Health Based Criteria for Use in Managing Airport and Aircraft Noise

Health Based Criteria for use in Managing Airport and Aircraft Noise

Bryan Johnson

A Thesis in the Field of Sustainability and Environmental Management

for the Degree of Master of Liberal Arts in Extension Studies

Harvard University

May 2018

Abstract

This thesis questions whether an exposure-dose relationship between measurable aircraft sound and health can be established. The significance of this research is that highly concentrated global populations live near airports and are receiving a dangerous unknown and undefined health exposure. The question addressed is if aircraft sound originating from various heights has enough energy left upon reaching the ground to create measurable vibrations in human tissue. Simulated body tissue was isolated from the internal walls of a mock-up structure to make this determination. Vibration and sound data were collected near the Phoenix Arizona airport from over 60 aircraft as they passed overhead at heights varying up to two-miles above the ground.

The measurements demonstrated that the open air significantly attenuates most aircraft sound frequencies before they reach the ground. The experimental measurements were compared and contrasted to a non-health based sound criteria used by the Federal Aviation Authority (FAA) to determine variances against presently defined acceptable human impact. It was determined that most of the aircraft produced sound is not within the FAA criteria and that the portion that isn't included causes harmful health effects. The frequencies that are the most significant component of aircraft sound energy are low frequency (200 Hz and less) and infrasound (20 Hz and less).

Experimentation demonstrated that aircraft produced infrasound and low frequency sound can travel almost a mile with minimal attenuation and are not blocked by common construction material. These sounds readily pass through and into common dwellings.

Within the frequency range of about 5-40 Hz, similar amplitude/intensity infrasound and low frequency sound is being produced by each aircraft from approximately 4000 feet elevation and lower. This observation was generalized along the flight path of ascending aircraft from takeoff and allowed a description of a singular value of infrasound vibrational exposure beginning at the end of the runway to approximately five miles from the airport. Sound emanates out from either side of the aircraft and experimental data suggests a full exposure band of approximately one and a half miles wide. Partial reduced vibration exposures occur outside of the primary exposure band.

Low frequencies less than 40 Hz were measured in the experiment's simulated human tissue and this exposure range poses health concerns. These vibrations match natural human body frequencies leading to human cell damage and the thickening of tissue (Alves-Pereira, 2007). A serious health issue caused by this vibration is increased cardiovascular risk, which has been identified near several airports throughout the world (Correia, 2013). This research strongly suggests that human tissue damage can occur from each flight event.

NextGen navigation is the future of aviation and its implementation poses a special additional health risk in that its application intentionally concentrates aircraft flight into tight corridors. This practice increases the number of exposures and conversely the health risk for those directly beneath the flight paths. When the flight path is over densely populated communities, a significant increased cardiovascular health risk for those exposed can be expected. This thesis did not determine a dose-thresh hold health relationship to overflights. This is an important suggested area for future research.

Acknowledgements

Special thanks to my wife Susan for providing insight, encouragement and support during the years I was a graduate student at Harvard. She graciously listened to all of my ideas and fears during the planning and implementation of this thesis project. She offered her thoughts when needed to move the project forward. She was my more than capable assistant in helping gather and record data during the experiments. This effort would not have been possible without her. I owe and offer her my thanks.

Special thanks for the persistence of my thesis director, Megan Epler Wood, as she successfully nudged me towards this topic. I was fortunate to meet Megan early in my studies and enjoyed her passion towards tourism and envied how she applied her expertise and the manner in which she helped others. It became evident to me that I needed to follow her example as I progressed through the sustainability program in that my passion centered on the relationship of the industrial societies induced environmental impacts and degraded human health. Megan is a thorough and careful researcher and as my thesis director encouraged me towards those same attributes. I am grateful for her guidance, persistence and help, as she is an influential part of this document.

I offer a special thanks to my research advisor Mark Leighton. Mark encouraged me towards excellence and showed interest in this project. He always responded to my questions and ideas by offering suggestions to ensure a high quality document. I appreciate that he set a high standard for quality.

Special thanks to my longtime friend David King for the time spent brainstorming ideas.

Table of Contents

List of Tables

List of Figures

Definition of Terms

A-weighted sound: A weighting factor applied to the overall sound range of 20 – 20,000 Hz that focuses the sound measurement reported to that portion of audible sound that most people hear while de-rating the contribution all other sound measurements. This weighting system focuses on the frequency range of 1,000 – 6,000 Hz.

Decibels (dB): a logarithmic unit used to represent sound intensity.

DNL 65: The criteria used by the FAA to determine aircraft sound intensity averaged over a year with an adjustment made for nighttime sound. When used by the FAA, DNL sound utilizes "A" weighted sound.

Federal Aviation Authority (FAA): United States Government organization charged with regulating aircraft and flights.

Hertz (Hz): The time in seconds that one single wave can complete a single cycle.

Infrasound: Very low frequency sound waves that are beneath the audible hearing range of humans.

Low Frequency Sound: Sounds that occur at frequencies less than 200 Hz. Infrasound is sound at 20 Hz and less.

Resonance: The combining of energy to increase the amplitude or intensity of a single frequency. Resonance is a function of the mass and stiffness of material

Chapter I

Introduction

Hearing is one of the five human senses. Listening to sound at similar sound intensities provides great pleasure or can cause angst or even pain. Undesirable sound is called noise or noise pollution depending upon its source. Aviation serves as the primary mode for the transport of consumer goods and has made the world accessible to the masses through travel with airports located near both large and small communities. Airports located close to population centers produce negative human and environmental impacts from the sound emitted from planes. High-density populations near airports exacerbate the impact of aircraft sound conditions. Aircraft sound is considered to be highly undesirable and it is treated as a social nuisance rather than as a pollutant or a health concern.

Policy makers throughout the world use criteria to manage noise based upon the audible portion of sound. They gauge the acceptance of aircraft generated noise using a public nuisance scale. The criteria are based upon social perceptions of the impact of noise and the guidelines in place were developed and placed into service with the intent that they minimize public "annoyance" from the sound source (Fidel, 2003).

The Federal Aviation Authority (FAA) defines sound intensity as the average sound from all aircraft over the course of a year. Their threshold for an acceptable average level of day-night sound (DNL) is known as 65 day-night DNL (ESA, 2015). The DNL 65 noise criterion utilizes a sound weighting system that de-emphasizes sound away from low frequency and infrasound. DNL sound measurement is a manufactured noise criterion that accounts for sleep disruption by adding a 10-dBA penalty to aircraft noise events for the nighttime hours of 10:00 PM to 07:00 AM. The 15 daylight hours do not include a noise penalty, as the criterion rationalizes that humans are less sensitive to noise when they are awake. The criterion also does not consider health effects.

The possibility of health impacts stemming from aircraft noise exposures at lower sound levels than those set by the FAA has been explored. Greiser (2010) suggested that increased health risk begins at 40 dB at night and 50 dB during daylight hours. This compares to 65dB allowable by the FAA. Studies in both Europe (Hansell et al., 2013) and at 89 airports in the United States (Correia, Peters, Levi, & Dominici, 2013) concluded that those who lived closest to airports have a higher incidence of cardiovascular health issues due to both sleep disruption and from sound intrusions during daylight hours. The Correia findings of increased risk were deemed to be statistically significant with a 3.5% increase established across a broad population of individuals over 65 years of age. A study at three French airports determined that the mortality rate from cardiovascular factors increased 1.18% with each 10-dBA increase in sound (Evrard et al., 2015). A metastudy review of 10 investigations that related transportation noise to cardiac ischemia identified a relative risk increase of 1.06 (6%, SD= 1.03-1.09) for each 10 dB increment beginning at 50 dB.

The success in using the 65 DNL average noise criteria to manage public annoyance from aircraft noise as prescribed by the US FAA needs further review. Evidence suggests that the public voices displeasure at noise levels much lower than the allowable DNL 65 (Wasser, 2015). In contrast to the FAA, the European Union set its aircraft sound criteria at a much lower threshold of 55 DNL. Significant European complaints also occur at this sound level, suggesting that if the FAA were to lower its sound criteria to match the European criteria, little public relief from aircraft noise would be expected (Osborne, 2013).

Annoyance is categorized using a social measure that is scaled with increasing noise levels (Fidell, 2003). The FAA has acknowledged the ineffectiveness of this criterion through its announcement of a review of their sound criteria (FAA, 2015). This suggests that to manage aircraft and airport noise, the FAA's use of average sound requires an update based upon science and health indicators, not social annoyance. Chronic health exposure to aircraft noise and its statistical relationship to cardiovascular health indicate that more research is required to ascertain the cause and extent of the public health problem. The adopted FAA sound threshold criteria for noise generated by aircraft flyover events presently do not include science-based public health indicators.

In addition, the present criteria only include the most audible portion of the frequency range that is heard and not the low frequency inaudible infrasound that causes measurable vibrations in human body mass. The low frequency aircraft generated sounds cause vibrations that coincide with natural frequencies found in human bodies. Exposure to these frequencies may become dangerous. These vibrations have been shown to interfere with body and health functions to including cardiovascular disease (Branco; Alves-Pereria, 2004).

Research Significance & Objectives

The FAA does not include low frequency aircraft noise as part of its criteria. The FAA announced in 2015 that its aircraft noise-based policy was under review and that it would consider changes. Restructuring the 65 DNL sound criteria used by the FAA has the potential to benefit the public if the changes includes criteria for low frequency and infrasound and if these criteria are used to consider aircraft sound impact on public health. Implementing these criteria would be expected to produce changes in how aircraft noise and flight patterns are managed while also reducing the extent and severity of the sound exposures received by the public. The findings of this research could help guide this review and would be expected to contribute to the design of the new regulation.

Objectives

The primary goal of this research was to evaluate low frequency and infrasound emanating from the aircraft engines and airframe as a health exposure, and to reduce this health risk by proposing an alternative criterion that is exposure based and can be assigned a dose. A secondary goal was to increase understanding of why the existing FAA sound criterion does not produce public relief from sound exposure as expected. Specific objectives of my research were:

- To measure the overall sound profile for a commercial aircraft flyover event
- To review the existing FAA DNL 65 aircraft noise criteria and determine if it correlates to low frequency and infrasound exposure
- To determine if existing public information, measurement and monitoring systems can be used to manage aircraft noise
- To investigate the health impact that would likely occur through the implementation of the FAA NextGen navigation system

- To determine the extent or presence of low frequency and infrasound sound originating from aircraft and if these sounds can penetration through common construction elements similar to modern dwellings
- To determine the significance of the contribution of infrasound and the vibrations they produce towards degraded cardiovascular health consequences and if these effects apply to aircraft noise

Background

Audible sound is a grouping of waves consisting of many different frequencies at different amplitudes that occur together. Sound is a complex pressure wave that causes air to vibrate. A sound wave oscillates back and forth in a similar manner to a spring that stretches and then compresses. As it does this, it moves energy from one location to another while retaining most of sound wave energy. Some energy loss occurs as the waves cycle through their interaction with materials such as air or structures. One complete oscillation is a cycle. The number of complete cycles that occur within a full second is the frequency in units of Hertz (Hz). The amplitude of a wave is the intensity of the displacement caused by the oscillation (University of Toronto, 2001).

A Pascal (Pa) is a unit of measurement of pressure that is used to measure sound waves. The air pressure caused by a sound wave varies from 10^{-6} Pa (soft sound) to 10^{2} Pa (painfully loud). Due to this wide range of pressure, a logarithmic scale is used to express the wave's energy in decibels (dB). The decibel scale (dB) is a logarithmic based measurement of sound set to cover the broad acoustical range heard by humans of 20-20,000 Hz. Humans are most sensitive to sound in the range of 1,000-6,000 Hz. High frequencies (above 6,000 Hz) and low (below 1000 Hz) are progressively scaled back (or have their intensity artificially reduced) to approximate the human ear's sensitivity to hear these sounds. This adjustment is known as A-weighted sound (PSU, 2017).

Sound waves vary dramatically in length from 17 meters for low frequency 20 Hz waves to just 17 millimeters for high frequency 20,000 Hz waves. Sound waves that occur at less than 20 Hz are known as infrasound while those greater than 20,000 Hz are classified as ultrasounds (Wikipedia, 2017). Low frequency sound is defined as sound within the range of 20-200 Hz. "The A-weighting sound function is not designed to evaluate noise that contains significant low-frequency content" (MIT, 2007).

FAA's DNL 65 Threshold for Public Annoyance

The study determined environmental annoyance from industrial sources, using construction activities as the primary source of unwelcome sound (Fidell, 2003). Loud sounds were studied using the elements of a survey to determine what threshold of sound intensity would cause people that were exposed to noise to become annoyed. The outcome of this study was a scale that characterized progressively more severe social responses to increasing sound levels. The responses were developed into a system of Annoyance Levels (Figure 1). In this scaling system, the dependent variable begins from a zero point of "no annoyance" and maximizes at response level of "vigorous legal action." This concept is the underlying rating system used by the FAA to manage aircraft sound impact. The criterion has been codified through the United States Code of Federal Regulations CFR.14, which specifies the use of the DNL at 65 decibels. FAA set this threshold for aircraft noise nearly 40 years ago.

The use of 65 DNL with its designated failure criteria of “highly annoyed” doesn’t consistently produce expected feedback or public response (Fidel, 2003). While the 65 DNL threshold should result in 12.3% of the effected individuals becoming highly annoyed, the data clearly shows no difference in the percentage of highly annoyed individuals over a DNL range from 57.5 to 67.5 (Figure 2). This suggests that a DNL of 57.5 to 67.5 produces a similar public response. It follows that the DNL criterion to manage human response to aircraft noise pollution using annoyance is an ineffective choice even at a setting of 65.

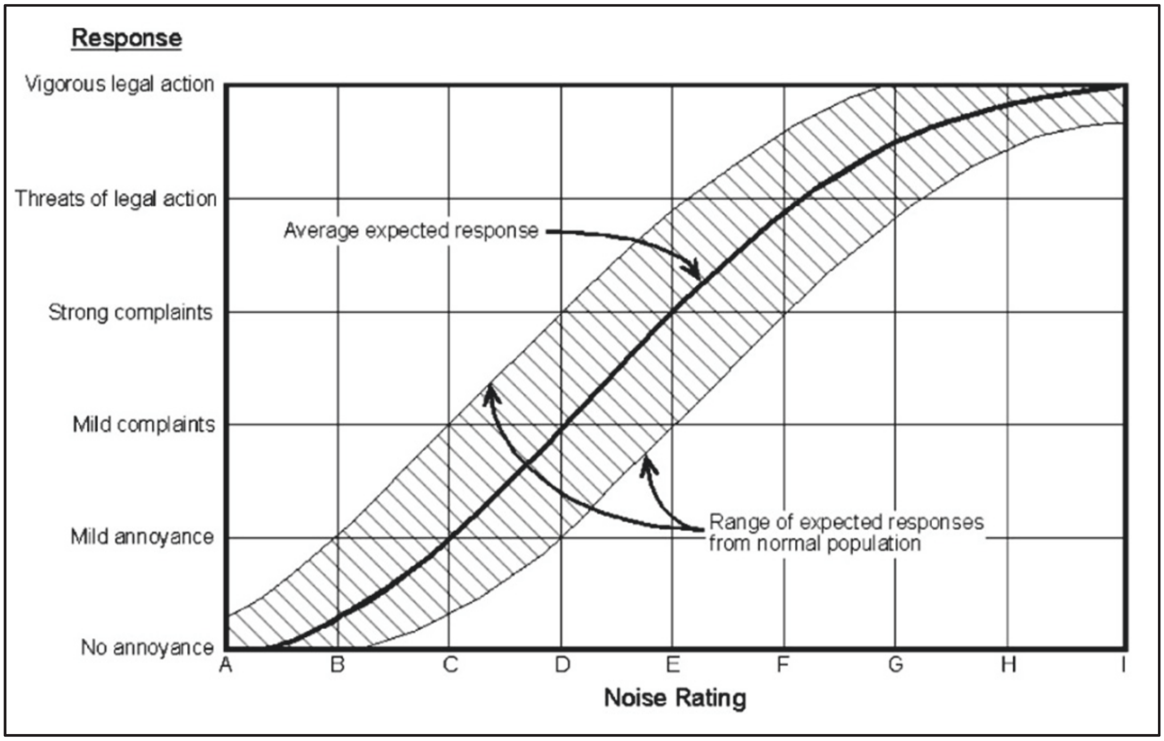

Figure 1. Comparison of noise to expected response (Fidell, 2003).

Other alternate systems to report annoyance from noise have been developed. It was thought that the design of annoyance to noise experiments is based upon a perceived response to a sound stimulus. Using only annoyance to assign the psychological impact of aircraft noise may have been flawed as its structure has used too narrow of a response to the noise. Alternatively, the choice of how the question of aircraft noise is framed is also thought to introduce error in the rating system.

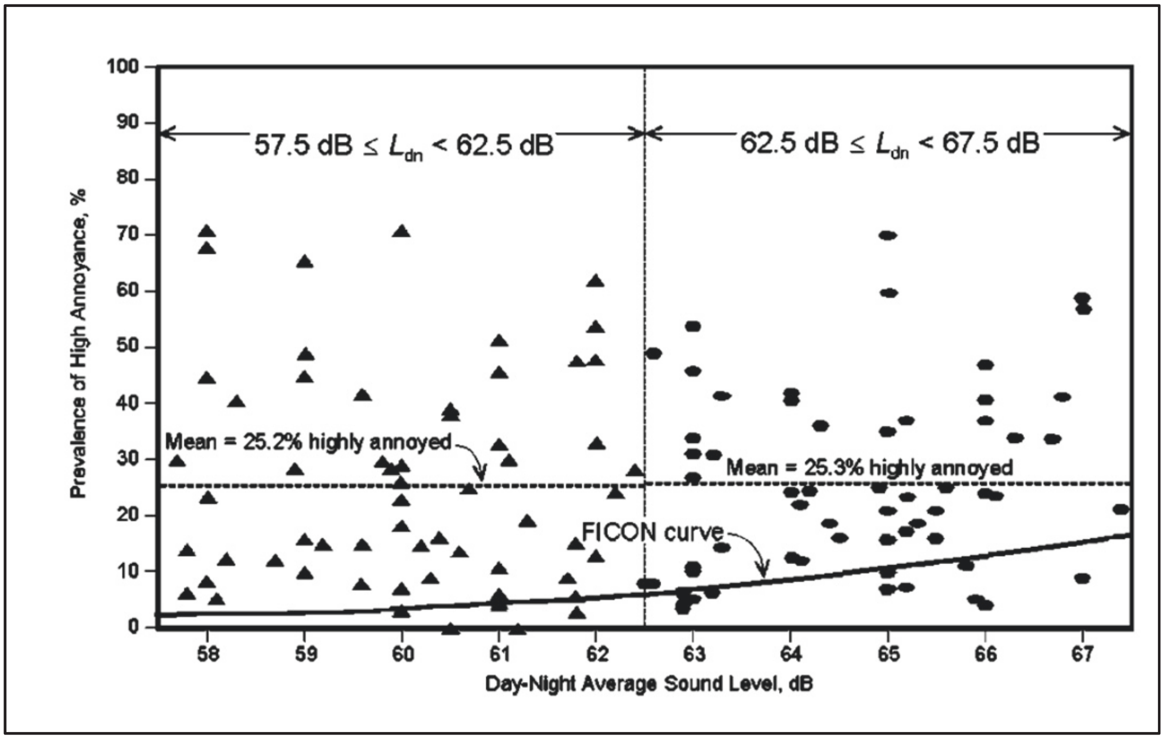

Figure 2. Public annoyance to sound (Fidell, 2003).

To obtain a better correlation of the public reaction to aircraft noise, the terms of “dissatisfaction and perceived affectedness” has been suggested (Job, 2001). This concept was developed further with another social model to include the elements of annoyance, activity disturbance and anxiety to the noise (Kroesen, 2011). Each of these new models added complexity in their attempt to obtain better correlation to the negative public response. Each of these proposed concepts also relied on surveys to demonstrate their theories. Neither proposed theory has been adopted to date.

The FAA surmises that since the general population is not broadly making complaints, the public doesn't have significant issues with aircraft noise. This is based on the complaints that are being recorded, which have not been shown to have a direct relationship to the true annoyance level of the community (Airport Noise Law: FICON, 1992). These annoyance levels are not based upon statistical sampling of both active and passive population groups, and capture only active complainers. To be valid, the design elements of any science-based survey must solicit a wide response from the public and do so in a manner that does not limit the response to one minority group within the larger population.

In spite of the lack of validity of self-reported survey methods, the FAA stated lack of public sensitivity to annoyance is readily dispelled. A relief map was generated by counting the number of complaints directed at the Hanscom Field Airport near Bedford, Massachusetts and the associating them with a location (Figure 3). The locations/homes of the complainers correspond to the flight paths with most of the complaints originating near the airport. The FAA 65 DNL sound boundary is superimposed on Figure 3 in yellow. The area reaching this threshold is relatively small when compared to overall pattern of complaints. This reflects a likely mismatch of public response to the expected impact based upon DNL 65 (Fidel, 2003). The FAA DNL criterion is not based on adequate sampling of aircraft sound and it has no statistical significance and is therefore not an indicator of the community's response to aircraft noise. For this reason, it does not meet its objective of measuring or managing public perception of annoyance.

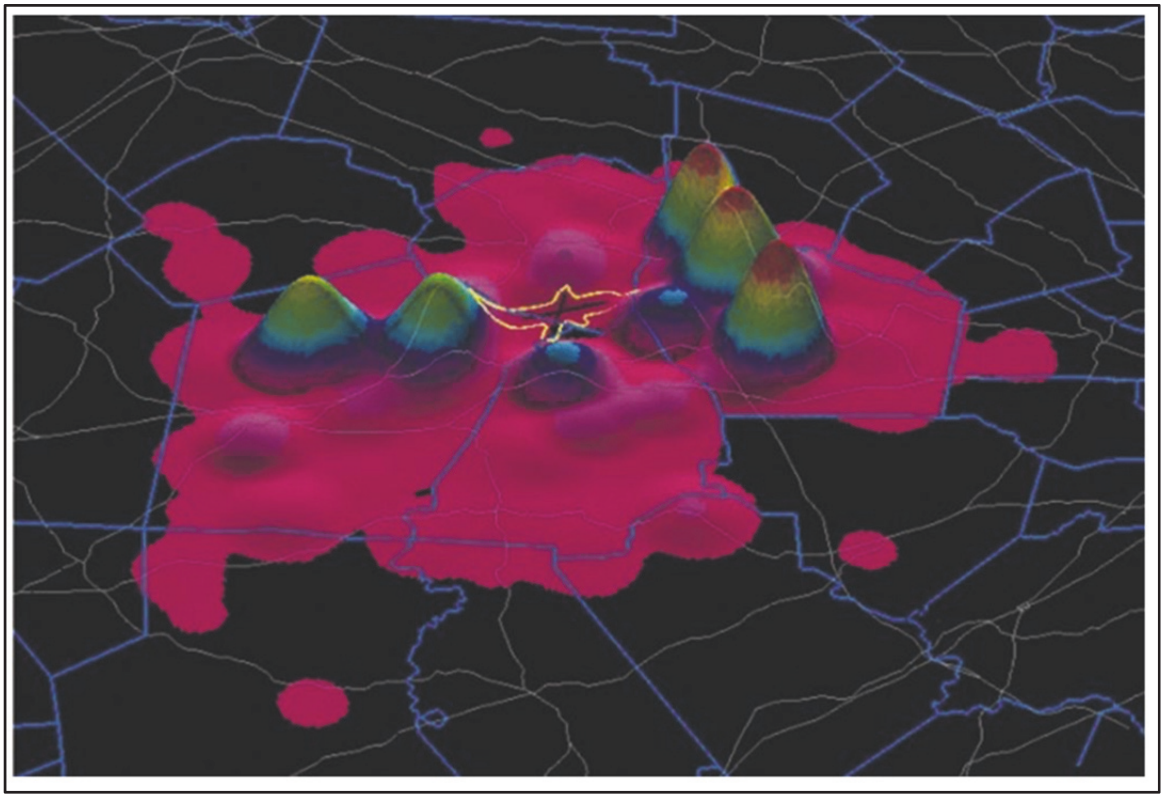

Figure 3. Complaints from aircraft noise at Hansom Field (Fidell, 2003). The changing of colors denotes a greater density of complaints from that location. The three peaks to the left are locations of maximum complaints. They are aligned with aircraft turns.

A-weighted Sound Measurements

A scaling system is applied to the overall sound spectrum used to report the sound energy generated from an aircraft jet engines and frames. The range and manipulation of the sound energy within this system is known as "A" weighted sound and it is identified with the "dBA" acronym with the "A" added to denote this sound measurement. A-weighted sound was chosen for use in measuring sound as it emphasizes the frequency range that humans hear (Fidell, 2003). While it includes energy from sound that is more difficult to hear, it does so by mathematically reducing the intensity of these sound frequencies. In doing so, this system de-emphasizes the contribution of low frequency sound. For the lowest frequencies, the discount is severe. A-weighting does not consider energy from infrasound at all as this sound range isn't heard. The result of this tool is a focus on sound primarily within the range of approximately1000-6000 Hz.

Sound intensity is not the same as sound loudness. Intensity differences are reported in a logarithmic scale of decibels. A measurement of 0 dB is used as zero sound as this is the level where human hearing doesn't occur (Bajdek, n.d.). The human ear perceives a 10-decibel (dB) increase in sound energy as being about twice as loud. De-rating sound by 30 dB using a weighting system such as dBA would have the effect of a decreased sound intensity of 800%. When a sound intensity is doubled, the measured sound level would increase by 3 dB. The DNL scale does not compensate for the difference in what is perceived and the loudness as it relates to energy (PSU, 2017). Newer aircraft are quitter than old ones. The current stage 4 noise standard requires a 10 dB cumulative reduction from the previous stage 3 noise certified aircraft (Federal register, 2005). The sound is measured using the dBA sound weighting system.

The Applied Math of Aircraft Sound

While most acoustically apparent aircraft noise is sound energy that travels in the form of complex waves through the air at frequencies that are audible to the human ear, some of the sound waves generated by aircraft are below the audible range. Though sound travels in complex waveforms, it seldom does so at a single constant volume or frequency. The naturally occurring variations in sound energy (intensity/volume) and tone make setting a sound-based criterion difficult. This is exasperated by the heights and speeds of passing aircraft. The FAA simplified and generalized the impact criterion of sound by summing the dBA weighted sound measurements from aircraft and taking their average contributions over the period of a year. Their threshold for an acceptable level of average sound energy is known as 65 DNL. DNL sound is a heavy manipulation of the audible emitted aircraft energy. Its measurement accounts for sleep disruption by adding a 10-decibel (dBA weighted) penalty to aircraft noise events for the nighttime hours of 10:00 PM to 07:00 AM. The 15 daylight hours do not include the use of a sound penalty adjustment, as humans are less sensitive to noise when they are awake (Bajdek, n.d.).

The DNL measurement uses a term identified as SEL to compile or add up all of the aircraft "A" weighted sound stemming from each single flyover event and then normalizes this sound into a single second (Figure 4). The significance of this manipulation is that each second of every day over the course of a year represents either an aircraft sound event or no sound at all (LAWA, 2012). This means that 0 dB is the most common contributor to the DNL average as that measurement represents all non-SEL seconds. All 86,400 (second) SEL calculations are then averaged over a full year. It is possible for a single aircraft noise event to generate enough sound energy to produce a 65 DNL for the entire day. For example, the level of sound at the tarmac from a plane taking off could equate to a single day's DNL 65.

Sound energy emitted from an airplane is comprised of high and mid frequency waves that either dissipates quickly or low frequency energy that is de-emphasized by the dBA sound weighting, resulting in a surprisingly high number of aircraft flight events needed to meet the DNL 65 threshold (Figure 5). The illustration provides a visual example of calculated SEL value for totals of 1, 10 and 100 over flights events (LAWA, 2012). An SEL sound event compression is 7-12 dBA greater than the maximum sound of its over flight (Bajdek, n.d.).

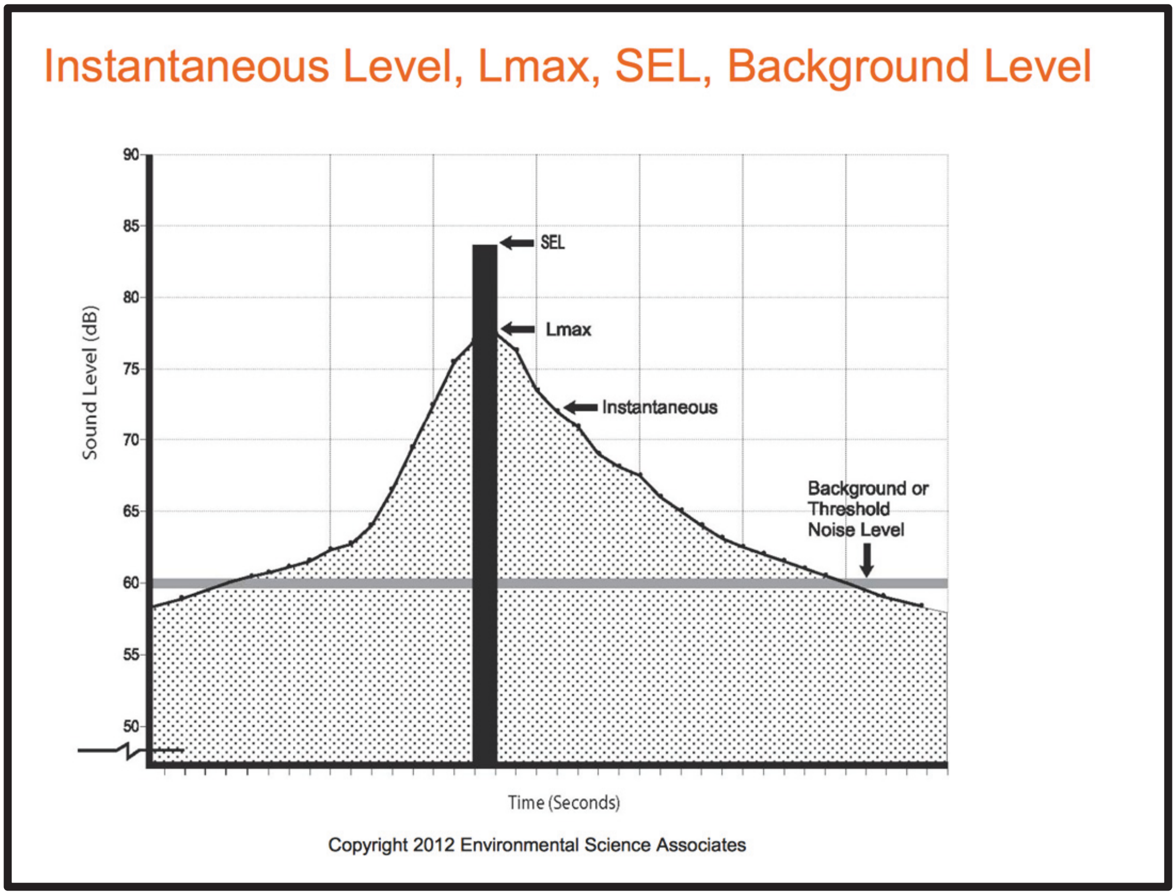

Figure 4. Aircraft flyover event compressed into one second of sound (Lawa, 2012). The black rectangular area of sound equals the sound energy of the greyed portion.

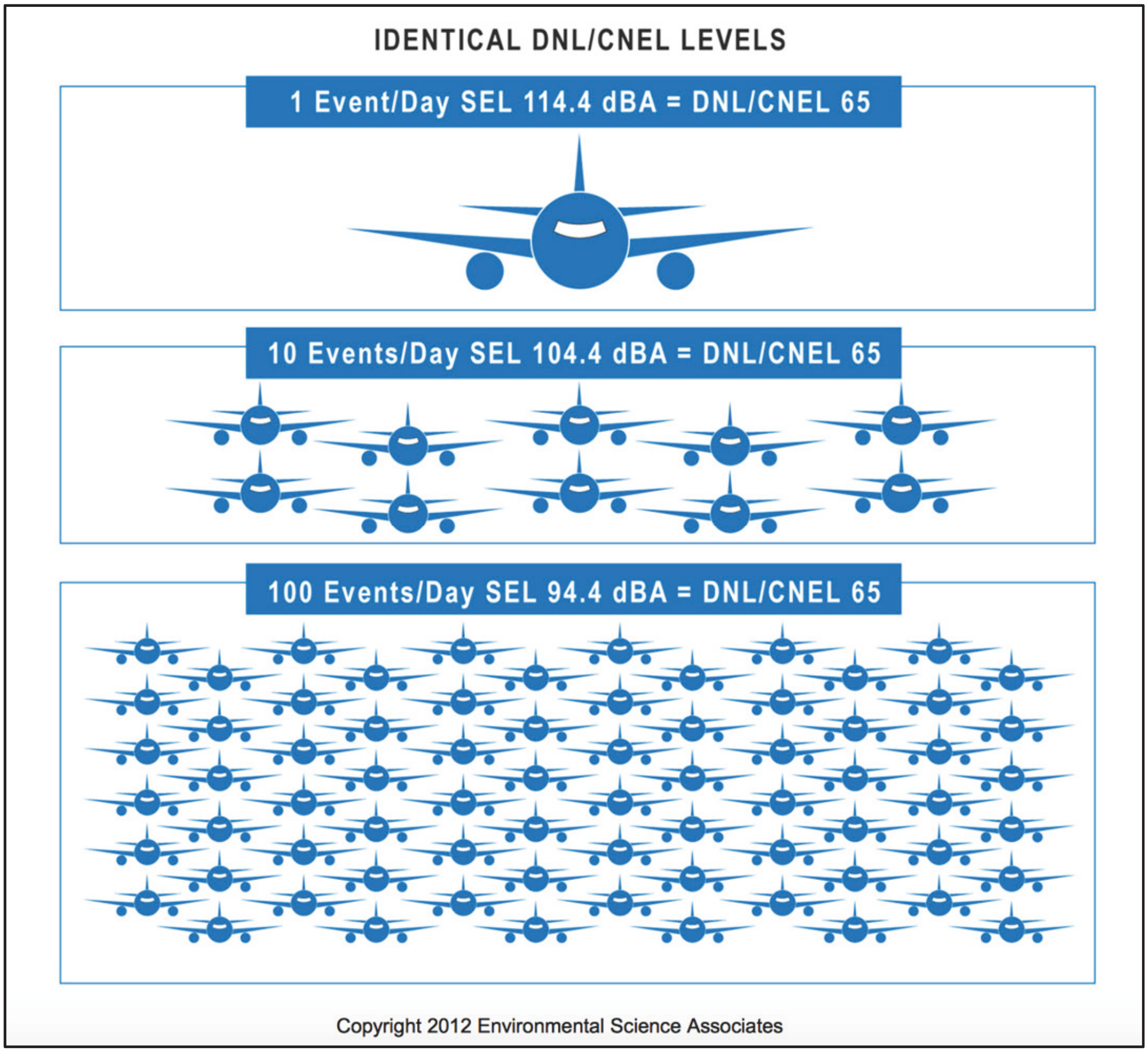

Figure 5. Daily flight events needed to equal one DNL 65 (Lawa, 2012).

The number of SEL flights that pass overhead can be counted. Subtracting 9 dBA from each SEL shown in Figure 5 allows the creation of a graph relating a number of similarly loud over flights to an estimated maximum dBA for each event (Figure 6). The European criterion of 55 Lden, also a sound averaging method, was added to the graph to illustrate differences in the number of flights between the FAA and European criterions. By inspection of this graph, about 1000 FAA measured over flight events having a maximum noise of 75 dBA and that occur within a single day would be needed to reach the DNL 65 criteria. One hundred similar flight events would meet the European criterion.

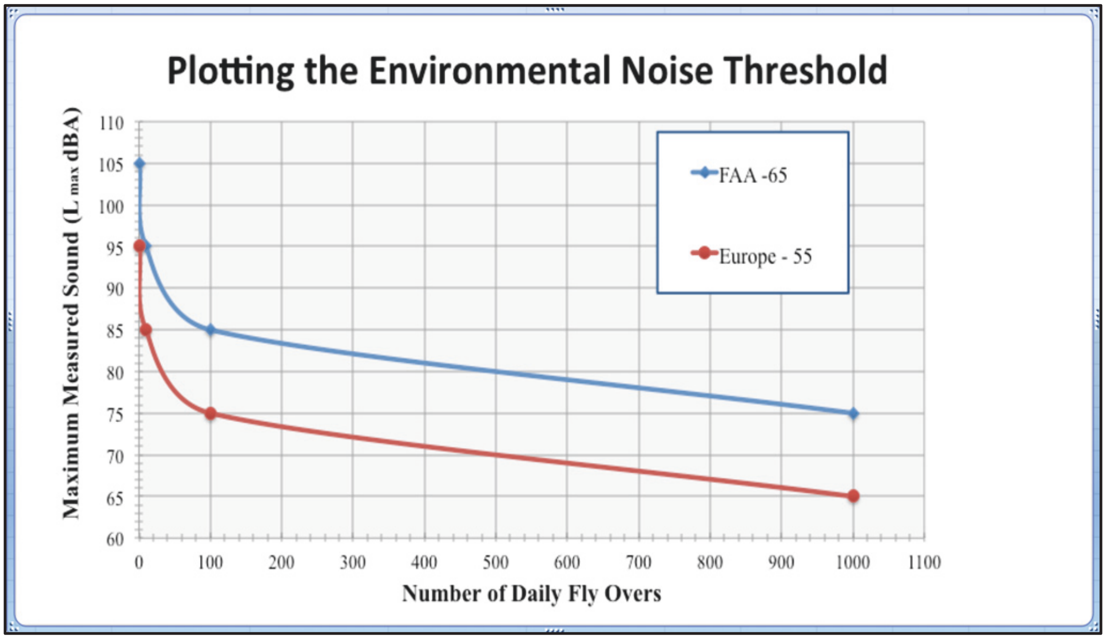

Figure 6. Comparison European Lden and FAA DNL criteria. These criteria are used as a threshold for publically funded sound impact remediation such as insulation installation.

Aircraft Noise

Air is gas that acts like a fluid when it is disturbed by a flying aircraft. Air passes through the jet turbine then mixes with air that flows around the aircraft airframe to include its wings leading to turbulent flow. Turbulence is a description of fluid flow and as implied by its name, includes significant local changes of pressure and flow velocity within its stream. Variations in aircraft and engine design have an effect on the sound produced. Operating conditions to include aircraft speed have an impact on the sound produced (Karabasov, 2010).

The mechanisms that create aircraft noise are thought to include localized small-scale turbulence, instability waves and oscillations of large-scale turbulent eddies. The mixing of air into turbulent flow produces oscillations that occur at frequencies that correspond to sound. The turbulent eddies disintegrate into smaller perturbations leading to a turbulent cascade. This in turn provides the main characteristics of the aircraft sound sources (Kopiev & Chernyshev, 2012). The sound produced by the interaction of the plane with the air includes infrasound, low frequency sound and through the A-weighted dBA sound frequencies (Figure 7).

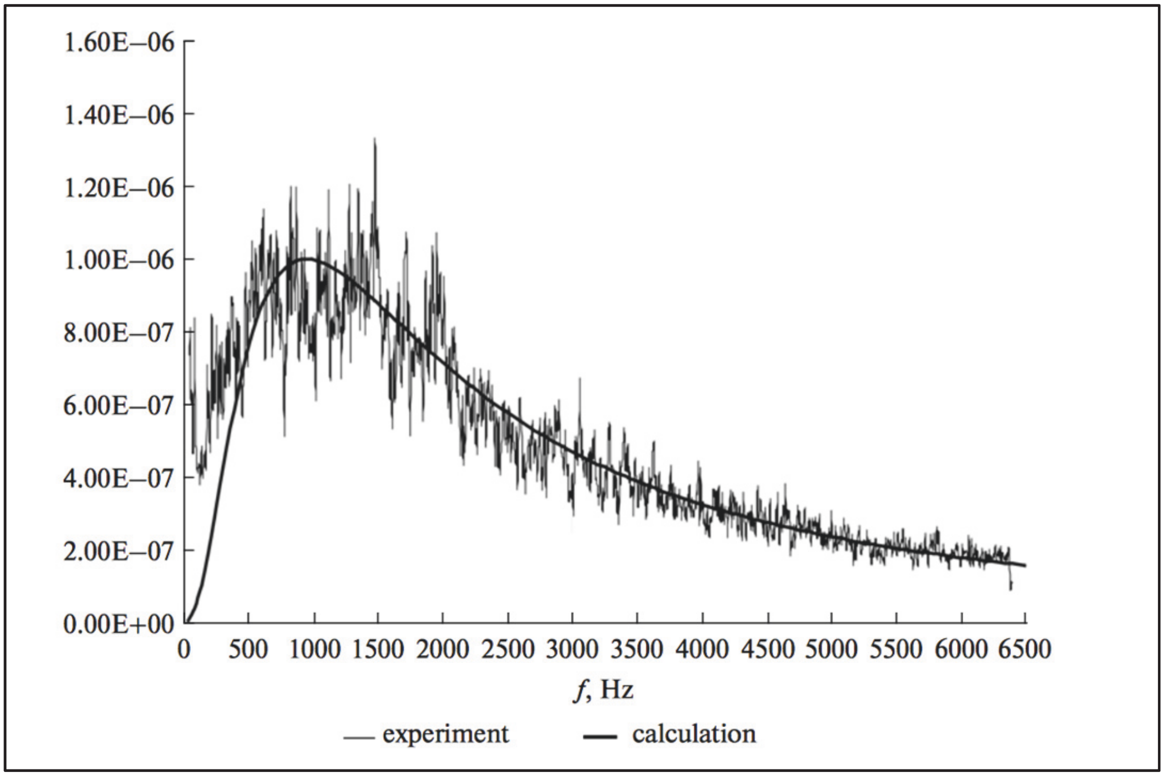

Figure 7. Aircraft noise profile model for subsonic jet at velocity of 120 m/s (Kopiev, 2012).

Sound energy is attenuated or loses its energy as it travels through open air. The smallest sound waves, with lengths as small as 17 mm, oscillate rapidly and lose their energy soon after they are formed. As the waves become larger (e.g., longer wave lengths), the waves take longer to lose their energy and fully attenuate in the open air. This can still occur in a short amount of time relative to the speed of sound. As the sound frequency lengths become larger still, they travel greater distances before they lose their energy and attenuate. The lowest frequency waves last the longest and travel the furthest. The WYLE Laboratory report WR 01-21 reviewed the physics of low frequency sound and concluded that low frequency airplane noise occurring at less than 1000 Hz does not dissipate as quickly in air and travels great distances before it loses its energy. The point of attenuation for each frequency of the overall the sound is related to the length of its sound wave, which is turn, is related to how far the sound travels before it is heard. The elevation of the aircraft from the ground as it passes overhead establishes a distance of sound travel and contributes to the amount of sound that reaches the ground. Less attenuation of sound waves as they pass through the air is why sound seems louder near the airport.

Sound within the 1000-6000 Hz range consists of small length waves that interact readily with air and then dissipate rapidly. At high altitude flyovers, the portion of the overall aircraft sound that is still within the A weighted sound range has dissipated leaving only the familiar low frequency “rumbling” component. Low frequency noise is strongest behind the aircraft engines making it particularly pronounced as aircraft pass overhead. It is difficult to shield humans from this type of sound energy exposure. Sharp stated that low frequency sound waves readily pass through sound insulation and common construction materials that common noise mitigation strategies used so sound that isn't heard, won't work well for low frequency aircraft noise (Sharp; Gurovich; Albee, 2001).

As noted earlier, none of infrasound sound frequencies generated by the aircraft are included within A-weighted sound and by extension within the DNL calculation. De-rating the low frequency sound is given with a rational provided that low frequency sound isn't as readily heard. While low frequency and infrasound either aren't readily heard or heard at all, they still consist of high-energy waves that may cause an adverse health impact to humans.

Sound as a Health Exposure

People also exhibit different sensitivities to sound. Ten percent of the population has been estimated to have a 10 dB or greater threshold sensitivity to low frequency sound. The sound exposure from low frequency sounds for these individuals may cause additional difficulties (Leventhall, 2005).

A group of 24 volunteers within a control chamber were exposed to low frequency / small amplitude sound and modulated 10 Hz vibrations as part of a sleep study. The modulations caused sidebands around the 10 Hz frequency from 8.7 to 11.7 Hz. Vibration amplitudes of 0.7 mm/s ("moderate") and 1.4 mm/s ("high") were applied. These frequencies are ones that could occur as a result of an infrasound exposure. Sound excursions of varied amplitudes up to 49.8 dB were applied randomly throughout the night. The exposure levels were set to mimic those produced by trains. The intent of the study was to determine if a direct sleep impact from the condition of low frequency sound with induced vibrations could lead to a measurable health related result. Disruptions of sleep and increases in heart rate were recorded. It was determined that when the vibration amplitudes (or intensity) were increased that greater sleep disturbance occurred (Smith, Croy, Hammar, & Persson Waye, 2016).

Sound waves at infrasound frequencies between 0.1 and 20 Hz may induce vibrations in the materials that they come into contact with. When this occurs in people, the sound energy vibrates human tissue and it may be sensed. This phenomenon occurs in tissue at frequencies up to 50 Hz (Havas, 2011). Some of the sound exposures match the frequencies that occur naturally in human cells (Havas, 2011). The body is made up of trillions of cells and infrasound has a capacity to affect human health because the low frequencies converge with those of the human body cell's natural vibrations (Persinger, 2014).

Natural body frequencies are described to primarily occur between 6 and 12 Hz with the range increasing slightly to 14 Hz during sleep (Persinger, 2014). Muscle produced sound and whole body vibrations are predominantly with the 5- to 40 Hz range. For example, a 20 Hz sound is generated by the body when human muscles are tightened and could conceivably be heard if human hearing were more sensitive. Persinger noted that infrasound exposure has a moderately strong statistical correlation with the conditions of "nausea, malaise and fatigue." This indicates that a low frequency exposure could cause an instantaneous feeling of illness. An interesting example of a harmful forcing frequency includes fluctuations at 12 Hz, as this exposure may cause instantaneous intense feelings of illness. He stated that this cell interaction occurs at remarkably low levels of sound pressure. Low and infrasound exposure can cause other health effects. Identified health impacts include increased thyroid activity at 14 Hz, impaired brain response at 12 and 36 Hz and reduced cognitive learning between 6-25 Hz with a mean peak at 13 Hz. Balance issues may also occur at 40 Hz (Persinger, 2014).

Changes in blood pressure were measured in an experiment using 20 healthy 20-30 yr old male volunteers that were exposed to frequencies of 6, 12 and 16 Hz at high pressures of 95, 110 and 125 dB (Lden). Exposures ranged from 20 to 60 minutes and the test sequence included control periods without these frequencies present. Blood pressure and heart rate were measured. Blood samples were also drawn. Significant increases in systolic (at 6 and 16 Hz) and diastolic (at 12 and 16 Hz) blood pressure were recorded. The heart rate did not change (Danielsson & Landström, 1985).

Cells have a structural component that can be stressed to the point of rupture by low frequency and infrasound exposure. A medical-mechanical explanation of how cell damage occurs centers on the structural properties of cells. Stress on these components from sound exposure can lead to cell break down. When stressed, collagen and elastin growth occurs leading to thickening of the cells (Alves-Pereira, Nuno, & Branco, 2007). These structural changes within the cells are described as mechanotransductions and have been assigned as symptoms of a malady recently identified as Vibroacoustic disease (VAD). The thickening of effected tissue can have very significant health impact when it restricts lung function or causes alterations of cardiovascular tissue such as pericardial or cardiac valve thickening.

Resonance is a condition within a material in which the exciting forces increase the amplitude (or severity) of the response at different frequencies. A material may have multiple natural frequencies. Resonance occurs if the forcing frequency matches the natural occurring frequency of a material and is affected by the stiffness and mass of the material. Resonance produces a condition where the forces become additive and its occurrence can be extremely damaging.

The human body has resonance frequencies that have been defined by ISO standard 2631 (Havas & Colling, 2011). The frequencies identified include the inner ear (0.5-10 Hz), the eye (20-90 Hz), the head (20 & 30 Hz), chest wall (50 & 100), abdomen (4 & 8 Hz) and the spinal column (10 & 12 Hz). "The biological effects of low-frequency noise (20-100 Hz) and infrasound (less than 20 Hz) are a function of intensity, frequency, duration of exposure, and direction of the vibration" (Havas, 2011).

Wind turbines are an acknowledged source of infrasound and have been associated with human health issues. The rapid global installation of wind turbines is driving an active emerging field to study how these low frequency and infrasound frequencies impact humans. A distance from the source of the exposure was identified as a remedy. The French Academy of Science stated that wind turbines constitute a permanent risk for those exposed and recommended that dwellings should are not be built closer than 1.5 km which is about a mile (Chourad, 2006). Infrasound and low frequency sound exposure from sources other than wind turbines would be expected to produce similar results.

Aircraft Noise and Cardiovascular Health

Degraded cardiovascular health has been associated with increasing proximity to an airport (Hales, 2010). Low frequency sound exposure is believed to be a significant contributor to this health concern. Vibroacoustic disease is an identified cause of increased cardiovascular risk (Branco, 1999). A German study concluded that myocardial infarction (heart attack) was a primary aircraft noise related health risk (Greiser, 2010). Greiser determined an increased daytime cardiovascular risk was present for noise above 50 dBA. The increased measured risk at nighttime begins at 40 dBA with the risk growing in step with additional decibel increases. Women were determined to have a particularly high myocardial infarction risk factor of 1.72, even at the average sound level of 55 dBA. This study reviewed health data from 1.02 million people in the Cologne-Bonn region of Germany. Continuous repetitive aircraft noise interruptions that peaked above ambient background noise levels were the key identified contributor.

A French study of 161 communities near Paris, Lyon and Toulouse reviewed mortality data over a three-year period and associated it with aircraft noise exposure. The study concluded a mortality rate ratio per 10-dBA increase of 1.18. This study concluded that noise aircraft was associated with mortality from cardiovascular disease, coronary heart disease, and myocardial infarction. However, the potential contribution from air pollution was not accounted for (Evrard, 2015).

A meta review study of 12 noise studies performed since the mid-1990's pooled data to determine an ischemic heart disease (IHD) risk increase of 1.06, beginning at 50 dB of annualized average sound. Three of the studies reviewed specifically considered aircraft noise. They include a study performed in the USA that was based upon a sample size of approximately 6 million people, a study in London with a sample size of about 20 million and a Switzerland study based upon a population of approximately 22.5 million (Vienneau, Schindler, Perez, Probst-Hensch, & Roosli, 2015).

A US study was limited to those admitted to emergency room for myocardial infarction. It determined an increased risk of occurrence of 3.5% for individuals over 65 that were living within a 10-dBA higher noise zone near airports (Correia, 2013). This study used data from national medical insurance (Medicare) and included a population of over 6 million. Another health study (Hansell, 2013) focused on a population of 3.6 million living near Heathrow airport. It concluded there is a significant risk increase from stroke (1.24 with a confidence interval of 1.08 to 1.43), coronary heart disease (1.21 with a confidence interval of 1.12 to 1.31) and cardiovascular disease (1.14 with a confidence interval of 1.08 to 1.20) for those exposed to higher noise levels (noise > 63 dBA) when compared to those with lower exposure (exposure >63 dBA v $\leq$51 dBA). About 725,000 individuals living near Heathrow were exposed to an average aircraft sound exposure of 55 dBA or greater (Osborne, 2013), but noise less than 55 dBA was also sufficiently loud to adversely impact health.

Sleep interruption is stated to increase the risk of cardiovascular disease. Blood pressure was measured from 4861 people near major European airports (Jarup, 2008). Sleep interruption increases hypertension beginning at low sound levels of 40 dBA (Figure 8). In a laboratory sleep study, 128 test subjects were exposed to recorded aircraft noise over a period of 13 consecutive nights. Noise events at different loudness and length of exposure were used with subject responses measured. The noise was associated with stage 1 (non-rem sleep) sleep disruptions but not stage 2 (Basner, 2005).

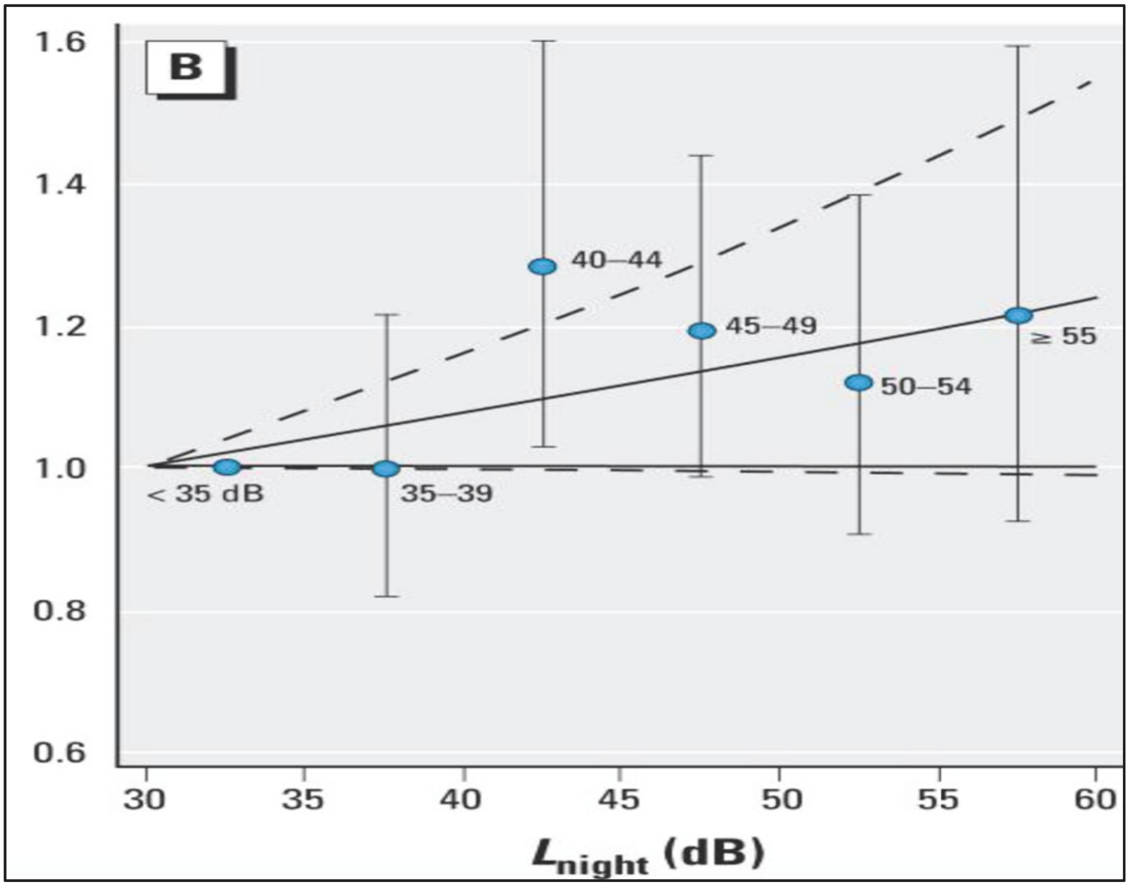

Figure 8. Increased risk of hypertension (Jarup, 2008). The y-axis is an increase in the odds ratio based upon the noise level to develop hypertension. The x-axis is an increase in nighttime noise.

In a report produced on behalf of FAA/NASA and Transport Canada, Hales (2010) postulated an example of aircraft noise and its cardiovascular impact occurring at night at the Newark Airport (Figure 9). Increased calculated hypertension risk from sleep disturbance was charted in conjunction with existing airport sound contours. The health impact of increased risk of myocardial infarction was evident across a broad region in the vicinity of the airport, with highest risk factor nearest to the airport (Figure 9). The tiny DNL 65 size envelope compared to the very large cardiovascular risk color overlay further demonstrates the need for a full science-based public health review of the failure of the 65 DNL criterion to capture human health impacts of aircraft noise.

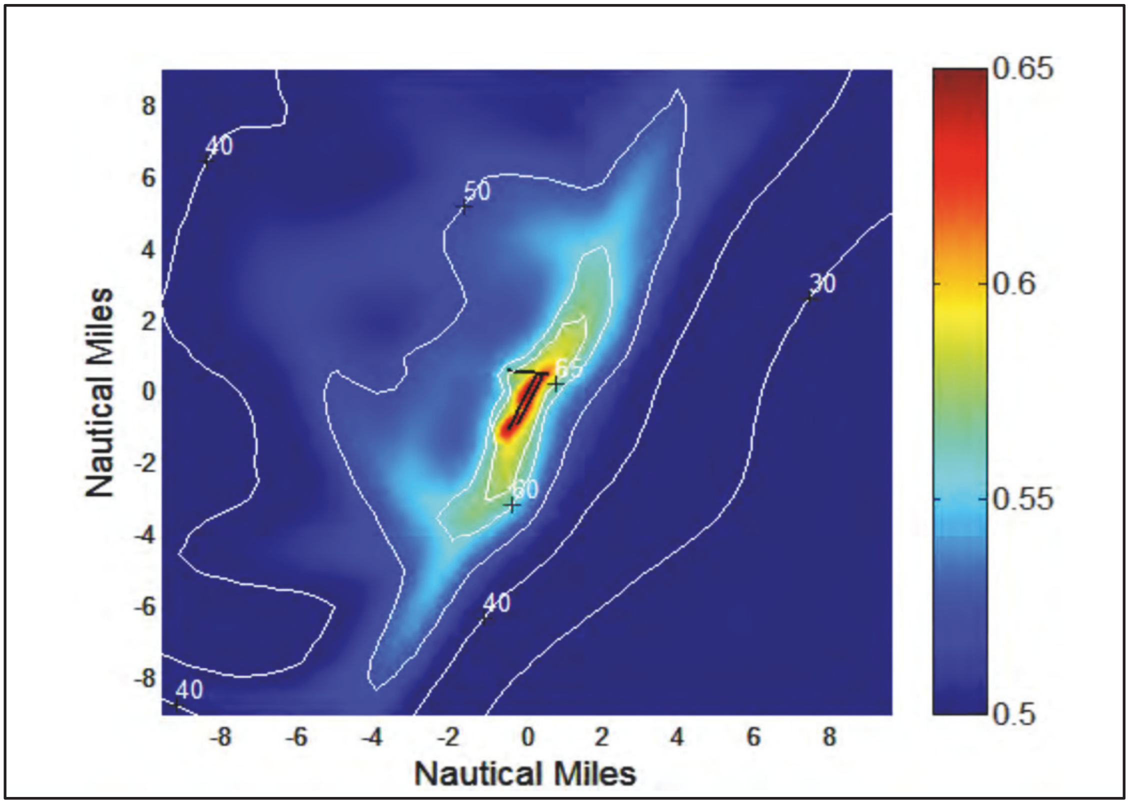

Figure 9. The Newark airport DNL sound boundary with cardiovascular overlay (Hales, 2010). The DNL 65 boundary is the black line at the center. The cardiovascular overlay shows isoclines in units of averaged sound.

While some aircraft noise studies have associated increased cardiovascular risk with sleep disruption as a primary cause, this association has also been challenged. The primary reason given is that the causes of sleep disturbances are difficult to determine due to the state of the subjects being studied. Age, hearing capacity, gender and sleep stage are among these factors. Many common causes of sleep interruption are not associated with aircraft noise. The ANSI 2008 and Passchier-Vermeer 2003 models predict rates much greater than zero (Fidel, Tabachnick, Mestre, 2013). A-weighted sound exposure is based upon single events rather than the yearly weighted average of the DNL criteria. Drawing a conclusion of a strong association of sleep interruptions through sound levels of 80-85 dBA would be difficult (Figure 10).

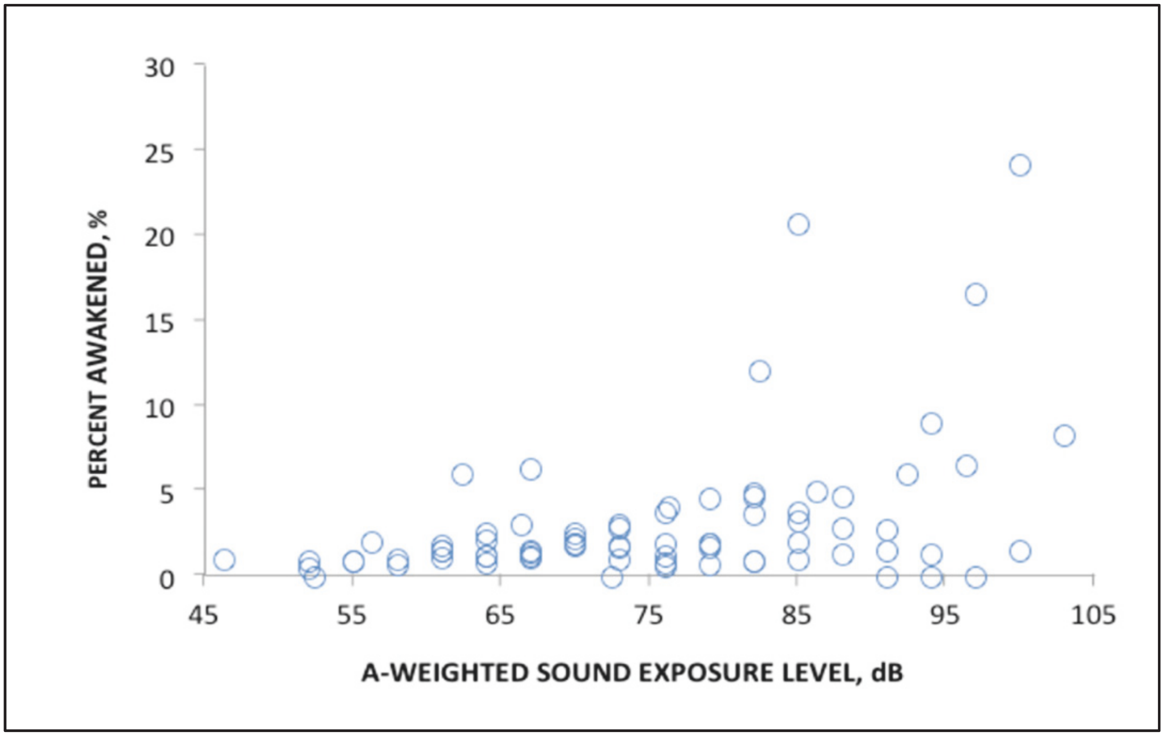

Figure 10. Sound exposure levels causing sleep disturbances (Fidell, 2013).

NextGen Navigation: Exacerbating the Noise Problem

The NextGen navigation system is a significant update in how aircraft flight management is conducted. Airplanes with NextGen navigation gradually descend upon approach while holding their engine speed constant rather than descending with a series of down throttling stair steps. GPS navigation allows precise in-route spacing between aircraft and reduced taxi time on the runways. Reduced emissions, fuel savings and overall noise generation are expected benefits of NextGen. These benefits come from GPS navigation and should be the basis for an "easy FAA win" with each NextGen navigation implementation (FAA: NextGen, 2013).

NextGen became active in the Phoenix, Arizona market without community knowledge on September 18, 2014. The Phoenix NextGen project optimized flight paths by changing their routes and locating them nearer to the airport. Previous to its implementation, it could be argued that the city of Phoenix was commendably managing aircraft noise at Sky Harbor airport in that very few complaints were being received from the public. The number of Sky Harbor flights hadn't changed from one day to the next with the NextGen implementation but the number of complaints did. The complaints filed were a direct result of flight path alterations that relocated aircraft over new locations within the community and concentrated their occurrence. The Phoenix New Times investigated and reported (Wasser, 2015): "For the most part, the old flight paths at Sky Harbor required planes to ascend and descend over a nine-mile stretch of the Salt River before turning or landing, which concentrated the worst noise in non-residential areas."

With the implementation of NextGen flight path changes, turns were occurring in precise repeating positions closer to the airport. This placed planes directly over densely populated residential areas and in some cases, these neighborhoods had not been previously exposed to aircraft noise. An overlay of flight operations before and after the implementation of the NextGen project at the Phoenix Sky Harbor Airport clearly shows the flight path changes (Figure 11). The purple lines show broad variation of individual departure paths prior to NextGen while the blue lines illustrate improved GPS navigation precision of NextGen. These changes shifted a somewhat random community impact of broadly distributed flyover events to highly concentrated flights paths. This resulted in a small number of individuals experiencing a significant increase in the number of flights.

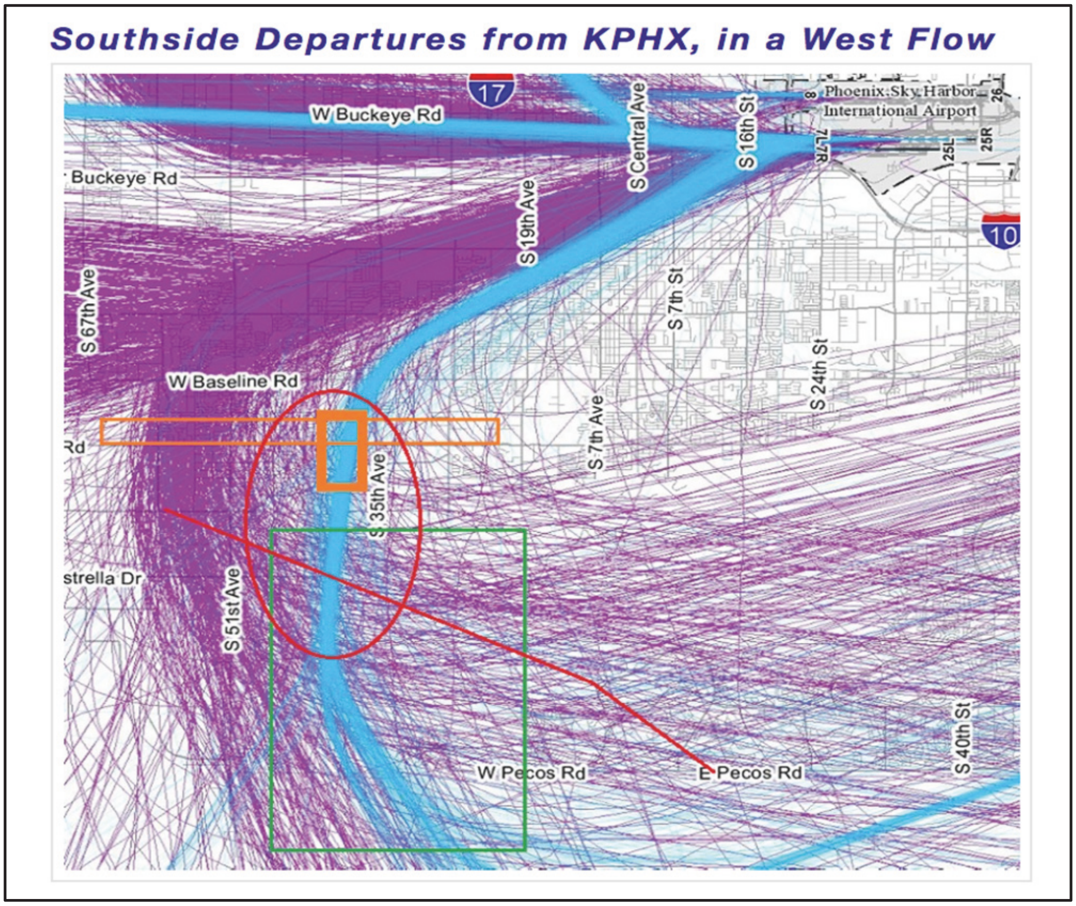

Figure 11. Precise flight path management (Aviation Impact reform, 2015). Purple lines are individual departure paths prior to NextGen; blue lines concentrated flight paths with improved GPS navigation precision of NextGen.

This background review suggests two significant problems related to health impacts from aircraft noise. The first is that noise as defined by public policy presumes that the only impact that occurs from sound is from the most audible frequencies. This underlying assumption discounts low frequency and infrasound. The second, related problem is that the extent of the contribution of low frequency and infrasound is unknown as it is not available for review through public literature.

Research Questions, Hypotheses and Specific Aims

My research investigates the following questions and associated hypotheses:

- Question 1: Are low frequency and infrasound vibrations being generated from aircraft over flights and can they be measured at frequencies that correspond to human health concerns?
- Hypothesis: Low and infrasound frequency sounds resulting from aircraft flyover events at less than 100 Hz transfer through the walls of a structure and leading to vibrations in the body mass of human tissue.
- Question 2: Can exposure to infrasound from aircraft flyovers provide an explanation for the poor correlation between public annoyance and DNL sound levels?
- Hypothesis: Measurable frequencies occur at or near 12 Hz and these frequencies provide an explanation for public annoyance.
- Question 3: Should a new aircraft noise measurement policy include health-based criteria?
- Hypothesis: Infrasound exposure from aircraft can be measured and assigned as the likely cause of increased cardiovascular risk from aircraft flyovers.

Specific Aims

To address these questions and hypotheses, I:

1. Monitored aircraft over flight events and measure their generated infrasound and low frequency sound profiles.
2. Compared low frequency and infrasound measurements to ones obtained with a conventional sound meter (dBA weighted) for their contributions towards aircraft noise exposure
3. Related sound pressure to vibrational energy in a pair of environments including surfaces within a structural space and in an open air environment
4. Correlated aircraft noise and infrasound with distance from the ground and from the monitored position.

Chapter II

Methods

A field experiment was designed to measure aircraft sound and its interaction with surfaces exposed to the sound and the resulting vibrations. The experiment was designed to measure sound pressure waves being emitted from jet turbine engines using increasing distances from the airport. These locations chosen for monitoring resulted in different aircraft heights at the time of their flyovers.

Aircraft Noise Monitoring Sites

The Phoenix Sky Harbor Airport is positioned in the middle of the Phoenix metro area. Three monitoring locations were chosen near the airport to match locations currently established by the airport by FAA sound contours as 75, 70 and 65 DNL (Figure 12). A red "X" pinpoints each exact monitoring location on the map (Figure 12). Obtaining the field data by aligning it to DNL sound contours was chosen to allow comparison with others research. Monitoring locations were chosen to minimize city noises, so measurements were taken on weekend mornings to better manage automobile and other background influences.

The 75 DNL monitored location was on airport property at the end of an outdoor parking lot. It was positioned between the two airport runways. Although not directly beneath the flight path, this allowed measurements to be taken almost immediately after takeoff. The second monitored location on the 70 DNL contour was at an industrial parking lot approximately ¼ mile south and east of the airport. This location was not directly beneath the flight paths but also in close proximity. The third monitored location was positioned on the DNL 65 contour at a public performing arts center parking lot in the town of Tempe. The art center is approximately 2 miles from the end of the runway. Planes generally flew directly over this location.

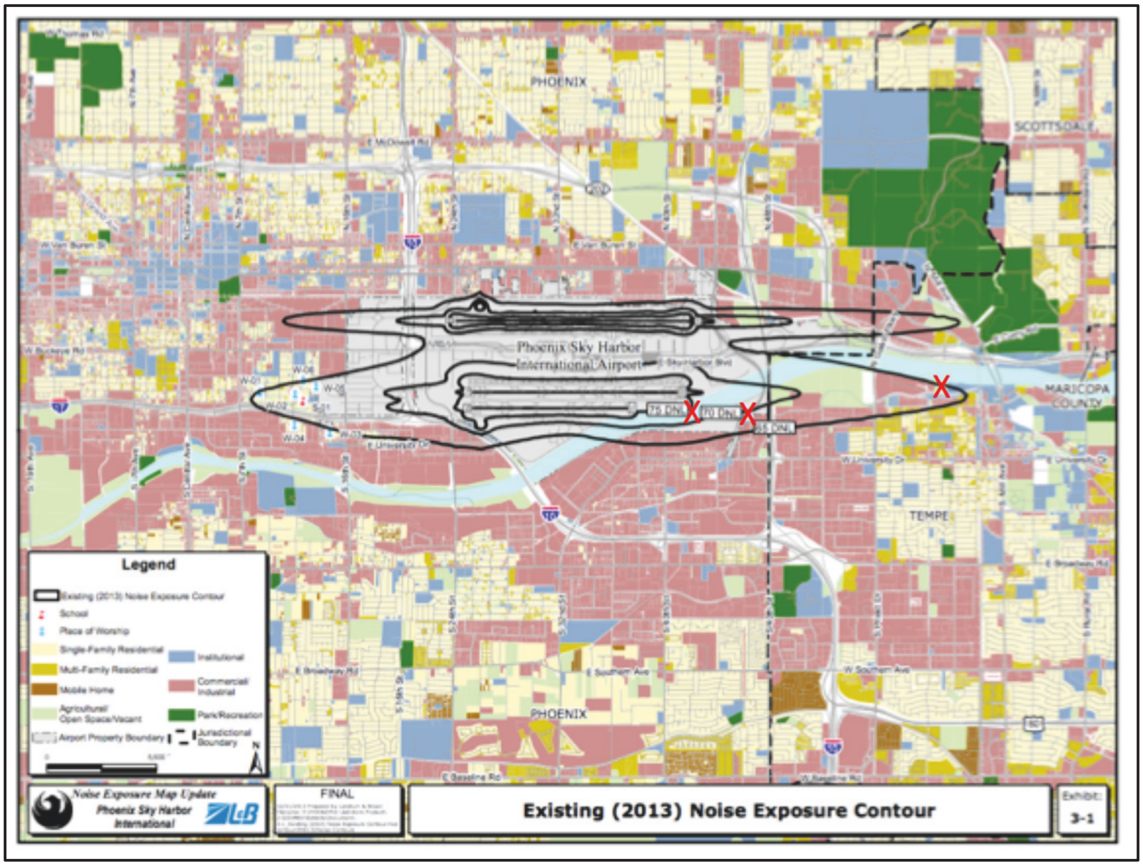

Figure 12. Sound sampling locations (PHX, 2014). Monitoring sites are red X(s).

The broad population based health studies that addressed cardiovascular risk included noise exposures with defined risk at aircraft noise levels less than 65 DNL. Therefore, it was decided that a fourth monitoring location was needed that would be just over four miles from the airport. That positioning allowed even spacing from the previous DNL 65 position and from the end of the airport runway. This fourth location will be identified throughout this thesis as “sub-DNL 65.” Sound contour maps were not available to provide a DNL level for this location. In watching the flight patterns, it was apparent that most of the planes that flew over the Tempe Performing Arts Center, or DNL 65 location, continued on and also flew over the sub DNL 65 position. Most of the planes flights that were monitored at this fourth primary location were in general nearly directly overhead.

With a projected even flight path slope between the runway and the fourth position at sub DNL 65, a gradually diminishing level of aircraft noise levels with distance were expected. Two additional remote locations were chosen to add additional plane elevation to the overall experiment. These included locations about 10 and 17 air miles away from the end of the runway. The “10-mile” location had over flights at an elevation of about 1 mile from the ground level. The “17-mile” monitoring location had plane elevations at about two miles above ground level. The planes observed at both of these locations passed nearly directly overhead.

Airplane Flight Data

A Phoenix Sky Harbor maintains a software product identified as “PublicVue” which was used to identify detailed flight information from planes documented during the experiments (Phoenix Sky Harbor, 2017). The software product was limited in that it provided the flight information on a 10-minute security delay. The information retrieved and recorded from this web site included aircraft type, airline, height/elevation above ground (ft.), and speed (mph). The 10-minute time delay introduced uncertainty into the details of the flight information, as some of the time intervals between flights were as short as one minute. This led to active data collection occurring in conjunction with delayed documentation of earlier experiments. It also introduced the possibility of sound carryover from one flight into the next.

The flight data obtained through the airport could not be independently verified leading to additional potential uncertainty in the data captured and reported. Plane speed and height are believed to have been the most susceptible flight parameters to this uncertainty. In addition to the sound and vibration measurements recorded through the data acquisition system, an “A-weighted” dBA measurement was manually captured for each flight. A minimum of 10 aircraft flight events was recorded from monitoring locations 1-4 as described. A minimum of five measurements was recorded from the remote fifth and sixth locations.

Experimental Design for Measuring Low Frequency and Infrasound

A mock-up structure was constructed to simulate the elements of common residential structures (Figure 13). Construction elements commonly used to build houses/apartments include wood framing, exterior plywood sheathing, fiberglass insulation, an interior drywall covering and windows. The mock-up structure built used these materials and was sized to be transportable and fit into the back of an SUV vehicle with dimensions of approximately 24 x 24 x 24 inches. Handles and knobs were added to allow transportation and access into the interior of the enclosure to allow the positioning of sensors. A dual pane window approximately 9 x 9 inches was placed on a single side surface. Sealant was used to fill all air gaps.

Figure 12. Structural mock-up platform for data collection.

The mock-up structure was instrumented with a pair of accelerometers (calibrated from 2-5000 Hz) and microphones (calibrated from 20-20,000 Hz) capable of low frequency and infrasound vibration measurements (Figure 14). The microphone measured pressure caused by the sound with pressure defined as a force divided by an area. Acceleration is the change in velocity of an object divided by time. The orientation of the microphones and accelerometers can introduce a source of error and become a significant impact to the test measurements. To avoid this, a common orientation was chosen for each pair of sensors to avoid data bias. The two microphones were positioned pointing straight up with one outside the box and the second microphone centered within the cavity of the box. The two accelerometers were located inside and outside of the box and positioned pointing down into or onto the top of monitored surfaces. Hard-set epoxy glue was used to attach vibration-mounting pads to each surface. The outside accelerometer was located on the top lid of the mock-up structure. The inside accelerometer was fixed, glued to a gelatinous material, commonly known as ballistic gel. The gelatinous material was centered within the cavity.

Ballistic gel was chosen as it has similar properties to human tissue. It was ordered from Clear Ballistics (Fort Smith, Arkansas). This gel is moderately rubbery to the touch with a texture not unlike a soft pliable dried bead of construction silicon. Ballistic gel is designed to have a similar response to the force of a projectile (e.g., a bullet) striking and entering into human tissue. The ballistic gel chosen was advertised as meeting FBI grade. FBI grade means that when a standard projectile (a bullet) is shot into a defined volume of the material with a standardized rifle, that it will penetrate into the material a specified distance. This distance would be similar to the distance of travel of the same projectile into body tissue. Five pounds of this material was melted and then reformed in a cylindrical cone shape. A medium sized glass bowl was used to obtain the form.

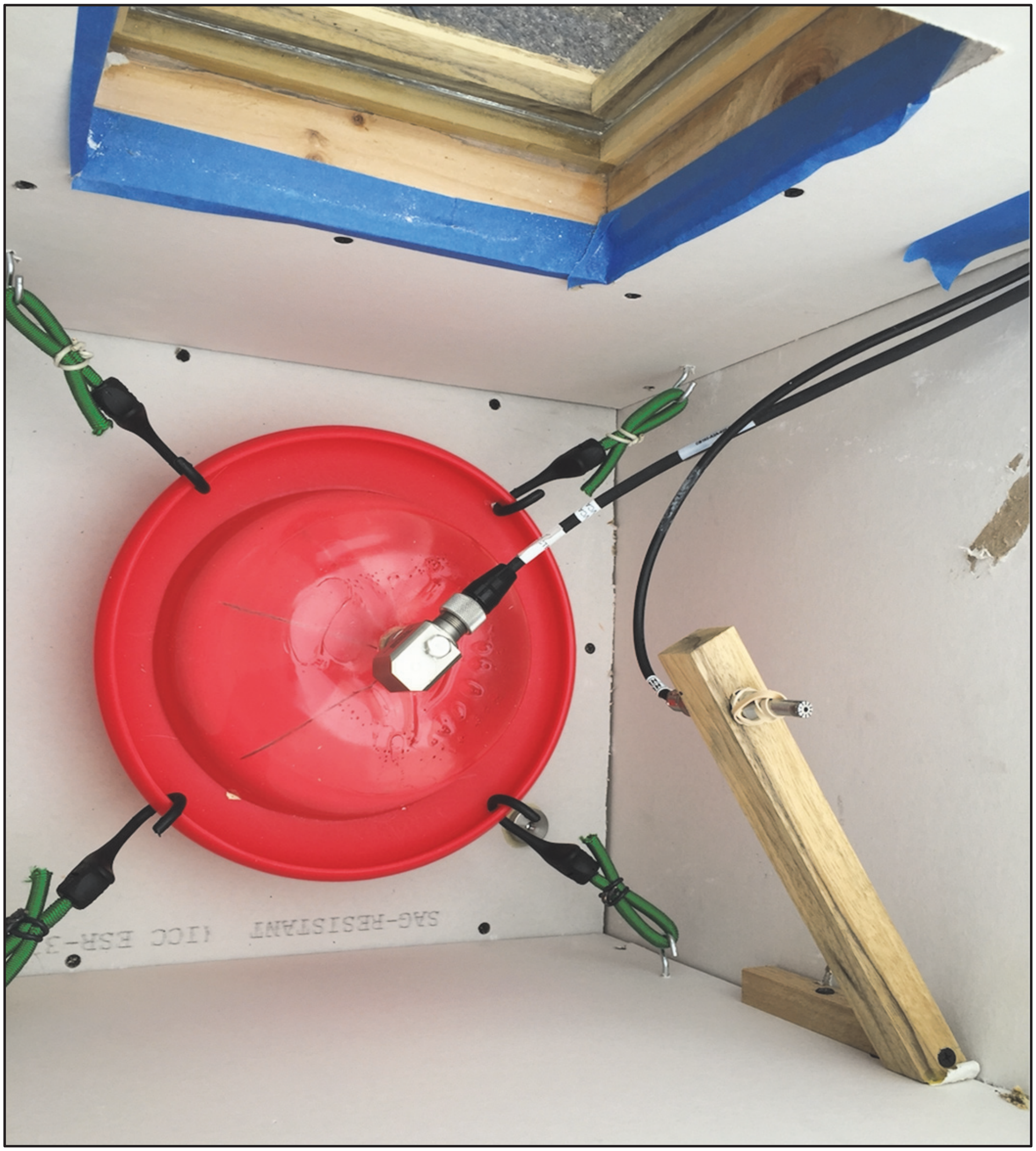

Figure 13. Instrumentation setup for the microphone and accelerometer.

Energy that enters into a material, such as the lid of the box, causes it to vibrate and these vibrations can travel throughout other material that it contacts. Vibrations would be expected to move from outside of the mock-up passing through the wood framing and extending into the drywall material. Such a transfer of energy from the outside could move to the box’s inside surfaces and conceivably transfer to the ballistic gel. To avoid this occurring to the ballistic gel, the gel was isolated from the interior surfaces of the container. Elastic “bungee” cords were connected within the box to a soft poly disc centered within the cavity. The disc was positioned upside down to allow its edges and slightly curved shape to center and hold the gel. The disc chosen for this purpose was a “Wham O” branded Frisbee product. Thin steel rods were placed into the gel emanating from the top center to allow gluing of the vibration-mounting disc to the gel. These rods were inserted so that they did not come in contact with the poly disc to ensure that an unaltered volume of the ballistic gel was in direct contact with its surface. The vibration mount was positioned to completely cover the tips of the rods.

Instrumentation and Settings

Concurrent spectrum measurements to include the amplitudes and frequencies for both sound pressure and vibration excitations were obtained using a data acquisition instrument. A data acquisition instrument was chosen to allow continuous and simultaneous collection of data from the two microphones and low frequency accelerometers. The data was processed through the data acquisition device with settings of 5-5000 Hz and 6400 lines of resolution resulting in data accuracy of 0.3125 Hz. A handheld microphone designed to register dBA sound from 20 Hz to 10,000 was obtained to provide reference to currently specified sound data.

The accelerometer calibration to 2 Hz exceeded the microphone calibration of “to 20 Hz”. Sound measurements were a secondary objective to the vibrations that they induced. It was assumed that if the microphones and accelerometer produced data at the same simultaneous frequencies and their amplitudes scaled similarly, that the sound data below 20 Hz would be acceptable for use. The limitations of the sound calibration frequency of 20 Hz were discussed at the time of the rental with their sound engineers. The microphones are not limited in their usable response range to 20 Hz and greater, rather the calibration is limited to the standard define sound range. They agreed with the assumption of the relationship of the accelerometer and microphone usable data ranges. It should also be noted that the focus of the experiments was to measure low frequency vibrations and that the microphone calibration would not have any impact on the measured vibrations. A complete listing of instrumentation used to obtain data measurements is included in Table 1.

Table 1. List of instrumentation.

Instrument	Specification	Comments
PCB Piezotronics	Model 482A16 signal conditioner	For use with microphones
IO Tech	Model: Zonicbook/618E	Data acquisition to collect continuous data
IO Tech	eZ-Analyst Software	To manage data experiments
Low Frequency Accelerometer	500 mv/g (NOM)	For use in obtaining vibration measurements
PCB Piezotronics ICP Electret Array Microphone	20-10,000 Hz @ +/- 2 dB 45 mV/Pa	For use in obtaining sound measurements
Tekcoplus sound level meter	30-130 dBA @ +/- 1.5 dB Frequency response of 31.5-8500 Hz	Handheld instrument used to obtain dBA measurements

Each flyover event was recorded for 45-90 seconds. This period was broken into 30-50 unique time segments and then stacked to record the full overall flight duration.

As such, each of the 60+ flyover experiments recorded in support of this research consists of 30-50 unique approximate 1.2-second duration individual segments/experiments that were compiled separately and then stacked into the 45-90 seconds needed to cover the approach, flyover and departure. While each flyover event was being processed through the data acquisition system, the A-weighted dBA hand held instrument was manually monitored to determine and record the maximum sound measurement that occurred during the flyover period.

Air temperature and humidity affect the density of air and how sound travels through it. Airport published measurements were used to document these test conditions. Temperatures varied from 40-70 degree F and humidity ranged from 4-20% over the duration of the experiments. No adjustments to the data were made to account for these effects. It should be noted that the humidity and temperature measurements listed are ground measurements and that air temperature decreases with altitude. Relative humidity increases in conjunction with temperature decreases.

Data Output

The data acquisition process produced an enormous amount of raw data for each of the 60+ aircraft flyover events studied. Each increment or experiment segment of an over flight had its own data variations from one segment to the next due to the location of the aircraft relative to the monitoring station as well as the speed and height of the aircraft. Each segment of each experiment captured its own unique time waveforms from all four of the sensors. A time waveform is complex mixture of all waves at all frequencies. This data is displayed in a peak-to-peak format with the microphone recording the data in amplitudes of pressure in Pascal (Pa) units and the vibration as acceleration in units of "g's."

Inspection of the time waveforms provided useful insight for the overall analysis. The inspections indicated the presence of less complex waves and at smaller amplitudes inside the structural mock-up than outside of it. This indicates that the materials of the box are attenuating or reducing the energy as sound waves pass into the internal void and that the sound waves are the source of energy excitation and induced vibrations (Figure 15).

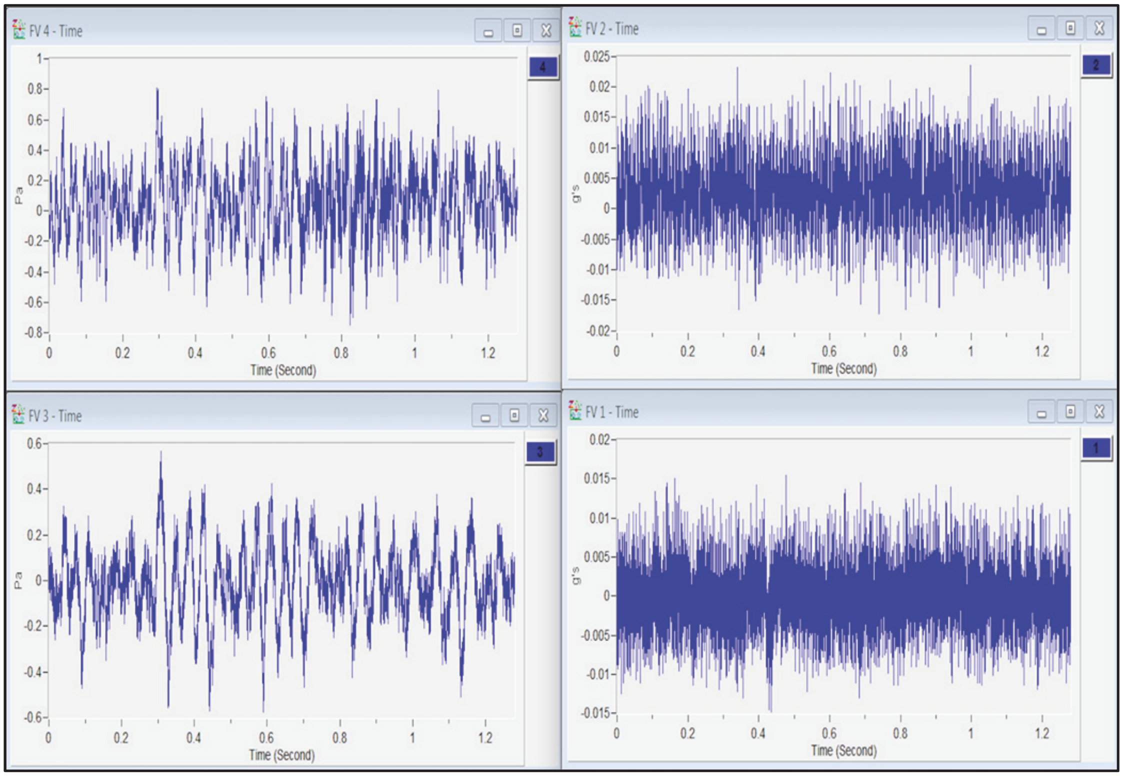

Figure 14. Sound is a pressure measurement (Pa) while vibration is acceleration (g's). The pressure is converted to rms. The x-axis is a time segment. Sound time waveforms are shown on the left and vibration waveforms are on the right. The top two images are from outside the box with the bottom two recorded at the ballistic gel inside of the box.

The time waveforms from each of the four probes were resolved into spectrum (or frequency plots) using a Fast Fourier Transform (FFT) to simplify the data by resolving the waveforms into unique peaks with defined locations (the frequency or Hz) and amplitudes (peak heights). The processing was performed using eZ-Analyst Software. This software is part of the Zonicbook Data Acquisition System. The heights or amplitudes of the peaks within the spectrum indicate the intensity of the energy at particular frequencies in which they occur. Simplifications were introduced to represent similar data and to extract data of greatest interest.

A common graphical display for the data was chosen as a standard output view and then used to allow comparative visual inspection of each segment of each flight. The display chosen for the data frequency plots includes two frequency scales. For the sensors located outside of the box (one sound probe and one accelerometer), a frequency range of 0-1000 Hz was chosen. This frequency range shows the low frequency portion of the dBA sound weighting that is de-emphasized due to its reduced impact on the sound frequencies that humans hear. A range from 0-200 Hz was chosen to represent the interior measurements (one sound probe and one accelerometer), as low frequency sound was previously defined in the range of 20-200 Hz.

The data were organized on the graphs with the open-air sound measurement in the upper left corner, the interior sound in the upper right corner, the lid vibration in the lower left corner and the vibration in the ballistic gel in the lower right. This same pattern was used for all segments from each flight monitored (Figure 16). As data was retrieved from six locations, six examples of this same standardized graphical display are included in the Appendix.

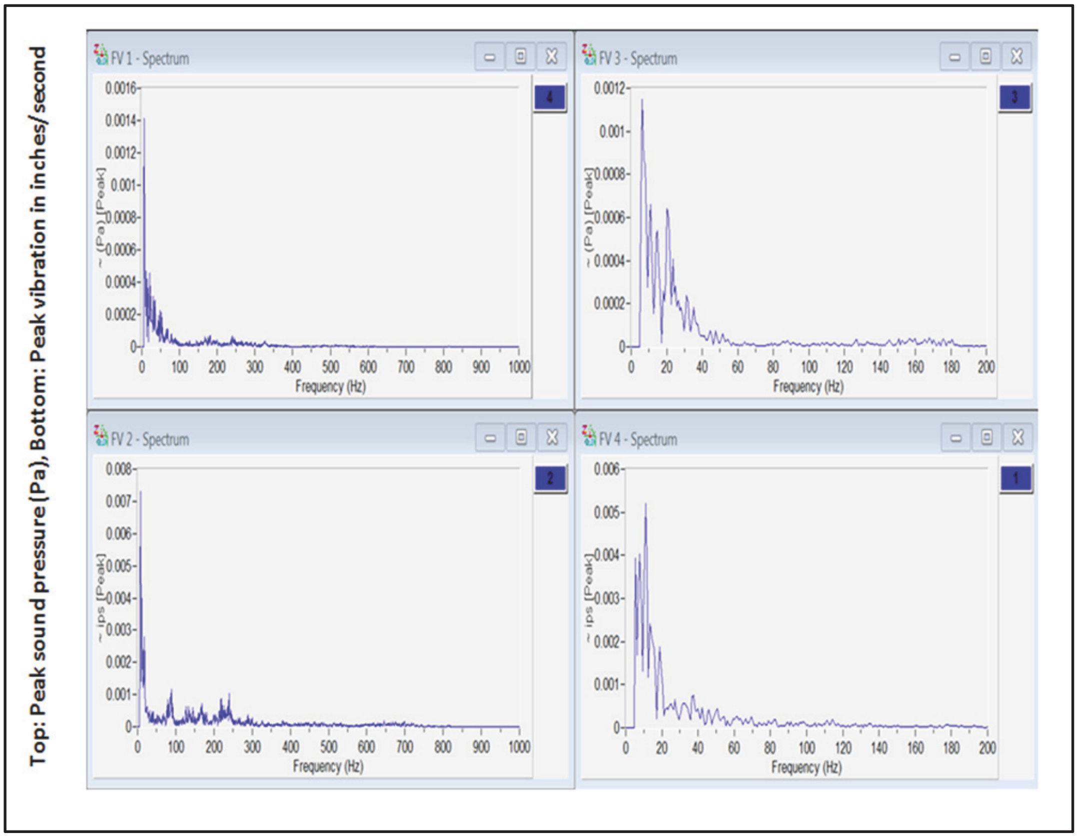

Figure 15. Representative frequency spectrum obtained from the sub 65 DNL location four miles from the airport. Top two are sound measurements. The bottom two measurements are vibration. The left two were taken outside of the mock-up structure with the two on the right measured from inside.

Chapter III

Results

Data recorded by the two accelerometers and microphones created a significant data stream. Although a variety of aircraft body styles with an unknown variety of engines and flight elevations were monitored, the respective data from each of the four primary data gathering locations and from all of the 30-50 segments that made up a full flight were highly similar. In addition, the key infrasound and low frequency generated vibration measurements that were obtained were also highly similar in terms of frequency and amplitude both inside and outside of the box. Due to this similarity, only a single segment of vibration data from each experiment was considered as representation data for each individual flight irrespective of other data throughout the remainder of this document. As people spend approximately 90% of their times indoors (EPA, 2017), the ballistic gel, located within the mock-up enclosure is the most suitable monitored data set to determine the human impact from the flyover event. These vibrations will be the focus for the analysis and review.

Single Flight Segments

The ordering of the data in the tables is random with each row comprised of data from a single segment from the “next” airplane that flew overhead. Background information from the Phoenix web page “PublicVue” from each flight captured, including elevation, speed and aircraft type, is listed in Table 2. Vibration measurements obtained at the ballistic gel from a single segment is also listed against its corresponding flight.

Table 2. Aircraft description and experimental measurements.

Monitored Location	Plane Type	Elevation (ft)	Attenuation Convergence (Hz)	Speed (mph)	Max dBA	Overall Vibration (ips)
DNL 75	B738	500	4300	169	84.1	0.01308
DNL 75	B757	500	4500	178	84.4	0.01257
DNL 75	A319	500	4500	163	80.2	0.01102
DNL 75	A321	500	4700	165	83.4	0.01390
DNL 75	CRJ7	500	3700	169	79.6	0.01115
DNL 75	B738	500	3900	171	83.6	0.01246
DNL 75	A321	500	4800	161	87.1	0.01521
DNL 75	A319	500	4700	165	80.5	0.01056
DNL 75	B738	500	3300	178	84.4	0.00920
DNL 75	CRJ7	815	4000	163	73.3	0.01328
DNL 75	A321	500	3900	175	86.5	0.01244
DNL 75	A320	500	3800	163	80.4	0.01323
DNL 75	A319	500	4300	163	82.4	0.01256
DNL 75	A320	500	3300	175	80.8	0.01344
DNL 70	A319	1215	2400	159	80.4	0.01352
DNL 70	GFL4	1708	2150	201	74.4	0.01486
DNL 70	A319	1252	2000	157	76.8	0.01992
DNL 70	CRJ4	1646	1900	157	60.1	0.01630
DNL 70	CRJ9	1071	2500	165	79.9	0.01011
DNL 70	A319	1390	2400	169	72.6	0.01544
DNL 70	CRJ7	1345	2300	171	73.4	0.01022
DNL 70	CRJ9	990	2600	173	78.6	0.02090
DNL 70	B737	1321	2100	153	78.6	0.01922
DNL 70	B738	1140	2300	165	78.6	0.01611
DNL 70	A319	1577	2250	140	77.3	0.01355
DNL 70	CRJ7	1065	2400	177	77.7	0.01703
DNL 65	CRJ7	1790	2100	176	68	0.01095
DNL 65	CRJ9	2165	2200	158	73.3	0.01515
DNL 65	B738	1458	2300	202	75.5	0.01518
DNL 65	B738	1433	2300	175	78.2	0.01118
DNL 65	LJ60	2590	1500	209	62.3	0.01421
DNL 65	CRJ7	1990	1600	170	66.5	0.01267
DNL 65	CRJ7	2940	1950	213	62.4	0.01703
DNL 65	A320	1990	2100	167	76.4	0.01490
DNL 65	B737	1346	2200	191	75	0.01375
DNL 65	CRJ9	1594	1650	183	73.3	0.01183
DNL 65	B737	2052	2100	190	66.3	0.01471
DNL 65	A319	1558	2200	163	77.8	0.01463
Sub DNL 65	A319	3565	1750	217	64.2	0.01020
Sub DNL 65	B752	3365	1750	200	65.6	0.01346
Sub DNL 65	CRJ7	5115	850	195	56.8	0.01261
Sub DNL 65	CRJ9	3540	1050	229	57.2	0.01314

Sub DNL 65	CRJ9	4365	2000	218	58.5	0.01138
Sub DNL 65	CRJ9	4065	1100	216	58.8	0.01073
Sub DNL 65	B738	3483	1300	226	67.4	0.01049
Sub DNL 65	B738	3333	1250	219	64.9	0.01423
Sub DNL 65	B737	4015	1800	205	64.1	0.01669
Sub DNL 65	A321	3612	1200	224	66.9	0.01193
17 Miles	B738	9888	70	315	53.6	0.00266
17 Miles	A320	9763	80	285	49.6	0.00200
17 Miles	B737	9463	100	301	51.7	0.00280
17 Miles	B738	11538	50	360	56.1	0.00277
17 Miles	CL30	12688	50	241	47.5	0.00220
10 Miles	Unknown	5488	850		77.1	0.00458
10 Miles	Unknown	4788	900	267	61.9	0.0036
10 Miles	Unknown	6388	850	267	64.3	0.00456
10 Miles	Unknown	4881	1100	Unknown	64.6	0.00713
10 Miles	CRJ7	5263	575	260	64.7	0.00367

These include the aircraft maximum frequency sound measurement (Hz) at the attenuation converge and an overall vibration value in inches per second (ips). It should be noted that the airport software for the DNL 75 location did not report/provide elevation data with a single exception of 815 feet for the tenth flight. A plane height of 500 ft was assumed for the rest of these flights, based upon my observations.

The vibrations within the gel were observed to vary or modulate as they were being recorded from flight segment to segment. Vibration data can be reported either by their spectrum at the specific amplitudes and frequency at which they occur or they can be represented by summing all of the amplitudes into a single measurement identified by the term of “overall vibration.” The use of the overall vibration level characterization is a commonly reported measurement. Due to the modulations observed, the decision was made to represent the vibrations occurring within the gel with the overall measurement value. The vibration software that was used did not have the capability to sum the vibrations automatically so the peak heights were manually tabulated. Some of the smallest peaks were not included in the summing as they were one to two orders of magnitude smaller than the major peaks and their contributors would have been minor. This simplification likely resulted in moderate underreporting of the overall energy. This simplifying assumption, however, was uniformly applied.

The overall vibration values from each monitored location were averaged (mean values +/-standard deviation) and are as follows: 75 DNL (0.01244 ips +/- 0.00153), 70 DNL (.01560 ips +/- 0.0034), 65 DNL (0.01378 ips +/- 0.0019), Sub 65 DNL (0.01268 ips +/- 0.002), 10 mile (0.004708 ips +/- 0.0013) and 17 mile (.00249 ips +/- 0.00032). The uniformity of the experimental data at the first four monitored locations indicates highly similar overall infrasound energy is being produced for plane heights less than 4000 feet. This is a reasonable observation as the intensity of the infrasound being produced is unrelated to the small elevation difference. The sound energy that reaches the ground is however related to the distance that the sound travels.

The two remote locations, however, were markedly different as they had considerably lower overall vibration measurements (Figure 17). These data strongly suggest that infrasound frequency attenuation begins at a similar and repeatable elevation distance from the ground. At a distance of a mile up from the ground, the overall vibration is reduced to about 1/3 of the overall vibration reported at ~4000 feet and lower. At a distance of two miles up, it reduced to about 1/6 of the overall reported at ~4000 feet and lower (Figure 17).

The dBA measurements listed in Table 2 were correlated to aircraft elevation (distance from ground) and to the infrasound overall vibration measurements to determine if correlations exist (Figure 18). It’s not surprising that the Max dBA

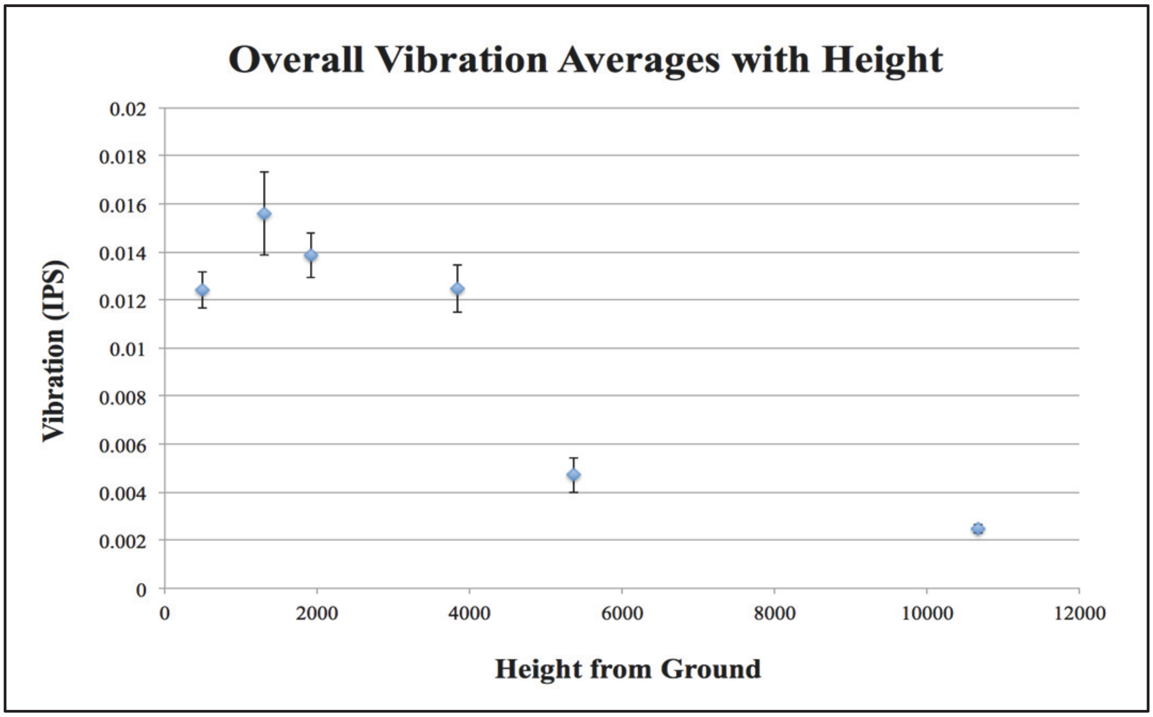

Figure 17. Average infrasound vibration intensity for six measurement sites.

measurements show good agreement to the planes distance from ground. The R^2 of 0.69614 supports this statement. As low frequency sound infrasound is de-emphasized or discounted by the dBA weighting, it is also not surprising that the overall vibration measurements obtained from the ballistic gel showed no correlation with the dBA measurements with an R^2 of 0.0003. While dBA sound measurements can identify differences in aircraft sound, this measurement system doesn't have any value in monitoring aircraft generated infrasound or forecasting its induced vibrations (Figure 18). Another system is required for these low frequency measurements.

Materials have inherent properties related to their mass and stiffness. At times, these properties align to increase the strength of the vibration energy through resonance.

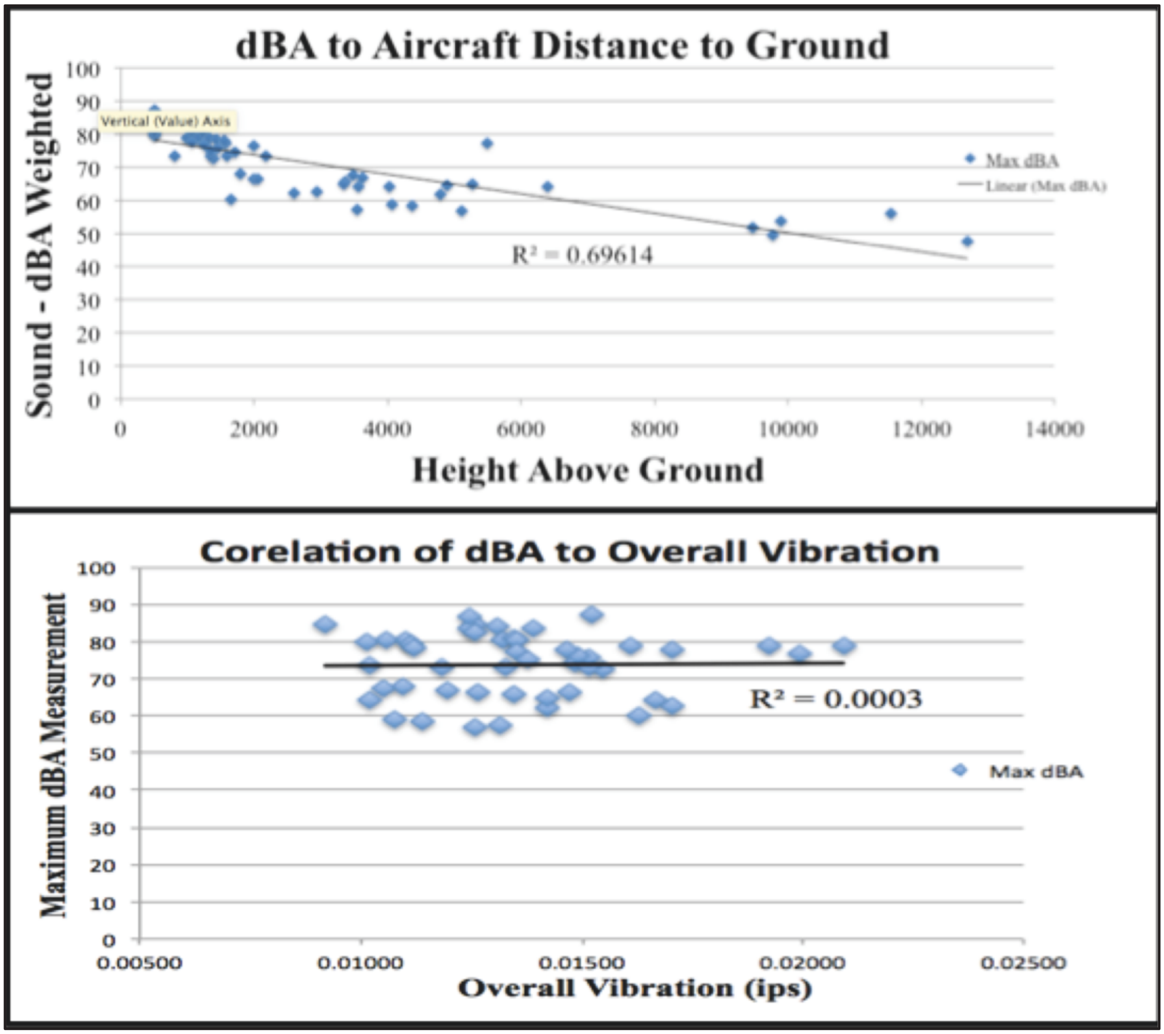

Figure 18. Correlation of sound to aircraft distance from ground (top) and infrasound (bottom).

Vibrational resonance means that the excitation vibrational energy amplifies while within the material. When this occurs, it does so at a specific frequency that has a relationship with the mass and stiffness of the material. In some cases, the excitation frequency may be a direct match to the primary resonance frequency. The amplification of the vibration causes the amplitudes of the peaks to become larger and creates potentially more damaging energy input to the material that is vibrating.

All of the experiments resulted in measurable vibrations in the ballistic gel. Many of these experiments also had clear examples of vibrational resonance occurring within the gel. An example of this is evident at 6.25 Hz of Figure 19 with the vibration amplitude measured in the ballistic gel (blue peaks) about 20% greater than the vibration measured on the exterior lid (red peaks).

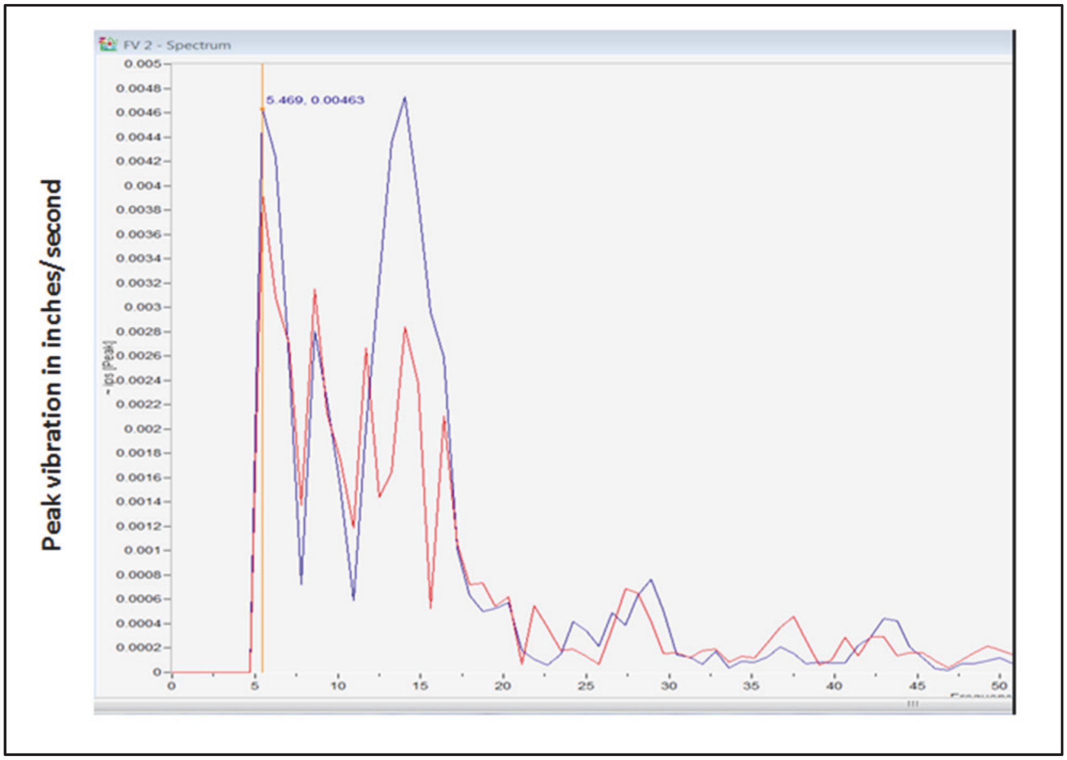

Figure 19. Infrasound energy induces ballistic gel vibration. The x-axis displays frequencies.

Infra and low frequency vibrations were excited in the ballistic gel at frequencies between 5 to 40 Hz. Segment-to-segment variations in peak location and amplitudes within each flight suggest constant modulation of the source sound. The modulation would limit the energy damage as it moved off the offending frequency being produced by the resonance but may also allow multiple other short duration resonance spikes to occur at those same frequencies. The modulations were highly dynamic indicating non-steady state sound perturbation conditions occurring from the plane followed by the same frequencies being received within the gel. This observation is reasonable due to the expectation of highly turbulent flow being produced by the airplane.

Many of the specific measured infrasound frequencies (Table 3) have been associated with specific health issues and if resonance where to occur at these frequencies, it would cause amplifications of these vibrations. The listed frequencies are from a single time segment randomly chosen to represent each flight event. The frequencies listed should not be taken to mean that only those frequencies were present for that flight, rather due to the effects of modulation the body of frequencies of all of the flights should be considered as representative of frequencies that are produced. The order of appearance for each of these flight experiments mirrors the order used in Table 2.

Single Flight Profile

Each of the individual segments of a single flight was independently and sequentially examined with each segment's overall vibration energy tabulated. In considering the body of measurements, the entire segment grouping had similar frequency modulations and variations to those listed in table 3. The representative single flight reviewed had a total of 32 segments measured (Figure 20). The representative flight did not follow the shape of the expected overall energy profile for a flight of starting at a low energy during the approach, increasing to a high point as it passed overhead and then decreasing to a minimum as the plane flew away. Instead the energy increased during the experiment, indicating that the test was prematurely terminated.

Table 3. Representative infrasound vibration peak frequencies and amplitudes. Data taken from a single measured segment from each monitored flight.

Experiment		Primary Vibration Measurements in Ballistic Gel									Overall (ips)
DNL 75	*Frequency*	6.25	8.594	11.72	14.06	17.19	21.88	42.97			
	Amplitude	0.00304	0.00216	0.00213	0.00193	0.00226	0.00092	0.00064			0.01308
DNL 75	*Frequency*	6.25	8.59	10.16	12.5	20.31	31.25	34.38	50		
	Amplitude	0.00325	0.00222	0.00237	0.00121	0.00094	0.00117	0.00099	0.00042		0.01257
DNL 75	*Frequency*	7.813	10.16	17.19	20.31	28.91	31.25	84.38			
	Amplitude	0.00268	0.00217	0.0018	0.00114	0.00152	0.00137	0.00034			0.01102
DNL 75	*Frequency*	6.25	8.594	10.16	18.75	22.66	27.34	29.69			
	Amplitude	0.0048	0.00293	0.00177	0.00149	0.00123	0.0008	0.00088	0.0139		0.0139
DNL 75	*Frequency*	5.469	10.16	15.63	26.56	29.69			0.0139		
	Amplitude	0.00488	0.00226	0.00126	0.0013	0.00145					0.01115
DNL 75	*Frequency*	5.469	7.813	10.94	14.06	89.84					
	Amplitude	0.00575	0.00349	0.00158	0.00119	0.00045					0.01246
DNL 75	*Frequency*	5.469	10.16	12.5	15.56	19.53	23.44				
	Amplitude	0.00748	0.00211	0.00211	0.00159	0.00095	0.00097	0.01521			0.01521
DNL 75	*Frequency*	6.25	9.375	21.09	24.22	27.34					
	Amplitude	0.00356	0.00319	0.00112	0.00169	0.001					0.01056
DNL 75	*Frequency*	5.469	10.16	15.63	26.56						
	Amplitude	0.00357	0.00172	0.00126	0.00148	0.00117					0.0092
DNL 75	*Frequency*	5.469	7.031	8.594	11.72	18.75	21.09				
	Amplitude	0.00491	0.00223	0.00216	0.00144	0.00127	0.00127				0.01328
DNL 75	*Frequency*	6.25	10.16	18.75	21.88	25					
	Amplitude	0.00505	0.00296	0.00149	0.00164	0.0013					0.01244
DNL 75	*Frequency*	5.469	7.031	10.16	11.72	14.84	21.88				
	Amplitude	0.00317	0.00301	0.00295	0.00176	0.00121	0.00113				0.01323
DNL 75	*Frequency*	7.031	12.5	15.63	18.75	21.09					
	Amplitude	0.00469	0.00168	0.00192	0.0025	0.00177					0.01256
DNL 75	*Frequency*	5.469	7.83	9.375	17.19	21.09					
	Amplitude	0.00585	0.0024	0.00185	0.00201	0.00133					0.01344
DNL 70	*Frequency*	6.25	11.72	17.97	20.31						
	Amplitude	0.00705	0.00288	0.00176	0.00183						0.01352
DNL 70	*Frequency*	5.469	9.375	14.06	1797	20.31					
	Amplitude	0.00633	0.00175	0.00197	0.0028	0.00201					0.01486

DNL 70	*Frequency*	5.496	7.031	8.594	10.94	12.5	15.63	17.97	20.31	38.28	
	Amplitude	0.00341	0.00234	0.00304	0.00151	0.0014	0.00248	0.00272	0.00143	0.00159	0.01992
DNL 70	*Frequency*	5.469	7.031	9.375	13.28	15.63	17.97				
	Amplitude	0.00374	0.00294	0.00328	0.00237	0.00204	0.00193				0.0163
DNL 70	*Frequency*	6.25	11.72	17.19	42.19						
	Amplitude	0.00452	0.00227	0.00233	0.00099						0.01011
DNL 70	*Frequency*	5.469	7.813	11.72	13.28	18.75					
	Amplitude	0.00432	0.00465	0.00228	0.00261	0.00158					0.01544
DNL 70	*Frequency*	5.469	12.5	16.41							
	Amplitude	0.00662	0.00183	0.00177							0.01022
DNL 70	*Frequency*	5.469	9.375	12.5	14.4	17.97					
	Amplitude	0.00725	0.00415	0.00408	0.00256	0.00286					0.0209
DNL 70	*Frequency*	5.469	7.813	11.72	14.84						
	Amplitude	0.0103	0.0036	0.00302	0.0023						0.01922
DNL 70	*Frequency*	5.469	8.594	10.94	13.28						
	Amplitude	0.00727	0.00474	0.00251	0.00159						0.01611
DNL 70	*Frequency*	6.25	9.375	10.94	14.84						
	Amplitude	0.00871	0.00149	0.00169	0.00166						0.01355
DNL 70	*Frequency*	5.469	7.031	9.375	10.94						
	Amplitude	0.00488	0.00774	0.00271	0.0017						0.01703
DNL 65	*Frequency*	5.469	10.16	34.38							
	Amplitude	0.00765	0.00189	0.00141							0.01095
DNL 65	*Frequency*	6.25	7.031	10.94	17.19						
	Amplitude	0.00634	0.00525	0.00194	0.00162						0.01515
DNL 65	*Frequency*	6.25	7.813.00173	10.94	13.28	15.63	17.97	20.31	22.66		
	Amplitude	0.00332	0.00141	0.00172	0.0021	0.0023	0.0026	0.00136	0.00104		0.01518
DNL 65	*Frequency*	7.031	10.16	13.28							
	Amplitude	0.00521	0.00325	0.00272							0.01118
DNL 65	*Frequency*	5.469	7.813	10.94	16.41						
	Amplitude	0.00792	0.00221	0.00296	0.00112						0.01421
DNL 65	*Frequency*	5.469	7.813	10.16	12.5	15.63	20.31	23.54			
	Amplitude	0.00235	0.00353	0.00247	0.00188	0.00093	0.00069	0.00082			0.01267
DNL 65	*Frequency*	6.25	12.5	14.84	17.97						
	Amplitude	0.00879	0.00238	0.00303	0.00283						0.01703
DNL 65	*Frequency*	6.25	8.594	12.5	14.06	22.66	24.22				
	Amplitude	0.00576	0.00314	0.00209	0.00143	0.00144	0.00104				0.0149
DNL 65	*Frequency*	6.25	10.94	14.84	17.97						
	Amplitude	0.00595	0.00179	0.00343	0.00258						0.01375
DNL 65	*Frequency*	5.469	14.84	17.97							
	Amplitude	0.00793	0.00171	0.00219							0.01183
DNL 65	*Frequency*	5.469	10.16	12.5	17.19	21.31	22.66	25			

	Amplitude	0.00511	0.00162	0.00155	0.00149	0.00232	0.00168	0.00094			0.01471
DNL 65	*Frequency*	5.469	7.031	10.94	21.88	25.78					
	Amplitude	0.00609	0.00464	0.00095	0.00133	0.00125					0.014626
Sub DNL 65	*Frequency*	5.469	7.031	9.375	12.5						
	Amplitude	0.00325	0.00421	0.00157	0.00099						0.0102
Sub DNL 65	*Frequency*	5.469	7.031	12.5	0.00099						
	Amplitude	0.00766	0.00423	0.00157							0.01346
Sub DNL 65	*Frequency*	5.469	7.813	10.16	16.41						
	Amplitude	0.00633	0.00305	0.00228	0.00095						0.01261
Sub DNL 65	*Frequency*	5.469	7.813	9.375	14.06						
	Amplitude	0.00443	0.00413	0.00319	0.00139	0.01314					0.01314
Sub DNL 65	*Frequency*	6.25	10.16	14.84							
	Amplitude	0.00843	0.00133	0.00162							0.01138
Sub DNL 65	*Frequency*	6.25	10.16	15.63							
	Amplitude	0.00583	0.00327	0.00163							0.01073
Sub DNL 65	*Frequency*	7.31	8.594	12.5	16.41	21.09	26.56				
	Amplitude	0.00383	0.00212	0.00177	0.00102	0.00113	0.00062				0.01049
Sub DNL 65	*Frequency*	6.25	10.16	12.5	14.84	16.41					
	Amplitude	0.0054	0.00261	0.00303	0.0018	0.00139					0.01423
Sub DNL 65	*Frequency*	5.469	7.813	10.94	14.84	17.19					
	Amplitude	0.0071	0.0031	0.00291	0.00181	0.00177					0.01669
Sub DNL 65	*Frequency*	5.469	8.594	14.84	19.53						
	Amplitude	0.00529	0.00194	0.00148	0.00322						0.01193
17 Miles	*Frequency*	5.625	6.875	12.5	13.75						
	Amplitude	0.00112	0.00076	0.00039	0.00039						0.00266
17 Miles	*Frequency*	6.25	7.5	10	16.25	18.13	21.88	27.5	34.38		
	Amplitude	0.00057	0.00033	0.00024	0.00022	0.0002	0.00017	0.00015	0.00012		0.002
17 Miles	*Frequency*	5.625	6.875	8.125	12.5						
	Amplitude	0.0011	0.0008	0.00054	0.00036						0.0028
17 Miles	*Frequency*	5.625	8.125	10	15.63						
	Amplitude	0.00066	0.00112	0.00049	0.0005						0.00277
17 Miles	*Frequency*	6.875	10.63	15.63	25.63	29.38	51.88				
	Amplitude	0.00068	0.00043	0.0003	0.0003	0.00026	0.00023				0.0022
10 Miles	*Frequency*	5.313	6.875	9.375							
	Amplitude	0.00134	0.00106	0.00218	0.00458						0.00458
10 Miles	*Frequency*	5.939	7.813	9.375	10.63	11.59					
	Amplitude	0.00074	0.00058	0.00088	0.00059	0.00081					0.0036
10 Miles	*Frequency*	5.625	9.375	10.31	11.56						
	Amplitude	0.00056	0.00188	0.00095	0.00117						0.00456
10 Miles	*Frequency*	5.313	6.25	9.063	9.688						
	Amplitude	0.00197	0.00174	0.00128	0.00214						0.00713

10 Miles	*Frequency*	5.313	6.563	9.375	10.31	11.56					
	Amplitude	0.00038	0.00041	0.00181	0.00056	0.00051	0.00367				0.00367

The finding of carry over energy from one flight to the next due to spacing density of takeoffs could provide an explanation why the second and third locations of Figure 17 had higher overall average low frequency vibration measurements than the first and fourth locations. The second location was also off centered from the runway centerline and very close to the airport. Sound bleed or carryover from other airport aircraft (e.g., landings and departures) was likely contributing background sound to the measurements. Note that the first and fourth locations would be expected to have less background sound bleed than the two middle locations and they also had almost the same overall vibrations.

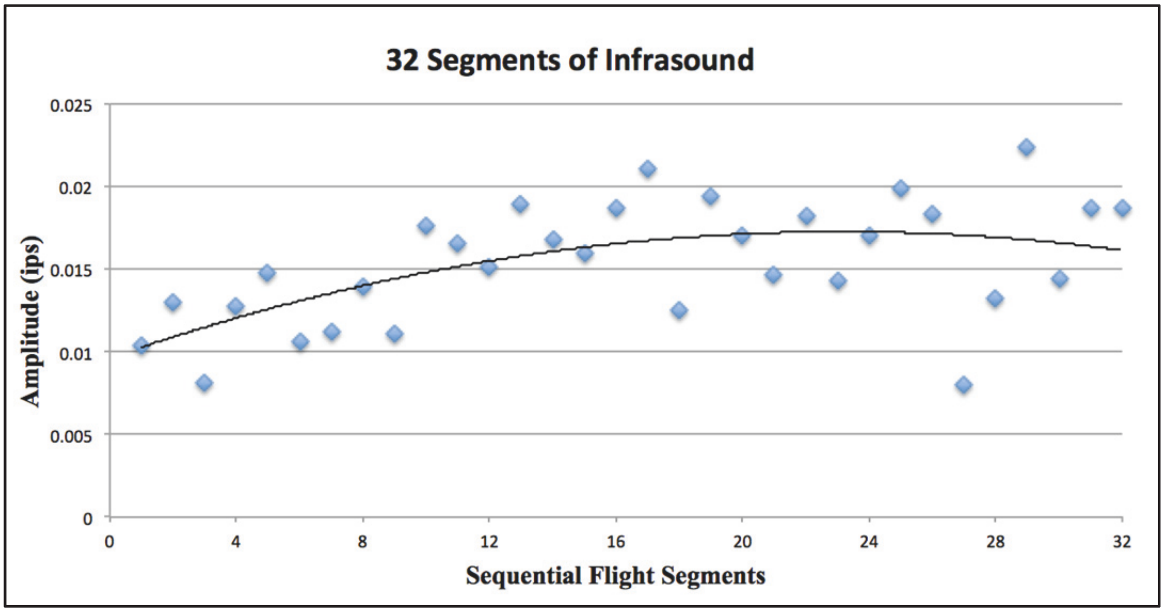

Figure 20. Overall vibration measurements from a single flight.

Measurements taken from the inside and outside of the mock-up differed. Only the lowest frequency sound waves of less than 50 Hz passed through the materials of the mock-up structure and entered into the void. The sound waves with frequencies greater than 50 Hz were attenuated (absorbed) as they passed through the box. An example of open air and interior sound were scaled to see the effects of the attenuation of the sound through the box (Figure 21). The attenuation of the sound after it has passed into the structure is readily apparent, as most of the sound wave frequencies greater than 40 Hz are gone.

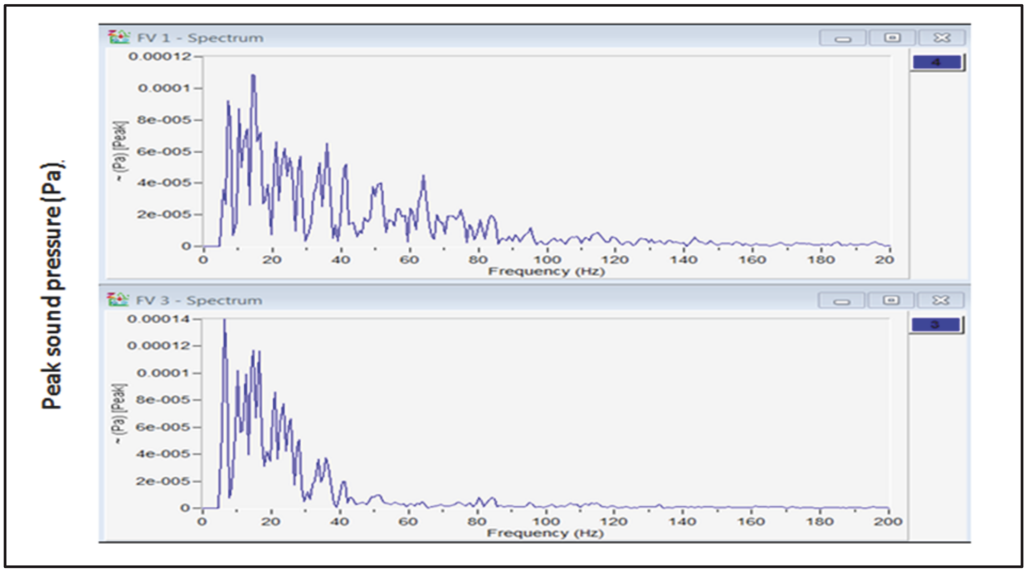

Figure 21. Attenuation of the sound inside the structural mock-up (bottom) and the sound present outside of the mock-up (top).

Inspection of Figure 21 appears to show that almost no sound energy beyond about 150 Hz is present either in the open air or within the mock-up. The apparent lack of sound, or flatness of the data outside of the mock-up and beyond 150 Hz is misleading as sound frequencies can be seen at higher frequencies by zooming in on the data.

Chapter IV

Discussion

Newton's third law states that that for every action there is an equal and opposite reaction. This law has interesting application to aircraft. Aircraft are extremely large and heavy machinery that are capable of accelerating and being supported within the air media and thereby allowing flight to occur. The forces produced by the airplane and the co-responding forces produced in the air surrounding and behind the airplane can be seen as a coupled reaction pair in that the force that the air applies to the airplane balances the force generated from the engines to propel and suspend the airplane. A tremendous amount of air is required to provide a force balance to the thrust of the plane. This pairing leads to massive volumes of turbulent flow behind and around the airplane that in turn leads to the pressure pulses within the air that then travel until they dissipate or reach the ground. These pressure pulses are distributed over a broad area of the sky with only some reaching the ground and causing the aircraft sound exposure.

The first hypothesis raised a question whether aircraft flyovers were generating sound at infrasound frequencies and if so if this sound could pass into a structure and then transfer energy into human body mass leading to measurable vibrations. This question was investigated through a series of experiments sequenced to measure aircraft at various elevations. The findings were interesting in that low frequency and infrasound waves were measurable from a height of over two miles above the ground level. It was determined that for all but the lowest frequencies (e.g., less than 50 Hz) of sound, that the wall elements of the mock-up structure attenuated or removed virtually all of the sound energy coming from the aircraft and that this pattern was consistent at all elevations measured.

The experiments demonstrated that the aircraft sound energy remaining after passing through the walls of the mock-up would make contact with internal objects and that the sound pressure could then transfer into that material, leading to measurable vibrations. For the simulated human tissue material of interest, these vibrations occurred at the same frequencies as the sound that passed into the void of the structure. It should also be pointed out that the external sound arriving at the mock-up resulted in these same low frequency vibrations being produced on the outside surface of the wood lid. The vibration energy being captured by both the soft gel and hard wood materials could be measured and then summed and tabulated. Vibration measurements were recorded at frequencies of less than 100 Hz for each aircraft from all elevations tested. The hypothesis and question concerning the occurrence of and ability to measure low frequency induced vibrations stemming from aircraft sound was successfully verified.

Dose-Exposure Area

Most of the test data obtained was taken during aircraft departure. The airplanes at each location were generally observed to depart at a steady rise angle while maintaining a speed of less than 200 miles per hour. The constant speed and take off angle would have resulted in a relatively consistent power level from the turbine engines and would have produced a similar reaction force due to air disturbance for the time period when these conditions were maintained. As the first four monitored locations maintained these flight conditions, the steady flight environments lasted several minutes. The sub DNL 65 location was the furthest location monitored that maintained the observed departure conditions of speed and rise angle. That group of aircraft averaged 3677 (SD=552) feet elevation and these aircraft still produced similar overall vibration measurements to the previous three closer to-the-airport monitored locations. A drop off in the overall vibration energy was evident at the 10-mile location. This location had an average elevation height of 5363 ft. This information suggests that the overall vibration measurement induced from the infrasound remained relatively constant to a distance of about 5 miles from the airport before it began to drop off (Table 2). Different plane types did not result in variations to the overall infrasound induced vibrations (see discussion in limitations section).

The two remote monitored locations at 10 and 17 miles from the airport showed a change in the amount of overall vibrations being produced in that attenuation of the infrasound was evident. The overall vibrational energy measurements in the ballistic gel dropped significantly to about 1/3 for the 10-mile and 1/6 for the 17-mile of the overall measurements observed from the four locations closer to the airport. The increased elevation of the aircraft seemed to be the differentiator. To validate the observation that adding distance from the aircraft would reduce the vibration energy measurement, an additional monitoring location was chosen near the 65 DNL monitoring position but perpendicular to and removed a distance from the flight path. The additional test location chosen was approximately one mile directly to the side of the flight path. The actual distance to the aircraft was greater than a mile as the vertical position of the plane added additional distance to the horizontal mile. This experiment was used to determine if attenuation of infrasound also occurred in a similar manner irrespective of either vertical or horizontal positioning.

Seven aircraft flyovers were measured from the horizontal offset location and they averaged a 0.0044 IPS (SD +/- 0.0015) overall vibration. It should be noted that the aircraft elevations during these experiments were similar to the elevations recorded and reported from the DNL 65 location. In adding a horizontal offset distance, a reduction of the overall vibration to approximately 1/3 of the full vibration energy recorded for the DNL 65 location occurred. A similar drop off from the four-location baseline to about 1/3 of overall energy was also found for measurements taken from the 10-mile location. Those planes measured were approximately one vertical mile from ground.

The energy reductions from one-mile vertical and one-mile horizontal conditions indicate that for the four-location baseline, that the infrasound centered at the plane is arriving to the ground at or with full un-attenuated energy over a band approximately one and one half miles wide. Stated otherwise, beyond a distance of about 4000 feet measured either vertically or horizontally, the infrasound energy appears to decay with increased distance from the plane. The energy decays further, to about 1/6 of the full overall levels at two miles. Additional horizontal off set distances were not pursued. The potential impact to the experimental data from influences such as aircraft speed, air humidity and temperature were not considered.

In that the infrasound induced vibrations were highly similar for the first four locations and in that distance from aircraft influences the overall vibration beyond approximately a mile for the conditions notes, a band of similar low frequency vibration exposures can be postulated. The impact area of infrasound induced vibrations for each individual flight can be estimated at a five by one and one half-mile band exposure from the end of the runway. Humans within this band would be expected to receive a similar sound exposure. This spatial association can be used to on a flight-by-flight basis to count the number of exposures being received by those impacted. Those living just outside of the full exposure band would receive a partial exposure related to an increase of distance. The development of drop off or decay curves would be needed to account for partial exposures.

Health Impact of Aircraft Sound

Counting individual sound exposures rather than averaging sound is the first step towards converting the aircraft sound narrative. Setting health as an aircraft noise criterion can be explained in an intuitive manner to the public and the use of such a criterion is readily measurable. Having science-based certainty that comes from criteria based upon health would be beneficial to the travel and air transport industries as well as impacted communities. Further benefits would be expected from the use of an exposure-dose based criteria as public health would be expected to improve. Furthermore, the use of a simple health-based criterion allows public monitoring. Industry conformance or the lack thereof can become reportable and actionable.

Proposal for Health Based Sound Criteria

The industrial revolution brought machinery along with convenience opportunities and an improved quality of life to humans. Modernization and convenience carries health risk. The first step in risk management is to identify and acknowledge the risk. Risk is then managed through public policy and is based upon an understanding of causality, severity of consequence and perceived societal benefit. Sound and noise are not recognized as health risks, so it follows that aircraft noises are not managed in this manner.

Health issues that take years or perhaps decades to develop can be classified as chronic health issues. It can be argued that using DNL averaged long-term sound exposure at varying contour thresh holds that then lead to a cardiovascular impact is an ineffective starting point from which to set public health policy as the relationship of health to exposure and dose is overly difficult to determine. A better starting point for criteria may be at the exposure level itself. Infrasound exposure has been identified as a health risk with cardiovascular health stated as a primary negative health impact. Vibrations induced from the infrasound have been identified as the source health exposure (Havas, 2011).

Infrasound exposure has been shown to cause damaging vibrations in cells (Alves-Pereira et al, 2007). It was determined that exposures create vibrations and that the vibration cause stress at the structural components of cells. This leads to cell damage and thickening of tissue that in turn creates health risk. Elevated blood pressure was identified as a risk factor caused by aircraft over flight events. Blood pressure rises were demonstrated to occur from infrasound exposure (Danielsson, 1985). Sleep deprivation was shown to result from 10 Hz vibrations with greater amplitudes resulting in poorer sleep (Smith, 2016). Thickening of cellular tissue, elevated blood pressure and sleep deprivation are all factors that contribute to increase cardiovascular risk.

Heart disease is a leading cause of death in the United States (Holland, 2017). Numerous health based meta studies of millions of people living near airports across the world has been shown to cause increased cardiovascular health risk including heart attacks (Vienneau, 2015). Aircraft noise is the identified risk factor for this health issue. An increasing risk was determined for those that leave closer to the airport. The risk was expressed as 1.06 for each 10 dB increase. These risks begin at an annualized average sound of 50 dB (Branco, 1999). Infrasound induced vibrations of human tissue explains the increase in cardiovascular risk from aircraft noise and is the likely source exposure that is causing this harm. In that exposures can be tabulated, dose-response curves can be established for aircraft fly over events to help manage the risk.

Modern aircraft control using GPS navigation allows precise control and documentation of aircraft flight paths. In reviewing the example of the Phoenix Sky Harbor post NextGen navigation implementation; this capability is clearly evident in the precise placement of flights (Figure 10). The compilation of this figure also suggests that a full recording of the history of plane positioning is also reasonably attainable information.

Field test data obtained through this study has demonstrated that a reoccurring and repeatable infrasound exposure level for the conditions of gradual assent at low speeds could be set around the flight path over a band approximately five by one-and-one half miles. The research also demonstrated that a drop off or decay exposure level could be determined for aircraft flyovers outside of the primary five by one-and-one half-mile window. Exposure counts that include full and partial exposure doses can be readily tabulated.

It is proposed that rather that summing and averaging an annualized aircraft sound level using a criterion such as the FAA DNL sound rating, that the sound criteria should be converted to one that simply counts flyover events a individual exposures leading to cumulative infrasound induced vibration doses. Public maps include specific domicile locations and communities have details of the number of inhabitants the dwellings. Coupling this geographic information with a count of flight exposures would allow the accurate assessments needed to build dose-result relationships. Further research is needed to determine a threshold number of flight sound exposures where health would be impacted and to then set the dose-response curves. This information could be used in turn to set constructive public policy.

Aircraft and air travel are vital economic components of modern society. In identifying infrasound as a dangerous public health issue, it is not being suggested to abondon or curtail of any portion of this sector of the global ecomony. Rather it is being suggested that this economic sector should be managed in a manner that considers public health impact. The cost to humans and subequenctly the cost to provide health care resulting from environmental exposures is high and is not being included. The intent of this document is to include health as a key factor in setting the aircraft noise criteria and then using this input for related policy decessions.

NextGen Flight Path Health Impact

Prior to the implementation of GPS navigation precision, flight paths were increasingly random with increased distance from the airport. This changed with the introduction of GPS navigation (Figure 11). It is intuitive that the greater randomness of the flight paths further away from the airport would produce fewer fly over events to any given member of the public at those geographic locations. As a result of NextGen, many members of the public received fewer or no exposures while others experience more events through concentration. Increasing the number of flights experienced would increase infrasound exposures and likely health consequences. In that a dose-relationship is not known, a threshold number of safe exposures is not understood. Both the randomness of previous flight paths and the change to precision of the NextGen flight paths is readily apparent through inspection of figure 11.

This investigation suggests a similar health risk for all those that receive same number of individual exposures. The risk would be independent of the average annualized sound boundaries. Cardiovascular health risks were reported to be greater nearer the airport. These two positions can be reconciled by considering randomness of flight paths. With path variations most limited near the airports, more flyover exposures would be expected. Randomness or additional variations in flight paths would have been introduced as the planes were further removed from the airport. Those further out would have experience fewer aircraft fly over events. It is also reasonable to believe that with time, additional sound exposures to those within the infrasound exposure flight band will result in additional cardiovascular health events.

The observation of a dose-exposure relationship raises questions about the true health impact of highly repetitive flight paths such as those dictated by implementation of NextGen navigation. The change to NextGen navigation could be beneficial for many provided they would have previously experienced a “greater than” dose response as their exposures would drop. If their exposures were less than threshold, then no health benefit would be realized and those more heavily impacted by NextGen navigation would have experienced unnecessary additional exposures.

NextGen flight paths are designed using the FAA DNL 65 sound boundaries. The boundaries exist in close proximity to the airports. Therefore flight paths can be legally set within existing guidelines directly over high concentrations of people. It is likely that the highly repetitive NextGen could in effect result in a similarly high cardiovascular risk for all those living within the five by one-and-one half-mile flight path band to those living at the edge of the runway. High concentrations of people would amplify the number of impacts. By including the impact from the partial exposures into a cumulative dose, the cardiovascular risk zone could be extended to significantly more people.

Setting general public policy for flight paths or variations in flight paths based upon a maximum allowable dose exposure from over flights would in effect manage the potential health impacts of precise NextGen navigation in that as each over flight would be considered as a unique exposure and the use of such a policy would self-limit the public impact. The likely air traffic controller response to the health-based criteria would be to stagger the centerline of flight paths to avoid exceeding the dose acceptance criteria. It is reasonable to believe that this could be implemented while still obtaining the safety and fuel reduction benefits of NextGen navigation.

The FAA is considering making changes to its DNL average sound-based noise criteria. The dBA sound weighting system does not include infrasound as an input and it should. The use of the current dBA/DNL criteria should be abandoned in favor of an exposure-dose based system. The United States has a strong global health and environmental leadership role. Converting the existing FAA environmental sound criteria to a health-based criterion would be expected to result in other countries and regulators considering a similar action.

Open Air Attenuation

A primary point of interest in these experiments, relative to the FAA sound criteria being used, is the height of the aircraft to the ground with higher aircraft elevation experiments expected to have more noise attenuation than lower elevation aircraft strictly due to greater exposure to the air. The lowest frequency sounds being generated at the aircraft are expected to remain in the open air over a wider range of elevations. In that sound measurements were taken at the same time both inside and outside of the box, a direct and concurrent comparison of the inside/outside sound conditions could be observed.

For example, in the case of the 10-miles from airport location, the attenuation of sound exposed only to open air occurred at approximately 750 Hz (Figure 22). The red or upper line is sound arriving at and being measured outside of the mock-up. The blue data in the figure is the sound remaining after it has passed through the mock-up structure. The frequency where the two data sets converge on the graph illustrates where open air attenuation occurred. Taken together, the image shows a frequency of attenuation convergence of 750 Hz. An arrow is included in this figure to illustrate the attenuation convergence.

Figure 16. Open-air attenuation frequency for sound energy. Each graph continues the frequency of the previous. The smallest amplitude pressure on each y-axis from the previous frequency was used to set the starting point frequency for the next figure. This was done to magnify the data for improved inspection.

The amount of open-air sound attenuation is the same for all of the generated sound prior to arriving at the mock-up. The long wave length and lower frequency sound passes directly into the inside of the mock-up structure with minimal or no losses while the shorter and higher frequency sound is attenuated through contact with the elements of the structure. This convergence frequency has a directly relationship with the vibration amplitudes and frequencies of occurrence that are available to cause the induced vibrations. This is also the total sum of the sound available for measurement by the sound meter (dB A-weighted instrument) for all of the flights from each of the six positions used to collect sound measurements. The heights of the planes above the ground were averaged in terms of the attenuation convergence (Figure 23). Convergence graphs illustrating sound attenuation affects for each of the six monitored locations are included in the Appendix.

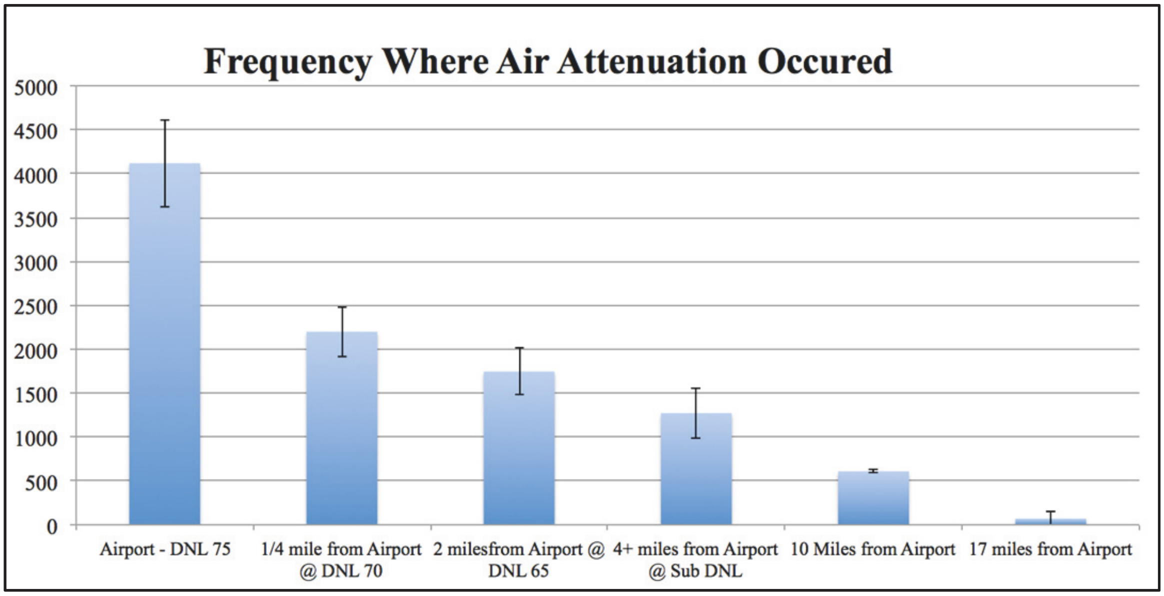

Figure 173. Sound attenuation convergence frequencies aircraft.

Care was taken to ensure contact isolation of the ballistic gel from the mock-up structure to avoid a path for the direct transference of the sound energy from the solid material elements of the mock-up. This was done to ensure that the source of the portion of the sound that successfully passed through the structure and into the void of the mock-up and then made direct contact with the ballistic gel arrived only from open air and was then the only source of energy available to cause vibrations in the gel.

The internal vibrations recorded at the ballistic gel and their frequencies are of primary interest as this represents direct energy transfer from the aircraft generated noise to inhabitants within a dwelling and then into the simulated human tissue. Low frequency vibrations were measured in the ballistic gel for each of the 1.2s segments (30-50 recorded) for all of the flight experiments (Figure 24).

It is important to note that the vibrations measured at the low frequencies of less than 30 Hz are highly similar at both the lid on the outside of the mock-up structure and the ballistic gel material inside. This similarity confirms the assumption that the sound data obtained below 20 Hz was usable data in spite of the microphone calibration range that these instruments were tested to.

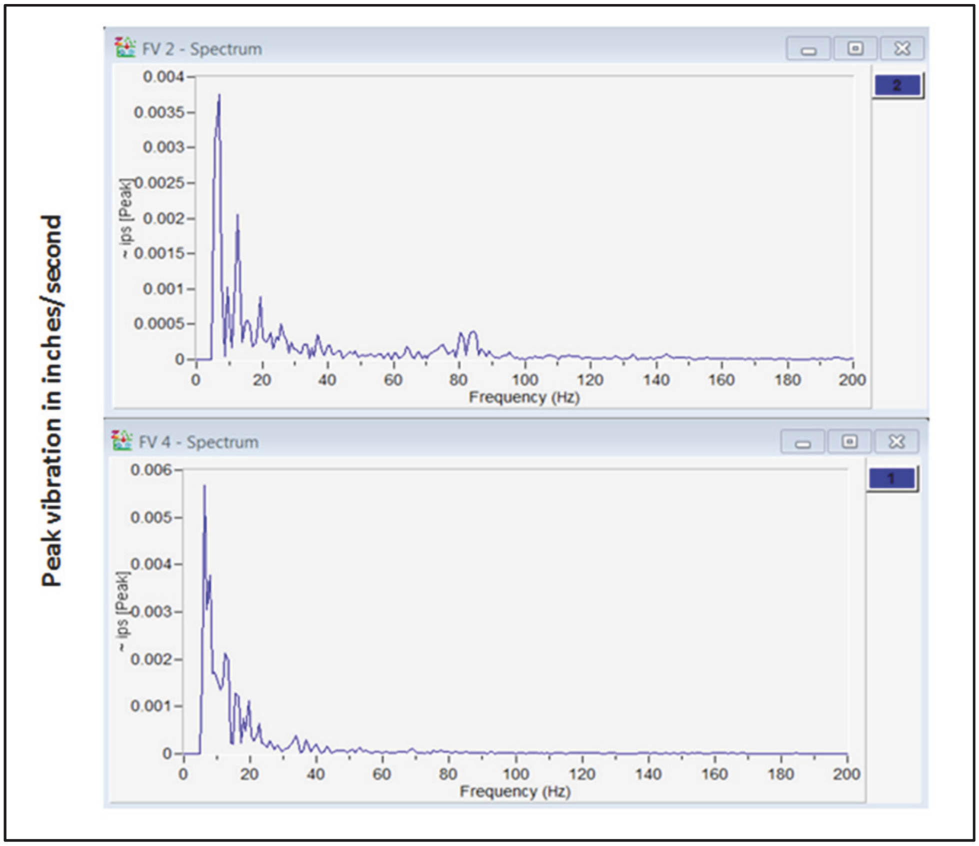

Figure 24. Vibration energy spectrum outside the mock-up (top) and remaining or attenuated vibration spectrum in the ballistic gel (bottom)

FAA DNL 65 Annoyance Criteria

It was surprising to learn that most of the air aircraft noise is fully attenuated through interaction with air by the time it has reached the ground. This means that much of the aircraft sound that is initially generated, even standing at the edge of the runway, is gone before it can be included in the regulatory DNL sound average criteria. Furthermore, virtually all of the sound greater than 50 Hz that did arrive at the ground was then attenuated or removed when it passed through the mockup test structure (Figures 21, 22).

The irony of these observations is that the remaining sound energy that is then remaining to be reported as public annoyance is significantly reduced by the dBA sound weighting system. This is done through dBA weighting calculation as these sounds are largely outside the defined sound frequency range of the sound that most people hear. This finding is evident through an overlay of the dBA sound weighting scale and the effects of attenuation (Figure 25). The A-weighted sound has an exaggerated scale at the low frequency end to better illustrate the attenuation effects and also to show where sound is de-emphasized through the use of this weighting system. The figure includes the A-weighted sound curve plotted against the range of sound frequency.

The size of the subtraction in gross dB of low frequency sounds used to reduce the sound contribution increase with lower frequencies. For example, at the mock-up attenuation red boundary line, a 30-decibel subtraction of that portion of the overall sound occurs. The attenuation frequency that result from the sound passing through the air as shown on Figure 22 and the similar Appendix figures have been transferred to this figure. As a side note, the A-weighting curve is greater than the "green baseline" for a portion of its curve and actually adds reported sound to the prime 1000-6000 Hz range that corresponds to the sound range that people are most able to hear.

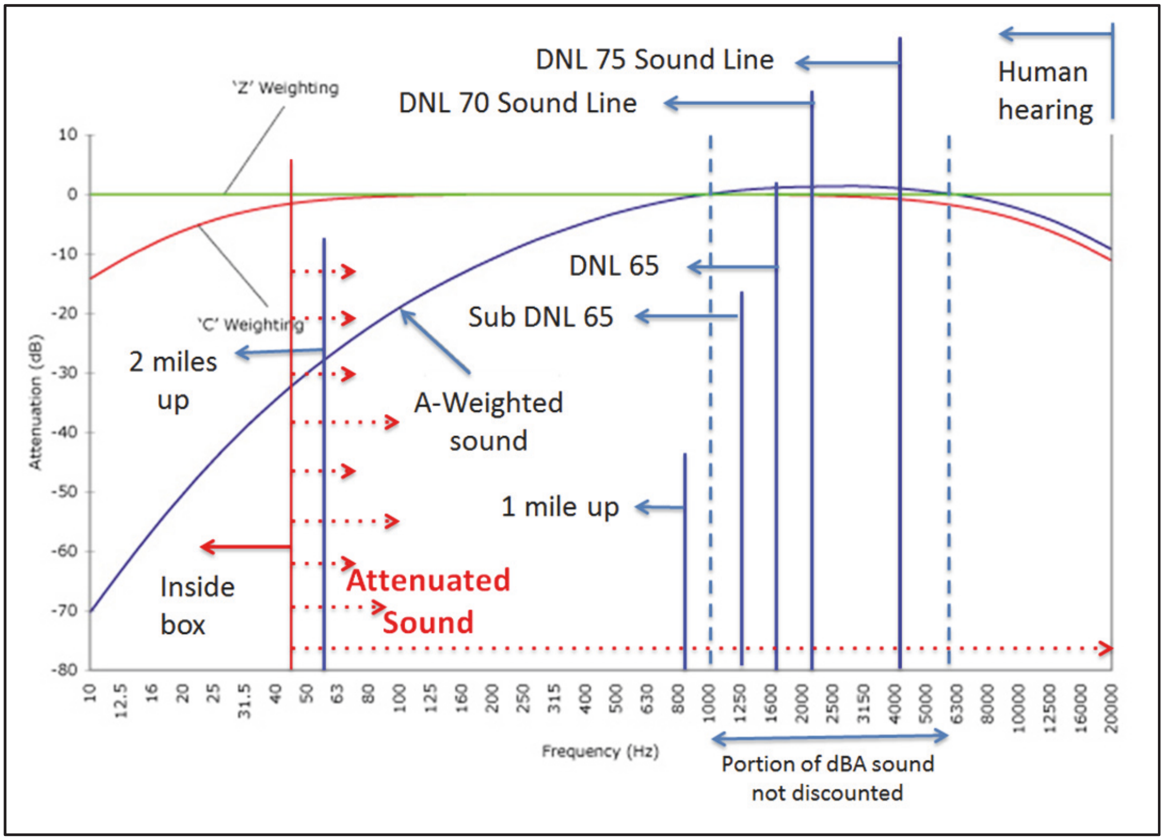

Figure 25. Elevation based noise attenuation through interaction with the air. Image includes data from table 2 and the underlying graph from Cirrus Research plc (Tingay, 2011).

The FAA DNL 65 sound criteria has its roots in social studies that were associated with negative public response from loud construction site noises and the annoyance levels that the sound caused. Humans can hear sound from 20-20, 000 Hz with most people limited to a range of 50-12,000 Hz. The FAA criterion utilizes A-weighted dB (dBA) sound measurements. The A-weighing (dBA) of sound manipulates the overall sound that is present to only that portion of the sound that is most readily heard. This manipulation is evident in Figure 25. The illustration of sound using the A-weighting criteria is not intuitive. Disregarding a significant portion of sound (infrasound) and then reporting only a minor portion of the sound that remains it is not intuitive. This criterion and its de-emphasizing of a significant portion of the sound pressure that could be measured indicates a poor initial design for the original research.

The sound was investigated further from an alternate perspective. The highest overall energy measured using the A-weighted sound meter was at the monitoring position nearest the end of the runway. As this location had the highest dBA sound measurements, its data is a worst case to the regulatory criteria being used. A graph of the 80.2-dBA-flight sound measurement was developed using the open-air microphone sound recorded. Maximum local sound pressure peaks spaced from 5 through about 4000 Hz were plotted using a curve fit to obtain an overall sound profile. The intent was to see how the entire spectra of aircraft sound compared when based only upon the amplitude of the sound being generated. The resulting graph includes both the audible and inaudible portions of the overall sound (Figure 26).

Dashed line markers were placed onto this figure to illustrate the portion of the overall sound profile that is primarily used within the FAA DNL 65 criteria and in similar locations to Figure 25. By inspection of this figure, it is difficult to discern the sound defined as audible sound (< 1000 Hz) due to the significant amplitude difference between low frequency (> 200 Hz) and other sound being produced. To overcome this limitation, the sound signature was magnified and is included at the bottom part of the figure. A red line was added to mark the boundary between the portion of sound that attenuates as it passes into the mock-up structure and open-air sound. The sound pressure or energy to the left of the red line is a reasonable representation of the actual sound energy that would be experienced by someone inside a typical wood framed dwelling or similar structure.

Visual inspection of the distribution of the sound energy in Figure 26 clearly shows a heavy skew of the sound profile towards low frequency and infrasound. It turns out that the A-weighted portion of the overall aircraft sound profile is a very minor component of the sound that is being experienced. When the effects of attenuation from passing through a structure are also overlaid on the graph, the audible sound relative to the remaining low frequency and infrasound is further minimized. It's unfortunate that the DNL sound criterion utilizes A-weighted sound as this tool severely under reports the sound exposure resulting from aircraft over flights. This presentation of the sound data raises a salient question; what sound remains from the aircraft to cause the public annoyance and to generate public complaints that are being made?

The DNL sound criterion has been shown to have a poor correlation between the expected public annoyance levels for sound levels from 57 to 67 dB (Fidell, 2003). Complaints of noise from aircraft that were mapped at Hansom field appeared to line up principally with the flight paths to including locations where turns were made (Figure 3). As illustrated in figure 26, the sound being measured as and reported may in fact not be the sound that is the source of the complaints that are being made as little of dBA measured sound is still left.

An alternate theory for public sound annoyance from aircraft can be offered. The poor correlation of annoyance to aircraft sound may in fact have its roots in the decision to not include infrasound within the sound measurement. It can be suggested that the presence of infrasound is a likely potential source of public annoyance and that it has better alignment to the annoyance criteria than DNL reported sound.

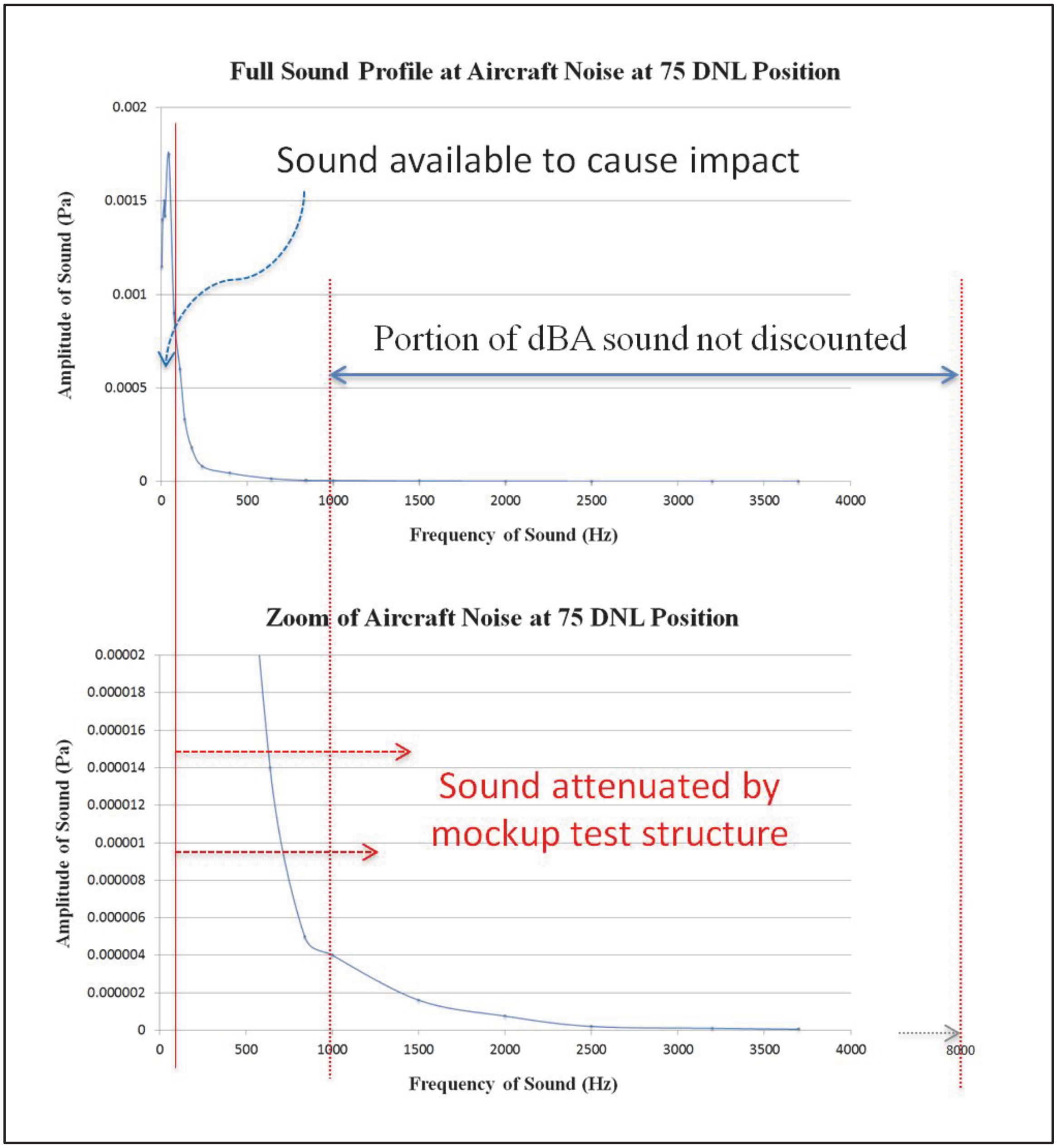

Figure 26. Full spectrum true sound measurement with attenuation.

ISO standard 2631 identifies human tissue as susceptible to resonance at frequencies less than 100 Hz (Havas; Colling, 2011). Different portions of the human body will be susceptible to resonance from different frequencies. Resonance is a function of mass and stiffness and when it occurs, significant amplification of the harmful effects of the vibration will take place. The unique structural differences of people can be expected to cause different susceptibilities of sound resonance to individuals receiving the same exposure. Resonance would introduce variance in the degree of expected public response for some and would explain why some experience a greater impact from aircraft sound than others.

Inspection of Figure 25 indicates that the sound that is measured at 40 Hz is reduced through the dBA weighting system by 30 dB and that at 20 Hz, the sound is reduced by about 60 dB. Recall that a 30 dB reduction reduces the sound intensity being measured by 800%. While this excluded sound energy is being significantly under reported, the vibration measurements from the ballistic gel show that the effects of the sound are clearly causing a human impact. The 12 Hz infrasound frequency is an interesting example of this impact. This frequency was identified to cause feeling of illness (Persinger, 2014). The negative feelings caused by this exposure increase with increasing sound amplitude.

Overall aircraft vibration measurements of less than 40 Hz were captured over a broad area with highly similar intensities of energy from the airport to a location about five miles away. Frequencies of about 12 Hz were very commonly measured during over flights (Table 3). People within the five-mile area are being exposed with similar doses of this energy over the full flight path. Fidell illustrated with Figure 2 that public annoyance correlates poorly to aircraft sound exposures. That figure suggests an almost random relationship although it had a similar data average. The 12 Hz infrasound exposure frequency would cause a similar intensity exposure across the 57-67 DNL range and is a possible explanation for the consistent 25% average annoyance reported. It may be suggested that the 12 Hz frequency infrasound exposure is a cause of the higher than expected incidences of public annoyance than would be suggested by the DNL sound criteria. Inclusion of infrasound into the determination of public annoyance would bring closer alignment to aircraft noise using only the annoyance concept. Its inclusion; however, would require the abandonment of the A-weighted dB sound measure.

Conclusions

Experimental data of aircraft noise from six locations chosen at increasing distances from the airport demonstrated the broad presence of low frequency and infrasound. The overall energy produced from this sound had a highly similar intensity over a band extending +/- three quarters of a mile from the plane centerline up to an elevation of about 4000 feet. This sound contained sufficient energy to pass through the walls of an insulated mock-up test structure and cause vibrations in a gelatin material used to mimic human tissue. These vibrations correspond to natural human frequencies at a cellular level and can lead to cellular and as consequence, tissue damage. Degraded cardiovascular health was identified as a primary risk from the infrasound exposure.

The existing FAA sound criterion does not include low frequency and infrasound, as these frequencies are not readily heard. This omission is significant, as a dangerous public health issue is not being taken into account when flight paths are planned and as a result, it is likely that a significant public and individual burden is occurring. The FAA is reviewing its aircraft sound criterion. The findings of this study strongly suggest that the existing DNL 65 sound criteria should be abandoned in favor of a health based criteria that tabulates the number of aircraft sound exposures using a dose threshold relationship.

Research Limitations

Strucutres made with dense or thick materials may attenuate a greater percentage of infrasound. The level of infrasound attenuation would depend upon the thickness, location and density of these materials. Examples of dense materials would be cement or brick walls and cement or clay tile roofs. My work did not account for these structural differences and is not considering the cost or value that would result from modifications to existing strucures with dense materials.

Windows are a significant and common architectural element. The mock-up included a small double pane window on one of its sides. While structures may have high density construction elements that would attenuate some or all of the infrasound, they would still have windows. The contribution of windows in allowing infrasound to pass relative to other common construction materials is unknown.

The mock-up struture used to support data gathering for my thesis was intended to demonstrate how low frequency and infrasound are attenuated by travel through a structure made with with common wood framed construction elements. The construction material tested did not attenuate infrasound. As structral elements of existing housing are difficult to modify, little initial benefit would be expected by the implementaion of a health based criteria for those closest to the airport as the flight paths can not be varied.

The speed of the aircraft and its rate of ascention or descention may effect the level of sound energy being produced. The elevations, plane types and aircraft speeds listed within this document were extracted from a software product made available to the public by the Sky Harbor Airport which is located in the Phoenix Metro area. This product had a designed 10-minute delay for flights being reported by the web link with safety consideration given as the reason for the delay. Flights were at times very frequent with only about one minute or so between flights. The 10 minute delay and frequency of flights introduced the possibility of incorrectly associating a flight's measurements to the time listed by the software. A second individual participated in the data gathering and took careful notes to reduce the risk of mis-associating the data.

The flight specific data associated with each flight could not be independently verfied. It is possible that some variations in the speed or elavation that were reported could also have been introduced by the manner in which the software tool operated. To reduce this uncertainty, the data from each primary location was averaged. This included considerations of aircraft type. Table 3 contains the aircraft model information. The aircraft types were grouped and then their data was averaged. Appreciable differences in the data were not observed so this information was not included in the body of the document.

Most of the data was obtained during the first five miles of aircraft ascent following take off. The planes appeared to follow a moderate but similar speed and lift angle. Their speed was relatively slow to other aircraft speeds observed and both the speed at lift off and lift angle could be expected to vary from the set of aircraft monitored.

Different aircraft speed and lift angle may result in different overall vibration levels and exposure from the over flight event.

Additional test locations to access the shape and rate of rate of change of the infrasound energy drop-off from the maximum band were not monitored as part of this thesis. This decision was two-fold. First, the finding of a clear energy drop off was a surprise observation and its inclusion in the overall design of the experiements was not considered within the original project scope. A second point relates to environmental conditions of temperature and humity within the air. It expected that each of these environmental factors will influence the intensity or amplitude of the infrasound energy and the measurements that would be recorded. These influences could in turn alter the size of the maximum exposure band being reported (e.g., the 5 x 1.5 mile band dicussed within this document). It recommend that these factors along with speed and lift variations should be explored to determine if the differences are large enough that different exposure bands would need to be designated for different conditions, or if a single “average” band could be used to represent all of the exposures.

The sound intensity varied from the approach of the plane to its over flight and then as it departed. The entirety of the overflight should be equated into a single exposure and dose event. The complexities of determining an average overall dose from an overflight to include the humity and temperature effects were outside the scope of this project. Demonstrating an infrasound energy dropoff occurred outside of a maximum 5 x 1.5 mile window was believed to be sufficient to provide an indication of the overall impact zone magnitude, and conceptually, that aircraft noise could be managed with a dose-result policy driven model.

Appendix

Supplemental Figures of Attenuation and Common Data Plots

Supplemental figures are included for each of the six monitored locations, for a total of 12 supplemental figures. The figures include a typical segment from a single flight for the 75, 70, 65, sub 65 DNL locations and the 10-mile and 17-mile locations. The figures descend from closest to furthest locations from the airport. Accelerometers were used to collect vibration data and microphones were used to collect sound. These probes were positioned as sets outside of and inside the mock-up structure. Each four-plot data display is followed by a typical figure showing an attenuation convergence frequency for that location. Outside sound measurements are plotted in blue and inside are shown as red. Some convergence figures display multiple frequency ranges that are rescaled to clearly illustrate the data and their convergence and differences.

Figures with four plots display two types of frequency spectrum. The top two are sound measurements. Sound is a pressure pulse and the y-axis is the amplitude (or intensity) of the sound. The x-axis is the frequency where the sound occurs. A larger frequency denotes a higher pitch sound. The bottom two plots are vibration measurements. The y-axis captures the velocity (or speed) of the vibration in units of inches per second. The x-axis for the bottom two plots is the frequency of the vibration. A higher frequency denotes a faster cycle (back and forth) vibration. The left two plots were collected on the outside of the mockup structure while the two on the right were collected inside.

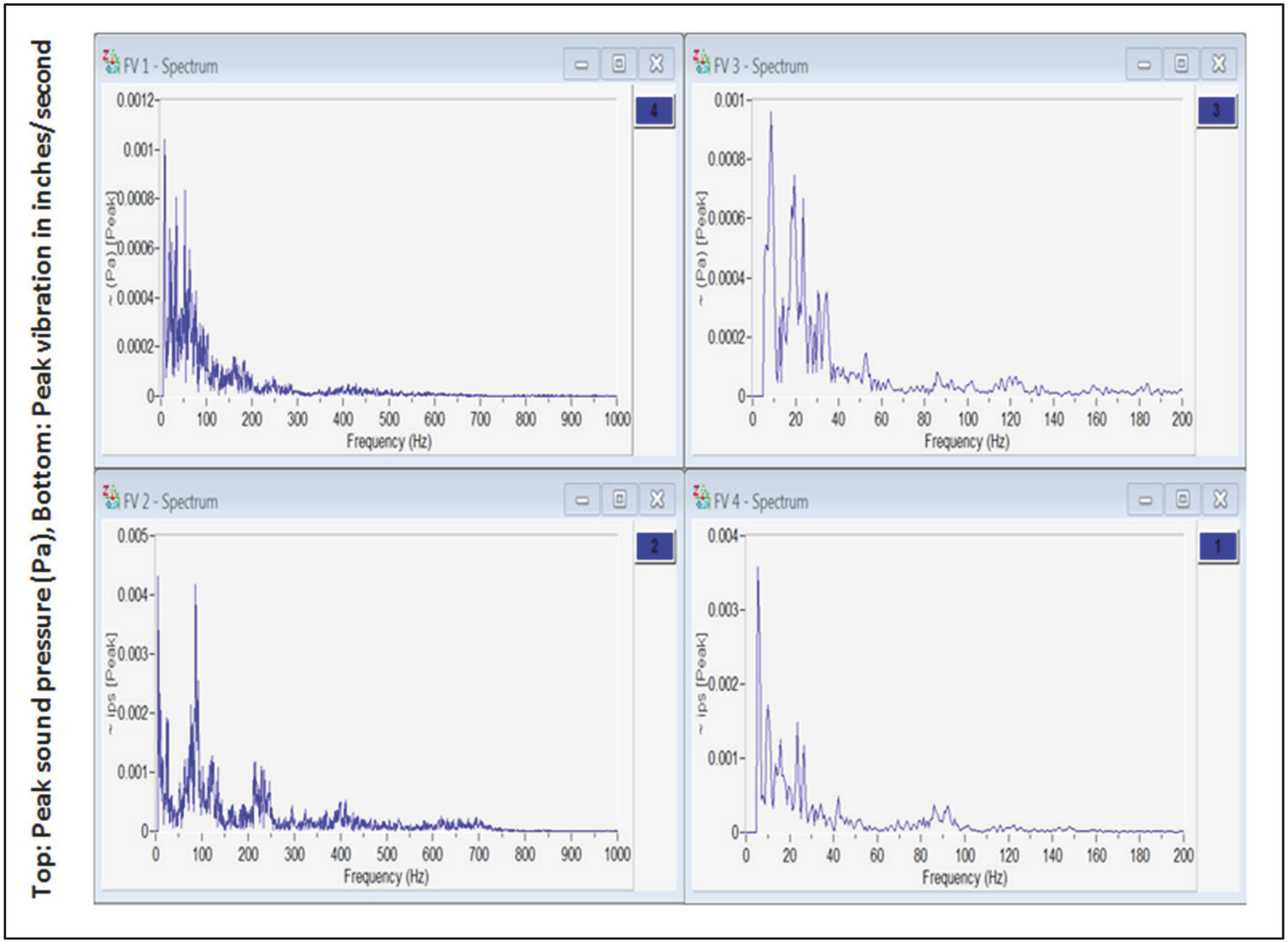

Figure 27. Typical data from DNL 75 location. Top two are sound measurements. The bottom two measurements are vibration. The left two were taken outside of the mock-up structure with the two on the right measured from inside.

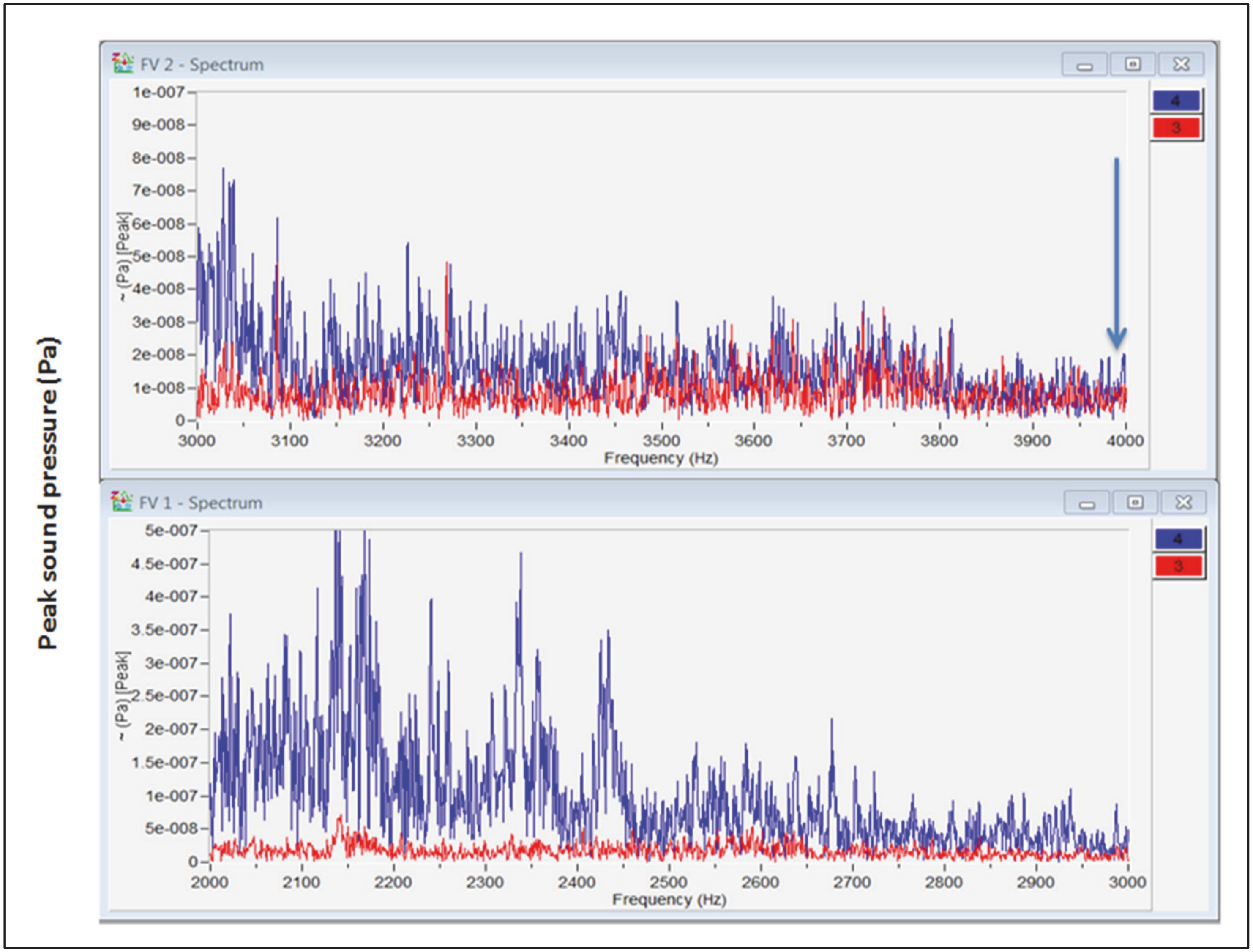

Figure 28. DNL 75 attenuation convergence of 4000 Hz. Each figure continues the frequency of the previous. The smallest amplitude pressure on each y-axis from the previous frequency was used as a starting point frequency for the next figure to magnify the data for improved inspection.

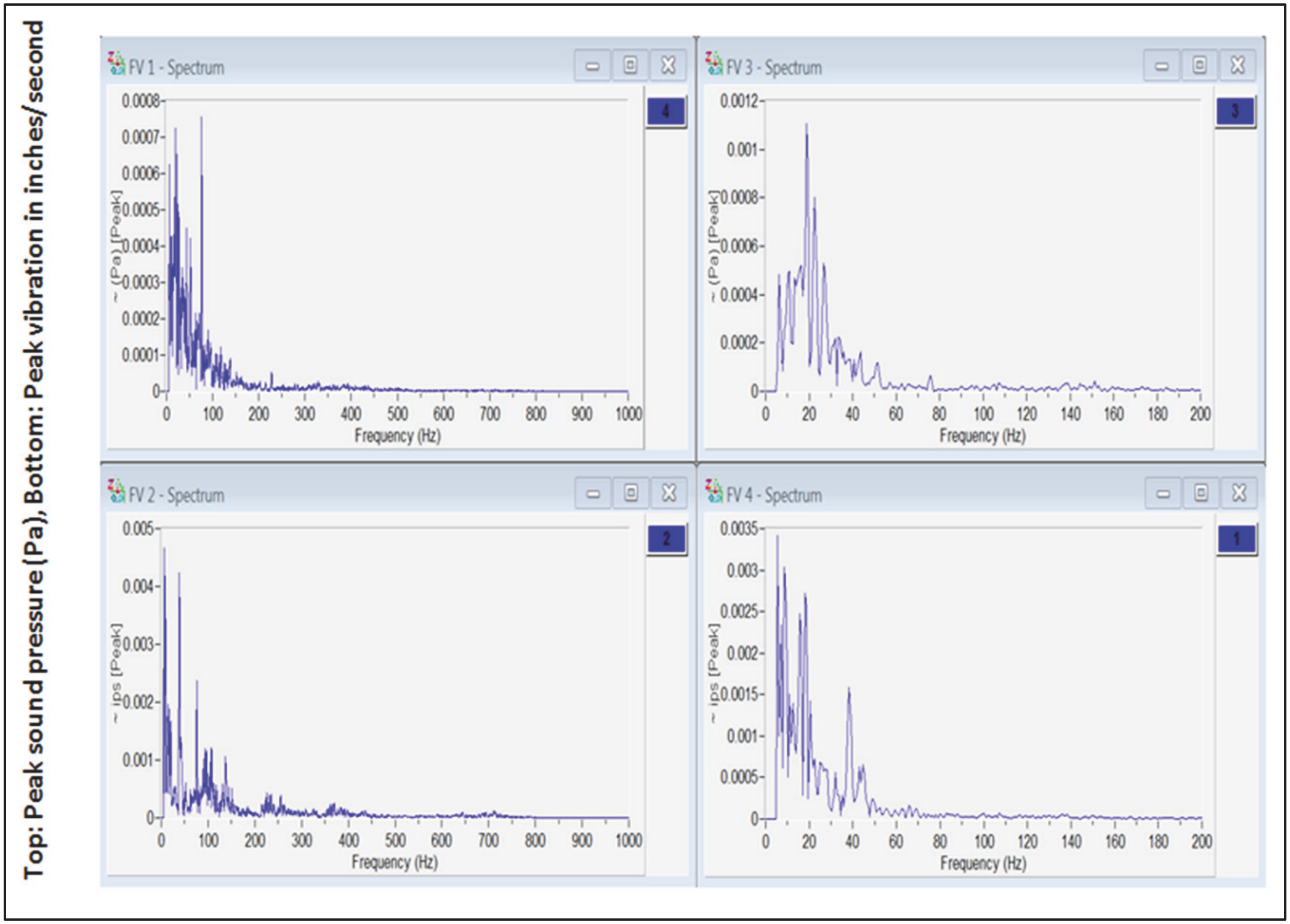

Figure 29. Typical data from DNL 70 location. Top two are sound measurements. The bottom two measurements are vibration. The left two were taken outside of the mock-up structure with the two on the right measured inside.

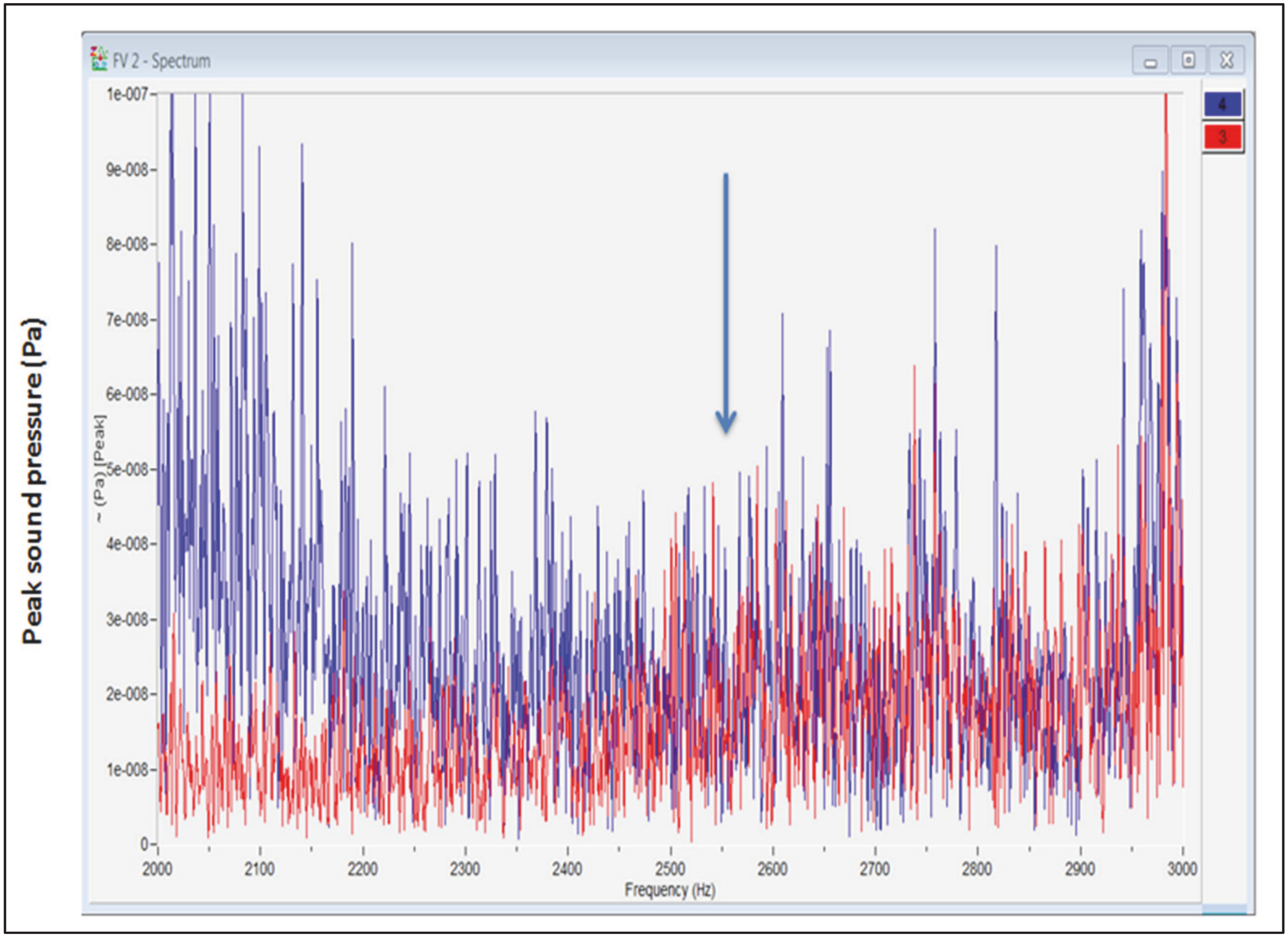

Figure 30. DNL 70 attenuation convergence of 2500 Hz.

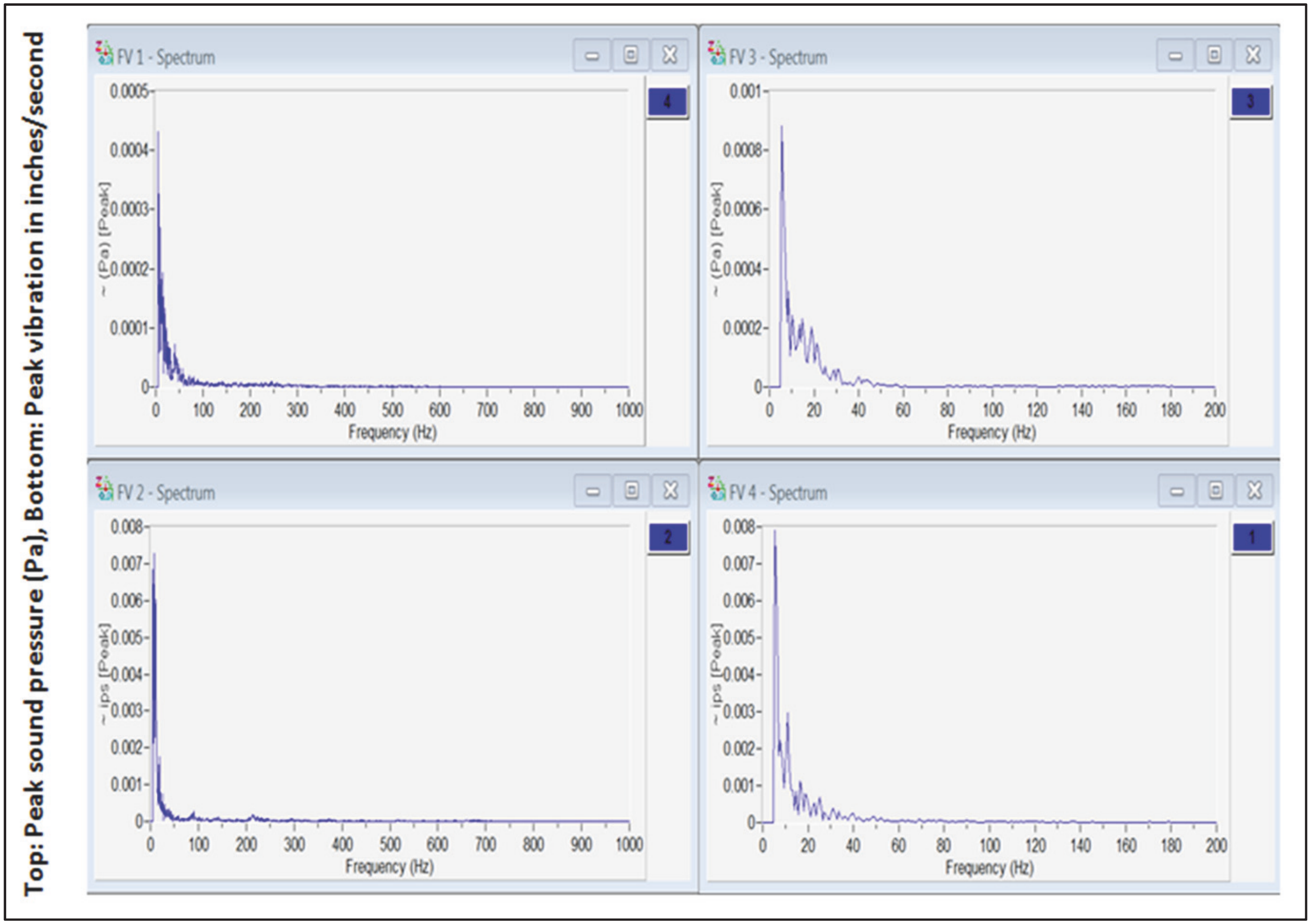

Figure 31. Typical data from DNL 65 location. Top two are sound measurements. The bottom two measurements are vibration. The left two were taken outside of the mock-up structure with the two on the right measured from inside.

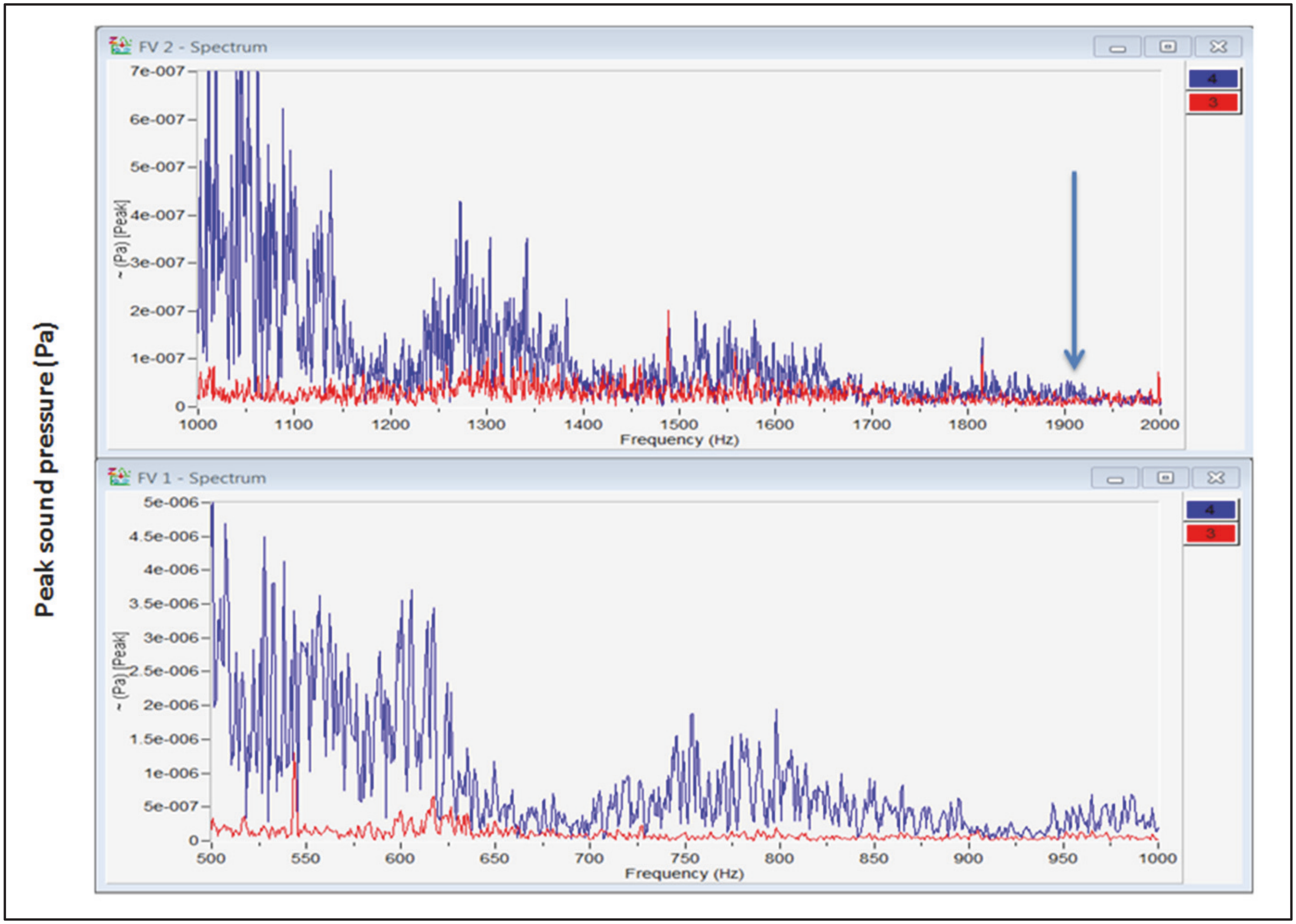

Figure 32. DNL 65 attenuation convergence at 1950 Hz. Each figure continues the frequency of the previous. The smallest amplitude pressure on each y-axis from the previous frequency was used as a starting point frequency for the next figure to magnify the data for improved inspection.

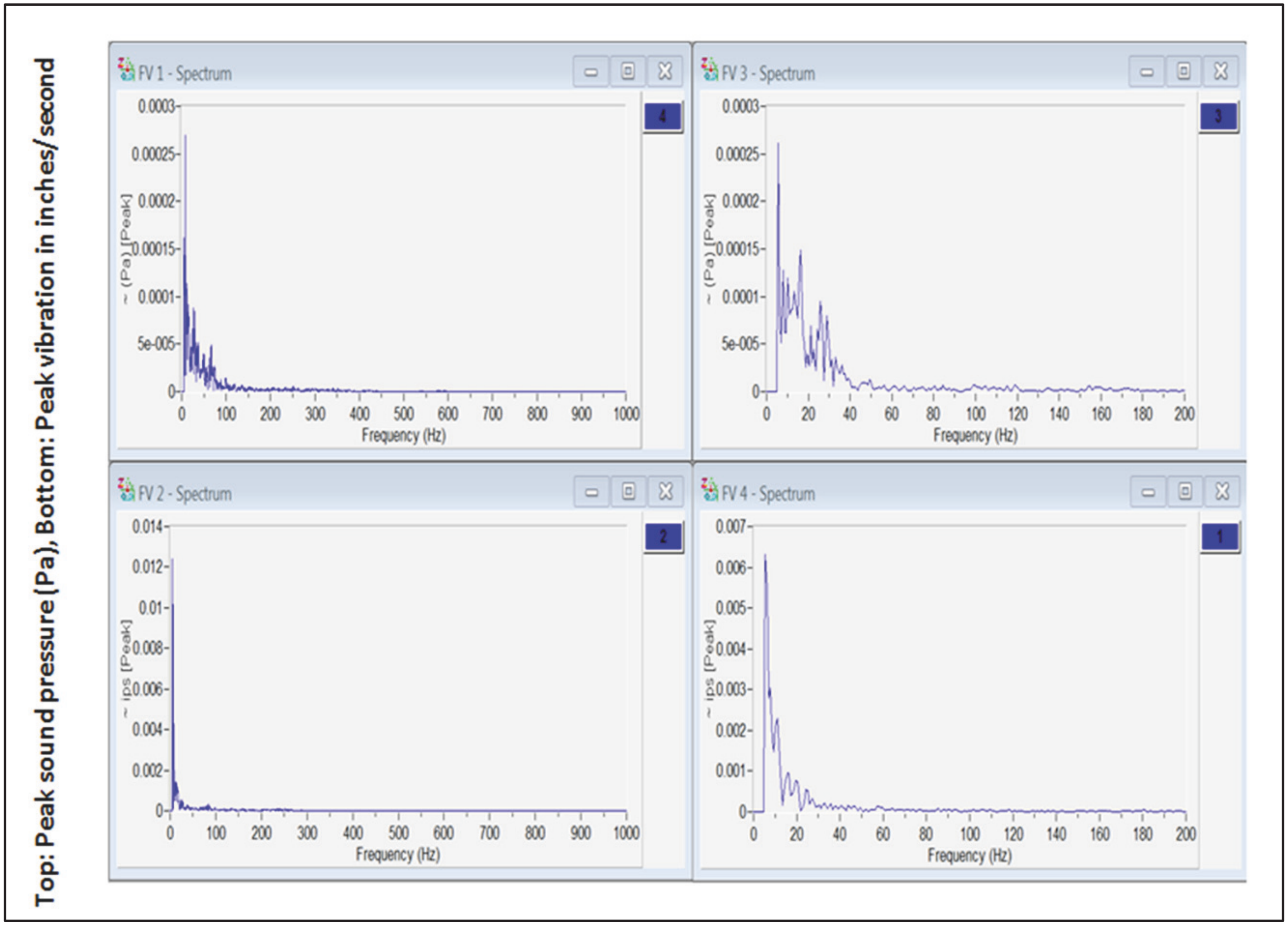

Figure 33. Typical data from sub 65 DNL location. Top two are sound measurements. The bottom two measurements are vibration. The left two were taken outside of the mock-up structure with the two on the right measured from inside.

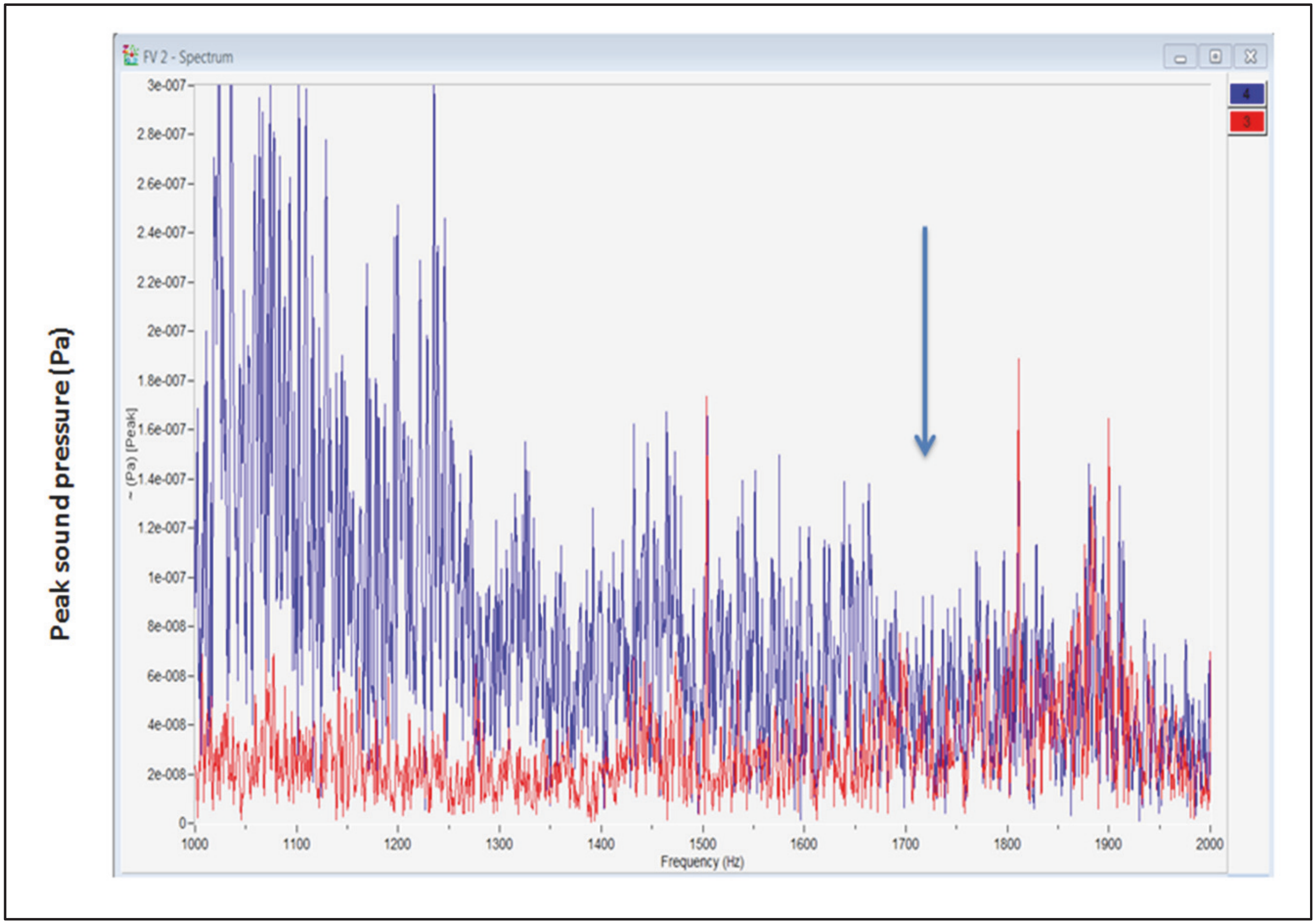

Figure 34. Sub 65 DNL attenuation convergence of 1750 Hz.

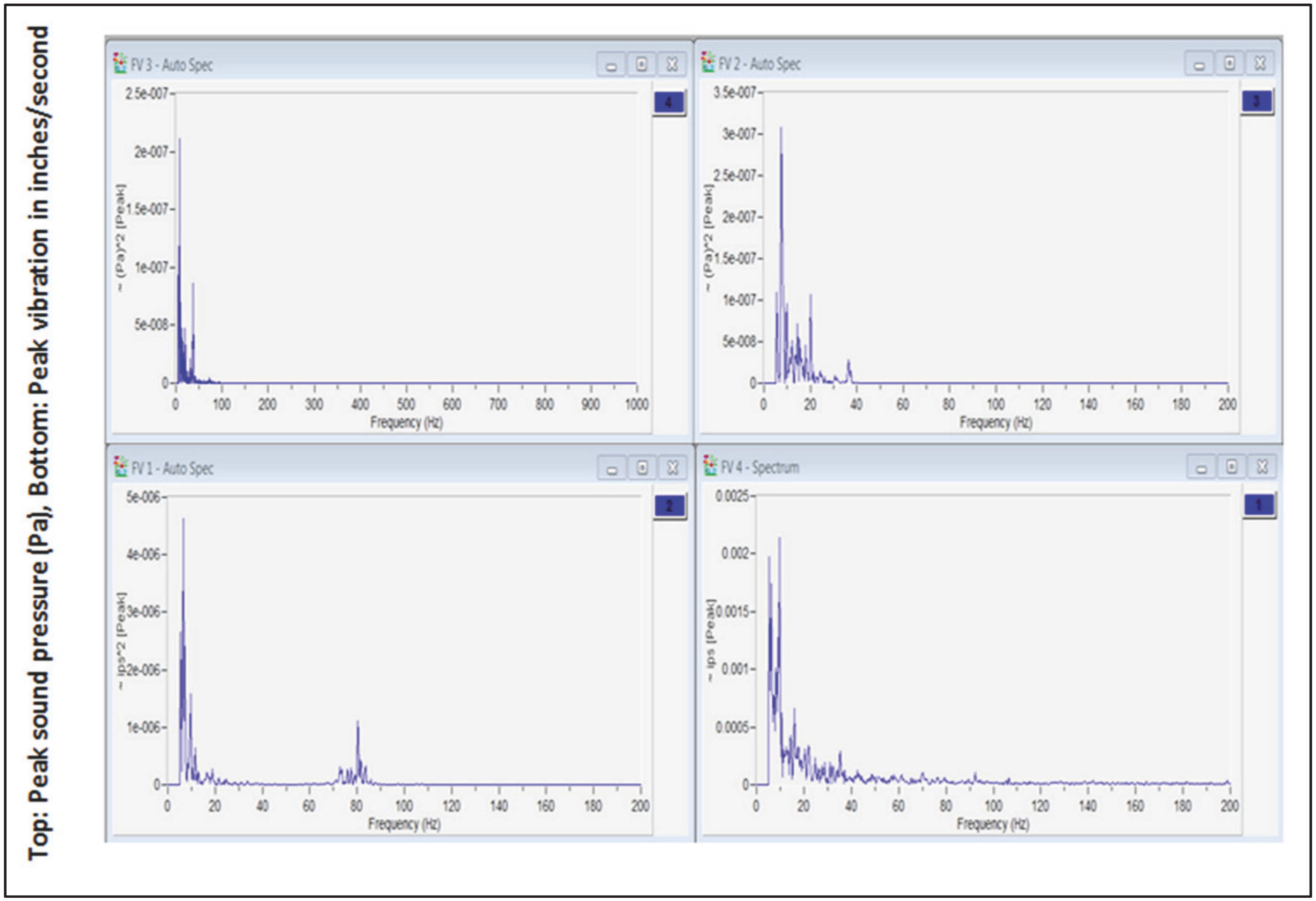

Figure 35. Typical data from 10-mile location. Top two are sound measurements. The bottom two measurements are vibration. The left two were taken outside of the mock-up structure with the two on the right measured inside.

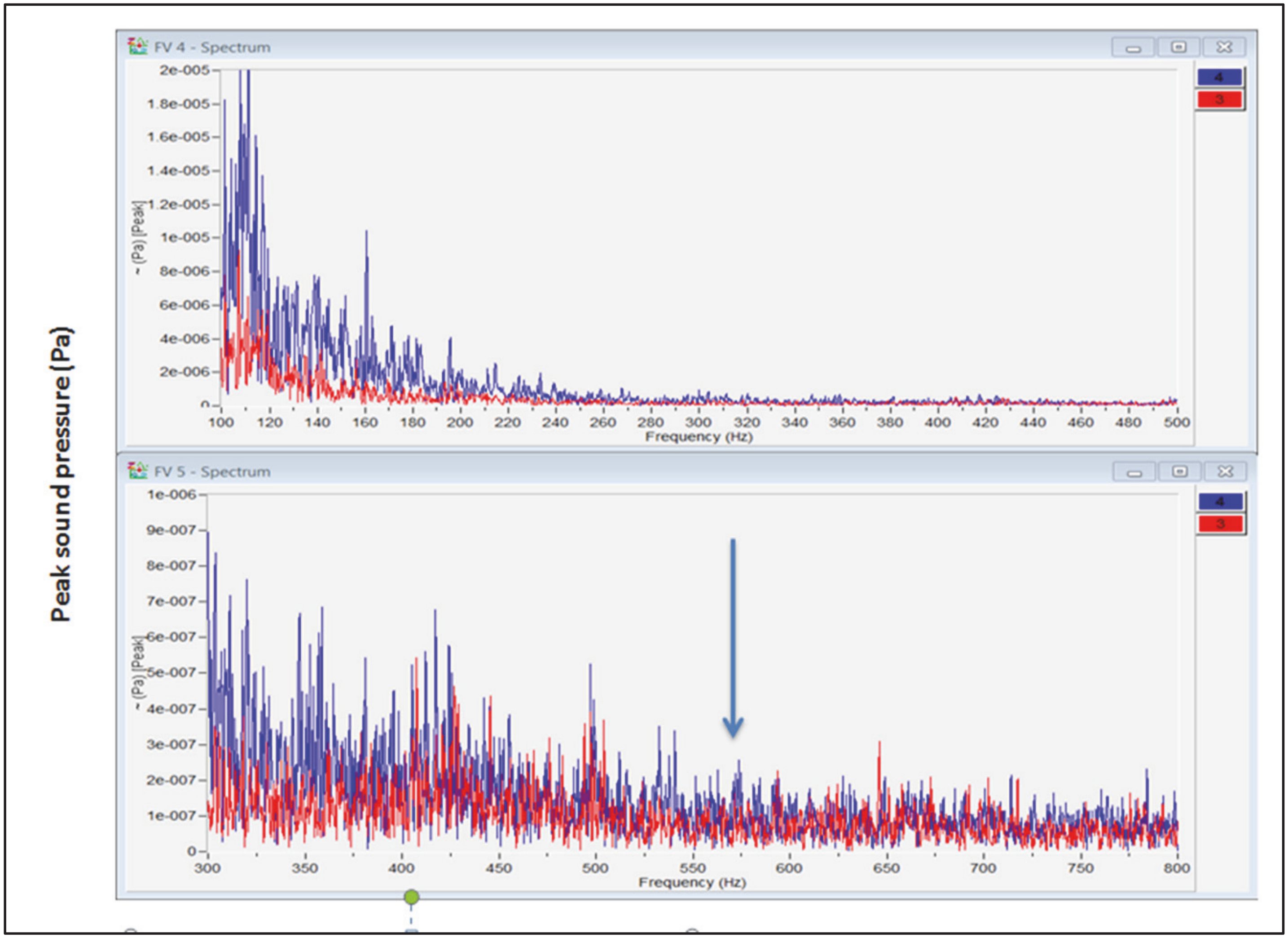

Figure 36. 10-mile attenuation convergence of 575 Hz. Each figure continues the frequency of the previous. The smallest amplitude pressure on each y-axis from the previous frequency was used as a starting point frequency for the next figure to magnify the data for improved inspection.

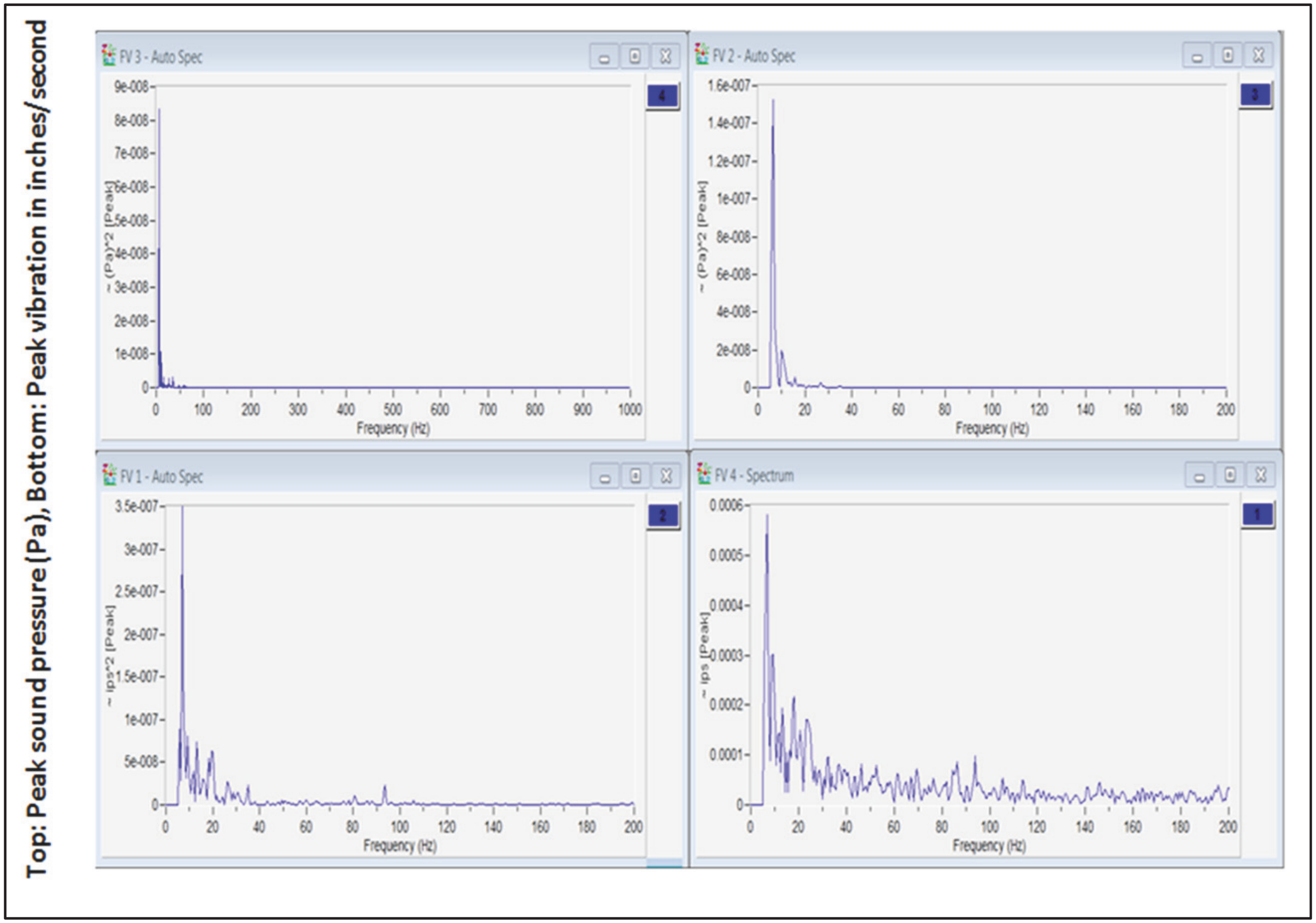

Figure 37. Typical data from 17-mile location. Top two are sound measurements. The bottom two measurements are vibration. The left two were taken outside of the mock-up structure with the two on the right measured from inside.

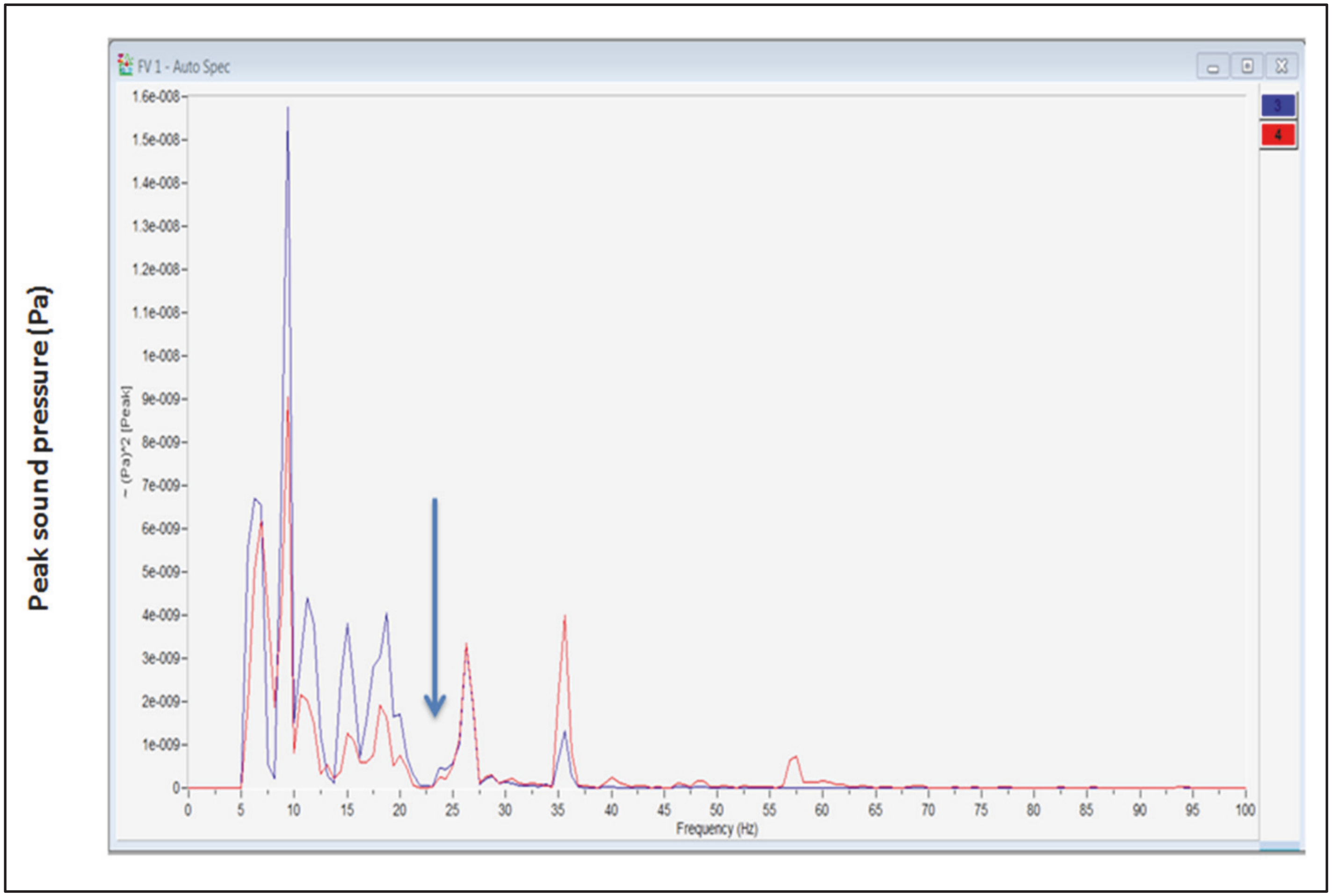

Figure 38. 17-mile attenuation convergence of 25 Hz.

References

Airport Noise Law, Statutes and Regulations (n.d.). FICON 1992. Retrieved 11/29/2015 from http://airportnoiselaw.org/65dnl.html

Alves-Pereira, M., & Castelo Branco, N. A. A. (2007). Vibroacoustic disease: Biological effects of infrasound and low-frequency noise explained by mechanotransduction cellular signaling. *Progress in Biophysics and Molecular Biology, 93*(1), 256-279. doi:10.1016/j.pbiomolbio.2006.07.011

Aviation Impact Reform, The case for FAA Reform. Retrieved 10/11/2015 from http://aireform.com/analysis-flight-tracks-showing-noise-impacts-in-the-phoenix-area/

Bajdek, C. (n.d.). Noise 101: Introduction to Acoustics and Aircraft Noise Terminology. Airport Noise Mitigation Symposium. Retrieved Nov 14, 2015 from http://www.noise-mitigation-symposium.com/Presentations/Background%20Noise_Bajdek.ppt

Basner, M., & Samel, A. (2005). Effects of nocturnal aircraft noise on sleep structure. *Beeinträchtigungen Der Schlafstruktur Durch Nächtlichen Fluglärm., 9*(2), 84-95.

Branco, C. (1999). The clinical stages of Vibroacoustic disease. Retrieved from https://www.ncbi.nlm.gov/pubmed/10189154

Chouard, C.-H. (2006). Le retentissement du fonctionnement des eoliennes sur la sante de l'homme [Repercussions of wind turbine operations on human health]. *Panorama du medecin*. Retrieved from http://ventdubocage.net/documentsoriginaux/sante/eoliennes.pdf

Correia, A., Peters, J., Levi, J., Melly, S. Dominici, F. (2013). Residential exposure to aircraft noise and hospital admissions for cardiovascular diseases: multi-airport retrospective study. *The BMJ* 2013 page 347. Retrieved from http://www.bmj.com/content/347/bmj.f5561. *BMJ* 2013;347:f5561

Danielsson, A., & Landström, U. (1985). Blood pressure changes in man during infrasonic exposure. an experimental study. *Acta Medica Scandinavica, 217*(5), 531-535. doi:10.1111/j.0954-6820.1985.tb03258.x

Dominici F, Peng RD, Bell ML, et al. (2006). Fine Particulate Air Pollution and Hospital Admission for Cardiovascular and Respiratory Diseases. *JAMA.* 2006;295(10):1127-1134. doi:10.1001/jama.295.10.1127.

EPA, Indoor Air Quality. (2017). EPA's Report on the Environment (ROE). Retrieved 2/17/2018 from web https://cfpub.epa.gov/roe/chapter/air/indoorair.cfm

EPA, Water: Nonpoint Source Success Stories. (n.d.). Retrieved 11/27/2015 from web https://www.epa.gov/polywaste/nps/success319/ca_chorro.cfm

ESA. Appendix D, Aviation Noise Fundamentals. Retrieved 11/11/2015 from http://www.miamairport.com/library/Appendix_D_Noise.pdf

Evrard, A., Bouaoun, L., Champelovier, P., Lambert, J., & Laumon, B. (2015). Does exposure to aircraft noise increase the mortality from cardiovascular disease in the population living in the vicinity of airports. results of an ecological study in France. *Noise & Health, 17*(78), 328-336. doi:10.4103/1463-1741.165058

FAA, NextGEN: Performance Success Stories. Retrieved 10/10/2015 from https://www.faa.gov/nextgen/snapshots/airport/?locationId=43

FAA, Press Release. (2015). Retrieved 11/19/2015 from https://www.faa.gov/news/press_releases/news_story.cfm?newsId=18774

Federal Register (2005). Stage 4 Aircraft Noise Standards. Retrieved from https://www.federalregister.gov/documents/2005/07/05/05-13076/stage-4-aircraft-noise-standards

Fidell, S. (2003). The Schultz curve 25 years later: A research perspective. DOI: 10.1121/1/1/628246

Fidell, S., Tabachnick, B., Mestre, V., & Fidell, L. (2013). Aircraft noise-induced awakenings are more reasonably predicted from relative than from absolute sound exposure levels. *Journal of the Acoustical Society of America, 134*(5), 3645-3653. doi:10.1121/1.4823838

Greiser, E., & Greiser, C. (2010). Riskofaktor nachtlicher Flugarlm. Umweltbundesamt. Retrieved from https://www.umweltbundesamt.de/sites/default/files/medien/461/publikationen/3774.pdf

Hales, S. (2010). A Review of literature Related to the Potential Health Effects of Aircraft Noise. Partner Project 19 Final Report

Havas, M., & Colling, D. (2011). Wind turbines make waves: Why some residents near wind turbines become ill. *Bulletin of Science, Technology & Society, 31*(5), 414-426. doi:10.1177/0270467611417852

Hansell, A., Blangiardo, M., Fortuato, L., Floud, S., de, K., Fetch, D., Ghosh, R., et al. (2013). Aircraft noise and cardiovascular disease near Heathrow airport in London: small area study. The BMJ. Retrieved http://www.bmj.com/content/347/bmj.f5432. BMJ 2013; 347:f5432

Holland, K. (2017). Health line Newsletter. What are the 12 leading causes of death in the United States?. Retrieved from https://www.healthline.com/health/leading-causes-of-death

Jarup, L., Babyish, W., Houthis, G., Katsouyan, K., Cadum, E., Dudley, M., Savigny, P., et al. (2007). Hypertension and Exposure to Noise Near Airports: the HYENA Study. *Environ Health Perspect*. 116(3), 329–333. Published online 2007 Dec 11. doi: 10.1289/ehp.10775

Job, R. F., Hatfield, J., Carter, N. L., Peploe, P., Taylor, R., & Morrell, S. (2001). General scales of community reaction to noise (dissatisfaction and perceived affectedness) are more reliable than scales of annoyance. *The Journal of the Acoustical Society of America, 110*(2), 939-46. doi:10.1121/1.1385178

Karabasov, S. A. (2010). Understanding jet noise. *Philosophical Transactions of the Royal Society A-Mathematical Physical And, 368*(1924), 3593–3608. doi:10.1098/rsta.2010.0086

Kopiev, V., & Chernyshev, S. (2012). New correlation model for the cascade of turbulent pulsations as a noise source in jets. *Acoustical Physics, 58*(4), 442-456. doi:10.1134/S1063771012040112

Kroesen, M., & Schreckenberg, D. (2011). A measurement model for general noise reaction in response to aircraft noise. *Journal of the Acoustical Society of America, 129*(1), 200-210. doi:10.1121/1.3514542

LAWA, (2012). Aircraft Noise 101. LAX Community Noise Roundtable. Retrieved from https://www.lawa.org/uploadedFiles/lax/noise/presentation/noiseRT_120509_Aircraft%20Noise%20101.pdf

Leventhall, G. (2005). Assessment and regulation of low frequency noise. *ASHRAE Transactions, 111*(1), 665-660. Retrieved from http://ezp-prod1.hul.harvard.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=aph&AN=20295301&site=ehost-live&scope=site

Links, J. (2006). John Hopkins University. Principles of Exposure, Dose, and Response. Retrieved from http://ocw.jhsph.edu/courses/EnvironmentalHealth/PDFs/Lecture5.pdf Appendix

MIT. (2007). Partner. Low Frequency Noise Study. Retrieved from http://web.mit.edu/aeroastro/partner/reports/proj1/lfnreport-2007-001.pdf

Osborne, A. (2013) Noisy Heathrow ranks Last in Airport Commission study. *The Telegraph*. Retrieved 11/19/2015 from http://www.telegraph.co.uk/finance/newsbysector/transport/10162703/Noisy-Heathrow-ranks-last-in-Airports-Commission-study.html

Persinger, M. (2014). Infrasound, human health, and adaptation: An integrative overview of recondite hazards in a complex environment. *Natural Hazards, 70*(1), 501-525. doi:10.1007/s11069-013-0827-3

Phoenix Sky Harbor International Airport (2014). Noise Exposure Map Updates. Retrieved from https://www.skyharbor.com/docs/default-source/pdfs/2-chapters-1-4.pdf

Phoenix Sky Harbor International Airport (PHX), Airport Statistics (2014). Retrieved 11/29/2015 from https://skyharbor.com/About/Information/AirportStatistics

Phoenix Sky Harbor International Airport (PHX), Updates/Reports (2015). Retrieved 11/29/2015 from https://skyharbor.com/FlightPaths/UpdatesReports

Phoenix Sky Harbor International Airport (2017). Welcome to the Phoenix Sky Harbor International Airport (PHX) Aircraft Noise and Operations Portal. Symphony View. Retrieved from https://secure.symphonycdm.com/publicvue/Frames.asp?sys=PHX&HeaderFrame=HeaderPage.asp&MenuFrame=LeftMenu.asp&ContentFrame=welcome_redirect.asp?sys=PHX

Pennsylvania State University (PSU). (2017). Noise Quest, Noise Basics. Retrieved from http://www.noisequest.psu.edu/noisebasics-basics.html

Sharp, B., Gurovich, Y., Albee, W. (2001). Status of Low-Frequency Aircraft Noise Research and Mitigation. *Wyle Report WR 01-21*. Retrieved 21/2/2015 from http://www.oaklandairport.com/pdf/low_frequency_noise_report.pdf

Smith, M., Croy, I., Hammar, O., & Persson Waye, K. (2016). Vibration from freight trains fragments sleep: A polysomnographic study. Retrieved from http://gup.ub.gu.se/publication/234880-vibration-from-freight-trains-fragments-sleep-a-polysomnographic-study

Tingay, J. (2011). Noise News. What are A, C & Z Frequency Weightings? Retrieved from https://www.cirrusresearch.co.uk/blog/2011/08/what-are-a-c-z-frequency-weightings/

University of Toronto. (2001). Department of Computer Science. What is sound. Retrieved from http://www.cs.toronto.edu/~gpenn/csc401/soundASR.pdf

Vienneau, D., Schindler, C., Perez, L., Probst-Hensch, N., & Roosli, M. (2015). The relationship between transportation noise exposure and ischemic heart disease: A meta-analysis. *Environmental Research, 138*, 372-380. doi:10.1016/j.envres.2015.02.023

Wasser, M. (2015). Sound and Fury: Frustrated Phoenix Residents are roaring ever since the FAA changed Sky Harbor Flight Paths, *Phoenix New Times*. Retrieved 10-10-2015 from http://www.phoenixnewtimes.com/news/sound-and-fury-frustrated-phoenix-residents-are-roaring-ever-since-the-faa-changed-sky-harbor-flight-paths-6654056

Wikipedia (2017). Sound. Retrieved from https://en.m.wikipedia.org/wiki/Sound

University of Wisconsin. (2010). Survey Fundamentals, A Guide to Designing and Implementing Surveys. Retrieved from https://oqi.wisc.edu/resourcelibrary/uploads/resources/Survey_Guide.pdf