The Pennsylvania State University

The Graduate School

Graduate Program in Acoustics

QUANTIFYING SONIC BOOM METRIC VARIABILITY

A Thesis in

Acoustics

by

Joshua D. Palmer

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science

December 2017

The thesis of Joshua Palmer was reviewed and approved* by the following:

Victor W. Sparrow
Director of the Graduate Program in Acoustics
Thesis Advisor

Dan Russell
Teaching Professor of Acoustics & Distance Education Coordinator

Michelle Vigeant
Assistant Professor of Acoustics & Architectural Engineering

Kathleen Hodgdon
Research Associate
Penn State Applied Research Laboratory

*Signatures are on file in the Graduate School

ABSTRACT

Various sonic boom noise metrics have been calculated for a number of sonic booms, N-wave signatures. The newly computed metrics dataset utilized high-quality recordings from the Superboom Caustic Analysis and Measurement Program (SCAMP) and Farfield Investigation of No-Boom Thresholds (FaINT) experiments conducted by NASA. With these signature datasets comprised of microphone measurements by long linear arrays, one can assess the waveform variability due in part to atmospheric turbulence influences across the arrays. Preferred boom events from these NASA datasets were then chosen after review of the flight conditions, flight objectives and actual waveforms generated in order to study only the non-focused, N-wave sonic boom signatures. The sonic boom noise metrics calculated for the preferred boom events include Stevens Mark VII Perceived Level (PLdB), un-weighted Sound Exposure Level (SELz) as well as Sound Exposure Level with A, B, C, D, and E weightings applied to the waveforms. A preliminary metric currently under development by NASA, the Indoor Sonic Boom Annoyance Predictor (ISBAP), was also briefly analyzed. The results show, for example, that the A-weighted sound exposure levels and Steven's Mark VII Perceived Levels had standard deviations in the range of 1.4 dB to 6.1 dB for the SCAMP measurements and 1.2 dB to 6.1 dB for FaINT measurements. Such sensitivity results should be helpful in assessing the applicability of sonic boom metrics for use in future en-route certification standards for civilian supersonic aircraft.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

I would like to acknowledge the following sources for their help and resources: NASA, Gulfstream, Wyle and Northrup Grumman for the use of the SCAMP and FaINT sonic boom data recordings and the Pennsylvania State University Applied Research Lab for their support through a Walker graduate assistantship. I would also like to thank Kathleen Hodgdon for her advice regarding data representation. None of this work would have been possible without the great support and guidance of my advisor, Dr. Victor Sparrow. Many thanks to Dr. Sparrow for his advice, teaching and countless hours invested into supporting my research. Lastly, I would also like to thank my wife, Danielle, for her patience and support of my work.

This work was funded by the US Federal Aviation Administration (FAA) Office of Environment and Energy as a part of ASCENT Project 7 under FAA Award Number 13-C-AJFE-PSU. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the FAA or other ASCENT Sponsors.

Chapter 1

INTRODUCTION

1.1 Overview of sonic boom

Chuck Yeager was the first pilot to fly past the sound barrier when he flew the Bell X-1 at a speed of Mach 1.07 on October 14, 1947. This breakthrough led to the incorporation of supersonic fighter jets in the 1950s and then to research beginning in the 1960s toward the United States Supersonic Transport (SST) and British-French Concorde civilian aircraft programs. Civilian supersonic flight was last utilized with the Concorde service, with operations ending in 2003. While the Concorde represented a major advance in air transportation, over 40 years have passed since the last new supersonic civil transport jet began service. The main reason civilian supersonic flight did not expand was due to many governments prohibiting overland supersonic flight, due in large part to the noise impact of the sonic boom created by the Concorde. From initial sonic boom studies, the Federal Aviation Administration (FAA) passed a prohibition on overland supersonic flight over the United States in 1973. That restriction still stands today.

Aircraft flying faster than the speed of sound will create a sonic boom at all points while the plane is flying faster than Mach 1.0. To emphasize this important point: in contrast to the common misunderstanding, a sonic boom is present continuously for aircraft flying faster the speed of sound and is not simply a one-time event generated by an aircraft’s initial crossing of the sound barrier. The simple generation of the sonic boom is not inherently bad, but the type of noise that reaches the ground and the loudness of that sound have the possibility for creating community noise issues. A sonic boom traveling through the atmosphere will impact the ground below in what is called the sonic boom carpet, typically hyperbolic in shape and shown in Fig. 1-1.

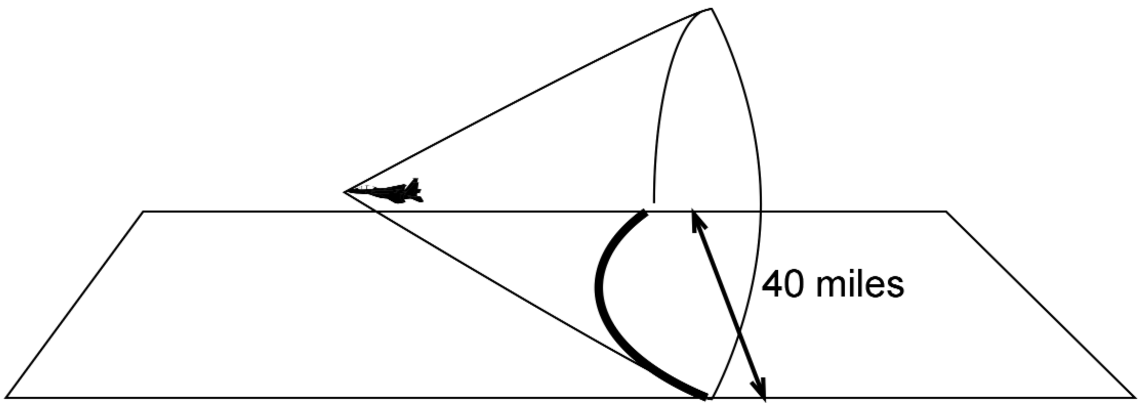

Figure 1-1: Schematic of sonic boom primary boom carpet swept over the ground.[11]

The location of the boom carpet where the shock is no longer heard on the ground is called the lateral cutoff. This point is the location in which the sonic boom rays are being refracted upward; this location merely depends on the altitude of the aircraft flight, the Mach number and the atmospheric conditions.[10] Market studies in the past have demonstrated that there is a demand for as many as 450 small supersonic civilian aircraft, pending approval of overland supersonic flight.[1] With the future goal of pursing overland supersonic aircraft in mind, a need currently exists to answer the question of what noise levels due to sonic booms created by these aircraft are acceptable to the community. A multitude of factors will lead to an adequate answer to this question; however, one piece of this puzzle is the determination of a suitable acoustic pressure waveform metric for use in both aircraft certification as well as noise level measurement. The determination of which metric is most suitable for these purposes is currently ongoing.

1.2 Research objectives

To provide an idea of the robustness of differing metrics with regards to atmospheric turbulence, aircraft operating conditions, and atmospheric changes, the observation of the variability of each metric measured across a short travel distance can be useful. Visual inspection of sonic boom waveforms measured over short linear distances can reveal fluctuations in both the shape of the waveform and drastic changes in the overpressures. Small variance measured over a linear ground microphone array may indicate robustness in the metric with respect to turbulence in the propagation path of the sonic boom noise. Likewise, high variance may show that a metric is inadequate for producing predicable ground based measurements of a sonic boom event. With these facts in mind, the sensitivities of the Stevens Mark VII Perceived Level (PLdB), Sound Exposure Level (SEL) and indoor annoyance metrics were examined by comparing variability for steady flights from existing sonic boom datasets.

Currently available sonic boom datasets were analyzed for their applicability in variability measurements. These datasets were gathered from existing measurements that have been utilized in previous sonic boom studies unrelated to variability calculations. Because none of this available data was collected with the intent of measuring metric variability in mind, great caution was taken in selecting appropriate data. The two datasets chosen for further investigation were the SCAMP (Superboom Caustic Analysis and Measurement Program) and FaINT (Farfield Investigation of No-Boom Thresholds) measurements. Further details of the conditions and differences between each will be explored in Chapter 3. Before beginning an in-depth description of the metrics to be analyzed, Chapter 2 will provide background details detailing the role the atmosphere plays in sonic boom propagation. Factors related to human perception of sonic booms will be briefly discussed.

Chapter 2

BACKGROUND INFORMATION

2.1 Atmospheric effects on sonic booms

Any aircraft moving faster than the local speed of sound will generate shock waves which are conical in shape and radiate from parts of the aircraft. These shocks will be emitted from the nose, canopy, inlet, wing and tail of most aircraft; however, in the far field it is common that only the bow and tail shocks are observed. Once reaching the ground, compression causes the local pressure to rise above atmospheric pressure; a slow expansion follows until a certain value below atmospheric pressure is achieved at which point recompression occurs at the tail shock.[10] Due to both these shocks, in the far field an undisturbed sonic boom will exhibit a classic N-wave shape in the pressure-time domain. The changes in a sonic boom waveform as it propagates toward the ground are illustrated in Figure 2-1.

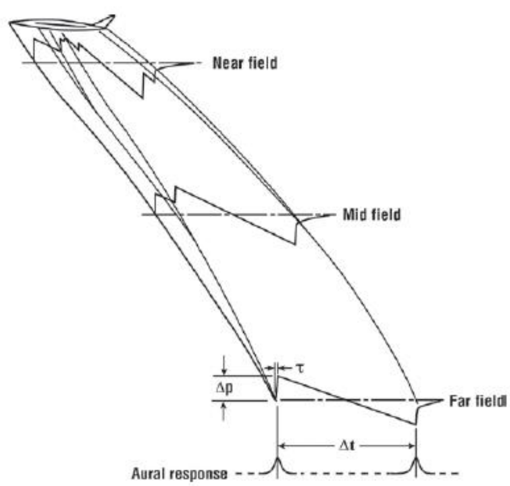

Figure 2-1: Example signatures of a sonic boom in the near, mid and far field. As the boom propagates through the atmosphere shocks from the canopy, inlet and wing will generally coalesce until only the nose and tail shocks remain in the far field.[10]

The sonic boom must propagate a great distance through the atmosphere before reaching the ground. While an N-wave shape is expected under calm/quiescent conditions, the majority of ground measured sonic boom waveforms tend to exhibit features differing from the typical N-wave. These variations can be small spikes (particularly at the front and end shocks of the waveform), rounding of the shocks and/or amplitude modulations. Numerous atmospheric factors work together to shape the final sonic boom waveform observed at a ground level. Figure 2-1 illustrates the macro and micro atmospheric effects that may be encountered during sonic boom propagation from aircraft to ground.

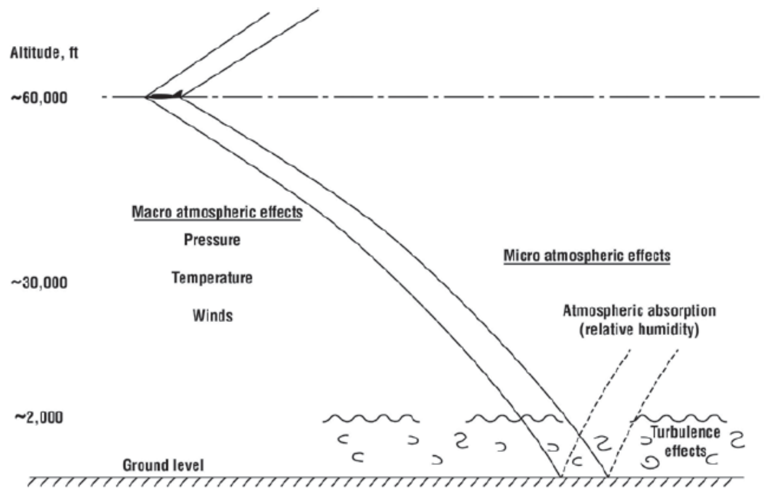

Figure 2-2: Macro and micro atmospheric effects on the propagation of sonic booms.[10]

The macro atmospheric effects of pressure, temperature and wind are well understood and included in the majority of outdoor propagation modeling approaches. Conversely, the micro atmospheric effects are much more complex and (in many cases) not modeled. The micro atmospheric effect of turbulence has been previously reported to be the principal source of sonic boom waveform variations. Turbulence can be described as the fluctuations that occur in the local sound speed in the atmosphere due to fast variations (occurring on time scales of seconds or minutes) of the temperature and wind profiles. These changes in the local sound speed produce irregular flow, with fluid particles traveling on looped paths called eddies. A sonic boom waveform will be altered by any turbulence encountered in the propagation path from aircraft to ground, as was the case for the waveforms on the right side of Figure 2-3. These waveforms are signatures measured from five microphones in a cruciform array under an aircraft flight track. The left and right sides are separate flights measured on different days and under very different atmospheric conditions.[10]

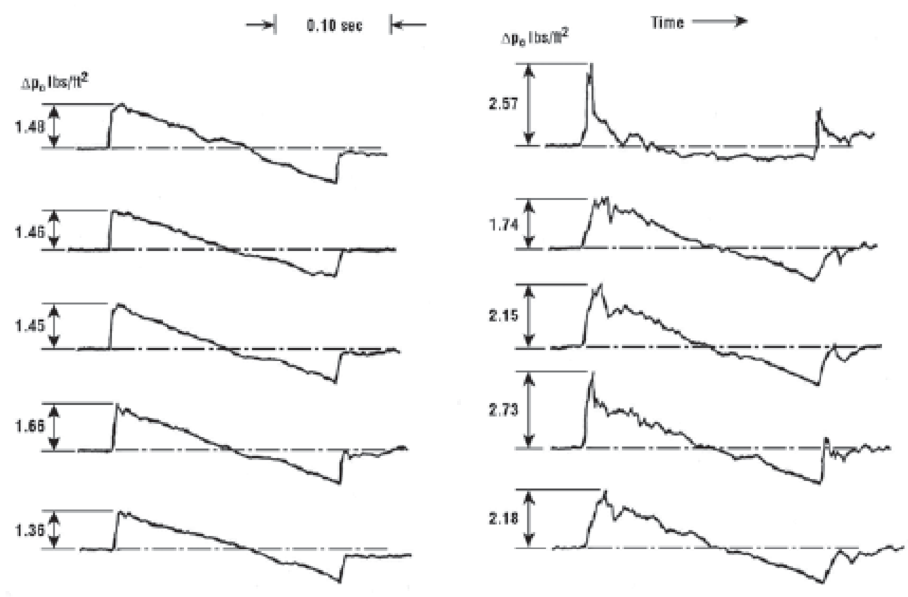

Figure 2-3: Example of sonic boom waveforms under different atmospheric conditions. Measurements are from two B-58 flights over Chicago. The booms measured on the left correspond to calm conditions whereas the waveforms on the right were measured during higher winds and turbulence.[10]

While the effects of turbulence on waveforms are widely known, there is no other current work on the amount of variability caused in metric measurement. The turbulent boundary layer, a section of the atmosphere that lies between the ground and the first few kilometers of the atmosphere, is extremely important in sonic boom propagation. Another aspect of sonic boom noise to consider is how the sound is perceived once it has reached an observer.

2.2 Human perception of sonic booms

Human perception of sonic booms is incredibly important and involves several factors. A key concern underlying existing federal regulations is how people may respond to sonic boom noise. One challenge in the understanding of human response and acceptability of sonic boom noise is the lack of significant data on low-amplitude shaped signature boom noise. NASA reports that the “vast majority of the community response database is for N-wave signatures having overpressure in the 1.0 lb/ft^2 to 3.0 lbs/ft^2 and durations of 100 msec to 300 msec. For this boom level range, 13 to 33 percent of the population was highly annoyed.”[10]

However, sonic booms from future supersonic aircraft will almost certainly have overpressures below this range. Due to this fact, a recent study has been conducted on human annoyance to lower overpressure sonic booms (ranging from 0.13 lbs/ft^2 to 0.53 lbs/ft^2). This study was the Waveforms and Sonic boom Perception and Response Program (WSPR).[13] The WSPR utilized 49 subjects living in Edwards Air Force Base Housing area and had them rate annoyance using a cell phone application. Throughout a two week period, WSPR asked these subjects to respond to social surveys to rate annoyance according to six dimensions of subjective response to noise. Some amount of annoyance was reported in 24% of the sonic booms responded to by the subjects.[12]

For an outdoor sonic boom event, annoyance is related to multiple facets of the sonic boom signature spectrum. Overpressure is a key factor in annoyance but not the only contribution. It has also been shown that rise time is important in the annoyance level. As an example an increase in shock rise time from 1 msec to 10 msec decreases loudness and annoyance by about 13dB.[10] The concept of startle is also very important in the impact of sonic boom noise. Sonic boom noise can be unexpected and cause a subject to become startled, similar to startle that can be caused by thunder.

Sonic booms with higher overpressures (much above the low booms expected to be produce by future aircraft designs) can have significant impact on structures, causing things to rattle and even fall off shelves. This impact on structures can directly relate to human annoyance of sonic boom noise. The indoor stimuli received by a listener are made up of components from three primary senses: auditory, visual and tactile. An individual may be influenced by the sight of objects shifting or shaking slightly as a boom propagates through the house; they may also have a sense of discomfort attributed to any vibration that is directly felt. The indoor boom waveform experiences attenuation and is at times an amplitude of magnitude smaller than the outdoor signal. It is, however, still thought to be important to the overall impact of the sonic boom exposure in an indoor environment.

Chapter 3

SONIC BOOM DATASET OVERVIEW

3.1 Recordings from Superboom Caustic Analysis and Measurement Program (SCAMP)

From the available sonic booms datasets, the determination for data which were useful for further analysis was based upon a specific set of criteria. These sonic boom datasets were collected from available measurements initially taken between 1964 and 2012. They were collected and compared for the purposes of finding high fidelity recorded booms which closely resembled a typical N wave boom waveform. Due in part to the fact that no specific data compilation was collected with the intended purpose of metric sensitivity analysis, careful consideration was given into which booms would be most suitable for use outside of the purposes for which they were original measured. There were four main criteria used when narrowing the available datasets and booms to be selected for analysis. With the comparison of the sensitivity of various metrics in mind, the criteria that the booms be recording using a linear array of microphones was thought to be ideal for simplifying any analysis of the potential causes of variability found. An additional criterion was that measurements used should also be outdoor measurements. Thirdly, data with a high enough sampling frequency for adequate fidelity was required in order to calculate all of the metrics in a meaningful way. Finally, there was a criterion for booms to have an N-wave shape; this criterion was adopted to root out booms that were shaped because of measurement objectives such as Mach or lateral cutoff. One such sonic boom dataset that contained measurements that fit the four criteria is the Superboom Caustic Analysis and Measurement Program (SCAMP), collected at the Cuddeback Gunnery Range in California.

The primary objective of the SCAMP program was validation of sonic boom propagation models providing predictions for a focus boom, occurring typically during acceleration of the aircraft to supersonic speeds.[3] For the SCAMP supersonic flights, measurements were primarily made along a 3048 meter array consisting of 81 microphones spaced at a distance of 38.1 meters. Microphones were connected to four different recorders with different organizations operating each. The first section included microphones 00-12 and was run by Northrup Grumman. The second section was microphone array locations 13-32 and was run by NASA Dryden. The third section of the array was operated by Wyle, NASA Langley and Penn State University and included microphones 33-60. Finally, microphones 61-80 were run by The Boeing Corporation.[15] An F-18B fighter jet created the desired sonic boom at varying altitudes depending upon the flight objective. Sonic boom measurements were collected at a sampling frequency of 24 kHz. A total of 70 boom signatures were gathered during the course of 14 flights during June of 2011. While most of the booms measured in SCAMP do create a focus event at some point on the array, the nine selected flights contained only steady non-focus event measurements. Thus, these nine separate sonic boom measurements were chosen for variability analysis from the SCAMP project. For these flights the F-18B aircraft flew either directly over the linear array or 3840.5 to 5700 meters off track (still flying parallel to the array) at Mach numbers ranging from 1.17-1.30. Figure 3-1 depicts the pressure waveforms for boom 12741, one particular case of a non-focus boom event, across microphone channels 13 to 60.

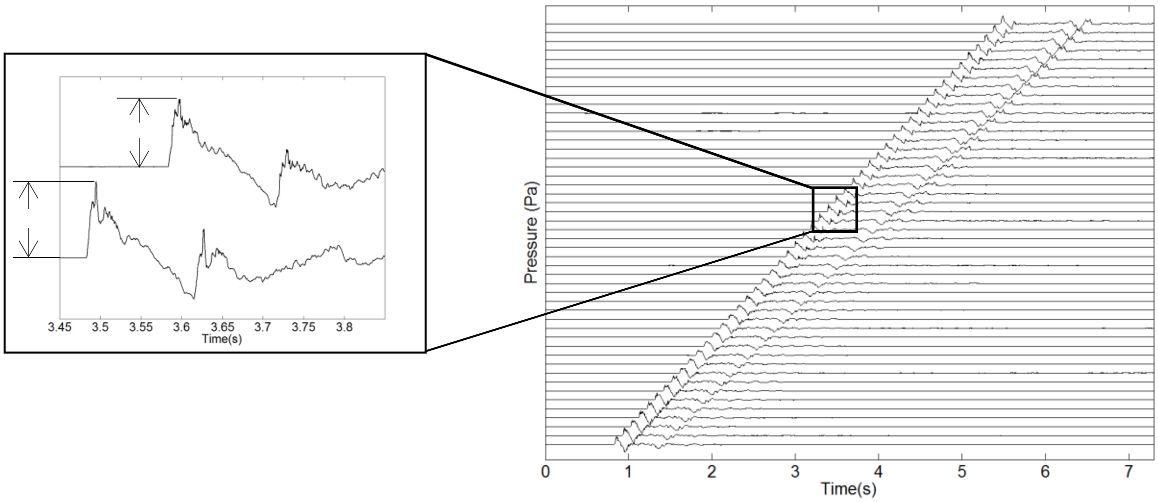

Figure 3-1: Waterfall pressure plot of SCAMP boom 12741. 7.3 seconds of data from Channels 13-60 is shown with microphone channels in ascending order.

Flights flown off track from the linear microphone array will be useful in showing any disparity in the observed variability due to differences in propagation path length. Figure 3-2 illustrates the difference between off track and on track flight paths.

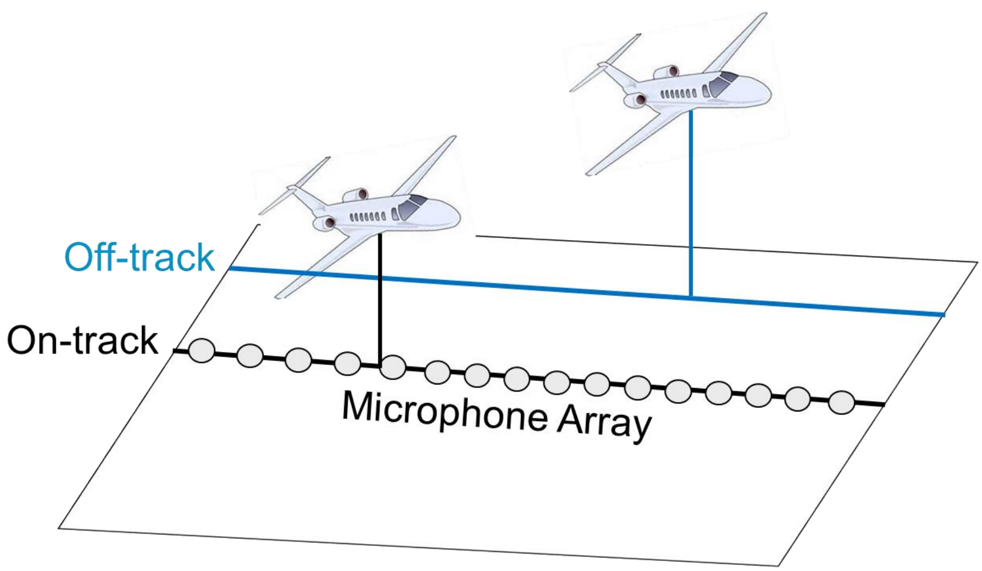

Figure 3-2: SCAMP on-track versus off-track measurements. The distance separating the off-track flights from the microphone array varied from 3840 m to 8230 m.

As stated, these off-track flights create a difference in the propagation path length. This difference is especially important in the estimated distance the sonic boom will travel through the turbulent boundary layer (TBL). This propagation distance was calculated with the assumption flight tracks were directly parallel to the direction of the microphone array. Additionally, an estimate for the turbulent boundary layer thickness was made based upon the weather data available and time of day of the flights. Gionfriddo[5] provides a calculation for the path length through as shown in equation (1).

$$l_{TBL} = \left(\frac{B}{A}\right)\frac{\sqrt{A^2+D^2}}{\cos\theta_m} \quad \text{for } B \leq A. \tag{1}$$

In the above equation, θ_m is the Mach angle in radians; D is the lateral distance between the microphone array and flight track and Figure 3-3 depicts the geometry for terms A and B.

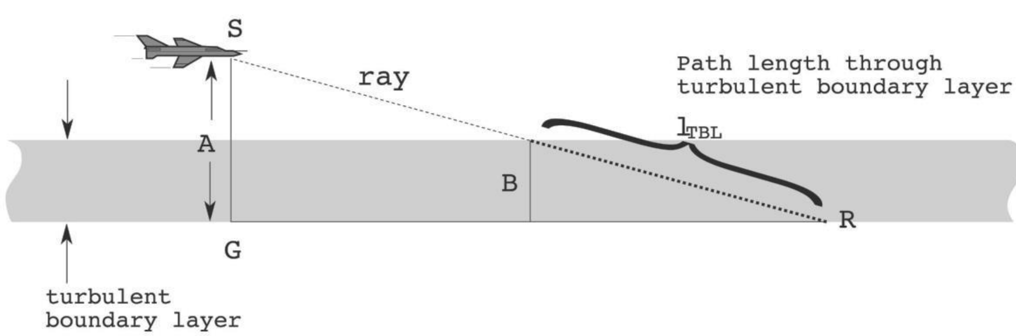

Figure 3-3: Path length portion through the turbulent boundary layer. Drawing is not to scale, i.e. the altitude A is usually several times greater than the TBL thickness B.[5]

For the SCAMP flights analyzed, Table 3-1 shows results of calculating the total propagation distance and the distance through the turbulent boundary layer of the different maneuver types used in variability analysis. Here, a boundary layer of 1200 m thickness was assumed in all cases, to compare differences between the propagation distances.

Table 3-1: Propagation distances for SCAMP flight maneuvers: both steady on-track and off-set Mach 1.17, 1.2 and 1.3 flights. Total propagation distance and propagation distance through a turbulent boundary layer with a thickness of 1200 m are given.

Maneuver	Offset 1.17	Steady 1.17	Offset 1.2	Steady 1.2	Offset 1.3	Steady 1.3
Altitude [m]	12192	12192	10668	10668	10668	10668
Offset [m]	3840	0	5699.76	0	8229.6	0
Mach angle [rad]	1.025	1.025	0.985	0.985	0.878	0.878
Propagation Distance [m]	24624	23486	21881	19299	21086	16696
Distance in TBL [m]	2462	2349	2501	2206	2410	1908

From the data shown in Table 3-1, there is a maximum difference of about 500 m in the distance traveled through the TBL between the offset and on-track Mach 1.3 flights. The higher speed flights yield a greater decrease in distance traveled in TBL; this is produced by the decreasing Mach angle yielding a more direct (steeper) propagation path from aircraft to ground. An initial hypothesis from increased distance traveled through the TBL is that the metrics measured with longer propagation distances in the TBL should exhibit higher amounts of variability. This will be examined further in Chapter 5's results.

Another important piece of information in interpretation of any variability results is an understanding of the atmospheric conditions at the time of the SCAMP flights. All on-track flights (booms 12611-12616) were measured on May 10th, while all off-track flight data was gathered on May 20th. GPSsonde balloon data was gathered for each flight during the SCAMP project; the gathered data from the two days of importance for this analysis are shown in Figures

3-4 and 3-5. Additional information on the focused sonic boom experiment execution and measurement can be found in AIAA report.[14]

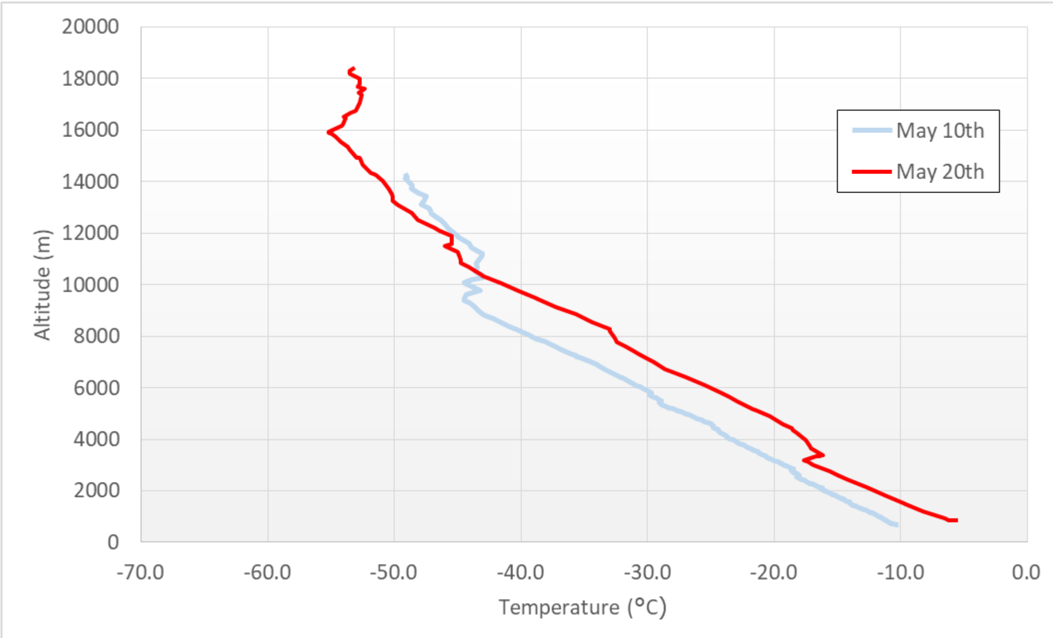

Figure 3-4: Temperature versus altitude data for SCAMP on May 10th and 20th. Similar temperature profiles are seen both days, with a static difference of about 5°C from ground level to nearly 10 km.

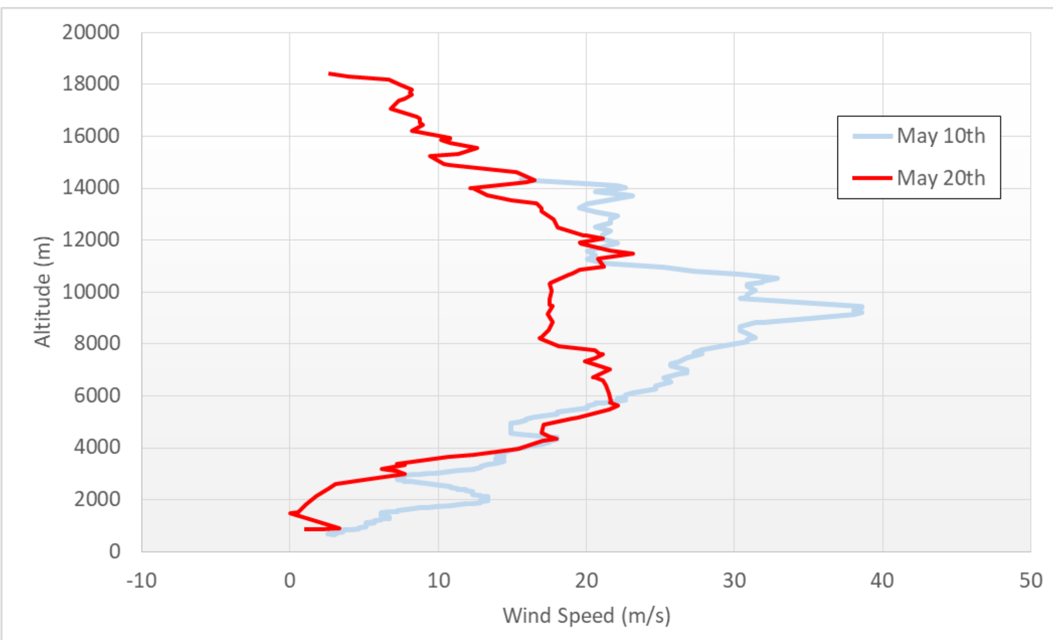

Figure 3-5: Wind speed versus altitude data for SCAMP on May 10th and 20th. A large difference in wind speed is observed between 6 km and 10 km, which is altitudes the SCAMP sonic booms will propagate through due to their flight altitudes being between roughly 10 km and 12 km.

3.2 Recordings from Farfield Investigation of No-Boom Thresholds (FaINT)

A second dataset that fit the required criteria was the Farfield Investigation of No-Boom Thresholds or FaINT data. The FaINT program was conducted at Roger Dry Lake on Edwards Air Force Base in November of 2012. The purpose of FaINT was to measure specific maneuvers that could create evanescent waves due to lateral or Mach cutoff conditions.[16] Lateral cutoff conditions exist near the edges of the sonic boom carpet, whereas Mach cutoff conditions exist when an aircraft cruises beyond the speed of sound without a boom reaching the ground. Similar to SCAMP, the FaINT program employed the use of F-18 aircraft to produce sonic booms. A linear microphone array of sixty microphones each separated by roughly 38.1 m is also useful, as it matches the same spacing as the SCAMP microphone array. Data was also collect on a spiral pattern microphone array but will not be used in this metric variability analysis. Depending on the array and specific microphone channel, measurements were collected at sampling frequencies varying from 24 kHz to 32.768 kHz. A total of 73 boom signatures were observed over the course of 13 supersonic flights. Through use of the ground reports and manual inspection of the waveforms it was determined that 11 of the booms may be useful in metric sensitivity analysis due to showing only small or no signs of lateral/Mach cutoff. One key difference in some of the measurements obtained from SCAMP and FaINT is in the flight path relative to the microphone array placement for a portion of the data. When the objective of FaINT was in measuring lateral cutoff, the flight paths were perpendicular to the microphone array. This measurement layout for lateral cutoff flights is illustrated in Figure 3-6. Figure 3-2 can be used for reference of the flight path of the Mach cutoff flights.

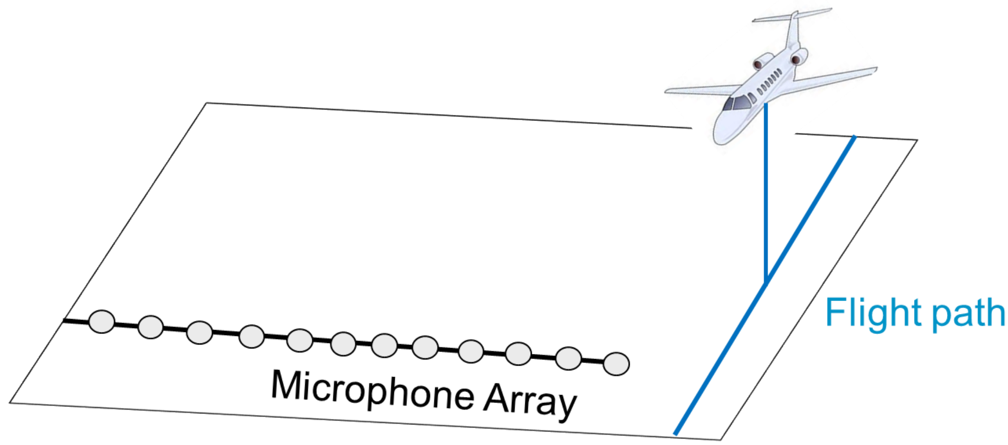

Figure 3-6: Flight path and microphone array location for FaINT lateral cutoff measurements. The flight path was offset the microphone array near 20 km, varying slightly depending on each flight and the objective.

Using the same calculation as the SCAMP program, the sonic boom propagation distance can be estimated. However, now instead of assuming the same propagation distance for the entire microphone array the distance will increase along the array. Exact latitude and longitude locations of both the array and flight path were used for this calculation. Figures 3-7 and 3-8 show the total propagation distance and distance through the TBL, respectively, for a representative flight.

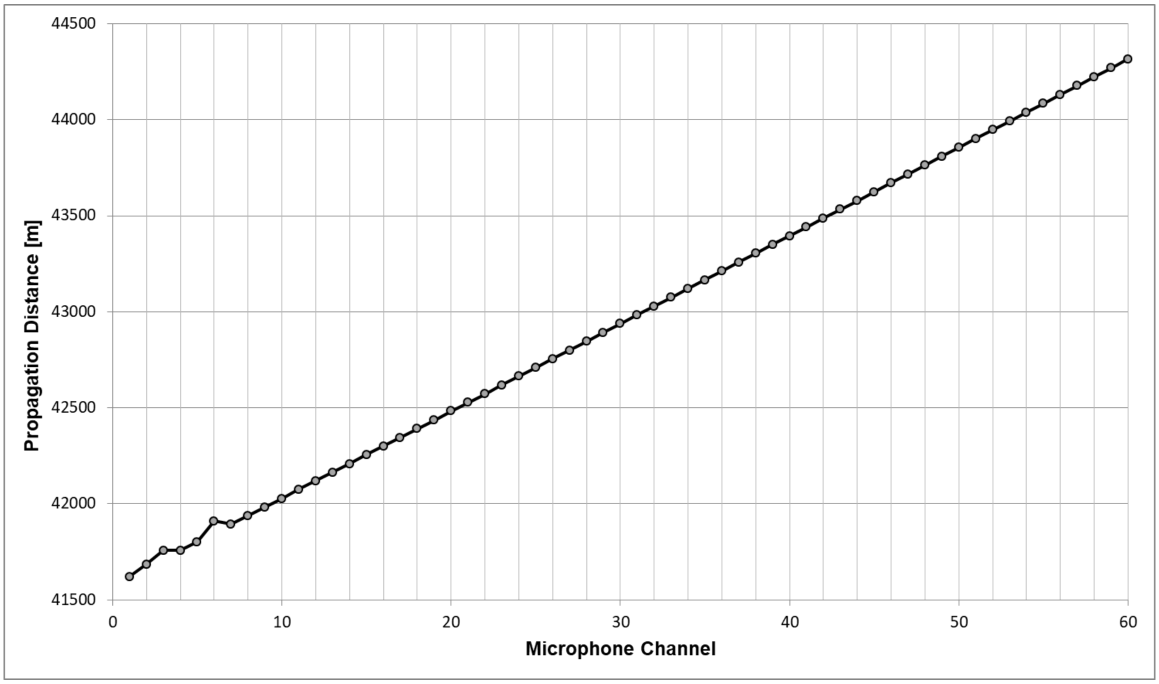

Figure 3-7: Total propagation distance from aircraft to each microphone channel.

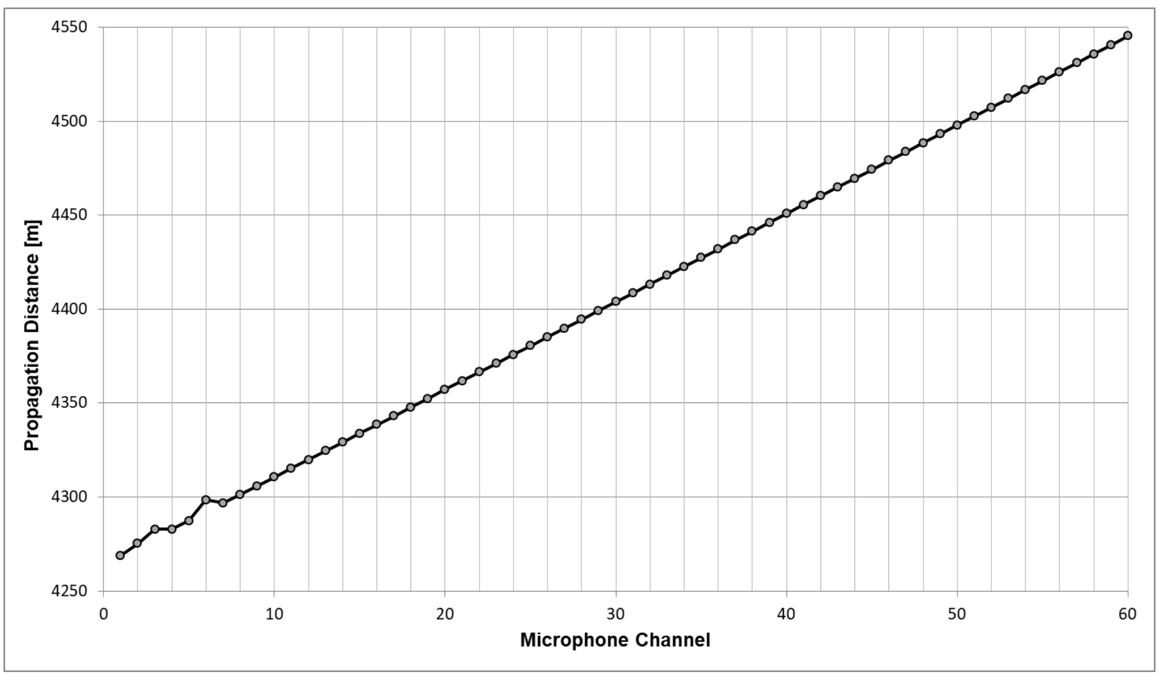

Figure 3-8: Propagation distance through the turbulent boundary layer for each microphone channel. Note that the propagation distance shown through the boundary layer is directly related to the total propagation distance in this case. This is because the only parameter that is changed across the microphone array as l_{TBL} is calculated at each location is D, the lateral distance of the flight to the microphone.

3.3 Additional datasets

A total of twelve additional datasets were collected and examined for their usefulness in sensitivity and variability analysis. These twelve datasets were not chosen for various reasons. One of the most common restrictive factors was the desire for outdoor boom measurements. This requirement eliminated data from the Vibro-Acoustic Response of Buildings due to Sonic Boom Exposure (VIBES) and Boom on Big Structure (BOBS) measurements. Another restrictive requirement was that the measurements should have been collected along a linear microphone array, which eliminated most of the NASA/USAF data compilation. See the table supplied in Appendix C for a short description of these additional sonic boom measurements.

Chapter 4

SONIC BOOM METRICS

4.1 Overview

The metrics selected for sensitivity analysis were chosen due to their high correlation with human perception data of sonic boom annoyance, ease of calculation, and availability within the engineering community. A recent analysis of numerous sonic boom metrics was consulted to guide the selection of metrics to consider.[8] Sound exposure level (with and without weighting functions applied), perceived level, and indoor annoyance will be the three metrics of our primary focus. Sound exposure levels were calculated with A, B, C, D and E weighting functions applied to the sonic boom waveform, applied according to ANSI S1.42-2001. Sound exposure level was calculated according to ANSI/ASA S1.4-2014, where sound exposure is the time integral of the square of a frequency-weighted signal over a given time interval. The second metric, perceived level, was calculated in accordance with the Mark VII method[2] using a combination of MATLAB providing input for FORTRAN code originally developed at NASA Langley. The indoor annoyance metric is a preliminary metric developed by NASA and will be further discussed later in the chapter. Lastly, the calculation of each of these metrics was independently verified through the use of crosschecking in conjunction with other organizations.

4.2 Perceived level

Perceived level (PL) is a measure of the loudness or noisiness of a sound. The Mark VII method for calculation of PL was developed by Stevens and published in the Journal of the

Acoustical Society of America in 1971.[2] One notable difference between the earlier Mark VI and Mark VII method was the inclusion of an extension of the calculation to lower frequency bands, a fact which is very important for sonic booms. The calculation of this metric begins with the assumption of a waveform which has been measured in terms of sound pressure levels in either one-third octaves or single octave bands. These measured sound pressure levels are converted to perceived values in sones, in accordance with the loudness contours shown in Figure 4-1.

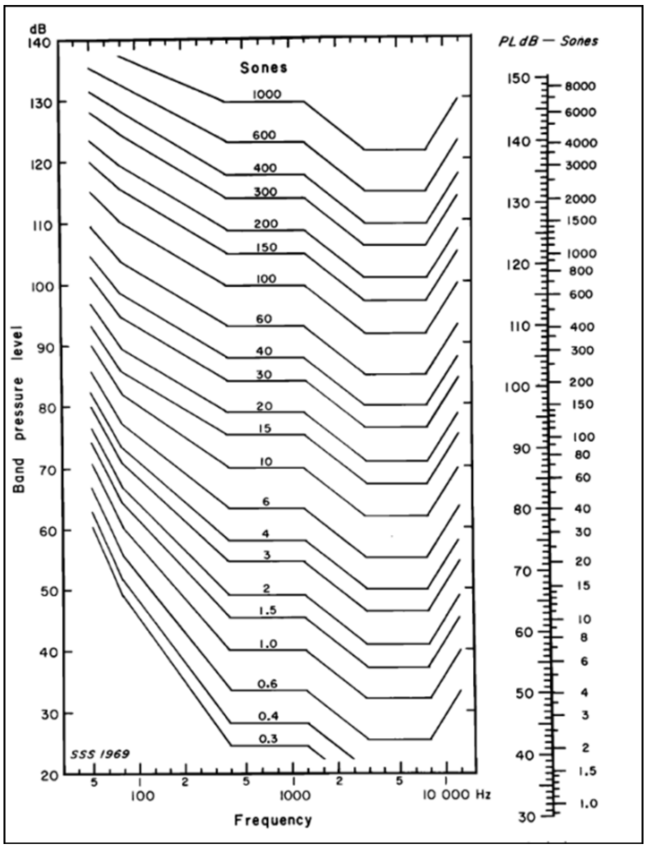

Figure 4-1: The figure depicts perceived level loudness contours for use in the calculation of Steven's Mark VII Perceived Level. To the right is a nomogram giving a relationship between the sound level magnitude in sones and perceived level in PLdB.[2]

These loudness levels at each band level are summed into a total loudness, S_t, using the following summation rule with S_m being the loudness of the loudest band and $\sum S$ the total of the loudnesses of all bands:

$$S_t = S_m + F * (\sum(S - S_m) \, [sones]. \quad (2)$$

In the summation rule the factor, F, is the fractional loudness contributed by each band. This value varies depending on whether octave or one-third octave bands are being used. This variation is depicted graphically in Figure 4-2.

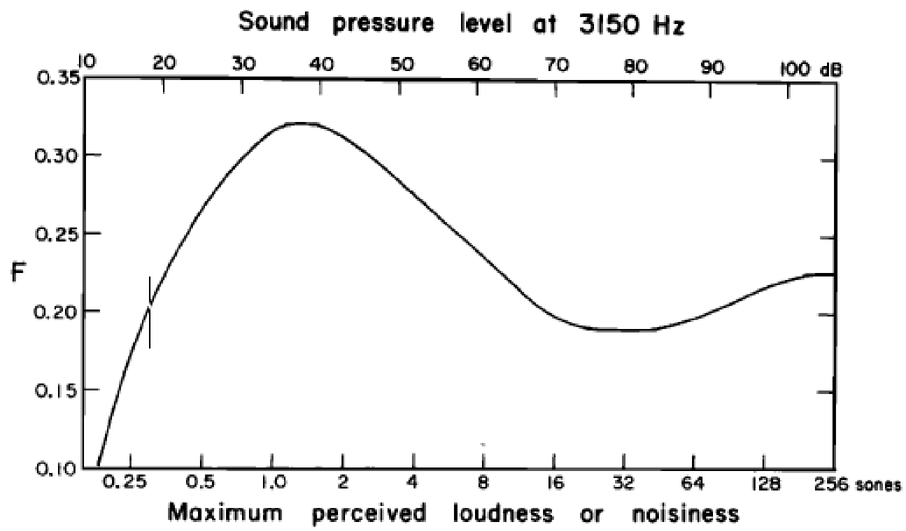

Figure 4-2: This figure depicts how F, the fractional loudness contribution, varies depending on maximum perceived loudness. As an example, the value of F used for one-third octave bands with a sound pressure level at 3150 Hz is displayed. There is a peak in the fractional loudness contribution between a maximum loudness value of 1.0 and 2 sones.[2]

After converting the band levels to a single total loudness level, this value is converted from sones to decibels (PLdB). This is accomplished by use of a power function which gives a direct relationship between the perceived magnitude of the sound and the sound pressure level. For levels above a threshold of 20 dB S_t is converted to the perceived level, PL, with the following equation:

$$PL = 32 + 9\log_2 S_t. \tag{3}$$

This equation is based upon the power law relationship of the reference signal perceived magnitude, S, and power of the reference signal, E:

$$S = k(E - E_0)^{\frac{1}{2}}. \tag{4}$$

E_0 is a threshold value which corresponds to a sound pressure level of around -3 dB (re: 20 μPa). More in depth discussion on some of the specifics on the use of PLdB for sonic booms and impulsive noise can be found in Stevens [2].

Appendix A.2 displays how this metric was implemented in MATLAB. For this research, the majority of the calculation of the perceived level metric was handled by a FORTRAN code originally developed at NASA, with which the MATLAB code shown interfaces with. In MATLAB, inputs for FORTRAN are written to a .txt file and sent to FORTRAN with the waveform data for evaluation. FORTRAN produces a results file which is then procedurally read back into MATLAB. This process is repeated for each microphone channel along the array.

4.3 Sound exposure level

Sound exposure level provides a measure of the time averaged pressure squared to a reference value. The standard reference, E_0, is a squared pressure over a time period. For all sound exposure level calculations for metric sensitivity analysis, a reference pressure of twenty micro-pascals and reference time frame of one second is used, giving a value of E_0 = 400 pico-pascal squared seconds. The sound exposure level, $L_{E,T}$, was calculated according to ANSI/ASA S1.4-2014, whose equations are defined as follows:

$$L_{E,T} = 10\log_{10}\left[\frac{\int_{t_1}^{t_2} p^2\,(t)dt}{p_0^2 T_0}\right], \tag{5}$$

$$E_0 = p_0^2 T_0 = (20\ \mu\text{Pa})^2 \times \left(1\ \text{s}\right) = 400 \times 10^{-12}\ \text{Pa}^2\text{s}. \tag{6}$$

Details of the calculation of this metric in MATLAB are shown in Appendix A.3. The input signal was first up-sampled and zero-padded by a length of 33% to allow for a weighted function response. The calculation takes into account the energy lost by adding these zeros, scaling by the factor *upfact*. A Butterworth filter was used to interpolate the now zero-padded samples and this result was then squared and multiplied by the time differential. Finally we divide by the reference factor, E_0, and convert the calculated exposure level to decibels. This calculation provides what is referred to as the unweighted sound exposure level. It is also important to consider the impact of different weighting functions on the sonic boom waveforms in regards to the sound exposure level.

4.4 Weighting functions

Weighting functions were applied to waveforms alongside the use of the sound exposure level metric. The comparison of these weighting functions may be important in assessment of metric robustness to turbulence due to certain weightings capturing much more low frequency energy of the sonic boom waveform. Weightings A, B, C, D and E were evaluated for their benefit on the measured variability. The relative frequency response of each can be viewed in Figures 4-3 and 4-4:

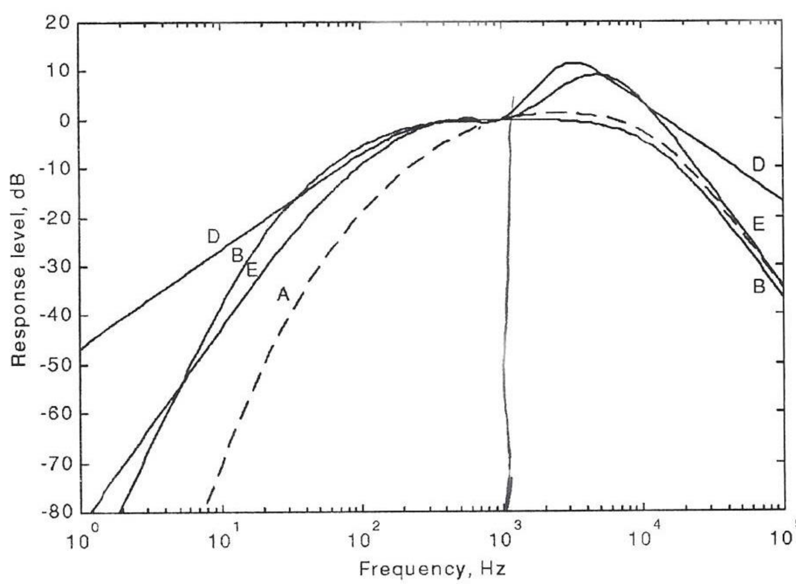

Figure 4-3: The relative frequency response of the A, B, D and E weighting functions are shown. Note the 1 kHz frequency has the same response level for all weighting functions.[9]

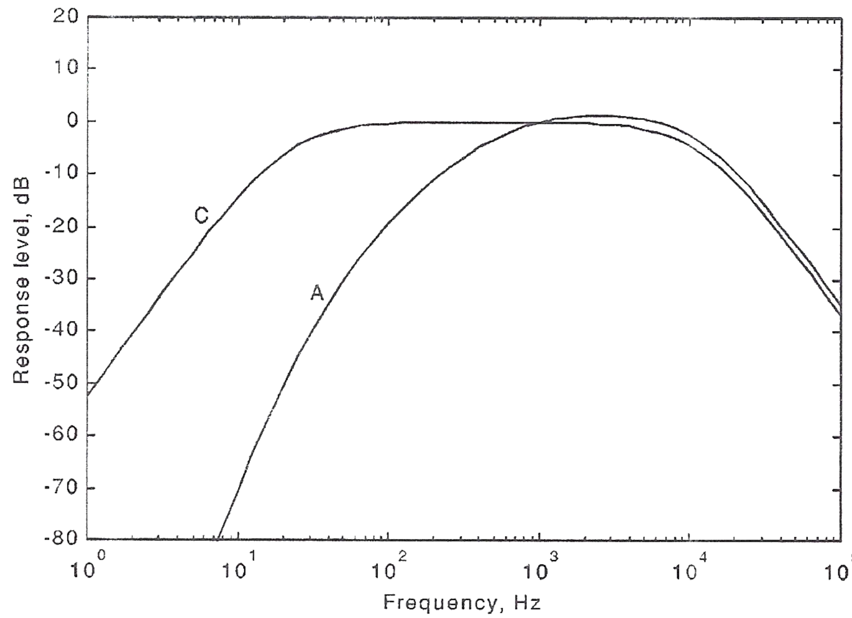

Figure 4-4: The relative frequency response of the A and C weighting functions are shown.

Each weighting network was developed using ANSI S1.42-2001, Design Response of Weighting Networks for Acoustical Measurements.[9] Due to complex poles in the D and E weightings two different methods were utilized in the process of creating the weighting function in MATLAB. For the A, B and C networks a Laplace transform method was used and for D and E networks the zero pole gain method was selected. These methods were chosen for each of the networks based on ease of implementation in MATLAB and correct functionality. For both methods a linear time-invariant filter is applied to the input signal, $s_i(t)$, according to equation (7):

$$s_0(t) = \int_0^{\infty} s_i(t-\tau)h(\tau)d\tau. \tag{7}$$

ANSI S1.42-2001 provides the zero and pole frequencies of the transfer function for each weighting network from which a Laplace transform or zero pole gain model is utilized to obtain $h(\tau)$, the impulse response of the filter.[9] Appendices A.4-A.7 are given for reference to the implementation of the weighting networks in MATLAB. Perceived level and weighted sound exposure level are established metrics that have been used commonly in the past for both sonic boom and other acoustic measurements; next, a newer metric in development at NASA Langley will be introduced.

4.5 Indoor Sonic Boom Annoyance Predictor

The Indoor Sonic Boom Annoyance Predictor (ISBAP) is a preliminary metric, currently under development at NASA. The purpose behind this metric is to obtain a metric that could give insight into annoyance caused by sonic boom noise indoors using only outdoor measurements. To achieve this goal Steven's Mark VII perceived level, A-weighted sound exposure level and C-weighted sound exposure level are combined linearly with adjustment factors. The formula for ISBAP provided at the time of this research is:

$$ISBAP \ = \ -6.827 + 0.0864(PL) + 0.0363(SEL_C - SEL_A). \tag{8}$$

The subtraction between A and C sound exposure levels is intended to capture the low frequency impact of the sonic boom that has been noted to correlate with human annoyance to rattles. Please note NASA changed the above definition of ISBAP in late 2015. The coefficients in the equation were rescaled so that ISBAP would be in decibels instead of in annoyance units. For this research we will use the original definition with an output in annoyance units. Additional details concerning the implementation of this calculation in MATLAB can be found in Appendix A.8.

4.6 Variability in metric values

Variability of the metrics was calculated by utilizing MATLAB functions for determination of the standard deviation, mean and median of the calculated metric at each microphone channel in the array. The mean is the statistical average of a dataset while the median is the number that divides the lower half of a dataset from the upper half. The median can also be referred to as the second quartile. Generally, the median can be thought of as a more robust statistical measure in comparison to the mean; that is to say, it has less variation in the presence of outlier points. Related more to the mean than median, the standard deviation provides a numerical description of the proximity of a dataset to the expected value (mean). For a set of data, A, composed of N observations, the standard deviation, σ, can be defined as:

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}|A_i - \mu|^2}. \qquad (9)$$

In this equation the exact relationship between variance and the mean value, μ, is observed. Another way of thinking about standard deviation is that it describes the spread of numbers in a set of data points.[4] Comparing the standard deviations of one dataset to another is a useful tool in quantifying the difference in variance.

Metric variance is graphically depicted in the results through use of a box-and-whisker plot representation of the datasets. Figure 4-5 provides a detailed description of the various sections of the type of box-and-whisker plot for one of the results from SCAMP for the PLdB metric. This same representation will be applied to all other box-and-whisker plots throughout the results.

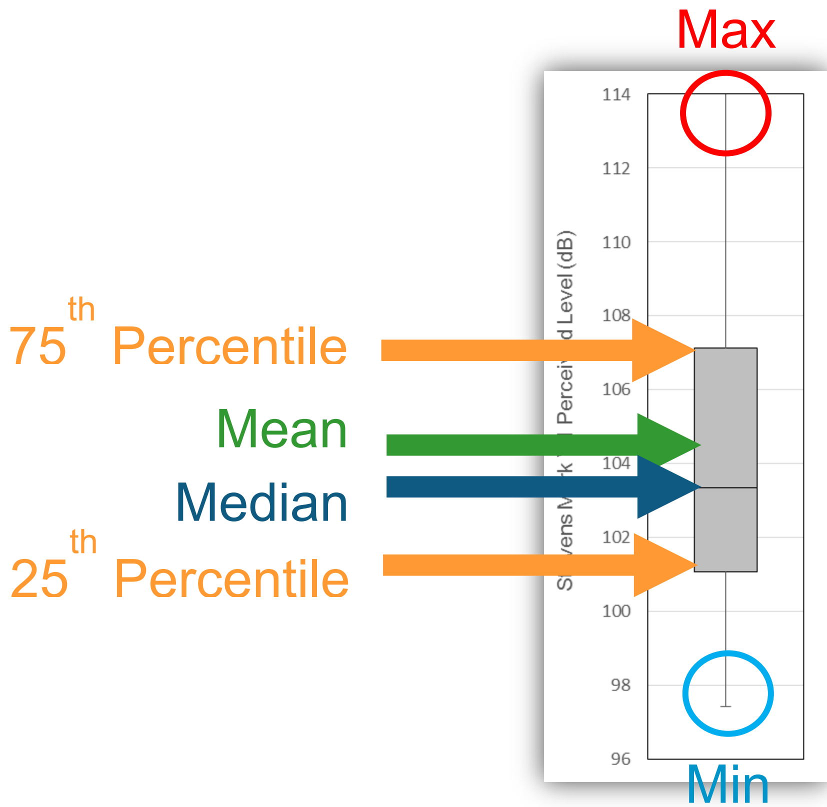

Figure 4-5: Graphical explanation of box and whisker plot graphical data representation. The top and bottom whiskers represent the minimum and maximum value in the dataset. The box represents half the range of values, from the 75th percentile to the 25th percentile. The mean and median can also be seen, the median being visually displayed as a line across the box and the mean being imagined as the midpoint of the box.

A box-and-whisker plot is a useful way in using the quartiles of a set of data to show variation. One tremendous advantage of this type of data representation is that it allows for comparison between multiple sets of data on one plot, as will be evidenced in the results. Now armed with some knowledge of the implementation and calculation of these metrics, we can continue on to results found in the SCAMP and FaINT datasets.

Chapter 5

METRIC SENSITIVITY RESULTS

5.1 Introduction to SCAMP flights

Metric sensitivity results were computed for both on track and off track flights for the SCAMP dataset. This analysis focuses on booms 12611-12616 for on-track flights and booms 12741-12743 for off-track. The SCAMP supersonic flight measurements were obtained primarily along a 3048 meter array consisting of 81 microphones spaced at a distance of 38.1 meters. The variability of metric measurements will be displayed both on a single boom basis (all channels visible) and in comparisons with the information condensed utilizing the box-and-whisker method as was illustrated in Figure 4-3. The SCAMP program contained six flights that were steady and on track. The speed of each of the flights is as follows: the flight for booms 12611 and 12612 was flown at Mach 1.17, the flight for booms 12613 and 12614 was at a slightly faster Mach 1.20 and the final steady on track flight, for booms 12615 and 12616 was flown at Mach 1.30. The mean A-weighted SEL for these six on track flights ranged from 82.9 to 91.4 dBA, compared to mean PL ranging from 98.5 to 106.5 dB. Figure 5-1 depicts a typical measurement of PL across the microphone array. For the boom shown, a maximum PL of 114.6 dB was measured at channel 60, with a minimum of 97.4 dB being measured at channel 7.

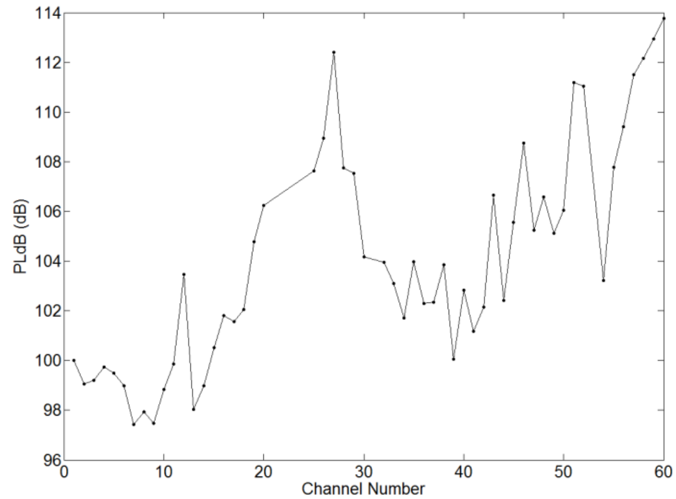

Figure 5-1: Stevens Mark VII Perceived Level across microphone channels of boom 12613, from a flight flown at Mach 1.20. This metric has a range of 8.4 dB and mean value of 104.1 dB. Channels 21-24, 31 and 53 are omitted due to microphone malfunctions.

Figure 5-2 displays the A-weighted sound exposure level across the microphone channels for the same boom, 12613. Most of the major features of the variability between channels remain the same for both metric calculations. The same is seen of the other weighted sound exposure level metrics and ISBAP metric. Visually it is apparent that there is a substantial amount of variability in the calculated metrics depending on the microphone location in the array.

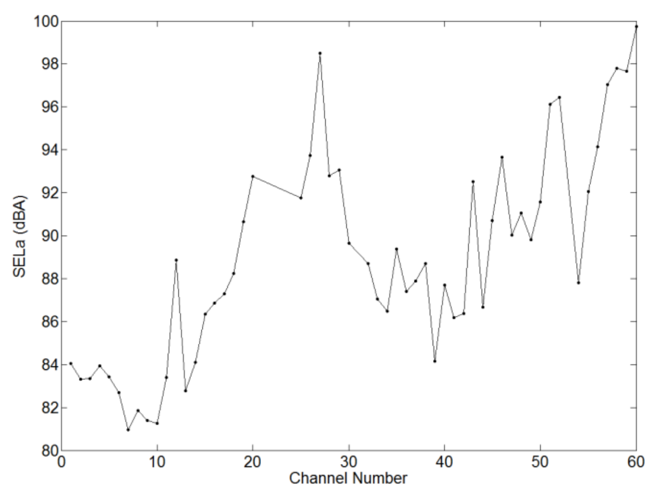

Figure 5-2: A-weighted sound exposure level across microphone channels of boom 12613. Channels 21-24, 31 and 53 are omitted due to microphone malfunctions.

5.2 On track SCAMP Results

5.2.1 Sound Exposure Level (SEL) Results

The following figures provide an informative way of viewing changes in the variance of each metric. The box and whisker plots shown here display the metrics for all on track SCAMP boom measurements selected for analysis. Figure 5-3, displays the results for E-weighted sound exposure level for the six on track booms. Of the six booms, 12612 showed the most variability with a standard deviation of 5.4 dBE while boom 12615 exhibited the smallest variability, with a measured standard deviation of 3.5 dBE. The mean E-weighted SEL values were calculated to be between 88.8 dBE (for boom 12611) and 97.2 dBE (for boom 12612).

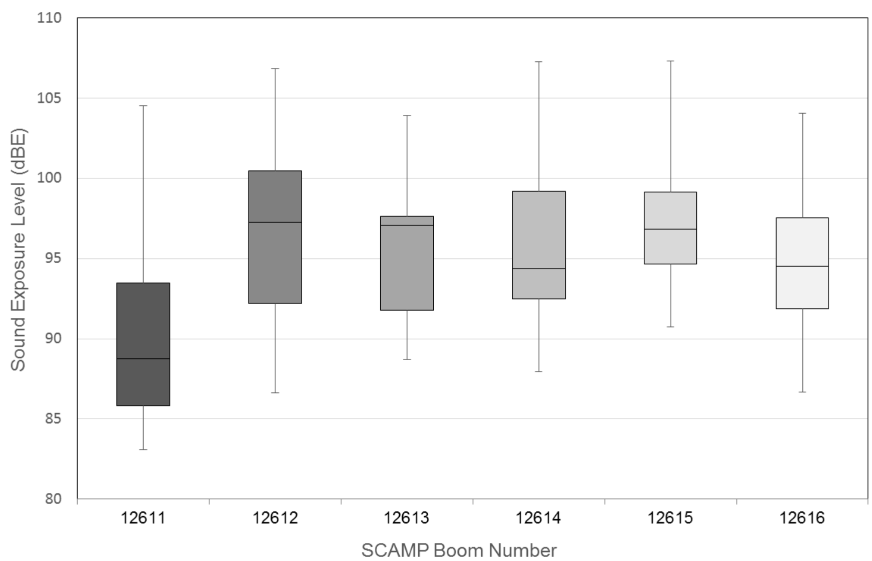

Figure 5-3: E-weighted sound exposure level measurements for on track booms of the SCAMP data set.

Table 5-1: E-weighed sound exposure level mean, standard deviation, median, maximum and minimum values for on track booms of the SCAMP data set.

SCAMP Boom Number	Description	E-Weighted SEL Mean (dB)	E-Weighted SEL Std. Deviation (dB)	E-Weighted SEL Median (dB)	Max (dB)	Min (dB)
12611	On-track Steady Mach 1.17	89.9	5.3	88.8	104.5	83.1
12612	On-track Steady Mach 1.17	96.4	5.3	97.2	106.8	86.6
12613	On-track Steady Mach 1.20	95.0	4.0	97.1	103.9	88.7
12614	On-track Steady Mach 1.20	95.7	4.7	94.4	107.3	88.0
12615	On-track Steady Mach 1.30	97.1	3.5	96.8	107.3	90.7
12616	On-track Steady Mach 1.30	94.5	3.8	94.5	104.0	86.7

Similar results to that of the E-weighted shown above are seen across the different weighting networks for sound exposure level; this is evidenced by the results shown in Figures 5-4 to 5-7. For the A-weighted sound exposure level measurements of the on track SCAMP booms, the standard deviations ranged from 4.2 dBA (for boom 12615) to 6.0 dBA (for boom 12611). While these variabilities are similar in range, it is considerable that in a comparison between metrics, the E-weighted SEL had a lower standard deviation than its counterpart A-weighted SEL for all six on track flights. As will be displayed later, this trend will continue for all the analyzed data. When comparing the mean values of The A-weighted and E-weighted networks, as expected due to the low frequency content in a sonic boom captured by the E-weighting network, application of an A-weighting network yields consistently lower mean values. In the case of the SCAMP on track measurements, the mean A-weighted sound exposure level measurements were a minimum of 82.9 dBA (for boom 112611) and a maximum of 91.4 dBA (for boom 12615).

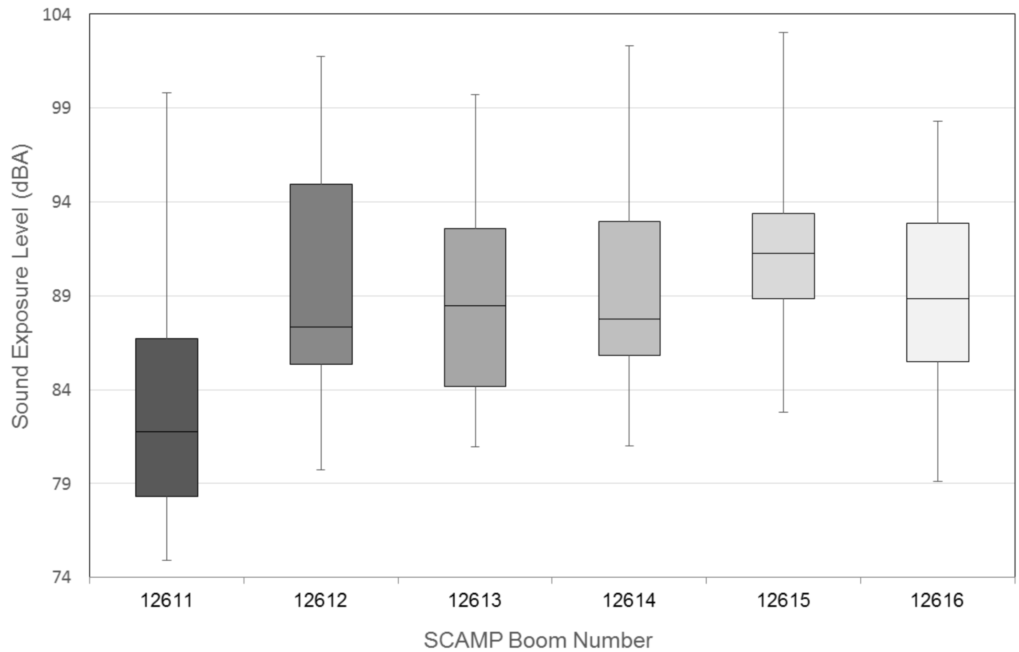

Figure 5-4: A-weighted sound exposure level measurements for on track booms of the SCAMP data set.

Table 5-2: A-weighed sound exposure level mean, standard deviation, median, maximum and minimum values for on track booms of the SCAMP data set.

SCAMP Boom Number	Description	A-Weighted SEL Mean (dB)	A-Weighted SEL Std. Deviation (dB)	A-Weighted SEL Median (dB)	Max (dB)	Min (dB)
12611	On-track Steady Mach 1.17	82.9	6.0	81.7	99.8	74.9
12612	On-track Steady Mach 1.17	90.3	5.9	91.3	101.7	79.7
12613	On-track Steady Mach 1.20	88.9	4.9	88.5	99.7	81.0
12614	On-track Steady Mach 1.20	89.5	5.5	87.8	102.3	81.0
12615	On-track Steady Mach 1.30	91.4	4.2	91.2	103.0	82.8
12616	On-track Steady Mach 1.30	88.7	4.7	88.8	98.3	79.1

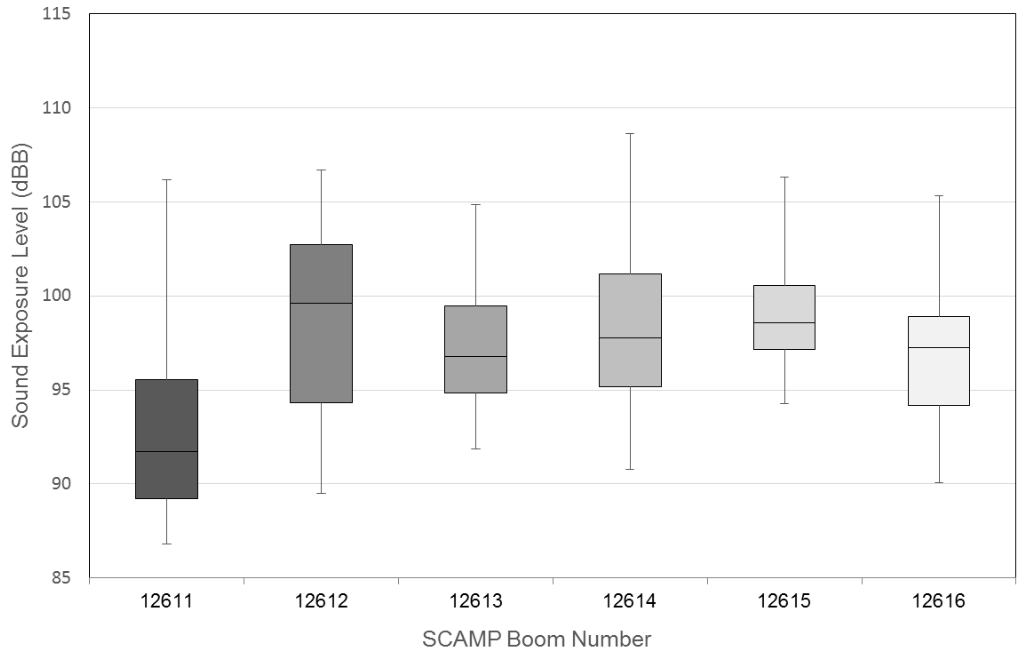

Figure 5-5: B-weighted sound exposure level measurements for on track booms of the SCAMP data set.

Table 5-3: B-weighed sound exposure level mean, standard deviation, median, maximum and minimum values for on track booms of the SCAMP data set.

SCAMP Boom Number	Description	B-Weighted SEL Mean (dB)	B-Weighted SEL Std. Deviation (dB)	B-Weighted SEL Median (dB)	Max (dB)	Min (dB)
12611	On-track Steady Mach 1.17	93.0	4.9	91.7	99.8	74.9
12612	On-track Steady Mach 1.17	98.6	5.0	99.6	106.7	89.5
12613	On-track Steady Mach 1.20	97.8	3.4	96.8	104.8	91.9
12614	On-track Steady Mach 1.20	98.2	4.0	97.8	108.6	90.8
12615	On-track Steady Mach 1.30	99.1	2.7	98.6	106.3	94.2
12616	On-track Steady Mach 1.30	96.6	3.1	97.3	105.3	90.1

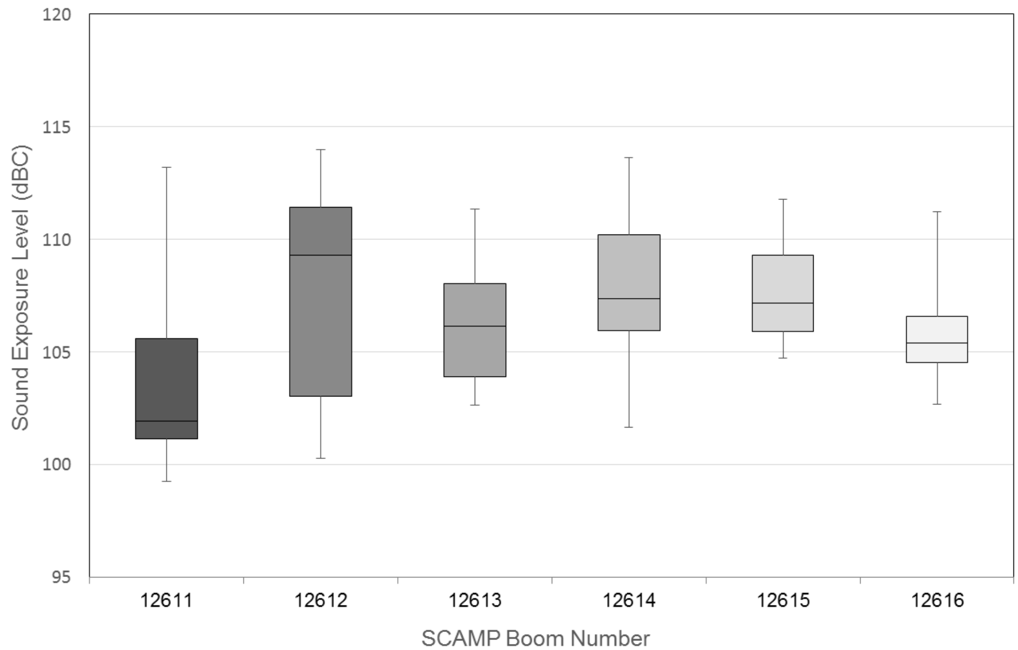

Figure 5-6: C-weighted sound exposure level measurements for on track booms of the SCAMP data set.

Table 5-4: C-weighed sound exposure level mean, standard deviation, median, maximum and minimum values for on track booms of the SCAMP data set.

SCAMP Boom Number	Description	C-Weighted SEL Mean (dB)	C-Weighted SEL Std. Deviation (dB)	C-Weighted SEL Median (dB)	Max (dB)	Min (dB)
12611	On-track Steady Mach 1.17	103.7	3.8	101.9	113.2	99.3
12612	On-track Steady Mach 1.17	107.5	4.5	109.3	114.0	100.3
12613	On-track Steady Mach 1.20	106.2	2.4	106.2	111.3	102.7
12614	On-track Steady Mach 1.20	107.8	2.8	107.4	113.6	101.6
12615	On-track Steady Mach 1.30	107.5	1.9	107.2	111.8	104.7
12616	On-track Steady Mach 1.30	105.6	1.7	105.4	111.2	102.7

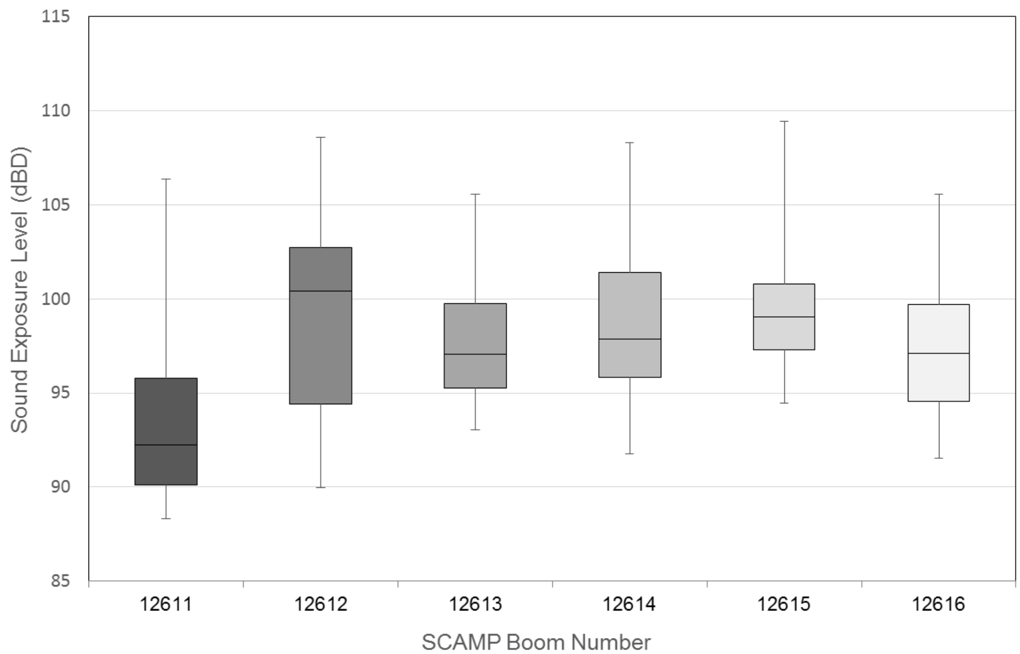

Figure 5-7: D-weighted sound exposure level measurements for on track booms of the SCAMP data set.

Table 5-5: D-weighed sound exposure level mean, standard deviation, median, maximum and minimum values for on track booms of the SCAMP data set.

SCAMP Boom Number	Description	D-Weighted SEL Mean (dB)	D-Weighted SEL Std. Deviation (dB)	D-Weighted SEL Median (dB)	Max (dB)	Min (dB)
12611	On-track Steady Mach 1.17	93.6	4.5	92.2	106.4	88.3
12612	On-track Steady Mach 1.17	98.9	5.1	100.4	108.6	90.0
12613	On-track Steady Mach 1.20	97.7	3.3	97.1	105.6	93.1
12614	On-track Steady Mach 1.20	98.7	3.9	97.9	108.3	91.8
12615	On-track Steady Mach 1.30	99.5	3.1	99.0	109.4	94.5
12616	On-track Steady Mach 1.30	97.1	3.0	97.1	105.5	91.5

5.2.2 Steven's Mark VII Perceived Level (PLdB) Results

Perceived level calculations for on track SCAMP data tend to have standard deviation values that are somewhere between the A-weighted SEL and E-weighted SEL. Figure 5-8 displays the results of the on track measurements for the Stevens Mark VII perceived level metric. The mean values for perceived level range between 98.5 dB to 106.5 dB and the standard deviations have a range from 3.8 dB to 6.2 dB.

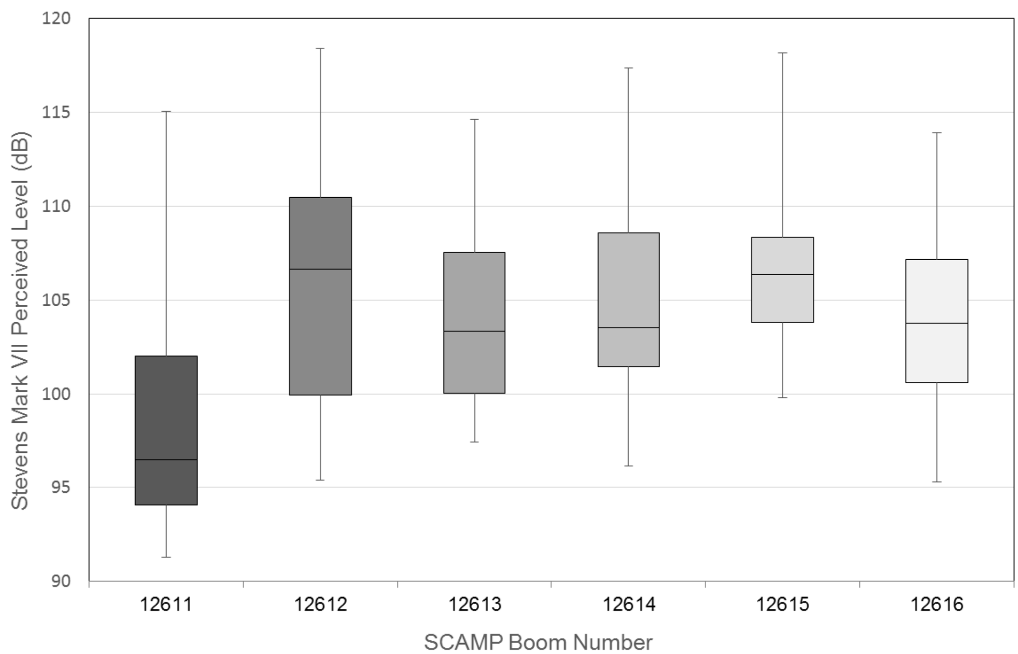

Figure 5-8: Perceived level measurements for on track booms of the SCAMP data set.

Table 5-6: Perceived level mean, standard deviation, median, maximum and minimum values for on track booms of the SCAMP data set.

SCAMP Boom Number	Description	PLdB Mean (dB)	PLdB Std. Deviation (dB)	PLdB Median (dB)	Max (dB)	Min (dB)
12611	On-track Steady Mach 1.17	98.5	6.0	96.5	115.1	91.3
12612	On-track Steady Mach 1.17	105.7	6.2	106.6	118.4	95.4
12613	On-track Steady Mach 1.20	104.1	4.5	103.4	114.6	97.4
12614	On-track Steady Mach 1.20	105.0	5.3	103.5	117.4	96.2
12615	On-track Steady Mach 1.30	106.5	3.8	106.3	118.2	99.8
12616	On-track Steady Mach 1.30	103.5	4.1	103.8	113.9	95.3

5.2.3 Indoor Sonic Boom Annoyance Predictor (ISBAP) Results

The final metric to be shown is the preliminary indoor sonic boom annoyance predictor. Figure 5-9, shows the ISBAP values calculated for the on track SCAMP data. Again, a reminder that the ISBAP metric is calculated here in terms of annoyance units and not decibels as is the case with the other metrics. As was seen in the calculation procedure of this metric in Chapter 4, ISBAP is a combination of the C and A-weighted SEL as well as the perceived level metrics. Due to this, the annoyance predictor metric follows similar trends as the previous metrics. The maximum standard deviation observed in the on track SCAMP measurements is a value of 0.40 for boom 12612; in comparison, the minimum standard deviation was for boom 12613 and is a value of 0.19.

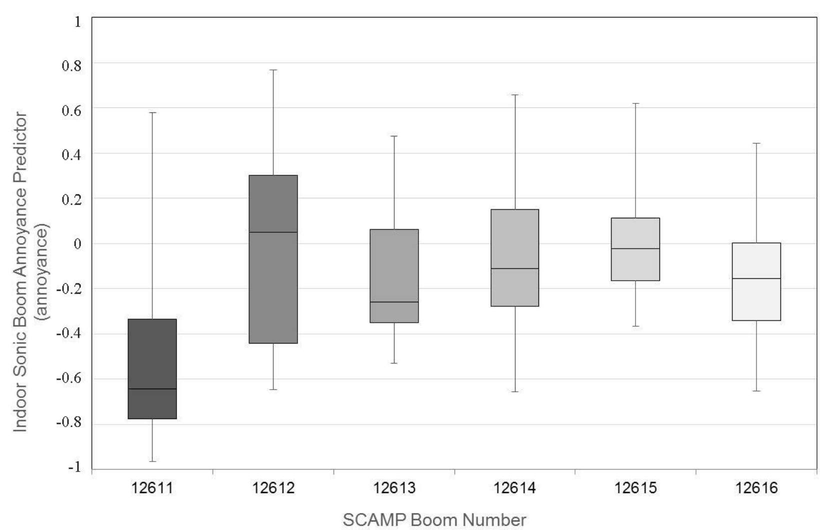

Figure 5-9: Indoor sonic boom annoyance predictor measurements for on track booms of the SCAMP data set.

Table 5-7: Indoor sonic boom annoyance predictor mean, standard deviation, median, maximum and minimum values for on track booms of the SCAMP data set.

SCAMP Boom Number	Description	ISBAP Mean	ISBAP Median	ISBAP Std. Deviation	Max	Min
12611	On-track Steady Mach 1.17	-0.49	-0.64	0.40	0.58	-0.96
12612	On-track Steady Mach 1.17	-0.03	0.05	0.40	0.77	-0.65
12613	On-track Steady Mach 1.20	-0.14	-0.26	0.19	0.47	-0.53
12614	On-track Steady Mach 1.20	-0.07	-0.11	0.32	0.66	-0.66
12615	On-track Steady Mach 1.30	0.00	-0.02	0.22	0.62	-0.36
12616	On-track Steady Mach 1.30	-0.19	-0.16	0.24	0.44	-0.65

5.3 Off track SCAMP results

5.3.1 Sound Exposure Level (SEL) Results

The calculated metrics for the three off track SCAMP booms measured are shown in the following figures. Figure 5-10, illustrates the general trend of smaller variabilities seen in these off track SCAMP flights in comparison to the on track flights. Boom 12742 shows a consistent large outlier on one microphone channel across all metric calculations. It was unclear whether this outlier was caused by equipment malfunction or some sonic boom focusing in a small area, so the measurement has been left in the data.

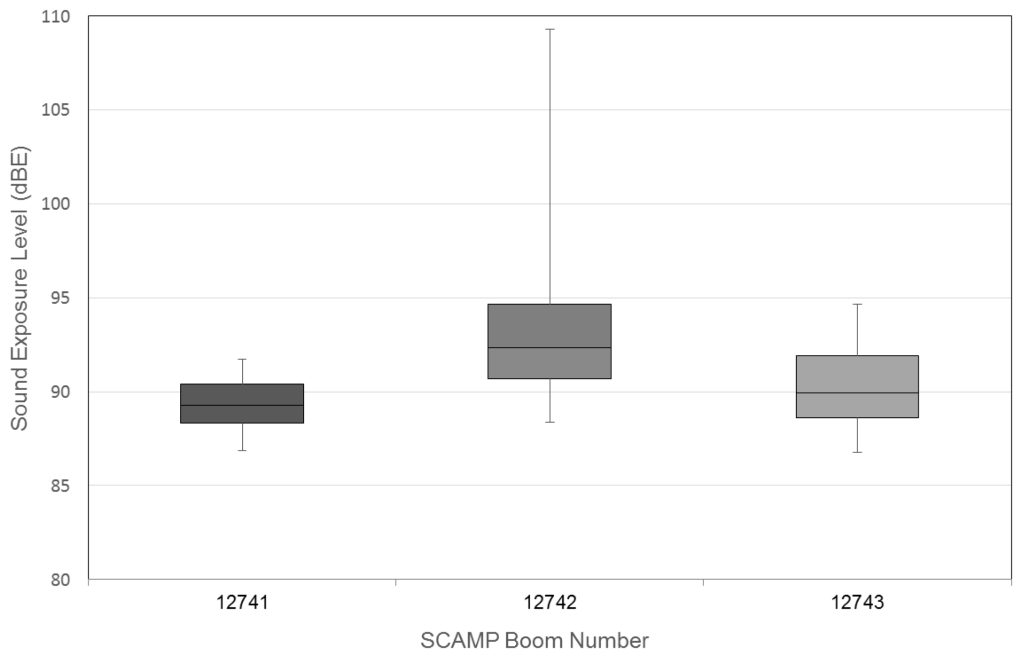

Figure 5-10: E-weighted sound exposure level measurements for off track booms of the SCAMP data set.

Table 5-8: E-weighted mean, standard deviation, median, maximum and minimum values for off track booms of the SCAMP data set.

SCAMP Boom Number	Description	E-Weighted SEL Mean (dB)	E-Weighted SEL Std. Deviation (dB)	E-Weighted SEL Median (dB)	Max (dB)	Min (dB)
12741	5.7km offset Steady 1.20	89.4	1.3	89.3	91.7	86.9
12742	8.2km offest Steady 1.30	93.4	4.2	92.3	109.3	88.4
12743	3.8km offset Steady 1.17	90.3	2.0	89.9	94.7	86.8

The E-weighted SEL mean values trend a few decibel lower than that of the on track data. The means of the three booms 12741, 12742 and 12743 are 89.4, 93.4 and 90.3 dBE, respectively. The standard deviations for these booms are 1.3, 4.2 and 2.0 dBE. Figure 5-11, depicts the A-weighted sound exposure metric for off track SCAMP booms. Similar to results for the on track booms, the A-weighting network yields higher standard deviation values in the metric. The A-weighted SEL standard deviations are 1.4, 4.7 and 2.2 dBA for the off track booms. Figures 5-12 through 5-14 depict the results for the B, C and D weighted sound exposure levels, respectively.

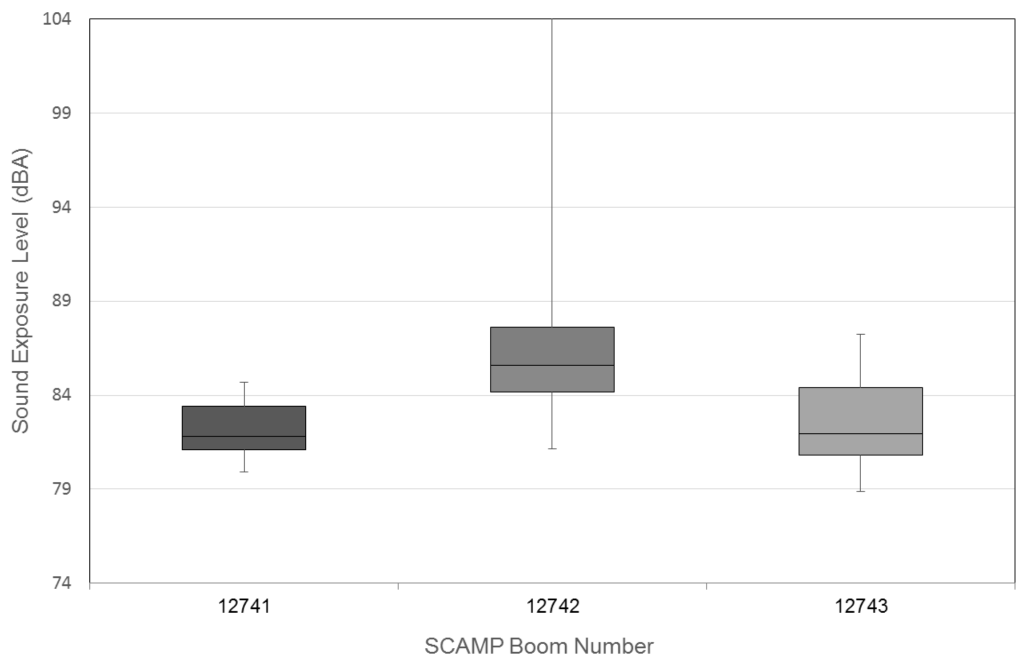

Figure 5-11: A-weighted sound exposure level measurements for off track booms of the SCAMP data set.

Table 5-9: A-weighted mean, standard deviation, median, maximum and minimum values for off track booms of the SCAMP data set.

SCAMP Boom Number	Description	A-Weighted SEL Mean (dB)	A-Weighted SEL Std. Deviation (dB)	A-Weighted SEL Median (dB)	Max (dB)	Min (dB)
12741	5.7km offset Steady 1.20	82.1	1.4	81.8	85.2	79.9
12742	8.2km offest Steady 1.30	86.8	4.7	85.6	104.0	81.1
12743	3.8km offset Steady 1.17	82.4	2.2	82.0	87.1	78.9

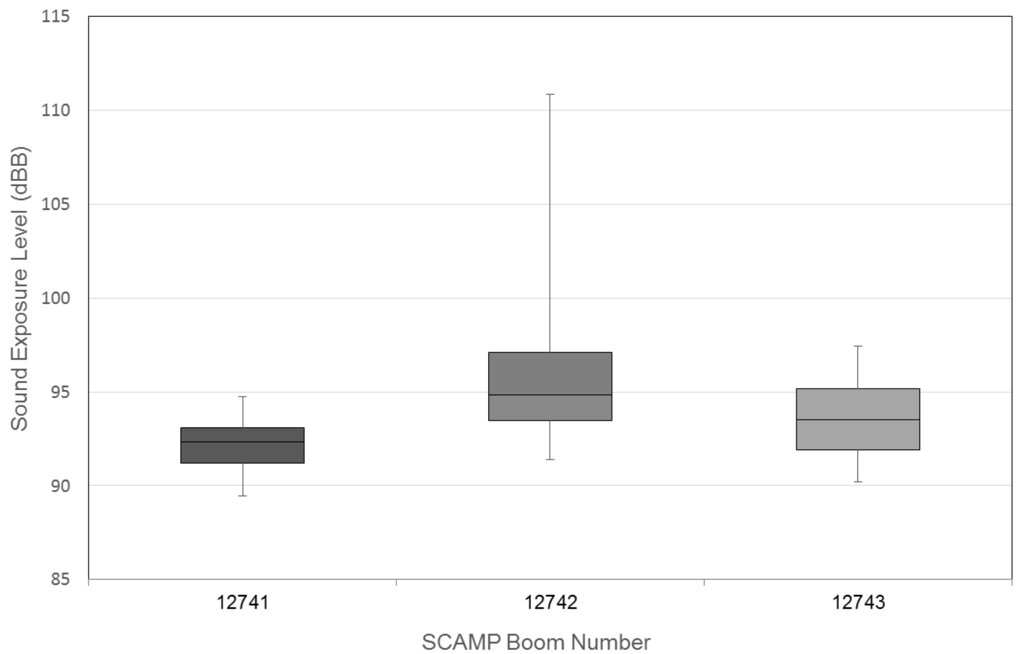

Figure 5-12: B-weighted sound exposure level measurements for off track booms of the SCAMP data set.

Table 5-10: B-weighted mean, standard deviation, median, maximum and minimum values for off track booms of the SCAMP data set.

SCAMP Boom Number	Description	B-Weighted SEL Mean (dB)	B-Weighted SEL Std. Deviation (dB)	B-Weighted SEL Median (dB)	Max (dB)	Min (dB)
12741	5.7km offset Steady 1.20	92.2	1.3	92.3	94.7	89.5
12742	8.2km offest Steady 1.30	95.9	3.9	94.8	110.8	91.4
12743	3.8km offset Steady 1.17	93.6	1.9	93.5	97.4	90.2

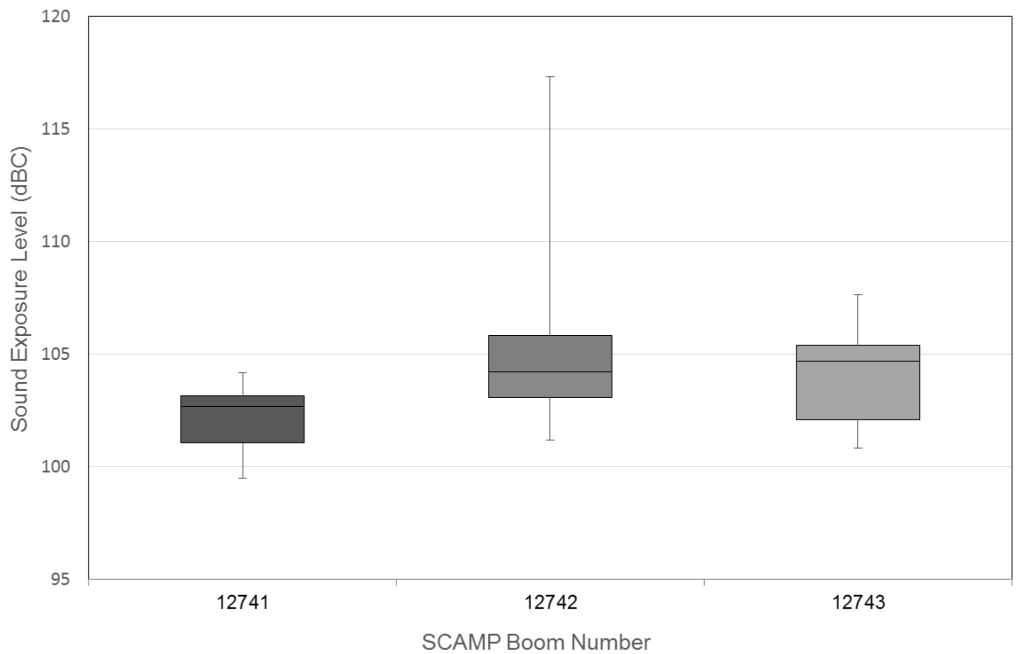

Figure 5-13: C-weighted sound exposure level measurements for off track booms of the SCAMP data set.

Table 5-11: C-weighted mean, standard deviation, median, maximum and minimum values for off track booms of the SCAMP data set.

SCAMP Boom Number	Description	C-Weighted SEL Mean (dB)	C-Weighted SEL Std. Deviation (dB)	C-Weighted SEL Median (dB)	Max (dB)	Min (dB)
12741	5.7km offset Steady 1.20	108.3	1.3	102.7	104.2	99.5
12742	8.2km offest Steady 1.30	105.1	3.3	104.2	117.3	101.2
12743	3.8km offset Steady 1.17	104.2	1.8	104.7	107.6	100.8

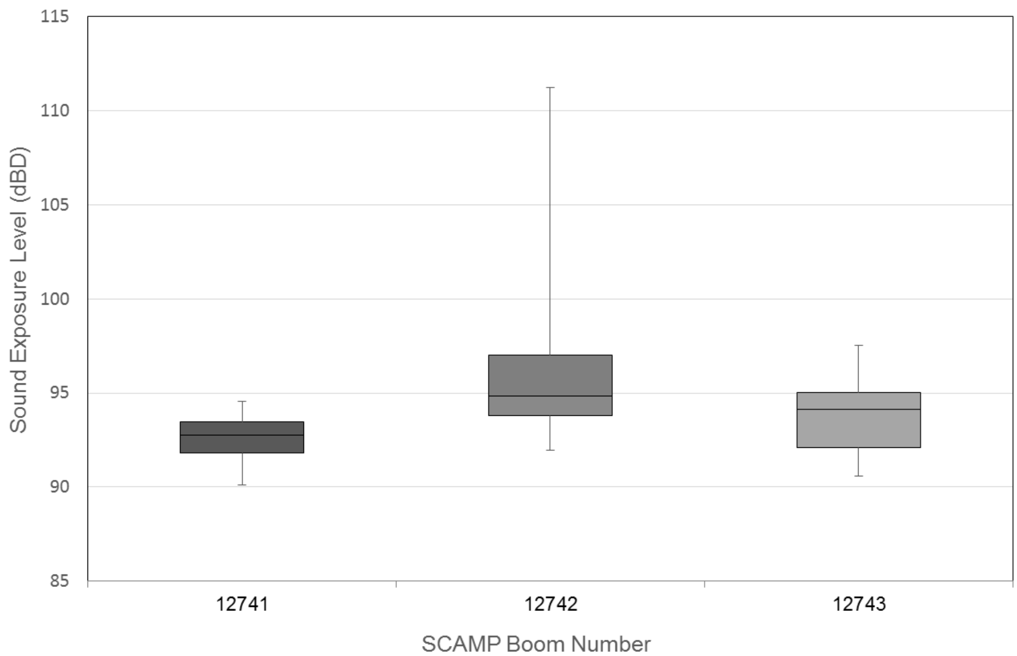

Figure 5-14: D-weighted sound exposure level measurements for off track booms of the SCAMP data set.

Table 5-12: D-weighted mean, standard deviation, median, maximum and minimum values for off track booms of the SCAMP data set.

SCAMP Boom Number	Description	D-Weighted SEL Mean (dB)	D-Weighted SEL Std. Deviation (dB)	D-Weighted SEL Median (dB)	Max (dB)	Min (dB)
12741	5.7km offset Steady 1.20	92.6	1.2	92.8	94.5	90.1
12742	8.2km offest Steady 1.30	96.1	3.9	94.9	111.2	92.0
12743	3.8km offset Steady 1.17	93.9	1.8	94.1	97.5	90.6

5.3.2 Steven's Mark VII Perceived Level (PLdB) Results

Figure 5-15 shows the perceived levels calculated for the off track booms in the SCAMP data set. As with the other metrics, the mean perceived levels average a bit lower than the mean of the six on track booms. The PLdB of the off track booms had standard deviations of 1.4, 4.8 and 2.2 dB for the three booms shown.

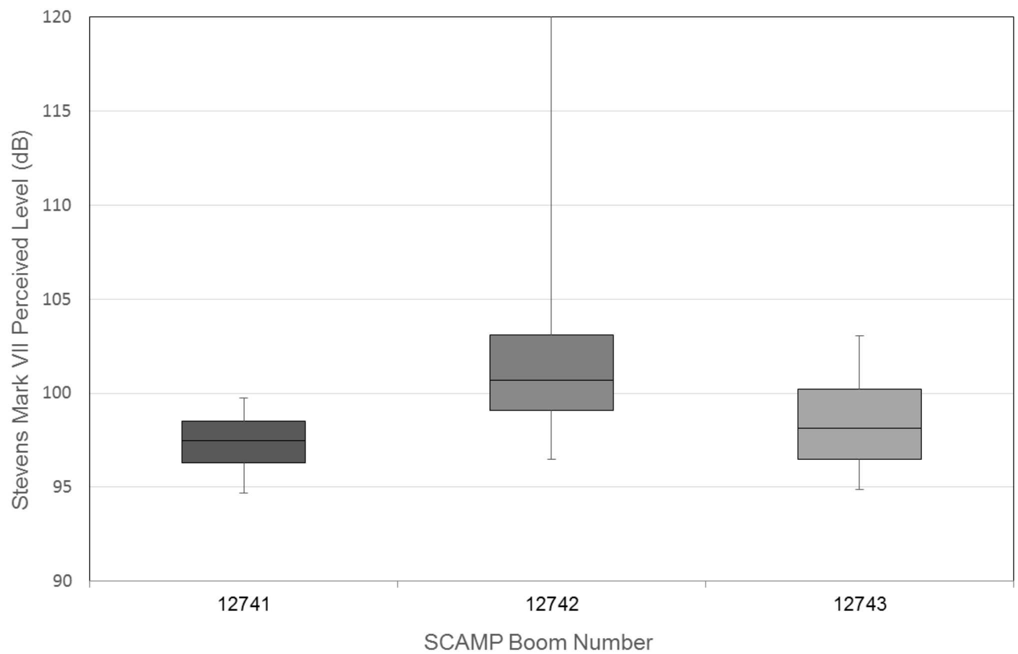

Figure 5-15: Perceived level measurements for off track booms of the SCAMP data set.

Table 5-13: Perceived level mean, standard deviation, median, maximum and minimum values for off track booms of the SCAMP data set.

SCAMP Boom Number	Description	PLdB Mean (dB)	PLdB Std. Deviation (dB)	PLdB Median (dB)	Max (dB)	Min (dB)
12741	5.7km offset Steady 1.20	97.4	1.4	97.5	99.8	94.7
12742	8.2km offest Steady 1.30	102.1	4.8	100.7	120.1	96.5
12743	3.8km offset Steady 1.17	98.4	2.2	98.2	103.1	94.9

5.3.3 Indoor Sonic Boom Annoyance Predictor (ISBAP) Results

Lastly, Figure 5-16 depicts the indoor sonic boom annoyance predictor metric for SCAMP off track booms. As has been the trend with the other metrics, both the mean values and standard deviation trended lower for these off track measurements in comparison to the six on track booms. The standard deviations of the ISBAP were 0.10, 0.33 and 0.13 annoyance units.

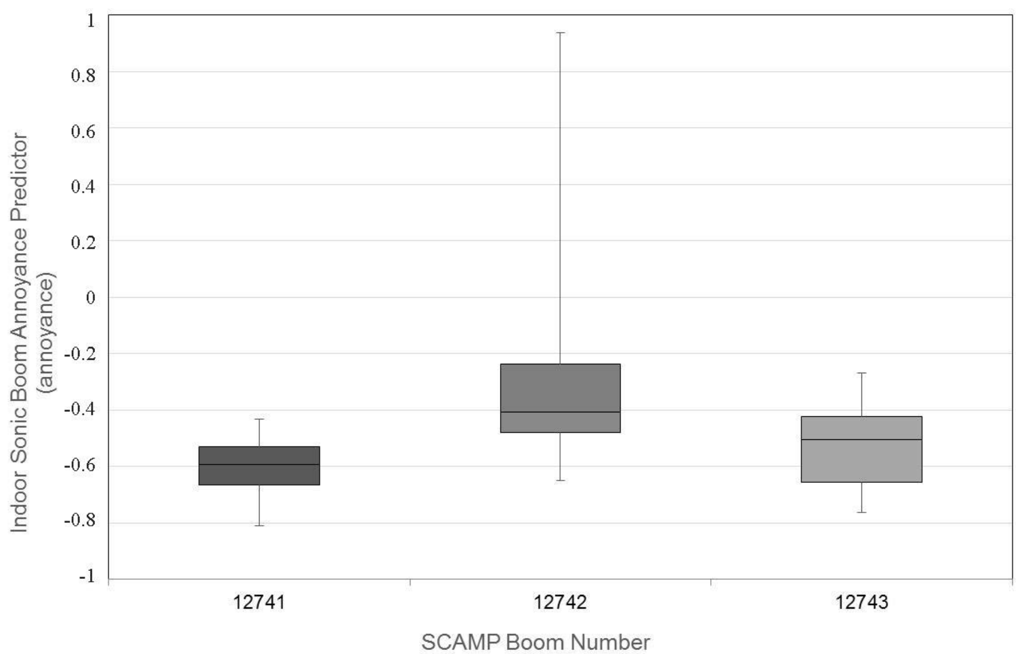

Figure 5-16: Indoor sonic boom annoyance predictor measurements for off track booms of the SCAMP data set. These values (in units of annoyance) are offset by a value of 1 to facilitate graphing of the metric on a positive axis.

Table 5-14: Indoor sonic boom annoyance predictor mean, standard deviation, median, maximum and minimum values for off track booms of the SCAMP data set.

SCAMP Boom Number	Description	ISBAP Mean	ISBAP Median	ISBAP Std. Deviation	Max	Min
12741	5.7km offset Steady 1.20	-0.60	-0.59	0.10	-0.43	-0.81
12742	8.2km offest Steady 1.30	-0.30	-0.41	0.33	0.94	-0.65
12743	3.8km offset Steady 1.17	-0.52	-0.51	0.13	-0.27	-0.76

5.4 Lateral Cutoff FaINT results

5.4.1 Sound Exposure Level (SEL) Results

The FaINT data results will be presented in two sections: the lateral cutoff flights and Mach cutoff flights. Booms 138301, 138302, 138501 and 138701 were lateral cutoff measurements that exhibited small or no amounts of cutoff across the microphone array. Figures 5-17 through 5-21 show the different weighted sound exposure level results. Boom 138302 exhibits consistently lower variability and range compared to the three other lateral cutoff booms. From the four booms displayed in each figure, the mean measured values for the booms were a maximum of 80.1 dBA, 91.2 dBB, 101.6 dBC, 91.8 dBD and 92.1 dBE, all measured for boom 138701. The minimum mean values of the exposure levels were 64.7 dBA, 78.5 dBB, 91.9 dBC, 80.5 dBD and 74.4 dBE. The minimum mean values were observed in either boom 138302 or 138501 depending on the weighting function.

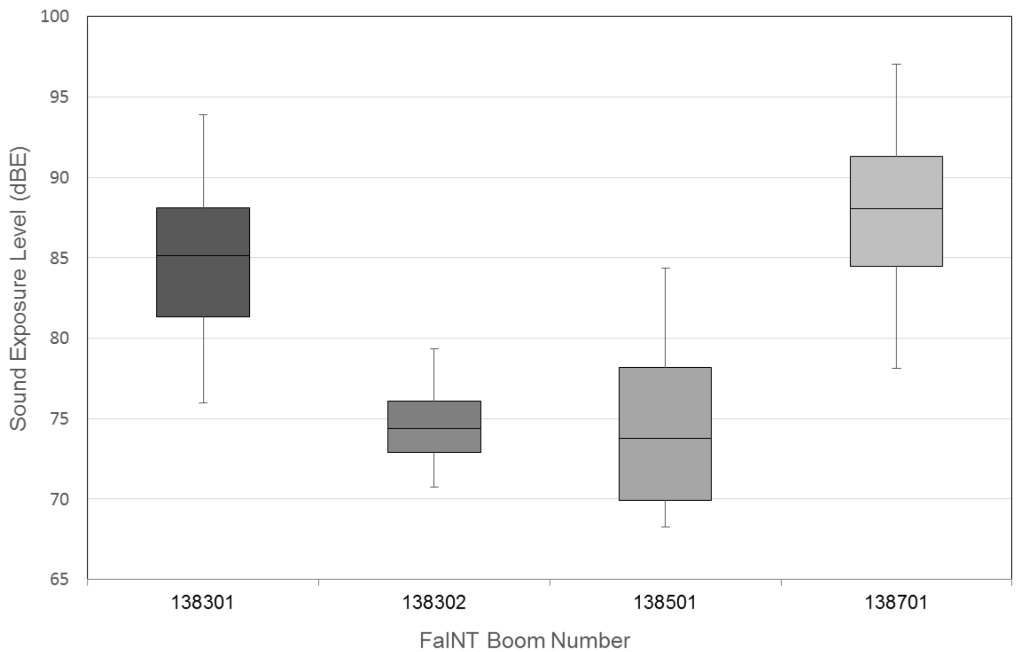

Figure 5-17: E-weighted sound exposure measurements for lateral cutoff flights of the FaINT dataset.

Table 5-15: E-weighted mean, standard deviation, median, maximum and minimum values for lateral cutoff booms of the FaINT data set.

FaINT Boom Number	Description	E-Weighted SEL Mean (dB)	E-Weighted SEL Std. Deviation (dB)	E-Weighted SEL Median (dB)	Max (dB)	Min (dB)
138301	Lateral Cutoff	85.0	4.7	85.1	93.9	76.0
138302	Lateral Cutoff	74.5	2.3	74.4	79.3	70.7
138501	Lateral Cutoff	74.4	4.5	73.8	84.4	68.2
138701	Lateral Cutoff	87.9	4.7	92.1	97.0	78.1

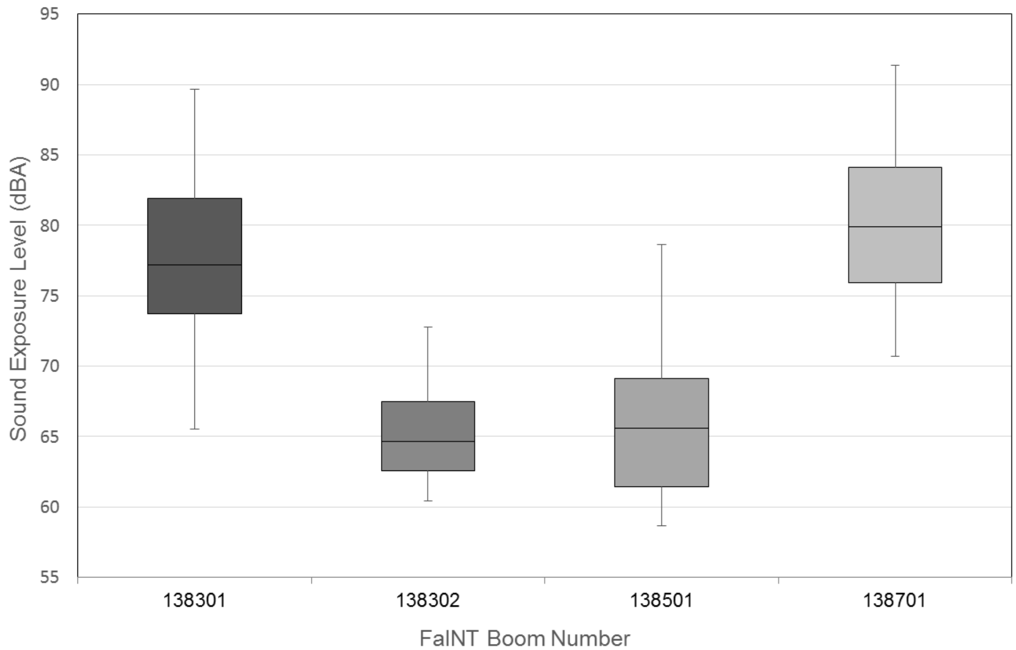

Figure 5-18: A-weighted sound exposure measurements for lateral cutoff flights of the FaINT dataset.

Table 5-16: A-weighted mean, standard deviation, median, maximum and minimum values for lateral cutoff booms of the FaINT data set.

FaINT Boom Number	Description	A-Weighted SEL Mean (dB)	A-Weighted SEL Std. Deviation (dB)	A-Weighted SEL Median (dB)	Max (dB)	Min (dB)
138301	Lateral Cutoff	77.8	6.1	77.2	89.6	65.5
138302	Lateral Cutoff	65.3	3.3	64.7	72.8	60.4
138501	Lateral Cutoff	65.9	5.1	65.6	78.6	58.7
138701	Lateral Cutoff	80.1	5.3	79.9	91.4	70.7

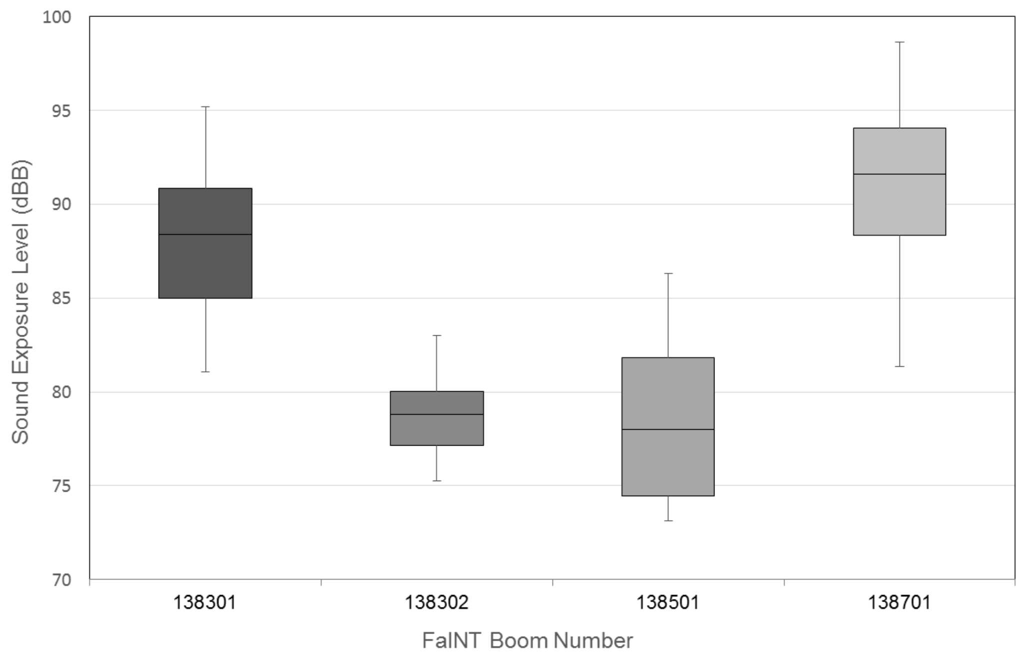

Figure 5-19: B-weighted sound exposure measurements for lateral cutoff flights of the FaINT dataset.

Table 5-17: B-weighted mean, standard deviation, median, maximum and minimum values for lateral cutoff booms of the FaINT data set.

FaINT Boom Number	Description	B-Weighted SEL Mean (dB)	B-Weighted SEL Std. Deviation (dB)	B-Weighted SEL Median (dB)	Max (dB)	Min (dB)
138301	Lateral Cutoff	88.2	3.9	88.4	95.2	81.1
138302	Lateral Cutoff	78.7	1.9	78.8	83.0	75.3
138501	Lateral Cutoff	78.5	3.9	78.0	86.3	73.1
138701	Lateral Cutoff	91.2	4.2	91.6	98.6	81.3

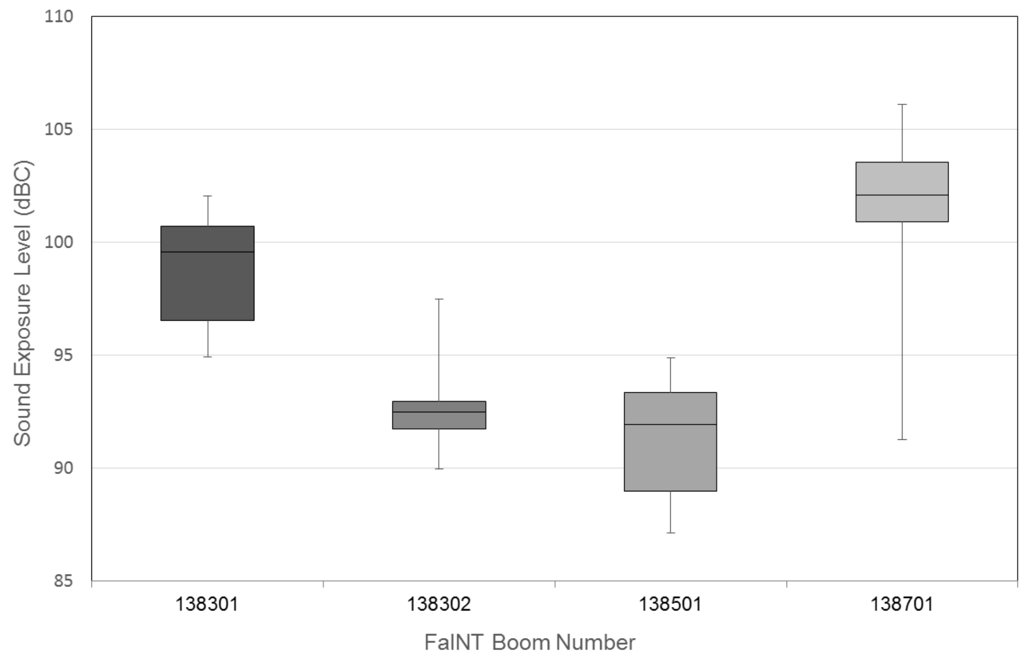

Figure 5-20: C-weighted sound exposure measurements for lateral cutoff flights of the FaINT dataset.

Table 5-18: C-weighted mean, standard deviation, median, maximum and minimum values for lateral cutoff booms of the FaINT data set.

FaINT Boom Number	Description	C-Weighted SEL Mean (dB)	C-Weighted SEL Std. Deviation (dB)	C-Weighted SEL Median (dB)	Max (dB)	Min (dB)
138301	Lateral Cutoff	98.7	2.3	99.6	102.0	94.9
138302	Lateral Cutoff	92.5	1.4	92.5	97.5	90.0
138501	Lateral Cutoff	91.3	2.4	91.9	94.9	87.1
138701	Lateral Cutoff	101.6	3.1	102.1	106.1	91.3

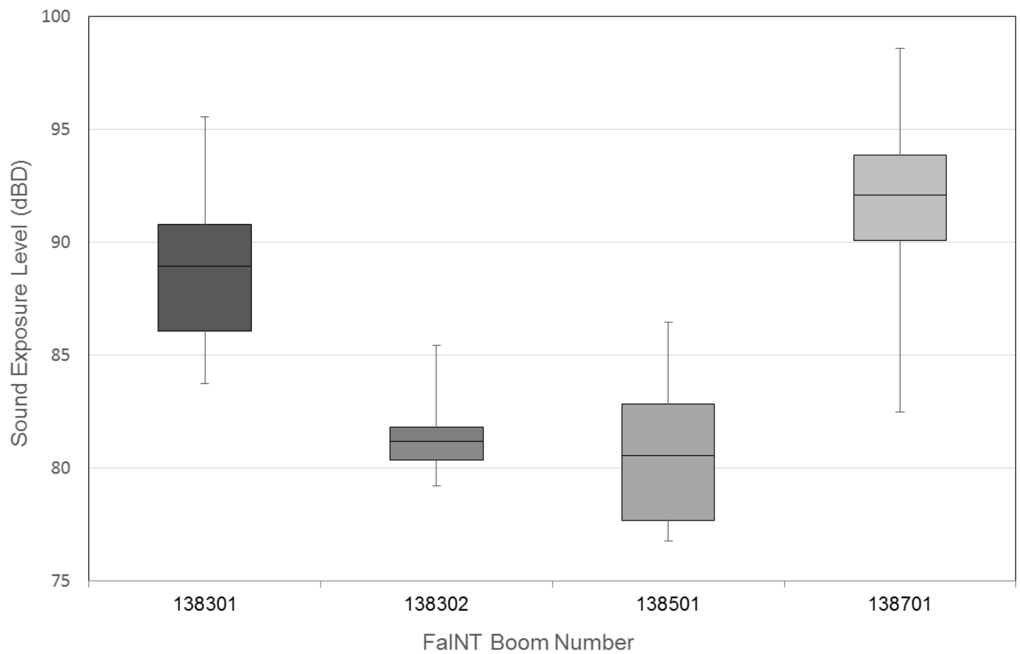

Figure 5-21: D-weighted sound exposure measurements for lateral cutoff flights of the FaINT dataset.

Table 5-19: D-weighted mean, standard deviation, median, maximum and minimum values for lateral cutoff booms of the FaINT data set.

FaINT Boom Number	Description	D-Weighted SEL Mean (dB)	D-Weighted SEL Std. Deviation (dB)	D-Weighted SEL Median (dB)	Max (dB)	Min (dB)
138301	Lateral Cutoff	88.9	3.2	89.0	95.6	83.7
138302	Lateral Cutoff	81.2	1.2	81.2	85.4	79.2
138501	Lateral Cutoff	80.5	2.8	80.5	86.5	76.8
138701	Lateral Cutoff	91.8	3.6	92.1	98.6	82.5

5.4.2 Steven's Mark VII Perceived Level (PLdB) Results

Figure 5-22 depicts the perceived level calculations for the FaINT lateral cutoff flights analyzed. Perceived level showed variabilities most similar to the E-weighted sound exposure level with standard deviations between 2.7 and 5.3 dB.

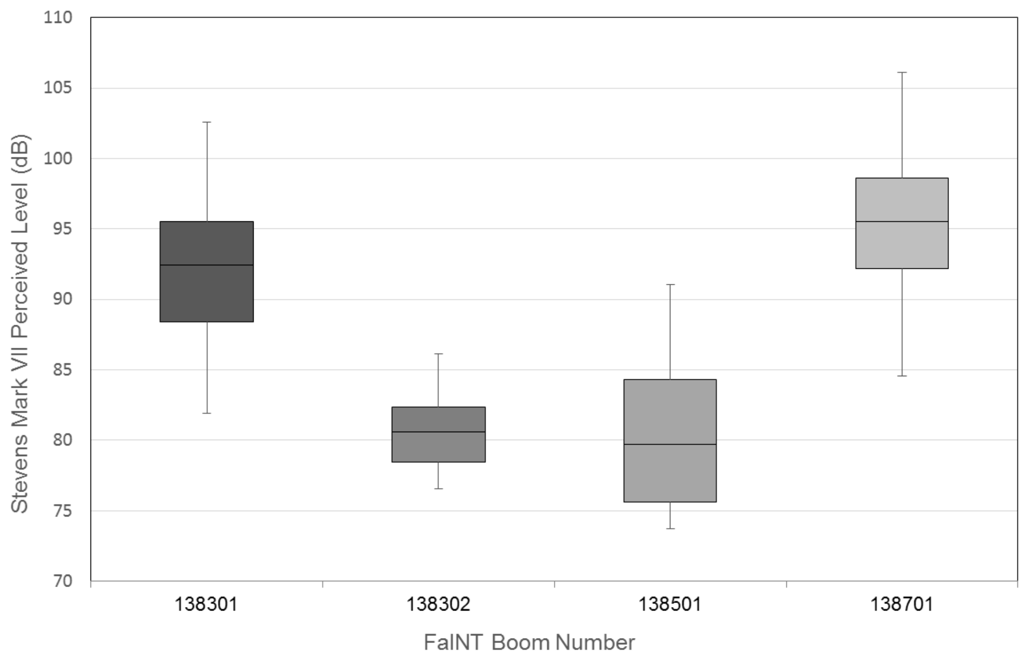

Figure 5-22: Perceived level measurements for lateral cutoff flights of the FaINT dataset.

Table 5-20: Perceived level mean, standard deviation, median, maximum and minimum values for lateral cutoff booms of the FaINT data set.

FaINT Boom Number	Description	PLdB Mean (dB)	PLdB Std. Deviation (dB)	PLdB Median (dB)	Max (dB)	Min (dB)
138301	Lateral Cutoff	92.3	5.3	92.4	102.6	81.9
138302	Lateral Cutoff	80.6	2.7	80.6	86.2	76.5
138501	Lateral Cutoff	80.3	4.8	79.7	91.0	73.7
138701	Lateral Cutoff	95.5	5.0	95.5	106.1	84.5

5.4.3 Indoor Sonic Boom Annoyance Predictor (ISBAP) Results

The results from the lateral cutoff FaINT flights for ISBAP are shown in Figure 5-23. The standard deviations for the four booms are as shown in Table 5-21.

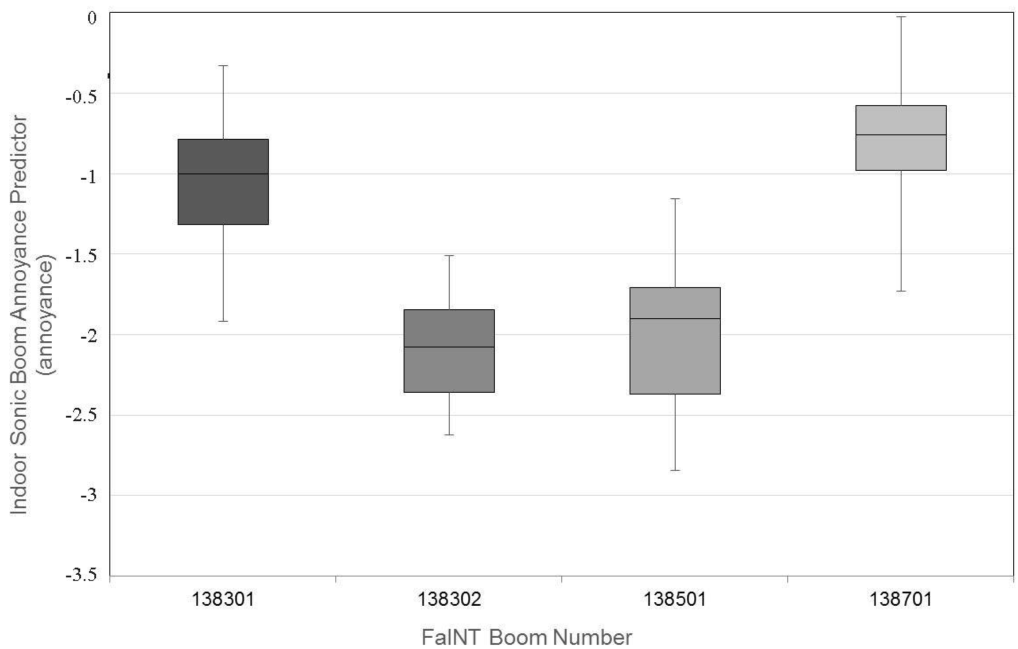

Figure 5-23: Indoor sonic boom annoyance predictor measurements for lateral cutoff flights of the FaINT dataset.

Table 5-21: Indoor sonic boom annoyance predictor mean, standard deviation, median, maximum and minimum values for lateral cutoff booms of the FaINT data set.

FaINT Boom Number	Description	ISBAP Mean	ISBAP Median	ISBAP Std. Deviation	Max	Min
138301	Lateral Cutoff	-1.04	-1.00	0.40	-0.33	-1.92
138302	Lateral Cutoff	-2.08	-2.07	0.30	-1.51	-2.62
138501	Lateral Cutoff	-2.01	-1.90	0.46	-1.16	-2.84
138701	Lateral Cutoff	-0.79	-0.76	0.37	-0.02	-1.73

5.5 Mach Cutoff FaINT results

5.5.1 Sound Exposure Level (SEL) Results

Along with the four lateral cutoff measurements, four Mach cutoff booms were selected for analysis from the FaINT data. Booms 138801, 139106, 139205 and 139305 are the Mach cutoff measurements from the FaINT dataset that had waveforms considered appropriate for analysis. Note again that the Mach cutoff FaINT flights were flown on track similar to SCAMP measurements presented in section 5.1. Figures 5-24 through 5-28 show the E, A, B, C and D weighted sound exposure levels for these booms. The scales on these plots have been chosen to match the scales from the lateral cutoff measurements of the same metric type for easier visual comparisons of the variability changes between the lateral and Mach cutoff measurements. Figure 5-24, depicts the E-weighted sound exposure level measurements. The standard deviations for the four booms are 1.2, 1.9, 1.5 and 1.3 dBE.

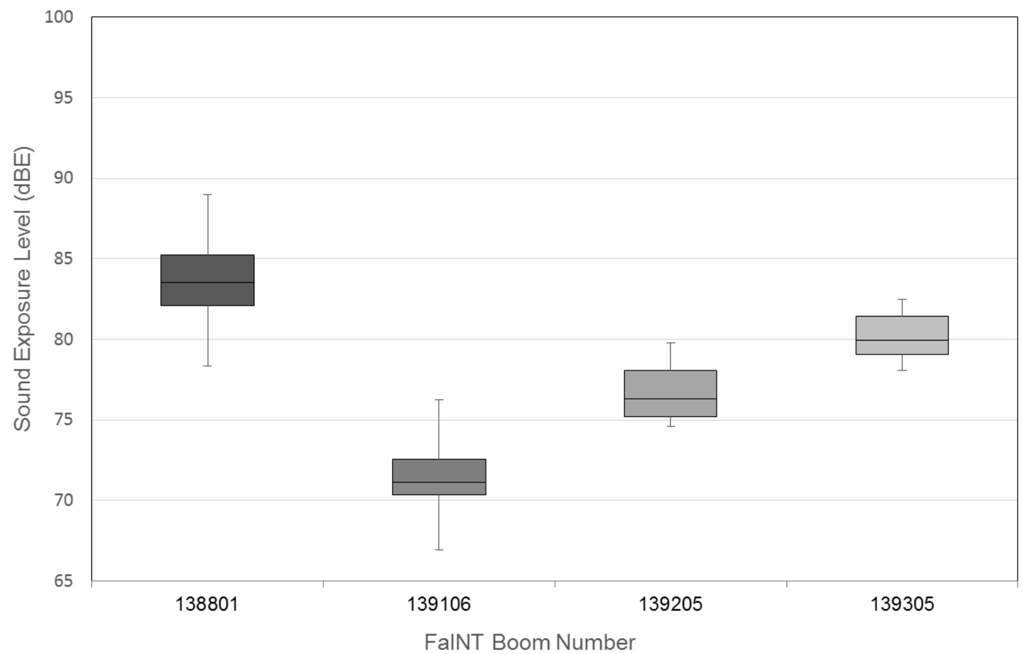

Figure 5-24: E-weighted sound exposure measurements for Mach cutoff flights of the FaINT dataset.

Table 5-22: E-weighted mean, standard deviation, median, maximum and minimum values for Mach cutoff booms of the FaINT data set.

FaINT Boom Number	Description	E-Weighted SEL Mean (dB)	E-Weighted SEL Std. Deviation (dB)	E-Weighted SEL Median (dB)	Max (dB)	Min (dB)
138801	Mach Cutoff	83.0	1.2	83.5	89.0	78.3
139106	Mach Cutoff	71.4	1.9	71.1	76.2	66.9
139205	Mach Cutoff	76.6	1.5	76.3	79.8	74.6
139305	Mach Cutoff	80.2	1.2	80.0	82.5	78.1

Figure 5-25 displays the A-weighted sound exposure measurements of the four Mach cutoff booms of interest. The standard deviations of the booms were found to be 3.2, 2.1, 1.3 and 1.2 dBA, respectively. In particular for A-weighted SEL, boom 138801 performed much worse in terms of the variability when compared to the other weightings with more emphasis on the low frequency content.

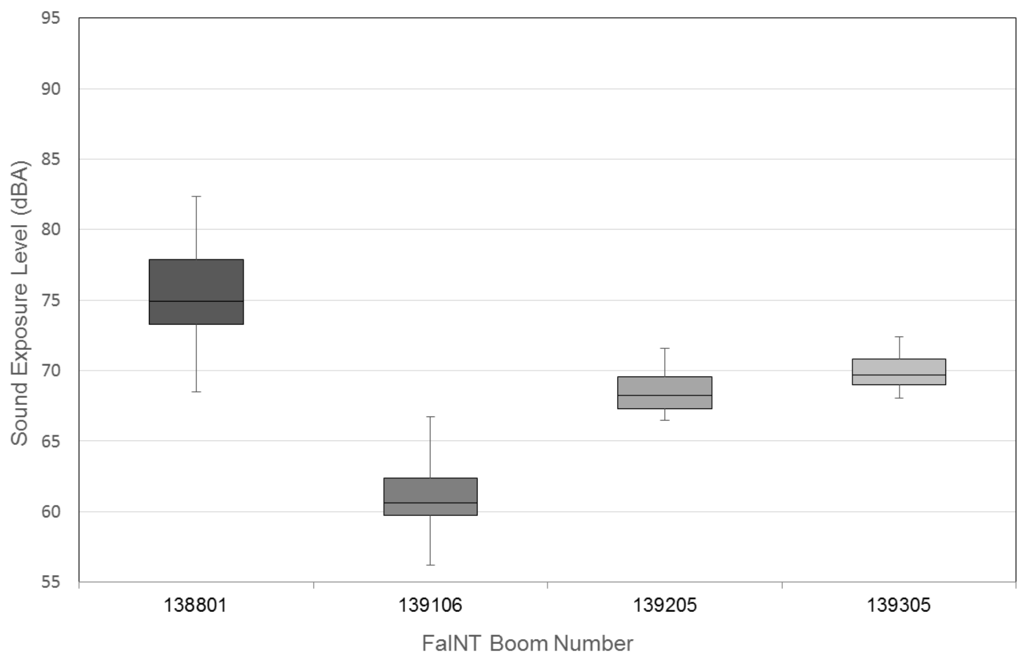

Figure 5-25: A-weighted sound exposure measurements for Mach cutoff flights of the FaINT dataset.

Table 5-23: A-weighted mean, standard deviation, median, maximum and minimum values for Mach cutoff booms of the FaINT data set.

FaINT Boom Number	Description	A-Weighted SEL Mean (dB)	A-Weighted SEL Std. Deviation (dB)	A-Weighted SEL Median (dB)	Max (dB)	Min (dB)
138801	Mach Cutoff	75.3	3.2	74.9	82.3	68.5
139106	Mach Cutoff	60.9	2.1	60.6	66.8	56.2
139205	Mach Cutoff	68.5	1.3	68.2	71.6	66.5
139305	Mach Cutoff	69.9	1.2	69.7	72.4	68.1

The B-weighted sound exposure level measurements can be found in graphical form in Figure 5-26. The standard deviations of this metric for Mach cutoff results were 1.7, 1.7, 1.7 and 1.3 dBB. While the range in standard deviations of the A weighted metric was 2.0 dB, the range has lessened to only 0.4 dB for the B weighting. This closer grouping in the standard deviation values is also observable in the C and D weightings. In contrast to A weighting, because the other weightings capture more of the low frequency content of the sonic boom waveform, the more variable high frequency content has less of an effect on the measurements.

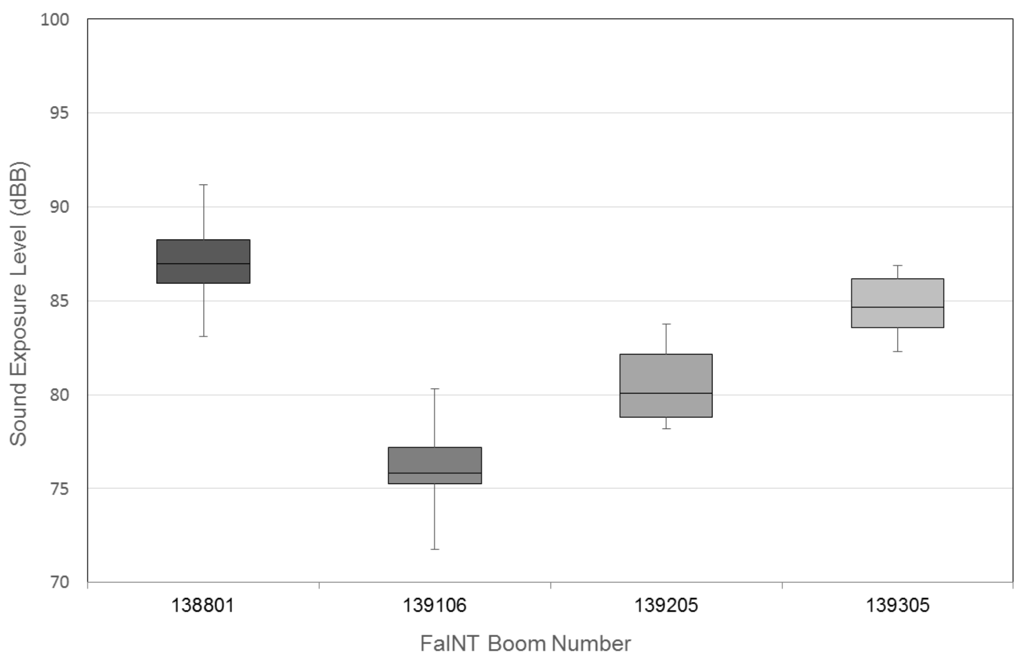

Figure 5-26: B-weighted sound exposure measurements for Mach cutoff flights of the FaINT dataset.

Table 5-24: B-weighted mean, standard deviation, median, maximum and minimum values for Mach cutoff booms of the FaINT data set.

FaINT Boom Number	Description	B-Weighted SEL Mean (dB)	B-Weighted SEL Std. Deviation (dB)	B-Weighted SEL Median (dB)	Max (dB)	Min (dB)
138801	Mach Cutoff	87.1	1.7	87.0	91.2	83.1
139106	Mach Cutoff	76.1	1.7	75.8	80.3	71.8
139205	Mach Cutoff	80.4	1.7	80.1	83.8	78.2
139305	Mach Cutoff	84.8	1.3	84.7	86.9	82.3

Figure 5-27 depicts the C-weighted sound exposure level Mach cutoff measurements selected to analyze. Standard deviations determined for this weighting were 0.8, 1.0, 1.9 and 1.5 dBC. These results represent the lowest measured standard deviations for booms 138801 and 139106 of any of the weighted SEL metrics.

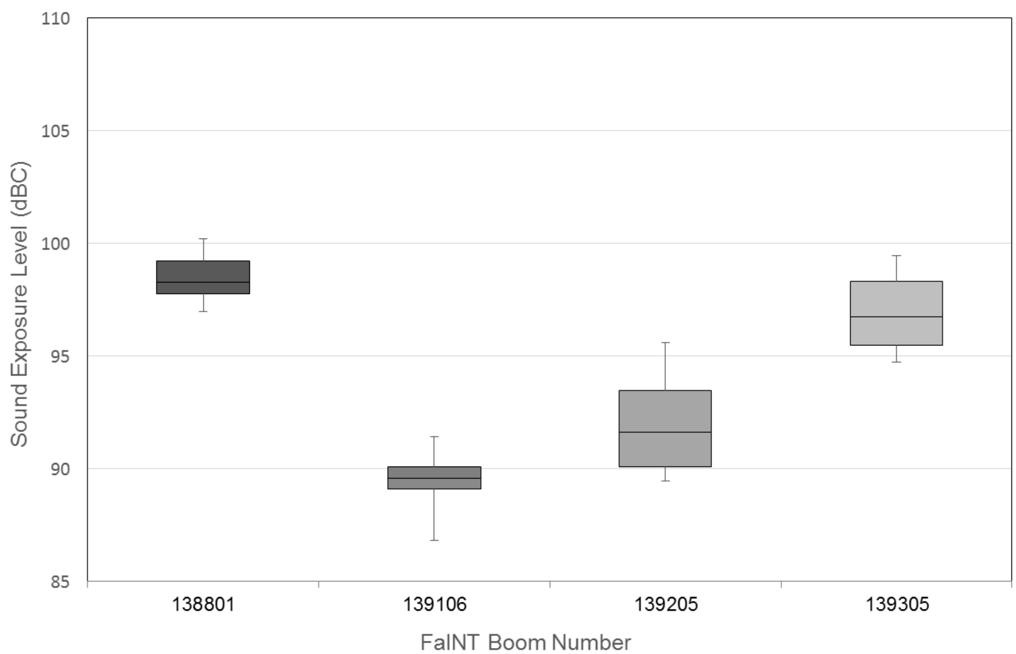

Figure 5-27: C-weighted sound exposure measurements for Mach cutoff flights of the FaINT dataset.

Table 5-25: C-weighted mean, standard deviation, median, maximum and minimum values for Mach cutoff booms of the FaINT data set.

FaINT Boom Number	Description	C-Weighted SEL Mean (dB)	C-Weighted SEL Std. Deviation (dB)	C-Weighted SEL Median (dB)	Max (dB)	Min (dB)
138801	Mach Cutoff	98.4	0.8	98.3	100.2	97.0
139106	Mach Cutoff	89.5	1.0	89.6	91.4	86.8
139205	Mach Cutoff	91.8	1.9	91.6	95.6	89.5
139305	Mach Cutoff	96.9	1.5	96.8	99.5	94.7

The final weighted sound exposure level presented, D-weighted, is shown in Figure 5-28. The calculated standard deviations are 1.2, 1.2, 1.3 and 1.4 dBD, respectively.

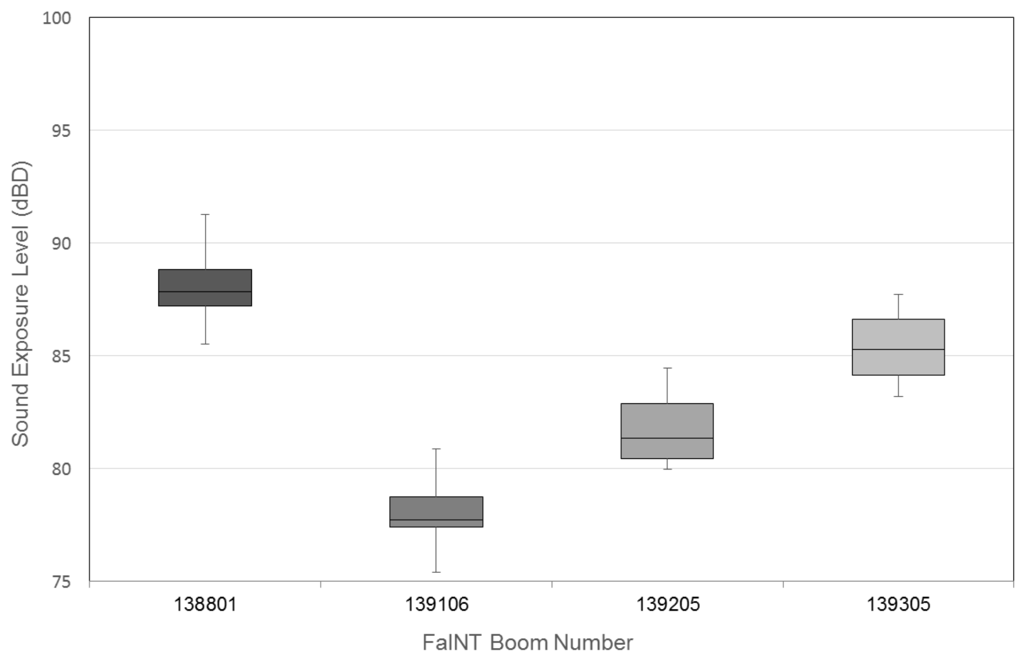

Figure 5-28: D-weighted sound exposure measurements for Mach cutoff flights of the FaINT dataset.

Table 5-26: D-weighted mean, standard deviation, median, maximum and minimum values for Mach cutoff booms of the FaINT data set.

FaINT Boom Number	Description	D-Weighted SEL Mean (dB)	D-Weighted SEL Std. Deviation (dB)	D-Weighted SEL Median (dB)	Max (dB)	Min (dB)
138801	Mach Cutoff	88.0	1.2	87.8	91.3	85.5
139106	Mach Cutoff	78.0	1.2	77.7	80.9	75.4
139205	Mach Cutoff	81.6	1.3	81.3	84.4	80.0
139305	Mach Cutoff	85.4	1.4	85.3	87.7	83.2

5.5.2 Steven's Mark VII Perceived Level (PLdB) Results

PldB is displayed for the FaINT Mach cutoff flights in Figure 5-29. The standard deviations for the four booms shown are 2.5, 1.9, 1.7 and 1.5 dB.

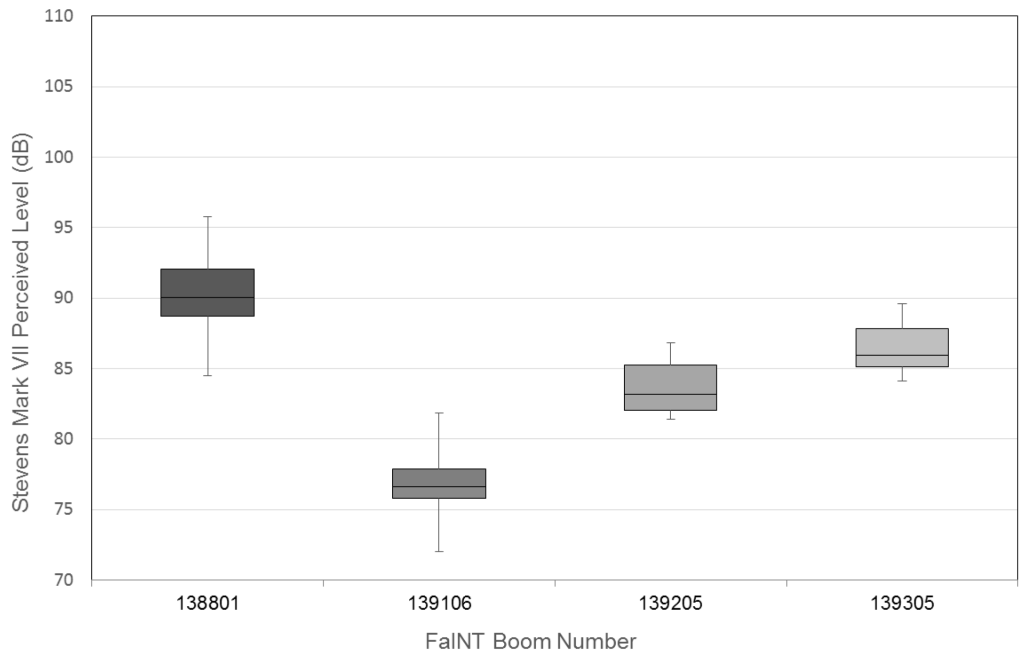

Figure 5-29: Perceived level measurements for Mach cutoff flights of the FaINT dataset.

Table 5-27: Perceived level mean, standard deviation, median, maximum and minimum values for Mach cutoff booms of the FaINT data set.

FaINT Boom Number	Description	PLdB Mean (dB)	PLdB Std. Deviation (dB)	PLdB Median (dB)	Max (dB)	Min (dB)
138801	Mach Cutoff	90.2	2.5	90.0	95.8	84.5
139106	Mach Cutoff	76.8	1.9	76.6	81.9	72.0
139205	Mach Cutoff	83.6	1.7	83.2	86.9	81.4
139305	Mach Cutoff	86.5	1.5	86.0	89.6	84.1

5.5.3 Indoor Sonic Boom Annoyance Predictor (ISBAP) Results

Lastly, ISBAP is shown for the Mach cutoff FaINT booms in Figure 5-30. The standard deviations measured are 0.18, 0.22, 0.17 and 0.13 annoyance units.

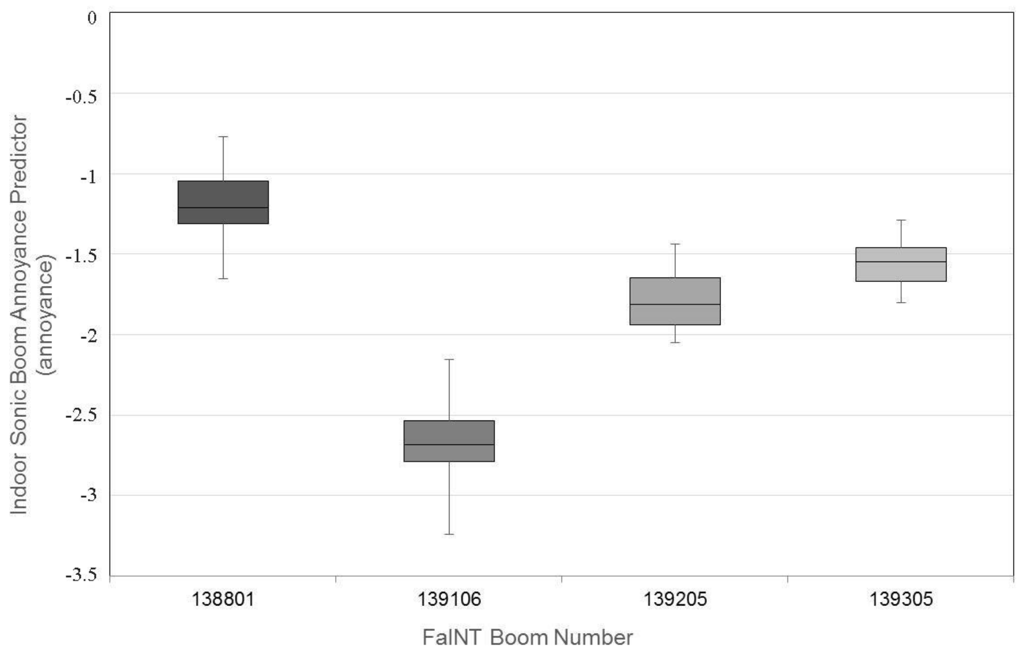

Figure 5-30: Indoor sonic boom annoyance predictor measurements for Mach cutoff flights of the FaINT dataset.

Table 5-28: Indoor sonic boom annoyance predictor mean, standard deviation, median, maximum and minimum values for Mach cutoff booms of the FaINT data set.

FaINT Boom Number	Description	ISBAP Mean	ISBAP Median	ISBAP Std. Deviation	Max	Min
138801	Mach Cutoff	-1.19	-1.21	0.18	-0.77	-1.66
139106	Mach Cutoff	-2.68	-2.68	0.22	-2.15	-3.24
139205	Mach Cutoff	-1.79	-1.81	0.17	-1.44	-2.05
139305	Mach Cutoff	-1.56	-1.55	0.13	-1.29	-1.80

Chapter 6

METRIC RESULTS DISCUSSION

The results shown in Chapter 5 can be analyzed for each data set individually and additional comparisons can be drawn between the SCAMP and FaINT data.

6.1 SCAMP Results Discussion

When considering N-wave sonic booms from the SCAMP data set, sonic boom events 12611 and 12612 have mean PL levels with a difference of over 7 dB, yet have very similar variances and display a similar total range. The standard deviations of the Perceived Level between the two flights differ by less than 0.2 dB. The next flight, flown at a higher Mach number, shows a slight decrease in variance along with a decrease in the range of the calculated metric. Whether this decrease is caused by other factors or by the increased flight speed is not certain at this point. Additionally, there is a very noticeable change in the amount of variance in measured data between the direct six on track boom measurements and the three off track measurements. As an example, the average standard deviation for perceived level of the on track flights is 5.0 dB, while the average standard deviation for the off track flights is nearly half at 2.8 dB. This decrease is substantial even taking into account the presence of the much calmer wind speeds measured on the day of the off track flights as was shown in Figure 3-5. The difference between off track and on track measurements of PLdB is shown in Figure 6-1:

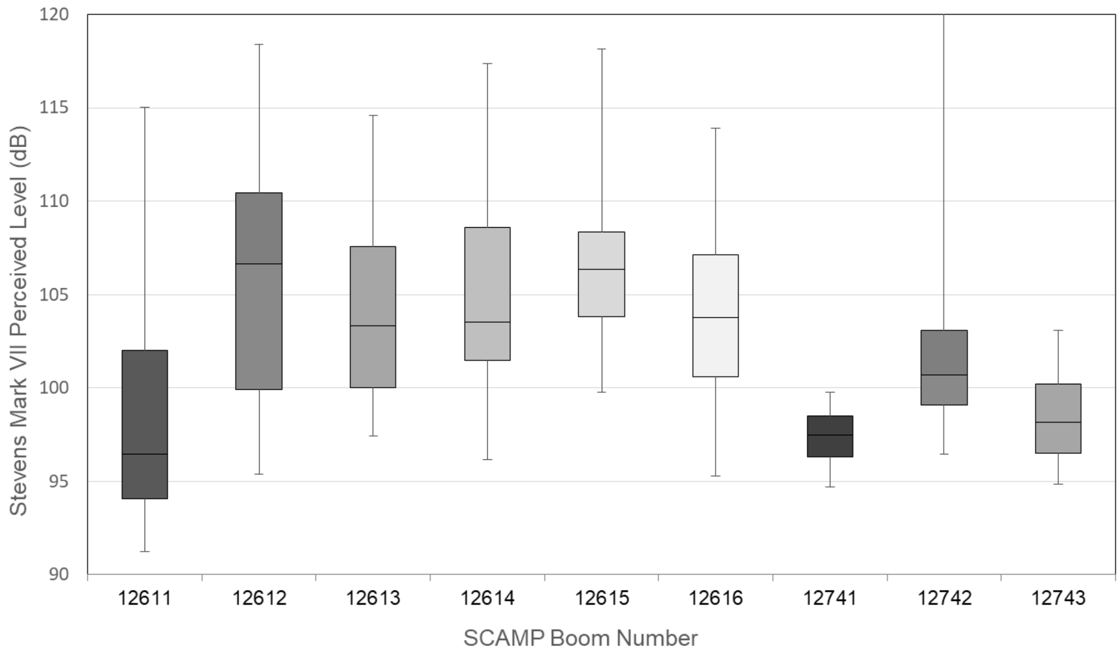

Figure 6-1: SCAMP booms on track and off track measurements for Steven's Mark VII Perceived Level. Off track results include booms 12741, 12742 and 12743. Off track results show a substantial decrease in variability as displayed in measured standard deviations.

Along with the decreased wind, this decrease in the variance of the off track measurements could be caused by the increased propagation path length and therefore increased absorption present. The increased absorption would generate a waveform with less high frequency energy in comparison to flights directly overhead, whose propagation path lengths would be shorter. Turbulence is known to have a greater effect on higher frequencies, and therefore the variance caused by turbulence may be decreased by this lengthened propagation path.

When considering the differences in metrics for the SCAMP dataset, the results show a small, but noticeable, decrease in the average variability of SEL in comparison with PL for the flights shown above for all weighting functions applied to SEL except A-weighting. This decrease may be in part to both the SEL metric itself, as well as the individual weighting functions applied to the waveform. The sensitivity of both metrics to changes in turbulences might be considered to be moderately high. In explanation of this, for A-weighted SEL there is a measured range of over 15 dBA for all five on track flights, and for PL all five flights have a range over 17 dB. For A-weighted SEL, along this highly controlled microphone array, the increase from the mean measured value to maximum measured value represented an increase of 20.4% in the most variable measurement and 12.2% at the least. For PL this increase from the mean ranged from 10.0% to 16.9%. With the relatively short distance of the microphone array in comparison to the speed of the aircraft, it is safe to say that these percent increases indicate a high amount of variability present in these measurements.

6.2 FaINT Results Discussion

Moving from the SCAMP dataset to N-wave sonic booms from FaINT, as stated in the dataset description in Chapter 3.2, there are two different flight paths to consider within the FaINT measurements. Lateral cutoff FaINT N-wave flights show a variability of the lateral extent of the sonic boom carpet as opposed to the on-track variability of SCAMP and the Mach cutoff N-wave FaINT tests. Again, this is due to the location of the microphone array placement perpendicular to the flight path rather than measuring parallel along the flight path. This array placement of the lateral cutoff flights is illustrated in Figure 3-6. FaINT results show a decreased variability of the Mach cutoff flights compared to the lateral FaINT flights. Figures 6-2 and 6-3 show this for one of the metrics, C-weighted sound exposure level. This pattern holds true for all additional metrics.

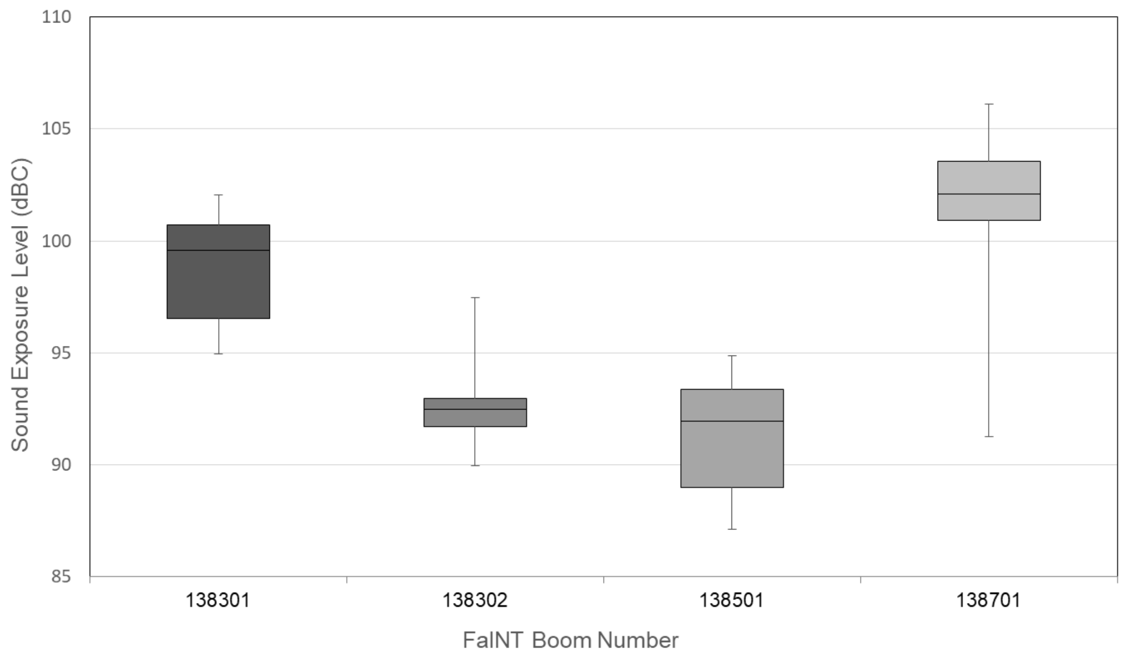

Figure 6-2: FaINT lateral cutoff measurements of C-weighted sound exposure level.

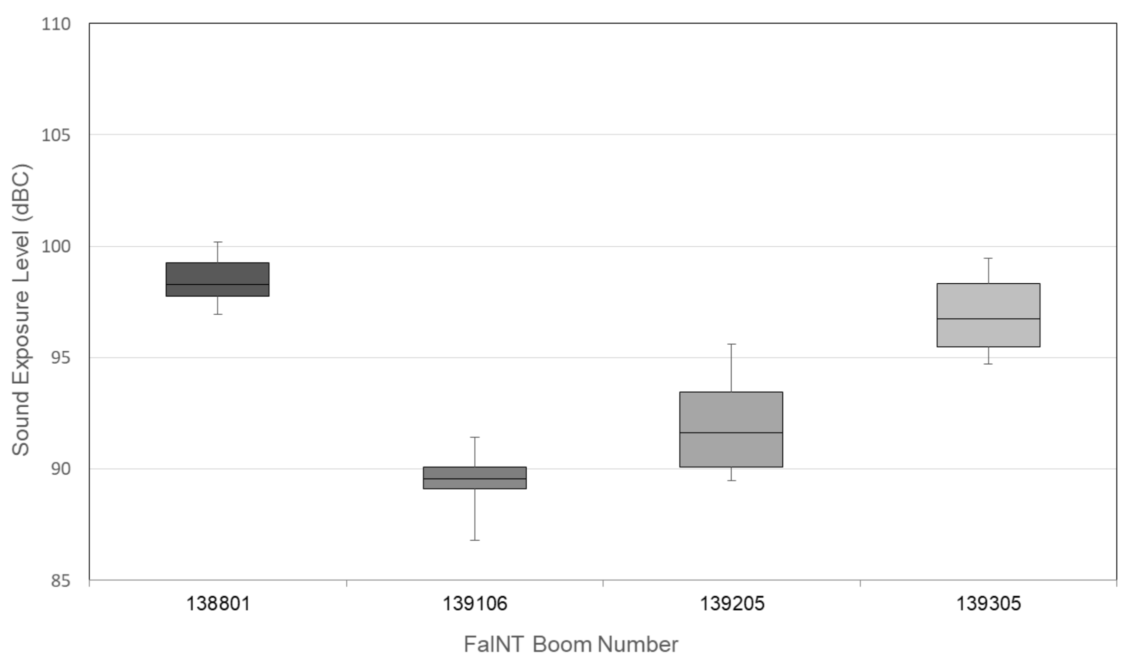

Figure 6-3: FaINT Mach cutoff measurements of C-weighted sound exposure level.

At least part of this decreased variability is because of much lower measured mean values for Mach cutoff results. The A-weighted SEL mean values for the four Mach cutoff N-wave booms ranged from 61 dB to 70 dB. This is in comparison to the lateral cutoff booms which exhibited mean A-weighted SEL of 65 dB to 80 dB and SCAMP on-track flights which ranged in mean A-weighted SEL values of 89 dB to 91dB. The Mach cutoff N-wave boom with the smallest change from its maximum to mean value was boom 139305, which had a percentage change in the A-weighted SEL metric of 3.6%. This is a lower percentage change from maximum to mean than any of the other measurements, including the SCAMP booms. It is highly likely part of this result can be attributed to the decreased mean measured value of this boom, an A-weighted SEL value of 69.9 dB. The standard deviation in A-weighted SEL for this boom was also measured at a low value of 1.2 dB. From the Mach cutoff N-wave data, there was not a singular boom that exhibited lower variability across all metrics. This is due to the weighting functions and the differing frequency content of the four booms. Boom 139305 does show a decreased variability for a majority of the metrics; the outliers in this case would be the C, D and E weighted exposure levels. A basic conclusion from this is that there is more low frequency content in boom 139305 causing decreased variability as the weighting functions increase the low frequency contributions to the measurement.

The four lateral cutoff FaINT booms each exhibited higher standard deviations than any of the Mach cutoff FaINT booms analyzed. The lowest variable lateral cutoff boom analyzed was FaINT boom 138302, with much lower standard deviation measurements than that of the other three. This boom had mean measured values smaller than the other three lateral cutoff booms, which could be a contributing factor in the decreased variance. However, comparing lateral cutoff booms to Mach cutoff booms of similar mean measured values shows there is still a substantial increase in the measured variability of the lateral cutoff booms. Individually, C-weighted sound exposure level exhibited lower levels of variance in the lateral cutoff measurements than the other metrics. Perceived level had lower standard deviations than A-weighted sound exposure level, but higher than the other weightings.

6.3 Overall Comparisons

Reviewing the results across all datasets we can gain an idea of which metrics perform better under a variety of measurement conditions. Between the weighting networks for sound exposure level, C weighting reduces the standard deviations calculated for the majority of the measurements analyzed. This is due to the frequency response of the C weighting emphasizing low frequencies without also including an increased bump in response above the 1 kHz frequency as D and E weightings both display. Figure 6-4 showcases how C weighting is a more robust metric giving different measurement conditions. The on track and off track SCMAP N-Wave sonic booms analyzed and shown were measured under very different atmospheric flight conditions and include a difference in propagation path length as outlined in Table 3-1. Despite this, the measured standard deviations between the booms are much closer than other metrics.

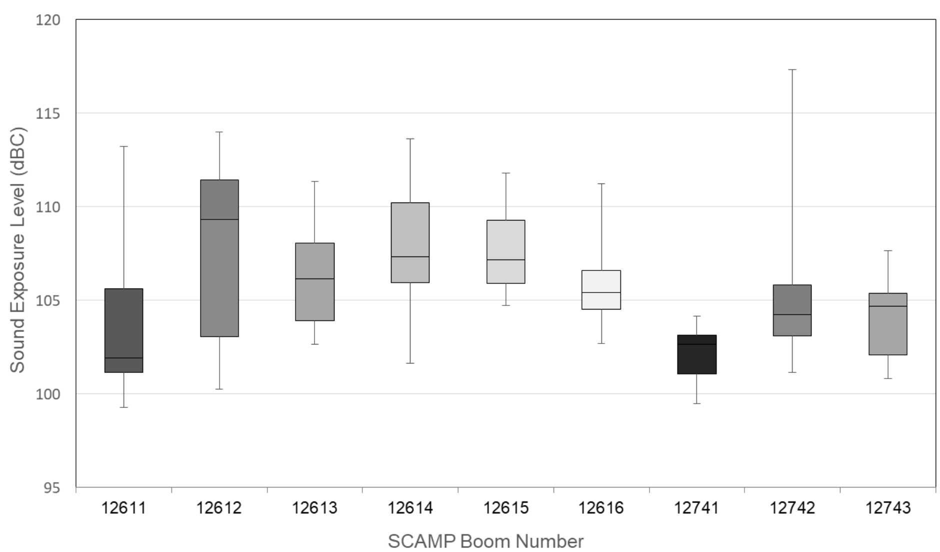

Figure 6-4: SCAMP on track and off track measurements for C-weighted sound exposure level. Off track results include booms 12741, 12742 and 12743. This metric displayed smaller differences in the standard deviations of the two separate flight conditions.

The worst weighting system (in terms of measured standard deviations) was the A weighting network. As an example, for SCAMP boom 12615, the standard deviations of the various weighting networks were: 4.2 dB for A weighting, 2.7 dB for B weighting, 1.9 dB for C weighting, 3.1 dB for D weighting and 3.5 dB for E weighting. Figure 6-5 also depicts the large difference in measured standard deviations between the two flight cases for SCAMP (on track and off track) for A-weighted sound exposure level.

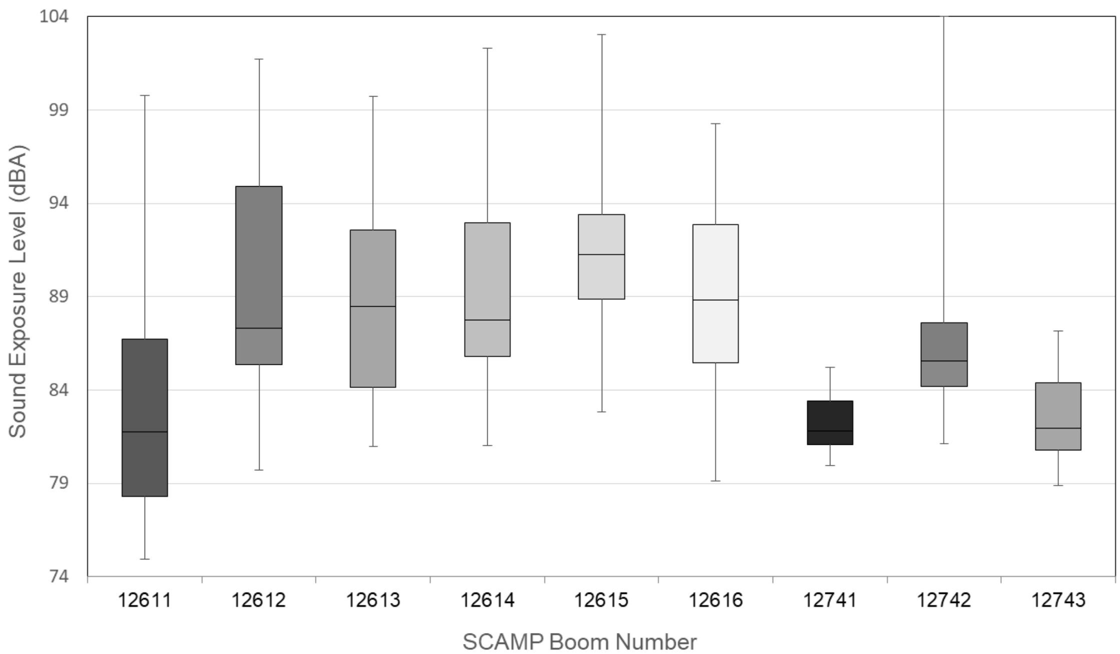

Figure 6-5: SCAMP on track and off track measurements for A-weighted sound exposure level. Off track results include booms 12741, 12742 and 12743. A-weighted SEL displayed a large difference in the standard deviations of the different flight conditions.

The only measured booms this pattern does not hold true for were FaINT 139205 and 139305. These two Mach cutoff N-wave booms had A-weighted sound exposure levels with a slightly lower measured standard deviation than the other metrics. For nearly all cases, perceived level exhibited standard deviation values that were higher than the C, D or E weighted sound exposure level metrics and lower than that of the A weighted values.

Chapter 7

CONCLUSIONS AND RECOMMENDATIONS

Metric comparison for the SCAMP N-wave measurements showed substantial variability for all on-track measurements. The off-track measurements had less variability than the on-track across all metrics. This decrease in variability was notable, even given the improved (less turbulent) weather conditions between the two days of flights. FaINT N-wave results showed a large increase in variability of the lateral cutoff results in comparison to Mach cutoff measurements. Additionally, all of the FaINT booms analyzed had lower mean measured values than that of the SCAMP booms. This fact may give some insight into the variability decrease of the FaINT measurements. The metric that performed best in terms of decreased variability across the most measurements was C weighted sound exposure level.

This research provides a comparison of metrics across sonic boom data sets with specific consideration of variability in the data. The findings can be expanded through the evaluation of additional metrics using additional data sets. A more in-depth look at flight information available (flight paths and weather conditions) to determine sources of variability in the measurements is highly recommended to provide further insight. Additionally, certain procedures have been examined to remove the turbulence from a sonic boom waveform. This de-turbing procedure could be utilized to show the difference in metric variance between the same sonic boom waveform with and without turbulent conditions. More information on de-turbing methods can be found in Chapter 2 of Sonic Boom: Six Decades of Research.[10] Finally, as stated in the boom dataset descriptions, these results have been achieved with sonic boom waveforms that were not initially measured with the purpose of studying metric variability. Applying this research to a new dataset that specifically targets metric variability as one of its objective could lead to more conclusive results due to a greater number of measurements, as well as measurement conditions chosen for study of metric variability.

REFERENCES

1. Preston Henne, “Case for Small Supersonic Civil Aircraft”. Journal of Aircraft. 42, 765-774 (2005).
2. Stanley S. Stevens, “Perceived level of noise by Mark VII and decibels (E)”. The Journal of the Acoustical Society of America. 51, 575-602 (1971).
3. Juliet A. Page, Kenneth J. Plotkin, Edward A. Haering, Jr., Domenic J. Maglieri, Robbie Cowart, Joe Salamone, Kevin Elmer, Bob Welge, John Ladd, “SCAMP: Superboom Caustic Analysis and Measurement Project Overview”. 51st AIAA Aerospace Sciences Meeting, 2013-0930, Grapevine, Texas, January 2013.
4. Jerrold H. Zar, Biostatistical Analysis. New Jersey: Prentice Hall, 2010.
5. Thomas A. Gionfriddo, "Quantification of Sonic Boom Signature Distortions from Propagation through Atmospheric Turbulence." Thesis. Pennsylvania State University, 1992.
6. Kevin P. Shepherd, Brenda M. Sullivan, “A Loudness Calculation Procedure Applied to Shaped Sonic Booms”. NASA Technical Paper 3134, 1991.
7. Erik M. Salomons, Computational Atmospheric Acoustics. Dordrecht: Kluwer Academic, 2001.
8. Alexandra Loubeau, Yusuke Naka, Brian G. Cook, Victor W. Sparrow, John M. Morgenstern, “A new evaluation of noise metrics for sonic booms using existing data”. Recent Developments in Nonlinear Acoustics: 20th International Symposium on Nonlinear Acoustics including the 2nd International Sonic Boom Forum. Vol. 1685. Melville: Amer Inst Of Physics, 2015. 090015-1-90015-4.
9. ANSI, American National Standard specification for sound level meters (2006), ANSI S1.4-1983(R2006).

10. Domenic J. Maglieri, Percy J. Bobbitt, Kenneth J. Plotkin, Kevin P. Shepherd, Peter G. Coen, David M. Richwine, "Sonic Boom Six Decades of Research." NASA SP-2014-622. 2014.

11. Victor W. Sparrow. "Lowering the Boom." Acoustics Today, vol. 2, no. 1, 2006, p. 20.

12. Sanford Fidell, Richard D. Horonjeff, Michael Harris, "Pilot Test of a Novel Method for Assessing Community Response to Low-Amplitude Sonic Booms" NASA/CR-2012-217767.

13. Juliet A. Page., Kathleen K. Hodgdon, Peg Krecker, Robbie Cowart, Christopher M. Hobbs, Clif Wilmer, Carrie Koening, Theresa Holmes, Trent Gaugler, Durland L. Shumway, James L. Rosenberger, Daisy Philips, "Waveforms and Sonic Boom Perception and Response (WSPR) Program Final Report, Low-Boom Community Response Program Pilot Test Design, Execution and Analysis," Wyle Research Report WR 12-15, NASA Contractor Report-2014-218180, March 2014.

14. Juliet A. Page, Christopher M. Hobbs, Edward A. Haering, Jr., Domenic J. Maglieri, Rebecca S. Shupe, Chris Hunting, Jim M. Giannakis, Scott Wiley, Franzeska Houtas, "SCAMP: Focused Sonic Boom Experiment Execution and Measurement Data Acquisition". 51st AIAA Aerospace Sciences Meeting, 2013-0933, Grapevine, Texas, January 2013.

15. Chris Hobbs, Juliet Page, Ken Plotkin, "SCAMP Acoustic Measurement Data". Wyle Report TN 11-02, prepared for NASA Langley Research Center, June 2011.

16. Larry J. Cliatt II, Michael A. Hill, Edward A. Haering Jr., "Mach Cutoff Analysis and Results from NASA's Farfield Investigation of No-boom Thresholds". 22nd AIAA/CEAS Aeroacoustics Conference, 2016-3011, Lyon, France, Jun.

Appendix A

MATLAB PROGRAMS

A.1 Sonic Boom Analyzer Program

```
% Pennsylvania State University
% Joshua Palmer
% Sonic Boom Analyzer, Metric Calculations
% This script performs a calculation of the PLdB/SEL/annoyance for
multiple booms
% and plots them as a function of distance across a microphone array.
% Includes an option to display a combined plot of both metrics or to
% display separate plots for each.
% NOTE: if using datasets other than SCAMP/FaINT slight modifications
may be
% necessary to ensure the code runs correctly
% Credit to Denise Miller for PLdB/SEL functions.
% Updated 09/03/15

clc
clear all
cd('E:\Data Analysis and Plotting');

% ********************************************************************
% Enter in sample rate (Hz) for boom data, chosen boom start/end
times(s),
% file location number and whether to produce a combined plot.
% ********************************************************************

sample_rate = 24000;
sample_rate2 = 25600;                              %(Hz)
t_start = 3.2;                                     %(s)
t_end = 10.5;                                      %(s)
boomfilenum = 12613;
combinedplot = 'n';                                % set to 'y' or 'n' to
create a combined PL/SEL plot or seperate plots of each
multichannel = 'n';                                % setting to use for
channels with seperate analysis required due to sample rates/etc.
units = 'psf';                                     % units of the signal
being used: set to 'Pa' of 'psf'
N = 2500;                                          % points to use in
Hanning window for PLdB calculation


%% Program Begins
```

```
boomfilenum = num2str(boomfilenum);
Channels = horzcat(1:20,25:30,32:52,54:60);
% good channels = horzcat(1:20,25:30,32:52,54:60);

% Pre-allocate memory for results files
PL = zeros(1,length(Channels));
SELa = zeros(1,length(Channels));
SELb = zeros(1,length(Channels));
SELc = zeros(1,length(Channels));
SELd = zeros(1,length(Channels));
SEL_z = zeros(1,length(Channels));
SELe = zeros(1,length(Channels));
annoyance = zeros(1,length(Channels));

for ii = 1:60
    numb = ii;
    str = num2str(numb);

    if ii<10
        direc = strcat('E:\SCAMP - May 2011\SCAMP-
DATA\Data\Main1\',boomfilenum,'_024000HZ_CH00',str,'.BIN');
    else
        direc = strcat('E:\SCAMP - May 2011\SCAMP-
DATA\Data\Main1\',boomfilenum,'_024000HZ_CH0',str,'.BIN');
    end

    % Read pressure data and store in p vector
    fid1=fopen(direc,'r');
    if fid1 == -1
        PL(ii) = 0;
        SELa(ii) = 0;
        SELc(ii) = 0;
        SEL_z(ii) = 0;
        SELe(ii) = 0;
    else
        p = fread(fid1,inf,'real*4');
        fclose(fid1);

        if t_start == 0;                                % calculate
first sample
            boom_start = 1;
        else
            boom_start = sample_rate.*t_start;
        end

        boom_end = sample_rate*t_end;                  % calculate last
sample
        Boom_data = p(boom_start:boom_end);            % truncate
pressure data to only include boom

        % Calculations with correct units  (both SEL/PLdB code now
expect
```

```
        % Pa as input units)
        if strcmp(units,'Pa')
            [SELa(ii), SELc(ii), SEL_z(ii)] =
SEL(Boom_data,sample_rate);        % Calculate SELa, SELc, and SELz
            PL(ii) =
PLdB(Boom_data,sample_rate,1 ,N);                        % Calculate
PLdB
            B_weighted =
Bweight(Boom_data,sample_rate);                        % B-weighted
SEL calculation
            SELb(ii) = SELz(B_weighted,sample_rate);
            D_weighted =
Dweight(Boom_data,sample_rate);                        % D-weighted
SEL calculation
            SELd(ii) = SELz(D_weighted,sample_rate);
            E_weighted =
Eweight(Boom_data,sample_rate);                        % Determine E-
weighted signal for SELe calculation
            SELe(ii) = SELz(E_weighted,sample_rate);
            annoyance(ii) = annoyance_indoor(Boom_data,sample_rate);
        elseif strcmp(units,'psf')
            Boom_data =
Boom_data.*47.8802083333;                              % convert to Pa
from psf for SEL code if needed
            [SELa(ii), SELc(ii), SEL_z(ii)] =
SEL(Boom_data,sample_rate);       % Calculate SEL
            PL(ii) =
PLdB(Boom_data,sample_rate,1,N);                         % Calculate
PLdB
            B_weighted =
Bweight(Boom_data,sample_rate);                       % B-weighted SEL
calculation
            SELb(ii) = SELz(B_weighted,sample_rate);
            D_weighted =
Dweight(Boom_data,sample_rate);                       % D-weighted SEL
calculation
            SELd(ii) = SELz(D_weighted,sample_rate);
            E_weighted =
Eweight(Boom_data,sample_rate);                       % Determine E-
weighted signal for SELe calculation
            SELe(ii) = SELz(E_weighted,sample_rate);
            annoyance(ii) = annoyance_indoor(Boom_data,sample_rate);
        else
            disp('Not a valid unit choice, enter psf or Pa')
        end


    end
end

switch multichannel
    case 'y'
        for jj = 30:60
            numb2 = jj;
```

```
            str2 = num2str(numb2);
            direc2 = strcat('E:\FaINT - Nov 2012\Data\Microphone
Data\Ground Array Microphone
Data\',boomfilenum,'_25600HZ_CHM0',str2,'.BIN');
            fid2 = fopen(direc2,'r');

            if fid2 == -1
                PL(jj) = 0;
                SELa(jj) = 0;
                SELc(jj) = 0;
                SEL_z(jj) = 0;
                SELe(jj) = 0;
            else
                p2=fread(fid2,inf,'real*4');
                fclose(fid2);

                if t_start == 0;                                    %
calculate first sample
                    boom_start2 = 1;
                else
                    boom_start2 = sample_rate2.*t_start;
                end

                boom_end2 = sample_rate2*t_end;                    %
calculate last sample
                Boom_data2 = p2(boom_start:boom_end2);              %
truncate pressure data to only include boom

                % Calculations with correct units  (both SEL/PLdB code
now expect
                % Pa as input units)
                if strcmp(units,'Pa')
                    [SELa(jj), SELc(jj), SEL_z(jj)] =
SEL(Boom_data2,sample_rate2);     % Calculate SEL
                    PL(jj) =
PLdB(Boom_data2,sample_rate2,1,N);                        % Calculate
PLdB
                    B_weighted =
Bweight(Boom_data2,sample_rate2);                        % B-weighted SEL
calculation
                    SELb(jj) = SELz(B_weighted,sample_rate2);
                    D_weighted =
Dweight(Boom_data2,sample_rate2);                        % D-weighted SEL
calculation
                    SELd(jj) = SELz(D_weighted,sample_rate);
                    E_weighted =
Eweight(Boom_data2,sample_rate2);                        % Determine E-
weighted signal for SELe calculation
                    SELe(jj) = SELz(E_weighted,sample_rate2);
                    annoyance(jj) =
annoyance_indoor(Boom_data2,sample_rate2);
                elseif strcmp(units,'psf')
```

```
                    Boom_data2 = 
Boom_data2.*47.8802083333;                              % convert to Pa 
from psf for SEL code if needed
                    [SELa(jj), SELc(jj), SEL_z(jj)] = 
SEL(Boom_data2,sample_rate2);     % Calculate SEL
                    PL(jj) = 
PLdB(Boom_data2,sample_rate2,1,N);                          % Calculate 
PLdB
                    B_weighted = 
Bweight(Boom_data2,sample_rate2);                       % B-weighted SEL 
calculation
                    SELb(jj) = SELz(B_weighted,sample_rate2);
                    D_weighted = 
Dweight(Boom_data2,sample_rate2);                       % D-weighted SEL 
calculation
                    SELd(jj) = SELz(D_weighted,sample_rate);
                    E_weighted = 
Eweight(Boom_data2,sample_rate2);                       % Determine E-
weighted signal for SELe calculation
                    SELe(jj) = SELz(E_weighted,sample_rate2);
                    annoyance(jj) = 
annoyance_indoor(Boom_data2,sample_rate2);

                end
            end
        end
    case 'n'
end

clc

% cut out unwanted channels
PL = PL(Channels);
SELa = SELa(Channels);
SELb = SELb(Channels);
SELc = SELc(Channels);
SELd = SELd(Channels);
SEL_z = SEL_z(Channels);
SELe = SELe(Channels);
annoyance = annoyance(Channels);

% Calculate the mean and standard deviation for the metrics
PLmean = mean(PL);
PLstd = std(PL);
SELamean = mean(SELa);
SELastd = std(SELa);
SELbmean = mean(SELb);
SELbstd = std(SELb);
SELcmean = mean(SELc);
SELcstd = std(SELc);
SELdmean = mean(SELd);
SELdstd = std(SELd);
SELemean = mean(SELe);
SELestd = std(SELe);
```

```
annoyance_mean = mean(annoyance);
annoyance_std = std(annoyance);

% Calculate the median of the metrics
Plmed = median(PL);
SELamed = median(SELa);
SELbmed = median(SELb);
SELcmed = median(SELc);
SELdmed = median(SELd);
SELemed = median(SELe);
annoyancemed = median(annoyance);

%% Plotting

% Generate Plot of SEL/PldB versus mic channel number and print to pdf
file
switch combinedplot
    case 'y'
        figure(1)
        subplot(2,1,1);
        plot(Channels,PL,'-o','MarkerFaceColor','k','MarkerSize',4);
        xlabel('Channel Number');
        ylabel('PLdB (dB)');
        title(strcat('FAiNT Boom ',boomfilenum,', PLdB across array'));
        axis tight;
        hold all
        errorbar(30,PLmean,PLstd);
        hold off

        subplot(2,1,2);
        plot(Channels,SELe,'-o','MarkerFaceColor','k','MarkerSize',4)
        xlabel('Channel Number');
        ylabel('SEL (dBE)');
        title(strcat('FAiNT Boom ',boomfilenum,', E-weighted SEL across
array'));
        axis tight;
        hold all
        errorbar(30,SELemean,SELestd);
        hold off

        cd('E:\Data Analysis and Plotting\Plotting\Combined PL_SEL
Analysis\SCAMP');
        print('-dpdf',strcat('SCAMP Boom ',boomfilenum,' SELe
comparison'),'-r300')

    case 'n'
        cd('E:\Data Analysis and Plotting\Plotting\Pldb
Analysis\SCAMP');
        figure(1)
        set(gca,'fontsize',20);
        plot(Channels,annoyance,'-
o','MarkerFaceColor','k','MarkerSize',4,'color',[0,0,0]);
        xlabel('Channel Number');
        ylabel('Annoyance');
```

```
        % title(strcat('SCAMP Boom ',boomfilenum,', PLdB across
array'));
        print('-dpdf',strcat('PldB',boomfilenum),'-r300')

        cd('E:\Data Analysis and Plotting\Plotting\SEL
Analysis\SCAMP');
        figure(2)
        plot(Channels,SELa,Channels,SELc,Channels,SEL_z);
        xlabel('Channel Number');
        ylabel('SEL (dB)');
        legend('SELa','SELc','SELz');
        title(strcat('SCAMP Boom ',boomfilenum,', SEL across array'));
        print('-dpdf',strcat('SEL',boomfilenum),'-r300')

    otherwise
        disp('Not a valid input for Combined Plot,')
        disp('Please enter y or n')
end

% plot all metrics on single figure
cd('E:\Data Analysis and Plotting\Plotting\All metrics');
figure(3)
subplot(3,1,1)
plot(Channels,PL,'-o','MarkerFaceColor','k','MarkerSize',4);
xlabel('Channel Number');
ylabel('PLdB (dB)');
title(strcat('FAiNT Boom ',boomfilenum,', PLdB across array'));
subplot(3,1,2)
plot(Channels,[SELa;SELb;SELc;SELd;SELe;SEL_z],'-
o','MarkerFaceColor','k','MarkerSize',4);
xlabel('Channel Number');
ylabel('SEL (dB)');
legend('SEL_a','SEL_b','SEL_c','SEL_d','SEL_e','SEL_z','Location','Sout
hWest');
title(strcat('FAiNT Boom ',boomfilenum,', SEL across array'));
subplot(3,1,3)
plot(Channels,annoyance,'-o','MarkerFaceColor','k','MarkerSize',4)
xlabel('Channel Number');
ylabel('Indoor Annoyance Metric');
title(strcat('FAiNT Boom ', boomfilenum,', Indoor Annoyance across
array'));
print('-dpdf',strcat(boomfilenum,'_all'));

% Return to home directory
cd('E:\Data Analysis and Plotting');
```

A.2 Steven's Mark VII Perceived Level Calculation

```
function [PLdBvalue,varargout]=PLdB(varargin)
% PLdB(waveform,Fs) Compute PLdB based on Stevens Mark VII
%
% PLdB(waveform,Fs) where waveform is the waveform in question and Fs
is
% the sampling frequency.
% PLdB(waveform,Fs,S,N) where S stands for symetry, (0 for symetric, 1
for
% non-symetric. The default is S=0 which is the symetric case.
% N stands for the number of points to use on the hanning
% window. If N is not specified, the default is 200.
inputs=nargin;

%%
switch nargin
  case 1
    disp('No sampling frequency specified')
    return
  case 2
    N=2500; % points used in the hanning window
    S=0; % symetric case
    waveform=varargin{1};

    Fs=varargin{2};
  case 3
    waveform=varargin{1};
    Fs=varargin{2};
    S=varargin{3};
    N=2500;
  case 4
    waveform=varargin{1};
    Fs=varargin{2};
    S=varargin{3};
    N=varargin{4};
  otherwise disp('something is wrong. Too many input arguments')
end

[rows,cols]=size(waveform);
if rows==1
  waveform=waveform';
end

%% Save current path
curdir=cd;

%% Change to the directory where the weightsv2.exe program is
cd('E:\Data Analysis and Plotting')
%%
fid=fopen('options.pl','wt');
count=fprintf(fid,'%1s\n','9');
count=fprintf(fid,'%1s\n',num2str(S));
```

```
count=fprintf(fid,'%1s\n','N');
count=fprintf(fid,'%1s\n','longmeas.pl');
count=fprintf(fid,'%7s\n','1 127.6');
count=fprintf(fid,'%13s\n','groundmeas.pl');
count=fprintf(fid,'%5s\n',num2str(Fs));
count=fprintf(fid,'%1s\n','0');
count=fprintf(fid,'%1s\n','0.02088545632547 ');
count=fprintf(fid,'%1s\n','0');
count=fprintf(fid,'%1s\n','1');
count=fprintf(fid,'%1s\n','1');
count=fprintf(fid,'%1s\n','1');
count=fprintf(fid,'%1s\n','0');
count=fprintf(fid,'%1s\n',num2str(N));
count=fprintf(fid,'%1s\n','0');
count=fprintf(fid,'%1s\n','0');
fclose(fid);



%%
if isstruct(dir('groundmeas.pl'))
  delete('groundmeas.pl');
end
save(['groundmeas.pl'], 'waveform','-ascii')
% send the ground measurement to Brenda's Code, along with the
% instructions contained in options.pl
if isstruct(dir('longmeas.pl'))
  delete('longmeas.pl');
end
dos('weightsv2.exe < options.pl');

fid=fopen('longmeas.pl'); % longmeas.pl =output data file from Sullivan
% code.
junk=textscan(fid,'%*[^\n]',9);
Pl=textscan(fid,'%*s%*s%*s%*s%f32*[^\n]',1)
if S==1
  junk=textscan(fid,'%*[^\n]',10);
  Front=double(cell2mat(textscan(fid,'%*s%*s%*s%*s%f32*[^\n]',1)));
  junk=textscan(fid,'%*[^\n]',10);
  Back=double(cell2mat(textscan(fid,'%*s%*s%*s%*s%f32*[^\n]',1)));
  varargout(1)={Front};
  varargout(2)={Back}; % tack on the front and back PL values
end
PLdBvalue=double(cell2mat(Pl));
fclose(fid);
delete('subf7_shape.txt');

%% change back to the working directory
cd(curdir)
```

A.3 Sound Exposure Level Calculation

```
function [SELz]=SELz(inpsig,srate)

%inpsig is assumed to be in Pascals
pref=20e-6;
tref=1;

ilen=size(inpsig,1);                              % we expect a column
vector
upfact=2;
ulen=ilen*upfact;

fs=srate*upfact;
dt=1/fs;

% first let's upsample the input signal and zero pad it to allow for
weighting function responses
zpad=floor(ulen/2);                               % append the signal
with a length of 33% for zero padding
utot=ulen+zpad;
uparr=zeros(utot,1);

ulocs=linspace(1,ulen-upfact+1,ilen);
uparr(ulocs)=inpsig*upfact;                       % we scale by upfact to
account for energy lost by adding the zeros

% now we apply a low pass filter to the upsampled signal to do the
interpolation for us
[b,a]=butter(20,5/(6*upfact));
uparr=filter(b,a,uparr);

% compute the energy levels
E=sum(abs(uparr).^2)*dt;

% compute the sound exposure levels
SELz=10*log10(E/(tref*pref^2));
```

A.4 B-Weighting Calculation

```
function [B_weighted] = Bweight(signal,fs)

% Function B Weighting
    % this function calculates the B weighted pressure of a given
signal
    % using time domain filters. REF: ACS 516 notes, CH5/ANSI S1.42-
2001

    % define constants (frequencies) according to ANSI S1.42-2001
    w1 = 2*pi*20.598997;
    w2 = 2*pi*158.48932;
    w4 = 2*pi*12194.22;

    % define laplace transform of the transfer function
    % laplace transform
    s=zpk('s');
    Hb = (w4^2*s^3)/((s+w1)^2*(s+w4)^2*(s+w2));
    [b, a] = tfdata(Hb,'v');

    % perform the bilinear transform to get filter coefficients
    [B,A] = bilinear_xform(b,a,fs);

    % filter the original signal
    B_weighted = filter(B,A,signal);
end
```

A.5 C-Weighting Calculation

```
function [C_weighted] = Cweight(signal,fs)

% Function C Weighting
    % this function calculates the C weighted pressure of a given
signal
    % using time domain filters. REF: ACS 516 notes, CH5

    % define constants (frequencies) according to ANSI S1.42-2001
    w1 = 2*pi*20.598997;
    w4 = 2*pi*12194.22;

    % define modified numerator and denominator polynomial coefficients
(w/
    % high frequency response pre-distorted prior to the bilinear
    % transform)
    num = [1.0072*(w4/1.4) 0 0];
    den = conv([1 2*w1 w1^2],[1 w4/1.4]);

    % perform the bilinear transform to get filter coefficients
    [B,A] = bilinear_xform(num, den, fs);

    % filter the original signal
    C_weighted = filter(B,A,signal);
end
```

A.6 D-Weighting Calculation

```
function [D_weighted] = Dweight(signal,fs)

% Function D Weighting
    % this function calculates the D weighted pressure of a given
signal
    % using time domain filters. REF: ACS 516 notes, CH5/ANSI S1.42-
2001

    % define poles/zeros according to ANSI S1.42-2001
    z1 = 2*pi*(-519.8+1j*876.2);
    z2 = 2*pi*(-519.8-1j*876.2);
    p1 = 2*pi*-282.7;
    p2 = 2*pi*-1160;
    p3 = 2*pi*(-1712+1j*2628);
    p4 = 2*pi*(-1712-1j*2628);

    % define zero and pole vectors and convert to transfer function
    zero = [0;z1;z2];
    pole = [p1;p2;p3;p4];
    ks = 91090;
    [b,a] = zp2tf(zero,pole,ks);

    %laplace method (unworking due to complex zeros/poles)
    %s = zpk('s');
    %Hd = 2e-6*C*s*(s+z1)*(s+z2)/((s+p1)*(s+p2)*(s+p3)*(s+p4));
    %[b, a] = tfdata(Hd,'v');

    % perform the bilinear transform to get filter coefficients
    [B,A] = bilinear_xform(b,a,fs);

    % filter the original signal
    D_weighted = filter(B,A,signal);
end
```

A.7 E-Weighting Calculation

```
function [E_weighted] = Eweight(signal,fs)

% Function E Weighting
    % this function calculates the E weighted pressure of a given
signal
    % using time domain filters. REF: ACS 516 notes, CH5/ANSI S1.42-
2001

    % define poles/zeros and constant according to ANSI S1.42-2001
    z1 = 2*pi*(-735+1j*918);
    z2 = 2*pi*(-735-1j*918);
    p1 = 2*pi*-53.5;
    p2 = 2*pi*-378;
    p3 = 2*pi*-865;
    p4 = 2*pi*(-4024+1j*3966);
    p5 = 2*pi*(-4024-1j*3966);
    p6 = 2*pi*-6500;

    % define zero and pole vectors
    zero = [0;0;z1;z2];
    pole = [p1;p2;p3;p4;p5;p6];
    ks = 7.73e9;
    [b,a] = zp2tf(zero,pole,ks);

    % laplace method (unworking due to complex poles/zeros)
%     s = zpk('s');
%     He =
C*s^2*(s+z1)*(s+z2)/((s+p1)*(s+p2)*(s+p3)*(s+p4)*(s+p5)*(s+p6));
%      [b, a] = tfdata(He,'v');

    % perform the bilinear transform to get filter coefficients
    [B,A] = bilinear_xform(b,a,fs);

    % filter the original signal
    E_weighted = filter(B,A,signal);
end
```

A.8 Annoyance Calculation

```
function [annoyance] = annoyance_indoor(signal,fs)

% Function Indoor annoyance
    % this function calculates the NASA indoor annoyance metric
    % this assumes that the signal is in Pascals

    % find C-weighted SEL
    C_weighted = Cweight(signal,fs);
    SELc = SELz(C_weighted,fs);

    % find A-weighted SEL
    [SELa] = SEL(signal,fs);

    % find PL
    % NOTE: convert to psf for this calculation
    signal = signal*0.0208854;
    PL = PLdB(signal,fs,0,1);

    % determine the annoyance metric
    annoyance = -6.827 + 0.0864*PL + 0.0363*(SELc - SELa);
end
```

A.9 Waterfall Plot Program

```
% Pennsylvania State University
% Joshua Palmer
% Waterfall Plotting
% This creates a waterfall plot of the selected range of datasets
% NOTE: for other data slight alterations will need to be made to
% correctly input the data
% Updated 05/13/14

clc
clear all
cd('E:\Data Analysis and Plotting');

%
***********************************************************************
**
% Enter in sample rate(Hz) for boom data, chosen boom start/end
times(s)
% and file number for the boom.
% NOTE: modifications required for files outside SCAMP dataset
%
***********************************************************************
**
sample_rate = 24000;                            % Specify Sample
Rate(Hz)
t_start = 3.2;                                  % Specify start time(s)
t_end = 10.5;                                     % Specify end time(s)
boomfilenum = 12613;                            % For SCAMP data
specify the boom filenumber
numchannels = 60;                               % specify number of mic
channels


% Program Begins
%
***********************************************************************
**
boomfilenum = num2str(boomfilenum);
Channels = 1:60;
spectralseries = ones(175201,numchannels);

for ii = 1:numchannels
    numb = ii;
    str = num2str(numb);
    if ii<10
        direc = strcat('E:\SCAMP - May 2011\SCAMP-
DATA\Data\Main1\',boomfilenum,'_024000HZ_CH00',str,'.bin');
    else
        direc = strcat('E:\SCAMP - May 2011\SCAMP-
DATA\Data\Main1\',boomfilenum,'_024000HZ_CH0',str,'.bin');
    end
```

```
% Read pressure data and store in p vector
    fid1=fopen(direc,'r');
    if fid1 == -1
        spectralseries(:,ii) = 0;
    else
        p=fread(fid1,inf,'real*4');
        fclose(fid1);

        if t_start == 0;                                  % calculate
first sample
            boom_start = 1;
        else
            boom_start = sample_rate.*t_start;
        end

        boom_end = sample_rate.*t_end;                  % calculate last
sample
        Boom_data = p(boom_start:boom_end);             % truncate
pressure data to only include boom

        spectralseries(:,ii) = Boom_data + 1.5*ii;
        distance(ii) = 125.*ii;
    end
end


    x = size(Boom_data)-1;                              % create time vector
using size of the boom and sample rate
    y = x./sample_rate;
    time = [0:(y/x):y]';

    % get rid of unwanted channels
    spectralseries = spectralseries(:,Channels);

%      % Generate 3D Waterfall Plot
%      set (gcf,'Visible','off')
%      h = waterfall(Channels,time,spectralseries);
%      colormap jet
%      xlabel('Channel Number');
%      ylabel('Time(s)');
%      zlabel('Pressure (psf)');
%      title(strcat('SCAMP Boom ',boomfilenum,', Waterfall Pressure
Amplitude'));
%      cd('E:\Data Analysis and Plotting\Plotting\Waterfall
Plots\SCAMP');
%      print('-dpdf',boomfilenum,'-r300')
%      cd('E:\Data Analysis and Plotting\');

% Generate 2D Waterfall
figure(1)
plot(time,spectralseries,'color',[0,0,0],'LineWidth',0.75)
```

```
set(gca,'fontsize',20);
set(gca,'YTickLabel',[]);
set(gca,'YTick',[]);
xlabel('Time(s)');
ylabel('Pressure (Pa)');
% title(strcat('SCAMP Boom ',boomfilenum,',Pressure Amplitude, Channels
13-60'));
xlim([0 y(1)]);
%xlim([3.45 3.85]);
ylim([0 93]);
cd('E:\Data Analysis and Plotting\Plotting\Waterfall Plots\SCAMP');
print('-dpdf',boomfilenum,'-r300')
cd('E:\Data Analysis and Plotting\');
```

Appendix B

ADDITIONAL SONIC BOOM DATASETS

Dataset	Date	Data File Type(s)	Ambient Conditions	Location	Sampling Frequency	Boom Signatures	Number Flights	Number of Sensors
NASA/USAF Data compilation - OKC	Jul-64	.dat	Upper air rawinsonde	Oklahoma City	-	3000	1225	3 main + 1 mobile van mic
NASA/USAF Data compilation - XB-70	May-66	.zz	Upper air rawinsonde	EAFB/Coaldate and Beatty	-	300	39	53 spread over 5 measurement sites
NASA/USAF Data compilation - SR-71	Jan-67	.dat	Upper air rawinsonde	EAFB	-	2000	35	multiple arrays at 10 locations
NASA/USAF Data compilation - NSBEO	Jul-67	.dat	Upper air rawinsonde	EAFB	-	1500	257	5 on ground/1 at 20' height
NASA/USAF Data compilation - F-104 8K Array	Feb-69	.dat	Upper air rawinsonde	EAFB	-	1400	34	42 (8000' linear array)
NASA/USAF Data compilation - USAF Boomfile	Aug-87	.dat	Upper air rawinsonde	EAFB	-	850	43	13 BEAR + 8 PATS systems
Shaped Sonic Boom Experiment (SSBE)	Mar-05	.txt/.tt8/ .dat	Balloon Data	EAFB/Harper Lake	-	>100	24	4 at Harper Lake, 28 at EAFB
Northrop Grumman NASA Dryden	Jun-05	.txt	Ambient Data	EAFB	24kHz	17	4	7
PSU NASA Dryden	Jun-05	.dat	none	EAFB	-	50	-	-
Vibro-Acoustic Response of Buildings Due to Sonic Boom Exposure (VIBES)	Jun-06	.mat	Weather Station Data	EAFB	25.6/51.2 khZ	112	19	207 in house/31 vertical array/32 horizontal array
NASA Dryden VIBES	Jul-07	.buff/.txt	none	EAFB	24kHz	43	7	10 on tower + 4 groundboards
NASA normal booms	Jul-07	.txt/.emf	Balloon Data/METAR	EAFB	-	21	-	1 + sailplane data
NASA Dryden Booms on Big Structures (BOBS)	Sep-09	.mat	Weather Data	EAFB	24kHz	37	-	13 mics + 22 pressure transducers
Superboom Caustic Analysis and Measurement Program (SCAMP)	Jun-11	.bin	Balloon Data	Cuddeback Gunnery Range, CA	24kHz	70	14	81 mics in main array
Farfield Investigations of No-boom Thresholds (FaINT)	Nov-12	.bin	Weather Balloons/Towers	EAFB	24kHz - 32.768kHz	73	13	linear array of 60 mics/spiral array