

# Statistical Engineering Toward Commercial Supersonic Flight: NASA's Quesst Mission



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# Outline

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- 1. Context for Quesst Mission**
- 2. Simulation Experiment on Noise Variability**
- 3. Community Survey Planning**
  - A. Dose Response Modeling
  - B. Challenges



# Supersonic Flight and Sonic Boom: A Brief History



- 1947** **First supersonic flight**  
Sonic boom a novelty
- 1950s** **Rapid development of supersonic military aircraft**  
Noise and damage concerns
- 1960s** **Supersonic commercial aircraft proposed**  
Community studies determine sonic boom exposure is unacceptable
- 1973** **US federal ban, international limits**
- 1976 – 2003** **Concorde commercial service**  
Supersonic operations only over the ocean
- 2003** **DARPA-NASA Shaped Sonic Boom Demonstration**  
First flight demonstration of sonic boom “shaping” theory
- 2018 – 2026** **NASA’s Quesst Mission**  
First flight demonstration of low noise supersonic design  
Community studies to gauge public reaction



# 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 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**

# Overcoming the barrier to overland flight

The Quest 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

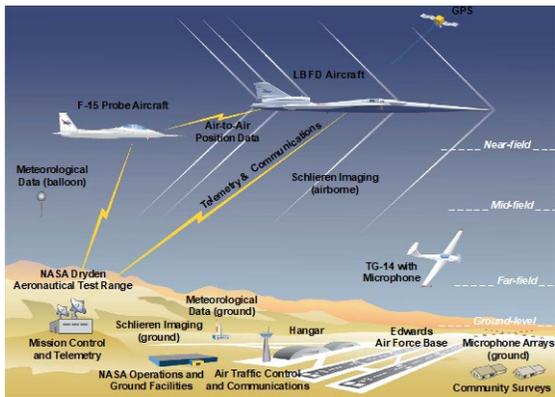
# What is NASA's Quesst Mission?



## Phase 1 – Aircraft Development

*In progress (FY18-23)*

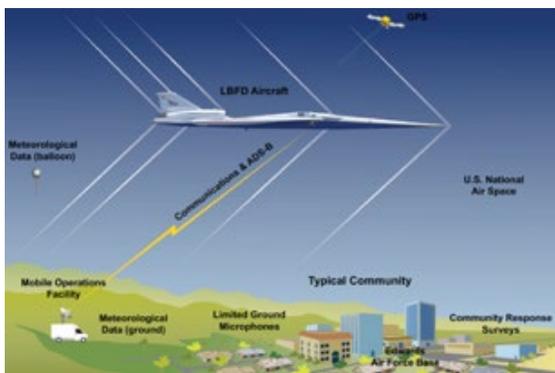
- Design, fabricate a quiet supersonic research aircraft
- Prove performance in test range flights
- Prove safety for flights in normal airspace



## Phase 2 – Acoustic Validation

*Preparation in progress (FY18-23), Execution FY23-24*

- Prove the acoustic characteristics match design targets
- Detailed in-flight and ground measurements in test range



## Phase 3 – Community Response Testing

*Preparation in progress (FY19-23), Execution FY24-27*

- Conduct community tests
  - Select communities
  - Outreach and engagement (including STEM)
  - Obtain necessary approval
  - Plan surveys and recruit participants
  - Collect ground measurements





# The X-59 Aircraft

## Key requirements drive X-59 design

- The acoustic signal of the X-plane must effectively replicate that of future larger supersonic commercial aircraft.
- The X-plane must conduct community overflight tests using normal commercial aircraft flight maneuvers.

## Design Parameters

- Length: 99' 7" ft
- Span: 29' 6" ft
- Speed: Mach 1.4 (925 mph)
- Altitude: 55,000 ft

## Design Features

- New, unique airframe design with acoustic signature shaping
- Many components from existing aircraft to reduce cost
- Payload capacity: single pilot/flight test instrumentation





# X-59 Aircraft Development Status

- Lockheed Martin is the lead for manufacturing
  - Major airframe components mated
  - Systems installation and checkout in progress
    - NASA supplied systems delivered
    - Engine delivered
- Ground testing in Texas
- First flight later this year

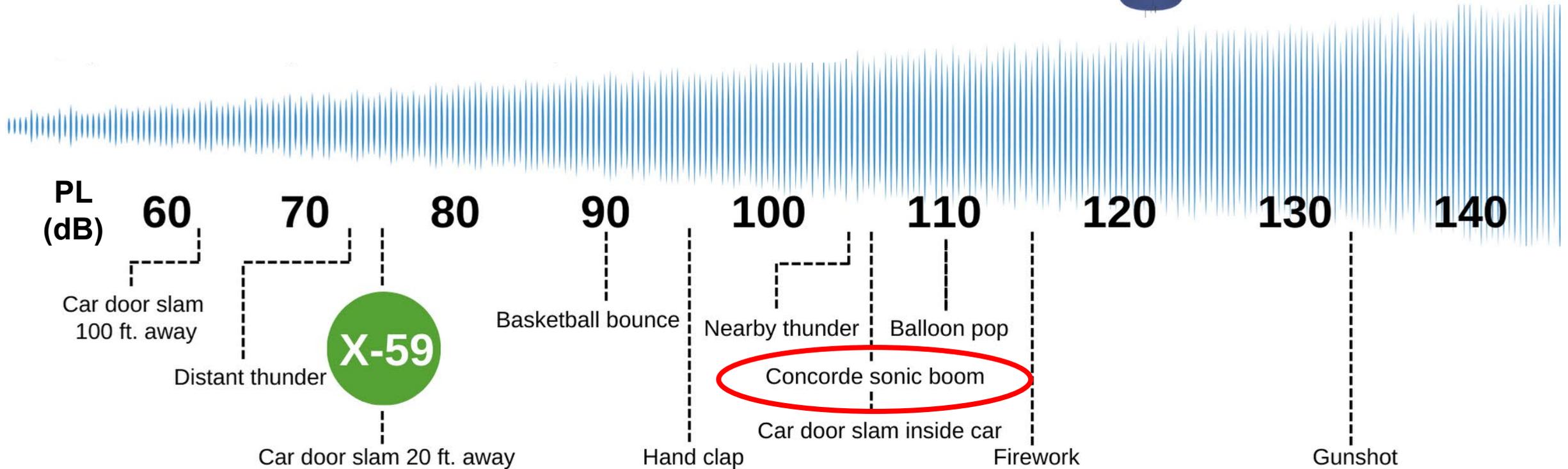
GE F414 engine



Simulator with External Vision System (XVS)

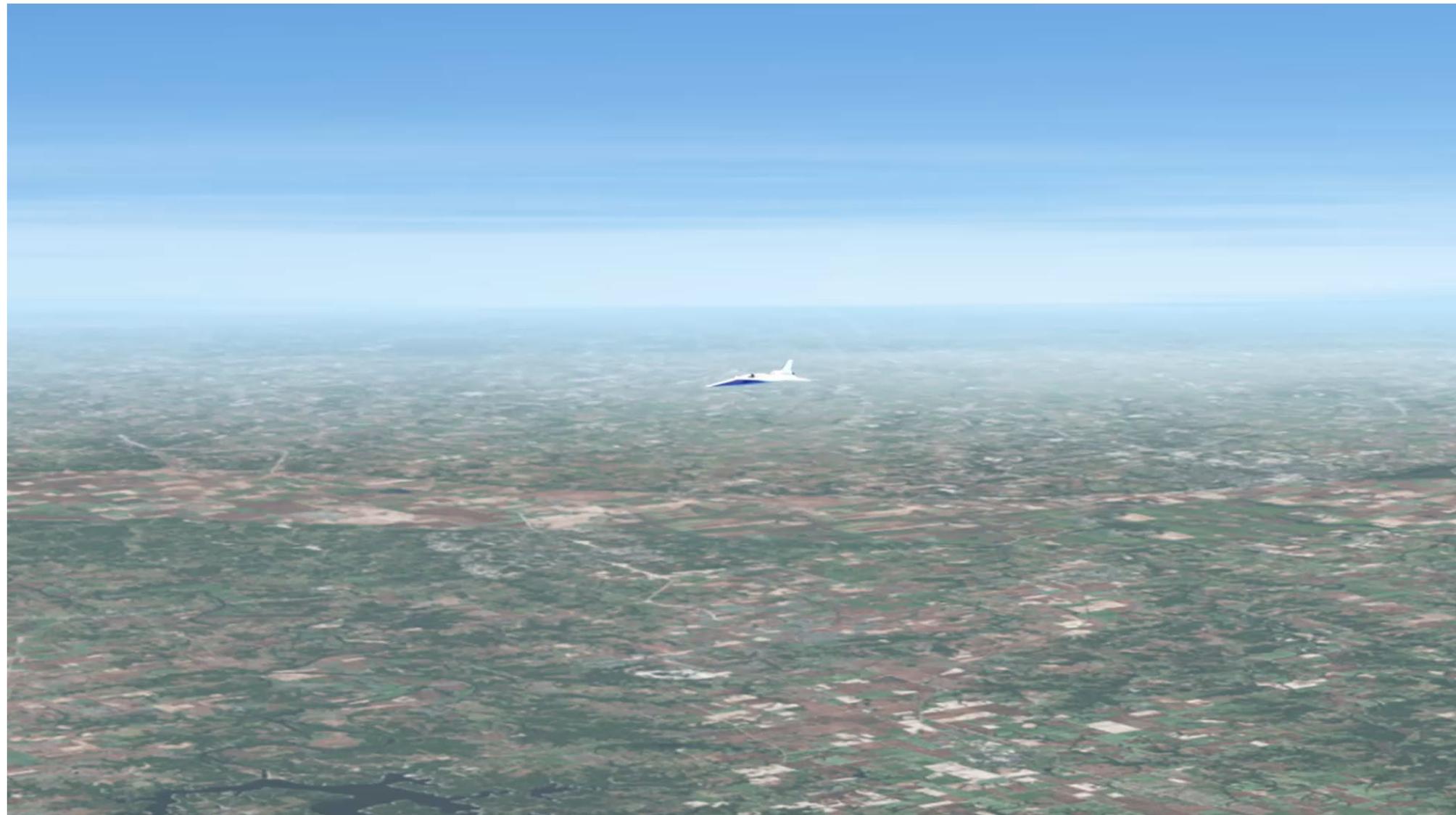


# Just how quiet will NASA's X-59 be?



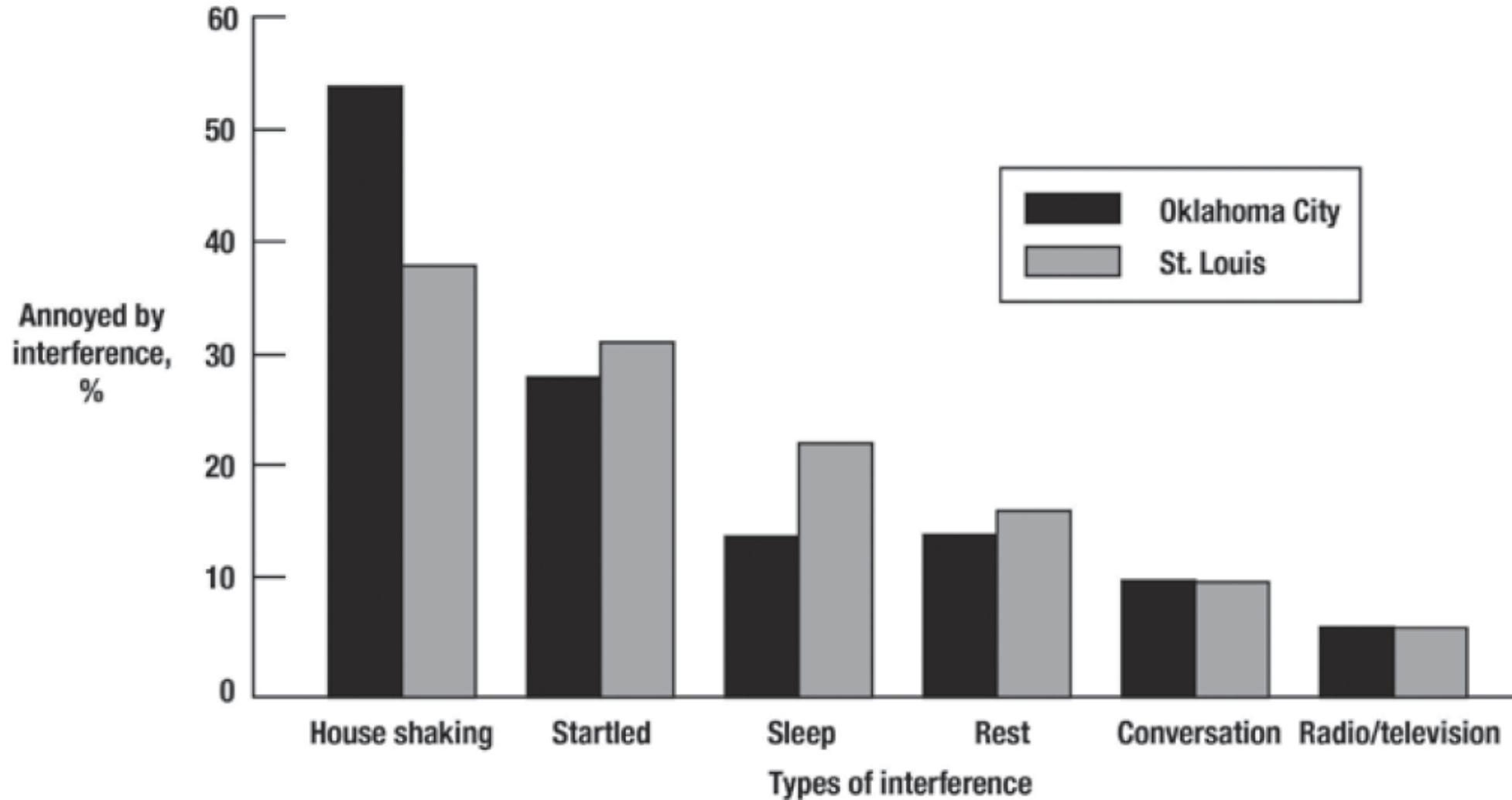
# How big is the noise exposure region from a supersonic overflight?

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# How did the public react historically to sonic booms?



Nixon and Borsky, AMRL-TR-65-196, 1965

# Why might a “sonic thump” from X-59 be quiet enough?

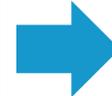
Human response and annoyance, particularly indoors, is the key concern.



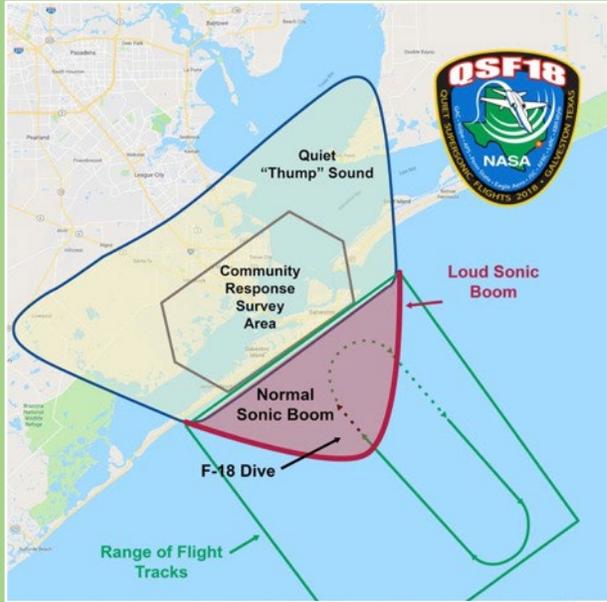
Laboratory Tests



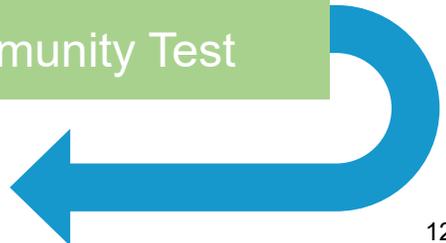
Small Community Test



Quiet Supersonic Flights 2018  
Galveston, Texas



Large Community Test



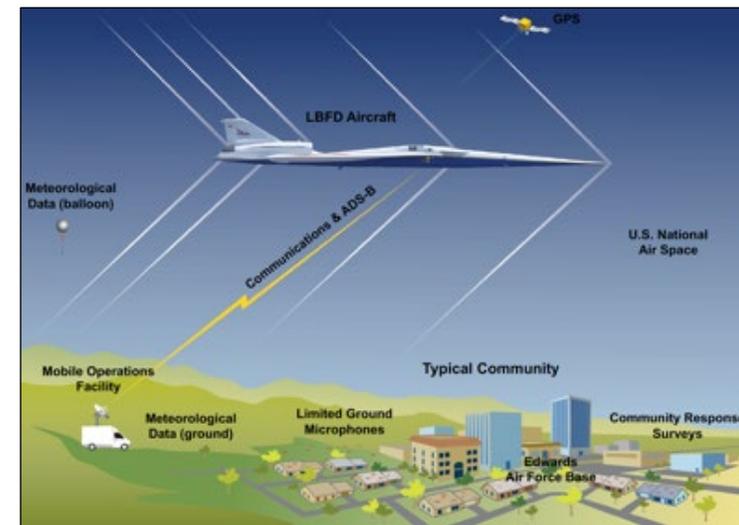
- Tests of increasing complexity have provided preparation and confidence
- Ready to take the next step with flight testing over very large communities



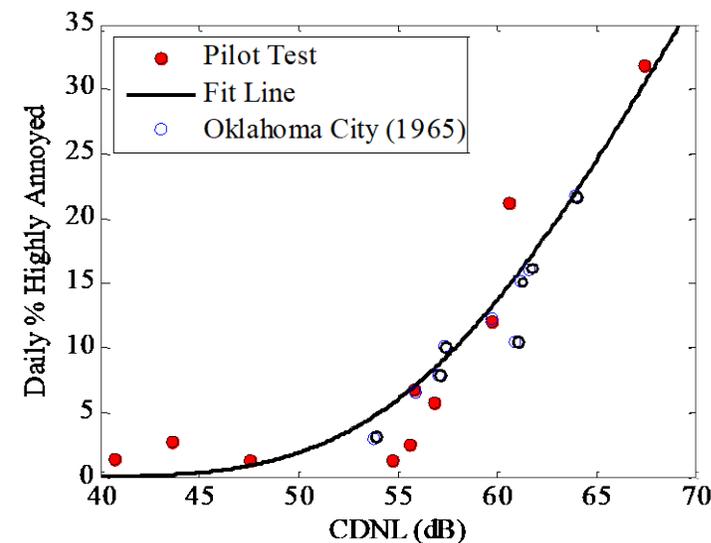
# Community Tests Create Response Data

**Objective: Create a dose-response relationship between level of sound exposure and community annoyance**

- Large, diverse representative population sample
- Tests in multiple U.S. locations and ideally at least one international location
- Sufficient test duration to establish effect of repeated exposure
- Account for test aircraft operational limitations
  - Airfield facilities
- Engage the local community to create a trust environment for test
  - Public and STEM engagement opportunities provided by NASA
- Engage the international research and regulatory community to ensure data acceptance



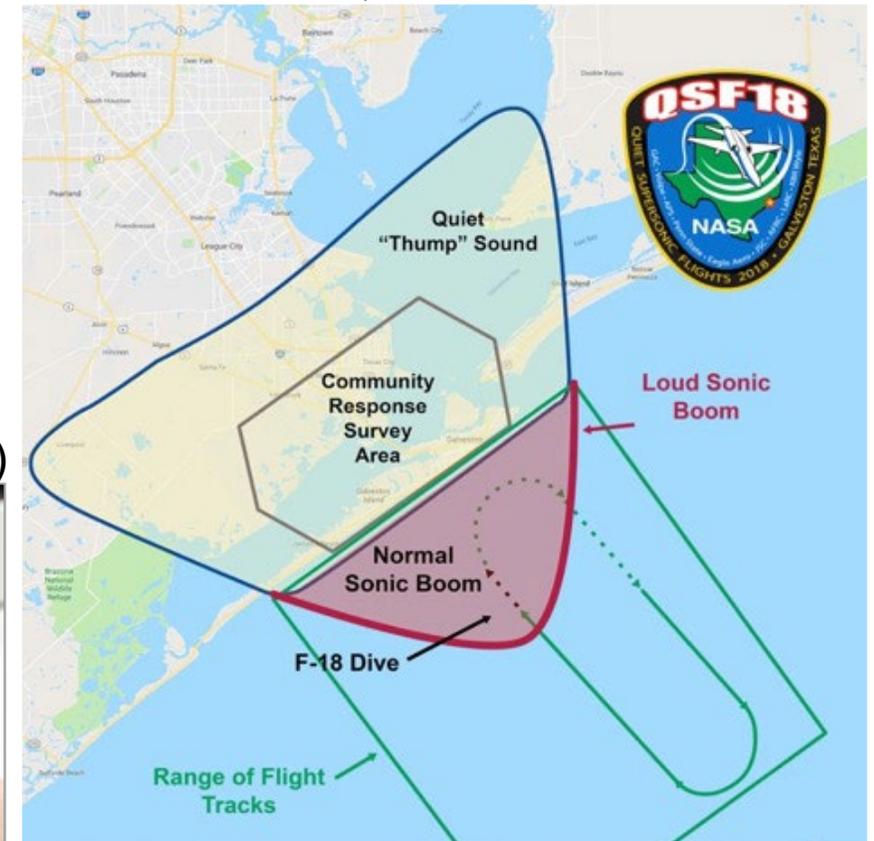
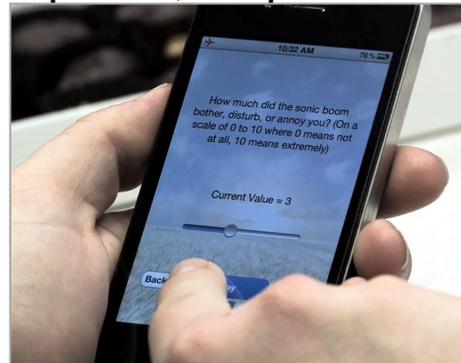
Notional Dose-Response Relationship





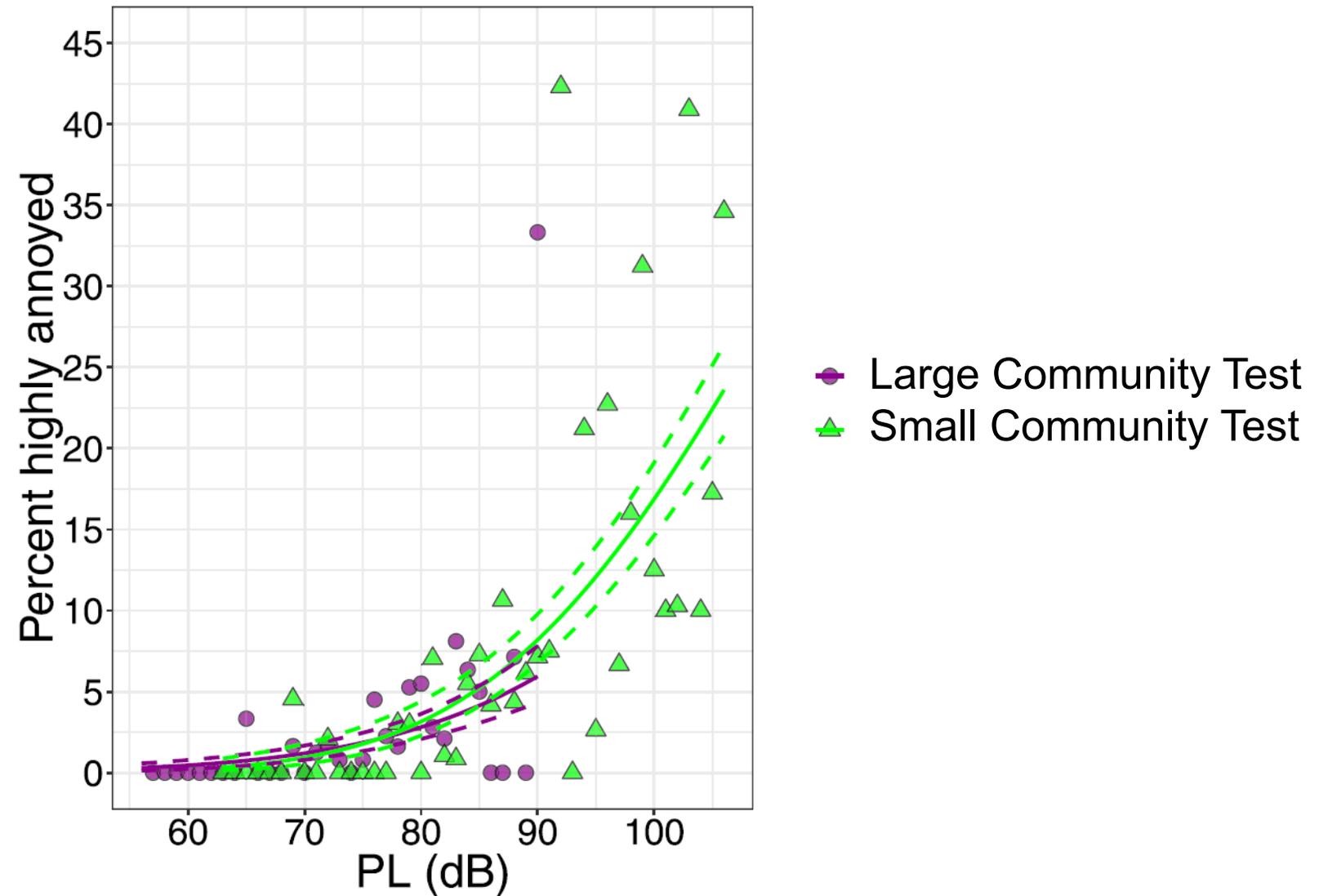
# Recent Experience with Community Tests

- 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 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 (elected officials, general public, respondents)
  - Lessons learned
    - Methods and planning
    - Test Execution
    - Data analysis





# Dose-Response Curves from Past NASA Tests





# Simulating X-59 Low-booms and Dose Variability Nationwide



**Outline of the  
Sonic Boom  
Simulation Goals**

**DoE Approach  
for X-59 Sonic  
Boom Simulation**

**Simulation Results  
and Visualizations**



Doebler, W.J., Wilson, S.R., Loubeau, A., Sparrow, V.W. (2022) "Simulation and Regression Modeling of NASA's X-59 Low-boom Carpets across the USA," Journal of Aircraft (to appear); doi: 10.2514/1.C036876

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# Goals of Sonic Boom Propagation Simulation

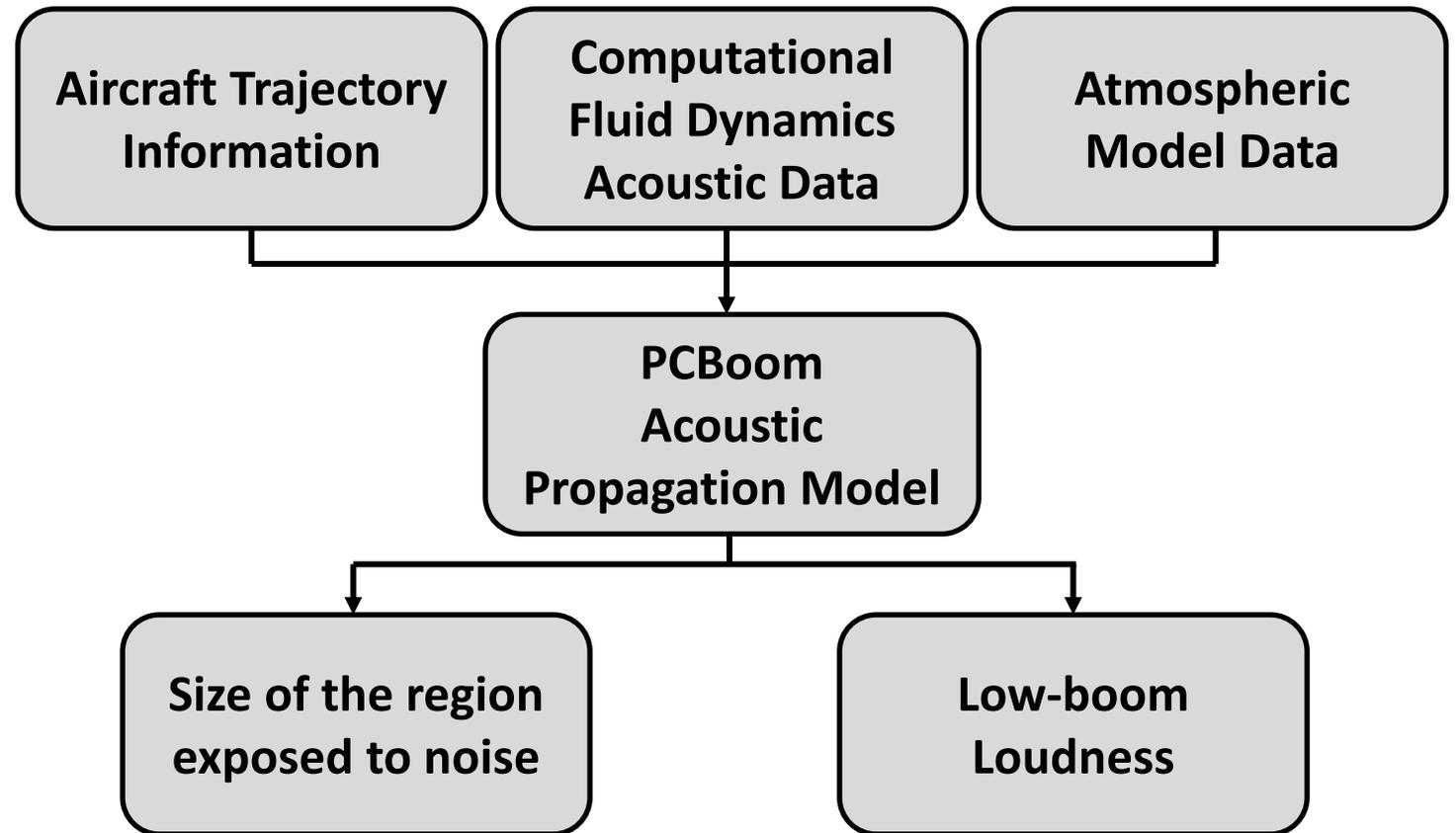
- **Assess nationwide X-59 low-boom**
  - Loudness and variability
  - Exposure region size and variability

## due to:

- Climate
- Season
- Flight direction
- Time of day
- Geographical location
- Ground elevation

## balancing:

- Computational constraints
- Project schedule





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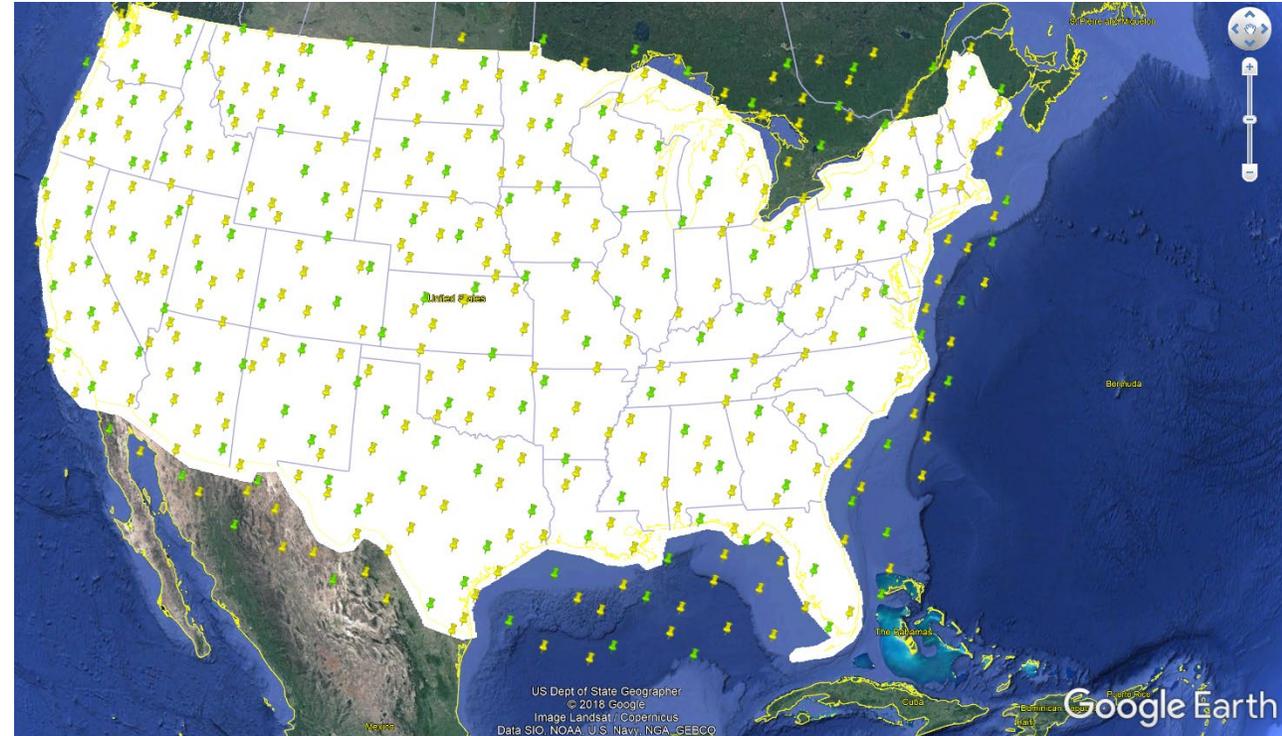


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# Design of Experiments Approach

- **Need to determine appropriate locations and times of atmospheric profiles through which to propagate**
- **Locations across USA chosen using Fast Flexible Filling Design**
  - Provides good space filling properties and can accommodate irregular shapes like the contiguous USA
- **Two spatial resolutions:**
  - 150 and 450 locations across USA

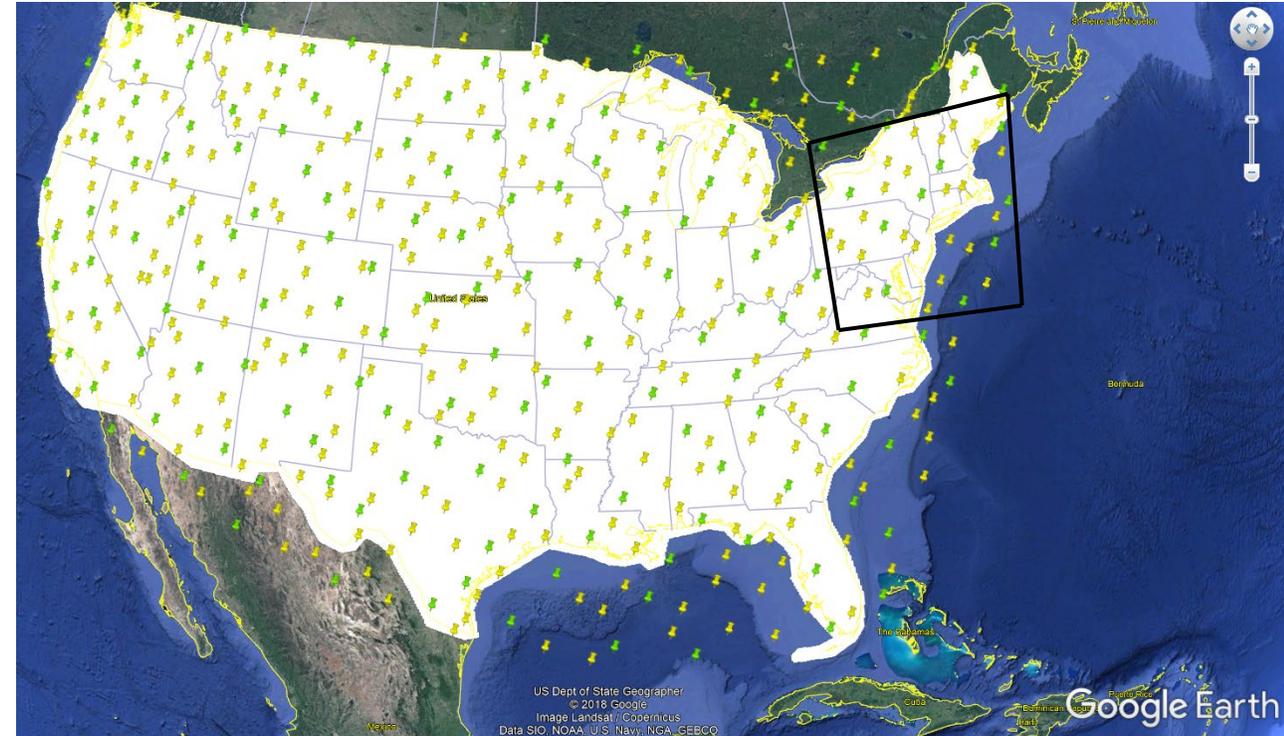


Lekivetz, R. and Jones, B., (2015) "Fast Flexible Space-Filling Designs for Nonrectangular Regions," *Qual. Reliab. Engng. Int.*, 31(5), 829-837



# Subset analysis to determine simulation resolution

- **Completed propagation simulation for subset of locations in the Northeast**
- **Compared results of designs with higher and lower spatial and temporal resolutions**
  - 34 vs. 10 locations in Northeast
  - 4 vs. 1 atmospheric profiles per day
- **5 years of atmospheric profiles, 4 aircraft headings**
- **Subset storage size**
  - About 1.5 TB total for nearly 1 million carpets





# To determine importance of input factors, used decision tree and bootstrap forest analysis



- **Input factors (predictors)**

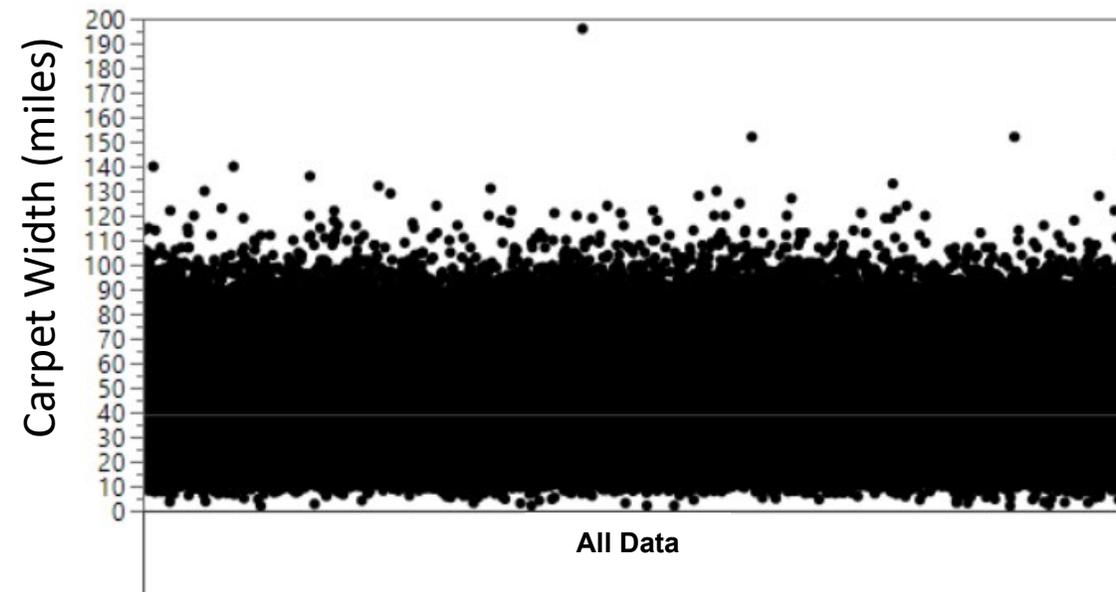
- Heading
- Latitude/longitude
- Season
- Datetime
- Ground elevation

- **Carpet quantifiers**

- Exposure Region Size
  - “Carpet width”
- Undertrack Perceived Level (PL)
- Range of PL



Example decision tree data for CW





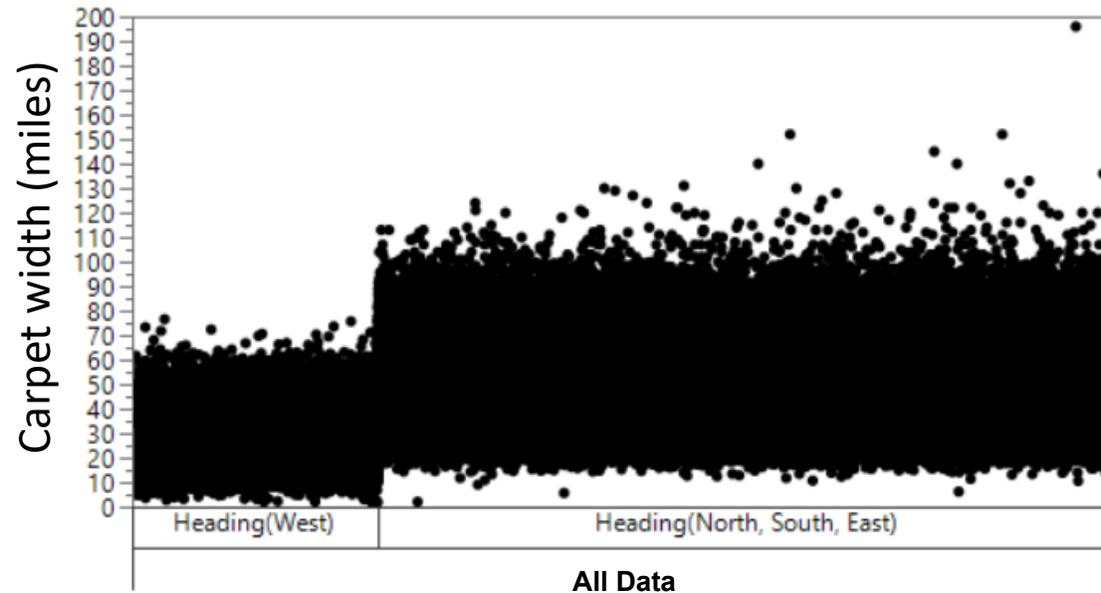
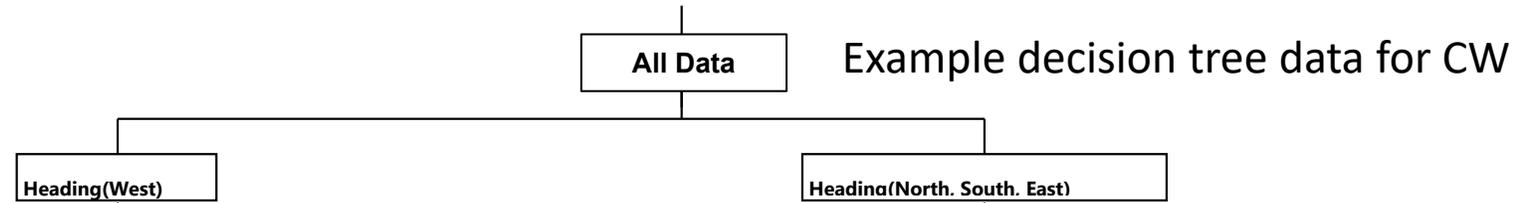
# To determine importance of input factors, used decision tree and bootstrap forest analysis

- **Input factors (predictors)**

- Heading
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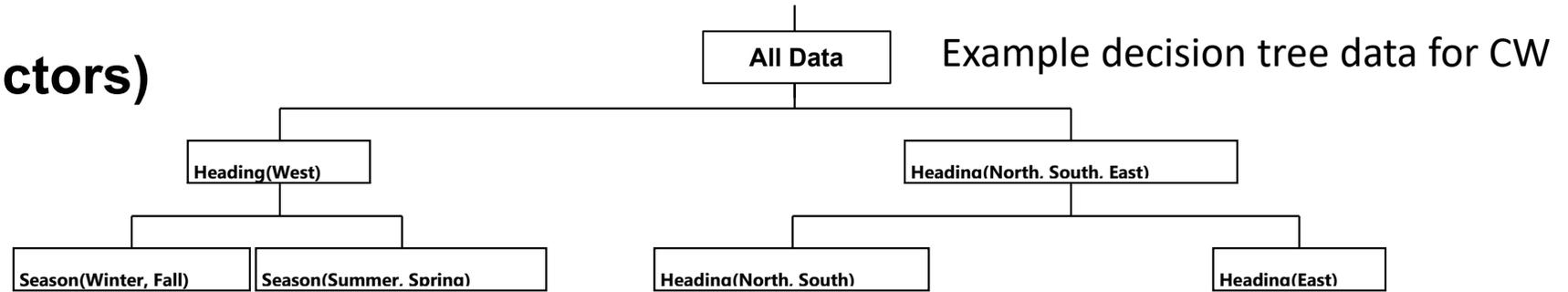




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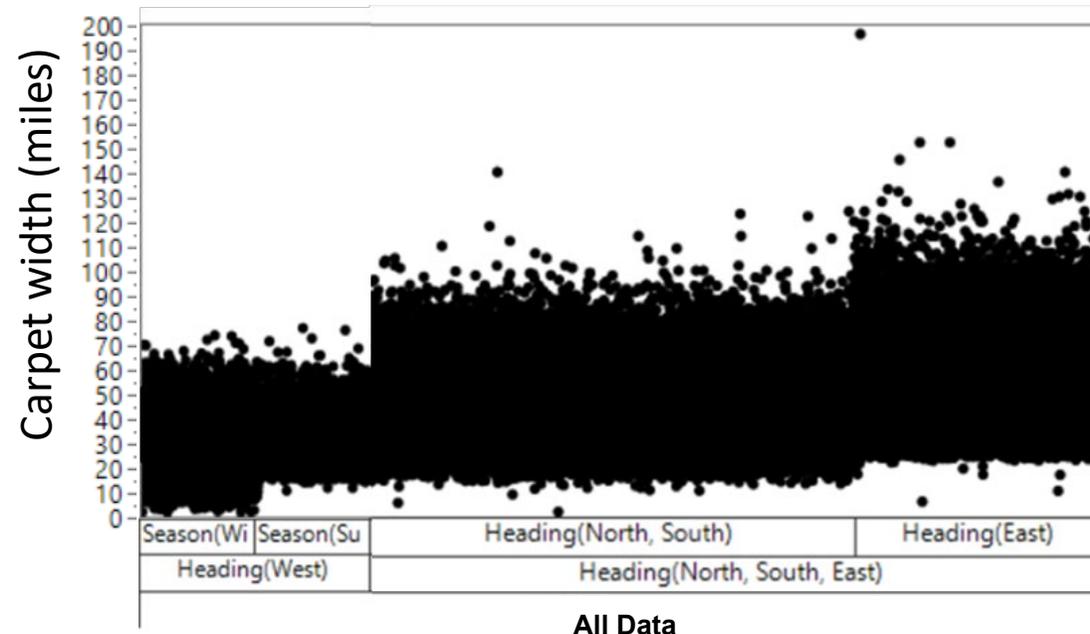
## • Input factors (predictors)

- Heading
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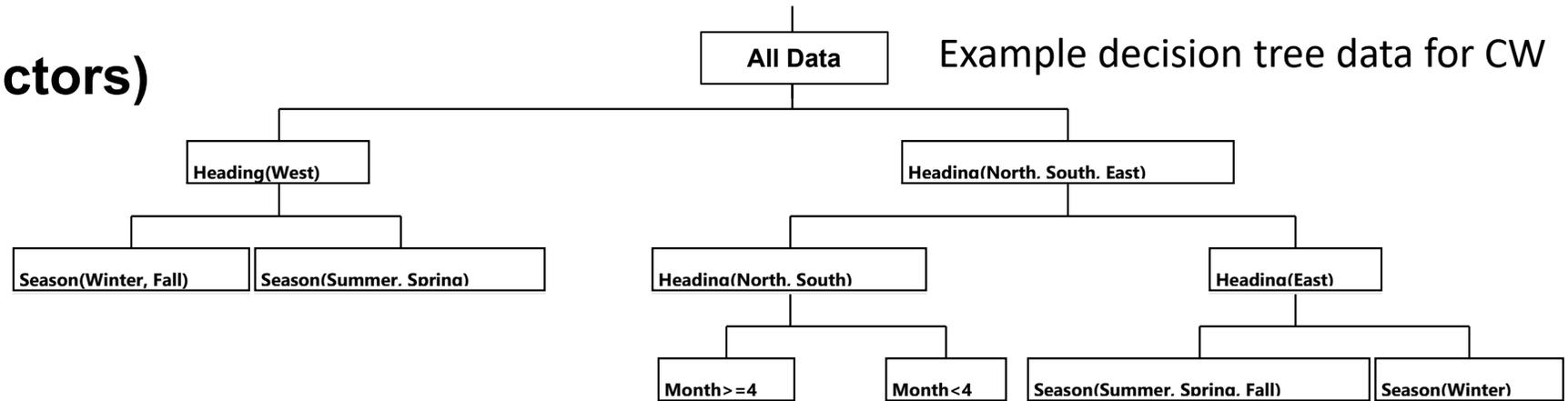




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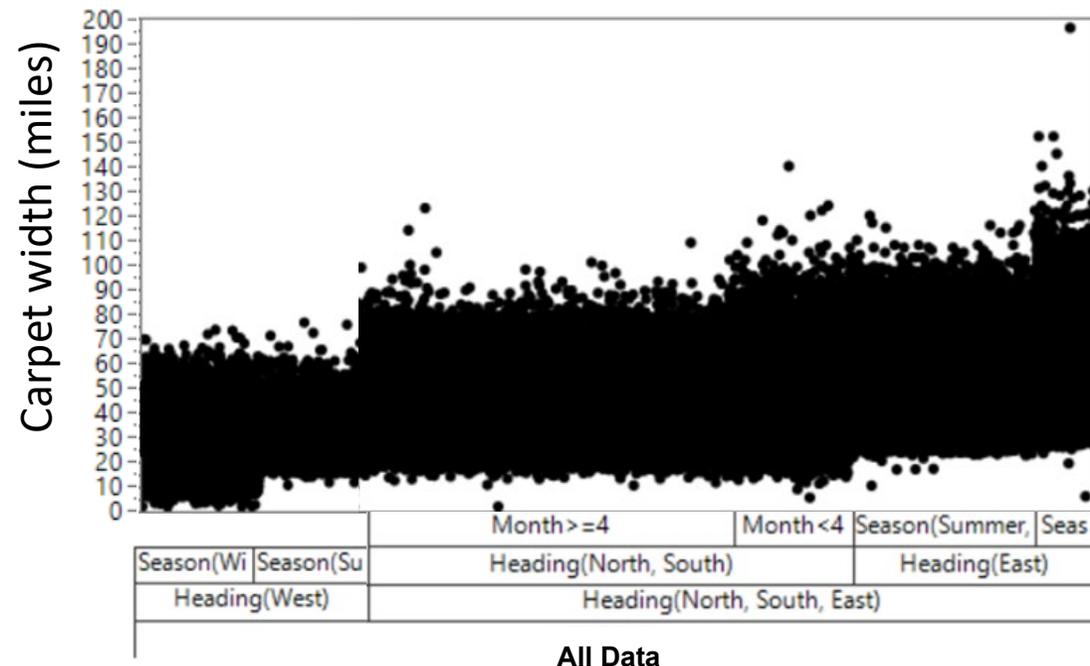
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## • Carpet quantifiers

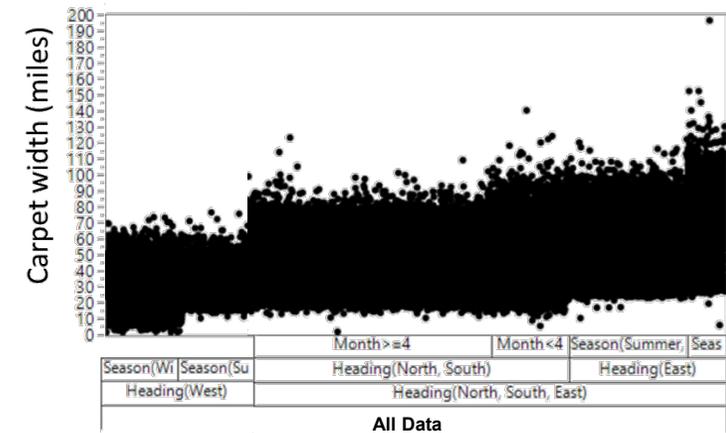
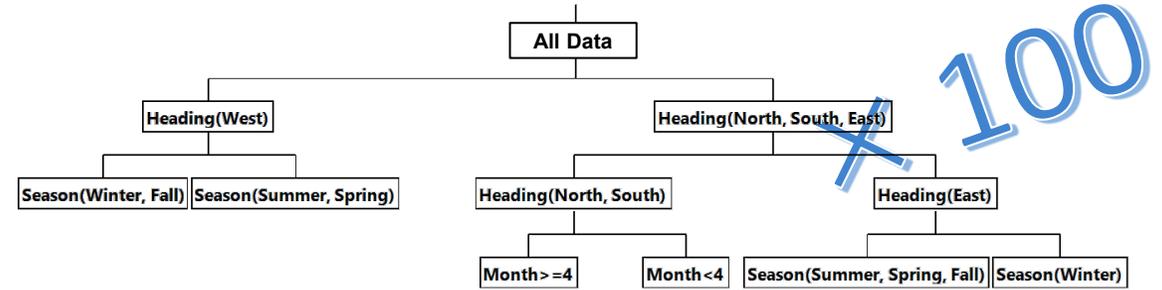
- Exposure Region Size
  - “Carpet width”
- Undertrack Perceived Level (PL)
- Range of PL





# Bootstrap forest analysis description

- **Bootstrap forest analysis was conducted to evaluate spatial and temporal resolution**
  - Randomly sampled from the dataset to build 100 decisions trees
  - Statistical decision tree recursively partitioned data according to the relationship between predictors and response variables
  - Contribution of each predictor was then ranked



Predictor	CW (mi)				Rank
Climate					6
Season	█				2
Latitude	█				4
Longitude					7
Ground Altitude (ft)					5
Heading	█	█	█	█	1
Year					8
Month	█				3
Time					9



# Bootstrap forest results

Fine spatial resolution (green 🌿 + yellow 📍)

Predictor	PL (dB)		PL range		CW (mi)	
	Bar	Rank	Bar	Rank	Bar	Rank
Climate	[Short bar]	6	[Short bar]	9	[Short bar]	6
Season	[Medium bar]	2	[Medium bar]	2	[Short bar]	2
Latitude	[Short bar]	4	[Short bar]	7	[Short bar]	4
Longitude	[Short bar]	8	[Short bar]	5	[Short bar]	7
Ground Altitude (ft)	[Short bar]	5	[Short bar]	4	[Short bar]	5
Heading	[Medium bar]	3	[Long bar]	1	[Long bar]	1
Year	[Short bar]	7	[Short bar]	8	[Short bar]	8
Month	[Medium bar]	1	[Short bar]	3	[Short bar]	3
Time	[Short bar]	9	[Short bar]	6	[Short bar]	9

Coarse spatial resolution (green 🌿 only)

Predictor	PL (dB)		PL range		CW (mi)	
	Bar	Rank	Bar	Rank	Bar	Rank
Climate	[Short bar]	8	[Short bar]	9	[Short bar]	7
Season	[Medium bar]	2	[Medium bar]	2	[Short bar]	3
Latitude	[Short bar]	4	[Short bar]	7	[Short bar]	4
Longitude	[Short bar]	5	[Short bar]	5	[Short bar]	6
Ground Altitude (ft)	[Short bar]	6	[Short bar]	4	[Short bar]	5
Heading	[Medium bar]	3	[Long bar]	1	[Long bar]	1
Year	[Short bar]	7	[Short bar]	8	[Short bar]	8
Month	[Medium bar]	1	[Short bar]	3	[Short bar]	2
Time	[Short bar]	9	[Short bar]	6	[Short bar]	9

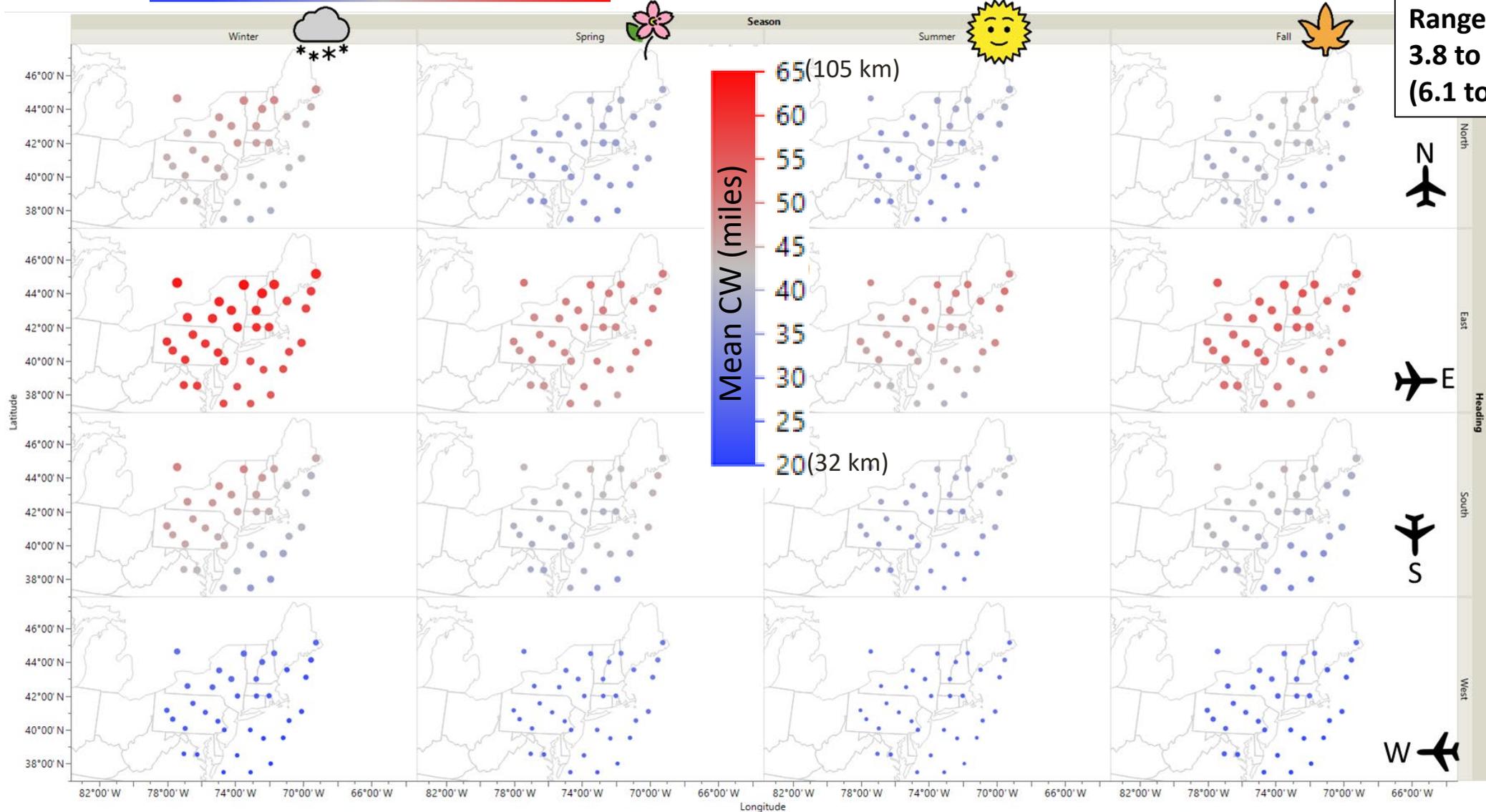
- **Time of day was not important**
- **Equivalent predictor importance for both spatial resolutions**



# Carpet width (CW) mean and standard deviation (SD) results

Dot color indicates mean

Dot size indicates standard deviation (SD)



Range of CW SD:  
3.8 to 14.8 mi  
(6.1 to 23.8 km)

➤ Values vary smoothly between nearby points



# Final Design



- **Inputs**

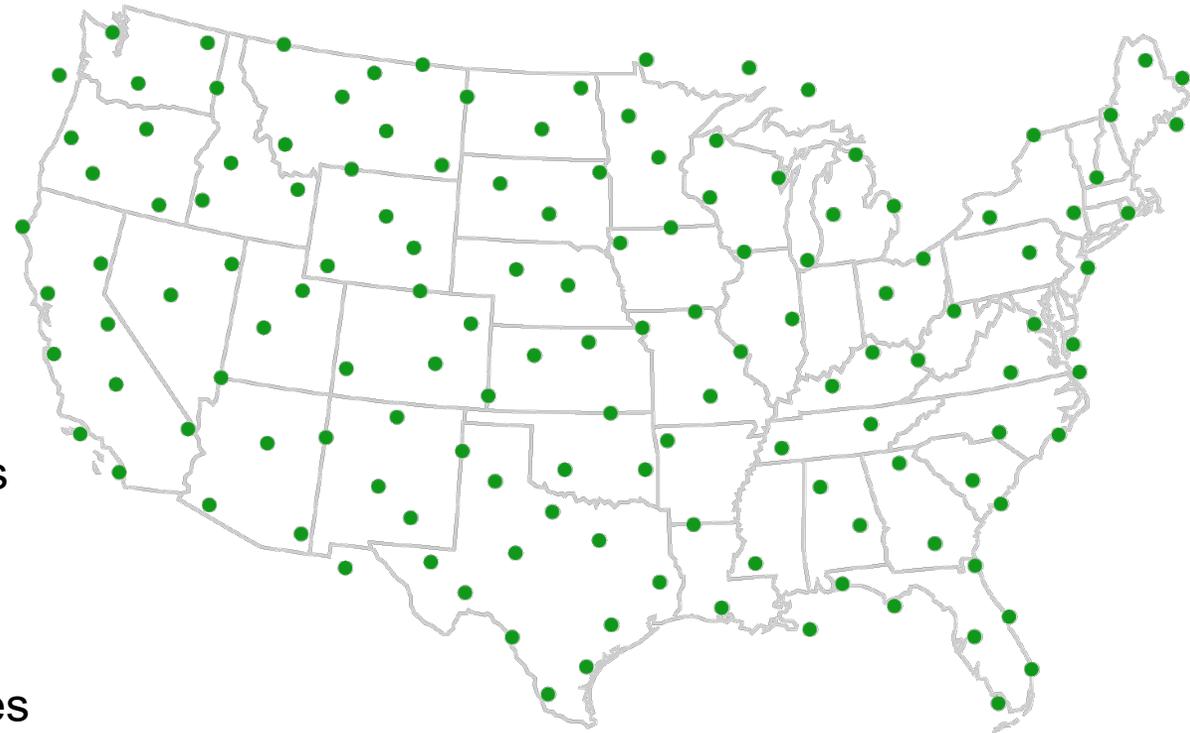
- 134 locations separated by about 200 km
- 5 years of atmospheric data at each location
- One time per day, 1800 UTC, 11 AM to 2 PM local
- 4 cardinal aircraft headings

- **Results**

- Over 1 million X-59 sonic boom exposure region sizes
- Over 18 million X-59 sonic boom waveforms

- **Follow-on analysis**

- Multiple linear regression models to estimate quantities in intermediate locations





# Simulating X-59 Low-booms and Dose Variability Nationwide



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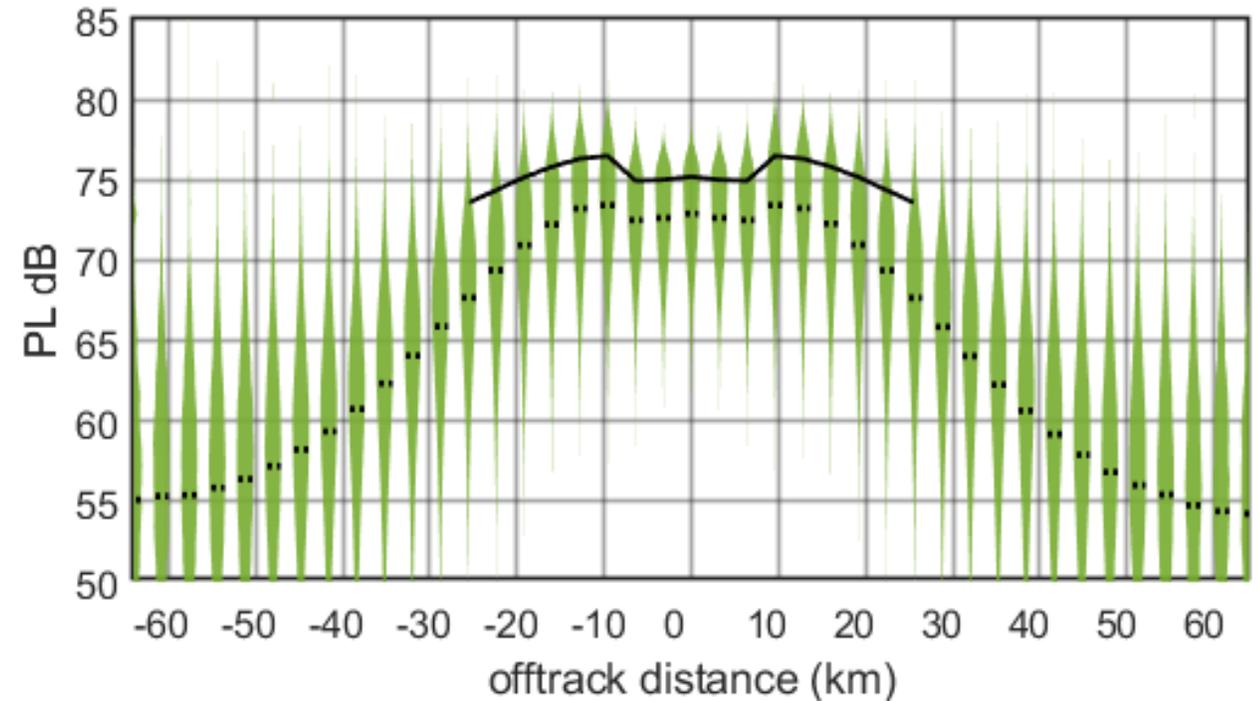
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# Visualization Techniques: Violin Plots for Loudness



## Lateral Loudness



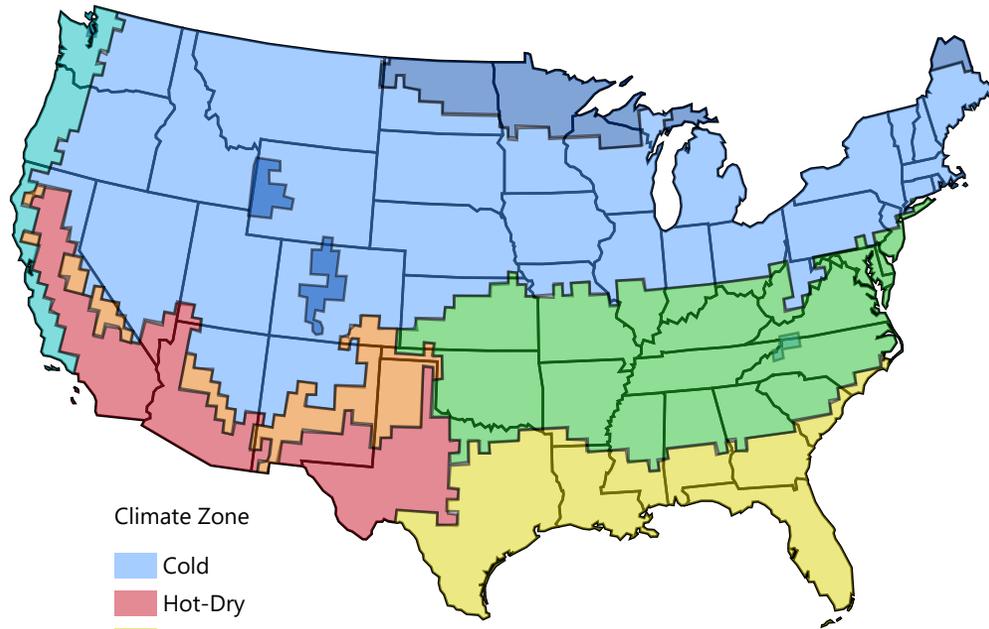
1. *Manual of the ICAO Standard Atmosphere Extended to 80 kilometres (262 500 feet)*. International Civil Aviation Organization ICAO 7488, 1993.
2. *Acoustics — Attenuation of sound during propagation outdoors — Part 1: Calculation of the absorption of sound by the atmosphere*, ISO Standard 9613-1:1993, 1993.

	Loudness in a standard atmosphere <sup>1,2</sup>
	Peak-normalized PDF “violins” of loudness in realistic atmospheres
	Median loudness of each violin



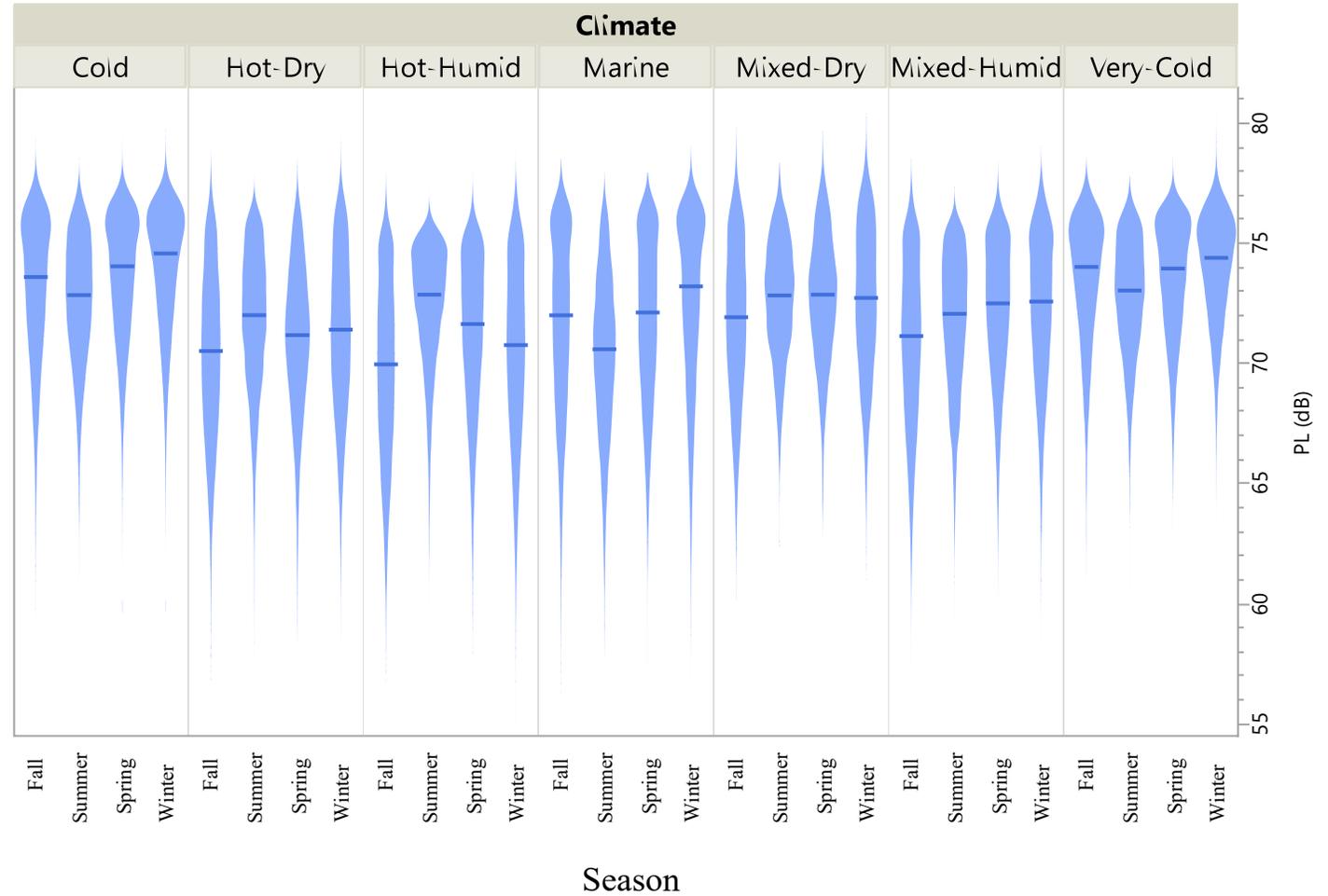
# Visualization Techniques: Violin Plots for Climate Results

## Seasonal Loudness



Climate Zone

- Cold
- Hot-Dry
- Hot-Humid
- Marine
- Mixed-Dry
- Mixed-Humid
- Very-Cold

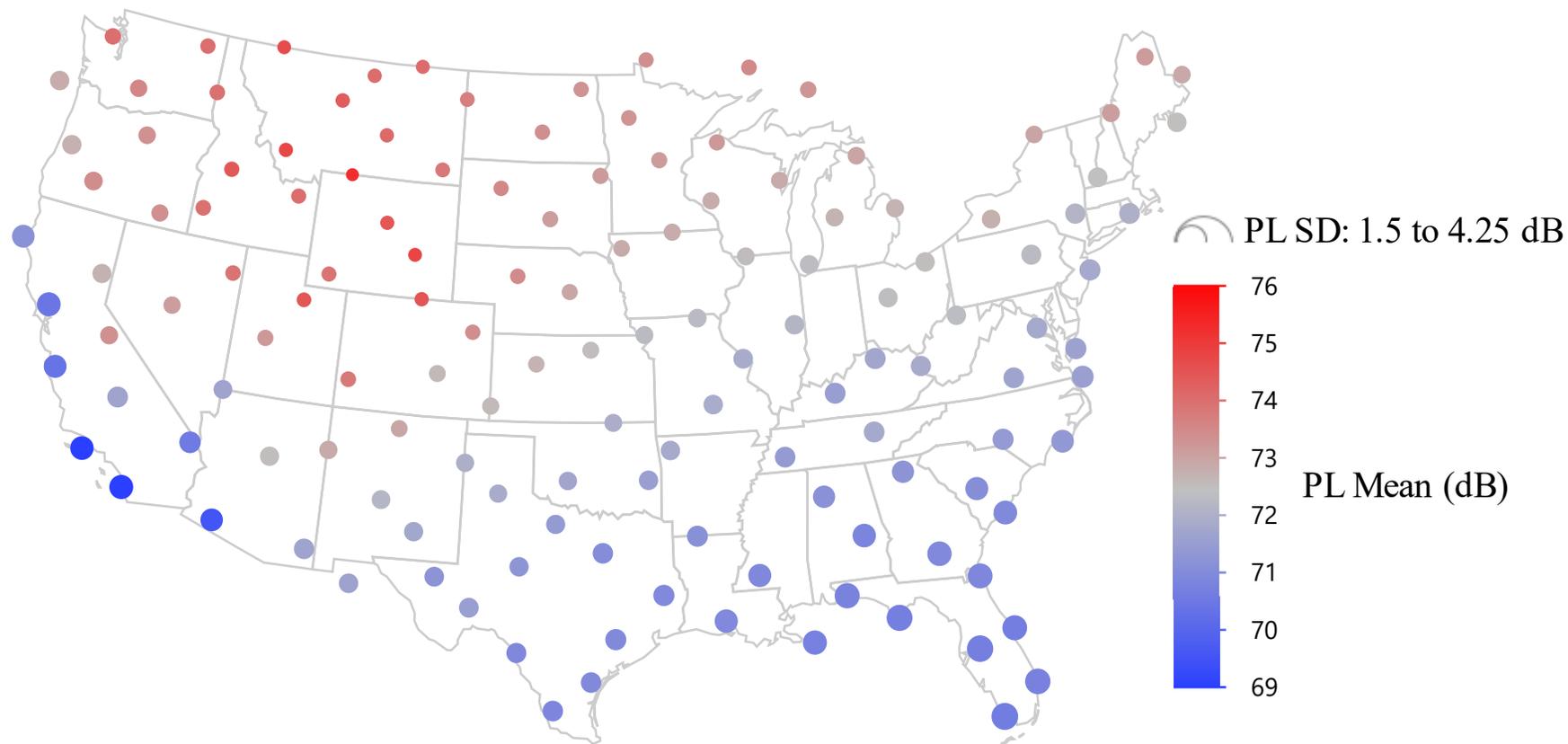




# Visualization Techniques: Map plots for Loudness and Variability



## Mean Loudness and SD





# Visualization Techniques: Map plots for Season and Heading



## Mean Loudness and SD

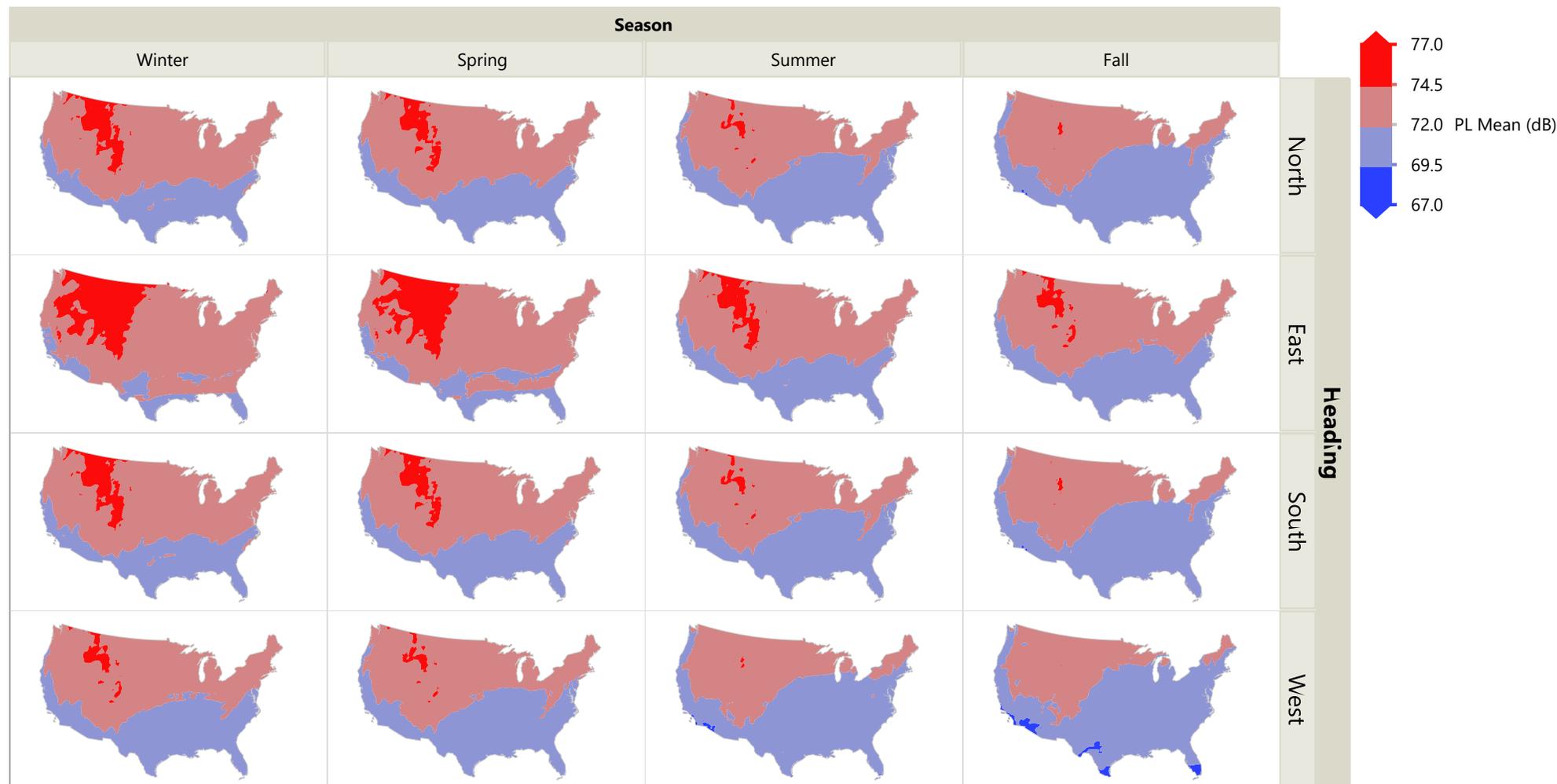




# Visualization Techniques: Contour plots for multiple linear regression



## Mean Loudness





# Simulation Study Summary

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- **Assessed impact of climate, heading, season, time of day, and geographical location on low-boom loudness, variability, and exposure region size**
- **Simulation resolution was decided by DoE**
- **Generated millions of sonic boom waveforms and exposure region sizes**
- **Multiple linear regression was used to estimate loudness, variability, and exposure region size at intermediate locations**
- **The simulated data will be used to aid X-59 community test plans**



# Transitioning to X-59 Community Response Testing Approaches

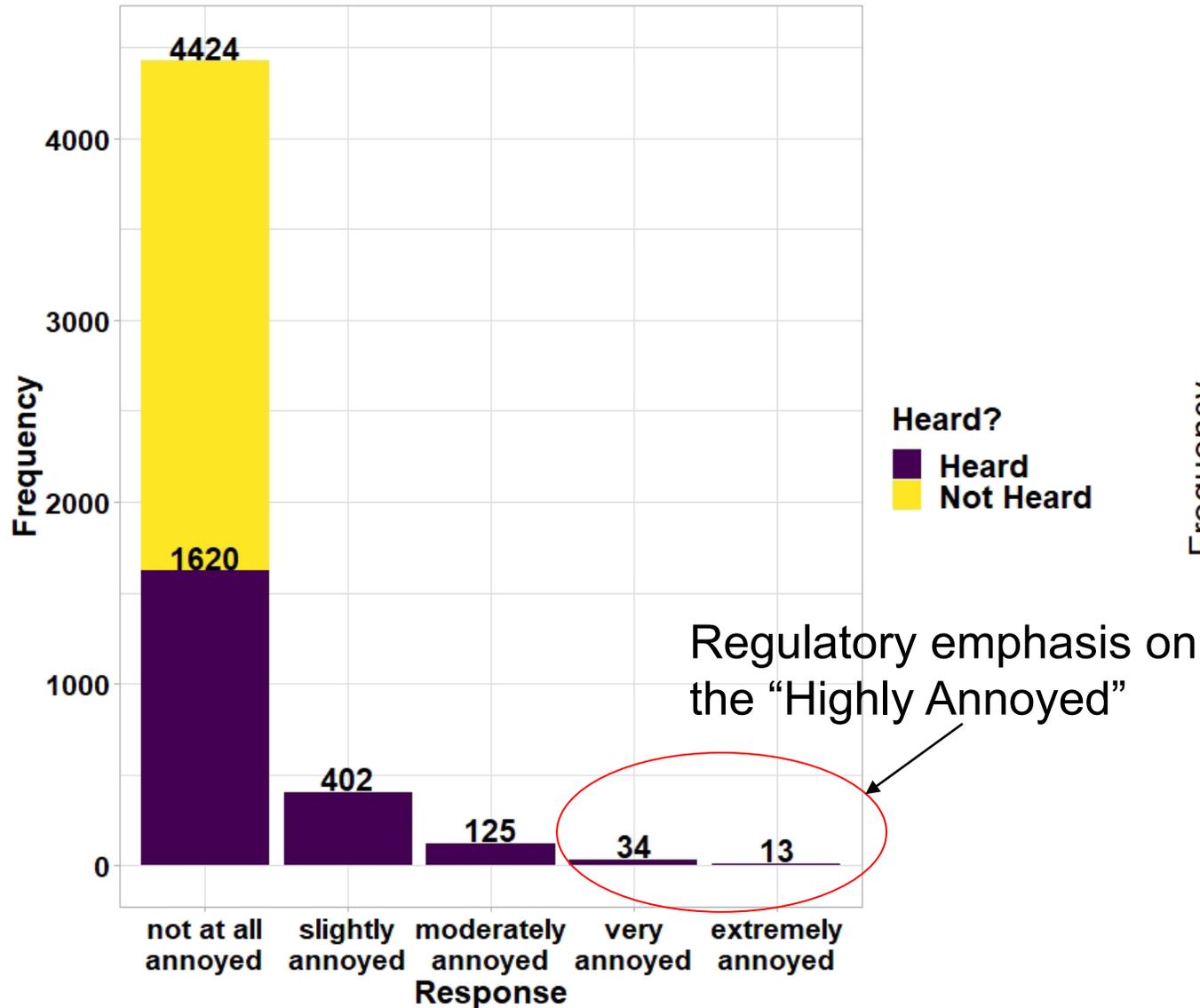
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- **Demonstrate a candidate statistical analysis approach for one site**
  - Single event data from large community test of 2018
  
- **Highlight some challenges and opportunities in this complex problem**
  - Survey mode: How do we deploy many surveys when test conditions change rapidly?
  - Sampling sites: How will we select community test sites?
  - Sampling study subjects: How will we recruit participants?
  - Dose uncertainty: What are the effects if dose is subject to some imprecision?
  - Pooling data: Can we combine data from distinct sites to produce a nationally representative curve?

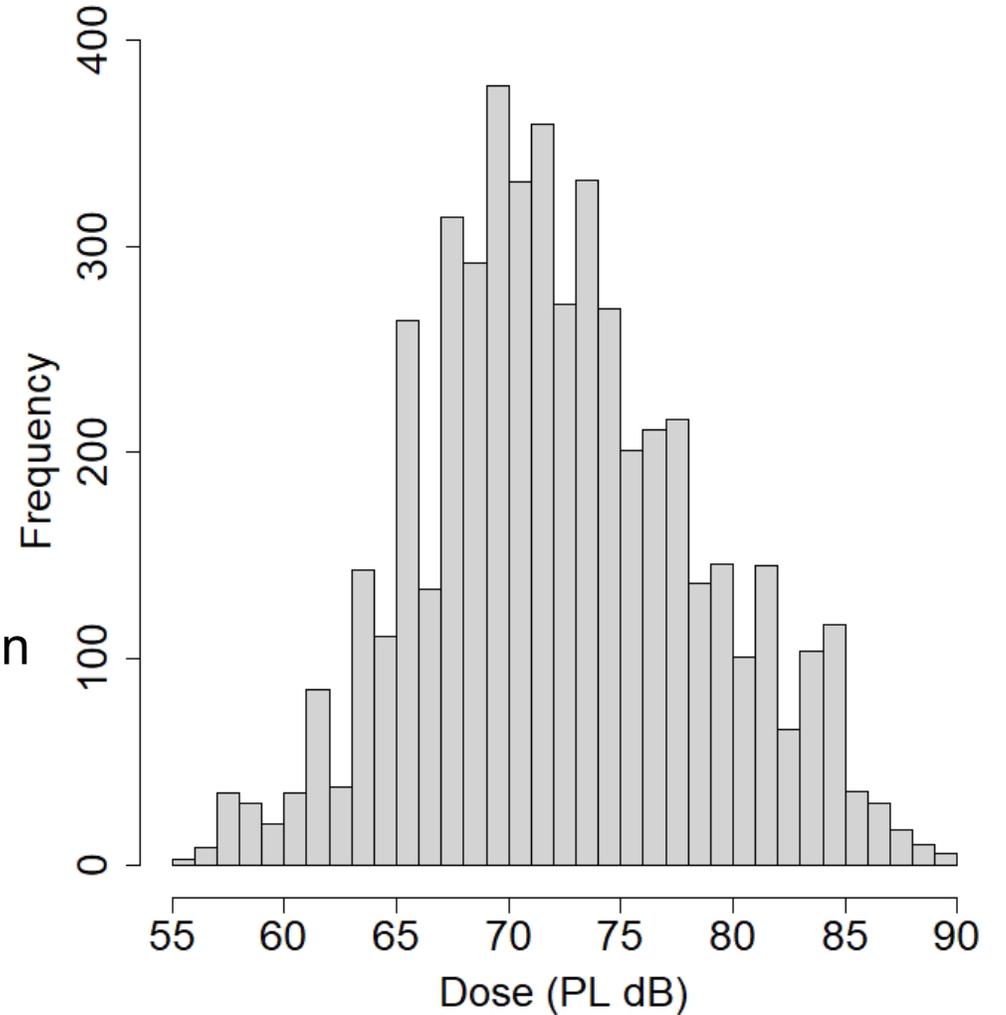
# Large Community Test: Single Event Data



### Perceptual Annoyance Responses



### Histogram of Doses



# QSF18: Conditional Dose-Response Relationship

- Reproducing Bayesian Random Intercept Logistic Regression of Lee et al. (2020)

- $i \in \{1, 2, \dots, 371\}$  individuals
- $j \in \{1, 2, \dots, n_i\}$  booms
- $H_{ij}$ , indicator of High Annoyance
- $p_{ij}$ , probability of High Annoyance
- $x_{ij}$ , dose, in PL dB
- $u_i$ , individual intercept
- $\beta_0, \beta_1, \sigma_u^2$ , parameters

$$\begin{aligned}
 H_{ij} | p_{ij} &\sim \text{Bernoulli}(p_{ij}) \\
 p_{ij} | \beta_0, \beta_1, u_i &= \text{logit}^{-1}((\beta_0 + u_i) + \beta_1 x_{ij}) \\
 u_i | \sigma_u^2 &\sim N(0, \sigma_u^2) \\
 \beta_0 &\sim N(0, 100) \\
 \beta_1 &\sim N(0, 100) \\
 \sigma_u^2 &\sim \text{IG}(0.01, 0.01)
 \end{aligned}$$

Parameter	Estimate	Lower 95% CI	Upper 95% CI	$\hat{R}$
$\hat{\beta}_0$	-19.0	-24.02	-14.25	1.00
$\hat{\beta}_1$	0.15	0.10	0.21	1.00
$\hat{\sigma}_u$	2.62	1.75	3.86	1.00

- Estimates for 371 subject-specific intercepts; family of individual dose-response curves

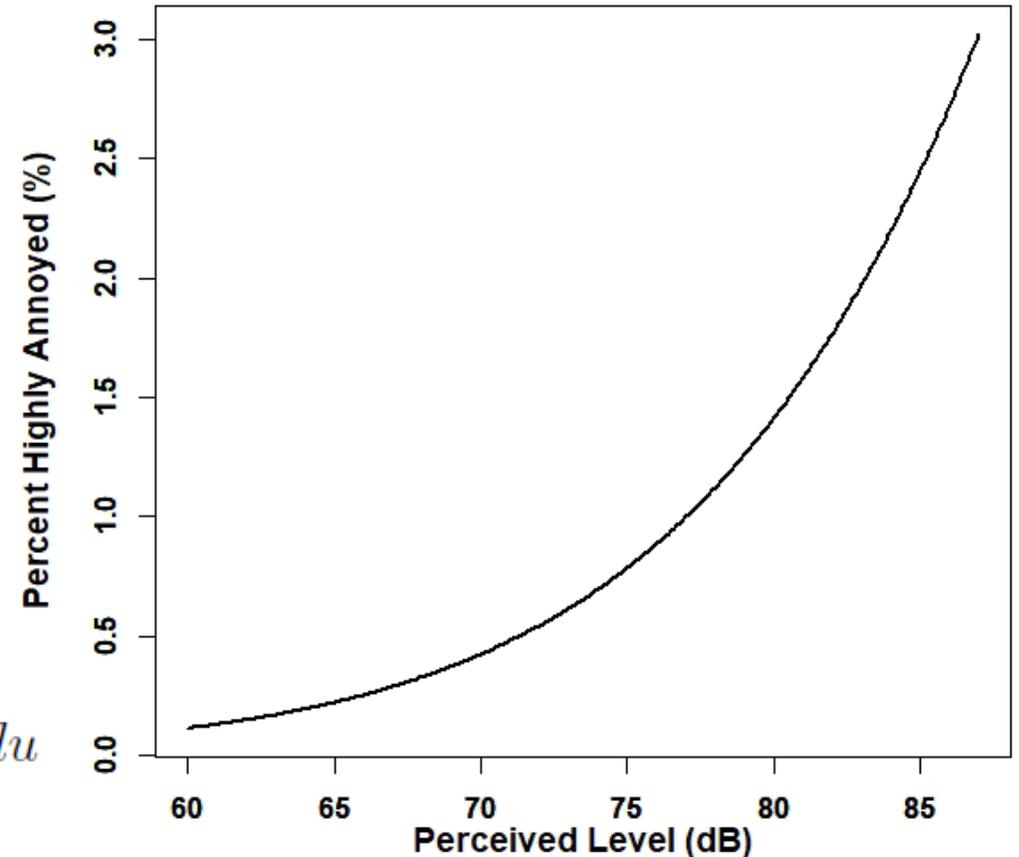
# QSF18: Marginal Dose Response Relationship

- Want population average relationship, rather than subject-specific curves
- Vaughn et al. (2021) compare Bayesian and GEE approaches to obtain marginal models
- Integrate over (prior) distribution of random effects (Pavlou et al. 2015)

$$P(H_{ij} = 1 | X_{ij} = x_{ij}) = \int_{-\infty}^{\infty} \frac{1}{1 + \exp(-[u - 19.0 + 0.15x_{ij}])} f(u) du$$

where  $f(u)$  denotes  $N(0, 2.62^2)$  distribution

QSF18 Marginal Dose Response Curve



# Challenge: Near Real-Time Data Collection Needs



- **Experimental conditions may change within the half hour—need prompt responses**
  - Multiple single event surveys and a daily summary survey each day of testing
  - Recruiting and retaining a panel sample is more practical than a cross-sectional study design
  
- **Survey modes—who participates and how**
  - Paper modes don't meet near real-time need, especially for single event survey
  - Consideration of interactive voice recording (IVR)—Fidell and Horonjeff (2019) noted low completion rates for telephone surveys without callbacks
  
- **Preferred modes: internet and custom smartphone applications**
  - Meets near real-time requirement
  - Mapping interface allows user to indicate location at point in time—solves significant linkage issue
  - Simplifies nonresponse follow up

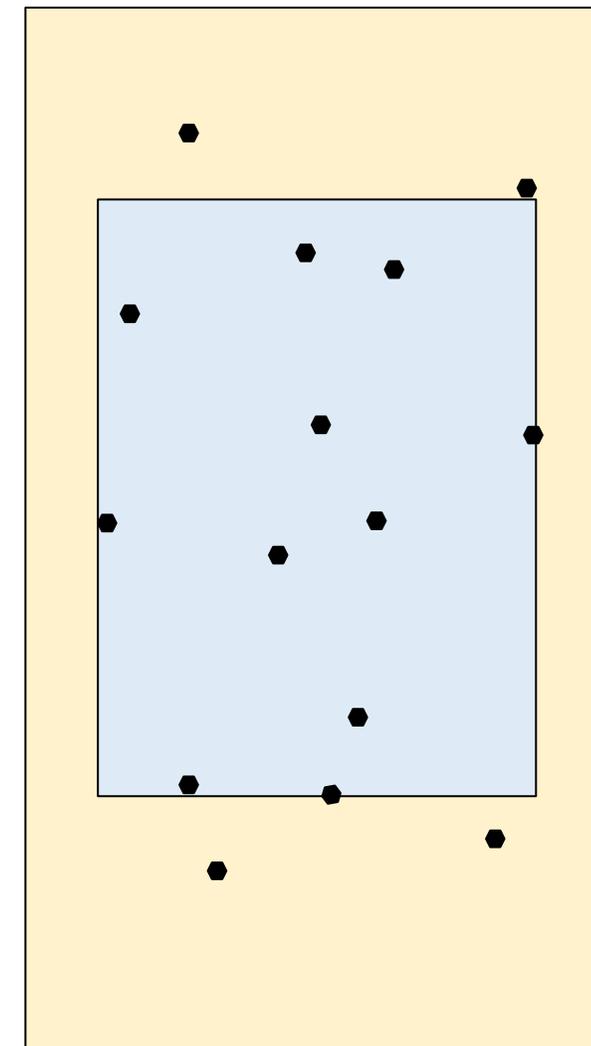
# Challenge: Sampling Sites Given Operational Constraints



- **In principle, thousands of airfields nationwide, but...**
  - Study aims require one month in place
  - Limited number of airfields can support needs of X-59
  - Some feasible sites are near each other
  
- **Site selection via purposive sampling**
  - At present, plans for selection of five distinct test sites
  - Defining orientation of study region and heading of aircraft through it
  - Climate factors
  - Demographic composition of the locality

# Challenge: Sampling Study Subjects

- **Dose will be administered across a large study area**
  - Sparse network of sensors obtain objective measurements at select points
  - Fused with predictive models to *estimate dose* and uncertainty throughout
- **Population: all residents of 20 NM x30 NM recruitment region**
  - Take union of Census Blocks within this recruitment region
  - Sampling frame is a list of postal addresses in member Census Blocks
- **Sample: recruited subset of residents of blue region**
  - Variance unit is the household (select every  $n^{\text{th}}$  address in a sorted list)
  - Within-household sampling to get person (Rizzo, Brick, and Park 2004)
  - In common with household surveys and probability-based internet panels
- **All in community exposed to dose, only sample surveyed**

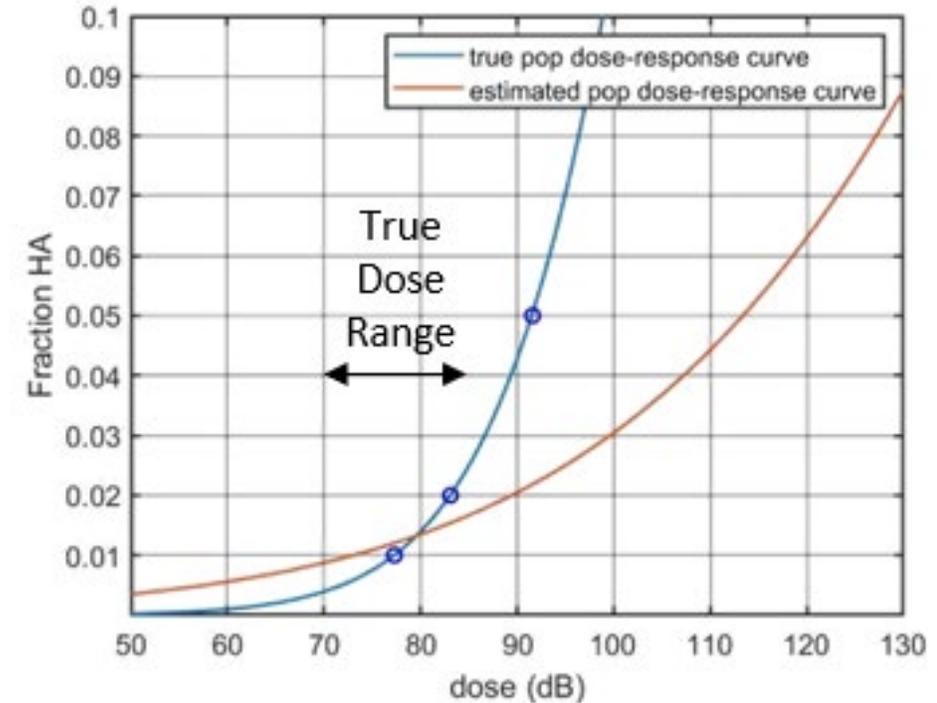


Notional Diagram

# Challenge: Accounting for Dose Uncertainty



- Means of dose estimation ongoing; see Klos (2020) for one example
- **Effects of measurement error on logistic regression**
  - “Underestimate the...probability for high-risk cases and overestimate for low-risk cases” (Stefanski and Carroll 1985, p. 1336)
  - Overestimated → policy may be unduly stringent on aircraft manufacturers
  - Underestimated → policy may subject public to unacceptable levels of noise
- **Measurement error statistics literature of recent interest in the acoustics literature**
  - Doebler et al. (2022), Horonjeff (2021,2022)





# Challenge: Pooling Data

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- **Many papers in acoustics literature seek to pool or combine data from distinct studies or from multiple noise sources**
  - Neighborhood Environmental Survey—Miller et al. (2021)
  
- **Two years from collecting live data—what will final analysis model look like?**
  - Categorical outcome, with regulatory emphasis on binary concept of “Highly Annoyed” or not
  - Repeated measurements through panel survey of respondents
  - Need for national, marginal dose-response relationships (single event and cumulative) from up to five distinct sites
  
- **A candidate: multilevel regression with poststratification (Gelman and Little 1997)**
  - Divide population into many categories (poststrata)
  - Averaging across dose-response relationships for poststrata, weighted in proportion to size in *population*



# Summary

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- NASA's Quesst Mission will provide key data to regulators for the development of noise standards for overland commercial supersonic flight.
- X-59 build is well underway, with a first flight planned for 2022
- Community testing will begin in 2024 and deliver dose response data from overflight of US communities
- A simulation study assessed impact of climate, heading, season, time of day, and geographical location on low-boom loudness, variability, and exposure region size
- X-59 booms will be slightly louder and less variable in the colder climates and with greater ground elevation.
- Exposure region is widest with east heading due to prevailing easterly wind.
- Exposure region does not change considerably with climate region except for Marine climate zone
- Relevant statistical models link perceptual response and objective measurements in dose-response curve
- Discussed challenges shape our decisions to date and continue to be areas of research in planning phase



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# Thank you

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