Review of Noise Metric Sensitivities for Analysis of Quiet Supersonic Overflight

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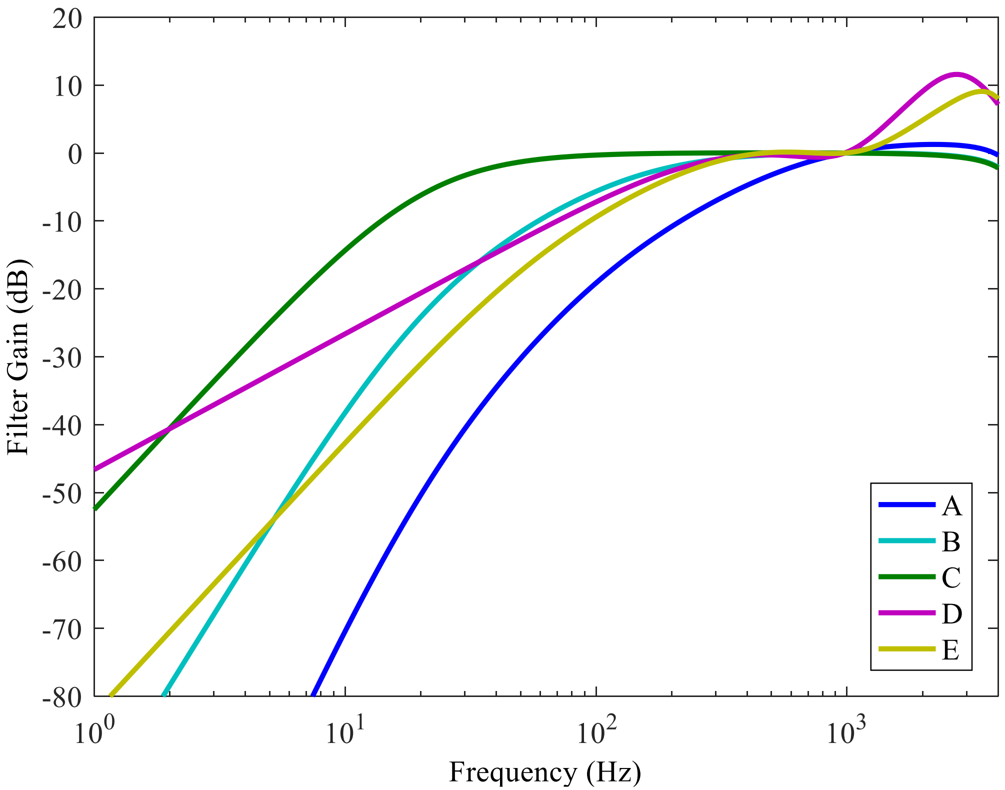
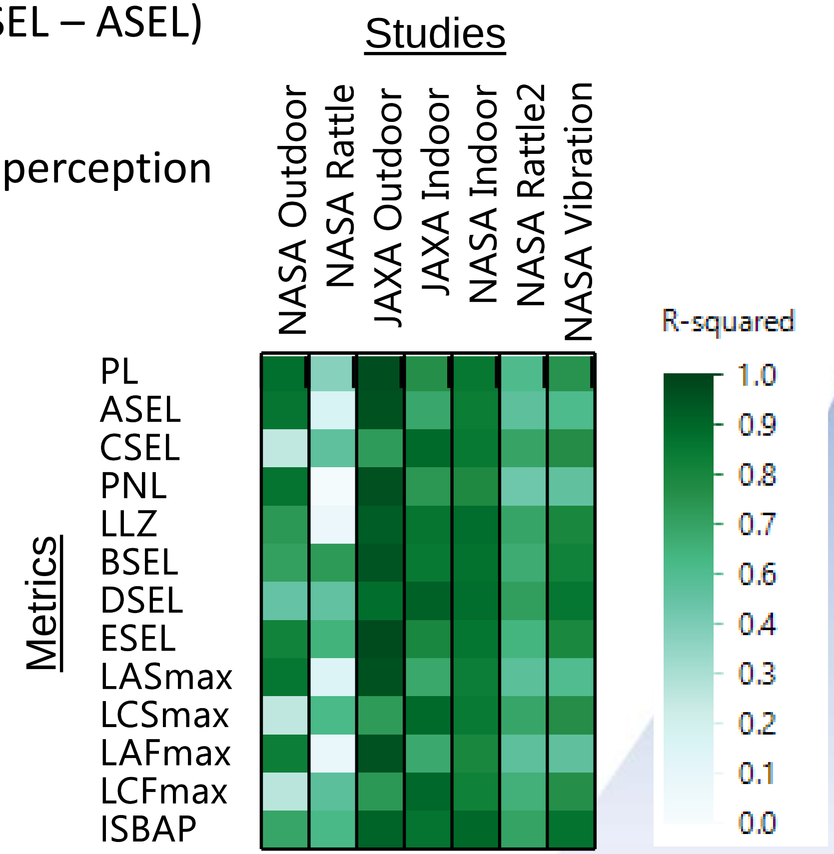
Introduction

- **NASA goal to enable development of noise-based standard for commercial supersonic aircraft**
- **Two regulatory issues for civil supersonic flight**
  - Limiting airport noise during subsonic flight
  - Limiting sonic boom noise during en route supersonic flight
- **Development of international standard**
  - Noise-based certification standard for supersonic en route (sonic boom) noise
  - Certification standard would include noise metric, test procedures, and noise limits
- **Required characteristics of noise metric**
  - Easy to implement and well-defined
  - Predict human perception of sonic booms experienced both outdoors and indoors
  - Robust to apply in real-world situations

Sonic Boom Noise Metrics: Human Perception

- **Six noise metrics identified in previous work[1,2]**
  - ASEL, BSEL, DSEL, ESEL, PL, ISBAP
    - Indoor Sonic Boom Annoyance Predictor = ISBAP = PL + 0.4201 (CSEL – ASEL)
  - No clearly preferred metric
    - PL has been used often because of good correlation with outdoor perception



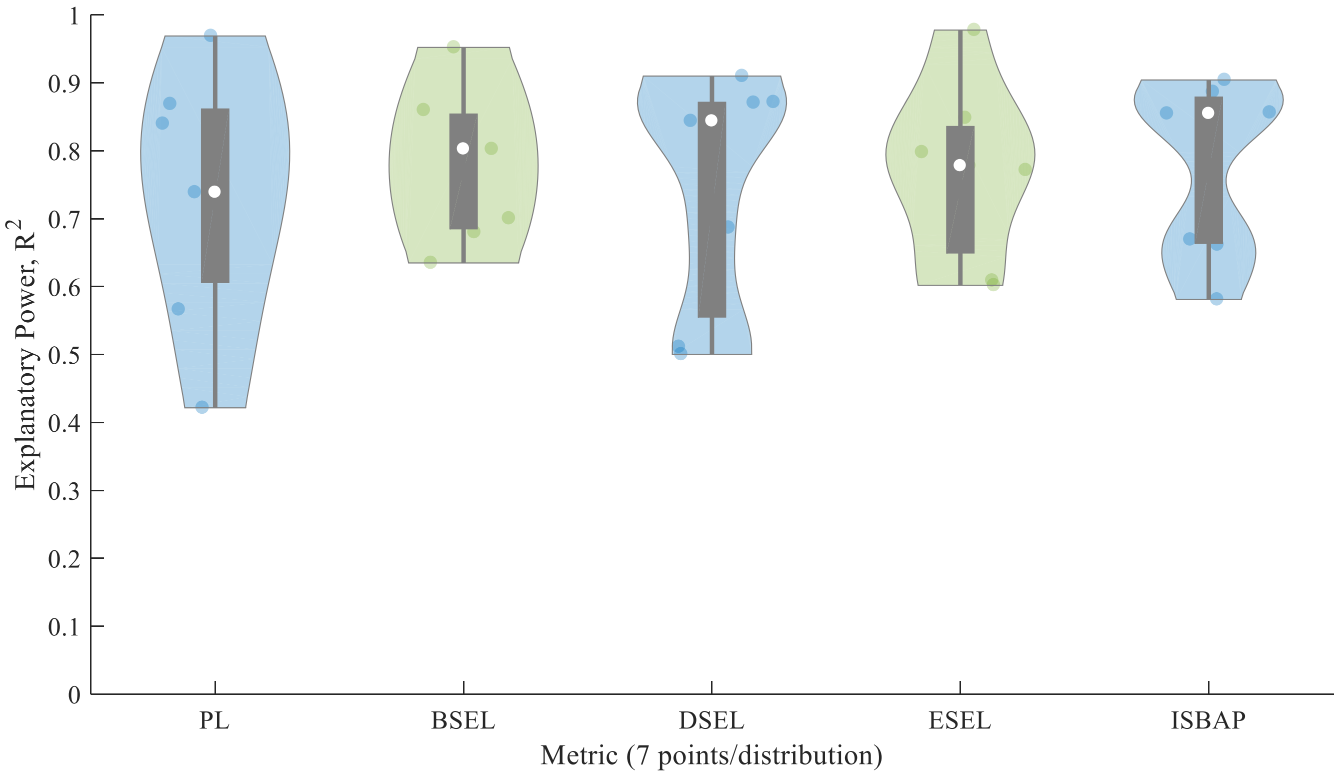


Graphical representation of R^2 values for each experiment

[1]ANSI 2020
[2]Loubeau 2018

Sonic Boom Noise Metrics: Human Perception

- **Meta-analysis**
  - Comprehensive evaluation of metrics
  - Several years of laboratory testing data (7 tests) at NASA and JAXA
- **Five metrics correlate well with human response outdoors and indoors[2]**
  - Sixth metric (ASEL) retained for historical reasons



[2]Loubeau 2018

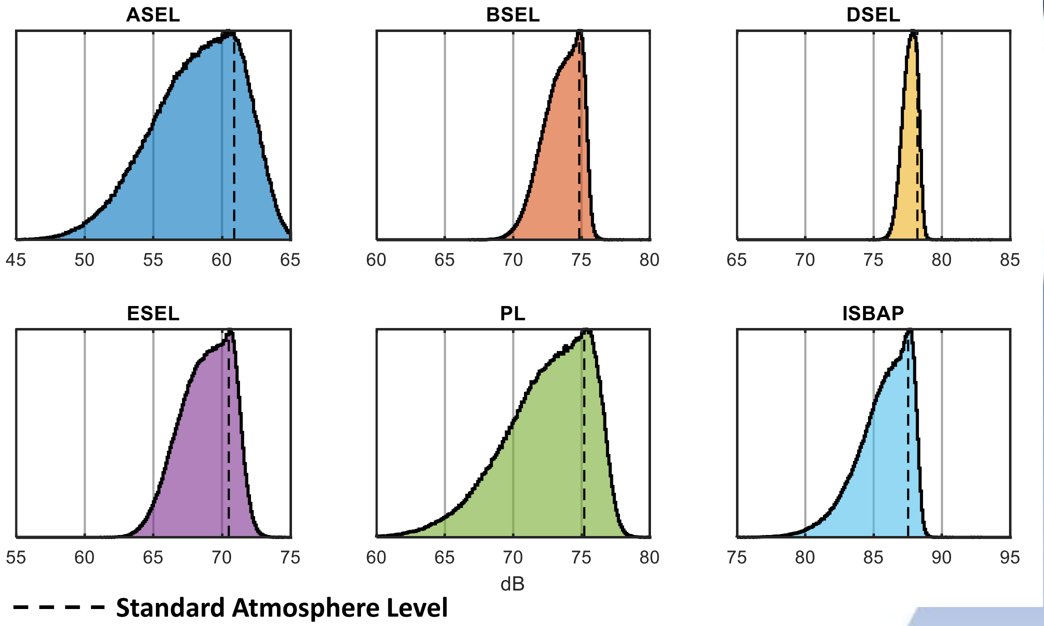
Sonic Boom Noise Metrics: Robustness

- **Meta-analysis did not identify a single metric that was significantly superior**
  - No internationally agreed-upon metric has been chosen for the quiet supersonic aircraft noise certification procedures currently under development
  - Current analyses apply all six metrics
- **Analyses of metric sensitivities using existing empirical and simulation datasets have shown significant differences between metrics**
- **Sources of metric variability**
  - Macro-atmospheric effects
  - Atmospheric turbulence
  - Microphone setup configurations
  - Ambient noise

Macro-atmospheric Effects

- **Simulation study of NASA X-59 sonic thumps across the U.S.**[3]
  - 138 locations, 5 years, 4 headings
  - DSEL has narrowest distribution
  - ASEL and PL distributions are widest
- **Simulation study of shaped booms across the world**[4]
  - 666 locations, 1 year
  - Confirms trends using different aircraft and locations
  - PL SD is 12 dB and ISBAP SD is 8 dB
- **Comparison to different standard atmospheres**
  - BSEL and DSEL show smallest differences between worldwide calculations and those with different humidity models
  - PL and ASEL have more significant differences

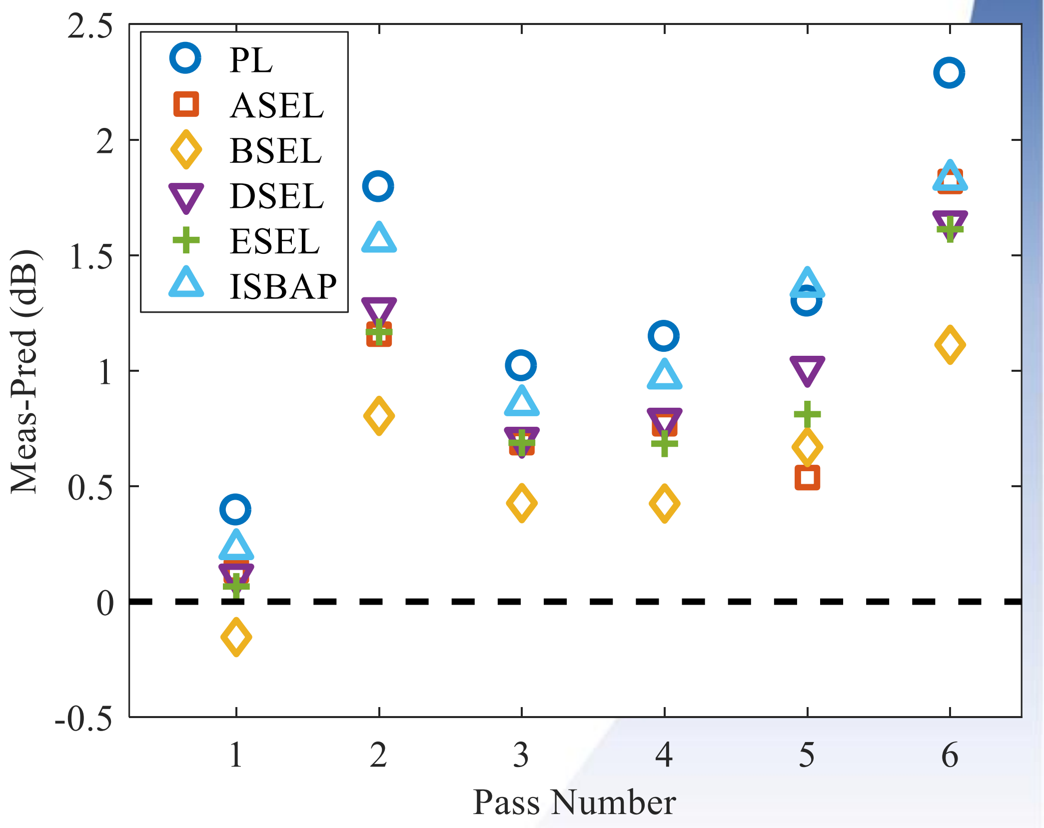
X-59 Undertrack Metrics Across U.S.



[3]Doebler 2020, [4]Normand 2020

Atmospheric Turbulence

- **Measurements and simulation of atmospheric turbulence variability effects[5]**
  - N-wave simulations show lower SD for ISBAP than for PL
  - FIR filter approximation vs. full simulations
    - Errors are less for BSEL and highest for ASEL and ESEL
- **Measurements of N-waves with turbulence variations along a mic array[6,8]**
  - BSEL and ISBAP were most “stable” and PL and ASEL were least stable
  - Similar conclusions for set of N-waves and shaped booms with turbulence filters applied[7]
- **Comparisons of predictions and measurements[9]**
  - BSEL differences are smallest and least sensitive to (low) turbulence effects

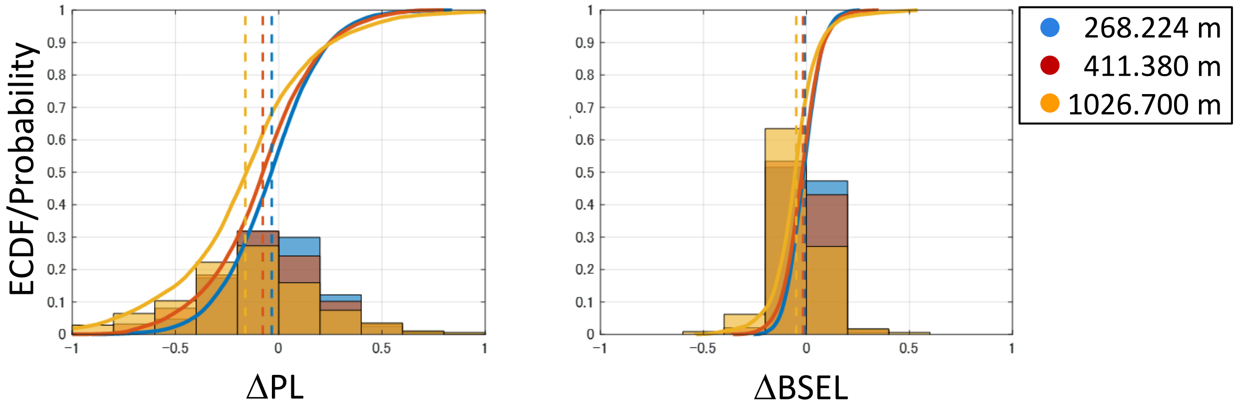


[5]Bradley 2020, [6]Doebler 2017a, [7]Doebler 2017b, [8]Loubeau 2019a, [9]Loubeau 2019b

Atmospheric Turbulence

Simulation datasets of shaped booms through turbulence[10]

- Input signature from NASA X-59 C609 design
- 3 different atmospheric boundary layer heights
- Multiple random realizations for one low/medium turbulence case
- Predictions at 4,000+ simulated microphone locations for each turbulence realization



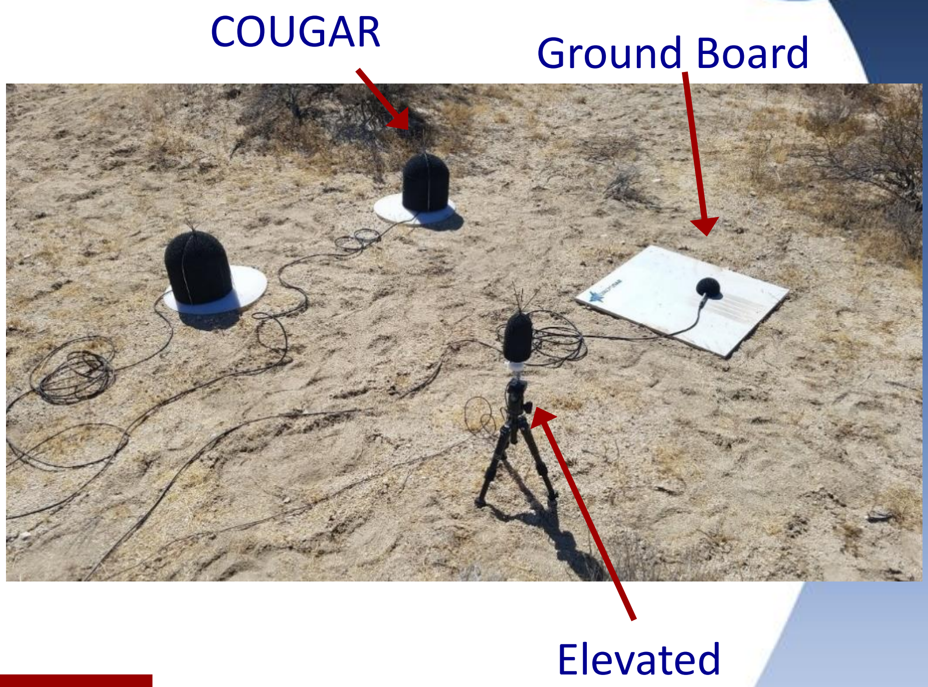
- As expected, some metrics like BSEL have less variability
  - 90% confidence intervals on means are smaller

[10]Loubeau 2021

Microphone Setup Configurations

Effect of elevating microphone above ground[11]

- Microphone elevated 0.5 m above ground
- Largest measured mean differences for ASEL, ESEL, and PL
- Due to dip in spectra of about 8 dB around 500 Hz
- Trends confirmed through modeling[12]



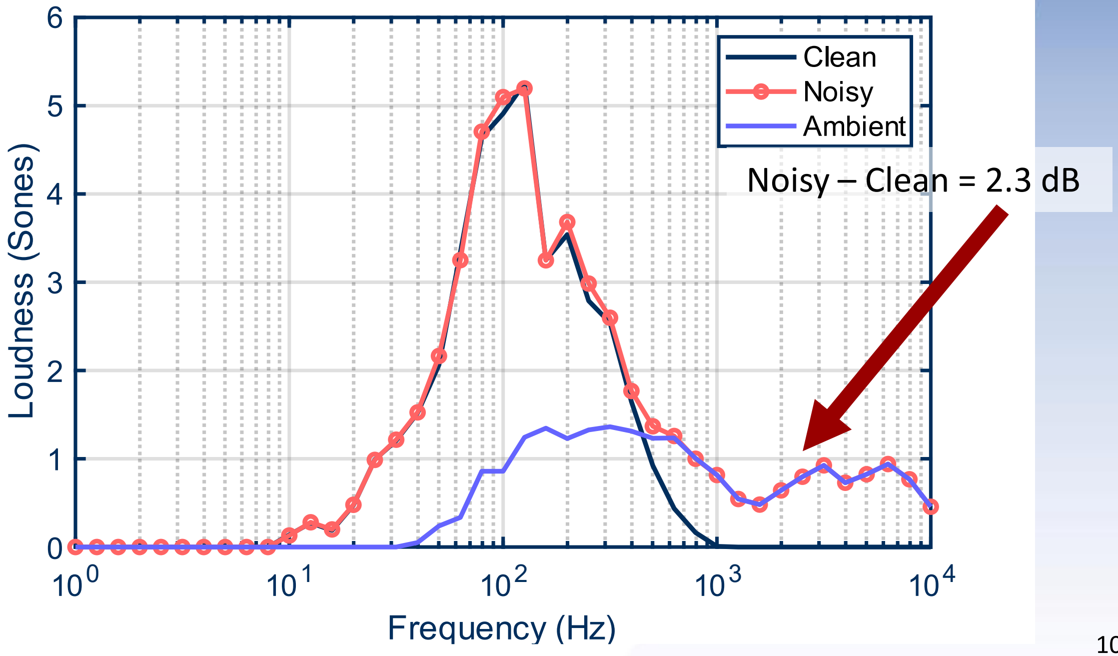
Mean Differences Relative to COUGAR Configuration

	PL	ASEL	BSEL	DSEL	ESEL	ISBAP
COUGAR	-	-	-	-	-	-
Ground-Board	−0.04	−0.2	−0.3	−0.2	−0.2	−0.02
Elevated	−2.1	−3.4	−1.4	−1.3	−2.2	−0.8

[11]Gee 2021, [12]Downs 2021

Ambient Noise

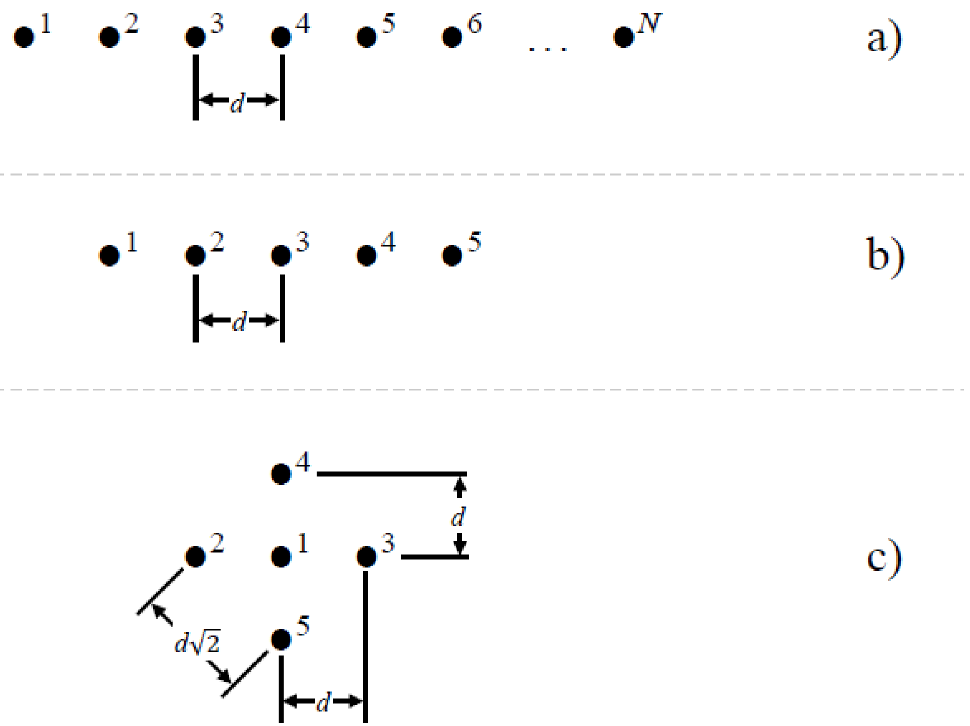
- **Low loudness sonic boom levels may be difficult to recover in field measurements without ambient noise corrections**
- **Simulations of X-59 signatures combined with real measurements of ambient noise**
- **Signal-to-noise ratio is poor above a few hundred Hz**
  - One option is to filter the signal
  - Another option is to correct the loudness levels or spectra in each band according to SNR
- **Metrics affected by signal bandwidth limitations[13]**
  - More uncertainty in final metric result for PL and ASEL than for BSEL



[13]Anderson 2021

Microphone Array Layouts

- **Choice of metric affects recommendations for number of sites and number of grouped monitors at each site for a distributed array across a community**
- **BSEL more consistent across tests and for different array geometries**
  - Less sensitive to differences for the limited datasets



Linear array

Linear array

Cross array

Summary

- **Small group of sonic boom metrics exist that correlate well with human perception**
  - Metrics apply different low-frequency weighting shapes
- **Reviewed prior studies that show differences in metric robustness**
  - Considered atmospheric effects, microphone configurations, and ambient environment
  - Included measurements and simulations for N-waves and shaped low booms
  - Similarity in findings across studies

BSEL and DSEL are most robust
while PL and ASEL are least robust

- **Additional studies are ongoing as analyses continue with the six metrics**
- **Differences in metric robustness could aid in further downselection for certification procedures**

References

1. ANSI/ASA S1.42-2020.
2. Loubeau et al. J. Acoust. Soc. Am., 144: 1706, 2018.
3. Doebler et al. e-Forum Acusticum, 2020.
4. Normand et al. ECCOMAS 2020.
5. Bradley et al. NASA/CR-2020-220509.
6. Doebler & Sparrow. J. Acoust. Soc. Am., 141(5): 3625, 2017.
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8. Loubeau et al. J. Acoust Soc. Am., 146: 2780, 2019.
9. Loubeau & Doebler. J. Acoust Soc. Am., 145: 1899, 2019.
10. Loubeau et al. J. Acoust. Soc. Am. 149(4): A102, 2021.
11. Gee et al. J. Acoust. Soc. Am. 149(4): A102, 2021.
12. Downs et al. J. Acoust. Soc. Am. 149(4): A103, 2021.
13. Anderson et al. J. Acoust. Soc. Am. 149(4): A103, 2021.

Backup Slides

Calculation Steps for Perceived Level (PL)

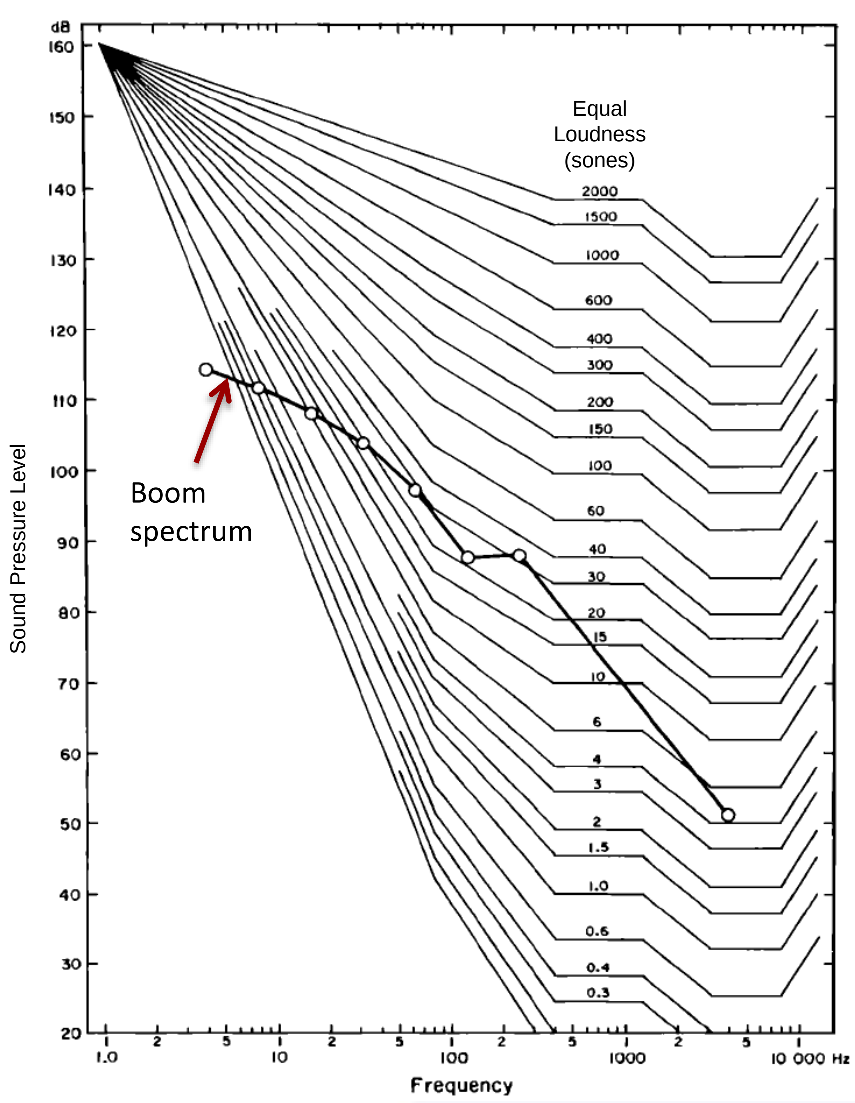
1. **Calculate Sound Pressure Level of signal in 1/3-octave bands**
2. **Apply frequency weighting for loudness of individual bands**
   - where loudness of 1 sone is referenced to 1/3-oct band of noise at 3150 Hz at 32 dB
3. **Apply summation rule for total loudness**

$$S_t = S_m + F(\Sigma S - S_m)$$

where
S_t = total loudness
S_m = loudness of loudest band
ΣS = sum of loudnesses of all the bands
F = fractional factor based on S_m

4. **Convert to PL in dB**

$$PL = 32 + 9\log_2(S_t)$$



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