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Stability of sonic boom metrics regarding signature distortions from atmospheric turbulence

William J. Doebler and Victor W. Sparrow
Graduate Program in Acoustics, The Pennsylvania State University, 201 Applied Science Building, University Park, Pennsylvania 16802, USA
wfd5057@psu.edu, vws1@psu.edu

Abstract: The degree of insensitivity to atmospheric turbulence was evaluated for five metrics (A-, B-, E-weighted sound exposure level, Stevens Mark VII Perceived Level, and NASA's Indoor Sonic Boom Annoyance Predictor) that correlate to human annoyance from sonic booms. Eight N-wave shaped sonic booms from NASA's FaINT experiment and five simulated "low-boom" sonic booms were turbulized by Locey's ten atmospheric filter functions. The B-weighted sound exposure level value changed the least due to the turbulence filters for twelve of thirteen booms. This makes it the most turbulence stable metric which may be useful for quiet supersonic aircraft certification.

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1. Introduction

Since 1973, civil supersonic transportation over land has been prohibited because of the loudness and annoyance of sonic booms.[1] Due to technological advances in aircraft design, this prohibition may soon be coming to an end. New aircraft are being developed that produce low amplitude sonic booms or "low-booms."[2–6] These aircraft designs aim to reduce the loudness of N-wave-type pressure signatures associated with traditional supersonic aircraft. N-waves develop due to nonlinear propagation effects where higher amplitude acoustic pressure travels at a faster speed than low amplitude acoustic pressure.[7] Traditionally, spikes in the near-field pressure field around the aircraft coalesce into a single high amplitude shock with a short rise time. The human ear is sensitive to abrupt changes in pressure, so this shock wave is typically loud and annoying. The new low-boom aircraft are expected to have much longer and smoother rise times which contain less high frequency energy.[2,4] This results in booms that are less annoying to the human ear. These aircraft may have booms with permissible loudness levels to fly commercially at supersonic speeds over land.

Progress on developing acceptable supersonic overland transport has been complicated by the current lack of an acceptable loudness standard. Supersonic aircraft designers currently do not have an official, internationally agreed upon supersonic aircraft regulatory noise standard (and loudness level) to confidently pursue without risk. Strides are being taken by NASA, the FAA, and many partners from the International Civil Aviation Organization (ICAO) to develop a certification standard that defines permissible loudness levels of low-boom aircraft. Results from a study compiled by Loubeau *et al.* found metrics that correlated highly with human perception of sonic booms.[8] Loubeau's results narrowed down a list of many loudness and annoyance metrics to five potentially viable metrics. These metrics are the A-, B-, and E-weighted sound exposure level (ASEL, BSEL, and ESEL),[9,10] the Steven's Mark VII Perceived Level (PL),[11] and the Indoor Sonic Boom Annoyance Predictor (ISBAP).[8] These metrics are described in detail below.

A notable issue for developing a certification standard and method for measuring this standard arises from turbulence in the atmosphere. As sonic booms from aircraft propagate toward the ground, the acoustic signal encounters eddies caused by convection as well as chaotic changes in local wind speed, air temperature, and chemical make-up.[12] The turbulence can cause focusing or defocusing of the sonic boom which can change the boom's amplitude and fine structure. Since these factors affect perception of the boom, development of a certification standard becomes difficult. If the boom's propagation is thought about in the context of ray acoustics, each acoustic ray from the sonic boom travels on a path through different turbulent conditions. Because of this, sonic boom pressure signatures measured using microphones on the ground are different at different locations even though nothing about the aircraft or its speed has changed.[13] This is true for measurements made along a flight track and for multiple flights of the same aircraft over the same measurement location. Thus, atmospheric turbulence complicates the process for determining whether a certain aircraft is quiet enough to be accepted by communities because each occurrence may sound different from the same aircraft.

It is the goal of the current study to identify which of the five viable metrics is most turbulence stable, or the metric whose value changes the least due to changes in atmospheric turbulence. Because a single aircraft will experience varying atmospheric conditions from flight to flight, a metric whose value does not change significantly due to these turbulence effects could be desirable. Since the five metrics chosen were shown to correlate with human annoyance from sonic booms, the most turbulence stable of these may be a good candidate for certifying that supersonic aircraft are acceptably quiet for overland flight.

2. Methods

2.1 Overview

Experimental N-wave and simulated low-boom signatures were turbulized by a set of ten atmospheric filters created experimentally in 2007 by Locey and Sparrow.[14–16] The process of turbulization is defined as passing the acoustic waveform through one of Locey's atmospheric filters which are described in Sec. 2.2. The filters encompass the linear physical effects of the atmosphere on the sonic boom waveforms. The metric values of the signatures were calculated before and after turbulization, and then their difference was calculated. The changes in metric values are due to the changes in the waveform from propagation through the atmosphere. Because there are ten atmospheric filters, each signature had ten of these difference values for each metric. These difference values' standard deviation was calculated for each metric. This process was undertaken for a variety of sonic boom signatures from experiment and simulation. Shown by its standard deviation, the expected variation in the metric's difference values pre- and post-filter express the change in human-correlated perception of the booms propagated through different atmospheric conditions. Thus, the metric with the lowest standard deviation of difference values is the most turbulence stable and may be useful for certification of quiet supersonic aircraft. A low standard deviation of difference value implies that the metric is insensitive to changes in atmospheric turbulence.

2.2 Atmospheric filters

In 2007, a set of ten atmospheric filters were created by Locey and Sparrow. These filters were created by measuring sonic booms above the turbulent boundary layer of the atmosphere and then at the ground. To do this, a microphone-equipped sailplane flew above the turbulent boundary layer of the atmosphere and measured each sonic boom. Then the same sonic boom was recorded with ground microphones. From these two input-output measurements, it is possible to create a filter. The atmosphere was treated as a linear finite impulse response filter, and filter coefficients were generated for ten different turbulent sonic boom paths. Unfortunately, the atmospheric conditions were not measured by NASA during the experiment in which the ten filters were generated. These ten filters are a limited sample of possible atmospheres through which booms may propagate.

By utilizing these filters, it is possible to estimate the effect of turbulence on other supersonic waveforms. For example, these filters can be applied to booms that are generated by computational fluid dynamics simulations and nonlinear propagation simulations to estimate turbulence effects on the signatures. Locey's filters can also be applied to experimentally measured sonic booms that appear to be minimally affected by turbulence. Experimentally measured booms, even with low amounts of obvious turbulence effects, have already passed once through the turbulent boundary layer, so applying these filters extends the turbulent propagation path. Both experimental conventional N-wave type and CFD-generated/computer propagated next-generation supersonic low-boom signatures were turbulized by Locey's filters in the current study to determine which metric is the most turbulence stable.

The high amplitude of sonic boom pressure waveforms and the long propagation path length from the aircraft to the ground necessitate careful consideration about the validity of using linear filters to approximate nonlinear acoustic propagation. The creation of each filter used in this study embedded any nonlinear propagation effects along the path from the sailplane to the ground into the linear transfer function. Including nonlinearity in the filters some other way would be much more complicated. The issue with using linear filters to represent nonlinear processes is that the shape of other input waveforms would result in different amounts of nonlinear steepening and stretching.

The planetary boundary layer of the atmosphere is where most of the effects of turbulence take place on the sonic booms. Since the planetary boundary layer is typically the "lower few thousand feet"[12] (lower few kilometers) of Earth's atmosphere, it is a relatively small distance through which the boom propagates compared to the total propagation path which may be well over thirty-two thousand feet (9.7 km) for supersonic aircraft. Additionally, propagation through the boundary layer is the last section of the path before the boom is heard on the ground. Therefore, the filters have assumed that the majority of nonlinear propagation effects have already occurred before the sonic boom reaches the planetary boundary layer. By comparing sailplane-measured boom data to the ground-measured boom data in Figs. 4.13 and 4.15, respectively, of Ref. 14, the shock-to-shock boom duration for propagation through the boundary layer is nearly constant. Thus, the linear filter approximation appears to be valid given the minimal boom lengthening of the N-waves used to generate the filters. Because the sonic booms used in the filter generation process had already steepened into N-waves at the sailplane, they may not approximate steepening that would occur for low-boom waveforms. Reiterated, these filters do not include nonlinear propagation effects. In the future, it may be worth exploring other techniques that include nonlinearity explicitly without resorting to a linear approximation.

2.3 Metrics

2.3.1 Sound exposure level

The sound exposure level (SEL) is given by

$$SEL = 10\,\log_{10}\frac{1}{t_0}\int_{t_1}^{t_2}\frac{p^2(t)}{{p_0}^2}dt, \qquad (1)$$

where t_0 is a reference time interval of 1 s, t_1 and t_2 are the time at the beginning and end of the pressure signal, $p(t)$ is the pressure signal as a function of time, and p_0 is the reference pressure for air, 20 μPa. The sound exposure level is a metric describing the power in an acoustic signal in a given time interval. The sonic boom pressure signatures in this experiment were frequency weighted so that the ASEL, BSEL, CSEL, or ESEL could be calculated. Note that CSEL by itself is not one of the metrics that was found to correlate with human perception of sonic booms. However, it is a component of the indoor sonic boom annoyance predictor metric described below which did correlate. The frequency weighting curves[9] applied to the acoustic waveform are shown in Fig. 1(a) over the typical range of human hearing, 20 Hz to 20 kHz.

2.3.2 Stevens Mark VII perceived level

The perceived level predicts how loud a reference tone must be in order to be judged the same loudness as noise of known band-levels. It is calculated by

$$PL = 32 + 9\log_2 S_t, \qquad (2)$$

where S_t is the total loudness which is calculated by

$$S_t = S_m + F\left(\sum S - S_m\right), \qquad (3)$$

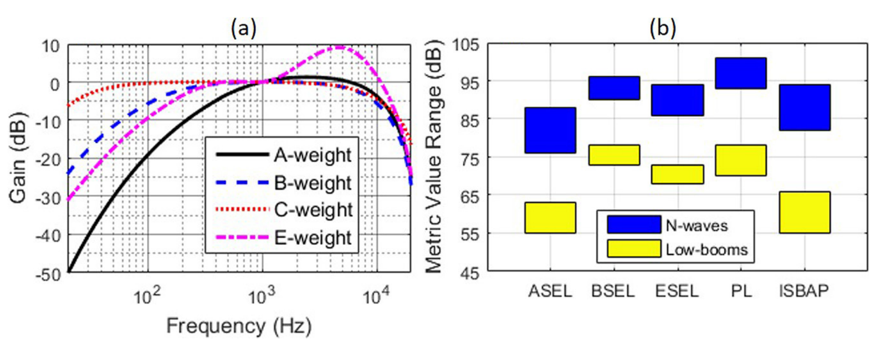

Fig. 1. (Color online) (a) The weighting functions that are applied to the sonic boom pressure signatures to calculate the frequency weighted sound exposure levels. (b) The range of metric values of the pre-turbulized N-waves and low-booms.

where S_m is the loudness of the loudest band, S is the loudness of an individual band, and F is a value that is dependent on the value of S_m (refer to Appendix A in Ref. 11). The individual band loudnesses are calculated by

$$S = k(E - E_0)^{1/3} \tag{4}$$

where E is the square of the sound pressure in the band, E_0 is the square of the pressure at a sound pressure level of -3 dB re: 20 μPa or about 2×10^{-10} Pa^2, and k is a value that depends on the band frequency and converts the band pressure level to perceived magnitude in sones (refer to Fig. 1 in Ref. 11).

2.3.3 Indoor sonic boom annoyance predictor

The indoor sonic boom annoyance predictor is a metric recently developed by NASA to determine boom annoyance for humans inside buildings. It is calculated by

$$ISBAP = PL + 0.4201\,(CSEL - ASEL), \tag{5}$$

where $CSEL$ is the C-weighted sound exposure level[8] and PL is the Stevens Mark VII perceived loudness from Eq. (2).

2.4 Determining metrics' atmospheric turbulence stability

Eight ground-measured sonic booms of various rise times and peak amplitudes from the Farfield Investigation of No-boom Threshold (FaINT)[17] experiment were chosen to be turbulized by Locey's atmospheric filters. While the goal of FaINT was to study lateral cutoff and Mach cutoff phenomena, there were several N-wave shaped booms recorded on the ground. The Mach number of the F-18B aircraft used to produce the booms varied between 1.164 and 1.286. The F-18B flew straight and level at a constant speed within 0.5% of the mean Mach number for the eight flights chosen here. The flight altitudes varied between 36 500 and 42 000 ft. (11.1 and 12.8 km) and were level within 0.2%. An example N-wave shaped boom from FaINT is shown in Fig. 2(a) along with the results of applying 5 of the 10 atmospheric filters (dashed lines) to the boom. The dashed lines show the effect of turbulizing the original experimental waveform (black line). These are examples of what the original waveform would look like if it experienced the same turbulent profile as the sonic boom that was used to create each filter. Note that some of the turbulized waveforms show spiking (e.g., filter 3) and some rounding (e.g., filter 5) as is typically seen when sonic booms pass through turbulence. In addition to the experimental waveforms, five low-boom signatures from an industry partner's CFD simulations were turbulized with the same filters. An example low-boom signature is shown in Fig. 2(b) along with the results of turbulizing the boom with five of Locey's filters.

The technique for evaluating the stability of the metrics is as follows.

(1) Before turbulization, the value of the metrics (ASEL, BSEL, ESEL, PL, and ISBAP) are calculated for each signature.
(2) Each signature had all of the ten filters applied to it (see Fig. 2, note: only 5 of 10 filtered signatures are shown).

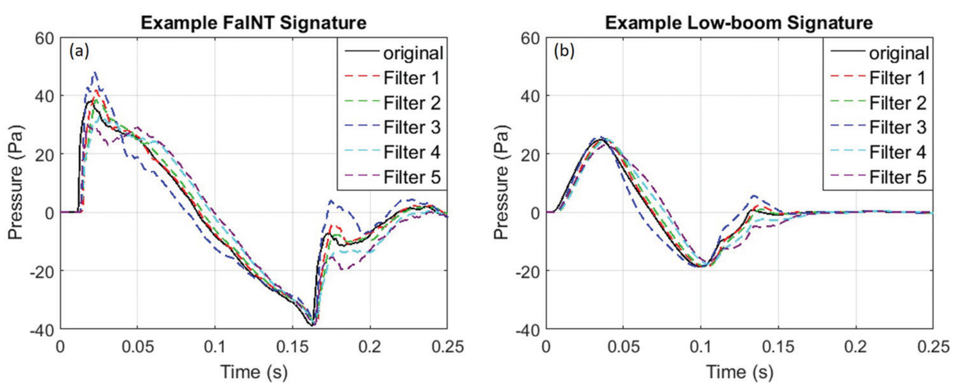

Fig. 2. (a) An example signature and turbulizations from FaINT. The black line shows an original N-wave shaped sonic boom measured on the ground from the FaINT experiment. This boom is an example of the sonic booms used for determining metrics' stability regarding turbulence. The dashed lines show the output of five of Locey's atmospheric filter functions. They show spiking and rounding. (b) An example industry partner-provided low-boom signature and turbulizations. The black line shows an original low-boom signature from an industry partner's simulations, and the dashed lines show the results applying an atmospheric filter function to the original signature.

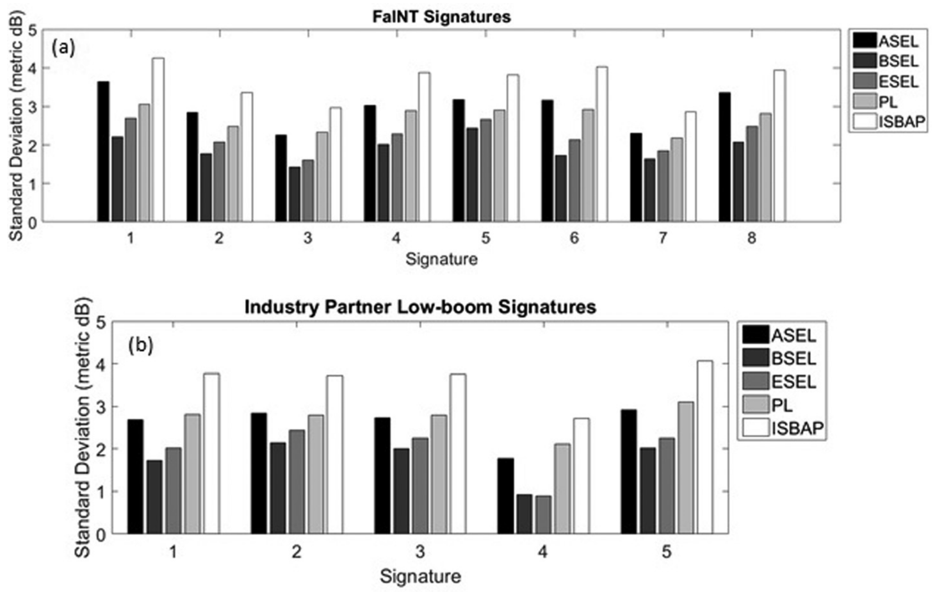

Fig. 3. (a) The standard deviation of the difference in metric value due to applying Locey's atmospheric filter functions for each of the eight FaINT N-waves. BSEL has the lowest standard deviation for all eight signatures. (b) The standard deviation of the difference in metric value due to applying Locey's atmospheric filter functions for each of the five low-boom signatures. BSEL has the lowest standard deviation for four out of five signatures.

(3) The metric values for each of the ten turbulized waveforms were calculated for each signature.
(4) The difference in metric values between each turbulized signature and original signature was calculated.
(5) The standard deviation between the sets of ten difference values was calculated for each metric and for each signature.
(6) Of the variety of metrics analyzed, the metric with the lowest standard deviation for a variety of sonic boom signatures influenced by turbulence is the most stable.

The ranges of metric values from the non-turbulized FaINT N-waves and low-boom signatures are shown in Fig. 1(b).

3. Results

The standard deviations for each signature's sets of the five metrics are shown as histograms in Fig. 3. The B-weighted sound exposure level had the lowest standard deviation for every ground-measured sonic boom from the FaINT experiment. It also had the lowest standard deviation for four out of five of the simulated low-boom waveforms. This makes it the most turbulence stable of the metrics analyzed using the ten turbulence filters. E-weighted sound exposure level was typically the next lowest standard deviation among the metrics.

4. Conclusions

With the advances in supersonic aircraft noise reduction comes the possibility of civil supersonic transport over land. In order for this to happen, a certification standard must be developed that ensures supersonic aircraft are quiet enough for community acceptance. Sonic booms sound different based on turbulence encountered along the acoustic path from the aircraft to the ground, so the certification process is not straightforward. The current study utilized Locey's linear atmospheric filters to approximate changes in a sonic boom pressure waveform at the ground due to propagation through the turbulent boundary layer of Earth's atmosphere. The goal was to find a metric whose value changes little with changes in atmospheric turbulence because it may be a useful metric for the aircraft certification process. It is likely that the limited number of filters available will not encompass the entirety of the physically realizable effects of atmospheric turbulence. More filters with known characteristic scales would be useful to verify the results shown here. However, for 12 of the 13 booms examined in the current experiment, BSEL had the lowest standard deviation. Its stability makes BSEL a good candidate for certifying supersonic aircraft for overland civil transportation.

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References and links

[1]C. Burleson, "Civil supersonic airplane noise type certification standards and operating rules," Federal Aviation Administration, Washington, DC (2008).

[2]J. D. Harrington and K. Barnstorff, "NASA begins work to build a quieter supersonic passenger jet," 29 February 2016, http://www.nasa.gov/press-release/nasa-begins-work-to-build-a-quieter-supersonic-passenger-jet (Last viewed 7 July 2016).

[3]J. Pawlowski, D. Graham, C. Boccadoro, P. Coen, and D. Maglieri, "Origins and overview of the shaped sonic boom demonstration program," in *43rd AIAA Aerospace Science Meeting and Exhibition*, Reno, NV (2005).

[4]D. Howe, F. Simmons III, and D. Freund, "Development of the gulfstream quiet spike (TM) for sonic boom minimization," *46th AIAA Aerospace Science Meeting and Exhibition*, Reno, NV (2008).

[5]D. Maglieri, P. Bobbitt, K. Plotkin, K. Shepherd, P. Coen, and D. Richwine, "Chapter 5: Approaches to sonic boom minimization," in *Sonic Boom: Six Decades of Research* (NASA, Hampton, VA, 2014), pp. 133–183.

[6]D. Maglieri, P. Bobbitt, K. Plotkin, K. Shepherd, P. Coen, and D. Richwine, "Chapter 7: Sonic boom minimization for various aerodynamic configurations," in *Sonic Boom: Six Decades of Research* (NASA, Hampton, VA, 2014), pp. 261–343.

[7]A. Pierce, "11-1 Nonlinear steepening," in *Acoustics: An Introduction to its Physical Principles and Applications* (Acoustical Society of America, Melville, NY, 1994), pp. 566–571.

[8]A. Loubeau, Y. Naka, B. Cook, V. Sparrow, and J. Morgenstern, "A new evaluation of noise metrics for sonic booms using existing data," AIP Conf. Proc. **1685**, 090015 (2015).

[9]ANSI, ANSI S1.42-2001 (R2016), *Design Response of Weighting Networks for Acoustical Measurement* (American National Standards Institute, New York, 2016).

[10]ISO, ISO 1996-1:2016 (en), *Acoustics—Description, Measurement and Assessment of Environmental Noise—Part 1: Basic Quantities and Assessment Procedures* (International Organization for Standardization, Geneva, Switzerland, 2016).

[11]S. Stevens, "Perceived level of noise by Mark VII and decibels (*E*)," J. Acoust. Soc. Am. **51**(2B), 575–601 (1972).

[12]D. Maglieri, P. Bobbitt, K. Plotkin, K. Shepherd, P. Coen, and D. Richwine, "Chapter 2: Influence of the amosphere," in *Sonic Boom: Six Decades of Research* (NASA, Hampton, VA, 2014), pp. 24–27, 35–41, 43–47, 59–62.

[13]D. J. Maglieri, V. Huckel, and H. R. Henderson, "Variability in sonic-boom signatures measured along an 8000-foot linear array," NASA, Washington, DC (1969).

[14]L. Locey, "The Atmosphere as a transfer function & filters from experimental data sets," in *Sonic Boom Postprocessing Functions to Simulate Atmospheric Turbulence Effects* (The Pennsylvania State University, State College, PA, 2008), pp. 23–70.

[15]L. Locey and V. Sparrow, "Modeling atmospheric turbulence as a filter for sonic boom propagation," Noise Cont. Eng. J. **55**(6), 495–503 (2007).

[16]L. Locey and V. Sparrow, "FIR models for sonic boom propagation through turbulence," AIP Conf. Proc. **838**, 623 (2006).

[17]L. Cliatt II, M. Hill, E. Haering, Jr., and S. Arnac, "A summary of the lateral cutoff analysis and results from NASA's farfield investigation of no-boom thresholds," in *AIP Conference Proceedings: Recent Developments in Nonlinear Acoustics: 20th International Symposium on Nonlinear Acoustics Including the 2nd International Sonic Boom Forum*, Écully, France (2015).