National Aeronautics and Space Administration

# Comparison of sonic boom propagation and loudness level calculations

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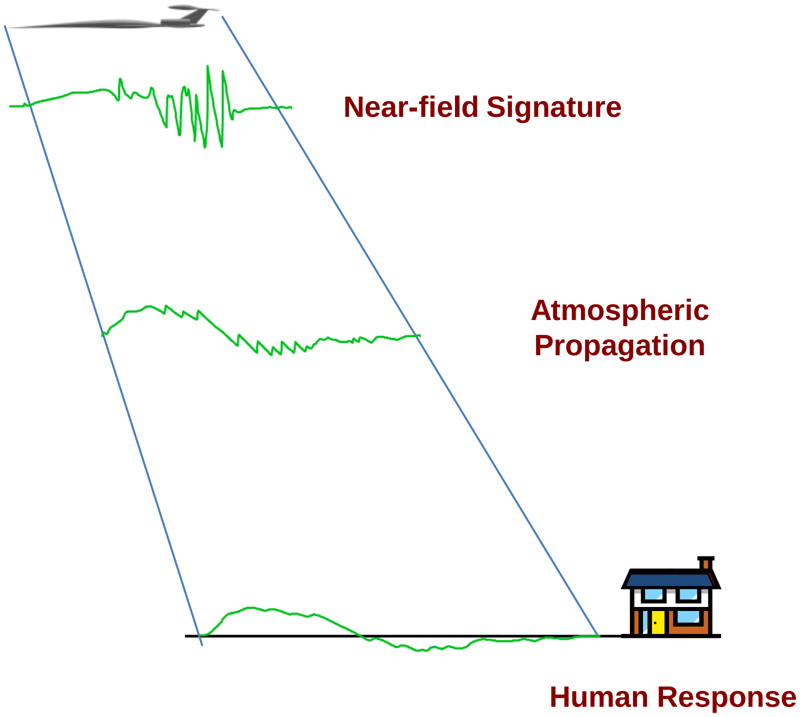
  - Kenneth Plotkin (Wyle)

# Introduction

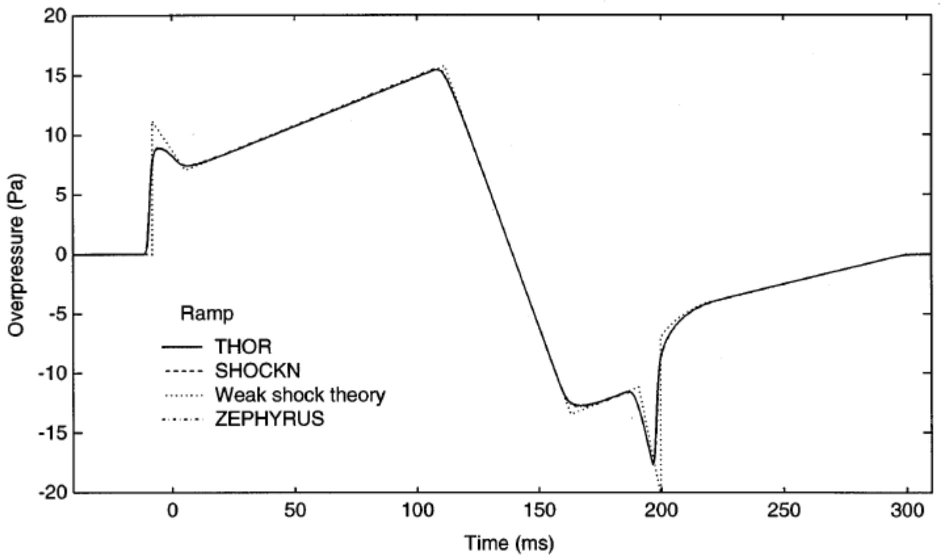
- Elements of sonic boom propagation



- Sonic boom propagation prediction and metrics calculation tools are used to evaluate supersonic aircraft designs
- Desire to compare predictions from different developers

# Previous Study

- Comparison of sonic boom propagation codes conducted by Cleveland et al.
  - Three codes compared favorably



- Reasons to conduct a new comparison
  - Codes have been modified over last 20 years
  - New codes have been developed
  - Boom waveforms of interest have changed
  - Cleveland analysis did not consider any noise metrics

Cleveland et al. Comparison of computer codes for the propagation of sonic boom waveforms through isothermal atmospheres. J. Acoust. Soc. Am. 100(5): 3017-3027, 1996.

# Sonic Boom Propagation and PL Comparison

- Objective
  - To achieve more consistent results across partners and to facilitate understanding of possible differences in computer codes used in sonic boom research

- Approach
  - Conducted a new baseline comparison of sonic boom atmospheric propagation and noise metric calculation tools
    - Developed a set of input cases for propagation and Perceived Level (PL) calculation
    - Participating organizations used their tools to run these cases and returned their results to NASA
    - All provided results were reviewed and compared with baseline results from NASA's tool suite

# Summary of Perceived Level (PL)

- Metric for perceived level of loudness developed by Stevens
  - Developed to predict behavior of human auditory system in response to sound
- Adapted for use with sonic booms by Shepherd and Sullivan
- PL has been shown to correlate well with human perception of sonic booms heard outdoors
  - PL is used today to evaluate supersonic aircraft designs

- Uses signal spectrum in one-third-octave bands
- Uses a set of frequency weighting contours that vary with level
  - (By contrast, A-weighting contour does not vary with level)
  - Based on equal loudness contours for bands of noise
  - Extends down to 1 Hz, but this is an approximation
- Band of highest weighted level is the most important to overall level

S. S. Stevens. Perceived level of noise by Mark VII and decibels (E). J. Acoust. Soc. Am., 51(2):575–601, 1972.
K. P. Shepherd and B. M. Sullivan. A loudness calculation procedure applied to shaped sonic booms. NASA Technical Report TP-3134, 1991.

# Calculation Steps for Perceived Level (PL)

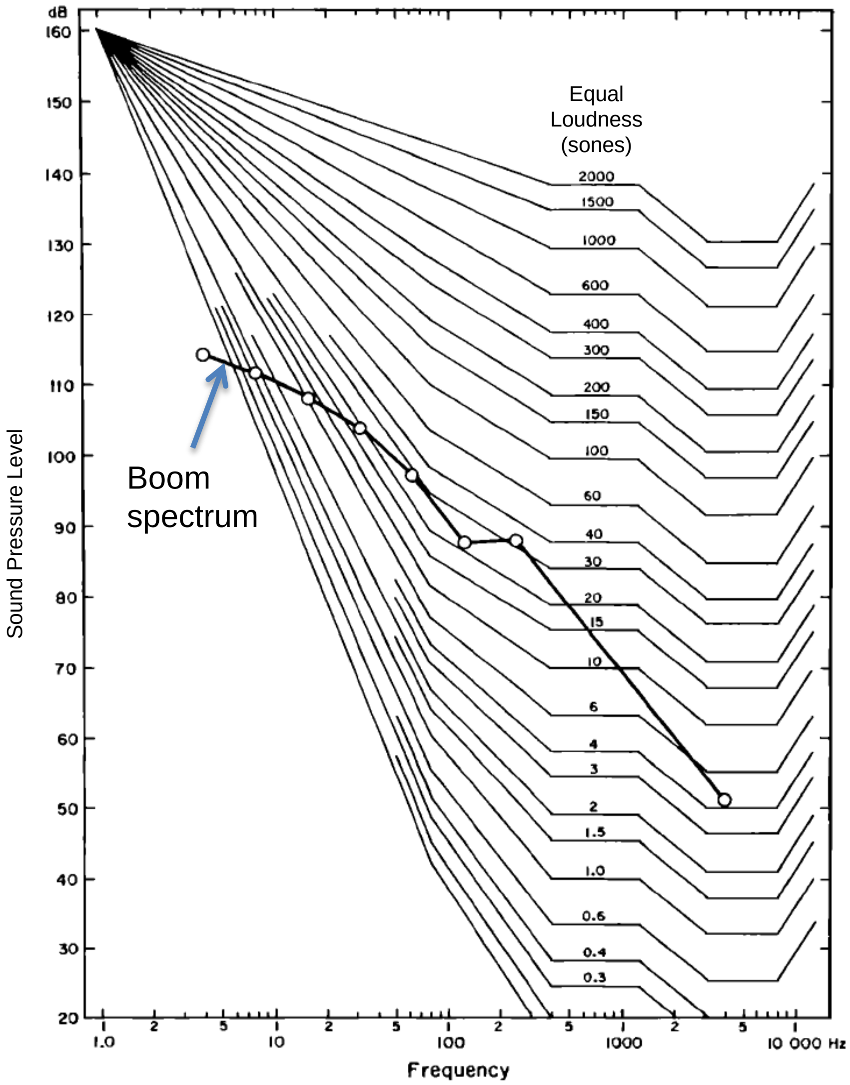
1. Calculate Sound Pressure Level of signal in 1/3-octave bands
2. Apply frequency weighting for loudness of individual bands
   - where loudness of 1 sone is referenced to 1/3-oct band of noise at 3150 Hz at 32 dB
3. Apply summation rule for total loudness

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

where
$S_t$ = total loudness
$S_m$ = loudness of loudest band
$\Sigma S$ = sum of loudnesses of all the bands
$F$ = fractional factor based on $S_m$

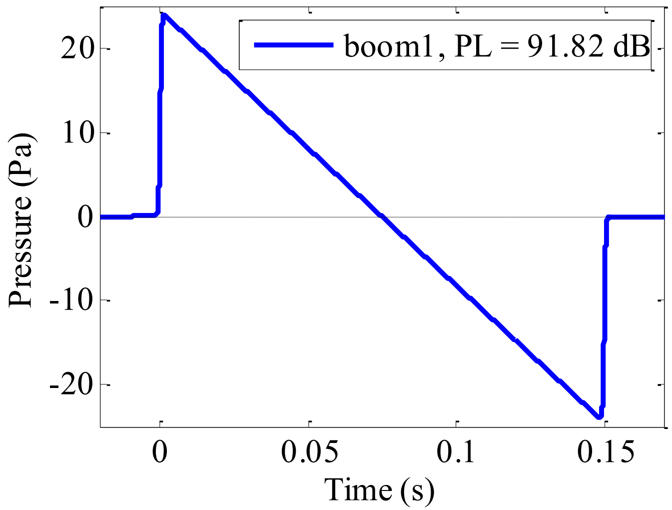
4. Convert to PL in dB

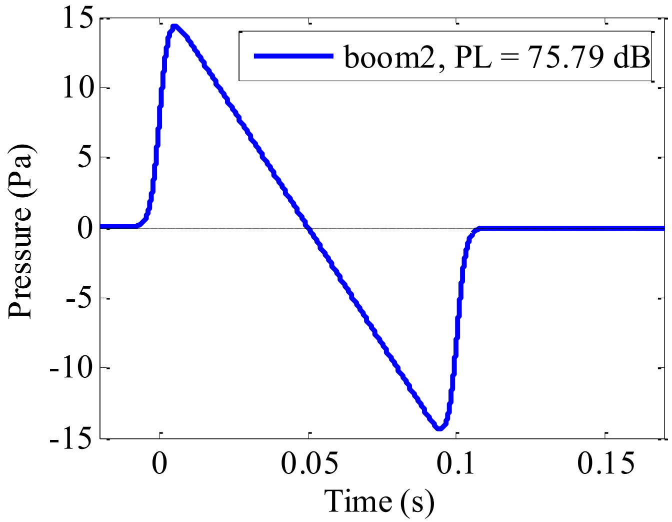
$$PL = 32 + 9\log_2(S_t)$$



S. S. Stevens. Perceived level of noise by Mark VII and decibels (E). J. Acoust. Soc. Am., 51(2):575–601, 1972.

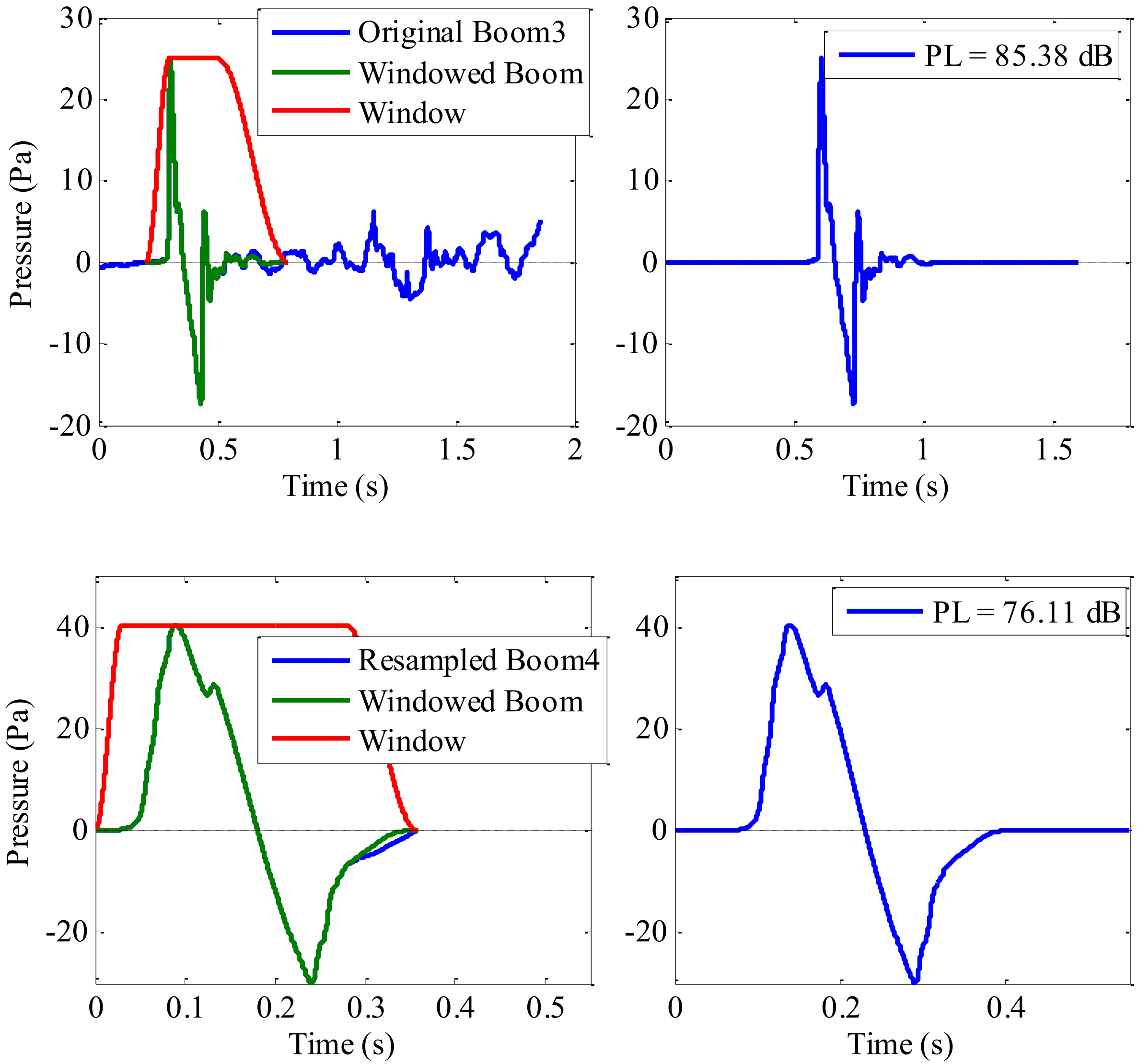
# PL Test Cases of Ground Booms





- Included to test that PL algorithms are implemented correctly
- Synthesized N-waves with different rise times, peak pressures, and durations
- Adequately sampled at 48 kHz with ample zero-padding
- Initial results indicated some codes needed to be modified to be in compliance with NASA's baseline method
- Majority of updated results within 0.1 dB of baseline (all within 0.45 dB of baseline)

# PL Test Cases of Ground Booms



- Included to highlight difficulties in processing measured booms and predicted booms
- Results more varied than for simpler cases
- Windowing, zeropadding, and resampling methods varied
- All calculations agree within 1 dB of baseline

# Sonic Boom Propagation Prediction Overview

- Input is the overpressure signature predicted at several body lengths away from the aircraft

- Geometrical acoustics method (ray tracing)
  - Determines propagation path from altitude to ground
  - Accounts for variations in speed of sound and wind speed

- Nonlinear, lossy propagation based on extended generalized Burgers equation
  - Predict evolution of sonic boom as it propagates along rays
  - Second-order nonlinearity and the formation of shocks
  - Atmospheric absorption due to thermoviscous and molecular relaxation effects
    - Varies according to input of atmospheric conditions (stratified atmosphere)
  - Geometrical spreading loss
  - Solved numerically with a finite-difference method

- Numerical implementation varies

# Inputs to Propagation Codes

- Overpressure signature predicted at several body lengths away from the aircraft
  - F-function
  - Overpressure distribution on a cylindrical surface from CFD flow predictions
  - Wind tunnel test measurement
  - In-flight near-field probing measurement

- Flight altitude and Mach number

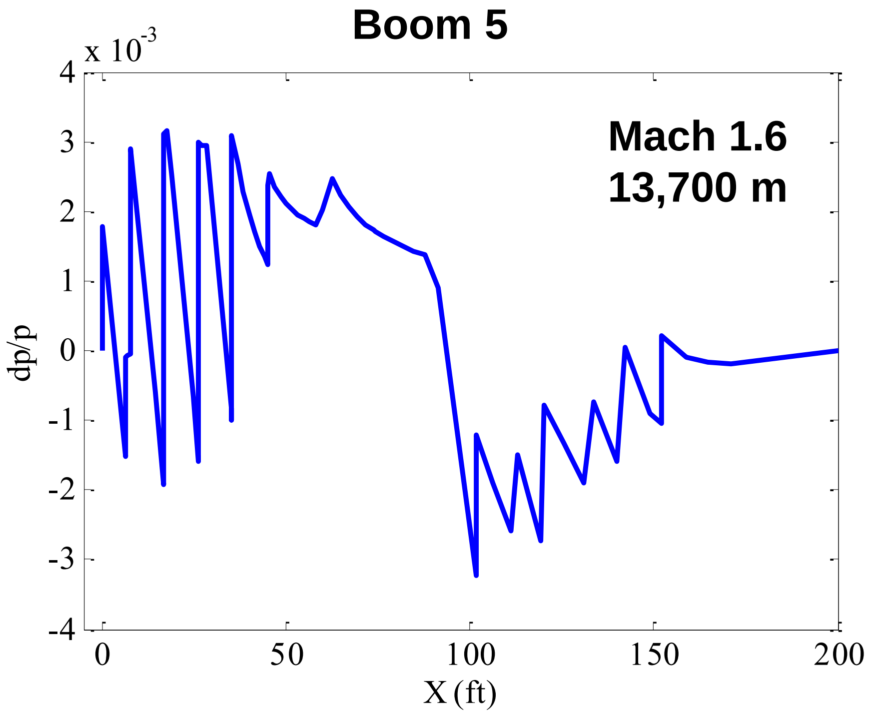
- Flight trajectory

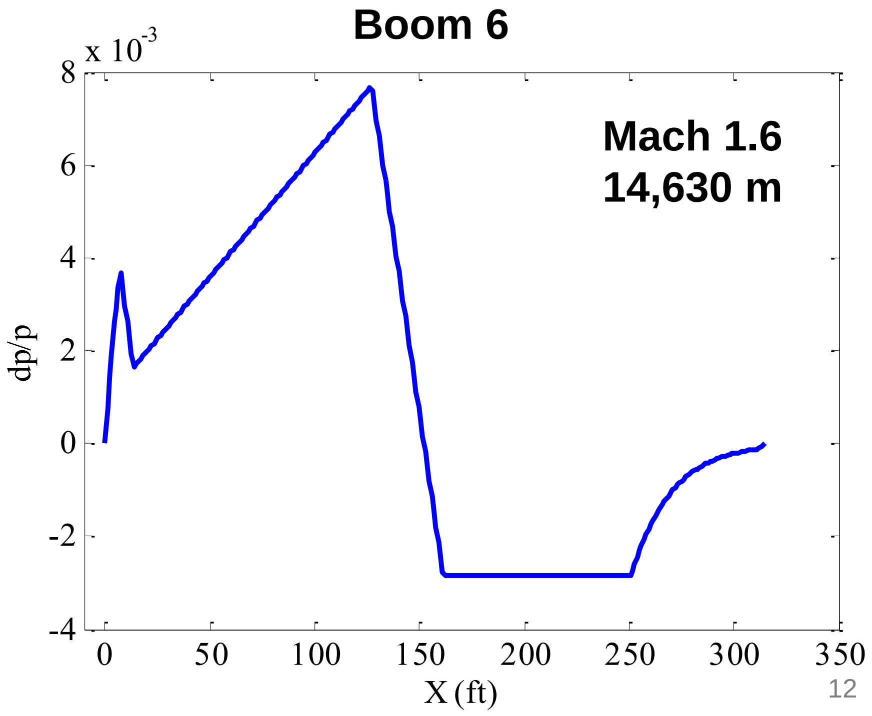
- Atmospheric conditions
  - Atmospheric pressure, temperature, relative humidity, winds

- Ground impedance or reflection factor

# Propagation Test Cases

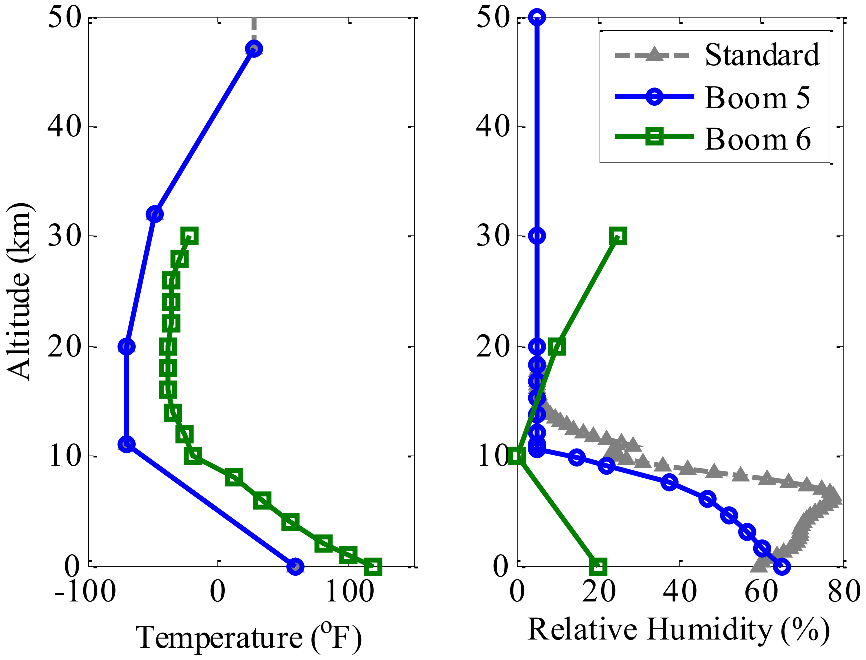
- Near-field signature, Mach number, altitude, and atmospheric conditions provided as input to sonic boom propagation codes
- Ground waveforms (undertrack) requested as output
- PL calculated with NASA baseline tool
- Boom 5: multi-shock low-boom configuration
- Boom 6: strong front shock



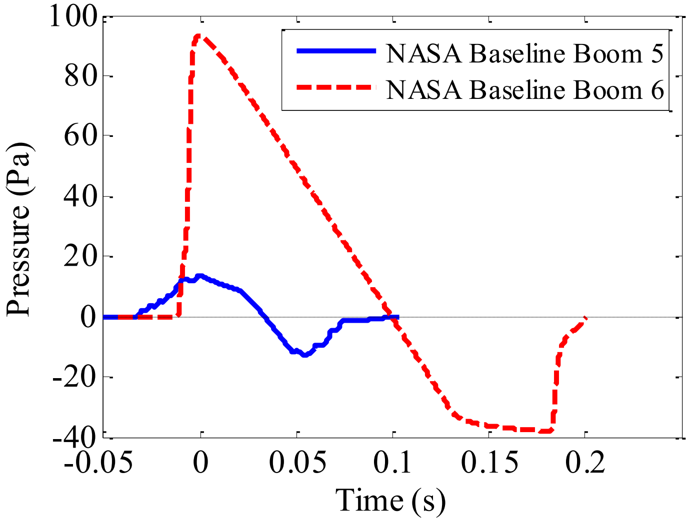


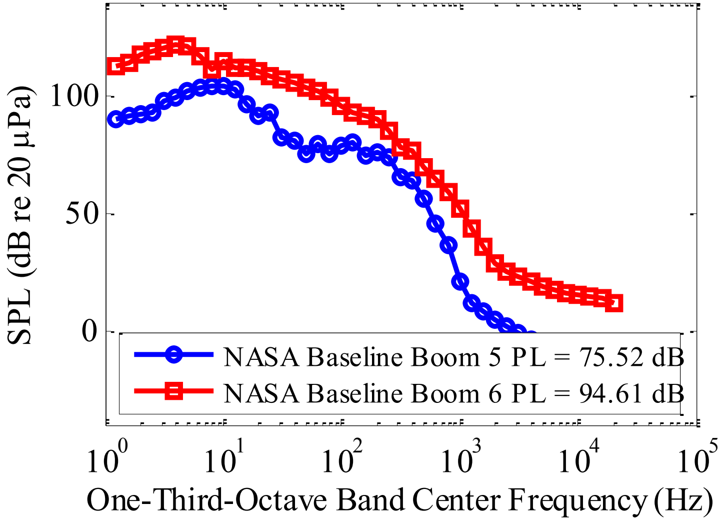
# Atmospheric Conditions

- No winds included
- Temperature and relative humidity provided
  - Boom 5 conditions are similar to U.S. Standard Atmosphere (1976) and ANSI S1.26-1995 App. C (2009)
  - Boom 6 conditions are non-standard and include unrealistic relative humidity values



# Initial Results for Propagation Test Cases





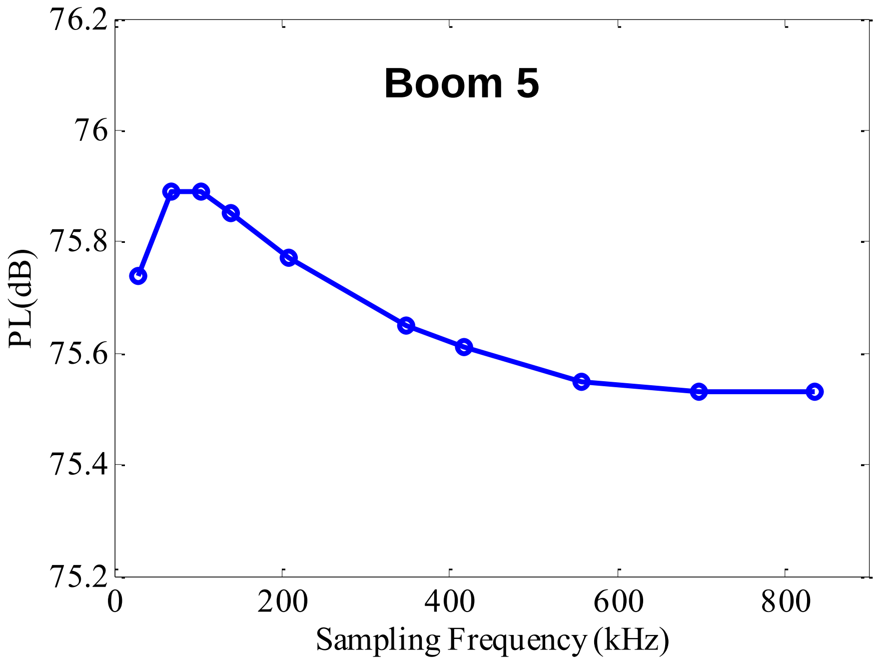
- Boom 5 results within 0.7 dB of baseline
- Boom 6 results varied by up to 10 dB from baseline
- Main variation across partners due to differences in mid-frequency content
- In addition to method differences, differences in PL may be due to assumptions and input settings of
  - Vehicle length
  - Atmospheric pressure
  - Sampling frequency
  - Step size

→ Examined using NASA baseline tool sBOOM

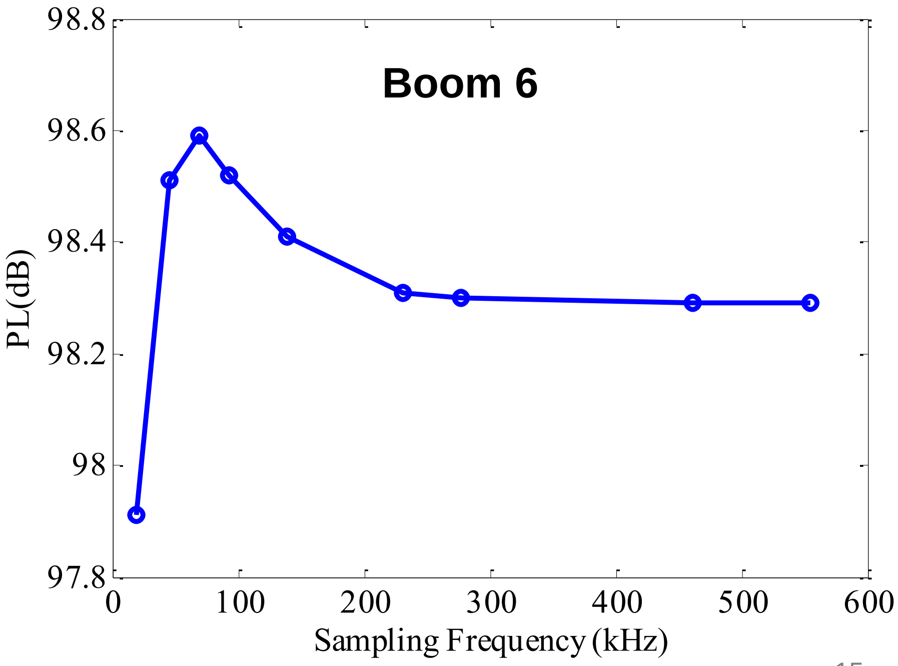
S. K. Rallabhandi. Advanced sonic boom prediction using augmented Burgers equation. AIAA-2011-1278, 2011.

# Effect of Sampling Frequency (sBOOM)

- Variations observed of 0.4-0.7 dB
- Convergence
  - Boom 5 sampling frequency = 697 kHz
  - Boom 6 sampling frequency = 462 kHz
- Sampling frequency/number of points needed depends on input waveform
  - Higher sampling frequency needed to resolve fine shock structure



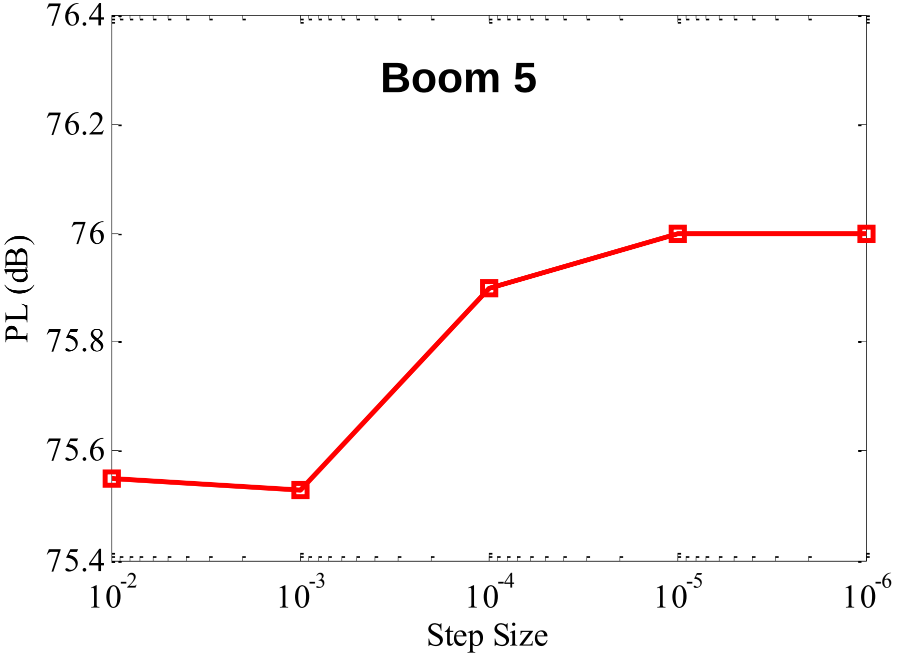
**Boom 5**

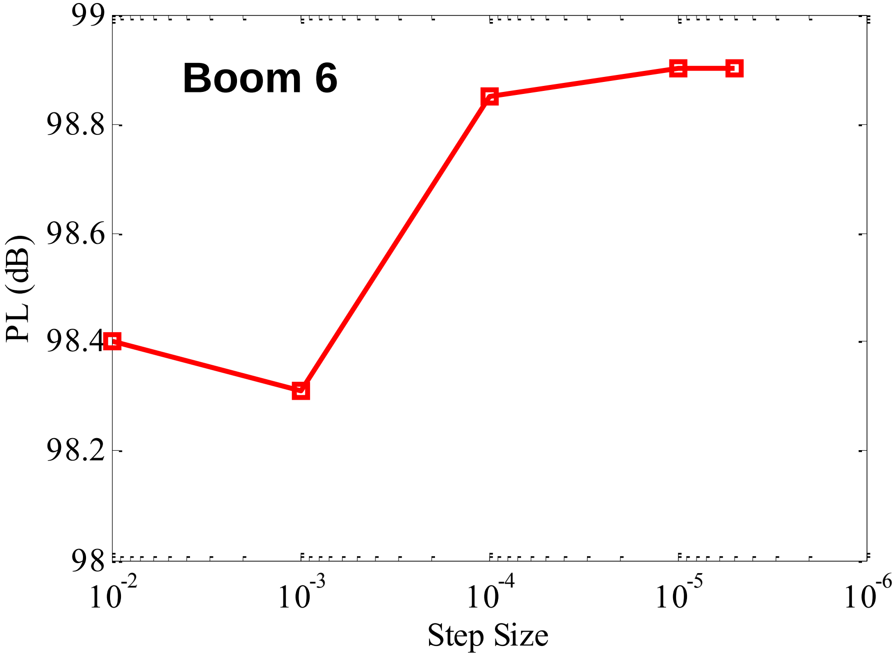


**Boom 6**

# Effect of Step Size (sBOOM)

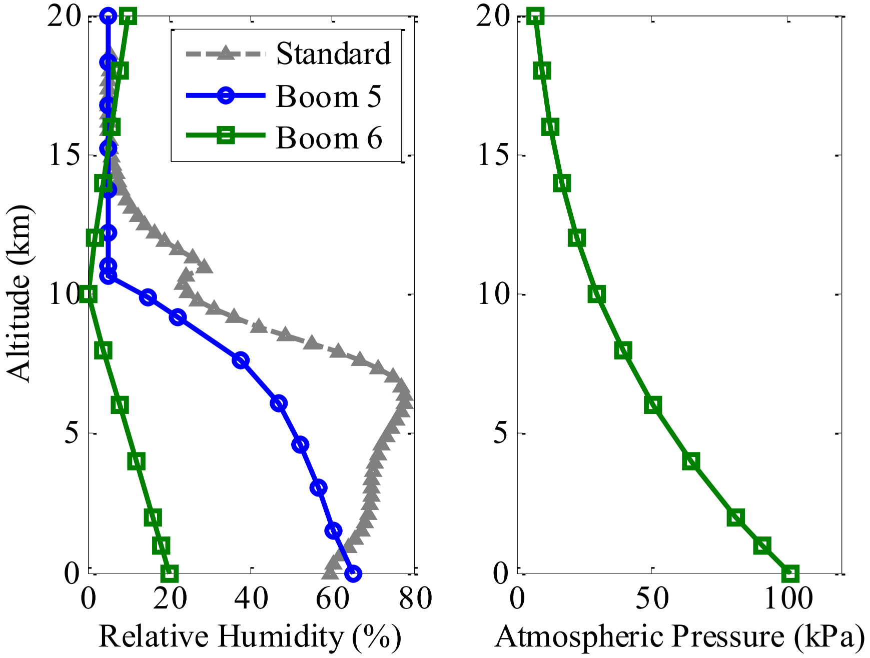
- Variations observed of ~ 0.5 dB
- Boom 5 and 6 convergence at $10^{-5}$ step size
- Step size needed depends on input waveform
- Computation time varies from 10-20 s for $10^{-3}$ to ~22 hours for $10^{-6}$



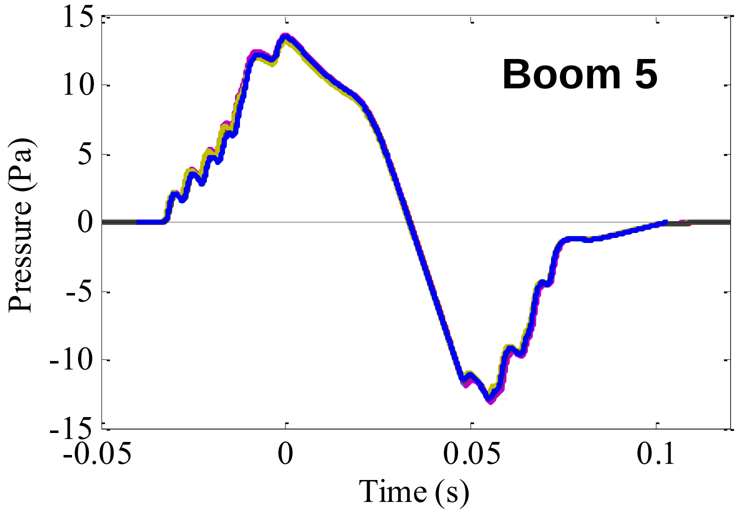


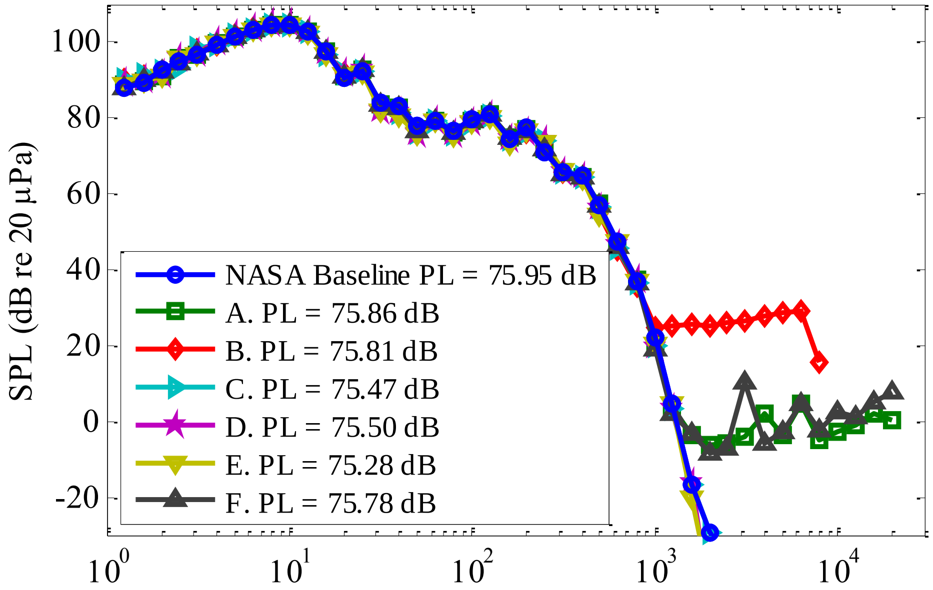
# 2nd Round: Revised Atmospheric Conditions

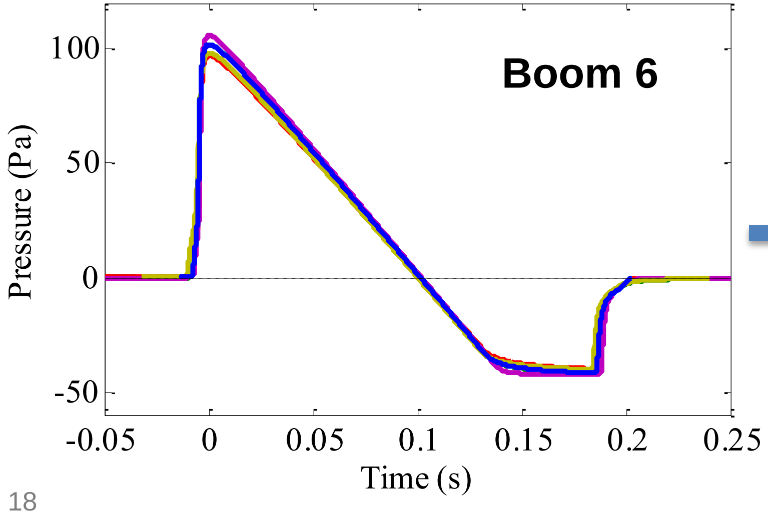
- Revised atmospheric conditions for Boom 6
  - More resolution in relative humidity definition
  - Specified atmospheric pressure due to suspected differences in built-in calculation of pressure in different codes
- Updated Boom 6 results are within 3.5 dB of baseline

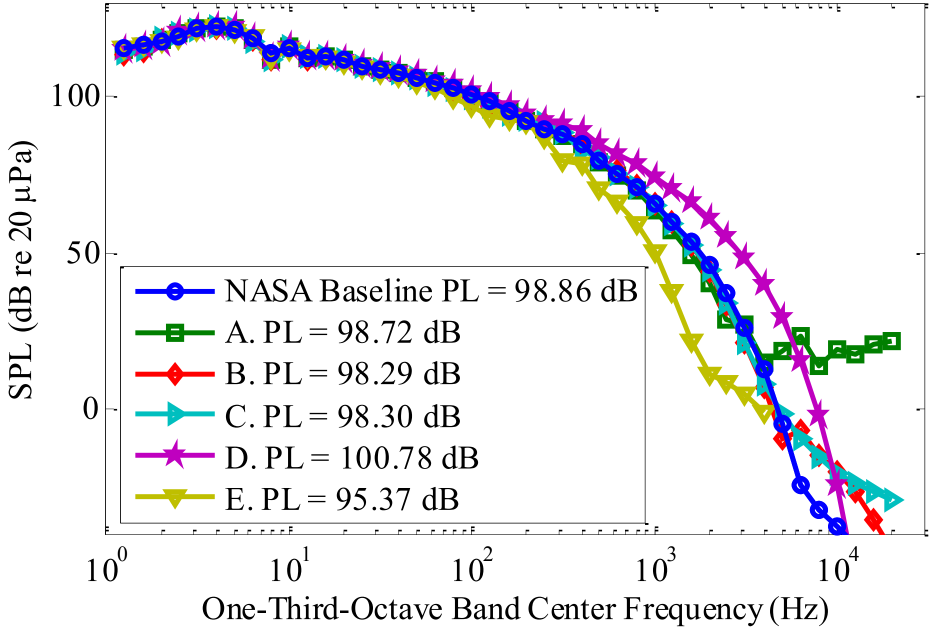


# Revised Results for Propagation Test Cases

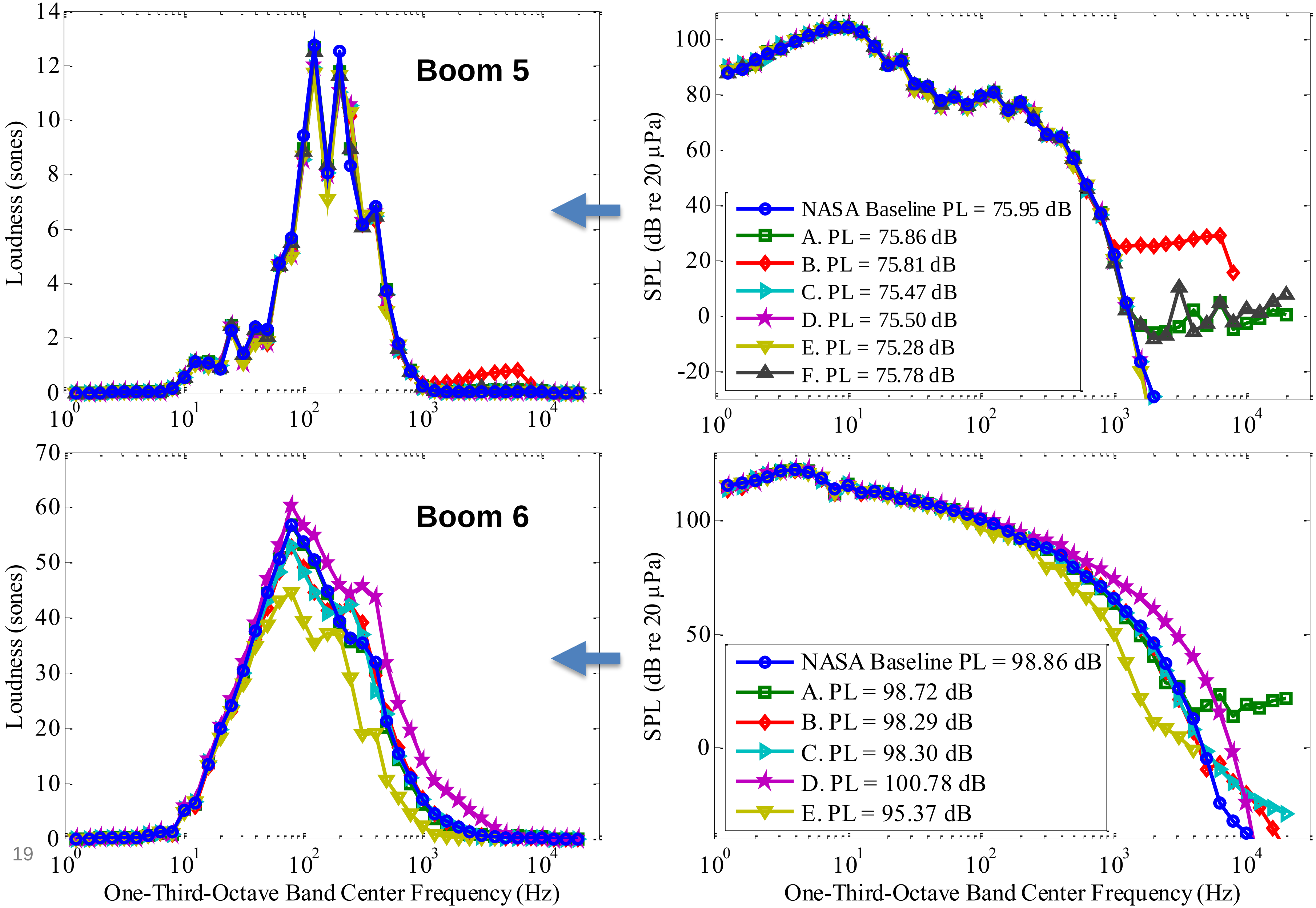








# Loudness for Propagation Test Cases



# Summary

- Comparison of PL calculations and boom propagation predictions for 6 test cases resulted in
  - Some modifications of codes for consistent implementation
  - Awareness of factors contributing to differences
    - Observed up to 3.5 dB variation due to propagation codes
    - Observed less than 1 dB variation due to sampling frequency and step size
    - Observed up to 1 dB variation due to ground signal processing

- Majority of submissions in very good agreement with baseline
  - Differences at high frequencies generally occur at very low levels that are not significant to PL or human response

- Based on these results, baseline calculation recommendations have been drafted for ease of evaluation of supersonic aircraft designs

- Future
  - Could be useful to consider the effect of winds in different codes
  - Include more participants

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# Backup Slides

# Baseline Boom Propagation Prediction Method

- Sonic boom propagation prediction
  - sBOOM is the preferred tool, and it is available from NASA
  - A standard atmosphere should be used (U.S. Standard Atmosphere, 1976):
    - Pressure, temperature, and humidity
    - No winds should be included
- sBOOM should be used for all boom predictions, with the exception of focus boom predictions. Since sBOOM does not include calculation of focus booms, other methods may be used.
- The step size should be set to 0.001
- The sampling frequency should be set to ≥ 40 kHz i.e. do NOT use resamp.dat from sBOOM output to calculate loudness metrics
- Propagation should start at a distance from the aircraft that gives a converged ground signature
- The ground reflection factor should be set to 1.9
- Sufficient zeropadding should be applied to the input waveform to avoid clipping the shocks during propagation

# Baseline PL Calculation Method

- LCASB is the preferred tool, and it is available from NASA
- PL should be calculated according to Shepherd and Sullivan (1991)
- PL should be calculated on the waveform with a sampling frequency ≥ 40 kHz
- A Hanning-type window should be applied to the beginning and ending of the waveform to ensure a smooth transition to zero acoustic pressure. This window should be applied so as not to affect the main boom event to be analyzed.
- Adequate zeropadding should be applied to allow for resolution of low frequencies (total signal length ≥ 0.5 s)
- PL values should be rounded to the nearest 0.1 dB