- **Lifting Body entry + Parafoil final descent & landing**
- **Length: 30 ft.**
- **Width: 15 ft.**
- **Mono-prop Hydrazine in disposable Deorbit Module**
- **Weight: 33,400 lbs.**
- **Human Rated Design**
- **Full ECLSS for 7 person capacity**

Mission Sequence



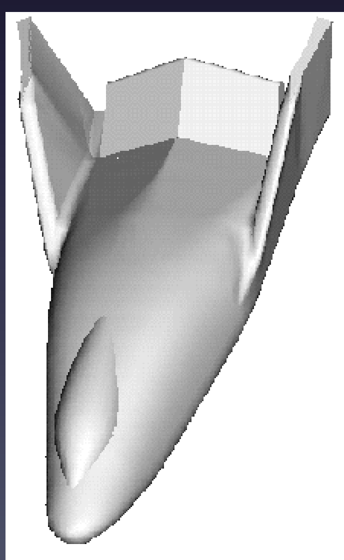
X-38 Aerodynamic Phases

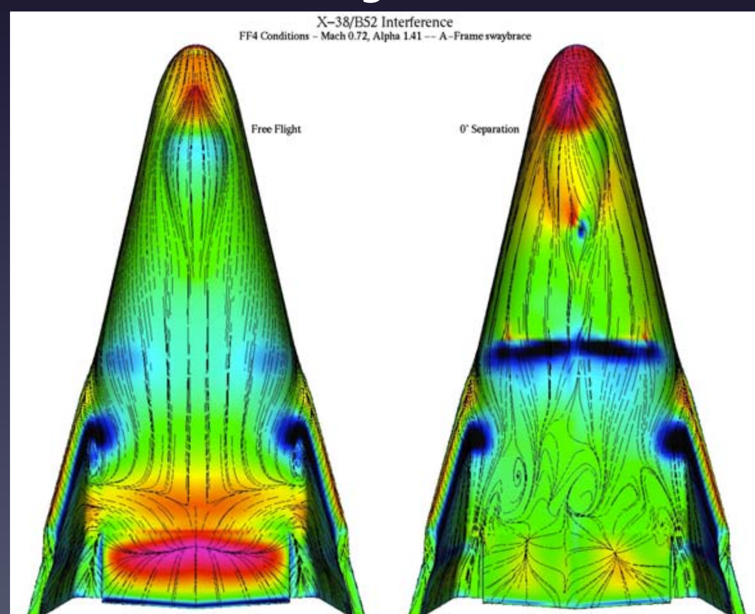
- **X-24A / X-23A Archives**
  - **Established Preliminary Aero Database**
- X-23A (PRIME/SV-5) CONFIGURATION
  - 28.3% scale Space Flight Test Vehicle
    - » Fixed 60° Upper Ramp (Full Span), Fixed Rudders (10° Outboard), Closed Base, Blended Canopy, Ablative Silicone TPS, No Center Fin, Slab OB Fin w/Hemispherical LE
    - » **3 Space Flight Tests** (Vr@26,000fps, h@600Kft, Demonstrated Cross Range of 710miles)
- X-24A (PILOT/SV-5P) CONFIGURATION
  - 100% scale Atmospheric Piloted Flt Test Vehicle
    - » Eight Control Surfaces (Upper & Lower Flaps/Rudders), Open Base, 'Bubble' Canopy, Cambered Fin Airfoil (w/drooped LE & thin TE), Aluminum Skin
    - » Mach 1.5 to runway landing **- 10 Glide + 18 Rocket Assist/Glide Piloted Flight Tests**

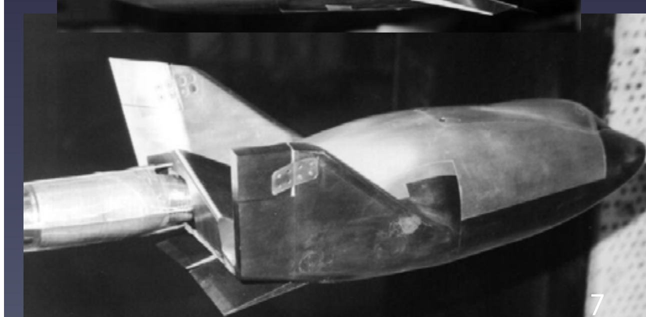


X-38 Aerodynamic Phases

- **Rev. 3.1 Configuration (Vehicle 131/132)**
  – 100% scale Atmospheric Flight Test Vehicle - X-24A Derivative
    - Retained the X-23 Hypersonic/Supersonic (Windward Surface) OML and the X-24A Transonic OML/Configuration
    - Four Control Surfaces, Thick Rudder Trailing Edge, Closed Base, Fixed Upper Ramp @ 40° (w/channels), No Center Fin
  – Subsonic through Hypersonic WT Testing & CFD Analysis
    - CFD Analysis validated by reproducing the X-24A aero - extended to X-38
  – Detailed Subsonic Aero Database Supports V131/132 Flight Tests
    - B-52 Release - Subsonic Flight Test Vehicles (V131/132)





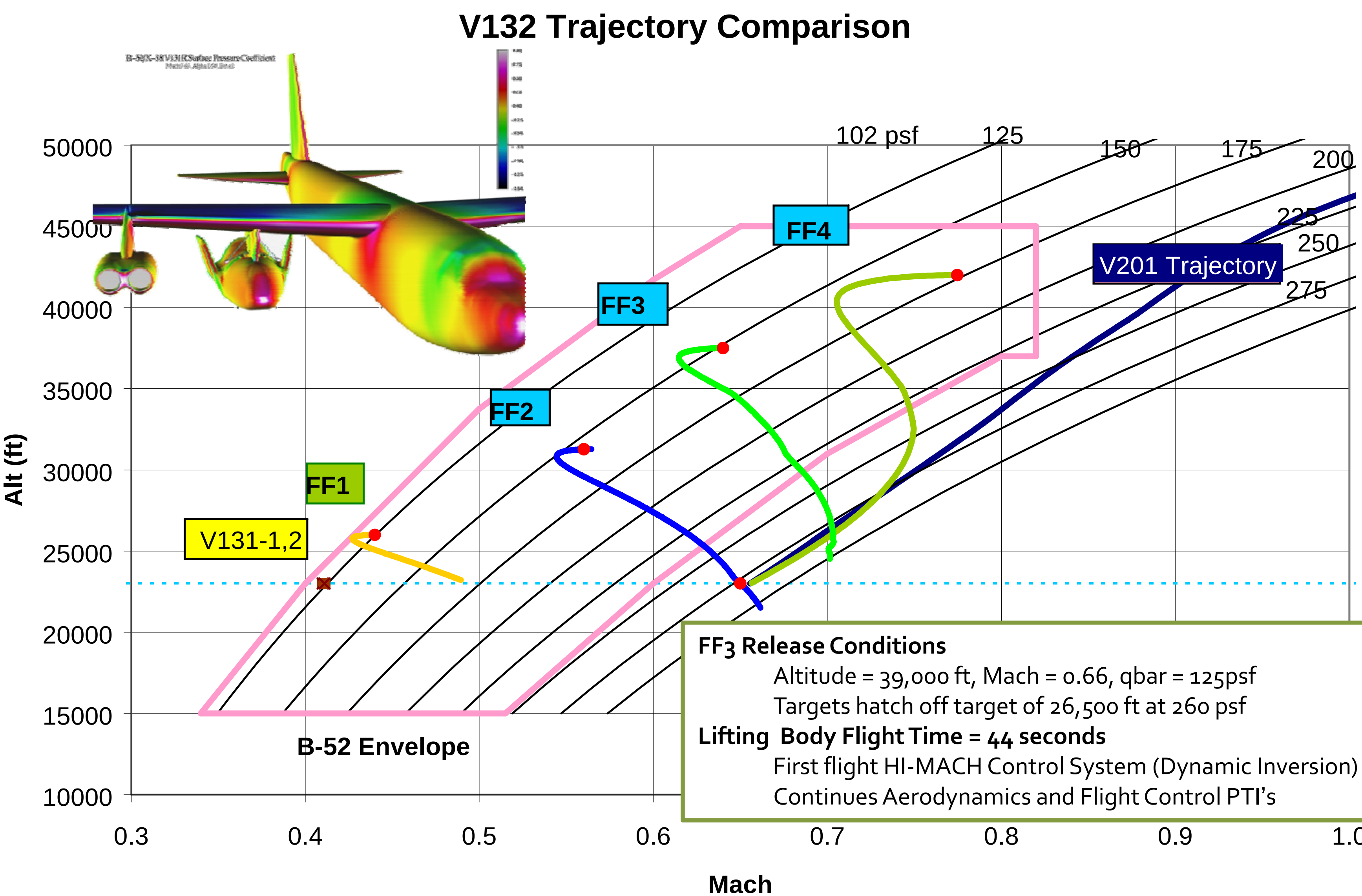


X-38 V-131/132 Flight Testing

- V-131 Flight Testing focused on the integrated Vehicle/Parafoil system design & performance
  - B-52 Separation Dynamics were considerably larger than initially estimated
    - Significant resource dedicated to ensure safe separation
- V-132 Flight Testing conducted to incrementally extend the flight envelope and develop/implement the HI-MACH Control System (Dynamic Inversion)
  - Flight Test conditions gradually increased to ultimately intercept the CRV entry flight conditions
  - PTI Maneuvers - extract aero verification data

X-38 above EAFB/ 1999
(Rev 3.1 / V-132)

V-131/132 Flight Testing



FF3 Release Conditions

Altitude = 39,000 ft, Mach = 0.66, qbar = 125psf

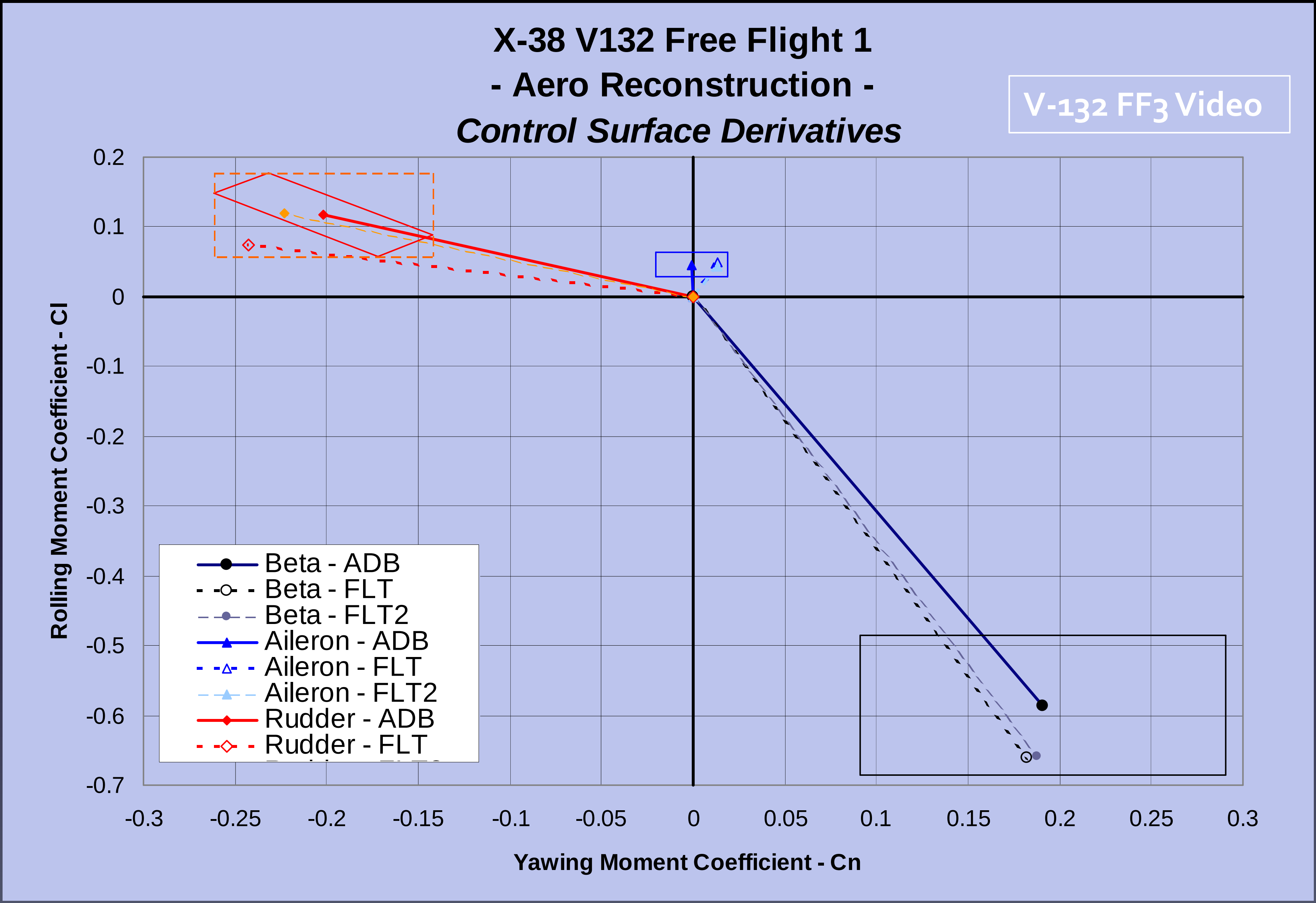
Targets hatch off target of 26,500 ft at 260 psf

Lifting Body Flight Time = 44 seconds

First flight HI-MACH Control System (Dynamic Inversion)

Continues Aerodynamics and Flight Control PTI's

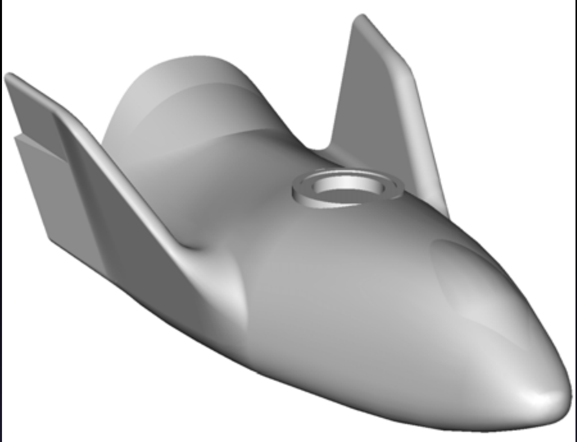
X-38 v-132 Flight Results



X-38 Aerodynamic Phases

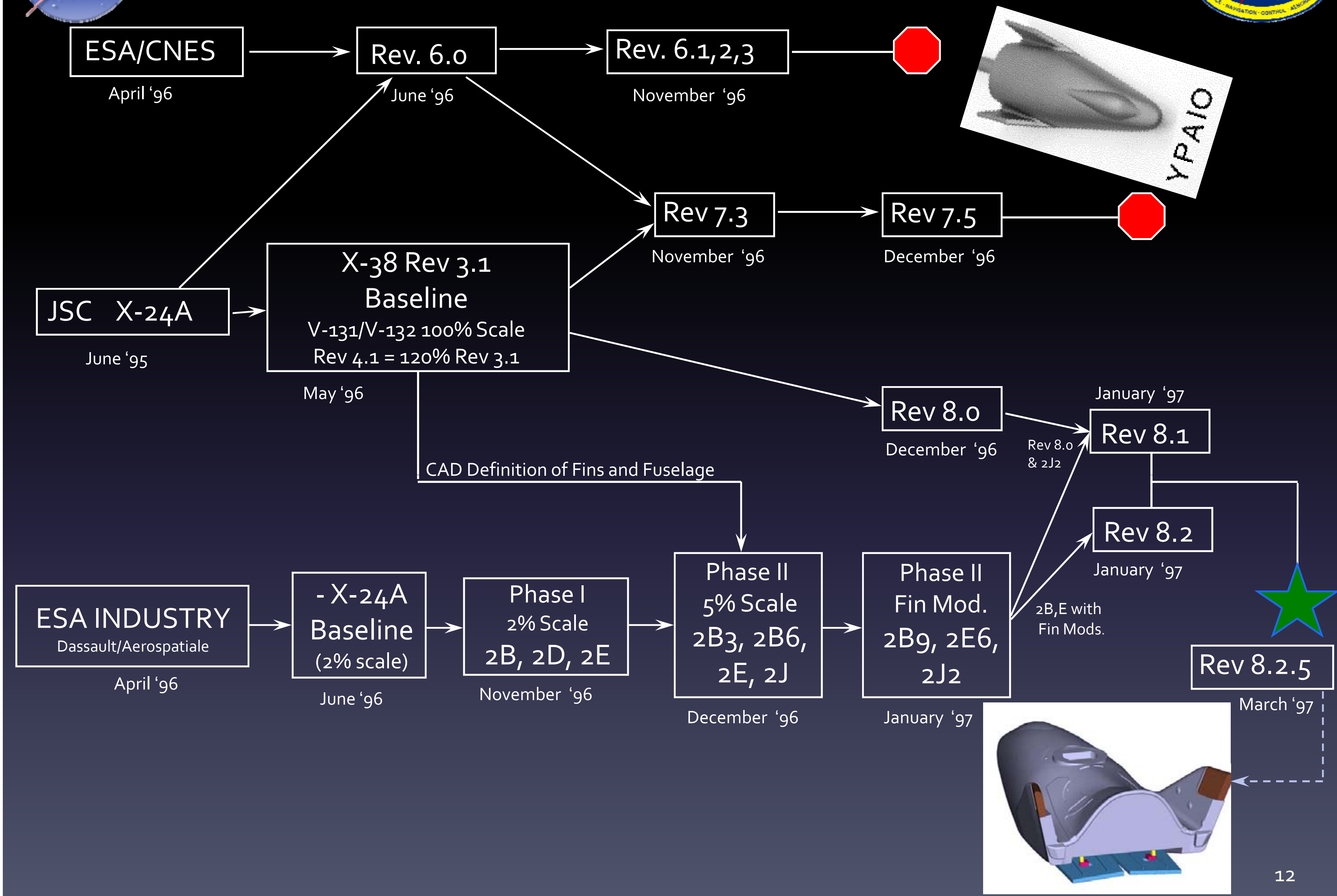
CRV Configuration Evolution - OBJECTIVES & CONSTRAINTS

- Modify the X-24A Configuration to Accommodate the CRV Requirements while maintaining the X-23/X-24A Aerodynamics
  - **Because the X-23A/X-24A Configuration is Flight Proven**
- Fulfill CRV Mission Requirements
  - Internal Volume (7 crewmembers)
  - Launch Capability (Shuttle or ELV)

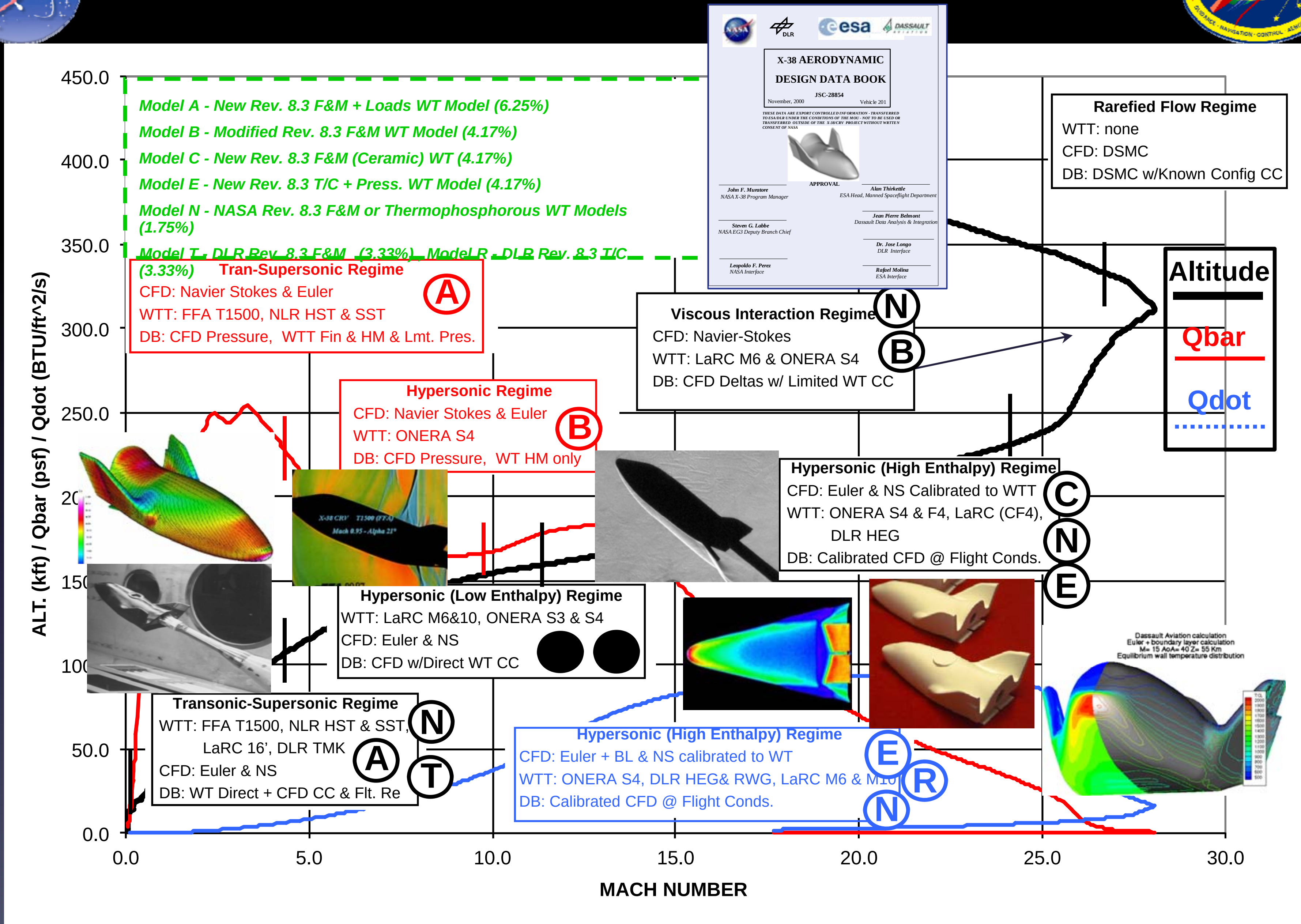


- Joint NASA/ESA CRV/CTV Configuration Development
  - Series of Transonic WT Tests & CFD Analysis
  - Rev. 8.3 Defined as Common Core Configuration
- Windward (Lower Surface) Unchanged Around to Waterline ~26”
  - » Fin Modification required new blend to windward surface
- Leeside Modifications (Rev. 3.1 Out)
  - » Center-Line raised / Lifting Body Airfoil Contour Substantially Diminished (aft)
  - » Upper Ramp to Rounded Surface, Hinge-Line Blended into body, Rounded T.E.
  - » Channel Shape & Fin Root-Body Fillet Contoured, “Karman” added at Fin L.E./Body
  - » Fin Leading Edge (Eliminate Droop/Camber), Fin Thickness increased
- 100% scale Atmospheric Flight Test Vehicle 131R
- 120% scale Space Flight Test Vehicle 201 & Crew Return Vehicle (CRV)

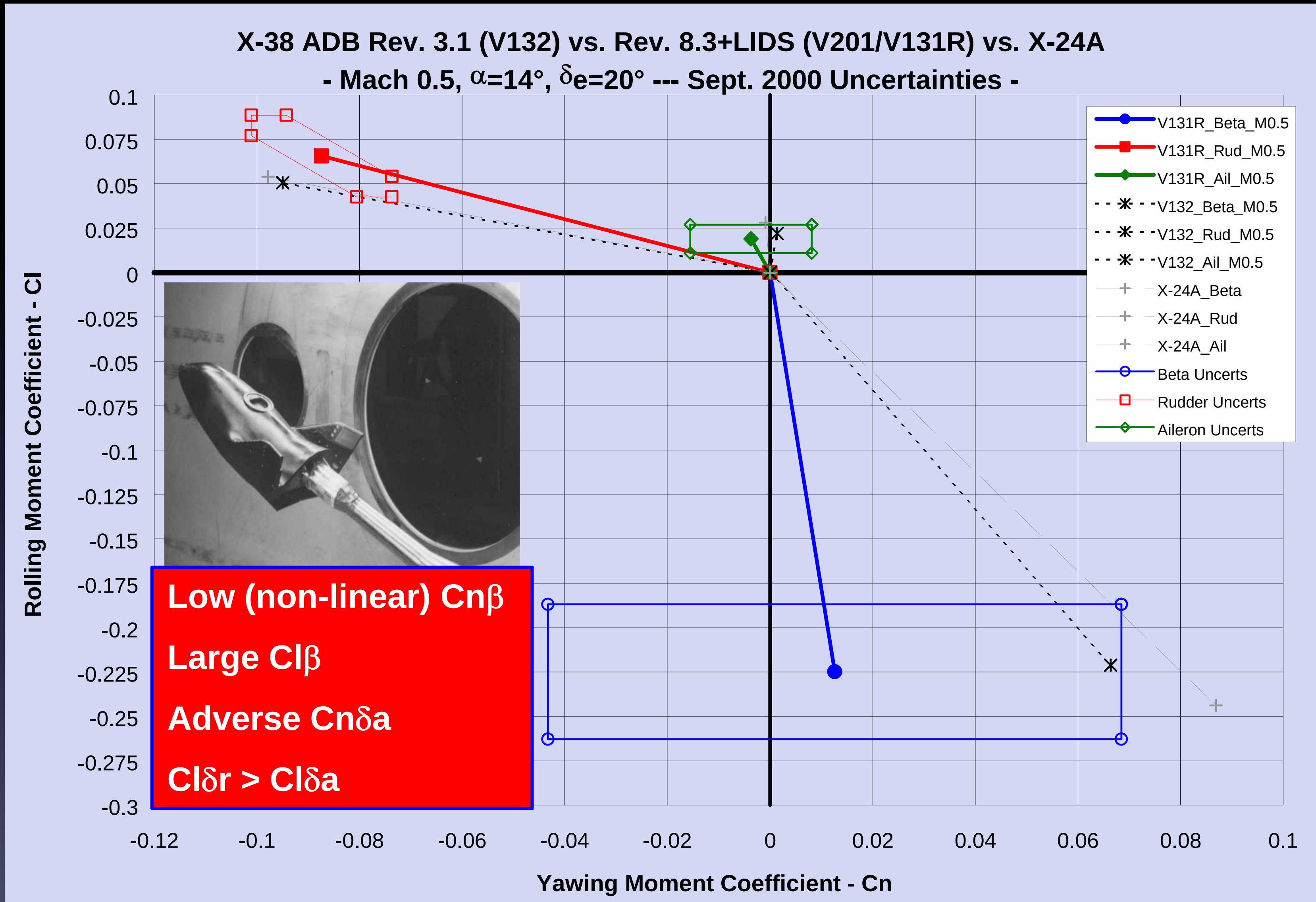
X-38 (Rev. 8.3) V-131r/201/CRV Roadmap



V-201 Aeroscience Database Definition



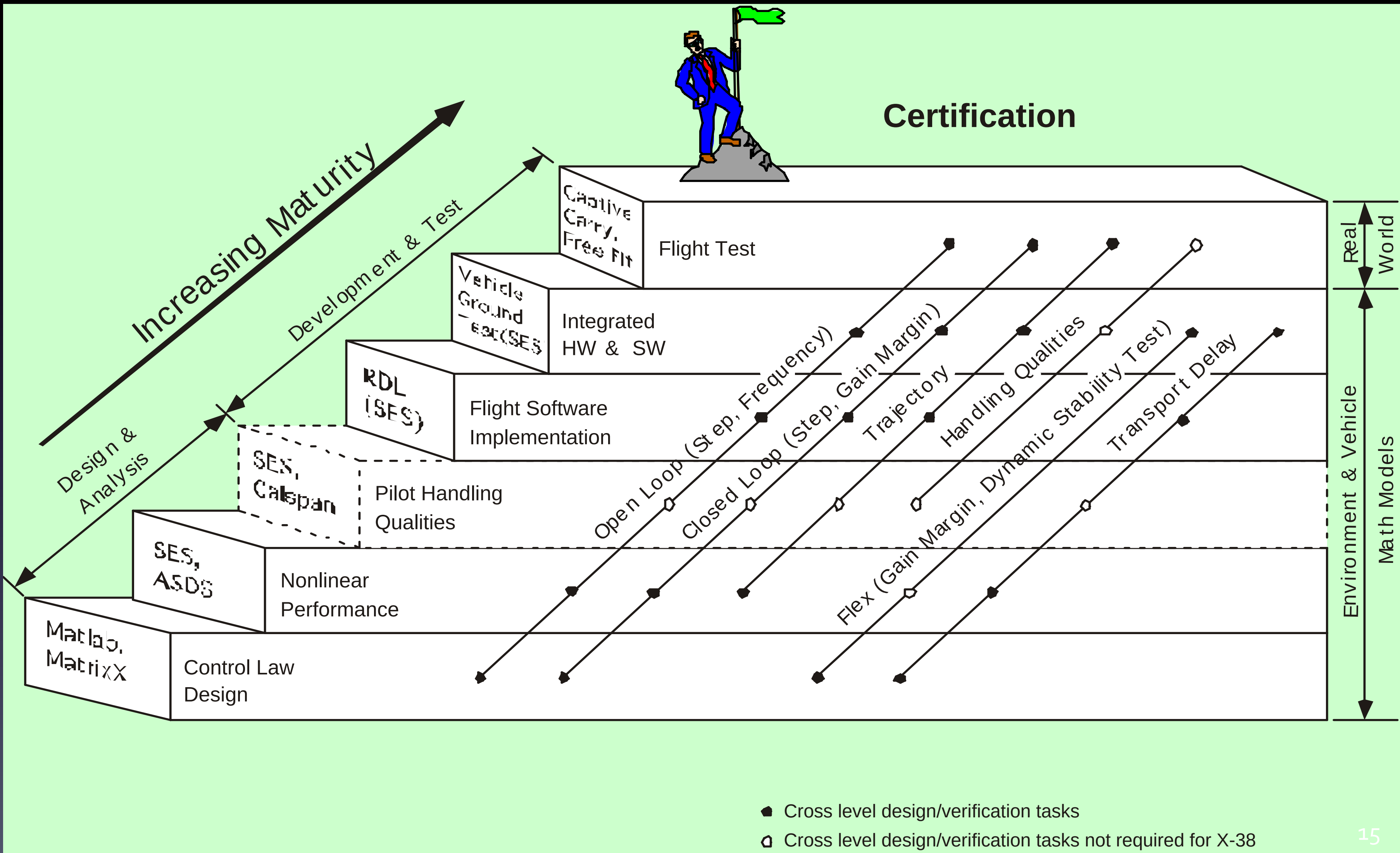
V-131R Lateral-Directional Flight Characteristics



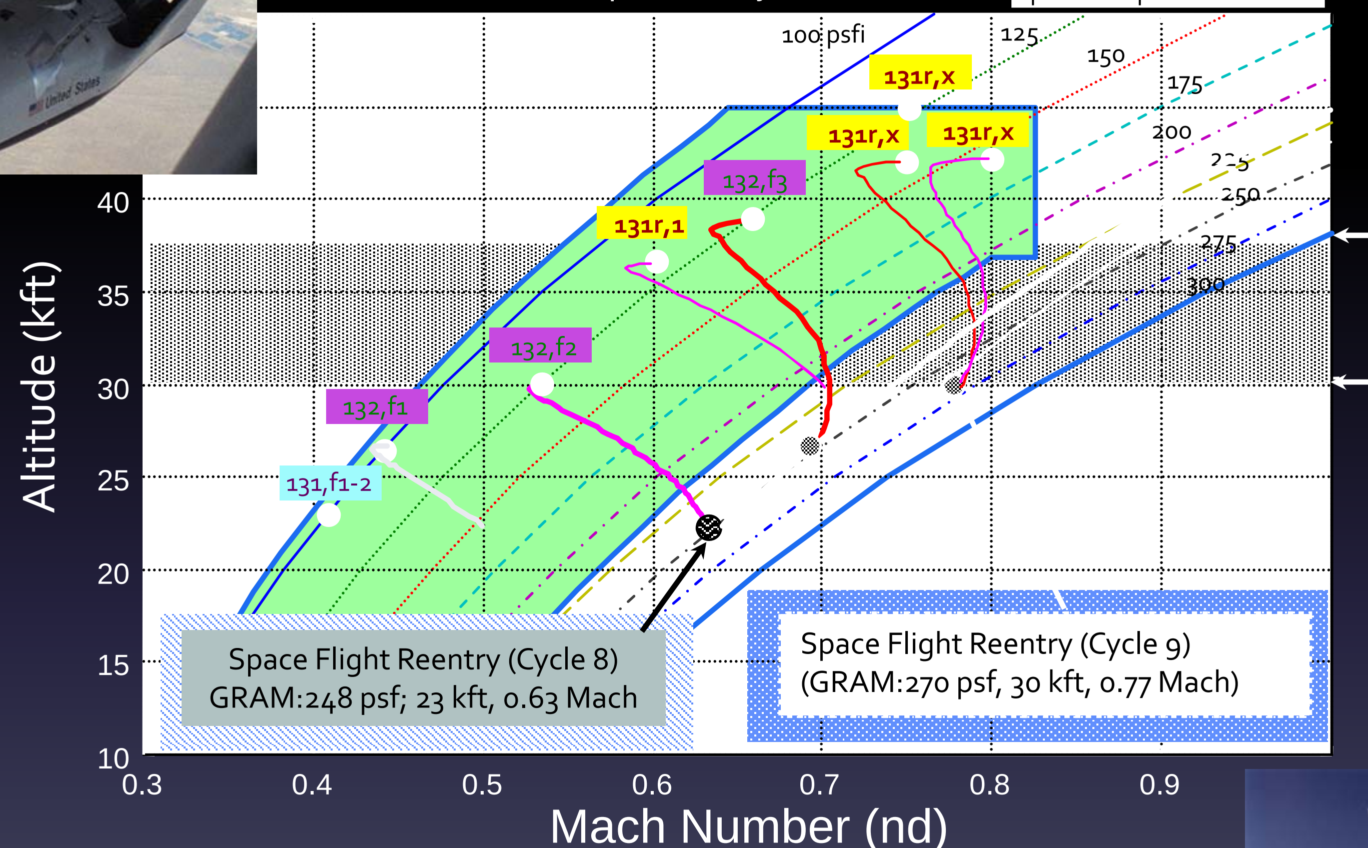
- Relationship of Sideslip, Rudder & Aileron Derivatives dictates flight control design
  - Conventional Aileron, Rudder, Sideslip Control not applicable to V-131R

Levels of Flight Control Certification

Uncertainty: The lack of certainty – a state of having limited knowledge where it is impossible to exactly describe existing state or future outcome, more than one possible outcome



V-132 & V-131R Drop Conditions & Flt Histories



Drogue Deploy qbar Constraint

Alt for Drogue Deploy (30 kft) for Cycle 9

→ Go to Nov. 2000 Video

X-38 V-131R Free Flight 2

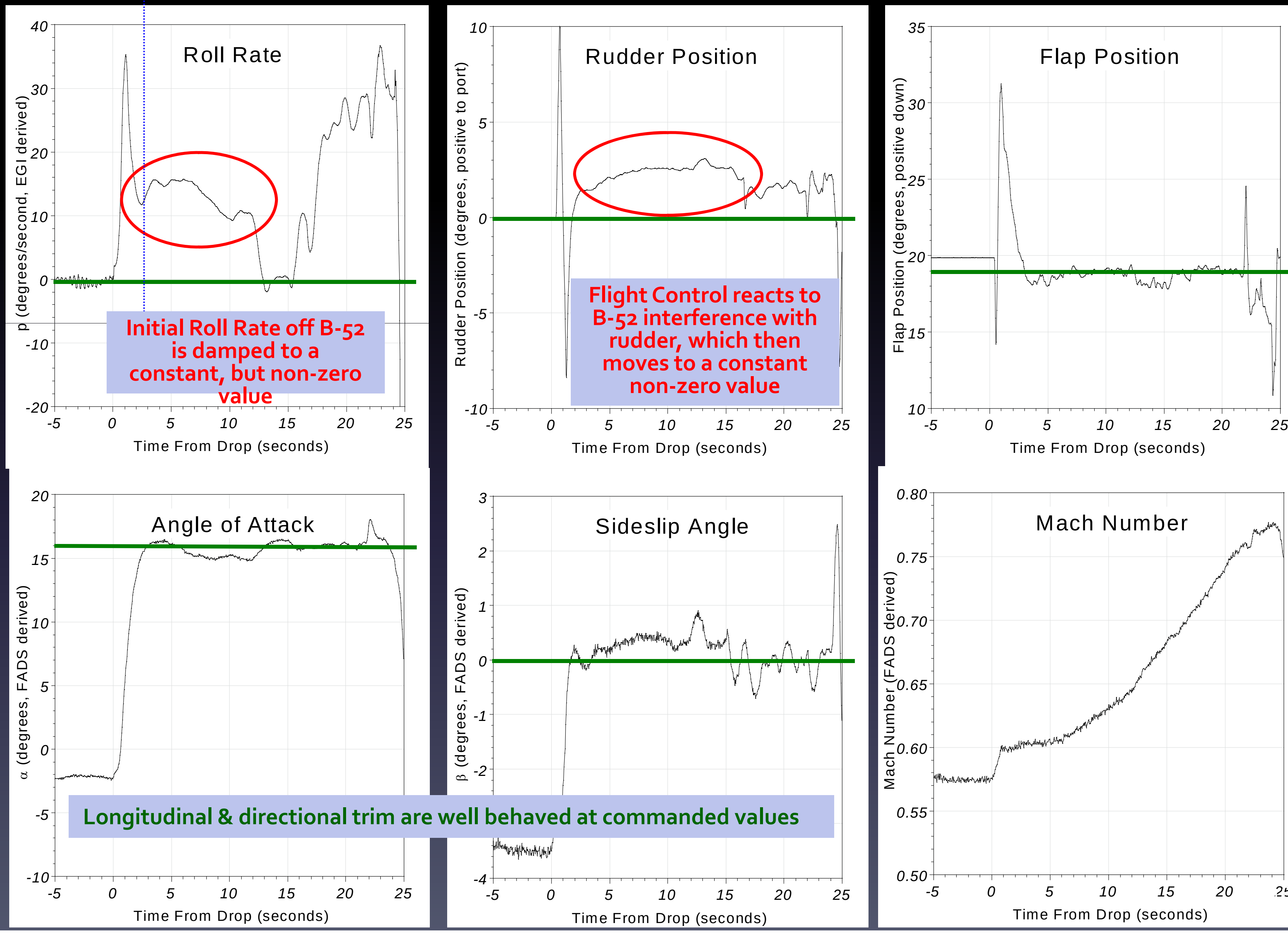
EA FRR

Aerodynamics

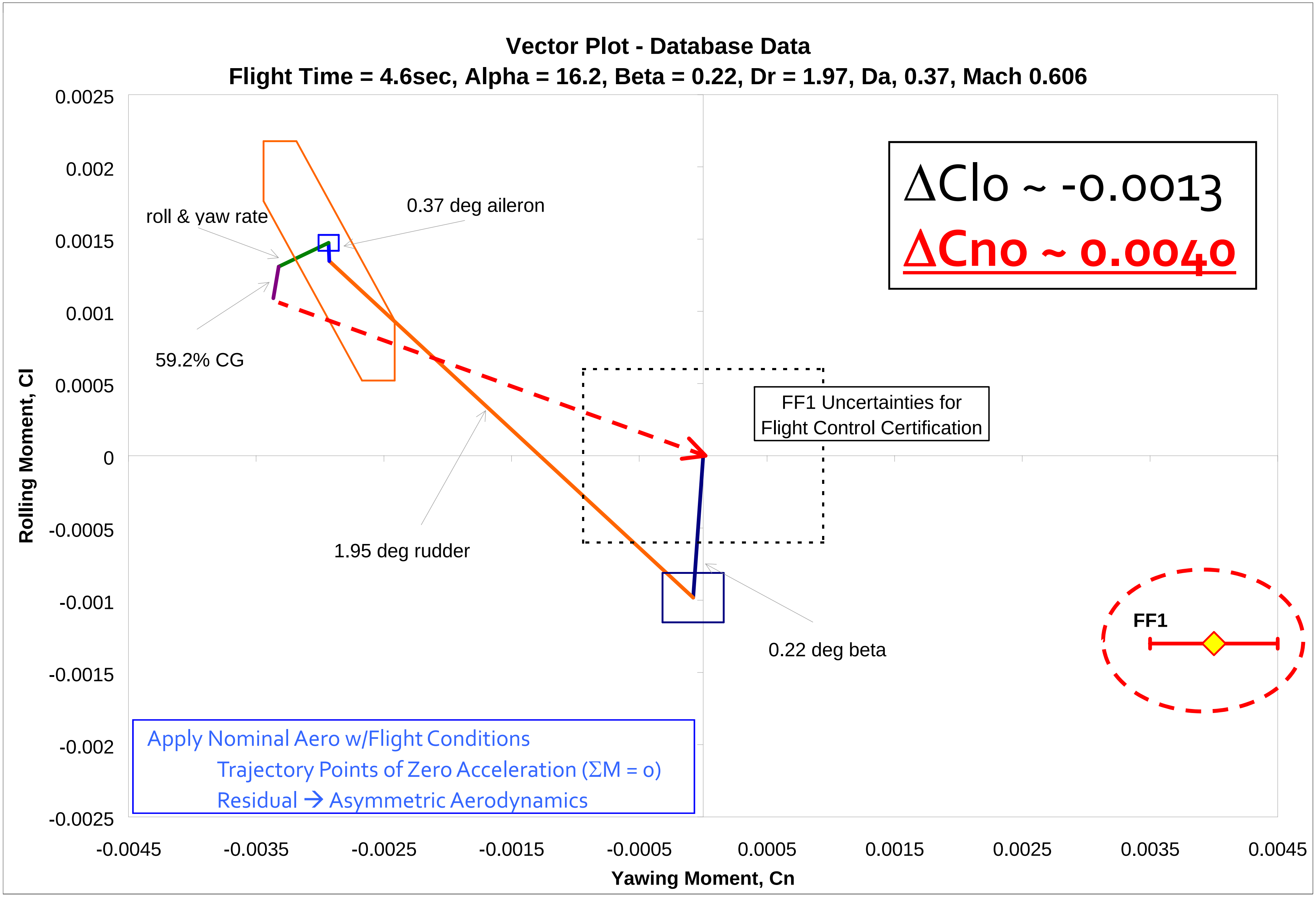
Asymmetric Aero Resolution

06-08-01

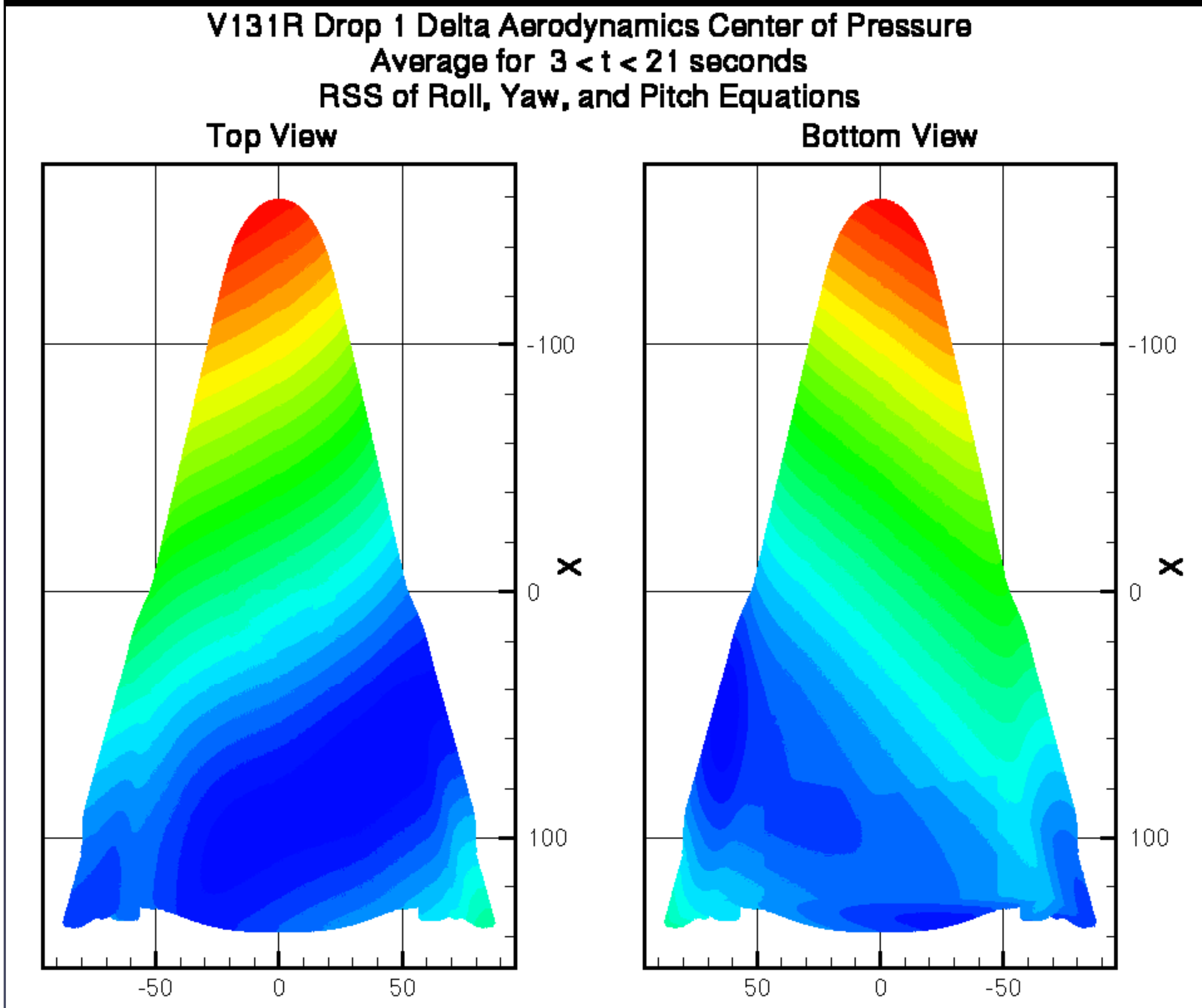
V-131R FF1 Flight Summary

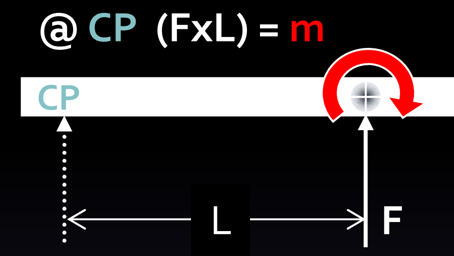


Asymmetric Aerodynamic Issue



X-38 V131R FF1 Asym Aero Source
Three Dimensional Center of Pressure





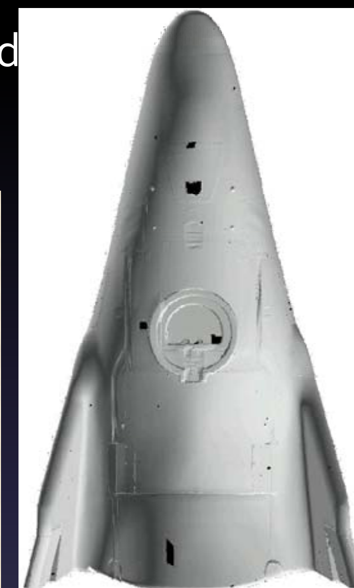
3-D CP ANALYSIS

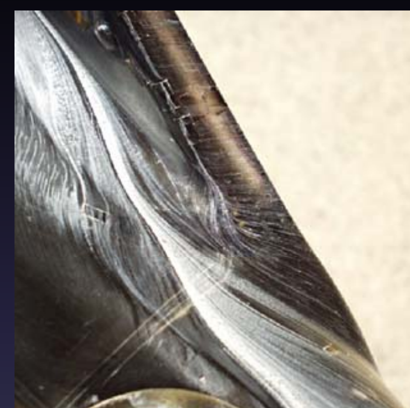
- Extracted Δ Aero Forces placed at surface x,y,z points
- Compute residual moment magnitudes @ each surface point
- Minimum residual (blue) indicates most probable location of Δ Aero
- **Δ Aero Originates Aft**

Asymmetric Aero Hypothesis
Three Asymmetric Aero Sources Identified

$\Delta Cno_{Total} = \Delta Cno_{BAF} + \Delta Cno_{Asym}$(Inboard Fin Flow + Body Flap Gap Cavity/Base)

- Two or three combined to produce the Cno_{Total} = **0.0040** observed on FF1
  - Coupling of the three effects is a characteristic of the vehicle flow field
  - Largest WT Test value observed Cno ~ 0.003 offset





- Three Asymmetric Aero Sources

ΔCno_{BAF} - Bent Air Frame (BAF) *i.e. alignment*

→ V-131R As Built – As Flown Geometry is Asymmetric

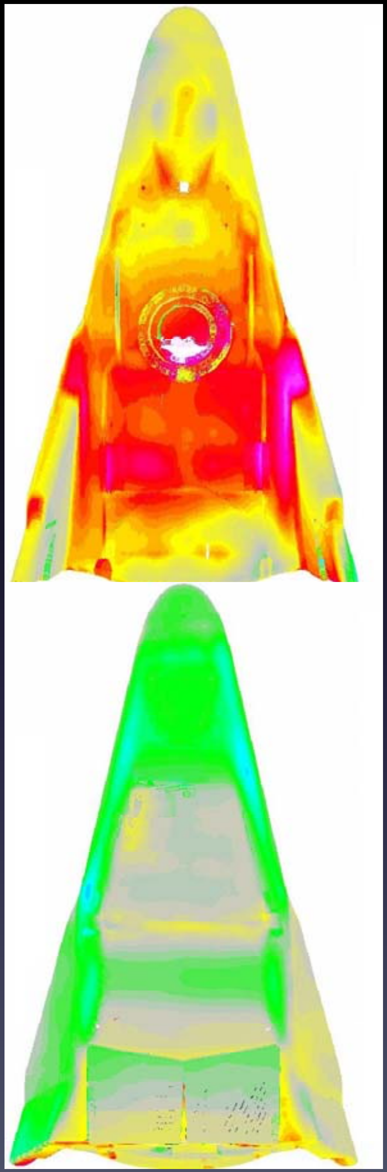
- Measured w/Photogrammetric Technique
- **Estimated via CFD Analysis**: **ΔCno_{BAF} ~ 0.0020, ΔClo_{BAF} ~ 0.0008**

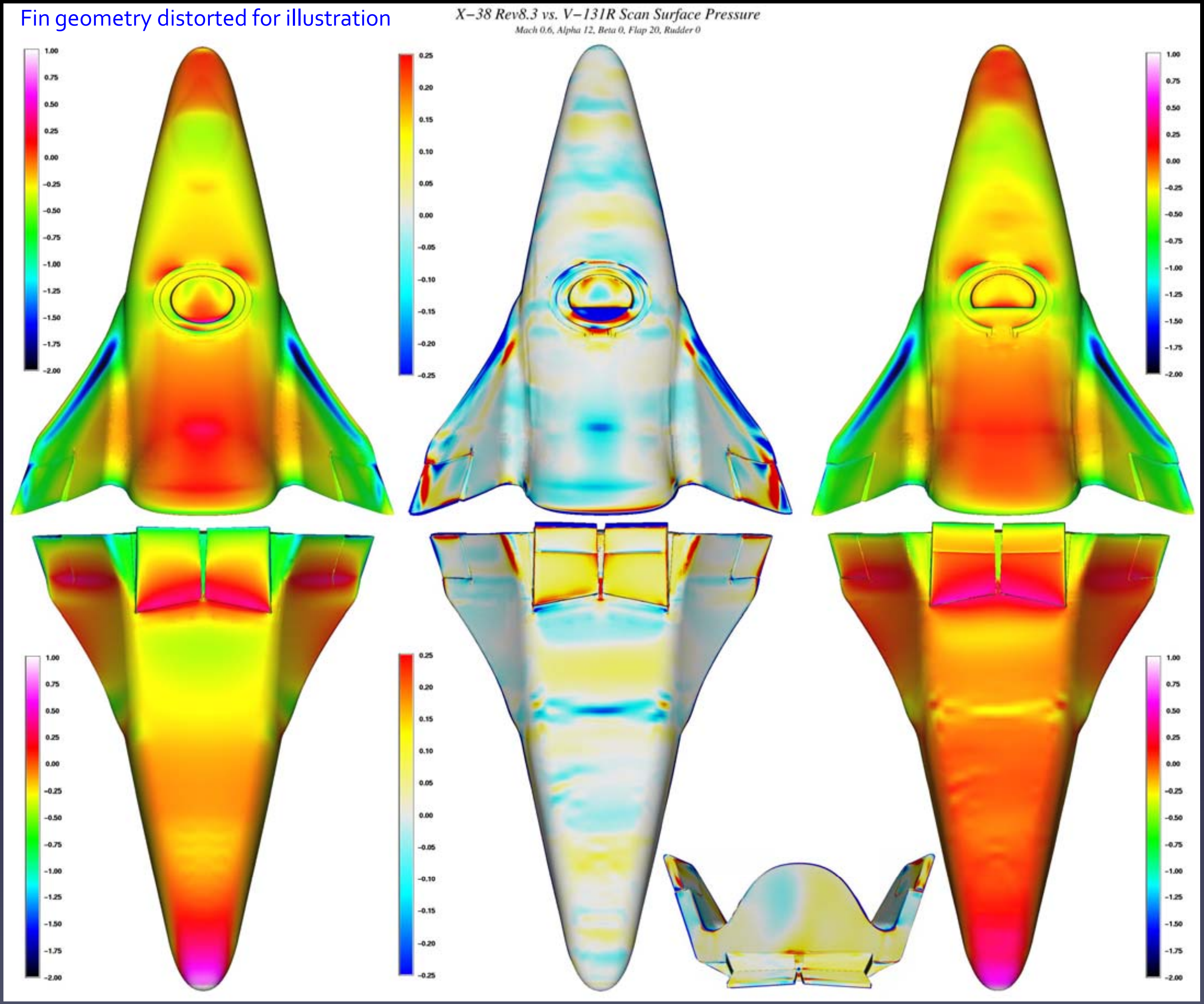
ΔCno_{Asym}(**Inboard Fin Flow**) - Unbalanced Fin Flow

→ Unbalanced leading edge vortex (strength / location)

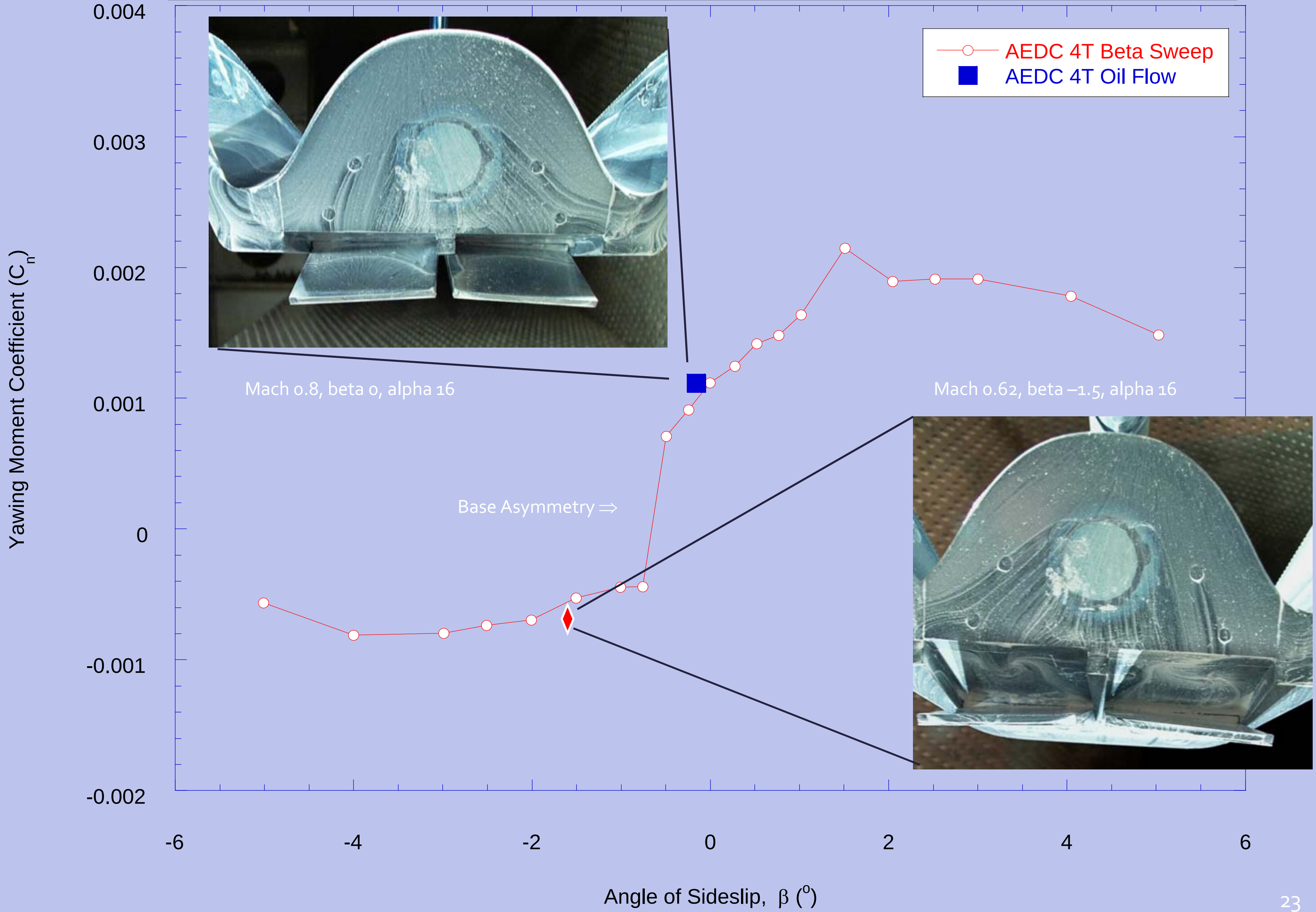
- Artificial trigger required
- Estimated Effect via CFD & WT Test: **ΔCno_{Asym} (IB Fin Flow) ~ ± 0.0020**

BAF Term - Scan vs. CAD Error





Base Asymmetry evident in Wind Tunnel

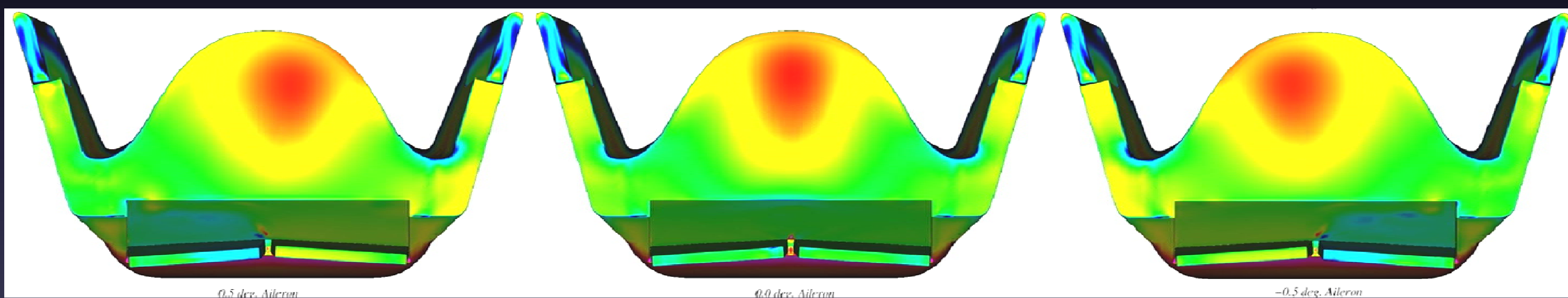


Asymmetric Aero Hypothesis
Three Asymmetric Aero Sources Identified

- Three Asymmetric Aero Sources (cont.)

ΔCno_{Asym}(Body Flap Gap Cavity/Base) - Bi-Stable flow thru body flap gap into cavity → Asymmetric base pressure

- – Evidenced in WT Testing and predicted via CFD Analysis
  - Correlates with Body Flap hinge moment, cavity & base pressure measurements
  - Sting Effects and/or V-131R Configuration Specific ("Central Fence") Effects
- – Estimated Effect via WT Test: ΔCno_{Asym}(Body Flap Gap Cavity/Base) ~ 0.001



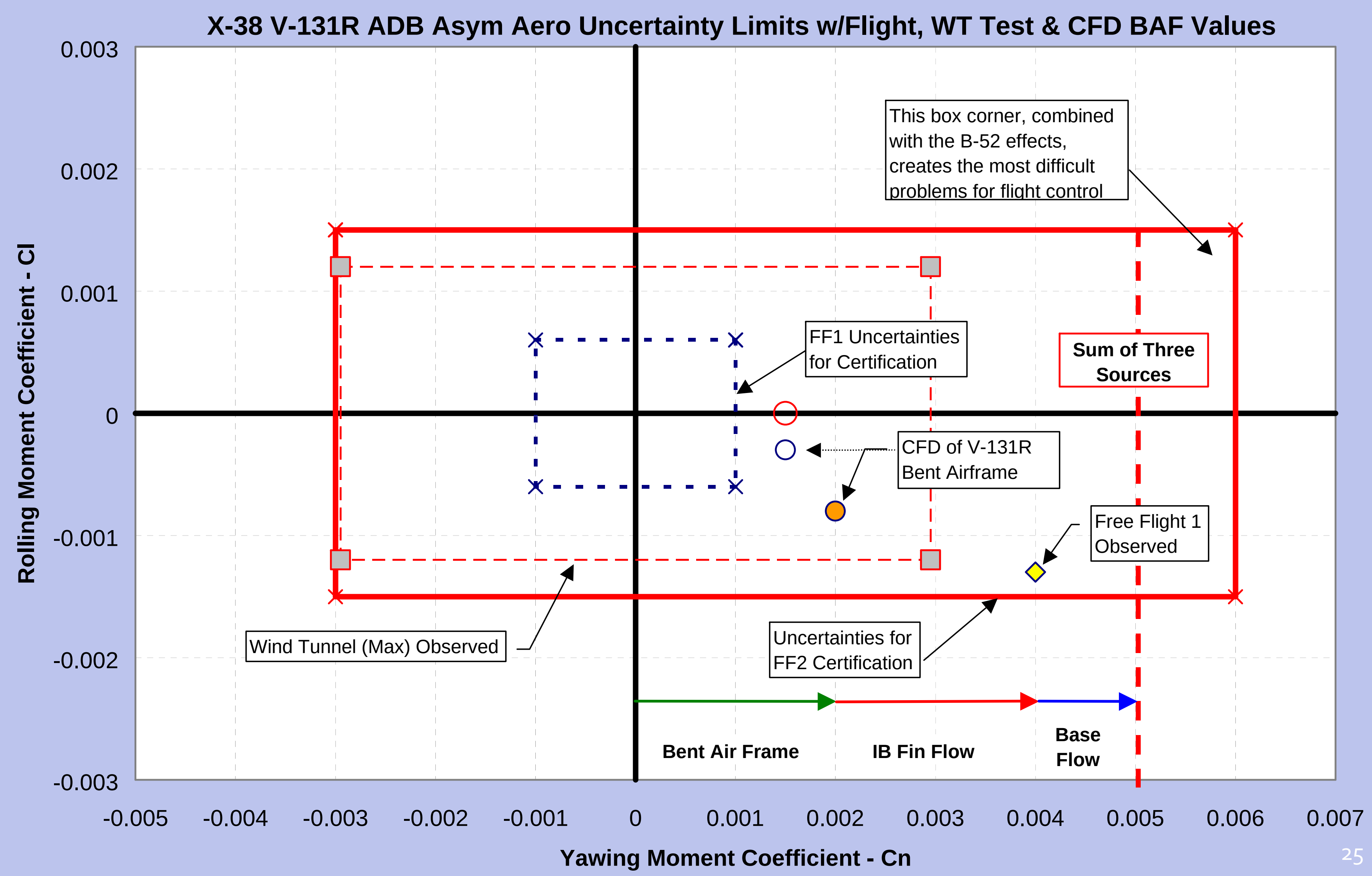
Summation of these effects exceeds the observed FF1 level of 0.004

$Cno_{Total} = \Delta Cno_{BAF} + \Delta Cno_{Asym}$(Inboard Fin Flow + BF Cavity/Base)

0.005 = (**0.002** + **0.002** + **0.001**)

ADB Model, Data Range & Uncertainty Box

- Asymmetric Aero Terms (Cno, Clo) Updated for Flight Control Certification
- Asymmetric Aero is bounded – Coverage encompasses all sources + Margin



The Last 7+ months

- V-131R FF1 to FF2 Activities – Aerodynamics
  - V-131R FF1 – "360° Roll Maneuver!" – 11/02/00
  - Flight Data Analysis / Aero Instrumentation Upgrades – 11/00 thru 05/01
  - ONERA S2 – Model A – Sub/Supersonic WTT – (large ΔCno ~0.003 observed) – 11/20 – 12/04/00
  - Photo-grammetric Scan of V-131R – 12/15/00
  - BAF CFD (NASA & ESA) Analysis w/Photo Scan Geometry – 01/01 thru 05/01
  - **Asym Aero Peer Review - 2/12-13/01 (JSC, ARC, LaRC, DFRC, TAMU, Rice)**
  - FFA4 T1500 - Model A - Asym Aero Investigation WTT - 3/7-3/28/01
  - preFRR w/EX – 04/03/01

- X-38 Project postponed the 2nd free flight of V-131R until further investigation of the asymmetric aerodynamic phenomena experienced on first flight could be completed
  - *Inconsistencies warrant that near term test & analysis be exhausted before committing to FF2*
  - Explain and/or account for data inconsistencies (Flt.vs.WTTvs.CFD) regarding sources

- V-131R FF1 to FF2 Activities – Aerodynamics (cont.)
  - Sting & Base Geometry Effects CFD Analysis – 03 thru 05/01
  - V-131R Instrumentation Upgrades / Re-Calibration, Etc. – 02 thru 06/01
  - AEDC 4T - Model N - Strut Mount WTT - 4/30-5/4/01
  - USAFA Subsonic – Component Buildup WTT – April, 2001
  - FFA5 T1500 - Model A - V131R Clearance WTT - 5/7-28/01
  - Aerodynamics TIM - 5/22-23/01
  - EX_FRR (w/X-38 Project Mgr.) - 5/25 & 6/04
  - ➢ **Project Recommendation: All sources identified and bounded by test & analysis**
  - → EA FRR (Mr. Benz) - 6/08/01 // AA FRR (Estes, Peterson) – 6/11/01

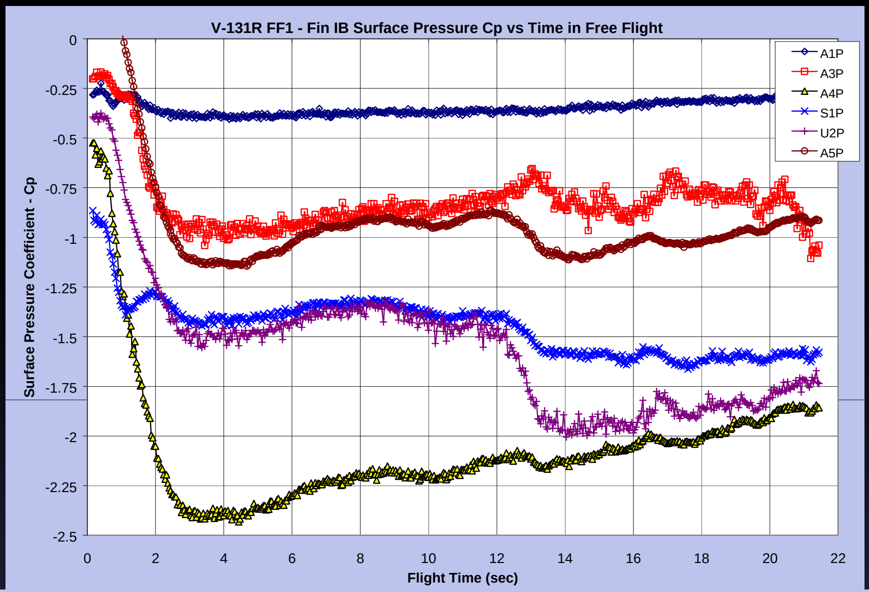
~280+ additional WTT Hours

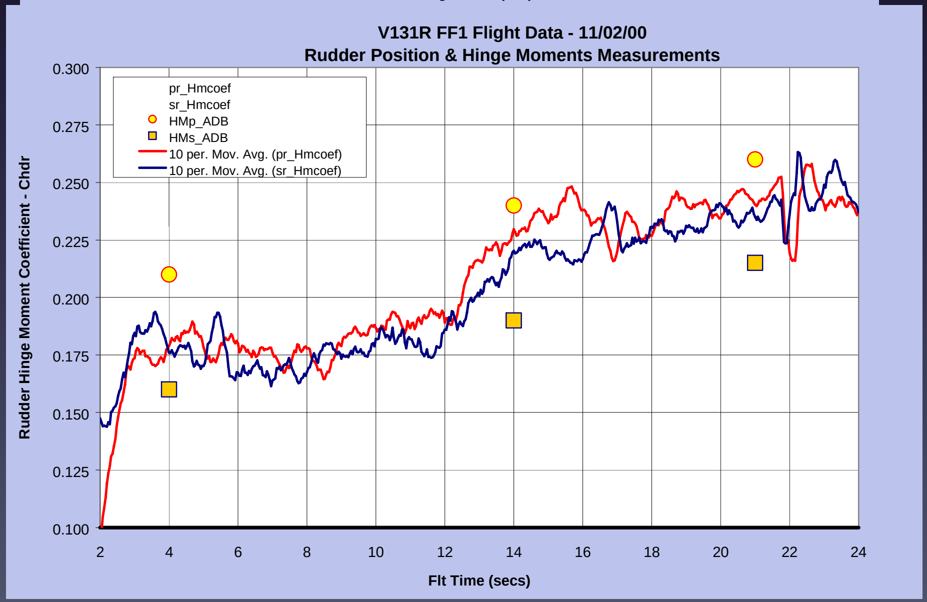
V-131R FF1 Flight Data Overview

- ✓ Flight Data recorded and time synchronized at 25Hz
  - FADS provides Air Data (Mach, α, β, q-bar)
  - Embedded GPS/INS (EGI) provides accurate vehicle rates & accelerations
  - Control Surf Position Sensors - Flap EMA Rod Extension & Rudder Aux Msmnt.
- Surface Pressures (21 operational)
  - Unreliable Data – Outside Compensated Temperature Range
  - Locations correspond with wind tunnel model locations
    - 11 Port Fin, 3 Base, 7 Body, 0 Cavity
  - Replaced & upgraded for V131R FF2
  - Added flow visualization (camera & tufts) on inboard fin surfaces
- Hinge Moments (Port & Starboard Flap(2) & Rudder(2))
  - Derived from EMA rod strain measurements
    - Flap Unreliable (incomplete) & Rudder indicates large zero shift
  - Upgraded Instrumentation and Calibrations (Rudder in place) for V131R FF2

- Summary
  - V-131R FF1 Aero Flight Data Measurements Unreliable
    - Unable to clearly identify source of the large FF1 aerodynamic asymmetry
  - Extensively Upgraded for FF2

Inboard Fin Flow Field is Effective
No Stall Experienced on FF1

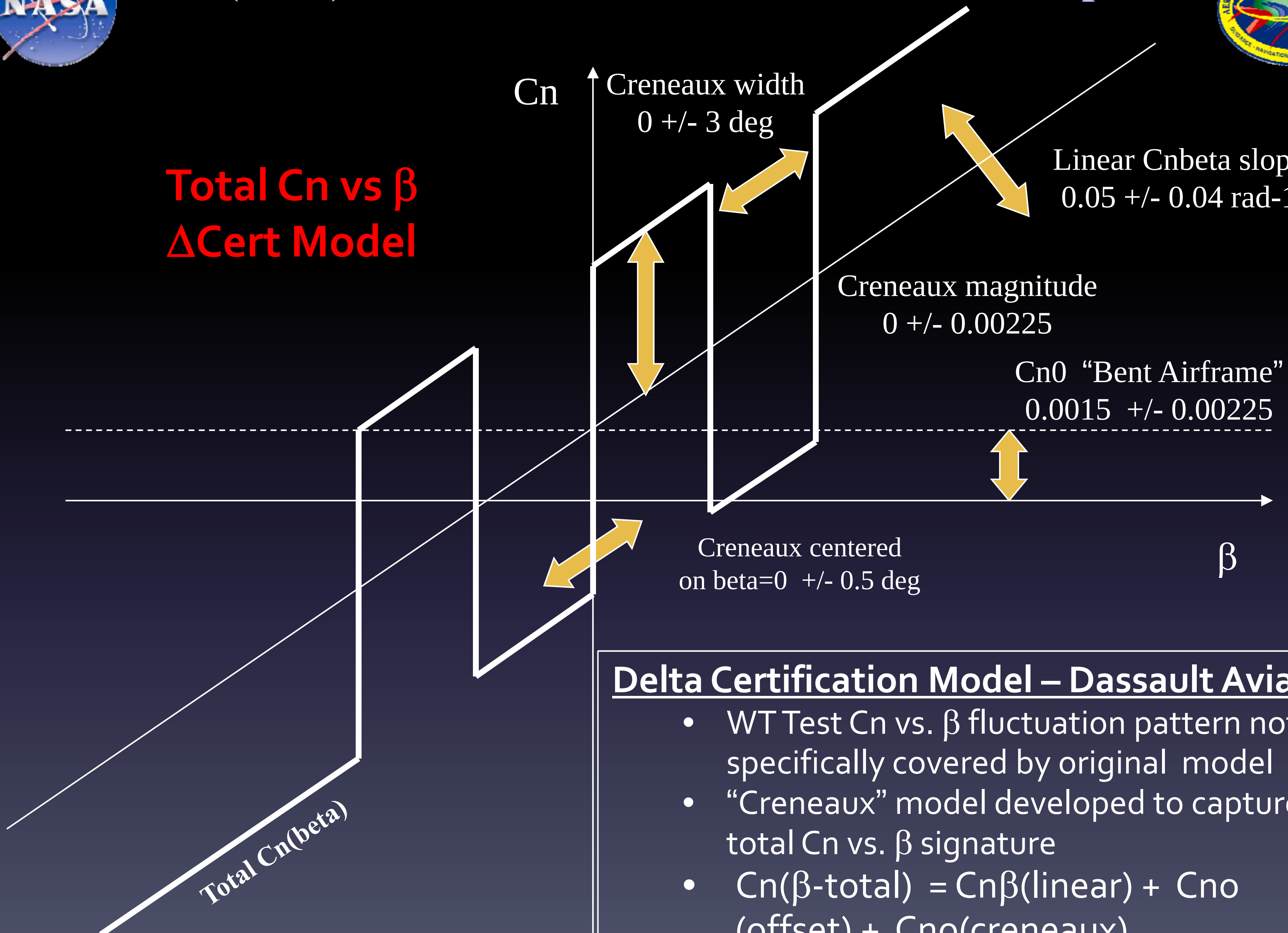




- Fin Pressures show deep expansion on fin leading edge as ƒ(AOA/Mach)
- Rudder Hinge Moments increase as ƒ(AOA/Mach)
- Drogue Chute deploy evidences large wake – fin vortex interaction

Cn(beta) "Creneaux" ModelGeneral description

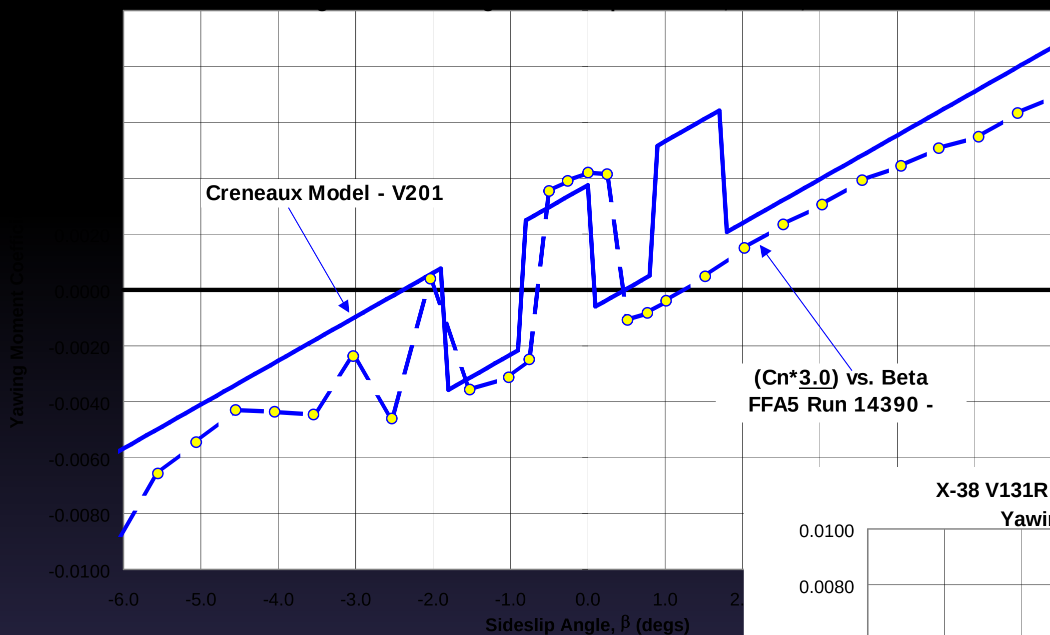
Total Cn vs β
ΔCert Model



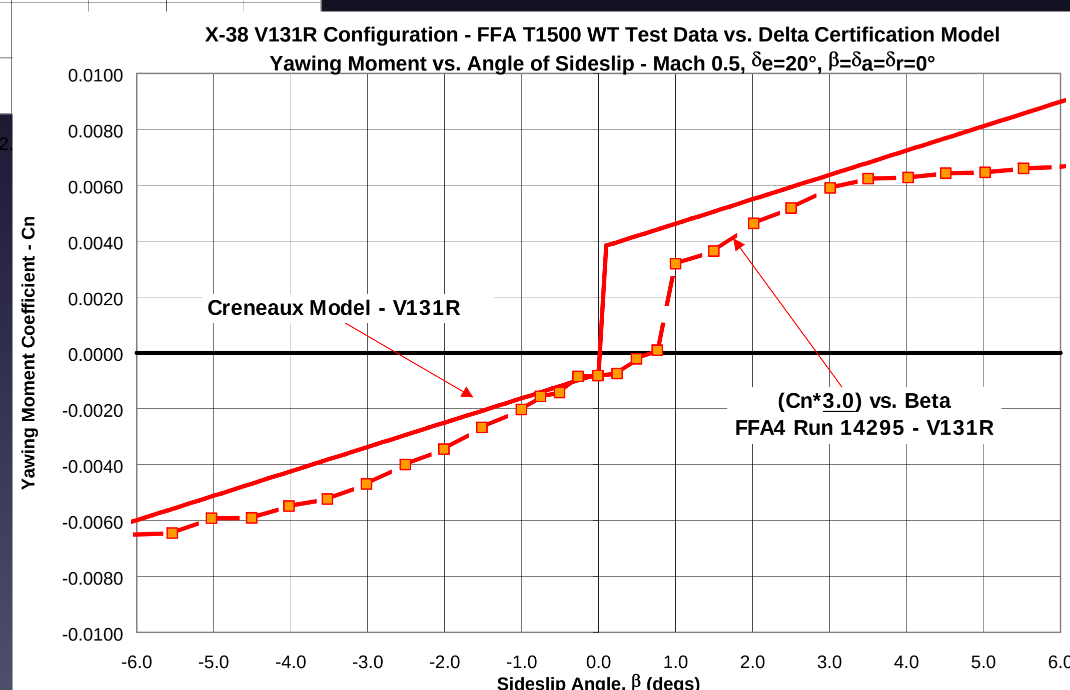
Delta Certification Model – Dassault Aviation

- WT Test Cn vs. β fluctuation pattern not specifically covered by original model
- "Creneaux" model developed to capture total Cn vs. β signature
- Cn(β-total) = Cnβ(linear) + Cno (offset) + Cno(creneaux)

Cnβ “Creneaux” Model vs. WT Test Data



V201 - Baseline



V131R – Central Fence

Conclusion & Recommendation

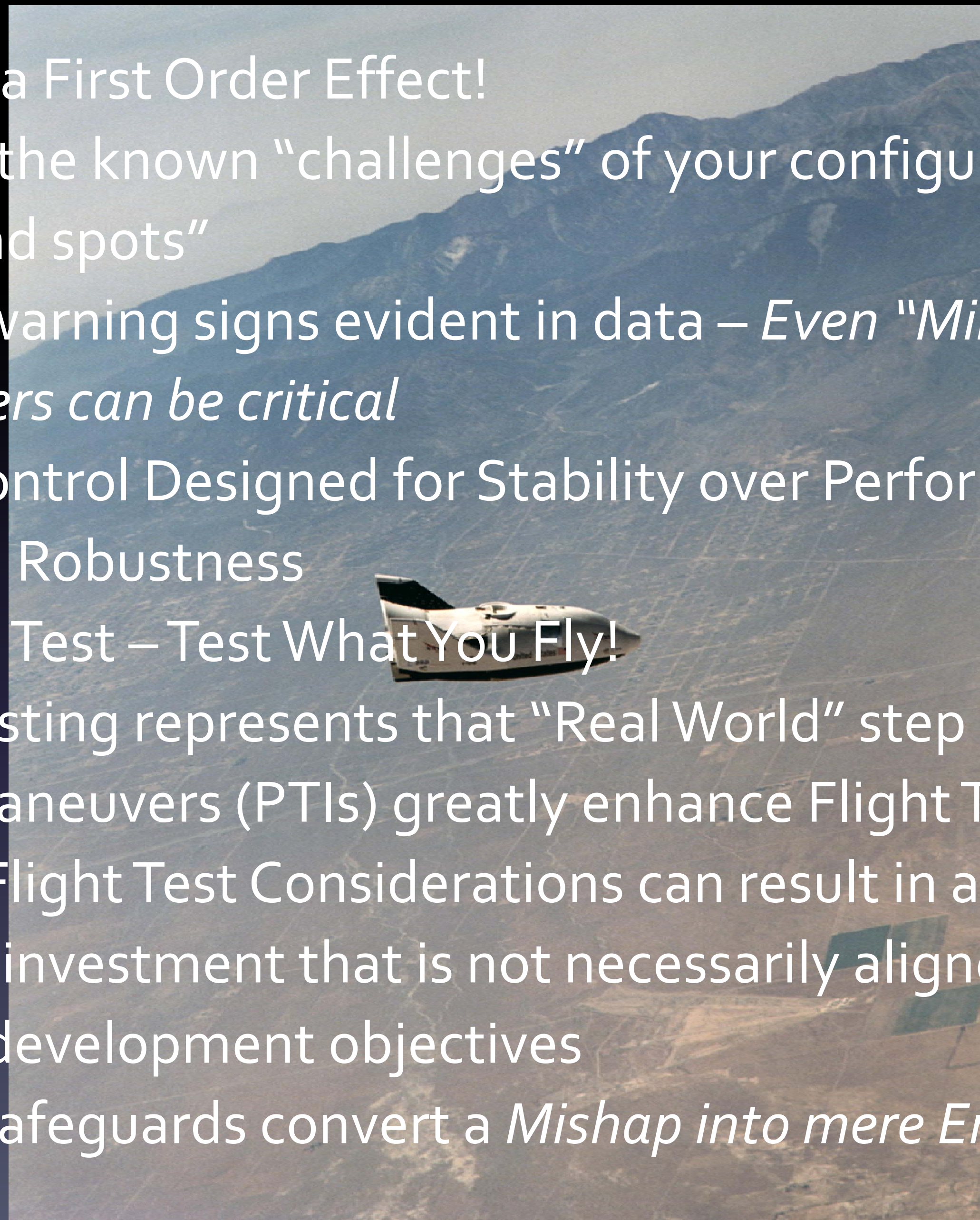
- Conclusion
  - Reconstruction of V-131R FF1 results in an ΔCno offset → = 0.0035 to 0.0040
  - Unable to pinpoint the exact source of the FF1 asymmetry
    - Asymmetric aero has multiple causes → not a single source (no "smoking gun")
  - In response, Aerodynamic Team has Exhausted Near Term Wind Tunnel Test & CFD Analysis to resolve V-131R FF1 Asymmetric Aerodynamics
  - Identified, Characterized & Bounded Contributing Sources of ΔCno

    1) Bent Air Frame

    2) Body Flap-Cavity / Base interaction

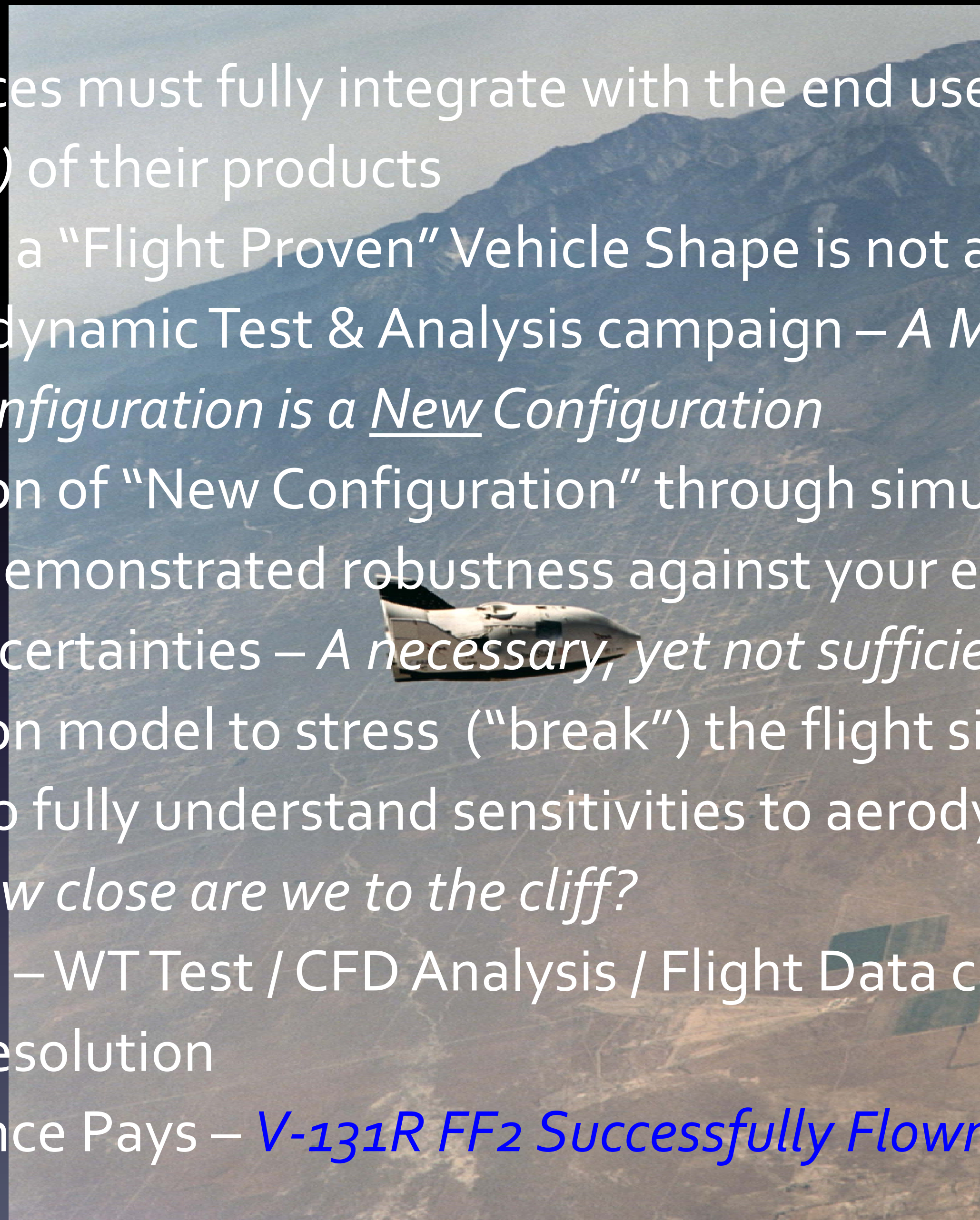
    3) Fin flow field behavior or a combination (coupling) of a subset thereof
  - Verified Aero Data Base Definition & Produced Δ Certification Model
    - The current Aero Database ΔCno_{Asym} covers beyond the range of ΔCno values observed in all V131R Wind Tunnel Testing, CFD Analysis & V-131R Free Flight 1
    - Certification model covers the worst case combination with margin
- Recommendation
  - Aerodynamics is ready to proceed with V-131R Free Flight 2
    - Upgraded V-131R Aero Instrumentation and planned test maneuvers should enable identification of asymmetric aerodynamic source on FF2

X-38 Aerodynamic Lessons Learned



- ✧ Geometry is a First Order Effect!
- ✧ Focusing on the known "challenges" of your configuration can produce 'blind spots"
  - → Missed warning signs evident in data – *Even "Minor" Aero Parameters can be critical*
  - → Flight Control Designed for Stability over Performance yielding mistaken Robustness
- ✧ Fly What You Test – Test What You Fly!
  - → Flight testing represents that "Real World" step
  - → Flight Maneuvers (PTIs) greatly enhance Flight Test retur
  - → Unique Flight Test Considerations can result in a substantial resource investment that is not necessarily aligned with the primary development objectives
- ✧ Flight Test Safeguards convert a *Mishap into mere Embarrassment*

X-38 Aerodynamic Lessons Learned



- ✧ Aerosciences must fully integrate with the end user *(GN&C, TPS, Loads, etc.)* of their products
- ✧ Employing a "Flight Proven" Vehicle Shape is not a substitute for a full Aerodynamic Test & Analysis campaign – *A Modified "Flight Proven" configuration is a* *<u>New</u>* *Configuration*
- ✧ Certification of "New Configuration" through simulation means you have demonstrated robustness against your existing models/uncertainties – *A necessary, yet not sufficient step*
- ✧ Certification model to stress ("break") the flight simulation is essential to fully understand sensitivities to aerodynamic model
  - → *How close are we to the cliff?*
- ✧ All sources – WT Test / CFD Analysis / Flight Data can aid in anomaly resolution
- ✧ Perseverance Pays – *V-131R FF2 Successfully Flown – July 10, 2001*

QUESTIONS? COMMENTS!

The Struggle for Certification
X-38 V-131R Free Flight 2

Backup Charts

X-38 Flight Dynamics Team Organization

CRV/X-38 Project (EX)
- J. Muratore

→ Funds
→ Requirements

A&FMD (EG)
- D. Kanipe

→ Manpower
→ Task Responsibility

X-38 Flight Dynamics Team Lead
- J. Caram (EG)

Project Lead for Aerothermodynamics
- S. Labbe (EG3)

- Aerodynamics
- Aero Loads & Interactions
- Aerothermodynamics
- Flush Air Data System Cal. Data & Algorithm
- Computational Fluid Dynamics
- Direct Simulation Monte Carlo
- Wind Tunnel Testing
- Surface Instrumentation Definition
- Operations Support*

Project Lead for Flight Mechanics & Guidance
- C. Cerimele (EG5)

- Entry Guidance
- DeOrbit Guidance
- On-Orbit Guidance
- Mission Planning
- Trajectory Design
- Landing Site Opportunities
- DPS Sep., Breakup & Footprint
- Multi-DOF Simulation
- Recovery Systems Analysis & Test Support
- Operations Support*

Project Lead for Flight Control
-M. Hammerschmidt(EG4)

- Entry Flight Control
- DeOrbit Flight Control
- On-Orbit Flight Control
- Linear Analysis
- 6 DOF Simulation, HW & SW
- Effector Requirements
- Sensor Requirements
- MACH Development
- Int. G&C SW Tests
- IGN&C HW/SW Tests
- Operations Support*

Project Lead for IGN&C Flight Software
- C. Soderland (EG2)

- GN&C Executive
- IGN&C FSW Dev. & Testing
- IGN&C IronBird Tests
- IGN&C Vehicle Tests
- Operations Support*

Project Lead for Integrated Navigation
- J. Borrer (EG2)

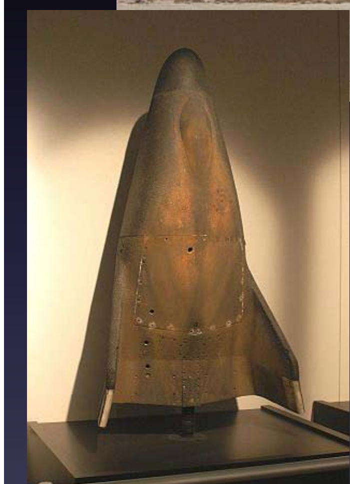
- Navigation System Integration & Test
  - SIGI
  - GPS Antennas
  - FADS
  - Radar Altimeter
  - Horizon Sensor
  - Navigation FSW
- Nav. Sensors DDT&E
  - SIGI & SIGI Firmware
  - Horizon Sensor
  - FADS
- Nav. Sensor Installation & Checkout
- Operations Support*

* All Groups are responsible for the development of Flight Test Objectives, Flight & Ground System Software & Displays, Command & Telemetry Definition, Flight Operations Support and Post Flight Analysis.

Entry Vehicle Shape Evolution

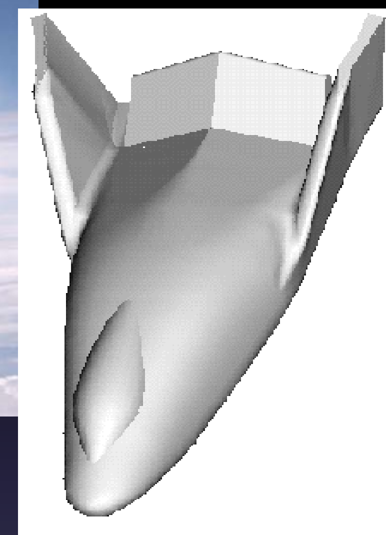
X-24A @ EAFB (1969)

- w/X-23A provides entry concept



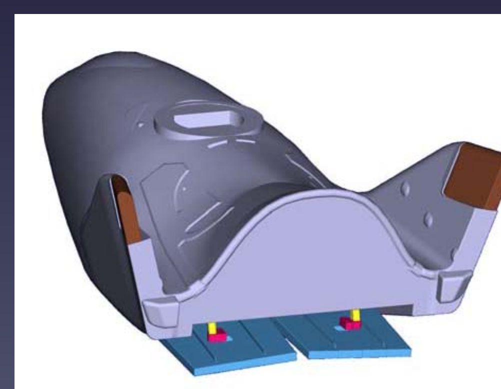
X-38 Rev. 3.1 (1996)

- Crew of 4 / SSLV Compatible



X-38 Rev. 8.3 + LIDS (1999)

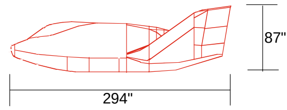
- Crew of 7 & ELV Compatible

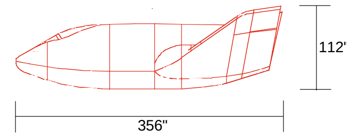


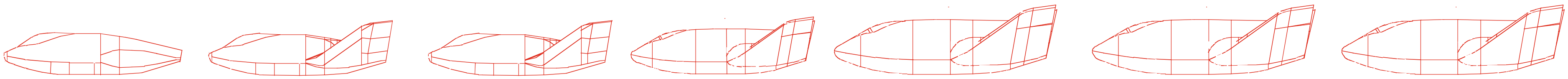
THE

X-38

PROJECT



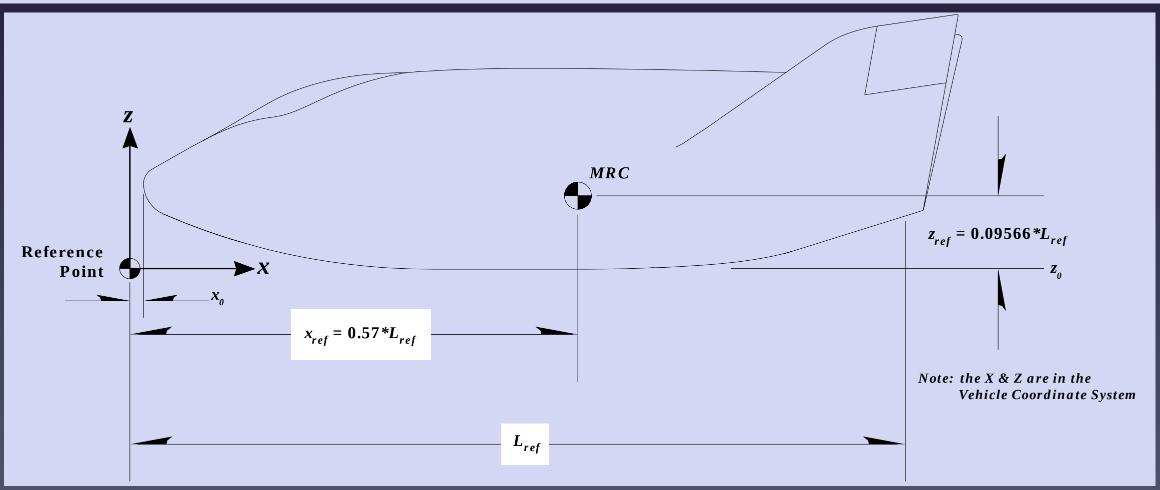




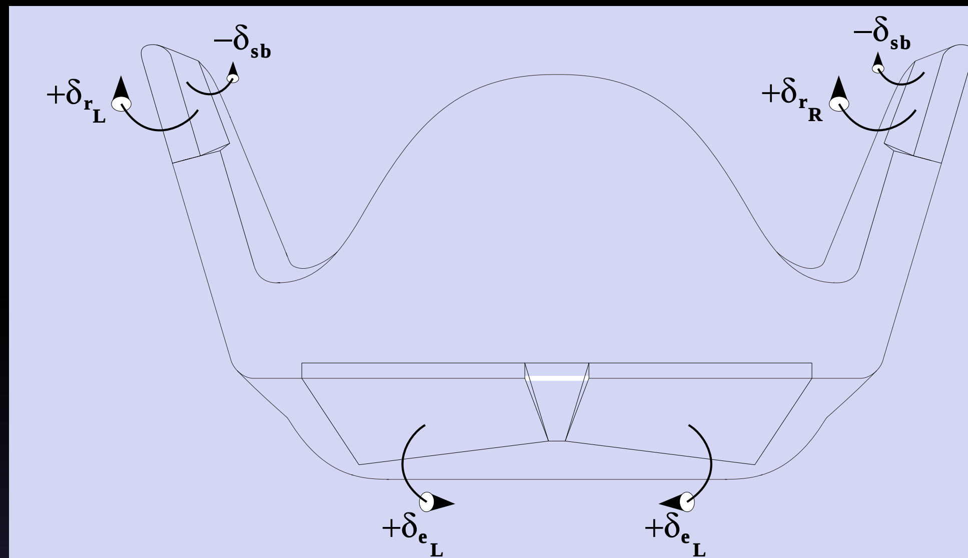
Vehicle 121 (Drop Vehicle)	**Vehicle 131** (Inert Flight Vehicle)	**Vehicle 132** (Free Flight Vehicle)	**Vehicle 131-R** (Free Flight Vehicle)	**Vehicle 133** (Full Size Free Flight Vehicle)	**Vehicle 201** (Space Flight Vehicle)	**Vehicle 301** (Operational CRV)
100 % Scale	100 % Scale	100 % Scale	100 % Scale	120 % Scale	120 % Scale	120 % Scale
X-24 A Shape	X-24 A Shape	X-24 A Shape	Modified X-24 A Shape	Modified X-24 A Shape	Modified X-24 A Shape	Modified X-24 A Shape
C130 Drop	B52 Drop	B52 Drop	B52 Drop	B52 Drop	STS Transport to LEO	STS Transport to IS
Fiberglass Structure	Fiberglass Structure	Fiberglass Structure	Fiberglass Structure	Fiberglass Structure	Aluminum/Composite Structure	Aluminum/Composit Structure
No Fins	5400 Sq. Ft. Parafoil	5400 Sq. Ft. Parafoil	7500 Sq. Ft. Parafoil	7500 Sq. Ft. Parafoil	7500 Sq. Ft. Parafoil	7500 Sq. Ft. Parafoil
	JSC Avionics & Instrumentation	JSC Avionics & Instrumentation	JSC Avionics & Instrumentation	JSC Avionics & Instrumentation	Complete Spaceflight Vehicle Systems	Complete Spaceflight Vehicle Systems
	Fixed Aerosurfaces	Active Aerosurfaces	Active Aerosurfaces	Active Aerosurfaces	Active Aerosurfaces	Active Aerosurfaces
		JSC Flight Control	JSC Flight Control	JSC Flight Control	Pressurized Cabin	Pressurized Cabin
						DPS
			New Aero-dynamic Shape	Fullscale Parachute Integration	Deorbit Propulsion Stage (DPS)	Accomodations for Crew of 7

References & Dimensions

REFERENCE	Vehicle 132 (100%)	Vehicle 131R (100%)	Vehicle 201 (120%)
Reference Length (Lref)	23 ft (276 in)	23 ft (276 in)	27.6 ft (331.2 in)
Reference Span (Bref)	10 ft (120 in)	23 ft (276 in)	27.6 ft (331.2 in)
Reference Area (S)	162 sq ft	162 sq ft	233.28 sq ft
Moment Ref. Center (MRC) Location:			
x_o (distance from vehicle nose)	5.00 in	5.00 in	6.00 in
xref (57% of Lref)	157.32 in	157.32 in	188.78 in
yref	0.0 in	0.0 in	0.0 in
zref (9.566% of Lref)	26.40 in	26.40 in	31.68 in



Control Surface Definitions



Elevon – Flap deflections (left + right) averaged

$$\delta e = (\delta e_L + \delta e_R)/2$$

Aileron – Flap deflections differenced (left - right) averaged

$$\delta a = (\delta e_L - \delta e_R)/2$$

Rudder – Rudder deflections (left + right) averaged

$$\delta r = (\delta r_L + \delta r_R)/2$$

Speed Brake – Rudder deflections differenced (left - right) averaged

$$\delta sb = (\delta r_L - \delta r_R)/2$$

Aerodynamic Model

- V-131R Aerodynamic Model is f(Mach, α, β, δe, δa, δr, δsb)
  - In General a Linear Aerodynamic Convention is Followed
  - Uncertainties on individual derivatives

  - Rolling Moment – linear derivatives

$$Cl_{mrc} = \mathbf{Clo} + (Cl_{\beta}+\Delta Cl_{\beta})*(\beta) + (Cl_{\delta a}+\Delta Cl_{\delta a})*(\delta a) + (Cl_{\delta r}+\Delta Cl_{\delta r})*(\delta r)$$
$$+ (Cl_{r}+\Delta Cl_{r})*(r*L_{ref}/V) + (Cl_{p}+\Delta Cl_{p})*(p*L_{ref}/V)$$

where (e.g.) $Cl_{\beta} = \{Cl_{(\beta=2)} - Cl_{(\beta=-2)}\}/4$; etc.

$$\mathbf{Clo = Clo_{Asymflow} + Clo_{BAF}}$$

  - Yawing Moment – non-linear sideslip derivative

$$Cn_{mrc} = \mathbf{Cno} + Cn(\beta) + \Delta Cn_{\beta}*(\beta) + (Cn_{\delta a}+\Delta Cn_{\delta a})*(\delta a) + (Cn_{\delta r}+\Delta Cn_{\delta r})*(\delta r)$$
$$+ (Cn_{r}+\Delta Cn_{r})*(r*L_{ref}/V) + (Cn_{p}+\Delta Cn_{p})*(p*L_{ref}/V)$$

where (e.g.) $Cn_{\beta} = f(\beta)$ – table lookup

$$\mathbf{Cno = Cno_{Asymflow} + Cno_{BAF}}$$

'Vector Plots' Revealed

Used to Express Lateral-Directional Stability & Control Characteristics

– Relative Relationship between Rudder (δr), Aileron (δa) and Sideslip (β) Yawing & Rolling Moment Derivatives at a Given Mach, Angle-of-Attack (α) and Body Flap Deflection (δe)

Equations | **Ideal *(realistic)* Aircraft**

Lateral Control Departure Parameters

$LCDP_{\delta a} = Cn_{\beta}*Cl_{\delta a} - Cl_{\beta}*Cn_{\delta a}$

$LCDP_{\delta r} = Cn_{\beta}*Cl_{\delta r} - Cl_{\beta}*Cn_{\delta r}$

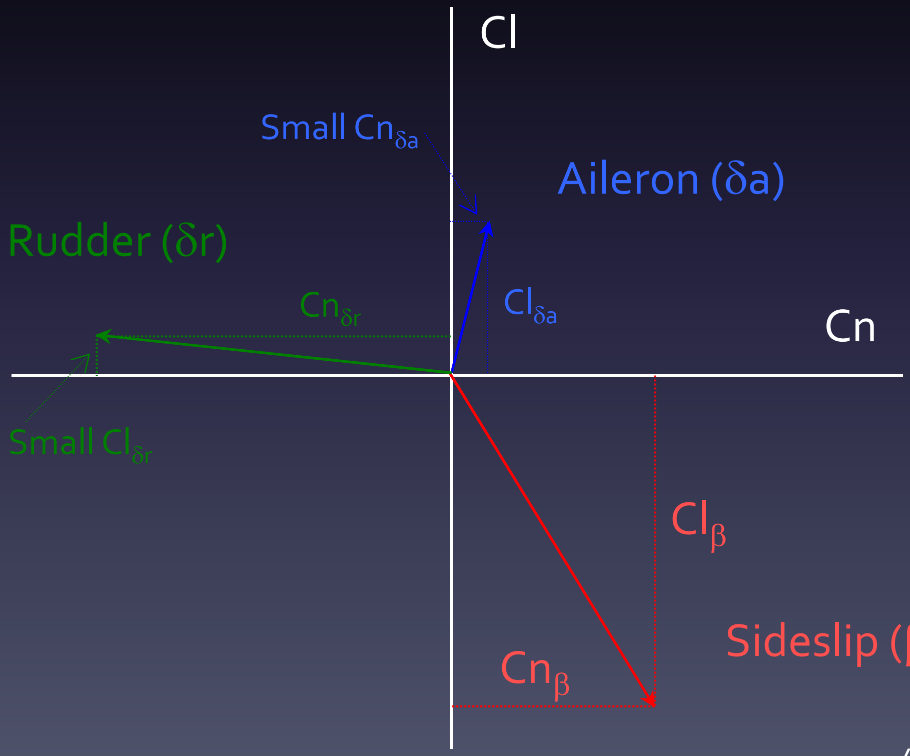
$LCDP_{\delta a - \delta r} = Cn_{\delta r}*Cl_{\delta a} - Cl_{\delta r}*Cn_{\delta a}$

Dutch Roll Frequency

$\omega_{DR} = [Cn_{\beta dyn}*q*S_{ref}*L_{ref}/Iz]^{1/2}$

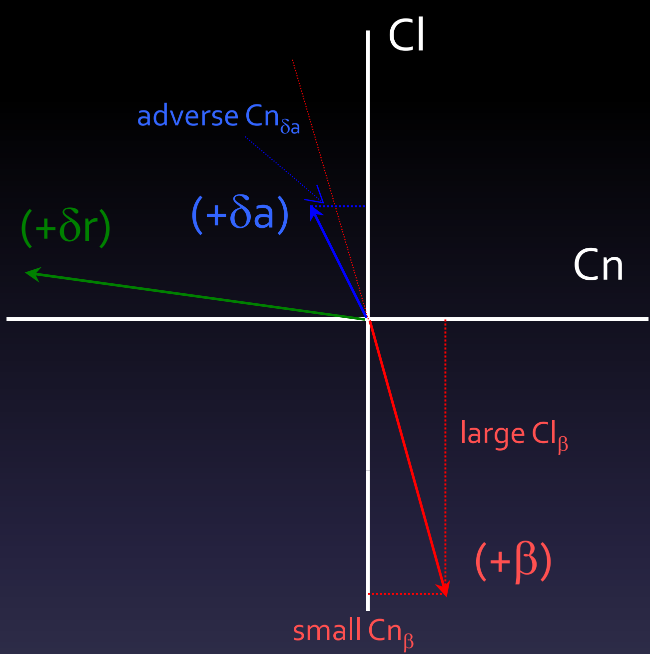
Dynamic Directional Stability Derivative

$Cn_{\beta dyn} = Cn_{\beta}*\cos(\alpha) - Clb*\sin(\alpha)*(Iz/Ix)$



Vector Plots - Aileron Roll Reversal

Aircraft Condition



large adverse yaw due to aileron ($-Cn_{\delta a}$)

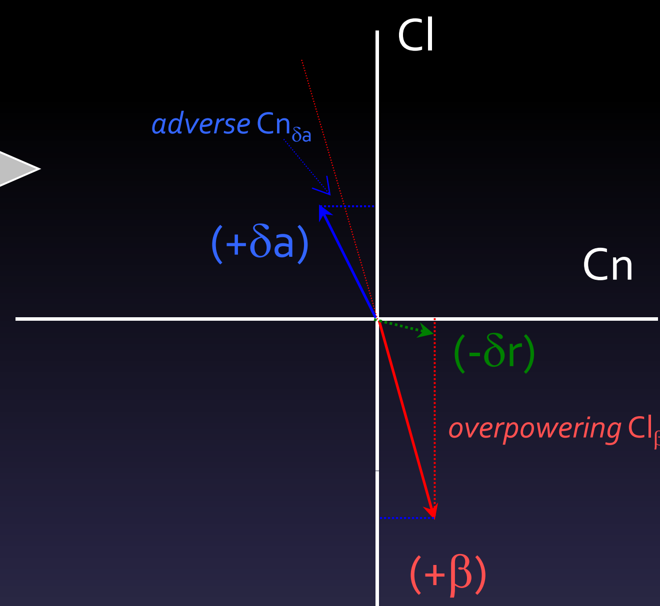
\+

low static directional stability (Cn_{β})

\+

large dihedral (Cl_{β})

Roll Reversal ($LCDP_{\delta a} < 0$)



Command +Roll (bank) using $+\delta a$ (right stick)

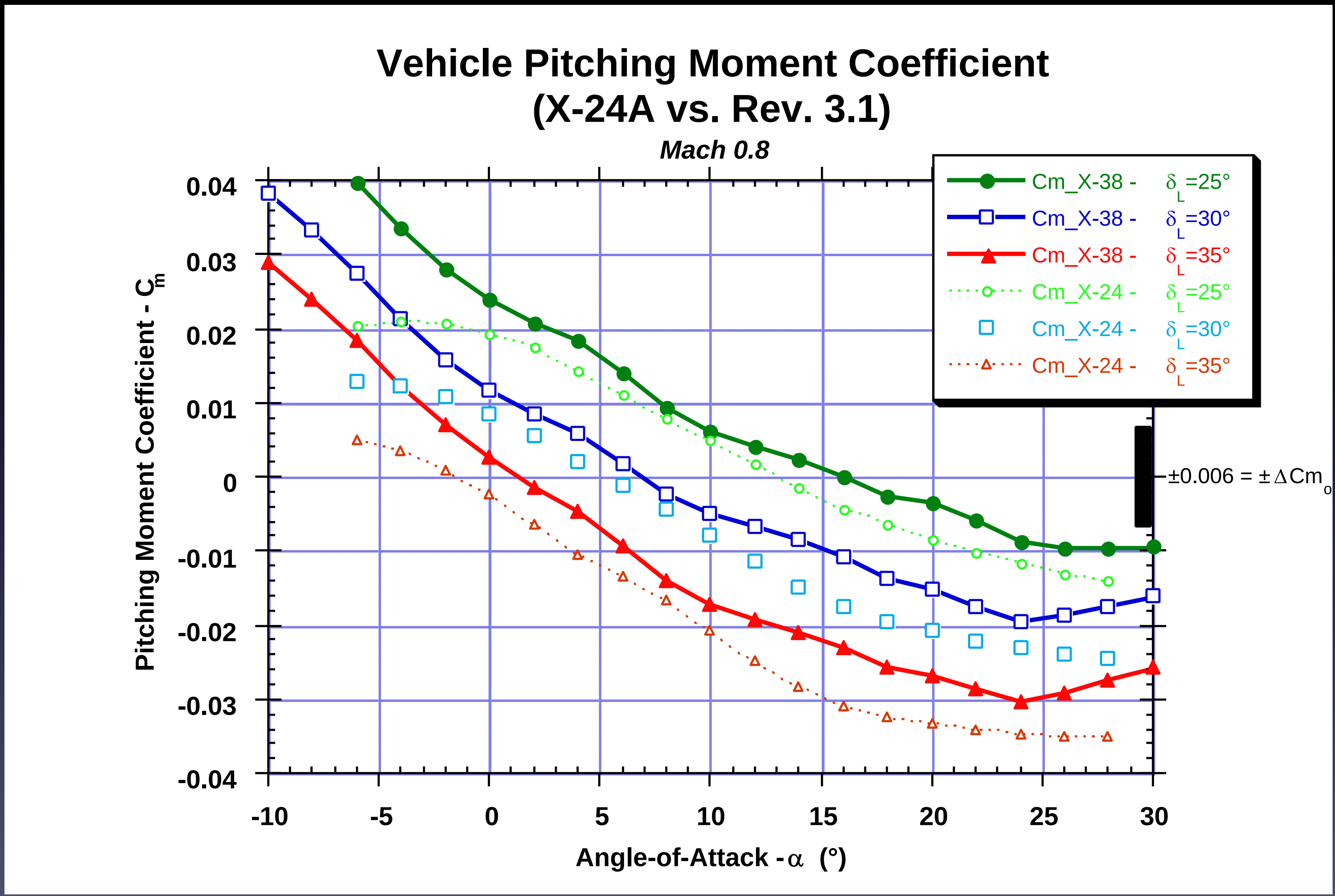
Adverse $Cn_{\delta a}$ induces -Yaw (nose left) introducing a $+\beta$

$+\beta$ produces an overpowering -Roll due to Cl_{β} -- resulting in the reverse of the desired roll

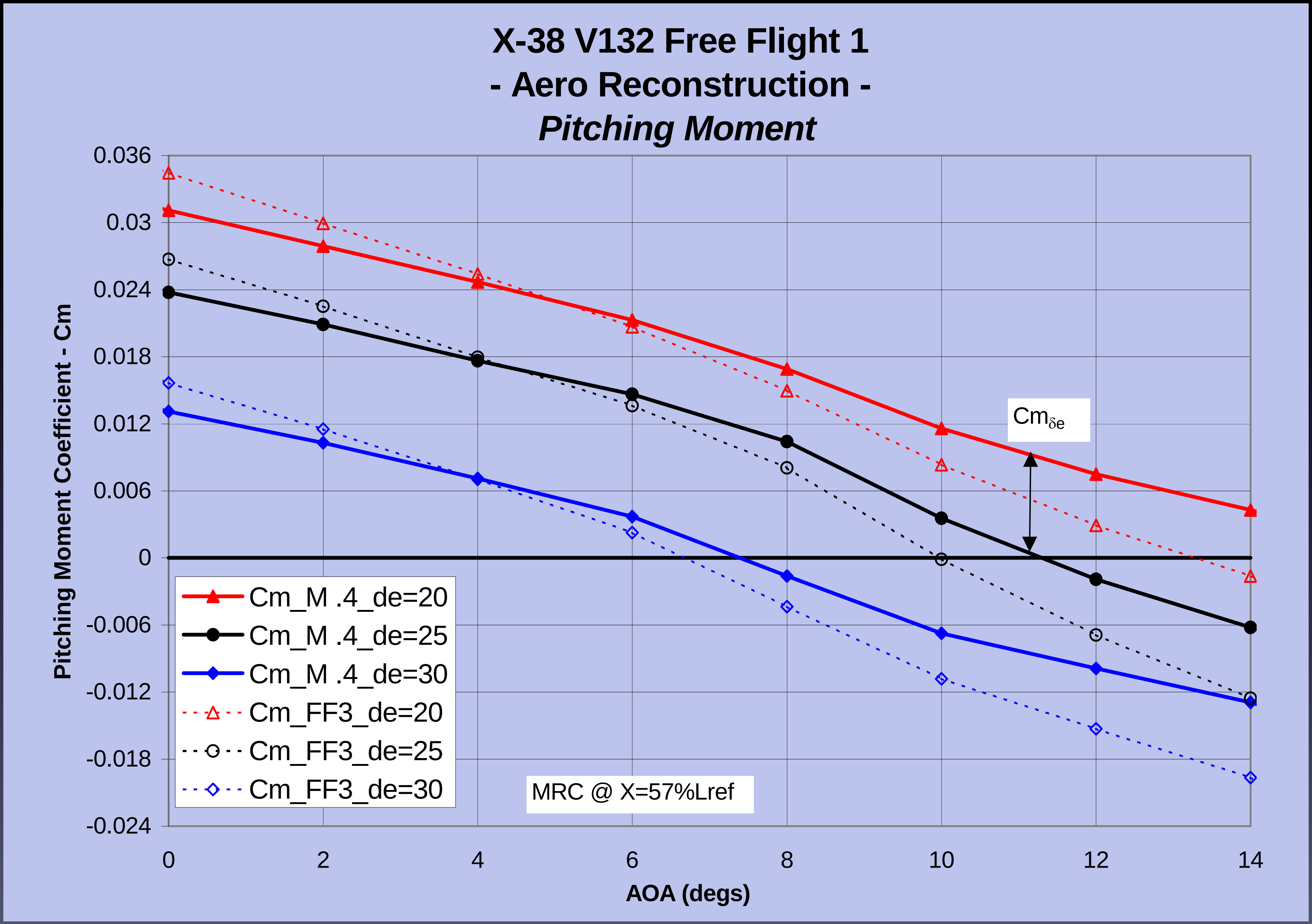
Coordinate turn by using $-\delta r$ (right rudder -'step on the ball') to null out β

-- works well with small $Cl_{\delta r}$

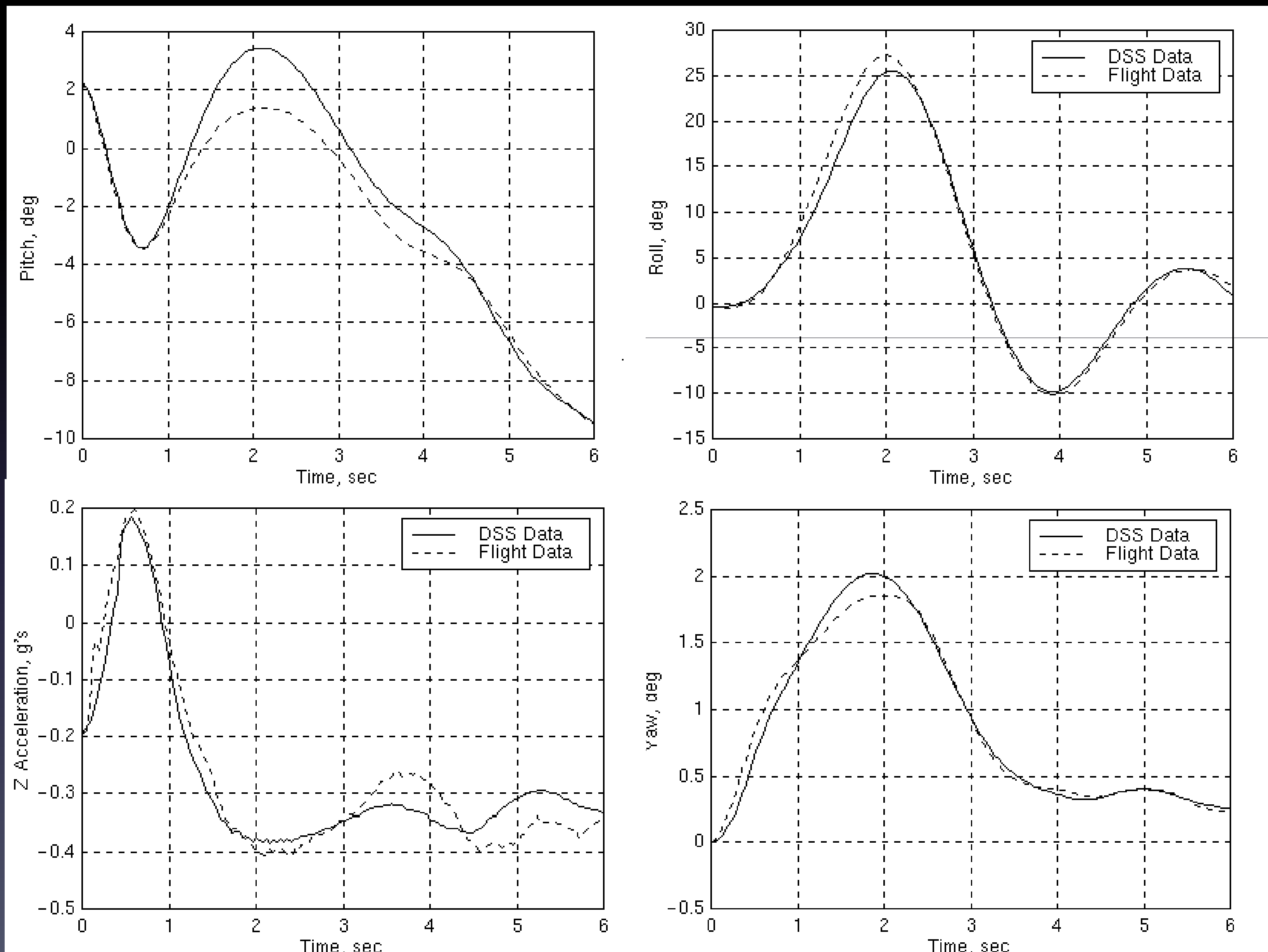
AERODYNAMIC COMPARISON - TRANSONIC -



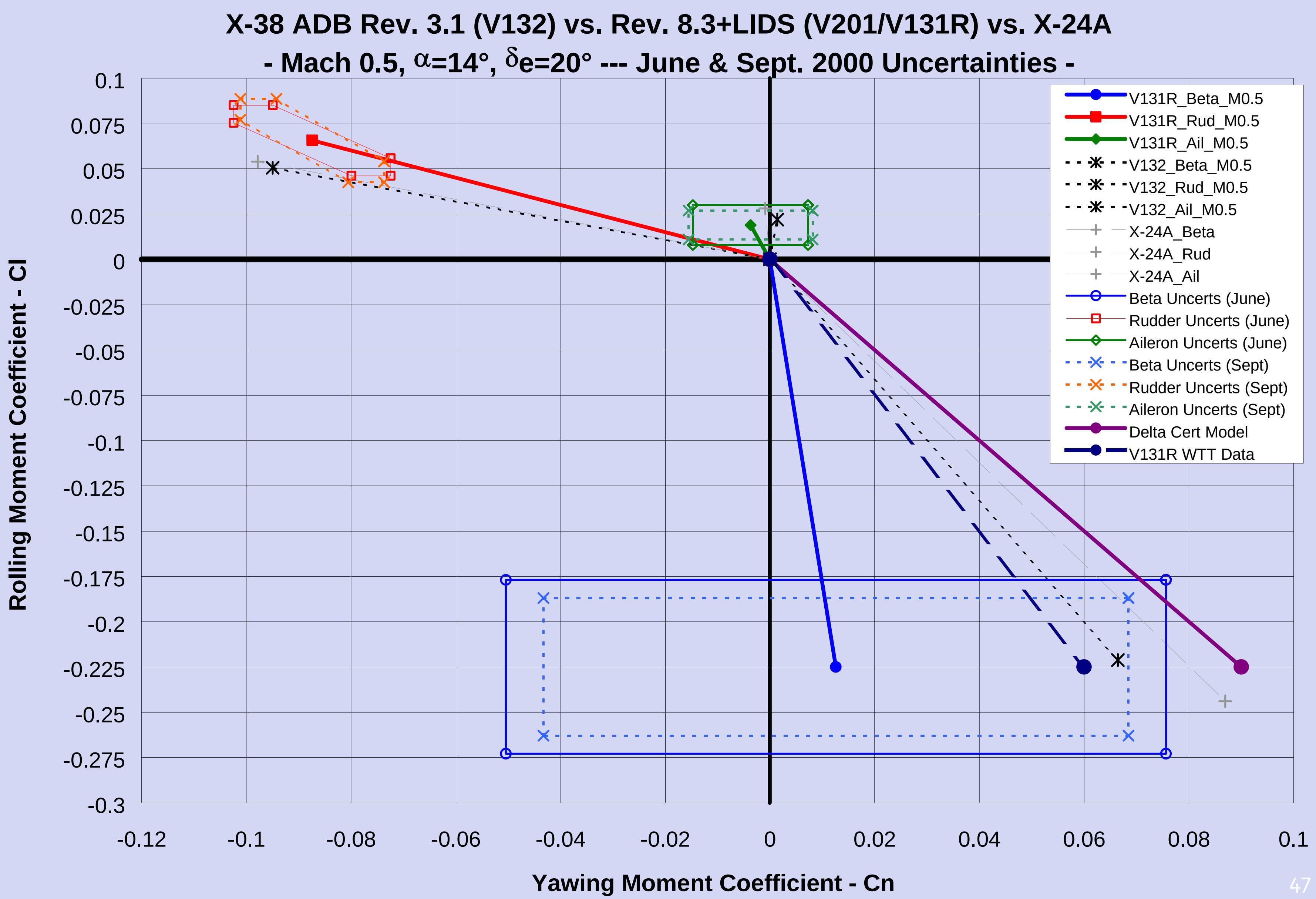
X-38 v-132 Flight Results

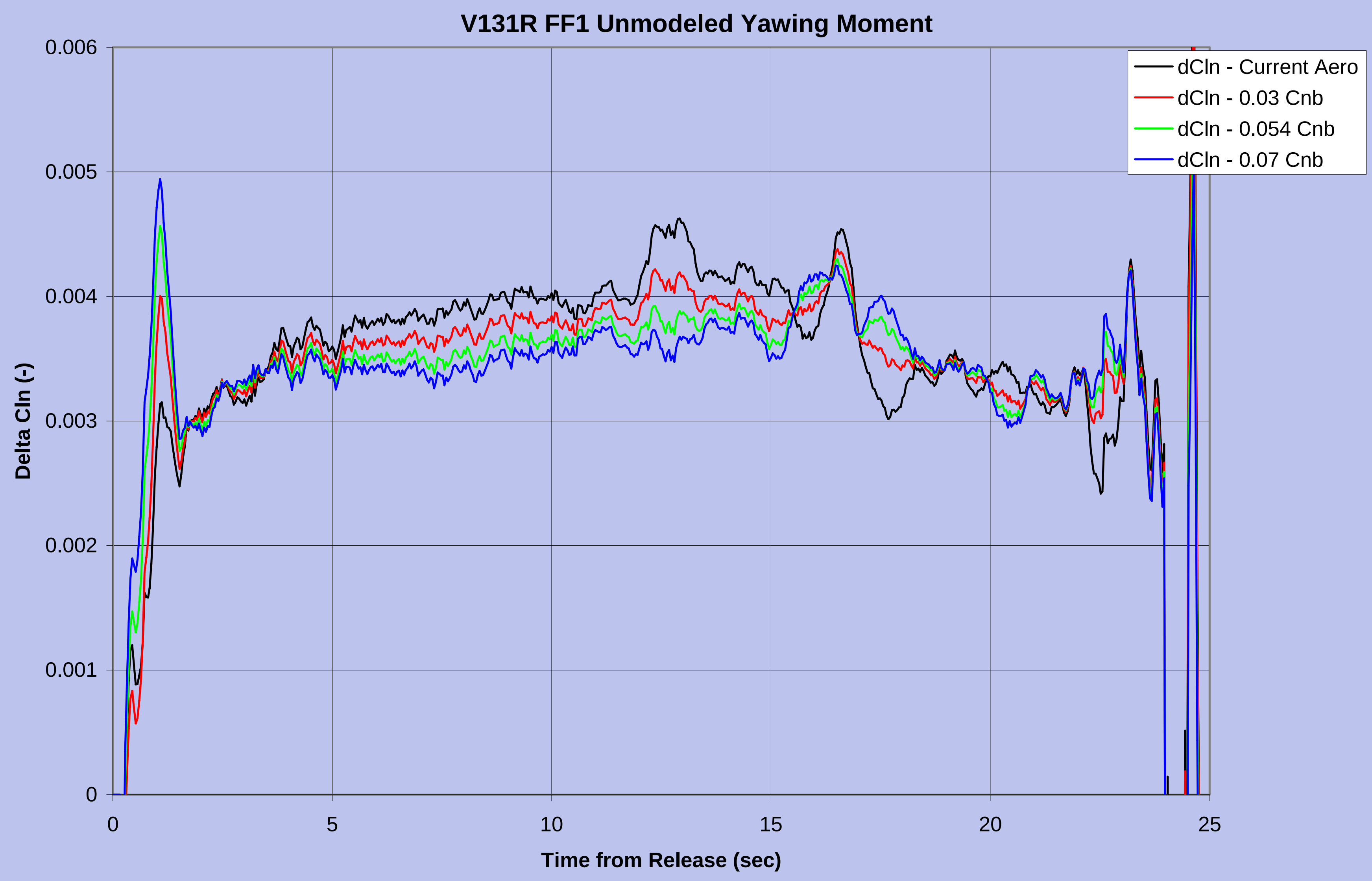


X-38 v-132 Flight Results

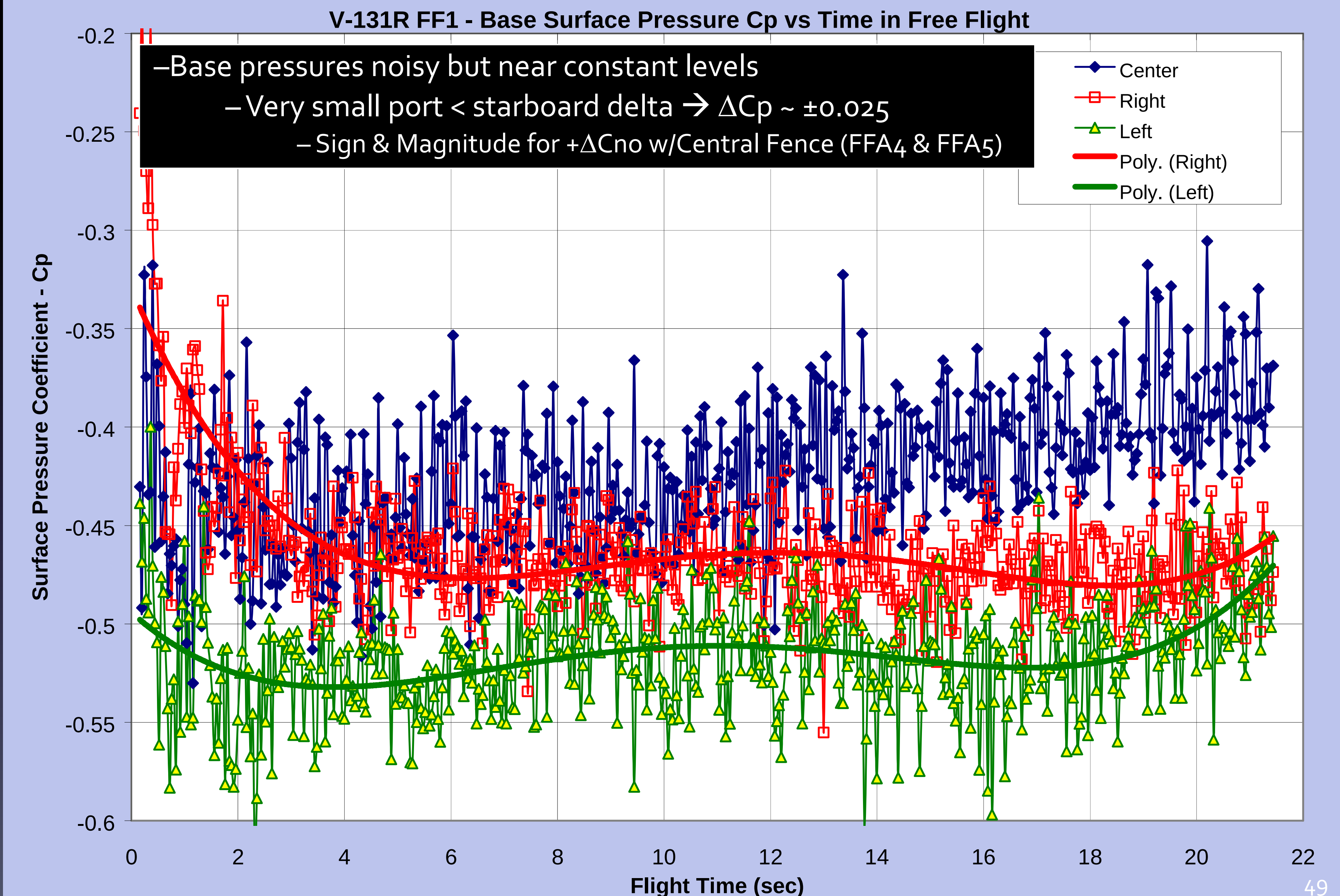


June vs. Oct. 2000 Uncertainties

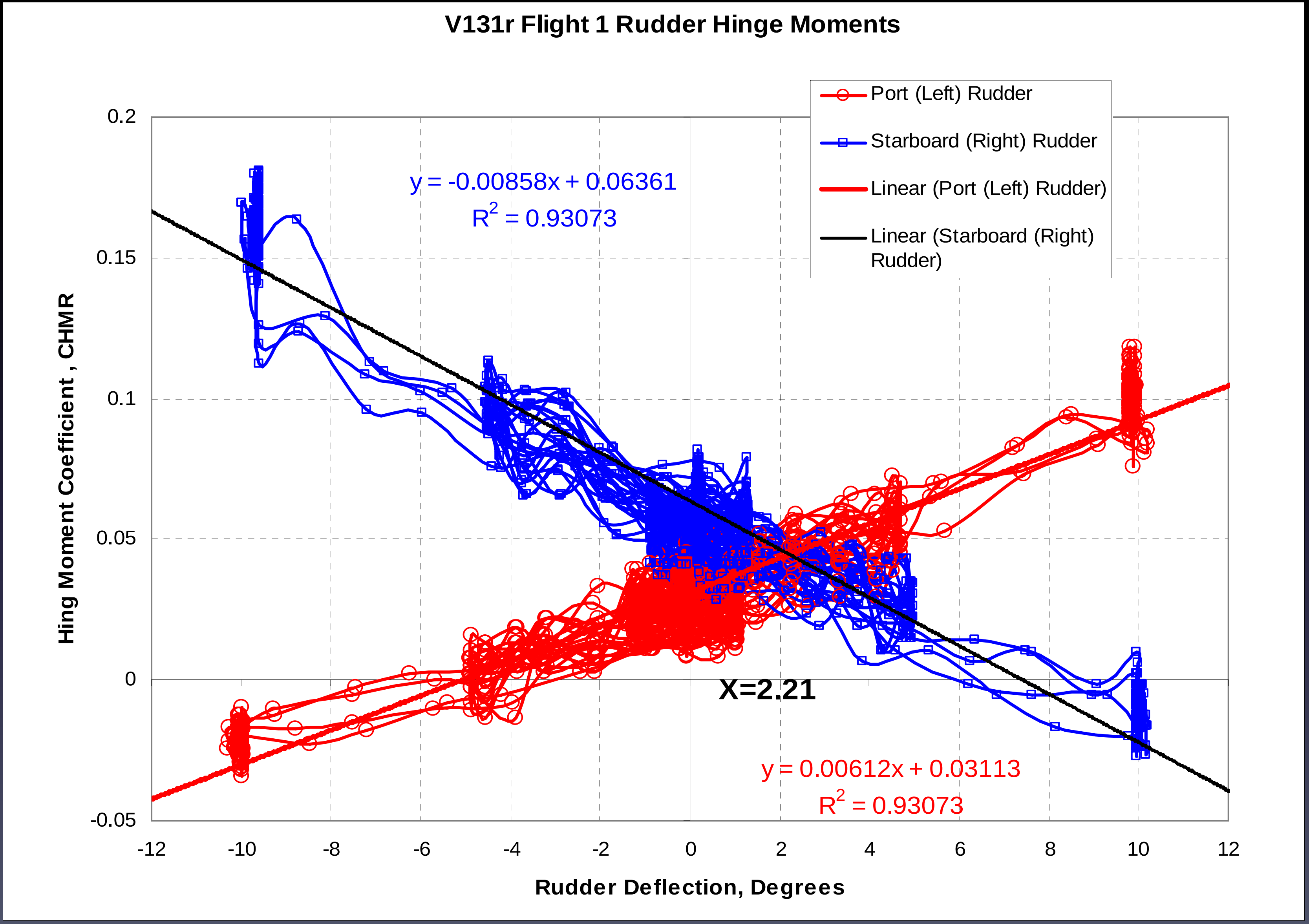



V131R FF1 Unmodeled Yawing Moment
0.006
0.005
0.004
0.003
0.002
0.001
0
Delta Cln (-)
0
5
10
15
20
25
Time from Release (sec)
dCln - Current Aero
dCln - 0.03 Cnb
dCln - 0.054 Cnb
dCln - 0.07 Cnb

V-131R FF1 Base Pressures



V-131R Rudder Hinge Moments
Captive Configuration (on B-52) -Hot Pass

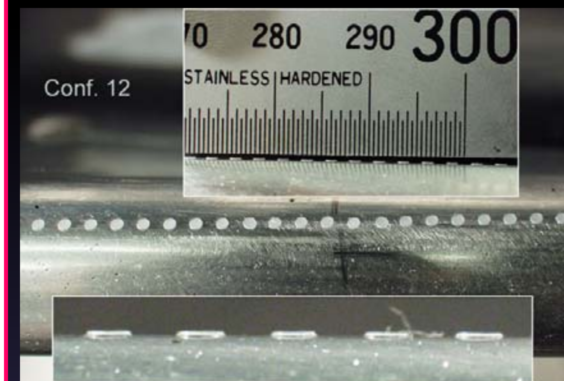


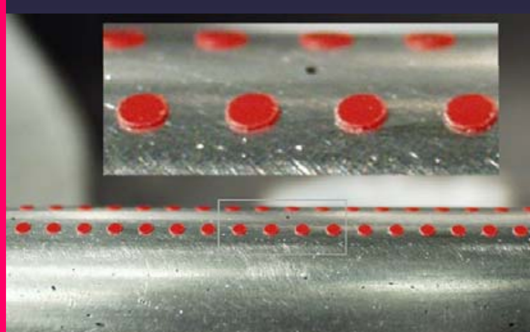
Reynolds / Trip Effectiveness Study
FFA5 WT Test

dots 3

dots 4.5

carborundum





ΔCno Sources / Bounding

ΔCno Source	Constant Offset	Uncertainty (±)	Fluctuation or Step
ΔCno(Bent Air Frame)	+0.0020	±0.0010	0.0000
ΔCno(Inboard Fin Flow)	0.0000	±0.0020	0.0040
ΔCno(BF Gap Cavity/Base)	0.0000	±0.0010	0.0020
Total	+0.0020	±0.0040	0.0060

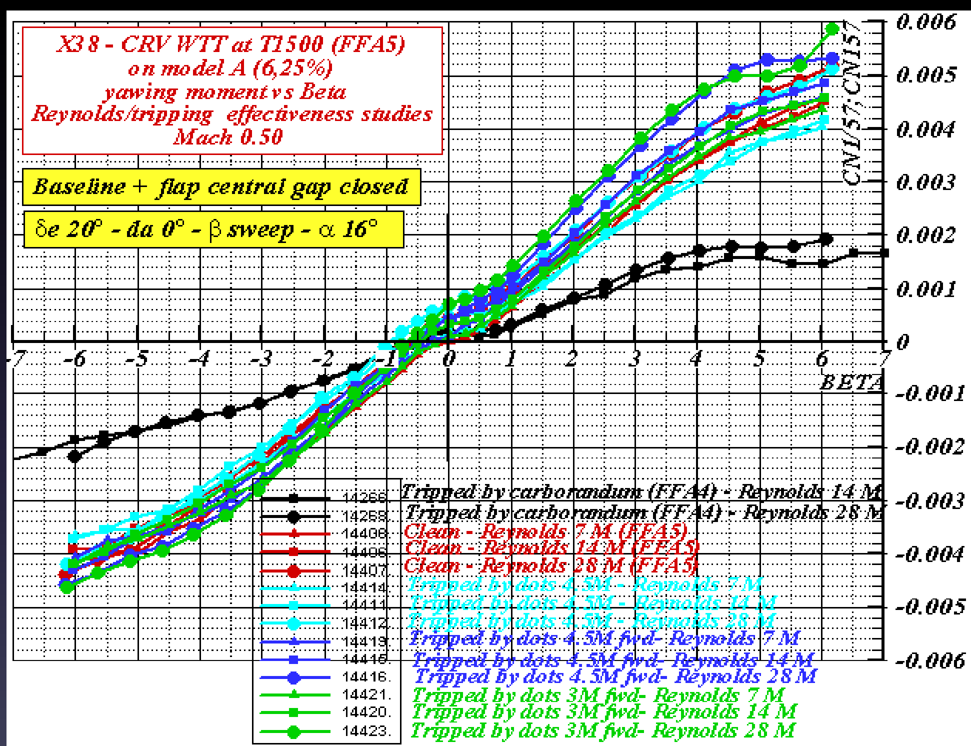
Current Bounds → ΔCno range of -0.0020 to 0.0060 w/potential 0.006 fluctuation

vs. Certification Model → ΔCno range of -0.0030 to 0.0060 w/potential 0.009 fluctuation

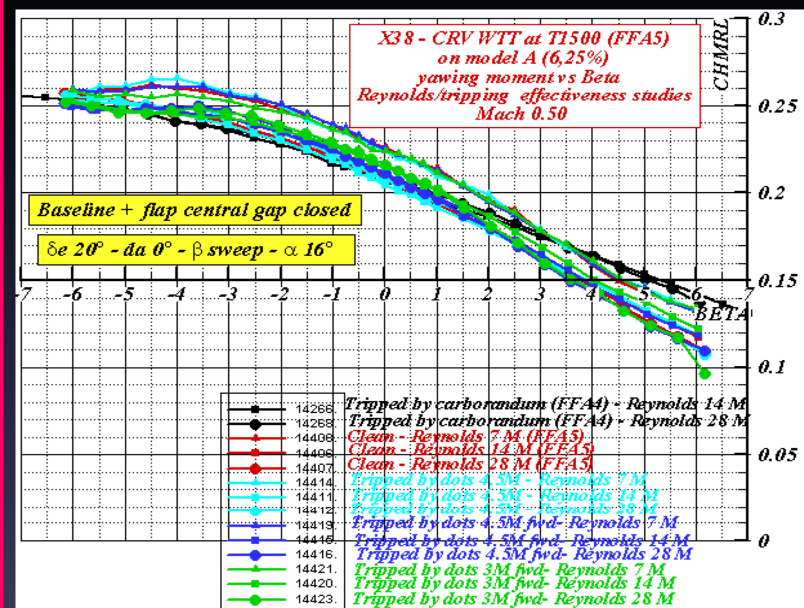
Certification model covers worst case combination with margin

Reynolds / tripping sensivity on fin

X38 - CRV WTT @ T1500_FFA5 (May 2001)
V131R_FF1 investigation - asymmetric aerodynamic
Mach 0.50 - β sweep - α 16 - δe 20 - flap gap filled



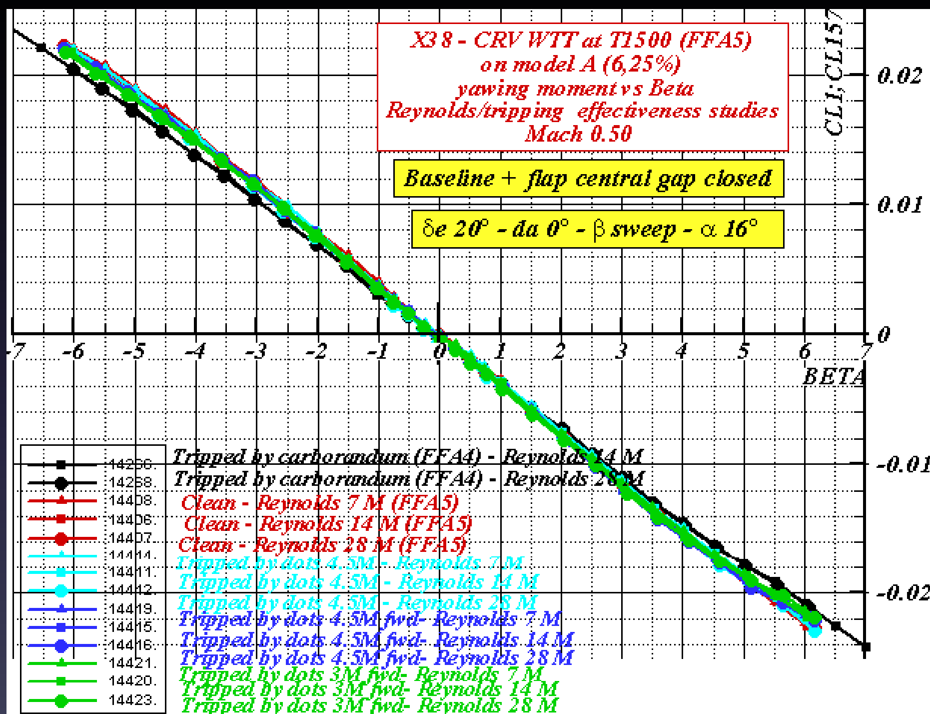
Yawing moment



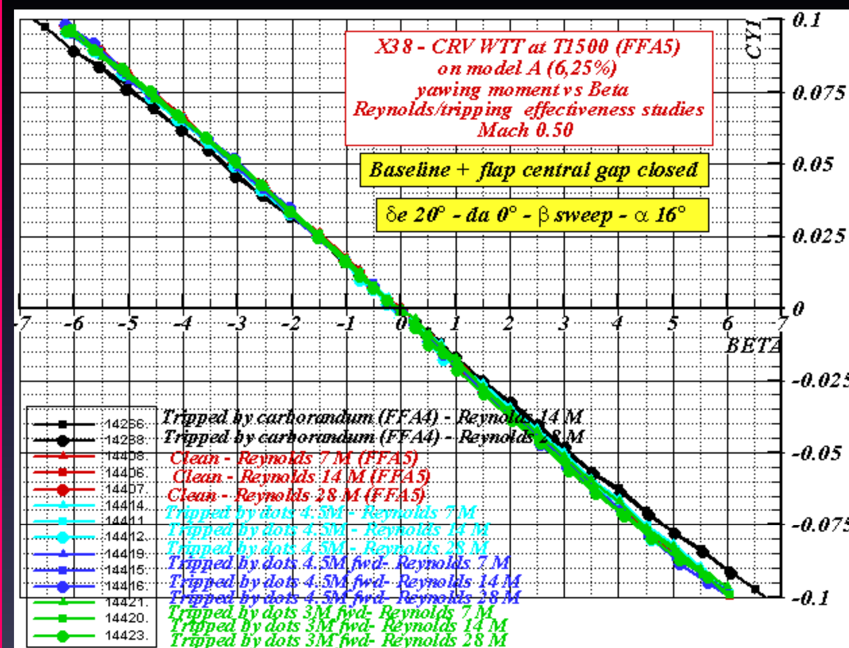
Rudder hinge moment

Reynolds / tripping sensivity on fin

X38 - CRV WTT @ T1500_FFA5 (May 2001)
V131R_FF1 investigation - asymmetric aerodynamic
Mach 0.50 - β sweep - α 16 - δe 20 - flap gap filled



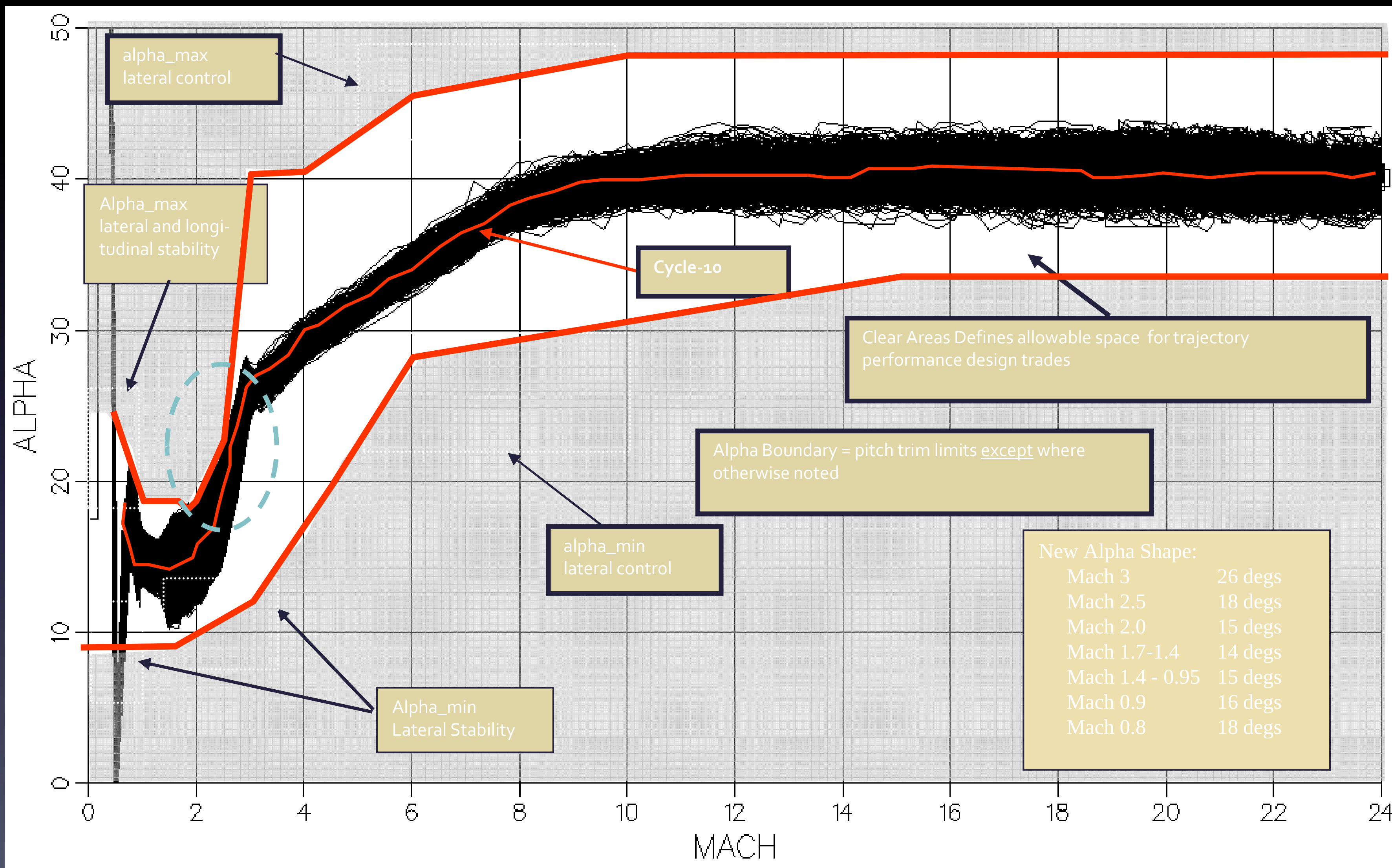
Rolling moment



Side force

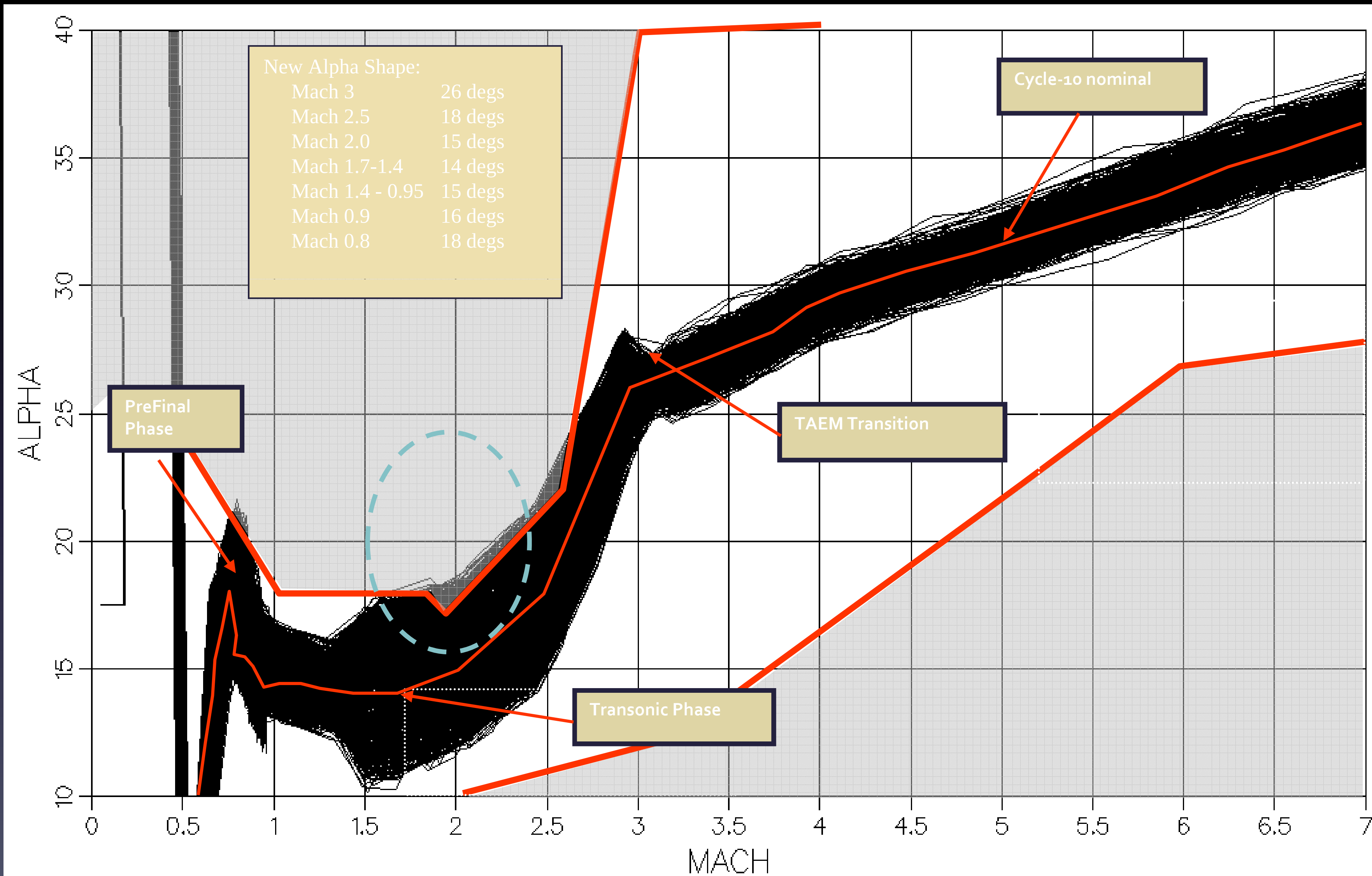
Cycle-10 - Monte-Carlo (1100 flight) Woomera, Australia

Angle-of-Attack (deg) vs Mach number



Cycle-10 - Monte-Carlo (1100 flight) Woomera, Australia

TAEM Angle-of-Attack (deg) vs Mach number



Cycle-10 Monte-Carlo (1100 flight)
Woomera, Australia

Drag Acceleration (fpss) vs Relative Velocity (fps)