APPENDIX D
WALLOPS FLIGHT FACILITY LAUNCH VEHICLE NOISE STUDIES

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Blue Ridge Research and Consulting, LLC

Technical Report

Launch Noise Study for the Wallops Flight Facility Programmatic Environmental Impact Statement

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Acronyms and Abbreviations

The following acronyms and abbreviations are used in the report:

AEE	Office of Environment and Energy
AFCEE	Air Force Center for Engineering and Environment
AST	Office of Commercial Space Transportation
BRRC	Blue Ridge Research and Consulting, LLC
dB	decibel
dBA	A-weighted decibel level
DI	directivity indices
DOD	Department of Defense
DSM-1	Distributed Source Method 1
ELV	Expendable Launch Vehicle
FAA	Federal Aviation Administration
ft	foot/feet
Kg	kilogram
lbf	pound force
lbm	pound mass
LFIC	Liquid Fueled Intermediate Class
LFMC	Liquid Fueled Medium Class
$L_{A,max}$	maximum A-weighted OASPL in decibels
L_{max}	maximum unweighted OASPL in decibels
L_{pk}	peak sound pressure level in decibels
LMLV	Lockheed Martin Launch Vehicle
LV	Launch Vehicle
NASA	National Aeronautics and Space Administration
N	newton
NEPA	National Environmental Policy Act
NIHL	noise-induced hearing loss
NIOSH	National Institute for Occupational Safety and Health
nm	Nautical miles
OASPL	overall sound pressure level in decibels
OSHA	Occupational Safety and Health Administration
PEIS	Programmatic Environmental Impact Statement
P_k	peak pressure
psf	pounds per square foot
psi	pounds per square inch
RUMBLE	The Launch Vehicle Acoustic Simulation Model
RSRM	reusable solid rocket motor
S.L.	sea level
sec	second
SEL	Sound Exposure Level in decibels
SFHC	Solid Fueled Heavy Class
SFMC	Solid Fueled Medium Class
µPa	micropascal
WFF	Wallop Flight Facility

1 Introduction

This report documents the noise study on rocket launch operations at the National Aeronautics and Space Administration's (NASA) Wallops Flight Facility (WFF) in Accomack County, Virginia. This study supports the analysis for WFF's Site-wide Programmatic Environmental Impact Statement (PEIS) for proposed future actions. Even though a number of launch vehicles could be flown from WFF in the future, this noise study examines four nominal launch vehicles representing the current baseline and, considering future mission growth, the largest orbital vehicles (in terms of thrust) that would be launched from WFF. The representative vehicles for WFF's current baseline are the Antares 200 Series (Antares 200) and Lockheed Martin Launch Vehicle (LMLV) III. Representative larger vehicles that could be launched in the future include a Liquid Fueled Intermediate Class Expendable Launch Vehicle (LFIC ELV) and Solid Fueled Heavy Class Expendable Launch Vehicle (SFHC ELV).

WFF consists of three separate parcels of land, as shown in Figure 1: the Main Base, the Mainland, and Wallops Island. The Mainland and Wallops Island are located side by side and the Main Base is approximately 7 miles northwest of the Island launch site. The focus of this noise study is specific to operations occurring at Wallops Island on Pad 0-A, Pad 0-B, and a future Pad 0-C.

This noise study describes the launch noise and sonic booms expected to be generated by the projected operations described within the PEIS. Section 2 summarizes the noise metrics discussed throughout this report; Section 3 describes the general methodology of the rocket launch noise and sonic boom noise models; Section 4 describes the acoustical modeling input parameters for WFF; and Section 5 presents the noise modeling results. A summary is provided in Section 6 to document the notable findings of this noise study.

Figure 1. Left, Wallops Flight Facility boundaries. Right, photo of an Orbital ATK Inc. Antares rocket launching from Wallops Flight Facility (photo credit NASA).

2 Noise Metrics and Criteria

2.1 Noise Metrics

Any unwanted sound that interferes with normal activities or the natural environment can be defined as noise. Noise sources can be continuous (constant) or transient (short-duration) and contain a wide range of frequency (pitch) content. Determining the character and level of sound aids in predicting the way it is perceived. Both launch noise and sonic booms are classified as transient noise events.

A decibel (dB) is a ratio that compares the sound pressure of a sound source of interest (e.g., the rocket launch) to a reference pressure (the quietest sound humans can hear, 20 µPa [micropascal]). A change in sound level of about 10 dB is usually perceived by the average person as a doubling (or halving) of the sound's loudness. 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 other-wise similar… events which differed in maximum sound level by < 3 dB" (Fayh and Thompson, 2015). Standard weighting filters help to shape the levels in reference to how they are perceived. An "A-weighting" filter approximates the frequency response of human hearing, adjusting low and high frequencies to match the sensitivity of human hearing. For this reason, the A-weighted decibel level (dBA) is commonly used to assess community noise. However, if the structural response is of importance to the analysis, a "flat-weighted" (unweighted) level is more appropriate.

Noise metrics are used to describe the noise event 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. Individual time-varying noise events have two main characteristics: a sound level that changes throughout the event and a period of time the event is heard. The overall sound pressure level (OASPL) provides a measure of the sound level at any given time and the maximum OASPL (L_{max}) indicates the highest level achieved over the duration of the event. Sound Exposure Level (SEL) represents both the magnitude of a sound and its duration. SEL provides a measure of the cumulative noise exposure of the entire acoustical 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 sound generated by rocket launches, which last more than one second, the SEL is greater than the L_{max} because an individual launch can last for minutes and the L_{max} occurs instantaneously. Sonic boom noise levels are described in units of peak overpressure in pounds per square foot (psf). Noise contour maps of these metrics are comprised of lines of equal noise level or exposure, and they serve as visual aids for assessing the impact of noise on a community.

The Day-Night Average Sound Level (DNL) is a cumulative noise metric that accounts for the SEL of all noise events in a 24-hour period. Typically, DNL values are expressed as the level over a 24-hour annual average day. In order to account for increased human sensitivity to noise at night, a 10 dB penalty is applied to nighttime events (occurring between the hours of 10:00 p.m. and 7:00 a.m.). DNL is based on long-term cumulative noise exposure and has been found to correlate well with adverse community impacts for regularly occurring events including aircraft, rail, and road noise (Schultz, 1978;

Finegold, et al., 1994). Noise studies used in the development of the DNL metric did not include rocket noise, which are historically irregularly occurring events. Thus, it is acknowledged that the suitability of DNL for infrequent rocket noise and sonic boom events is uncertain. The analysis in the current study is on a single event basis and does not include DNL.

2.2 Noise Criteria

Noise criteria have been developed to protect the public health and welfare of the surrounding communities. This report includes the analysis of maximum A-weighted and unweighted OASPL, as they relate to hearing conservation and structural damage criteria, respectively. In addition, sonic booms impacts are evaluated on a single-event basis in regards to hearing conservation and structural damage criteria.

2.2.1 Hearing Conservation

Rocket Noise

U.S. government 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). Three federal agencies have set upper limits on non-impulsive noise levels including the Occupational Safety and Health Administration (OSHA) (OSHA, 2008), Department of Defense (DOD) Occupational Hearing Conservation Program (Department of Defense, 2010), and the National Institute for Occupational Safety and Health (NIOSH). The most conservative of these limits has been set by OSHA at 115 dBA for an allowable exposure duration of 15 minutes, which is far greater than would be experienced during a rocket launch. Therefore, an L_{max} of 115 dBA is used as the best available, conservative threshold to identify potential locations where hearing protection should be considered for a rocket launch.

Sonic Boom

A sonic boom is the sound associated with the shock waves created by a vehicle traveling through the air faster than the speed of sound. Multiple federal government agencies have provided guidelines on permissible noise exposure limits on impulsive noise such as a sonic boom. These documented guidelines are in place to protect one's hearing from exposures to high noise levels and aid in the prevention of NIHL. In terms of upper limits on impulsive or impact noise levels, NIOSH (NIOSH, 1998) and OSHA (OSHA, 2008) have stated that levels should not exceed 140 dB peak sound pressure level, which equates to a sonic boom level of approximately 4 psf.[1]

[1] The peak pressure of a sonic boom, P_k (psf), can be converted to the peak sound pressure level in decibels (L_{pk}) by the mathematical relationship of: $L_{pk} = 127.6 + 20 \log_{10} P_k$

2.2.2 Structural Damage

Rocket Noise

Typically, the most sensitive components of a structure to launch noise are windows, and infrequently, the plastered walls and ceilings. The potential for damage to a structure is unique to the material of each element and its respective boundary conditions, the condition of the structure, and the incident sound. Due to these complexities, a number of generalized damage criteria have been proposed based on findings from anecdotal evidence, theoretical modeling, and rocket testing.

Regier published both observations on the response of building structures to noise and the development of a theoretical modeling technique to study the effects of intense low-frequency noise on structures (Regier, et al., 1962). He documented, "glass breakage and loosening of ceiling tile and fixtures" had occurred at a building near a large blowdown wind tunnel, which had similar frequency spectra to that of a Saturn rocket. At this building, sound-pressure levels up to 142 dB had been measured. As a result of the limited empirical data available, Regier developed a criterion for building damage based on theory for the response of a single-degree of freedom system to random loads. He proposed a 130 dB octave-band sound-pressure level threshold for well-maintained walls and windows. However, he noted that levels in this range will likely "cause some damage in highly stressed elements or poorly installed windows." Similarly, a report from the National Research Council on the "Guidelines for Preparing Environmental Impact Statements on Noise" (Committee on Hearing, 1977) 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 found a relationship between structural damage claims and overall sound pressure level, where "the probability of structural damage [was] proportional to the intensity of the low frequency sound" (Guest and Slone, 1972). This relationship estimated that one damage *claim* in 100 households exposed is expected at an average continuous level of 120 dB, and one in 1,000 households at 111 dB. The study was based on community responses to the 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 mean modeled sound levels. It is important to highlight the difference between the static ground tests in which the probability of structural damage is based on and the launch events of concern for this noise analysis. The ground tests occurred for durations much greater than the exposure duration expected for the proposed launch events. Additionally, during ground tests, the engine/motor remains in one position which results in longer exposure duration to continuous levels as opposed to the transient noise occurring from the moving vehicle during a launch event.

Notwithstanding the aforementioned differences between the Saturn V ground test conditions and the ELV launches from WFF, Guest and Slone's (1972) damage claim criteria represent the best available dataset regarding structural damage resulting from rocket noise. Thus, L_{max} values of 120 dB and 111 dB are used in this report as a conservative threshold for potential risk of structural damage claims.

Sonic Boom

Sonic booms are also commonly associated with structural damage. Most damage claims are for brittle objects, such as glass and plaster. Table 1 summarizes the threshold of damage that may be expected at various overpressures (Haber, et al., April 1989). A large degree of variability exists in damage experience, and much 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 (Sutherland, 1990) to one in a million (Hershey, et al., 1976). 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 (White, 1972) 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 a 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 from these factors. In general, for well-maintained structures, the threshold for damage from sonic booms is 2 psf (Haber, et al., 1989), below which damage is unlikely.

Table 1. Possible damage to structures from sonic booms (Haber, et al., 1989)

Sonic Boom Overpressure Nominal (psf)	Type of Damage	Item Affected
0.5 - 2	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	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	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.
Greater than 10	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.

3 Acoustic Modeling Methodology

Launch vehicle propulsion systems, such as solid rocket motors and liquid-propellant rocket engines, generate high amplitude, broadband noise. The majority of the noise is created by the rocket plume, or jet exhaust, interacting with the atmosphere along the entire plume, and 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 a specific direction.

In addition to the rocket noise, a launch 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 double 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.

3.1 Far-Field Launch Noise Modeling

The Launch Vehicle Acoustic Simulation Model (RUMBLE), developed by Blue Ridge Research and Consulting, LLC (BRRC), is the noise model used to predict the launch vehicle noise associated with the proposed operations from the WFF launch range. The noise model utilizes user inputs describing the facility, vehicle, engines/motors, and operations in conjunction with model databases to predict noise exposure to the communities surrounding launch sites. The model produces both overall and spectral sound pressure level time-history signatures at each receiver location. The core components of the model are visualized in Figure 2 and described in the following sub sections.

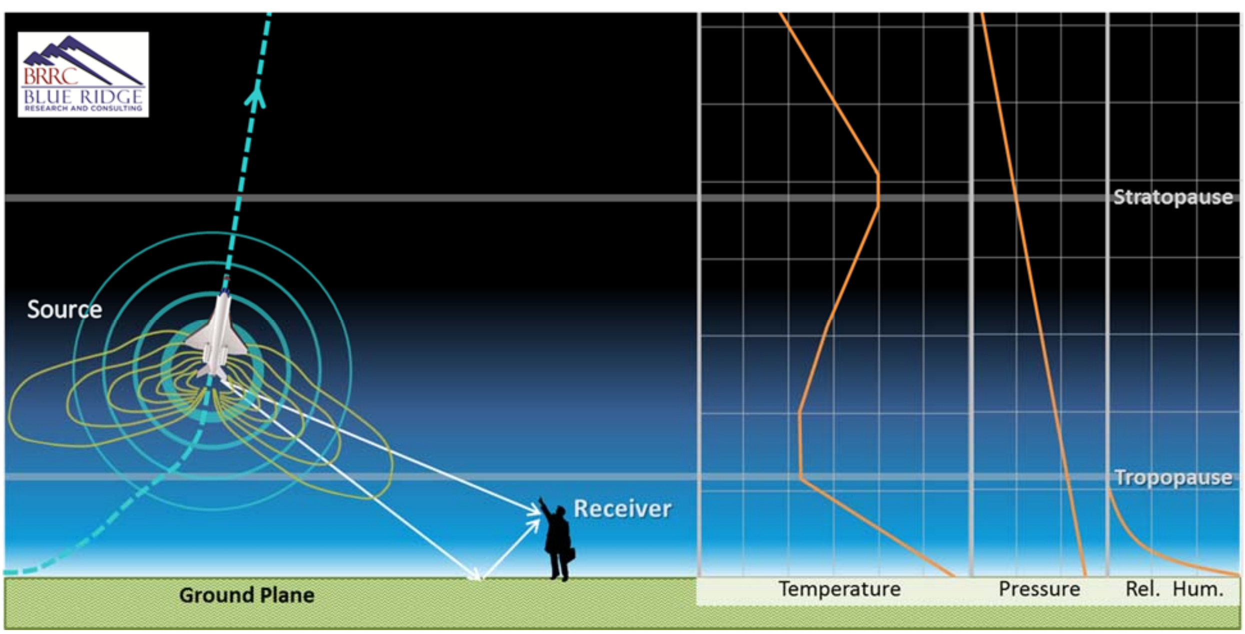

Figure 2. Conceptual overview of rocket noise prediction model methodology.

3.1.1 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) (Eldred, 1971) 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 (James, et al., 2014). 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 (Guest, 1964). Typical acoustic efficiency values range from 0.2% to 1.0% (Eldred, 1971). In the far-field, distributed sources are modeled as a compact source located at the nozzle exit with an equivalent total sound power and range of frequencies. 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 (Eldred, 1971). Additional boosters or cores (that are not considered to be tightly clustered) are handled by summing the noise contribution from each booster/core.

The presence of a launch pad flame duct relocates and redirects the primary noise source from the nozzle exit to the duct exit when the rocket is close to the pad (Panda, et al., 2013). The presence of the flame duct is modeled during the initial launch sequence when the rocket is close to the pad. The source is located at the duct exit and the direction of the plume is assumed to be equivalent to the heading of the flame duct exit.

Forward Flight Effect

A jet in forward flight radiates less noise than the same jet 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 and the outside airflow (Viswanathan, et al., 2011; Saxena, et al., 2012; Buckley, et al., 1983; Buckley, et al., 1984). 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. As the differential between the forward flight velocity and exhaust velocity decreases, jet mixing is reduced, which reduces the corresponding noise emission. Notably, the maximum OASPLs are normally generated before the vehicle reaches sonic velocity. Thus, the modeled noise reduction is capped at a forward flight velocity of Mach1.

Directivity

Rocket noise is highly directive, meaning the acoustic power is concentrated in specific directions and the sound pressure observed 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) (Haynes, et al., 2009). The RSRM directivity indices (DI) incorporate a larger range of frequencies and angles then previously available data. Subsequently improvements were made to the formulation of the RSRM DI (James, et al., 2014) 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 defined as the change in frequency of a wave for an observer moving relative to its source. 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 perceived frequency is related to the actual frequency by the speed of the source and receiver and the speed of the waves in the medium. The received frequency is higher (compared to the emitted frequency) during the approach, it is identical at the instant of passing by, and it is lower during the recession. 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 travelling, 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 3 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.

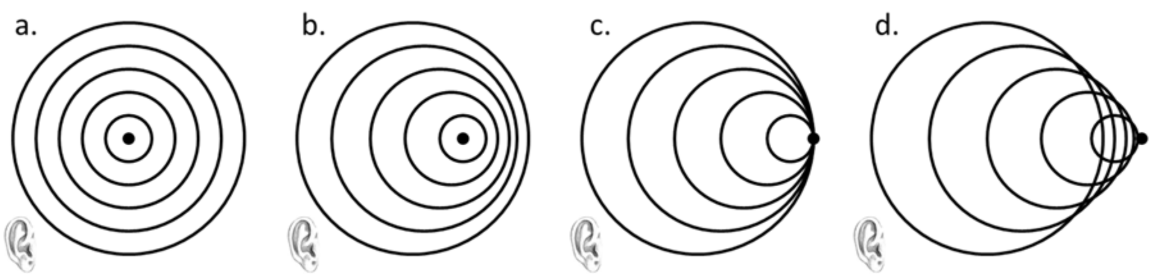

Figure 3. Effect of expanding wavefronts (decrease in frequency) that an observer would notice for higher relative speeds of the rocket relative to the observer for: a) stationary source b) source velocity < speed of sound c) source velocity = speed of sound d) source velocity > speed of sound

3.1.2 Propagation

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

Ray Path

The model assumes a straight line 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 noise model components are calculated based on the specific source (launch vehicle trajectory point) to receiver geometry (grid point). The position of the launch vehicle, described by the trajectory, is often provided in the angular geodetic coordinates of latitude and longitude, defined relative to a reference system (e.g., World Geodetic System 1984 [WGS84]) that approximates the Earth's surface by an ellipsoid. The receiver grid is described in geodetic latitude and longitude, referenced to the same reference system as the trajectory data. Maintaining the same reference system ensures greater accuracy in source to receiver geometry calculations

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. Figure 2 shows an example atmospheric profile. 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

Nonlinear propagation effects can result in distortions of high-amplitude sound waves (McInerny, et al., 2007) as they travel through the medium. These nonlinear effects are counter to the effect of atmospheric absorption (McInerny, et al., 2005; Pernet, et al., 1971). However, recent research shows that nonlinear propagation effects change the perception of the received sound (Gee, et al., 2007; Ffowcs, et al., 1975) , but the standard acoustical metrics are not strongly influenced by nonlinear effects (Gee, et al., 2008; Gee, et al., 2006). The overall effects of nonlinear propagation on high-amplitude sound signatures and their perception is an on-going area of research.

Ground Interference

The calculated results of the sound propagation using DSM-1 provide a free-field sound level (i.e., no adjacent 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) shown in Figure 2. 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 (Chessel, 1977; Embleton, et al., 1983) when estimating the received noise. A receiver height of 5 feet is assumed along with a homogeneous grass ground surface. It should be noted that noise levels directly above a water surface may see an increase of up to 3 dB because of the acoustical hardness of the water surface. To account for the random fluctuations of wind and temperature on the direct and reflected wave, the effect of atmospheric turbulence is also included (Chessel, 1977; Daigle, 1979).

3.1.3 Receiver

Combining the source and propagation components, the received noise is estimated. 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.

3.1.4 Validation

BRRC has performed comparisons of data predicted using RUMBLE to measured data from three Antares 100 series rocket launches from Pad 0-A at Wallops Launch Range. Figure 4 and Figure 5 present examples of comparative results for various distances from the launch pad. The model-predicted SEL and Maximum OASPL (both A-weighted) values agree very well to actual measurements of the launch event over distances ranging from less than 0.6 miles to 4.1 miles. Figure 5 shows a comparison of the modeled and measured OASPL time histories for distances of 0.6, 1.2, 2.5, and 4.1 miles from the launch site. The modeled time histories match the level, shape, and duration of the levels recorded during the three measured launches: ORB-D1 (Launch 1), ORB-1 (Launch 2), and ORB-2 (Launch 3).

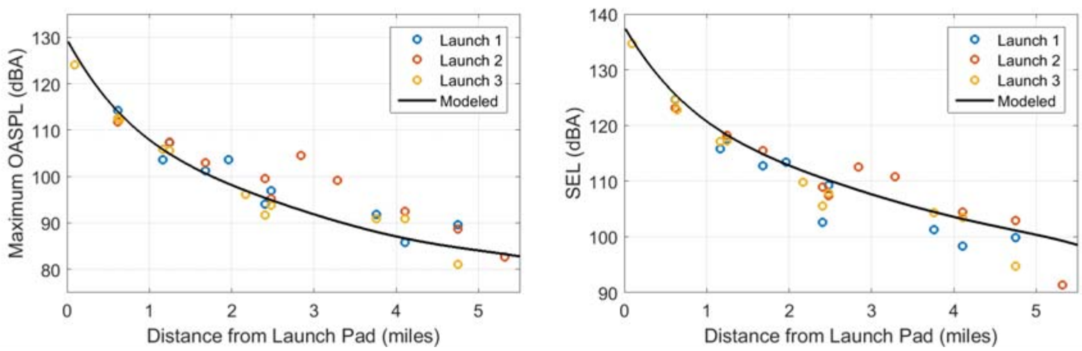

Figure 4. Measured versus predicted launch vehicle noise exposure levels. (Left) SEL values at set distances from the launch pad. (Right) Maximum OASPL at set distances from the launch pad.

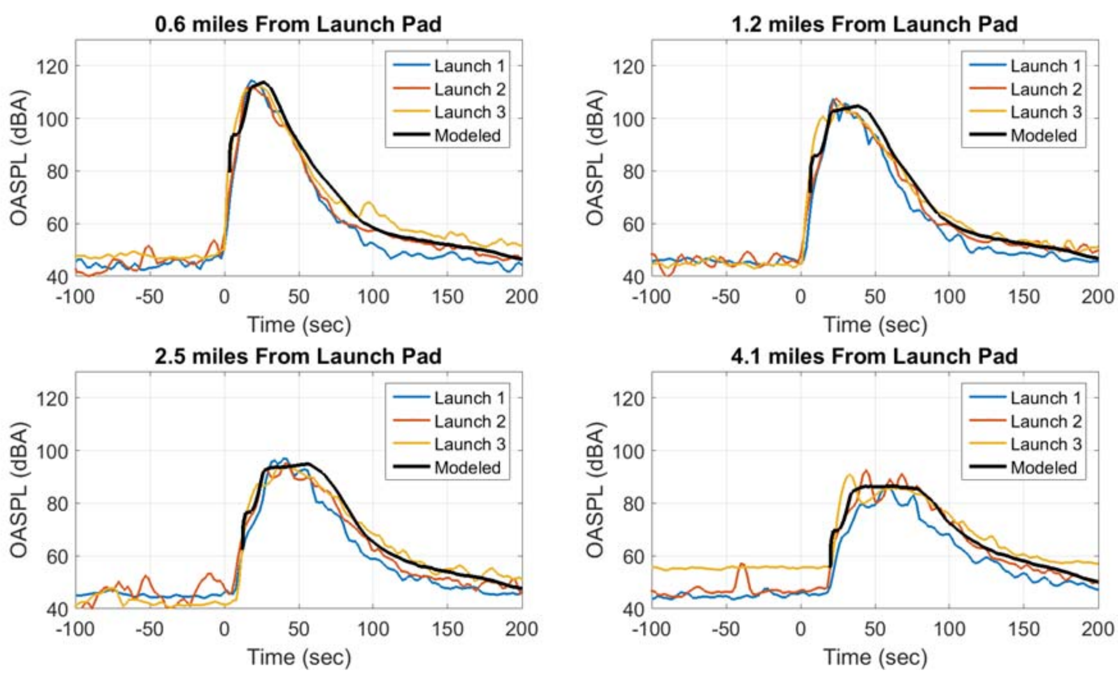

Figure 5. Measured versus predicted launch vehicle noise time histories.

3.2 Sonic Boom Modeling

When an aircraft 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 aircraft 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 aircraft, the other with the rear part) of approximately equal strength and (for fighter aircraft) separated by 100 to 200 milliseconds. For rockets, the separation can be extended because of the volume of the plume. Thus, their waveform durations can be as large as one second. 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 6 shows the generation and evolution of a sonic boom N-wave under the aircraft. Figure 7 shows the sonic boom pattern for an aircraft in steady, level supersonic flight. The boom forms a cone that 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 as the lateral distance increases to the cut-off edge of the "carpet." When the vehicle is maneuvering, the sonic boom energy can be focused in highly localized areas on the ground. This focusing will cause the N-wave boom to be amplified and transformed into a U-wave.

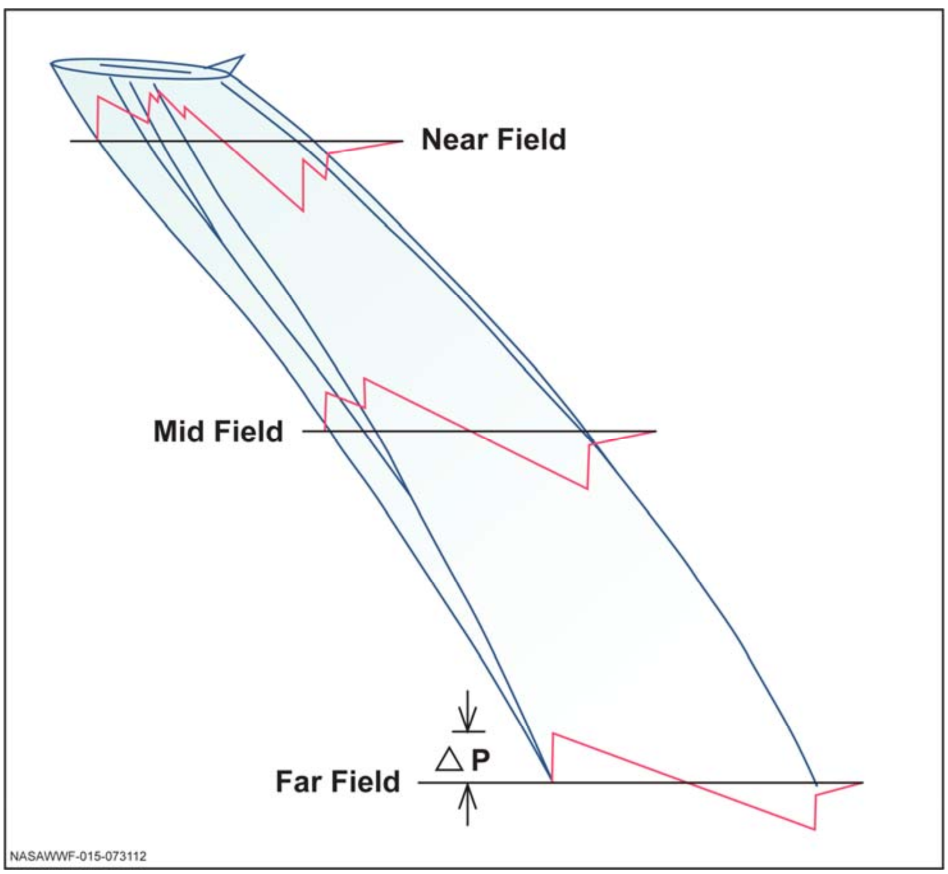

Figure 6. Sonic boom generation and evolution to N-wave (Carlson, 1967)

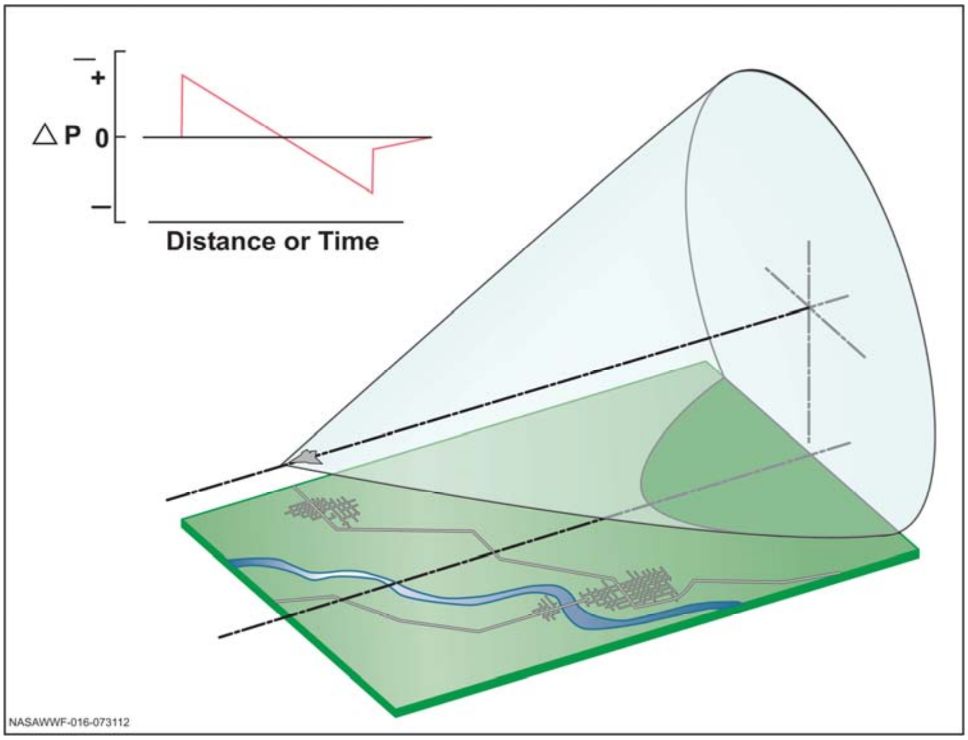

Figure 7. Sonic boom carpet in steady flight (Plotkin, et al., 1990)

The complete ground pattern of a sonic boom depends on the size, weight, shape, speed, and trajectory of the vehicle. Since aircraft fly supersonically with relatively low horizontal angles, the boom is directed toward the ground. However, for rocket trajectories, the boom is directed laterally until the rocket rotates significantly away from vertical, as shown in Figure 8. This difference causes a sonic boom from a rocket to propagate much further downrange compared to aircraft sonic booms. This extended propagation usually results in relatively lower sonic boom levels from rocket launches. For aircraft, the front and rear shock are generally the same magnitude. However, for a rocket the plume provides a smooth decrease in the vehicle volume, which diminishes the strength of the rear shock. During reentry of a rocket body, the vehicle can also generate sonic boom on the ground as the body descends back toward the earth. The sonic booms are somewhat reduced as the vehicle is decelerating. For this case, the propagation is direct toward the ground, so the boom is concentrated around the impact site. Figure 9 shows the sonic boom intercepting the ground for a reentering sounding rocket.

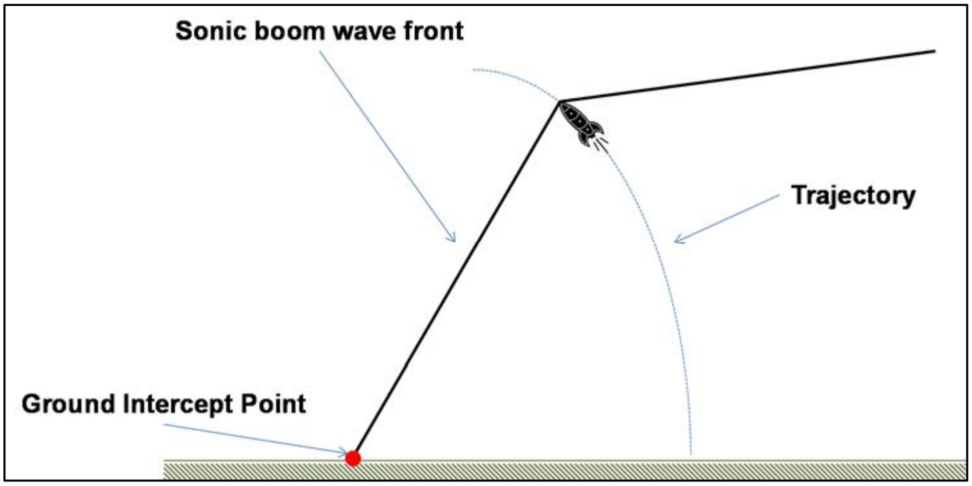

Figure 8. Sonic boom propagation for rocket launch

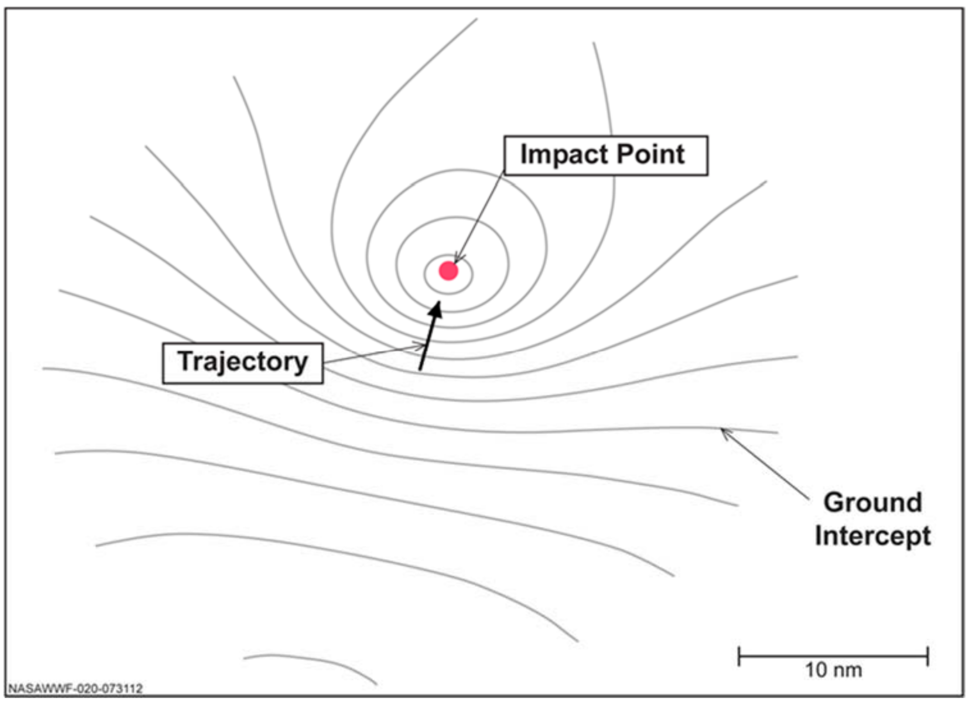

Figure 9. Sonic boom ground intercepts for reentry of a sounding rocket

The single-event prediction model, PCBoom4 (Plotkin, 1996; Plotkin, 1989; Plotkin, et al., 2002), is used to predict the sonic boom footprint. PCBoom4 calculates the magnitude and location of sonic boom overpressures on the ground from supersonic flight. Several inputs are required to calculate the sonic boom impact, including the vehicle model, the trajectory path, the atmospheric conditions and the ground surface height. Predicted sonic boom footprints are generally presented as contours of constant peak overpressure.

4 Wallops Island Launch Range

4.1 Launch Range Description

WFF is the NASA's principal facility for management and implementation of suborbital research programs. WFF supports missions for suborbital and orbital rocket vehicles. The launch range on Wallops Island currently includes seven launch pads, three blockhouses for launch control, and assembly buildings that support the preparation and launching of suborbital and orbital launch systems. The current modeling effort considers launches from three WFF launch pads, two of which are existing launch pads: Launch Pad 0-A (Pad 0-A) and Launch Pad 0-B (Pad 0-B). The third site, Launch Pad 0-C (Pad 0-C), is a future launch site that could support launches of SFHC ELV; its location is estimated for planning purposes. Although Pad 0-B is an existing launch site, plans could include updating its design to support launches of SFHC ELV's. All three launch pads, shown in Figure 10, are located within WFF facility boundaries, specifically within the southern portion of Wallops Island, south of Causeway Road and east of Bypass Rd. Table 2 includes the longitude, latitude, and altitude above ground level (AGL) of the three modeled launch pads at WFF. Table 3 presents the associated flame duct parameters corresponding to the three launch pads.

Figure 10. WFF launch range

Table 2. Launch pad locations at the WFF launch range

Launch Pad	Latitude	Longitude	Altitude	Associated Launch Vehicles
Pad 0-A	37.833864°	-75.487683°	17 ft AGL	Antares 200 and LFIC ELV
Pad 0-B	37.831200°	-75.491300°	28 ft AGL	LMLV III and SFHC ELV
Pad 0-C*	37.827284°	-75.494435°	28 ft AGL	SFHC ELV

**Pad-0C location is estimated at the UAS runway northern pad for planning purposes.*

Table 3. Launch pad flame duct locations and geometry at the WFF launch range

Launch Pad	Flame Duct Exit			Flame Duct Geometry				
	Latitude	Longitude	Centerline Height	Top Height	Bottom Lip Height	Length	Heading*	Exit Angle*
Pad 0-A	37.833722°	-75.487579°	11.2 ft	20.9 ft	1.4 ft	59.5 ft	~150°	~9.85°
Pad 0-B	37.831196°	-75.491251°	13.2 ft	25.4 ft	1.1 ft	14.1 ft	~95°	~0°
Pad 0-C	37.827280°	-75.494386°	13.2 ft	25.4 ft	1.1 ft	14.1 ft	~95°	~0°

**Heading is measured relative to True North and Exit Angle is measured relative to the Horizon*
***Pad 0-B and Pad 0-C flame duct parameters are estimated for modeling purposes*

The launch noise model utilizes an atmospheric profile, which describes the variation of temperature, pressure and relative humidity with respect to the altitude. Site-specific and standard atmospheric data sources, detailed in Table 4, were used to create a composite atmospheric profile for altitudes up to 66 miles. Figure 11 shows the composite atmospheric profile temperature, relative humidity, and pressure profile.

Table 4. Source of atmospheric profile data

Altitude Range	Source	Parameters
0 – 18 miles	WFF Climatology Summary 1963-2010	Temperature, Pressure and Relative Humidity
19 – 56 miles	NASA Technical Memo 4511	Temperature and Pressure
57 – 66 miles	"Handbook of Astronautical Engineering" (McGraw-Hill 1961)	Temperature and Pressure

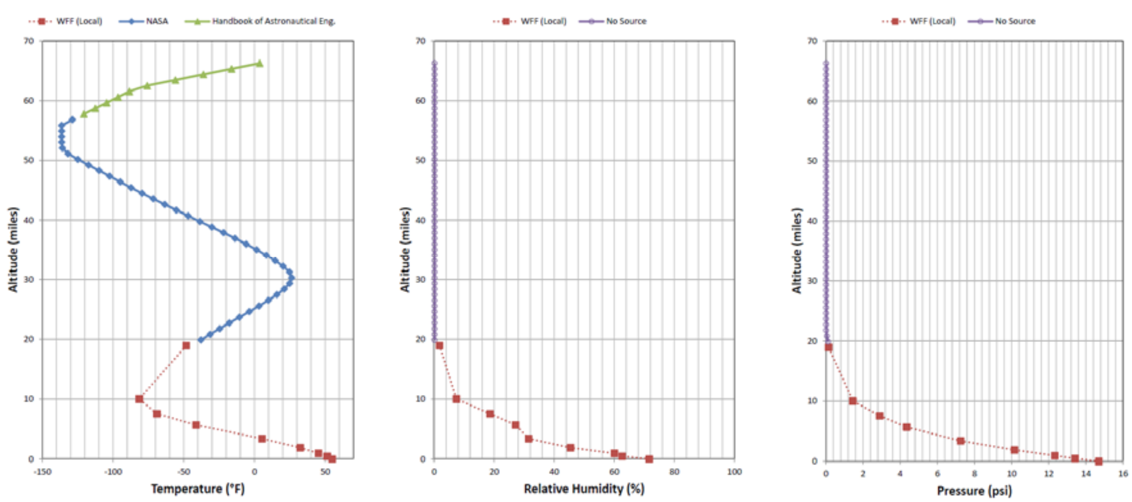

Figure 11. Atmospheric temperature, relative humidity, and pressure profiles (Note, above 20 miles, the relative humidity and pressure are assumed to asymptote to zero)

4.2 Vehicle and Engine Modeling Parameters

This noise study considers the operations of four representative launch vehicles, the current baseline: Antares 200 and LMLV III; and proposed future growth to an LFIC ELV and an SFHC ELV. The RUMBLE model requires specific vehicle/engine input parameters to determine the noise exposure resulting from the proposed operations of the four representative launch vehicles. Table 5 and Table 6 present the launch vehicle parameters utilized in the acoustic modeling.

Table 5. Vehicle parameters used in acoustic modeling

Reference Name/Acronym	Antares 200 (Baseline)	LMLV III (Baseline)	LFIC ELV (Proposed)	SFHC ELV (Proposed)
Launch Vehicle Class	Liquid Fueled Medium Class (LFMC)	Solid Fueled Medium Class (SFMC)	Liquid Fueled Intermediate Class (LFIC)	Solid Fueled Heavy Class (SFHC)
Representative Vehicle	**Antares 200 Series**	**Lockheed Martin Launch Vehicle (LMLV)/Athena III**	**SpaceX Falcon 9**	**ATK Castor-1200 based vehicle**
Length	133 ft	92.50 ft	224.4 ft	N/A (no assoc. vehicle)

Table 6. Vehicle parameters used in acoustic modeling

Reference Name/Acronym	Antares 200 (Baseline)	LMLV III (Baseline)	LFIC ELV (Proposed)	SFHC ELV (Proposed)
First Stage Engine/Motor	**RD-181**	**CASTOR 120**	**Merlin**	**CASTOR 1200**
Number of Engines/Motors	2	1	9	1
Propellant	LO2/RP (liquid)	TP H1246 (solid)	LO2/RP (liquid)	TP H1148 Type VIII (solid)
Single Engine/Motor Nozzle Exit Diameter	56.3 in	59.7 in	33.8 in	149.6 in
Exhaust Velocity	10,141 ft/s	8,202 ft/s	9,500 ft/s	8,301 ft/s
Single Engine/Motor Thrust (Sea Level)	432,104 lbf (100% Thrust)	325,972 lbf (Burn time average)	147,000 lbf	2,250,000 lbf (Burn time average)
Booster Engine/Motor		**CASTOR IVA**		
Number of Booster Engines/Motors		8		
Propellant		HTPB (solid)		
Single Booster Engine/Motor Nozzle Exit Diameter		32.15 in		
Exhaust Velocity		8,202 ft/s		
Single Booster Engine/Motor Thrust (Sea Level)		112,019 lbf		
Modeled Effective Diameter	**79.6 in**	**108.7 in**	**100.4 in**	**149.6 in**
Modeled Combined Total Thrust	**864,208 lbf**	**1,267,082 lbf**	**1,323,000 lbf**	**2,250,000 lbf**

4.3 Flight Trajectory Modeling

Launch trajectories departing from WFF's Wallops Island launch range are unique to each particular mission and the environmental conditions. However, all launches are conducted to the east over the Atlantic Ocean. For the purposes of this study, the noise model utilizes a nominal Antares 200 series launch trajectory to model noise emissions from the four representative launch vehicles. Figure 12 shows the nominal launch trajectory, with its ground path displayed within the inset map. The nominal launch trajectory, provided by WFF personnel, originates from Pad 0-A. The Pad 0-A launch trajectory is translated to Pad 0-B and Pad 0-C to model launches departing from these two launch sites. The translation process involves determining the distance and direction of each launch trajectory point in relation to Pad 0-A, then moves each launch trajectory point to an equivalent distance and direction in relation to the new pad location. The time-varying thrust profile for each vehicle was based on the Antares 200 series trajectory, normalized on a thrust basis.

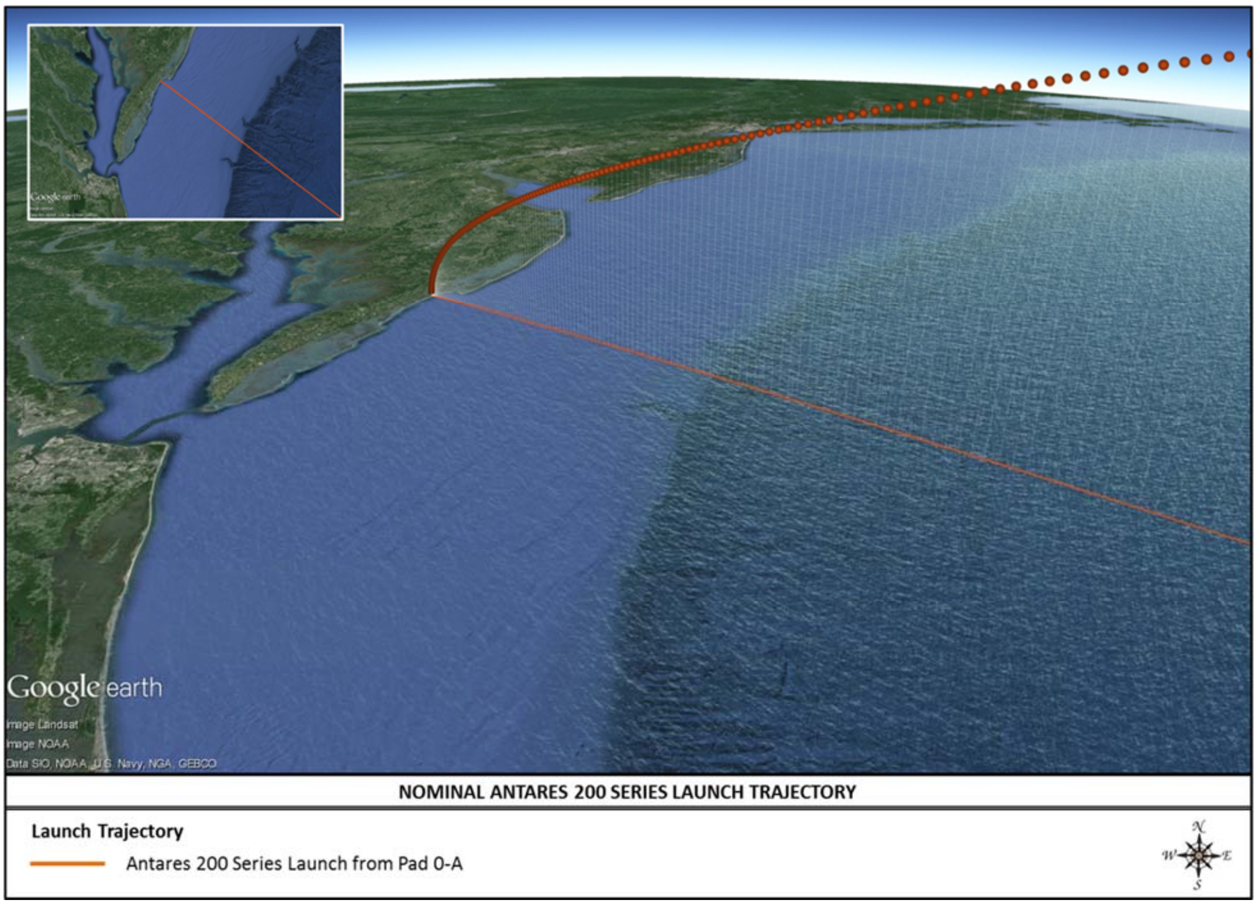

Figure 12. Nominal Antares 200 series trajectory launching from Pad 0-A

5 Results

The following sections present results of the noise study concerning the baseline and proposed future rocket launch operations at Wallops Island. Sections 5.1, 5.2 and 5.3, respectively, present the results of the launch noise impact, specific point analysis, and sonic boom analysis.

5.1 Launch Noise Analysis

5.1.1 Maximum A-weighted OASPL

The OASPL provides a measure of the sound level at any given time, while the maximum A-weighted OASPL ($L_{A,max}$) indicates the maximum OASPL achieved over the duration of the event. OSHA has set an upper limit noise level of 115 dBA for fifteen minutes as a guideline to protect human hearing from long-term continuous daily exposures to high noise levels and aid in the prevention of noise-induced hearing loss. As summarized in Table 7, the $L_{A,max}$ generated by a single launch event exceeds 115 dBA within a distance of approximately 0.6 miles from the launch pad for all four vehicles. The $L_{A,max}$ is a combination of a number of factors including the individual engines' thrust, acoustic efficiencies, exit velocity, effective diameter, and A-weighting. Note, the differences in these parameters, in some cases, can result in a larger $L_{A,max}$ associated with a vehicle with a smaller total thrust. Figure 13, Figure 14, and Figure 15 present the $L_{A,max}$ contours within the range of 85 to 115 dBA for vehicles launched from Pad 0-A, Pad 0-B, and Pad 0-C, respectively. Although the 115 dBA contours lie partially outside WFF boundaries, these areas do not include any residences as they are mainly over the ocean or the bay between Wallops Island and the mainland.

Table 7. Approximate distance (miles) from launch site for hearing conservation criteria.

Launch Vehicle	Antares 200	LMLV III	LFIC ELV	SFHC ELV
115 dBA Hearing Conservation Criteria	0.6 mi	0.6 mi	0.6 mi	0.6 mi

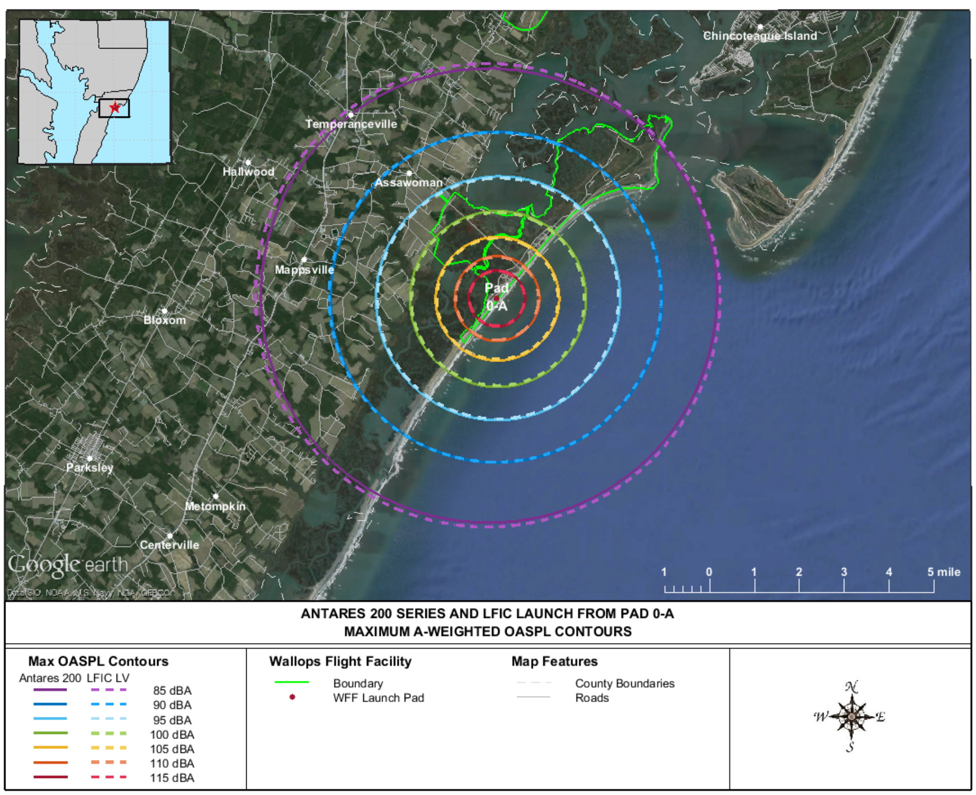

Figure 13. Maximum A-weighted OASPL ($L_{A,max}$) contours for vehicles launching from Pad 0-A

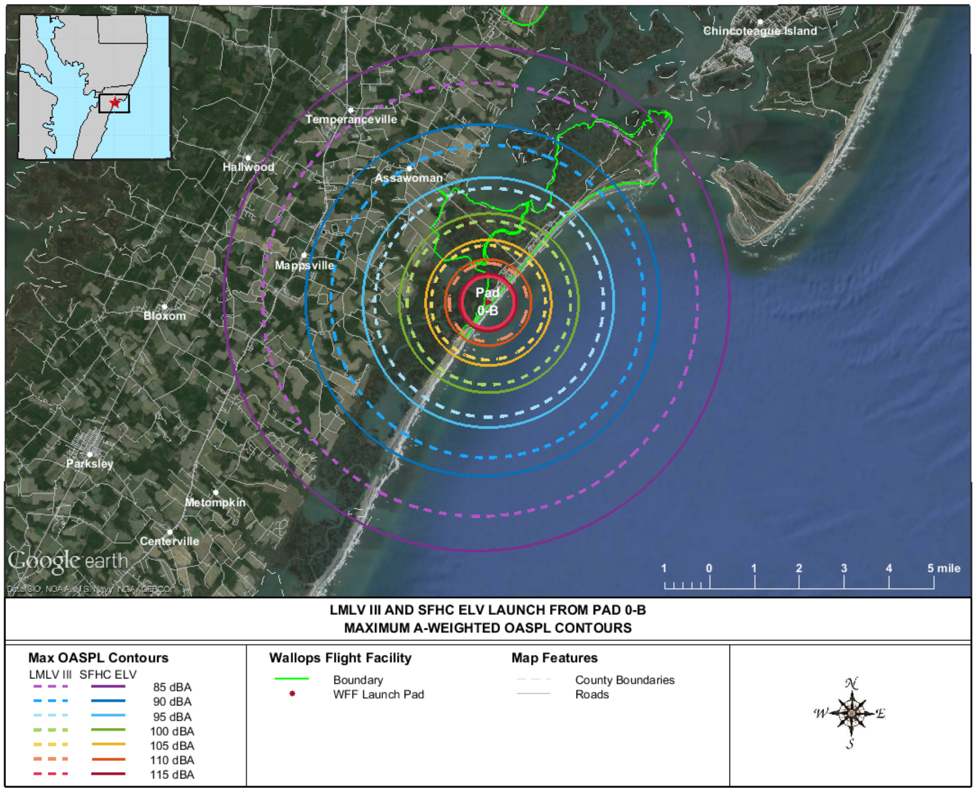

Figure 14. Maximum A-weighted OASPL ($L_{A,max}$) contours for vehicles launching from Pad 0-B

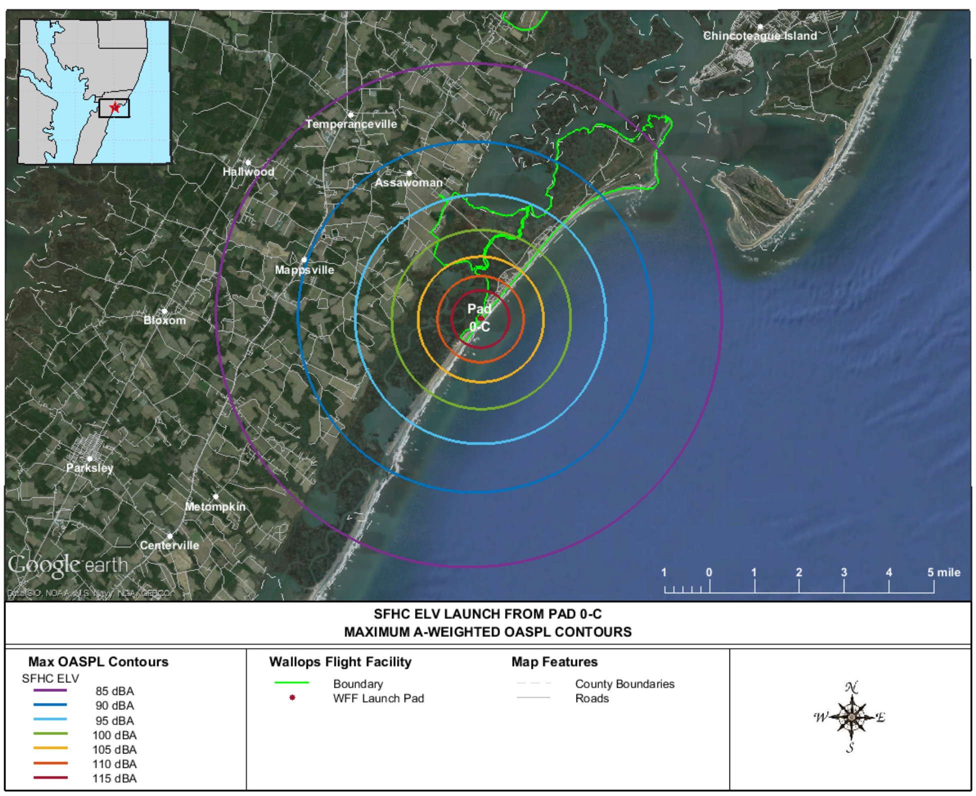

Figure 15. Maximum A-weighted OASPL ($L_{A,max}$) contours for vehicles launching from Pad 0-C

5.1.2 Maximum Unweighted OASPL

The OASPL provides a measure of the sound level at any given time, while the L_{max} indicates the maximum OASPL achieved over the duration of the event. To assess the potential risk to structural damage claims, the 111 dB and 120 dB contours are presented in Figure 16, Figure 17, and Figure 18 for vehicles launched from Pad 0-A, Pad 0-B and Pad 0-C respectively. The potential for structural damage claims is approximately one damage claim per 1,000 households exposed at 111 dB and one in 100 households at 120 dB. The 120 dB contour extends approximately 2.0 to 3.6 miles from the WFF launch pads, depending on the launch vehicle. Table 8 summarizes the approximate distances within which 111 dB and 120 dB are exceeded. The 120 dB contours include population in the region east of U.S. Route 13. The 111 dB contours extends approximately 5.1 to 8.8 miles from the WFF launch pads, depending on the launch vehicle. The 111 dB contours include populations in the regions of Chincoteague Island and Oak Hall to the north, Jenkins Bridge to the west, and Centerville to the south.

Table 8. Distance (miles) from launch site for structural damage claim criteria.

Launch Vehicle	Antares 200	LMLV III	LFIC ELV	SFHC ELV
111 dB Structural Damage Claim Criteria	5.1 mi	5.4 mi	6.1 mi	8.8 mi
120 dB Structural Damage Claim Criteria	2.0 mi	2.1 mi	2.4 mi	3.6 mi

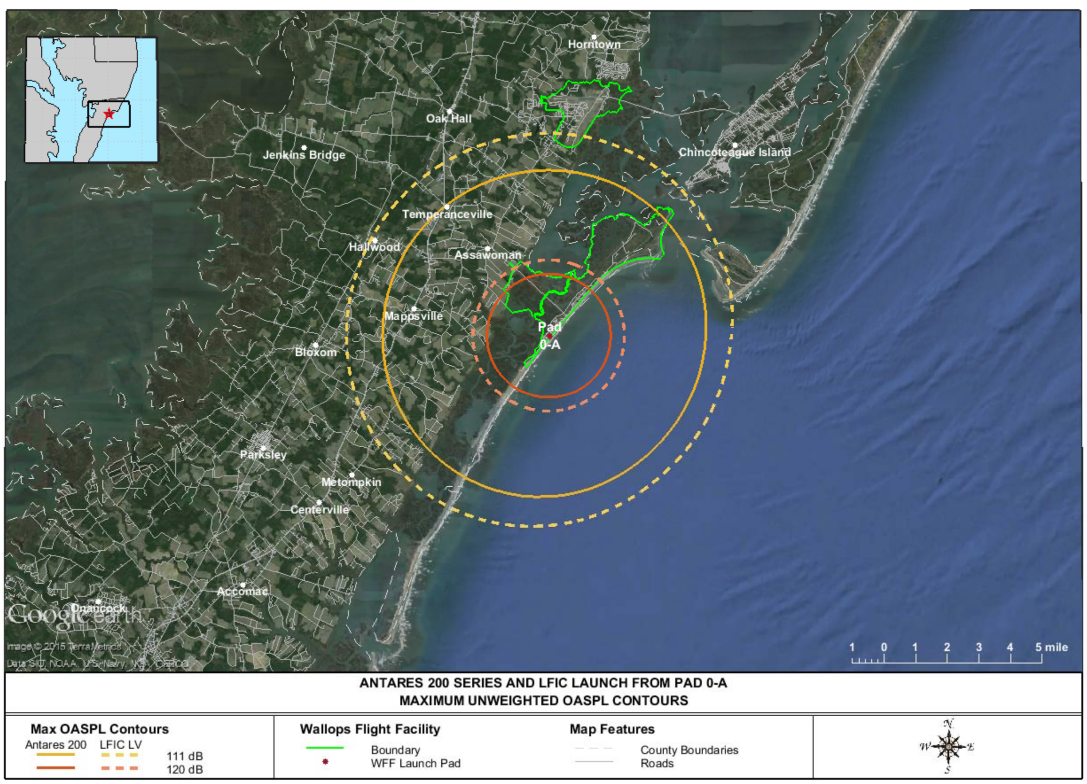

Figure 16. Maximum unweighted OASPL (L_{max}) contours for vehicles launched from Pad 0-A

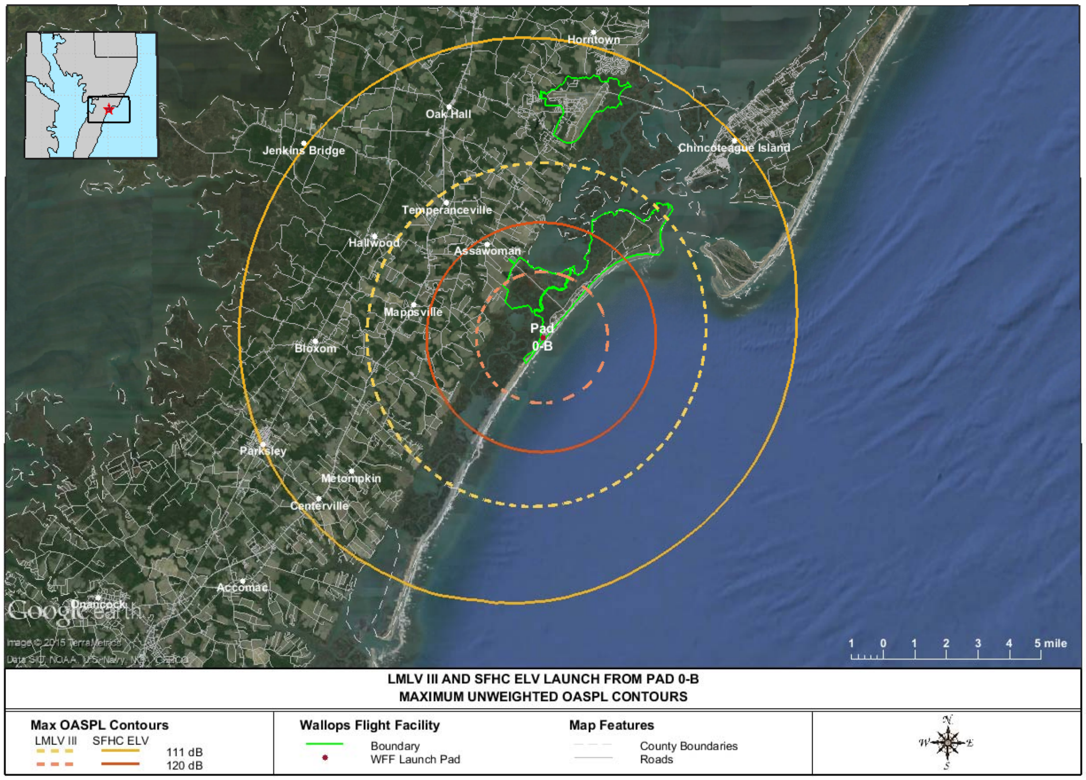

Figure 17. Maximum unweighted OASPL (L_{max}) contours for vehicles launched from Pad 0-B

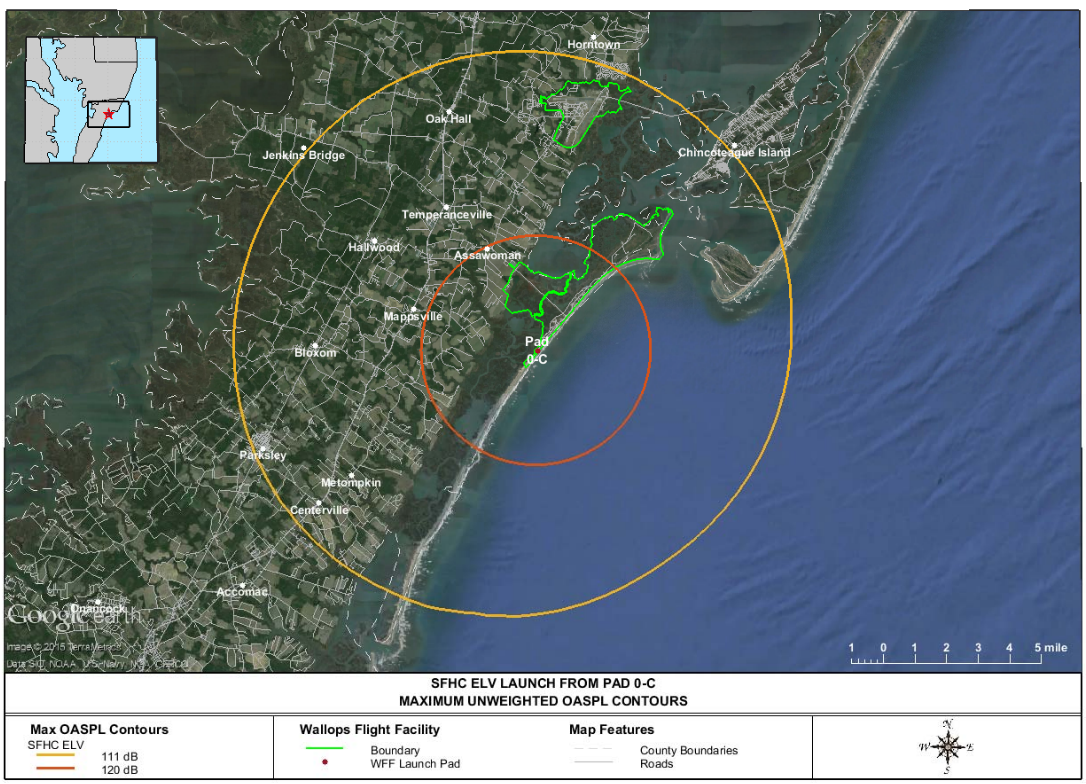

Figure 18. Maximum unweighted OASPL (L_{max}) contours for vehicles launched from Pad 0-C

5.1.3 A-weighted SEL

SEL represents both the magnitude of a sound and its duration. SEL provides a measure of the cumulative noise exposure 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, in one second, generate the same acoustic energy as the actual time-varying noise event. For sound generated by rocket launches, which last more than one second, the SEL is greater than the L_{max} because an individual launch can last for minutes and the L_{max} occurs instantaneously. Figure 19, Figure 20 and Figure 21 depict the A-weighted SEL contours for vehicles launched from Pad 0-A, Pad 0-B, and Pad 0-C respectively. Currently, there are no reported guidelines for SEL in reference to launch vehicle noise.

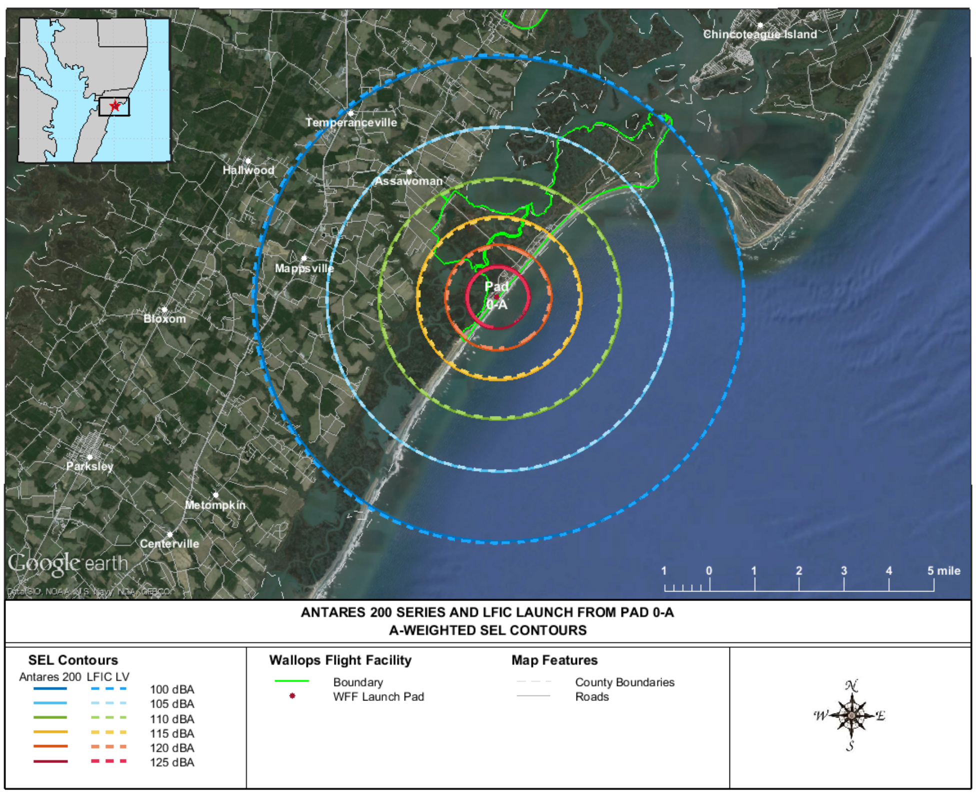

Figure 19. A-weighted SEL contours for vehicles launched from Pad 0-A

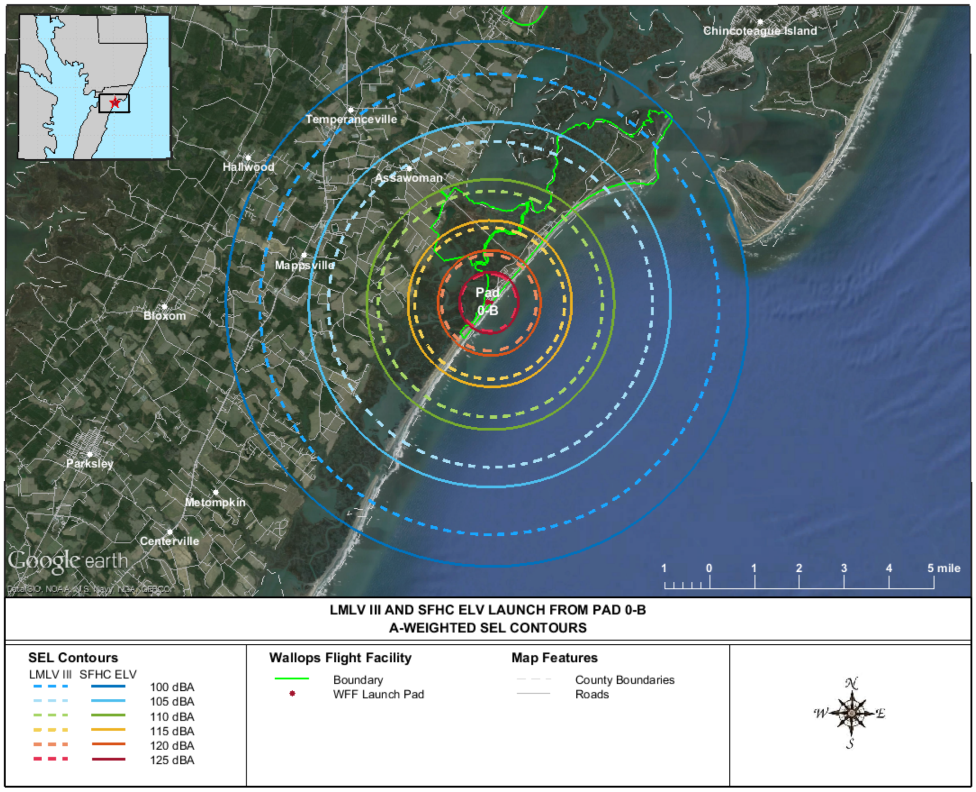

Figure 20. A-weighted SEL contours for vehicles launched from Pad 0-B

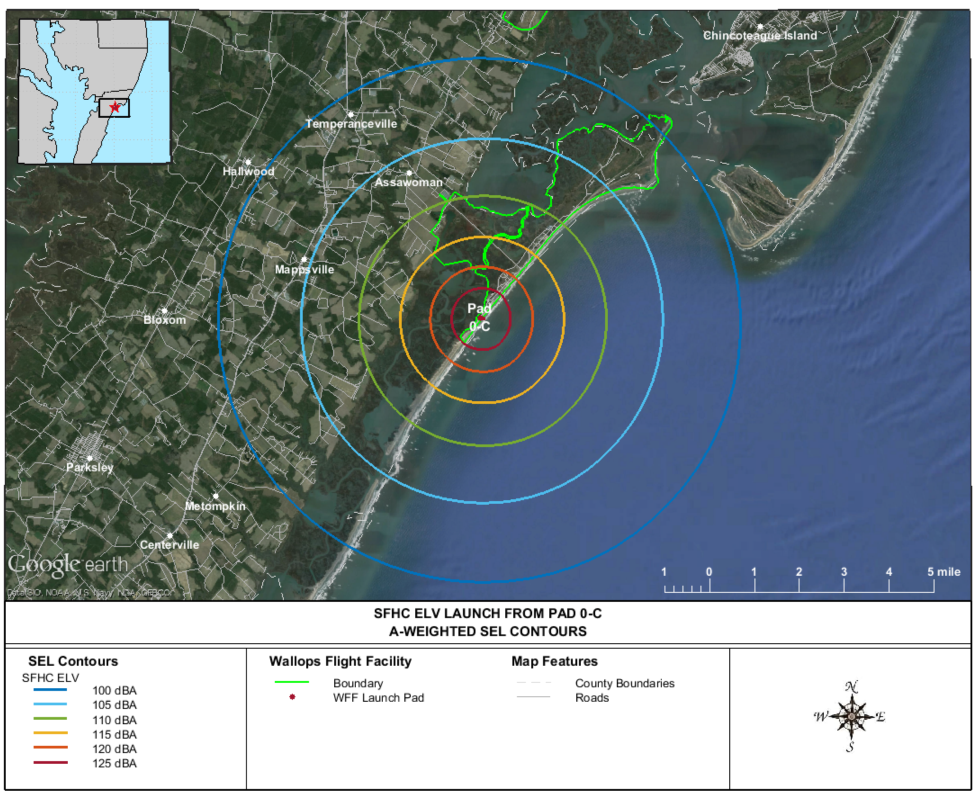

Figure 21. A-weighted SEL contours for vehicles launched from Pad 0-C

5.2 Specific Point Analysis at Nearest Residence

To provide more detail on potential community impacts when comparing the baseline to proposed future actions, the nearest residence location was modeled as a specific point of interest. The nearest residence, shown in Figure 22, is located approximately 1.7 to 1.9 miles west of the launch pads at a latitude and longitude of 37.838404° N and -75.522186° W. Figure 23 and Figure 24 present A-weighted and unweighted OASPL time histories, respectively, corresponding to the nearest residence. Although the launch event begins at time zero, it takes approximately 8 to 9 seconds for launch noise to propagate from the launch pads to the nearest residence. The time at which the maximum level occurs depends on the thrust profile, peak directivity angle, and distance between the source and the receiver. Maximum A-weighted OASPL at the nearest residence is less than the 115 dBA upper limit noise level associated with protecting human hearing. However, the maximum unweighted OASPL at the nearest residence exceeds 120 dB, indicating that, based on Guest and Slone (1972), the probability of a noise induced damage claim is greater than one in 100 for a launch event.

Figure 22. Location of the nearest residence shown in relation to the WFF launch pads

The maximum A-weighted OASPL, maximum unweighted OASPL, A-weighted SEL and Time Above an OASPL of 66 dBA at the nearest residence are presented in Table 9. Time above is a supplemental metric associated with speech interference measured in sentence intelligibility percentage. 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 3 ft (1 m) apart (U.S. EPA, November 1978). For launches at WFF, levels may exceed 66 dBA at the nearest residence for a period of up to 80 seconds per launch.

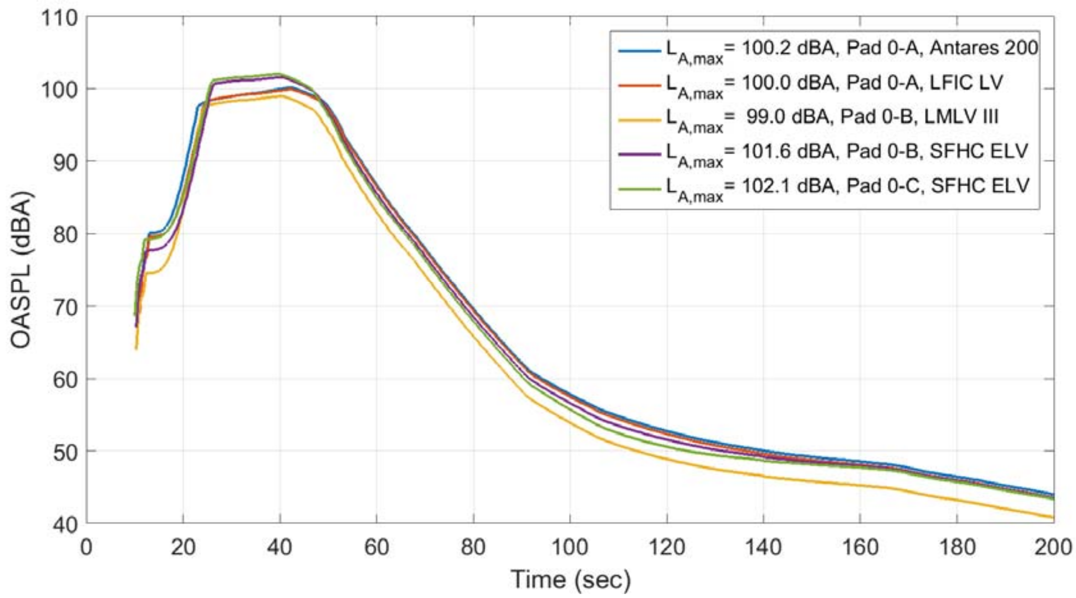

Figure 23. A-weighted OASPL time history at nearest residence

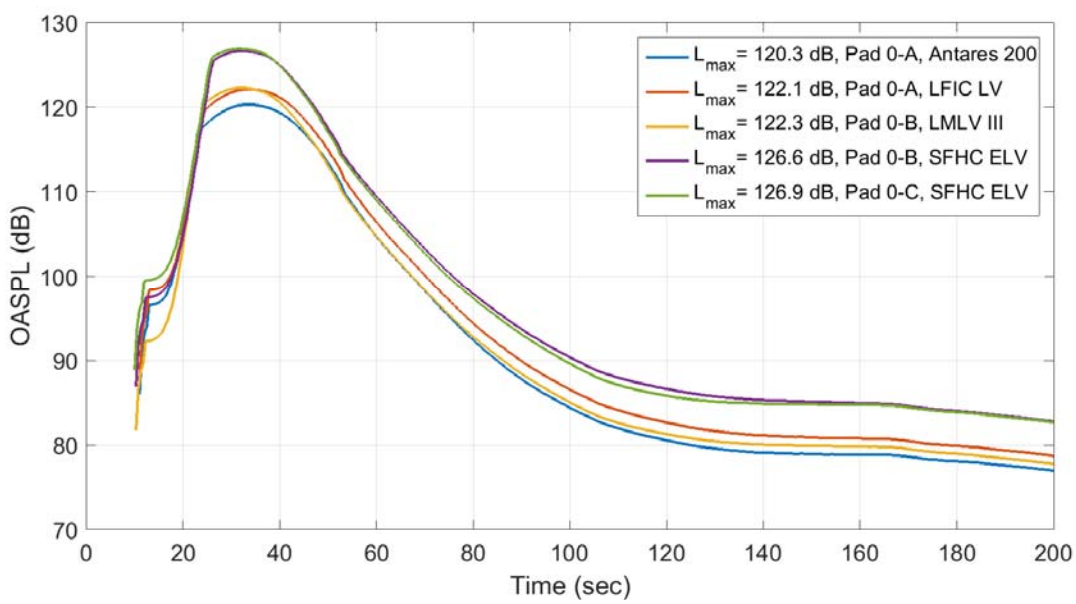

Figure 24. Unweighted OASPL time history at nearest residence

Table 9. Nearest residence noise analysis results

	Antares 200 Pad 0-A	LFIC ELV Pad 0-A	LMLV III Pad 0-B	SFHC ELV Pad 0-B	SFHC ELV Pad 0-C
Lmax (dB)	120	122	122	127	127
Lmax (dBA)	100	100	100	102	102
SEL (dBA)	114	114	114	115	115
Time Above (66 dBA)	< 80 sec	< 80 sec	< 80 sec	< 80 sec	< 80 sec

5.3 Sonic Boom Noise Analysis

Launches of the four representative launch vehicles from WFF would produce sonic booms during the vehicles' ascent. However, the resulting sonic booms would be directed southeasterly out over the ocean in the direction of the launch azimuth. Note that the presence and/or location of sonic boom regions will be highly dependent on the actual trajectory and atmospheric conditions at the time of flight. The nominal Antares 200 series launch trajectory would generate sonic booms that impact the ocean surface approximately 30 miles from the coast making them inaudible on the mainland. Therefore, with respect to human health and safety or structural damage, noise impacts due to sonic booms are not expected. Thus a quantitative analysis was not performed. However, to provide perspective, modeled sonic booms from ELVs at other launch sites ranged from 3.0 and 5.25 psf (FAA, April 2013), for a liquid-fueled medium class launch vehicle and liquid-fueled heavy class launch vehicle, respectively. A sonic boom due to the overflight of a Titan IV from Vandenberg AFB was measured at a number of locations in the Channel Islands, 30 to 40 miles from the launch pad (Downing and Plotkin, 1996). The over pressures recorded at these locations were less than 2.4 psf, with the exception one site which recorded an 8.4 psf focused sonic boom. Note, a vehicle's observed sonic boom peak overpressure is highly dependent on the vehicle trajectory and atmospheric conditions at the time of flight.

6 Summary

This noise study was performed to support the NASA WFF Site-wide PEIS for baseline and proposed future actions at WFF in Accomack County, Virginia. This noise study examines four nominal launch vehicles representing the largest orbital thrust vehicles currently and proposed to be launched from WFF: the two baseline vehicles Antares 200 Series and LMLV III, and the two future vehicles LFIC ELV and SFHC ELV.

To assess the impact of rocket noise with respect to hearing conservation, $L_{A,max}$ contours are presented. OSHA has set an upper limit noise level of 115 dBA for a fifteen minute exposure 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. Although the 115 dBA contours lie partially outside WFF boundaries, these areas do not include any residences as they are mainly over the ocean or the bay between Wallops Island and the mainland.

To assess the potential impact of rocket noise with respect to structural damage claims, L_{max} contours are provided. A NASA technical memo written by Guest and Slone (April 1972) estimated that one damage claim is expected in 1,000 households exposed at an average continuous level of 111 dB, and one in 100 households at 120 dB. The 120 dB contours include populations in the region east of U.S. Route 13. The 111 dB contours extends approximately 5.2 to 9.7 miles from the WFF launch pads, depending on the launch vehicle. The 111 dB contours include populations in the regions of Chincoteague Island and Oak Hall to the north, Jenkins Bridge to the west, and Centerville to the south.

As an additional supplemental metric, A-weighted SEL noise contours were provided to assess the impact of the entire launch event beyond the maximum noise level provided by the OASPL noise contours. Currently, there are no reported guidelines for limiting SEL in reference to launch vehicle noise.

To help further assess community impact as a result of the proposed future launches, the nearest residence location was modeled as a specific point of interest. $L_{A,max}$ at the nearest residence is less than the 115 dBA upper limit noise level associated with protecting human hearing. The maximum unweighted OASPL at the nearest residence exceeds 120 dB, indicating that, per Guest and Slone (1972), the potential for damage claims is greater than one in 100 for a launch event. For launches at WFF, noise levels at the nearest residence may exceed 66 dBA, and sentence intelligibility may decrease below 95%, for a period of up to 80 seconds per launch.

The potential for sonic boom impacts as a result of launches of the representative launch vehicles was qualitatively assessed and discussed. For vehicles launching from Wallops Island, little impact is expected since the launch trajectories are in a primarily southeasterly direction, which is out over the water. This direction precludes any structural damage since the booms will intercept the ocean. The nominal Antares 200 series launch trajectory would generate sonic booms that impact the ocean surface approximately 30 miles from the coast making them inaudible on the mainland. Therefore, with respect to human health and safety or structural damage, noise impacts due to sonic booms are not expected.

In the community, the smallest change in average noise level between two events that can likely be detected by the average listener is about 3 dB (Fayh and Thompson, 2015). At the nearest residence, the modeled proposed future mission growth is projected to increase the maximum sound pressure level up to 2 dBA, per launch, relative to the baseline, which will likely be difficult for people to detect.

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Blue Ridge Research and Consulting, LLC

Technical Report

Return to Launch Site Noise Study for the Wallops Flight Facility Programmatic Environmental Impact Statement

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Acronyms and Abbreviations

The following acronyms and abbreviations are used in the report:

BRRC	Blue Ridge Research and Consulting, LLC
dB	decibel
dBA	A-weighted decibel level
LFIC	Liquid Fueled Intermediate Class
$L_{A,max}$	maximum A-weighted OASPL in decibels
L_{max}	maximum unweighted OASPL in decibels
LV	Launch Vehicle
NASA	National Aeronautics and Space Administration
NIHL	noise-induced hearing loss
OASPL	overall sound pressure level in decibels
OSHA	Occupational Safety and Health Administration
PEIS	Programmatic Environmental Impact Statement
psf	pounds per square foot
RTLS	Return to launch site
RUMBLE	The Launch Vehicle Acoustic Simulation Model
sec	second
SEL	Sound Exposure Level in decibels
WFF	Wallop Flight Facility

1 Introduction

This report documents the results of a noise study conducted to evaluate potential noise impacts of return to launch site (RTLS) operations at the National Aeronautics and Space Administration's (NASA) Wallops Flight Facility (WFF) in Accomack County, Virginia. The analysis was performed in support of the WFF's Site-wide Programmatic Environmental Impact Statement (PEIS) for proposed future actions. This study examined the potential for impacts from a notational RTLS operation of a representative Liquid Fueled Intermediate Class Launch Vehicle (LFIC LV) to a notional WFF landing site located at Pad 0-C. The analysis employed the same noise metrics, impact criteria, acoustic modeling methodology, and input parameters documented in the previous noise analysis performed for launch operations at WFF titled "Launch Noise Study for the Wallops Flight Facility Programmatic Environmental Impact Statement" [1]. Section 2 provides a brief summary of the essential input parameters. Section 3 presents the noise modeling results, and a summary is provided in Section 4 to document the notable findings of this noise study.

2 Wallops Launch Range

2.1 Launch Range Description

WFF is the NASA's principal facility for management and implementation of suborbital research programs. WFF supports missions for suborbital and orbital rocket vehicles. The launch range on Wallops Island currently includes seven launch pads, three blockhouses for launch control, and assembly buildings that support the preparation and launching of suborbital and orbital launch systems [1]. This modeling effort considers RTLS operations to a notional WFF landing site located at Pad 0-C, shown in Figure 1. The Pad 0-C landing site is modeled to provide a conservative evaluation of the potential noise impacts, as landings on off-shore landing platforms will generate less noise impacts to people and/or structures.

Figure 1. WFF launch range

2.2 Vehicle and Engine Modeling Parameters

This noise study considered the RTLS operations of a representative LFIC LV. The Launch Vehicle Acoustic Simulation Model (RUMBLE) model requires specific vehicle/engine input parameters to determine the noise exposure resulting from the proposed RTLS operations. Table 1 presents the launch vehicle and engine parameters utilized in the acoustic modeling.

Table 1. Vehicle and engine parameters used in acoustic modeling

Reference Name/Acronym	LFIC LV
Launch Vehicle Class	Liquid Fueled Intermediate Class (LFIC)
Length	224.4 ft
Number of Engines/Motors	1
Propellant	LO2/RP (liquid)
Single Engine/Motor Nozzle Exit Diameter	33.8 in
Exhaust Velocity	9,500 ft/s
Single Engine/Motor Thrust (Sea Level)	147,000 lbf
Landing Pad	Notional Pad 0-C N 37.827284°, W -75.494435°

2.3 Flight Trajectory Modeling

Launch trajectories departing from WFF's Wallops Island launch range and associated landing trajectories are unique to each particular mission and the environmental conditions. However, all launches and landing operations are conducted to and from the east over the Atlantic Ocean, respectively. The propulsion noise modeling assumes a landing trajectory that returns along the same flight path as the representative nominal Antares 200 series launch trajectory with a southeasterly heading, since a detailed landing trajectory was not available. Recent LFIC LV landings have included two engine relights [2]. The first engine relight typically happens upon reentering the atmosphere, where the vehicle's altitude is too high to generate significant noise at ground level. The second relight occurs during the final portion of the landing operation, and its durations is approximately 35 seconds [3]. The landing propulsion noise is evaluated for this second relight of the LFIC LV's landing operation. Accurate analysis of the resultant sonic boom generated by this landing operations requires a more detailed kinematic trajectory that is not available for WFF at this time. Thus, the sonic boom analysis for this operation is based on a previous study of a similar vehicle and RTLS operation [4].

3 Results

The following sections present results of the noise study concerning the proposed LFIC LV RTLS rocket operations at Wallops Island. Sections 3.1 and 3.2, respectively, present the results of the propulsion noise impact and sonic boom discussion.

3.1 Propulsion Noise Analysis

RUMBLE, developed by Blue Ridge Research and Consulting, LLC (BRRC), was used to predict the propulsion noise associated with the proposed WFF LFIC LV RTLS operations. It should be noted that noise levels may be 3 dB louder over water surfaces compared to levels over ground surfaces which is assumed in the modeling.

3.1.1 Maximum A-weighted OASPL

The A-weighted Overall Sound Pressure Level (OASPL) provides a measure of the sound level relative to human hearing at any given time, while the maximum A-weighted OASPL ($L_{A,max}$) indicates the maximum A-weighted OASPL occurring during the duration of the event. OSHA has set an upper limit noise level of 115 dBA for fifteen minutes as a guideline to protect human hearing from long-term continuous daily exposures to high noise levels. This limit aids in the prevention of noise-induced hearing loss [5]. The $L_{A,max}$ generated by a single LFIC LV RTLS event exceeds 115 dBA within a distance of approximately 0.4 miles from the landing site. Figure 2 presents the $L_{A,max}$ contours within the range of 85 to 115 dBA. Although the 115 dBA contour extends partially outside WFF boundaries, these areas are mainly over the ocean or the bays between coast and the mainland and they do not include any residences.

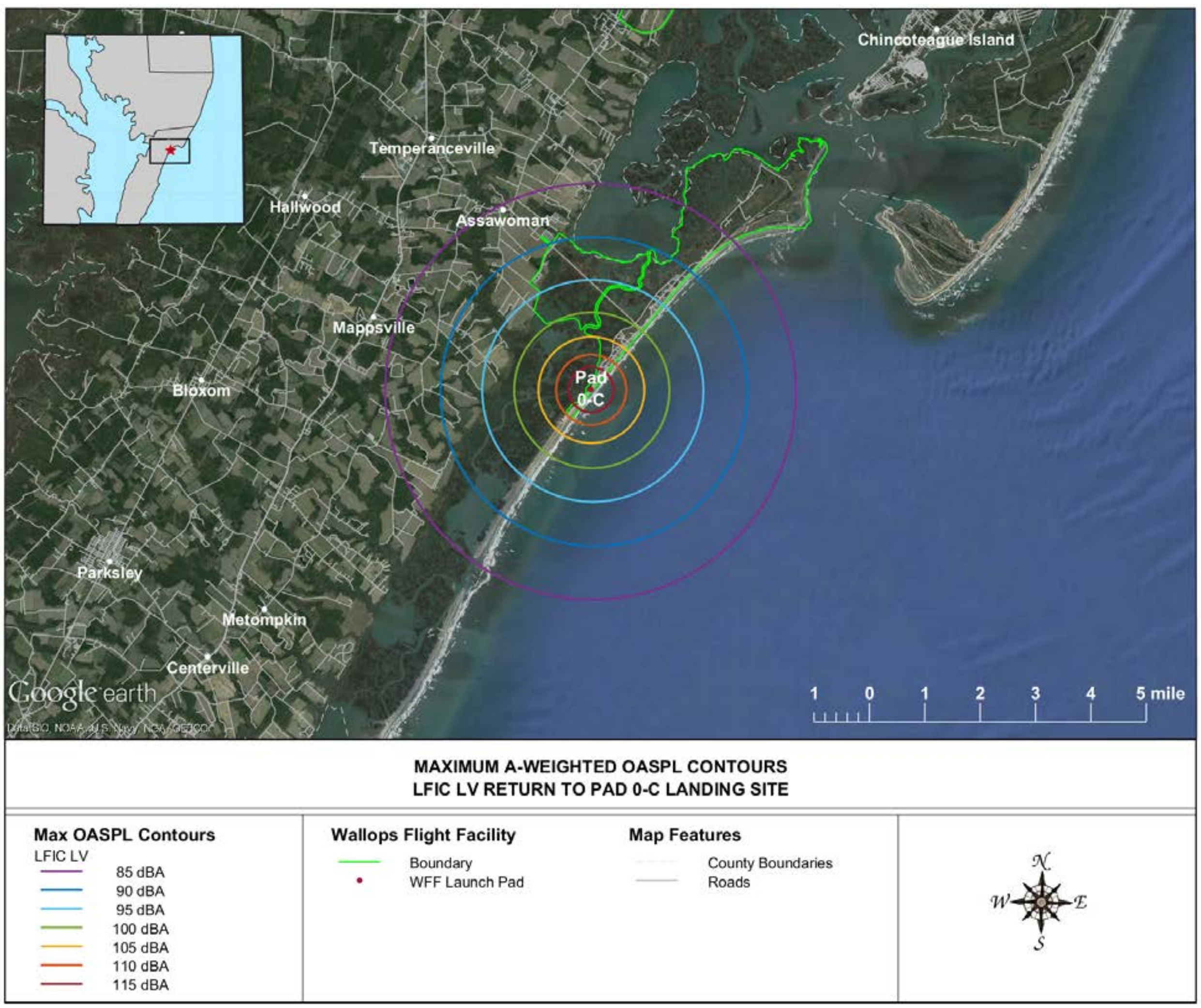

Figure 2. Maximum A-weighted OASPL ($L_{A,max}$) contours for a LFIC LV return to the Pad 0-C landing site

3.1.2 Maximum Unweighted OASPL

The OASPL provides a measure of the sound level at any given time, while the L_{max} indicates the maximum OASPL occurring during the duration of the event. OASPL of 111dB and 120dB are utilized to assess the potential risk of structural damage claims [6]. The 111 dB and 120 dB contours are presented in Figure 3. The potential for structural damage claims is approximately one damage claim per 1,000 households exposed at 111 dB and one in 100 households at 120 dB. The 120 dB and 111 dB contours extend approximately 0.6 to 1.6 miles from the landing site. Although the 111 dB and 120 dB contours extend outside WFF boundaries, these areas do not include any residential structures.

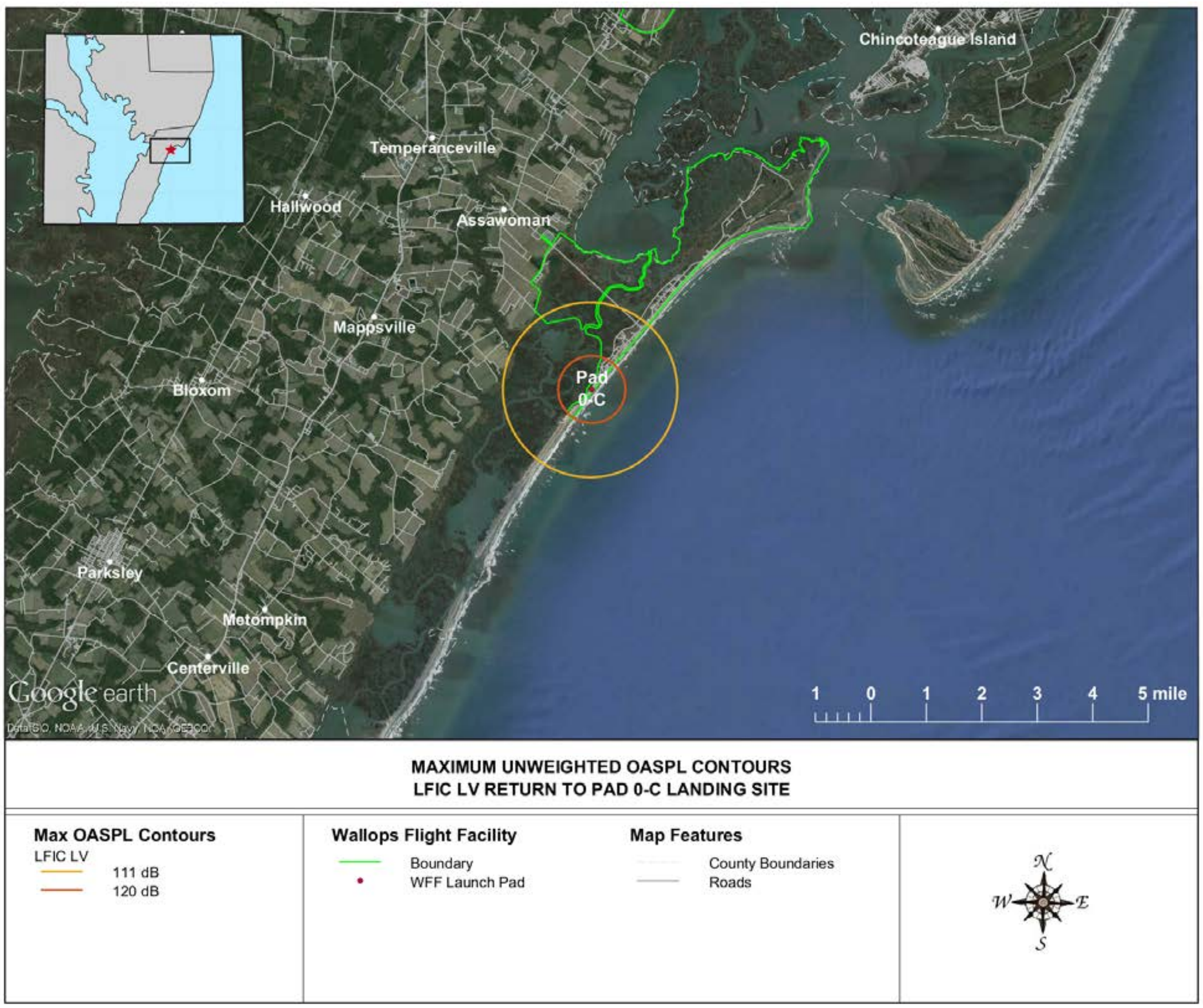

Figure 3. Maximum unweighted OASPL (L_{max}) contours for a LFIC LV return to the Pad 0-C landing site

3.1.3 A-weighted Sound Exposure level (SEL)

SEL represents the cumulative noise exposure of a transient noise event and includes both its magnitude and its duration. However, 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, in one second, generate the same acoustic energy as the actual time-varying noise event. For sound generated by rocket operations, which last more than one second, the SEL is greater than the L_{max} because an individual event can last for minutes and the L_{max} occurs instantaneously. Figure 4 depicts the A-weighted SEL contours for a single LFIC LV RTLS event. Currently, no reported guidelines have been established for SEL in reference to launch vehicle noise.

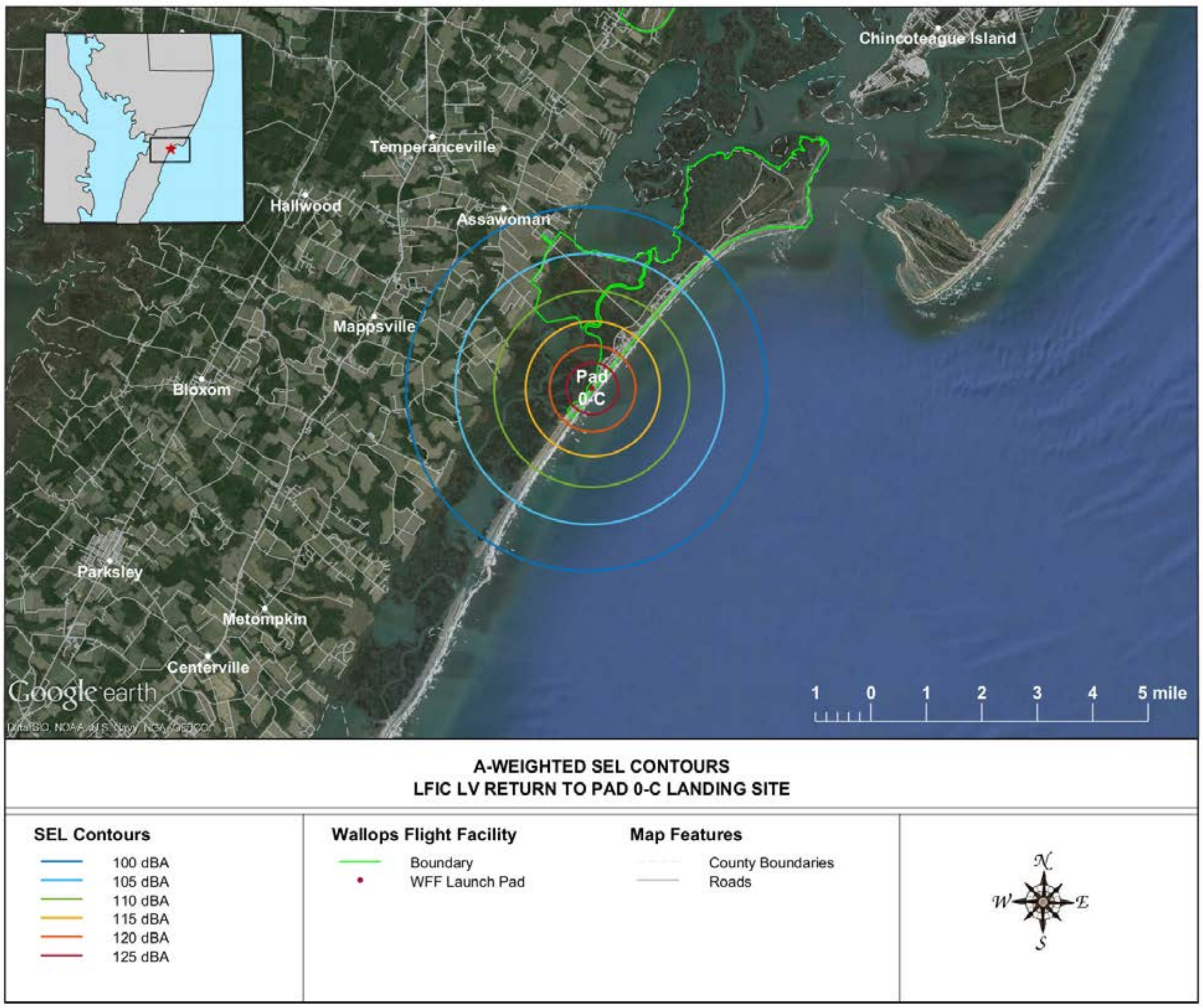

Figure 4. A-weighted SEL contours for a LFIC LV return to the Pad 0-C landing site

3.2 Sonic Boom Discussion

A sonic boom is the sound associated with the shock waves created by a vehicle traveling through the air faster than the speed of sound. NIOSH [7] and OSHA [8] have stated that sound pressure levels should not exceed 140 dB peak, which equates to a sonic boom level of approximately 4 psf.‡

Sonic booms are also commonly associated with structural damage. Most damage claims are for brittle objects, such as glass and plaster. In general, for well-maintained structures, the threshold for damage produced by sonic booms is 2 psf, below which damage is unlikely [9]. At levels between 2 and 4 psf, failures begin to show for structures that appear to be in nominally good condition that would have been difficult to forecast based on their existing localized condition [9]. As levels rise above 4 psf, the probability and significance of the potential for structural damage increases.

However, 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 [10] to one in a million [11]. 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 [12] 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.

RTLS operations of a LFIC LV landing at WFF would generate sonic booms when the vehicle is supersonic during descent. The observed sonic boom peak overpressure is highly dependent on the vehicle trajectory and atmospheric conditions at the time of flight. A detailed LFIC LV landing trajectory accurately representing the vehicle's supersonic descent to WFF was unavailable, therefore the following discussion is in general terms. For a notional RTLS operation returning from a southeasterly direction toward WFF, a majority of the sonic boom would occur over the Atlantic Ocean. The sonic boom overpressure levels near the landing site will reach a maximum of 6 psf, decreasing with distance from the landing site and approaching a level of 0.5 psf at 20 miles. The levels approach 2 psf at 6 miles from the landing site, near the communities of Atlantic to the north, Macedonia to the west, and Gargatha to the southwest. The majority of land area exposed to levels greater than 4 psf is within WFF boundaries but may include land east of Route 679 within 2 miles of the landing site. Note, that these levels and relative locations are representative of a nominal landing trajectory returning from a southeasterly direction. The potential impacts may differ based on actual mission trajectories and atmospheric conditions.

Given that the expected sonic boom overpressure levels are greater than 2 psf for communities within 6 miles of the landing site, there is a potential for structural damage as a result of a LFIC LV RTLS operation [9, 10, 11, 12]. Additionally, there is a potential for hearing damage (to humans) within 2 miles of the landing site, where sonic boom overpressure levels may be greater than the ~4 psf impulsive hearing conservation noise criteria [5, 13].

‡ The peak pressure of a sonic boom, P_k (psf), can be converted to the peak sound pressure level in decibels (L_{pk}) by the mathematical relationship of: $L_{pk} = 127.6 + 20 \log_{10} P_k$

4 Summary

This noise study was performed to support the NASA WFF's Site-wide PEIS for proposed future actions. inclusion of RTLS rocket operations at WFF in Accomack County, Virginia. This study examines the potential for impacts from a notational RTLS operation of a representative LFIC LV to a notional WFF landing site located at Pad 0-C. The Pad 0-C landing site is modeled to provide a conservative evaluation of the potential noise impacts, as landings on off-shore landing platforms will generate less noise and sonic boom exposures to people and/or structures. This conservative evaluation found that the propulsion noise impacts generated by the proposed landing operation are less than those experienced from any of the launch operations analyzed for the WFF PEIS.

To assess the impact of rocket noise with respect to hearing conservation, $L_{A,max}$ contours are presented. OSHA has set an upper limit noise level of 115 dBA for a fifteen-minute exposure 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 [5]. Although the 115 dBA contour extends partially outside WFF boundaries, these areas are mainly over the ocean or the bays between the coast and the mainland and they do not include any residences.

To assess the potential impact of rocket noise with respect to structural damage claims, L_{max} contours are provided. A NASA technical memo written by Guest and Slone [6] estimated that one damage claim is expected in 1,000 households exposed at an average continuous level of 111 dB, and one in 100 households at 120 dB. Although the 111 dB and 120 dB contours lie partially outside WFF boundaries, these areas do not include any residential structures.

As an additional supplemental metric, A-weighted SEL noise contours were provided to assess the impact of the entire launch event beyond the maximum noise level provided by the OASPL noise contours. Currently, no reported guidelines have been established for limiting SEL in reference to launch vehicle noise.

Given that the expected sonic boom overpressure levels are greater than 2 psf for communities within 6 miles of the landing site, there is potential for structural damage as a result of a LFIC LV RTLS operation [9, 10, 11, 12]. The levels approach 2 psf at 6 miles from the landing site, near the communities of Atlantic to the north, Macedonia to the west, and Gargatha to the southwest. The majority of land area exposed to levels greater than 4 psf is within WFF boundaries but may include land east of Route 679 within 2 miles of the landing site. Additionally, there is potential for hearing damage (to humans) within 2 miles of the landing site, where sonic boom overpressure levels may be greater than the ~4 psf impulsive hearing conservation noise criteria [5, 13].

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