# Modeling Measurement Error in Dose-Response Models of Community Annoyance to Low-Noise Supersonic Flight

Nathan B. Cruze

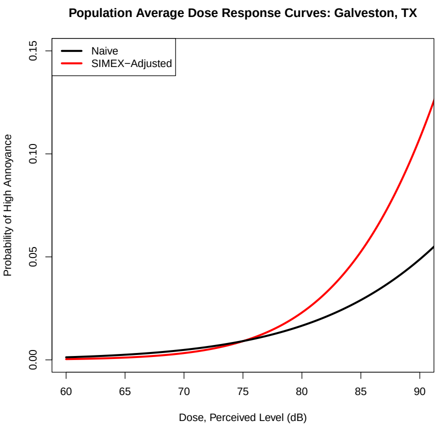
NASA Langley Research Center

Department of Biostatistics and Data Science Virtual Seminar
UTHealth Houston School of Public Health

April 30th, 2024

# Presentation Overview

1. Sonic boom and the NASA Quesst mission
2. Generalized linear mixed measurement error models
   - Functional: Simulation extrapolation (SIMEX)
   - Structural: Bayesian hierarchical models
3. Discussion and conclusions




**What happens to the dose-response relationship if we use a surrogate for dose (in dB) instead of the actual level?**

# Sonic Boom Moves with the Aircraft

Created by pressure waves as object moves faster than the speed of sound[1]

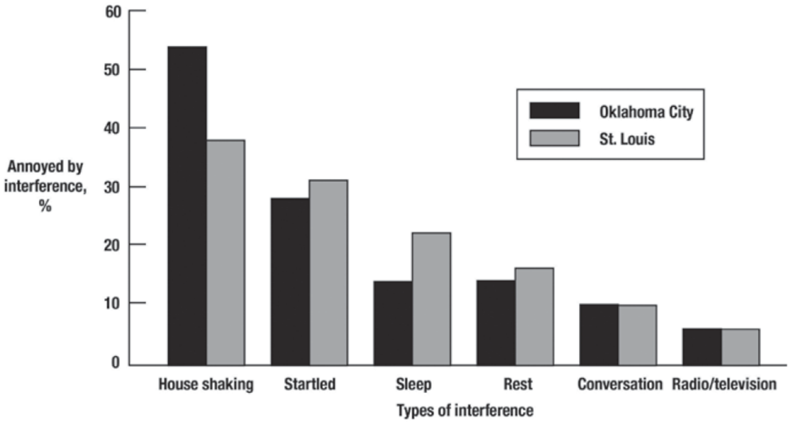
- Thunder-like boom(s) due to two rapid pressure changes
- Like wake of a boat–carried for duration of supersonic travel
- Width of 'carpet' approximately 1 mile per 1,000 feet altitude

June 4, 2023–Virginia, Maryland, D.C.

- F-16 aircraft scrambled to contact unresponsive Cessna aircraft
- NORAD, FAA statements
- Generated news stories and social media reactions

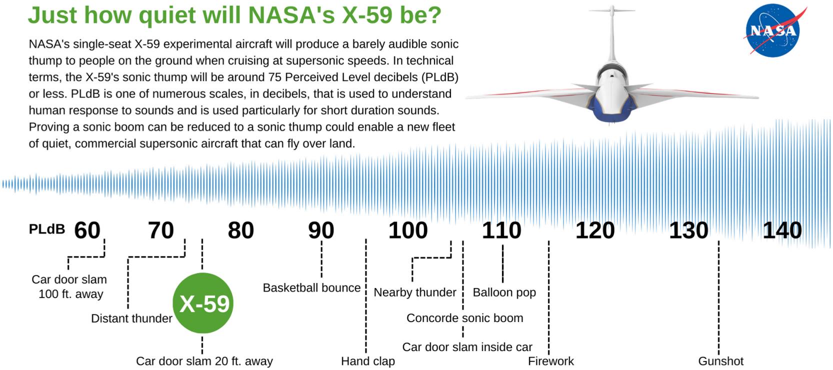
[1] NASA Sonic Boom Fact Sheet [Accessed 4/23/2024]

# Testing in the 1960s Contributed Data Supporting Current Ban



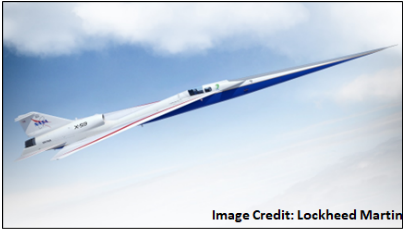

- National Opinion Research Center (Borsky, 1965)
- Overland civil supersonic flight prohibited since 1973 (14 CFR §91.817)

# Aircraft Design Can Reduce the Sonic Boom to a ‘Thump’

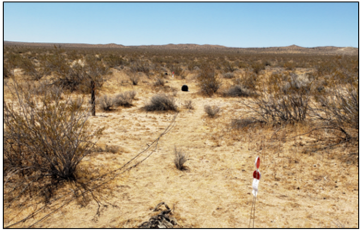



- *Sonic Boom: Six Decades of Research* (Maglieri et al., 2014)
- Loudness of X-59 shaped sonic boom (Doebler & Rathsam, 2019)
- Prospective commercial designs in engineering literature (Sun & Smith, 2022)

# X-59 and the NASA Quesst Mission




**Build and Test X-59**



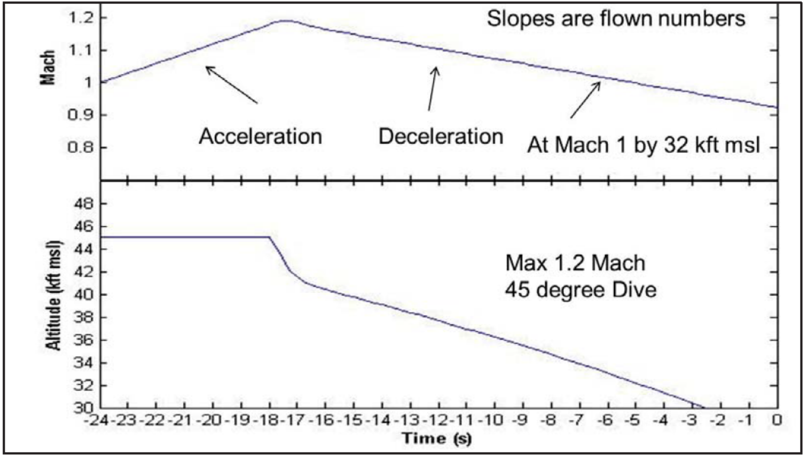
**Acoustic Validation**

**Community Studies**

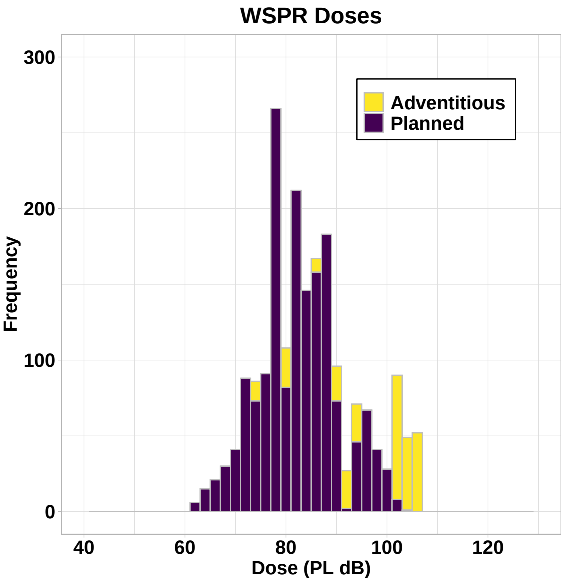
- Collect community response data for noise certification standards (Rathsam et al., 2023)
- Community test campaigns with X-59 expected to begin in 2026
- NASA conducted a survey test in Nashville, TN, in Autumn 2023 (Rathsam 2024)

**If X-59 has not yet made its first flight, how could NASA conduct pilot studies?**

# Waveforms and Sonic Boom Perception and Response (WSPR)




- NASA developed inverted dive maneuver (Haering et al., 2006)
- Test details in Page et al. (2014)




110 total boom events at Edwards AFB, CA

- 84 low-boom maneuvers ('sonic thumps')
- 5 NASA-planned 'traditional' sonic booms
- 21 Unplanned booms due to USAF activity

Dose interpolation in 1 sq. mile area

- Estimated dose uncertainty, $\boldsymbol{\widehat{\sigma}_u = 3.7}$ dB

| | Mean Level (PL dB) | Std. Dev (PL dB) |
|---|---|---|
| Planned | 82.8 | 7.8 |
| Adventitious | 97.4 | 9.2 |
| Overall | 85.1 | 9.6 |

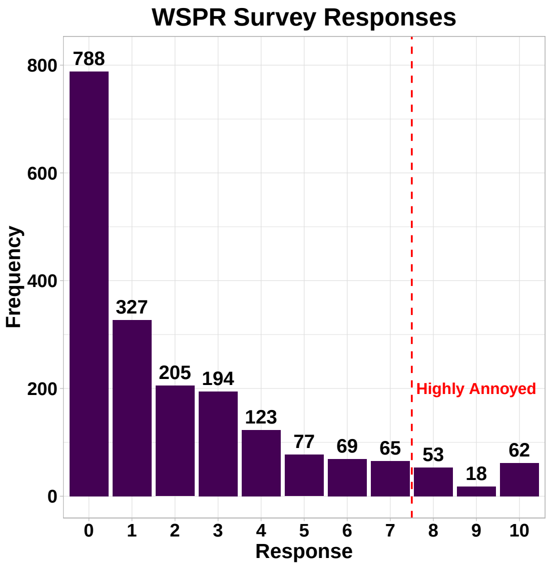
Table: Summary statistics for doses as measured

Small convenient sample at Edwards AFB, CA

- **Prompt single-event survey**
- Daily summary survey
- Experimentation with survey modes

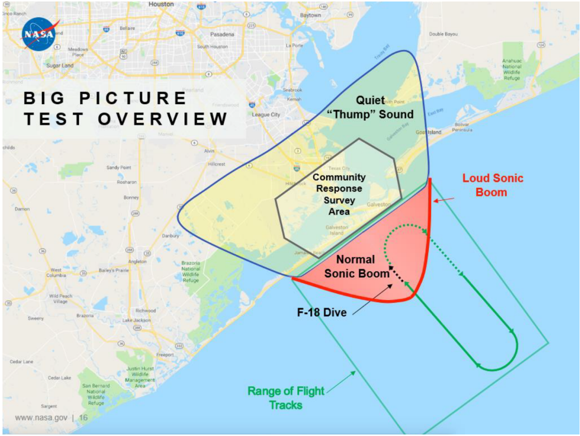
**How much did the sonic boom bother, disturb, or annoy you?**

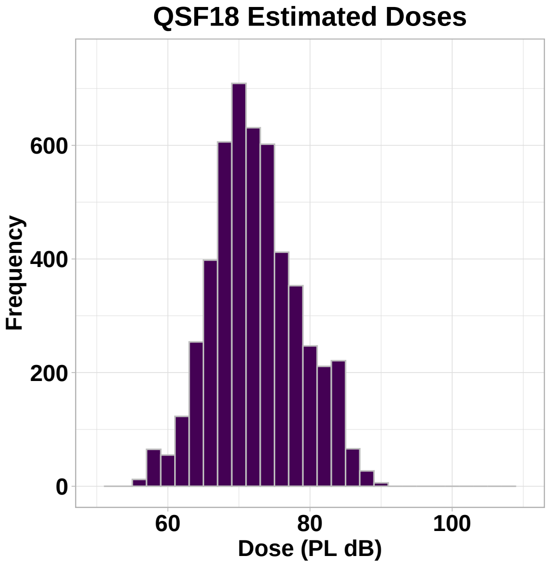
- 11-point scale
- 'Highly Annoyed' dichotomization

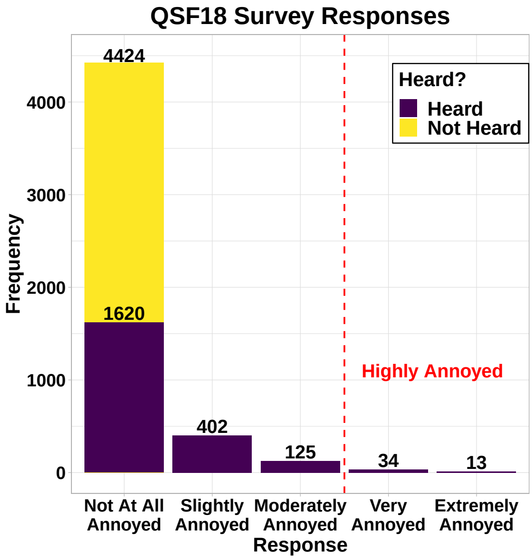


# Quiet Supersonic Flights 2018 (QSF18)

- The Galveston advantage
- Address-based sample capped at 500
- Estimate dose over 60 sq. mile area
- Estimated dose uncertainty, $\widehat{\boldsymbol{\sigma}}_{\boldsymbol{u}} = \mathbf{4.9}$ dB
- Test details in Page et al. (2020a,b)




QSF18 Estimated Doses
Frequency
600
400
200
0
60
80
100
Dose (PL dB)


QSF18 Survey Responses
Frequency
4000
3000
2000
1000
0
4424
1620
402
125
34
13
Heard?
Heard
Not Heard
Highly Annoyed
Not At All Annoyed
Slightly Annoyed
Moderately Annoyed
Very Annoyed
Extremely Annoyed
Response

# Risk Reduction Study Data Summaries and Notation

**Subject-Specific Model**

$$p(x_{ij}, c_i) = logit^{-1}\left(\beta_0 + \beta_1 x_{ij} + c_i\right)$$
$$\phi\left(c_i | \sigma_c\right) \sim N\left(0, \sigma_c\right)$$

$\beta_0$, $\beta_1$, $\sigma_c$ parameters to be estimated

$i \in \{1, \ldots, I\}$ indexes study subject
$j \in \{1, \ldots, J_i\}$ indexes the $j^{th}$ sonic boom

$y_{ij}$ binary indicator of high annoyance

$x_{ij}$ actual dose, Perceived Level (dB)
$w_{ij}$ dose as measured, Perceived Level (dB)
$\widehat{\sigma}_u$ estimated standard deviation

| Study | WSPR | QSF18 |
|---|---|---|
| No. Subjects, $I$ | 49 | 371 |
| No. Supersonic Maneuvers | 110 | 52 |
| Total Responses | 1,981 | 4,998 |
| Total Highly Annoyed, $\sum_i \sum_j y_{ij}$ | 133 | 47 |
| Range of Doses, $w_{ij}$, in PL dB | 63 to 106 | 56 to 90 |
| Deviation, $\hat{\sigma}_u$, in PL dB | 3.7 | 4.9 |

Table: Summary of NASA study data

# Subject-Specific Models, Population Average Models, and $\widehat{d}_{50}$

Subject-specific (conditional) model depends on predicted subject intercepts $\widehat{c}_i$

Policy instrument is population average (marginal) model; see, e.g., (Pavlou et al., 2015; Hedeker et al., 2018; Wakefield, 2013, Sec. 9.13.1)

$$p\left(x\right) = \int_{-\infty}^{\infty} logit^{-1}\left(\widehat{\beta}_0 + \widehat{\beta}_1 x + k\right)\phi\left(k|\widehat{\sigma}_c\right) dk \tag{1}$$

Dose (in dB) that elicits high annoyance from subject $i$ with probability $p$

$$\widehat{d}_p = \left[\log\left(p/(1-p)\right) - \left(\widehat{\beta}_0 + \widehat{c}_i\right)\right]/\widehat{\beta}_1$$

Fact: For $\widehat{c}_i = 0$, $\widehat{d}_{50} = \frac{-\widehat{\beta}_0}{\widehat{\beta}_1}$ is also $50^{th}$ percentile on *marginal* curve

**What happens when we use $w_{ij}$ in lieu of $x_{ij}$ in a dose-response model?**

# Terminology and Literature

Measurement error renders regression estimators *inconsistent*, i.e., $\text{plim}_{n\to\infty} \widehat{\beta}_n \neq \beta$

- Direction and magnitude of bias depends on many things
- Restrict attention to following case
  - *Nondifferential*, i.e., $Y \perp\!\!\!\perp W|X$
  - *Classical*, constant-variance measurement error, i.e., $W = X + U$ for $U \sim N\left(0, \sigma_u^2\right)$
- **Attenuation bias in logistic regression** (Stefanski & Carroll, 1985)

Vast literature on measurement error theory and application

- Books: Fuller (1987), Gustafson (2004), Carroll et al. (2006), Yi et al. (2021)
- Review articles: Keogh et al. (2020), Shaw et al. (2020), Sevilimedu & Yu (2022)
- Acoustics: Doebler et al. (2022), Erciulescu & Opsomer (2023), Horonjeff (2023)

Distinction between *functional* and *structural* methods

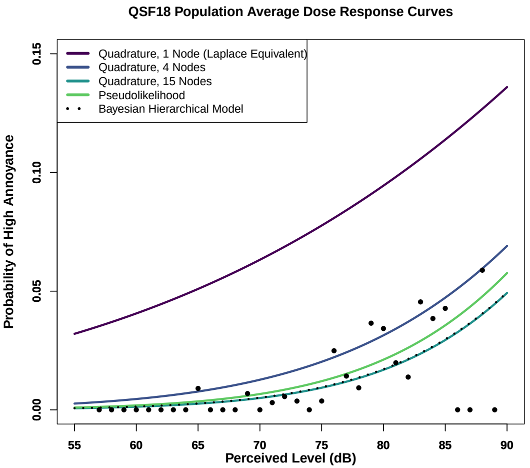
# Biases in Subject-Specific Model Affect Population Average Response

Cruze et al. (2022) examined QSF18 data

- Naive estimators only
- Biases from numerical analysis employed
- Other GLMM examples (Kim et al., 2013)

Use 25-node AGHQ naive estimator

- Repeated use in SIMEX estimator
- Comparison with naive Bayesian models



# Naive Estimators-Maximum Likelihood

| Estimator | $\widehat{\beta}_0$ (SE) | $\widehat{\beta}_1$ (SE) | $\widehat{\sigma}_c$ | $\widehat{d}_{50}$ (dB) |
|---|---|---|---|---|
| **AGHQ** | **-19.29 (1.70)** | **0.154 (0.015)** | **3.34** | **125.3** |
| Laplace | -20.34 (2.20) | 0.155 (0.015) | 3.98 | 131.2 |
| PQL | -18.41 (1.02) | 0.153 (0.010) | 2.68 | 120.3 |

Table: WSPR: Maximum Likelihood Estimates and Standard Errors

| Estimator | $\widehat{\beta}_0$ (SE) | $\widehat{\beta}_1$ (SE) | $\widehat{\sigma}_c$ | $\widehat{d}_{50}$ (dB) |
|---|---|---|---|---|
| **AGHQ** | **-18.67 (2.40)** | **0.151 (0.028)** | **2.49** | **123.6** |
| Laplace | -22.29 (2.65) | 0.158 (0.031) | 7.13 | 141.1 |
| PQL | -18.90 (0.79) | 0.153 (0.010) | 2.72 | 123.5 |

Table: QSF18: Maximum Likelihood Estimates and Standard Errors

# Simulation Extrapolation (SIMEX)

Functional method developed by Cook & Stefanski (1994), expanded by Stefanski & Cook (1995), Carroll et al. (1996) and others; see Sevilimedu & Yu (2022)

Intuition

- Learn impacts of measurement error experimentally (Simulation)
- 'Undo' these effects based on observed pattern (Extrapolation)

Estimating SIMEX standard errors

- Larger than naive standard errors
- Asymptotic sandwich estimators (Carroll et al., 1996)
- **Jackknife estimators** (Stefanski & Cook, 1995; Carroll et al., 2006, Appendix B.4.1)

# Simulation Extrapolation (SIMEX): Simulation

Consider $b = 1, \ldots, B$ remeasurements of $W_{ij}$ for $\lambda \geq 0$

$$W_{b,ij}(\lambda) = W_{ij} + \sqrt{\lambda} U_{b,ij}$$

- $var\left(W_{b,ij}(\lambda) | X_{ij}\right) = (1 + \lambda)\, \sigma_u^2 = (1 + \lambda)\, var\left(W_{ij} | X_{ij}\right)$
- **Key property:** $MSE \equiv E\left[\left\{W_{b,ij}(\lambda) - X_{ij}\right\}^2 | X_{ij}\right] \rightarrow 0$ as $\lambda \rightarrow -1$

$\widehat{\Theta}_b(\lambda)$ denotes naive estimator using remeasured predictors $\left\{W_{b,ij}(\lambda)\right\}_{\forall i,j}$ with average

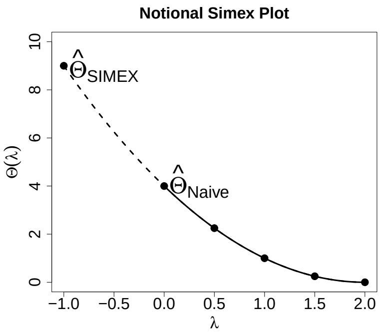
$$\widehat{\Theta}(\lambda) \equiv B^{-1} \sum_{b=1}^{B} \widehat{\Theta}_b(\lambda) \tag{2}$$

$\left\{\boldsymbol{\lambda_m}, \widehat{\boldsymbol{\Theta}}(\boldsymbol{\lambda_m})\right\}_{\boldsymbol{m=1}}^{\boldsymbol{M}}$ **constitute the simulation phase for $\boldsymbol{M}$ levels of $\boldsymbol{\lambda}$ and large $\boldsymbol{B}$**

# Simulation Extrapolation (SIMEX): Extrapolation

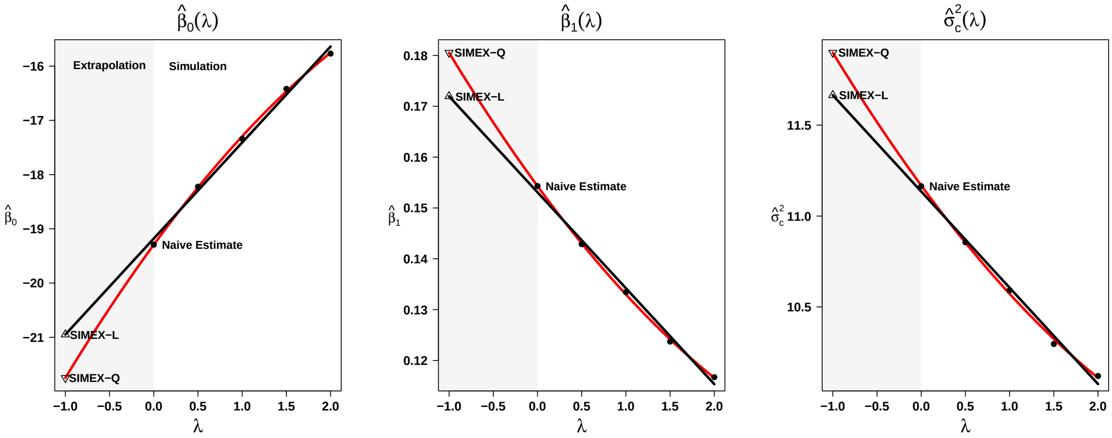
Fit model to averaged, error-contaminated estimates $\widehat{\Theta}(\lambda)$

- $\widehat{\Theta}_{SIMEX} \equiv \widehat{\Theta}(\lambda = -1)$, i.e., extrapolate to $\lambda = -1$
- 'Existence lemmas' of Stefanski & Cook (1995)
- In practice, linear, quadratic, or rational linear forms

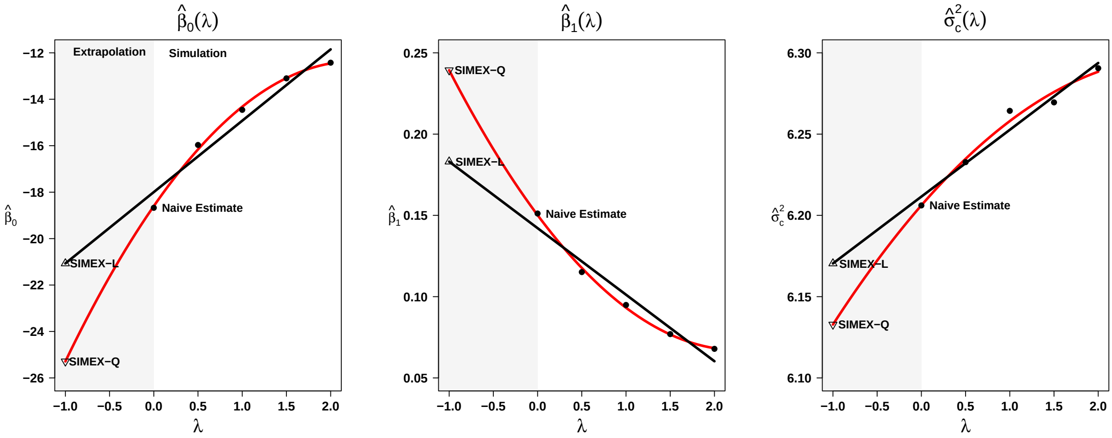



**SIMEX is an approximate method and quadratic extrapolation often works well**

# WSPR–SIMEX with AGHQ Estimator, $\lambda_m \in \{0.5, 1, 1.5, 2\}$, $B = 250$



# QSF18–SIMEX with AGHQ Estimator, $\lambda_m \in \{0.5, 1, 1.5, 2\}$, $B = 250$



# SIMEX Results–Subject-Specific Models

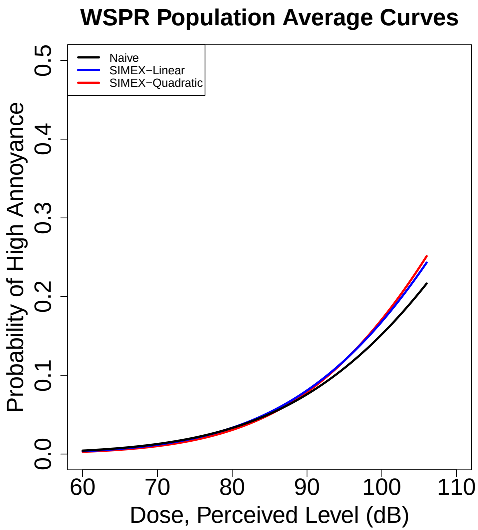
| Estimator | $\widehat{\beta}_0$ (SE) | $\widehat{\beta}_1$ (SE) | $\widehat{\sigma}_c$ | $\widehat{d}_{50}$ (dB) |
|---|---|---|---|---|
| Naive (AGHQ) | -19.29 (1.70) | 0.154 (0.015) | 3.34 | 125.3 |
| SIMEX-L | -20.95 (1.80) | 0.172 (0.016) | 3.42 | 121.8 |
| **SIMEX-Q** | **-21.75 (1.86)** | **0.181 (0.017)** | **3.45** | **120.2** |

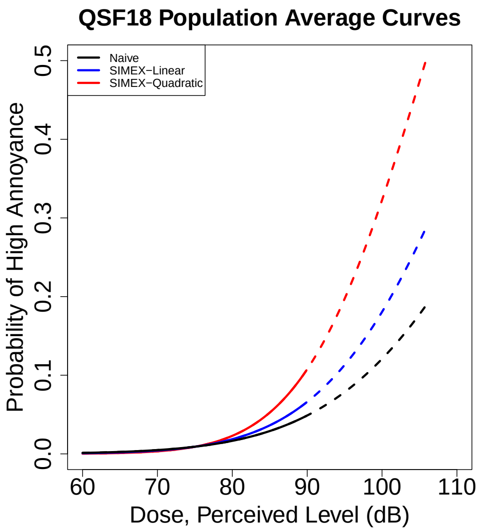
Table: Naive and SIMEX estimates from WSPR study

| Estimator | $\widehat{\beta}_0$ (SE) | $\widehat{\beta}_1$ (SE) | $\widehat{\sigma}_c$ | $\widehat{d}_{50}$ (dB) |
|---|---|---|---|---|
| Naive (AGHQ) | -18.67 (2.40) | 0.151 (0.028) | 2.49 | 123.6 |
| SIMEX-L | -21.07 (2.63) | 0.183 (0.031) | 2.48 | 115.1 |
| **SIMEX-Q** | **-25.29 (3.02)** | **0.239 (0.037)** | **2.48** | **105.8** |

Table: Naive and SIMEX estimates from QSF18 study

# SIMEX Results–Population Average Dose-Response Curves



# Naive Estimators–Bayesian Hierarchical Models

Bayesian methods treat parameters as random quantities–sampling versus optimization

$$f\left(\beta_0, \beta_1, \sigma_c \middle| \boldsymbol{w}, \boldsymbol{y}\right) \propto$$

$$\prod_{i=1}^{I} \prod_{j=1}^{J_i} p\left(w_{ij}, c_i\right)^{y_{ij}} \left[1 - p\left(w_{ij}, c_i\right)\right]^{1-y_{ij}} \phi\left(c_i \middle| \sigma_c\right) \tag{3}$$

$$\times f\left(\beta_0\right) f\left(\beta_1\right) f\left(\sigma_c\right) \tag{4}$$

Early NASA efforts–normal, inverse-gamma priors in naive models (Lee et al., 2019, 2020)

Discussion on selection of priors for mixed models (Browne & Draper, 2006; Gelman, 2006; Gelman et al., 2008; Polson & Scott, 2012)

# Naive Estimators–Bayesian Hierarchical Models

Following Gelman et al. (2008) and Polson & Scott (2012) choose Cauchy priors:

$$\beta_0 \sim t(0, 10, 1),\ \beta_1 \sim t(0, 2.5, 1),\ \sigma_c \sim t^+(0, 1, 1)$$

Practical computing: R and JAGS; 4 chains, length 30,000 iterates; 10,000 posterior samples

| Data | Estimator | $\widehat{\beta}_0$ (SD) | $\widehat{\beta}_1$ (SD) | $\widehat{\sigma}_c$ (SD) | $\widehat{d}_{50}$ (dB) |
|---|---|---|---|---|---|
| **WSPR** | **Bayes** | **-19.22 (1.69)** | **0.154 (0.015)** | **3.43 (0.72)** | **125.0** |
| WSPR | AGHQ | -19.29 (1.70) | 0.154 (0.015) | 3.34 (—) | 125.3 |
| **QSF18** | **Bayes** | **-18.62 (2.40)** | **0.150 (0.029)** | **2.50 (0.50)** | **124.1** |
| QSF18 | AGHQ | -18.67 (2.40) | 0.151 (0.028) | 2.49 (—) | 123.6 |

Table: Posterior means and standard deviations compared to naive AGHQ estimates

# Structural Bayesian Hierarchical Measurement Error Models

A 'recipe' (Gustafson, 2004): outcome, measurement, exposure models and priors

$$
\begin{aligned}
& f\left(\boldsymbol{x}, \beta_0, \beta_1, \sigma_c \middle| \boldsymbol{w}, \boldsymbol{y}\right) \propto \\
& \quad \prod_{i=1}^{I} \prod_{j=1}^{J_i} p\left(x_{ij}, c_i\right)^{y_{ij}} \left[1 - p\left(x_{ij}, c_i\right)\right]^{1-y_{ij}} \phi\left(c_i \middle| \sigma_c\right) && (5) \\
& \quad \times f\left(w_{ij} \middle| x_{ij}\right) && (6) \\
& \quad \times f\left(x_{ij}\right) && (7) \\
& \quad \times f\left(\beta_0\right) f\left(\beta_1\right) f\left(\sigma_c\right) && (8)
\end{aligned}
$$

- Retain classical measurement error model: $w_{ij} | x_{ij} \sim N(x_{ij}, \widehat{\sigma}_u)$
- Retain Cauchy priors: $\beta_0 \sim t(0, 10, 1)$, $\beta_1 \sim t(0, 2.5, 1)$, $\sigma_c \sim t^+(0, 1, 1)$
- Structural: distributional assumption about exposure model $f\left(x_{ij}\right)$
- See also: Richardson & Gilks (1993), Carroll et al. (1997), Richardson & Leblond (1997)

# Specifying the Exposure Model

1. NASA controls noise stimulus
   - Record of study design, e.g., test ‘thump’ versus ‘boom’ in WSPR (Page et al., 2014)
   - Target levels as possible mode(s) (Page et al., 2020a, Tables 4-2, 4-3)
2. NASA subject matter expertise (Doebler et al., 2023; Doebler & Rathsam, 2019, p. 4)
   - Geographic differences in mean and spread
   - Sonic boom 105 PL dB versus X-59 design target 75 PL dB
   - “...distant thunder sone spectrum matches the X-59’s sone spectrum quite well...”

Literature on prior elicitation may be useful for structural methods (Johnson et al., 2010)

# WSPR–Bayesian Subject-Specific Models

| Exposure Model, $f(x_{ij})$ | $\widehat{\beta_0}$ (SD) | $\widehat{\beta_1}$ (SD) | $\widehat{\sigma}_c$ (SD) | $\widehat{d_{50}}$ (dB) |
|---|---|---|---|---|
| Naive (Bayes) | -19.22 (1.69) | 0.154 (0.015) | 3.43 (0.72) | 125.0 |
| $Uniform(-100, 200)^2$ | -20.33 (2.02) | 0.162 (0.018) | 3.64 (0.79) | 125.5 |
| $\frac{84}{110} t_1 + \frac{26}{110} t_2$ | -20.75 (2.01) | 0.167 (0.018) | 3.67 (0.79) | 124.3 |
| $\frac{84}{110} N_1 + \frac{26}{110} N_2$ | -21.87 (2.14) | 0.180 (0.019) | 3.65 (0.79) | 121.5 |
| $t(\mu = 85, \sigma = 10, \nu = 4)$ | -21.93 (2.15) | 0.180 (0.019) | 3.69 (0.79) | 121.8 |

Table: Posterior means and standard deviations from WSPR study; $t1 = t(\mu = 83, \sigma = 7, \nu = 4)$ and $t2 = t(\mu = 105, \sigma = 6, \nu = 4)$; $N_1 = N(\mu_1 = 83, \sigma_1 = 8)$ and $N_2 = N(\mu_2 = 97, \sigma_2 = 9)$

[2] Assumed by Doebler et al. (2022)

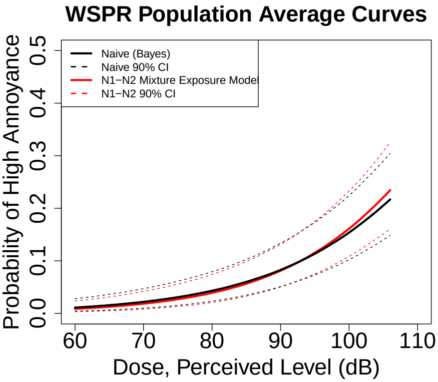
# QSF18–Bayesian Subject-Specific Models

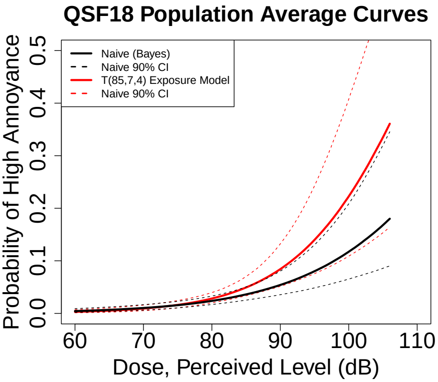
| Exposure Model, $f(x_{ij})$ | $\widehat{\beta}_0$ (SD) | $\widehat{\beta}_1$ (SD) | $\widehat{\sigma}_c$ (SD) | $\widehat{d}_{50}$ (dB) |
|---|---|---|---|---|
| Naive (Bayes) | -18.62 (2.40) | 0.150 (0.029) | 2.50 (0.50) | 124.1 |
| $Uniform(-100, 200)$[3] | -20.34 (3.00) | 0.165 (0.034) | 2.69 (0.54) | 123.3 |
| $Triangular(35, 70, 105)$ | -21.53 (3.35) | 0.181 (0.038) | 2.73 (0.58) | 119.0 |
| $N(\mu = 70, \sigma = 12)$[4] | -22.29 (3.54) | 0.193 (0.041) | 2.65 (0.55) | 115.5 |
| $t(\mu = 70, \sigma = 7, \nu = 4)$ | -24.07 (4.07) | 0.217 (0.047) | 2.76 (0.59) | 110.9 |
| $Triangular(50, 70, 90)$ | -25.64 (4.54) | 0.237 (0.053) | 2.73 (0.59) | 108.2 |

Table: Posterior means and standard deviations from QSF18 study

[3] Assumed by Doebler et al. (2022)
[4] Similar to Erciulescu & Opsomer (2023)

# Bayesian Population Average Curves



# Conclusion: Measurement Error Methods Counteract Bias

WSPR versus QSF18

- Modest changes in WSPR data (3-4% reduction in $\widehat{d}_{50}$)
- Remarkable changes in QSF18 data (up to 15% reduction in $\widehat{d}_{50}$)

Functional versus structural methods

- The world has not heard shaped sonic boom before–no gold standard data
- SIMEX used experimentation and pattern to 'undo' biases
- Structural Bayesian hierarchical models embody knowledge in the exposure model
- Noted sensitivity to specification of exposure model

On potential measurement error during Quesst campaigns with X-59

**This work is funded by the NASA Commercial Supersonic Technology Project**

**Community Test Planning and Execution Survey Team**
Engineers: Jonathan Rathsam (technical lead), Matthew Boucher, Will Doebler, Aaron Vaughn
Statisticians: Pete Parker, Kate Ballard, Nathan Cruze

QUESST

https://www.nasa.gov/mission/quesst/

# References I


Borsky, P. N. (1965). Community Reactions to Sonic Booms in the Oklahoma City Area. Technical report, National Opinion Research Center. Accession Number: AD0613620. https://apps.dtic.mil/sti/citations/AD0613620

Browne, W. J. & Draper, D. (2006). A Comparison of Bayesian and Likelihood-Based Methods for Fitting Multilevel Models. *Bayesian Analysis*, 1(3), 473 – 514. https://doi.org/10.1214/06-BA117

Carroll, R., Ruppert, D., Stefanski, L., & Crainiceanu, C. (2006). *Measurement Error in Nonlinear Models: A Modern Perspective* (2nd ed.). Chapman and Hall/CRC. https://doi.org/10.1201/9781420010138

Carroll, R. J., Küchenhoff, H., Lombard, F., & Stefanski, L. A. (1996). Asymptotics for the SIMEX Estimator in Nonlinear Measurement Error Models. *Journal of the American Statistical Association*, 91(433), 242–250. http://www.jstor.org/stable/2291401

Carroll, R. J., Lin, X., & Wang, N. (1997). Generalized linear mixed measurement error models. *Modelling Longitudinal and Spatially Correlated Data*, 321–330. https://doi.org/10.1007/978-1-4612-0699-6_28

Cook, J. R. & Stefanski, L. A. (1994). Simulation-extrapolation estimation in parametric measurement error models. *Journal of the American Statistical Association*, 89(428), 1314–1328. https://doi.org/10.1080/01621459.1994.10476871

Cruze, N. B., Ballard, K. M., Vaughn, A. B., Doebler, W. J., Rathsam, J., & Parker, P. A. (2022). Comparison of Likelihood Methods for Generalized Linear Mixed Models with Application to Quiet Supersonic Flights 2018 Data. Technical Memorandum, NASA Langley Research Center. NASA/TM–20220014998. https://ntrs.nasa.gov/citations/20220014998

# References II


Doebler, W. J. & Rathsam, J. (2019). How Loud is X-59's Shaped Sonic Boom? *Proceedings of Meetings on Acoustics*, volume 36. https://doi.org/10.1121/2.0001265

Doebler, W. J., Vaughn, A. B., , Ballard, K. M., & Rathsam, J. (2022). Simulation and Application of Bayesian Dose Uncertainty Modeling for Low-Boom Community Noise Surveys. *Proceedings of Meetings on Acoustics*, volume 45. https://doi.org/10.1121/2.0001592

Doebler, W. J., Wilson, S. R., Loubeau, A., & Sparrow, V. W. (2023). Simulation and Regression Modeling of NASA's X-59 Low-Boom Carpets Across America. *Journal of Aircraft*, 60(2), 509–520. https://doi.org/10.2514/1.C036876

Erciulescu, A. & Opsomer, J. (2023). Accounting for Dose Uncertainty in Dose-Response Curve Estimation Uning Hierarchical Bayes Models. *2023 Joint Statistical Meetings*. [Conference Presentation]. https://ntrs.nasa.gov/citations/20230007198

Fuller, W. (1987). *Measurement Error Models*. John Wiley and Sons, Inc. https://doi.org/10.1002/9780470316665

Gelman, A. (2006). Prior Distributions for Variance Parameters in Hierarchical Models (comment on article by Browne and Draper). *Bayesian Analysis*, 1(3), 515 – 534. https://doi.org/10.1214/06-BA117A

Gelman, A., Jakulin, A., Pittau, M. G., & Su, Y.-S. (2008). A Weakly Informative Default Prior Distribution for Logistic and Other Regression Models. *The Annals of Applied Statistics*, 2(4), 1360 – 1383. https://doi.org/10.1214/08-AOAS191

# References III


Gustafson, P. (2004). *Measurement Error and Misclassification in Statistics and Epidemiology: Impacts and Bayesian Adjustments*. Chapman & Hall/CRC. https://doi.org/10.1201/9780203502761

Haering, E. A., Smolka, J. W., Murray, J. E., & Plotkin, K. J. (2006). Flight Demonstration Of Low Overpressure N-Wave Sonic Booms And Evanescent Waves. *AIP Conference Proceedings*, 838(1), 647–650. https://doi.org/10.1063/1.2210436

Hedeker, D., du Toit, S. H. C., Demirtas, H., & Gibbons, R. D. (2018). A Note on Marginalization of Regression Parameters from Mixed Models of Binary Outcomes. *Biometrics*, 74(1), 354–361. https://doi.org/10.1111/biom.12707

Horonjeff, R. D. (2023). Correcting for bias effects due to exposure uncertainty in community noise exposure-response analyses. *The Journal of the Acoustical Society of America*, 154(3), 1614–1627. https://doi.org/10.1121/10.0020545

Johnson, S. R., Tomlinson, G. A., Hawker, G. A., Granton, J. T., & Feldman, B. M. (2010). Methods to Elicit Beliefs for Bayesian Priors: A Systematic Review. *Journal of Clinical Epidemiology*, 63(4), 355–369. https://doi.org/https://doi.org/10.1016/j.jclinepi.2009.06.003

Keogh, R. H., Shaw, P. A., Gustafson, P., Carroll, R. J., Deffner, V., Dodd, K. W., Küchenhoff, H., Tooze, J. A., Wallace, M. P., Kipnis, V., & Freedman, L. S. (2020). STRATOS Guidance Document on Measurement Error and Misclassification of Variables in Observational Epidemiology: Part 1—Basic Theory and Simple Methods of Adjustment. *Statistics in Medicine*, 39(16), 2197–2231. https://doi.org/10.1002/sim.8532

# References IV


Kim, Y., Choi, Y.-K., & Emery, S. (2013). Logistic regression with multiple random effects: A simulation study of estimation methods and statistical packages. *The American Statistician*, 67(3), 171–182. https://doi.org/10.1080/00031305.2013.817357

Kryter, K. D., Johnson, P. J., & Young, J. R. (1968). Pyschological Experiments on Sonic Booms Conducted at Edwards Air Force Base. Research Report, Stanford Research Institute, Menlo Park, CA. Final Report, AD689844.

Lee, J., Rathsam, J., & Wilson, A. (2019). Statistical Modeling of Quiet Sonic Boom Community Response Survey Data. Technical Memorandum. NASA/TM-2019-220427. https://ntrs.nasa.gov/citations/20190033466

Lee, J., Rathsam, J., & Wilson, A. (2020). Bayesian Statistical Models for Community Annoyance Survey Data. *The Journal of the Acoustical Society of America*, 147(4), 2222–2234. https://doi.org/10.1121/10.0001021

Maglieri, D. J., Bobbitt, P. J., Plotkin, K. J., Shepherd, K. P., Coen, P. G., & Richwine, D. M. (2014). *Sonic Boom: Six Decades of Research*. NASA Langley Research Center. https://ntrs.nasa.gov/citations/20150006843

Page, J. A., Hodgdon, K. K., Hunte, R. P., Davis, D. E., Gaugler, T., Downs, R., Cowart, R. A., Maglieri, D. J., Hobbs, C., Baker, G., Collmar, M., Bradley, K. A., Sonak, B., Crom, D., & Cutler, C. (2020a). Quiet Supersonic Flights 2018 (QSF18) Test: Galveston, Texas Risk Reduction for Future Community Testing with a Low-Boom Flight Demonstration Vehicle. Contractor Report, NASA Langley Research Center. NASA/CR-2020-220589/Volume I. https://ntrs.nasa.gov/citations/20200003223

# References V

Page, J. A., Hodgdon, K. K., Hunte, R. P., Davis, D. E., Gaugler, T., Downs, R., Cowart, R. A., Maglieri, D. J., Hobbs, C., Baker, G., Collmar, M., Bradley, K. A., Sonak, B., Crom, D., & Cutler, C. (2020b). Quiet Supersonic Flights 2018 (QSF18) Test: Galveston, Texas Risk Reduction for Future Community Testing with a Low-Boom Flight Demonstration Vehicle. Contractor Report, NASA Langley Research Center. NASA/CR-2020-220589/Appendices/Volume II. https://ntrs.nasa.gov/citations/20200003224

Page, J. A., Hodgdon, K. K., Krecker, P., Cowart, R., Hobbs, C., Wilmer, C., Koening, C., Holmes, T., Gaugler, T., Shumway, D. L., Rosenberger, J. L., & Philips, D. (2014). Waveforms and Sonic Boom Perception and Response (WSPR): Low-Boom Community Response Program Pilot Test Design, Execution, and Analysis. Contractor Report, NASA Langley Research Center. NASA/CR-2014-218180. https://ntrs.nasa.gov/citations/20140002785

Pavlou, M., Ambler, G., Seaman, S., & Omar, R. Z. (2015). A Note on Obtaining Correct Marginal Predictions from a Random Intercepts Model for Binary Outcomes. *BMC Medical Research Methodology*, 15(59). https://doi.org/10.1186/s12874-015-0046-6

Polson, N. G. & Scott, J. G. (2012). On the Half-Cauchy Prior for a Global Scale Parameter. *Bayesian Analysis*, 7(4), 887 – 902. https://doi.org/10.1214/12-BA730

Rathsam, J., Coen, P., Loubeau, A., Ozoroski, L., & Shah, G. (2023). Scope and Goals of NASA's Quesst Community Test Campaign with the X-59 Aircraft. *Proceedings of the Fourteenth ICBEN Congress on Noise as a Public Health Problem*. https://ntrs.nasa.gov/citations/20230004142

# References VI


Richardson, S. & Gilks, W. R. (1993). Conditional Independence Models for Epidemiological Studies with Covariate Measurement Error. *Statistics in Medicine*, 12(18), 1703–1722. https://doi.org/https://doi.org/10.1002/sim.4780121806

Richardson, S. & Leblond, L. (1997). Some comments on misspecification of priors in bayesian modelling of measurement error problems. *Statistics in Medicine*, 16(2), 203–213. https://doi.org/10.1002/(SICI)1097-0258(19970130)16:2<203::AID-SIM480>3.0.CO;2-T

Sevilimedu, V. & Yu, L. (2022). Simulation extrapolation method for measurement error: A review. *Statistical Methods in Medical Research*, 31(8), 1617–1636. PMID: 35607297. https://doi.org/10.1177/09622802221102619

Shaw, P. A., Gustafson, P., Carroll, R. J., Deffner, V., Dodd, K. W., Keogh, R. H., Kipnis, V., Tooze, J. A., Wallace, M. P., Küchenhoff, H., & Freedman, L. S. (2020). STRATOS Guidance Document on Measurement Error and Misclassification of Variables in Observational Epidemiology: Part 2—More Complex Methods of Adjustment and Advanced Topics. *Statistics in Medicine*, 39(16), 2232–2263. https://doi.org/10.1002/sim.8531

Stefanski, L. A. & Carroll, R. J. (1985). Covariate Measurement Error in Logistic Regression. *The Annals of Statistics*, 13(4), 1335 – 1351. https://doi.org/10.1214/aos/1176349741

Stefanski, L. A. & Cook, J. R. (1995). Simulation-Extrapolation: The Measurement Error Jackknife. *Journal of the American Statistical Association*, 90(432), 1247–1256. http://www.jstor.org/stable/2291515

Sun, Y. & Smith, H. (2022). Conceptual Design of Sonic Boom Stealth Supersonic Transports. *CEAS Aeronautical Journal*, 13, 419–432. https://doi.org/10.1007/s13272-021-00567-x

# References VII

Wakefield, J. (2013). *Bayesian and Frequentist Regression Methods*. Springer Series in Statistics. Springer. https://link.springer.com/book/10.1007/978-1-4419-0925-1

Yi, G. Y., Delaigle, A., & Gustafson, P., editors (2021). *Handbook of Measurement Error Models*. Handbooks of Modern Statistical Methods. Chapman and Hall/CRC. https://doi.org/10.1201/9781315101279