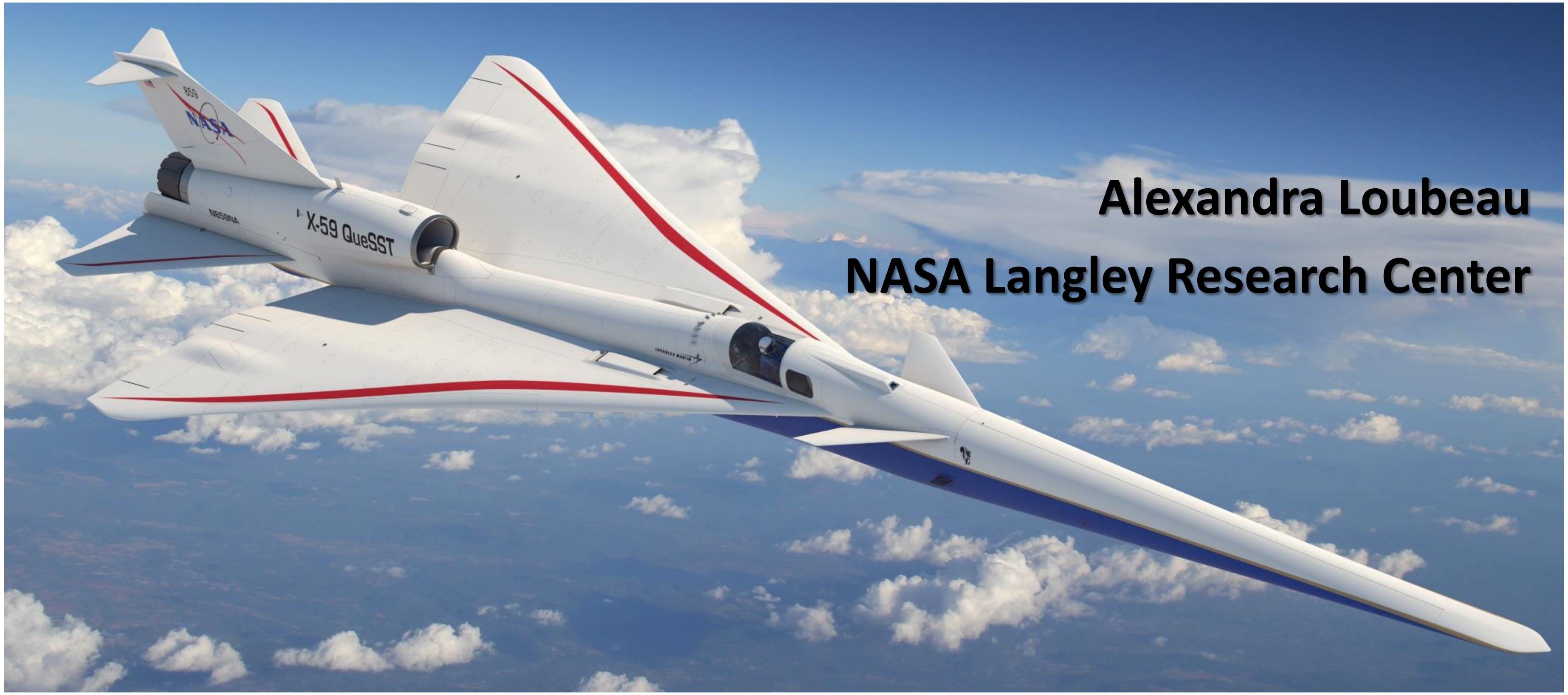
Sonic Booms and Community Testing

NASA's role in enabling commercial supersonic overland flight



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AIAA St. Louis Section
Virtual Meeting
March 10, 2021

Acknowledgments

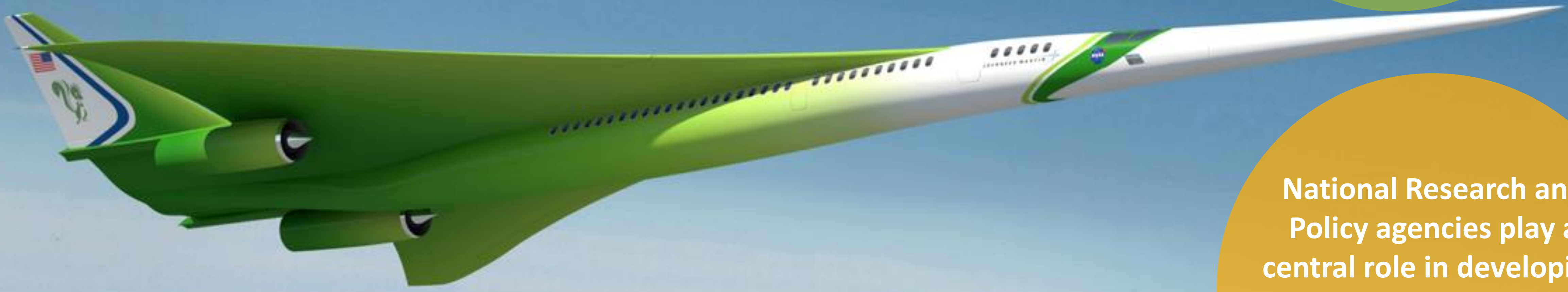
- **NASA**
  - Commercial Supersonic Technology project
  - Community Test Planning & Execution team
- **Industry, government, and university partners**

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 compared to Concorde and SST will be efficient, affordable, and environmentally responsible

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 Low-Boom Flight Demonstration 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

NASA is developing a new low-boom X-Plane

Built by Lockheed Martin Skunk Works

This X-59 QueSST aircraft will first fly in 2022

Flights will confirm that a full-scale supersonic aircraft can produce just a "thump"

Key data will be gathered on public perception of quiet supersonic flights in several cities across the nation

Outline

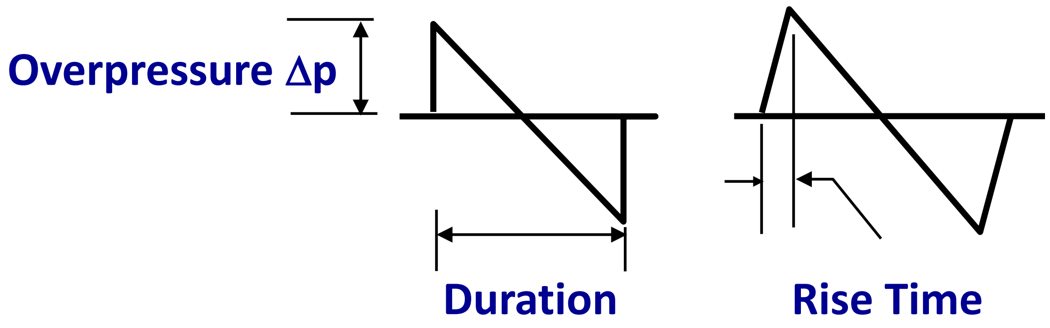
- **Sonic boom overview**
- **Supersonic aircraft noise regulations**
- **Research progress in key areas**
  - Atmospheric propagation
  - Sonic boom noise measurement systems
  - Human response
- **X-59 Quiet Supersonic Technology (QueSST) aircraft**
- **Preparations for community testing**

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.

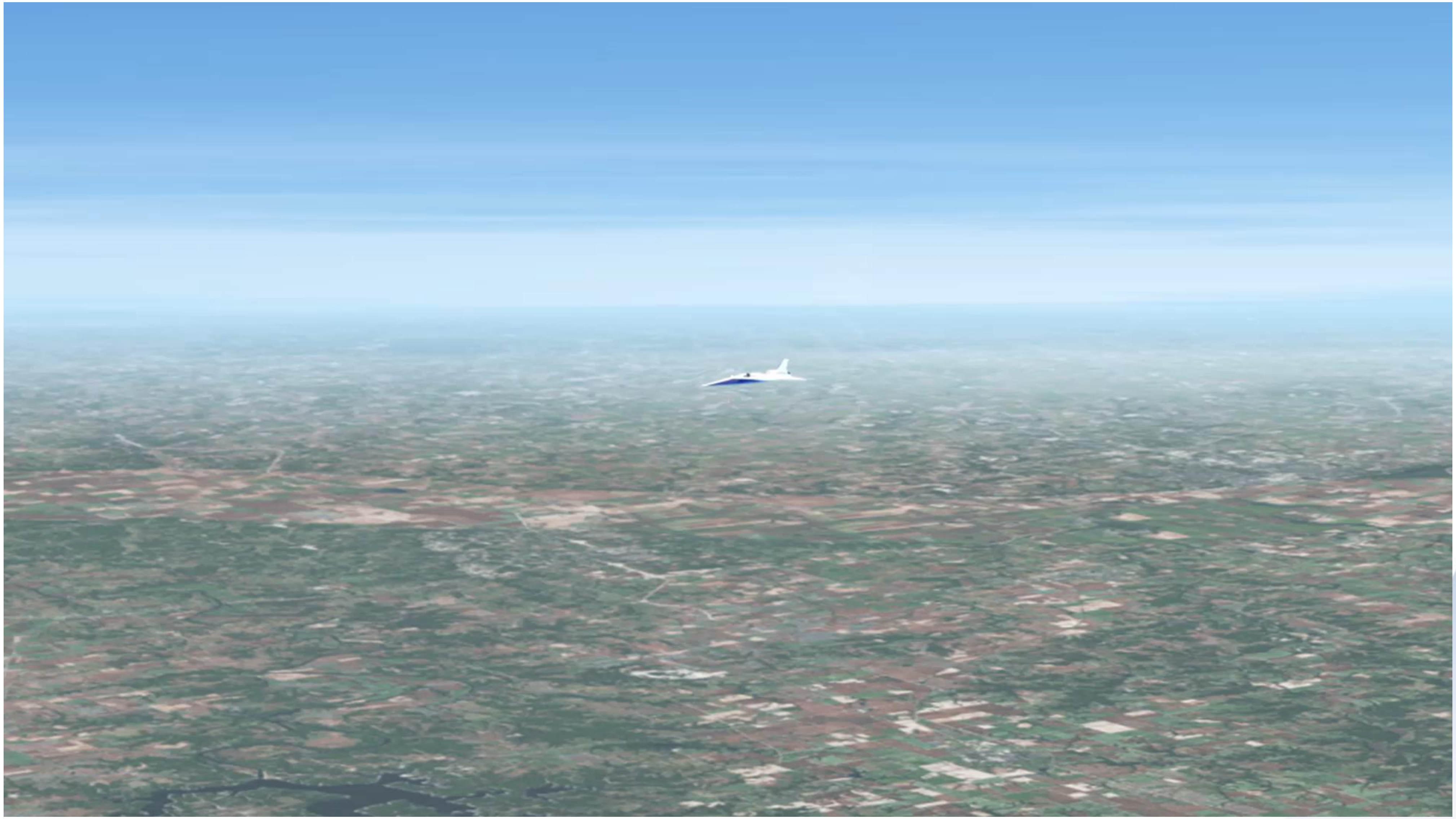
Sonic Boom Overview

Sonic Boom Basics

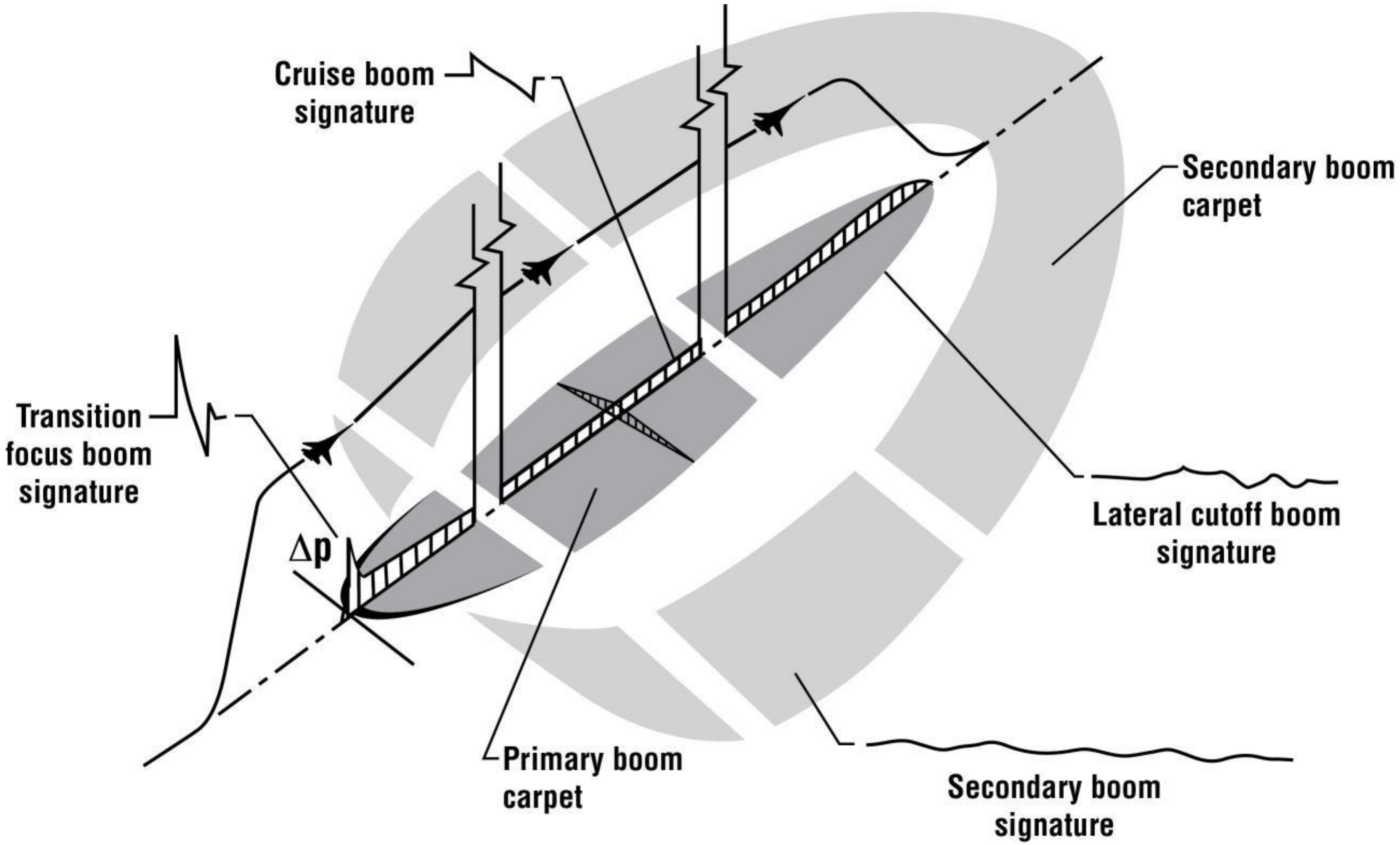
- **Supersonic flight ➡ aircraft flies faster than speed of sound**
  - Shockwaves travel away from vehicle
  - Shockwaves merge as they travel through the atmosphere
  - Heard on the ground as a sonic boom
- **For traditional supersonic aircraft**
  - Shockwaves eventually merge into bow and tail shocks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



Sonic Boom Moves with the Aircraft



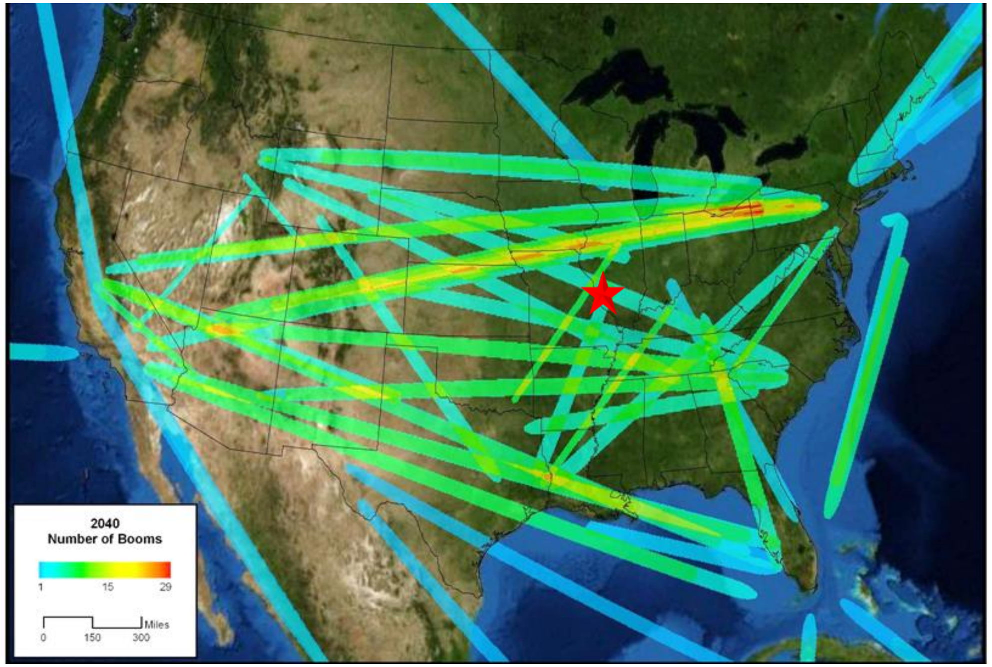
Sonic Boom Ground Exposure



Sonic Boom Waveforms and Spectra

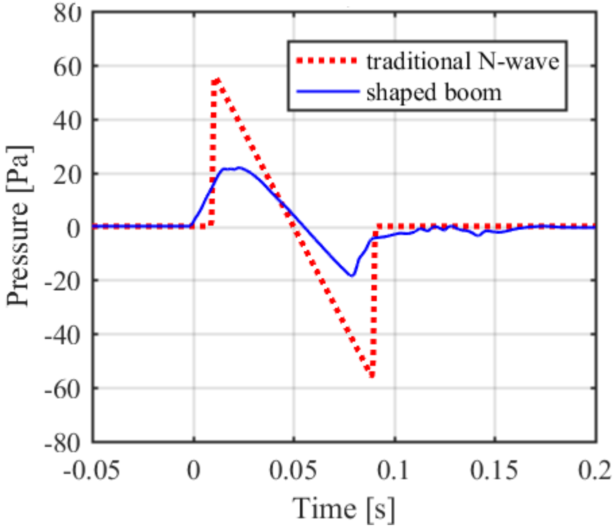
- **Unique aspects of sonic booms**
  - Transient nature of sonic boom
  - Low-frequency energy
  - Created along entire supersonic path (en route)
  - Cannot use the same methods/metrics as for subsonic aircraft

Number of booms predicted in 2040

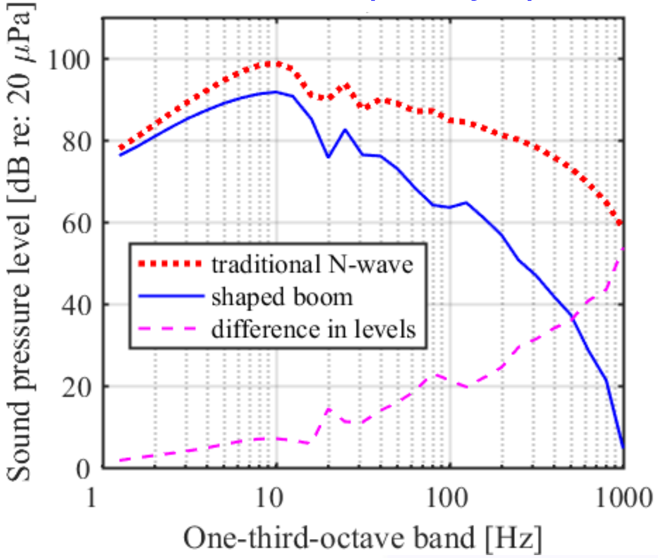


J. Rachami and J. Page. AIAA 2010-1385.

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

NASA is developing a new low-boom X-Plane

Built by Lockheed Martin Skunk Works

- **Aircraft design controls shock amplitudes and positions**
- **Shocks do not merge into an N-wave**
- **Cruise design PL = 75 dB**

This X-59 QueSST aircraft will first fly in 2022

Flights will confirm that a full-scale supersonic aircraft can produce just a "thump"

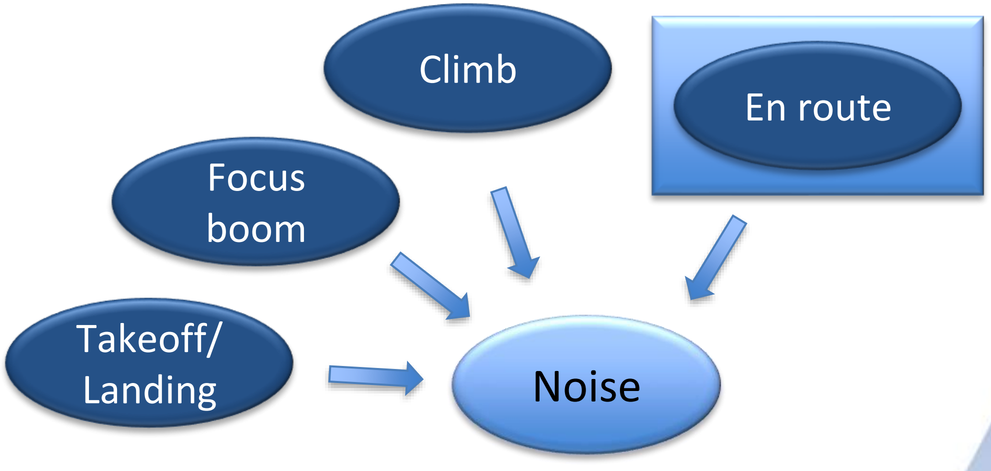
Key data will be gathered on public perception of quiet supersonic flights in several cities across the nation

Supersonic Aircraft Noise Regulations

Civil Supersonic Flight

- **Civil supersonic overland flight prohibited**
- **Recent advances to significantly reduce sonic boom noise**
- **Industry interest in lifting the ban**

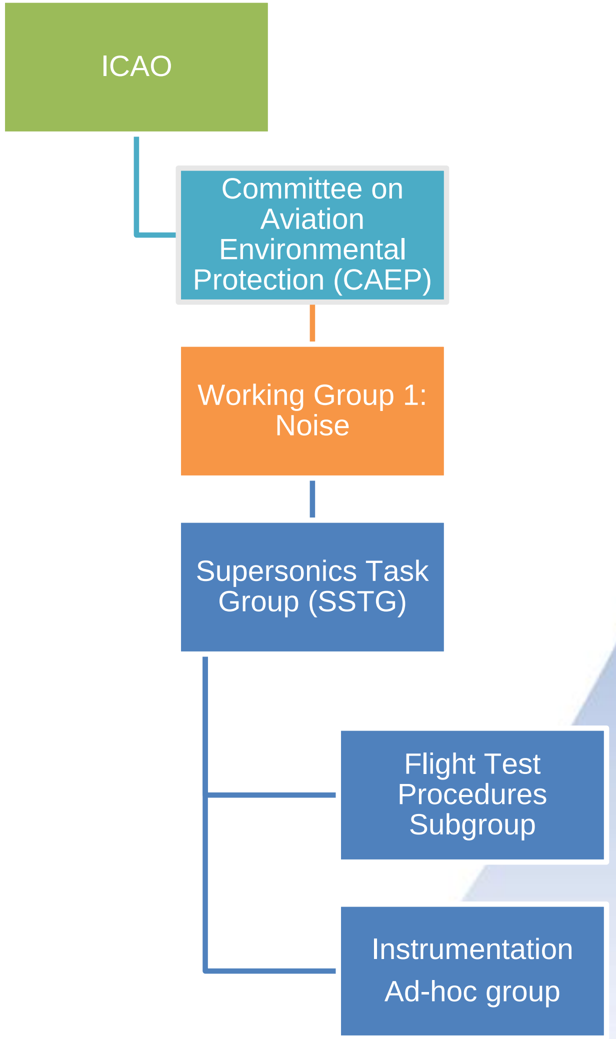
- **NASA is working with regulators**
  - Providing data
  - To enable development of a new noise standard
    - Noise metric, test procedures, noise limit



- **What are the payoffs if we are successful?**
  - Replace current prohibition of civil supersonic overland flight with a noise-based standard for aircraft certification
  - Open the door for development of a new generation of supersonic civil transport aircraft

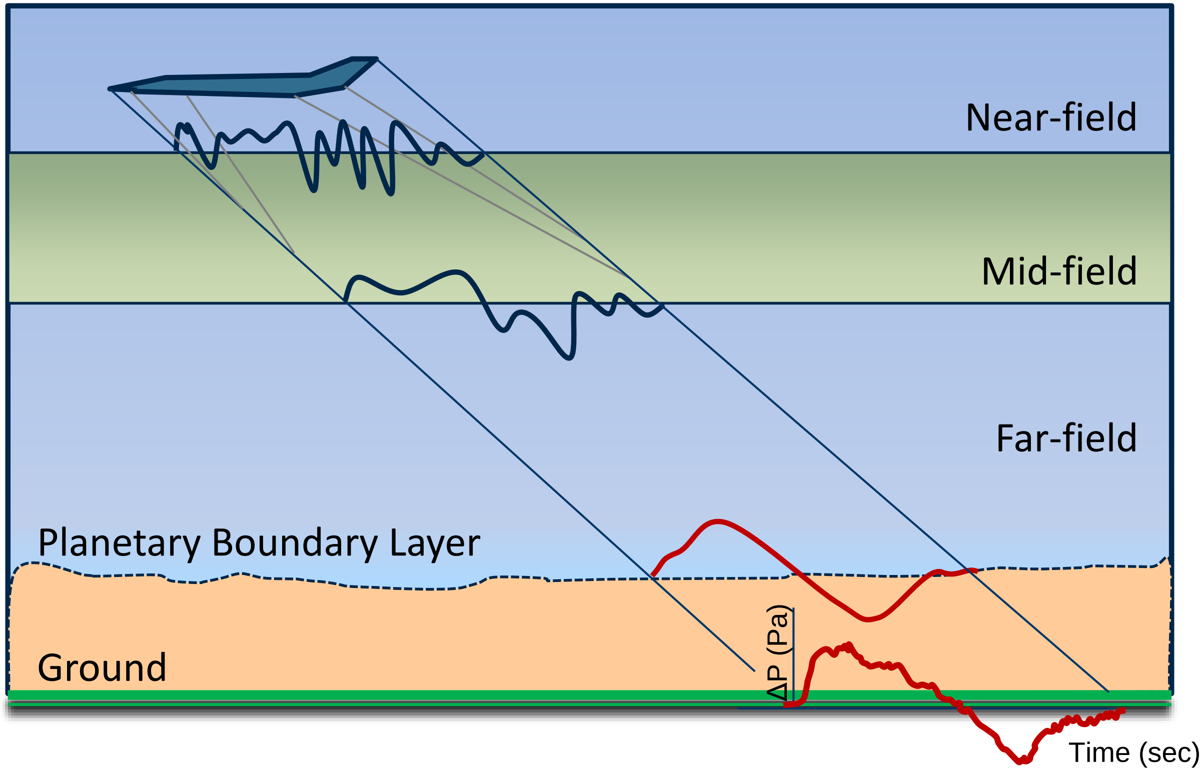
International Civil Aviation Organization (ICAO)

- **ICAO is a specialized agency of the United Nations**
  - Coordinates and regulates international air travel
  - Standards organization for global harmonized aviation
- **Convention on International Civil Aviation**
  - Rules that include standards and recommended practices
    - Annex 16, 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
  - In addition to regulators, industry groups and subject matter experts are represented

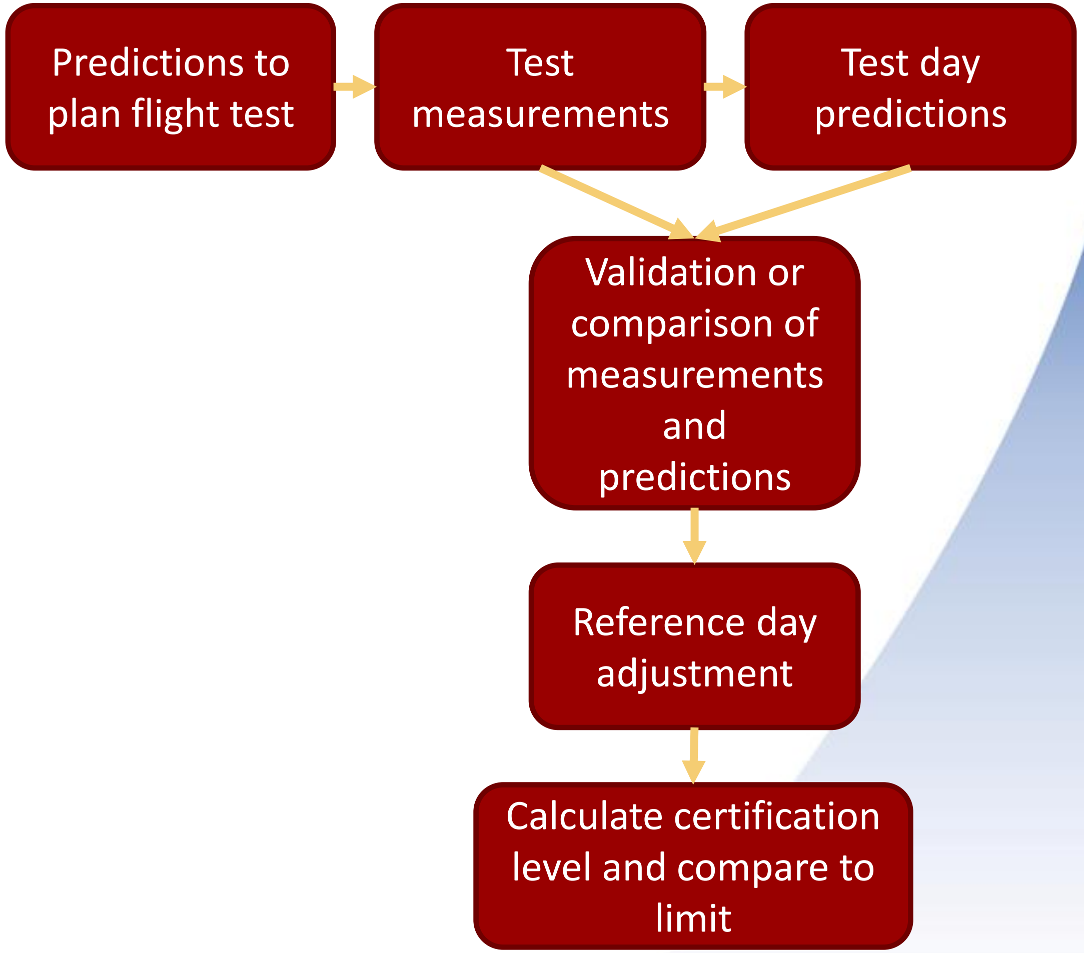


Notional Certification Procedure

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.*

Highlights of Research Progress in Key Areas

PCBoom Propagation Prediction Tool Overview

- **Inputs:**
  - Aircraft nearfield pressure
  - Aircraft trajectory
    - Altitude, heading, latitude/longitude, Mach, derivatives
  - Atmospheric profile
    - Temperature, pressure, relative humidity, winds, ground elevation
- **Output:**
  - Ray landing position
  - Sonic boom waveform
- **Propagation methods:**
  - Ray tracing
  - Implements the extended generalized Burgers equation
    - Nonlinearity, absorption/dispersion, geometrical spreading
  - Includes realistic atmospheric turbulence effects

New PCBoom Version 7.1 coming soon!

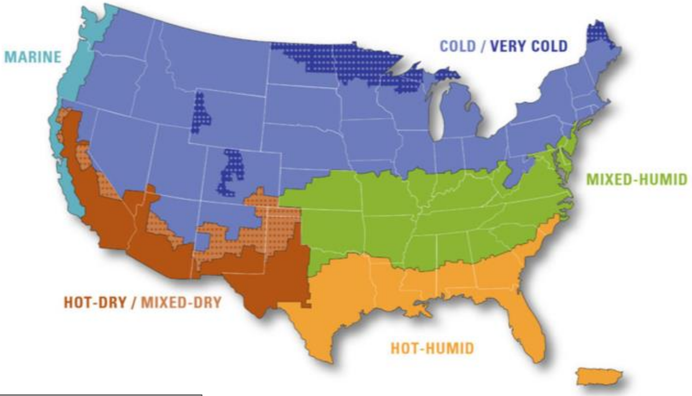
- Faster Burgers calculation
- Updated tools for atmosphere and nearfield inputs
- Updated atmospheric turbulence models

https://software.nasa.gov

Page et al., PCBoom Version 7.1 User's Guide, NASA/TM-20205007703, 2020.

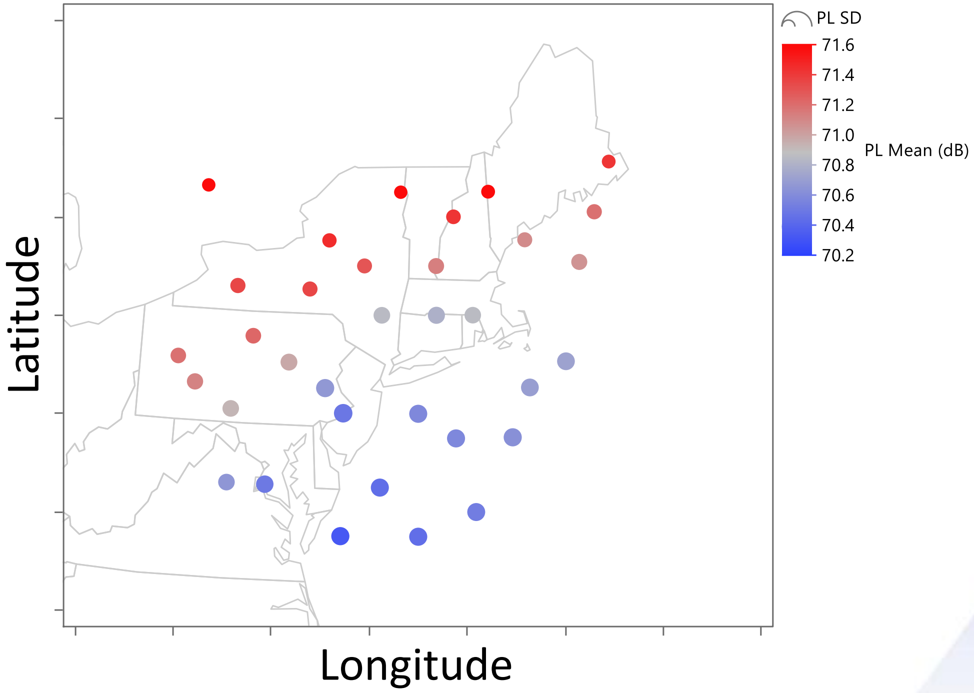
X-59 Predictions Across U.S.

- **Predict potential impact of realistic atmospheres**
  - X-59 nearfield source, designed for PL=75 dB in standard atmosphere
- **Study variables**
  - Atmospheric conditions (5 years) (no turbulence), location, season, time of day, aircraft heading angle
- **Northeast subset**
  - Carpet widths
  - Undertrack PL
  - Lower spatial and temporal resolutions determined to be sufficient for full set



Building America Best Practices Series, Volume 7.3, U.S. Department of Energy

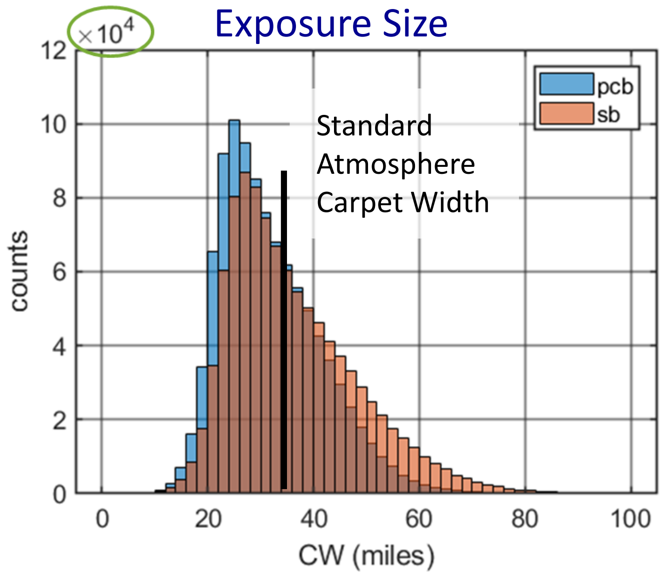
Undertrack PL

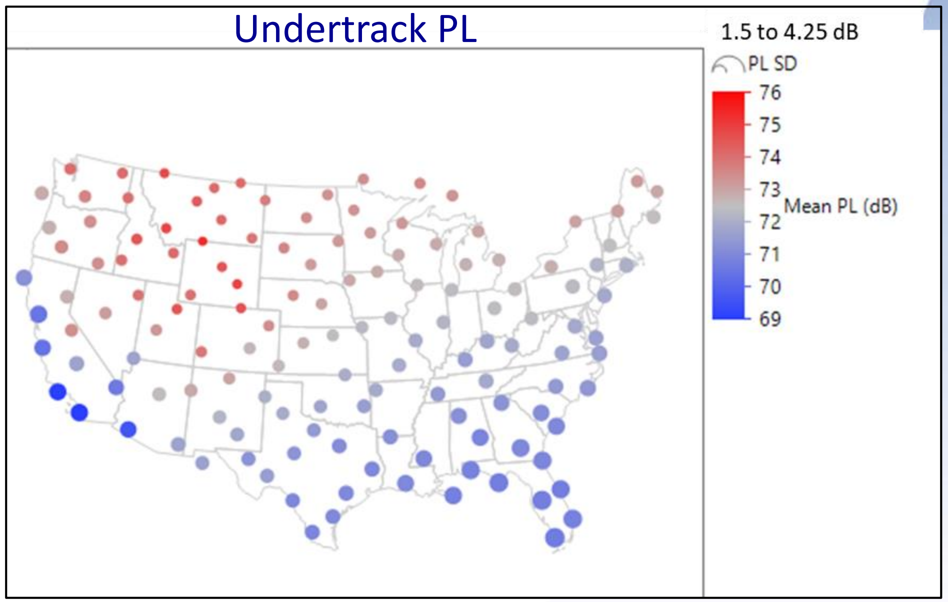


Doebler et al., “Design of experiments: X-59 sonic thump carpets in the eastern United States,” ASA, 2019.

X-59 Predictions Across U.S.

- **5 years of atmospheric profiles with 1 profile per day at 138 locations**
- **Observations**
  - Exposure size
    - Carpet width (CW) is typically 20 to 60 miles
  - Variability in loudness across the CONUS
    - Undertrack PL standard deviation ~3 dB due to the atmospheric profile
    - 78% of carpets had lower PL < 75 dB
    - Other metrics had lower variability than PL
- **Can use CONUS propagation results to:**
  - Assess climate and seasonal effects on booms
  - Assist with X-59 community test planning
    - Help select locations, seasons, and flight profile





Doebler et al., "Five-year simulation study of NASA's X-59 low-boom carpets across the contiguous United States of America," Forum Acusticum, 2020.

Measurements of Variability in Lateral Carpet

- **Goal: understand challenges with measuring across lateral carpet**
  - 56 km (25 nmi.) half carpet width measurement
  - Ground microphone deployment logistics and operations
- **Three phases of risk reduction tests with F-18**
  - CarpetDIEM Phase 1 conducted in Summer 2019
    - Near Edwards Air Force Base, CA
    - Assessed/demonstrated deployment of a large microphone array
    - Opportunity to collect sonic boom data using different microphone recording system setups in a quiet environment
    - Deployed 17 recorders for 23 supersonic passes
      - 92.6% of possible 391 events recorded
      - Challenges with dirt road access, communications, and recording hardware
- **Joint effort between NASA, Brigham Young University, and Volpe National Transportation Systems Center**

CarpetDIEM = Carpet Determination in Entirety Measurements

Gee et al., Development of a Weather-Robust Ground-Based System for Sonic Boom Measurements, NASA/CR-2020-5001870, 2020.

Noise Monitor Strategies for Community Studies

- **Computational study to investigate how to use sparse measurements of boom loudness levels within a survey area**
  - Measurements to be used as part of process to estimate noise “dose” for correlation with survey responses during X-59 testing
- **Number of measurement sites, grouping of noise monitors, and noise monitor spacing**
- **Effects of survey area size on recommended number of sites**
  - 150 noise monitors when survey area is large
  - 50 noise monitors when survey area is small
- **Mitigations for ambient noise contamination and turbulence effects**
  - Group monitors (5) at sites and average their levels to reduce turbulence effects
  - Spacing > 500 ft. apart
  - Method to estimate dose even when ambient noise level is within 1 dB of boom

Klos, Recommendations for using noise monitors to estimate noise exposure during X-59 community tests, NASA/TM-20205007926, 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)
- Engineering metrics
- Loudness metrics
- “Hybrid” metrics

25 (2014-2015)
- Expert judgment, including non-acoustic factors

8 (2015)
- Meta-analysis of three lab studies

5 (2015)
- Additional analysis with 4th study
- PL, ASEL, BSEL, ESEL, and ISBAP

6 (2016)
- Additional analysis with 5th study
- DSEL added

6 (2017)
- Additional analysis with 6th study
- Three methods for metric evaluation

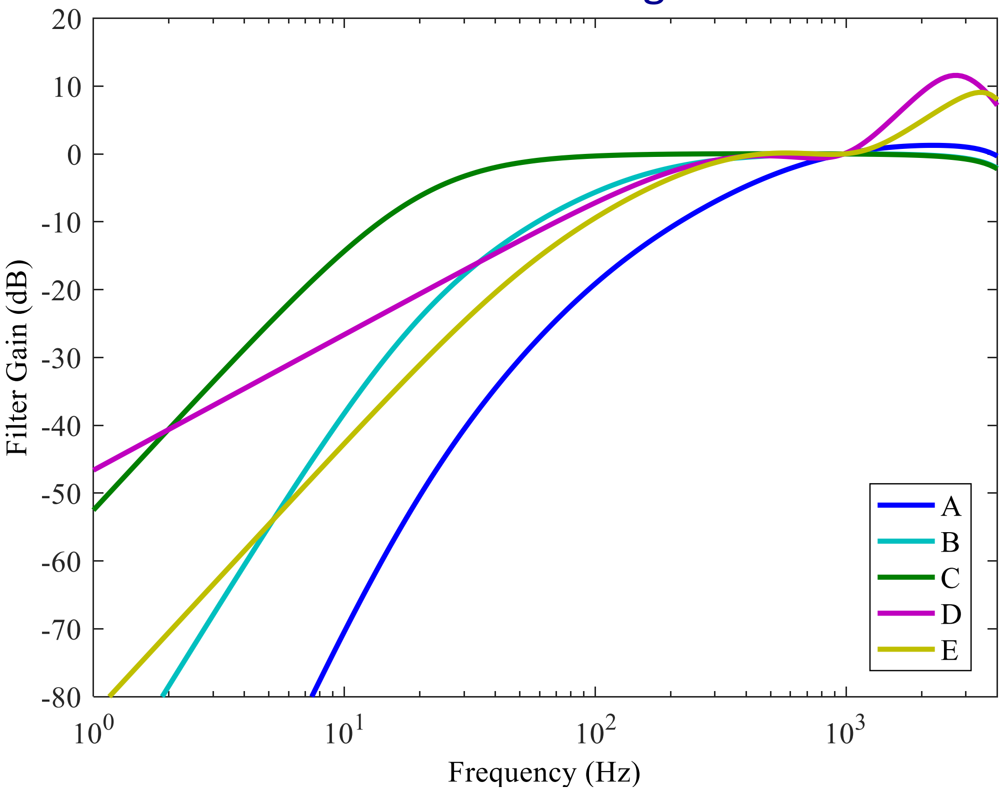
Sonic Boom Noise Metrics

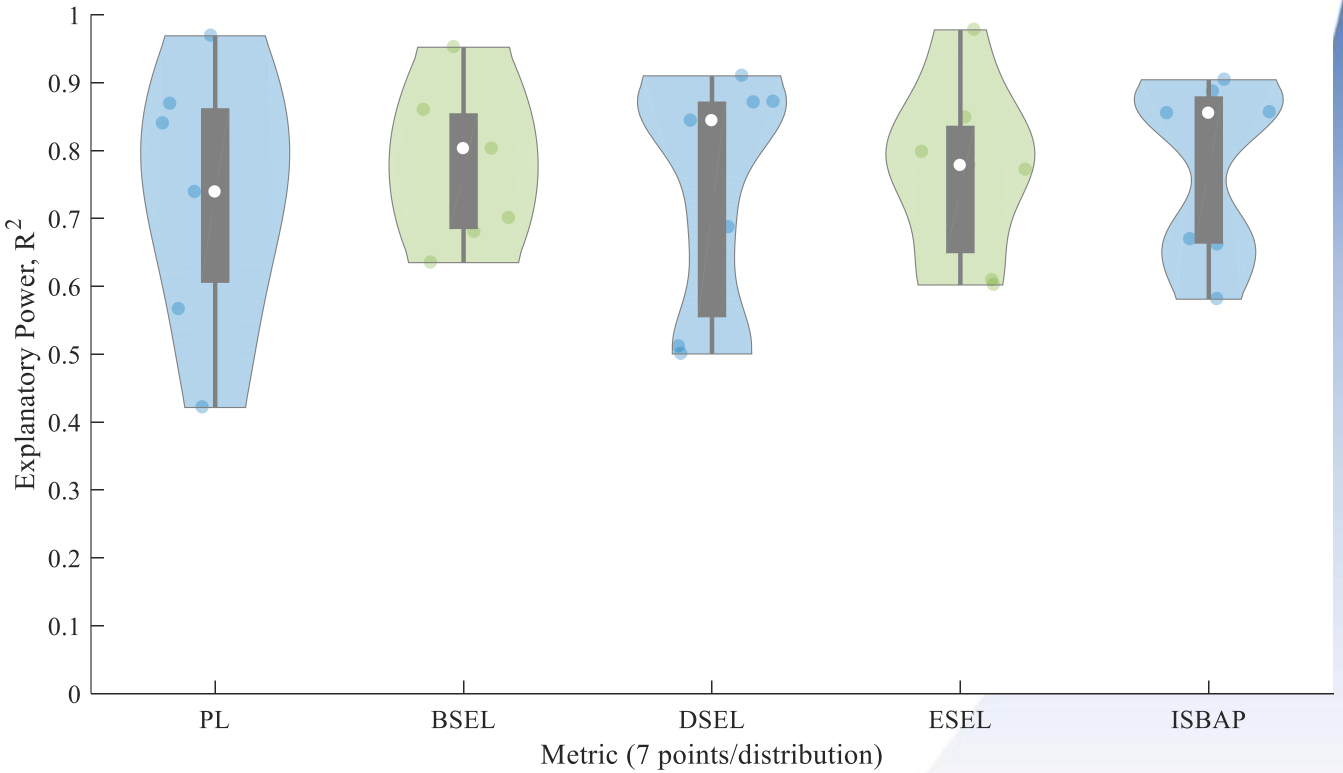
Six metrics for further consideration:

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.

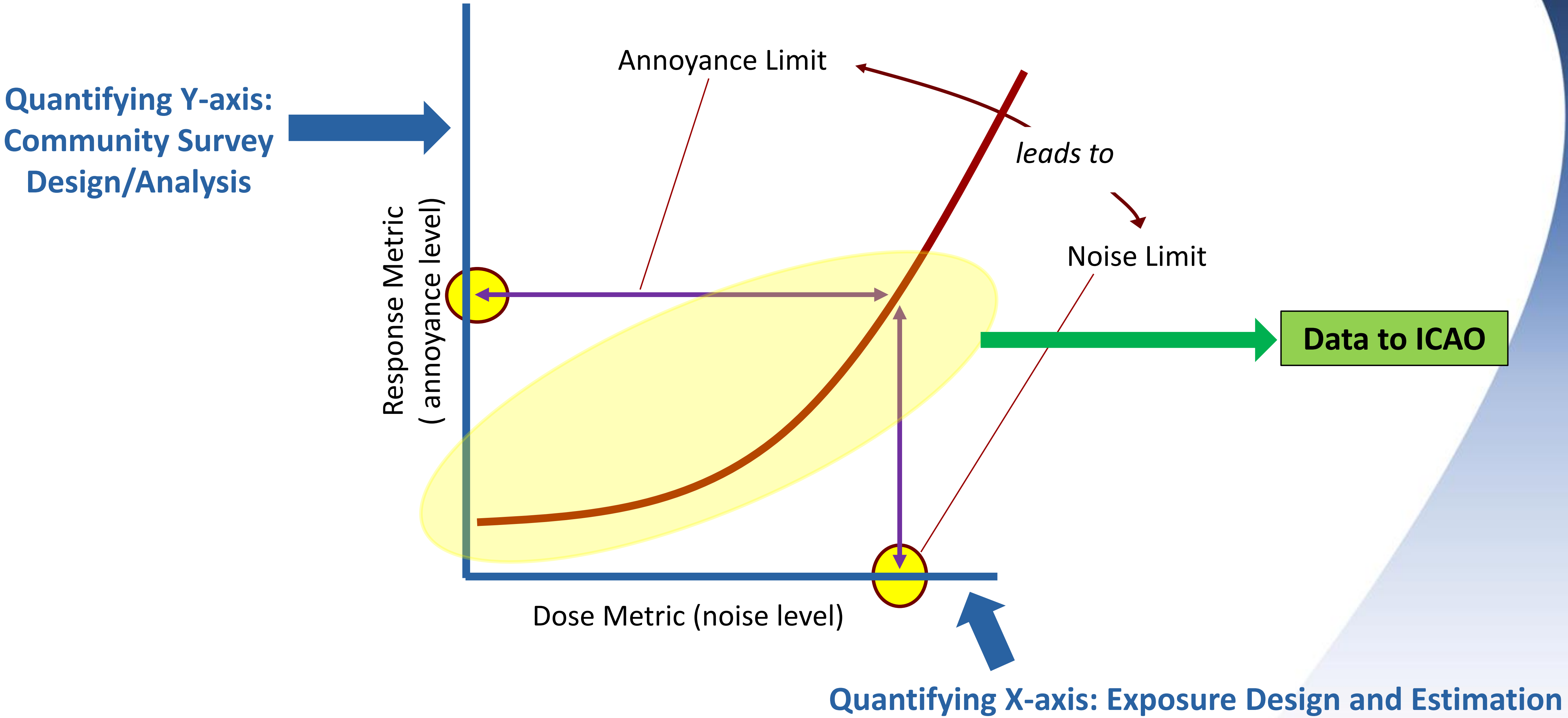
Low Boom Community Response Testing

- **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.

Dose – Response Characterization



Dose-Response Analysis Example

Overview

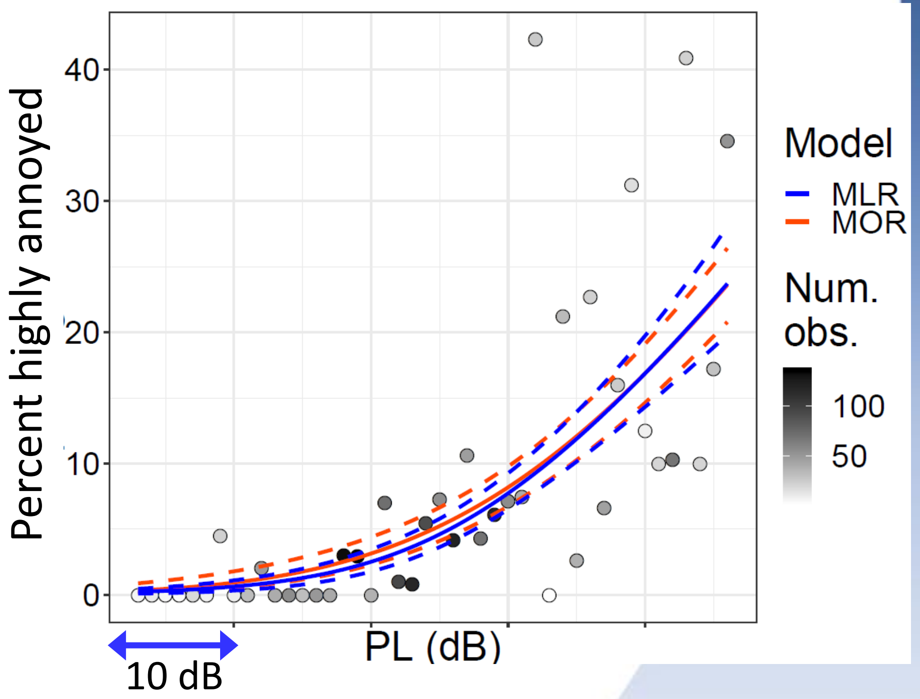
- Evaluated 7 different statistical modeling techniques for single-event community response survey data (2011)
- Used multilevel models to account for correlation in responses from the same participant

Results

- Multilevel models fit data better than non-multilevel models

Significance

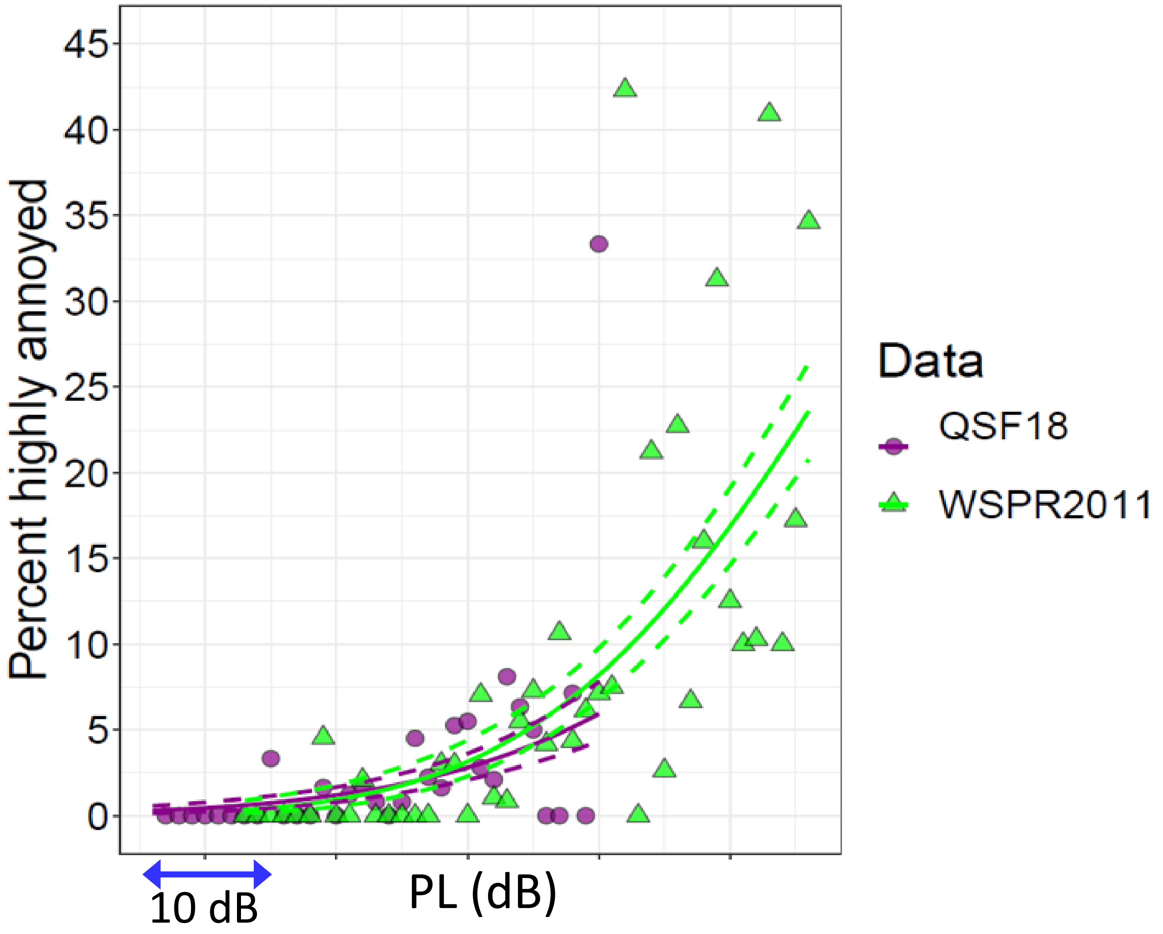
- Traditional modeling techniques for independent samples are not recommended for panel samples



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

Dose-Response Analysis Example

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

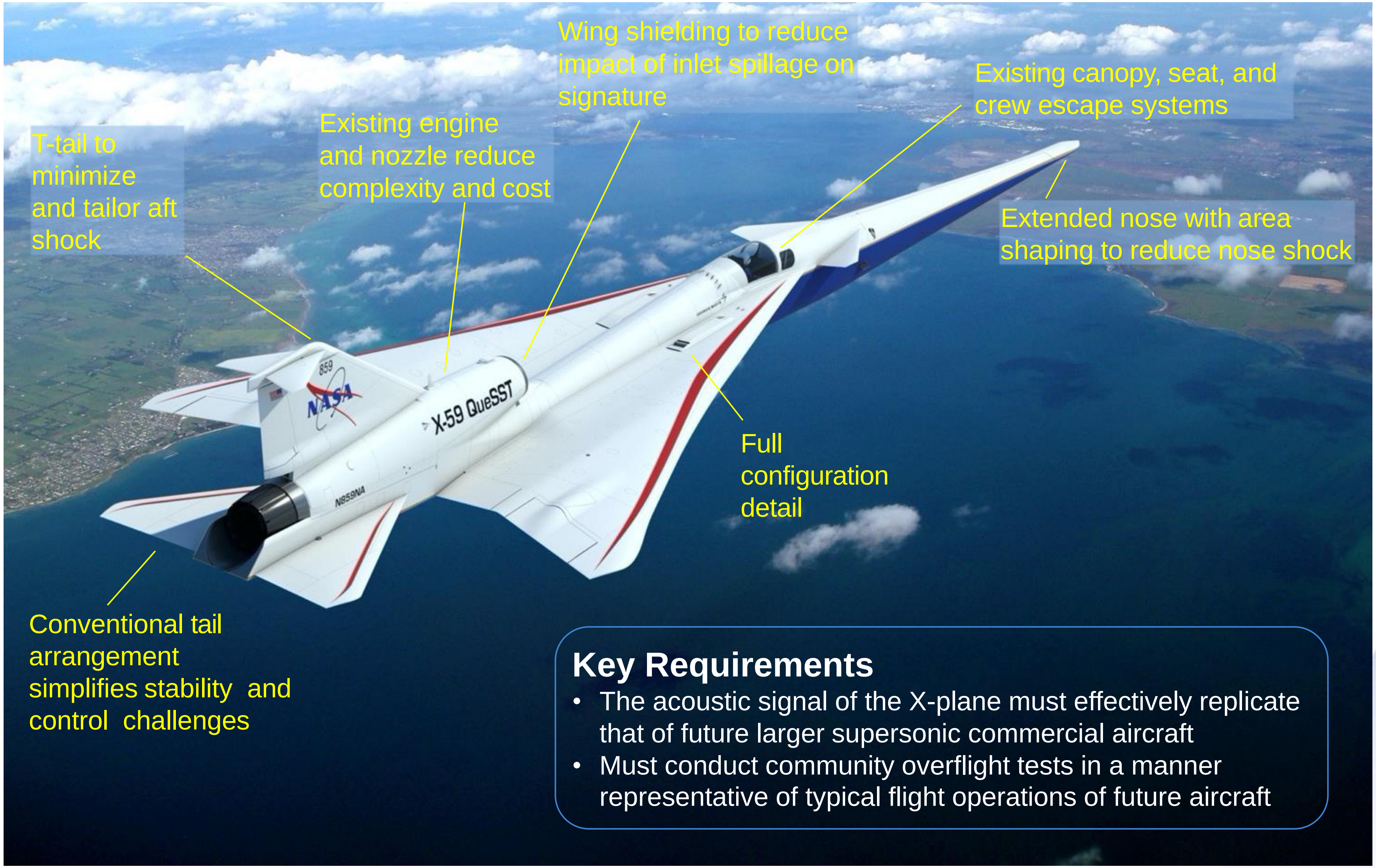


Lee et al., "Bayesian statistical models for community annoyance survey data, J. Acoust. Soc. Am. 147(4), 2222, 2020.

X-59 QueSST

X-59 Design Features

Quiet design approaches adapted for a unique flight demonstrator



Key Requirements

- The acoustic signal of the X-plane must effectively replicate that of future larger supersonic commercial aircraft
- Must conduct community overflight tests in a manner representative of typical flight operations of future aircraft

X-59 Development Progress

- **Overall good progress in all aspects of aircraft design/build**
  - Lockheed internal design, fab, and assembly
  - Contracted fabrication and supply
  - NASA-developed systems
  - Donor aircraft parts and components
- **Some impacts due to design challenges and COVID-19**

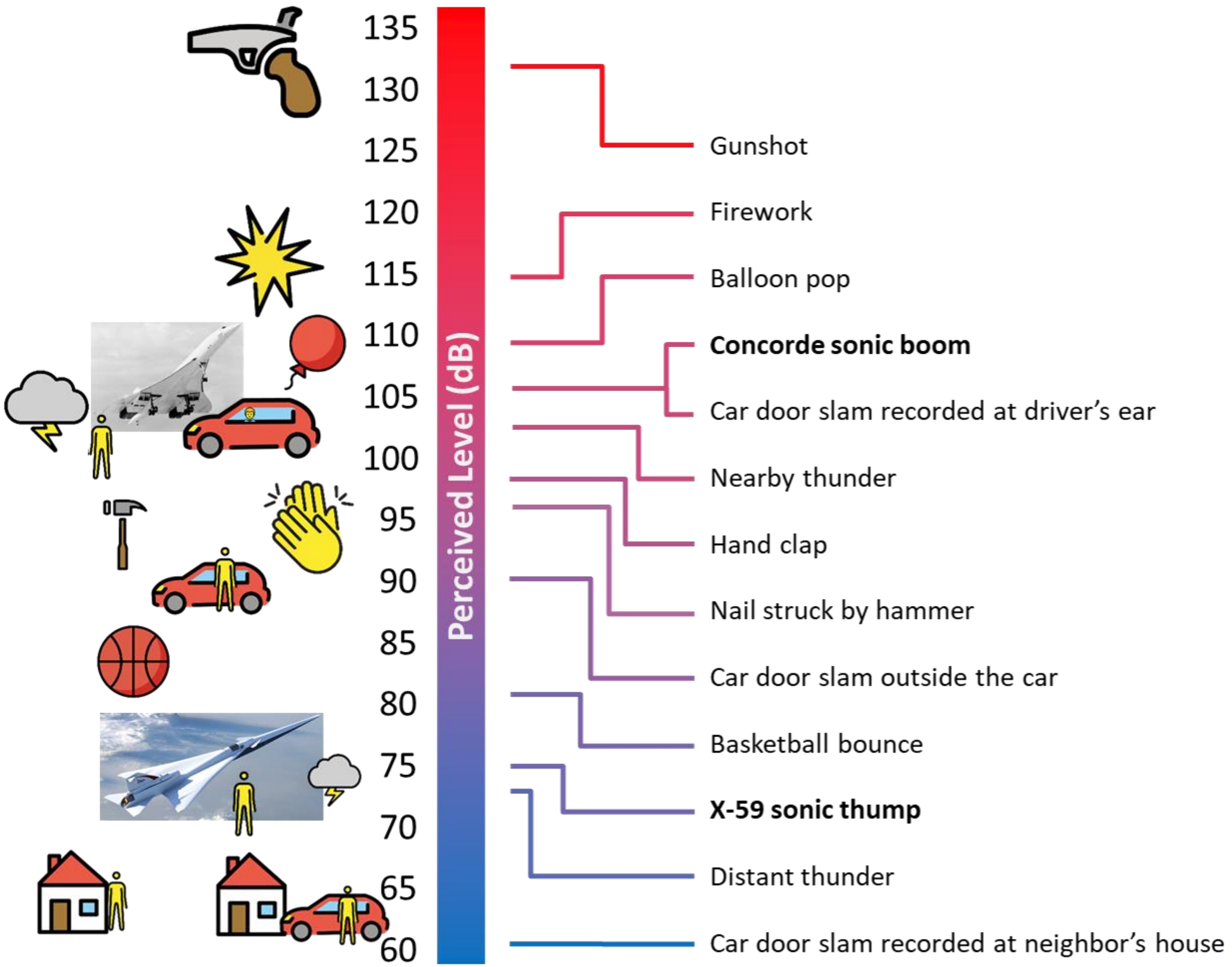
Lockheed Martin Manufacturing

GE F414-GE-100 Engine

Supplier Manufactured Components

"Donor Aircraft" Components

X-59 Sonic Thump Noise Level

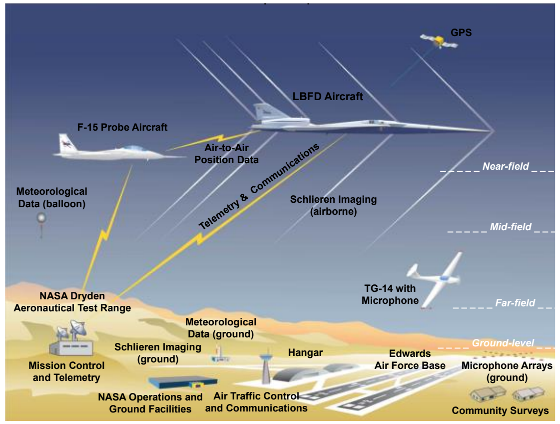


Doebler and Rathsam, "How loud is X-59's shaped sonic boom?", Proc. Mtgs. Acoust. 36, 040005 2019.

Low Boom Flight Demonstration Mission Overview

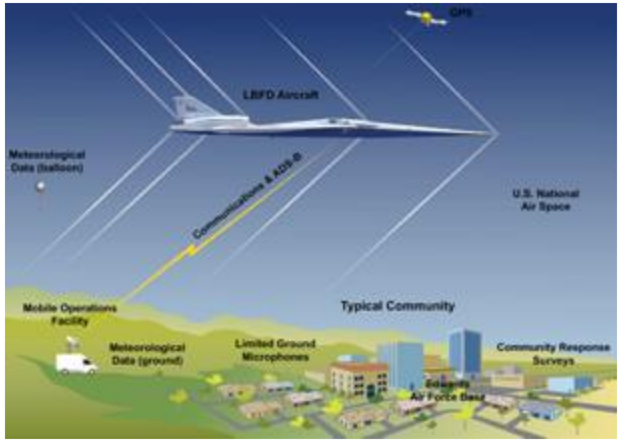
<u>Phase 1 – Aircraft Development – *In progress 2018-2022*</u>

- Detailed design
- Fabrication, integration, ground test
- Checkout flights
- Subsonic and supersonic envelope expansion



<u>Phase 2 – Acoustic Validation – *Preparation in progress 2023-2024*</u>

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



<u>Phase 3 – Community Testing</u>

<u>*Preparation in progress 2024-2026*</u>

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

Systematic Approach Leading to Community Response Testing

Preparations for Community Testing

Community Testing Technical Challenges

- **Plan and execute overflight tests with the X-59 over large nonacclimated communities in the U.S.**
  - Obtain relevant interagency and institutional approvals – FAA, OMB, EPA, local governments
  - Develop survey design and statistical analysis methods to quantify sonic boom annoyance levels
  - Develop methods to acquire and process low signal-to-noise acoustic data for exposure estimation
  - Develop large-scale geolocation methods and means to correlate annoyance with exposure

- Conduct overflight tests with the X-59 in multiple representative U.S. communities
- Correlate survey and acoustic data to establish dose-response relationships for sonic boom exposure
- ***Provide dose-response database to ICAO***

Key Technical Challenge – Scaling-Up

Non-NASA locations

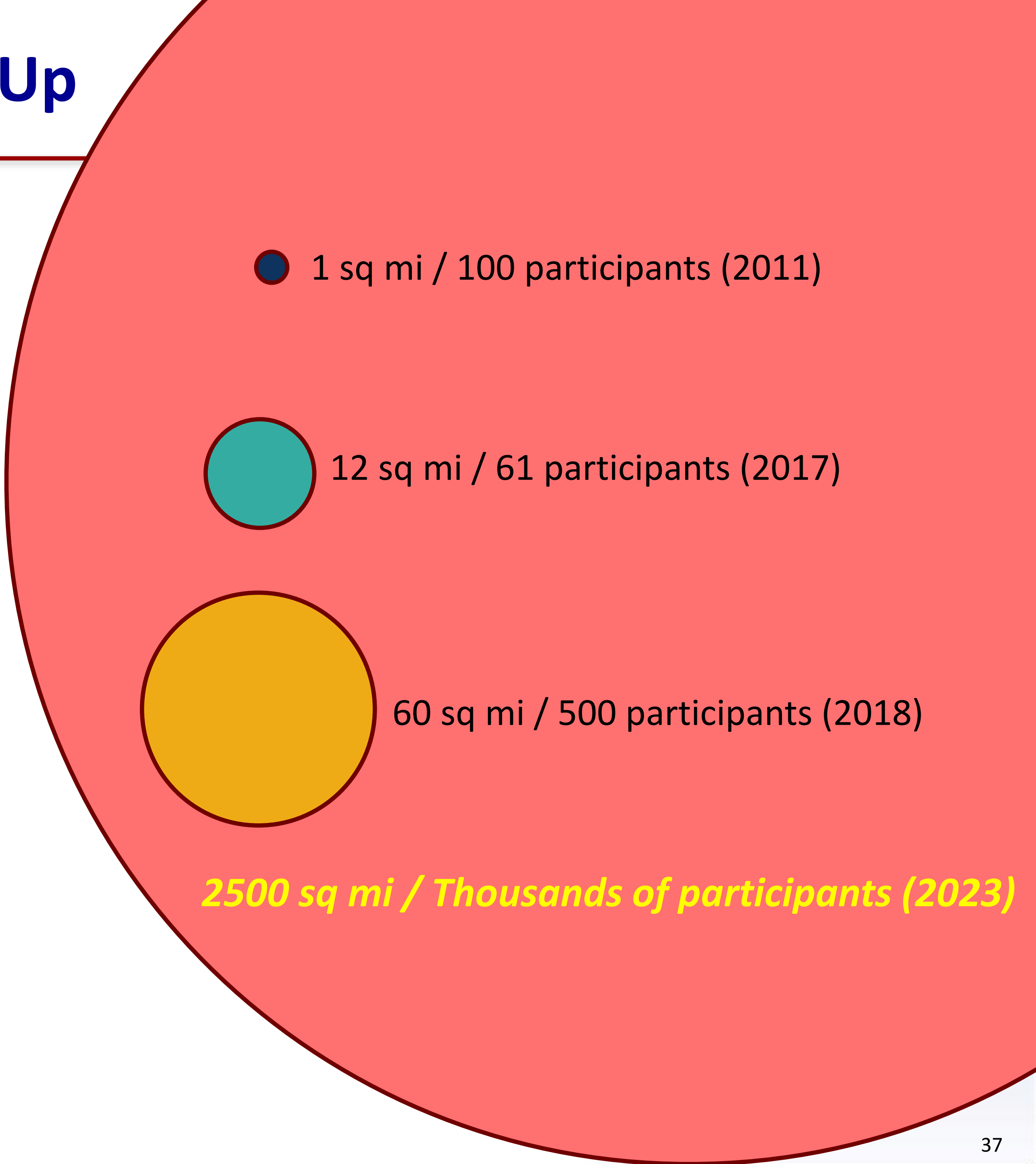
- X-59 operations infrastructure
- Expanded public outreach
- Flight planning / airspace coordination

Survey design/management

- Multi-thousands of participants
- Aggregation/geolocation of responses
- Automation of data processing

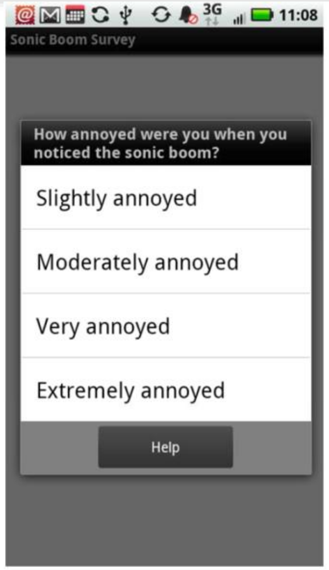
Acoustic measurements

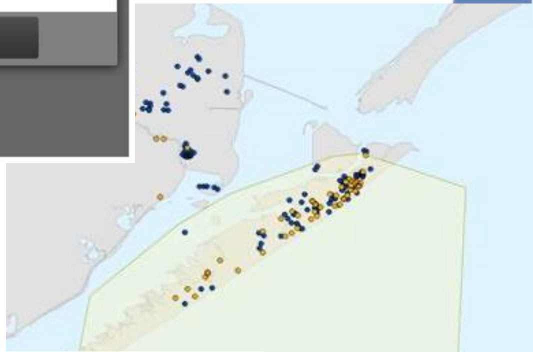
- Land use / approvals
- Hardware robustness
- Remote operation/data transmission required
- Communications connectivity/reliability
- Automation of data processing

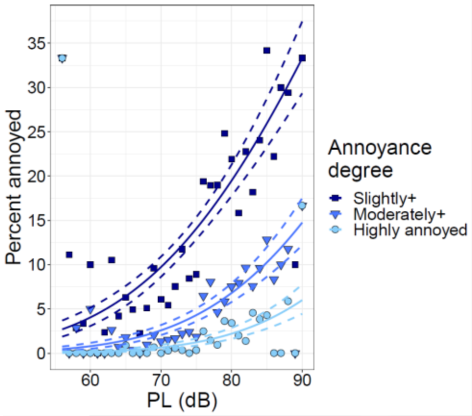


Survey Design and Analysis – Key Challenges

- Deliberate sample design to enable nationally representative results from a limited number of community studies
- Automation of survey response acquisition and processing to support X-59 deployment pace
- Large-scale participant geolocation processing
- Statistical analysis approaches for multiple responses per participant (typically 1 per participant)
- Creating effective survey when unable to mask its purpose
- 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







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Exposure Design and Estimation – Key Challenges

- Estimating exposure level across large survey areas (combining predictions with measured levels)
- Estimating meteorological conditions from measurements and forecasting/modeling across survey area to support noise predictions
- Automation of acoustic data acquisition (and transmission) and exposure estimation methods to support X-59 deployment pace
- Acquiring acoustic data with low signal-to-noise ratio (low sonic boom loudness relative to background noise)
- Acoustic sensor placement strategy to accommodate uncertainty due to expected variability in weather and ambient noise
- Strategies to address challenges include:
  - Development and testing of rapid, automated methods of exposure estimation based on acoustic and meteorological sensor data
  - Hardware/software testing and validation of remote operation and robustness during LBFD Phase 2

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Airfield and Community Test Site Selection

- Community Test 1 – Conducted from NASA AFRC
- Follow-on Community Test airfield/site selections in progress
- Operational criteria
  - X-59 requirements (runway, elevation, etc.)
  - Airfield/Airspace considerations
  - Meteorological constraints
- Data Criteria
  - Survey population
  - Range of exposure level (meteorological or other influences)
- Importance of climate zones vs other considerations
- Sequencing considerations
- Ensuring database is nationally representative

U.S. Climate Zones

Summary

- NASA and partners are fully engaged with the international standards and regulatory community
- NASA's commitment is to deliver data supporting development of standards for quiet supersonic flight overland
- Standards require metrics, procedures, and limits
- The LBFD Mission timeline and activities offer opportunities to collect valuable data for all 3 elements of the standard
- NASA seeks international engagement in development of LBFD test plans

What you should know about NASA's supersonics 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/X59