Appendix 8.1 Blue Ridge Noise Modelling Assessment

Blue Ridge Research and Consulting, LLC

Technical Report

Noise Study for Launch Vehicle Operations at Shetland Space Centre

October 2, 2020 (Final)

Prepared for:
Scott Hammond
Operations Director
Shetland Space Centre
Inverness, United Kingdom
scott.hammond@shetlandspacecentre.com

Blue Ridge Research and Consulting, LLC
29 N Market St, Suite 700
Asheville, NC 28801
(p) 828-252-2209
(f) 831-603-8321
BlueRidgeResearch.com

Prepared by:
Michael James, M.S.
Matt Calton, M.S.
Alex Salton, M.S.

Contract Number:
PO # 200309

BRRC Report Number:
BRRC 20-07

Table of Contents

List of Figures

List of Tables

Acronyms and Abbreviations

The following acronyms and abbreviations are used in the report:

ASEL	A-Weighted Sound Exposure Level in Decibels
BRRC	Blue Ridge Research and Consulting, LLC
dB	Decibel
dBA	A-weighted Decibel Level
dBC	C-weighted Decibel Level
CDNL	C-weighted Day Night Average Sound Level
DI	Directivity Indices
DNL	Day Night Average Sound Level
DSM-1	Distributed Source Method 1
EIA	Environmental Impact Assessment
Hz	Hertz
km	Kilometers
$L_{A,max}$	Maximum A-weighted OASPL in Decibels
L_{den}	A-weighted Day-Evening-Night Sound Level in Decibels
L_{max}	Maximum Unweighted OASPL in Decibels
L_{pk}	Peak Sound Pressure Level in Decibels
N	Newtons
NIHL	Noise-Induced Hearing Loss
NIOSH	National Institute for Occupational Safety and Health
OASPL	Overall Sound Pressure Level in Decibels
OSHA	Occupational Safety and Health Administration
Pa	Pascal
psf	Pounds per Square Foot
RUMBLE	The Launch Vehicle Acoustic and Emissions Simulation Model
SEL	Sound Exposure Level
SCLV	Small Class Launch Vehicles
S.L.	Sea Level
TA	Time Above
UK	United Kingdom

1 Introduction

This report documents the noise study performed as part of efforts on the Environmental Impact Assessment (EIA) for proposed launch operations at Shetland Space Centre (SSC). SSC plans to conduct launch and static operations of various launch vehicles from three pads. Although a number of small class launch vehicles (SCLV) could operate from the proposed launch sites, this noise study examines a single nominal launch vehicle representing the largest SCLV (in terms of thrust) projected to be launched from SSC. The potential impacts from propulsion noise and sonic booms are evaluated in relation to human annoyance, hearing conservation, and structural damage.

This noise study describes the environmental noise associated with proposed operations. Section 2 describes the proposed operations at SSC; Section 3 summarizes the basics of sound and describes the noise metrics and impact criteria discussed throughout this report; Section 4 describes the general methodology of the propulsion noise and sonic boom modeling; and Section 5 presents the propulsion noise and sonic boom modeling results. A summary is provided in Section 6 to document the notable findings of this noise study.

Figure 1. Image of SSC launch site (credit: Shetland Space Centre Ltd)

2 Launch and Static Operations

SSC plans to conduct up to 30 launch and 30 static fire operations of various small class launch vehicles per year. The annual operations are presented in Table 1 in terms of acoustic time of day.

The representative SCLV length, diameter, weight, and sea level (S.L.) thrust are presented in Table 2. The noise and sonic boom modeling use the time varying weight and thrust profiles, with the first stage reaching a maximum thrust of 736,200 N.

Launch trajectories departing from SSC will be unique to the vehicle, mission, and environmental conditions. For the purposes of this study, the noise modeling utilized a nominal launch trajectory provided by the SCLV manufacturer with an azimuth of 343°, relative to true north. An overview of the facility and nominal trajectory from each pad is shown in Figure 2.

Table 1. Proposed SCLV operations

				Annual Operations			
Pad	**Coordinates**	**Event**	**Duration**	Daytime 0700 – 1900	Evening 1900 – 2300	Nighttime 2300 – 0700	Total
Pad 1	60.8188° N	Launch	--	6	2	2	10
(Eastern)	0.7751° W	Static Fire	5 seconds	6	2	2	10
Pad 2	60.8184° N	Launch	--	6	2	2	10
(Central)	0.7700° W	Static Fire	5 seconds	6	2	2	10
Pad 3	60.8178° N	Launch	--	6	2	2	10
(Western)	0.7613° W	Static Fire	5 seconds	6	2	2	10

Table 2. SCLV modeling parameters

Modeling Parameters	**Values**
Length	29 m
Diameter	1.8 m
Gross Mass	10,049 kg
Propellant Description	LOX/RP-1
S.L. Thrust	633,658 N (158,415 N/engine x Qty. 4 engines)

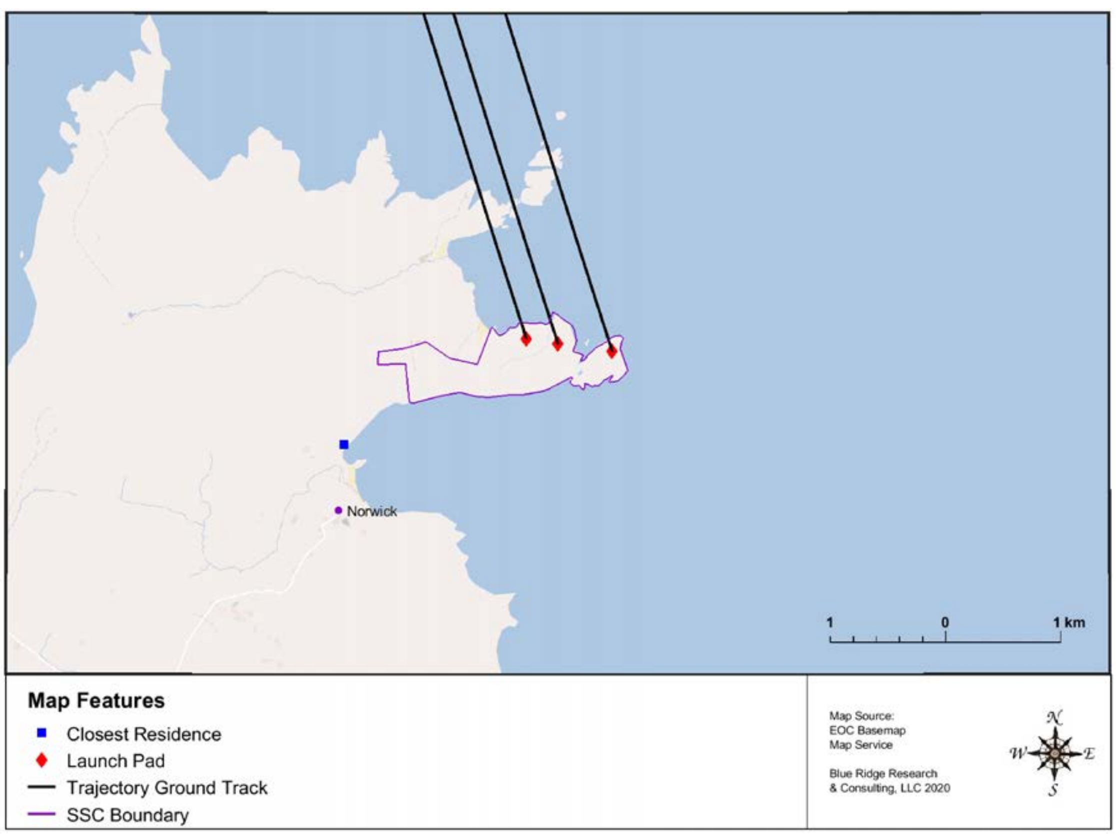


Figure 2. SSC facility boundary, launch pads, and trajectory ground tracks from each pad.

3 Acoustics Overview

An overview of sound-related terms, metrics, and effects, which are pertinent to this study, is provided to assist the reader in understanding the terminology used in this noise study.

3.1 Fundamentals of Sound

Any unwanted sound that interferes with normal activities or the natural environment is defined as noise. Three principal physical characteristics are involved in the measurement and human perception of sound: intensity, frequency, and duration [1].

- **Intensity** is a measure of a sound's acoustic energy and is related to sound pressure. The greater the sound pressure, the more energy is carried by the sound and the louder the perception of that sound.
- **Frequency** determines how the pitch of the sound is perceived. Low-frequency sounds are characterized as rumbles or roars, while high-frequency sounds are typified by sirens or screeches.
- **Duration** is the length of time the sound can be detected.

3.1.1 Intensity

The loudest sounds that can be comfortably detected by the human ear have intensities a trillion times higher than those of sounds barely audible. Because of this vast range, using a linear scale to represent the intensity of sound can become cumbersome. As a result, a logarithmic unit known as the decibel (abbreviated dB) is used to represent sound levels. A sound level of 0 dB approximates the threshold of human hearing and is barely audible under extremely quiet listening conditions. Normal speech has a sound level around 60 dB. Sound levels above 120 dB begin to be felt inside the human ear as discomfort. Sound levels between 130 and 140 dB are experienced as pain [2].

Because of the logarithmic nature of the decibel unit, sound levels cannot be simply added or subtracted and are somewhat cumbersome to handle mathematically. However, some useful rules help when dealing with sound levels. First, if a sound's intensity is doubled, the sound level increases by 3 dB, regardless of the initial sound level. For example:

$$50\text{ dB} + 50\text{ dB} = 53\text{ dB, and } 70\text{ dB} + 70\text{ dB} = 73\text{ dB.}$$

Second, the total sound level produced by two sounds with different levels is usually only slightly more than the higher of the two. For example:

$$50.0\text{ dB} + 60.0\text{ dB} = 60.4\text{ dB.}$$

On average, a person perceives a change in sound level of about 10 dB as a doubling (or halving) of a sound's loudness. This relation holds true for both loud and quiet sounds. A decrease in sound level of 10 dB represents a 90% decrease in sound intensity but only a 50% decrease in perceived loudness because the human ear does not respond linearly [1]. In the community, "it is unlikely that the average listener would be able to correctly identify at a better than chance level the louder of two otherwise similar events which differed in maximum sound level by < 3 dB" [3].

The intensity of sonic booms is quantified with physical pressure units rather than levels. Intensities of sonic booms are traditionally described by the amplitude of the front shock wave, referred to as the peak overpressure. The peak overpressure is normally described in units of pounds per square foot (psf). The amplitude is particularly relevant when assessing structural effects as opposed to loudness or cumulative community response. In this study, sonic booms are quantified by either dB or psf, as appropriate for the particular impact being assessed [4].

3.1.2 Frequency

Sound frequency is measured in terms of cycles per second or hertz (Hz). Human hearing ranges in frequency from 20 Hz to 20,000 Hz, although perception of these frequencies is not equivalent across this range. Human hearing is most sensitive to frequencies in the 1,000 to 4,000 Hz range. Most sounds are not simple pure tones, but contain a mix, or spectrum, of many frequencies. Sounds with different spectra are perceived differently by humans even if the sound levels are the same. Weighting curves have been developed to correspond to the sensitivity and perception of different types of sound. A-weighting and C-weighting are the two most common weightings. These two curves, shown in Figure 3, are adequate to quantify most environmental noises. A-weighting puts emphasis on the 1,000 to 4,000 Hz range to match the reduced sensitivity of human hearing for moderate sound levels. For this reason, the A-weighted decibel level (dBA) is commonly used to assess community sound.

Very loud or impulsive sounds, such as explosions or sonic booms, can sometimes be felt, and they can cause secondary effects, such as shaking of a structure or rattling of windows. These types of sounds can add to annoyance and are best measured by C-weighted sound levels, denoted dBC. C-weighting is nearly flat throughout the audible frequency range and includes low frequencies that may not be heard but cause shaking or rattling. C-weighting approximates the human ear's sensitivity to higher intensity sounds. Note, "unweighted" sound levels refer to levels in which no weighting curve has been applied to the spectra. Unweighted levels are appropriate for use in examining the potential for noise impacts on structures.

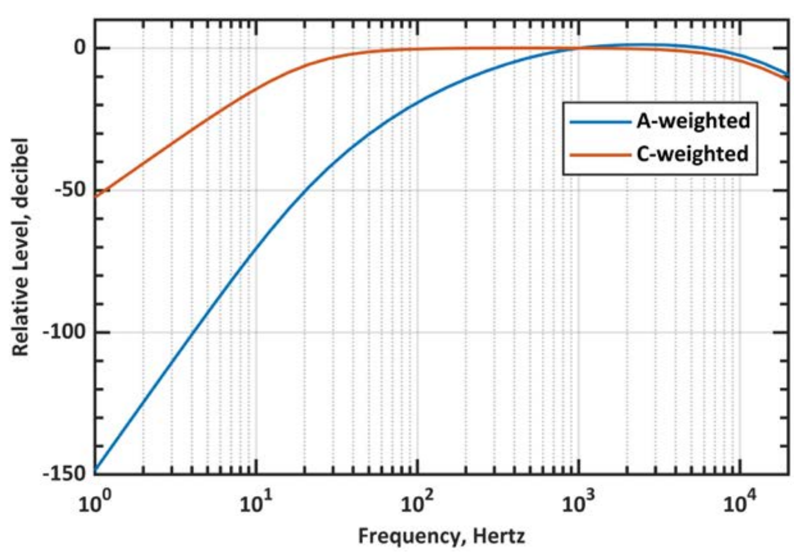


Figure 3. Frequency adjustments for A-weighting and C-weighting [5]

3.1.3 Duration

The third principal physical characteristic involved in the measurement and human perception of sound is duration, which is the length of time the sound can be detected. Sound sources can vary from short durations to continuous, such as back-up alarms and ventilation systems, respectively. Sonic booms are considered low-frequency impulsive noise events with durations lasting a fraction of a second. A variety of noise metrics have been developed to describe noise over different time periods. These are discussed in detail in Section 3.2.

3.1.4 Common Sounds

Common sources of noise and their associated levels are provided for comparison to the noise levels from the proposed action.

A chart of A-weighted sound levels from everyday sound sources [6] is shown in Figure 4. Some sources, like the air conditioners and lawn mower, are continuous sounds whose levels are constant for a given duration. Some sources, like the ambulance siren and motorcycle, are the maximum sound during an intermittent event like a vehicle pass-by. Other sources like "urban daytime" and "urban nighttime" (not shown in Figure 4) are averages over extended periods [7]. Per the US Environmental Protection Agency, "Ambient noise in urban areas typically varies from 60 to 70 dB but can be as high as 80 dB in the center of a large city. Quiet suburban neighborhoods experience ambient noise levels around 45-50 dB" [8].

A chart of typical impulsive events along with their corresponding peak overpressures in terms of psf and peak dB values are shown in Figure 5. For example, thunder overpressure resulting from lightning strikes at a distance of one kilometer is estimated to be near two psf, which is equivalent to 134 dB [9].

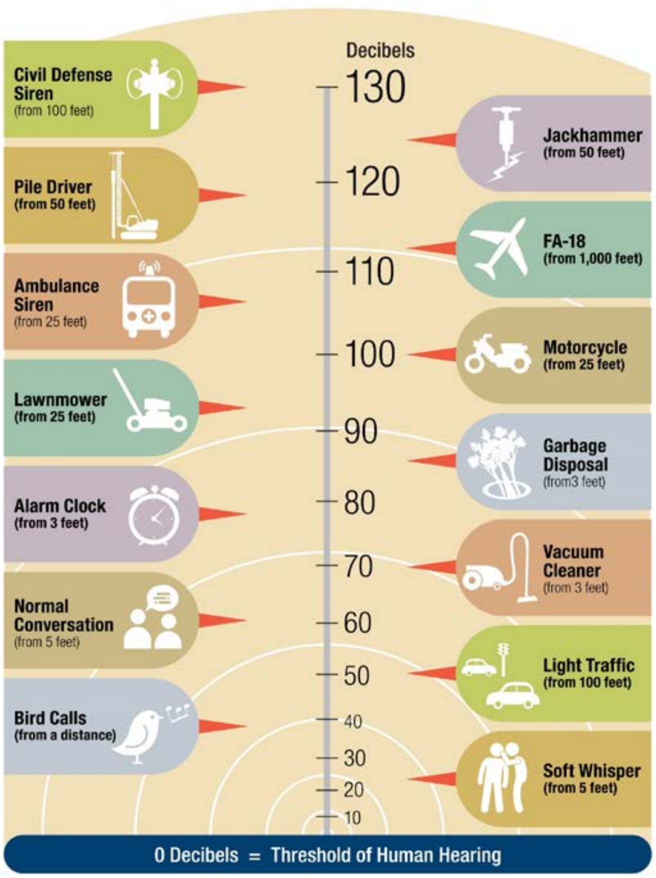


Figure 4. Typical A-weighted levels of common sounds [10]

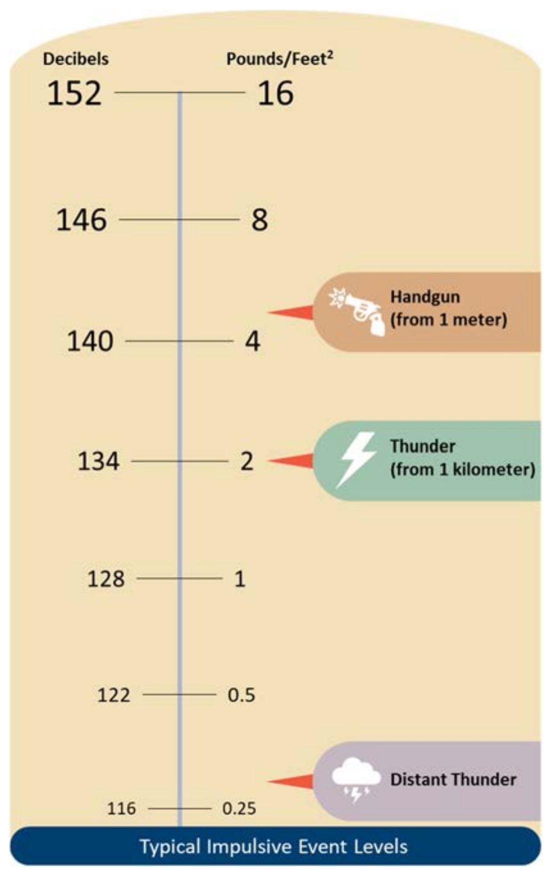


Figure 5. Typical impulsive event levels [9]

3.2 Noise Metrics

A variety of acoustical metrics have been developed to describe sound events and to identify any potential impacts to receptors within the environment. These metrics are based on the nature of the event and who or what is affected by the sound. A brief description of the noise metrics used in this noise study are provided below.

3.2.1 Maximum Sound Level (L_{max})

The highest unweighted sound level measured during a single event, in which the sound changes with time, is called the Maximum Sound Level (abbreviated as L_{max}). The highest A-weighted sound level measured during a single event is called the Maximum A-weighted Sound Level (abbreviated as $L_{A,max}$). Although it provides some measure of the event, L_{max} (or $L_{A,max}$) does not fully describe the sound because it does not account for how long the sound is heard.

3.2.2 Peak Overpressure (L_{pk})

For impulsive sounds, the true instantaneous peak sound pressure level, which lasts for only a fraction of a second, is important in determining impacts. The peak overpressure of the front shock wave is used to describe sonic booms, and it is usually presented in psf. Peak sound levels are not frequency weighted.

3.2.3 Day-Night Average Sound Level (DNL) and Day-Evening-Night Average Sound Level (L_{den})

Day-Night Average Sound Level is a cumulative metric that accounts for all noise events in a 24-hour period. To account for increased sensitivity to noise at night, DNL applies an additional 10 dB adjustment to events during the acoustical nighttime period, defined as 10:00 PM to 7:00 AM. DNL represents the average sound level exposure for annual average daily events.

The United Kingdom (UK) uses the Day-Evening-Night Average Sound Level (L_{den}), a variant of the DNL. In addition to a 10 dB (i.e. 10 times weighting) adjustment during the acoustical nighttime period (11:00 pm to 7:00 am), the L_{den} includes a 5 dB adjustment (i.e. 3 times weighting) to events during the acoustical evening period (7:00 PM to 11:00 PM) to account for decreased community noise during this period. DNL and L_{den} do not represent a level heard at any given time but represent long term exposure to noise.

3.2.4 Sound Exposure Level (SEL)

Sound exposure level is a composite metric that represents both the intensity of a sound and its duration. Individual time-varying noise events have two main characteristics: a sound level that changes throughout the event and a period of time during which the event is heard. SEL provides a measure of the net impact of the entire acoustic event, but it does not directly represent the sound level heard at any given time. Mathematically, it represents the sound level of a constant sound that would generate the same acoustical energy in one second as the actual time-varying noise event. For sounds that typically last more than one second, the SEL is usually greater than the L_{max} because a single event takes seconds and the maximum sound level (L_{max}) occurs instantaneously. A-weighted sound exposure level is abbreviated as ASEL.

3.2.5 Time Above (TA)

The Time Above a threshold level is a measure of the total time the noise level exceeds the A-weighted threshold level during a defined time period. TA is expressed in seconds and describes the time noise levels are elevated above a level. For example, TA66 represents the time that the noise levels are above 66 dBA. However, it does not describe the magnitude of the elevated noise levels.

3.3 Noise Effects

Noise criteria have been developed to protect the public health and welfare of the surrounding communities. The impacts of launch vehicle noise and sonic booms are evaluated on a cumulative basis in terms of human annoyance. In addition, potential impacts are evaluated on a single-event basis in relation to hearing conservation, sleep disturbance, speech interference, and structural damage.

3.3.1 Human Annoyance

DNL is based on long-term cumulative noise exposure and has been found to correlate well with long-term community annoyance for regularly occurring events including aircraft, rail, and road noise [11, 12]. Noise studies used in the development of the DNL metric did not include rockets, which are historically irregularly occurring events. Thus, it is acknowledged that the suitability of DNL for infrequent rocket noise events is uncertain. Additionally, it has been noted that the DNL "threshold does not adequately address the effects of noise on visitors to areas within a national park or national wildlife refuge where other noise is very low and a quiet setting is a generally recognized purpose and attribute" [13]. However, DNL is the most widely accepted metric to estimate the potential changes in long-term community annoyance. For launch propulsion noise, A-weighted DNL is used to assess the community impacts with regards to human annoyance. For impulsive noise sources with significant low-frequency content such as sonic booms, C-weighted DNL (CDNL) is preferred over A-weighted DNL [14]. In terms of percent highly annoyed, DNL 65 dBA is equivalent to CDNL 60 dBC [15]. Within the UK, the potential for community impacts with regards to human annoyance are assessed using L_{den} (see Section 3.2), a variant of DNL. Given that there are no formal thresholds incorporated into UK guidelines or legislation, the present study uses a criterion of 55 dBA L_{den} based on guidance from EU Directive 2002/49/EC [16].

3.3.2 Hearing Conservation

Launch Vehicle Noise

National agencies have provided guidelines on permissible noise exposure limits. These documented guidelines are in place to protect human hearing from long-term continuous daily exposures to high noise levels and aid in the prevention of noise-induced hearing loss (NIHL). A number of agencies have set exposure limits on non-impulsive noise levels, including the Occupational Safety and Health Administration (OSHA) [17], National Institute for Occupational Safety and Health (NIOSH) [18], and UK Legislation [19]. The most conservative of these upper noise level limits has been set by OSHA at 115 dBA. At 115 dBA, the allowable exposure duration is 15 minutes for OSHA and 28 seconds for NIOSH. $L_{A,max}$ contours are used to identify potential locations where hearing protection should be considered for rocket operations.

Sonic Booms

Multiple national agencies have provided guidelines on permissible noise exposure limits on impulsive noise such as sonic booms. In terms of upper limits on impulsive or impact noise levels, NIOSH [18], OSHA [20], and UK Legislation [19] have stated that levels should not exceed 140 dB peak sound pressure level, which equates to a sonic boom level of approximately 4 psf.

3.3.3 Sleep Disturbance

Launch Vehicle Noise

Sleep disturbance is a major concern for communities exposed to launch vehicle noise at night. A number of studies have attempted to quantify the effects of noise on sleep. Although no scientific evidence directly relates nighttime aircraft noise and irreversible long-term health effects such as stress-induced illnesses, sleep disturbance is a major cause of annoyance for the community.

The relationship between noise levels and sleep disturbance is complex and not fully understood. The disturbance depends not only on the depth of sleep, but also on the previous exposure to launch vehicle noise, familiarity with the surroundings, the physiological and psychological condition of the recipient, and a host of other situational factors. The most readily measurable effect of noise on sleep is the number of arousals or awakenings, and so the body of scientific literature has focused on predicting the percentage of the population that will be awakened at various single event noise levels, expressed in terms of SEL, and or the probability of awakening during the night from nighttime operations.

A UK study [21] concluded that "below outdoor event levels of 90 dB ASEL, aircraft noise events are most unlikely to cause any measurable increase in the overall rates of sleep disturbance experienced during normal sleep." An SEL of 90 dBA is used to identify potential locations where sleep disturbance may occur.

3.3.4 Speech Interference

Launch Vehicle Noise

Speech interference from noise is a primary cause of annoyance for communities. Disruption of routine activities such as radio or television listening, telephone use, or conversation leads to frustration and annoyance. The quality of speech communication is important in classrooms and offices. In the workplace, speech interference from noise can cause fatigue and vocal strain in those who attempt to talk over the noise. In schools it can impair learning.

There are two measures of speech comprehension:

1. Word Intelligibility - the percent of words spoken and understood. This might be important for students in the lower grades who are learning the English language, and particularly for students who have English as a Second Language.
2. Sentence Intelligibility – the percent of sentences spoken and understood. This might be important for high-school students and adults who are familiar with the language, and who do not necessarily have to understand each word in order to understand sentences.

A sentence intelligibility of 95% usually permits reliable communication because of the redundancy in normal conversation. Levels must remain below 66 dBA to maintain a speech intelligibility of 95% for two people standing outside, approximately 1 m apart [8].

3.3.5 Structural Damage

Launch Vehicle Noise

Typically, the most sensitive components of a structure to launch vehicle noise are windows, and infrequently, the plastered walls and ceilings. The potential for damage to a structure is unique interaction among the incident sound, the condition of the structure, and the material of each element and its respective boundary conditions. A report from the National Research Council on the "Guidelines for Preparing Environmental Impact Statements on Noise" [22] states that one may conservatively consider all sound lasting more than one second with levels exceeding 130 dB (unweighted) as potentially damaging to structures.

A NASA technical memo examined the relationship between structural damage claims and overall sound pressure level and concluded "the probability of structural damage [was] proportional to the intensity of the low frequency sound" [23]. This relationship estimated that one damage claim in 100 households exposed is expected at an average continuous sound level of 120 dB (unweighted), and one in 1,000 households at 111 dB (unweighted). The study was based on community responses to 45 ground tests of the first and second stages of the Saturn V rocket system conducted in Southern Mississippi over a period of five years. The sound levels used to develop the criteria were modeled mean sound levels.

It is important to highlight the difference between the static ground tests on which the rate of structural damage claims is based and the dynamic events modeled in this noise study. During ground tests, the engine/motor remains in one position, which results in a longer-duration exposure to continuous levels as opposed to the transient noise occurring from the moving vehicle during a launch event. Regardless of this difference, Guest and Slone's [23] damage claim criteria represents the best available dataset regarding the potential for structural damage resulting from rocket noise. Thus, L_{max} values of 120 dB (unweighted) and 111 dB (unweighted) are used in this report as conservative thresholds for potential risk of structural damage claims.

Sonic Booms

High-level sonic booms are also associated with structural damage. Most damage claims are for brittle objects, such as glass and plaster. Table 3 summarizes the threshold of damage that may be expected at various overpressures [24]. Additionally, Table 3 describes example impulsive events for each level range. A large degree of variability exists in damage experience, and much of the damage depends on the pre-existing condition of a structure. Breakage data for glass, for example, spans a range of two to three orders of magnitude at a given overpressure. The probability of a window breaking at 1 psf ranges from one in a billion [25] to one in a million [26]. These damage rates are associated with a combination of boom load and glass condition. At 10 psf, the probability of breakage is between one in 100 and one in 1,000. Laboratory tests involving glass [27] have shown that properly installed window glass will not break at overpressures below 10 psf, even when subjected to repeated booms. However, in the real world, glass is not always in pristine condition.

Damage to plaster occurs at similar ranges to glass damage. Plaster has a compounding issue in that it will often crack due to shrinkage while curing or from stresses as a structure settles, even in the absence of outside loads. Sonic boom damage to plaster often occurs when internal stresses are high as a result of these factors. In general, for well-maintained structures, the threshold for damage from sonic booms is 2 psf [24], below which damage is unlikely.

Table 3. Possible damage to structures from sonic booms [24]

Nominal level	Damage Type	Item Affected
0.5 – 2 psf *piledriver at construction site*	Plaster	Fine cracks; extension of existing cracks; more in ceilings; over doorframes; between some plasterboards.
	Glass	Rarely shattered; either partial or extension of existing.
	Roof	Slippage of existing loose tiles/slates; sometimes new cracking of old slates at nail hole.
	Damage to outside walls	Existing cracks in stucco extended.
	Bric-a-brac	Those carefully balanced or on edges can fall; fine glass, such as large goblets, can fall and break.
	Other	Dust falls in chimneys.
2 – 4 psf *cap gun/firecracker near ear*	Glass, plaster, roofs, ceilings	Failures show that would have been difficult to forecast in terms of their existing localized condition. Nominally in good condition.
4 – 10 psf *handgun at shooter's ear*	Glass	Regular failures within a population of well-installed glass; industrial as well as domestic greenhouses.
	Plaster	Partial ceiling collapse of good plaster; complete collapse of very new, incompletely cured, or very old plaster.
	Roofs	High probability rate of failure in nominally good state, slurry-wash; some chance of failures in tiles on modern roofs; light roofs (bungalow) or large area can move bodily.
	Walls (out)	Old, free standing, in fairly good condition can collapse.
	Walls (in)	Inside ("party") walls known to move at 10 psf.
> 10 psf *fireworks display from viewing stand*	Glass	Some good glass will fail regularly to sonic booms from the same direction. Glass with existing faults could shatter and fly. Large window frames move.
	Plaster	Most plaster affected.
	Ceilings	Plasterboards displaced by nail popping.
	Roofs	Most slate/slurry roofs affected, some badly; large roofs having good tile can be affected; some roofs bodily displaced causing gale-end and will-plate cracks; domestic chimneys dislodged if not in good condition.
	Walls	Internal party walls can move even if carrying fittings such as hand basins or taps; secondary damage due to water leakage.
	Bric-a-brac	Some nominally secure items can fall; e.g., large pictures, especially if fixed to party walls.

4 Noise Modeling

An overview of the propulsion noise and sonic boom modeling methodologies used in this noise study are presented in Section 4.1 and 4.2, respectively.

4.1 Propulsion Noise Modeling

Launch vehicle propulsion systems, such as solid rocket motors and liquid-propellant rocket engines, generate high-amplitude broadband noise. Most of the noise is created by the rocket plume interacting with the atmosphere and the combustion noise of the propellants. Although rocket noise radiates in all directions, it is highly directive, meaning that a significant portion of the source's acoustic power is concentrated in specific directions.

The Launch Vehicle Acoustic and Emissions Simulation Model (RUMBLE) 4.1, developed by Blue Ridge Research and Consulting, LLC (BRRC), is the noise model used to predict the noise associated with the proposed operations. The core components of the model are visualized in Figure 6 and are described in the following subsections.

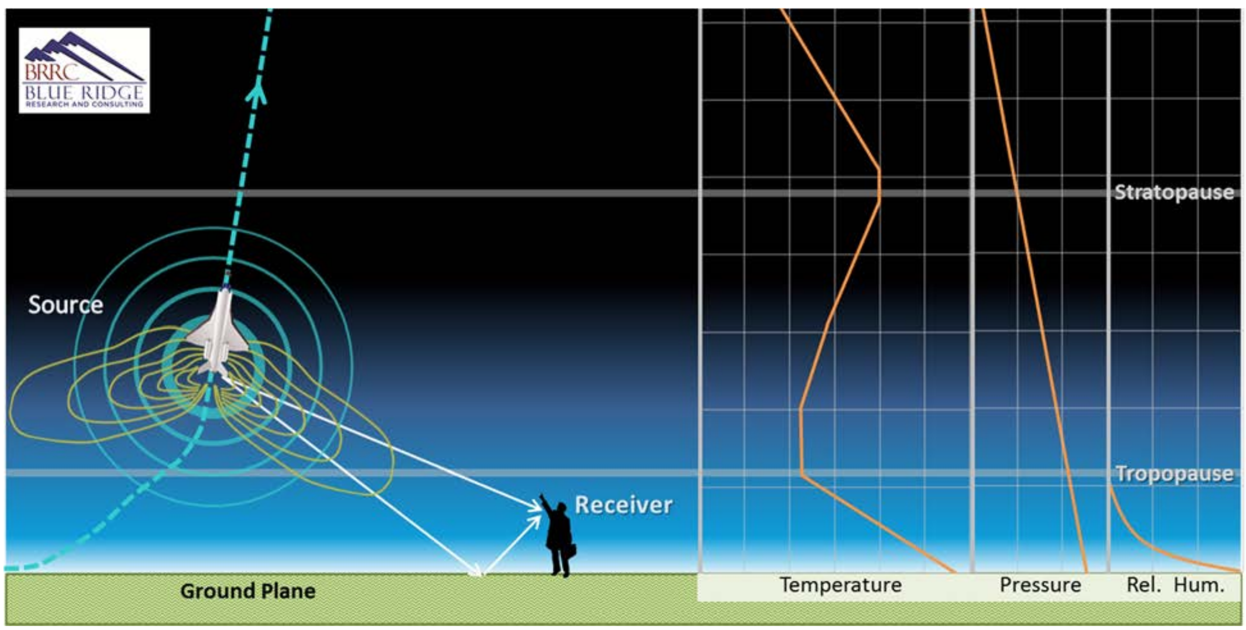


Figure 6. Conceptual overview of rocket noise prediction model methodology

4.1.1 Source

The rocket noise source definition considers the acoustic power of the rocket, forward flight effects, directivity, and the Doppler effect.

Acoustic Power

Eldred's Distributed Source Method 1 (DSM-1) [28] is utilized for the source characterization. The DSM-1 model determines the launch vehicle's total sound power based on its total thrust, exhaust velocity, and the engine/motor's acoustic efficiency. BRRC's recent validation of the DSM-1 model showed very good agreement between full-scale rocket noise measurements and the empirical source curves [29]. The acoustic efficiency of the rocket engine/motor specifies the percentage of the mechanical power converted into acoustic power. The acoustic efficiency of the rocket engine/motor was modeled using Guest's variable acoustic efficiency [30]. Typical acoustic efficiency values range from 0.2% to 1.0% [28]. In the far-field, distributed sound sources are modeled as a single compact source located at the nozzle exit with an equivalent total sound power. Therefore, launch vehicle propulsion systems with multiple tightly clustered equivalent engines can be modeled as a single engine with an effective exit diameter and total thrust [28]. Additional boosters or cores (that are not considered to be tightly clustered) are handled by summing the noise contribution from each booster/core.

Forward Flight Effect

A rocket in forward flight radiates less noise than the same rocket in a static environment. A standard method to quantify this effect reduces overall sound levels as a function of the relative velocity between the jet plume and the outside airflow [31, 32, 33, 34]. This outside airflow travels in the same direction as the rocket exhaust. At the onset of a launch, the rocket exhaust travels at far greater speeds than the ambient airflow. Conversely, for a vertical landing, the rocket exhaust and ambient airflow travel in opposing directions, yielding an increased relative velocity differential. As the differential between the forward flight velocity and exhaust velocity decreases, jet plume mixing is reduced, which reduces the corresponding noise emission. Notably, the maximum sound levels are normally generated before the vehicle reaches the speed of sound. Thus, the modeled noise reduction is capped at a forward flight velocity of Mach 1.

Directivity

Rocket noise is highly directive, meaning the acoustic power is concentrated in specific directions, and the observed sound pressure will depend on the angle from the source to the receiver. NASA's Constellation Program has made significant improvements in determining launch vehicle directivity of the reusable solid rocket motor (RSRM) [35]. The RSRM directivity indices (DI) incorporate a larger range of frequencies and angles than previously available data. Subsequently, improvements were made to the formulation of the RSRM DI [36] accounting for the spatial extent and downstream origin of the rocket noise source. These updated DI are used for this analysis.

Doppler Effect

The Doppler effect is the change in frequency of an emitted wave from a source moving relative to a receiver. The frequency at the receiver is related to the frequency generated by the moving sound source and by the speed of the source relative to the receiver. The received frequency is higher (compared to the emitted frequency) if the source is moving towards the receiver, it is identical at the instant of passing by, and it is lower if the source is moving away from the receiver. During a rocket launch, an observer on the ground will hear a downward shift in the frequency of the sound as the distance from the source to receiver increases. The relative changes in frequency can be explained as follows: when the source of the waves is moving toward the observer, each successive wave crest is emitted from a position closer to the observer than the previous wave. Therefore, each wave takes slightly less time to reach the observer than the previous wave, and the time between the arrivals of successive wave crests at the observer is reduced, causing an increase in the frequency. While they are traveling, the distance between successive wave fronts is reduced such that the waves "bunch together." Conversely, if the source of waves is moving away from the observer, then each wave is emitted from a position farther from the observer than the previous wave; the arrival time between successive waves is increased, reducing the frequency. Likewise, the distance between successive wave fronts increases, so the waves "spread out." Figure 7 illustrates this spreading effect for an observer in a series of images, where a) the source is stationary, b) the source is moving less than the speed of sound, c) the source is moving at the speed of sound, and d) the source is moving faster than the speed of sound. As the frequency is shifted lower, the A-weighting filtering on the spectrum results in a decreased A-weighted sound level. For unweighted overall sound levels, the Doppler effect does not change the levels since all frequencies are accounted for equally.

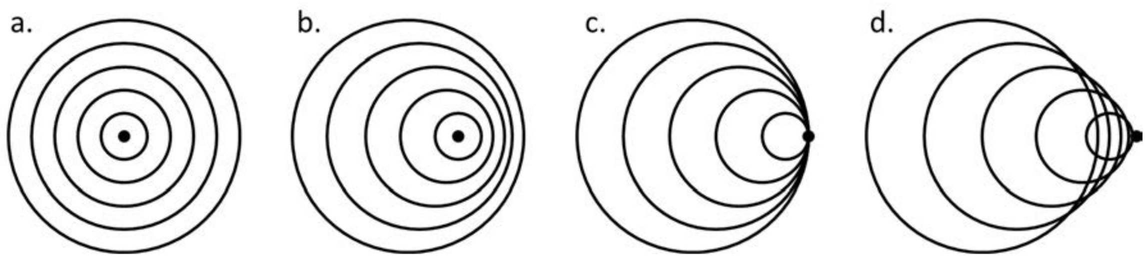


Figure 7. Effect of expanding wavefronts (decrease in frequency) that an observer would notice for higher relative speeds of the rocket relative to the observer for: a) stationary source b) source velocity < speed of sound c) source velocity = speed of sound d) source velocity > speed of sound

4.1.2 Propagation

The sound propagation from the source to receiver considers the ray path, atmospheric absorption, and ground interference.

Ray Path

The model assumes straight line propagation between the source and receiver to determine propagation effects. For straight rays, sound levels decrease as the sound wave propagates away from a source uniformly in all directions. The launch vehicle noise model components are calculated based on the specific geometry between source (launch vehicle trajectory point) to receiver (grid point). The position of the launch vehicle, described by the trajectory, is provided in latitude and longitude, defined relative to a reference system (e.g. World Geodetic System 1984) that approximates the Earth's surface by an ellipsoid. The receiver grid is also described in geodetic latitude and longitude, referenced to the same reference system as the trajectory data, ensuring greater accuracy than traditional flat earth models.

Atmospheric Absorption

Atmospheric absorption is a measure of the sound attenuation from the excitation of vibration modes of air molecules. Atmospheric absorption is a function of temperature, pressure, and relative humidity of the air. The propulsion noise model utilizes an atmospheric profile, which describes the variation of temperature, pressure, and relative humidity with respect to the altitude. Standard atmospheric data sources [37, 38, 39, 40] were used to create a composite atmospheric profile for altitudes up to 106 km. The atmospheric absorption is calculated using formulas found in ANSI Standard S1.26-1995 (R2004). The result is a sound-attenuation coefficient, which is a function of frequency, atmospheric conditions, and distance from the source. The amount of absorption depends on the parameters of the atmospheric layer and the distance that the sound travels through the layer. The total sound attenuation is the sum of the absorption experienced from each atmospheric layer.

Nonlinear propagation effects can result in distortions of high-amplitude sound waves [41] as they travel through the medium. These nonlinear effects are counter to the effect of atmospheric absorption [42, 43]. However, recent research shows that nonlinear propagation effects change the perception of the received sound [44, 45], but the standard acoustical metrics are not strongly influenced by nonlinear effects [46, 47]. The overall effects of nonlinear propagation on high-amplitude sound signatures and their perception is an ongoing area of research, and it is not currently included in the propagation model.

Ground Interference

The calculated results of the sound propagation using DSM-1 provide a free-field sound level (i.e. no reflecting surface) at the receiver. However, sound propagation near the ground is most accurately modeled as the combination of a direct wave (source to receiver) and a reflected wave (source to ground to receiver) as shown in Figure 6. The ground will reflect sound energy back toward the receiver and interfere both constructively and destructively with the direct wave. Additionally, the ground may attenuate the sound energy, causing the reflected wave to propagate a smaller portion of energy to the receiver. RUMBLE accounts for the attenuation of sound by the ground [48, 49] when estimating the received noise. The model assumes a five-foot receiver height and a homogeneous grass ground surface. However, it should be noted that noise levels may be 3 dB louder over water surfaces compared to the predicted levels over the homogeneous grass ground surfaces assumed in the modeling. To account for the random fluctuations of wind and temperature on the direct and reflected wave, the effect of atmospheric turbulence is also included [48, 50].

4.1.3 Receiver

The received noise is estimated by combining the source and propagation components. The basic received noise is modeled as overall and spectral level time histories. This approach enables a range of noise metrics relevant to environmental noise analysis to be calculated and prepared as output.

4.2 Sonic Boom Modeling

A vehicle creates sonic booms during supersonic flight. The potential for the boom to intercept the ground depends on the trajectory and speed of the vehicle as well as the atmospheric profile. The sonic boom is shaped by the physical characteristics of the vehicle and the atmospheric conditions through which it propagates. These factors affect the perception of a sonic boom. The noise is perceived as a deep boom, with most of its energy concentrated in the low frequency range. Although sonic booms generally last less than one second, their potential for impact may be considerable.

A brief sonic boom generation and propagation modeling primer is provided in Section 4.2.1 to describe relevant technical details that inform the sonic boom modeling. The primer also provides visualizations of the boom generation, propagation, and ground intercept geometry. An overview of the sonic boom modeling software used in the study, PCBoom, and a description of inputs are found in Section 4.2.2.

4.2.1 Primer

When a vehicle moves through the air, it pushes the air out of its way. At subsonic speeds, the displaced air forms a pressure wave that disperses rapidly. At supersonic speeds, the vehicle is moving too quickly for the wave to disperse, so it remains as a coherent wave. This wave is a sonic boom. When heard at ground level, a sonic boom consists of two shock waves (one associated with the forward part of the vehicle, the other with the rear part) of approximately equal strength. When plotted, this pair of shock waves and the expanding flow between them has the appearance of a capital letter "N," so a sonic boom pressure wave is usually called an "N-wave." An N-wave has a characteristic "bang-bang" sound that can be startling. Figure 8 shows the generation and evolution of a sonic boom N-wave under the vehicle.

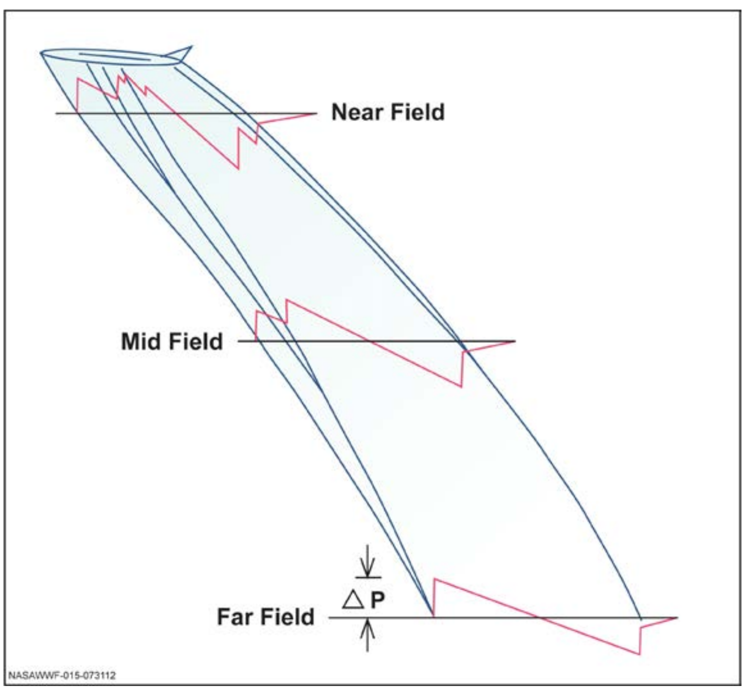


Figure 8. Sonic boom generation and evolution to N-wave [51]

For aircraft, the front and rear shock are generally the same magnitude. However, for rockets, in addition to the two shock waves generated from the vehicle body, the plume itself acts as a large supersonic body, and it generates two additional shock waves (one associated with the forward part of the plume, the other with the rear part) and extends the waveform duration to as large as one second. If the plume volume is significantly larger than the vehicle, its shocks will be stronger than the shocks generated by the vehicle.

Figure 9 shows the sonic boom wave cone generated by a vehicle in steady (non-accelerating) level supersonic flight. The wave cone extends toward the ground and is said to sweep out a "carpet" under the flight track. The boom levels vary along the lateral extent of the "carpet" with the highest levels directly underneath the flight track and decreasing levels as the lateral distance increases to the cut-off edge of the "carpet."

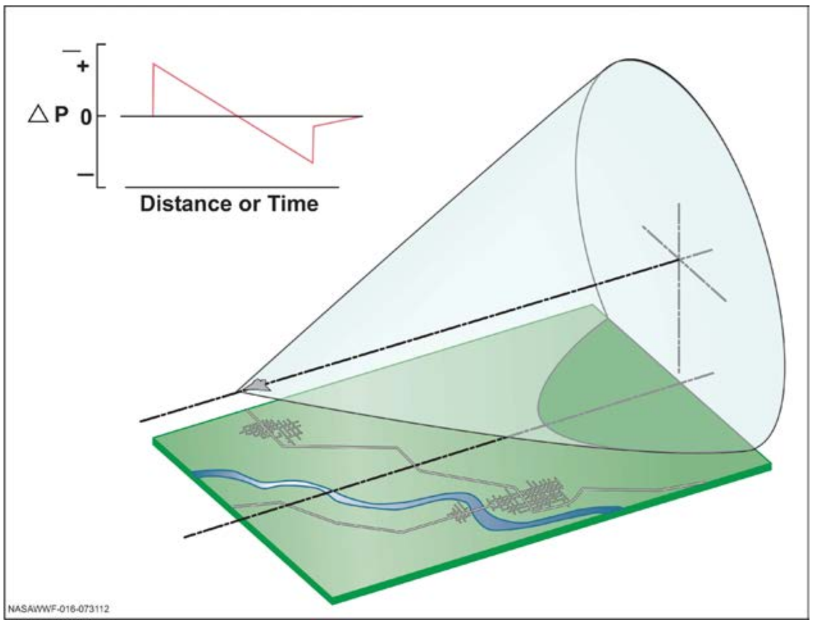


Figure 9. Sonic boom carpet for a vehicle in steady flight [52]

Although the wave cone can be calculated from an aircraft-fixed reference frame, the ray perspective is more convenient when computing sonic boom metrics in a ground-fixed observer's reference frame [53]. Both perspectives are shown in Figure 10. The difference in wave versus ray perspectives is described for level, climbing, and diving flight, in the PCBoom Sonic Boom Model User Guide [53]:

> Sonic boom wave cones are not generated fully formed at a single point in time, instead resulting from the accumulation of all previous disturbance events that occurred during the vehicle's time history. […] Unlike wave cones, ray cones are fully determined at a single point in time and are independent of future maneuvers. They are orthogonal to wave cones and represent all paths that sonic boom energy will take from the point they are generated until a later point in time when they hit the ground. The ray perspective is particularly useful when considering refraction due to atmospheric gradients or the effect of aircraft maneuvers, where rays can coalesce into high amplitude focal zones.

When the ray cone hits the ground, the resulting intersection is called an "isopemp." The isopemp is forward-facing [as shown in Figure 10] and falls a distance ahead of the vehicle called the "forward throw." At each new point in the trajectory, a new ray cone is generated, resulting in a new isopemp that strikes the ground. These isopemps are generated throughout the trajectory, sweeping out an area called the "boom footprint."

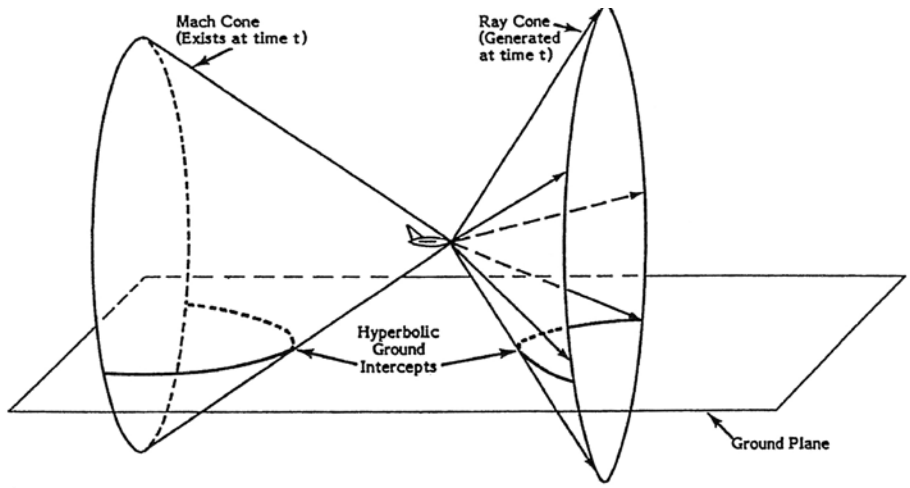


Figure 10. Mach cone vs ray cone viewpoints

Figure 9 and Figure 10 may give the impression that the boom footprint is generally associated with rays generated from the bottom of a vehicle. This is the case for vehicles at moderate climb and dive angles, or in level flight as shown in Figure 10. For a vehicle climbing at an angle steeper than the ray cone half angle, such as in the left image of Figure 11, rays from that part of its trajectory will not reach the ground. This is important for vertical launches, where the ascent stage of a launch vehicle typically begins at a steep angle. In these cases, sonic booms are not expected to reach the ground unless refracted back downwards by gradients in the atmosphere. Conversely, if a vehicle is in a sufficiently steep dive, such as in the right image of Figure 11, the entire ray cone may intersect the ground, resulting in an elliptical or even circular isopemp. This is of importance for space flight reentry analysis, where descent may be nearly vertical.

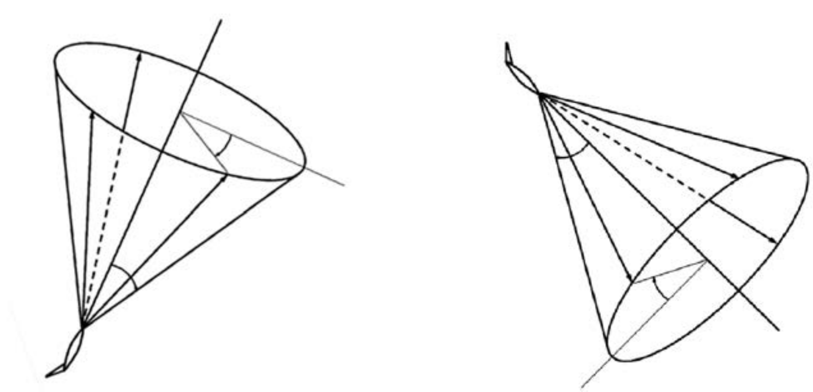


Figure 11. Ray cone in climbing (left) and diving (right) flight

4.2.2 PCBoom

The single-event prediction model, PCBoom 6.7b [54, 55, 56], is a full ray trace sonic boom program that is used to calculate the magnitude, waveform, and location of sonic boom overpressures on the ground from supersonic flight operations. Additionally, BRRC uses a custom version of PCBoom 6.7b that implements proper plume physics.

Several inputs are required to calculate the sonic boom impact, including the geometry of the vehicle, the trajectory path, and the atmospheric conditions. These parameters along with time-varying thrust, drag, and weight are used to define the PCBoom starting signatures used in the modeling. The starting signatures are propagated through a site-specific atmospheric profile that includes the mean temperature, wind speed, and wind direction [57].

5 Results

The following sections present the results of the environmental propulsion noise and sonic boom impacts associated with the proposed SCLV operations. Additionally, noise levels over water may be higher because of the acoustical hardness of the water surface. Single event propulsion noise and sonic boom noise metrics are presented in Section 5.1 and Section 5.2, respectively. Cumulative launch vehicle noise results are presented in Section 5.3.

5.1 Single Event Propulsion Noise Metrics and Effects

Single event propulsion noise events are evaluated using maximum A-weighted and unweighted levels, A-weighted sound exposure level, and time above.

5.1.1 Maximum A-weighted Sound Level ($L_{A,max}$)

The modeled $L_{A,max}$ contours associated with SCLV operations from SSC are presented in Figure 12 through Figure 17. An upper limit noise level of 115 dBA is used as a guideline to protect human hearing from long-term continuous daily exposures to high noise levels and to aid in the prevention of NIHL. There are no residences within the land area encompassed by the 115 dB noise contours resulting from SCLV operations. Thus, the potential for impacts to people in the community with regards to hearing conservation is negligible.

Launch Operations – The 115 dBA contour for SCLV launch events from Pad 1, Pad 2, and Pad 3 are shown in Figure 12, Figure 13, Figure 14, respectively. The SCLV launch event generates modeled levels at or above an $L_{A,max}$ of 115 dBA within 0.56 km of the pad nearest to the community.

Static Operations – The 115 dBA contour for SCLV static events from Pad 1, Pad 2, and Pad 3 are shown in Figure 15, Figure 16, and Figure 17, respectively. Note the difference in zoom level between the launch and static operation results. The SCLV static event noise contours are more directive than the launch event noise contours because the plume is redirected in-line with the deflector heading for the entire duration of the event. A receptor located along the peak directivity angle may experience an $L_{A,max}$ of 115 dBA at approximately 0.29 km from the pad during a static event. The levels produced by static events will remain constant over the duration of the event, whereas the levels produced by launch events will decrease as the rocket moves further away from the receptor.

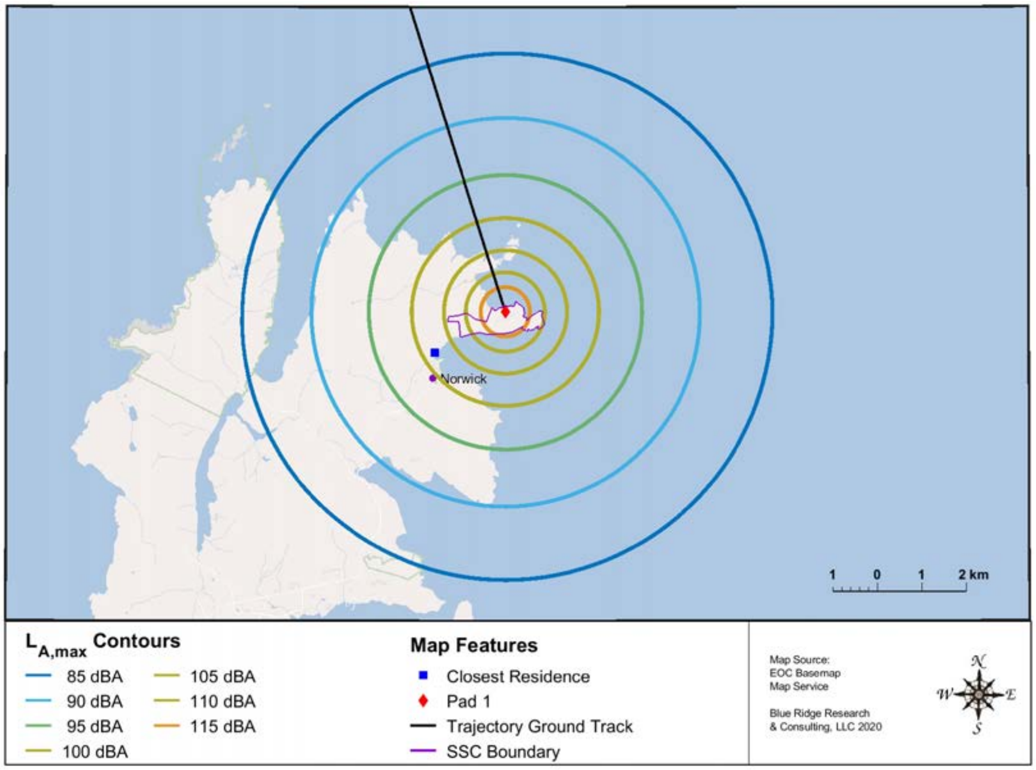


Figure 12. $L_{A,max}$ contours for a SCLV launch from SSC Pad 1

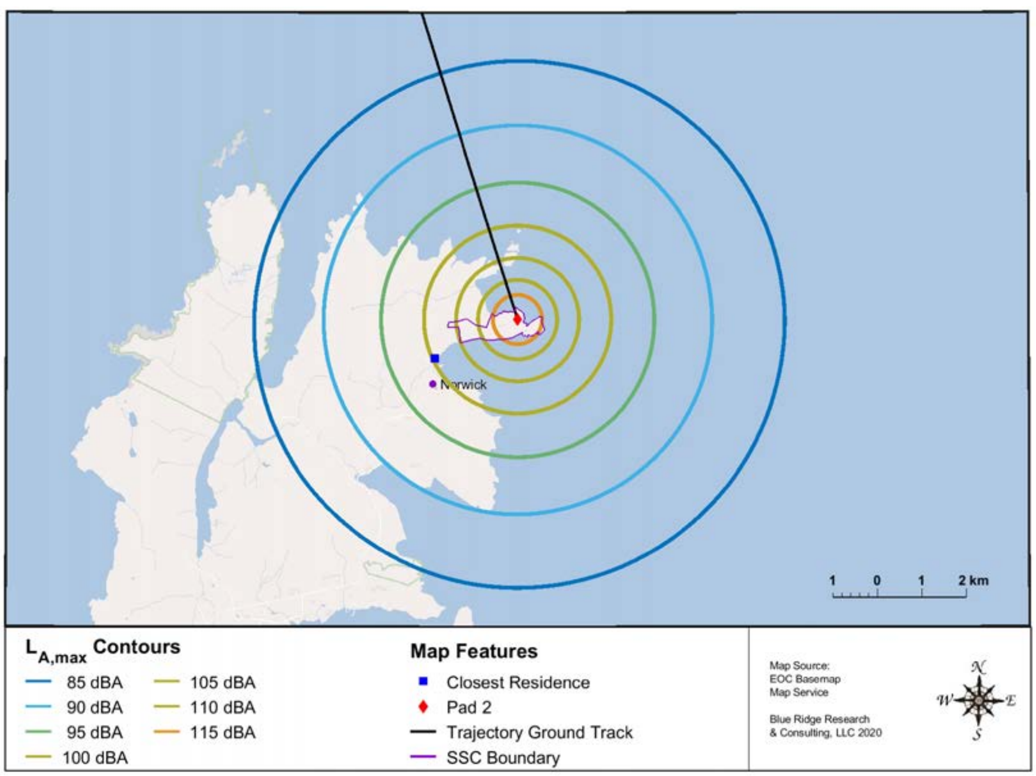


Figure 13. $L_{A,max}$ contours for a SCLV launch from SSC Pad 2

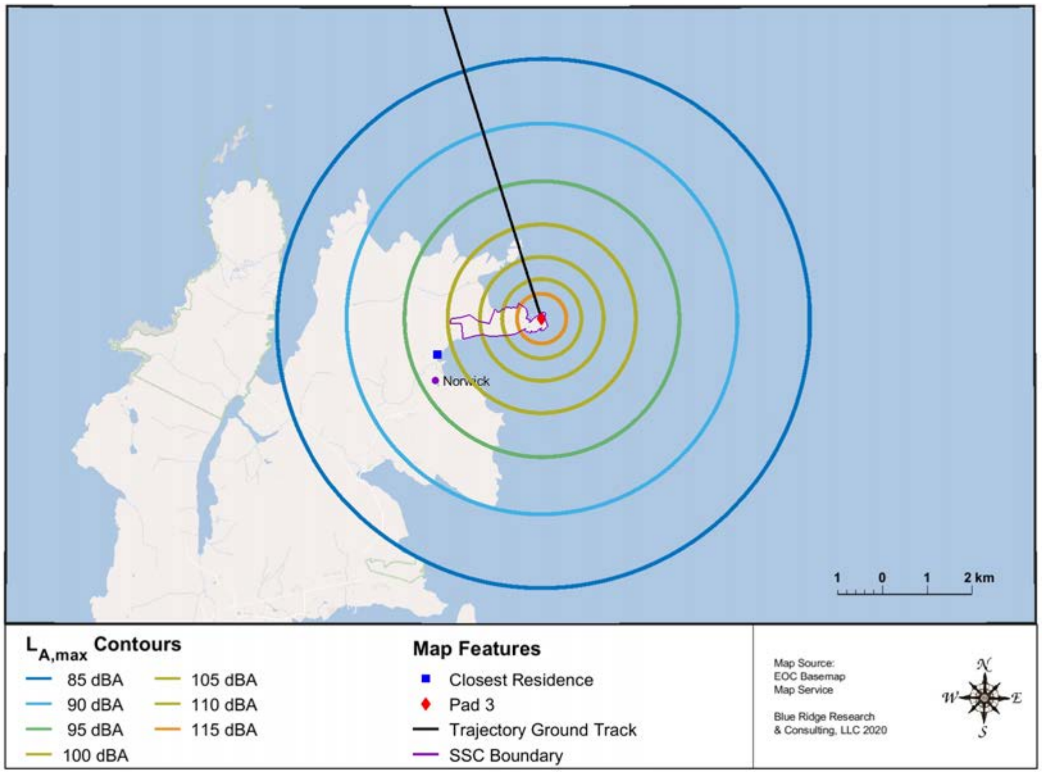


Figure 14. $L_{A,max}$ contours for a SCLV launch from SSC Pad 3

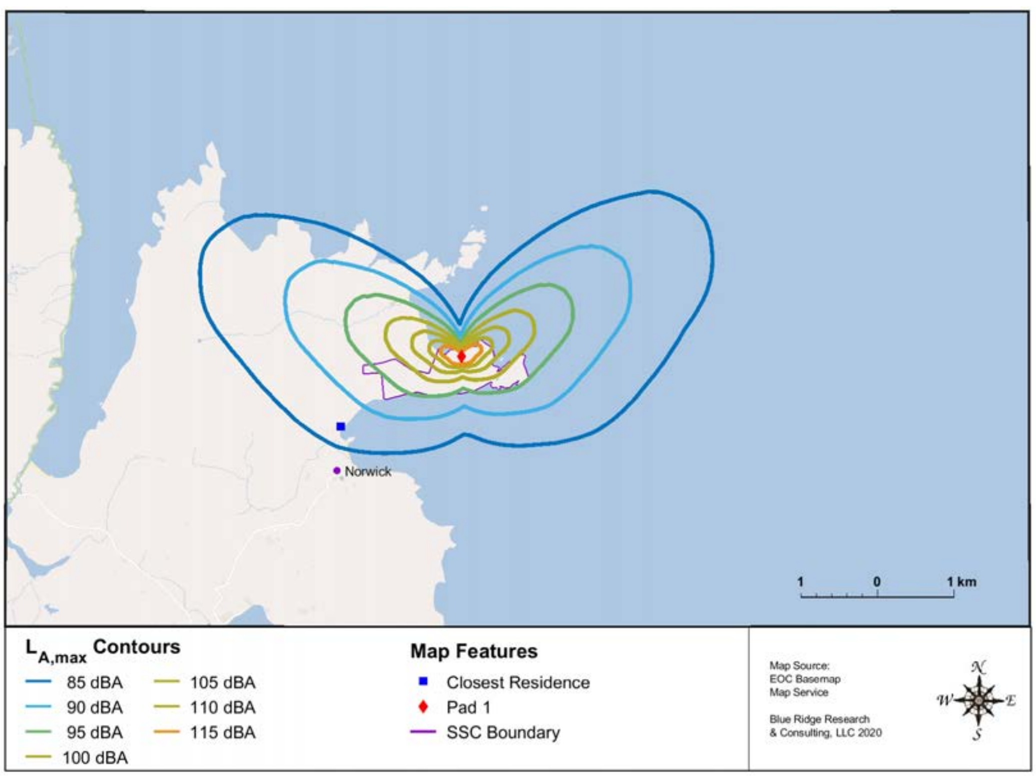


Figure 15. $L_{A,max}$ contours for a SCLV static fire from SSC Pad 1

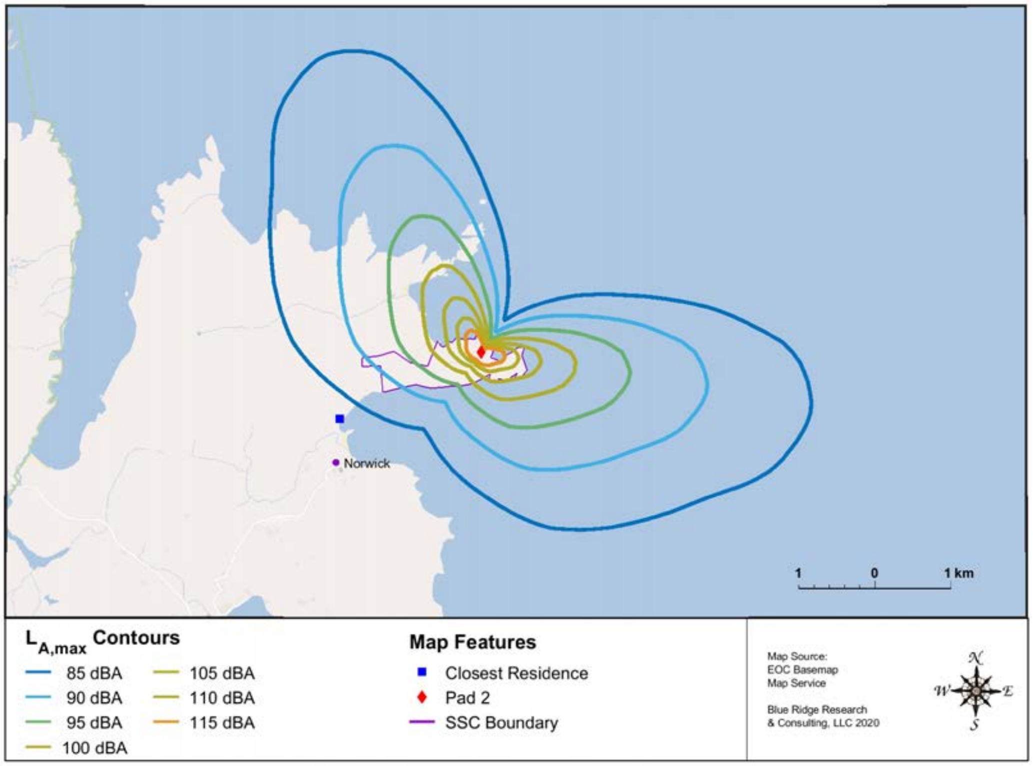


Figure 16. $L_{A,max}$ contours for a SCLV static fire from SSC Pad 2

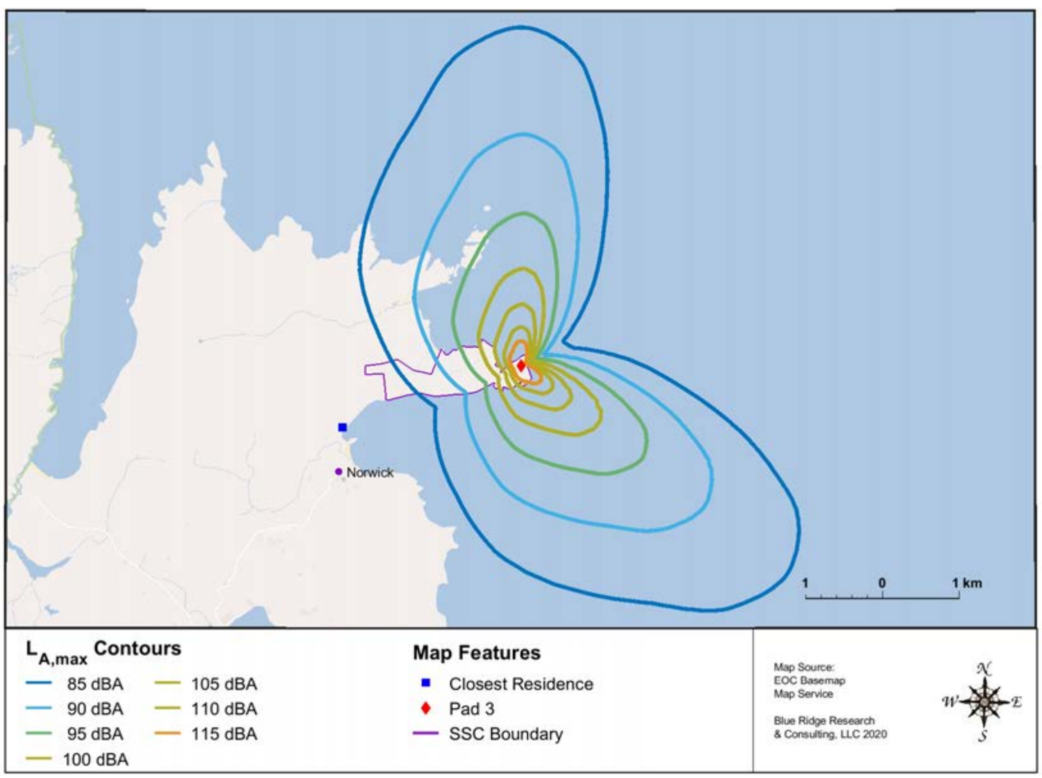


Figure 17. $L_{A,max}$ contours for a SCLV static fire from SSC Pad 3

5.1.2 Sound Exposure Level

The modeled ASEL contours associated with SCLV operations from SSC are presented in Figure 18 through Figure 23. Typically, ASEL levels in excess of 90 dBA indicate potential for sleep disturbance. Northern Unst is encompassed by the 90 dBA noise contours resulting from SCLV launch operations. Thus, the potential for sleep disturbance exists for nighttime launch operations.

Launch Operations – The 90 dBA contour for SCLV launch events from Pad 1, Pad 2, and Pad 3 are shown in Figure 18, Figure 19, and Figure 20, respectively. The SCLV launch event generates modeled levels at or above an ASEL of 90 dBA within 12.9 km of the pad nearest to the community.

Static Operations – The 90 dBA contour for SCLV static events at Pad 1, Pad 2, and Pad 3 are shown in Figure 21, Figure 22, and Figure 23, respectively. Note, the difference in zoom level between the launch and static operation results. The SCLV static event noise contours are more directive than the launch event noise contours because the plume is redirected in-line with the deflector heading for the entire duration of the event. A receptor located along the peak directivity angle may experience an ASEL of 90 dBA at approximately 4.2 km from the pad during a static event. Note, the levels produced by static events will remain constant over the duration of the event, whereas the levels produced by launch events will decrease as the rocket moves further away from the receptor.

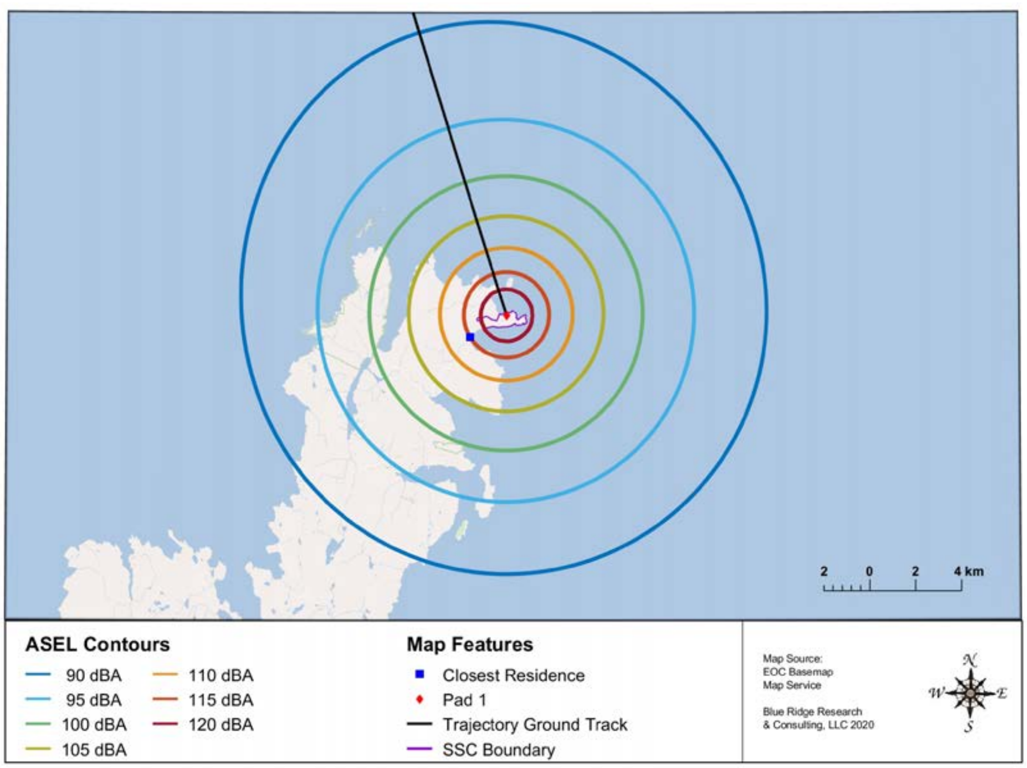


Figure 18. ASEL contours for a SCLV launch from SSC Pad 1

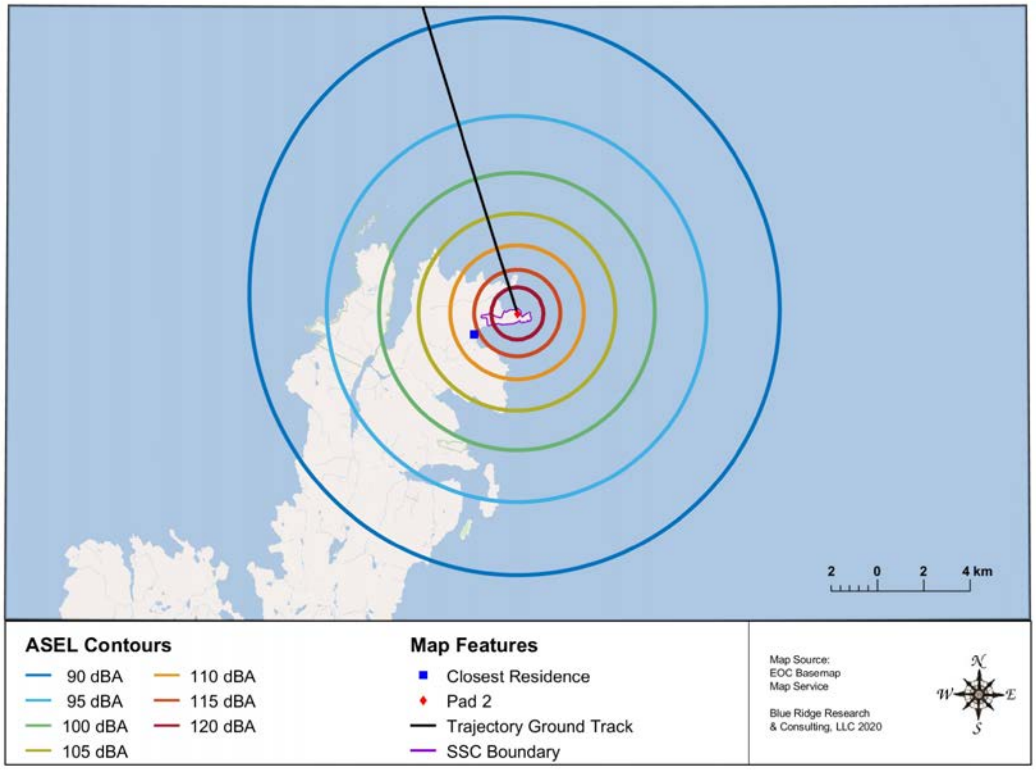


Figure 19. ASEL contours for a SCLV launch from SSC Pad 2

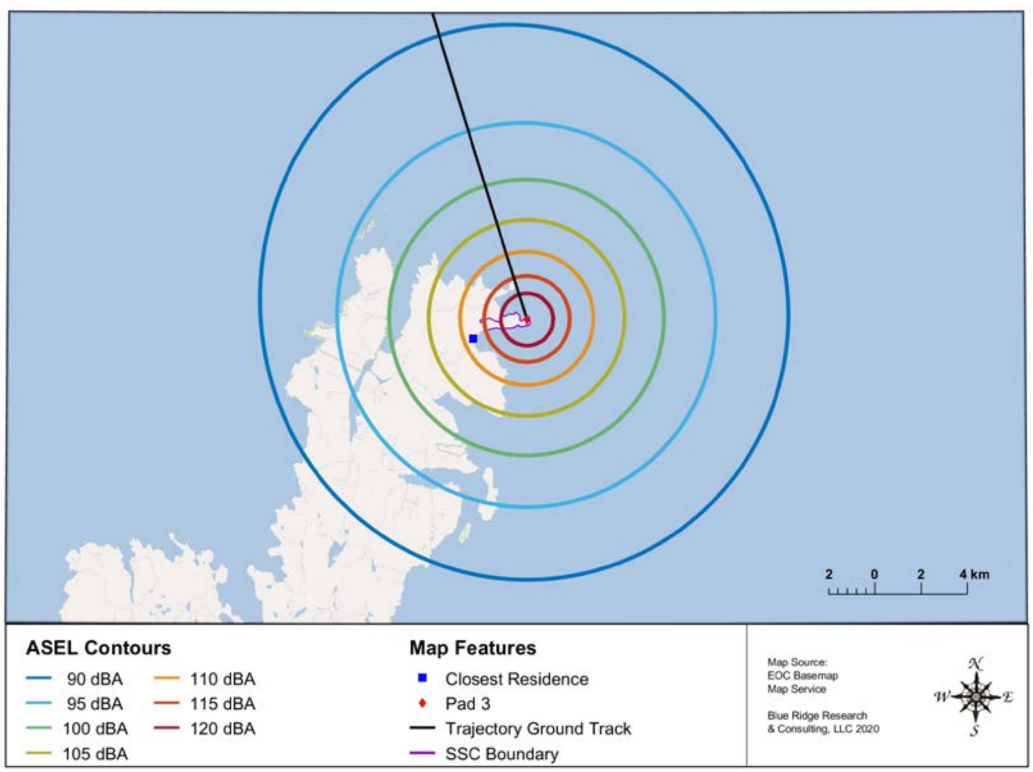


Figure 20. ASEL contours for a SCLV launch from SSC Pad 3

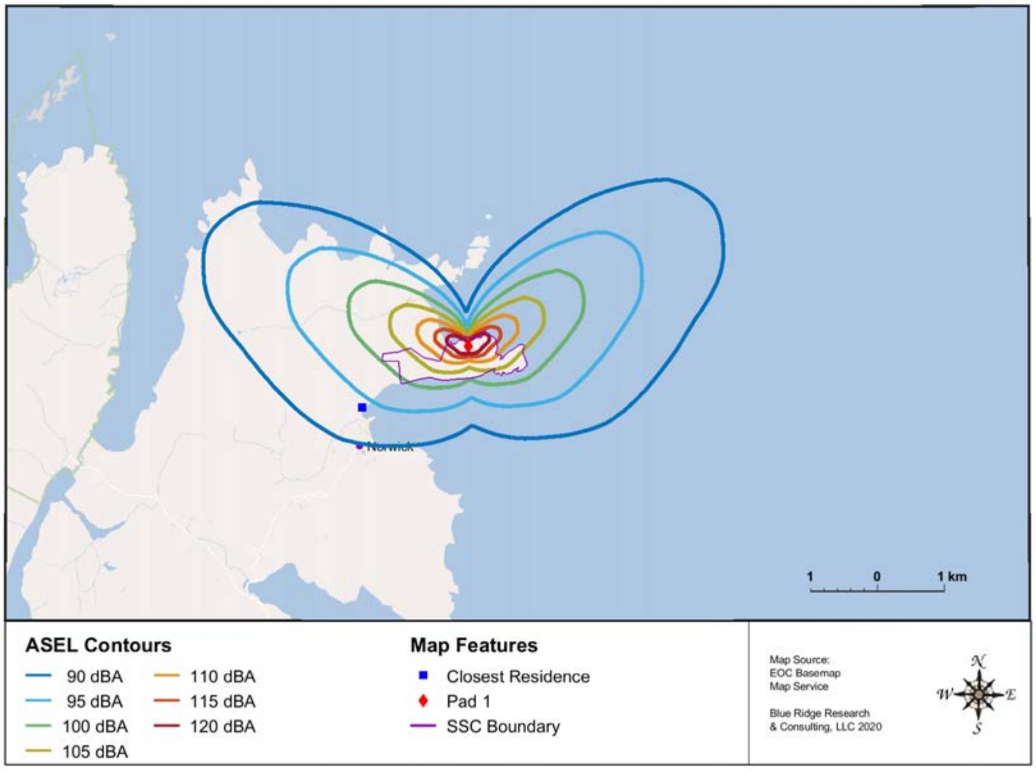


Figure 21. ASEL contours for a SCLV static fire from SSC Pad 1

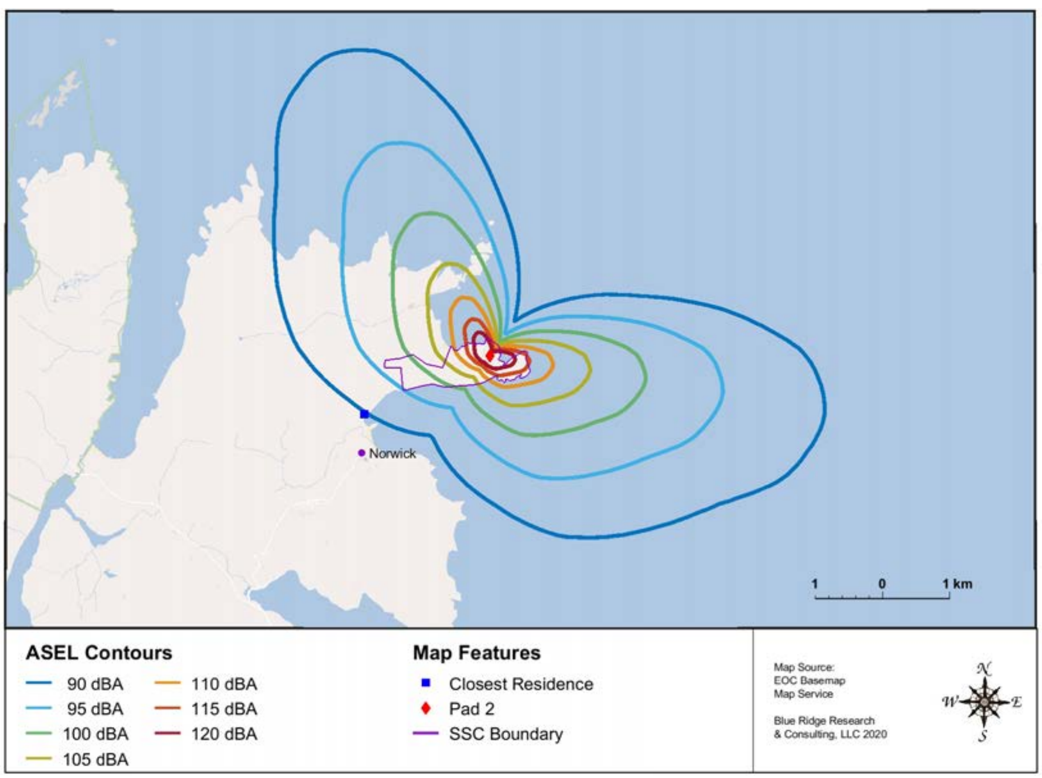


Figure 22. ASEL contours for a SCLV static fire from SSC Pad 2

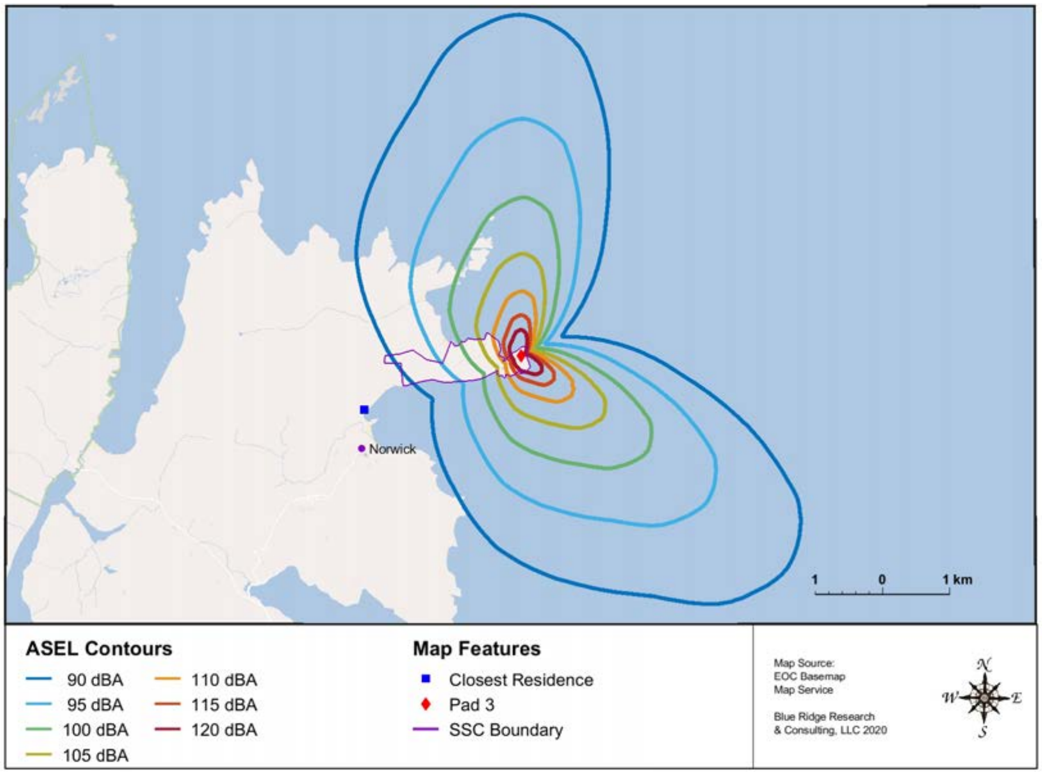


Figure 23. ASEL contours for a SCLV static fire from SSC Pad 3

5.1.3 Time Above

The modeled sound level time history for the event at the closest residence is shown in Figure 24. To provide additional context, Figure 24 displays the time above for four specified threshold levels which represent:

- A typical helicopter overflight (89 dBA);
- A speech intelligibility threshold of 95% (66 dBA);
- The average background noise level on Unst (45 dBA); and
- The background noise level on Unst that is exceeded 90% of the time (22 dBA).

To show the effect over the study region, the modeled time above contours associated with SCLV launch operations from SSC Pad 1, Pad 2, and Pad 3 are presented for 45 dBA, 66 dBA, and 89 dBA in Figure 25 to Figure 33. The shape of the contours depends on the selected time above threshold level. The TA45 contours, representing the time above the average background noise on Unst, increase from south to north over the study area and span a duration of 130-200 seconds. The TA66 contours, representing the time above the speech intelligibility threshold, shows a similar trend and span a duration of 60-95 seconds. The TA89 contours, representing the time above a typical helicopter overflight, generally decreases away from SSC and span a duration of 5-45 seconds.

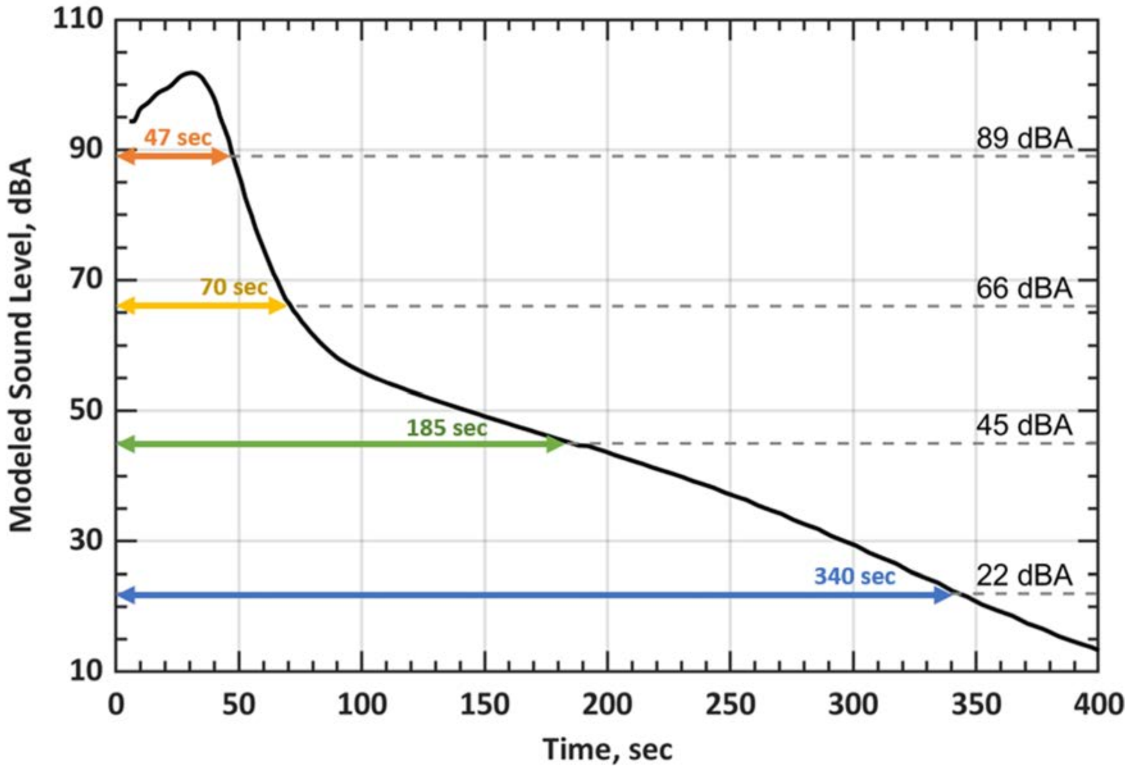


Figure 24. Modeled sound level time history at closest residence from SCLV launch operation.

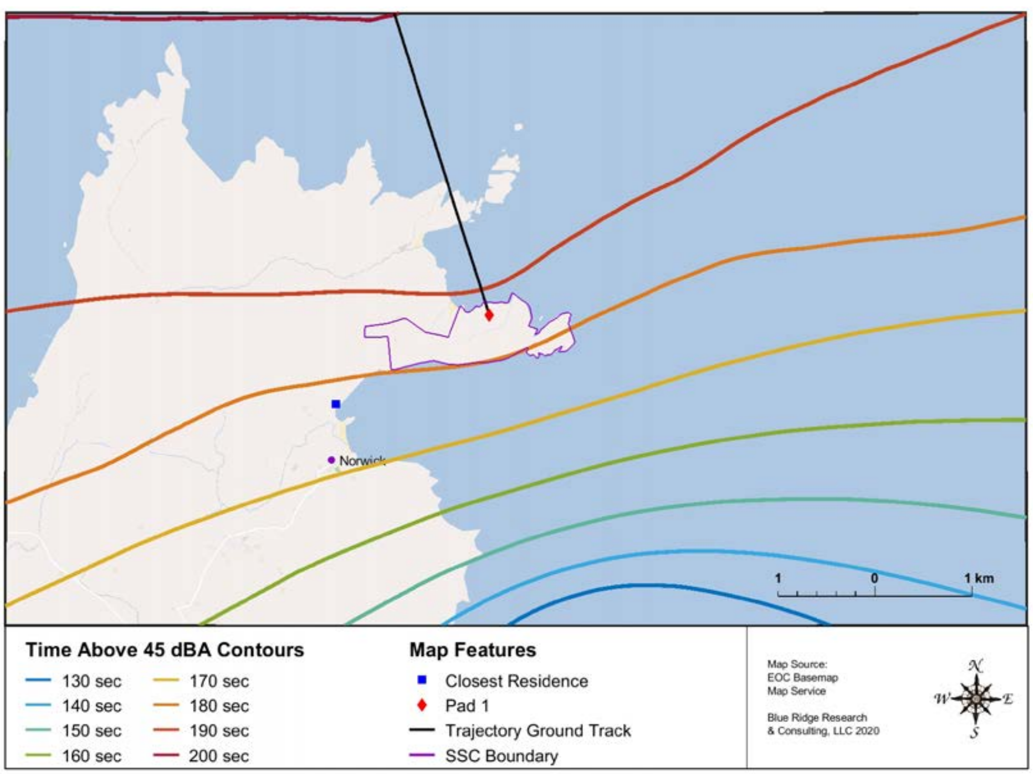


Figure 25. Time above 45 dBA contours for a SCLV launch from SSC Pad 1

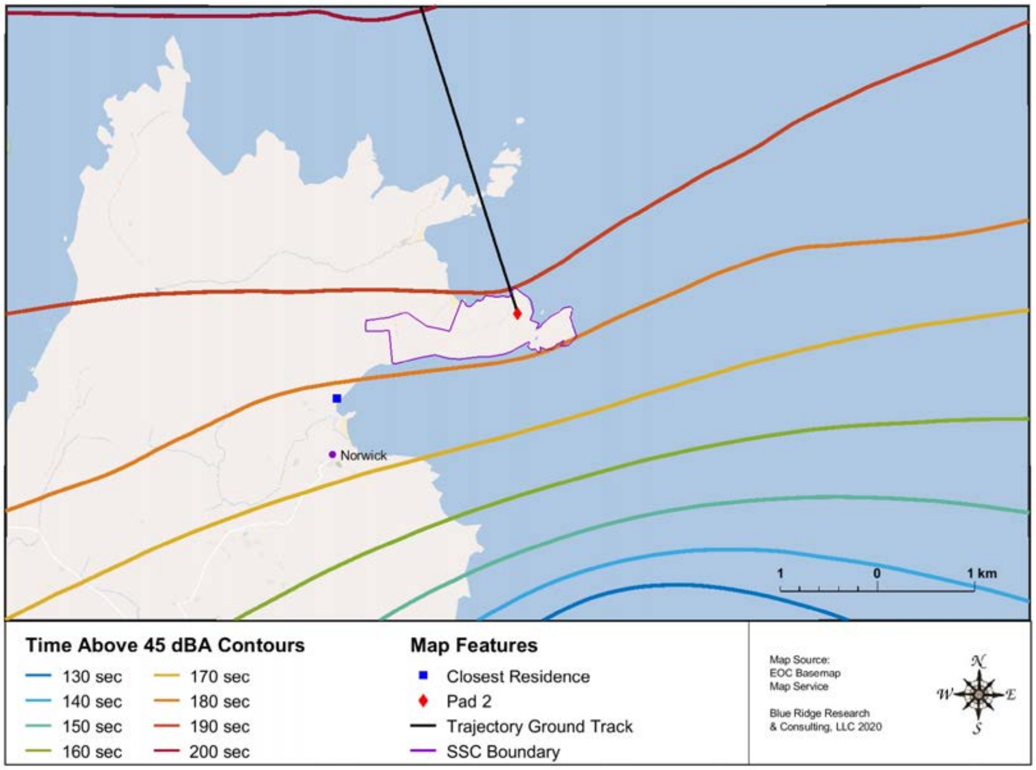


Figure 26. Time above 45 dBA contours for a SCLV launch from SSC Pad 2

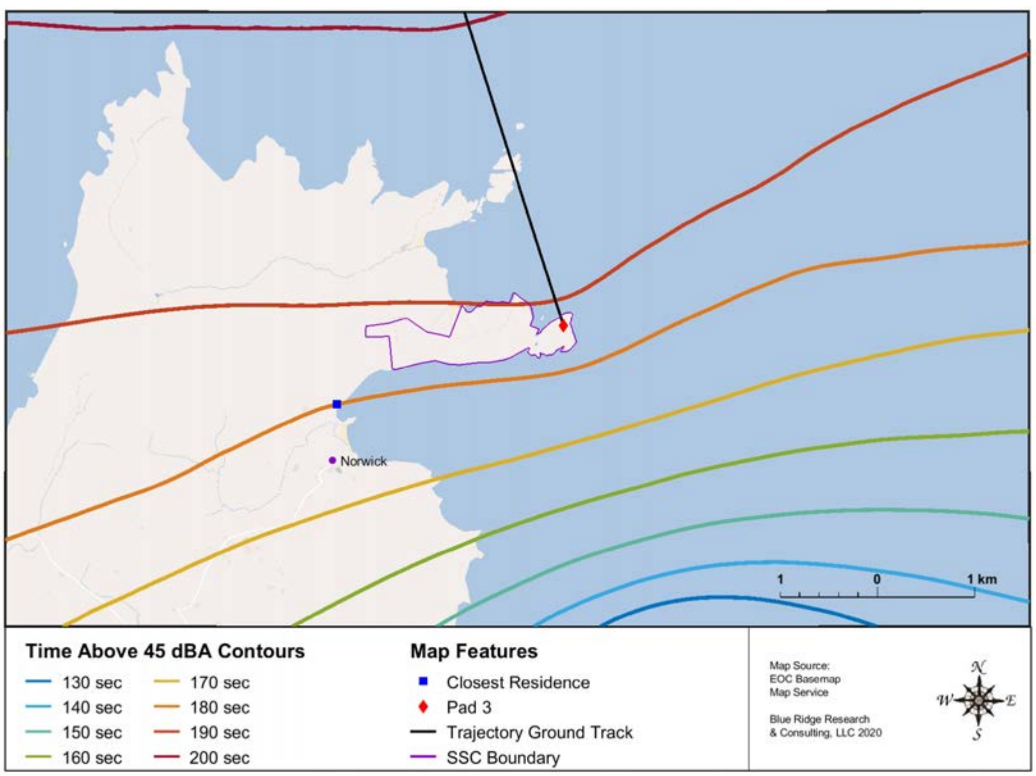


Figure 27. Time above 45 dBA contours for a SCLV launch from SSC Pad 3

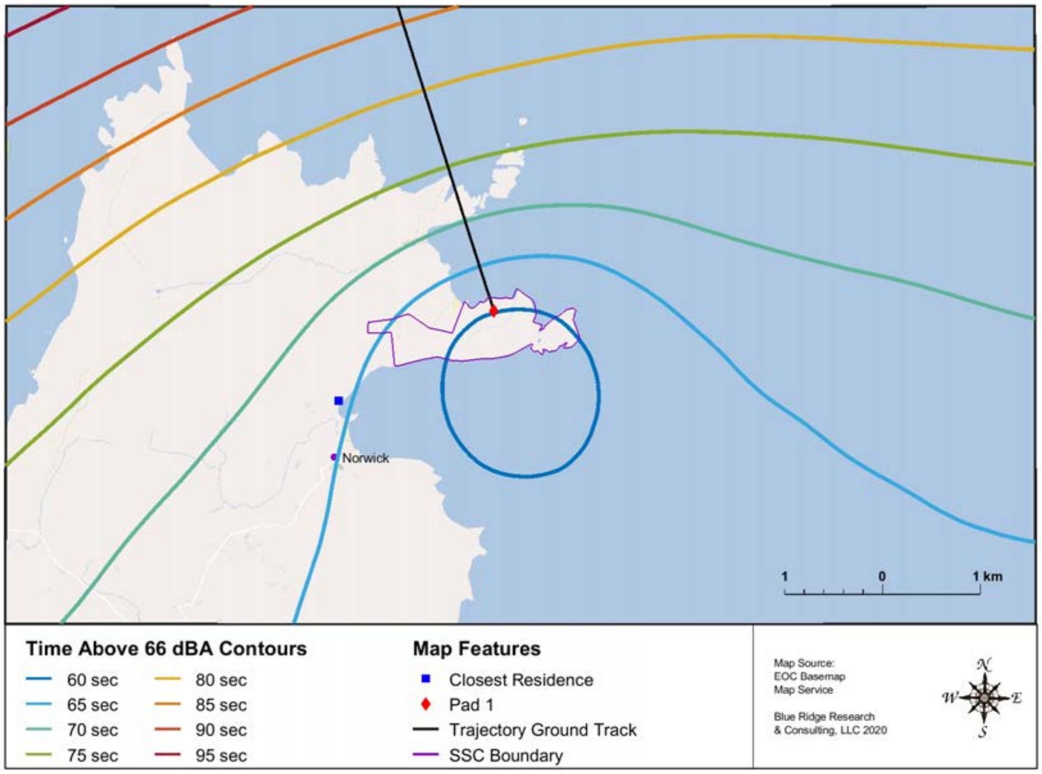


Figure 28. Time above 66 dBA contours for a SCLV launch from SSC Pad 1

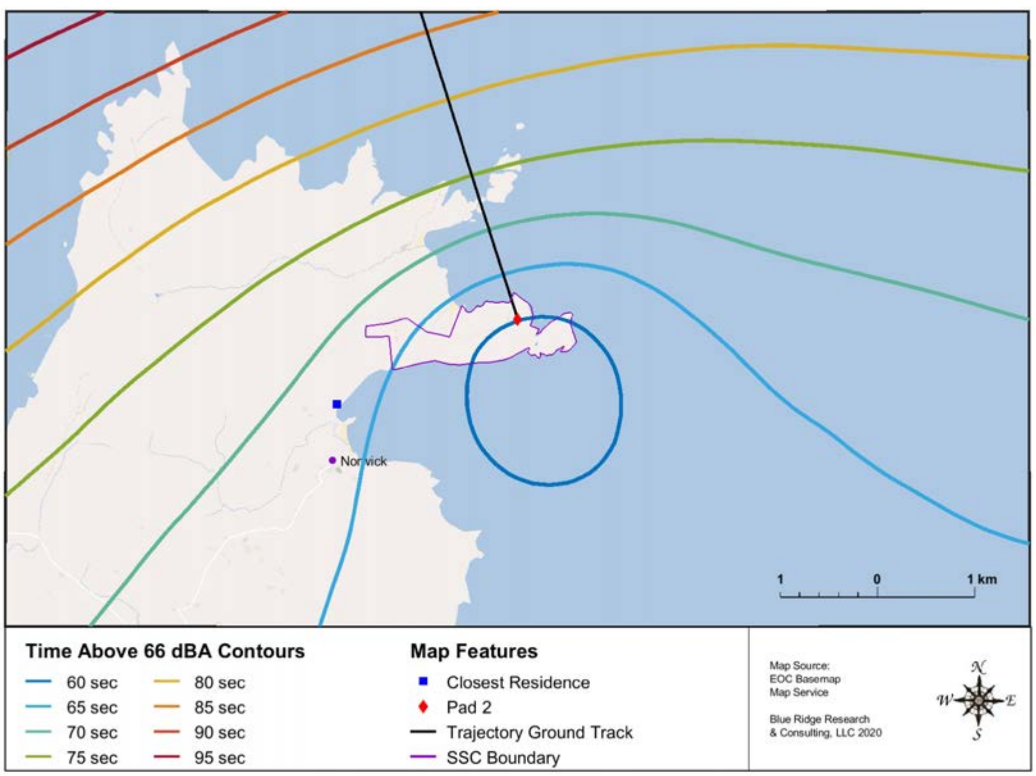


Figure 29. Time above 66 dBA contours for a SCLV launch from SSC Pad 2

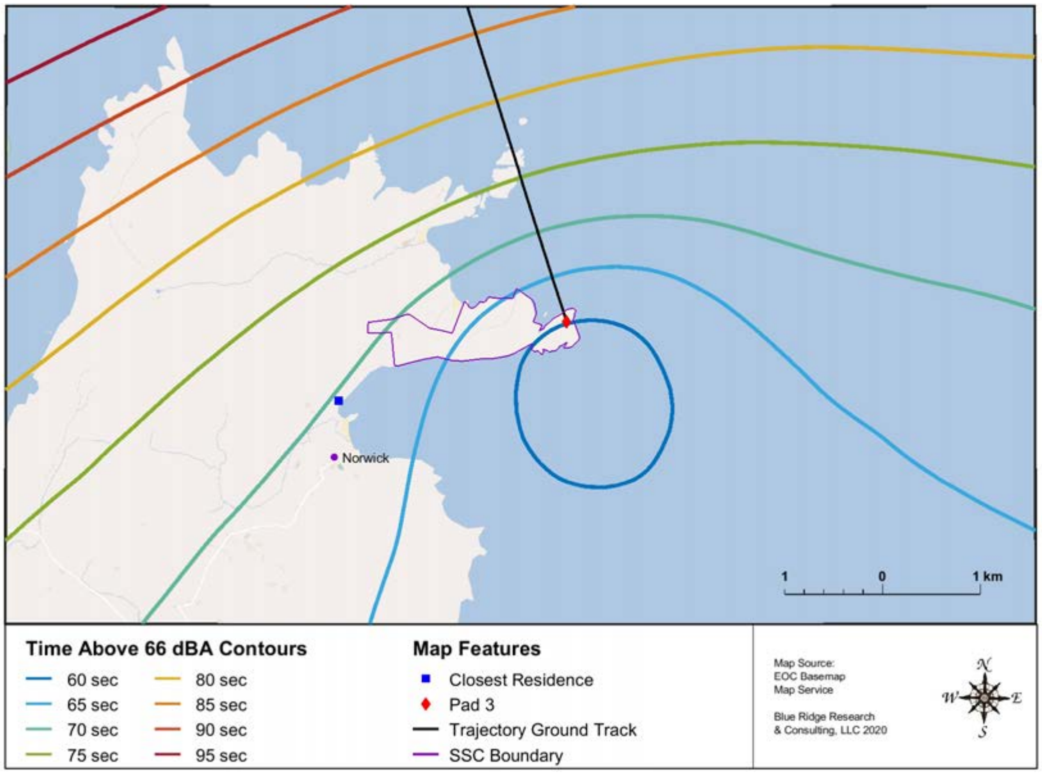


Figure 30. Time above 66 dBA contours for a SCLV launch from SSC Pad 3

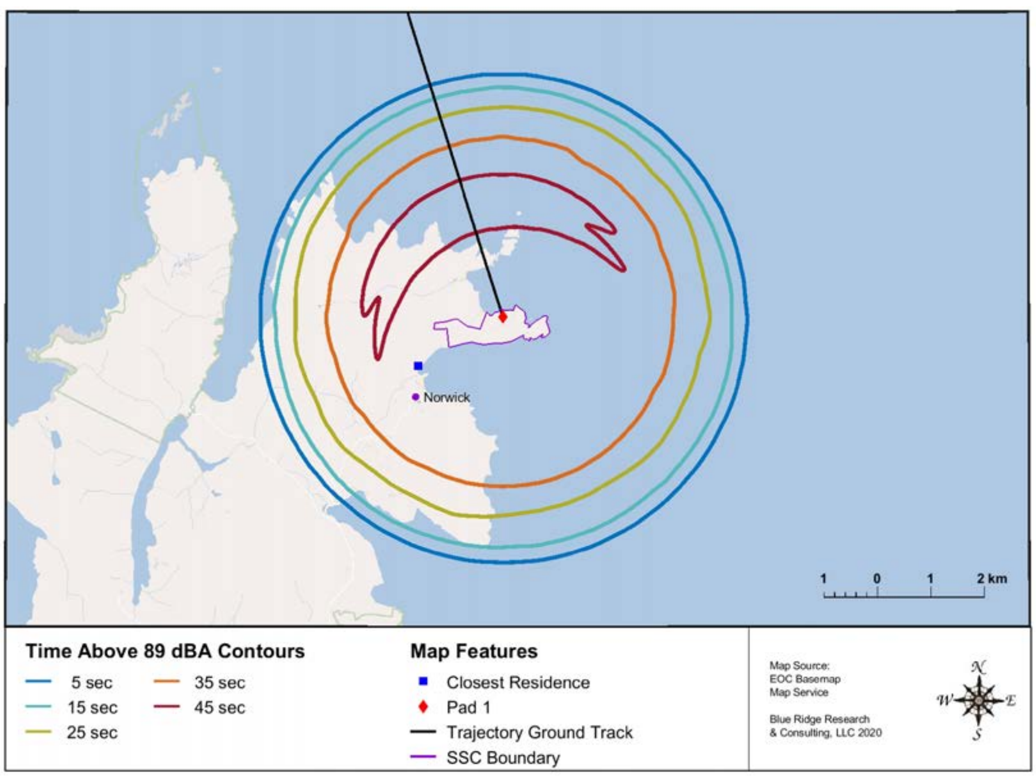


Figure 31. Time above 89 dBA contours for a SCLV launch from SSC Pad 1

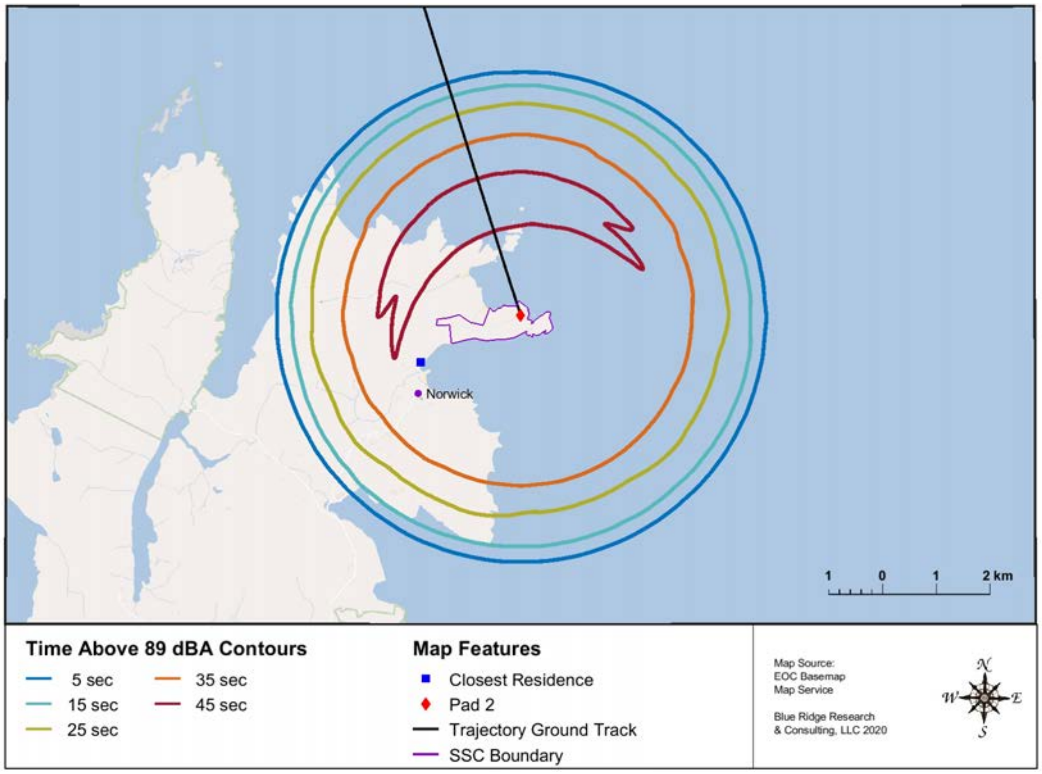


Figure 32. Time above 89 dBA contours for a SCLV launch from SSC Pad 2

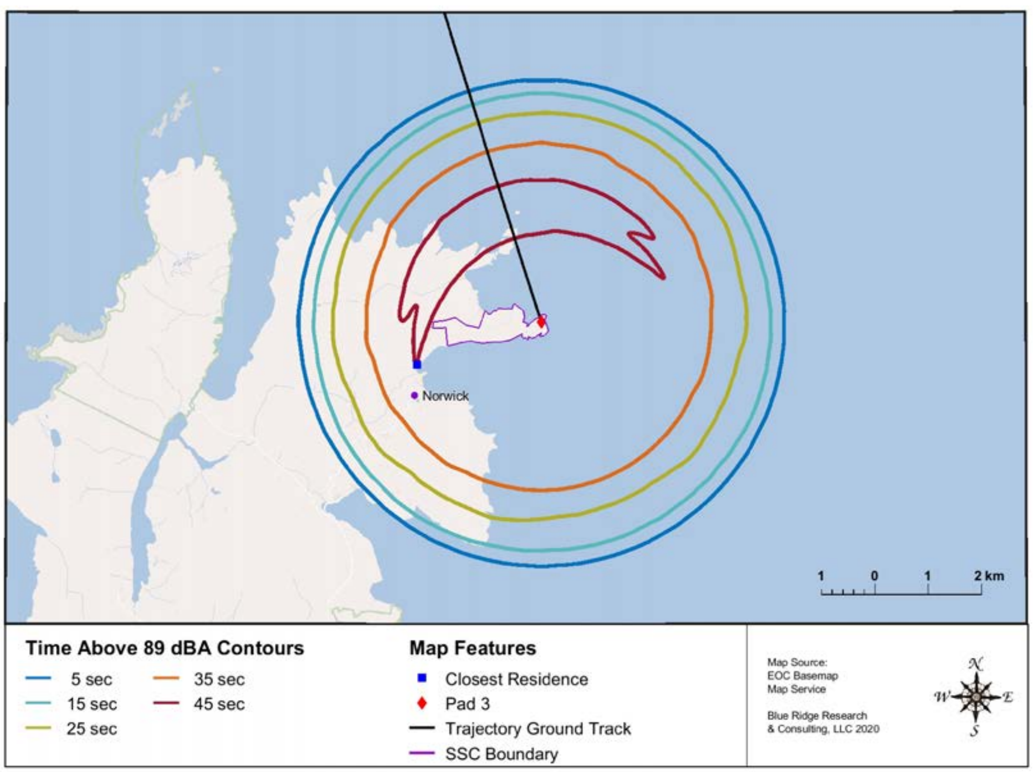


Figure 33. Time above 89 dBA contours for a SCLV launch from SSC Pad 3

5.1.4 Maximum Unweighted Sound Level (L_{max})

The modeled L_{max} contours associated with SCLV operations from SSC are presented in Figure 34 to Figure 39. For reference, the potential for structural damage claims is approximately one damage claim per 100 households exposed at 120 dB and one in 1,000 households at 111 dB [23].

Launch Operations – The 120 dB and 111 dB contours for SCLV launch events from Pad 1, Pad 2, and Pad 3 are shown in Figure 34, Figure 32, and Figure 36, respectively. The modeled 120 dB and 111 dB contours are limited to radii of 1.0 km and 2.5 km from the pad nearest the community, respectively. The closest residence and Norwick lie outside the 120 dB contour, but within the 111 dB contour.

Static Operations – The 120 dB and 111 dB contour for SCLV static events at Pad 1, Pad 2, and Pad 3 are shown in Figure 37, Figure 38, and Figure 39, respectively. For a SCLV static event, a receptor located along the peak directivity angle may experience L_{max} values of 120 dB and 111 dB at approximately 1.0 km and 2.4 km from the pad nearest the community, respectively.

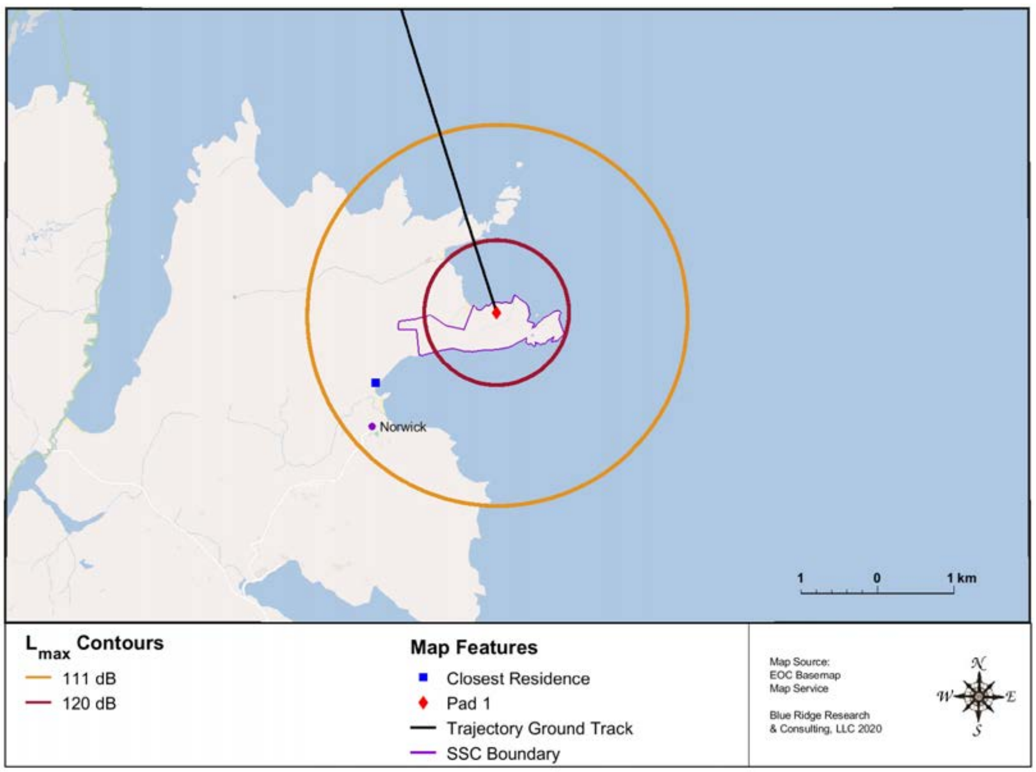


Figure 34. L_{max} contours for a SCLV launch from SSC Pad 1

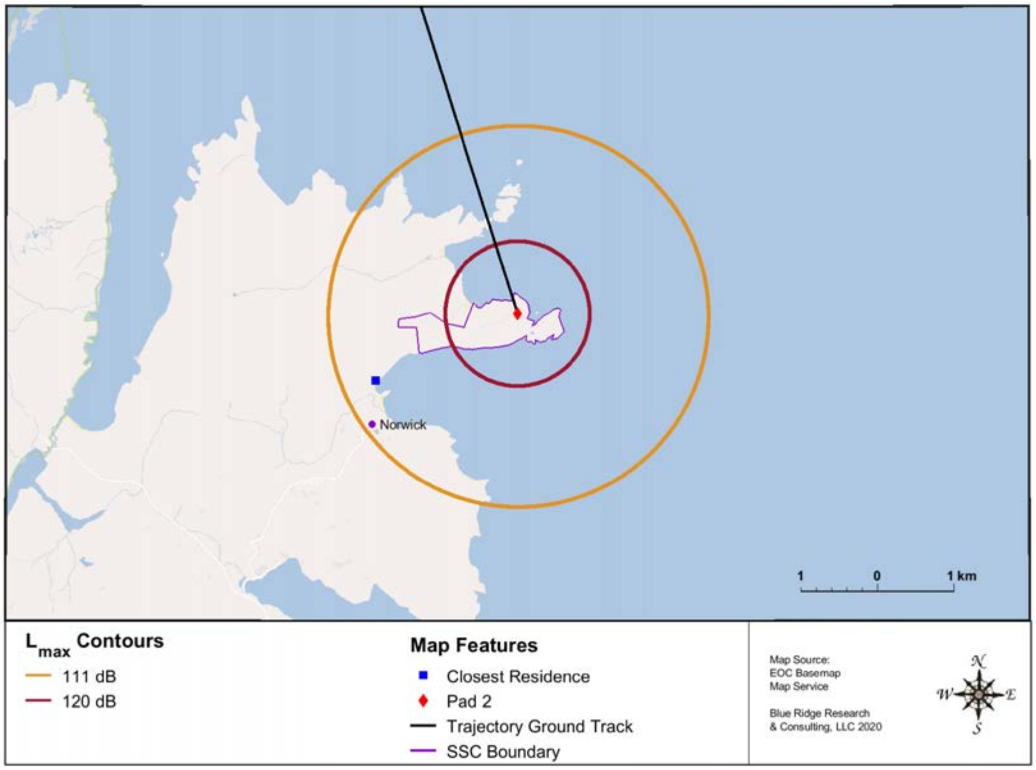


Figure 35. L_{max} contours for a SCLV launch from SSC Pad 2

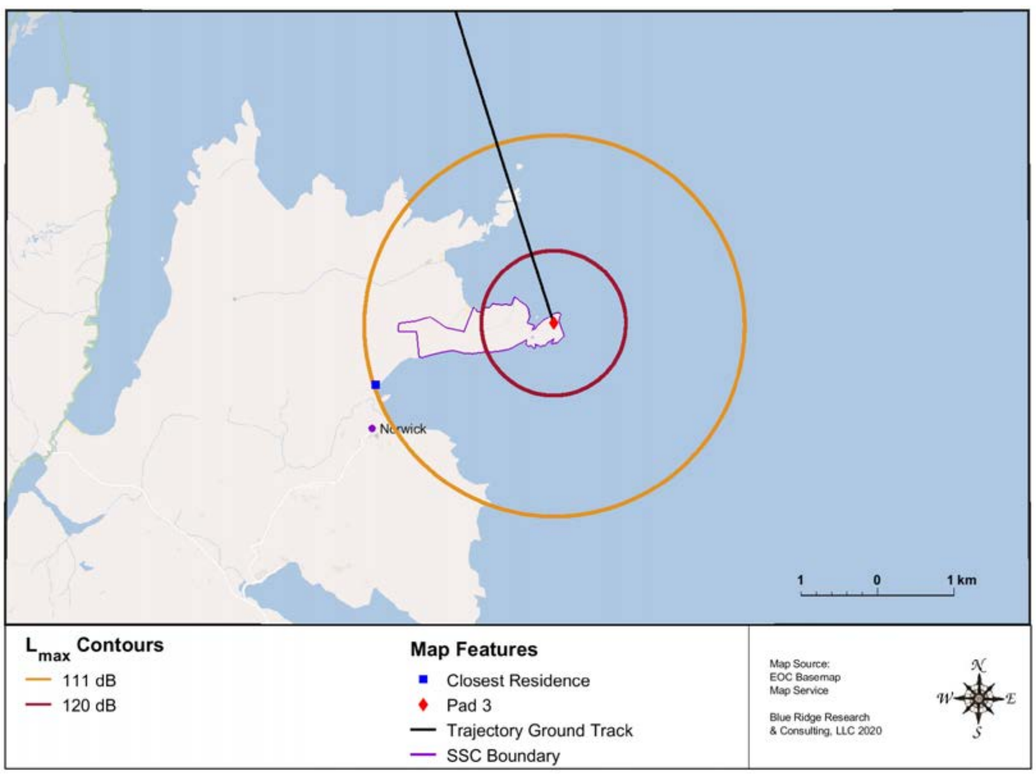


Figure 36. L_{max} contours for a SCLV launch from SSC Pad 3

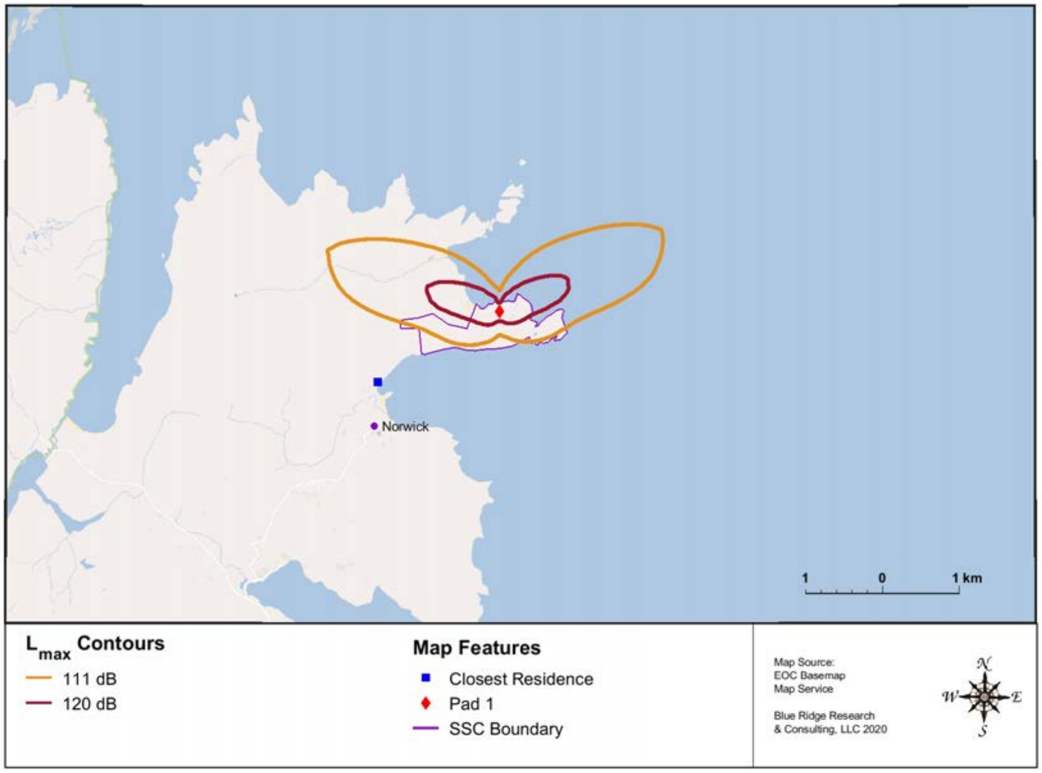


Figure 37. L_{max} contours for a SCLV static fire from SSC Pad 1

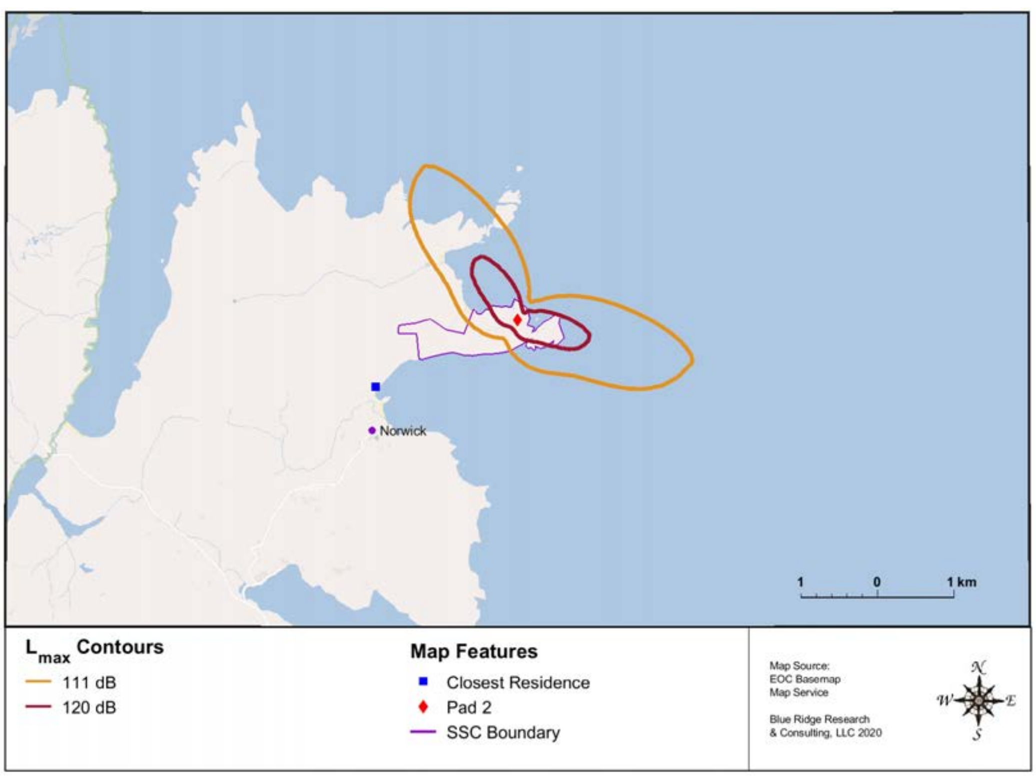


Figure 38. L_{max} contours for a SCLV static fire from SSC Pad 2

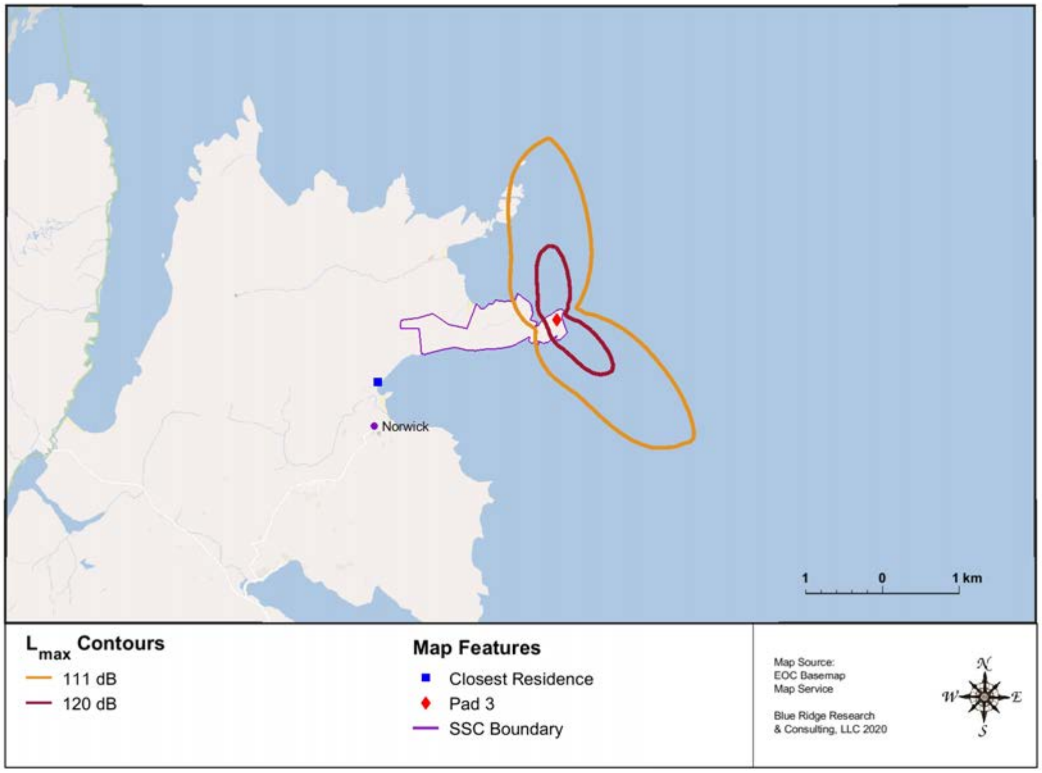


Figure 39. L_{max} contours for a SCLV static fire from SSC Pad 3

5.2 Single Event Sonic Boom Metrics and Effects

Individual launch site operations are evaluated using peak overpressure for sonic booms. To evaluate the sonic boom impacts from SSC operations, the nominal trajectory from the center launch site (Pad 2) was modeled. The resulting sonic boom footprint spans a much larger geographic area relative to the distance between adjacent pads, thus the results from Pad 1 and Pad 3 will produce similar levels with minor deviations to the precise location.

The sonic boom peak overpressure contours for the modeled SCLV launch operations are presented in Figure 40. The sonic boom footprint produced by the SCLV launch vehicle has a long, narrow, forward-facing, crescent-shaped focus boom region beginning 60 km downrange of the launch site. The focus boom region is generated because the launch vehicle continuously accelerates and pitches downward as it ascends. The maximum peak overpressure along the focus boom region is predicted to be approximately 5.4 psf. However, these high levels would only occur in extremely small areas along the focus boom region. As the rocket gains altitude, the sonic boom peak overpressure gradually decreases, and the crescent-shaped contours become slightly wider.

The sonic booms were modeled based on a single launch trajectory at a nominal azimuth of 343° relative to true north. The sonic boom peak overpressure contours for the modeled SCLV launch operation are predicted to be entirely over water. Thus, the potential for structural damage and hearing damage (with regards to humans) is not expected. The exact location of the sonic boom footprint produced by each SCLV launch operation will be highly dependent on the vehicle configuration, trajectory, and atmospheric conditions at the time of flight.

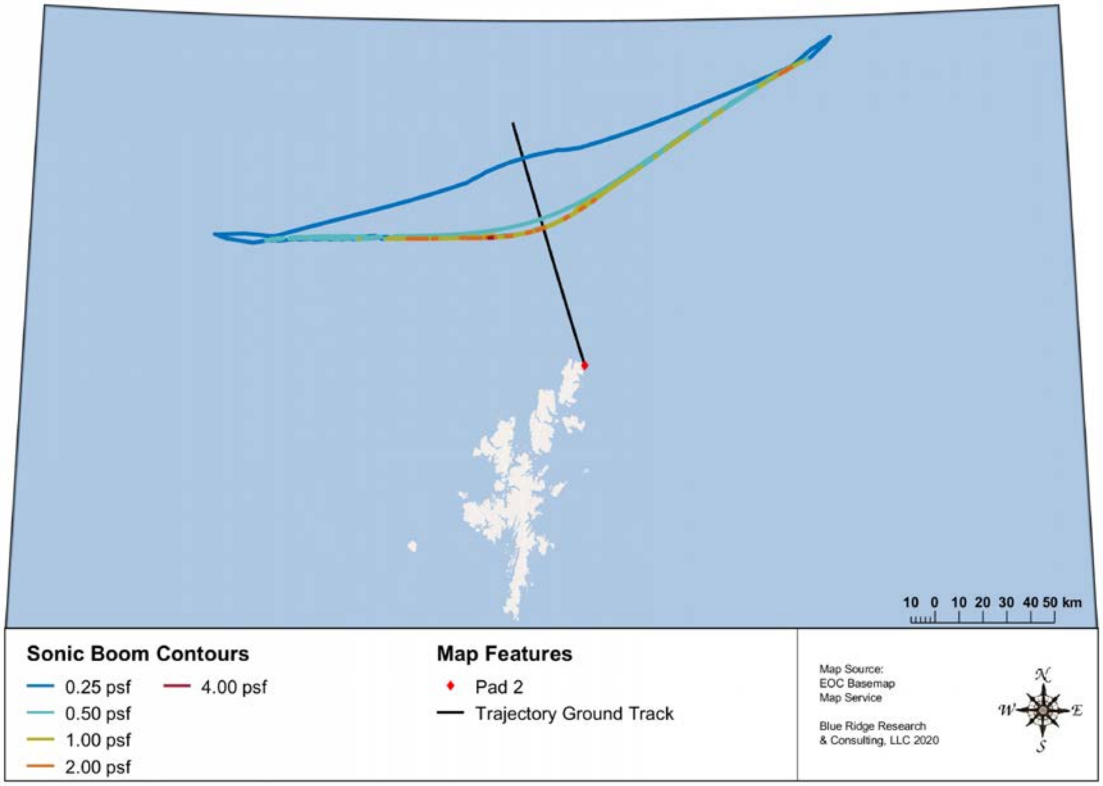


Figure 40. Sonic boom peak overpressure contours for a SCLV launch from SSC

5.3 Cumulative Noise Metrics

The potential for long-term community annoyance is assessed using A-weighted L_{den} for launch vehicle noise and C-weighted L_{den} for sonic booms.

Launch Site Operations

To assess cumulative noise impacts, a criteria of 55 dBA is used by the UK government. The L_{den} contours for all SSC launch and static operations are presented in Figure 41. The L_{den} 55 dBA contours extend approximately 3.3 km from the launch pad nearest the community. This area encompasses the closest residence, which is modeled to receive 59 dBA. Norwick is also encompassed by the 55 dBA contour.

The sonic booms resulting from the modeled launch trajectory occur entirely over the Atlantic Ocean. Therefore, with respect to human annoyance, noise impacts due to sonic booms for the launch trajectory are not expected. Thus, a quantitative L_{den} analysis was not performed.

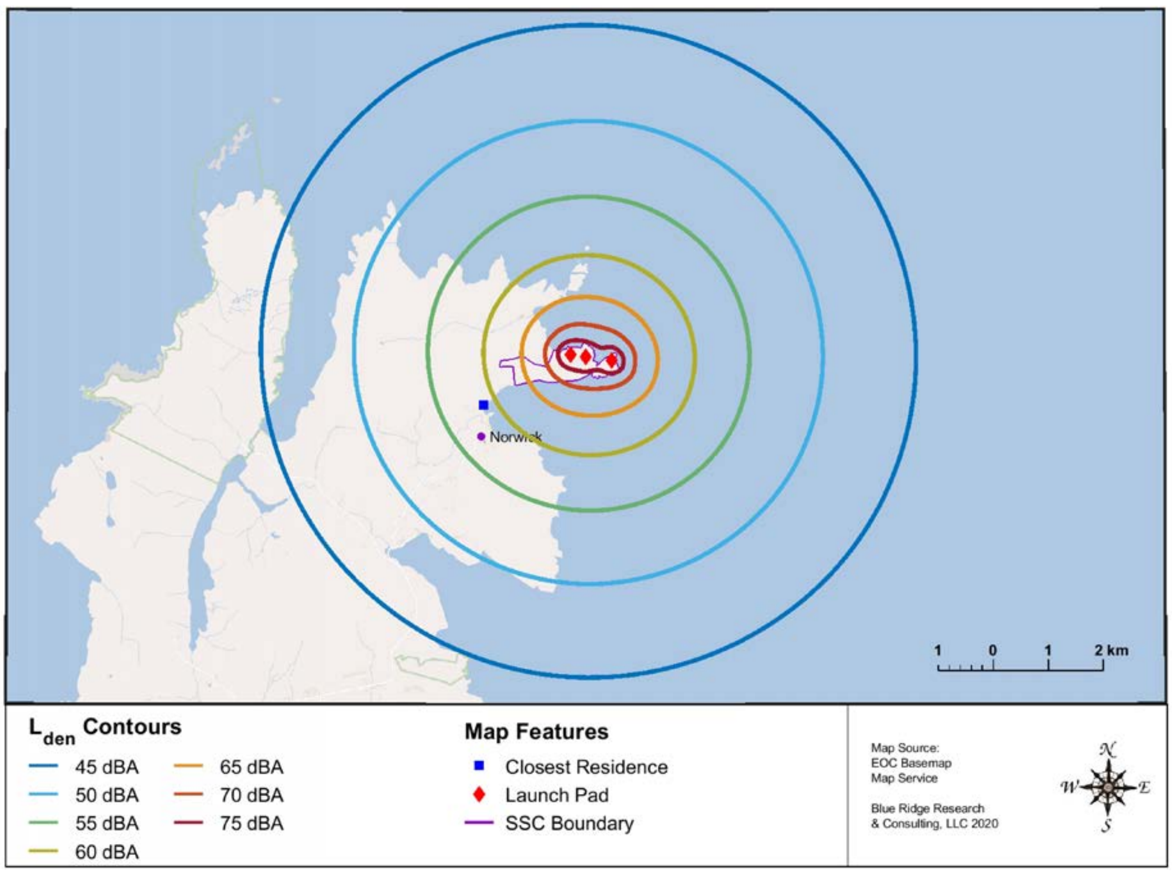


Figure 41. L_{den} contours for SCLV launch and static operations from all pads at SSC

6 Summary

This report documents the noise study performed as part of SSC's efforts on the EIA for the proposed SCLV operations. SSC plans to conduct launch and static operations of SCLV launch vehicles from three pads. The potential impacts of launch vehicle noise and sonic booms are evaluated on a cumulative basis in terms of human annoyance. In addition, potential impacts are evaluated on a single-event basis in relation to hearing conservation, sleep disturbance, speech interference, and structural damage.

Single Event Noise Results with respect to Hearing Conservation

An upper limit noise level of $L_{A,max}$ 115 dBA is used as a guideline to protect human hearing from long-term continuous daily exposures to high noise levels and to aid in the prevention of NIHL. There are no residences within the land area encompassed by the 115 dBA noise contours resulting from SCLV operations.

For impulsive noise events such as sonic booms, the potential for impacts to people in the community with regards to hearing conservation is not expected as the modeled sonic boom footprint is entirely over water.

Single Event Noise Results with respect to Sleep Disturbance

Studies have found that ASEL above 90 dBA generally leads to sleep disturbance. Northern Unst is encompassed by the 90 dBA noise contours resulting from SCLV launch operations. Thus, the potential for sleep disturbance exists for nighttime launch operations.

Single Event Noise Results with respect to Structural Damage

The potential for structural damage claims is approximately one damage claim per 100 households exposed at 120 dB and one in 1,000 households at 111 dB [23]. While there are no residences within the land area encompassed by the 120 dB noise contours resulting from SCLV operations, the closest residence and Norwick lie between the 120 dB and 111 dB contours.

For impulsive noise events such as sonic booms, noise impacts to structures are not expected as the modeled sonic boom footprint is entirely over water. Thus, the potential for structural damage is negligible.

Cumulative Noise Results

The L_{den} 55 dBA contour is used to identify the potential for significant noise impacts resulting from the propulsion noise generated by SCLV operations. The area identified within the 55 dBA contour for cumulative noise impacts includes the closest residence and Norwick.

For impulsive noise events such as sonic booms, cumulative noise impacts with respect to human annoyance are not expected as the modeled sonic boom footprint is entirely over water.

7 References

[1] US Navy, "Discussion of Noise and Its Effect on the Environment, Appendix H2," December 2016.

[2] B. Berglund and T. Lindvall, "Community Noise," Editors, Stockholm, Sweden, 1995.

[3] F. Fahy and D. Thomspon, Fundamentals of Sound and Vibration, 2nd ed., CRC Press, 2015.

[4] "F-22A Beddown Environmental Assessment," Appendix D Aircraft Noise Analysis and Airspace Operations, June 2006.

[5] ANSI S1.4A-1985, "Specification of Sound Level Meters," 1985.

[6] C. M. Harris, Handbook of Acoustical Measurements and Noise Control, 1998.

[7] US Air Force, "Supplemental Environmental Impact Statement for F-35 Beddown at Eglin Air Force Base, Florida, Draft Appendix E: Noise," September 2010.

[8] US Environmental Protection Agency (USEPA), "Protective Noise Levels," Office of Noise Abatement and Control, Washington, D.C. USEPA Report 550/9-79-100, November 1978.

[9] FAA, "Environmental Assessment for the Site, Launch, Reentry and Recovery Operations at the Kistler Launch Facility, Nevada Test Site (NTS)," April 2002.

[10] Department of the Navy, "Aircraft Noise Assessment," NAS Oceana Strike Fighter Transition: Final EA. Appendix A-53, October 2017.

[11] T. Schultz, "Synthesis of Social Surveys on Noise Annoyance," *J. Acoust. Soc. Am.,* vol. 64, no. 2, pp. 377-405, August 1978.

[12] L. Finegold, C. Harris and H. v. Gierke, "Community Annoyance and Sleep Disturbance: Updated Criteria for Assessing the Impacts of General Transportation Noise on People," *Noise Control Engineering Journal,* vol. 42, pp. 25-30, 1994.

[13] FAA, *Environmental Impacts: Policies and Procedures, Order 1050.1F,* 2015.

[14] FAA, "Order 1050.1 Desk Reference DRAFT," May 2018.

[15] Committee on Hearing, Bioacoustics, and Biomechanics (CHBB), "Assessment of community response to high-energy impulsive sounds," National Academy Press, National Research Council, Washington, D.C., 1981.

[16] European Comission, "Environmental Noise Directive 2002/49/EC," 2002.

[17] OSHA, "Federal Regulation Title 29 - Labor, Subtitle B, Capter XVII, Part 1910 - Occupational Saftey and Health Standards, Subpart G - Occupational Health and Environmental Control, 1910.95 -

Occupational noise exposure," [Online]. Available: http://www.ecfr.gov/. [Accessed December 2019].

[18] NIOSH, *Criteria for a Recommended Standard-Occupational Exposure to Noise – Revised Criteria 1998, DHHS (NIOSH) Pub. No. 98-126,* 1998.

[19] UK Statutory Instruments, "No. 1643, Regulation 4, The Control of Noise at Work Regulations," 2005.

[20] OSHA, "Federal Regulation Title 29 - Labor, Subtitle B, Capter XVII, Part 1910 - Occupational Saftey and Health Standards, Subpart G - Occupational Health and Environmental Control, 1910.95 - Occupational noise exposure," [Online]. Available: http://www.ecfr.gov/. [Accessed April 2017].

[21] J. Ollerhead and C. Jones, "Aircraft noise and sleep disturbance: a UK field study," *Proceedings Noise as a Public Health Problem,* 1993.

[22] B. a. B. Committee on Hearing, "Guidelines for Preparing Environmental Impact Statements on Noise," National Academy of Sciences, Washington DC, 1977.

[23] S. Guest and R. M. Slone Jr., *Structural Damage Claims Resulting from Acoustic Environments Developed During Static Firing of Rocket Engines,* San Antonio, Texas, April 1972.

[24] J. Haber and D. Nakaki, "Sonic Boom Damage to Conventional Structures. HSD-TR-89," 1989.

[25] L. Sutherland, *Effects of Sonic Boom on Structures, Lecture 3 of Sonic Boom: Prediction and Effects, AIAA Short Course,* 1990.

[26] R. L. Hershey and T. H. Higgins, *Statistical Model of Sonic Boom Structural Damage. FAA RD-76-87,* 1976.

[27] R. White, *Effects of Repetitive Sonic Booms on Glass Breakage,* 1972.

[28] K. M. Eldred, *NASA SP-8072: Acoustic Loads Generated By the Propulsion Systems,* NASA, 1971.

[29] M. M. James, A. R. Salton, K. L. Gee, T. B. Neilsen and S. A. McInerny, *Full-scale rocket motor acoustic tests and comparisons with empirical source models,* vol. 18, J. Acoust. Soc. Am., 2014.

[30] S. H. Guest, *NASA TN D-1999: Acoustic Efficiency Trends for High Thrust Boosters,* NASA Marshall Space Flight Center: NASA, 1964.

[31] K. Viswanathan and M. J. Czech, *Measurements and Modeling of Effect of Forward Flight on Jet Noise,* vol. 49, AIAA, 2011.

[32] S. Saxena and P. Morris, *Noise Predictions for High Subsonic Single and Dual-Stream Jets in Flight,* Colorado Springs, CO, 2012.

[33] R. Buckley and C. L. Morfey, *Flight Effects on Jet Mixing Noise: Scaling Laws Predicted for Single Jets from Flight Simulation Data,* Atlanta, GA: AIAA, 1983.

[34] R. Buckley and C. L. Morfey, *Scaling Laws for Jet Mixing Noise in Simulated Flight and the Prediction Scheme Associated,* Williamsburg, VA: AIAA, 1984.

[35] J. Haynes and J. R. Kenny, *Modifications to the NASA SP-8072 Distributed Source Method II,* Miami, Florida: AIAA, 2009.

[36] M. M. James, A. R. Salton, K. L. Gee, T. B. Neilsen, S. A. McInerny and R. J. Kenny, *Modification of directivity curves for a rocket noise model,* vol. 18, J. Acoust. Soc. Am., 2014.

[37] NASA, "Terrestrial Envrionment (Climatic) Criteria Gudelines for use in Aerospace Vehicle Devlopment," NASA TM-4511, 1993.

[38] Handbook of Astronautical Engineering, McGraw-Hill, 1961.

[39] NOAA, NASA, USAF, "U.S. Standard Atmosphere, 1976," U.S. Government Priting Office, Washington, D.C..

[40] National Climatic Data Center, "Global gridded upper air statistics, 1980-1995," National Climatic Data Center, Asheville, NC, 1996.

[41] S. A. McInerny, K. L. Gee, J. M. Downing and M. M. James, *Acoustical Nonlinearities in Aircraft Flyover Data,* Rome, Italy: AIAA, 2007.

[42] S. A. McInerny and S. M. Ölçmen, *High-Intensity Rocket Noise: Nonlinear Propagation, Atmospheric Absorption, and Characterization,* vol. 117, J. Acoust. Soc. Am., 2005, pp. 578-591.

[43] D. F. Pernet and R. C. Payne, *Non-linear propagation of signals in airs,* vol. 17, Journal of Sound and Vibration, 1971, pp. 383-396.

[44] K. L. Gee, V. W. Sparrow, A. A. Atchley and T. B. Gabrielson, *On the Perception of Crackle in High Amplitude Jet Noise,* vol. 45, AIAA, 2007, pp. 593-598.

[45] J. E. Ffowcs, J. Simson and V. J. Virchis, *Crackle: an annoying component of jet noise,* vol. 71, Journal of Fluid Mechanics, 1975, pp. 251-271.

[46] K. L. Gee, V. W. Sparrow, M. M. James, J. M. Downing, C. M. Hobbs, T. B. Gabrielson and A. A. Atchley, *The role of nonlinear effects in the propagation of noise from high-power jet aircraft,* vol. 123, J. Acoust. Soc. Am., 2008, pp. 4082-4093.

[47] K. L. Gee, V. W. Sparrow, M. M. James, J. M. Downing, C. M. Hobbs, T. B. Gabrielson and A. A. Atchley, *Measurement and Prediction of Noise Propagation from a High-Power Jet Aircraft,* Cambridge, Massachusetts: AIAA, 2006.

[48] C. Chessel, *Propagation of noise along a finite impedance boundary,* vol. 62, J. Acoust. Soc. Am., 1977, pp. 825-834.

[49] T. Embleton, J. Piercy and G. Daigie, *Effective flow resistivity of ground surfaces determined by acoustical measurements,* vol. 74, J. Acoust. Soc. Am., 1983, pp. 1239-1244.

[50] G. A. Daigle, *Effects of atmospheric turbulence on the interference sound waves above a finite impedance boundary,* vol. 65, J. Acoust. Soc. Am., 1979.

[51] H. W. Carlson, *NASA SP-147: Experimental and Analytical Research on Sonic Boom Generation at NASA,* NASA Langley Research Center: NASA, 1967, p. 10.

[52] K. J. Plotkin and L. C. Sutherland, *Sonic Boom: Prediction and Effects,* Tallahassee, FL, Florida: AIAA, 1990, pp. 1-7.

[53] K. A. Bradley, C. Wilmer and V. S. Miguel, "PCBoom: Sonic Boom Model for Space Operations, Version 4.99 User Guide," Wyle Laboratories, Inc., Arlington, VA, 2018.

[54] K. Plotkin, "Review of Sonic Boom Theory," *AIAA,* pp. 89-1105, 1989.

[55] J. A. Page, K. J. Plotkin and C. Wilmer, "PCBoom Version 6.6 Technical Reference and User Manual," December 2010.

[56] K. J. Plotkin and F. Grandi, "Computer Models for Sonic Boom Analysis: PCBoom4, CABoom, BooMap, CORBoom, Wyle Research Report WR 02-11," 2002.

[57] N. C. D. Center, "Global gridded upper air statistics, 1980-1995," National Climatic Data Center, Asheville, 1996.

[58] J. Panda, R. N. Mosher and B. J. Porter, *Identification of noise sources during rocket engine test firings and a rocket launch using a microphone phased-array, TM 216625,* NASA, 2013.

[59] NASA, "Kennedy NASA Procedural Requirements," 2013.

[60] H. W. Carlson, "NASA Technical Paper 1122: Simplified Sonic-Boom Prediction," NASA, 1978.

Appendix 8.2 Summary of Legislation and Guidance

PAN1/2011

PAN1/2011 (Scottish Government, 2011), sets out a series of noise issues for planning authorities to consider when making decisions on planning applications. A Technical Advice Note (TAN) on Assessment of Noise (Scottish Government, 2011) has been published to accompany PAN 1/2011. In Appendix 1 of the TAN are codes of practice for the assessment of various sources of noise. It also identifies British Standard BS 5228 for guidance on construction site noise control, and as a method of prediction of noise from construction sites.

The TAN recommends that the daytime period includes the hours 07:00 – 23:00 and the night-time period 23:00 – 07:00.

The TAN suggests that equivalent continuous noise level over a time period, T ($L_{Aeq,T}$), is a good general purpose index for environmental noise; this index is commonly referred to as the "ambient" noise level. It further notes that road traffic noise is commonly evaluated using the $_{LA10,18hr}$ level, and the $L_{A90,T}$ index is used to describe the "background" noise level.

Table 2.4 of the TAN (reproduced here as Table 1) provides an example method for determining the magnitude of noise impacts at proposed noise sensitive developments.

Table 1 - PAN1/2011 TAN Example of associating changes in noise levels with magnitudes of impacts for a new road in a residential area

(existing – target) Noise level, x dB $L_{A10,18hr}$ (07:00 – 23:00)	Magnitude of impact
x = 5	Major adverse
3 = x < 5	Moderate adverse
1 = x < 3	Minor adverse
0 < x < 1	Negligible adverse
x = 0	No change

Table 2.6 of the TAN (reproduced here as Table 2) provides a matrix for determining the level of impact significance dependent on the sensitivity of the receptor.

Table 2 - PAN1/2011 TAN Significance of effects

Magnitude of impact	Level of significance relative to sensitivity of receptor		
	Low	Medium	High
Major	Slight/Moderate	Moderate/Large	Large/Very Large
Moderate	Slight	Moderate	Moderate/Large
Minor	Neutral/Slight	Slight	Slight/Moderate
Negligible	Neutral/Slight	Neutral/Slight	Slight
No change	Neutral	Neutral	Neutral

Table 2.1 of the TAN (reproduced below as Table 3) provides the criteria to define levels of sensitivity for each type of NSR.

Table 3 - PAN1/2011 TAN Level of Noise Sensitivity for Different Types of NSR

Sensitivity	Description	Example of NSR
High	Receptors where people or operations are particularly susceptible to noise	• Residential, including private gardens where appropriate • Quiet outdoor areas used for recreation • Conference facilities • Theatres/Auditoria/Studios • Schools during the daytime • Hospitals/residential care homes • Places of worship
Medium	Receptors moderately sensitive to noise, where it may cause some distraction or disturbance	• Offices • Bars/Cafes/Restaurants where external noise may be intrusive • Sports grounds when spectator noise is not a normal partof the event and where quiet conditions are necessary (e.g. tennis, golf, bowls)
Low	Receptors where distraction or disturbance from noise is minimal	• Buildings not occupied during working hours • Factories and working environments with existing high noise levels • Sports grounds when spectator noise is a normal part for the event • Night clubs

BS4142:2014+A1:2019 - Methods for Rating and Assessing Industrial and Commercial Sound

BS 4142 (BSI, 2014) describes methods for rating and assessing sound[1] from industrial or commercial premises. The methods detailed in BS4142 use outdoor sound levels to assess the likely effects on people inside or outside a residential dwelling upon which sound is incident.

The Standard provides methods for determining the following:

- Rating levels for sources of industrial and commercial sound; and
- Ambient, background and residual sound levels.

These may be used for assessing sound from proposed, new, modified or additional sources of sound of a commercial or industrial nature.

The Standard makes use of the following terms:

- **Ambient sound level, L_a = $L_{Aeq,T}$** – the equivalent continuous sound pressure level of the totally encompassing sound in a given situation at a given time, usually from multiple sources, at the assessment location over a given time interval, T;
- **Background sound level, $L_{A90,T}$** – the A-weighted sound pressure level that is exceeded by the residual sound at the assessment location for 90 percent of a given time interval, T, measured using time weighting F and quoted to the nearest whole number of decibels;
- **Specific sound level, L_s = $L_{Aeq,T}$** – the equivalent continuous sound pressure level produced by the specific sound source at the assessment location over a given reference time interval, T;
- **Rating level, $L_{Ar,Tr}$** – the specific sound level plus any adjustment for the characteristic features of the sound; and
- **Residual sound level, $L_{r = LAeq,T}$** – the equivalent continuous sound pressure level at the assessment location when the specific sound source is suppressed to such a degree that it does not contribute to the ambient sound, over a given reference time interval, T.

The Standard determines the degree of noise impact by comparison of the background noise level at noise sensitive receptors (NSR) in the absence of the industrial facility (the specific source) with the ambient sound level when the specific source is operational.

Where particular characteristics, such as tonality, intermittency or impulsivity are present in the noise emissions of the specific source, the Standard requires that "penalties" be added to the specific sound level to derive the rating level, to account for the increased annoyance that these can cause. Where no such characteristics are present, or where they are inaudible at the receptor locations then no penalties apply and the rating level is the same as the specific level.

The following impact significance identifiers are provided in the Standard, in which the difference between the specific sound level and measured background level are considered:

- The greater the difference, the greater the magnitude of impact;
- A difference of around +10 dB or more is likely to be an indication of a significant adverse impact;

[1] The Standard refers to sound levels, rather than noise levels, however, these terms can be used interchangeably, as noise is defined as "unwanted sound". This assessment uses the term "noise".

- A difference of around +5 dB is likely to be an indication of an adverse impact;
- The lower the rating level, relative to the measured background level, the less likely that the specific sound source will have an adverse (or significant adverse) impact; and
- Where the rating level does not exceed the background sound level, this is an indication of the specific sound source having a low impact.

Appendix 8.3 Baseline Survey Records

ITPENERGISED
Earth. Smart. Solutions

NOISE DATA PROCESSING

Template Version Tracker

Version	Date	Changes	Updated by	Approved By
1	12/08/2019	Template Setup	Jonas B	Simon W

Project Information

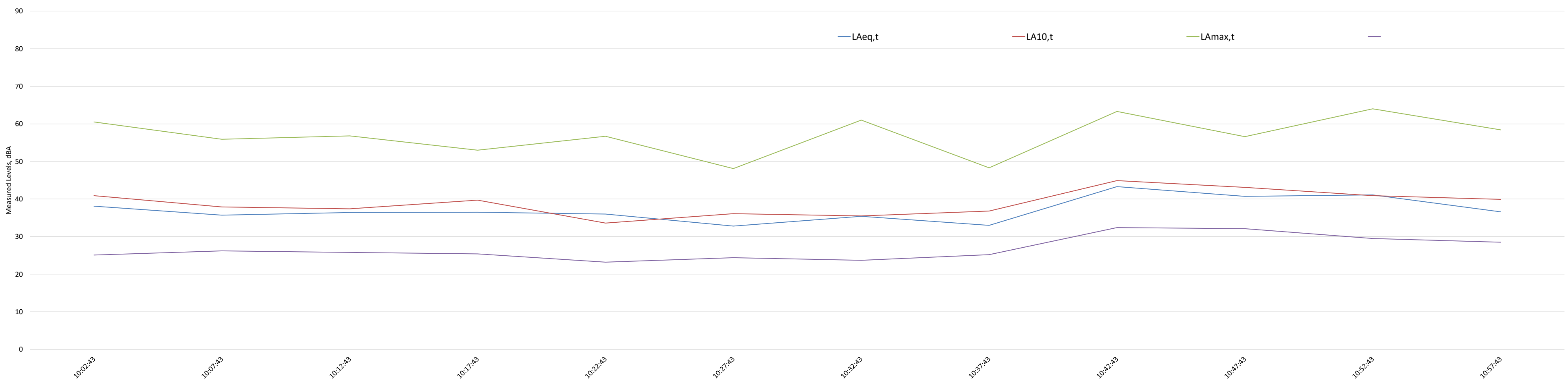
Client
ITPE Project Code

Project Name
Date
File Locations

Version	Date	Notes	Prepared by	Approved By

NMP1 - Unst Airport - Day

NMP Description	Open fields on access track to Unst airfield. Scattered dwellings along road to north, with Balta Sound inlet to the north
Weather Conditions	Dry, 15°C, overcast, low - moderate wind speed (<5 m/s)
Coordinates	HP624478,08115
File #	
Main Noise Sources	Bird calls, bleating sheep
Secondary Noise Sources	Very infrequent vehicle movements on loacl roads (8 movements during measurement), children playing at nearby house
Sound Level Meter Settings	5min averaging period, A-wt, Fast averaging.

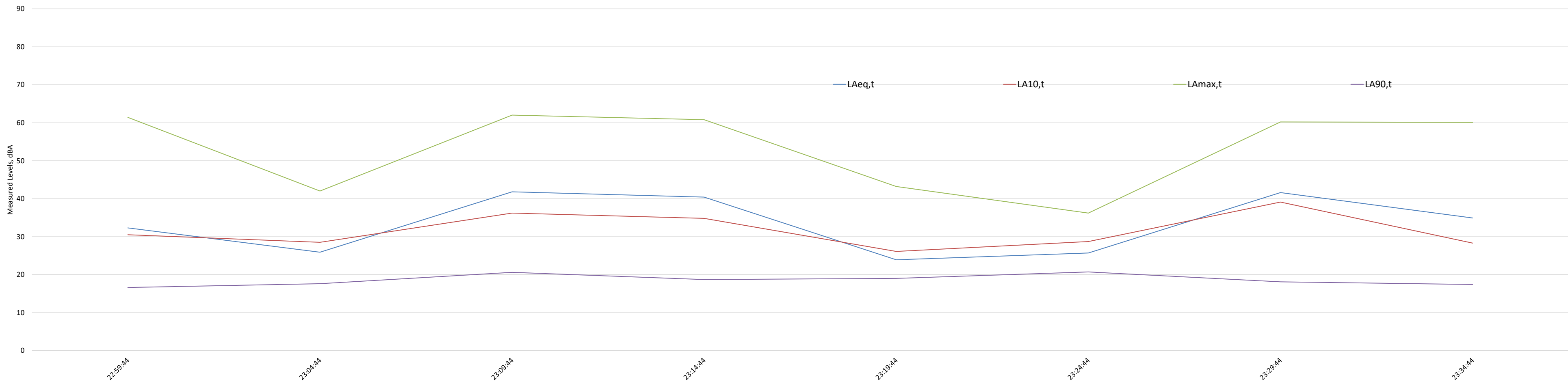


Date	Start Time	Measurement Time	$L_{Aeq.t}$	$L_{Amax.t}$	$L_{A10.t}$	$L_{A90.t}$	Notes
19/07/2018	10:02:43	00d 00:05:00.0	38.1	60.5	40.9	25.1	
19/07/2018	10:07:43	00d 00:05:00.0	35.7	55.9	37.9	26.2	
19/07/2018	10:12:43	00d 00:05:00.0	36.4	56.8	37.4	25.8	
19/07/2018	10:17:43	00d 00:05:00.0	36.5	53.0	39.7	25.4	
19/07/2018	10:22:43	00d 00:05:00.0	36.0	56.7	33.6	23.2	
19/07/2018	10:27:43	00d 00:05:00.0	32.8	48.1	36.1	24.4	
19/07/2018	10:32:43	00d 00:05:00.0	35.4	61.0	35.5	23.7	
19/07/2018	10:37:43	00d 00:05:00.0	33.0	48.3	36.8	25.2	
19/07/2018	10:42:43	00d 00:05:00.0	43.3	63.3	44.9	32.4	
19/07/2018	10:47:43	00d 00:05:00.0	40.7	56.6	43.1	32.1	
19/07/2018	10:52:43	00d 00:05:00.0	41.1	64.0	40.9	29.5	
19/07/2018	10:57:43	00d 00:05:00.0	36.6	58.4	39.9	28.5	

Period	Time (T)	$L_{Aeq.t}$	$L_{Amax.t}$	$L_{A10.t}$	$L_{A90.t}$
Mean	1 hr	38.2	56.9	38.9	26.8
Mode	1 hr	#N/A	#N/A	40.9	#N/A
Min	1 hr	32.8	48.1	33.6	23.2
Max	1 hr	43.3	64.0	44.9	32.4

NMP1 - Unst Airport - Night

NMP Description	Open fields on access track to Unst airfield. Scattered dwellings along road to north, with Balta Sound inlet to the north
Weather Conditions	Still - no wind. 15C, 60% cloud cover, dry.
Coordinates	HP 65083,15077
File #	
Main Noise Sources	Bird calls.
Secondary Noise Sources	Infrequent vehicles passing by on the nearby road.
Sound Level Meter Settings	5min averaging period, A-wt, Fast averaging.

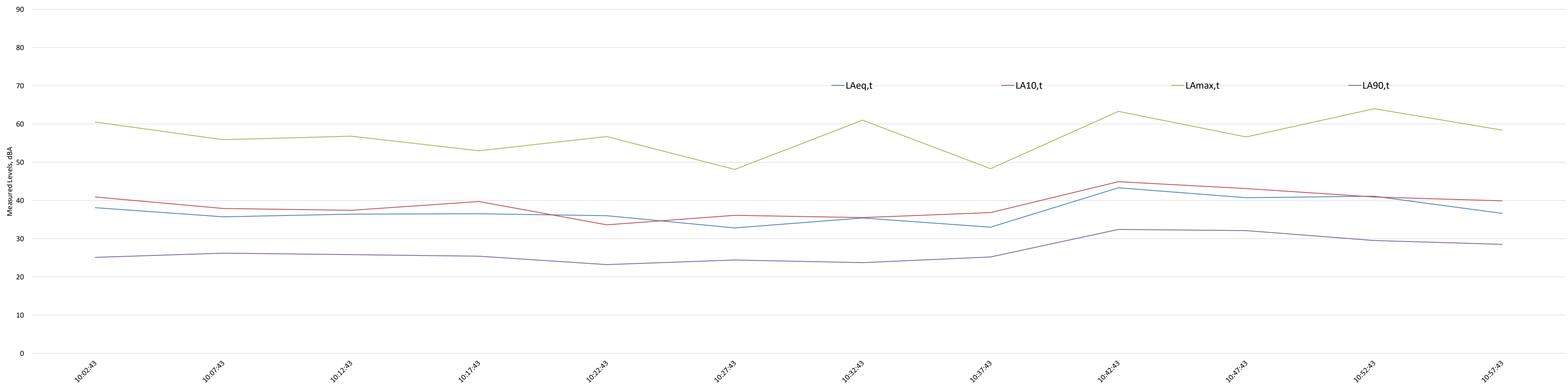


Date	Start Time	Measurement Time	$L_{Aeq.t}$	$L_{Amax.t}$	$L_{A10.t}$	$L_{A90.t}$	Notes
19/07/2018	22:59:44	00d 00:05:00.0	32.3	61.4	30.5	16.6	
19/07/2018	23:04:44	00d 00:05:00.0	25.9	42.0	28.5	17.6	
19/07/2018	23:09:44	00d 00:05:00.0	41.8	62.0	36.2	20.6	
19/07/2018	23:14:44	00d 00:05:00.0	40.4	60.8	34.8	18.7	
19/07/2018	23:19:44	00d 00:05:00.0	23.9	43.2	26.1	19.0	
19/07/2018	23:24:44	00d 00:05:00.0	25.7	36.2	28.7	20.7	
19/07/2018	23:29:44	00d 00:05:00.0	41.6	60.2	39.1	18.1	
19/07/2018	23:34:44	00d 00:01:51.5	34.9	60.1	28.3	17.4	

Period	Time (T)	$L_{Aeq.t}$	$L_{Amax.t}$	$L_{A10.t}$	$L_{A90.t}$
Mean	35 min	37.6	53.2	31.5	18.6
Mode	35 min	#N/A	#N/A	#N/A	#N/A
Min	35 min	23.9	36.2	26.1	16.6
Max	35 min	41.8	62.0	39.1	20.7

NMP2 - North Dale - Day

NMP Description	Open field near access track leading to Saxa Vord radar station.
Weather Conditions	Dry, 15°C, overcast, low - moderate wind speed (<5 m/s)
Coordinates	HP62478,08115
File #	
Main Noise Sources	Bird calls, sheep bleating, rustling of grasses in the wind.
Secondary Noise Sources	Very infrequent road traffic. Very distant/almost inaudible low hum.
Sound Level Meter Settings	5min averaging period, A-wt, Fast averaging.

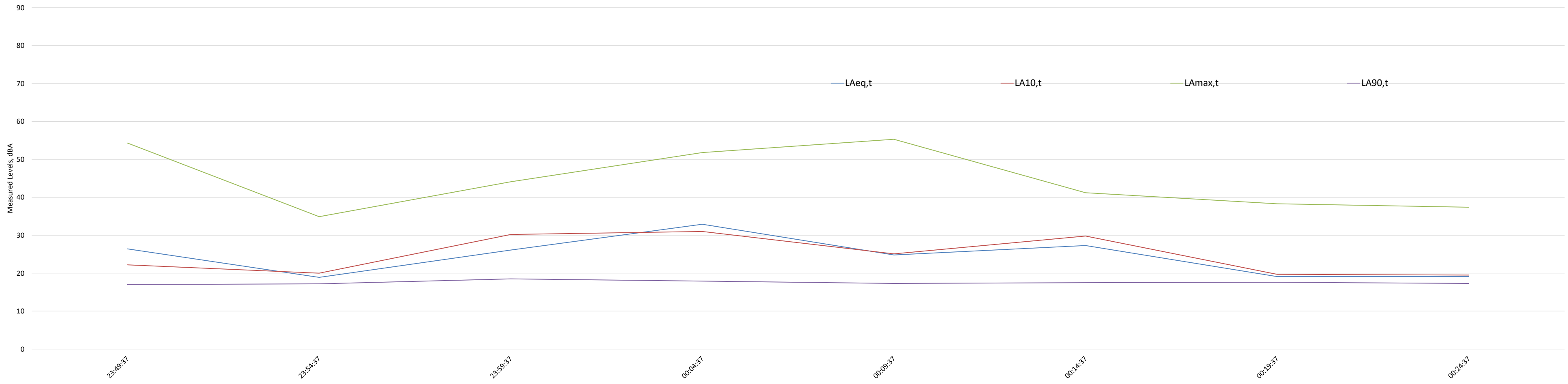


Date	Start Time	Measurement Time	$L_{Aeq,t}$	$L_{Amax,t}$	$L_{A10,t}$	$L_{A90,t}$	Notes
19/07/2018	11:29:47	00d 00:05:00.0	38.4	55.2	40.5	30.9	
19/07/2018	11:34:47	00d 00:05:00.0	37.1	55.5	39.5	30.9	
19/07/2018	11:39:47	00d 00:05:00.0	37.4	52.4	40.2	31.2	
19/07/2018	11:44:47	00d 00:05:00.0	39.5	54.7	42.3	31.9	
19/07/2018	11:49:47	00d 00:05:00.0	37.7	54.0	40.1	33.0	
19/07/2018	11:54:47	00d 00:05:00.0	37.7	51.1	40.5	31.4	
19/07/2018	11:59:47	00d 00:05:00.0	36.4	53.1	39.2	31.5	
19/07/2018	12:04:47	00d 00:05:00.0	36.6	51.4	39.5	31.5	
19/07/2018	12:09:47	00d 00:05:00.0	37.2	53.9	39.6	31.6	
19/07/2018	12:14:47	00d 00:05:00.0	38.2	53.4	40.6	33.3	
19/07/2018	12:19:47	00d 00:05:00.0	40.8	56.6	41.9	34.0	
19/07/2018	12:24:47	00d 00:05:00.0	41.7	59.7	43.4	33.2	
19/07/2018	12:29:47	00d 00:05:00.0	38.2	53.0	41.4	31.9	
19/07/2018	12:34:47	00d 00:05:00.0	39.0	50.1	41.7	34.1	
19/07/2018	12:39:47	00d 00:05:00.0	39.2	49.0	42.4	34.2	
19/07/2018	12:44:47	00d 00:05:00.0	44.6	62.8	46.1	35.1	
19/07/2018	12:49:47	00d 00:05:00.0	40.0	50.9	43.0	34.5	
19/07/2018	12:54:47	00d 00:05:00.0	41.2	53.7	44.4	35.3	
19/07/2018	12:59:47	00d 00:00:00.5	40.2	43.9	43.7	36.8	

Period	Time (T)	$L_{Aeq,t}$	$L_{Amax,t}$	$L_{A10,t}$	$L_{A90,t}$
Mean	1.5hr	39.5	53.4	41.6	33.0
Mode	1.5hr	37.7	#N/A	40.5	30.9
Min	1.5hr	36.4	43.9	39.2	30.9
Max	1.5hr	44.6	62.8	46.1	36.8

NMP2 - North Dale - Night

NMP Description	Open field near access track leading to Saxa Vord radar station.
Weather Conditions	Dry, no wind, 15C, 75% cloud cover
Coordinates	HP62478,08115
File #	
Main Noise Sources	Barely audible running water in nearby small watercourse.
Secondary Noise Sources	
Sound Level Meter Settings	

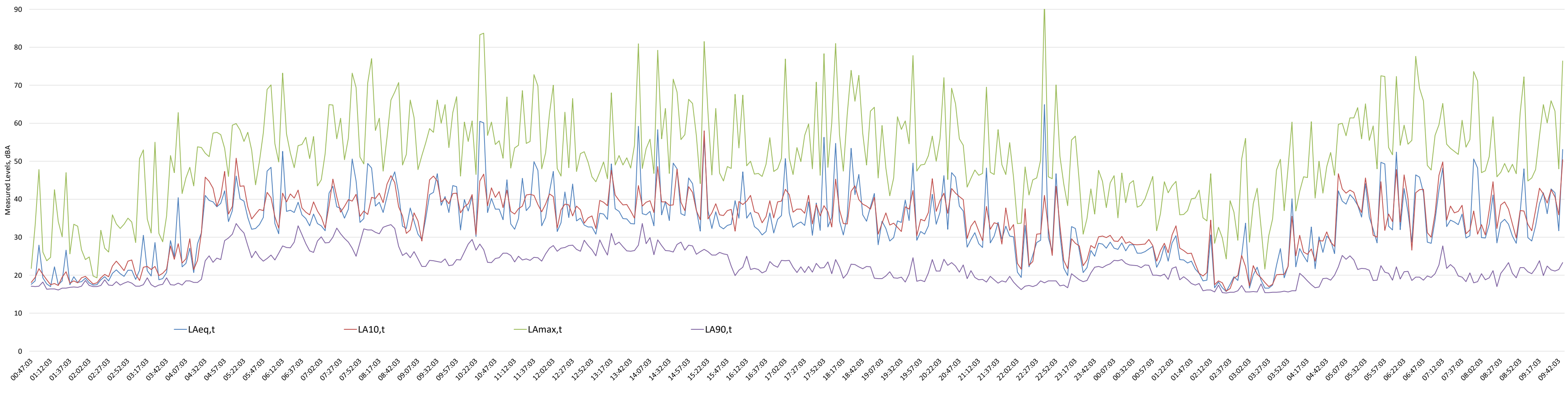


Date	Start Time	Measurement Time	$L_{Aeq,t}$	$L_{Amax,t}$	$L_{A10,t}$	$L_{A90,t}$	Notes
19/07/2018	23:49:37	00d 00:05:00.0	26.4	54.3	22.2	17.0	
19/07/2018	23:54:37	00d 00:05:00.0	18.9	34.9	20.0	17.2	
19/07/2018	23:59:37	00d 00:05:00.0	26.1	44.1	30.2	18.5	
20/07/2018	00:04:37	00d 00:05:00.0	32.9	51.8	31.0	17.9	
20/07/2018	00:09:37	00d 00:05:00.0	24.8	55.3	25.1	17.3	
20/07/2018	00:14:37	00d 00:05:00.0	27.3	41.2	29.8	17.5	
20/07/2018	00:19:37	00d 00:05:00.0	19.1	38.3	19.7	17.6	
20/07/2018	00:24:37	00d 00:05:00.0	19.1	37.4	19.5	17.3	

Period	Time (T)	$L_{Aeq,t}$	$L_{Amax,t}$	$L_{A10,t}$	$L_{A90,t}$
Mean	40 min	27.1	44.7	24.7	17.5
Mode	40 min	19.1	#N/A	#N/A	17.3
Min	40 min	18.9	34.9	19.5	17.0
Max	40 min	32.9	55.3	31.0	18.5

NMP3 - Saxa Vord - long term

NMP Description	Grounds of Saxa Vord hostel
Weather Conditions	Dry, no wind, 15C, 75% cloud cover
Coordinates	
File #	
Main Noise Sources	Wind and birdsong
Secondary Noise Sources	Infrequent traffic movements. People moving around the grounds.
Sound Level Meter Settings	



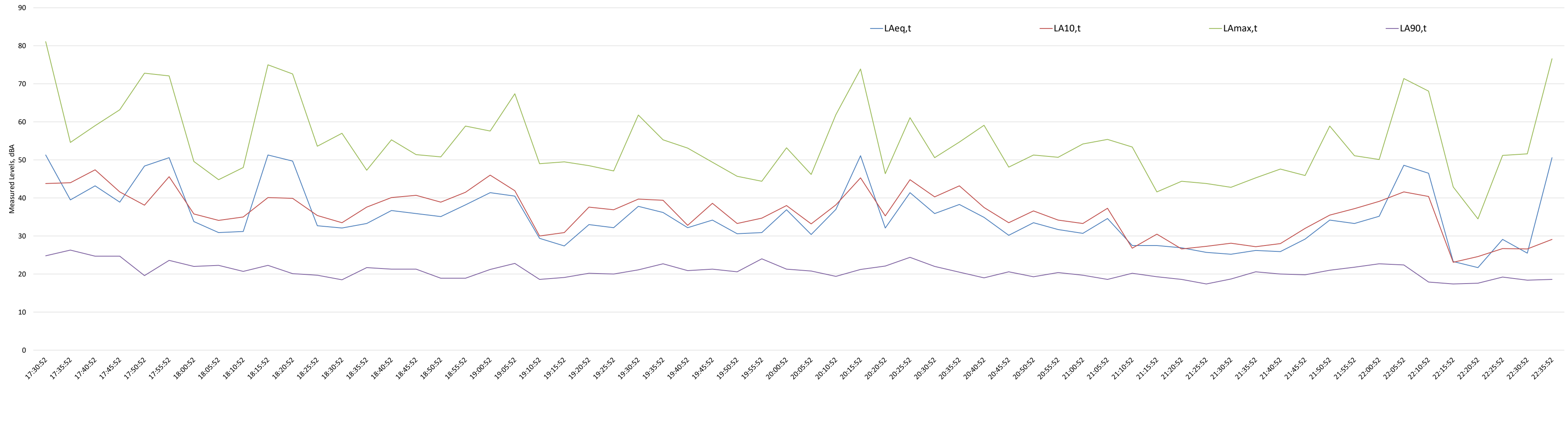
Period	Time (T)	$L_{Aeq,t}$	$L_{Amax,t}$	$L_{A10,t}$	$L_{A90,t}$
Mean	30 hr	44.8	51.4	33.8	22.2
Mode	30 hr	36.5	45.6	39.3	17.4
Min	30 hr	15.7	19.3	15.8	15.3
Max	30 hr	64.9	92.2	58.0	33.6

ITPENERGISED
Earth. Smart. Solutions

NMP3 - Saxa Vord - Day

MAP Location (Google Earth Screenshot)

NMP Description	Open field near access track leading to Saxa Vord radar station.
Weather Conditions	Dry, with light to moderate wind (5 m/s), 15°C, 70% RH
Coordinates	HP 64404,13441
File #	
Main Noise Sources	Bird calls. Infrequent vehicles passing by on the nearby road.
Secondary Noise Sources	Distant sheep bleating
Sound Level Meter Settings	5min averaging period, A-wt, Fast averaging.

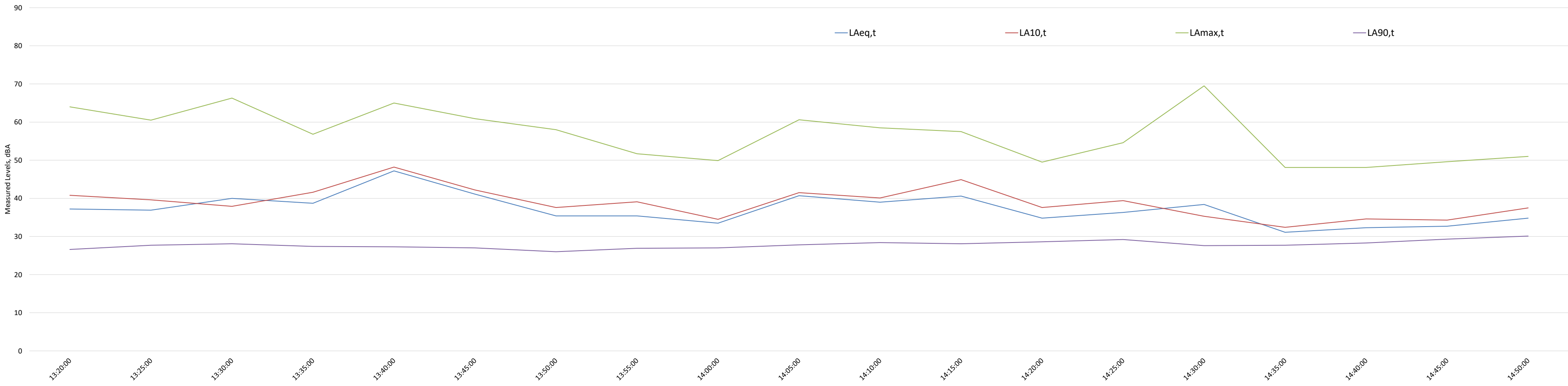


Period	Time (T)	$L_{Aeq,t}$	$L_{Amax,t}$	$L_{A10,t}$	$L_{A90,t}$
Mean	5 hr	42.4	54.6	36.1	20.7
Mode	5 hr	51.3	55.3	41.6	21.3
Min	5 hr	21.7	34.5	23.1	17.4
Max	5 hr	51.3	81.1	47.4	26.3

NMP5 Skaw - Day

MAP Location (Google Earth Screenshot)

NMP Description	
Weather Conditions	Moderate wind (5 m/s), 15°C, 70% RH, with wind increasingly gusty. Measurement abandoned due to onset of rain and increased wind speed.
Coordinates	HP 65083,15077
File #	
Main Noise Sources	Bird calls, running water in nearby small burn.
Secondary Noise Sources	Ocasional bangs from closing of gate in fence. Vehicle engines from nearby car park and farmer's quadbike. Pickup towing very rattly trailer
Sound Level Meter Settings	5min averaging period, A-wt, Fast averaging.



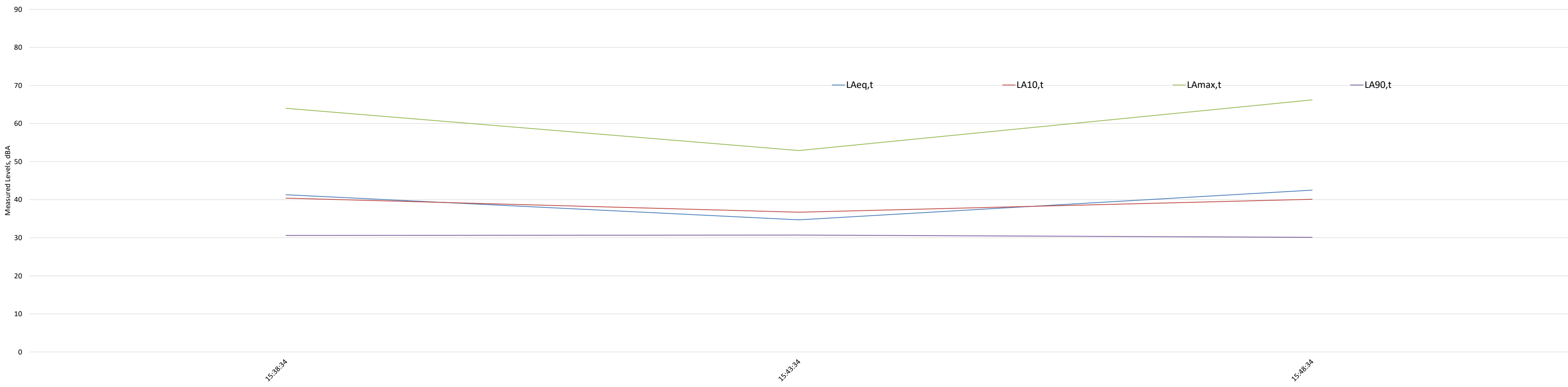
Date	Start Time	Measurement Time	$L_{Aeq.t}$	$L_{Amax.t}$	$L_{A10.t}$	$L_{A90.t}$	Notes
19/07/2018	13:20:00	00d 00:05:00.0	37.2	64.0	40.8	26.6	
19/07/2018	13:25:00	00d 00:05:00.0	36.9	60.5	39.6	27.7	
19/07/2018	13:30:00	00d 00:05:00.0	40.0	66.3	37.9	28.1	
19/07/2018	13:35:00	00d 00:05:00.0	38.7	56.8	41.6	27.4	
19/07/2018	13:40:00	00d 00:05:00.0	47.2	65.0	48.2	27.3	Pickup towing very rattly trailer leaves farm
19/07/2018	13:45:00	00d 00:05:00.0	41.1	60.9	42.2	27.0	
19/07/2018	13:50:00	00d 00:05:00.0	35.4	58.0	37.6	26.0	
19/07/2018	13:55:00	00d 00:05:00.0	35.4	51.7	39.1	26.9	
19/07/2018	14:00:00	00d 00:05:00.0	33.5	49.9	34.5	27.0	
19/07/2018	14:05:00	00d 00:05:00.0	40.7	60.6	41.5	27.8	
19/07/2018	14:10:00	00d 00:05:00.0	39.0	58.5	40.1	28.4	
19/07/2018	14:15:00	00d 00:05:00.0	40.6	57.5	44.9	28.1	
19/07/2018	14:20:00	00d 00:05:00.0	34.8	49.5	37.6	28.6	
19/07/2018	14:25:00	00d 00:05:00.0	36.3	54.6	39.4	29.2	
19/07/2018	14:30:00	00d 00:05:00.0	38.4	69.5	35.3	27.6	
19/07/2018	14:35:00	00d 00:05:00.0	31.1	48.1	32.4	27.7	
19/07/2018	14:40:00	00d 00:05:00.0	32.3	48.1	34.6	28.3	
19/07/2018	14:45:00	00d 00:05:00.0	32.7	49.6	34.3	29.3	
19/07/2018	14:50:00	00d 00:01:59.0	34.8	51.0	37.5	30.1	

Period	Time (T)	$L_{Aeq.t}$	$L_{Amax.t}$	$L_{A10.t}$	$L_{A90.t}$
Mean	1.5 hr	39.1	56.8	38.9	27.8
Mode	1.5 hr	35.4	48.1	37.6	27.7
Min	1.5 hr	31.1	48.1	32.4	26.0
Max	1.5 hr	47.2	69.5	48.2	30.1

ITPENERGISED
Earth. Smart. Solutions

NMP4 Battles Kirk - Day

NMP Description	
Weather Conditions	Moderate wind (5 m/s), 15°C, 70% RH, with wind increasingly gusty. Measurement abandoned due to onset of rain and increased wind speed.
Coordinates	HP 65083,15077
File #	
Main Noise Sources	Bird calls. Infrequent vehicles passing by on the nearby road.
Secondary Noise Sources	Distant sheep bleating
Sound Level Meter Settings	5min averaging period, A-wt, Fast averaging.



Date	Start Time	Measurement Time	$L_{Aeq.t}$	$L_{Amax.t}$	$L_{A10.t}$	$L_{A90.t}$	Notes
19/07/2018	15:38:34	00d 00:05:00.0	41.3	64.0	40.4	30.6	
19/07/2018	15:43:34	00d 00:05:00.0	34.7	52.9	36.7	30.7	
19/07/2018	15:48:34	00d 00:05:00.0	42.5	66.2	40.1	30.1	

Period	Time (T)	$L_{Aeq.t}$	$L_{Amax.t}$	$L_{A10.t}$	$L_{A90.t}$
Mean	15 min	40.6	61.0	39.1	30.5
Mode	15 min	#N/A	#N/A	#N/A	#N/A
Min	15 min	34.7	52.9	36.7	30.1
Max	15 min	42.5	66.2	40.4	30.7

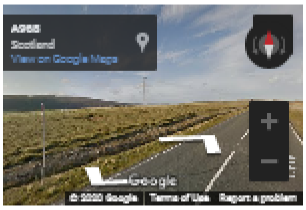
Appendix 8.4 Traffic Flow Data

Site number: 80332

Site details

Region	Scotland
Local authority	Shetland Islands
Road name	A968
Road classification	'A' road
Managed by	Local authority
Road type	Major
Start junction	Belmont ferry
End junction	B9086
Link length	16.50km (10.25 miles)
Easting, northing	460000, 1205400
Latitude, longitude	60.72720200, -0.90191201

Location



Annual Average daily flow

Year	Count method	Pedal cycles	Two wheeled motor vehicles	Cars and taxis	Buses and coaches	Light goods vehicles	Heavy goods vehicles	All motor vehicles
2019	Estimated using previous year's AADF on this link	2	150	333	0	0	11	494
2018	Estimated using previous year's AADF on this link	1	151	332	0	0	11	493
2017	Estimated using previous year's AADF on this link	1	144	334	0	0	11	488
2016	Estimated using previous year's AADF on this link	1	136	334	0	0	10	480
2015	Estimated using previous year's AADF on this link	1	126	330	0	0	10	466
2014	Estimated using previous year's AADF on this link	1	118	325	0	0	10	453
2013	Estimated using previous year's AADF on this link	2	109	321	0	0	9	439
2012	Estimated using previous year's AADF on this link	2	101	320	0	0	10	431
2011	Estimated using previous year's AADF on this link	2	105	326	0	0	10	441
2010	Estimated using previous year's AADF on this link	2	100	328	0	0	10	438