Aeronautics Research Mission Directorate

Low Boom Flight Demonstrator Project

X-59: GNC Architecture for NASA's Supersonic X-Plane

EuroGNC 2024 Conference Keynote

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Bristol, UK

Jay Brandon, NASA X-59 Chief Engineer

Outline

- Introduction
- Barriers to Successful Supersonic Commercial Aircraft
- Sonic Boom Overview
- X-59 QueSST Airplane
- Challenges to S&C
- Control Laws
- Gain & Phase Margins and Other Metrics
- Variance Approach for Rigid Body Gain and Phase Margins
- Status – Integrated testing, Engine, AL Bird, EMI, Taxi
- Quesst Timeline
- Summary
- NASA Quesst Mission Web Page (https://www.nasa.gov/X-59)

Barriers to Commercial Supersonic Flight

Sonic Boom Noise and Overland Flight Prohibitions

- First supersonic flight: 1947
- Introduction of supersonic commercial transports in 1970s brought the problem of sonic boom noise to public attention & showed sonic boom noise to be unacceptable
- Supersonic overflight restrictions followed
  - US: FAA Regulation (FAR) prohibits supersonic flight over US
  - Worldwide: ICAO Assemble Resolution – “No unacceptable situation for the public due to sonic boom”
- Restriction dramatically limited market potential for supersonic commercial flight
- The creation of a market for supersonic commercial aircraft requires eliminating sonic boom as a barrier to overland flight

Vision for Commercial Supersonic Flight

An emerging potential market has generated renewed interest in civil supersonic aircraft

- Evidenced by the appearance of several commercial programs despite lack of standards for en route noise or landing and takeoff noise, emissions

Overland Flight Restrictions based on unacceptable sonic boom noise are viewed as the main barrier to this vision

Illustration Credit: Lockheed Martin

NASA plays a vital role in developing technology and the data that will enable this transformative new market

The vision of the Supersonics Community is a future where fast air travel is available for a broad spectrum of the traveling public.

- Future supersonic aircraft will not only be able to fly overland without creating an “unacceptable situation” but will also be environmentally responsible, affordable and sustainable

Overcoming the Barrier to Overland Supersonic Flight

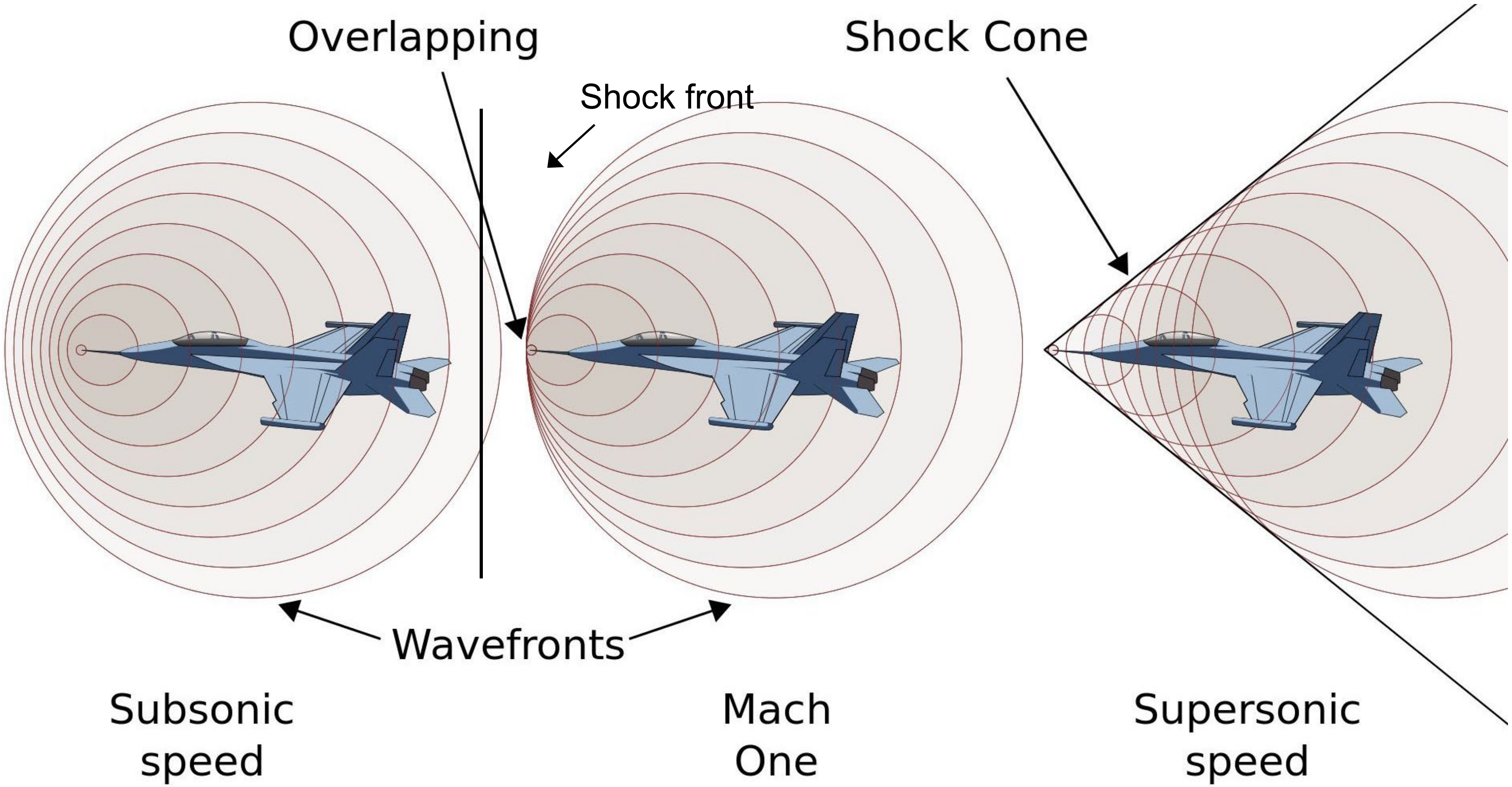
NASA's Quesst Mission is specifically planned to generate key data supporting the development of en route certification standards based on acceptable sound levels

- **New Environmental Standards are needed to open the market to supersonic flight**
- **An En route Noise Standard is the biggest challenge**
  - Requires proof of new design approaches
  - Must replace current prohibitions
  - No relevant data exists to define limits
    - Community data from large, diverse population is a requirement
  - Standard must be accepted internationally

Illustration Credit: Lockheed Martin

Manned Supersonic X-Planes

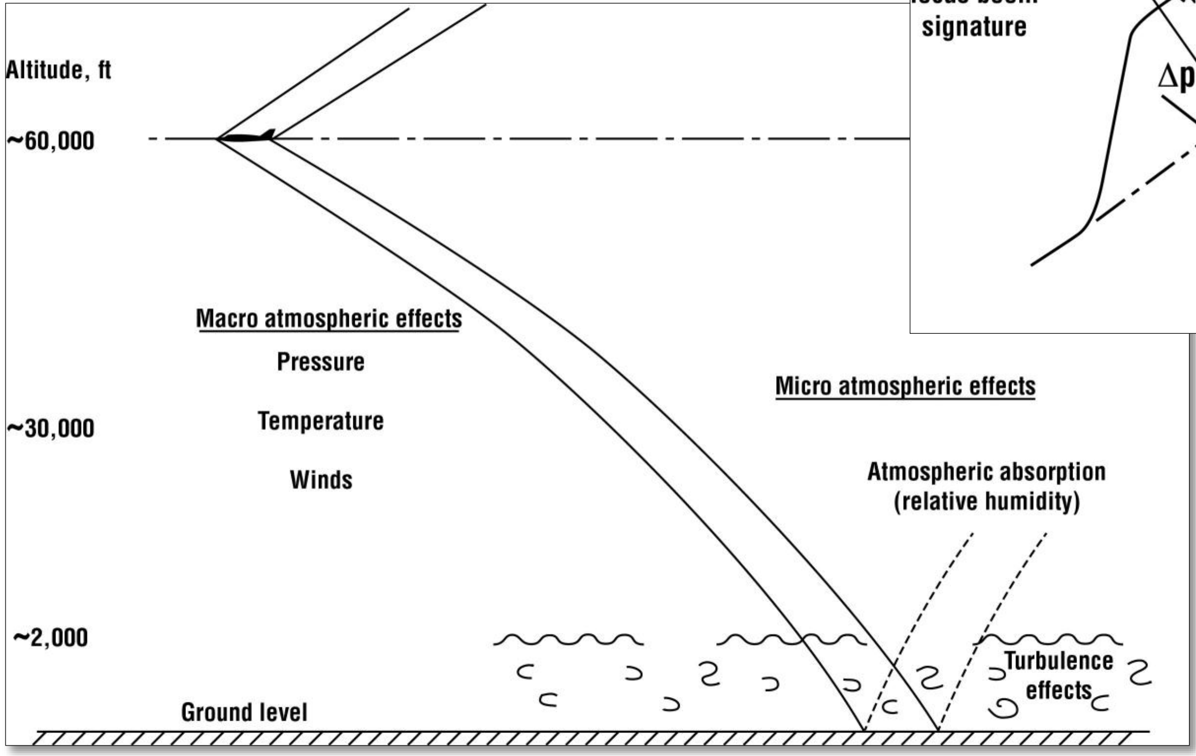
What Makes a Sonic Boom?

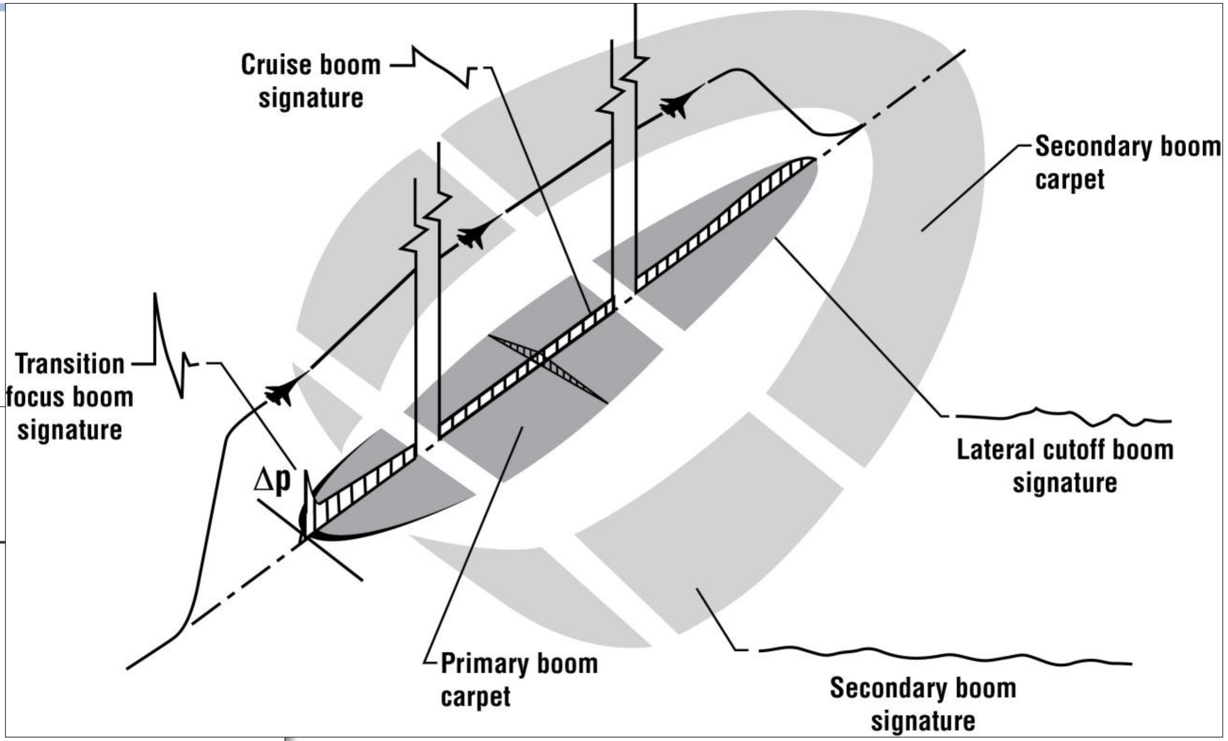


- Conical shock wave produces sonic boom at ground which moves with the airplane
- Boom is created over entire length of supersonic flight path, just as a boat wake is continuous

Sonic Boom 101

Sonic Boom With Atmospheric Effects

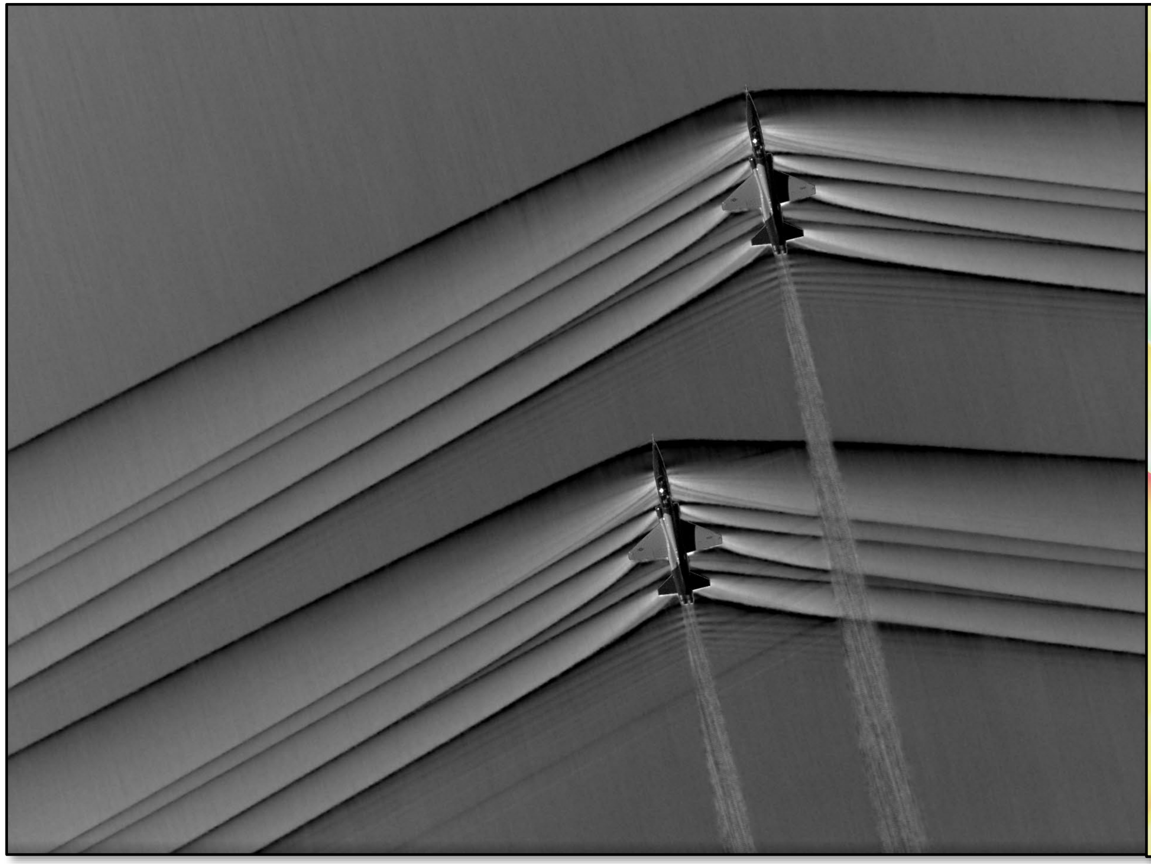


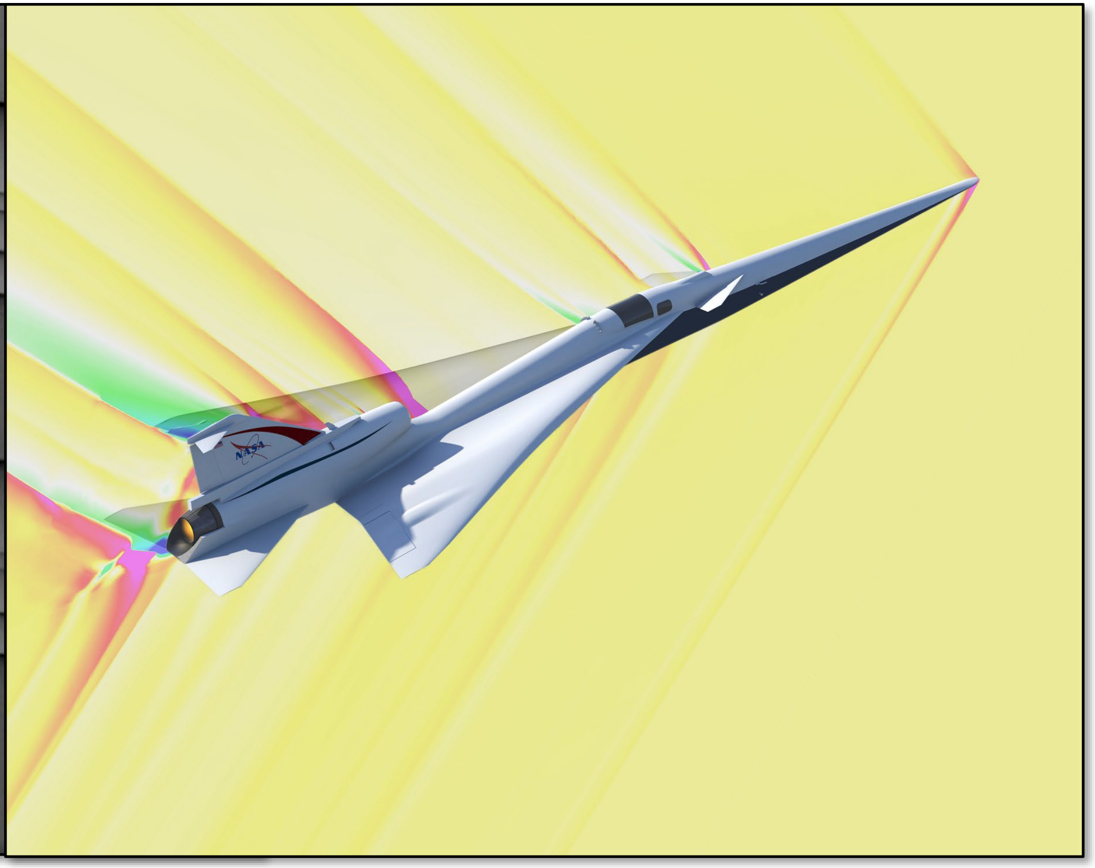


Boom Signature Carpet

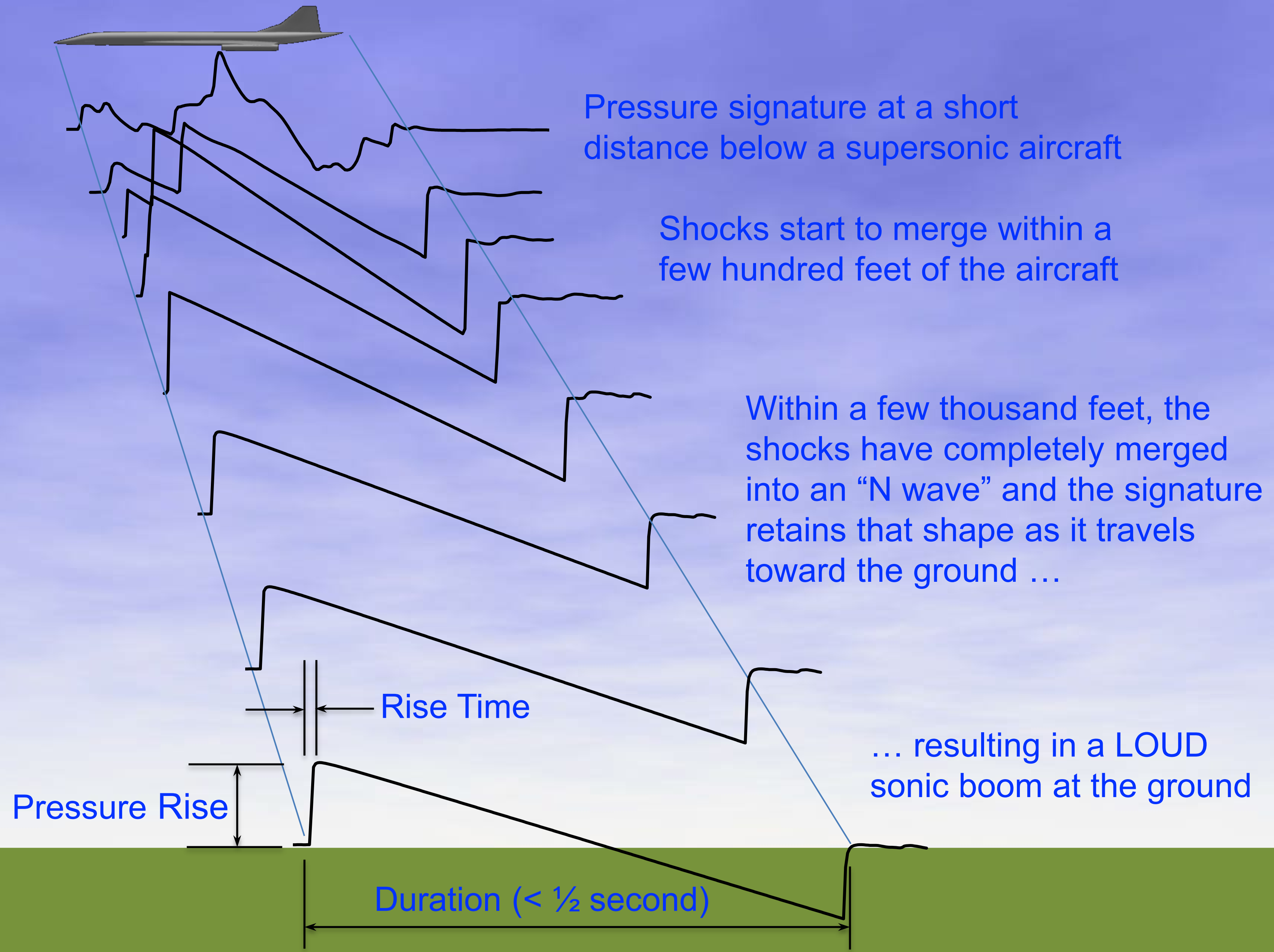
Shock Wave Visualization

The X-59's design shape prevent shockwaves from coming together, reducing the loud sonic boom to a barely audible thump.

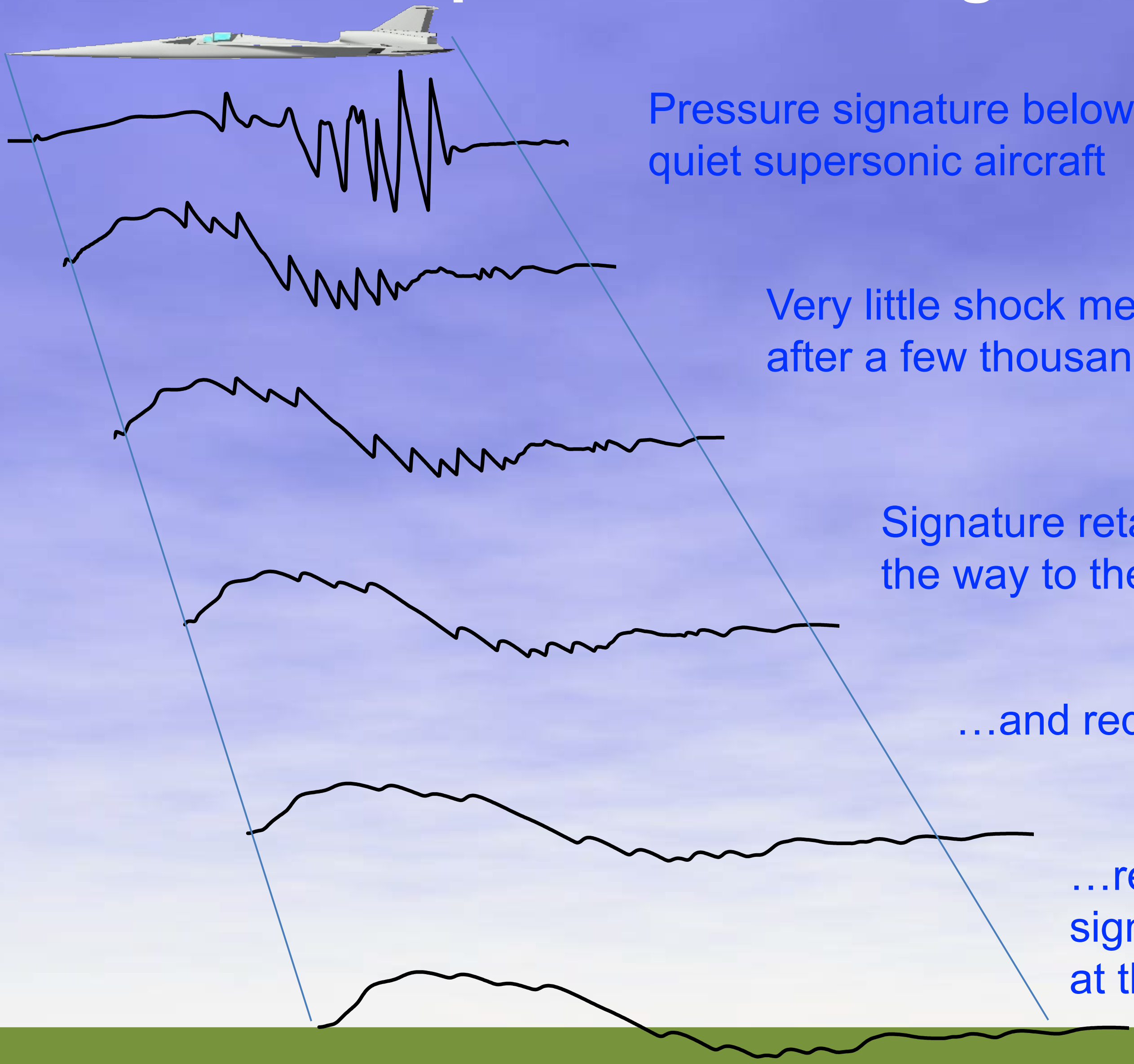




Sonic Boom Basics: N-Wave Sonic Boom



Sonic Boom Basics: Shaped Pressure Signal



Pressure signature below a quiet supersonic aircraft

Very little shock merging after a few thousand feet

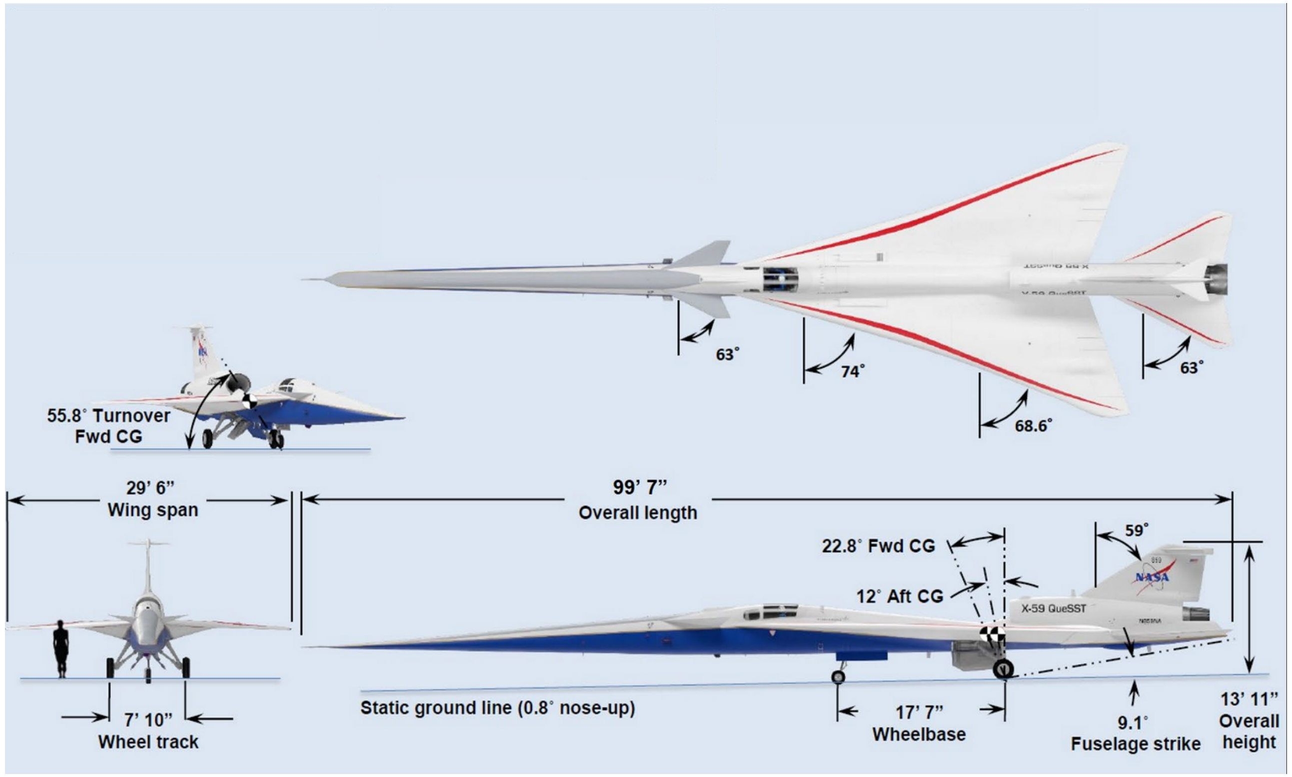
Signature retains its shape all the way to the ground…

…and reduces in strength…

…resulting in a significantly quieter sound at the ground

Shaped-boom Vehicle Design Features

- Swept delta wing
  - Large rolling moments during sideslip
  - Pitching moment break at moderate angle-of-attack
- Aft center-of-gravity
  - Vehicle is unstable in pitch over much of flight envelope
    - Subsonic static margin ~15% unstable
    - Fixed-controls time to double ~ 220 ms
- Small tail to minimize weight and drag
  - Very low natural yaw damping
- Long, slender fuselage
  - Low roll inertia limits roll rates because of inertial coupling
- Flexible Structure
  - Coupling between control and flexible modes (first symmetric flex mode ~5 Hz)
- Aero Challenges on Margins
  - Large negative static stability in pitch axis subsonically
  - Large pitch inertia
  - Low rudder control authority
  - Large dihedral effect requiring high gain ARIs



Significant Stability and Control Challenges due to Shaped Boom Configuration

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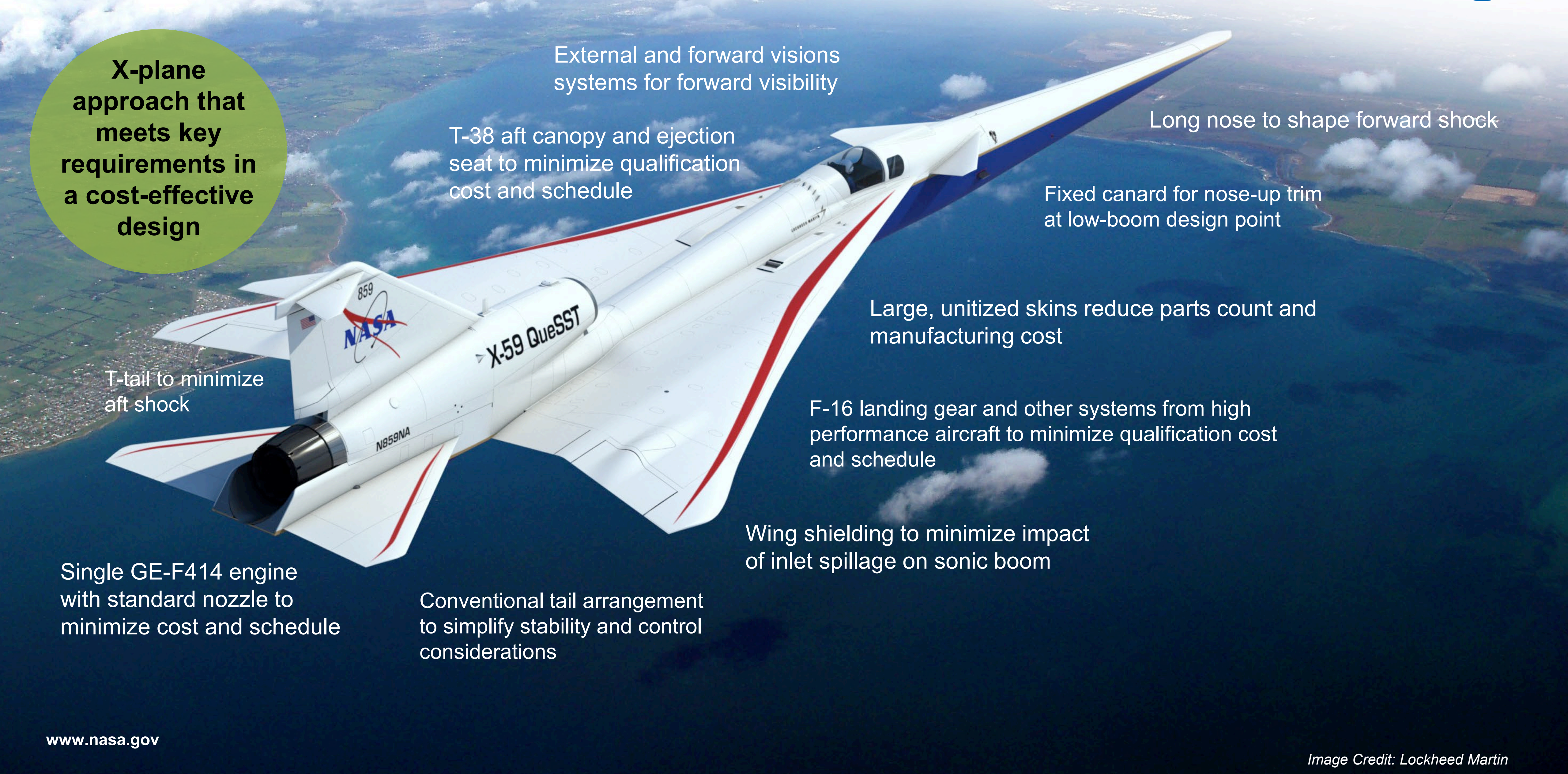
NASA
X-59
X-59

Overview of X-59 QueSST Aircraft Features



www.nasa.gov

Image Credit: Lockheed Martin

Wind Tunnel Validations

Low-and high-speed aerodynamic and Propulsion Airframe Interaction (PAI) wind-tunnel tests validate predictions and ensure readiness of the design

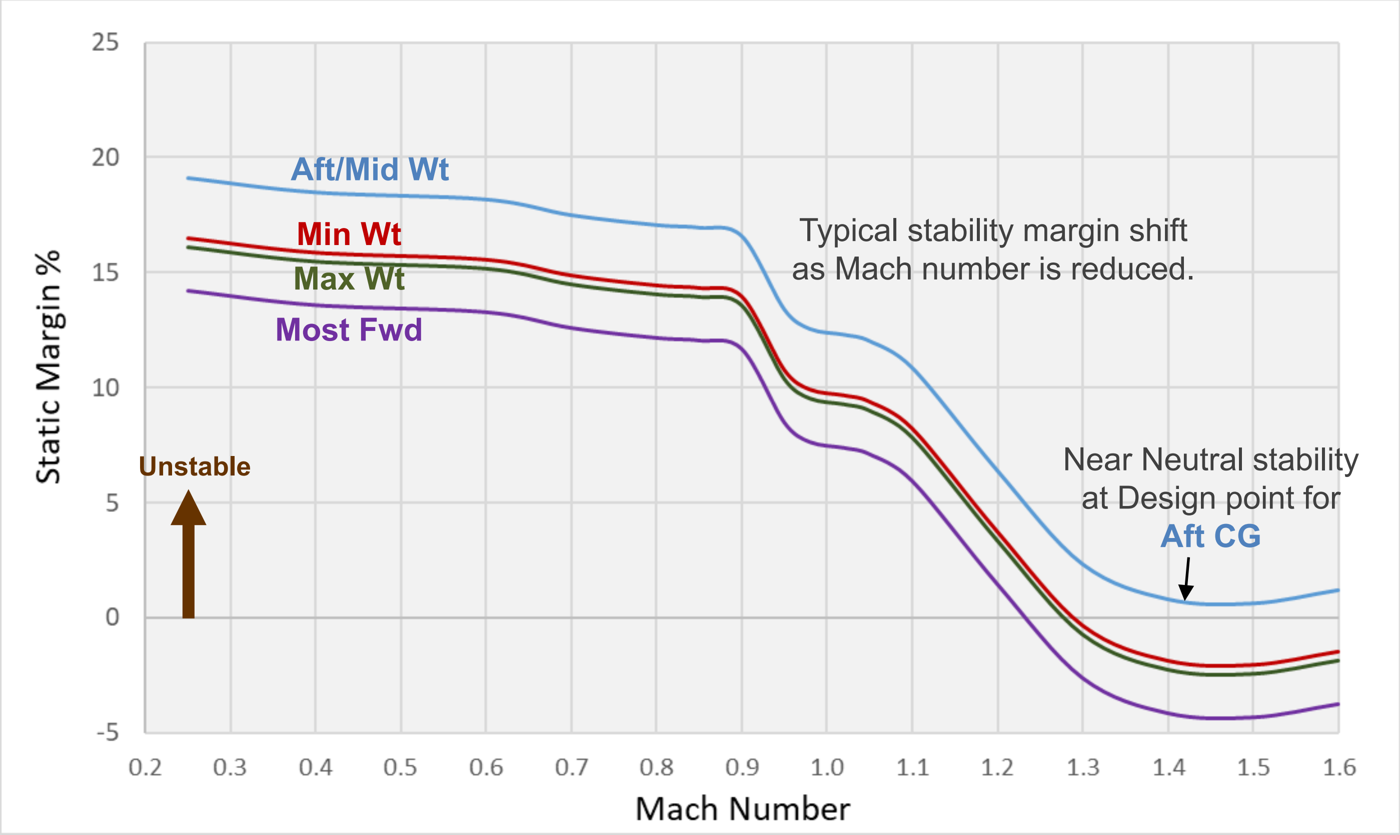
Photo Credit: Lockheed Martin

Photo Credit: Lockheed Martin

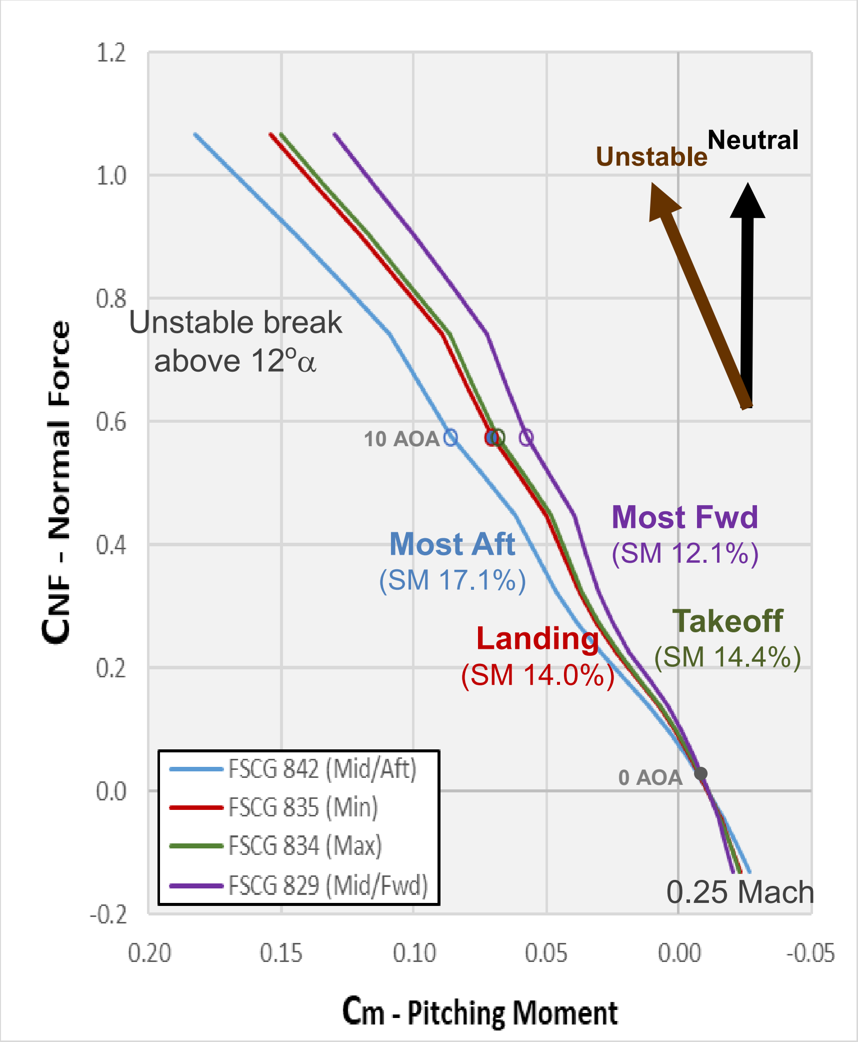
QUESST

Longitudinal Stability

Full Mach Range



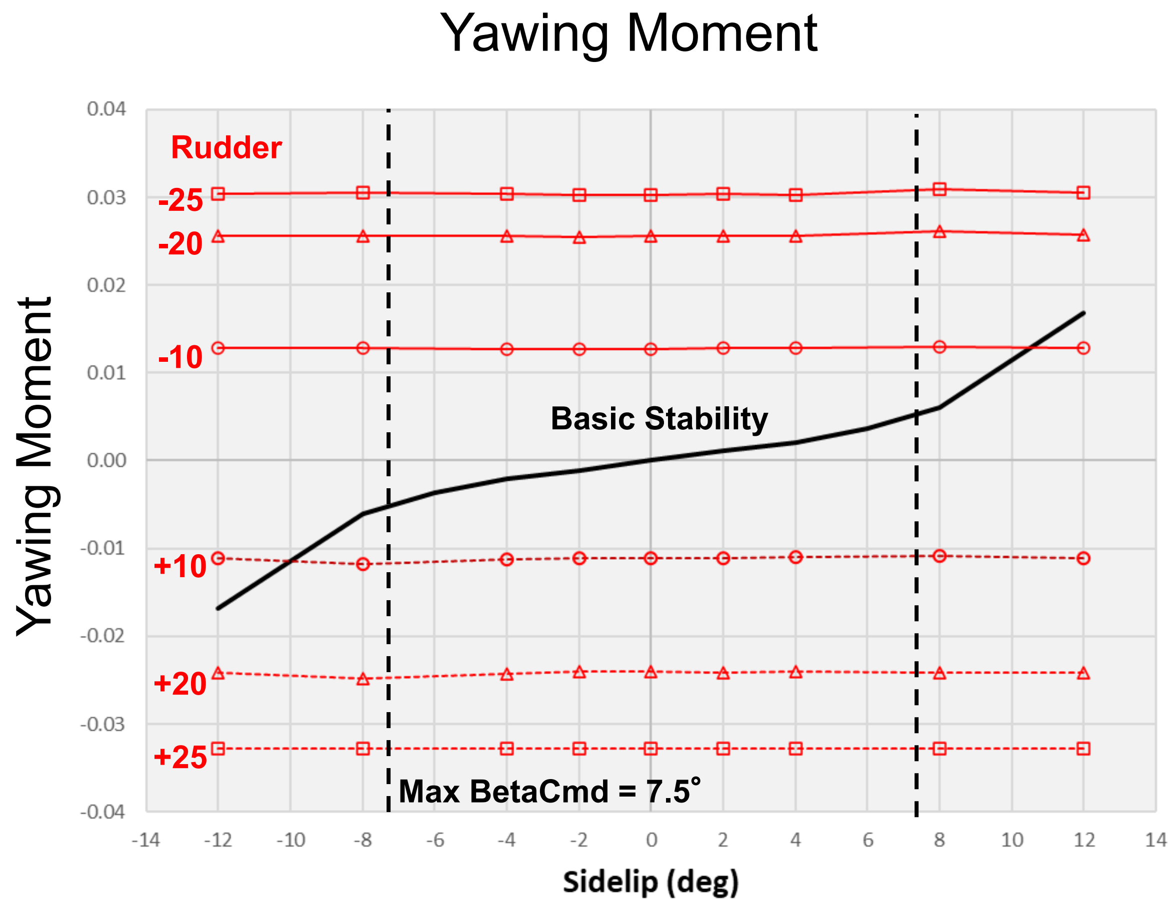
Approach Speed

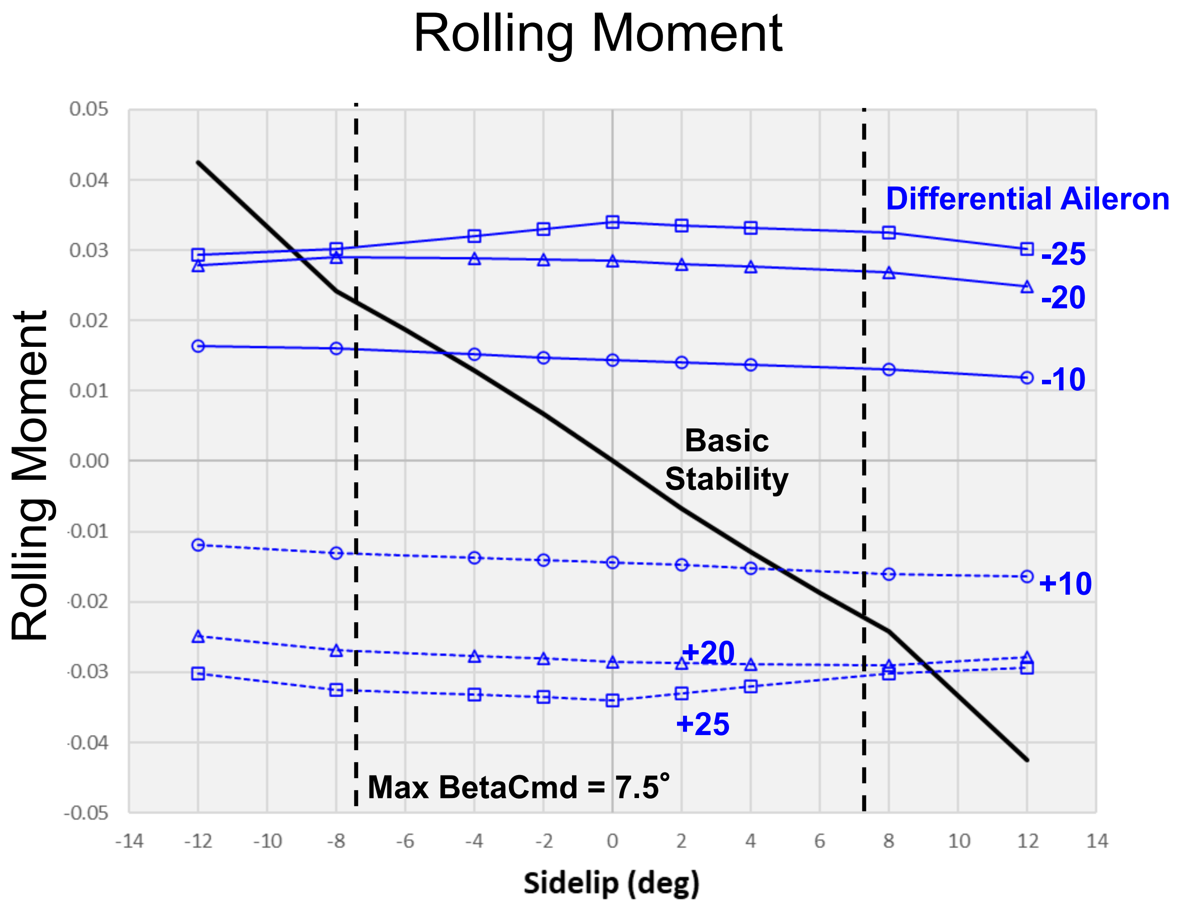


- Static margin changes roughly 20% across Mach range
- Up to 17% unstable for approach conditions
- Increased instability above AOA limiter (up to 23%) can lead to departure

Providing near neutral stability at design Mach results in a highly unstable aircraft for takeoff & landing

Lat/Dir Stability & Control on Approach





- Near neutral stability
- Adequate rudder control power to trim, even at large sideslips
- Sideslip effects on rudder control power are minimal

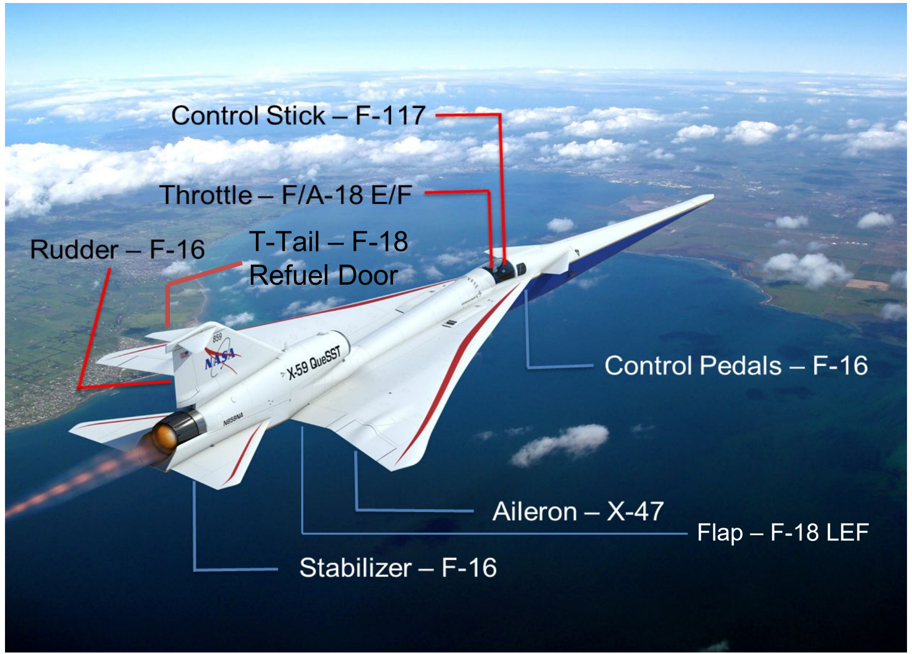
- Large dihedral effect
- Large sideslips can lead to roll control saturation
- Sideslip affects aileron at large deflections with non-zero β

Control power at low-speed conditions

Flight Control Architecture Overview

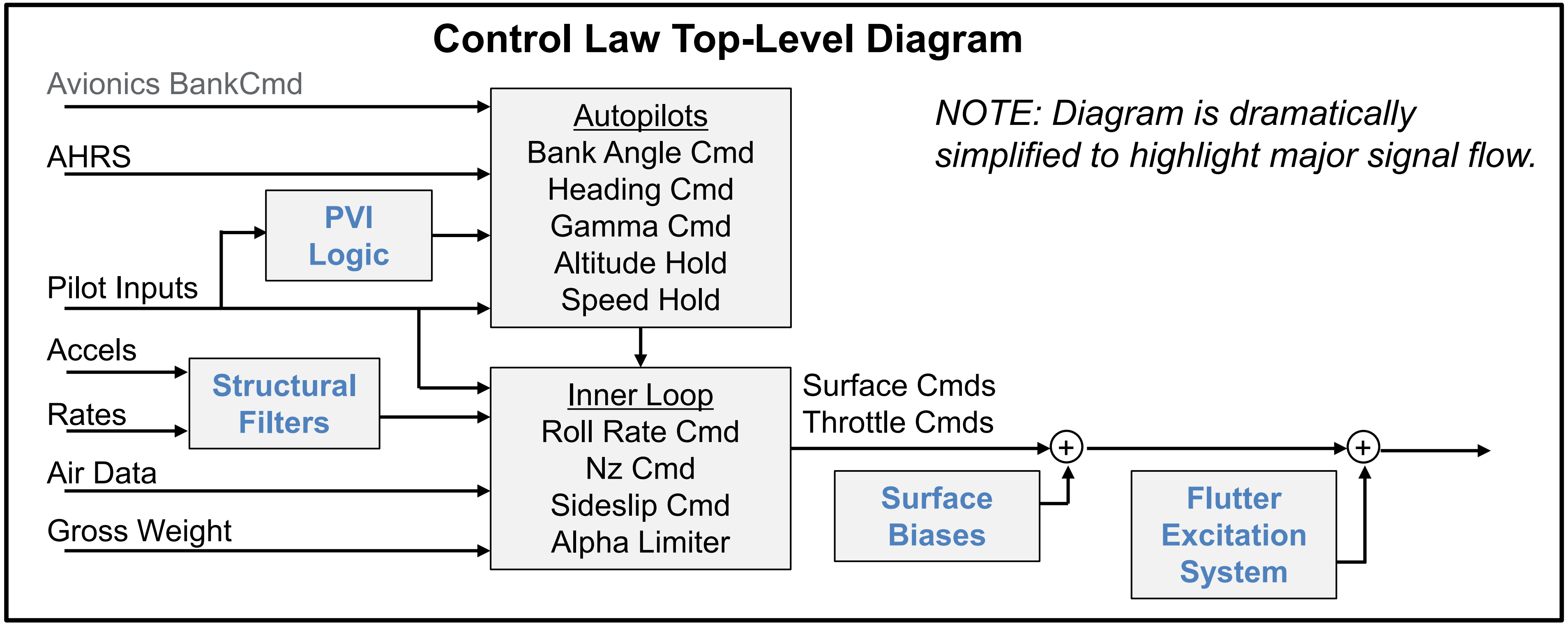
- Key features
  - Longitudinal
    - Nz-Command
    - Angle of attack and Nz limiters
    - Inertial data feedbacks
      - 2 IMU locations (node / anti-node)
      - Euler angles from AHRS
  - Lateral-Directional
    - Stability axes roll rate command
    - Sideslip command
  - Gains based on qbar, Mach, weight
- Autopilots
  - Altitude, Bank angle, Heading, Speed hold
  - Gamma command
  - NAV mode (with Avionics)

- Flight Test Aids
  - Dial-A-Trim
  - Excitation System
    - Flutter
    - Real-time margins (Flutter & Controls)
    - System identification (stability and control)
  - Bank-to-bank auto roll
  - Adjustable limiters
    - Nz, angle of attack, angle of sideslip, roll rate



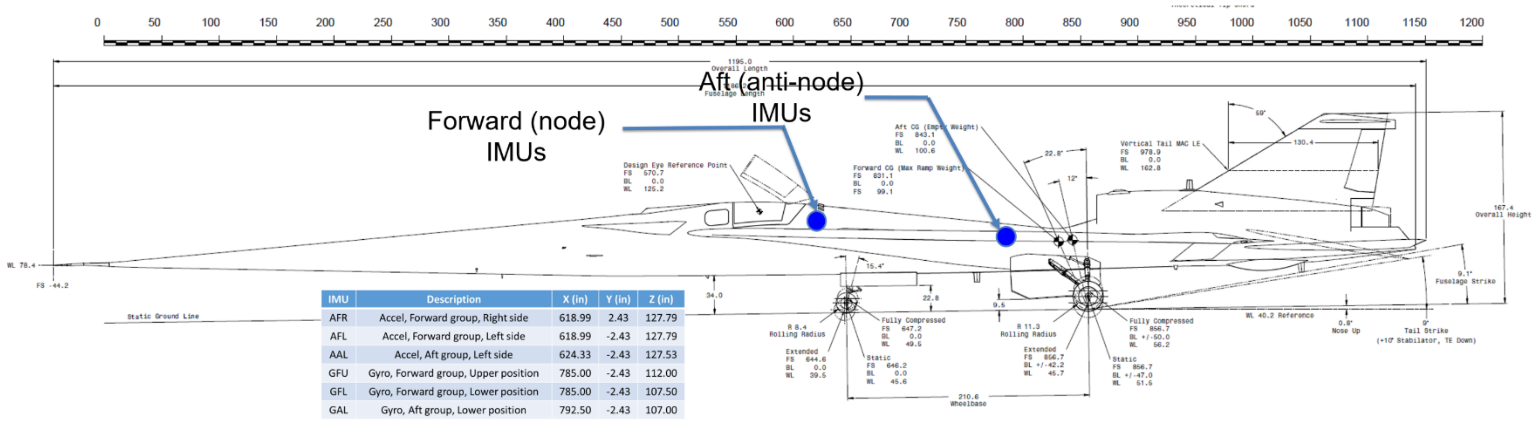
System Description

- CLAW is in OFP downstream of Failure Management
  - CLAW operates on selected values in engineering units (knots, lbs, etc)
  - CLAW receives failure flags only when all redundancy lost
- CLAW Determines Mode (in air or on ground)
  - Feedbacks / CLAW features fade in or out depending on speed while on the ground
- CLAW contains Flight Test Aids (limiters, surface biases, gain changes, etc)

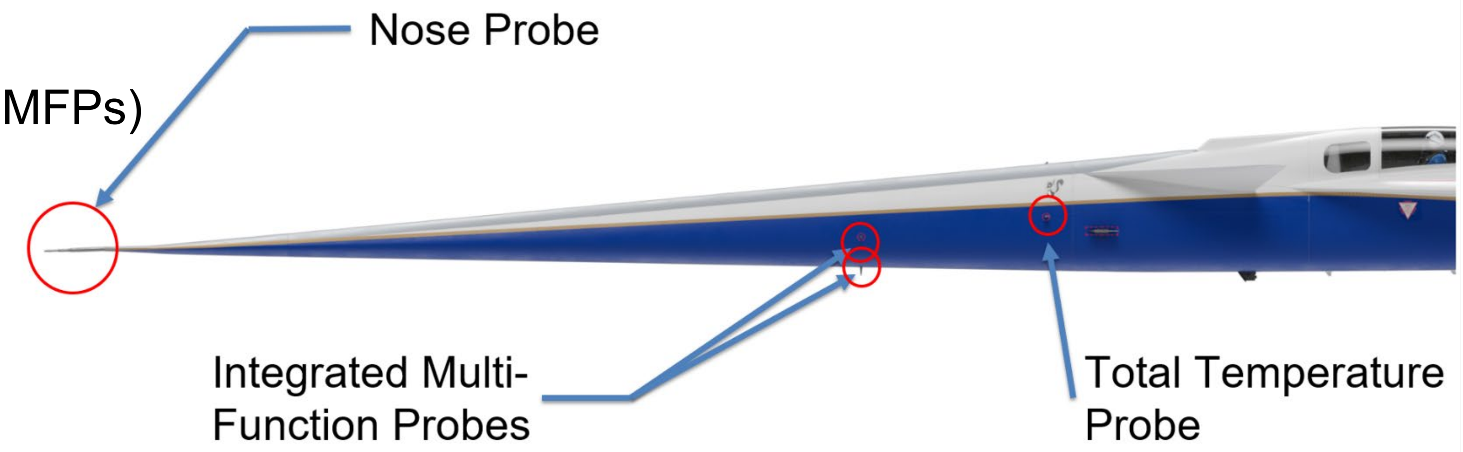


Primary Feedback Sensors

- Inertial Data
  - 2 sets of IMUs
    - Node – for accelerations
    - Anti-node for rates
  - AHRS
    - 2 Units
    - Pilot selectable in addition to VMC failure monitoring
      - Miscompare warnings in cockpit
- Air Data
  - Multi-function Nose Probe
    - Primary source for α, β, M, KEAS, h
  - 3 Integrated Multi-Function Probes (IMFPs)
    - Redundancy
  - Total Temp Probe



IMU	Description	X (in)	Y (in)	Z (in)
AFR	Accel, Forward group, Right side	618.99	2.43	127.79
AFL	Accel, Forward group, Left side	618.99	-2.43	127.79
AAL	Accel, Aft group, Left side	624.33	-2.43	127.53
GFU	Gyro, Forward group, Upper position	785.00	-2.43	112.00
GFL	Gyro, Forward group, Lower position	785.00	-2.43	107.50
GAL	Gyro, Aft group, Lower position	792.50	-2.43	107.00



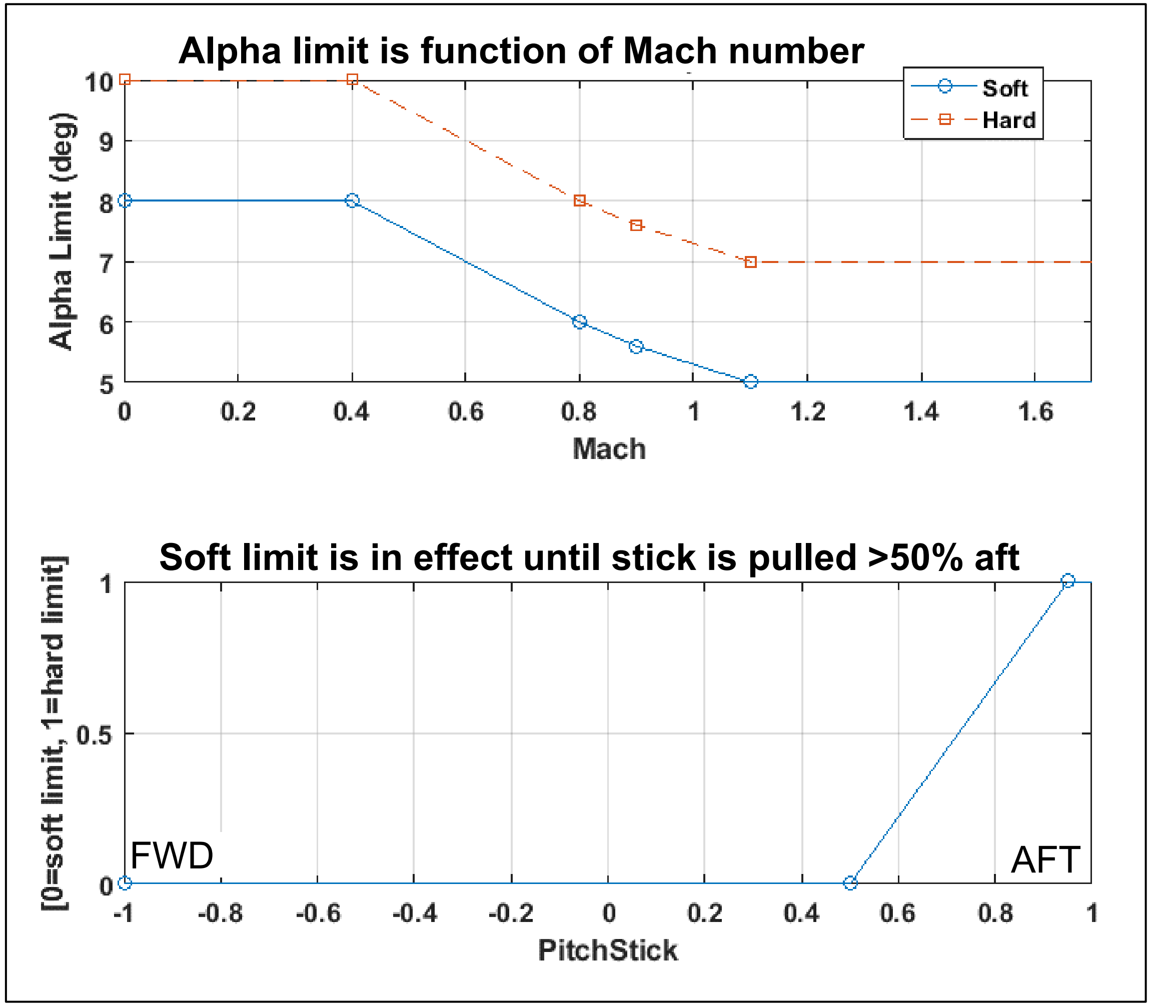
Angle of Attack Limiter

- Alpha limiter is a parallel longitudinal controller that is always running.
  - Most nose-down command of the two controllers is sent to actuator. Smooth transition.

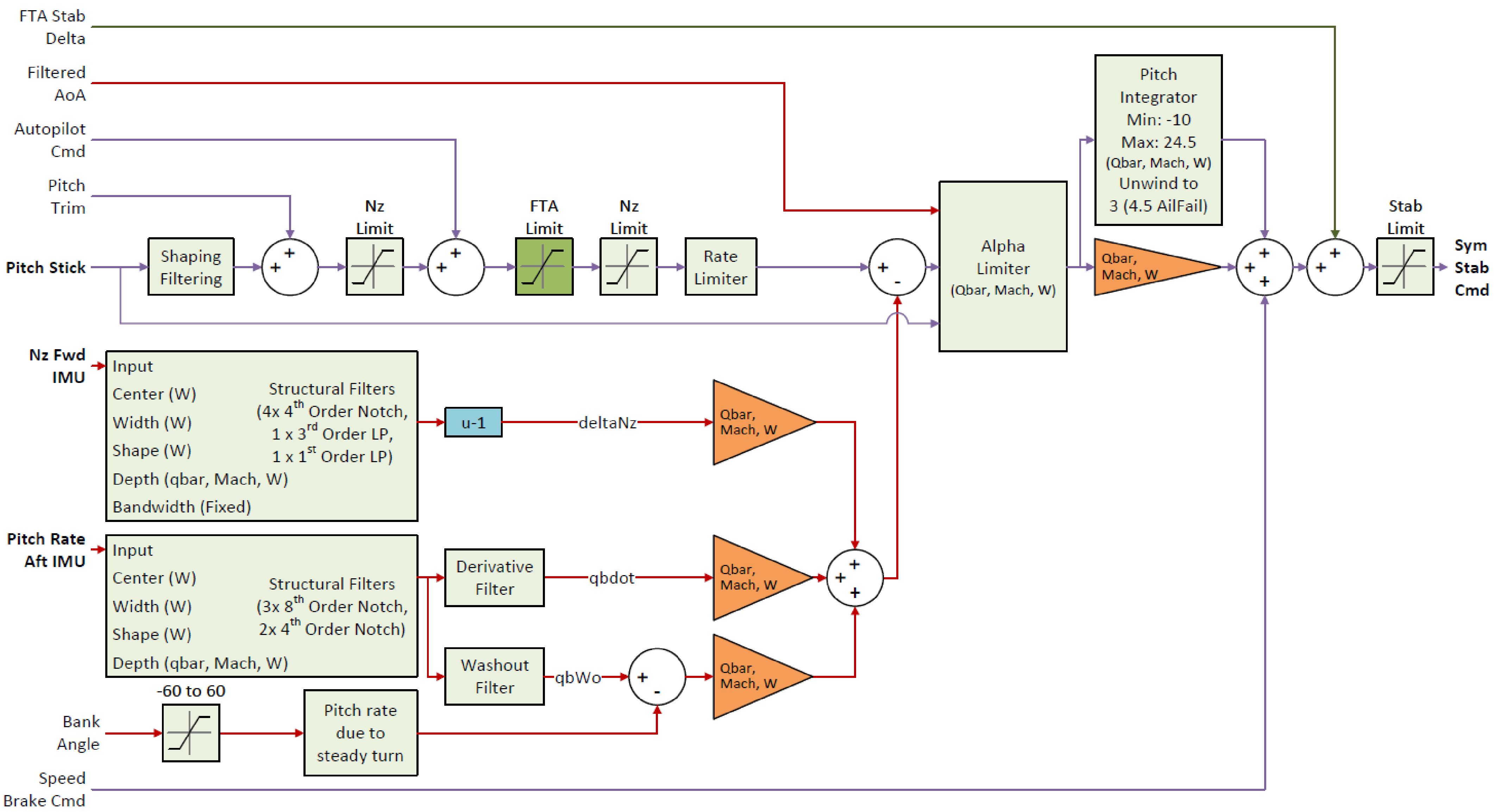
- Significant portion of operational envelope is affected by alpha limiter, especially at heavy weight

- Pilot can increase alpha limit for emergencies
  - Soft-limit is the nominal alpha limit
  - Pilot can pull to aft stick to increase alpha limit up to 2 deg
  - Pilot can hold paddle to increase hard limit additional 2 deg (new since CDR)

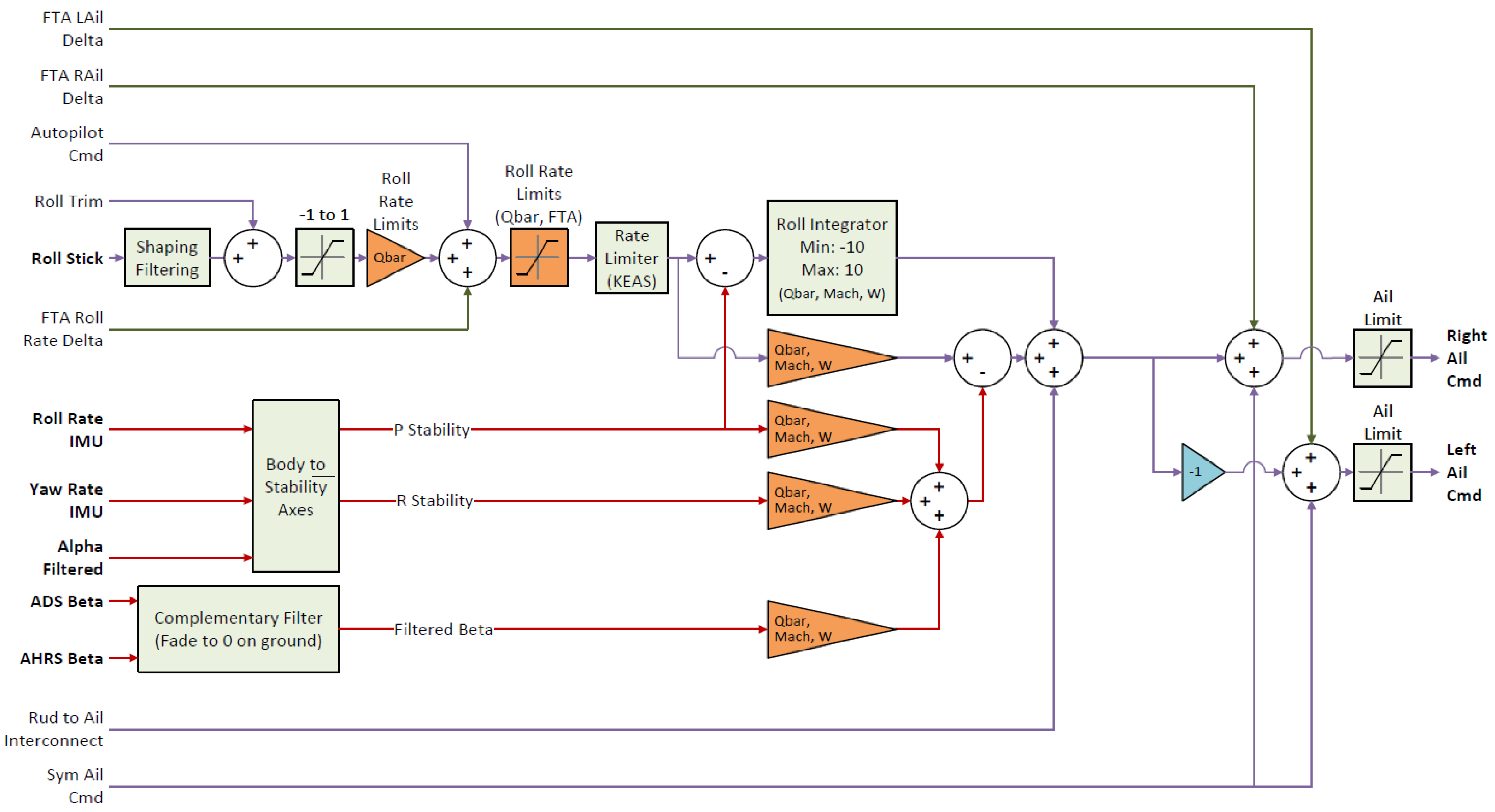
- Alpha limit tested and shown to be generally robust
  - Large amplitude push-pull maneuvers prohibited in flight



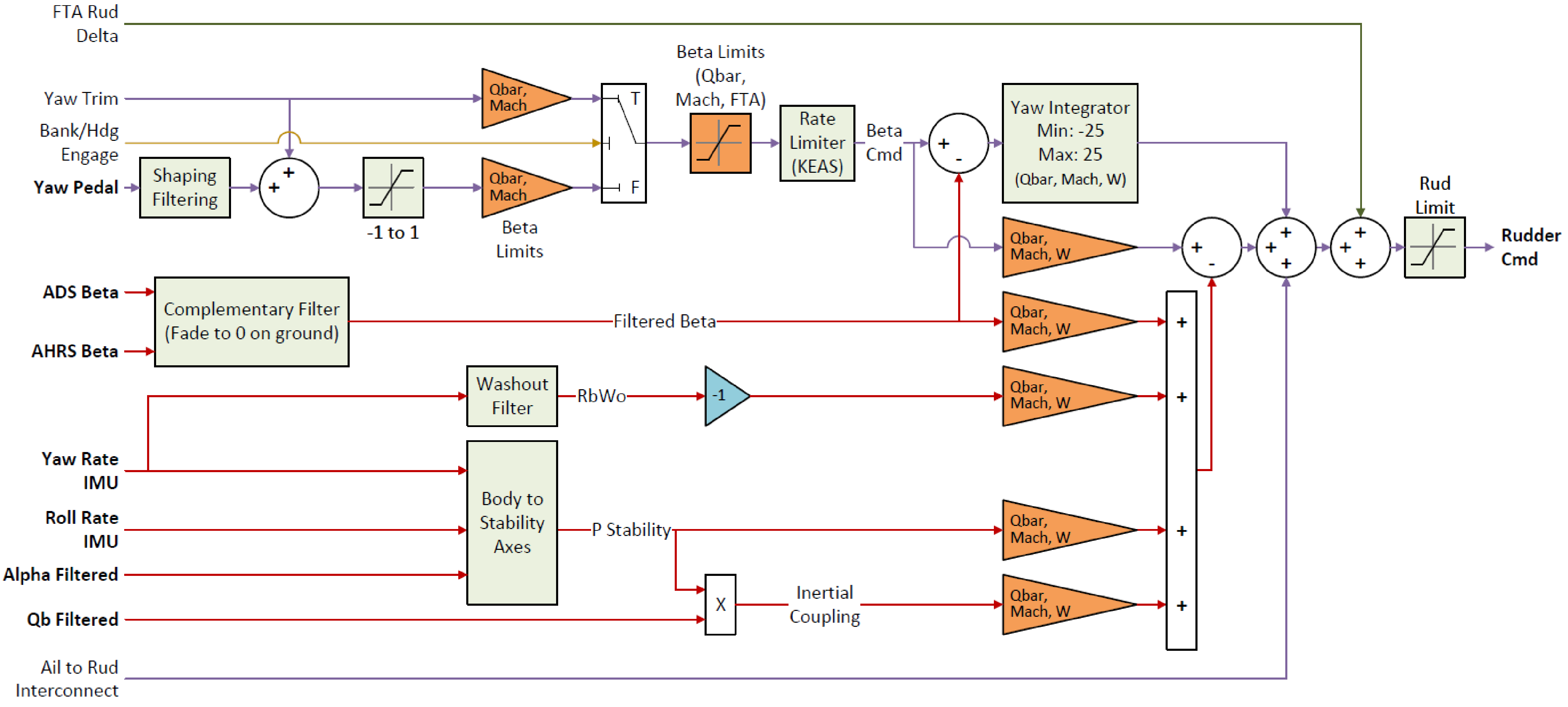
Simplified Longitudinal CLAW Diagram



Simplified Lateral CLAW Diagram



Simplified Directional CLAW Diagram



Emergency FCS Actions: Control Surface or Engine Failures

- **No Reconfiguration of Control Mixer with Control Surface Failures**
- **Only 1 "Reversion" Mode – to Sets of Fixed Gains**

- Aileron Failure
  - Disconnect aileron-rudder interconnects
  - Disallow symmetric aileron deflections
- Rudder Failure
  - Disconnect aileron-rudder interconnects
  - Unwind yaw integrator
- Stabilator Failure
  - No action
  - (Less margin to alpha departure. Keep speed up.)
- Flap Failure
  - No action
  - (Less lift during landing. Keep speed up.)

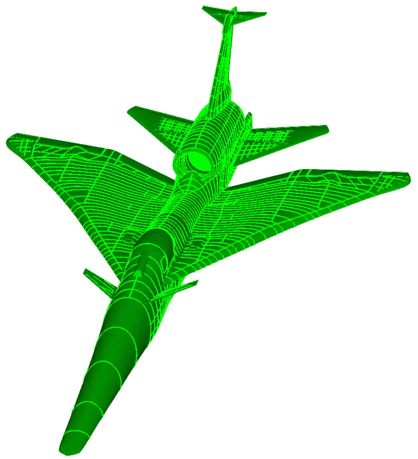
- T-tail Failure
  - No action
- Engine
  - Allow "speedbrake" for energy management
    - Lowering gear handle only drops flaps to half
    - SpeedHold HOTAS switches can be used to change flap setting (5 degree increments)

AeroServoElastic (ASE) Stability

- Background
  - Models initially rigid-body only
  - Simulation database is all rigid body
    - ASE is interaction of controls & structure
    - Controls group had no models to evaluate ASE stability with
  - Clumsy process initially between controls and structures to evaluate
  - Inconsistency in definition of required margins
- Configuration
  - Long / slender and relatively flexible
    - Not expected to be necessarily "in family" with fighter aircraft
  - FEM maturing
    - Requires iterations in analysis and design (filters)
    - Sensitivity study (NASA) to inform potential impacts
- Competing Requirements vs Rigid Body
  - Greater margin on ASE tends to reduce Rigid Body margins

The LBFD shall have the following aeroservoelastic stability margin for each flight control system feedback loop throughout the full flight envelope of the vehicle, as defined in the vehicle's Structural Criteria Document.

- Nominal Operation: All flexible modes shall be gain stabilized with a maximum peak gain of -6 dB. If a 180 degree phase cross-over occurs in the response of a flexible mode, at least an 8 dB gain margin shall be achieved. Phase margin is non-applicable because phase stabilization will not be used.
- Failure Scenarios: ASE margins shall meet the above requirements for single channel failure cases. For dual channel failures all flexible modes shall be gain stabilized with a maximum peak gain < 0 dB.

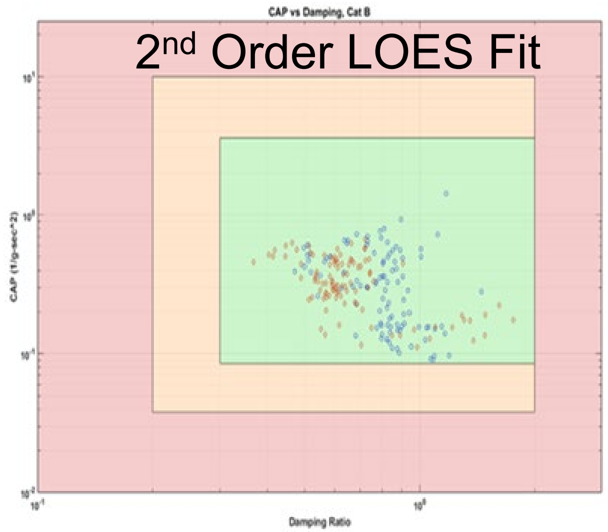


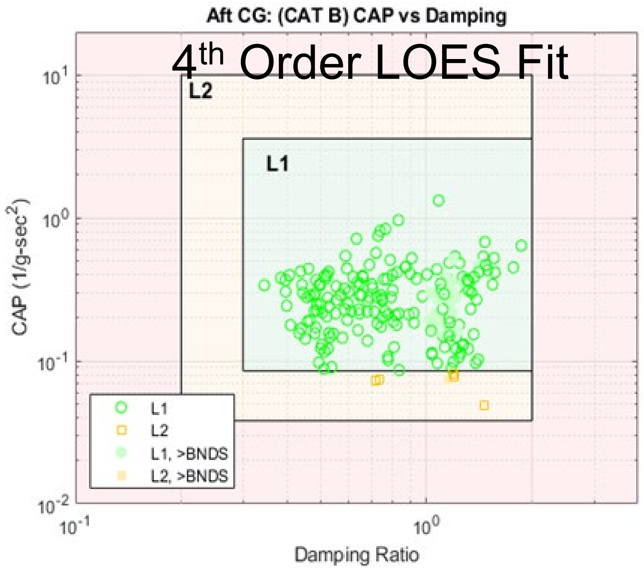
Metrics

- Rigid-Body Margins
  - PDR – mostly met 6 dB / 45 deg standards
  - Continued development resulted in reduced margins
    - Fidelity of structural modeling
    - Anti-aliasing filtering
    - Sensor models
    - Actuator dynamics
    - Latency models
    - Updated aerodynamics

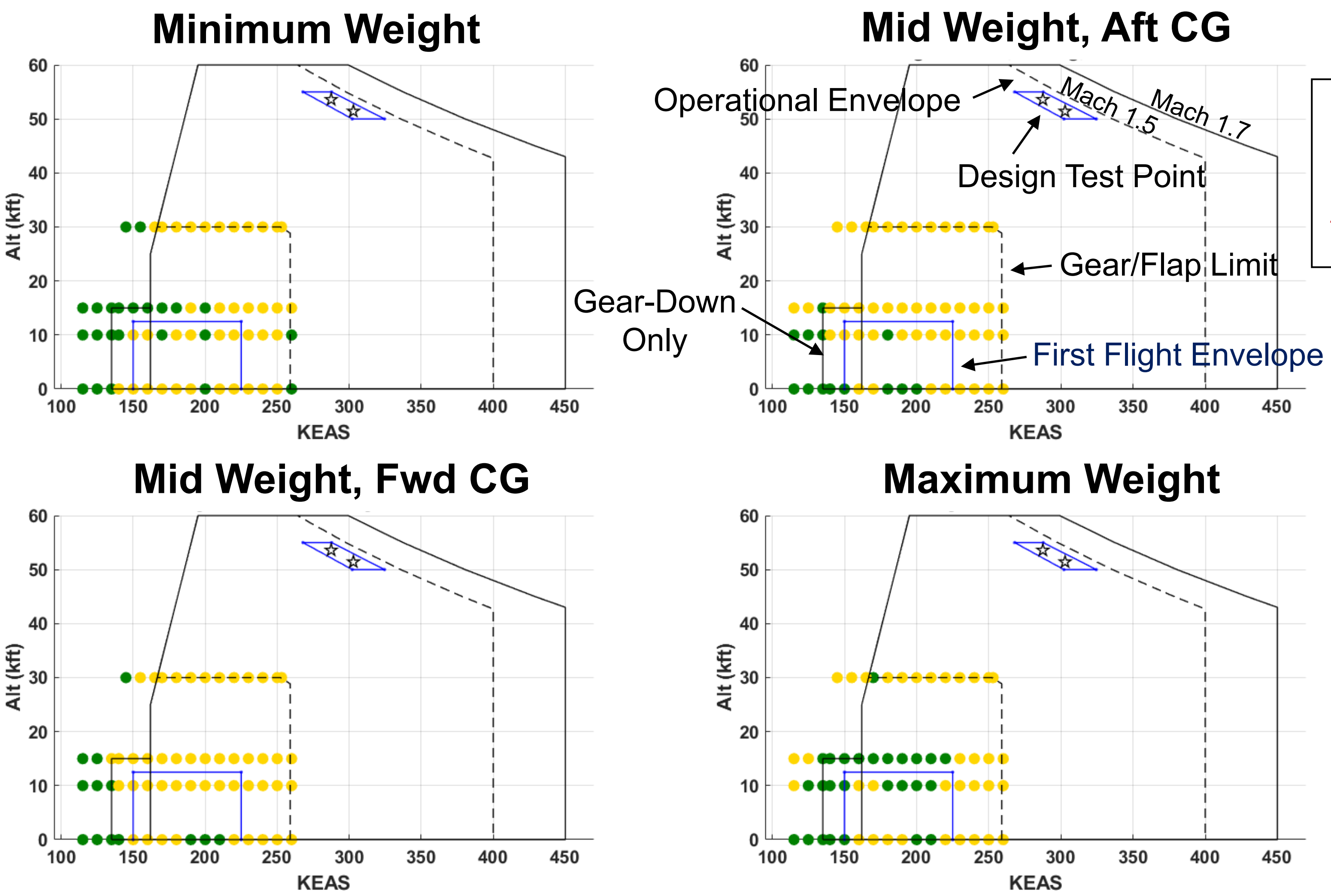
  } **Resulted in need for variance**

- Flying Qualities Predictions
  - Highly augmented vehicle / non-traditional modes
  - LOES – poor fits
    - Higher order fits with added zeros could result in adequate model fits
      - Resulted in some dubious modes like lateral phugoid…
    - Better LOES fits did not significantly change FQ predictions
  - Bandwidth Criteria
  - Neal/Smith Criteria
  - Simulation Studies (Monte Carlo, etc.)
  - **Piloted Simulations**





Inner-Loop Margins – Notional Example



Meets 6dB/45deg for all loops

Meets 4.5dB/34deg for all loops

At least one loop does not meet variance

Rigid-Body Margin Variance Approach

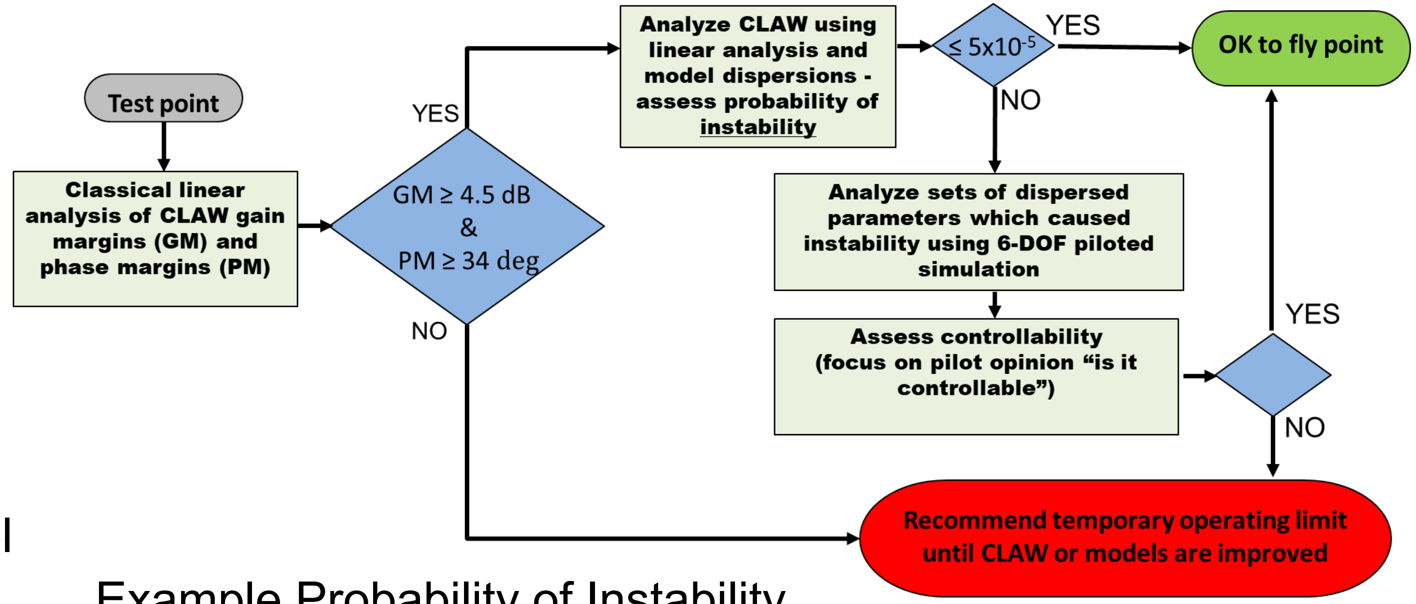
- Constraints of the Low-Boom Design Make Compliance with Traditional Margin Requirements Infeasible
  - High-gain control law required for significant unstable static margin
  - Low frequency structural modes (~5 Hz)
  - High dihedral effect & low rudder control authority
- Reviewed Requirements Heritage for Variance Guidance (AS94900A & others)
  - Standard attribution: margin = modeling error + wear & maintenance errors

	Modeling Errors	Wear & Maintenance Errors
Baseline	50%	50%
X-59 Variance	25%	50%

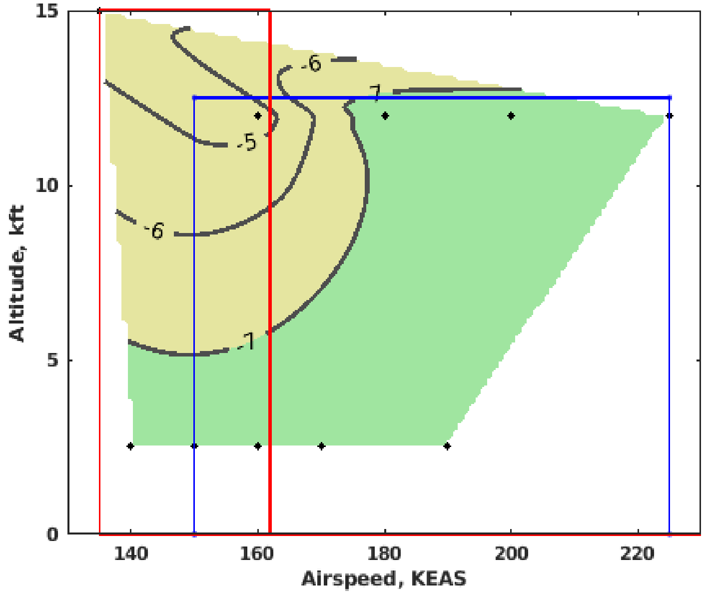
- New Proposed Rigid Body Margins – 4.5 dB / 34 deg
- Assess Likelihood of Instability
  - Since reduced margins are functions of modeling error of aero, latencies, sensors, actuators, etc – all those have uncertainties associated
  - Use threshold of $Pr < 5 \times 10^{-5}$
  - Monte Carlo analyses with Importance Sampling
  - *Interesting result – Prob of instabilities did not correlate to gain/phase margin

Execution of Variance Process

- Conduct Stability Margin Assessment
  - Includes probability of instabilities
  - Note – frequency and time to double matter – unstable doesn't necessarily mean uncontrollable
- Flight Test Build Up
  - Continuous evaluation of piloted HQs
  - Reasonable expectation that large model mispredictions will be identified prior to collapse of CLAW stability
- Real-Time Stability Monitor
  - FTCC: 3 dB / 22.5 deg
- Multisine surface command perturbations with PTIs for RTSM and estimation of aero model parameters during test



Example Probability of Instability



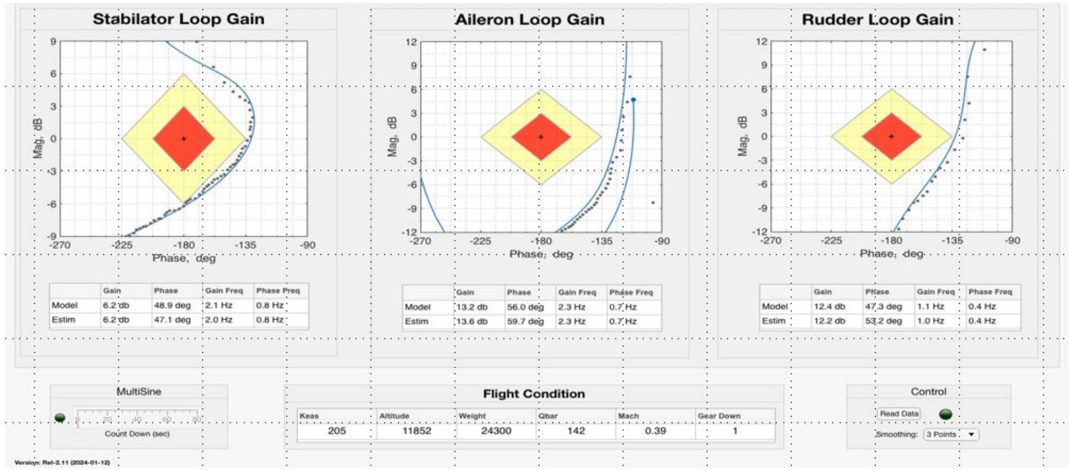
Uncertainty Models

- Aero Model Uncertainties
  - Added bias and gain factors
  - Based on wind tunnel repeatability (bias) and experience (factors)
  - Dynamic aero based on low-speed wind tunnel results
- Flex-to-Rigid, Hinge Moments, Ground Effect
  - Factor based on experience (up to +/- 50%)
- Sensors
  - Bias, gain, and noise
  - IMU latency = 0.01 sec
- Weight & Inertia
- Latencies
  - Sensor feedback input delays
  - VMC output delays
- Airdata – angle of attack and sideslip uncertainties
- Actuators
  - Gains only
  - Dynamics uncertainties small, not modeled

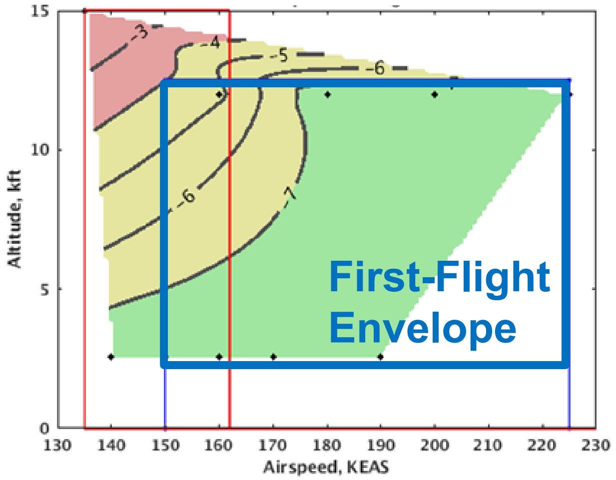
Stability Margins Variance – Mitigating Residual Risk

- Real-time Stability Monitor (RTSM) is a variance contingency
  - Control law stability margins monitored in control room
  - 3 dB and 22.5 deg continuation criteria
    - Allows us to still collect data to improve models/CLAW if margins are less than variance
- Flight Test Buildup Approach
  - Continuous pilot evaluation of airplane handling characteristics
  - Test techniques to evolve uncertainties, models, and CLAW

Real-Time Stability Monitor Tool



Log of Probability of Instability



X-59 Cockpit Simulations

Aircraft and cockpit simulations validate aircraft designs, systems, and performance – also used for pilot training and flight planning

Systems Integration Lab at Lockheed

Flight Simulator at NASA

Photo Credit: Lockheed Martin

Status

- **X-59 QueSST Airplane Developed for the Quesst Mission**
  - Demonstrator for low-boom design technology
  - Will be used to help develop noise-based speed limits and potentially open commercial supersonic market
- **Control Laws Developed**
  - Flight Test Aids incorporated
  - Excitation system implemented for flutter, stability margin, and aerodynamic parameter identification
  - Variable limiters and capability to modify CLAW parameters inflight if necessary
- **Extensive Stability and Control, HQs, and Margin Analyses**
  - Trade-offs between rigid-body and flex
  - Developed efficient Monte Carlo techniques to assess probabilities of instabilities and take-off and landing performance
  - Developed rational approach to view rigid-body control margins, and navigate a path forward when they are below traditional or initial required values
- **X-59 Nearing Flight**
  - Flight Readiness Review completed
  - On path to complete integrated ground tests and proceed to flight (Engine Runs, EMI, AL Bird,…)

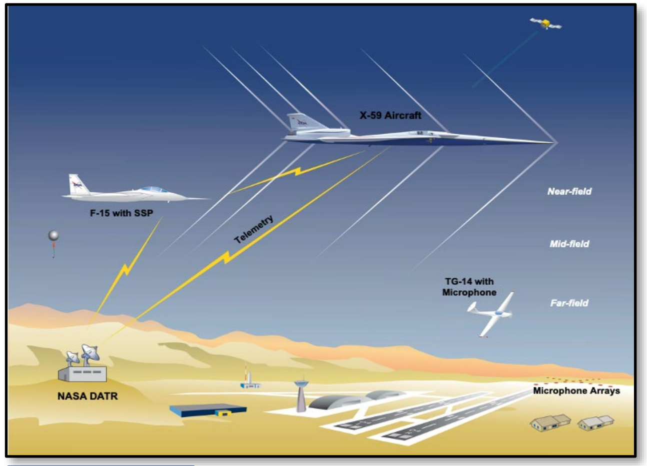
Quesst Timeline

Credit: *Lockheed Martin*

First Flight 2024

<u>Phase 1 – X-59 Aircraft Development</u>
Aircraft design, fabrication, and ground test
Checkout and envelope expansion

Systematic Approach Leading to Community Testing



2025

<u>Phase 2 – Acoustic Validation</u>
Detailed ground and flight measurements
Validation of sonic boom signature and prediction tools

2026

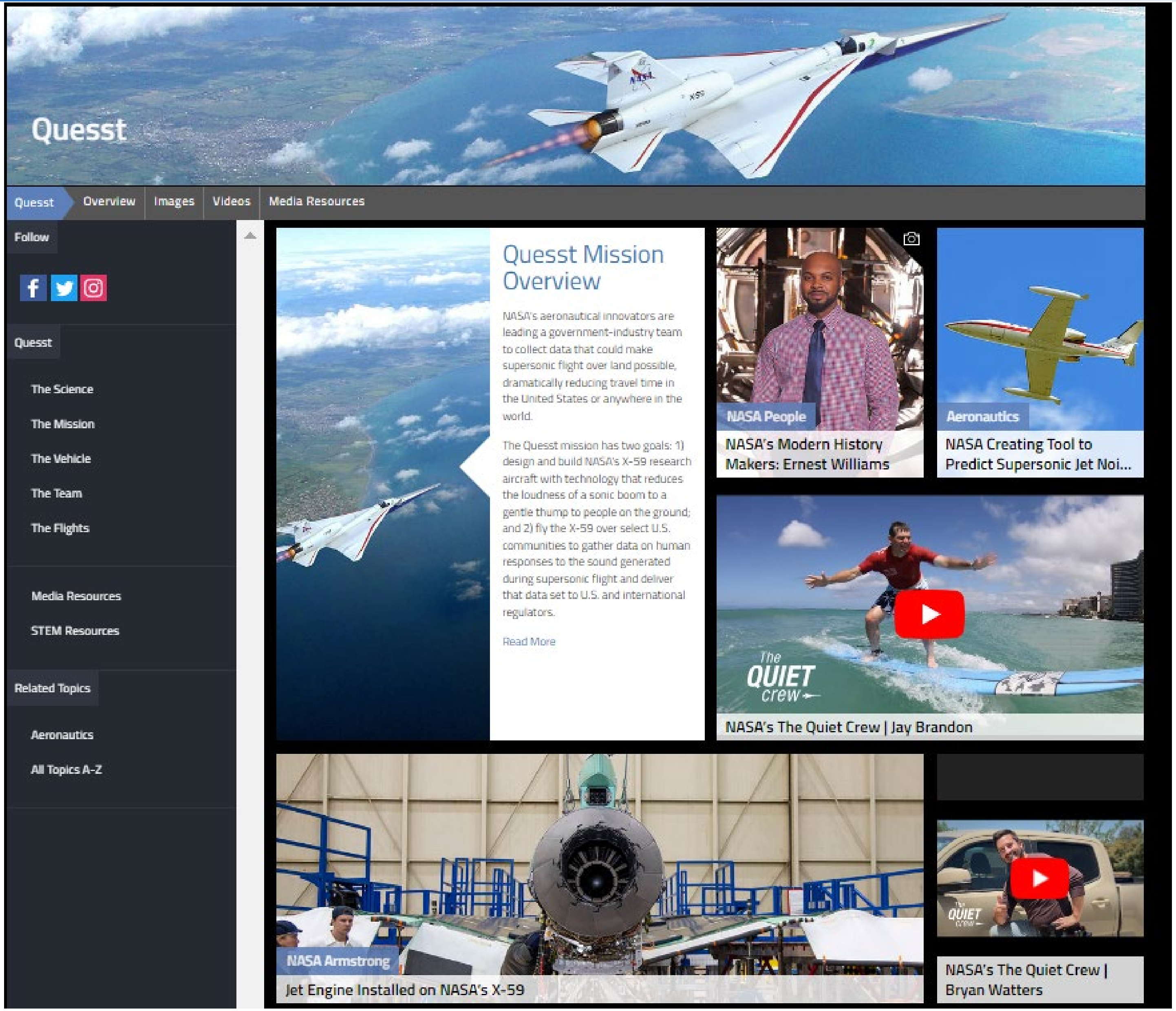
Credit: *Lockheed Martin*

<u>Phase 3 – Community Response</u>
Community response overflights, ground measurements, and surveys over representative communities across the U.S.

Summary

- **X-59 Designed for Low Sonic Boom Noise**
  - Configuration along with X-Plane development constraints result in controls challenges
- **Robust Test and Evaluation Process**
  - CFD and Wind Tunnel data for aerodynamic model
  - Re-use of legacy systems
  - Extensive Sim and SIL evaluations
  - Extensive Piloted Simulation evaluations
- **Developed Process to Safely Proceed with Reduced Control Margins**
  - High fidelity modeling
  - Extensive uncertainty modeling
  - Extended Monte Carlo methods for stability predictions with Importance Sampling
  - Process to evaluate all expected flight conditions
- **Flight Test Tools Developed**
  - Flight test aids in the cockpit
  - Real-time margin predictions
  - Real-time aero model estimates

Quesst Mission Web Page



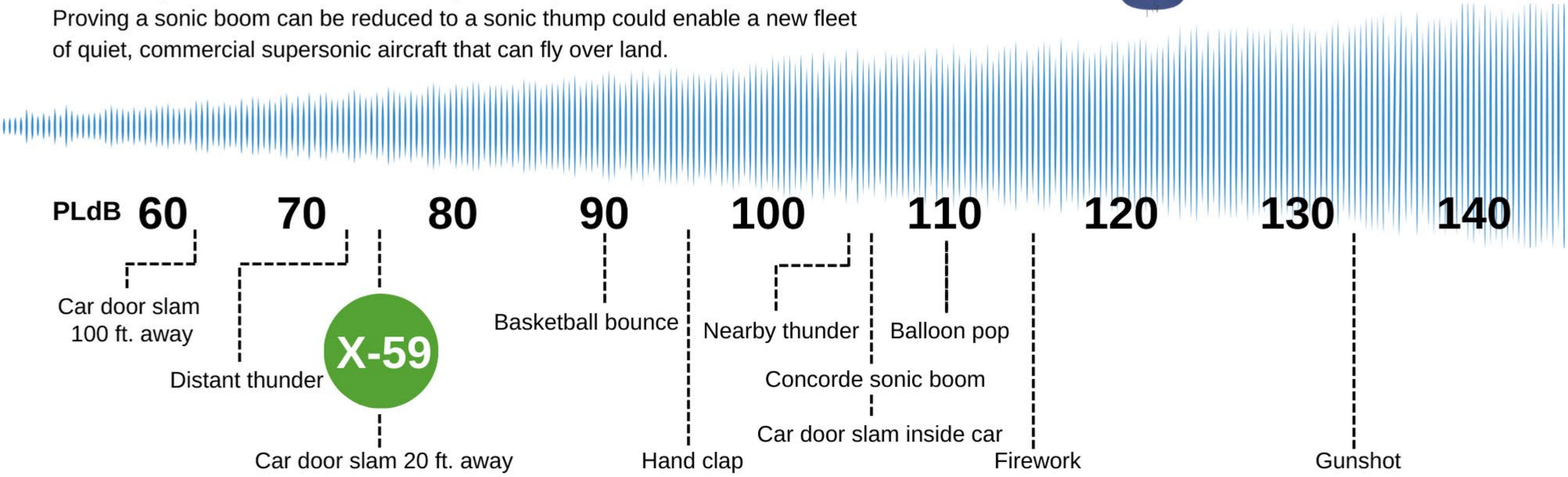
https://www.nasa.gov/X59

Questions?

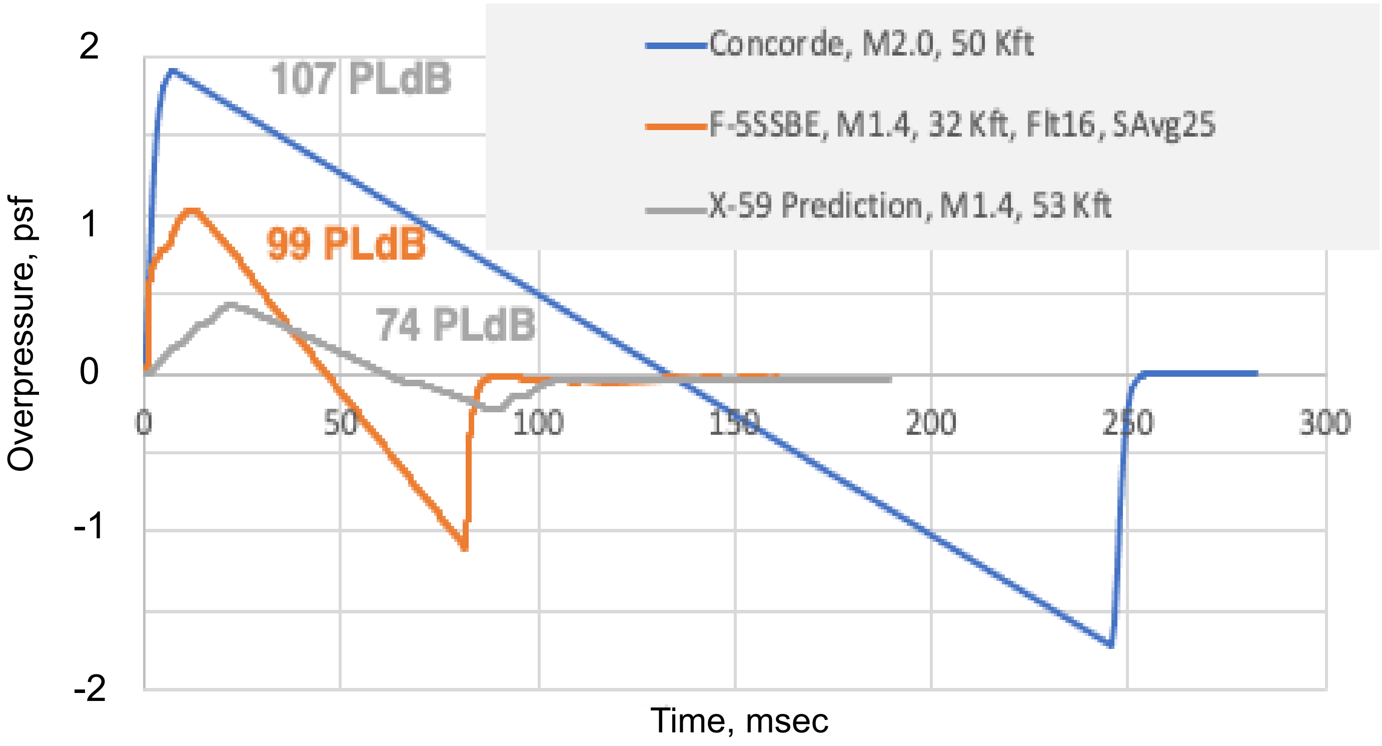
Sonic Thump

Just how quiet will NASA's X-59 be?

NASA's single-seat X-59 experimental aircraft will produce a barely audible sonic thump to people on the ground when cruising at supersonic speeds. In technical terms, the X-59's sonic thump will be around 75 Perceived Level decibels (PLdB) or less. PLdB is one of numerous scales, in decibels, that is used to understand human response to sounds and is used particularly for short duration sounds. Proving a sonic boom can be reduced to a sonic thump could enable a new fleet of quiet, commercial supersonic aircraft that can fly over land.



Comparison of Boom Signatures



- SR-71:
  - 0.9 psf, speed of Mach 3, 80,000 feet
- Concorde SST:
  - 1.94 psf, speed of Mach 2, 52,000 feet
- F-104:
  - 0.8 psf, speed of Mach 1.93, 48,000 feet
- Space Shuttle:
  - 1.25 psf, speed of Mach 1.5, 60,000 feet, landing approach

✓ Normal range for fighters is 1-3 psf
✓ Max recorded overpressure is 144 psf
✓ Focus booms can be 4x normal overpressure under track