An Overview of NASA Sonic Boom Flight Research:

What NASA is Doing to Fix the Sound Barrier

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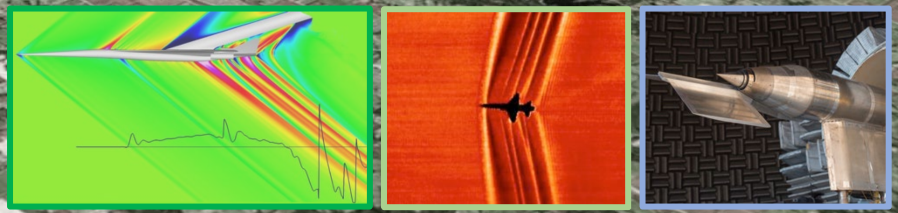
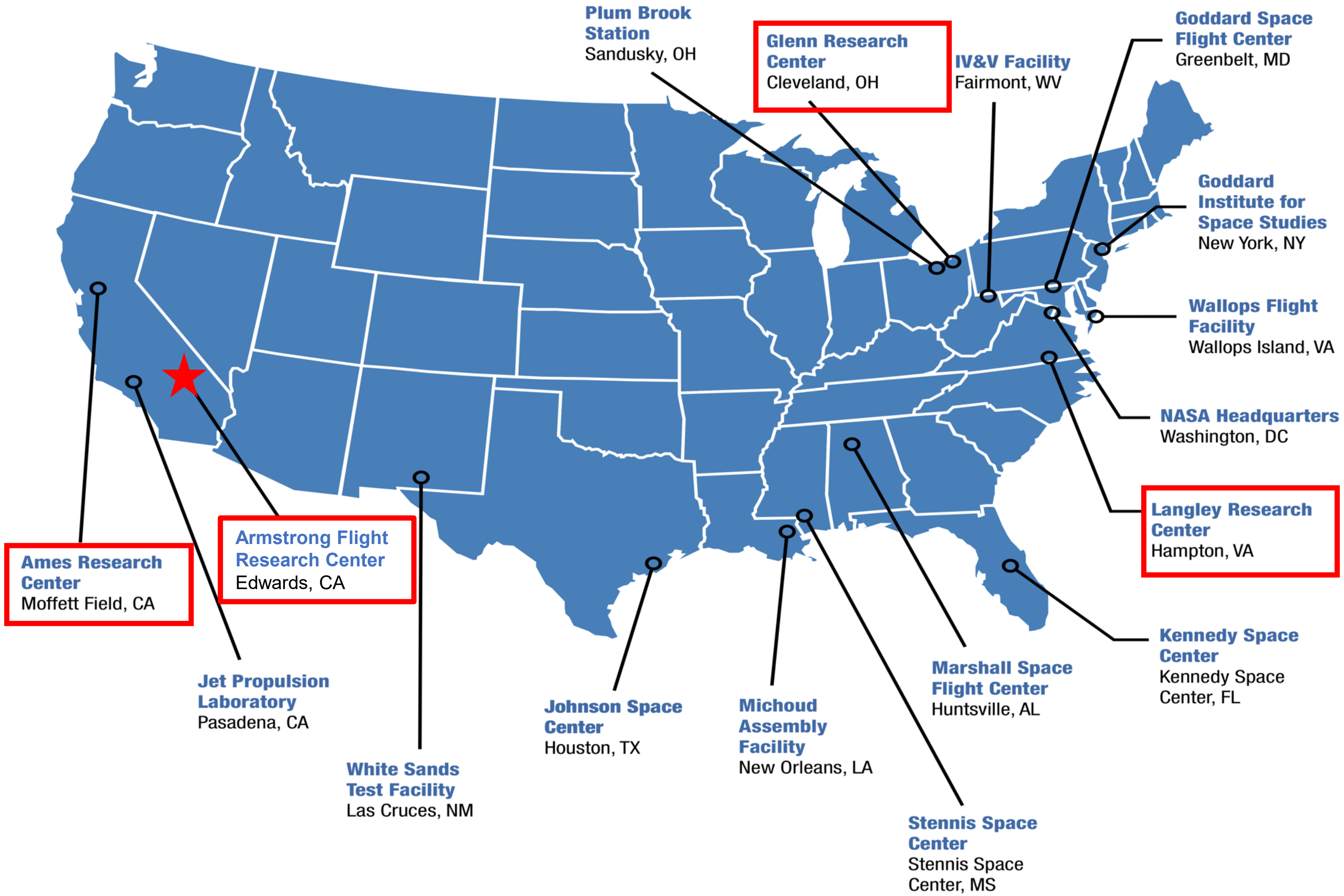


Topics of Discussion

- NASA's Motivation for Sonic Boom Flight Research
- Sonic Boom 101
- Measurement Techniques
  - Shock Structure Measurements
  - In-fight Shock Imagery
  - Effects of Turbulence
  - Focus Sonic Booms
  - Community Response
- Quesst Mission and X-59 Aircraft

NASA Centers and Facilities



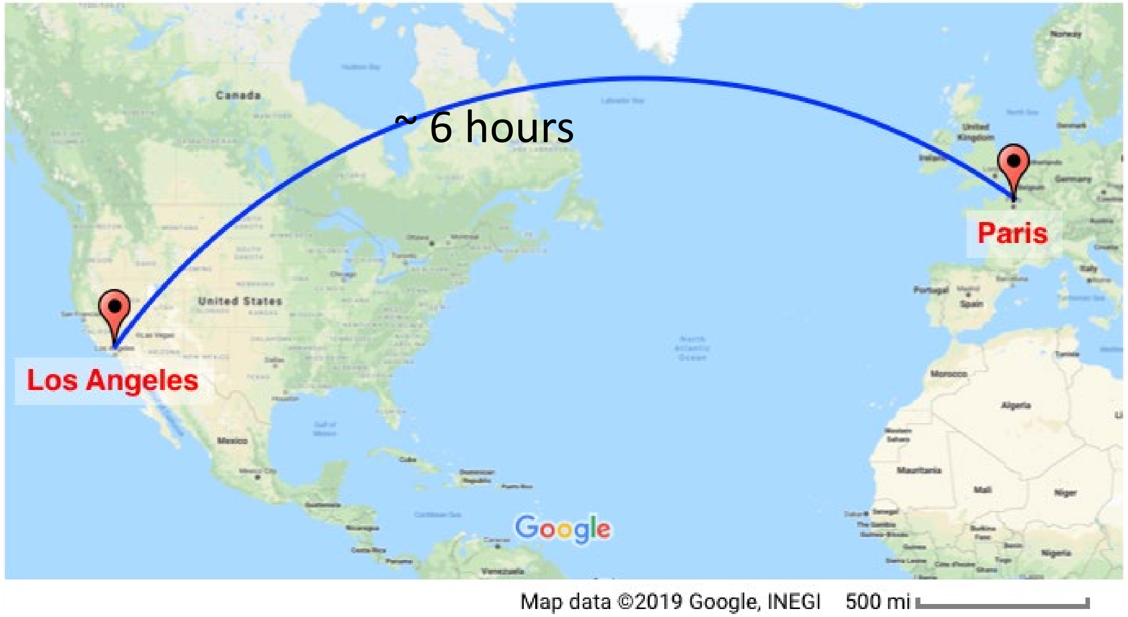
NASA Armstrong Flight Research Center (AFRC)

Aeronautics Flight Research

- Named after Neil A. Armstrong, first man on the moon (Apollo 11)
- Over 70 years of flight research (NACA Muroc Flight Test Unit)
- Edwards Air Force Base (EAFB)
- Remote Location
- 350 Testable Days Per Year
- Extensive Range Airspace
- Supersonic Corridor

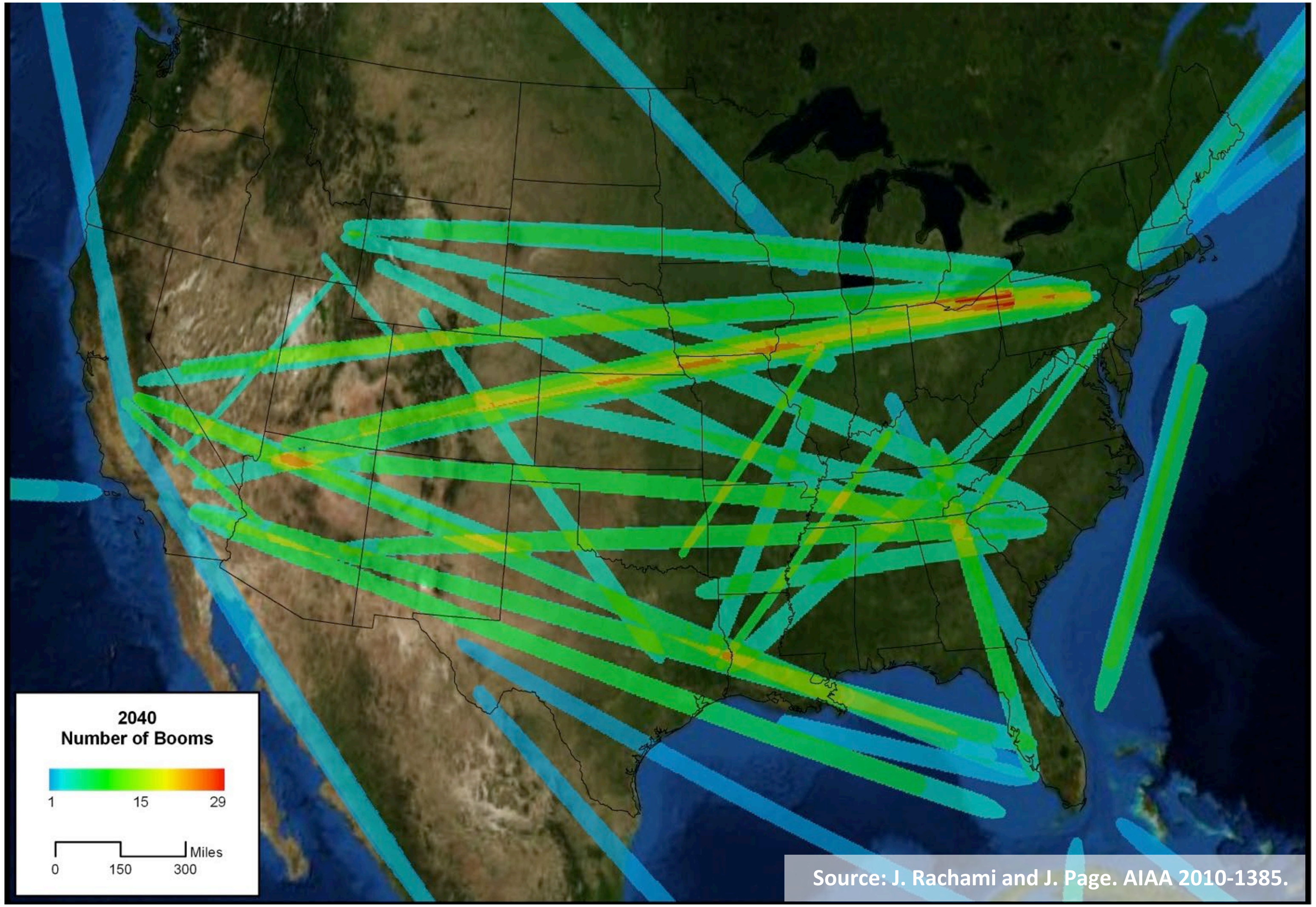
Why Are Quiet Sonic Booms Important?

- Current cruise speeds for jets are about 0.85 Mach, with high end business jets getting up to 0.9 Mach
- A commercial quiet supersonic jet could cruise at about 1.4 Mach
- Los Angeles to New York in 3 hours
- Los Angeles to Paris in 6 ½ hours
- This technology has the potential to one day more than double the speed of practical aviation travel



Goal: Acceptable Supersonic Flight Overland

NASA and Lockheed Martin have partnered to design, build, and fly the X-59 Quiet Supersonic Transport (X-59, Quesst) low boom flight demonstrator



The 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

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

National Research and Policy agencies play a central role in developing the data needed for the regulation change that is essential to enabling this new market

Credit: Lockheed Martin

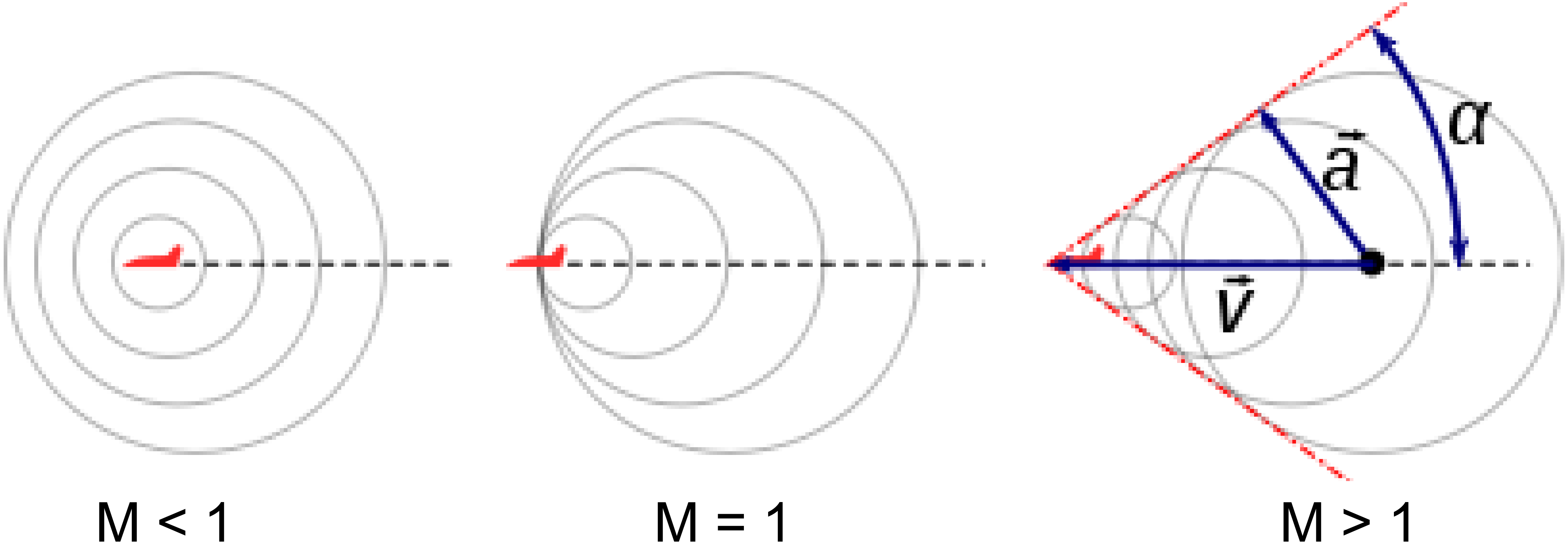
Overcoming the barrier to overland flight

The Quiet Supersonic Mission is specifically planned to generate key data for success in NASA's Critical Commitment to support 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

Mach Number

- Sound comes off aircraft at a certain speed, *a*
- Speed of aircraft is *v*
- Ratio of these two: $v/a = M$, Mach number
- Shockwaves form if $M > 1$ (when aircraft is faster than the speed of sound), can be very loud



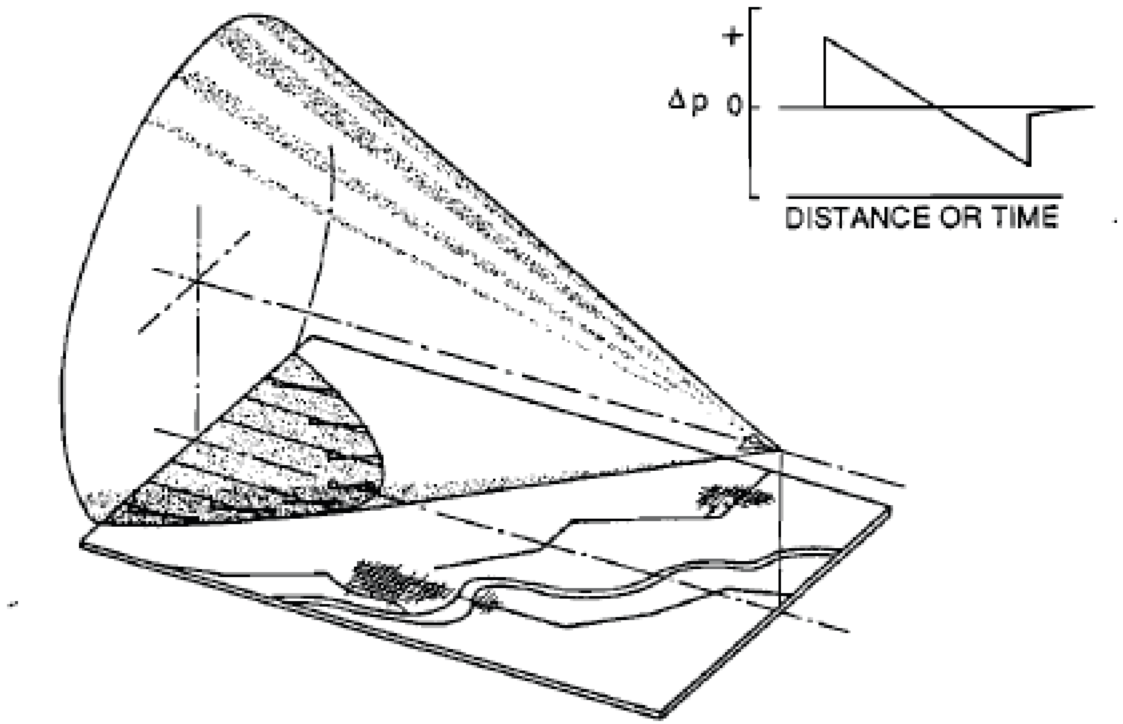
Water Wake Analogy

- Boats that move faster than the ripples in the water make a V-shaped wake

Supersonic Mach Cone

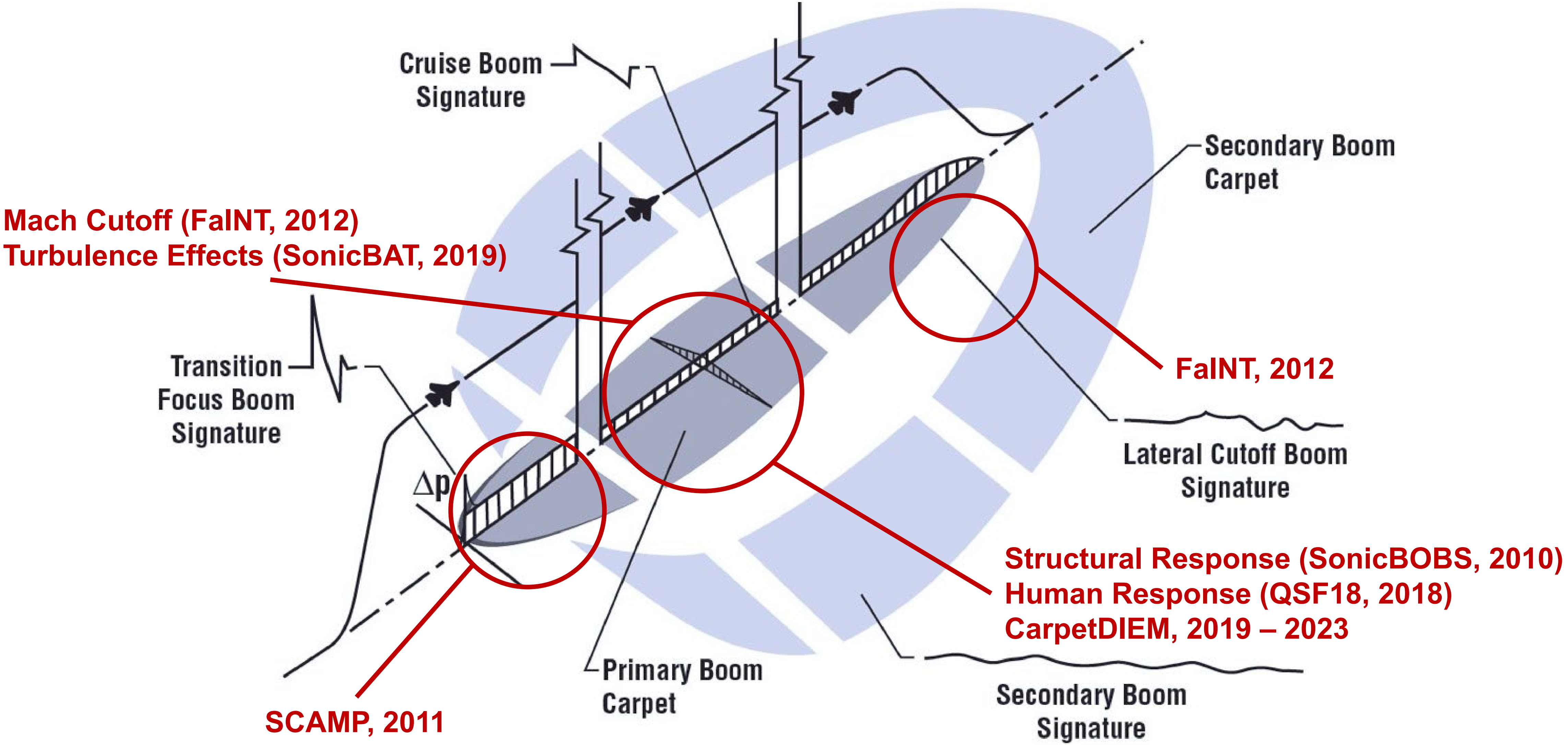
- Much as a motorboat makes a 2-D “V”- shaped wake on the water, a supersonic aircraft makes a 3-D cone-shaped shock wave pattern through the sky

Classic N-wave



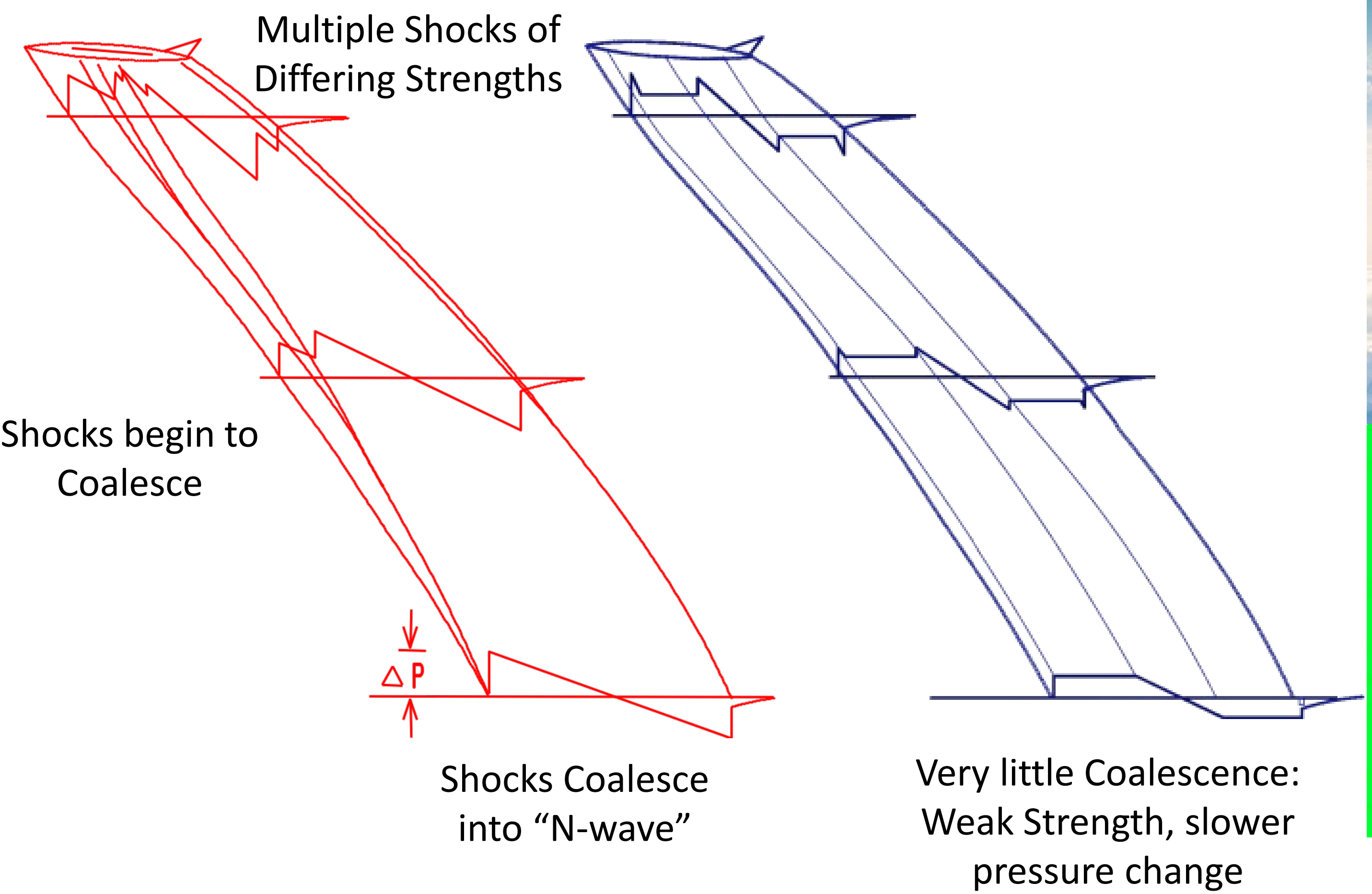
Actual T-38

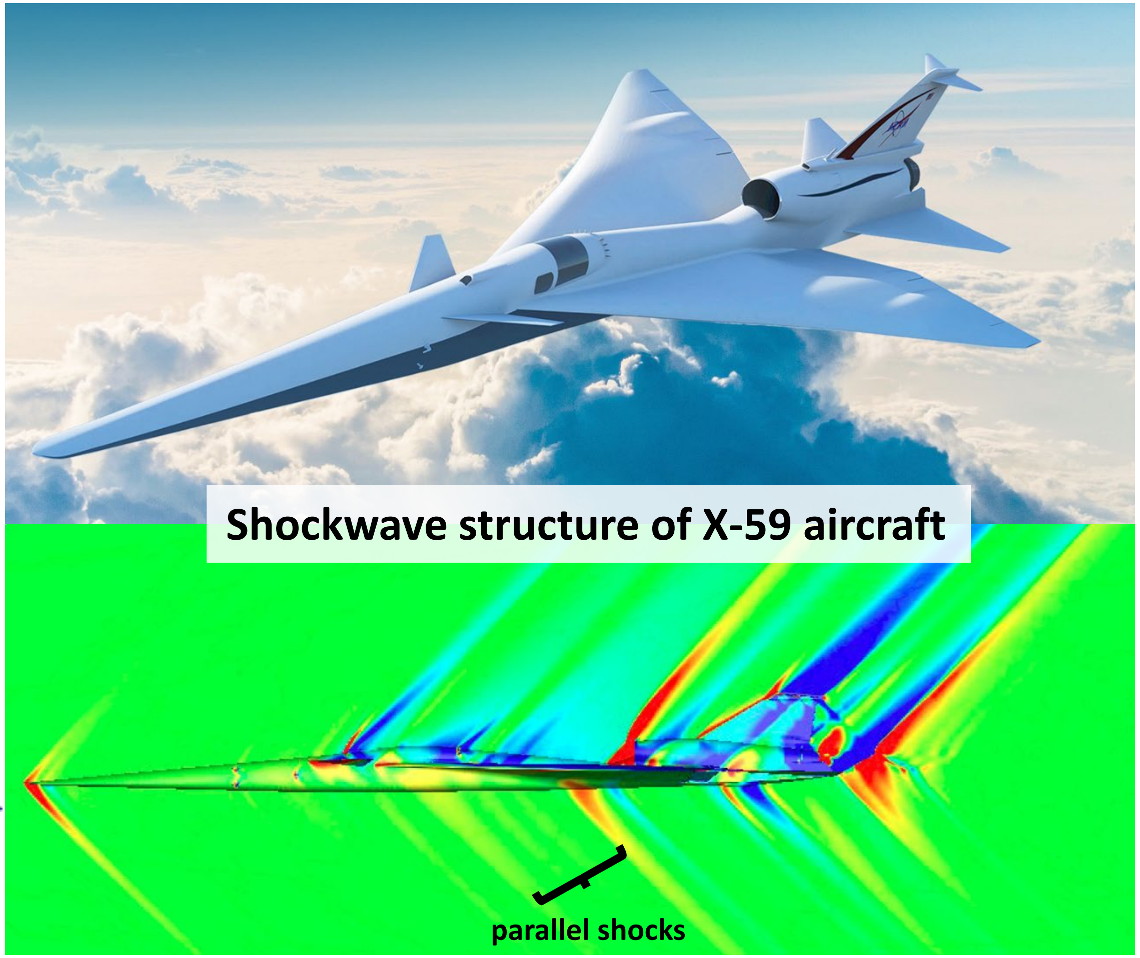
Sonic Boom Carpet



Shaped Sonic Booms

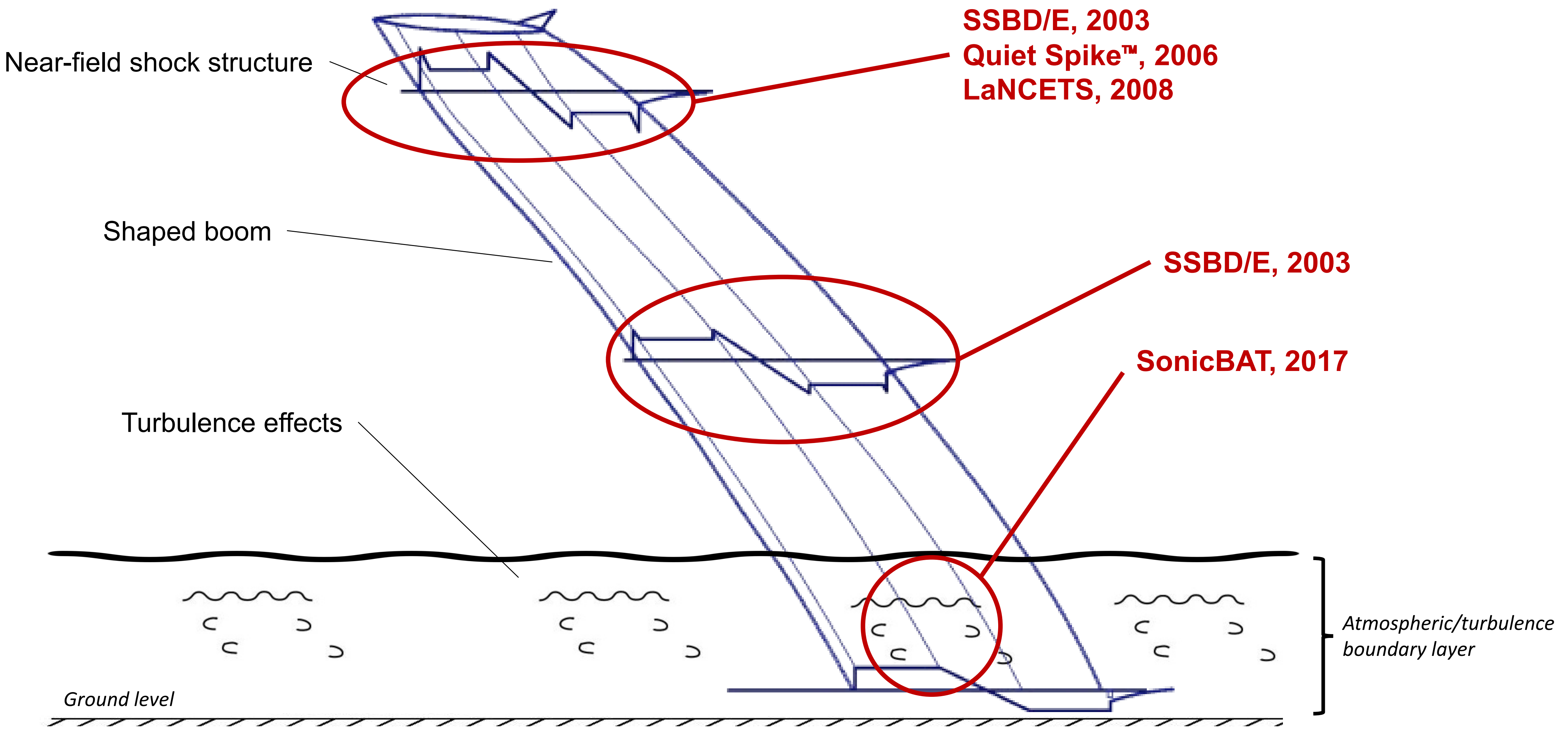
N-wave vs. Shaped wave: Strong, short △P causes loud noise





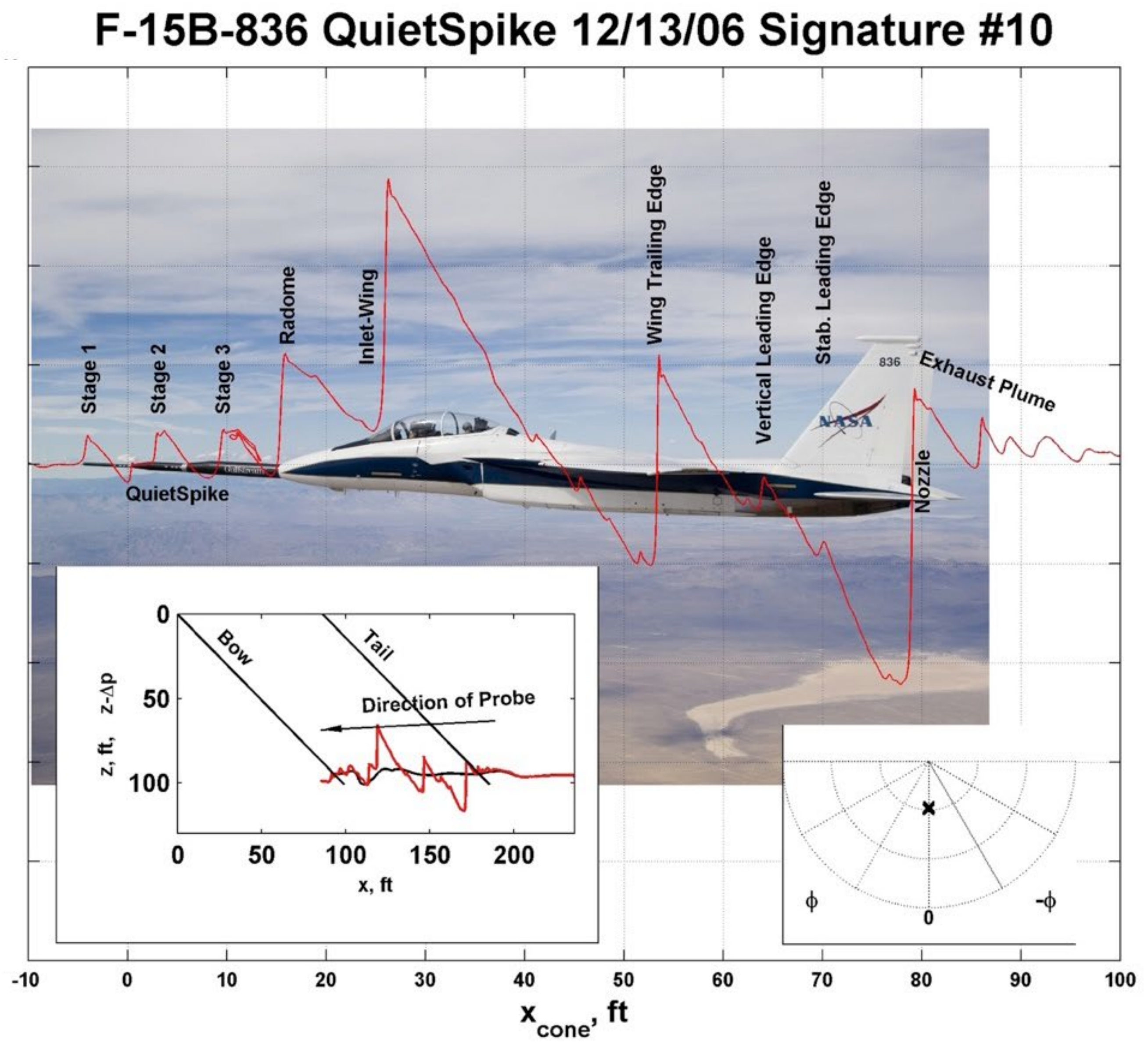
Shockwave structure of X-59 aircraft

Sonic Boom Propagation



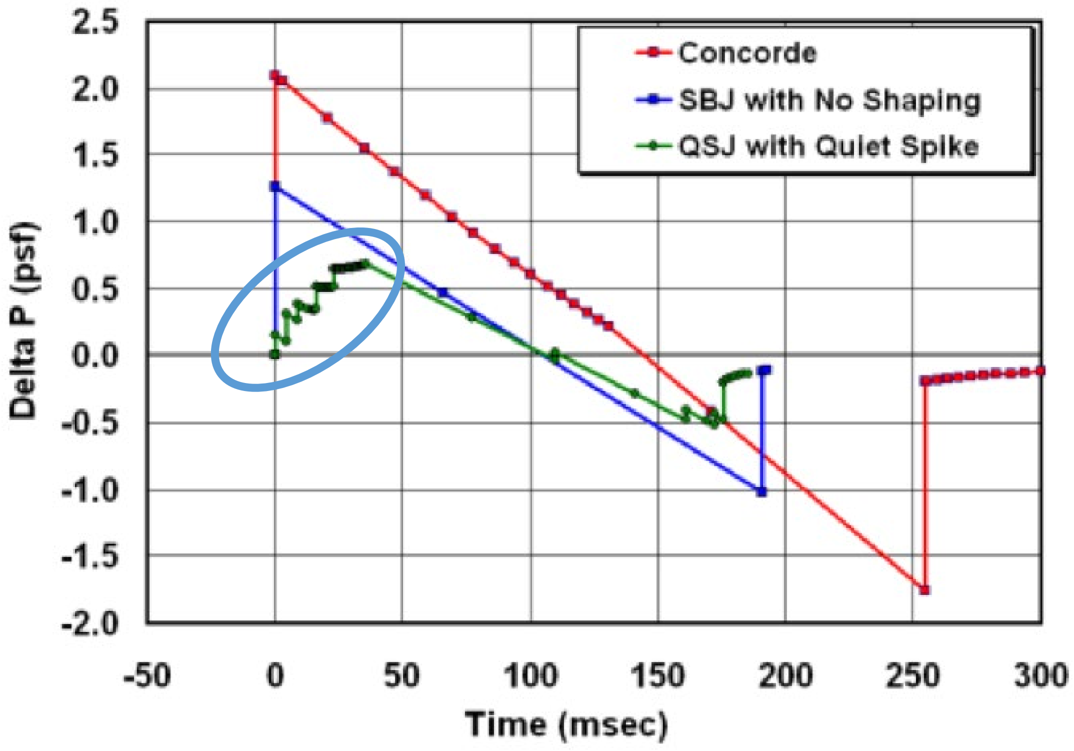
Shock Structure Measurements

Quiet Spike™ (Gulfstream Aerospace)



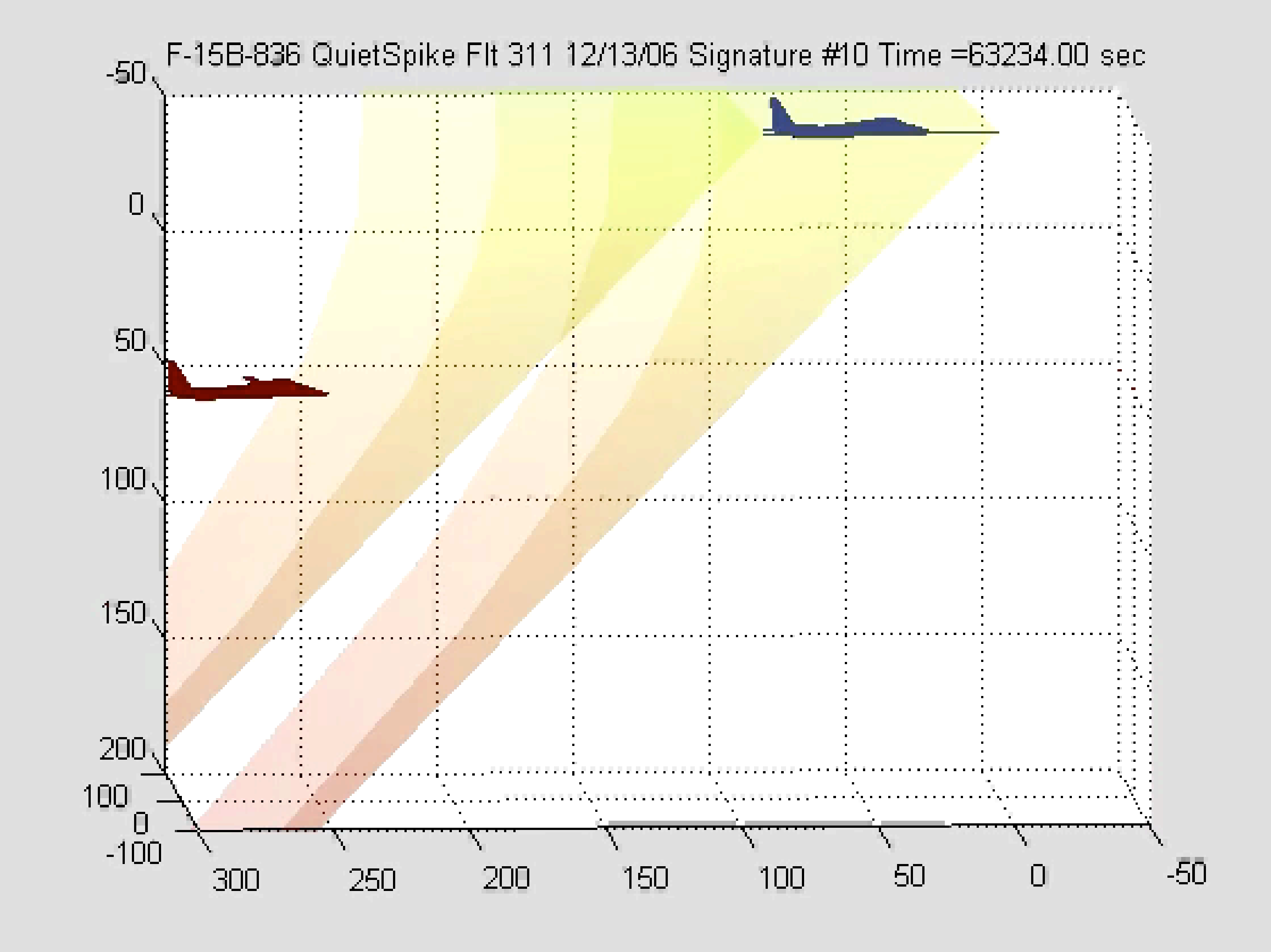
Quiet Spike™

- The long nose boom breaks the bow shock into a series of weak shocks
- These weak shocks propagate parallel to the ground and transform the sharp crack of a sonic boom into a quiet rumble
- The transformed n-wave can be seen in this graph

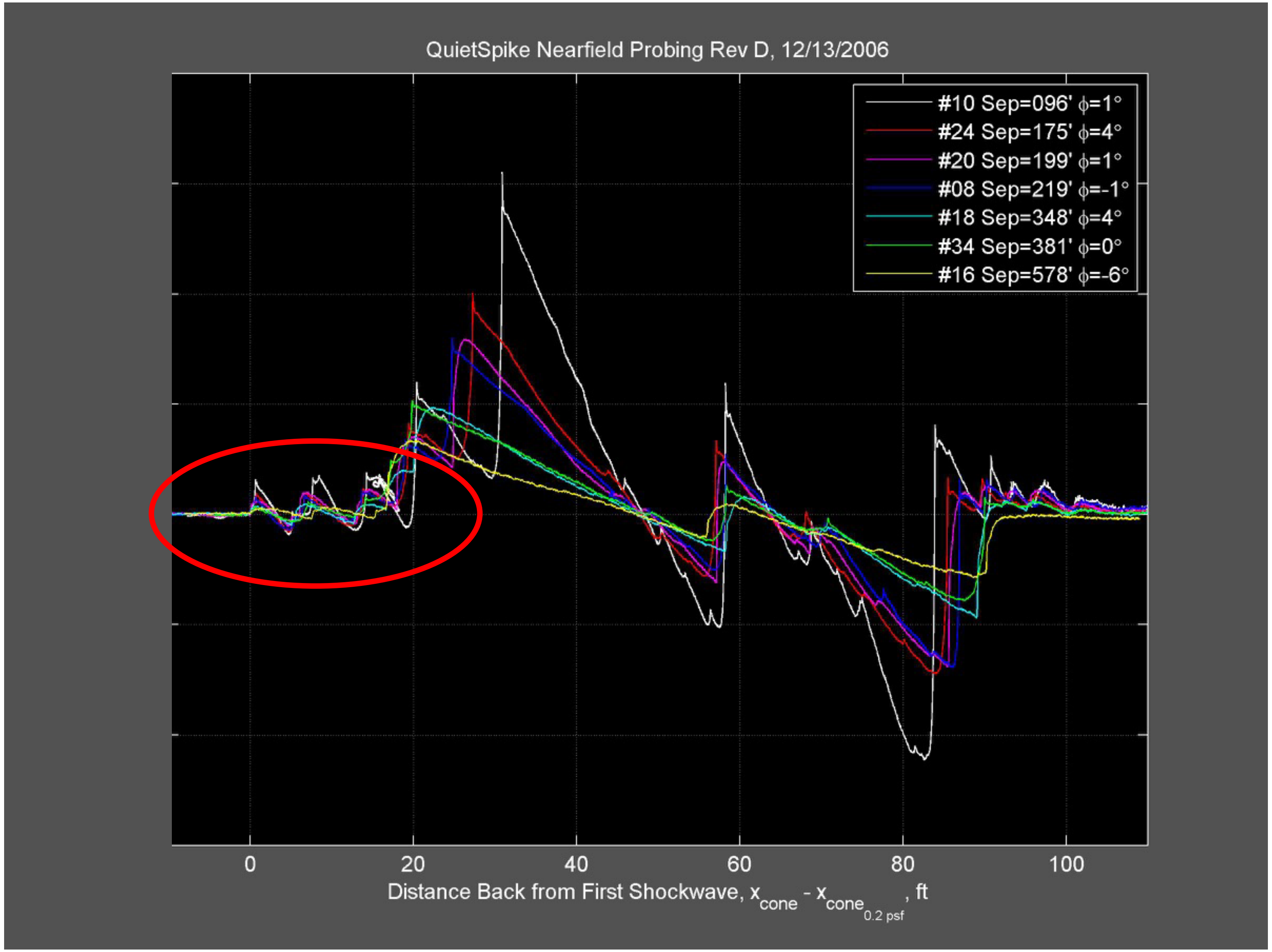


Predicted Result – Ground level

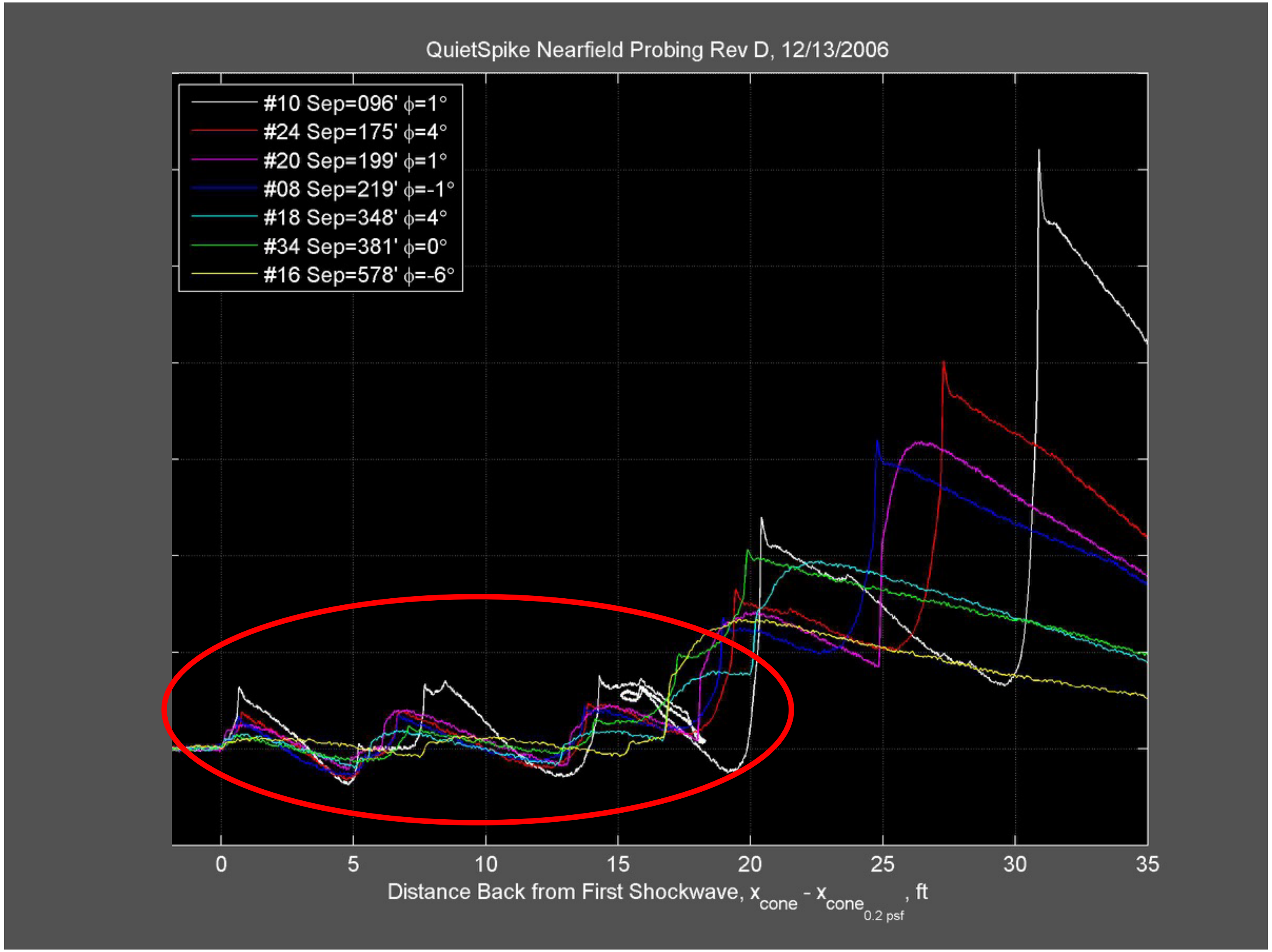
Quiet Spike™ – Nearfield Shock Measurements



Quiet Spike™ – Nearfield Shock Measurements Results



Quiet Spike™ – Nearfield Shock Measurements Results



In-flight Shock Imagery

Shockwave Imagery – Airborne Schlieren

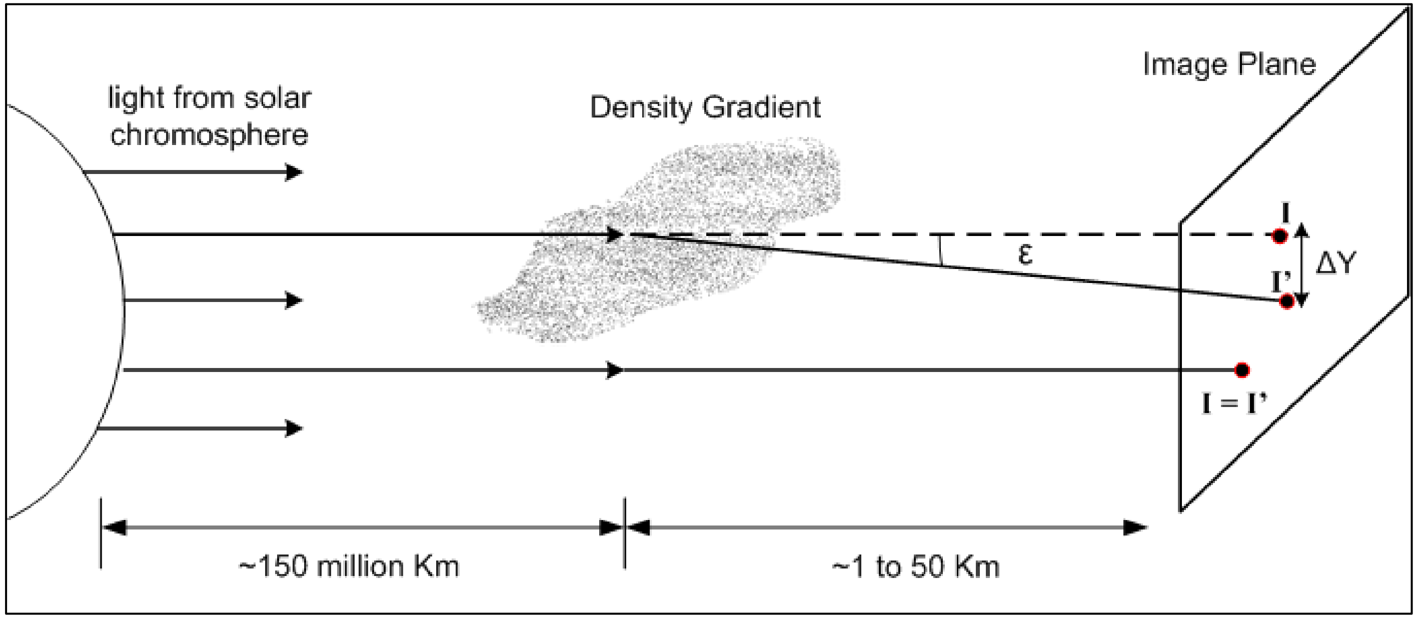
Background Oriented Schlieren (BOS) Concept

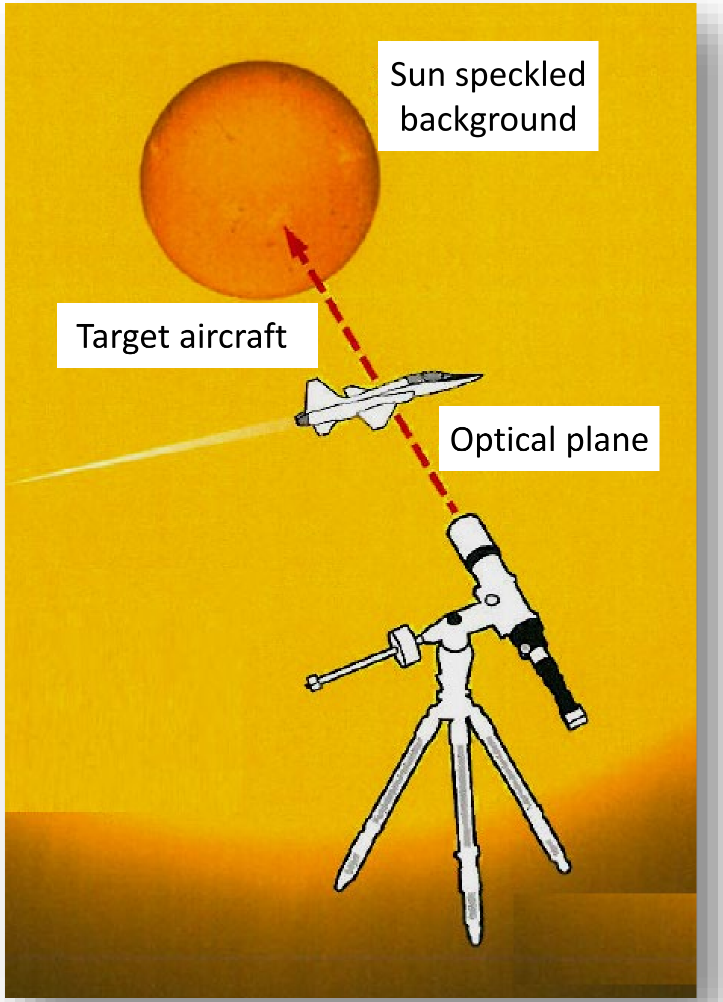
Visualizes light ray deflections by calculating movement of features in a background

BOSCO Concept

Background Oriented Schlieren using Celestial Objects (BOSCO)

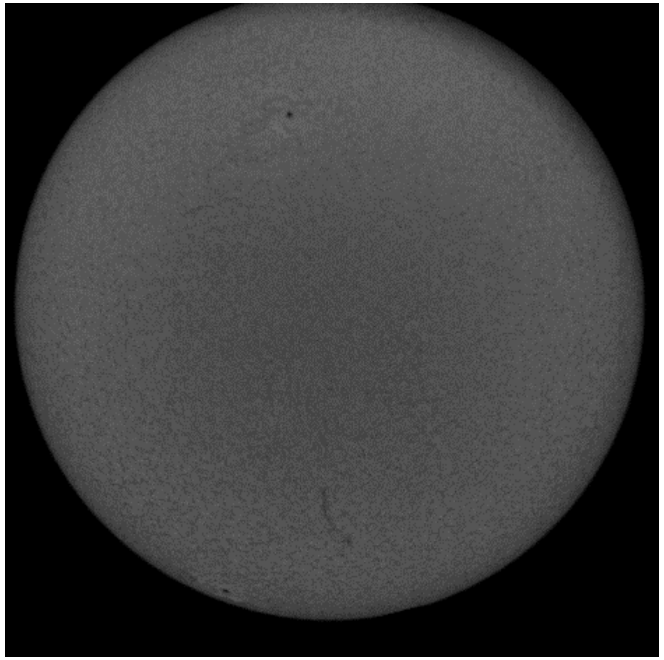
- Uses narrow band optical filters to give the sun a textured appearance. The texture allows for the Background Oriented Schlieren method
- Ability to image from below and to the side of the target aircraft

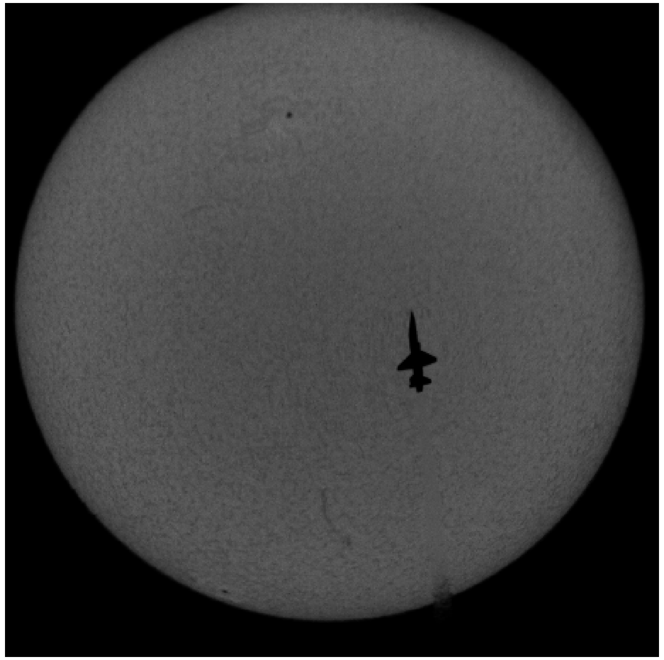




BOSCO – Processing

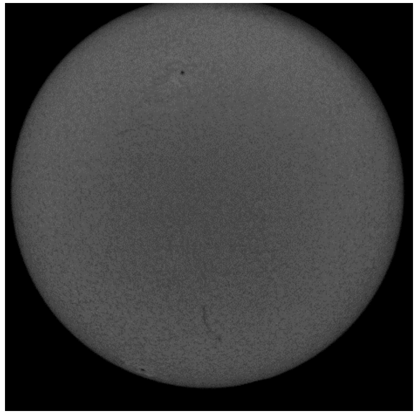
- Optical Flow
  - Developed for computer vision applications in the 1970’s/80’s
  - Uses the “brightness constancy criterion” – brightness is constant between 2 image pairs, differences in brightness correspond to motion
  - Outputs “flow” vectors, 2D solutions of pixel displacement



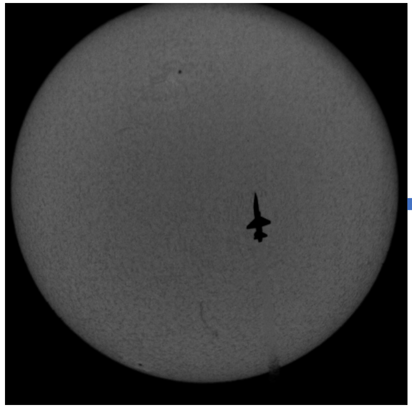


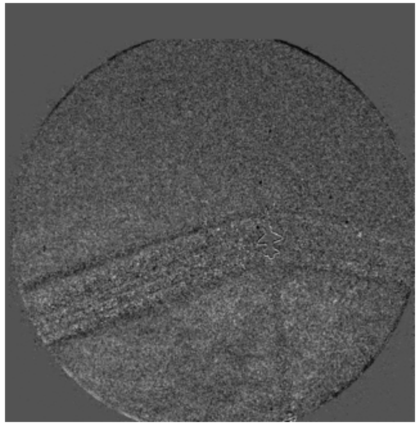
BOSCO – Image Processing

A frame before the aircraft eclipses is used for the reference background



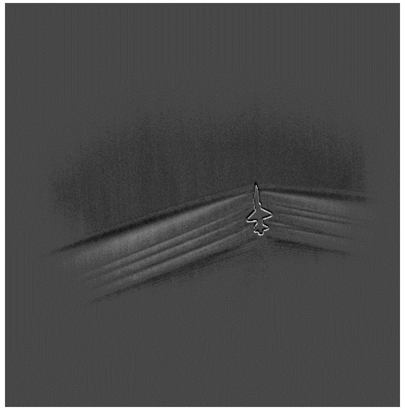
Each eclipse frame is aligned with the background frame





Single solution

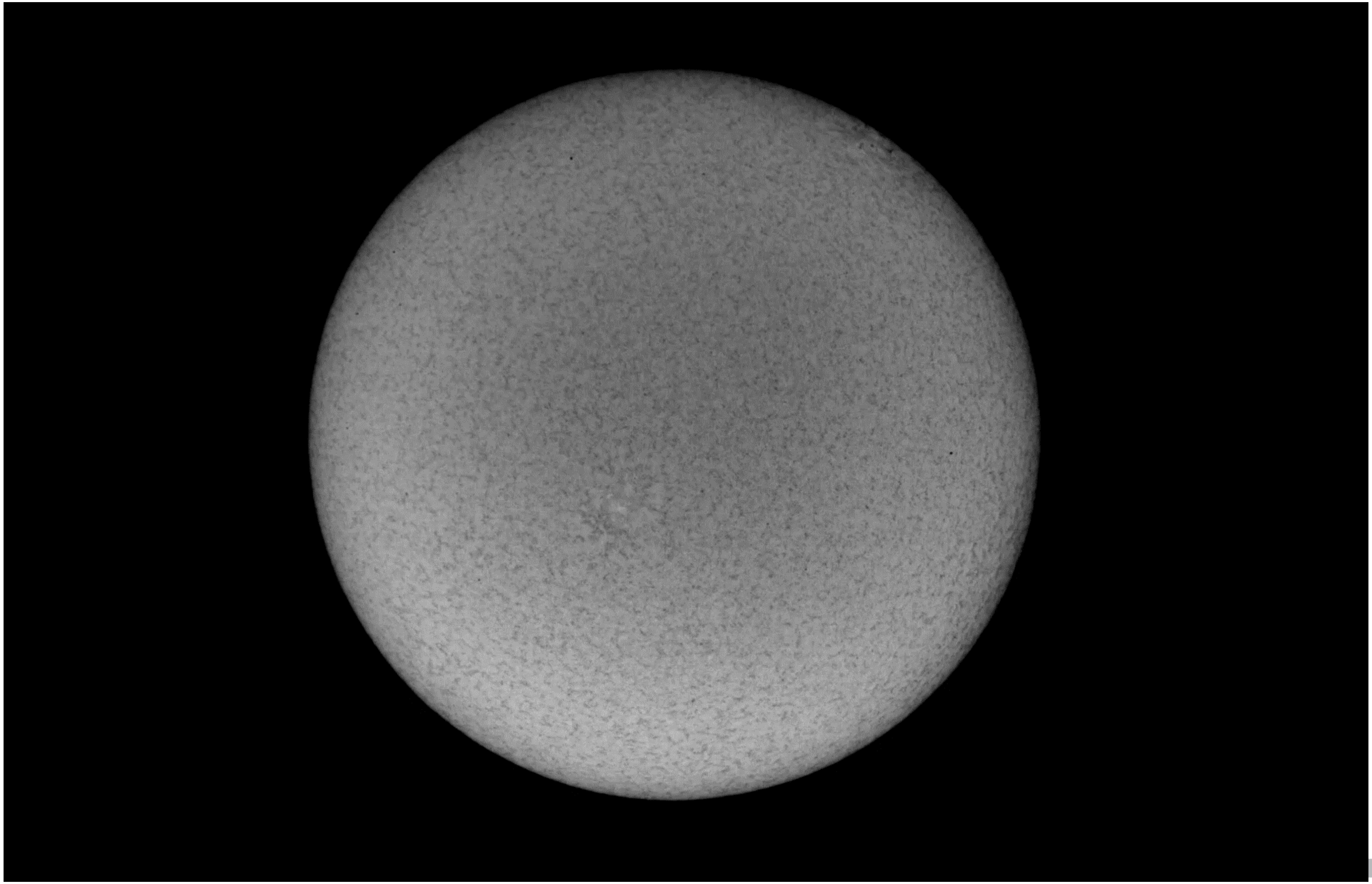
Optical Flow is performed on the image pair resulting in a magnitude of pixel displacements

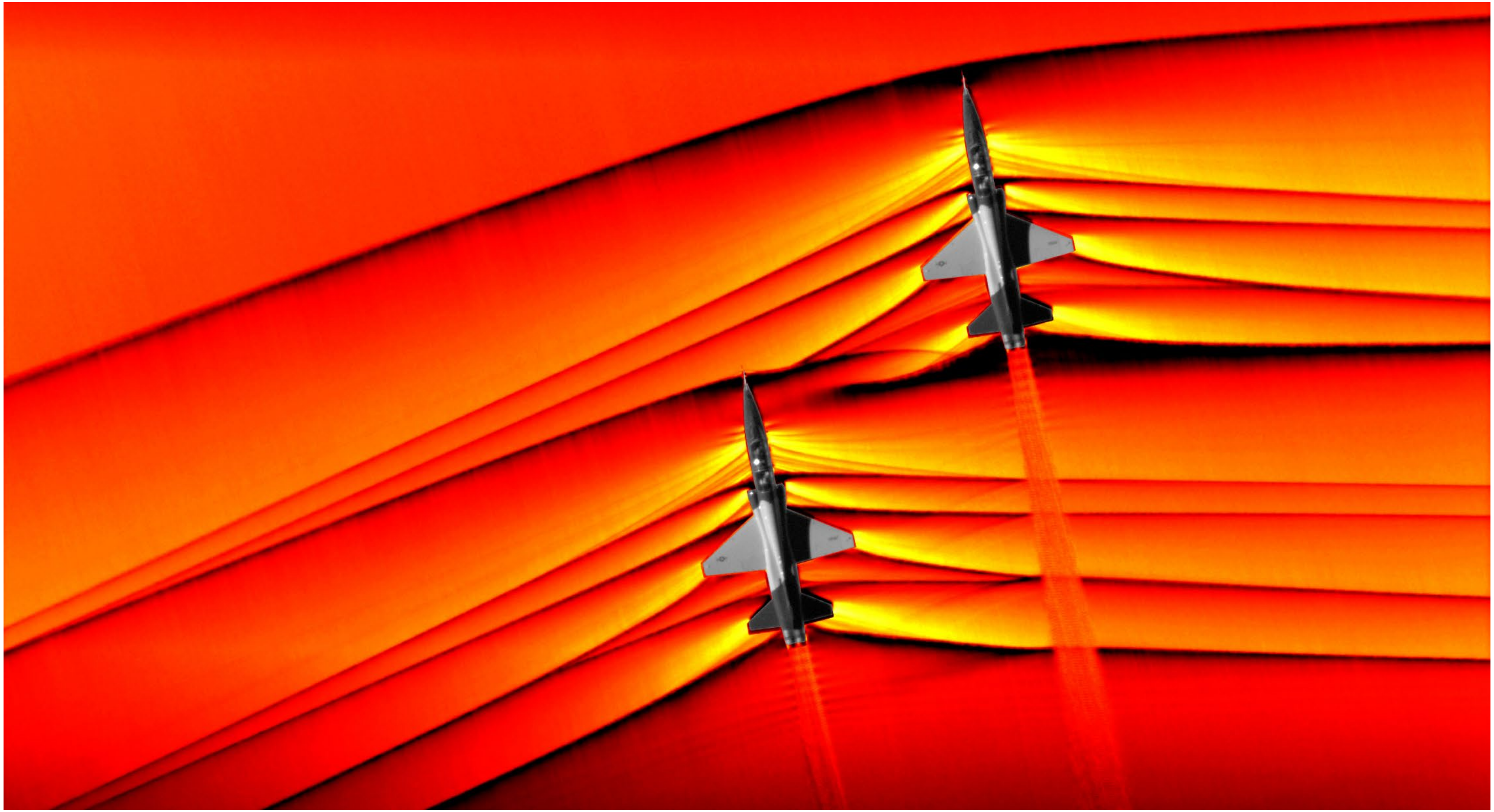


Final solution

This is repeated for all frames in the eclipse. The median of all the results of all the frames is taken, resulting in the final de-noised schlieren image

BOS using Celestial Objects – Raw Data

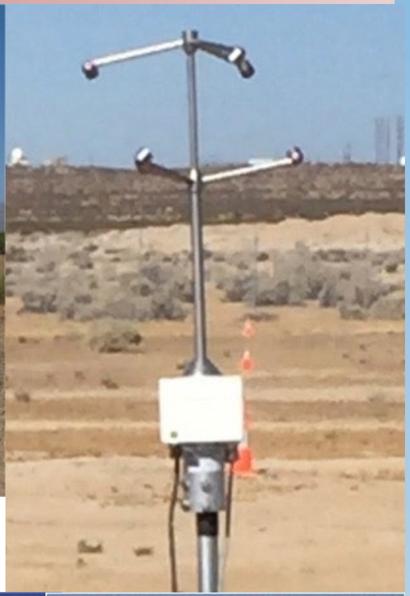




Effects of Turbulence

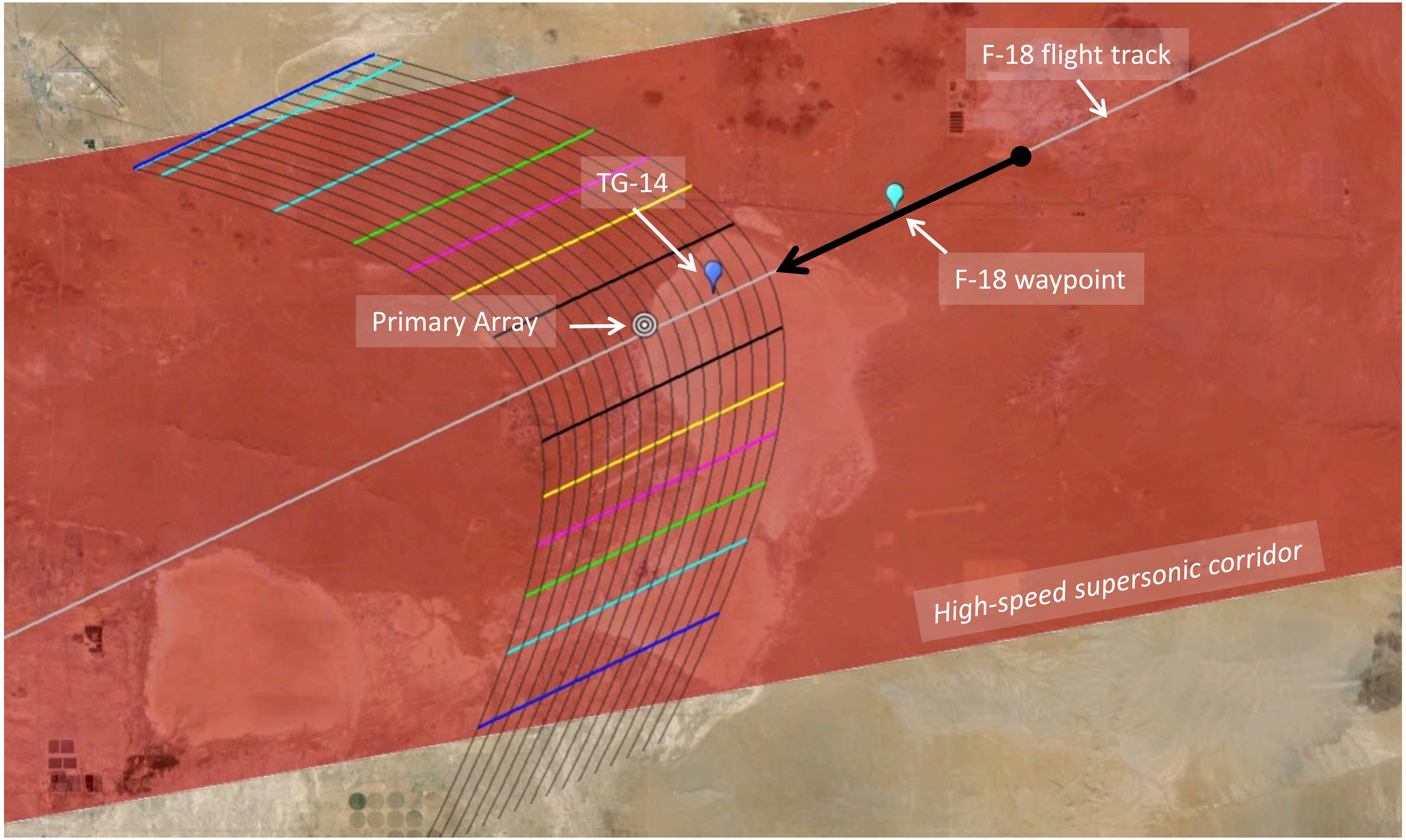
Atmospheric Instrumentation

- Sonic Anemometer
  - 10m (32.8 ft) tower
  - 44m (144 ft) tower
  - Amb. temperature, 30 sample/s
  - 3 component winds, 30 sample/s
  - Ct^2 and Cv^2
- SODAR
  - Model 4000 Mini-SODAR (250m=820 ft)
  - Model 2000 Large SODAR (700m=2296 ft)
  - 3 component winds
  - Ct^2 and Cv^2
- GPSsonde
  - One for each takeoff time to 12km (40K ft)
  - EAFB or local launch
- 3m (10 ft) weather tower
  - Temp., Press., Humidity, Wind Speed & Dir
  - One at each array



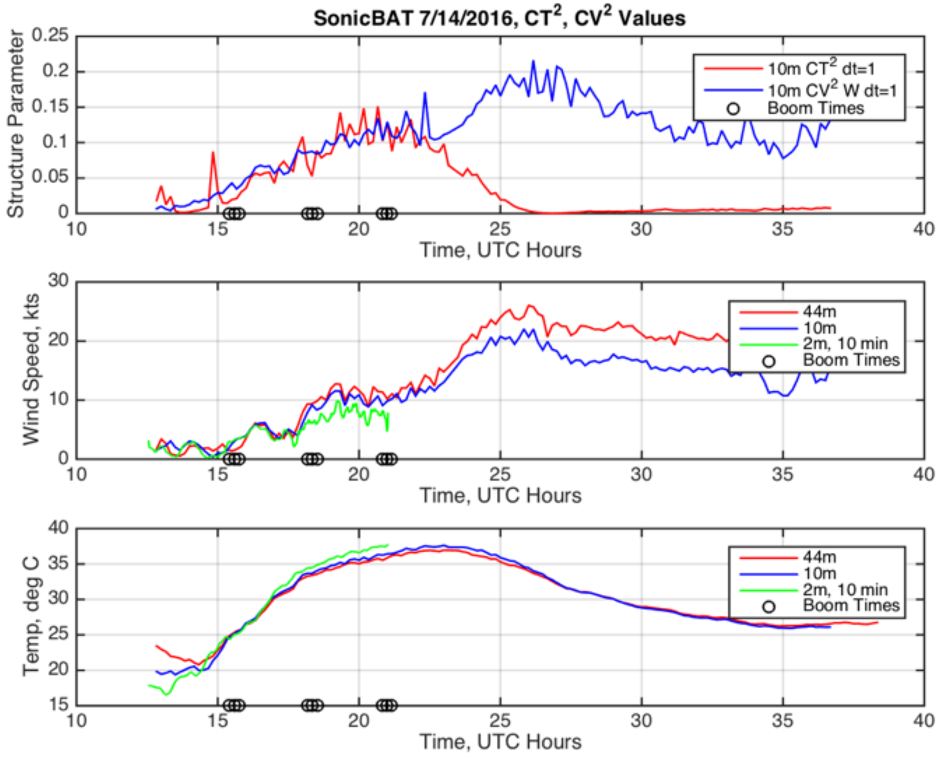
Research Flight Profile/Plan

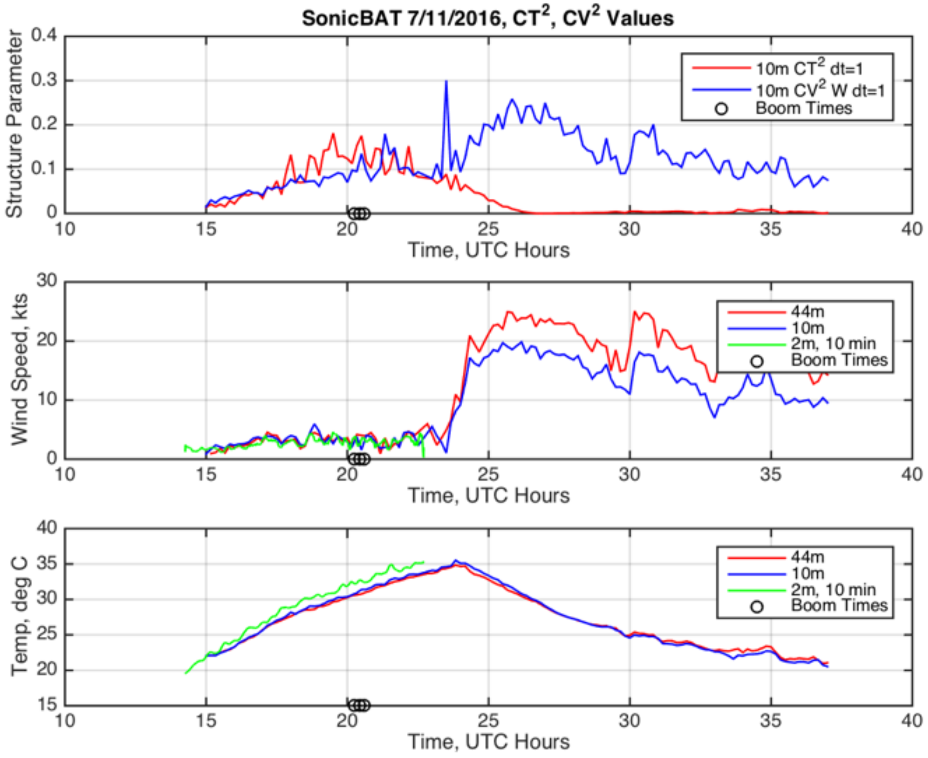
- Primary test point: F-18 On-track, Hp=32,000 ft, Mach 1.40, 245-deg true course



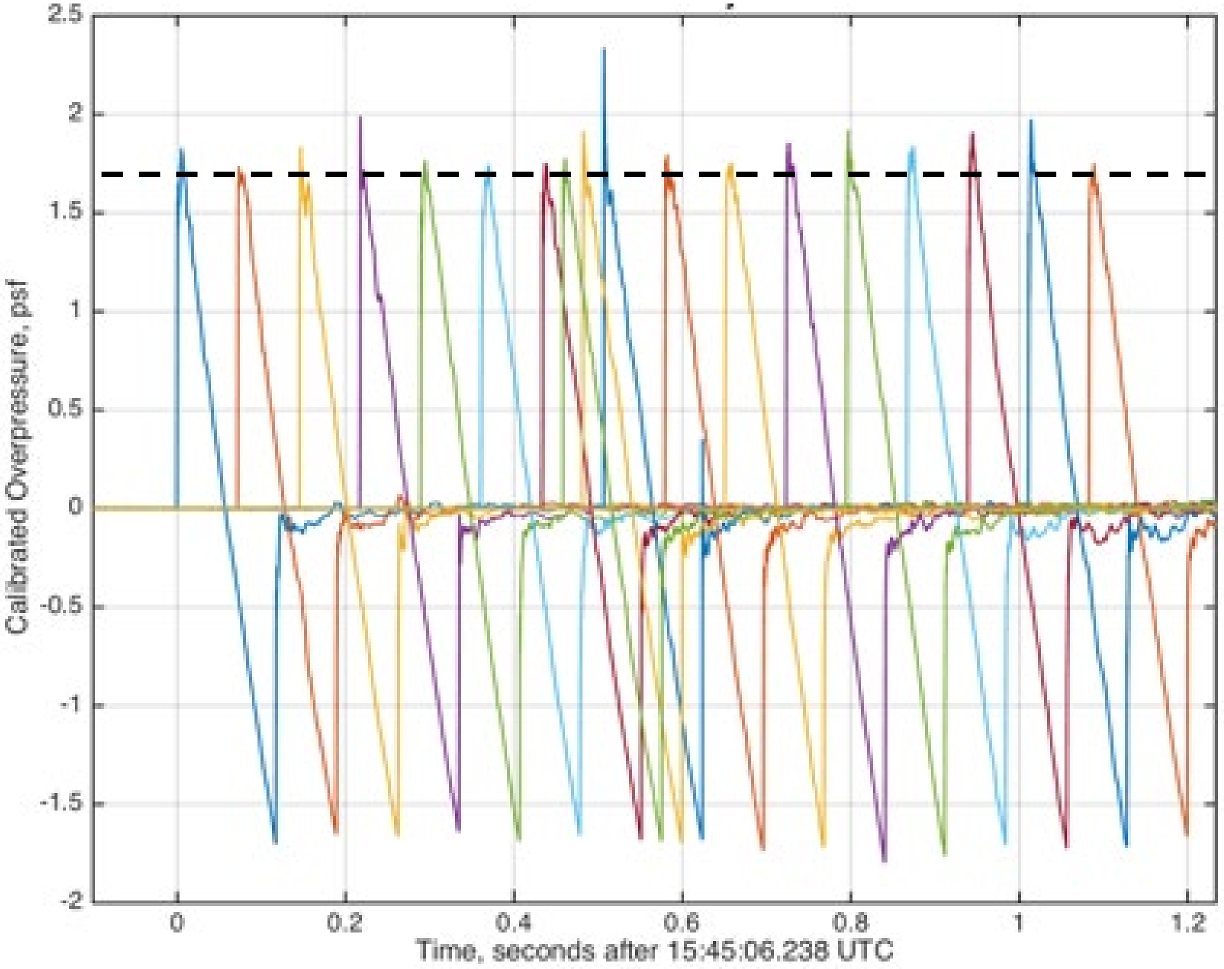
Turbulence Model inputs

- CT^2: solar heating, e.g. 0.02, 0.10, 0.13
- CV^2: winds, e.g. 0.04, 0.10, 0.13
- Boundary layer height: 2,000 – 13,000 ft range

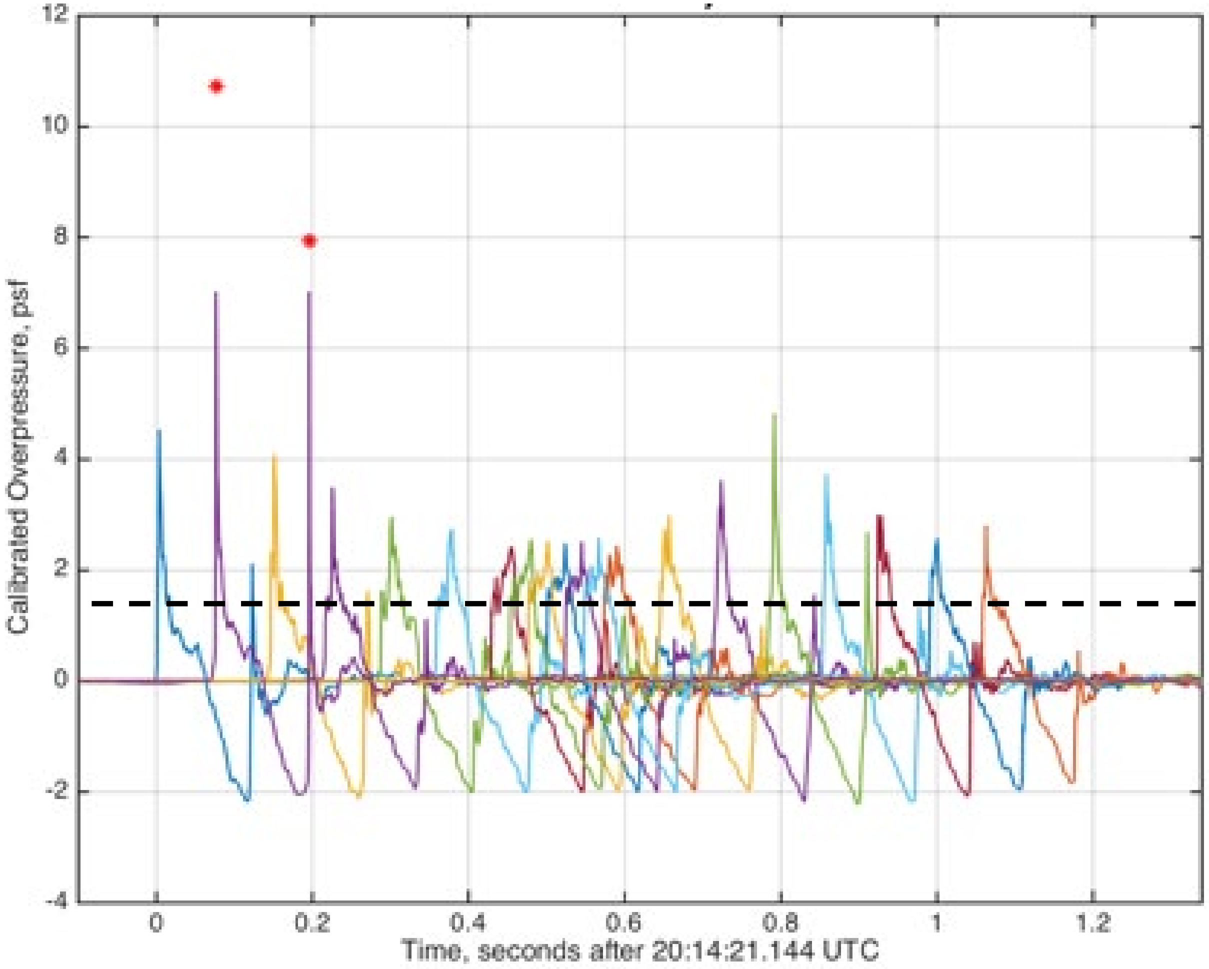




Sonic Boom Propagation – Effects of Turbulence



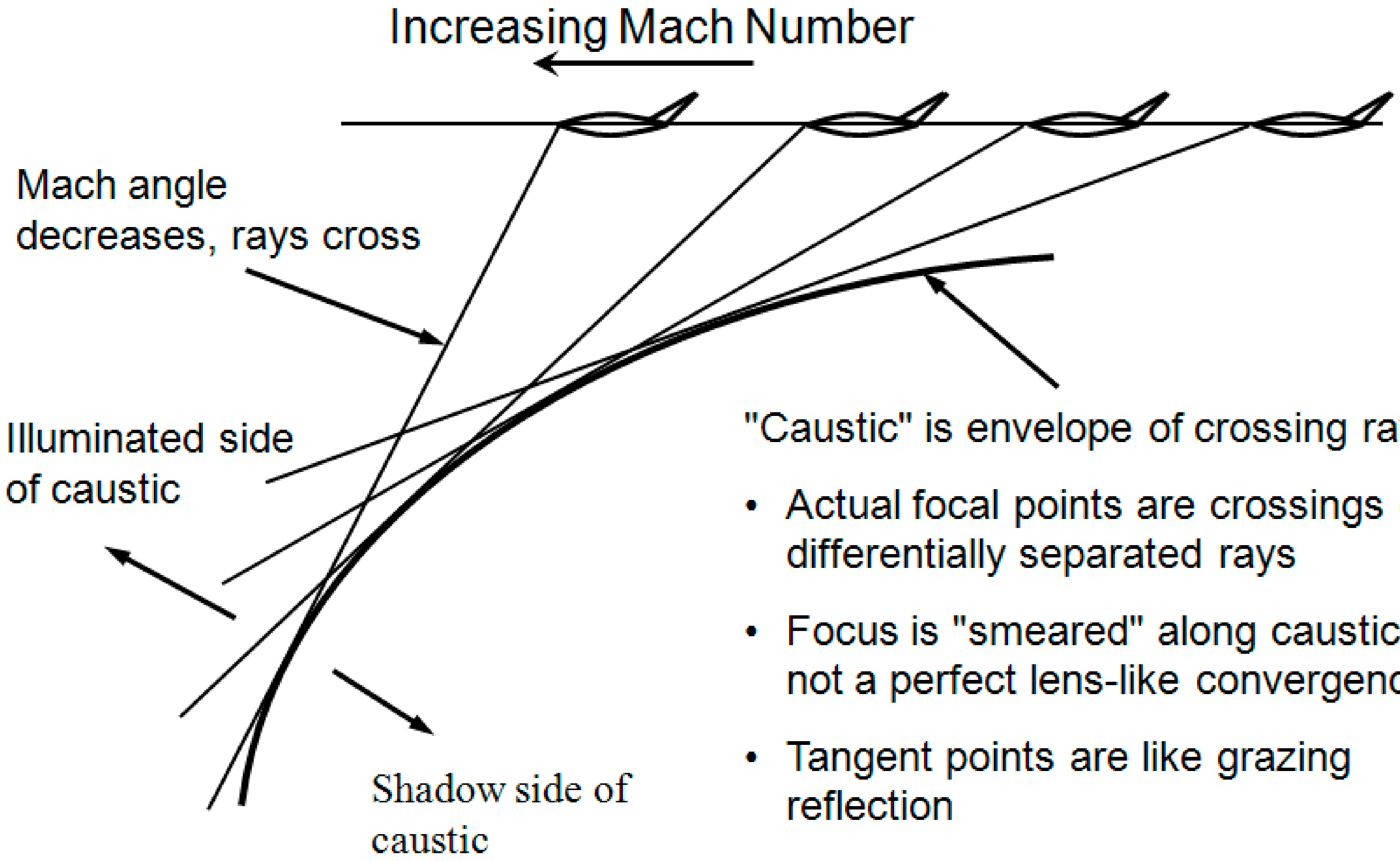
Low Turbulence , CT^2=0.02, CV^2=0.04



High Turbulence , CT^2=0.13, CV^2=0.13

Focus Sonic Booms

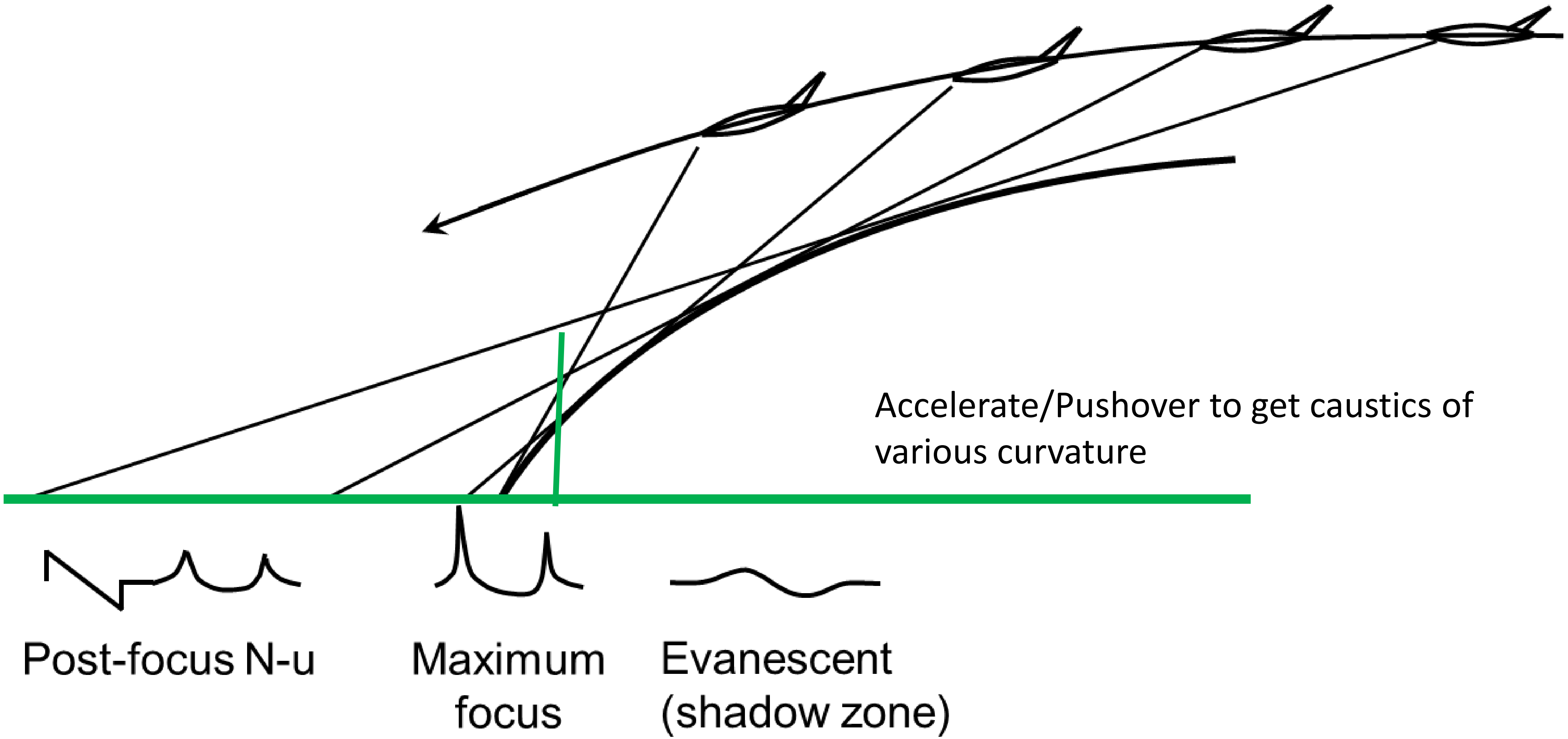
Acceleration Focus



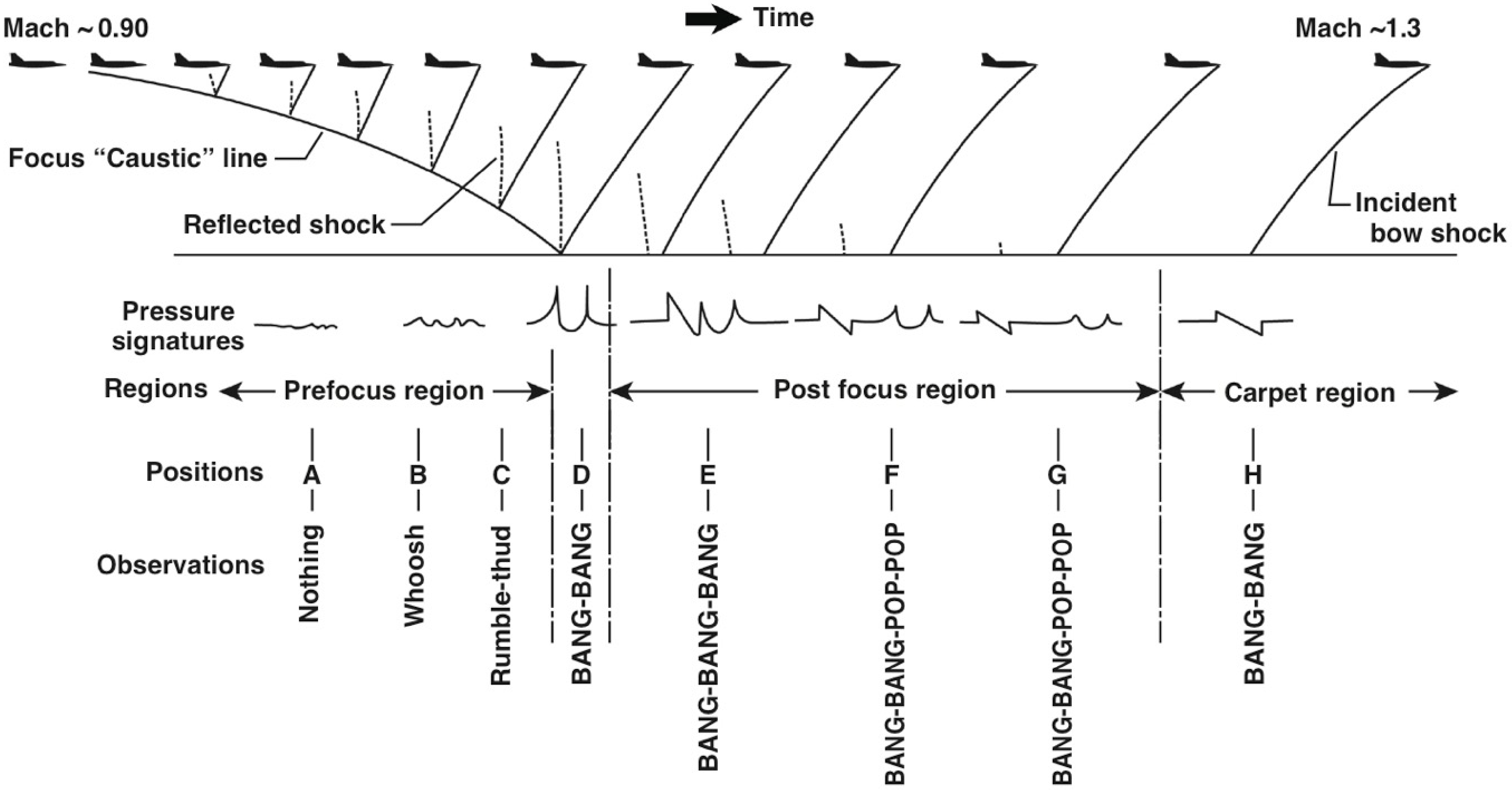
"Caustic" is envelope of crossing rays

- Actual focal points are crossings of differentially separated rays
- Focus is "smeared" along caustic – not a perfect lens-like convergence
- Tangent points are like grazing reflection

Pushover Focus

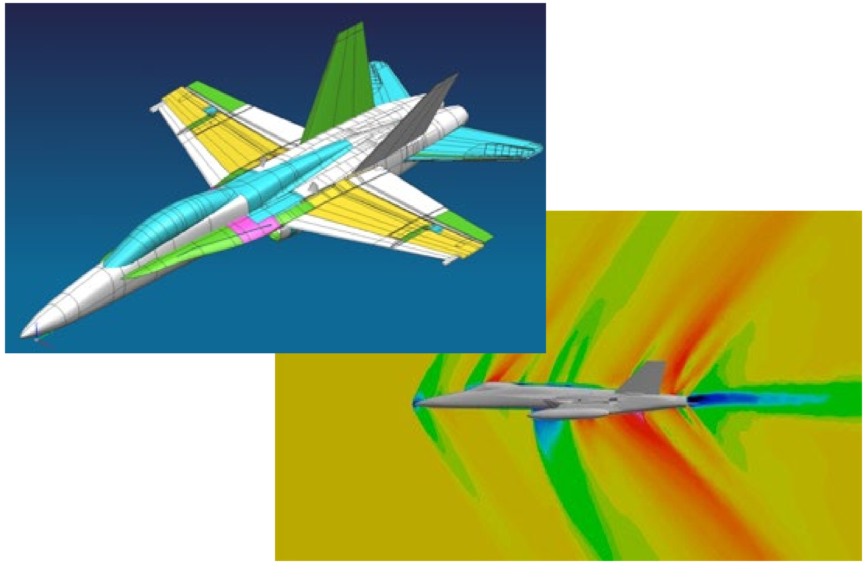


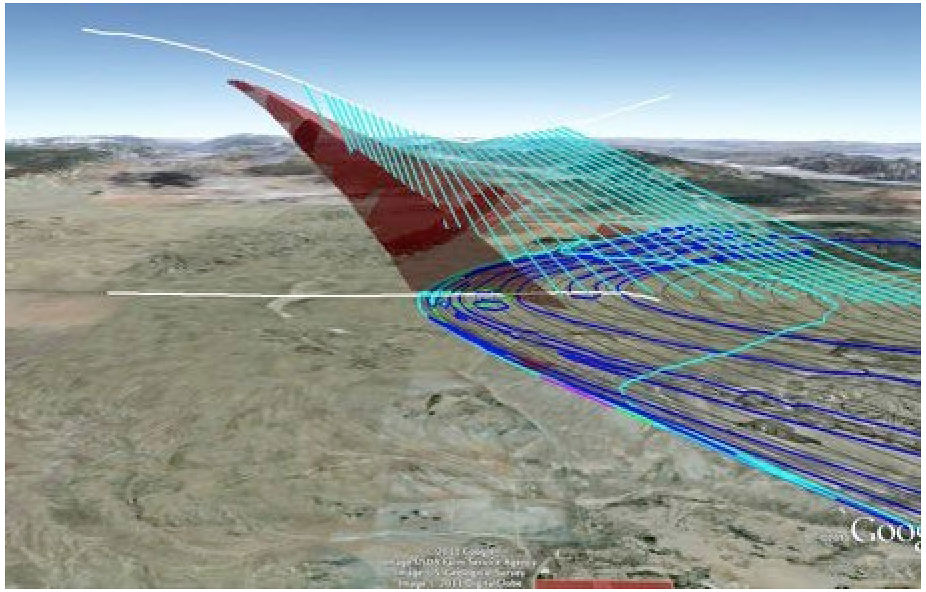
Focus Sonic Boom Carpet



Superboom Caustic Analysis and Measurements Project (SCAMP) Project Overview

- ***Flight test*** to collect high quality focus boom data: May 2011
- ***CFD*** for precise F-18 source characteristics
- ***Develop & Validate Three models*** for focus boom prediction using full signatures
- ***Apply to low-boom*** aircraft designs
- ***Profile Exploration:*** Initial strategies to mitigate focus boom impact

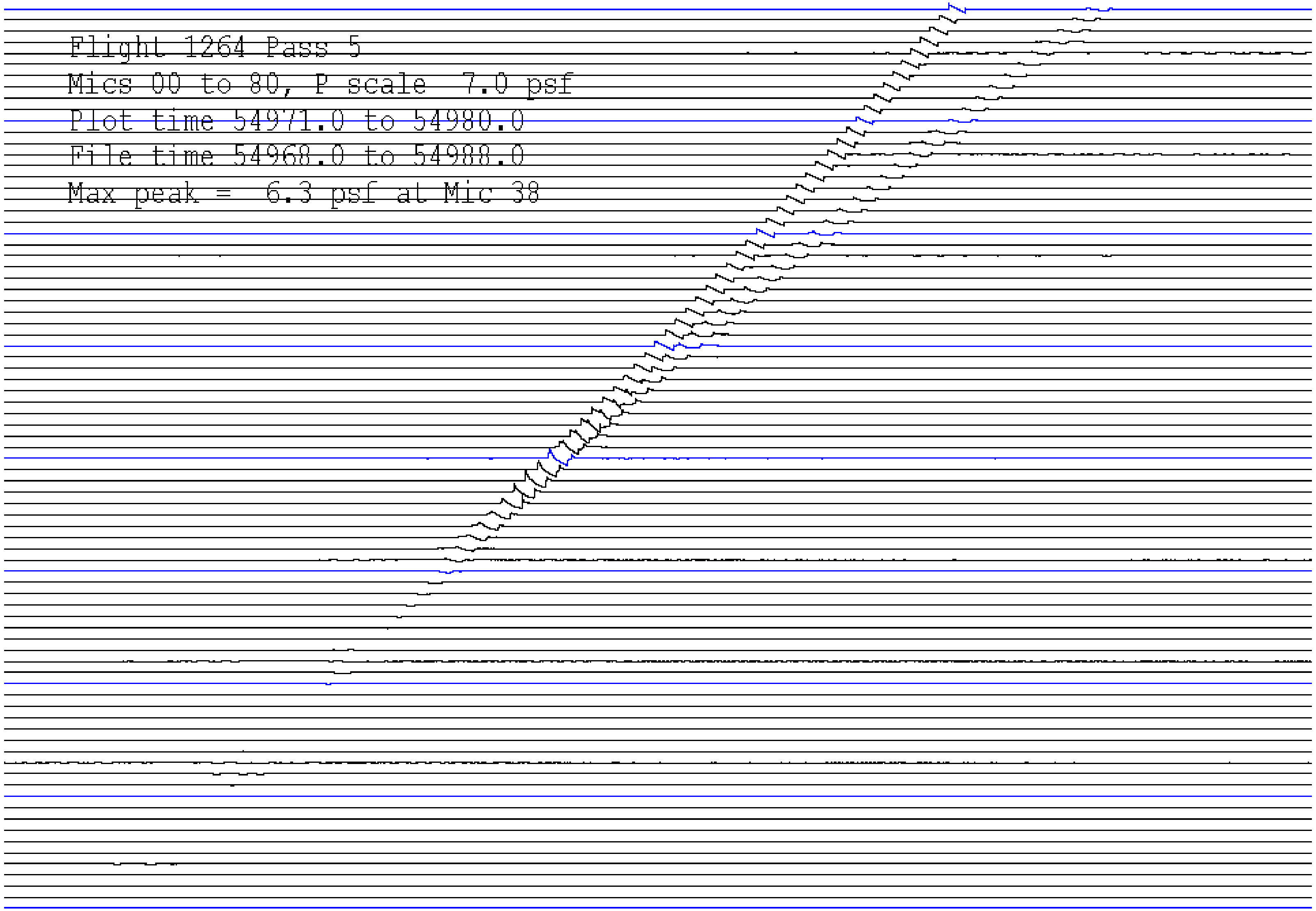




- F-18 Generated Focused Booms with a Range of Caustic Curvatures
- Extensive Flight Database: 13 flights, 70 supersonic runs, 81 ground mikes (10,000 ft array, 125 ft apart), 3 airborne mikes (sailplane & blimp), weather sensors, seismometers, cameras
- CFD for as-flown F-18 test points
- Developed alpha codes, analyzed SCAMP data and low boom configurations

Typical SCAMP Measured Focus

Regular progression from evanescent => U => N-u

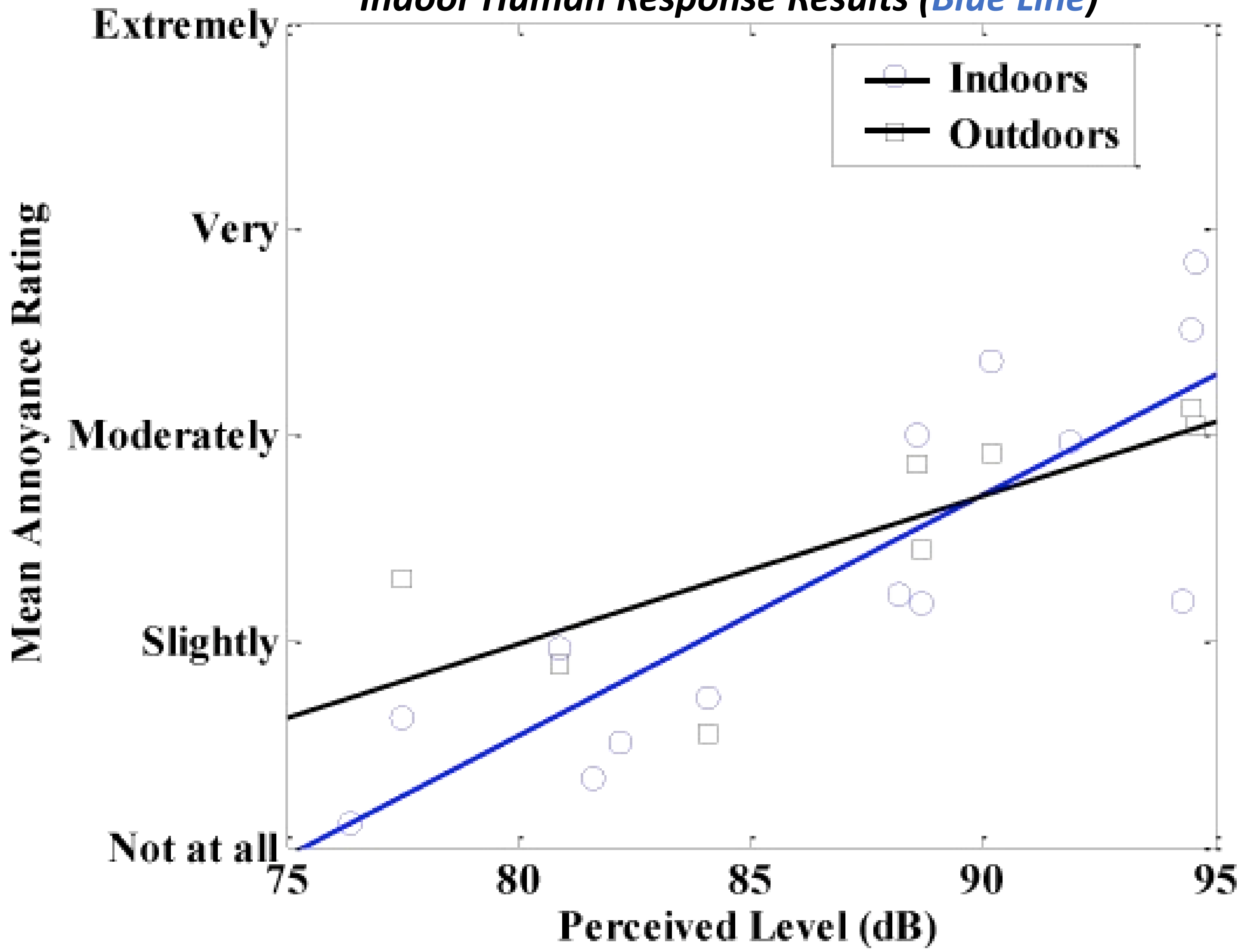


Sonic Boom Community Response

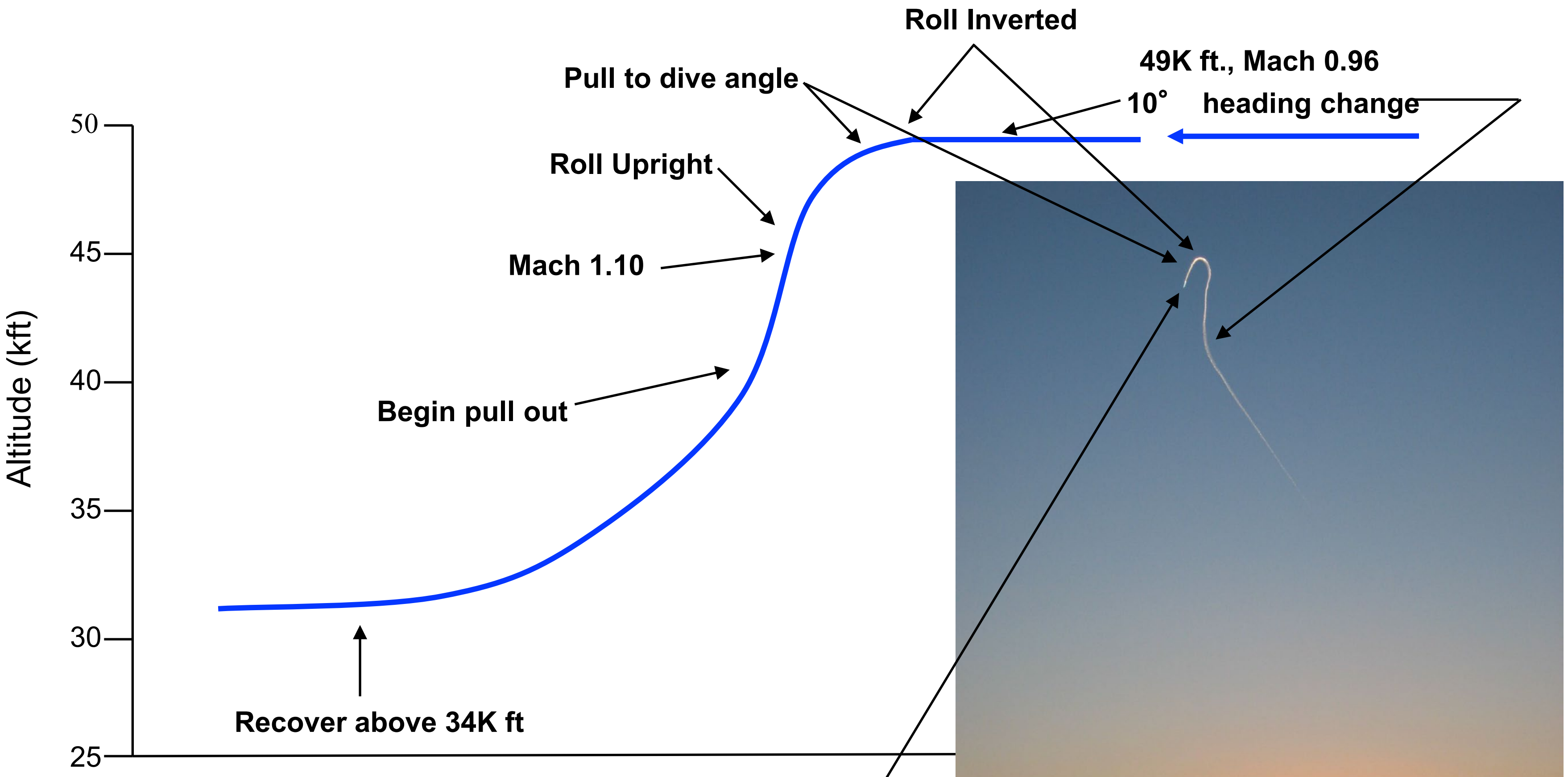
Example Human Response Results

- 14 sonic booms
- Perceived Loudness Decibels ranging from 75–95 PL (dB)

Indoor Human Response Results (Blue Line)

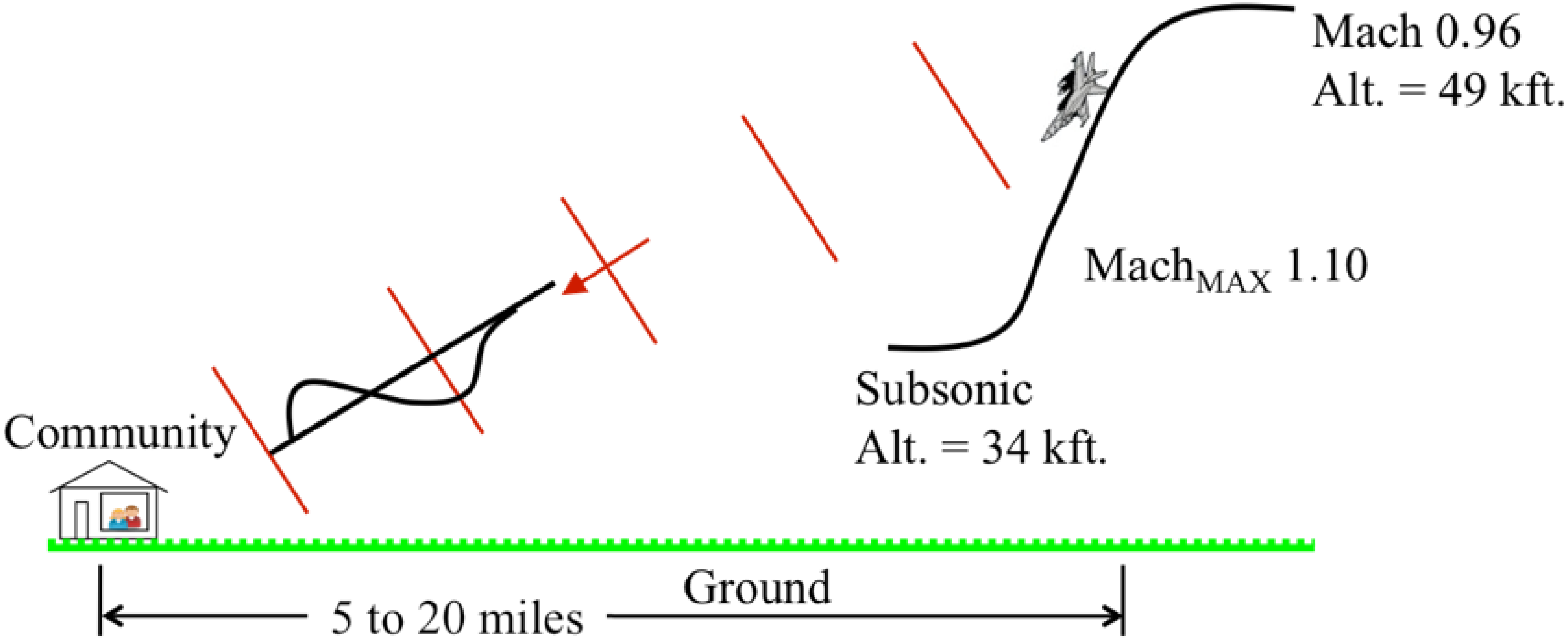


Low Boom Dive



- Contrail stops when engines to idle
- Boom hits 1-1/2 to 2 minutes later
- Microphones recording:
  - From 30 seconds after contrail stops
  - To 60 seconds after boom
- Recordings used for boom simulators

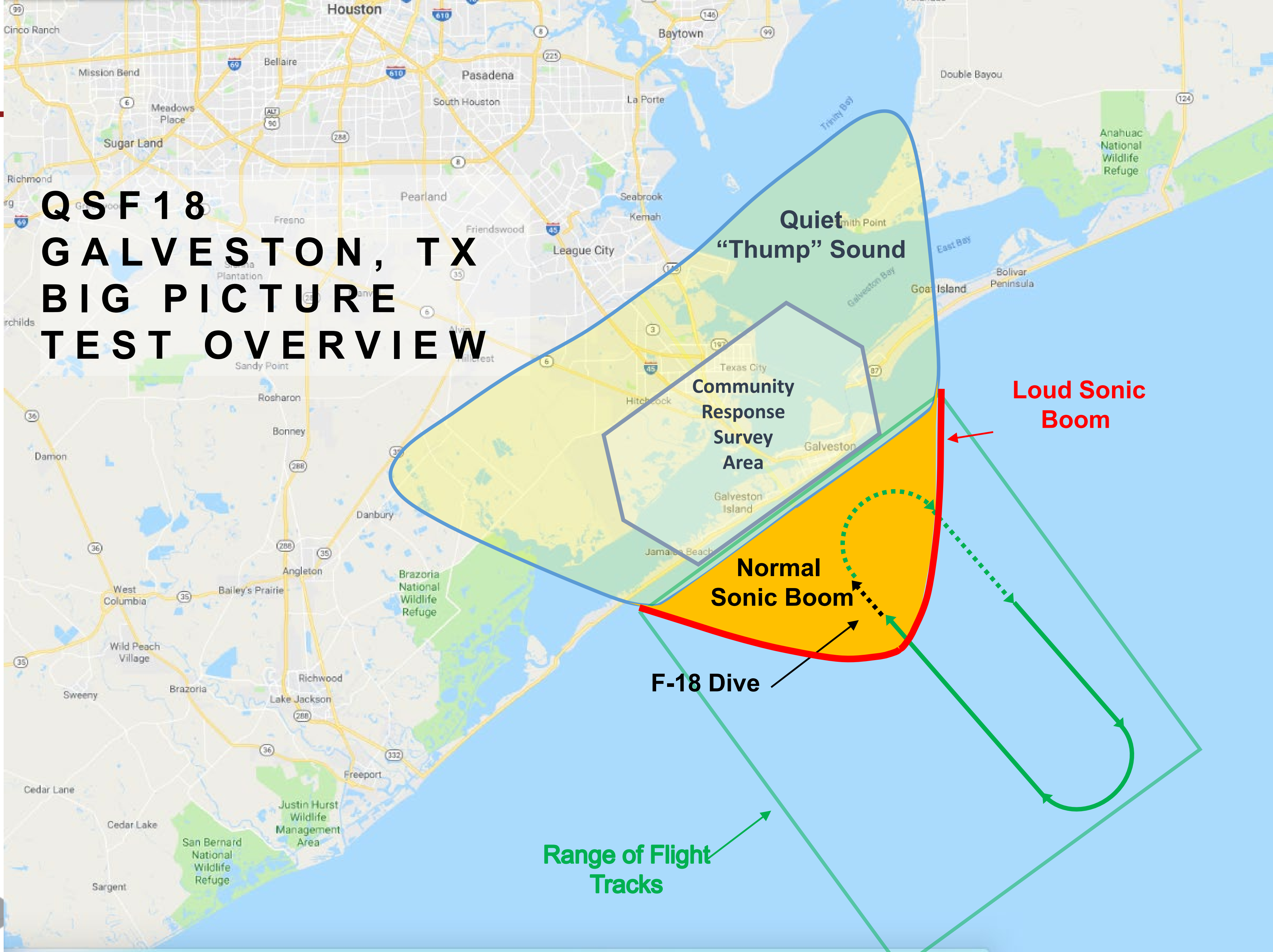
Low Boom Dive Maneuver – Propagation Distance



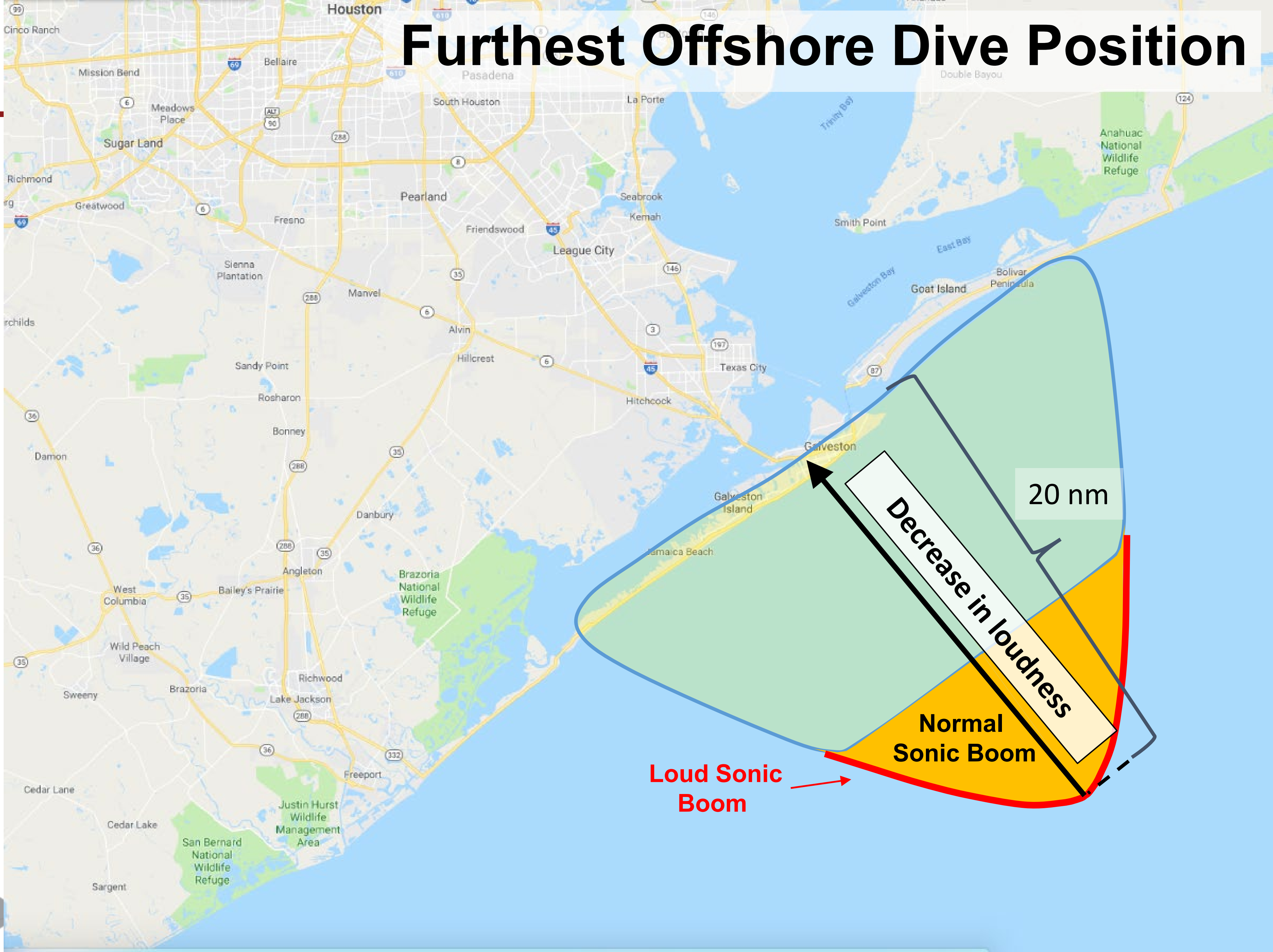
F-18 low boom dive maneuver

Low Boom Dive

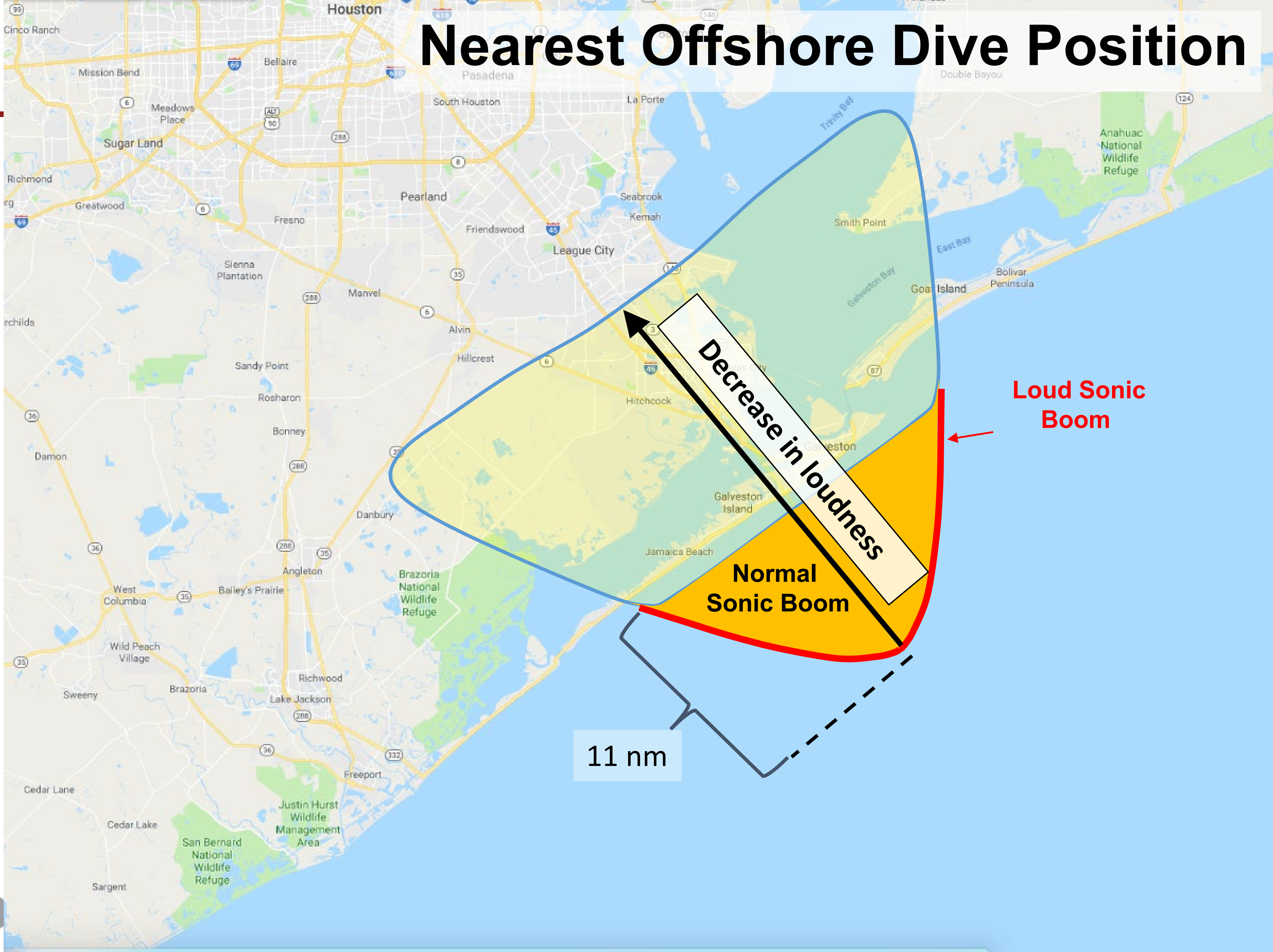
QSF18 GALVESTON, TX BIG PICTURE TEST OVERVIEW



Furthest Offshore Dive Position



Nearest Offshore Dive Position



Human Response Subject Surveys

National Aeronautics and Space Administration

Daily Summary Response Form

A1 Date: ______ / ______ (MM DD) ID: ____________

A2 Which parts of the day were you at home for at least one hour? (select all that apply)

1☐ Morning (7:00 AM to Noon) 3☐ Evening (5:00 PM to 7:00 PM)
2☐ Afternoon (Noon to 5:00 PM) 4☐ Not at home today *(end survey)*

A3 During the time you were at home today, how many sonic booms did you hear? (enter number below)

_____ # of sonic booms heard today *(If 0 booms heard today, go to A10)*

For the next questions, please think about the sonic booms you heard today while at home.

	(select one)	0 Not at all	1	2	3	4	5	6	7	8	9	10 Extremely
A4	How much did the sonic booms **bother, disturb,** or **annoy** you?	0☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	10☐

A5 Which of the following categories best describes how much the sonic booms **bothered**, **disturbed**, or **annoyed** you? (select one)

1☐ Not at all
2☐ Slightly
3☐ Moderately
4☐ Very
5☐ Extremely

	(select one for each)	0 Not at all	1	2	3	4	5	6	7	8	9	10 Extremely
A6	How **loud** were the sonic booms?	0☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	10☐
A7	How much did the sonic booms **interfere** with your activities?	0☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	10☐

	(select one for each)	0 None	1	2	3	4	5	6	7	8	9	10 A great deal
A8	Vibration is a motion. The motion may be seen or felt. How much **vibration** from the sonic booms did you see or feel in your home today?	0☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	10☐
A9	Rattle is a type of noise that can occur when objects move due to a vibration. How much **rattle** from the sonic booms did you experience in your home today?	0☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	10☐

A10 During the time you were at home today, were your windows closed most of the time or were they open most of the time? (select one)

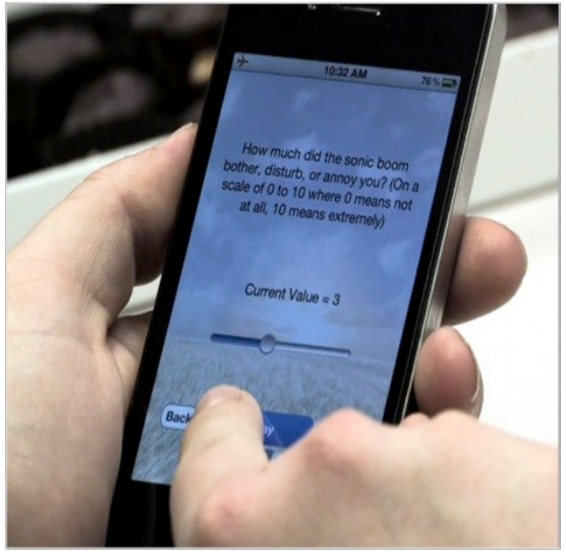
1☐ Closed most of the time 2☐ Open most of the time

A11 Did you hear any noises today that might have been sonic booms but you are not sure? (select one)

1☐ Yes —— A12 Please describe what that noise sounded like. ____________________
2☐ No

A13 Please enter any additional comments. ____________________

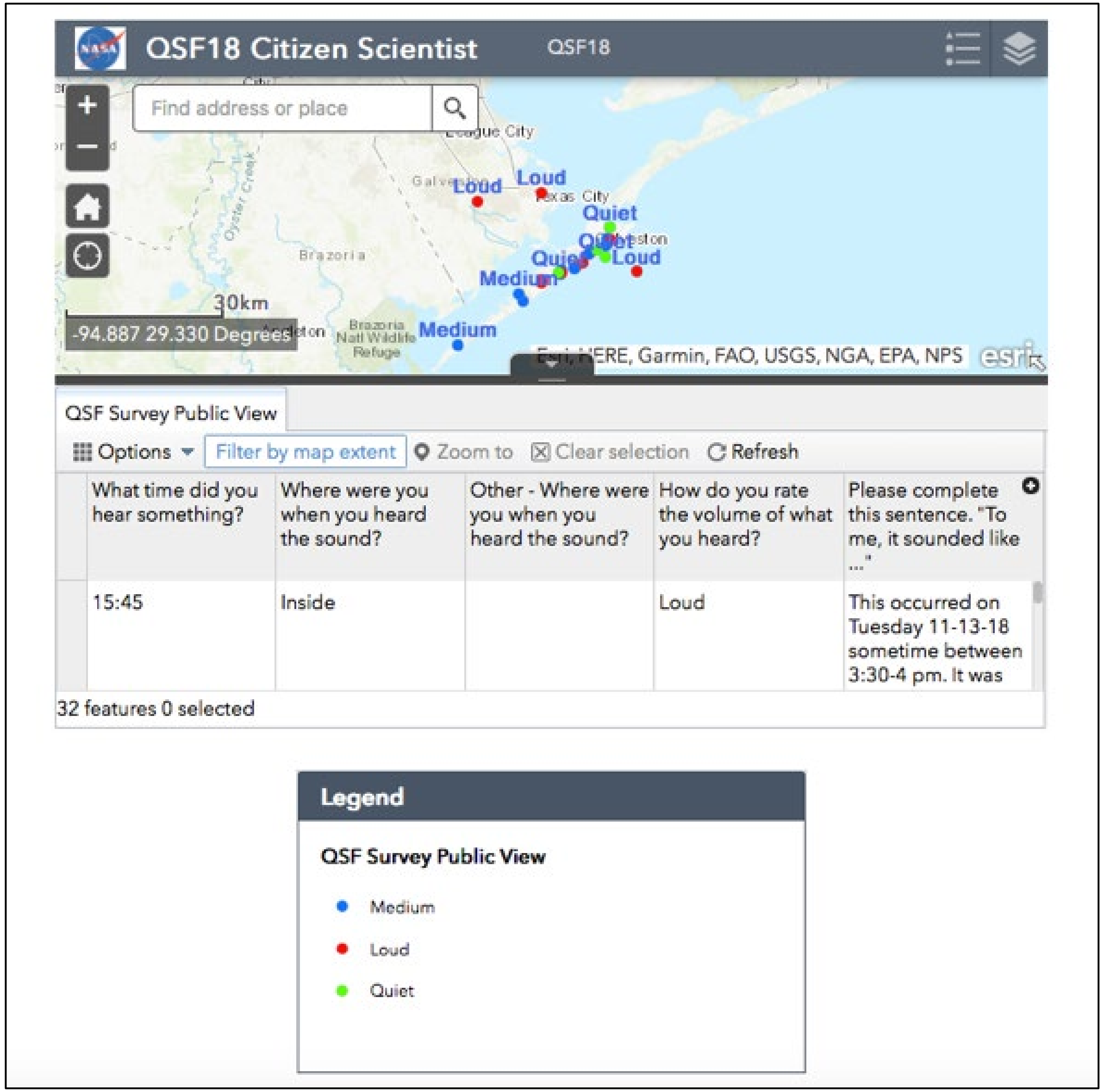
- Web-based surveys
  - Instruction via emails and phone calls
- Paper/Pencil surveys
  - Instructions and materials mailed via postal service
- Smartphone application surveys
  - Door-to-door installations for Apple® iOS application on subject-owned devices
  - Centralized meetings for distribution of Android™ phones with application pre-installed (to be returned after the project)



Source: Hodgdon, K. K., and Page, J. A., "Low Amplitude Sonic Boom Noise Exposure and Social Survey Design," Proceedings of Meetings on Acoustics, Vol. 19, ICA Montreal, Canada, 2013, pp. 1-6.

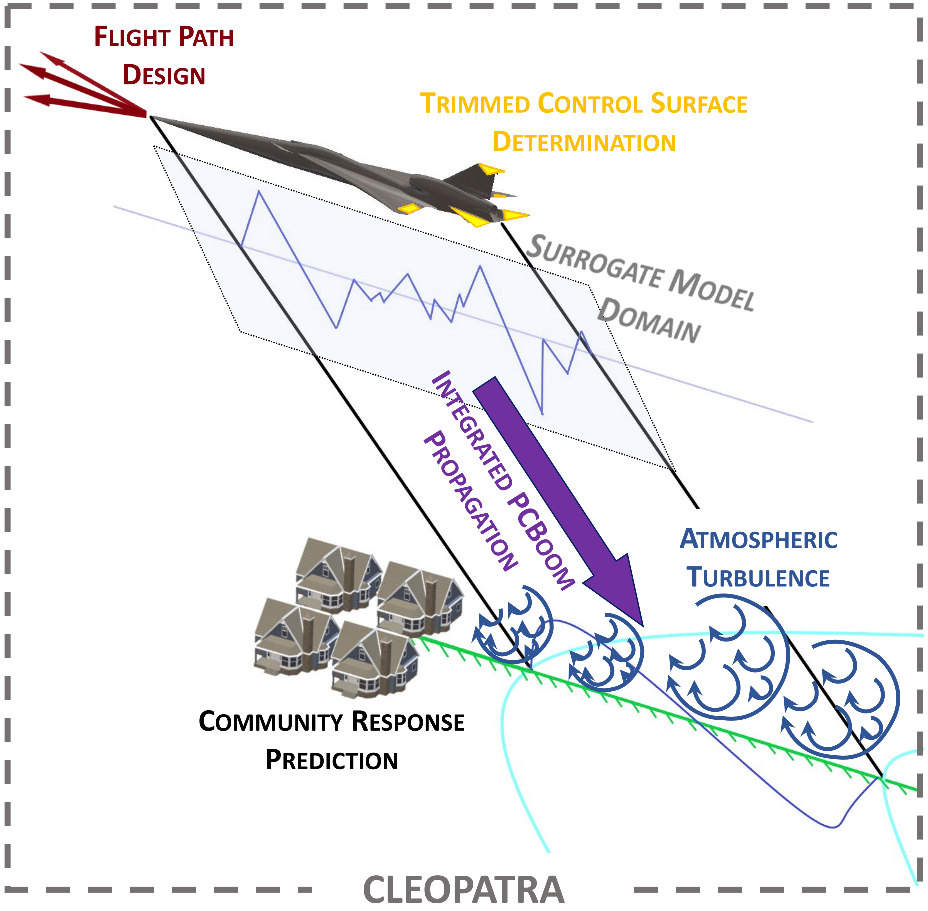
Citizen Scientist Activity

- Available to the general public via web page at nasa.gov
- Provided way for non-official respondents in the entire QSF affected area to comment
- Promoted via social media (Aero centers, JSC, Galveston City)
- Data was exported to researchers at end of flight campaign



CLEOPATRA - Community Low-boom Exposure, Operations, Piloting And Trimming Analyzer

- CLEOPATRA is a flight path planning tool developed for planning Quesst Phase 3 community overflights
  - Optimizes flight conditions and aircraft trajectory to meet a desired mean PLdB value placed over the test community
- CLEOPATRA relies on external, in-line execution of NASA PCBoom for sonic boom propagation
- Gaussian process surrogate model, trained with X-59 CFD data, queried during optimization to provide appropriate nearfield pressure field for sonic boom propagation
  - Surrogate model input are flight conditions (e.g., Mach, angle-of-attack, etc.) and trimmed control surface positions
- CLEOPATRA also capable of:
  - Training the nearfield surrogate model using CFD data
  - Determining “trimmed” values of angle-of-attack, engine throttle setting, and control surface positions needed as input to surrogate model
  - Applying empirical turbulence corrections to the desired PLdB
  - Performing post-flight analysis of as-flown trajectories
  - Performing simplified flight path planning without PLdB objective
- Programming Language: Python 3.8+



CLEOPATRA Software Architecture

- Software split into four operating modes: Train, Lite, Prime, and Post-flight:

"Train" Mode

- **Construct surrogate model from provided CFD database**

FEEDS INTO

"Lite" Mode

- **Used for pre-flight planning**
  - ✓ Quesst Phase II specific (and beyond)
- **Determines "optimal" trajectory placement needed to meet mission objective**
  - ✓ Example objective: place undertrack boom at (x, y)
  - ✓ Only modifies a trajectory's initial point and heading angle
- **Can be used without CFD surrogate model**

"Where to fly"

FEEDS INTO

"Prime" Mode

- **Used for pre-flight planning**
  - ✓ Quesst Phase III specific
- **Determines "optimal" cruise conditions (Mach, altitude, heading) to achieve desired loudness objective**
  - ✓ Surrogate modeling used to approximate CFD solution of trimmed aircraft nearfield cylinder for boom propagation
  - ✓ Atmospheric turbulence can be accounted for

"Where and how to fly"

FEEDS INTO

"Post-flight" Mode

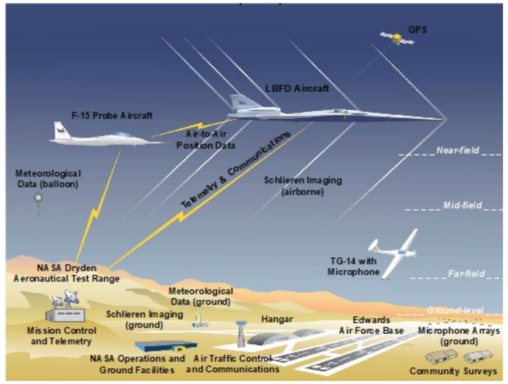
- **Used for post-flight analyses**
- **Utilizes measured data (e.g., trajectory, control surface positions, weather) to provide best prediction of conditions experienced**
  - ✓ CFD Surrogate model employed in a point-wise manner along trajectory to approximate "as-flown" nearfield conditions

"How loud do we think we were?"

Quesst Mission & X-59 Aircraft

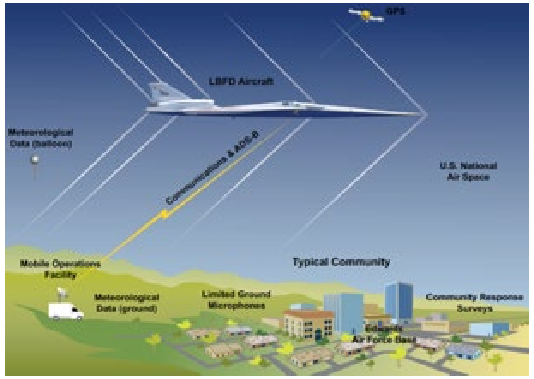
Quiet Supersonic Mission Overview – Phase 1

Phase 1 – Aircraft Development – *In progress (FY18-23)*
- Detailed design
- Fabrication, integration, ground test
- Checkout flights
- Subsonic envelope expansion
- Supersonic envelope expansion



Phase 2 – Acoustic Validation – *Preparation in progress (FY18-23) & Execution FY23-24*
- Aircraft operations & support, range Ops, support aircraft
- In-flight measurement capabilities
- Ground measurement capabilities
- Validation of X-59 boom signature and prediction tools
- Development of acoustic prediction tools for Phase 3

LBFD -	Low Boom Flight Demonstrator Project Integrated Aviation Systems Program
FDC -	Flight Demonstrations & Capabilities Project Integrated Aviation System Program
CST -	Commercial Supersonic Technology Project Advanced Air Vehicles Program

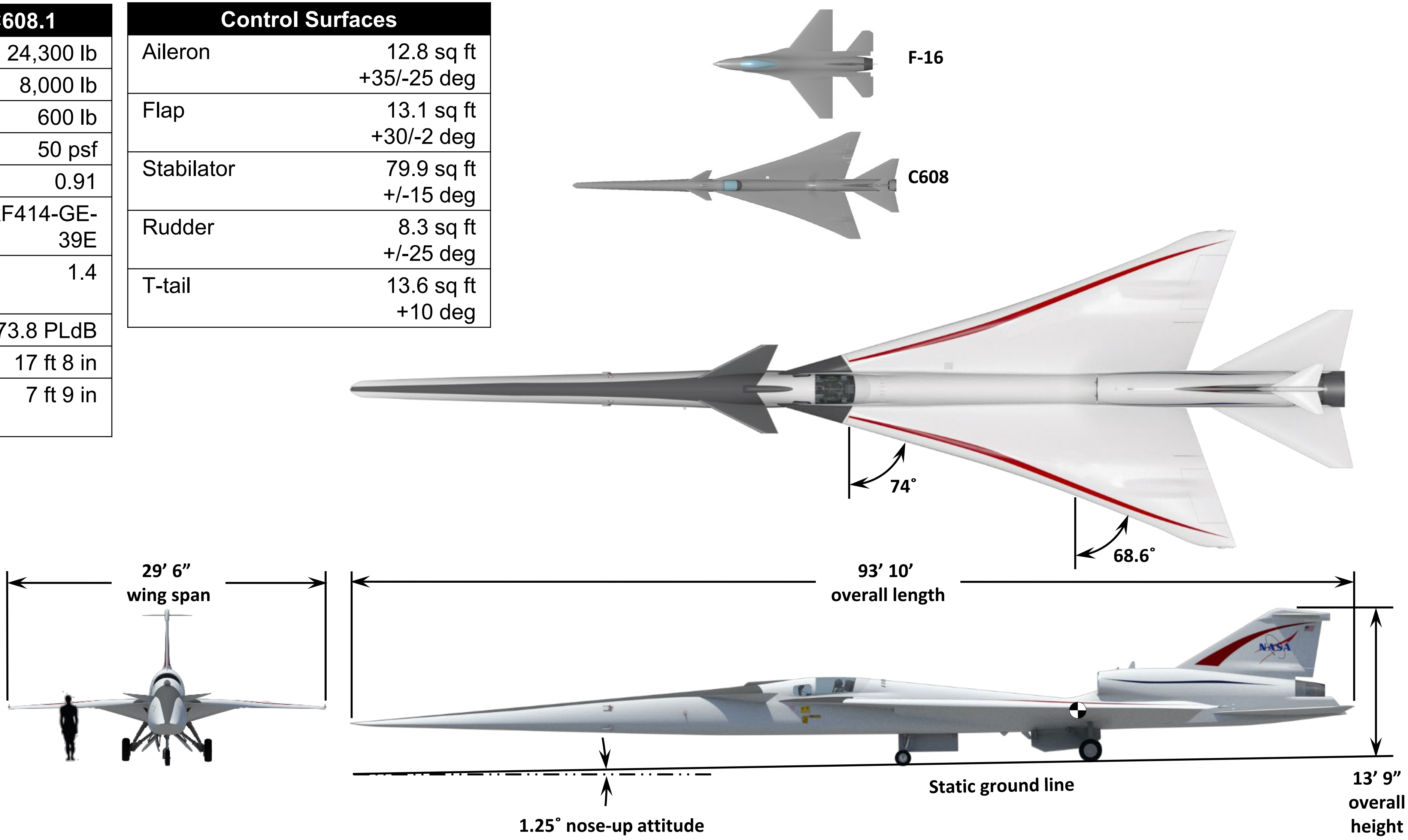


Phase 3 – Community Response Testing
Preparation in progress (FY19-24), Execution FY24-26
- Aircraft operations & support, deployment logistics
- Ground measurement capabilities
- Ground crew operations
- Noise exposure design
- Community response surveys
- Data analysis and database delivery

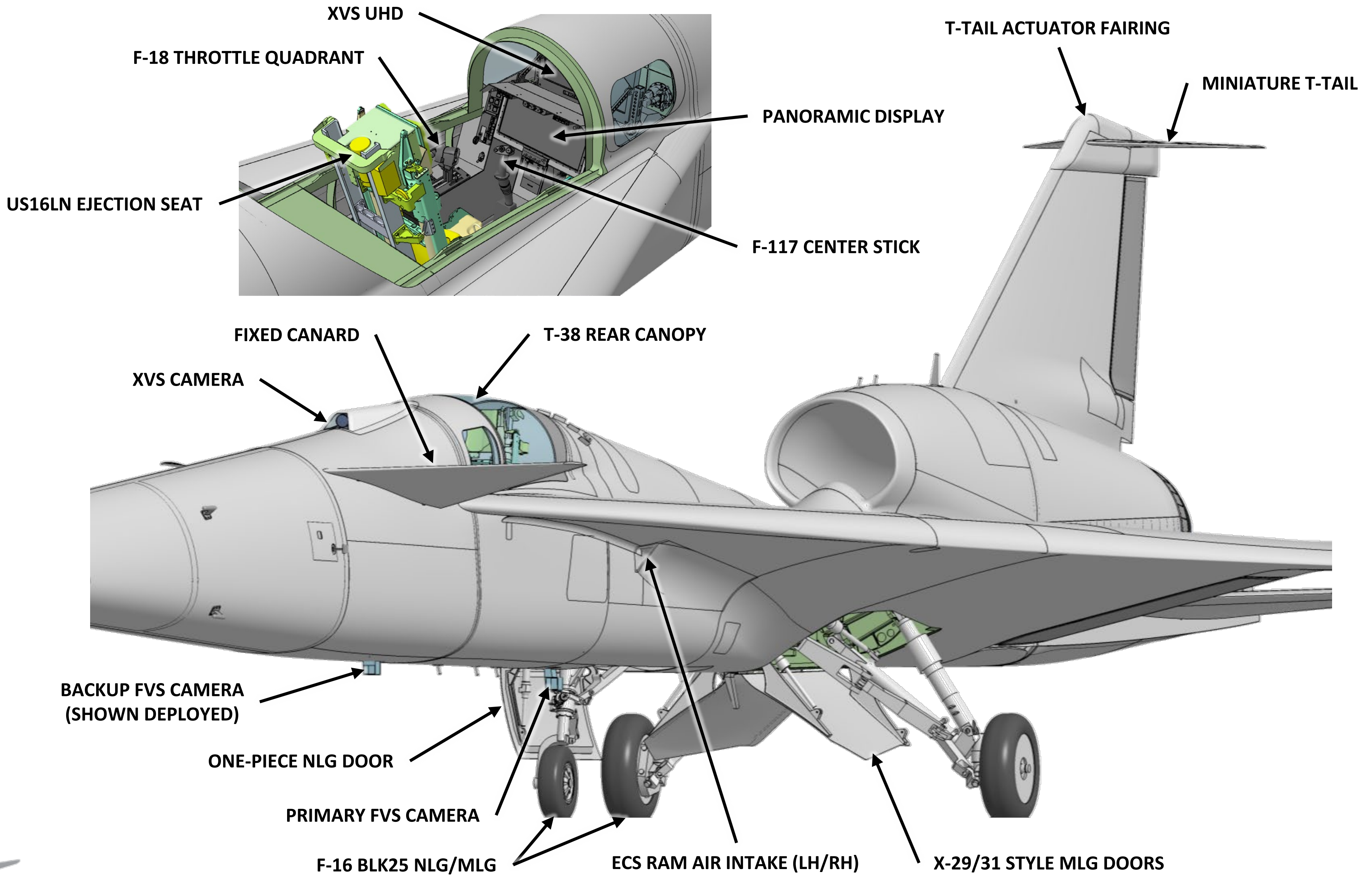
C608.1 General Arrangement

Configuration C608.1	
MTOW	24,300 lb
Fuel	8,000 lb
Payload	600 lb
W/S	50 psf
T/W	0.91
Engine	1xF414-GE-39E
Design Mach	1.4
Loudness	73.8 PLdB
Wheelbase	17 ft 8 in
Wheel track	7 ft 9 in

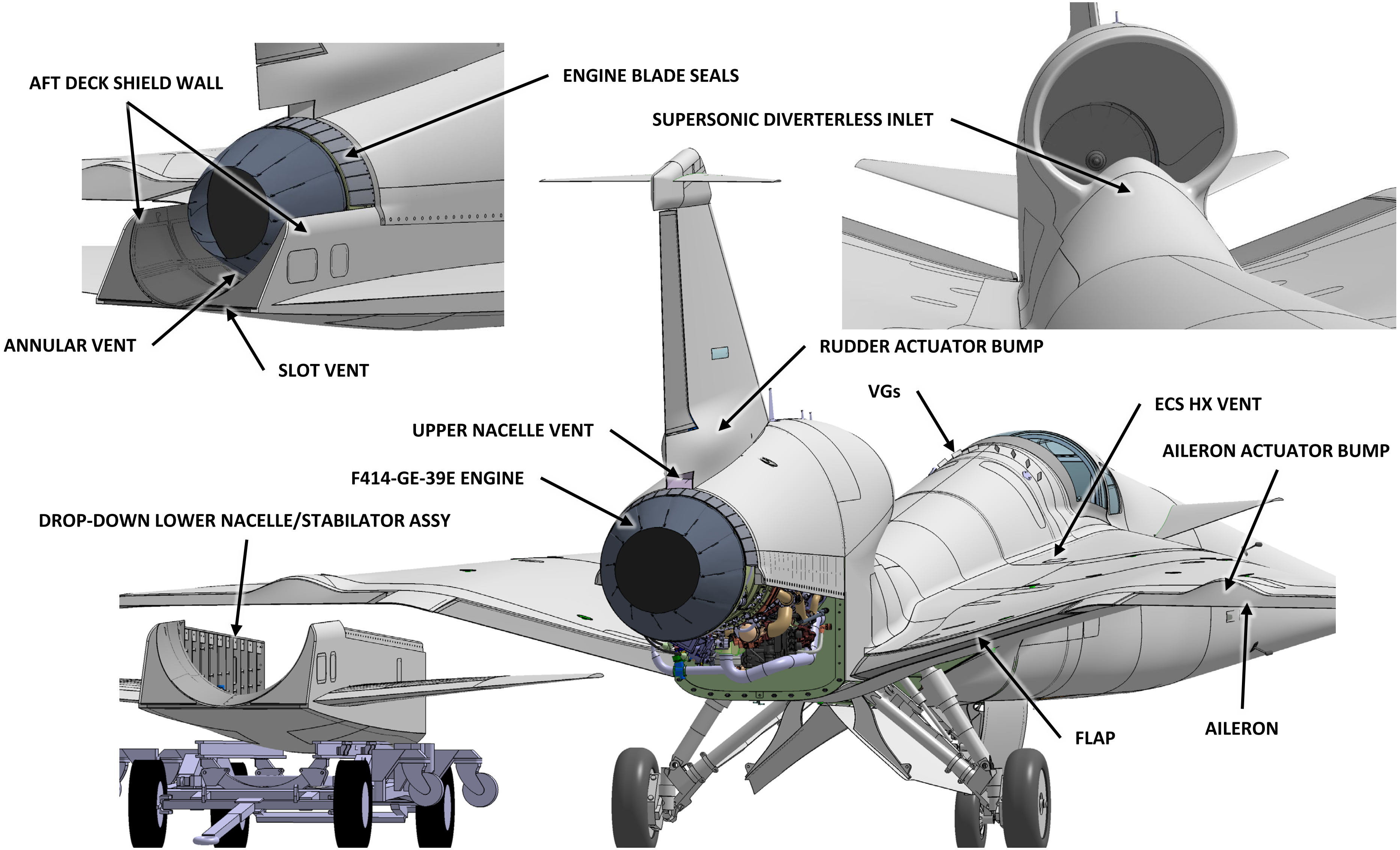
Control Surfaces	
Aileron	12.8 sq ft +35/-25 deg
Flap	13.1 sq ft +30/-2 deg
Stabilator	79.9 sq ft +/-15 deg
Rudder	8.3 sq ft +/-25 deg
T-tail	13.6 sq ft +10 deg



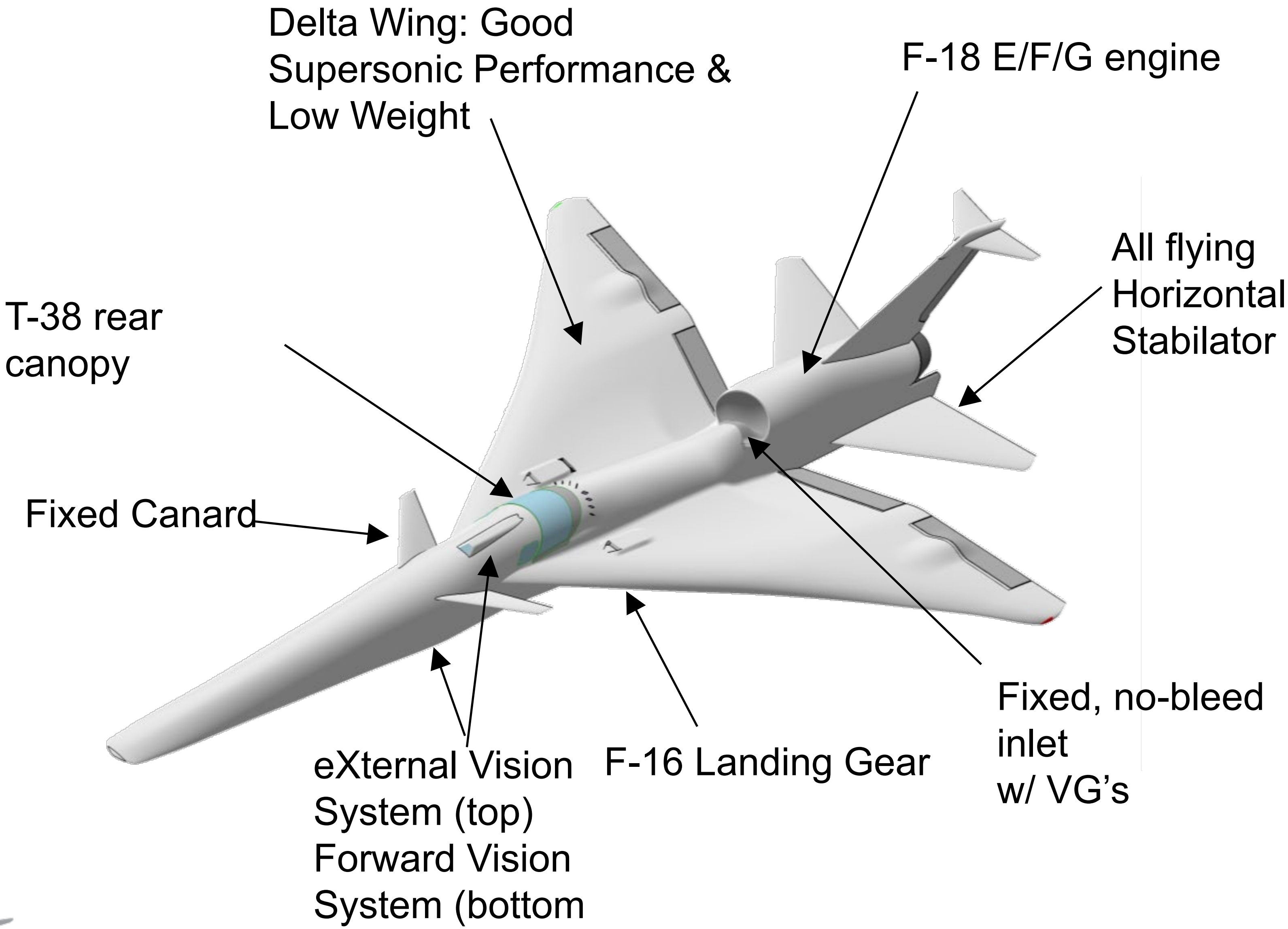
Walkaround – Aircraft Configuration: C608.1



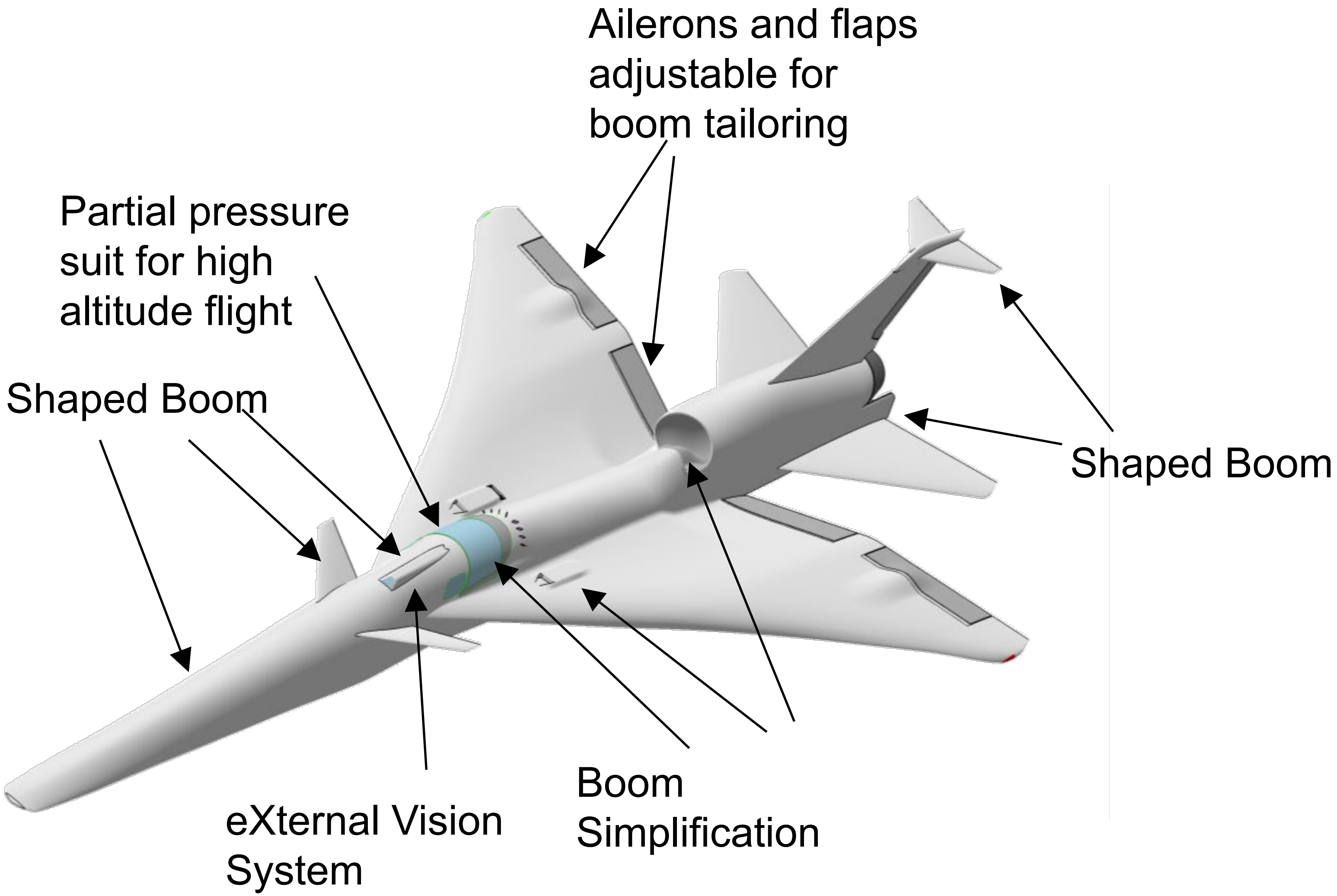
Walkaround (cont'd) – Aircraft Configuration: C608.1



X-59: Key features

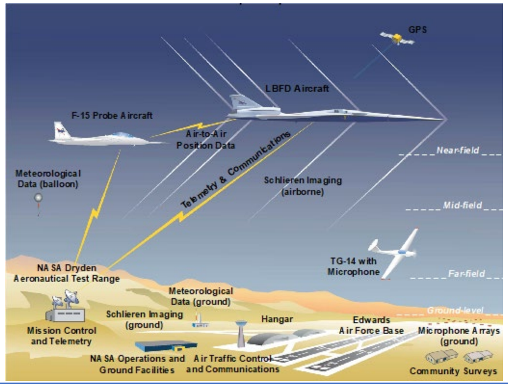


X-59: Key boom details



Quiet Supersonic Mission Overview – Phase 2

Phase 1 – Aircraft Development – *In progress (FY18-23)*
- Detailed design
- Fabrication, integration, ground test
- Checkout flights
- Subsonic envelope expansion
- Supersonic envelope expansion



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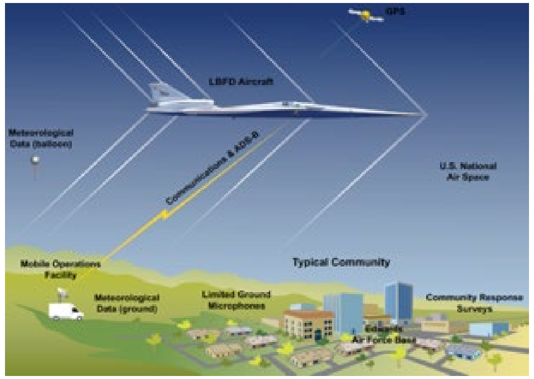

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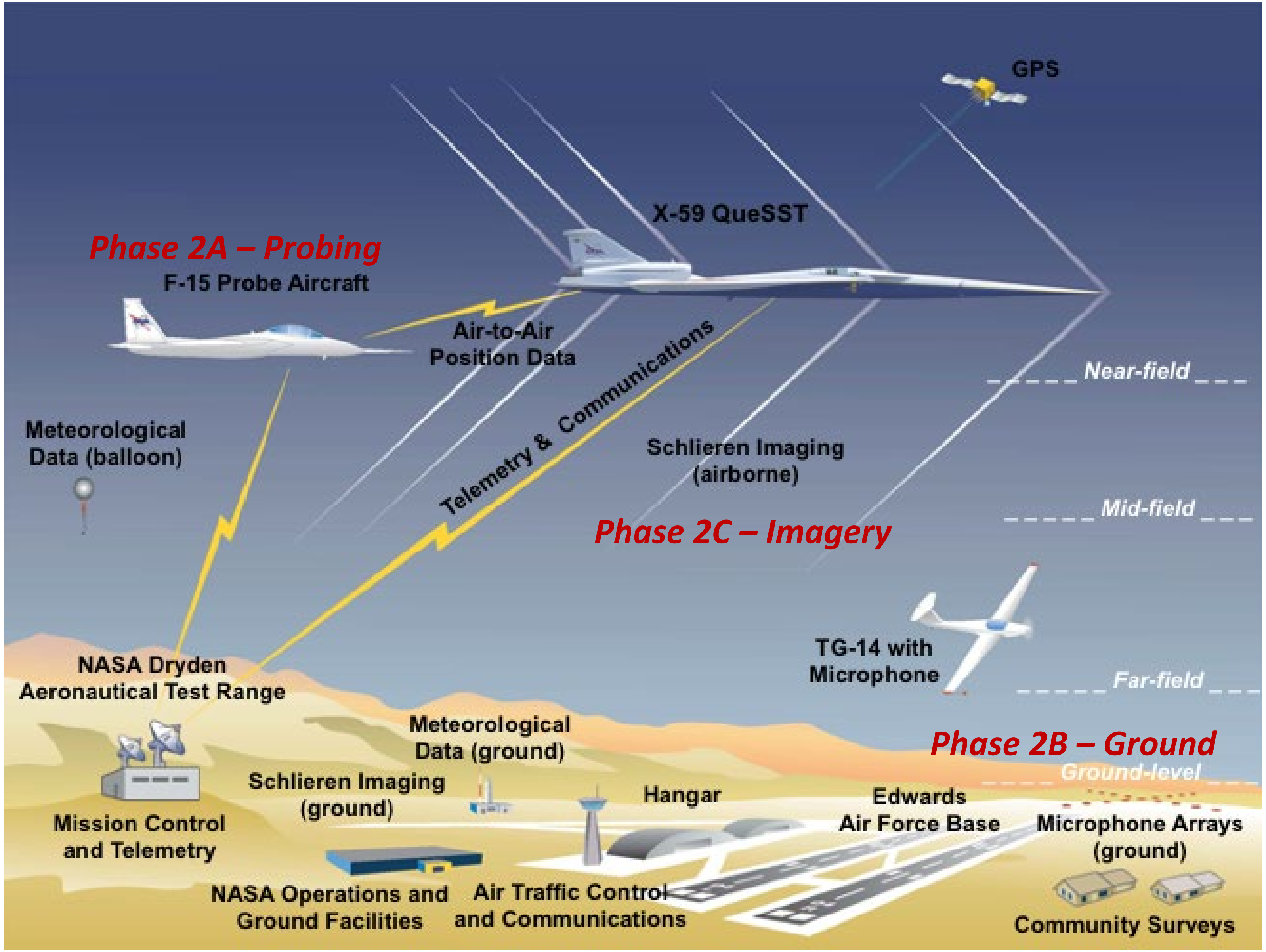
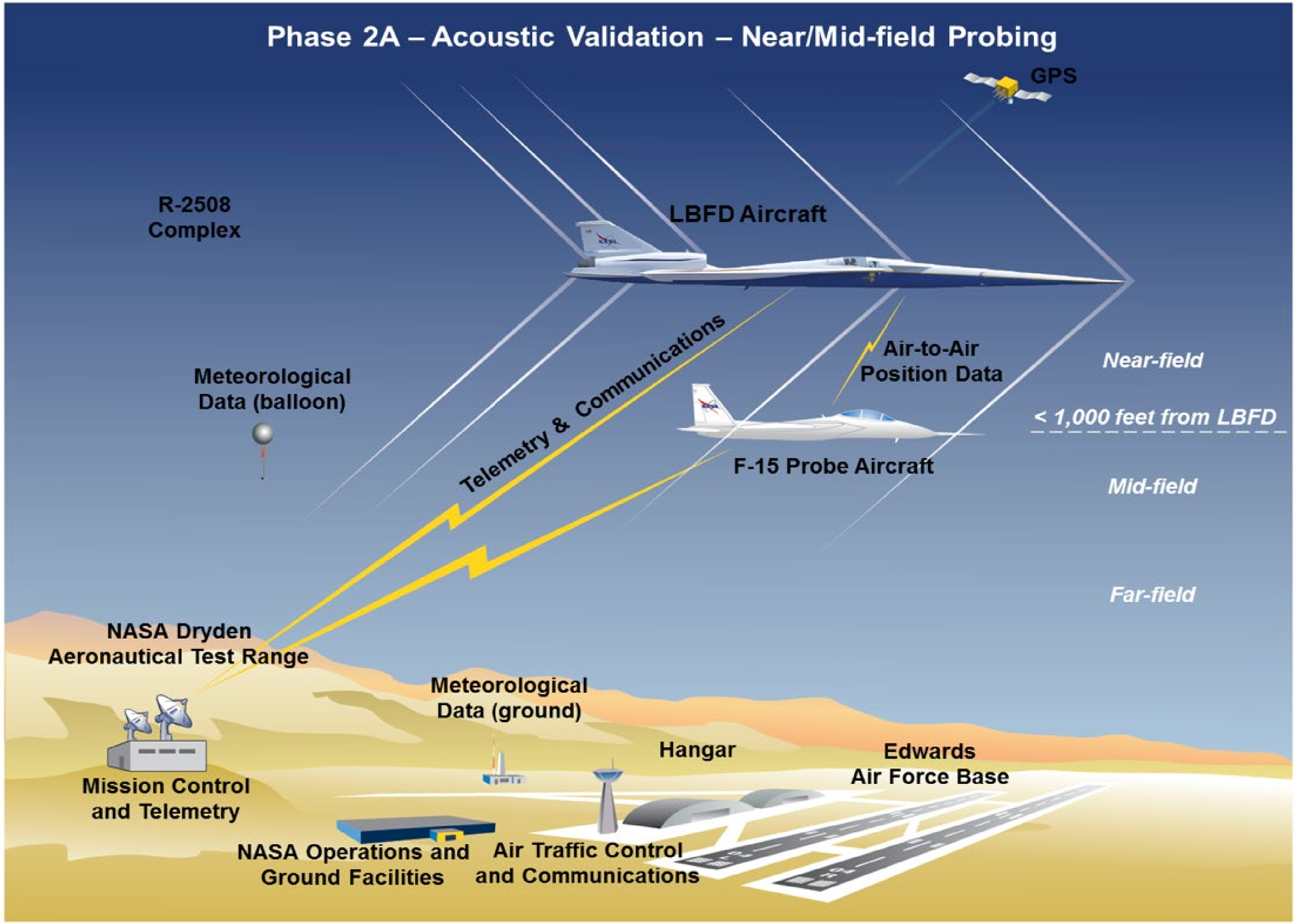


LBFD Phase 2 Combined Concept of Operations

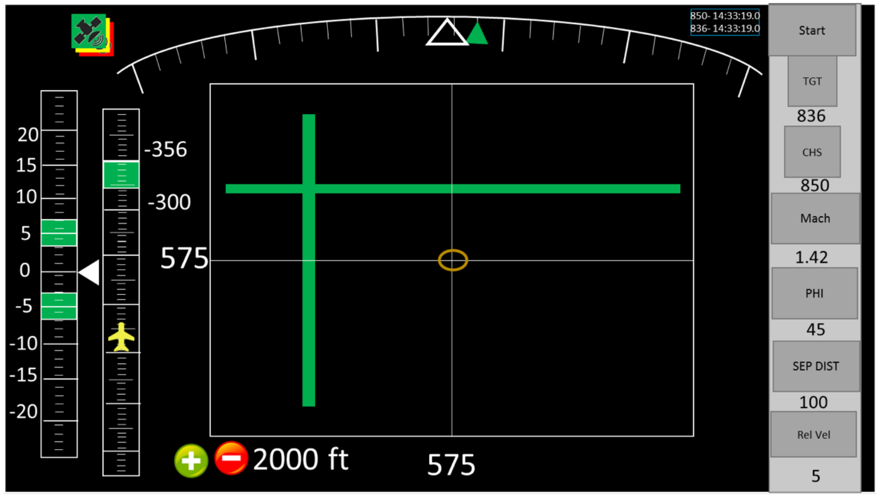
Phase 2A: Near/Mid-Field Probing Flights



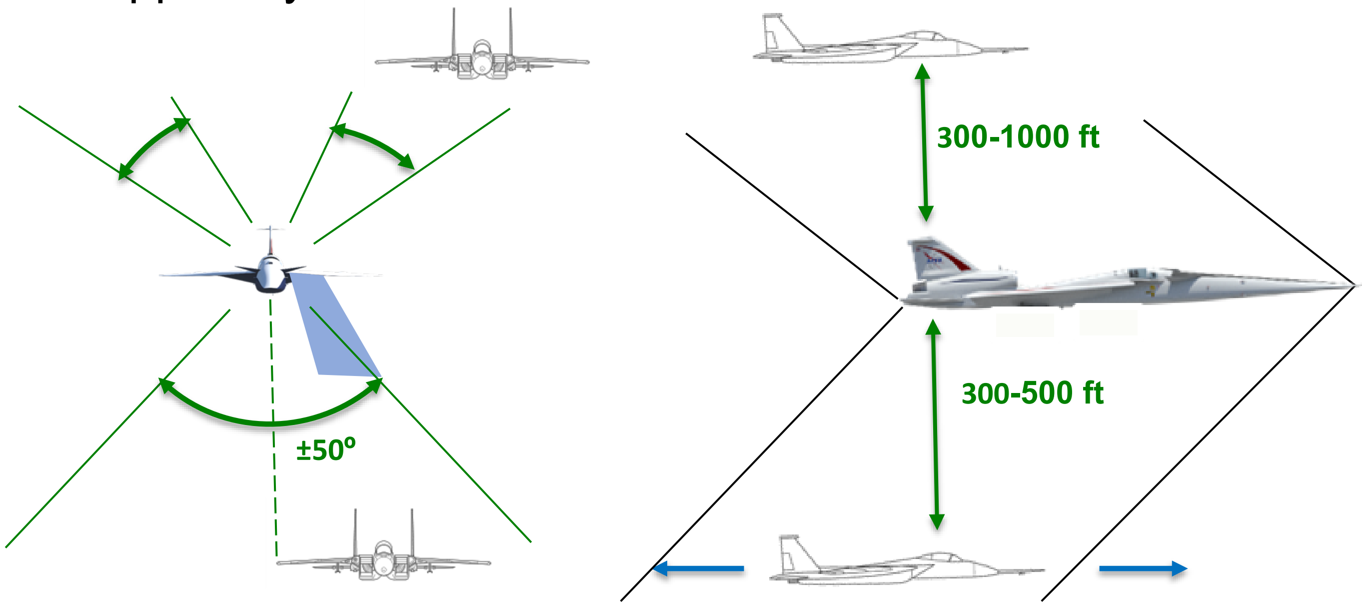
Phase 2A Probing: Flight Positioning

20 Flights	2 / day

- X-59 flies at low-boom design cruise conditions
- F-15 flies relative to X-59 – forward and aft for multiple passes
  - 25 test points 300-500 feet below X-59 (±50º lateral offset below)
  - Six test points 300-1,000 feet above X-59
  - Six test points 20,000 feet below X-59 (±20º mid-field)
- Research Support Aircraft (F-15)
  - Shockwave Sensing Probe and Modified Life Support System

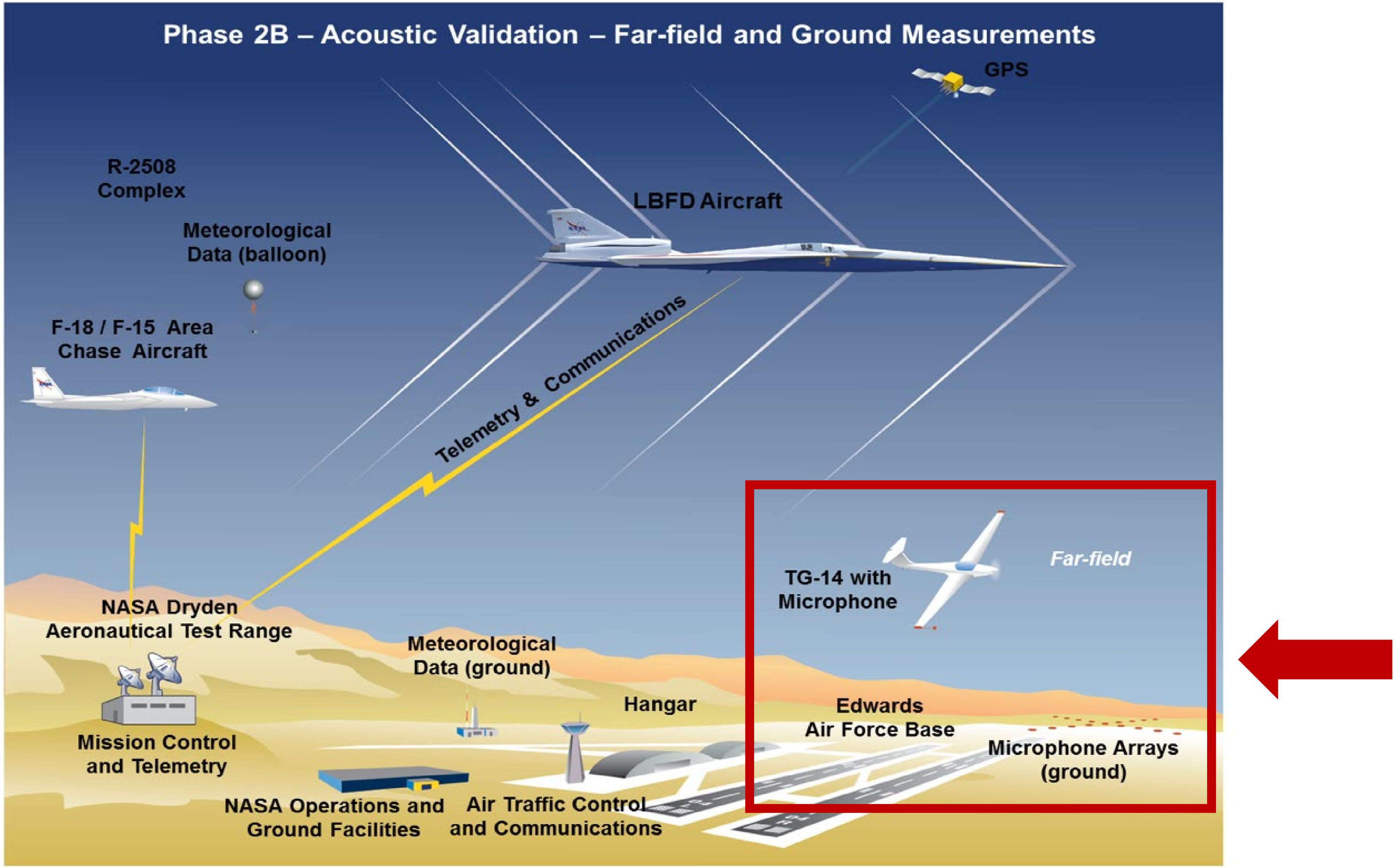


F-15 Probing Positioning Display Prototype
Source: FDC project (ALIGNS)



X-59 and F-15 Relative Positions

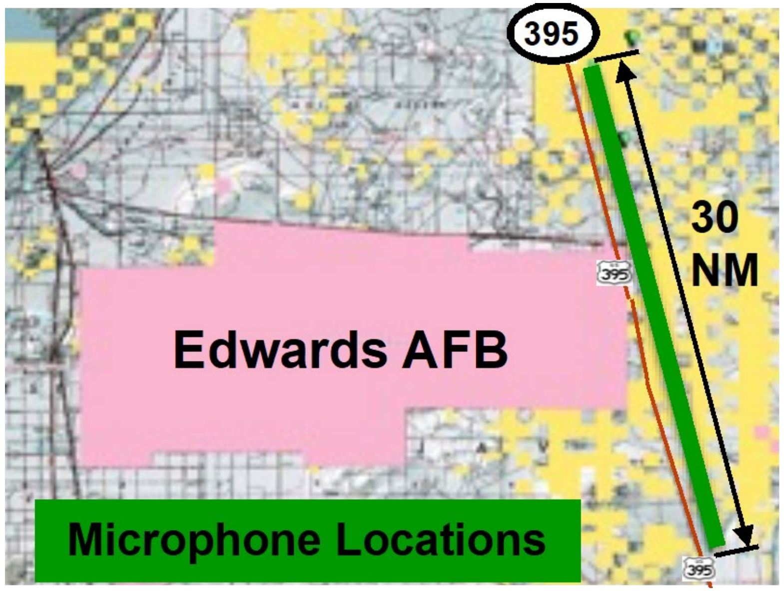
Phase 2B: Far-Field and Ground Measurement Flights

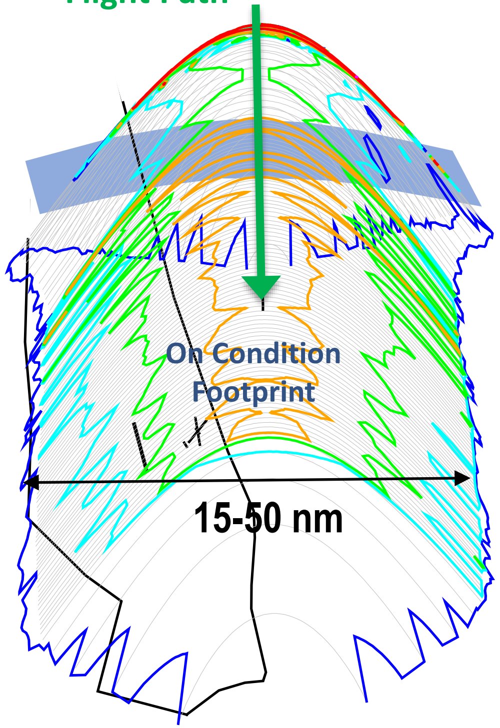


Phase 2B: Far-Field and Ground Measurement Flights

30 Flights	2-3 / day

- X-59 flies at low-boom design conditions
  - Flies a precise position based on weather data for the boom carpet to hit the microphone array
  - TG-14 above the turbulent layer in-line with microphones
- Large microphone array required
- Area Chase Aircraft (F-15 or F-18)
  - Used for departure, recovery and emergency support
  - Positioned away from X-59 during boom recording



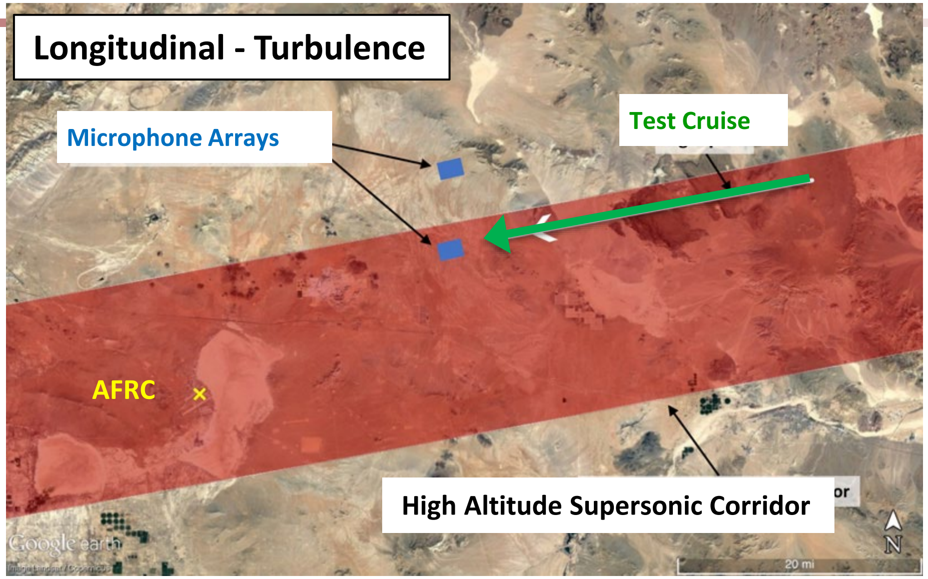


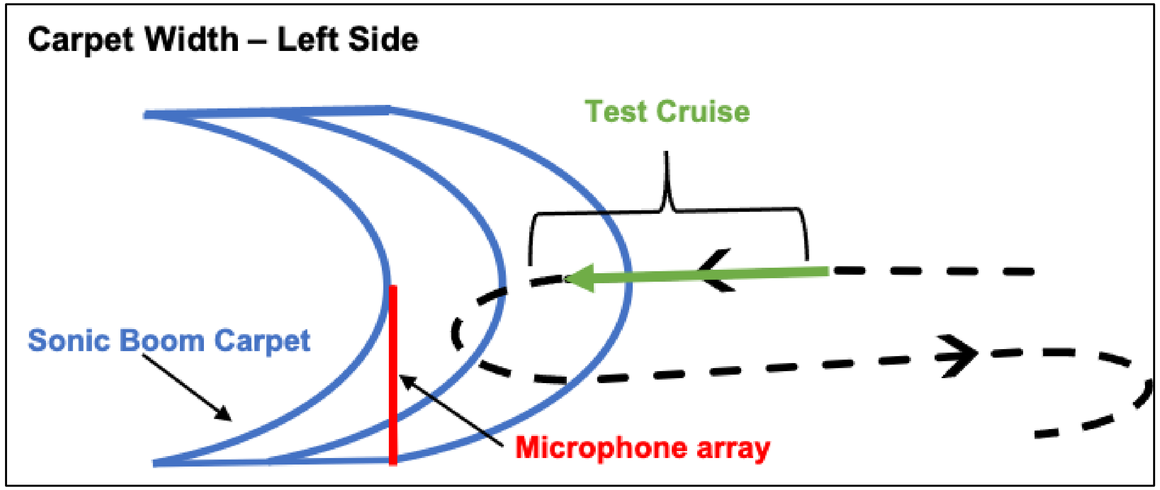
Sonic Boom Carpet

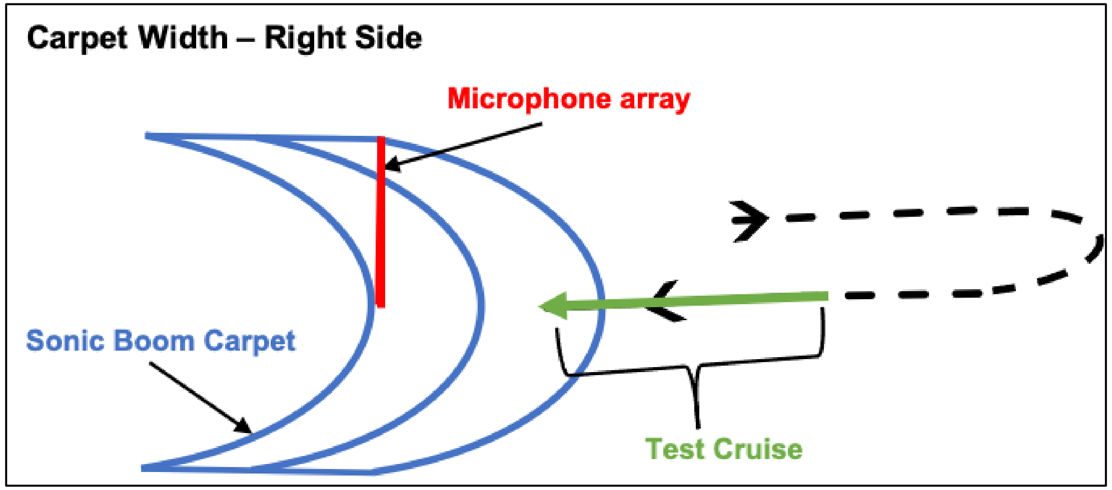
Source: CST Project (SonicBAT2)

Phase 2B Far-Field: Flight Profile and Airspace

- Longitudinal Measurements
  - Turbulence
  - Accel Boom Measurement
  - 2 passes per flight
- Carpet Width Measurements
  - Boom carpet < 50 nm 90% of time
  - 30 nm microphone array
  - Requires 2 passes

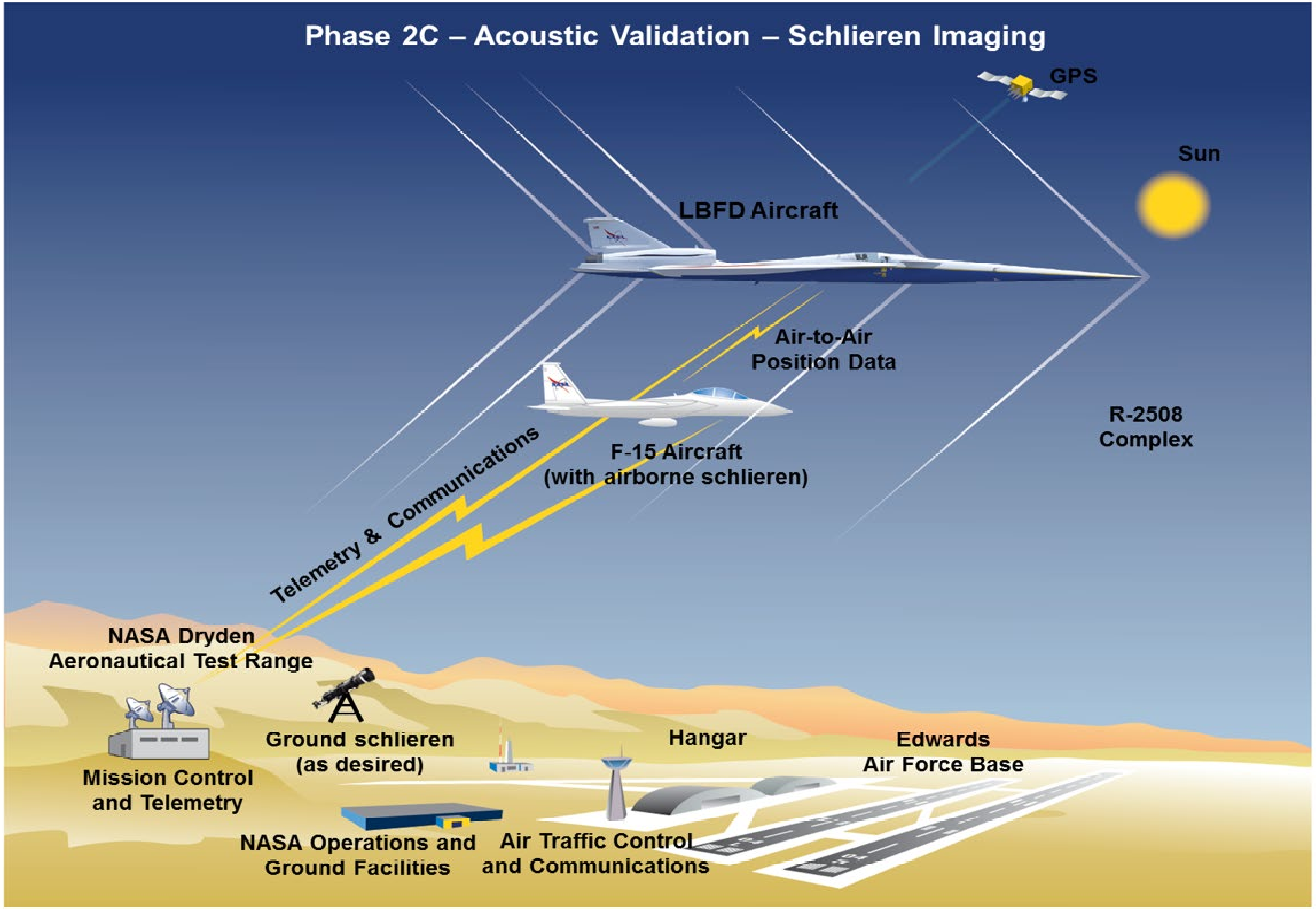






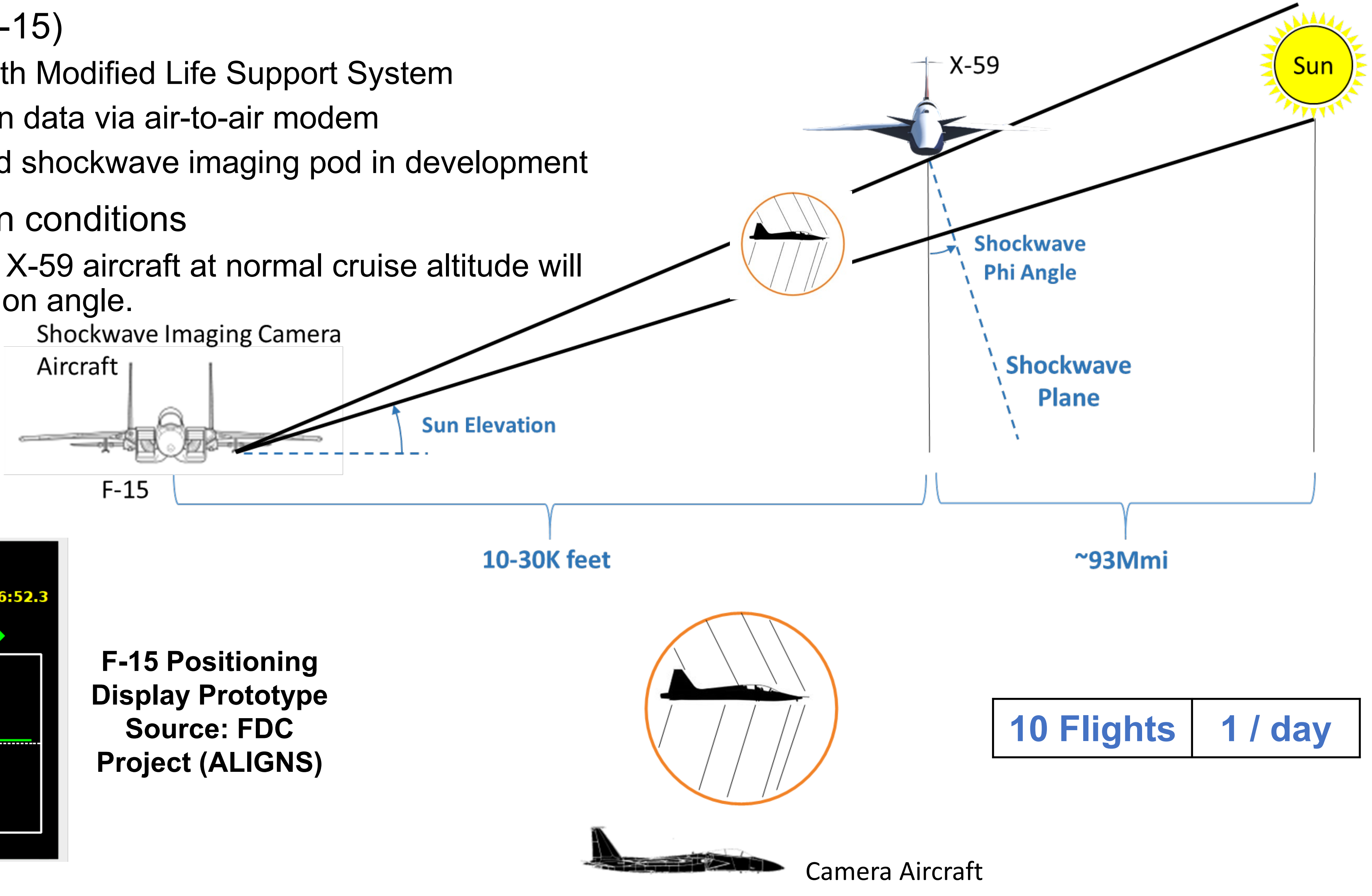
Carpet Width Measurements

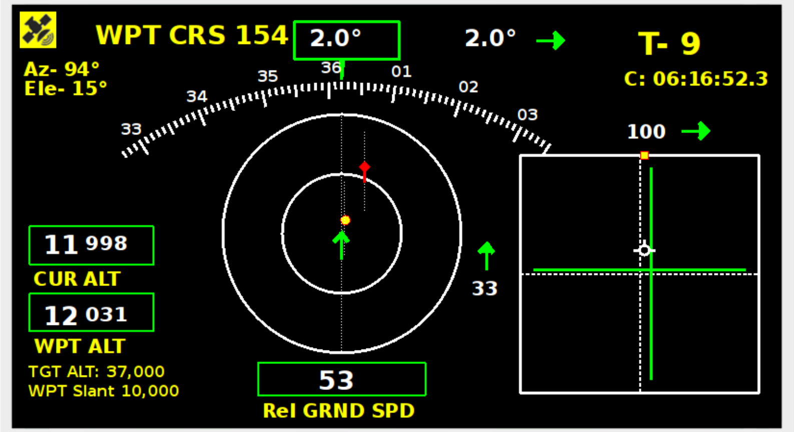
Phase 2C: Shockwave Imaging Flights



Phase 2C: Shockwave Imaging – BOSCO for X-59

- Research Support Aircraft (F-15)
  - Shockwave imaging pod with Modified Life Support System
  - Requires X-59 GPS position data via air-to-air modem
  - F-15 positioning display and shockwave imaging pod in development
- X-59 flies at low-boom design conditions
  - Imaging of shocks beneath X-59 aircraft at normal cruise altitude will require very low sun elevation angle.
  - Low elevation angles will require small differential altitude, So future imaging system will be airborne.





F-15 Positioning Display Prototype Source: FDC Project (ALIGNS)

10 Flights	1 / day

Quiet Supersonic Mission Overview – Phase 3

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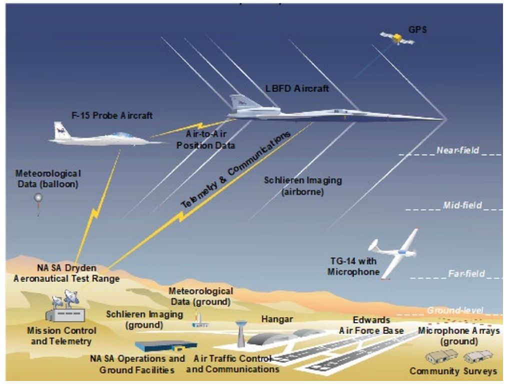

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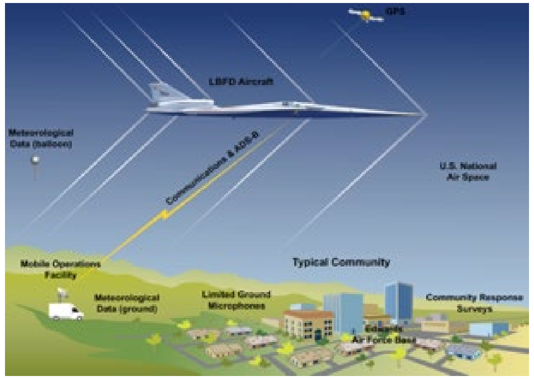

Phase 3 – Community Response Testing
Preparation in progress (FY19-24), Execution FY24-26
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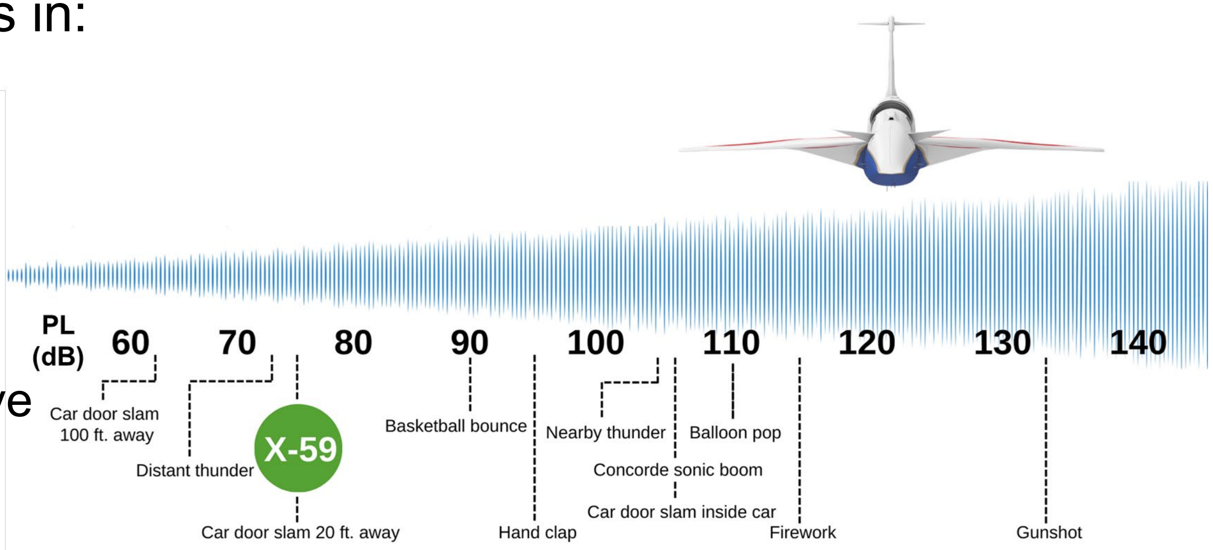
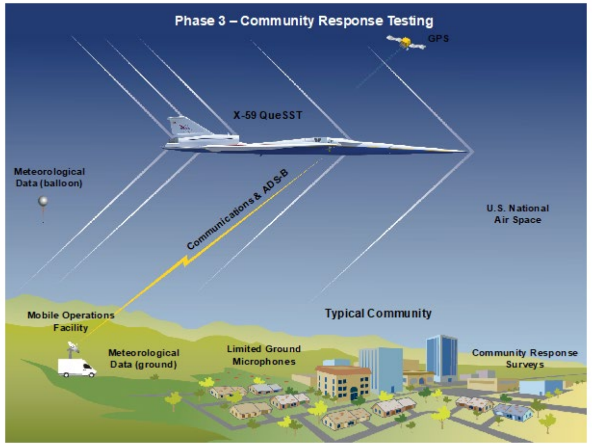
- Ground crew operations
- Noise exposure design
- Community response surveys
- Data analysis and database delivery

LBFD Mission Phase 3 – Community Response Testing

FOCUS: Provide data to support noise certification standards development

- 4-6 community tests over multiple sites, w/ variations in:
  - Climate zones
  - Population demographics
  - Urbanization levels
- Scope
  - Daytime/waking hours
  - Range of exposure levels, single-event and cumulative
  - Community response representative of general population

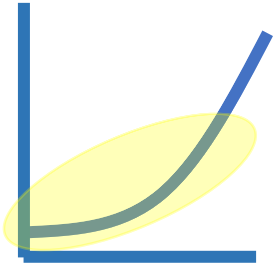




→

- **Exposure Estimation**
- **Community Surveys**

→



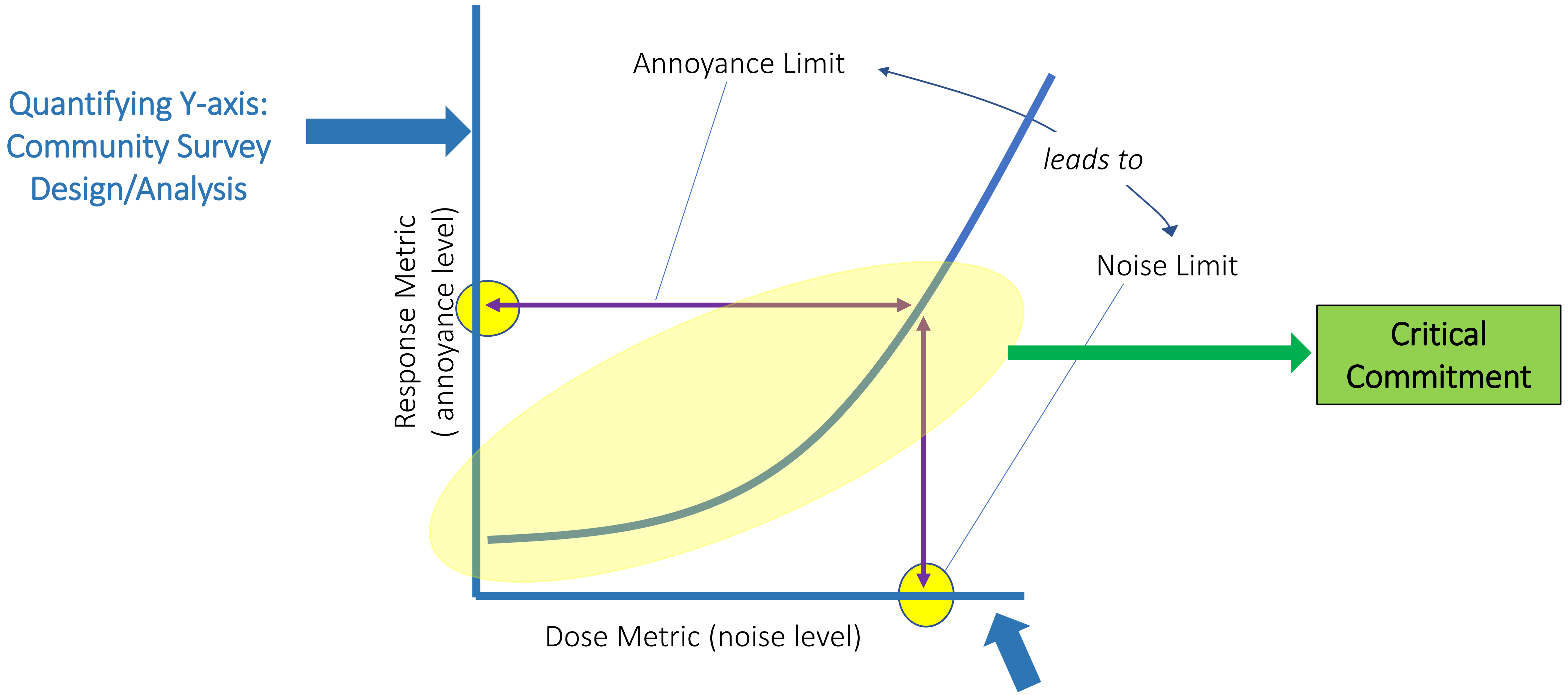
Dose-Response Relationship

→

ICAO CAEP 14

Credit: Gautam Shaw

Dose – Response Characterization



Quantifying X-axis: Exposure Design and Estimation

Credit: Gautam Shaw, NASA LaRC

X-59 Community Test – Expansion of Recent Studies

	WSPR 2011	WSPRRR 2017	QSF18 2018	X-59 2024-26
Research Goal	Pilot Study	Risk Reduction	Risk Reduction	Data for Regulators
Aircraft	F-18	F-18	F-18	X-59 Quesst
Location	AFRC/EAFB	AFRC/EAFB	Non-NASA	Non-NASA (multiple)
Acoustic Data Coverage (sq mi)	1	12	60	~2500
Number of survey participants	100	61	500	~10K
Number of flight days	10	3	9	20-30

Key Challenges of Scaling Up for X-59

- Non-NASA locations
  - X-59 operations infrastructure
  - Expanded public outreach
  - Flight planning / airspace coordination
- Survey design/management
  - Multi-thousands of participants
  - Aggregation/geolocation of responses
  - Automation of data processing
- Acoustic measurements
  - Land use / approvals
  - Hardware robustness and security
  - Remote operation/data transmission
  - Communications connectivity/reliability
  - Automation of data processing

Survey Goals

- Primary Goals
  - Develop an accurate nationwide estimate of the **single-event** dose-response relationship between the proportion of the population annoyed (to varying degrees) by supersonic overflights and acoustical data (measured and modeled) that characterize single-event noise exposure.
  - Develop an accurate nationwide estimate of the **cumulative** dose-response relationship between the proportion of the population annoyed (to varying degrees) by supersonic overflights and acoustical data (measured and modeled) that characterize cumulative noise exposure.
- Secondary Goals
  - Assess the effect of indoor **noise-induced rattle sounds and vibration** on dose-response relationships
  - Assess the effect of **location** (home vs. work. vs. somewhere else, indoor vs. outdoor, and indoor with windows open vs. closed) on dose-response relationships.
  - Assess the effect of **time-of-day** on sonic thump perceptions (daytime vs. evening).
  - Assess the prevalence of **"startle"** in sonic thump perceptions.

Credit: Jonathan Rathsam, NASA LaRC

Exposure Design

- Range of doses
  - Both single-event and daily dose are being considered
  - Limited by X-59 operational constraints
  - Single-event exposure design will target 15-20 dB range around X-59 cruise design point of PL = 75 dB
    - PL ~ 70-87 dB
  - Resulting cumulative dose range (1-6 thumps per day)
    - PLDNL ~ 20-45 dB
- Dose distribution and scheduling
  - Design allows for varying levels and number of events to achieve desired range and distribution
  - Times of day and weekdays/weekends will also be randomized
    - Spacing of at least 20 minutes
  - 80-90 thumps per community test
- Test length
  - ~20 flight days over one month

QUESTIONS?

Phase 2 Test Approach

- Near-Field shock measurements
  - ≈ 65 Total test points (two measurements each)
  - ≈ 12 measurements per flight
  - Conditions:
    - Design cruise
    - Control surface/CG/trim optimization
    - Off-condition, varying Mach
    - New optimal boom condition (if found)
  - Primary points are 3 BL separation, 0- and 20-deg phi
  - One flight over the microphone array, per flight
- Sonic boom carpet characterization
  - ≈ 24 measurements, 2 measurements per flight
  - Mostly design cruise
  - High PLdB points (Mach 1.3, 43 kft & Mach 1.4, 46 kft.)

Phase 1 - Aircraft Development	# Flights
Before Flight – System Checkouts	
• Functional Checkout (PMD)	5-10
• Envelope Expansion (AFRC)	35-50
	40-60
Phase 2 – Acoustic Validation	
2A Near/Mid-Field Probing	20
2B Far-Field & Ground Measurements	30
	10
2C Schlieren Shockwave Imaging	60
Phase 3 – Community Response	
3A Community Response (AFRC)	30
3B Community Response (deployed)	30 each
	300*

Planned Mission Flights

Phase 2 Test Approach (2)

- Mid-field shock measurements
  - ≈ 8 measurements, 2 measurements per flight (could improve with updated ALIGNS)
  - Design cruise
  - 20 kft separation, 0- and 25-deg phi
- Focus measurements
  - ≈ 12 measurements, 2 measurements per flight
  - Repeatable transition focus (could include push-over focus)
- Turbulence measurements
  - ≈ 12 measurements, 2 measurements per flight
  - Design cruise, varying turbulence levels
- Shockwave imaging (schlieren)
  - ≈ 8 measurements, 2 measurements per flight
  - Design cruise

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Planned Mission Flights