Development of an Acoustic Impedance Tube Testbed for Material Sample Testing

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Background

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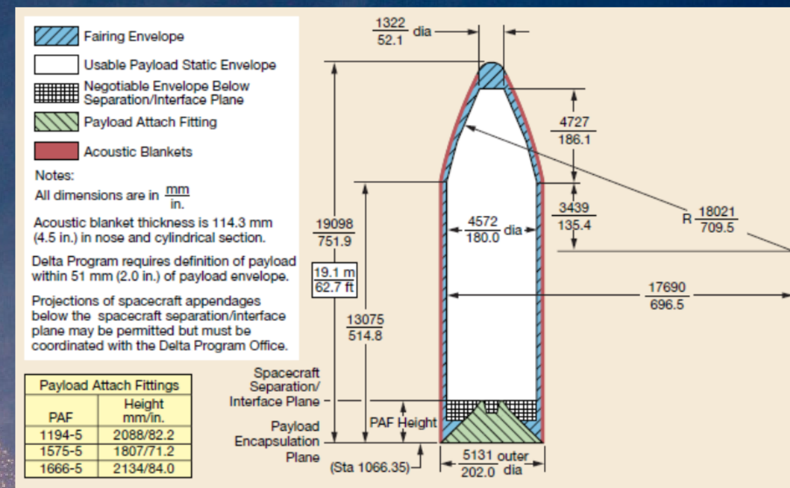
- Launch vehicle acoustics are transmitted through fairing wall and excite payload structure
- High acoustic levels drive design of lightweight, high-surface area structures and mounted components
- Improved acoustic blankets on fairing walls could mitigate fairing acoustic levels



Delta IV Payload Planners Guide, September 2007

Image of Atlas V launch, courtesy United Launch Alliance

Agenda

- Motivation and approach
- Impedance tube theory
  - Acoustic waveguide
  - Normal incidence transmission loss
- Design criteria, goals, and choices
- JPL impedance tube description
- Calibration and sample test data
- Next steps

Motivation

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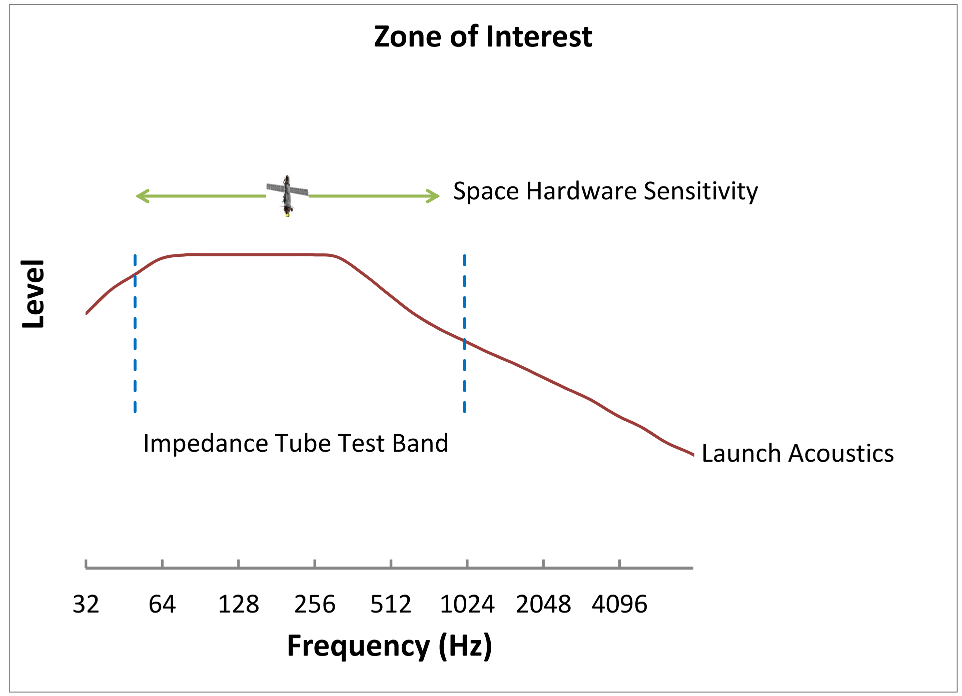
- Motivation:
  - Novel acoustic blanket materials require test method to characterize acoustic properties

- Goals
  - 50 to 1000 Hz measurement frequency band
  - 100+ dB SPL
  - High volume, quick turnaround
  - Easy to use
  - Inexpensive
  - Reliable data



Approach

- Possible acoustic blanket test methods
  - Reverberant chamber testing
    - Build a surrogate fairing, add blanket treatments, measure acoustic field inside and outside fairing
    - Most realistic test method, but also most expensive
  - Transmission loss testing
    - Two chambers are separated by a window where an acoustic panel is mounted, transmission loss through the panel is measured
    - Standard for transmission loss measurements, too expensive for high volume
  - Acoustic impedance tube
    - Traveling wave amplitudes are measured on either side of a sample in a tube. Many acoustic properties of the sample can be calculated.
    - Simple and inexpensive to set up, ideal for high volume optimization tests

Acoustic Waveguide Theory

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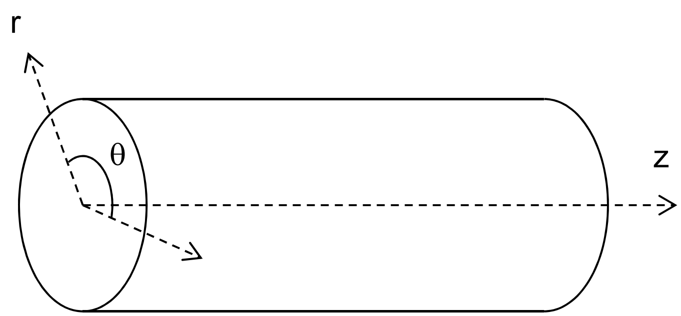
<u>Acoustic pressure in a rigid-walled pipe, diameter *D*:</u>

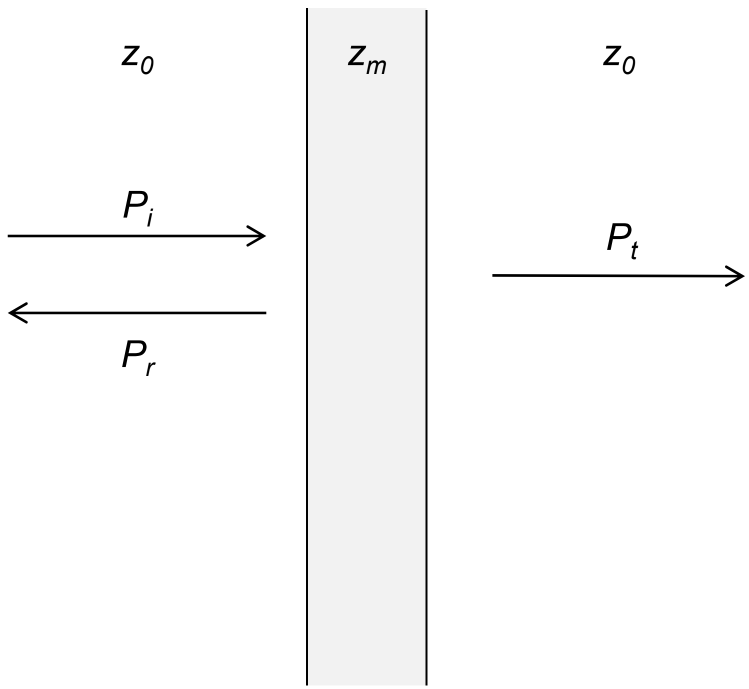
$$p_{nm} = \underbrace{J_m(k_r r)}_{\text{Radial Mode}} \underbrace{(A_{mn}\cos m\theta + B_{mn}\sin m\theta)}_{\text{Angular Modes}} \underbrace{e^{-ik_z z} e^{i\omega t}}_{\text{Axial and Time Dependence}}$$



$$k_r = \frac{2\alpha'_{mn}}{D} \qquad k_z = \sqrt{k^2 - {k_r}^2}$$

- When $k < k_r$, k_z is imaginary and waves decay exponentially.
- *For $\lambda > 1.707D$, only plane waves propagate.*

Normal Incidence Acoustic Properties



$$\text{Transmission Coefficient, } T = \frac{P_t}{P_i}$$

$$\text{Reflection Coefficient, } R = \frac{P_r}{P_i}$$

$$\text{Transmission Loss, } TL = 20 \log_{10} \left| \frac{1}{T} \right|$$

- z_0, z_m are acoustic impedances
- P_i, P_r, P_t are plane wave pressure amplitudes

Impedance Tube Overview

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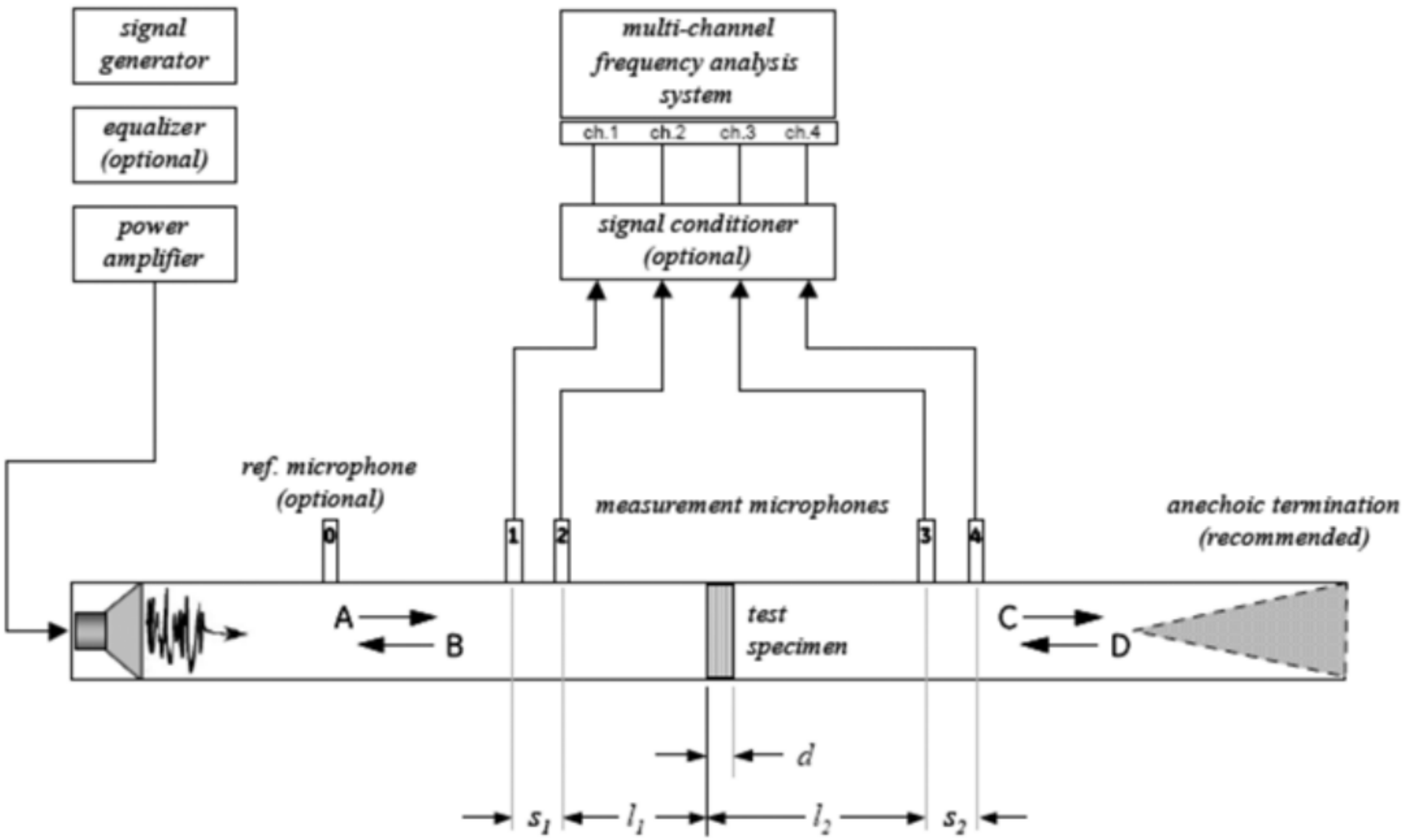

From: ASTM Standard E2611-09

Key Design Criteria (Tube)

- Diameter, $D < 0.586\lambda_{fmax}$
  - Effects the cut-off frequency of higher order modes
    - Larger diameter lowers high frequency limit of plane wave propagation
  - Limits sample size
- Length
  - Needs to be long enough for evanescent waves to decay ($e^{-|k_z|}$)
  - Limits low frequency end of useable bandwidth
    - Shorter tube increases low frequency limit
- Wall thickness and material
  - Transmission loss of wall should be high compared to samples to prevent "leakage"
  - Mass law transmission loss: $TL = 20\log_{10}\left(\frac{t\rho\pi f}{\rho_0 c_0}\right)$

Key Design Criteria (Microphones and Source)

- Microphones
  - Size should be small with respect to shortest wavelength
  - Spacing should be close enough to resolve the shortest wavelength (less than half a wavelength)
  - Number of microphones
    - Measurements can be made using one moveable microphone, but more mics improve accuracy and efficiency.
- Acoustic Source
  - Frequency response should be flat in the useable tube bandwidth
  - Significant power required to achieve high SPL levels

Other Design Considerations

- End termination
  - Two end terminations are required to resolve all traveling wave amplitudes
  - Open and anechoic are recommended by standard
- Sample Holder
  - Acoustic seals are critical between sample and tube wall, and between tube sections
  - Access from both sides of sample is convenient for installation/troubleshooting
- Data processing
  - BT > 50 (or 50 PSD averages) recommended by standard

JPL Impedance Tube Overview

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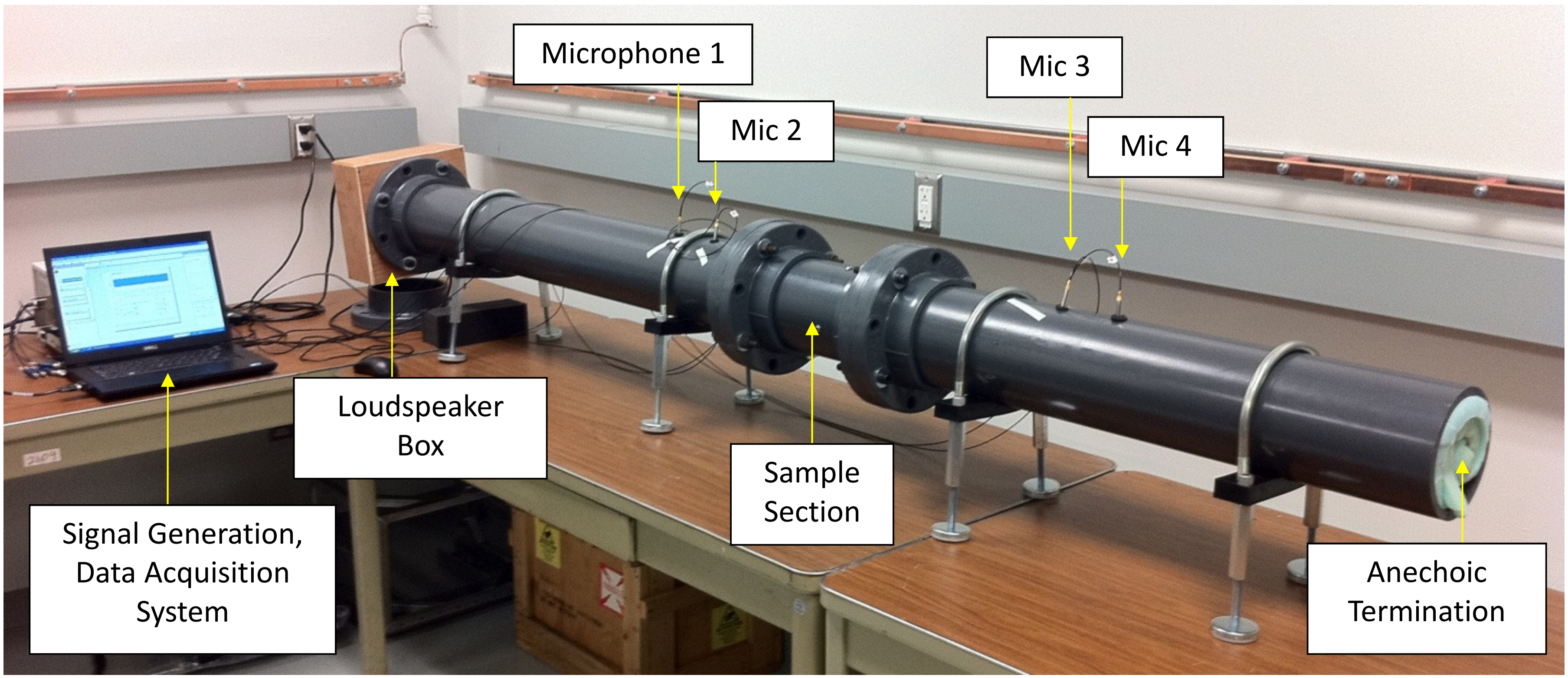
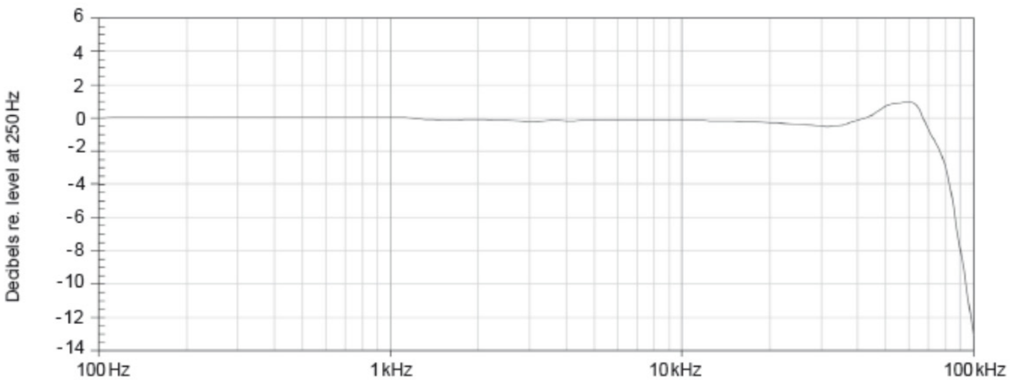


JPL Tube Description

- Tube Specs
  - 5.76-inch diameter
    - non-plane waves cut off above 1380 Hz
  - 3½ feet from source to mic 1
    - Evanescent waves decay to 1% amplitude in 10.5 inches
  - PVC pipe, 0.432 inch wall thickness
    - 15.4 dB mass law transmission loss at 50 Hz
- Microphones
  - G.R.A.S. “pressure” microphones
    - Do not compensate for a specific type of pressure/turbulence field
  - ¼-inch mics << λ_{1000} (13 ½ inches)
  - 4-inch spacing ~$0.3\lambda_{1000}$



JPL Tube Description (cont'd)

- Source
  - 50-watt, 8-ohm speaker
- Sample section
  - Mid tube cut-out, accessible from either side
- End termination
  - Removable lightweight foam
- Data processing
  - Time history data acquired using portable laptop DAQ system
    - 10s record length, 20kHz sample rate
  - Reduced to SPL, TL using MatLab

Baseline Calibration Test Results

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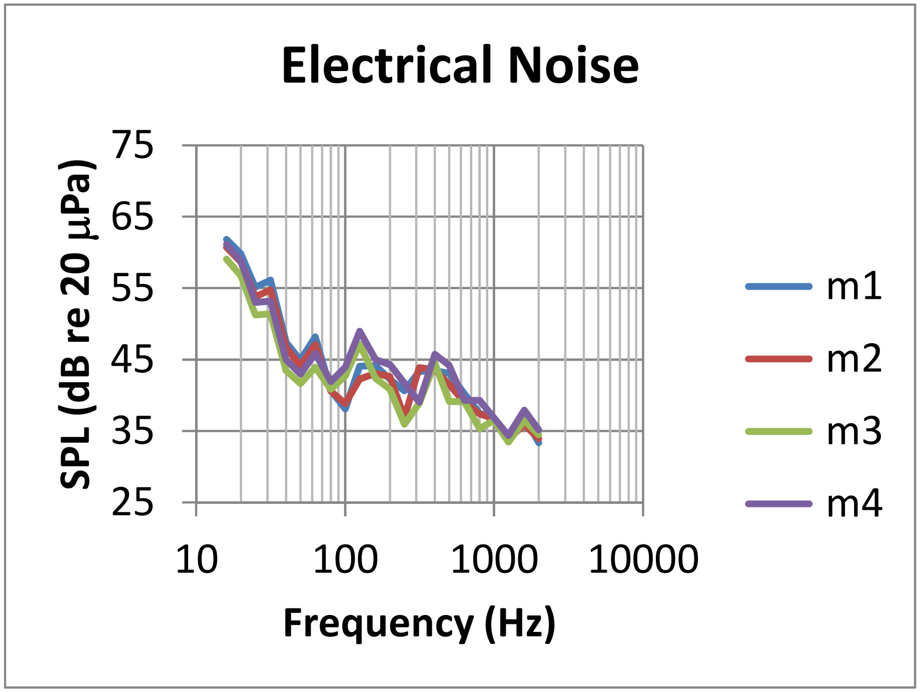

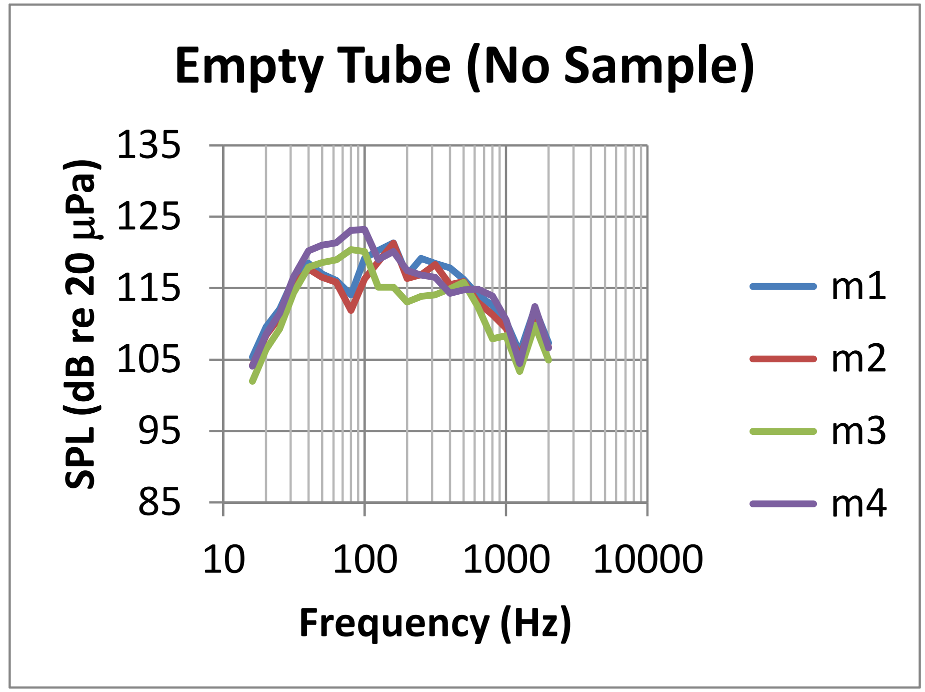

- End-to-end electrical noise is low compared to acoustic data
- Empty tube microphone data is reasonable, differences in magnitude and phase responses between microphones can be calibrated

Transmission Loss Data

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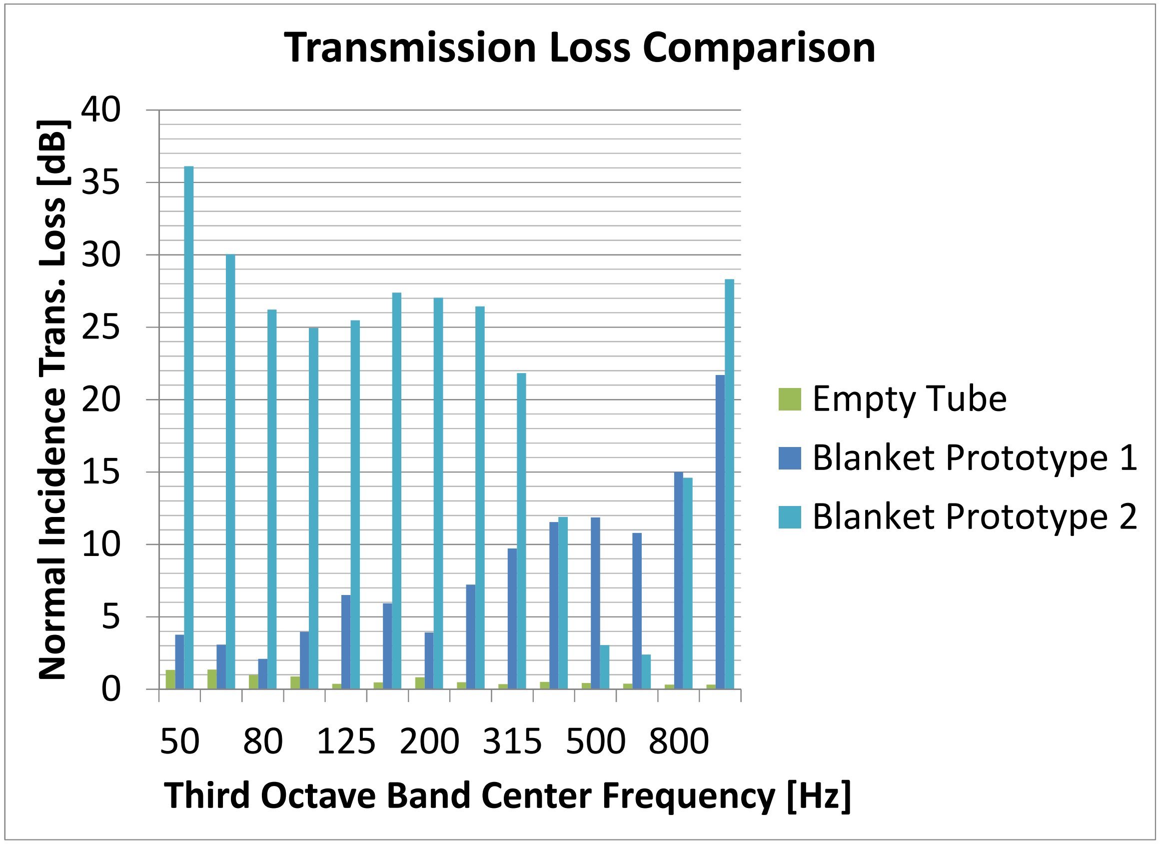

- Early results very promising, indicating broadband low frequency transmission loss improvements

Transmission Loss Data (cont'd)

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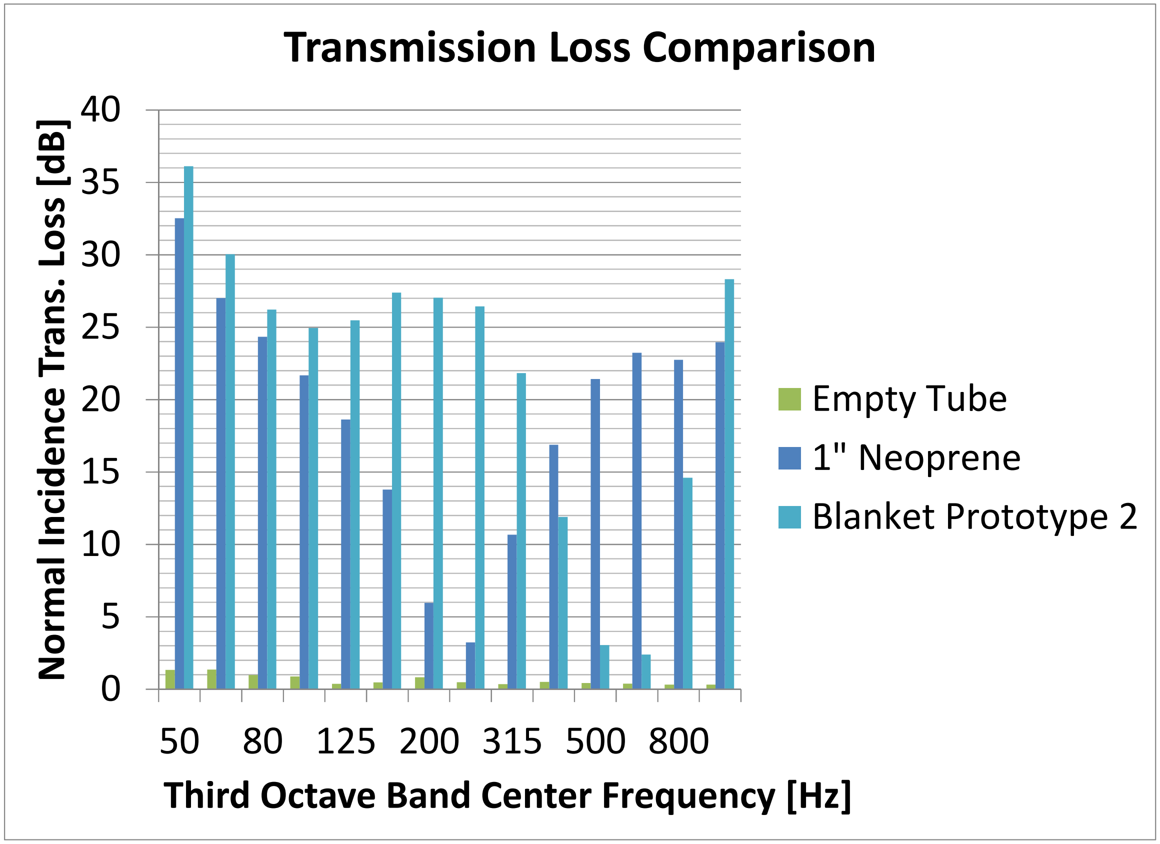

- 1" neoprene tests show unexpectedly good results, particularly in low frequency
- May indicate problem with testbed, putting earlier results in question

Possible Explanations for Anomalous Data

- Standing waves in tube
  - Should not effect measurements, unless microphones are located at antinode, causing low signal problem
- Leakage
  - Poor seal around sample, microphones, or between sections
  - Losses through pipe wall
- Structural vibration of pipe contaminating data
  - Later accelerometer measurements do not support this theory
- Radial pipe modes not decaying
  - Unlikely based on theory
- Speaker coupling with air mass in front pipe section
- Absorption of tube walls
- Drumheading of sample
- High amplitudes causing nonlinear behavior
- Microphones too close to wall, picking up near field effects
  - Standard says they should be flush

Next Steps

- Quantitatively evaluate possible explanations on previous slide
  - In progress
- Test material sample with published TL test data
- Replace pipe with denser material or insulate PVC pipe
- Try new acoustic source, possibly horn
- Add absorptive coating or lightweight material to pipe near source
- Create FE model of system and perform sensitivity analysis

Thank You