Community Testing with Quiet Supersonic Aircraft

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BYU Physics and Astronomy Colloquium

April 7, 2023

Image Credit: Lockheed Martin

Acknowledgments

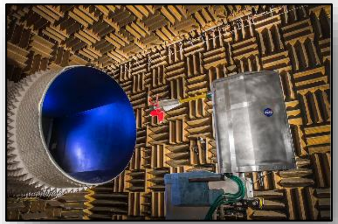
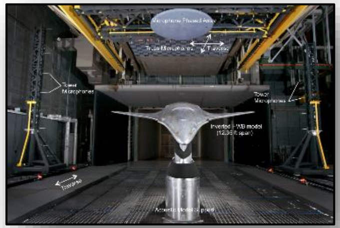
- **NASA**
  - Commercial Supersonic Technology project
  - Community Test Planning & Execution team
- **Industry, government, and university partners**

About Me

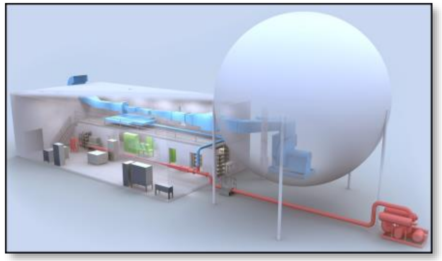
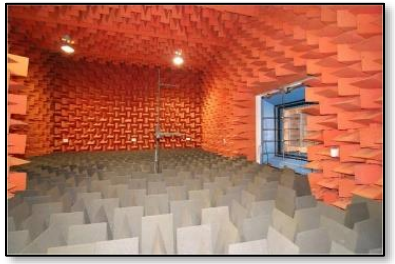
- **B.M. Music Engineering, minor Electrical Engineering**
  - University of Miami
- **M.S. and Ph.D. Acoustics**
  - Penn State
- **Post-doc in sonic boom propagation**
  - Sorbonne University, Paris, France
- **Research Aerospace Engineer**
  - Structural Acoustics Branch, NASA Langley Research Center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

Acoustics at NASA Langley

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


- **~60 engineers, technicians, and support staff**

Presentation Outline

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

This presentation contains information on NASA activities and plans that support an ongoing Standards development process in the International Civil Aviation Organization (ICAO) Committee on Aviation Environmental Protection (CAEP). The information contained in the presentation does not reflect any official positions or endorsement by ICAO CAEP.

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

Image Credit: Lockheed Martin

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

Image Credit: Lockheed Martin

NASA is building the X-59 research aircraft

Image Credit: Lockheed Martin

- 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

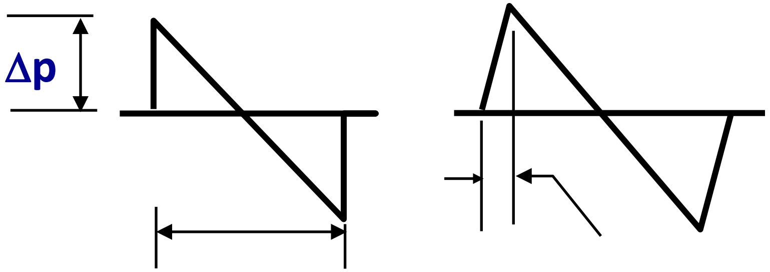
Cruise Altitude
55,000 feet

Sonic Boom Overview

Sonic Boom Basics

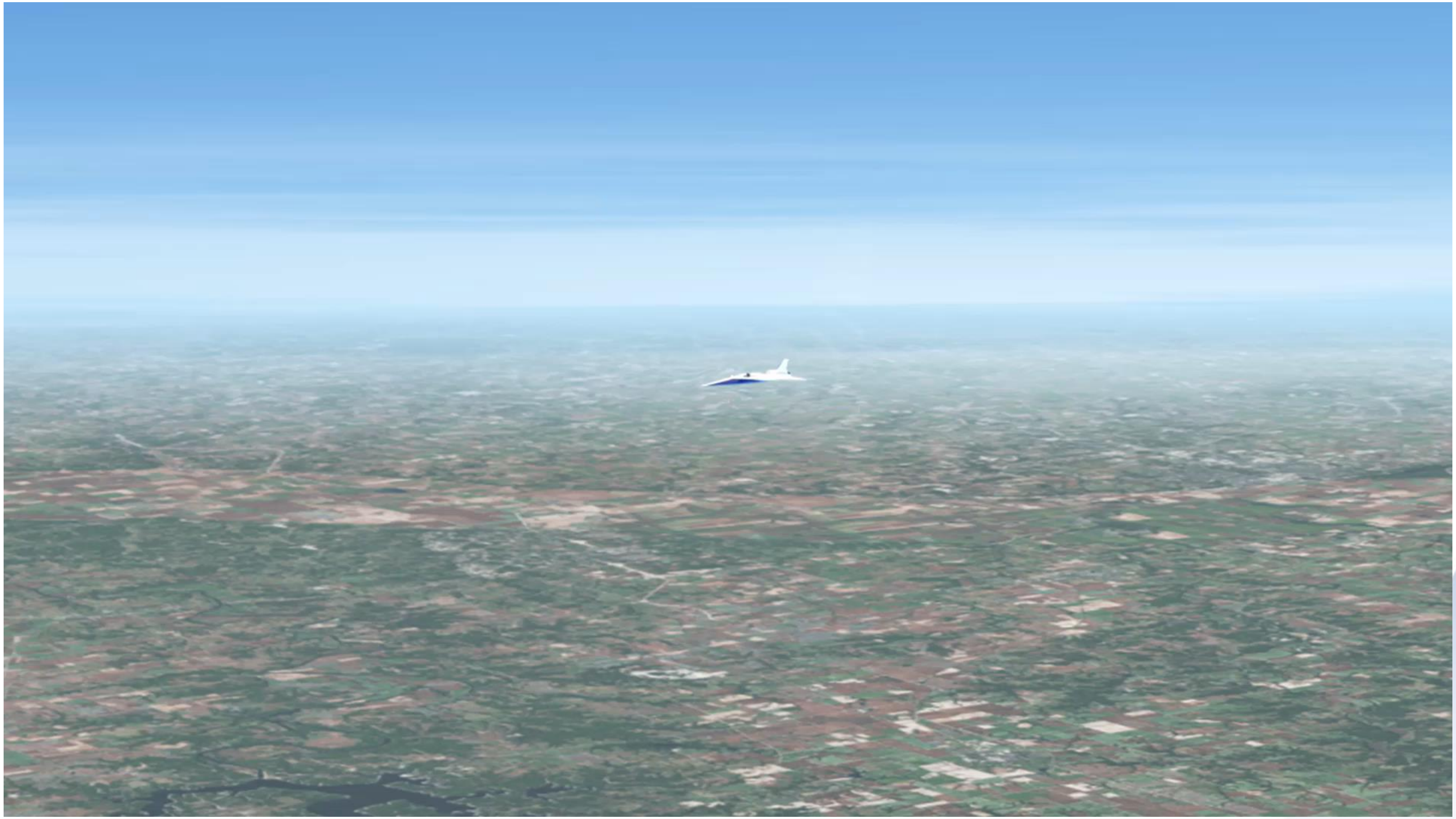
- **Supersonic flight ➡ aircraft flies faster than speed of sound**
  - Shockwaves travel away from vehicle
  - Shockwaves merge as they travel through the atmosphere
  - Heard on the ground as a sonic boom
- **For traditional supersonic aircraft**
  - Shockwaves eventually merge into bow and tail shocks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

Overpressure Δp

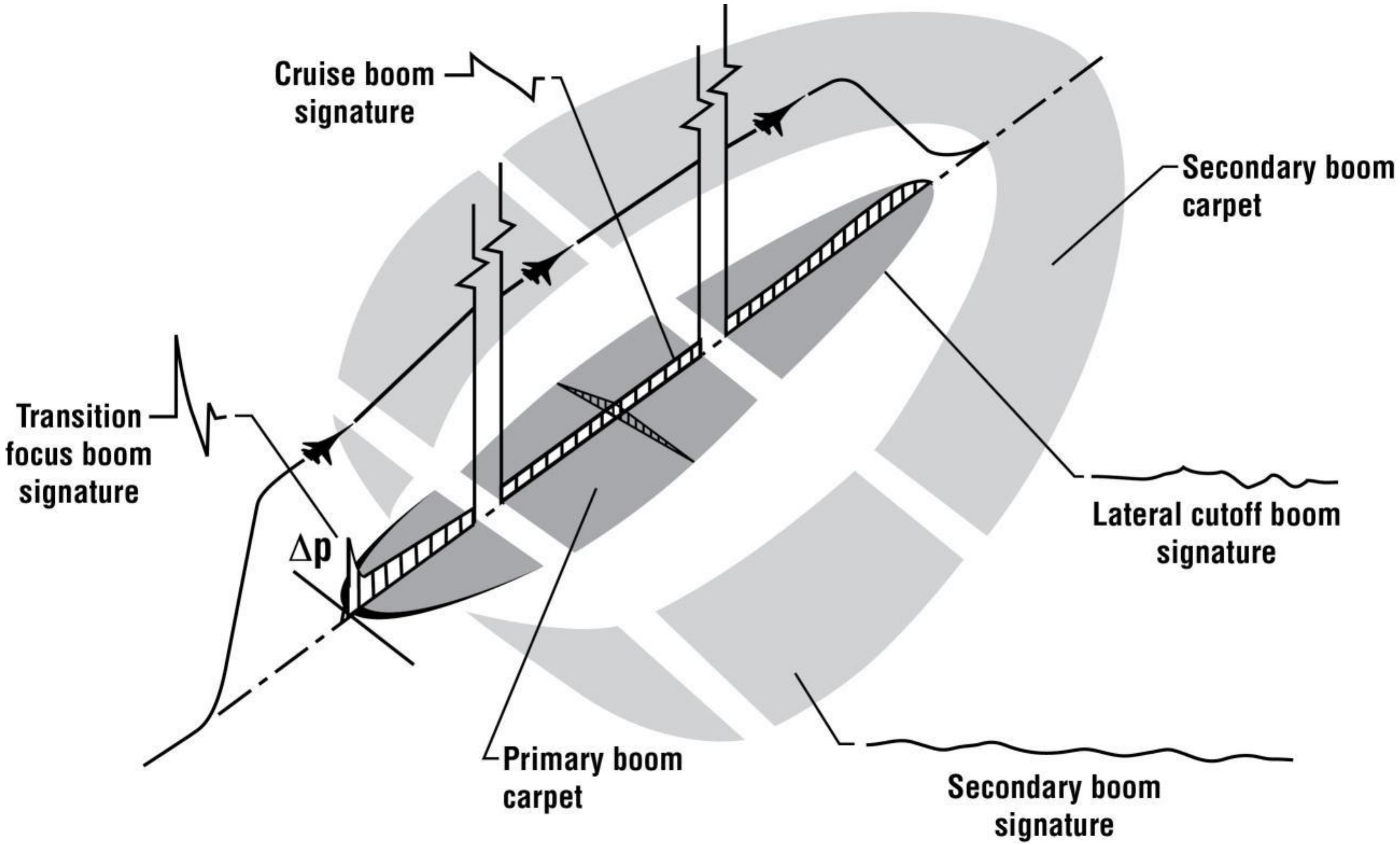


Duration **Rise Time**

Sonic Boom Moves with the Aircraft



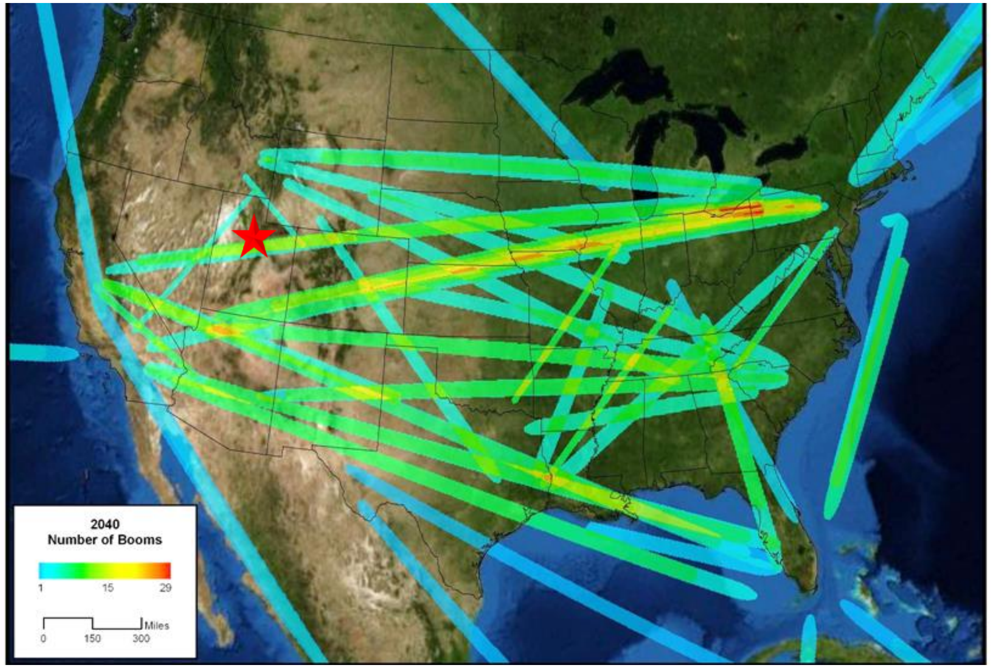
Sonic Boom Ground Exposure



Sonic Boom Waveforms and Spectra

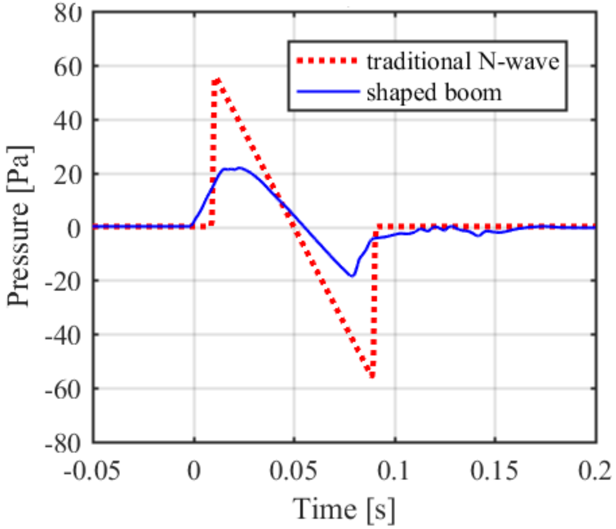
- **Unique aspects of sonic booms**
  - Transient nature of sonic boom
  - Low-frequency energy
  - Created along entire supersonic path (en route)
  - Cannot use the same methods/metrics as for subsonic aircraft

Number of booms predicted in 2040

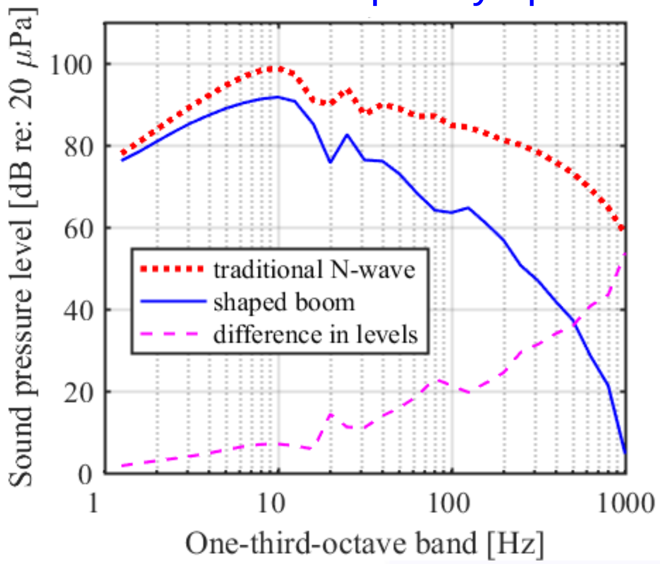


J. Rachami and J. Page. AIAA 2010-1385.

Example boom shapes



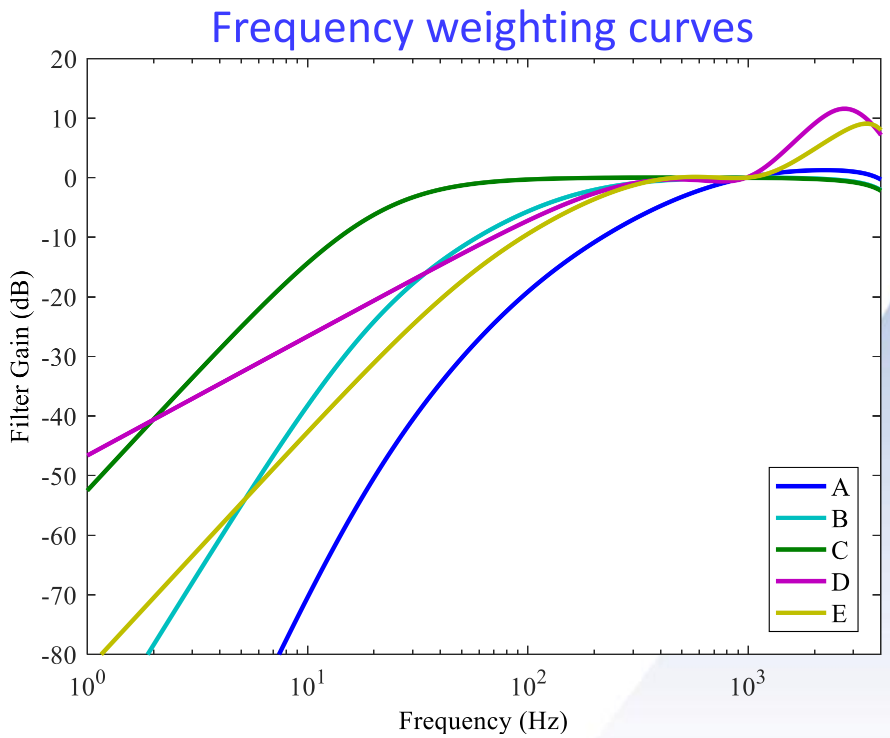
Variation in frequency spectra



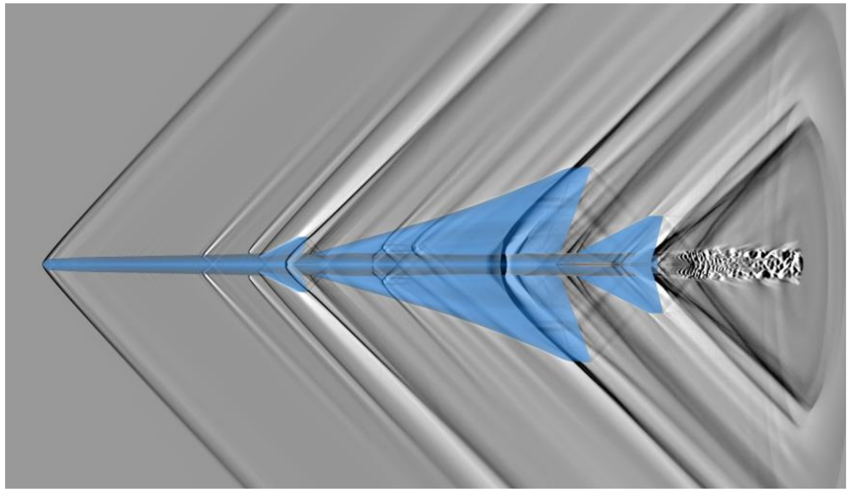
Sonic Boom Noise Metrics

- **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

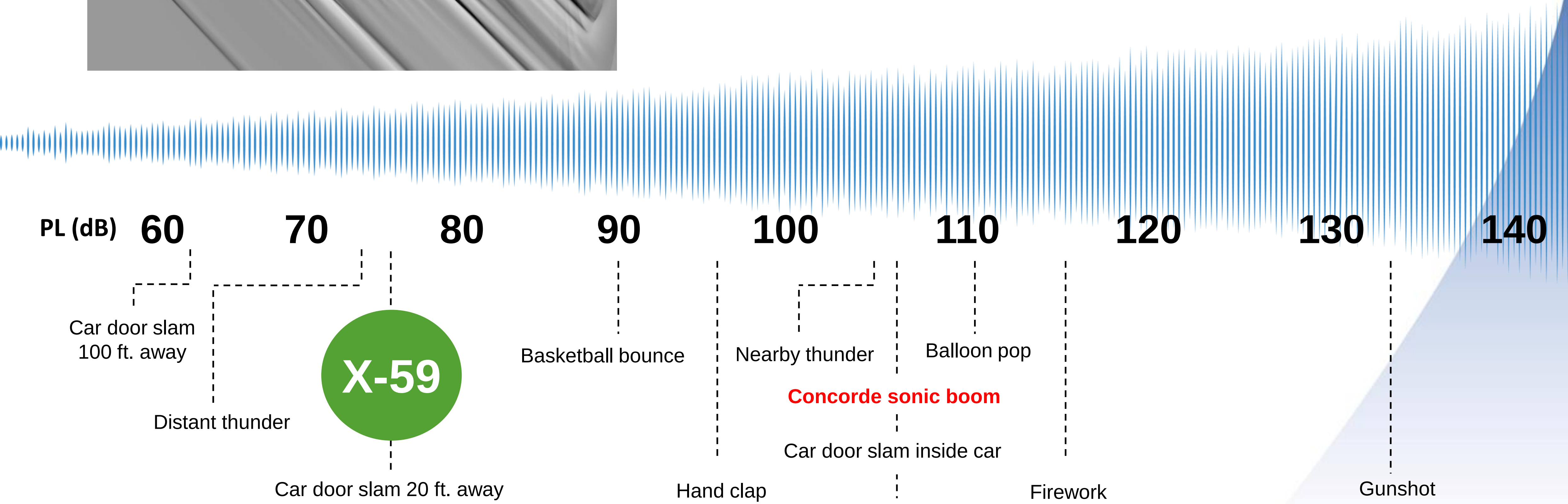
- **Several alternate metrics have been proposed**
  - Different metrics treat lower frequencies differently which is critical for describing sonic boom noise



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**



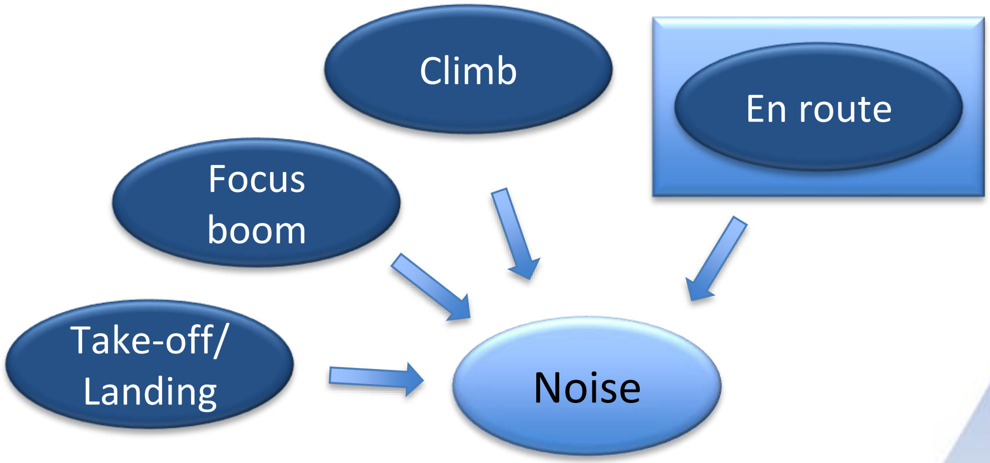
Supersonic Aircraft Noise Regulations

Civil Supersonic Aircraft Noise Certification

- **Civil supersonic overland flight prohibited**
- **Industry interest in lifting the ban and replacing with noise limit**

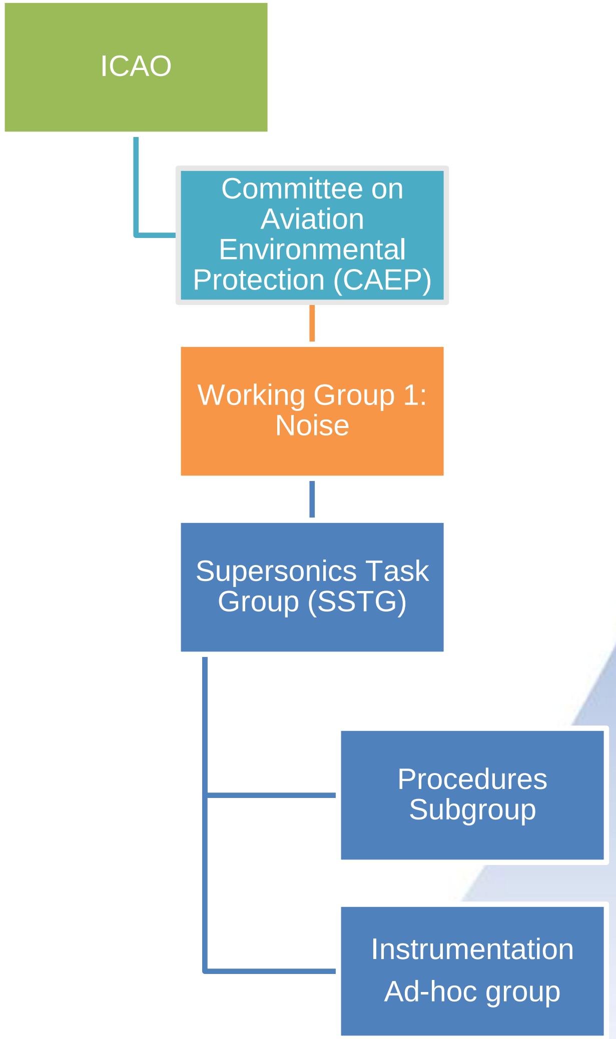
- **NASA is working with regulators**
  - Providing data
  - Enabling development of a new noise standard

- **Elements of a certification standard**
  - Noise metric, test procedures, noise limit
  - Different phases of flight



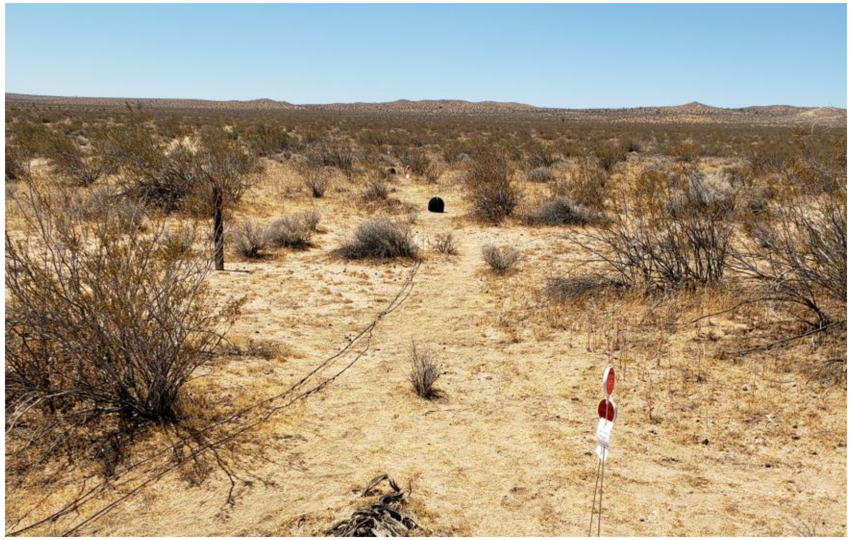
International Civil Aviation Organization (ICAO)

- **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



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

Image Credit: Lockheed Martin

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

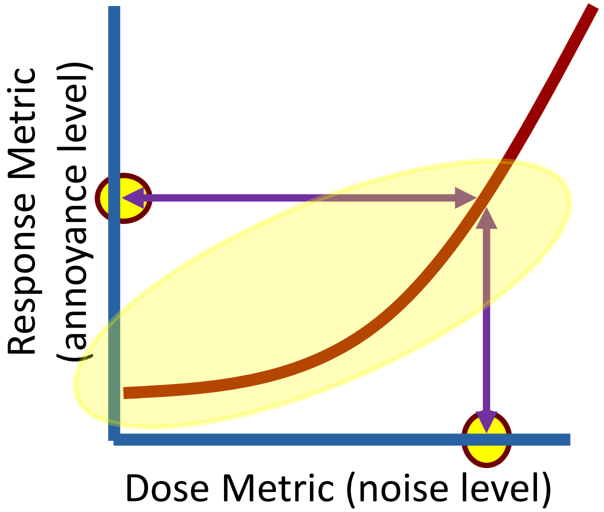
Images Credit: Lockheed Martin

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**

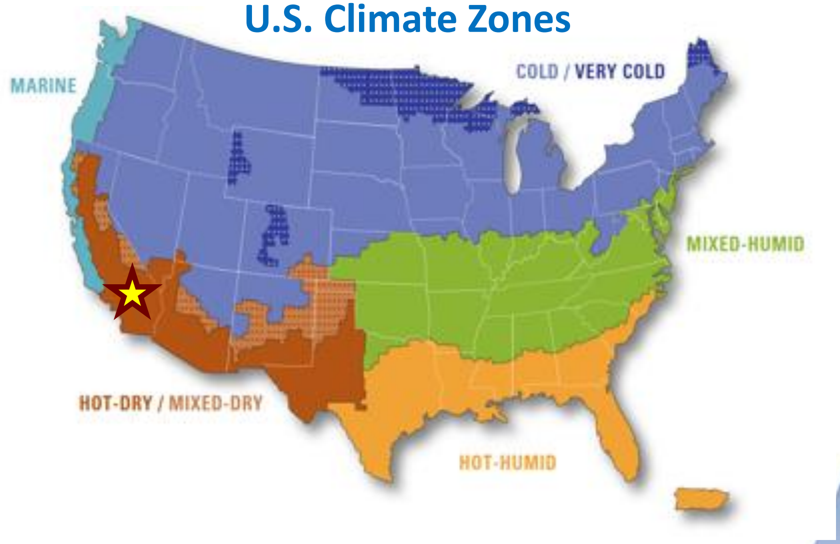


Provide dose-response data to ICAO

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**

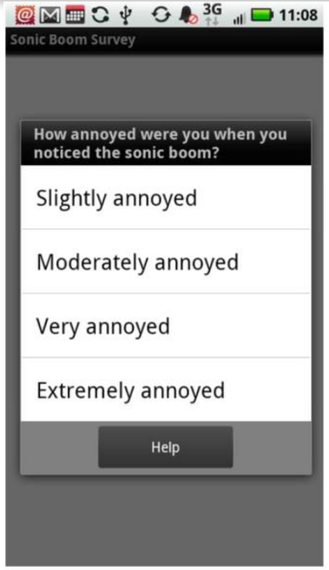
U.S. Climate Zones

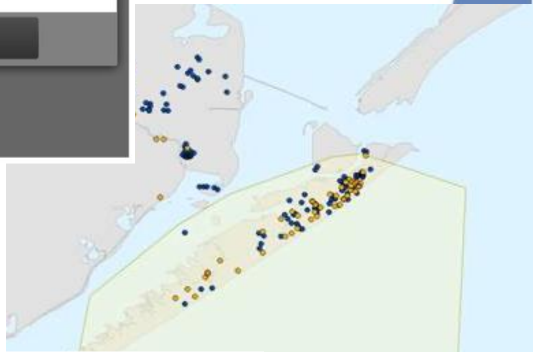


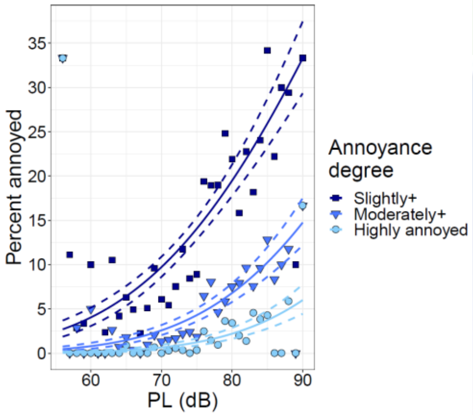
Survey Design and Analysis – Key Challenges

- Enable nationally representative results from a limited number of community studies
- Automation of survey response acquisition and processing
- Statistical methods for data analysis
  - Analyze multiple responses per participant
  - Limited range of levels
  - Aggregate results from multiple communities

- **Strategies to address challenges include:**
  - Testing/validation of survey methods and instruments through small-scale studies
  - Testing of automated processing methods to achieve target levels of usable/valid survey data







Exposure Design and Estimation – Key Challenges

- **Measurements**
  - Acoustic monitor placement strategy
  - Mitigating background noise in recordings
  - Automated acoustic data acquisition
- **Analysis**
  - Estimating meteorological conditions across survey area
  - Estimating exposure level across large survey areas
  - Automated exposure estimation methods to support X-59 deployment pace

- **Strategies to address challenges include:**
  - Hardware/software testing, validation of remote operation and robustness, and testing of rapid automated methods during Phase 2

Summary

- NASA and partners are fully engaged with the international standards and regulatory community
- NASA is committed to deliver data supporting development of standards for quiet commercial supersonic flight overland
- Standards require metrics, procedures, and limits
- The Quesst mission timeline and activities offer opportunities to collect valuable data for all 3 elements of the standard

What you should know about NASA's 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**

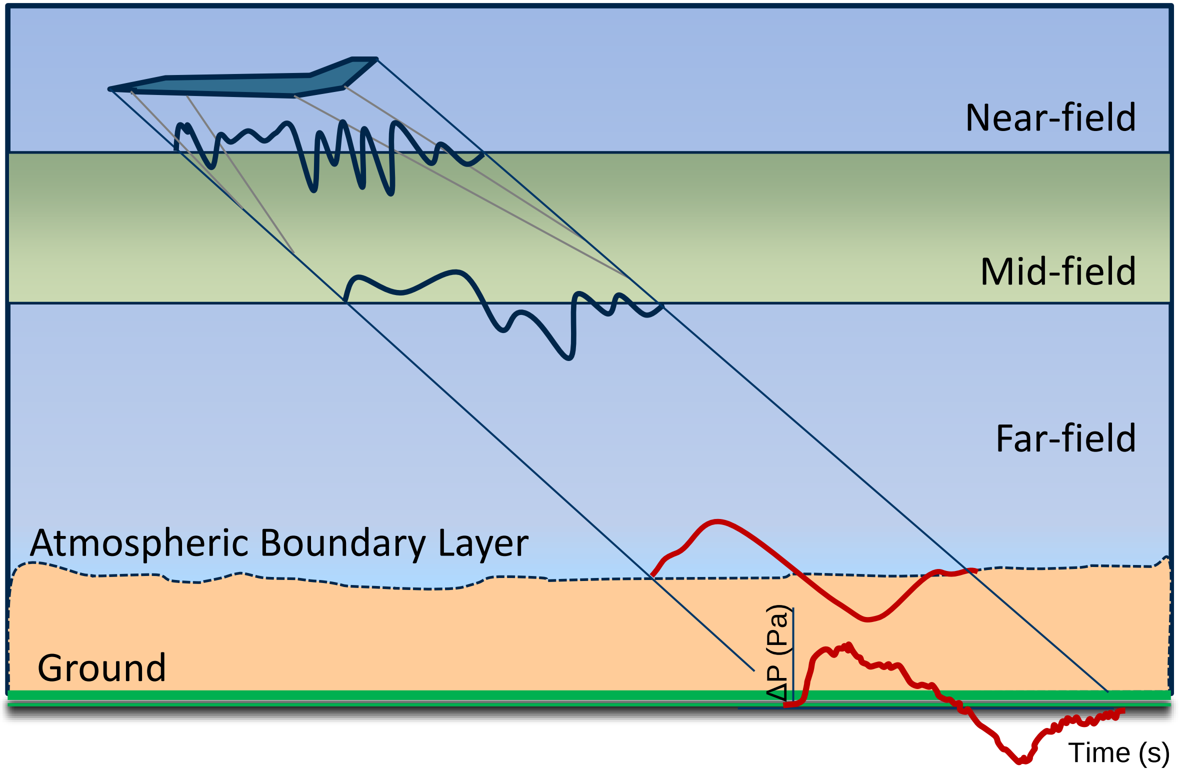
   Want to know more?

https://www.nasa.gov/quesst

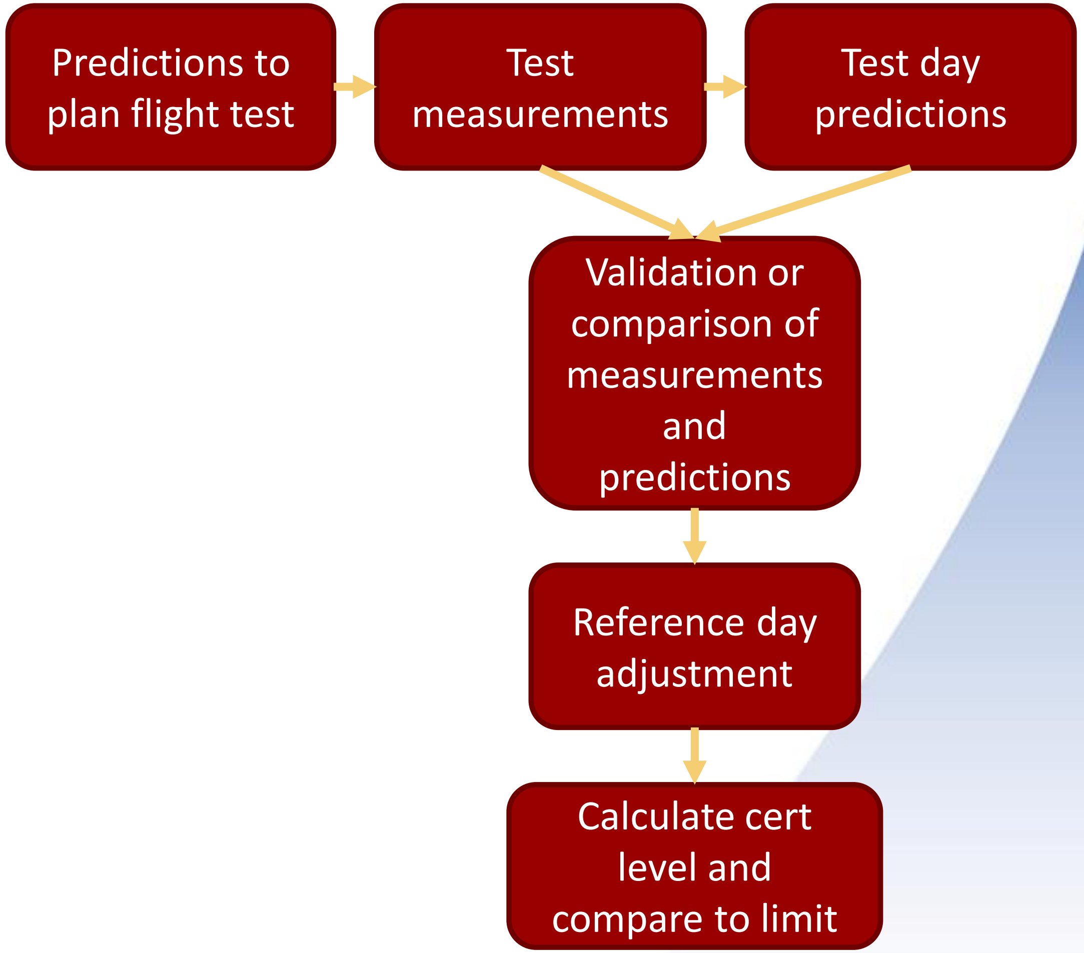
Backup Slides

Notional Certification Procedure

- **Reference Procedure Must Characterize Noise Performance at Reference Conditions**



Notional Certification Procedure Steps



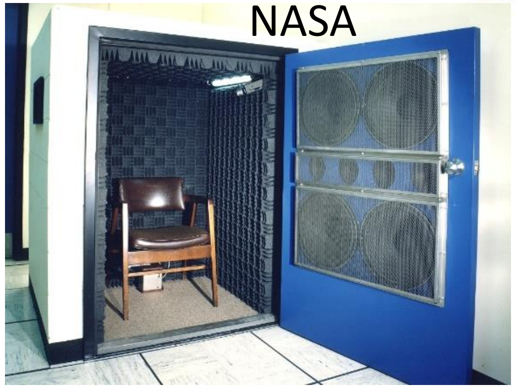
R. Cowart "Status of Certification Procedures for Quiet Supersonic Flight", *AIAA AVIATION 2019, Dallas, TX.*

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*

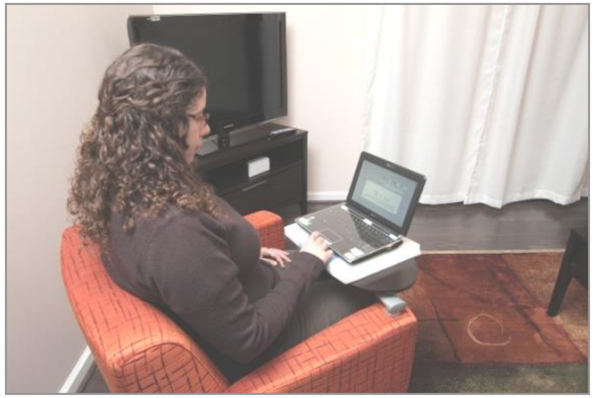
Another configuration

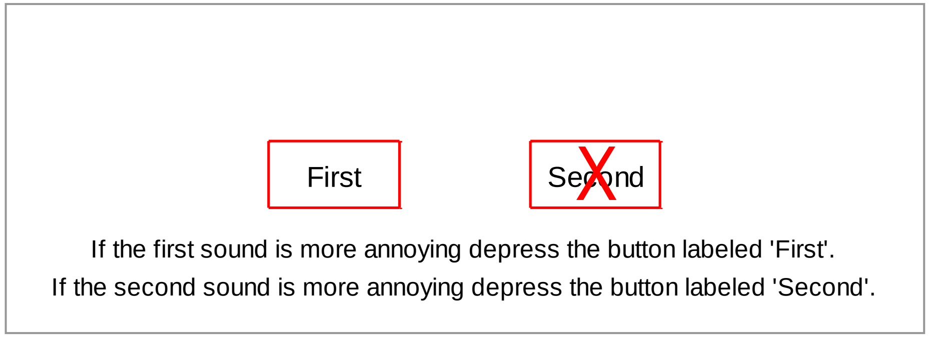
- Noise simulator constructed to mimic indoor environment acoustically and aesthetically
  - Realistic indoor soundscape and environment
  - Control secondary rattle noises and vibration for systematic study

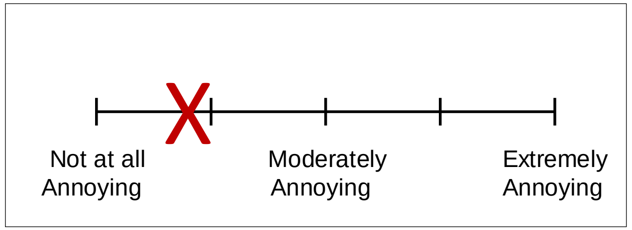
NASA's Interior Effects Room (IER)

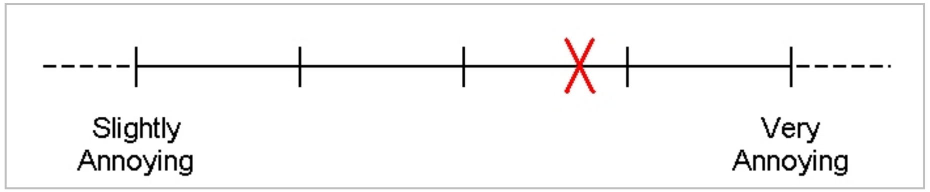
Laboratory Psychoacoustics Research

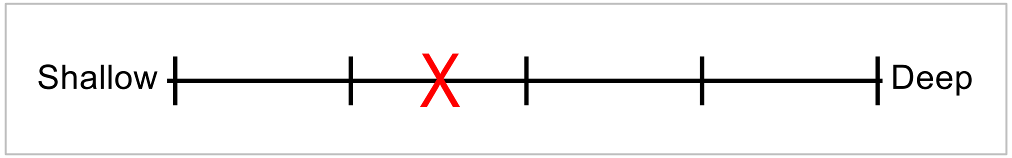
- **Participants from surrounding community**
  - Diversity in age and gender
  - Must pass hearing tests
- **Typically 30-40 participants**
  - Tested 2-3 at a time
- **Sessions for familiarization and practice**
- **Example rating screens**





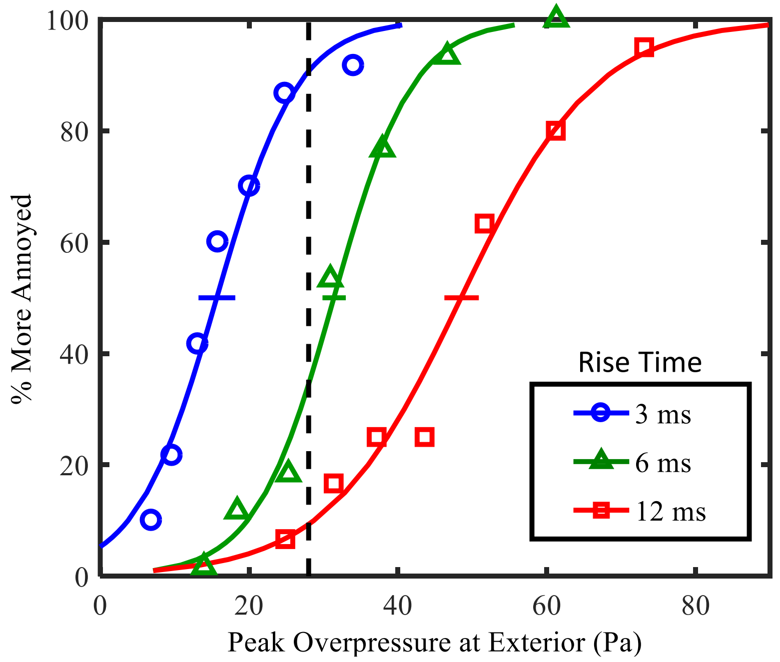


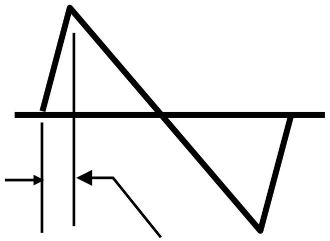




Human Response to Indoor Booms

- **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**





Rise Time

J. Rathsam, A. Loubeau, and J. Klos. A study in a new test facility on indoor annoyance caused by sonic booms. Technical Report TM-2012-217332, NASA, 2012.
A. Loubeau, J. Rathsam, and J. Klos. Evaluation of an Indoor Sonic Boom Subjective Test Facility at NASA Langley Research Center. Proc. Mtgs. Acoust., 12: 040007, 2013.

Aircraft Size: Full-scale vs. Sub-scale Aircraft

Objective

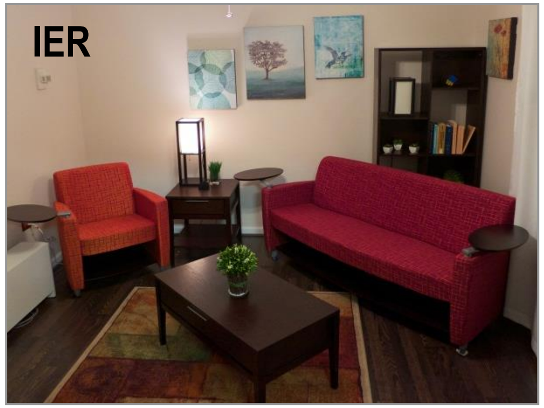
- Evaluate indoor annoyance to sonic booms predicted for sub-scale and full-scale supersonic aircraft
  - Smaller size and weight of demonstrator create a shorter sonic boom with less low-frequency energy than commercial airliner

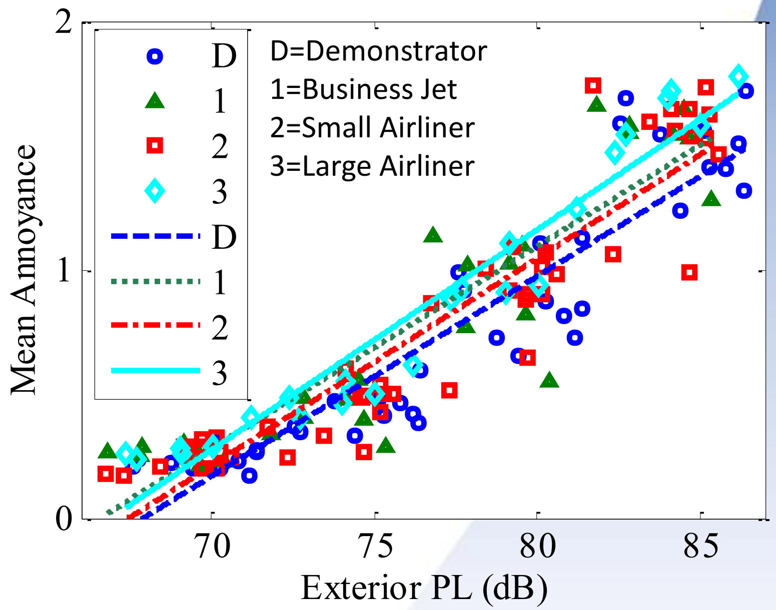
Approach

- 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 sub-scale 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

70 metrics (2014)	25 (2014-2015)	8 (2015)	5 (2015)	6 (2016)	6 (2017)
• Engineering metrics • Loudness metrics • “Hybrid” metrics	• Expert judgment, including non-acoustic factors	• Meta-analysis of three lab studies	• Additional analysis with 4th study • PL, ASEL, BSEL, ESEL, and ISBAP	• Additional analysis with 5th study • DSEL added	• Additional analysis with 6th study • Three methods for metric evaluation

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.

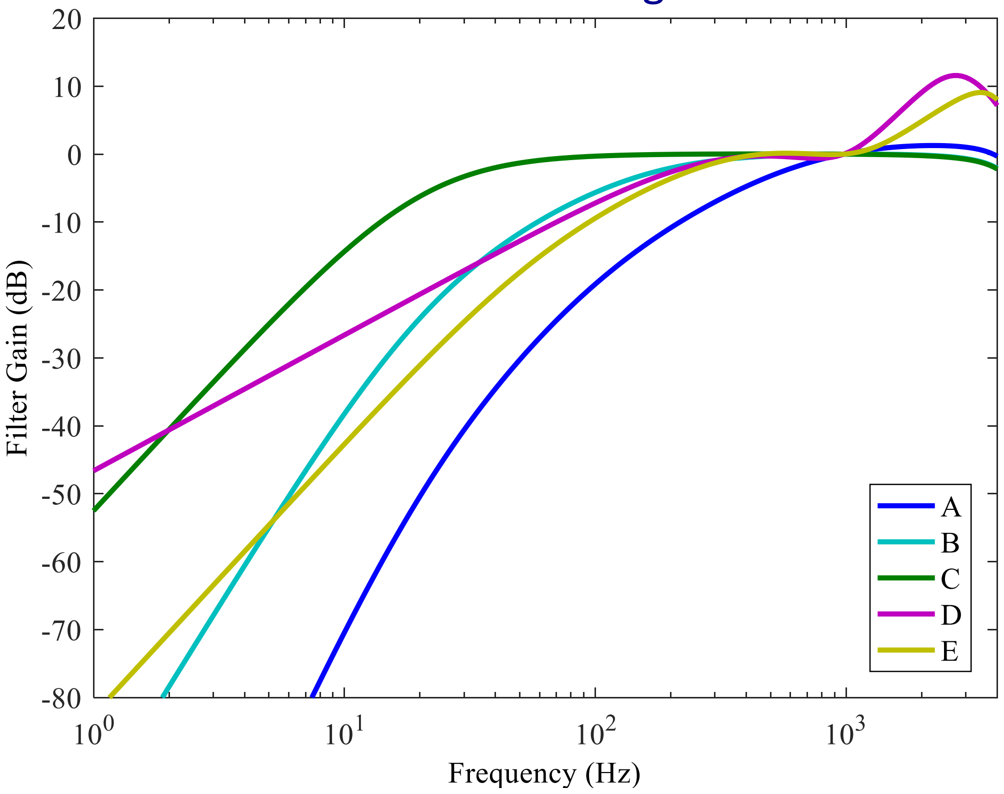
Sonic Boom Noise Metrics

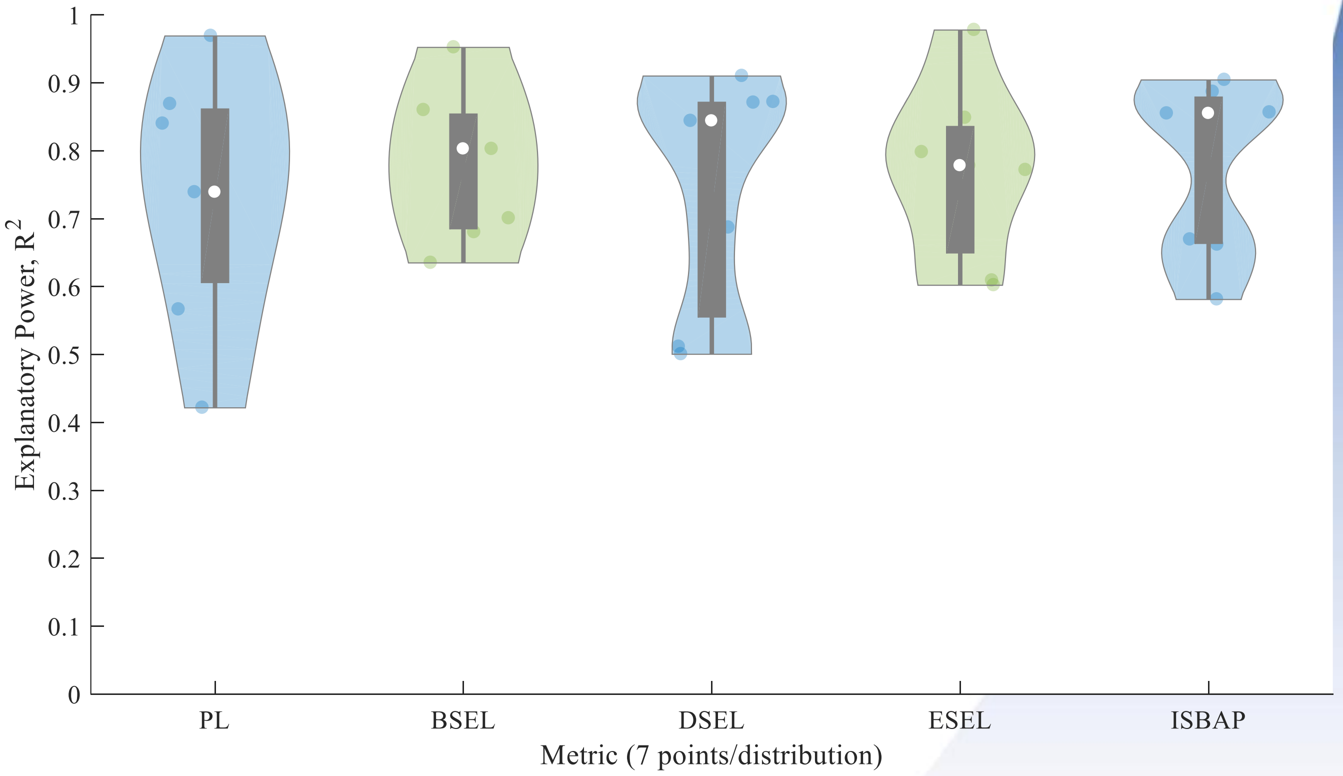
Six metrics for further consideration:

PL, ASEL, BSEL, DSEL, ESEL, ISBAP

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

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





A. Loubeau et al., "Updated evaluation of sonic boom noise metrics," J. Acoust. Soc. Am., 144: 1706, 2018.

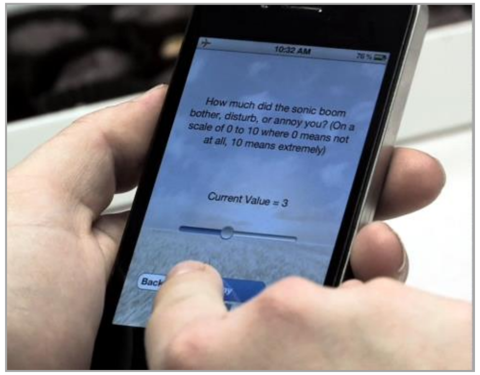
Laboratory Study Summary

- **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

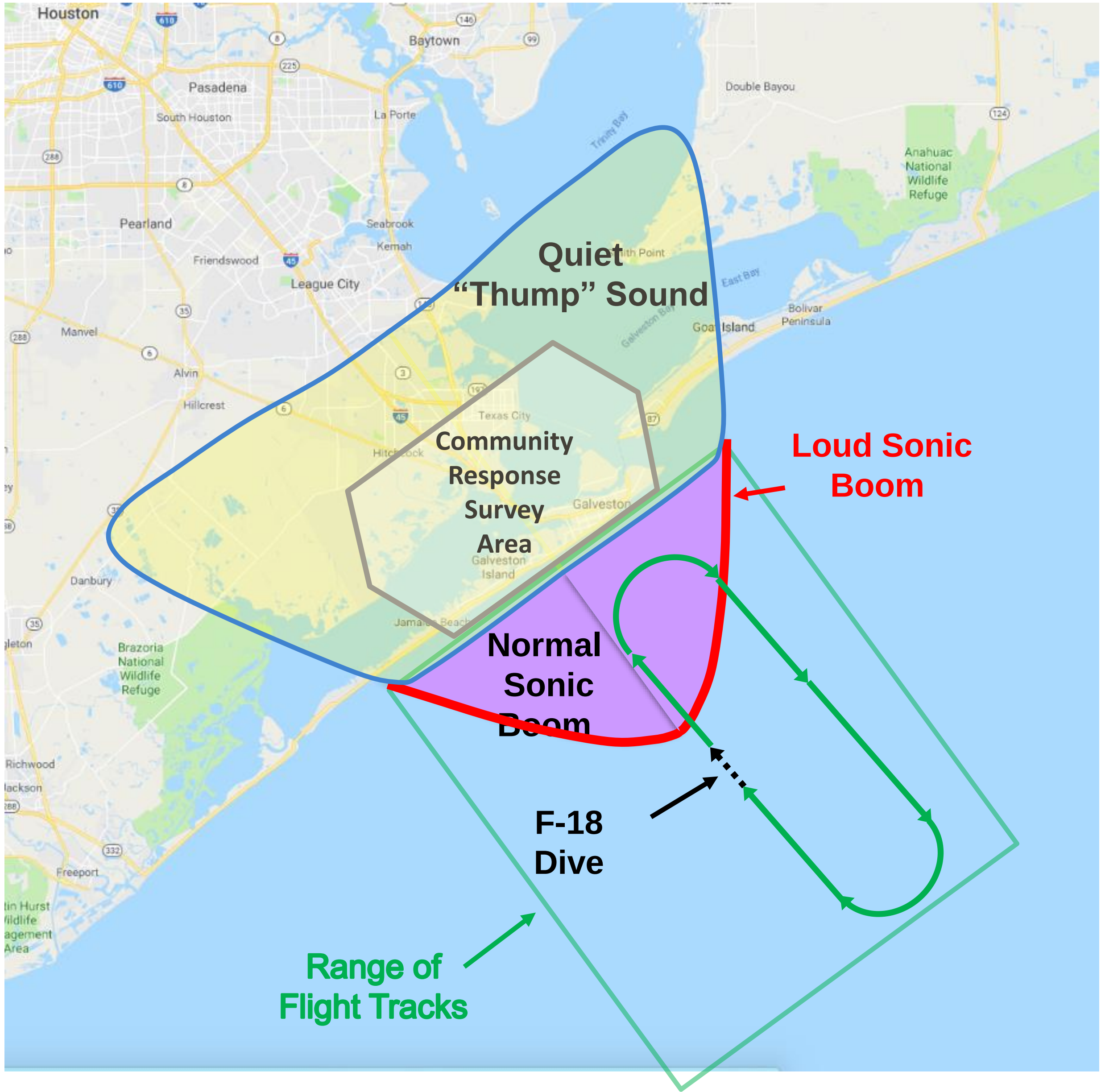
- **Identify, minimize, and/or mitigate risks for future X-59 community testing**
- **Quiet Supersonic Flights 2018 (QSF18)**
  - Low-amplitude sonic boom community test in Galveston, Texas, USA on November 5-15, 2018
  - Test methodologies in a city not used to hearing sonic booms
  - Low-boom dive 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

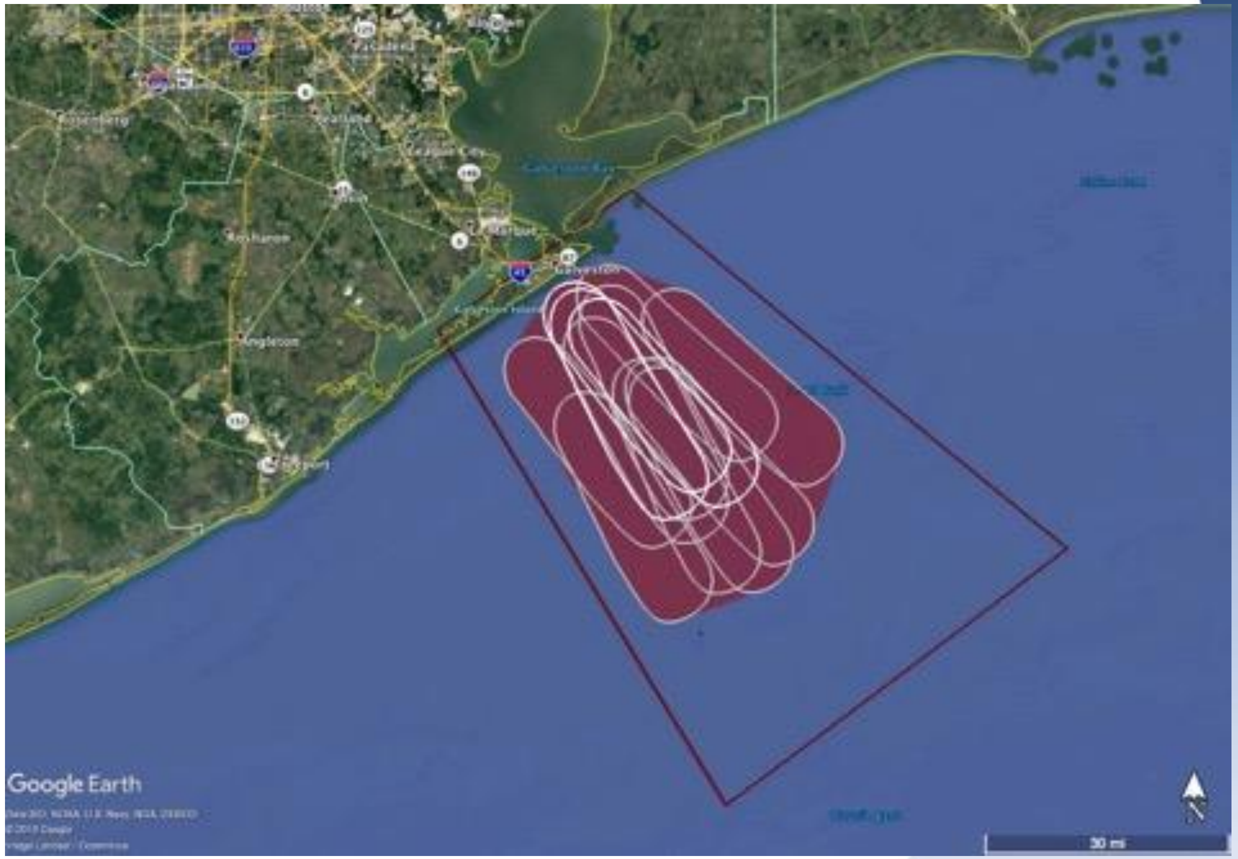


Noise Monitor Locations in Galveston

Page et al., Quiet Supersonic Flights 2018 (QSF10) Test: Galveston, Texas Risk Reduction for Future Community Testing with a Low-Boom Flight Demonstration Vehicle, NASA/CR-2020-220589, 2020.

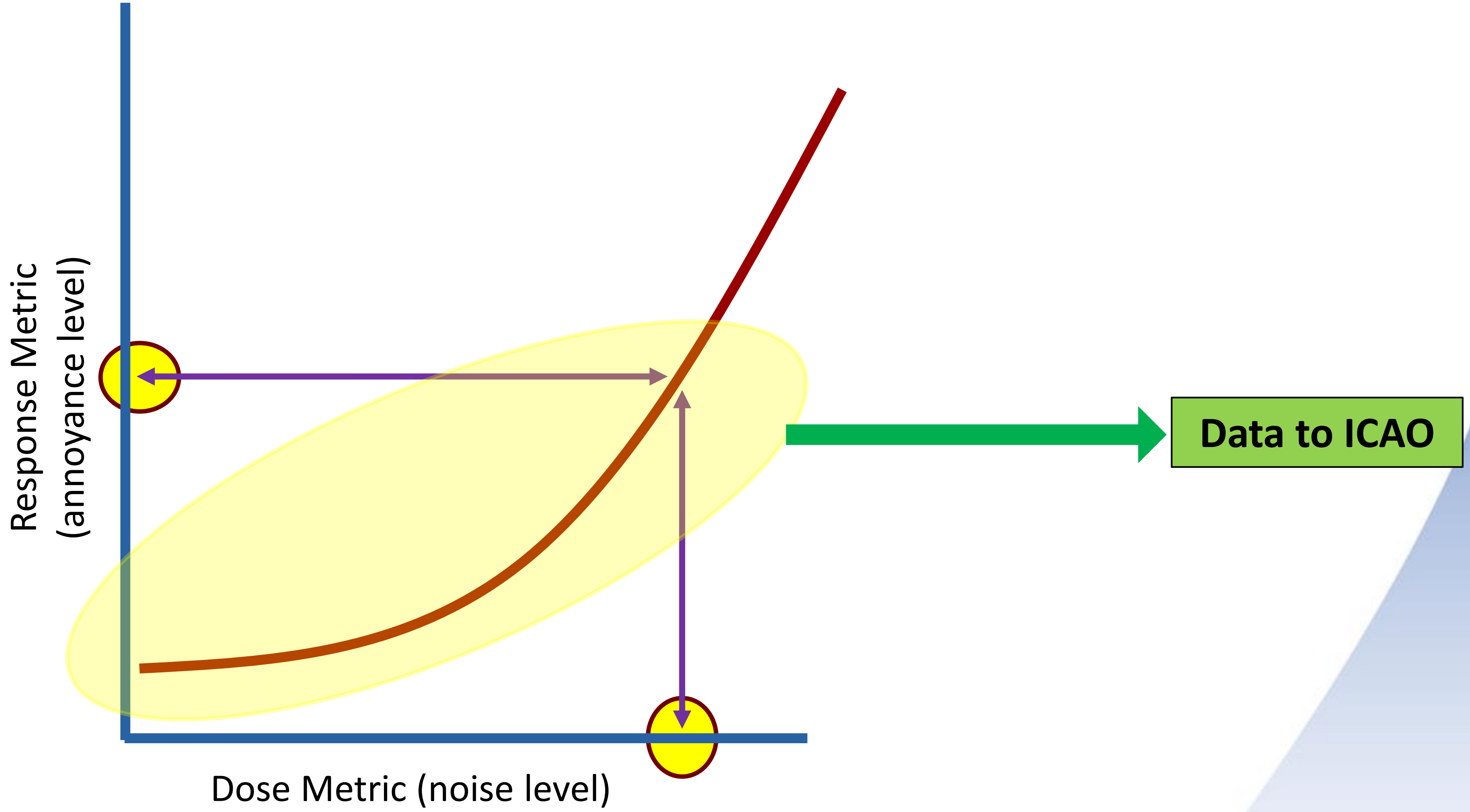
Low-boom Dive Maneuver Used in QSF18





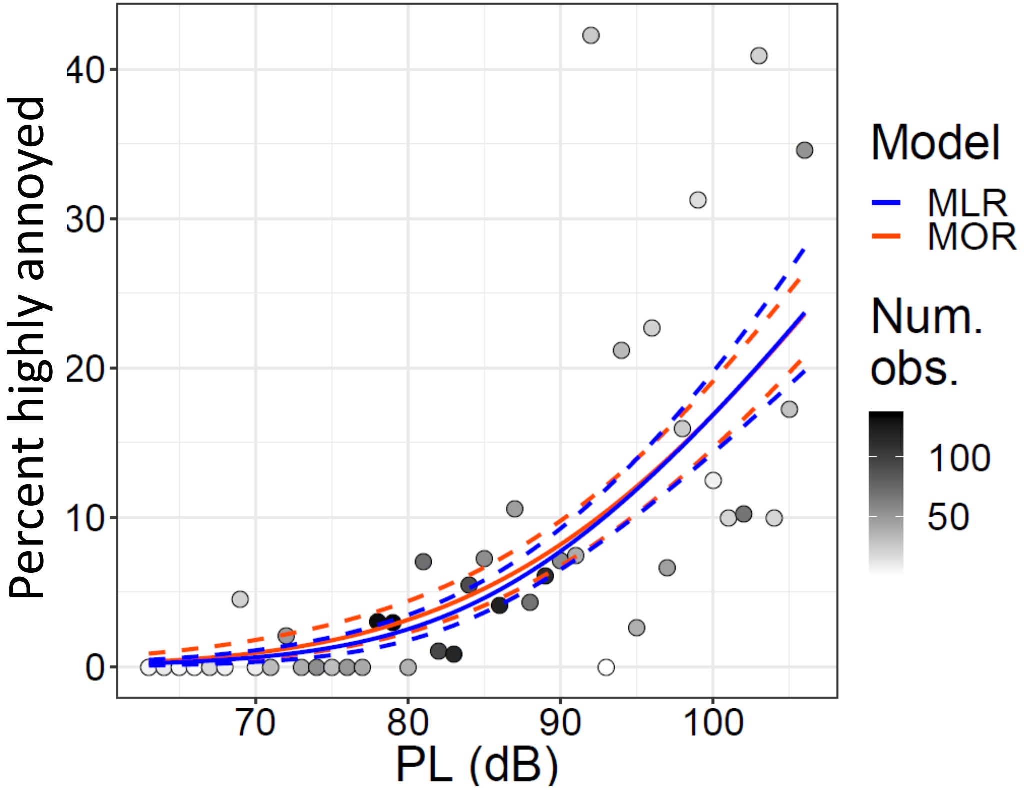
Return

Dose – Response Characterization



Dose-Response Analysis Example

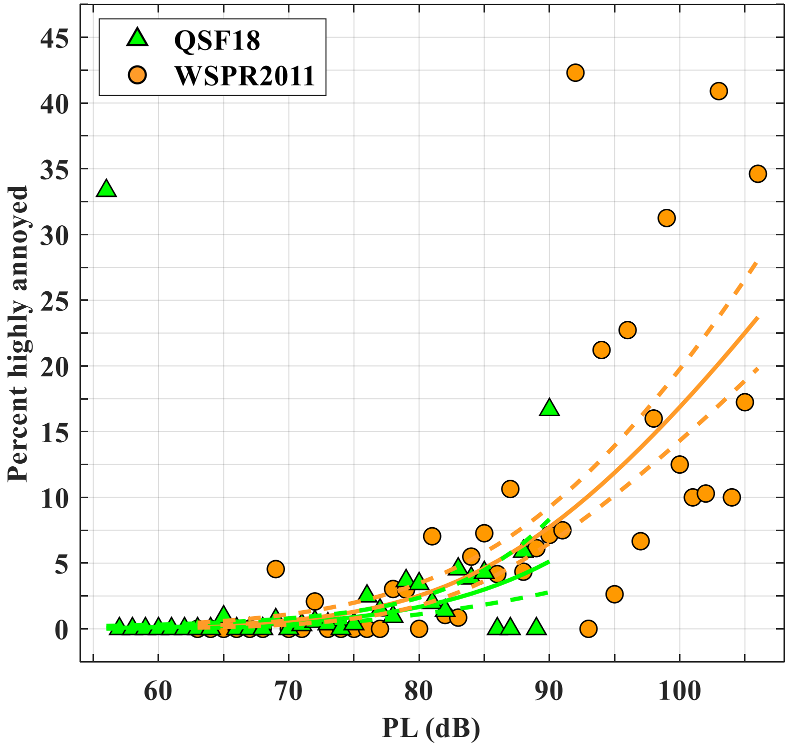
- **Analysis of community response survey data (2011)**
  - Evaluated 7 different statistical modeling techniques for single-event community response survey
  - Account for correlation in responses from the same participant



Lee et al., Statistical modeling of quiet sonic boom community response survey data, NASA/TM-2019-220427, 2019.

Dose-Response Analysis Examples

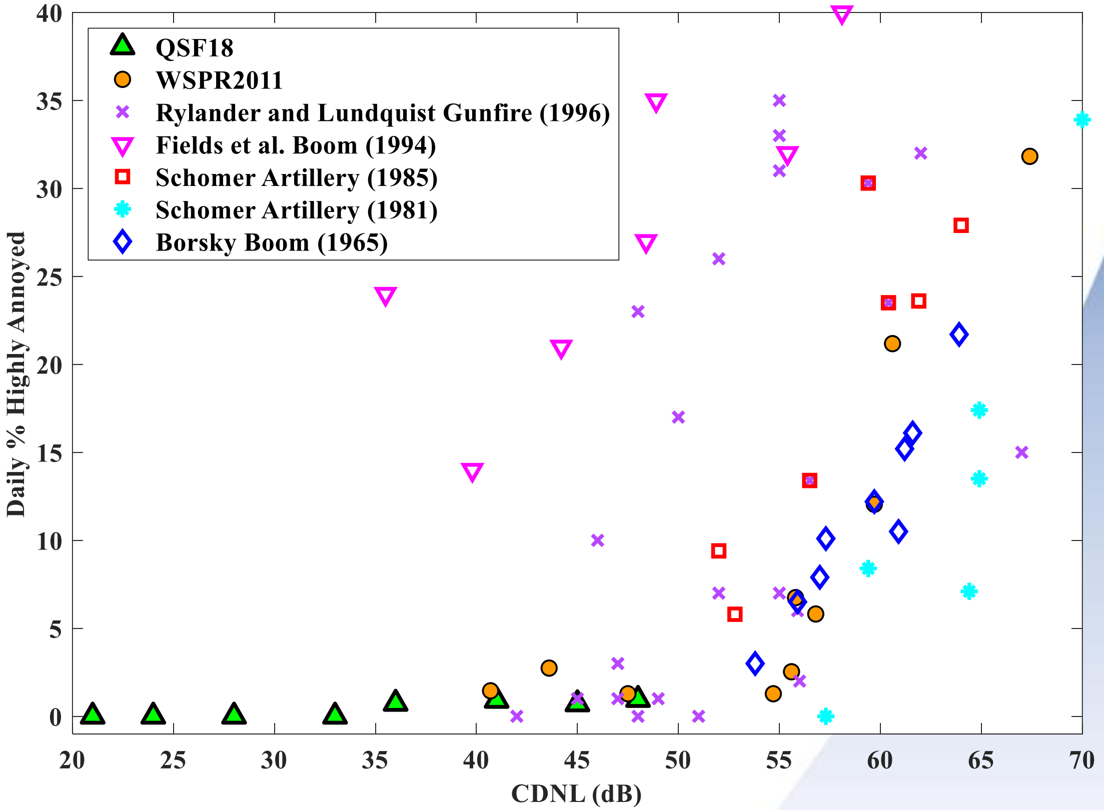
- **Applied the same models to more recent QSF18 data**
  - Larger panel size, smaller range of single-event levels



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.