

Acoustics at NASA

Community Testing with Quiet Supersonic Aircraft

Alexandra Loubeau, NASA Langley Research Center

University of Memphis Summer Camp - Acoustics

June 16, 2023

www.nasa.gov

Image Credit: Lockheed Martin

Acknowledgments



➤ NASA

- Commercial Supersonic Technology project
- Community Test Planning & Execution team

➤ Industry, government, and university partners



About Me

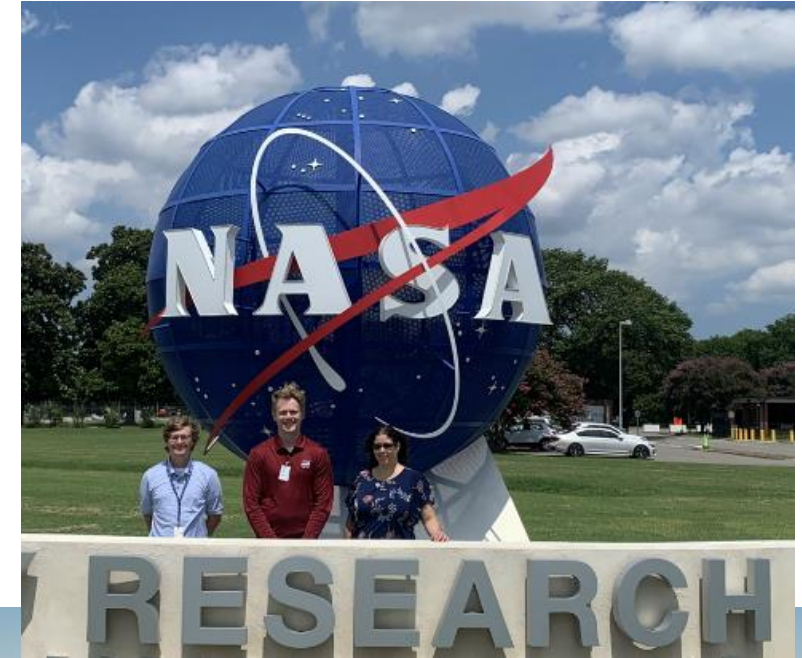


- **B.M. Music Engineering, minor Electrical Engineering**
 - University of Miami
- **M.S. and Ph.D. Acoustics**
 - Penn State
- **Post-doc in sonic boom propagation**
 - Sorbonne University, Paris, France
- **Research Aerospace Engineer**
 - Structural Acoustics Branch, NASA Langley Research Center



➤ Research Aerospace Engineer

- Structural Acoustics Branch
- Team co-lead for Community Testing with X-59
 - Planning, execution, and analysis of experimental, modeling, and psychoacoustics research
 - Field testing
- Mentor
- POC for agreements
 - Industry, government, universities, international
- ICAO standards development



NASA Mission Directorates

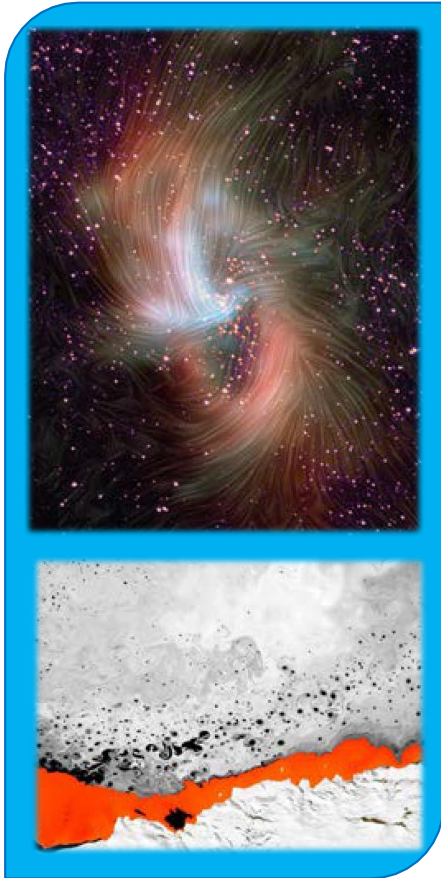


Aeronautics Research



Transform Aviation through R&D

Science



Understand the Sun, Earth, and Universe

Space Technology



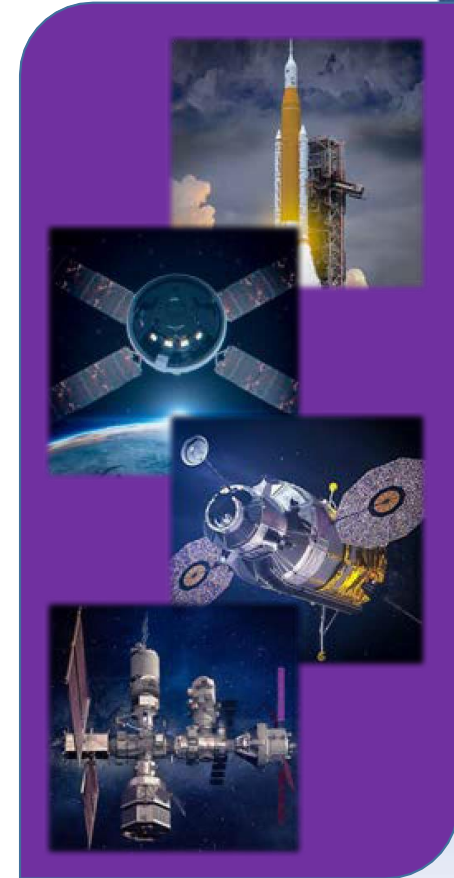
Develop and transfer revolutionary technologies

Space Operations



Launch and Space Operations

Exploration Systems Development



Moon to Mars Exploration



NASA Partnerships are found in every state and many other countries

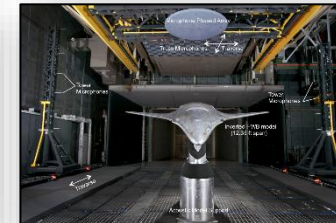


Acoustics at NASA Langley



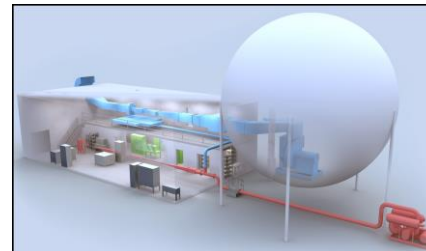
➤ Aeroacoustics Branch <https://aab.larc.nasa.gov>

- Understand and predict air vehicle noise and concepts for noise reduction
- Rotorcraft flight acoustics
- Noise from aircraft components
- Propulsion airframe acoustics
- System noise assessment, prediction, auralization



➤ Structural Acoustics Branch <https://stab.larc.nasa.gov>

- Understand and mitigate the impact of aircraft noise on people and structures
- Psychoacoustics
- Atmospheric acoustics
- Liner acoustics
- Sound interaction with structures
- Auralization



➤ ~60 engineers, technicians, and support staff

Opportunities @ NASA for Students



➤ Internships

- High school and college

➤ Graduate fellowships

- 2021: \$50k (M.S.) or \$55k (PhD) per year
- Aeronautics Fellowship

➤ Pathways Program

- Paid internships that are direct pipelines to full-time employment at NASA upon graduation
- Minimum 16 weeks on-site at NASA

➤ University grants and contracts

- Faculty PI and students
- Task-related

WHEN DO INTERNSHIPS TAKE PLACE?

There are three internship sessions:

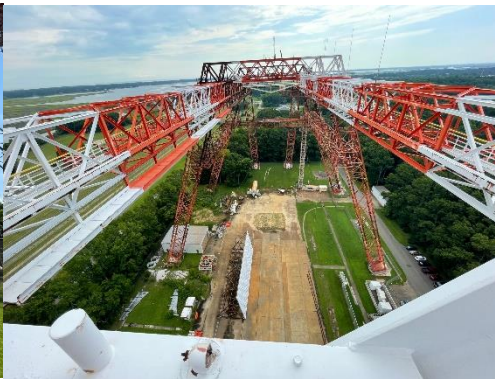
SESSION	DURATION	START/END	APP DEADLINE
Spring	16 Weeks	Mid January - Early May	Early November
Summer	10 Weeks	Late May/Early June - August	Early March
Fall	16 Weeks	Late August/Early September - Mid December	Early July

intern.nasa.gov

nspires.nasaprs.com

www.nasa.gov/centers/nssc/grants

What do opportunities at NASA Langley look like?



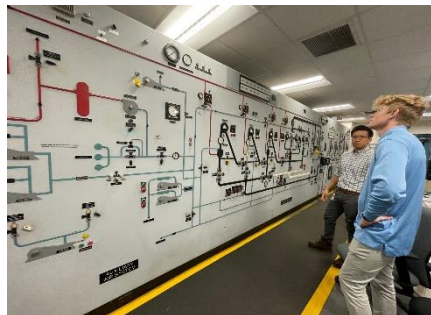
virtual or hybrid

8	10/25 - Holiday Monday	None
9	Halfway	None
10	Kate out 10/8-10/13	None
11	Meeting moved to Thursday 10/25	None
12	11/1	None
13	11/7	None
14	11/8 - Veterans Day 11/11	None
15	11/22 - Thanksgiving Week	None
16	11/29	None

Contacts:

- name and background
- assigned organization
- role on the project
- description of the project
- professional growth, accomplishments, and future plans
- relevant photos taken during their internship (if applicable)

Give: All presentations should go through Expert Control/STRIVES prior to the student's departure from the Center. Mentors should assist interns with the Expert Control process. For more information on this process, please contact Tronda Bates at wtandab@nasa.gov



Presentation Outline



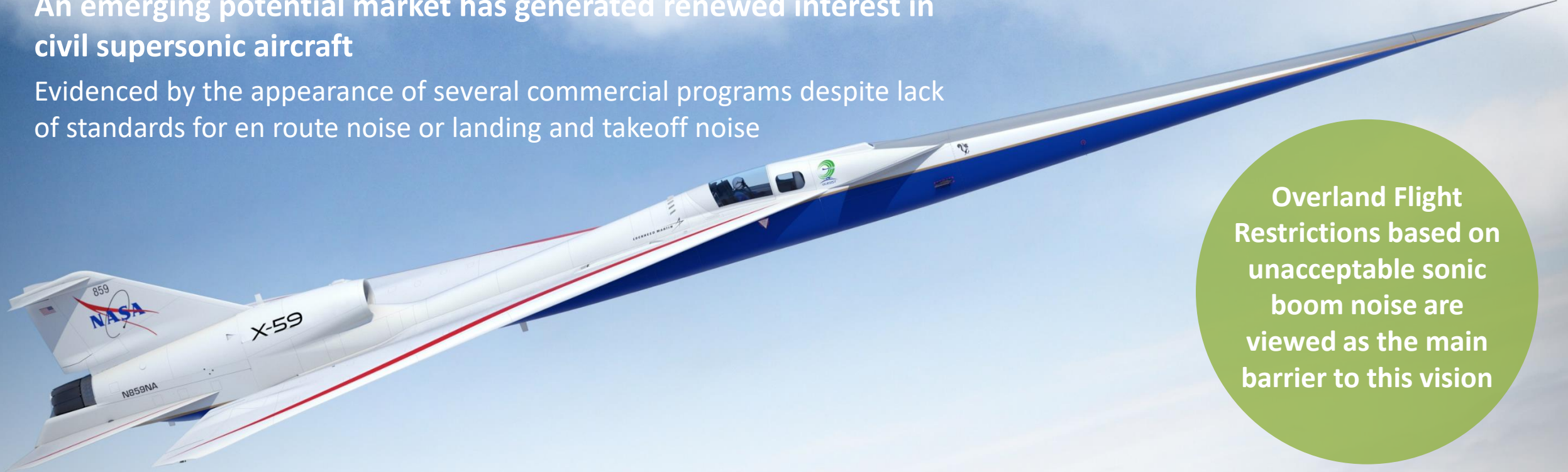
- **Commercial supersonic flight**
- **Sonic boom overview**
- **X-59 and the Quesst Mission**
- **Preparations for community testing**



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



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 be efficient, affordable, and environmentally responsible

Overcoming the barrier to overland flight

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
 - Standard must be accepted internationally

NASA is building the X-59 research aircraft



- Flights will confirm that a full-scale supersonic aircraft can produce just a gentle sonic “thump”
- Key data will be gathered on public perception of quiet supersonic flights in several cities across the nation

Length

99.7 feet long

Width

29.5 feet wingspan

Cruise Speed

Mach 1.4

Cruise Altitude

55,000 feet



Sonic Boom Overview

Sonic Boom Basics

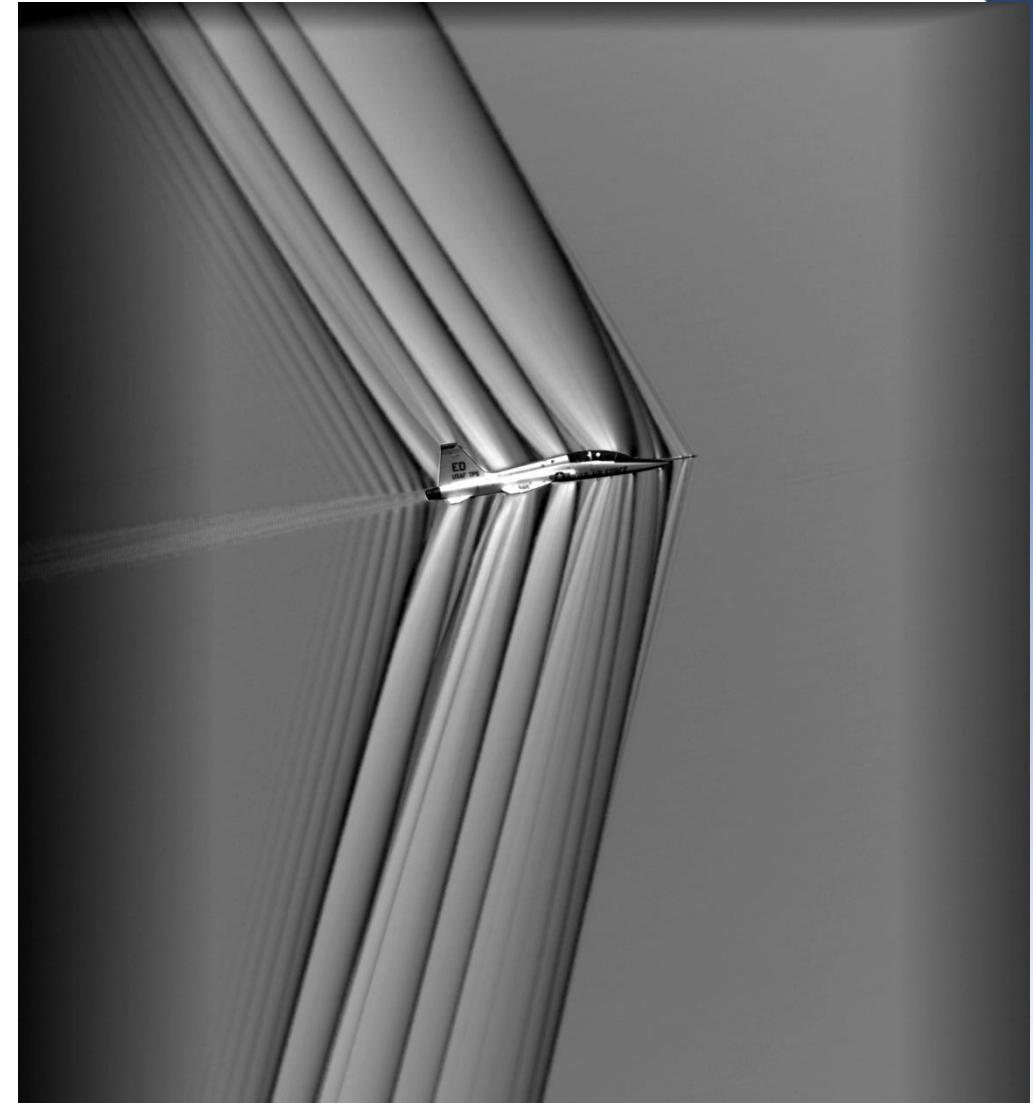
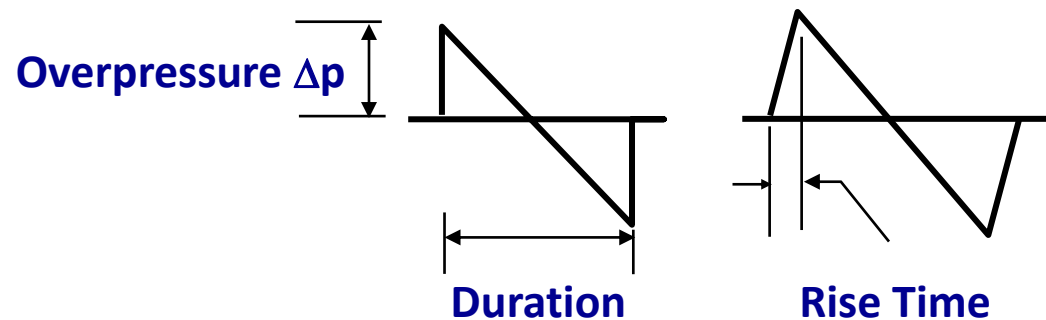


➤ **Supersonic flight** → aircraft flies faster than speed of sound

- Shockwaves travel away from vehicle
- Shockwaves merge as they travel through the atmosphere
- Heard on the ground as a sonic boom

➤ **For traditional supersonic aircraft**

- Shockwaves eventually merge into bow and tail shocks
- Sonic boom is an “N-wave” signature



Sonic Boom Basics

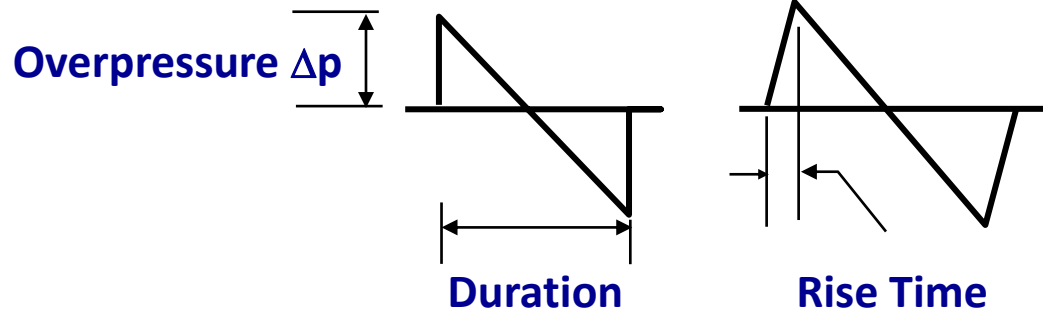
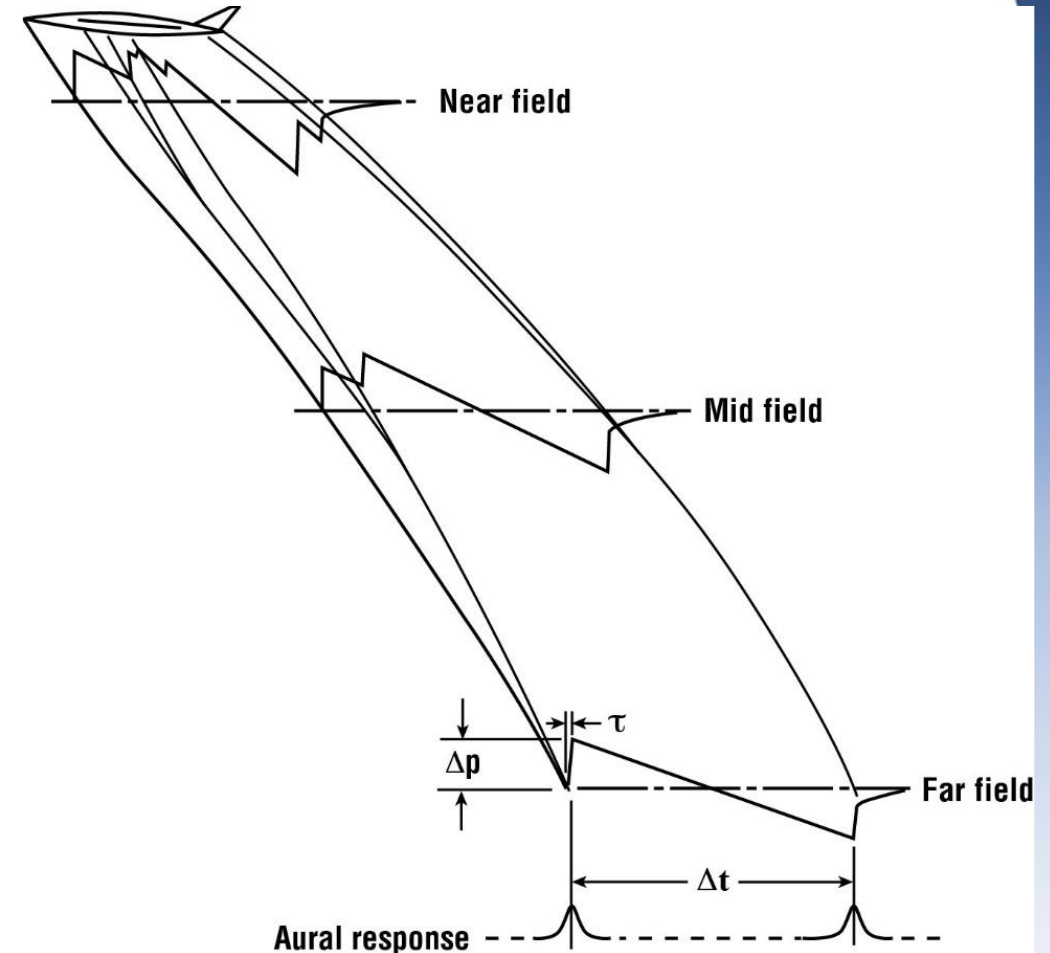


➤ Supersonic flight → aircraft flies faster than speed of sound

- Shockwaves travel away from vehicle
- Shockwaves merge as they travel through the atmosphere
- Heard on the ground as a sonic boom

➤ For traditional supersonic aircraft

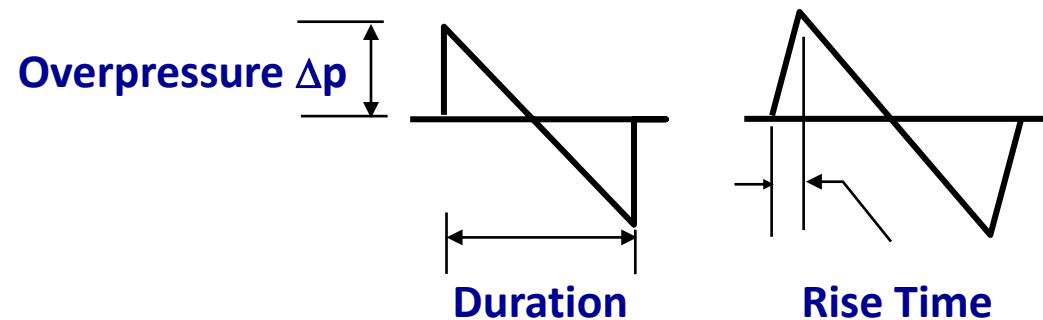
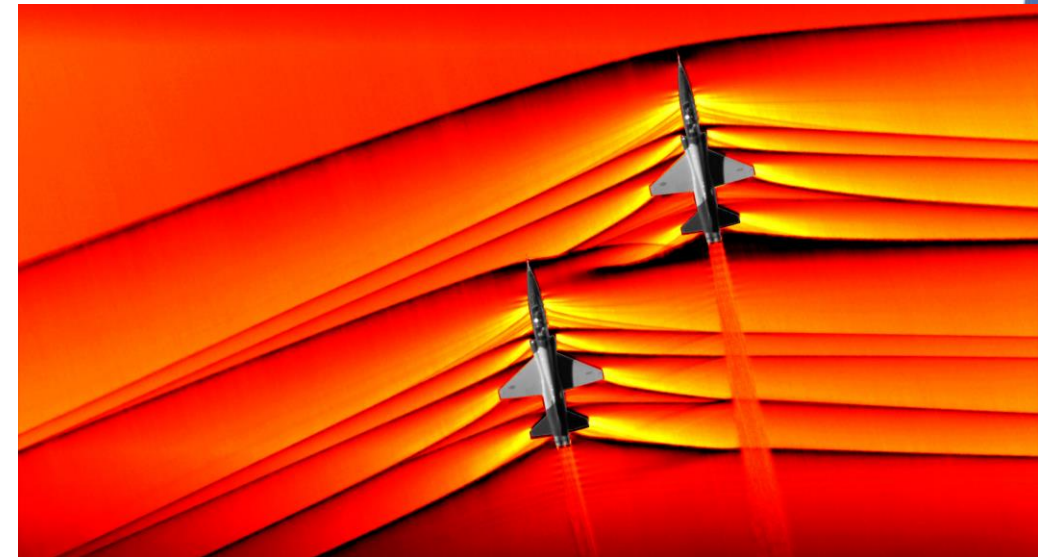
- Shockwaves eventually merge into bow and tail shocks
- Sonic boom is an “N-wave” signature



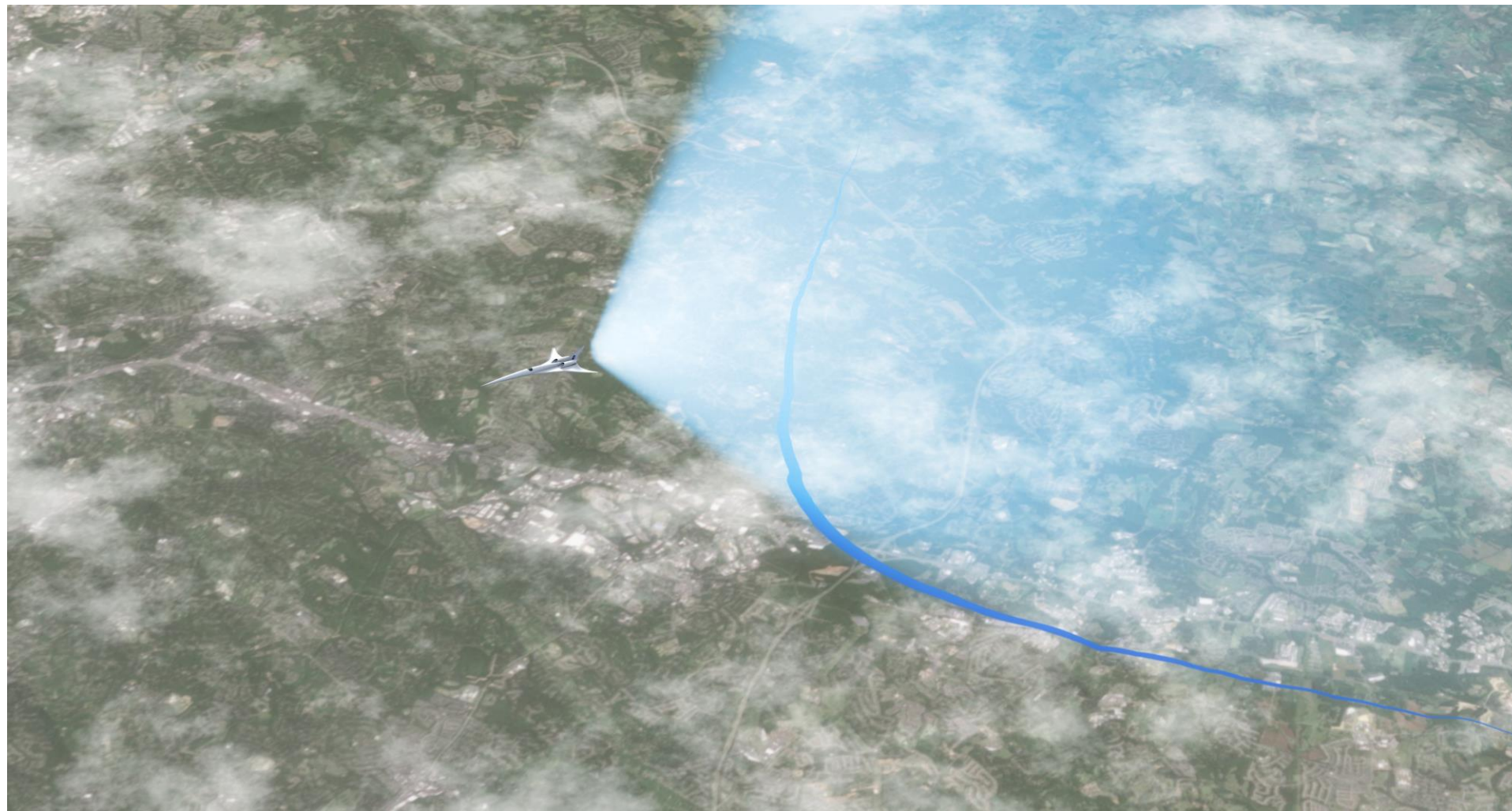
Sonic Boom Basics



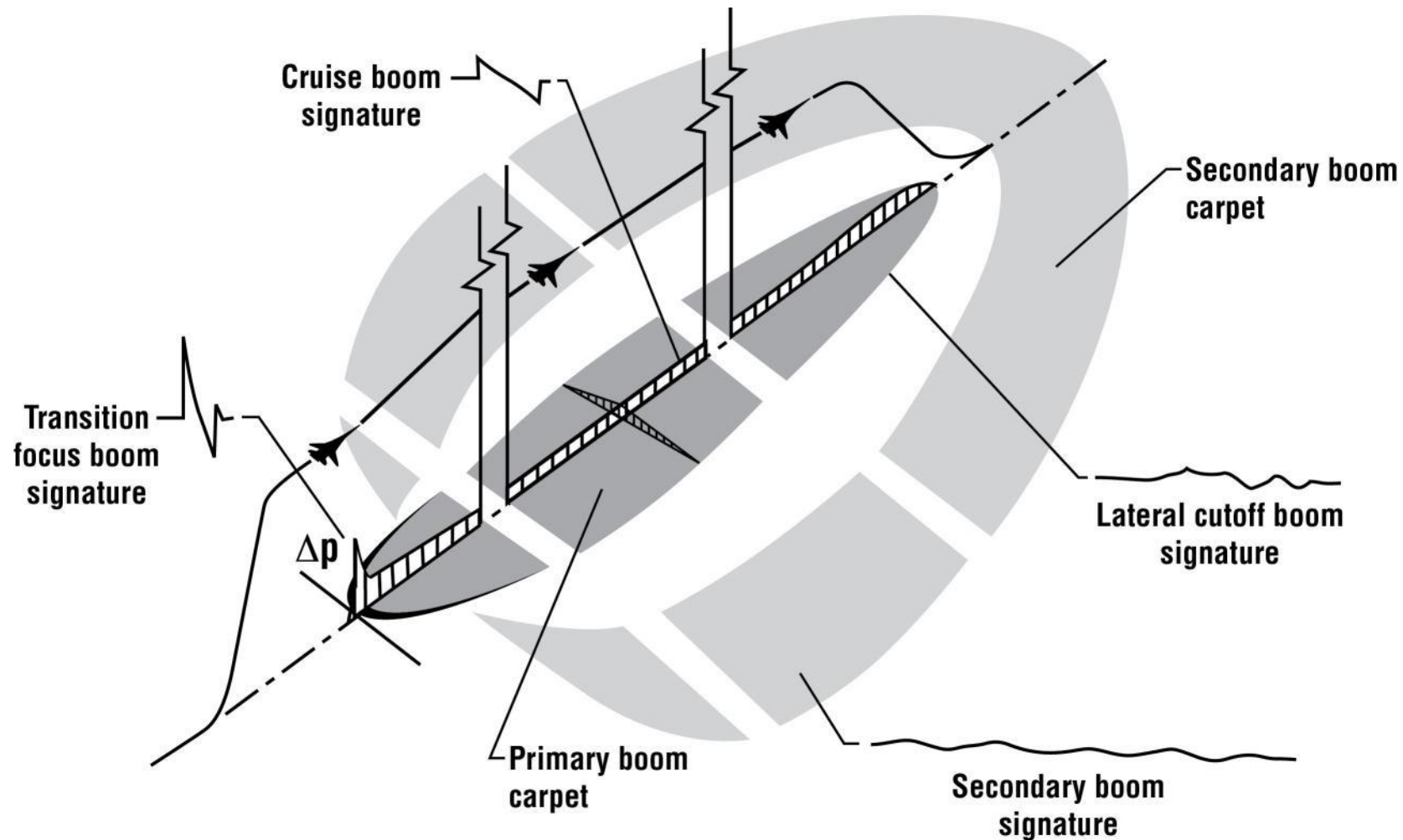
- **Supersonic flight** → aircraft flies faster than speed of sound
 - Shockwaves travel away from vehicle
 - Shockwaves merge as they travel through the atmosphere
 - Heard on the ground as a sonic boom
- **For traditional supersonic aircraft**
 - Shockwaves eventually merge into bow and tail shocks
 - Sonic boom is an “N-wave” signature



Sonic Boom Moves with the Aircraft



Sonic Boom Ground Exposure



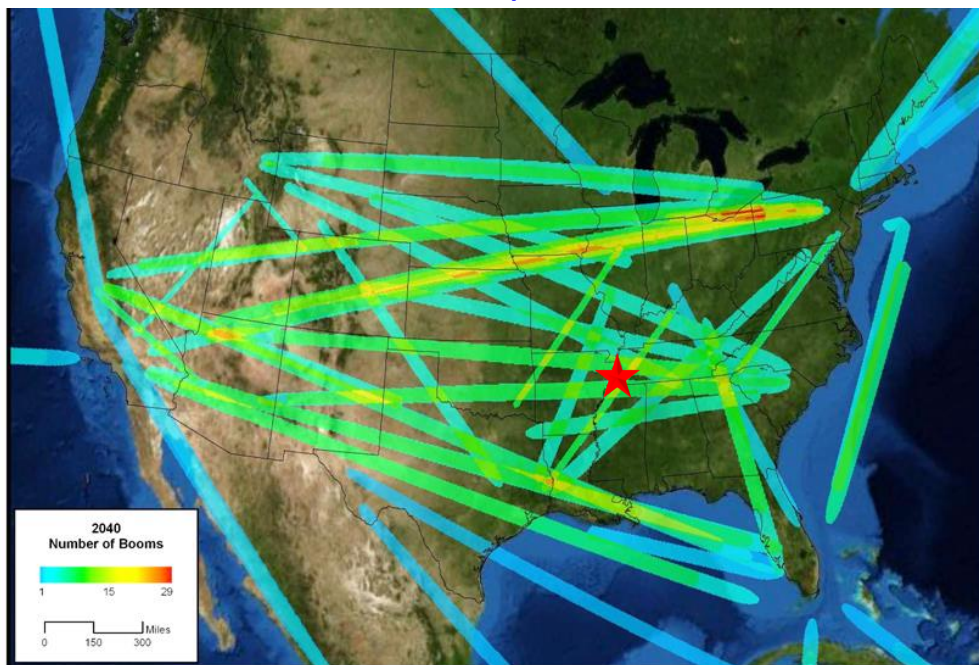
Sonic Boom Waveforms and Spectra



➤ Unique aspects of sonic booms

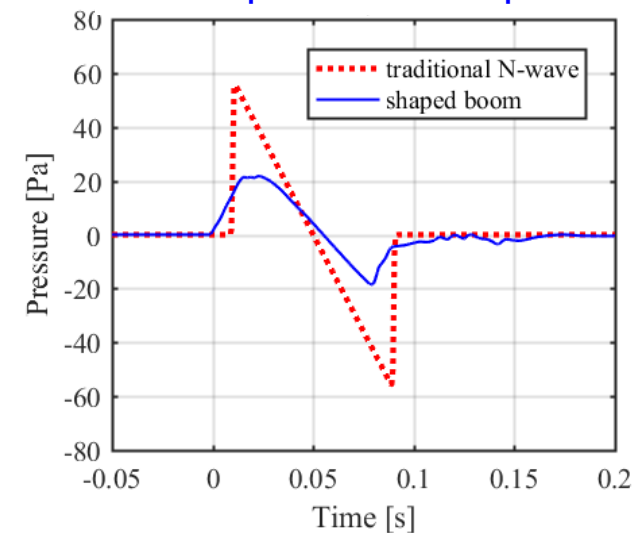
- Transient nature of sonic boom
- Low-frequency energy
- Created along entire supersonic path (en route)
- Cannot use the same methods/metrics as for subsonic aircraft

Number of booms predicted in 2040

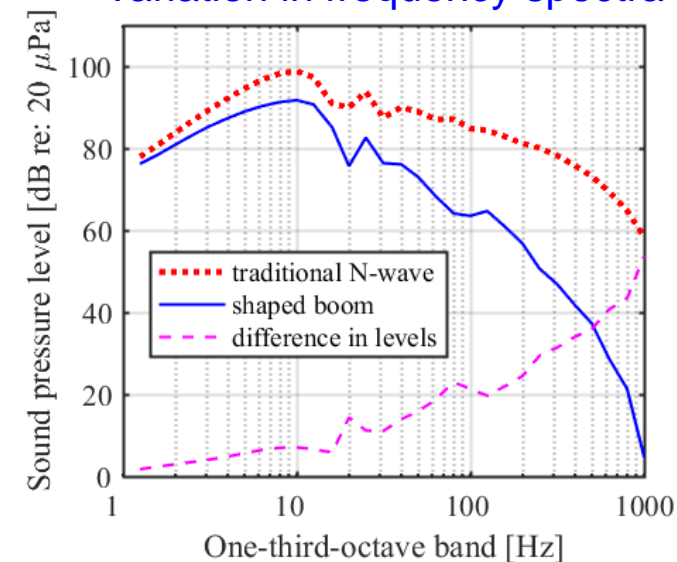


J. Rachami and J. Page. AIAA 2010-1385.

Example boom shapes



Variation in frequency spectra



Sonic Boom Noise Metrics

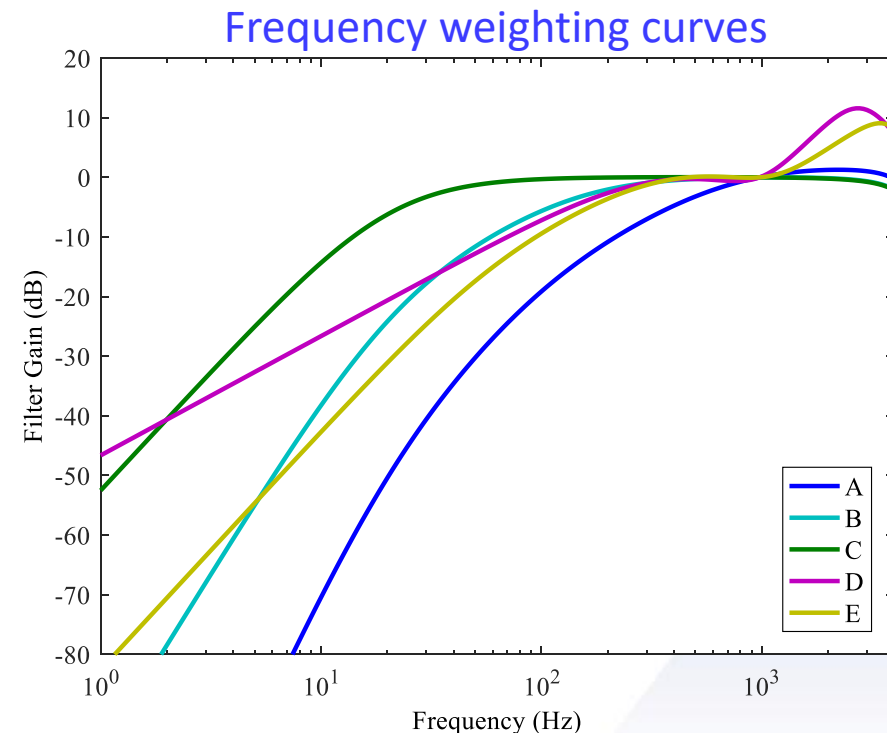


➤ Perceived Level (PL) has been widely used to describe sonic boom loudness levels

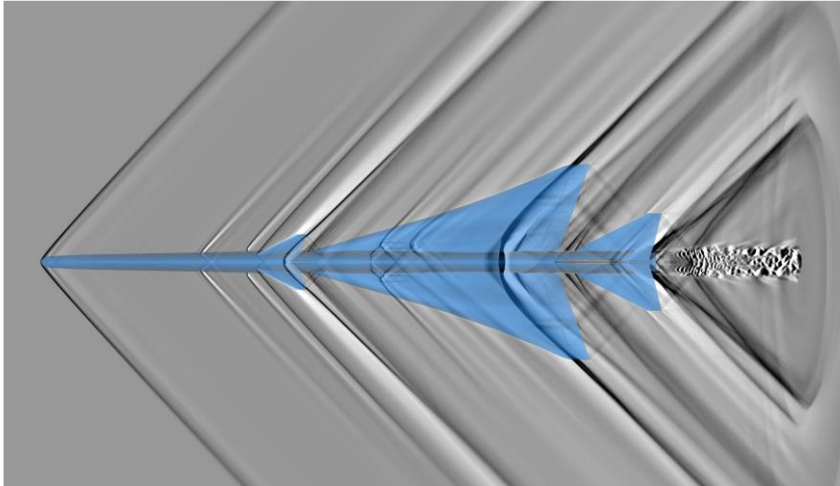
- Often used as a target when optimizing supersonic aircraft designs
- Uniquely prescribes different spectral weighting for different noise levels
- It works well for explaining human annoyance to outdoor booms
- It does not work as well for booms experienced indoors

➤ Several alternate metrics have been proposed

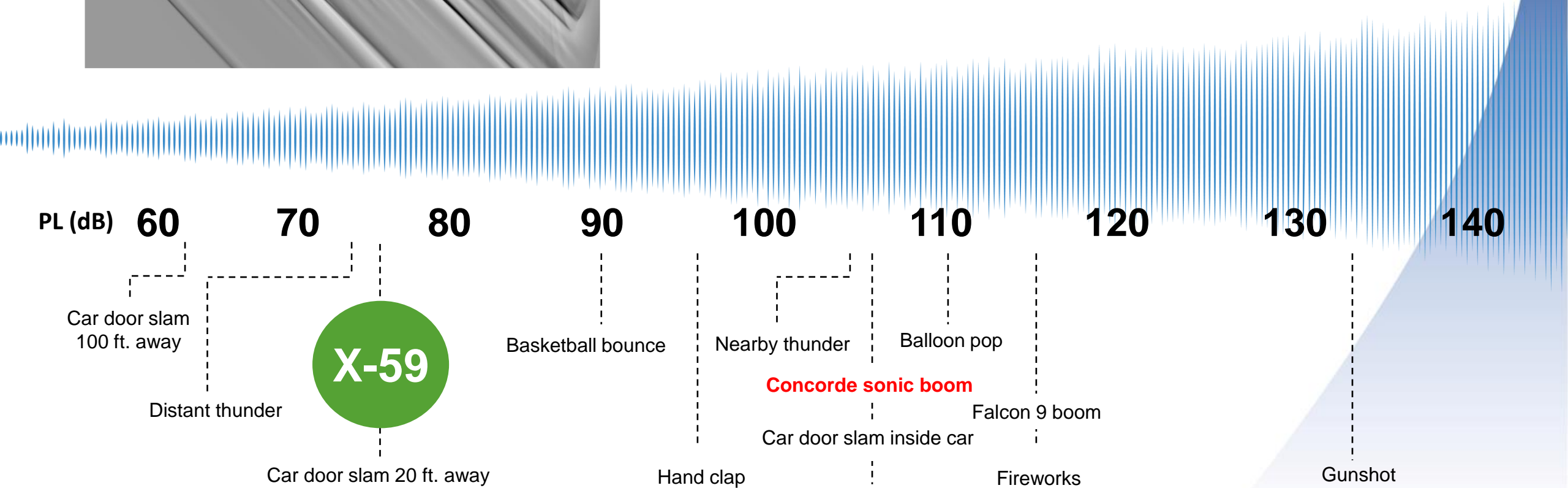
- Different metrics treat lower frequencies differently which is critical for describing sonic boom noise



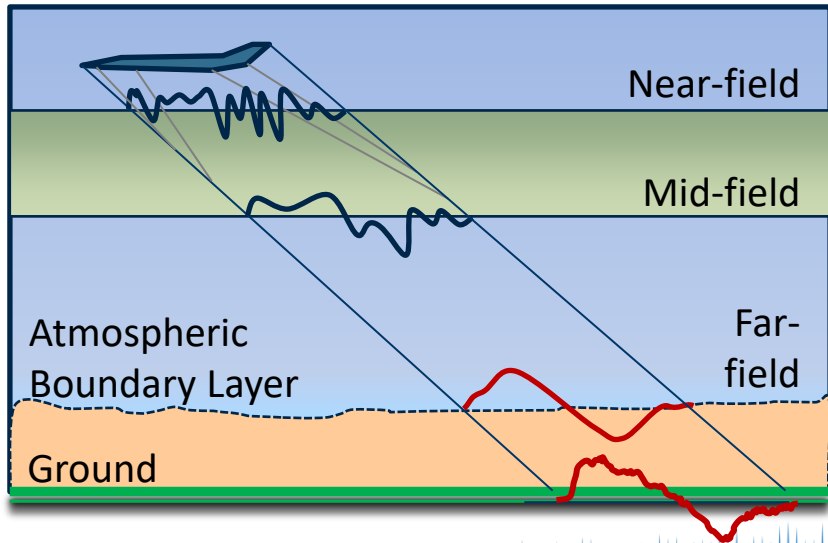
How Do We Quiet the Boom to a Thump?



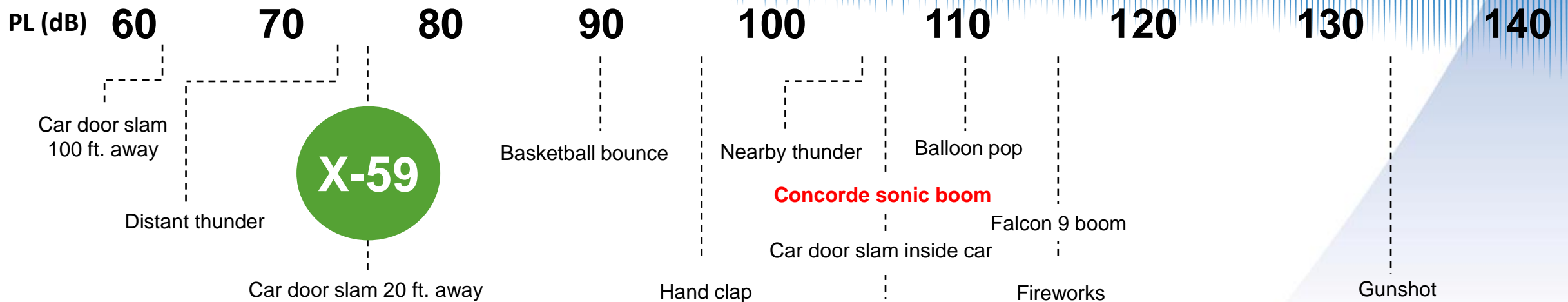
- Acoustic pressure wave is “shaped” by controlling the strength and position of shock waves generated by aircraft components
- Shocks do not merge into an N-wave



How Do We Quiet the Boom to a Thump?



- Acoustic pressure wave is “shaped” by controlling the strength and position of shock waves generated by aircraft components
- Shocks do not merge into an N-wave





X-59 and the Quesst Mission

Quesst Mission



Phase 1—X-59 Aircraft Development

- Detailed Design
- Fabrication, Integration, Ground Test
- Checkout Flights
- Subsonic Envelope Expansion
- Supersonic Envelope Expansion



Phase 2—Acoustic Validation

- In-flight and ground measurements
- Validation of X-59 signature and prediction tools
- Development of acoustic prediction tools for Phase 3



Phase 3—Community Response

- Ground measurements in communities
- Community response surveys
- Multiple campaigns across U.S.
- Data analysis and database delivery

X-59 Design Features

Quiet design approaches adapted for a unique flight demonstrator



X-plane approach that meets key requirements in a cost-effective design

External and forward vision systems for forward visibility

T-38 aft canopy and ejection seat minimizes qualification cost and schedule

Long nose to shape forward shock

Fixed canard for nose-up trim at low-boom design point

Large, unitized skins reduce parts count and manufacturing cost

F-16 landing gear and other systems from high performance aircraft minimize qualification cost and schedule

Wing shielding minimizes impact of inlet spillage on sonic boom

T-tail minimizes aft shock

Single GE-F414 engine with standard nozzle minimizes cost and schedule

Conventional tail arrangement simplifies stability and control considerations



X-59 Development Status

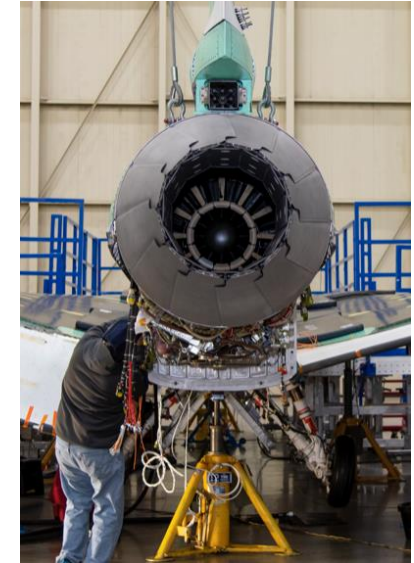


➤ Overall good progress in all aspects of aircraft design/build

- Lockheed Martin internal design, fab, and assembly
- Contracted fabrication and supply
- NASA-developed systems
- Donor aircraft parts and components



Flight instrumented landing gear installed



Engine installed

Manufacturing & subsystems installation essentially complete



Images Credit: Lockheed Martin

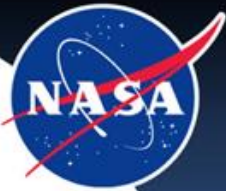


Cockpit systems installed

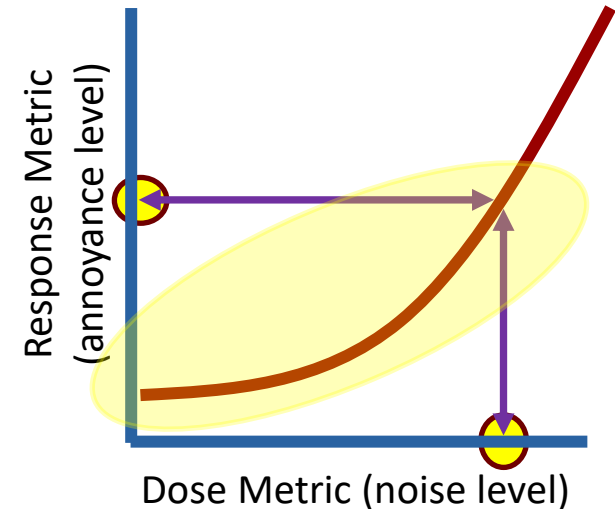


Preparations for Community Testing

Community Testing Goals



- **Conduct overflight tests with the X-59 over nonacclimated communities in the U.S.**
 - Large number of representative responses
- **Tests in multiple locations to cover range of conditions**
 - Geography and climate
 - Home and building construction
 - Community demographics
- **Range of exposures**
 - Vary noise levels with different flight conditions
 - Up to 6 daily exposures for a month
- **Engage the international research & regulatory community to ensure data acceptance**
- **Correlate survey and acoustic data to establish dose-response relationships**



Provide dose-response data to ICAO

Airfield and Community Test Site Selection



➤ Developing process for selecting 5 communities

- Purposive sampling
- Repeatable, traceable, defensible to regulators

➤ Operational criteria

- X-59 requirements (runway, elevation, etc.)
- Airfield/airspace considerations

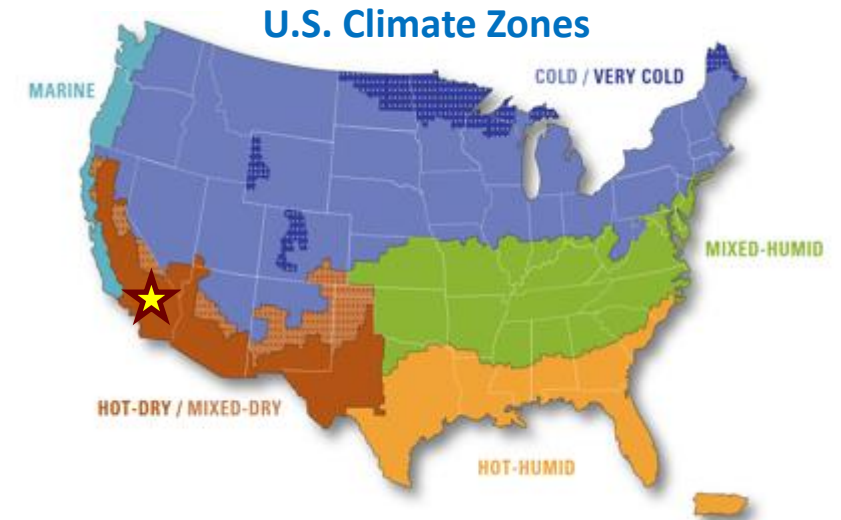
➤ Data Criteria

- Geographic and population demographic diversity
- Population density within test area (30 x 50 mi)

➤ Additional considerations

- Unique experimental aircraft
- Seasonal/meteorological constraints and sequencing considerations

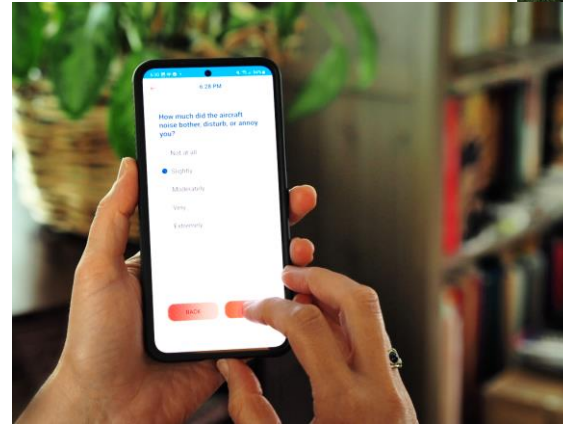
➤ Community Test 1 – Conducted from NASA AFRC



Key Challenges



- Limited number of community studies
- Automating surveys and audio recordings
- Combining results from multiple communities
- Measuring quiet sounds in noisy cities



- **What we are doing today to prepare**
 - Test methods and equipment in small studies
 - Test automated methods before going to communities



What you should know about the NASA Quesst mission



1 WE WANT TO
DRASTICALLY
REDUCE
TRAVEL TIME

But first, we need to
change the rules

2 WE'RE BUILDING
A NEW X-PLANE

It's not like any other

3 THE DESIGN
OF THE X-59
IS UNIQUE

It's all about being quiet

4 THE X-59 IS FOR
RESEARCH
PURPOSES ONLY

It will never carry
passengers

5 THE X-59 MAY
FLY OVER YOUR
COMMUNITY

Your role is crucial

6 THE FUTURE
OF AVIATION
IS HERE

Want to know more?

<https://www.nasa.gov/quesst>

Backup Slides



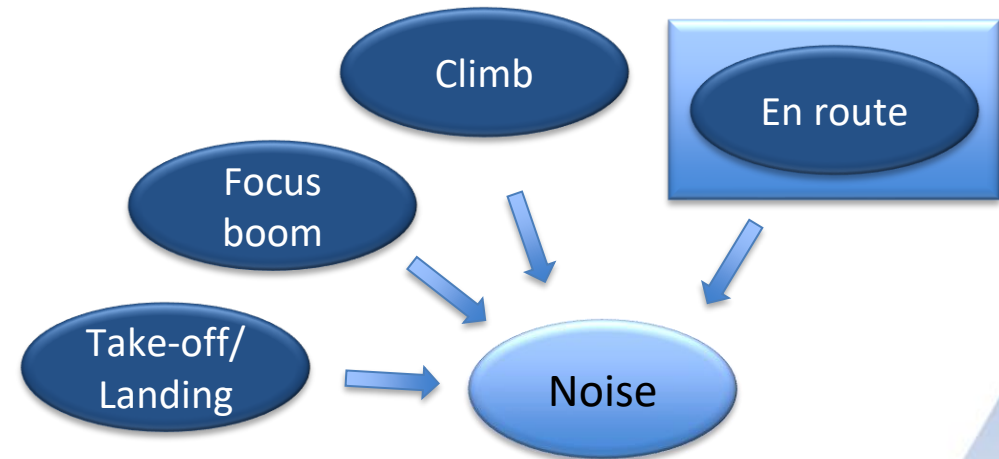


Supersonic Aircraft Noise Regulations

Civil Supersonic Aircraft Noise Certification



- **Civil supersonic overland flight prohibited**
- **Industry interest in lifting the ban and replacing with noise limit**
- **NASA is working with regulators**
 - Providing data
 - Enabling development of a new noise standard
- **Elements of a certification standard**
 - Noise metric, test procedures, noise limit
 - Different phases of flight



International Civil Aviation Organization (ICAO)



➤ ICAO is a specialized agency of the United Nations

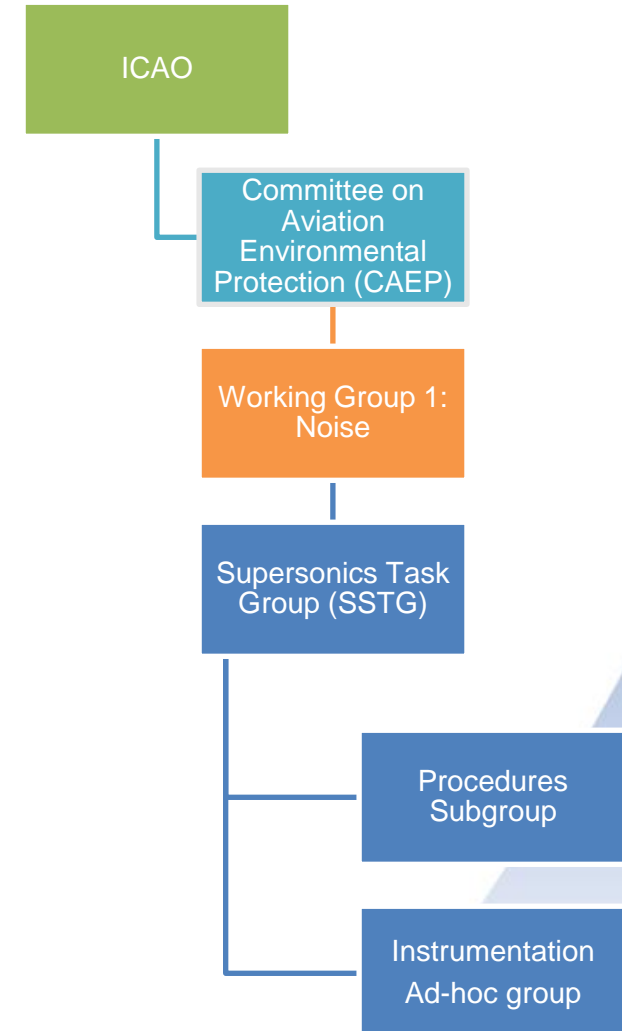
- Coordinates and regulates international air travel

➤ Convention on International Civil Aviation

- Rules that include standards and recommended practices
 - Environmental Protection
 - Aircraft noise
 - Aircraft engine emissions

➤ Committee on Aviation Environmental Protection (CAEP)

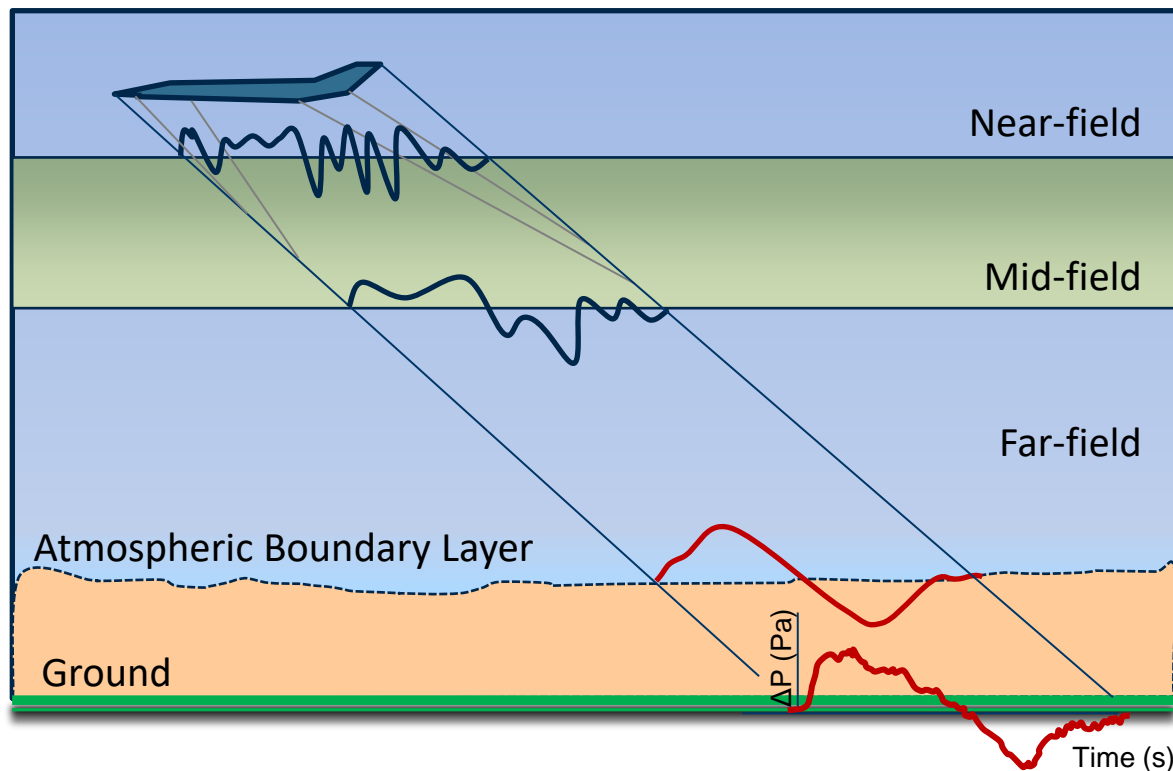
- In U.S., supported by FAA Office of Environment and Energy
- NASA serves as technical advisor to the FAA
- Industry groups and subject matter experts are also represented



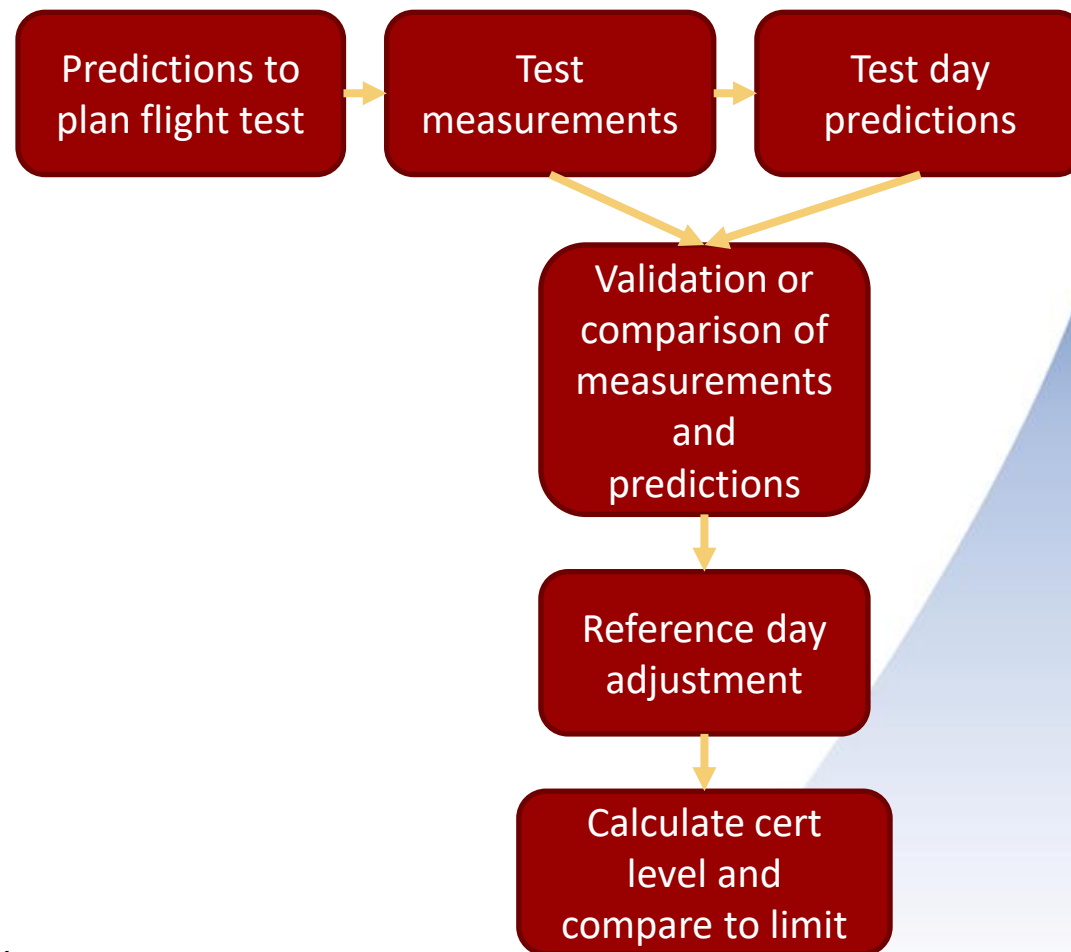
Notional Certification Procedure



➤ Reference Procedure Must Characterize Noise Performance at Reference Conditions



Notional Certification Procedure Steps





Psychoacoustics Research

Sonic boom simulators

Laboratory studies

Community studies

Review of Sonic Boom Simulators: *Outdoor Environment*



➤ Used effectively to study human annoyance to broad range of boom signals under controlled conditions

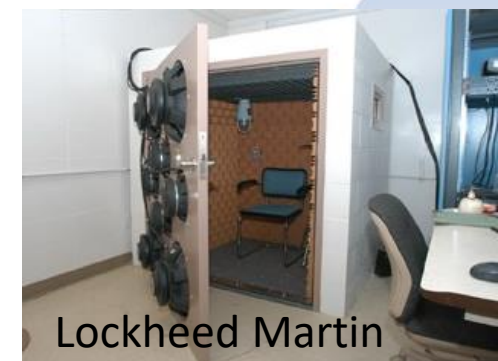
- Can reproduce measured booms and booms predicted for aircraft designs
- Can produce other boom shapes to study human response to different parameters and interactions

➤ Majority of simulators reproduce sonic booms as they would be experienced outdoors

- Filtered outdoor waveforms or recordings of indoor waveforms have been also presented to estimate indoor environment, but these simulators lack indoor realism
 - Absence of space and reverberation, secondary rattle and vibration, and aesthetic composition

➤ Most consist of airtight, small rigid-walled booth

- Driven with subwoofer loudspeakers to reproduce low frequencies characteristic of sonic booms



Outdoor Sonic Boom Simulator



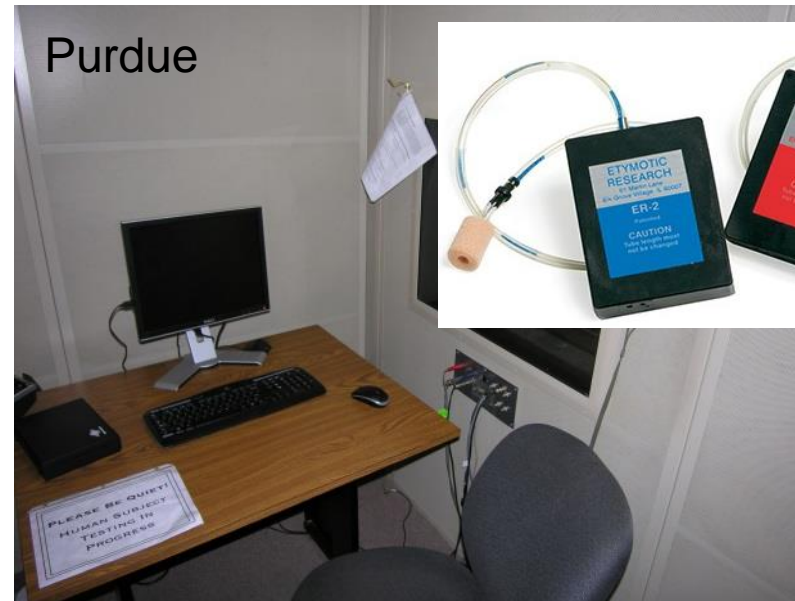
- **Mobile trailer that creates traveling wave using an array of loudspeakers, folded horn, and anechoic termination**



Review of Headphone Capabilities



- **High-quality headphones or earphones are also used**
 - Capable of reproducing audible content of sonic booms and secondary rattle noises that occur indoors
 - Binaural signals have been used to approximate auditory experience of boom and rattle exposure in different-sized rooms
- **Limitations**
 - Absence of real space and reverberation
 - Absence of vibration
 - Decreased realism due to limited low-frequency reproduction
 - Aesthetics



Review of Sonic Boom Simulators: *Indoor Environment*



- **Newer simulators allow for more realistic indoor soundscape**
 - Investigate causes for elevated annoyance to sonic booms experienced indoors
- **One configuration**
 - Small booth that can be configured for indoor listening using a partition with a window
 - Boom transmits from subwoofers on wall of simulator through window partition to listener space
 - Better approximates conditions of sonic boom impacting a building and transmitting indoors
 - Still does not address aesthetics or subject expectation of noise environment indoors vs. outdoors



JAXA



Review of Sonic Boom Simulators: *Indoor Environment*



➤ Another configuration

- Noise simulator constructed to mimic indoor environment acoustically and aesthetically
 - Realistic indoor soundscape and environment
 - Control secondary rattle noises and vibration for systematic study

NASA's Interior Effects Room (IER)



Laboratory Psychoacoustics Research



➤ Participants from surrounding community

- Diversity in age and gender
- Must pass hearing tests

➤ Typically 30-40 participants

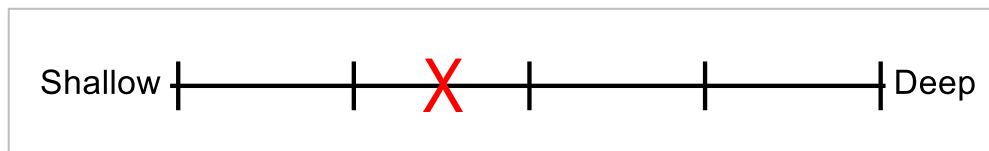
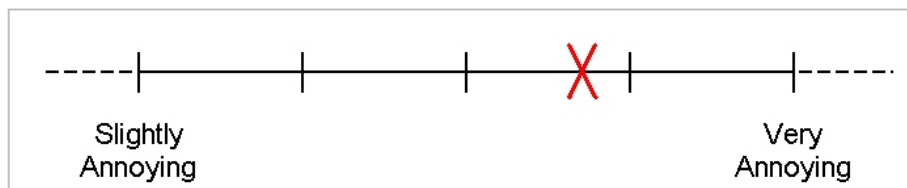
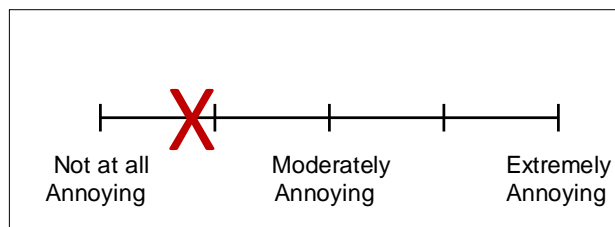
- Tested 2-3 at a time

➤ Sessions for familiarization and practice

➤ Example rating screens



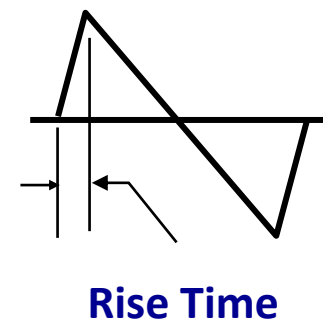
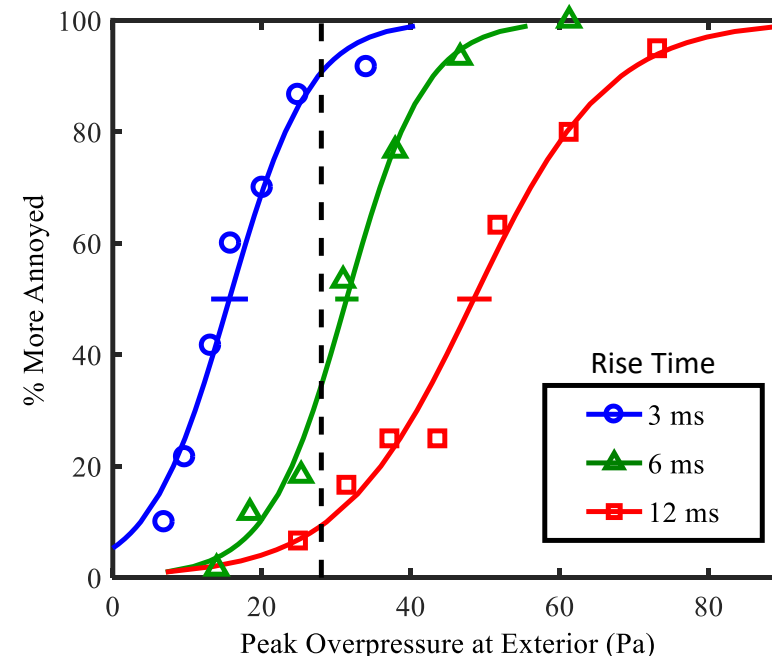
If the first sound is more annoying depress the button labeled 'First'.
If the second sound is more annoying depress the button labeled 'Second'.



Human Response to Indoor Booms



- Initial studies found that boom amplitude and rise time persist as important factors for indoor response
 - Longer rise times of low booms result in decreased annoyance
- No metric performs better than PL
- However, PL and other metrics evaluated do not fully account for effects of low frequencies



Aircraft Size: Full-scale vs. Subscale Aircraft



➤ Objective

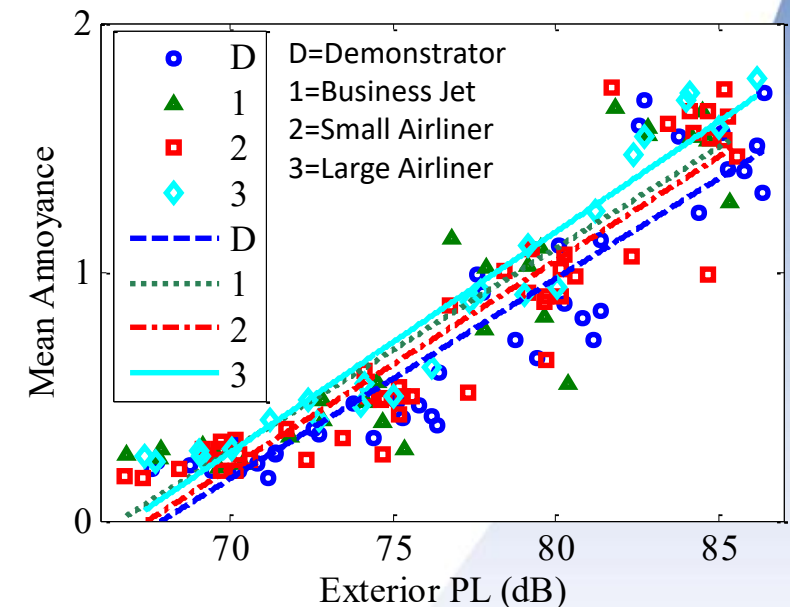
- Evaluate indoor annoyance to sonic booms predicted for subscale and full-scale supersonic aircraft
 - Smaller size and weight of demonstrator create a shorter sonic boom with less low-frequency energy than commercial airliner

➤ Approach

- Boom predictions collected from various partners
- 30 human test subjects rated their annoyance to booms in IER

➤ Main results and significance

- For a given exterior PL, annoyance to subscale aircraft booms is not very different than for full-scale aircraft booms
- Confirmation that exterior PL can be used to evaluate supersonic aircraft designs, regardless of size
- Results helped justify plans for use of a demonstrator for community studies



A. Loubeau, J. Rathsam, and J. Klos. Laboratory study of indoor annoyance caused by sonic booms from sub-scale aircraft. *J. Acoust. Soc. Am.*, 134(5): 4220, 2013.

A. Loubeau. Evaluation of the effect of aircraft size on indoor annoyance caused by sonic booms. *J. Acoust. Soc. Am.*, 136(4): 2223, 2014.

Rattle and Vibration Studies



➤ Objective

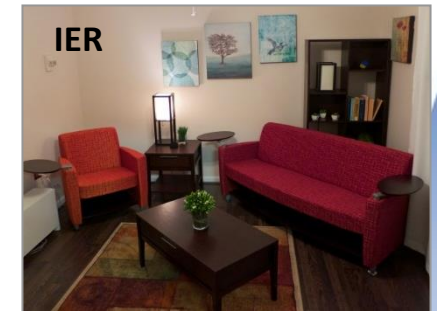
- Address concern from community studies that rattle and vibration are important to perception of sonic booms

➤ Approach

- 3 rattle studies using headphones with 40 binaural rattles
- 2 rattle studies in IER to validate headphone study results
- 2 vibration studies in IER using isolators on chair and shakers attached to seat

➤ Main results & significance

- “Large” (windows, walls, doors) rattle sounds more annoying than small ones
- Rattle and vibration increase indoor annoyance (penalties of 3-10 dB)



A. Loubeau, B. M. Sullivan, J. Klos, J. Rathsam, and J. R. Gavin. Technical Report TM-2013-217975, NASA, 2013.

J. Rathsam, A. Loubeau, and J. Klos. Proc. NoiseCon13 (INCE), 307-313, 2013.

J. Rathsam, A. Loubeau, and J. Klos. J. Acoust. Soc. Am., 138(1): EL43-EL48, 2015.

J. Rathsam, J. Klos, A. Loubeau, D. Carr, P. Davies. J. Acoust. Soc. Am., 143(1): 489-499, 2018.

A. Loubeau. J. Acoust. Soc. Am., 143: 1936, 2018.

Carr et al. J. Acoust. Soc. Am., 148(1): 414-429, 2020.

Sonic Boom Noise Metrics Evaluation



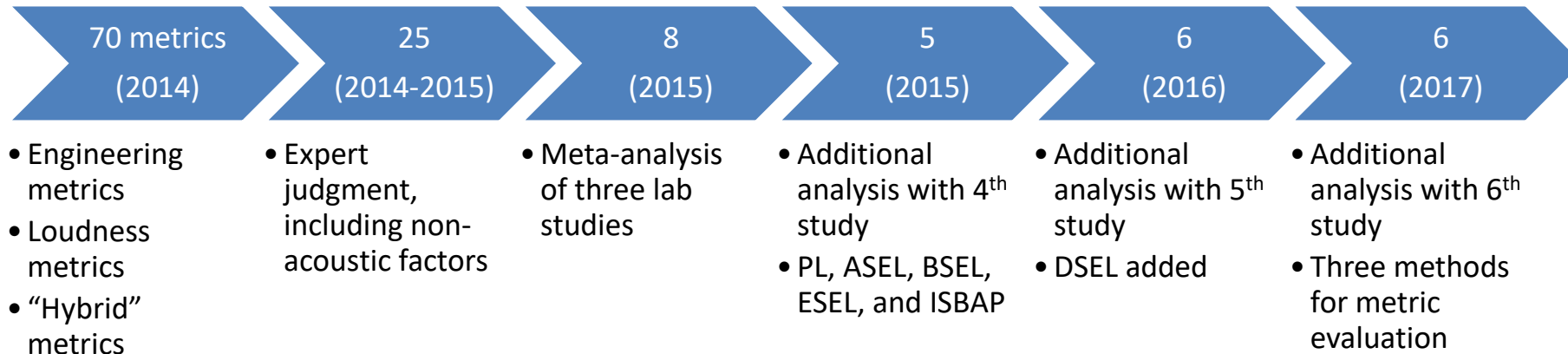
➤ Selection of datasets

- Laboratory subjective studies of isolated sonic booms
- Six datasets conducted in specialized labs at NASA Langley and JAXA
- Included indoor and outdoor response



➤ Metrics downselection meta-analysis

- In partnership with ICAO experts
- ICAO agreed to metrics subset for further consideration in a noise certification standard for supersonic aeroplanes en route above Mach 1



J. DeGolia and A. Loubeau. A multiple-criteria decision analysis to evaluate sonic boom noise metrics. J. Acoust. Soc. Am., 141: 3624, 2017.

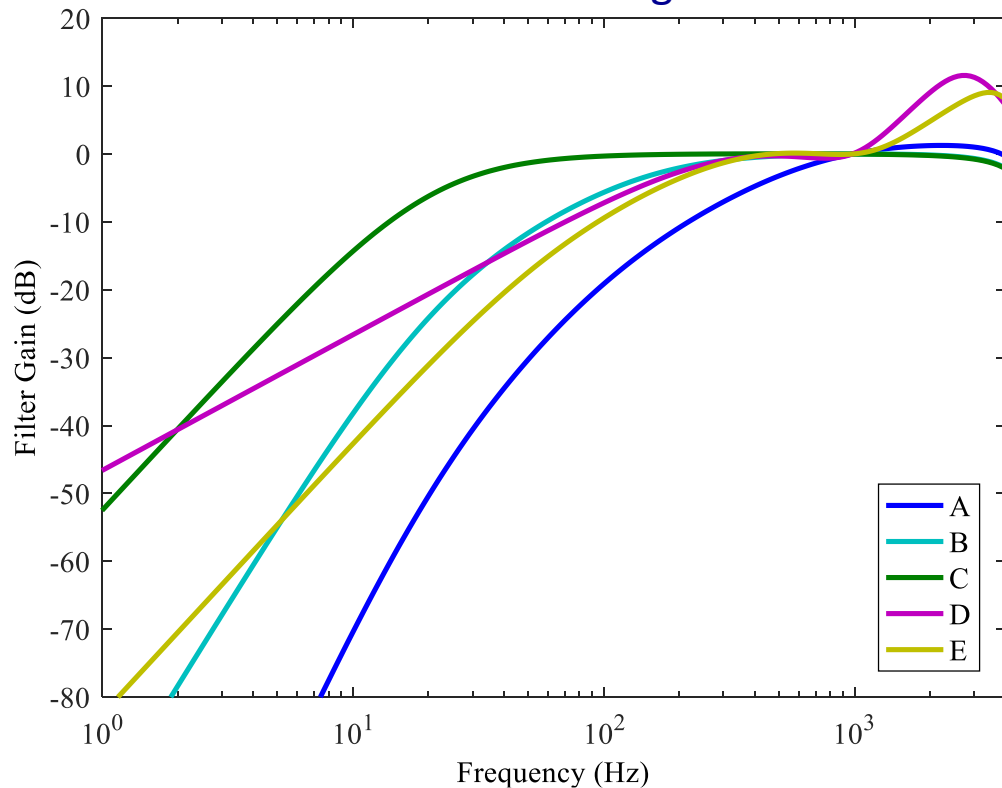
A. Loubeau et al. A new evaluation of noise metrics for sonic booms using existing data. 20th ISNA, 2015.

Sonic Boom Noise Metrics

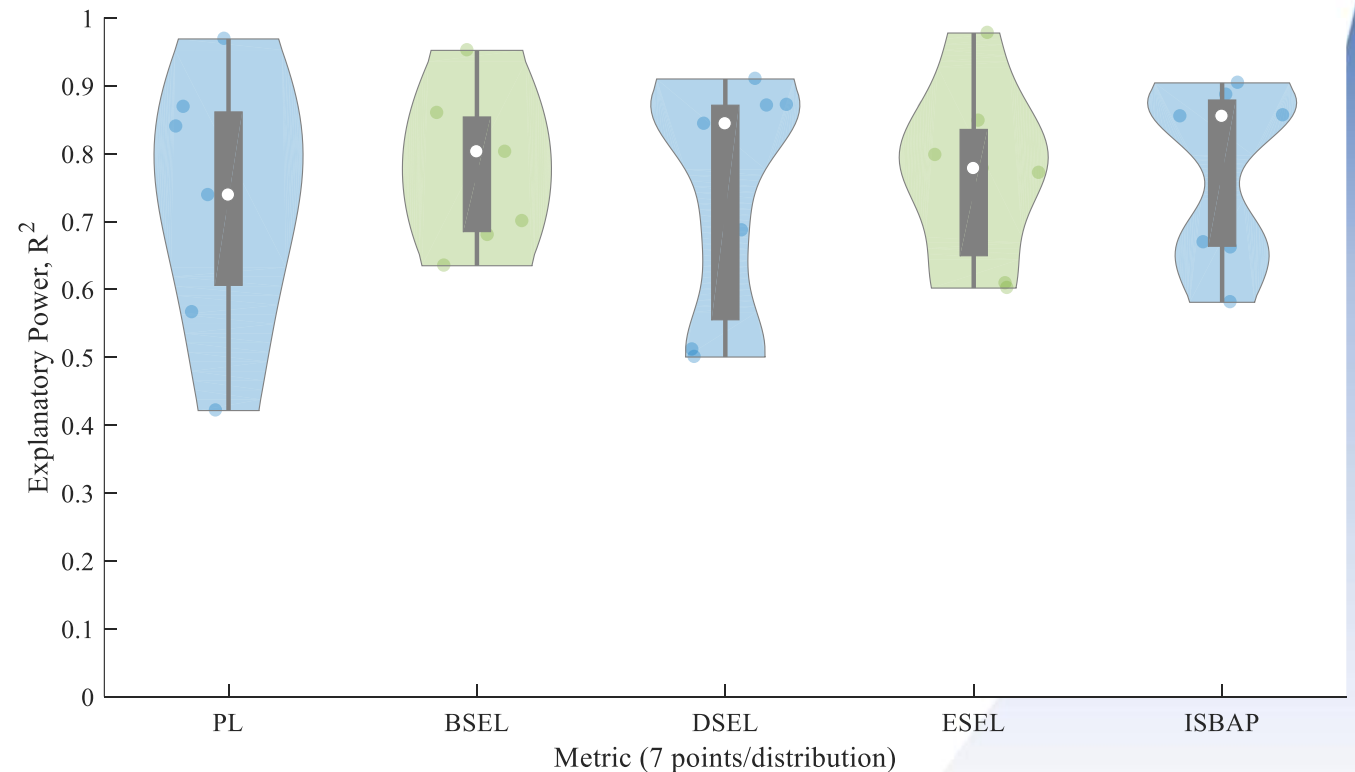


**Six metrics for further consideration:
PL, ASEL, BSEL, DSEL, ESEL, ISBAP**

Different metrics treat lower frequencies differently
which is critical for describing sonic boom noise



- Indoor Sonic Boom Annoyance Predictor = ISBAP = PL + 0.4201 (CSEL – ASEL)
- Meta-analyses showed that all correlate well with human response outdoors and indoors





- **Sonic boom simulators have been used to investigate human annoyance to sonic booms in outdoor and indoor environments**
 - Pros: simulators allow control over environment, testing of variety of booms
 - Cons: Setting not as realistic as at home, and only study single-event response
 - Most important factors studied separately
 - Confirmed notion that outdoor metric can be used to predict human response indoors
 - Results indicate that sonic booms with PL ~ 75 dB are much less annoying than conventional sonic booms
 - Annoyance levels to be confirmed with community testing

- **Results have been used in meta-analyses to evaluate candidate noise metrics**
 - Subset of recommended metrics will be used in future analyses of community field data

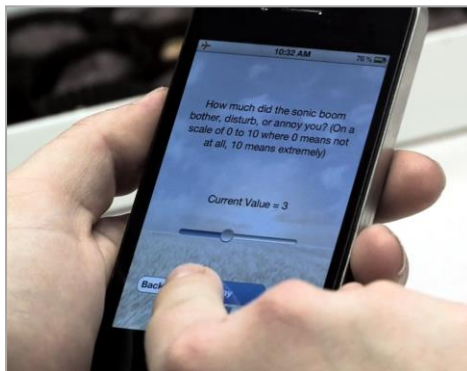
Low Boom Community Response Testing



➤ Identify, minimize, and/or mitigate risks for future X-59 community testing

➤ Quiet Supersonic Flights 2018 (QSF18)

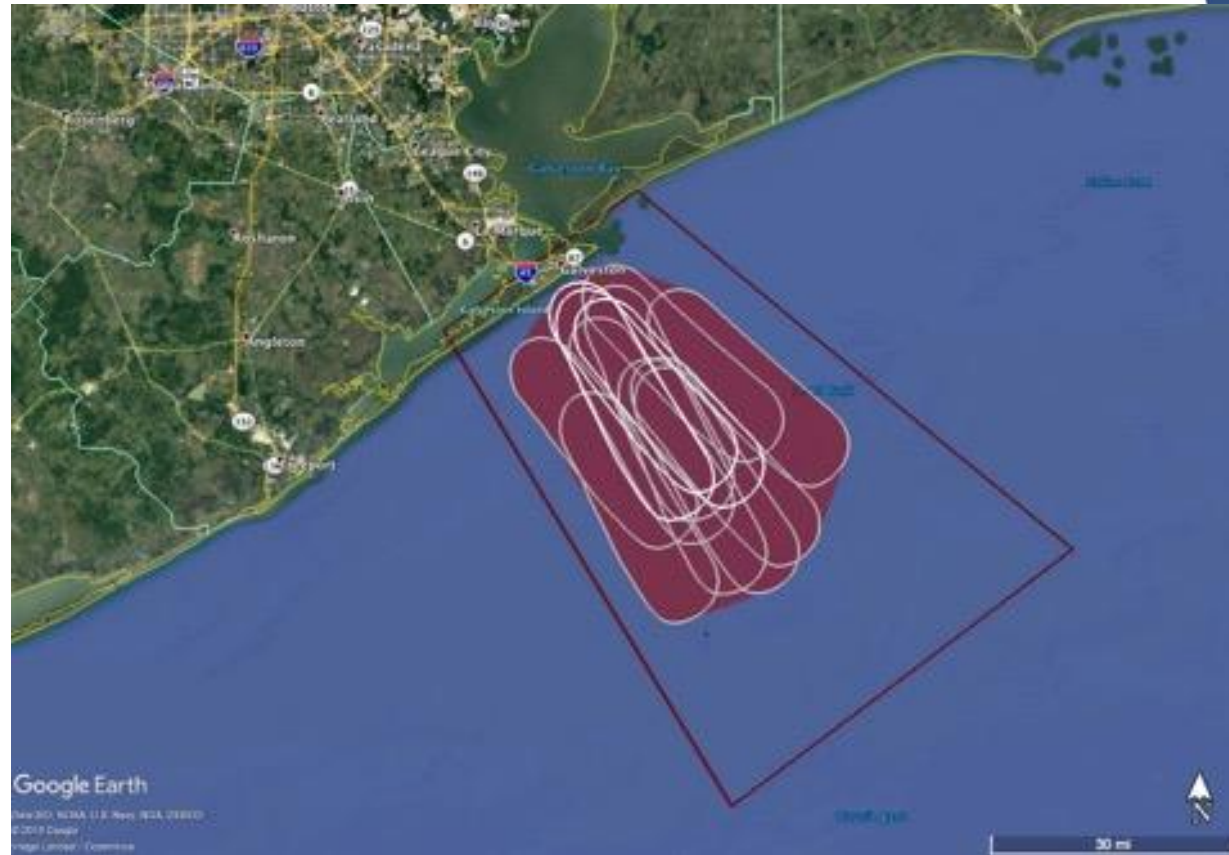
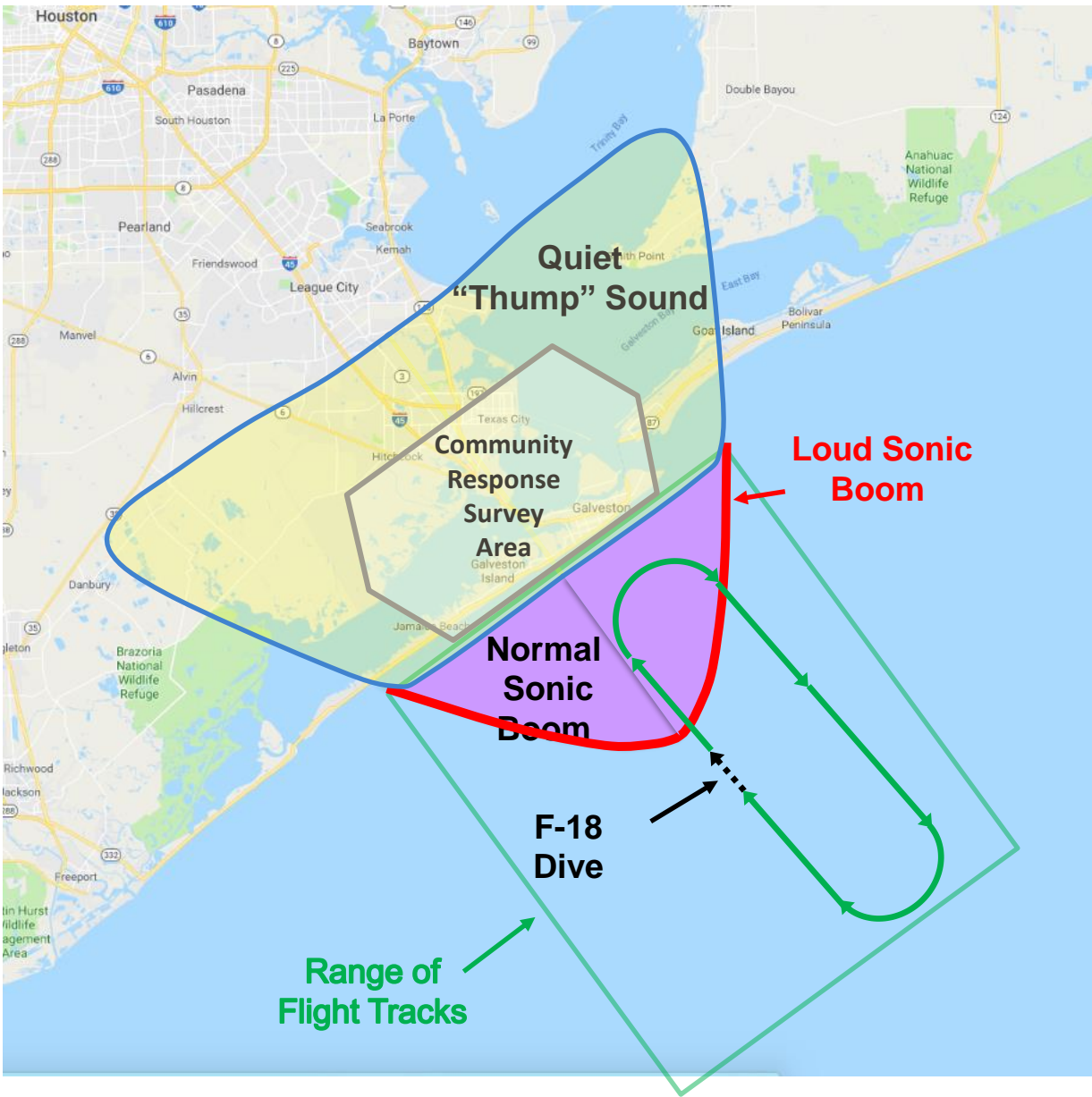
- Low-amplitude sonic boom community test in Galveston, Texas, USA on November 5-15, 2018
- Test methodologies in a city not used to hearing sonic booms
- Low-boom dive maneuver
 - 4 - 8 “sonic thumps” daily (52 total)
- 500 members of public recruited to participate in survey
 - Background, single event, and daily surveys
- 25 audio sensors set up to measure sound levels in survey area
- Public engagement
- Lessons learned
 - Methods and planning
 - Test Execution
 - Data analysis



Noise Monitor Locations in Galveston

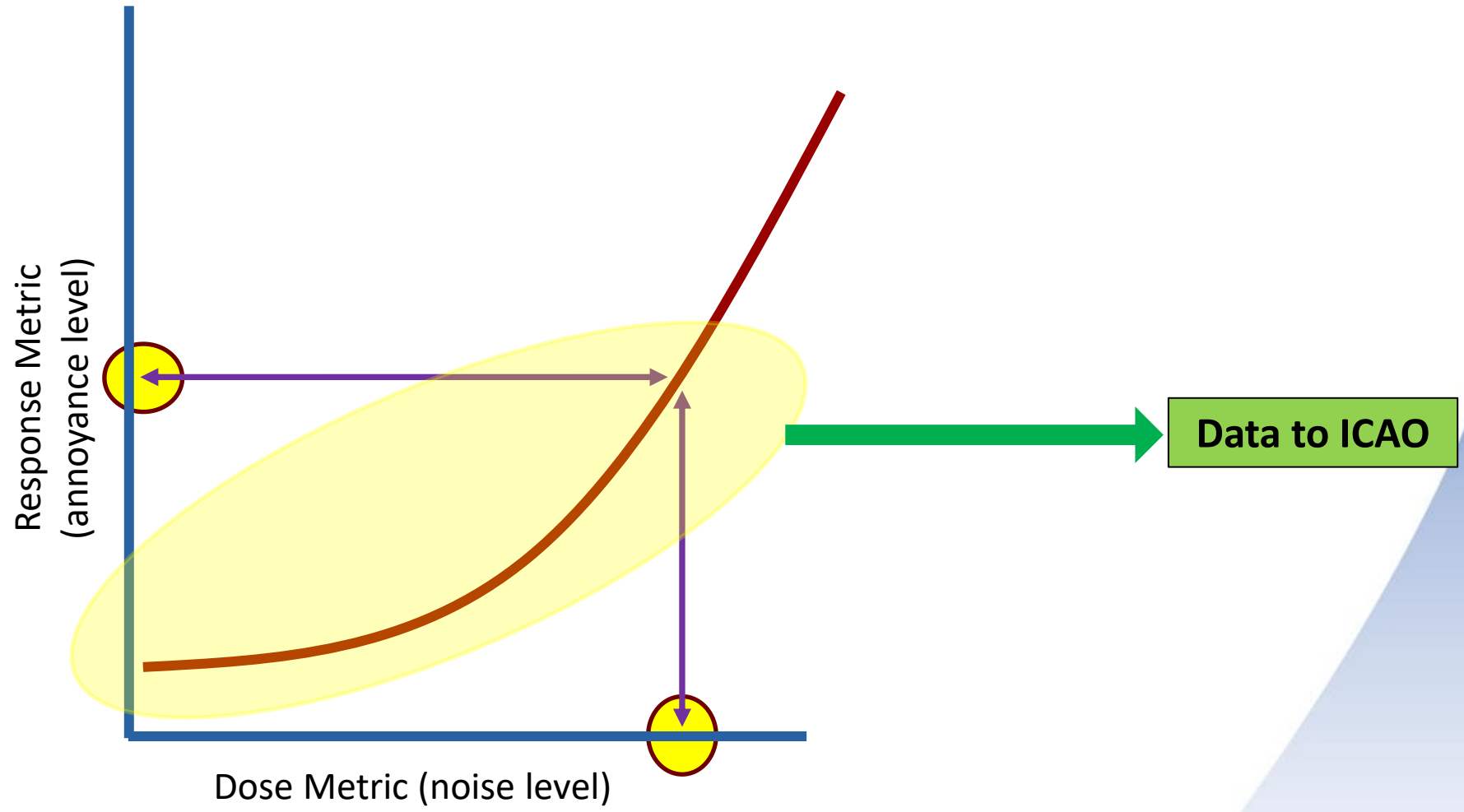


Low-boom Dive Maneuver Used in QSF18



Return

Dose – Response Characterization

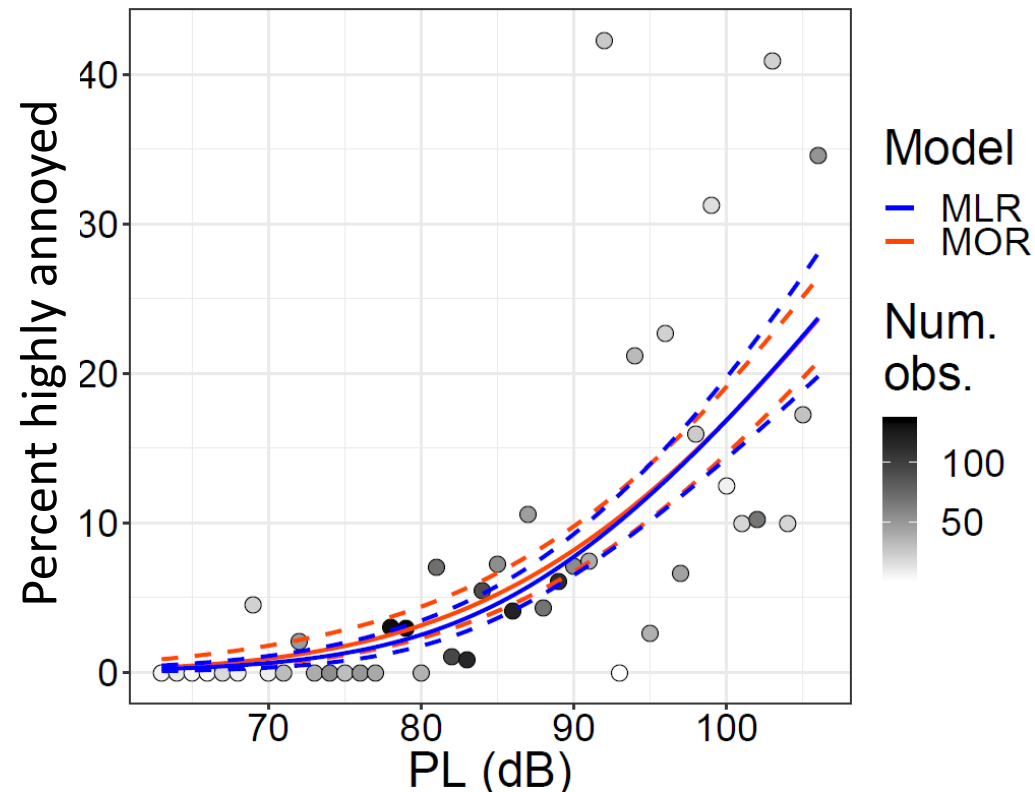


Dose-Response Analysis Example

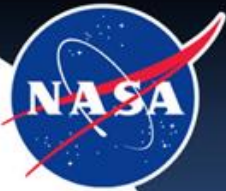


➤ Analysis of community response survey data (2011)

- Evaluated 7 different statistical modeling techniques for single-event community response survey
- Account for correlation in responses from the same participant

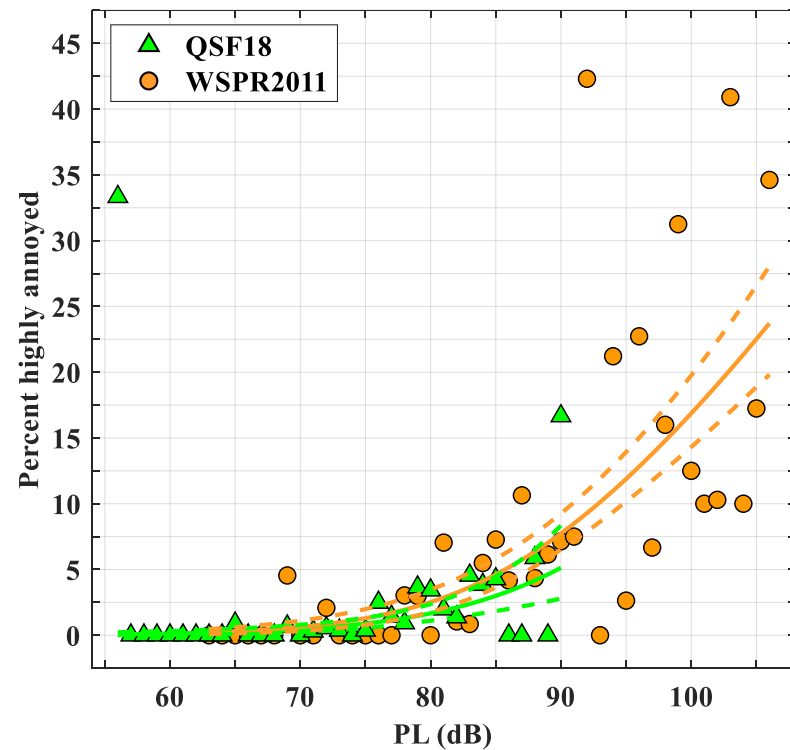


Dose-Response Analysis Examples



➤ Applied the same models to more recent QSF18 data

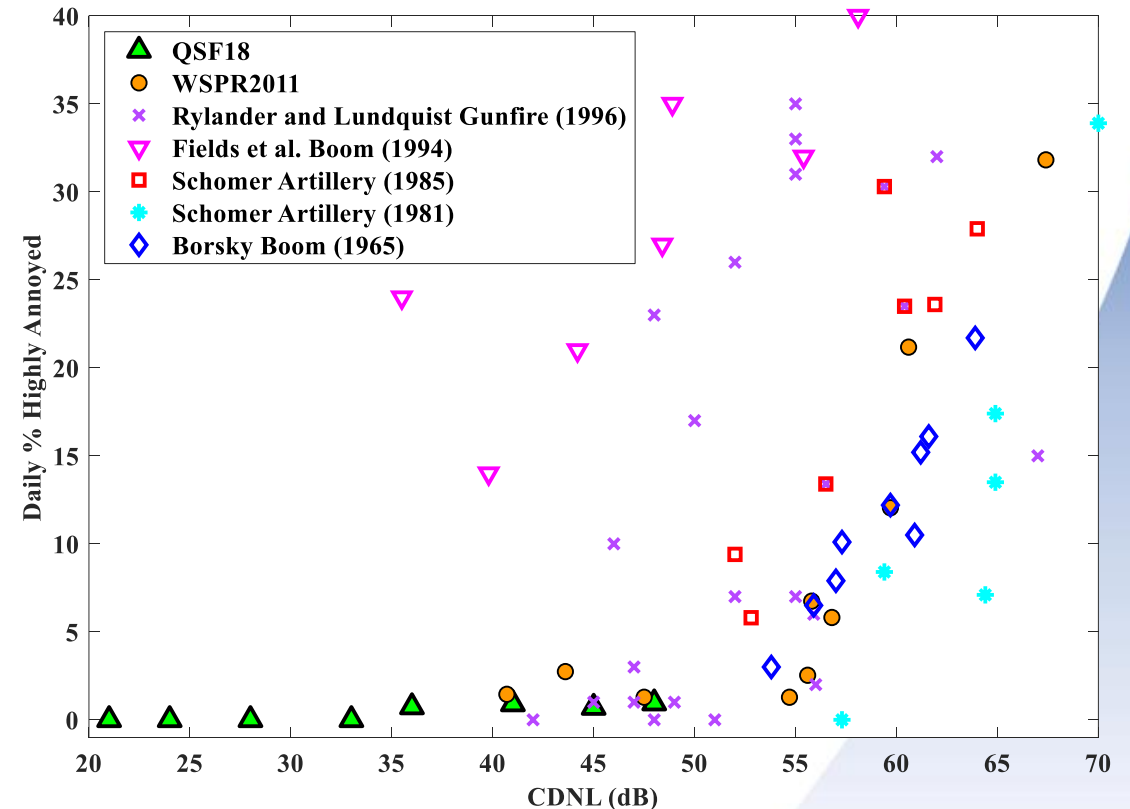
- Larger panel size, smaller range of single-event levels



J. Lee et al. J. Acoust. Soc. Am., 147:2222, 2020.

➤ Cumulative Dose-Response

Comparison of Impulse Noise Community Tests



S. Fidell, Community Response to High-Energy Impulsive Sounds: An Assessment of the Field Since 1981 (National Academy Press), 1996.