DRAFT

Environmental Assessment

BLUE ORIGIN NEW GLENN CADENCE INCREASE AT SPACE LAUNCH COMPLEX 36

CAPE CANAVERAL SPACE FORCE STATION, FLORIDA

Appendices B, C, and D

September 2026

Federal Aviation Administration
Department of the Air Force
United States Coast Guard
National Aeronautics and Space Administration

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Federal Aviation Administration

Photo credit Blue Origin

LIST OF APPENDICES

Acronyms and Abbreviations

Acronym	Definition
§/§§	section/sections
ACHP	Advisory Council on Historic Preservation
AHA	Aircraft Hazard Area
APE	Area of Potential Effects
ASEL	A-weighted sound exposure level
BCA	Biological and Conference Assessment
BGEPA	Bald and Golden Eagle Protection Act
Blue Origin	Blue Origin, LLC
CCP	Comprehensive Conservation Plan
CCSFS	Cape Canaveral Space Force Station
CDNL	C-weighted day-night average sound level
CFR	Code of Federal Regulations
CH_4	methane
CMP	Coastal Management Program
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
COMDTINST	Commandant Instruction
CZMA	Coastal Zone Management Act
DAF	Department of the Air Force
dB	decibel(s)
dBA	A-weighted decibels
DNL	day-night average sound level
DoD	Department of Defense
DOT	Department of Transportation
DoW	Department of War
EO	Executive Order
EA	Environmental Assessment
EFH	essential fish habitat
EIS	Environmental Impact Statement
ERD	Environmental Resources Document
ERP	Environmental Resource Permit
ESA	Endangered Species Act
FAA	Federal Aviation Administration
FDEP	Florida Department of Environmental Protection
FONSI	Finding of No Significant Impact
HAPC	habitat areas of particular concern
ILV	integrated launch vehicle
INRMP	Integrated Natural Resources Management Plan
IPaC	Information for Planning and Consultation
KSC	Kennedy Space Center
LAA	Limited Access Area
$L_{A,max}$	maximum A-weighted sound level
lbf	million pounds-force
LC	Launch Complex
LH_2	liquid hydrogen
L_{max}	maximum sound level
LNG	liquefied natural gas
LOX	liquid oxygen

Acronym	Definition
MBTA	Migratory Bird Treaty Act
MG	million gallons
MGD	million gallons per day
MINWR	Merritt Island National Wildlife Refuge
MMPA	Marine Mammal Protection Act
MSA	Magnuson-Stevens Fishery Conservation and Management Act
MT/yr	metric tons per year
N_2O	nitrous oxide
NAAQS	National Ambient Air Quality Standards
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NEI	National Emissions Inventory
NEPA	National Environmental Policy Act
NHPA	National Historic Preservation Act
NMFS	National Marine Fisheries Service
No.	Number
NOTAM	Notice to Airmen
NOTMAR	Notice to Mariners
NO_x	nitrogen oxides
NPDES	National Pollutant Discharge Elimination System
NRHP	National Register of Historic Places
OSHA	Occupational Safety and Health Administration
PDC	project design criteria
PLOC	Programmatic Letter of Concurrence
PM	particulate matter
PM_{10}	particulate matter with a diameter equal to or less than 10 microns
$PM_{2.5}$	particulate matter with a diameter equal to or less than 2.5 microns
PSD	Prevention of Significant Deterioration
psf	pound per square foot
RNA	Regulated Navigation Area
SCCC	Spaceport Command and Control Center
SHPO	State Historic Preservation Officer
SJRWMD	St. Johns River Water Management District
SLC	Space Launch Complex
SLD 45	Space Launch Delta 45
SpaceX	Space Exploration Technologies Corp.
U.S.	United States
U.S.C.	United States Code
USCG	United States Coast Guard
USEPA	United States Environmental Protection Agency
USFWS	United States Fish and Wildlife Service
USSF	United States Space Force
VOL	vehicle operator license

Appendix B Public and Agency Coordination

B.1 Tribal Coordination

Executive Order 13175 of November 6, 2000, *Consultation and Coordination with Indian Tribal Governments*, charges all executive departments and agencies with engaging in regular, meaningful, and robust consultation with tribal officials in the development of federal policies that have tribal implications. On September 29, 2026, as part of Draft Environmental Assessment (EA) coordination, the Federal Aviation Administration (FAA) initiated government-to-government consultation with the following Native American tribal leaders and Tribal Historic Preservation Officers: the Miccosukee Tribe of Indians of Florida, the Seminole Nation of Oklahoma, and the Seminole Tribe of Florida. Correspondence in this regard will be provided as part of the Final EA.

B.2 Government Agency Coordination

During the development of this EA, FAA and the Department of the Air Force (DAF) coordinated with various local, state, and federal agencies regarding the Proposed Action and will continue to coordinate with these agencies as required. In addition to Endangered Species Act consultation with the United States Fish and Wildlife Service (Appendix A.1, *Endangered Species Act Section 7 Consultation*) and National Historic Preservation Act Section 106 consultation with the Florida State Historic Preservation Officer, FAA submitted this Draft EA to the Florida State Clearinghouse for review by the Florida Department of Environmental Protection pursuant to the Coastal Zone Management Act. Correspondence in this regard will be provided as part of the Final EA.

B.3 Draft Environmental Assessment Public Review

B.3.1 Introduction

FAA released the Draft EA for a 30-day public review on September 29, 2026, and published a Notice of Availability in the Federal Register and in local newspapers. The Draft EA was made available electronically on the Federal Non-rulemaking Docket Portal (Docket Number FAA-2026-9841) and on the FAA website at https://www.faa.gov/space/stakeholderengagement/blue-origin-new-glenn. FAA also distributed the Draft EA to the Florida State Clearinghouse. FAA will hold a virtual public meeting on the Zoom virtual meeting platform on October 22, 2026 (the FAA project website provides meeting details).

This section and subsequent sections will be updated for the Final EA once the Draft EA public review process has been completed.

B.3.2 Methodology

This section will be updated to describe the process utilized for addressing Draft EA public comments.

B.3.3 Topical Summaries and Responses

This section will be updated with Draft EA public comment summaries and FAA/DAF responses.

Appendix C Noise Report

Blue Ridge Research and Consulting, LLC

BRRC Report 25-17 (Final)

Noise Study for Blue Origin New Glenn Operations at CCSFS LC-36

19 December 2025 (Rev 3, 3 March 2026)

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ACRONYMS AND ABBREVIATIONS

The following acronyms and abbreviations are used in the report:

ASEL	A-weighted Sound Exposure Level
BRRC	Blue Ridge Research and Consulting, LLC
CCSFS	Cape Canaveral Space Force Station
dB	Decibel
dBA	A-weighted Decibel Level
dBC	C-weighted Decibel Level
DI	Directivity Indices
DNL	Day-Night Average Sound Level
DoD	Department of Defense
DSM-1	Distributed Source Method 1
EA	Environmental Assessment
FAA	Federal Aviation Administration
ft	Foot/Feet
Hz	Hertz
KSC	Kennedy Space Center
lbf	Pound Force
lbs	Pound Mass
LC-36	Launch Complex 36
$L_{A,max}$	Maximum A-weighted Sound Level in Decibels
L_{max}	Maximum Unweighted Sound Level in Decibels
L_{pk}	Peak Sound Pressure Level in Decibels
NIHL	Noise-Induced Hearing Loss
NIOSH	National Institute for Occupational Safety and Health
OSHA	Occupational Safety and Health Administration
psf	Pounds per Square Foot
RUMBLE	The Rocket Propulsion Noise and Emissions Simulation Model
SEL	Sound Exposure Level
S.L.	Sea Level

1 INTRODUCTION

This report documents the noise exposure and the potential for noise impacts from the operations of Blue Origin's New Glenn launch vehicle from Cape Canaveral Space Force Station (CCSFS) Launch Complex 36 (LC-36). Blue Origin plans to conduct up to 50 launches and landings of New Glenn per year. Prior to each launch, Blue Origin may perform static fire tests of New Glenn's stage 1 and stage 2 engines. The first stage of New Glenn (Figure 1) is powered by seven BE-4 liquid oxygen (LOX) and methane (LNG) engines which generate a combined sea level thrust up to 4,620,000 lbf (20,550 kN). New Glenn's second stage is powered by two BE-3U LOX and liquid hydrogen (LH2) engines which generate a combined vacuum thrust of 450,000 lbf (2,002 kN).

Figure 1. New Glenn on the launch pad at LC-36 (Credit: Michael James)

This noise study describes the environmental noise associated with the proposed New Glenn operations at LC-36. The potential impacts from propulsion noise and sonic booms are evaluated in relation to annoyance, hearing conservation, sleep disturbance, speech interference, and structural damage. The following sections of this report are outlined below.

- Section 2 defines the proposed New Glenn operations at LC-36.
- Section 3 presents the propulsion noise modeling results.
- Section 4 presents the sonic boom modeling results.
- Section 5 summarizes the notable findings of this noise study.
- Appendix A gives an overview of the basics of sound, noise metrics, and noise effects.
- Appendix B describes the propulsion noise and sonic boom modeling methods.

2 NEW GLENN OPERATIONS

New Glenn is a heavy-lift launch vehicle designed and manufactured by Blue Origin. Figure 2 presents an illustration of the fully stacked two-stage rocket which is 320 ft tall and 23 ft wide. Beside the fully stacked New Glenn in Figure 2 is an illustration of New Glenn's first stage which is 188 ft tall and widens from 23 ft to 27 ft at its base. The design of the first stage also includes four actuated aerodynamic control surfaces called fins and two wing-like strakes. Blue Origin plans to launch their New Glenn rocket from LC-36 as illustrated in Figure 2. After stage separation, New Glenn's first stage will land on a landing platform in the Atlantic Ocean between 300 and 500 nautical miles downrange from the launch site. This study evaluates the noise and sonic booms from New Glenn operations that launch on an easterly launch azimuth between 35° to 118° as shown in Figure 3.

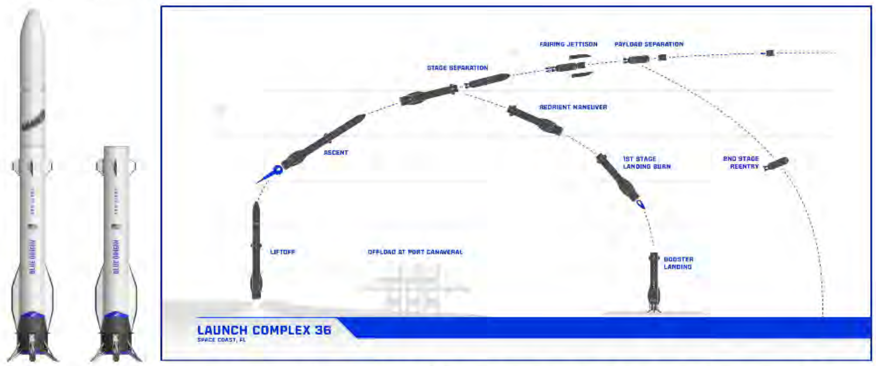

Figure 2. An illustration of the fully stacked New Glenn rocket beside its reusable first stage (left) and a sample New Glenn mission profile (right). (Credit: Blue Origin)

Figure 3. Range of LC-36 launch azimuths and potential landing platform locations.

Table 1 presents the proposed New Glenn operations at LC-36. In addition to 50 annual launch and landing operations, Blue Origin plans to conduct up to 50 static fire operations of New Glenn's stage 1 and stage 2 engines. Table 1 also presents the distribution of the New Glenn operations between acoustic day (0700 to 2200) and acoustic night (2200 – 0700). The acoustic time of day distribution is used to account for increased sensitivity to noise at night when computing the Day-Night Average Sound Level (DNL) metric, which applies an additional 10 dB adjustment (i.e., 10 times weighting) to events during the acoustic nighttime.

Table 1. Proposed New Glenn LC-36 operations.

		Annual Operations		
Event	Description	Daytime 0700 – 2200	Nighttime 2200 – 0700	Total
Launch	Easterly launch from LC-36	25	25	50
Landing	Landing on platform in the ocean	25	25	50
S1 Static Fire	Up to 30 second burn of 7 engines	25	25	50
S2 Static Fire	Up to 30 second burn of 2 engines	25	25	50

Table 2 presents the vehicle and engine modeling data for New Glenn. The first stage of New Glenn is powered by seven BE-4 LOX/LNG engines which generate a combined thrust of 4,620,000 lbf (20,550 kN) at the surface of the earth (i.e., sea level). The second stage of New Glenn is powered by two BE-3U LOX and liquid hydrogen (LH2) engines which generate a combined vacuum thrust of 450,000 lbf (2,002 kN). The vehicle's thrust varies with altitude, thus the noise and sonic boom modeling of New Glenn operations use the time varying weight and thrust profiles from the nominal launch and landing trajectories provided by Blue Origin.

Table 2. Vehicle and engine modeling parameters for New Glenn.

Modeling Parameters	New Glenn
Length	320 ft (98 m)
Diameter	23 ft (7 m)
First Stage Thrust (Max S.L)	4,620,000 lbf (20,550 kN) (660,000 lbf x Qty. 7 BE-4 engines)
Second Stage Thrust (Vacuum)	450,000 lbf (2,002 kN) (225,000 lbf x Qty. 2 BE-3U engines)

3 PROPULSION NOISE STUDY RESULTS

The following section presents the rocket noise modeling results for New Glenn operations at CCSFS LC-36. Propulsion noise generated by New Glenn operations was modeled using RUMBLE 4.1, BRRC's Rocket Noise and Emissions Model (see Appendix B.1). The propulsion noise results are presented in the form of noise contours, where a noise contour is a line drawn on a map that connects points of equal noise level. The noise contours are overlaid on map tiles from OpenStreetMap which contain helpful orienting features such as places, roads and boundaries, including CCSFS and Kennedy Space Center (KSC) boundaries and the state and international water boundaries (shown parallel to the coastline).

The launch noise contours represent the maximum sound levels over the proposed range of launch azimuths between 35° and 118° which is depicted by the grey shaded region. While the launch and landing noise contour shape is generally circular, the noise contour shape of static fire tests is a result of the flame trench directing the plume to the northeast and results in winged shaped contours. Note, the static fire contours should be viewed as conservative as LC-36's water deluge system is designed to reduce the noise generated when the vehicle is on the pad, which the model does not account for. Both the launch and static fire noise contours extend further over water than over land because water surfaces reflect more sound energy than land. Thus, the sound levels over water are elevated relative to the sound levels over land at comparable distances.

The noise levels and effects are presented in Section 3. The noise levels (Section 3.1) provide additional context regarding the intensity of the sound and its duration. The noise effects (Section 3.2) describe the potential environmental impacts with respect to annoyance, hearing conservation, sleep disturbance, speech interference, and structural damage.

3.1 Propulsion Noise Levels

The modeled noise levels generated by New Glenn operations at LC-36 are presented for three noise metrics: A-weighted Maximum Sound Level ($L_{A,max}$), Unweighted Maximum Sound Level (L_{max}), and A-weighted Sound Exposure Level (ASEL). The maximum sound levels (L_{max} and $L_{A,max}$) provide a measure of the loudest portion of the event but do not account for how long the sound is heard. Thus, Sound Exposure Level (SEL) contours are provided, which provide a measure of the net acoustic energy of the entire event by accounting for both the intensity of the sound and its duration. While SEL describes the total acoustic energy of the event it does not directly represent the sound level heard at any given time. The A-weighted SEL is also used in the calculation of DNL.

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

The modeled $L_{A,max}$ contours are presented in Figure 4 through Figure 7.

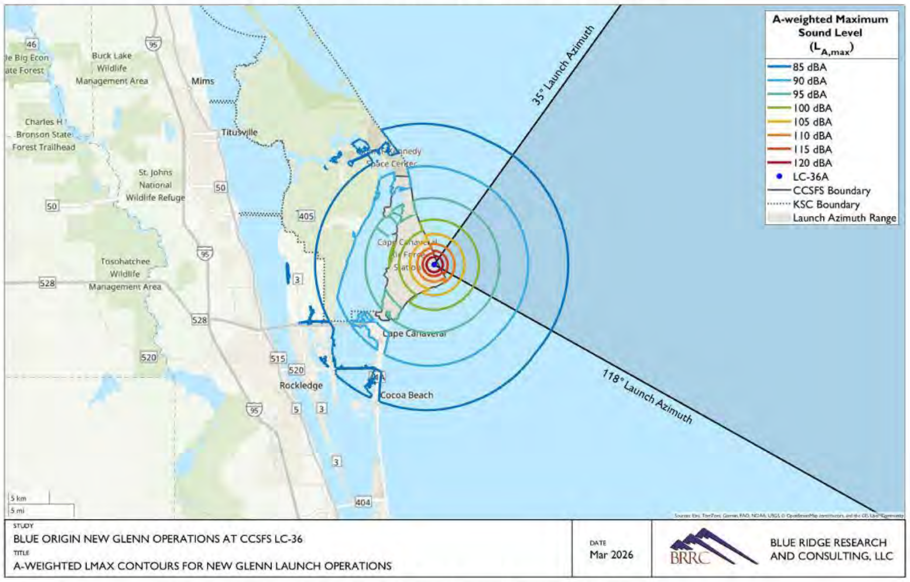

Figure 4. $L_{A,max}$ contours for LC-36 New Glenn launch operations.

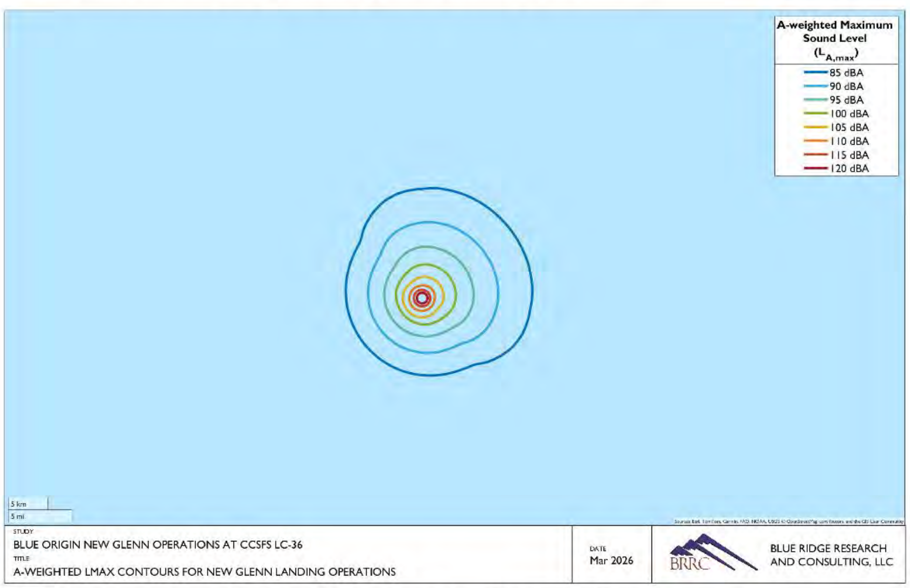

Figure 5. $L_{A,max}$ contours for LC-36 New Glenn landing operations.

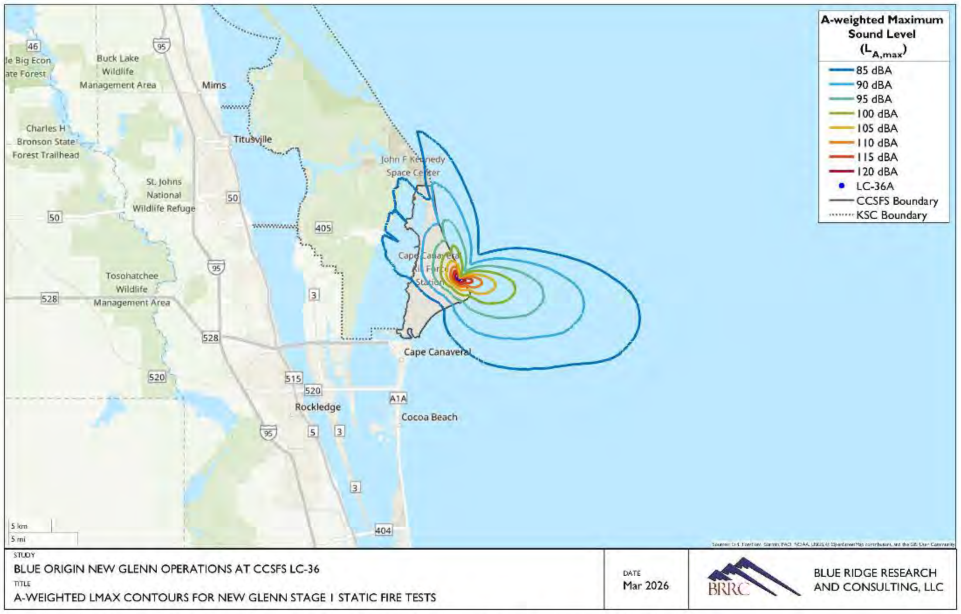

Figure 6. $L_{A,max}$ contours for LC-36 New Glenn first stage static fire tests.

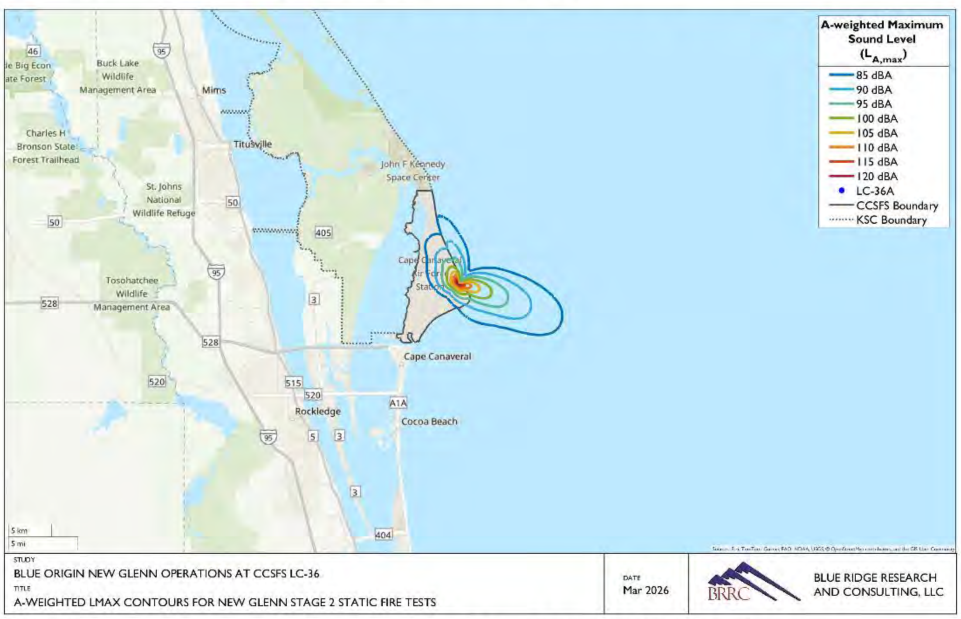

Figure 7. $L_{A,max}$ contours for LC-36 New Glenn second stage static fire tests.

3.1.2 Unweighted Maximum Sound Level

The modeled L_{max} contours are presented in Figure 8 through Figure 11.

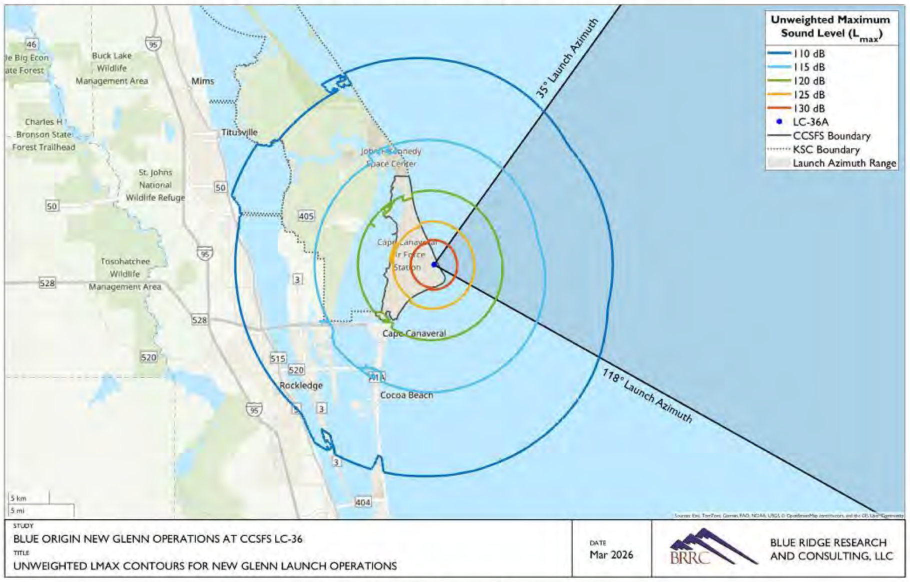

Figure 8. L_{max} contours for LC-36 New Glenn launch operations.

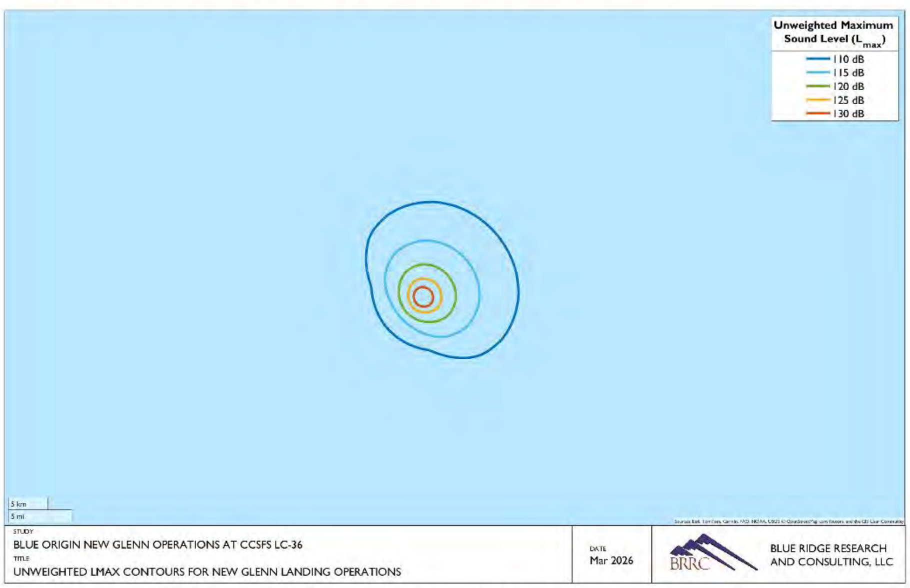

Figure 9. L_{max} contours for LC-36 New Glenn landing operations.

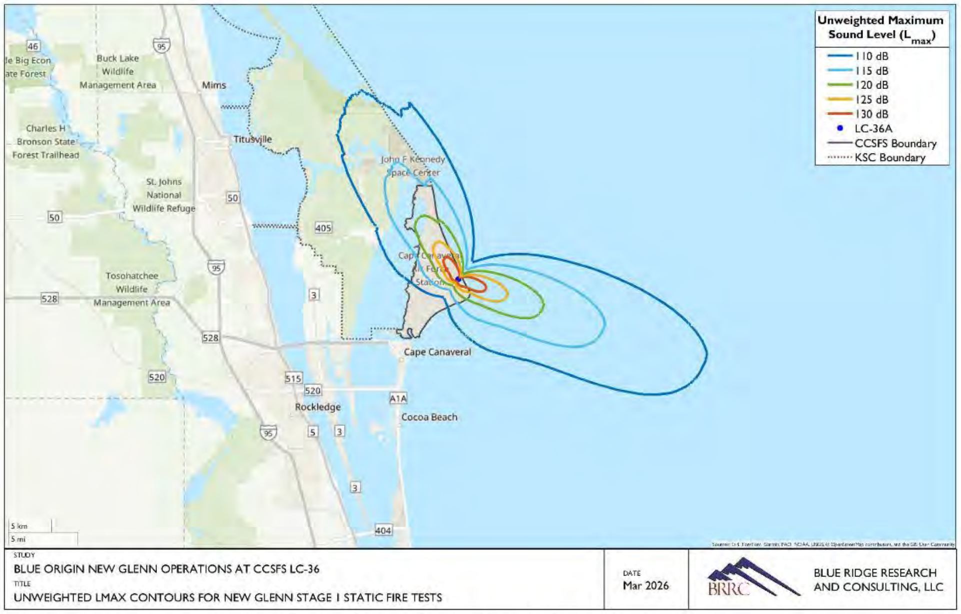

Figure 10. L_{max} contours for LC-36 New Glenn first stage static fire tests.

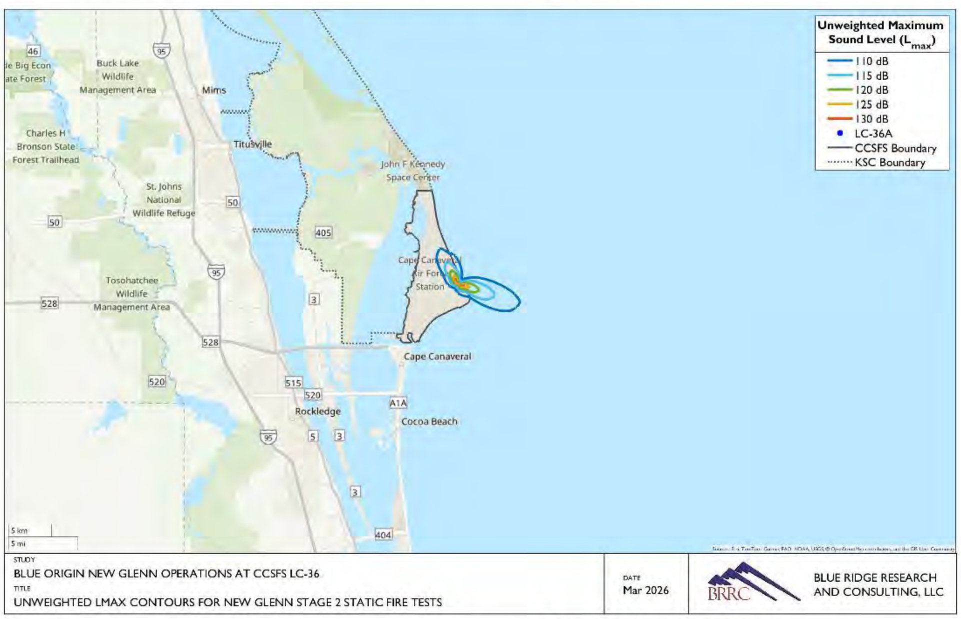

Figure 11. L_{max} contours for LC-36 New Glenn second stage static fire tests.

3.1.3 A-weighted Sound Exposure Level

The modeled A-weighted SEL contours are presented in Figure 12 through Figure 15.

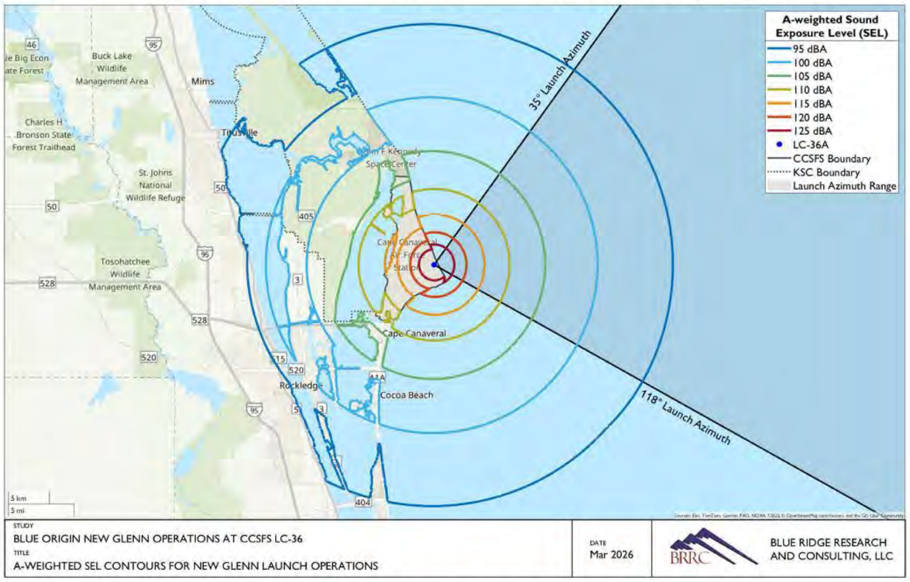

Figure 12. ASEL contours for LC-36 New Glenn launch operations.

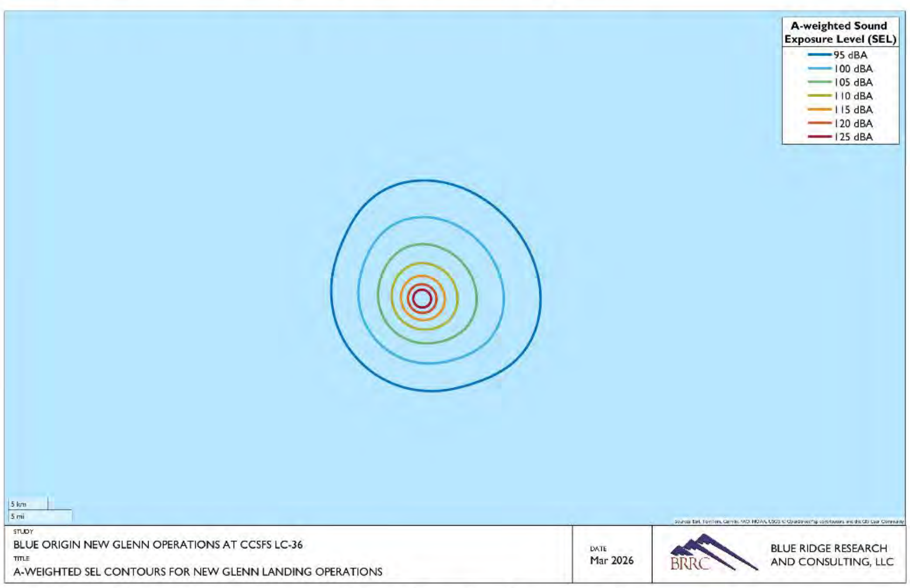

Figure 13. ASEL contours for LC-36 New Glenn landing operations.

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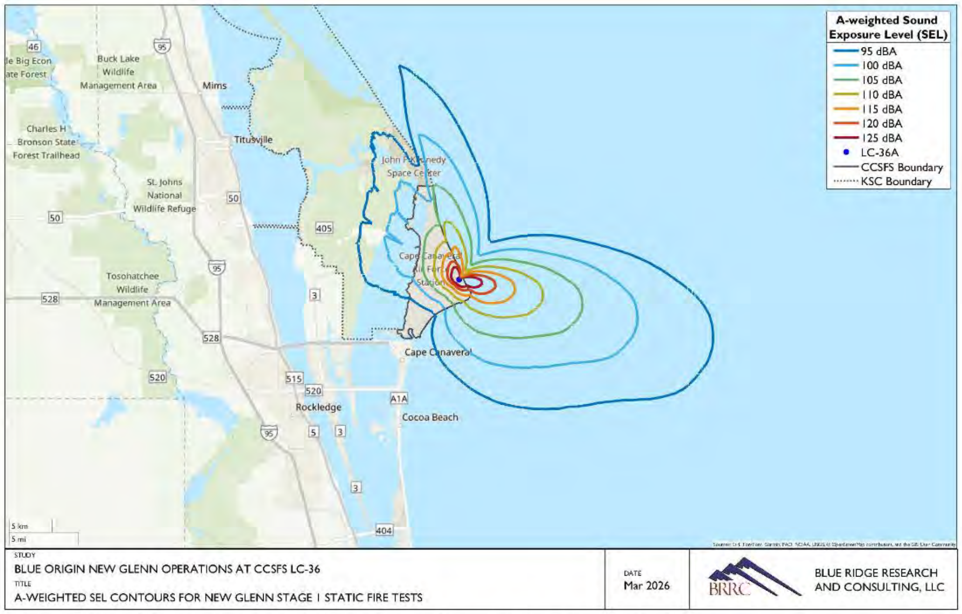

Figure 14. ASEL contours for LC-36 New Glenn first stage static fire tests.

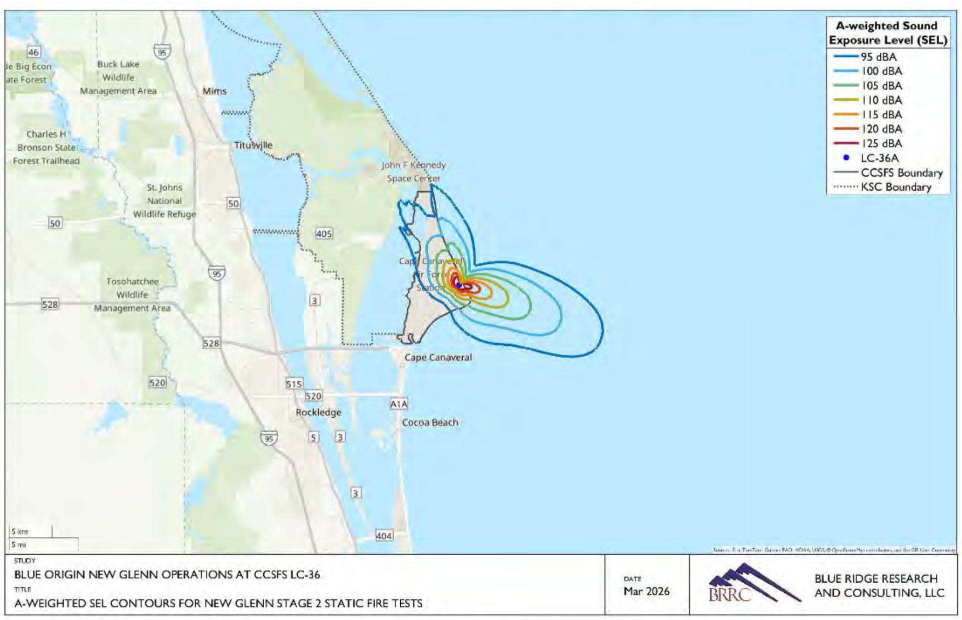

Figure 15. ASEL contours for LC-36 New Glenn second stage static fire tests.

3.2 Propulsion Noise Effects

The modeled noise generated by New Glenn operations at LC-36 is presented with respect to five noise effects: annoyance, hearing impairment, sleep disturbance, speech interference, and structural damage. The noise effects results are presented with respect to New Glenn launch and static fire operations. Noise from New Glenn landing operations will be over the Atlantic Ocean and will not affect humans or structures on the mainland.

3.2.1 Annoyance

The potential for long-term community annoyance is assessed using the Day-Night Average Sound Level (DNL) metric. The DNL noise metric is used to reflect a person's cumulative exposure to sound over a 24-hour period, expressed as the noise level for the average day of the year based on annual rocket operations. DNL accounts for how loud the noise is, how long it lasts, the time of day during which the noise occurs, and the frequency with which it occurs. To account for increased sensitivity to noise at night, DNL applies an additional 10 dBA adjustment to events during the acoustic nighttime period (2200 to 0700). DNL does not represent a level heard at any given time but represents an average yearly exposure to noise.

The Department of Defense (DoD) uses DNL to evaluate potential land use compatibility issues. The DoD's primary land use objective is to discourage noise-sensitive land uses in areas of higher noise exposure. In general, residential use is discouraged in areas exposed to DNL 65 – 70 dBA and strongly discouraged above DNL 70 dBA. Although land use compatibility recommendations are provided to support compatible land use planning both on- and off-base; they do not constitute a Federal determination that any use of land is acceptable or unacceptable in accordance with local zoning.

FAA uses DNL to quantify the potential impact of rocket noise. To evaluate the change-of-exposure due to an FAA action, the "Proposed Action" (i.e., new and continuing activities) must be compared to the "No Action Alternative" (i.e., continuing activities without new actions) for the same timeframe. FAA Order 1050.1G [1, 2] defines the FAA's significance threshold for noise. An action is considered significant if it would increase noise in a noise-sensitive area (e.g., residences, schools, churches, hospitals, parks, recreation areas, etc.) by DNL 1.5 dBA or more and the resulting noise exposure level is at least DNL 65 dBA. For example, an increase from DNL 63.5 dBA to 65 dBA is considered a significant impact.

Figure 16 presents the DNL contours of the LC-36 New Glenn operations (i.e., new activities) alone. The DNL 60 dBA contour can be used to conservatively identify the potential for significant noise impacts, as 60 dBA is the smallest level that could increase noise by DNL 1.5 dBA or more for a noise sensitive area that is exposed to noise at or above the DNL 65 dBA noise exposure level, or that will be exposed at or above this level due to the increase. The DNL 60 dBA contour from LC-36 New Glenn operations alone does not reach the community, and, thus no residences are expected to be impacted.

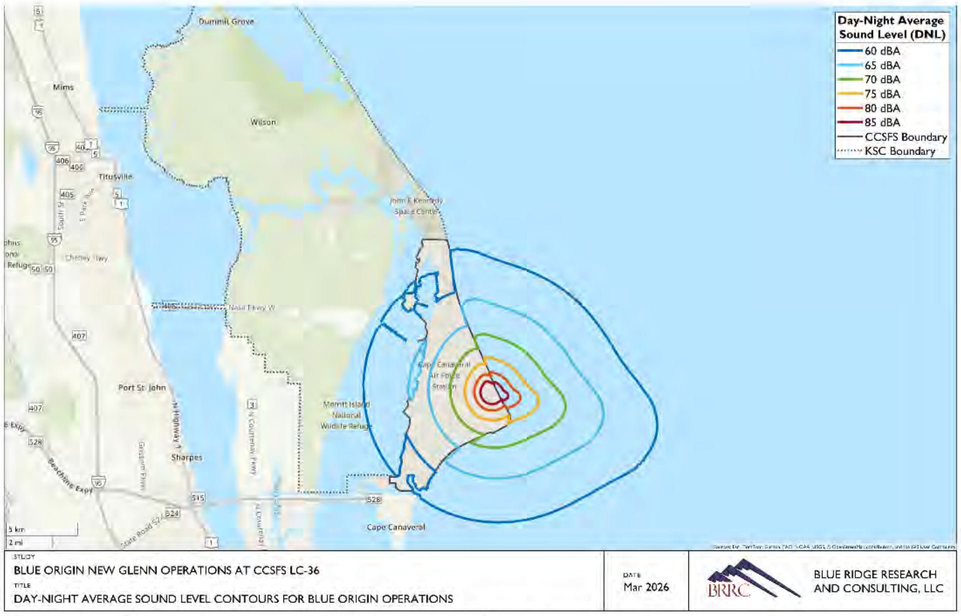

Figure 16. DNL contours for New Glenn operations from LC-36.

DNL contours representing the no action alternative at CCSFS were prepared by Blue Ridge Research and Consulting for FAA in 2024 [3]. The no action DNL contours represent the best available data currently, but do not account for changes occurring after August 2024. Figure 17 presents the proposed action (i.e., new and continuing activities represented by the solid line) versus the no action alternative contours (i.e., continuing activities without new actions represented by the dashed line). Although the proposed action contours are larger around LC-36, the DNL 65 dBA does not encompass any land area outside of CCSFS boundaries, and thus no residences are impacted. The modeled DNL contours do not indicate any potential land use compatibility issues or potential impacts based on the change-of-exposure analysis.

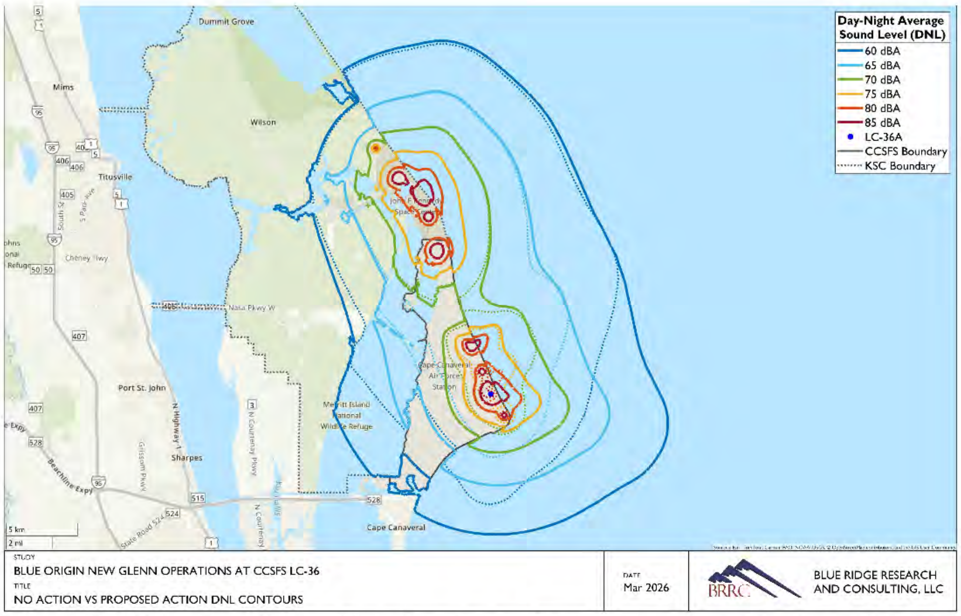

Figure 17. DNL contours for the No Action (dashed line) versus Proposed Action (solid line).

3.2.2 Noise-Induced Hearing Impairment

U.S. government agencies provide guidelines on permissible noise exposure limits to unprotected human hearing [4-6]. The most conservative upper noise level limit is the OSHA standard, which specifies that exposure to continuous steady-state noise is limited to a maximum of 115 dBA [4]. The $L_{A,max}$ 115 dBA contour can be used to identify potential locations where hearing protection should be considered for rocket operations. In addition to the maximum exposure limits, OSHA standards [4] also specify a daily noise dose based on the SEL which accounts for the energy over the duration of the event(s).

The modeled allowable daily noise dose contours and the $L_{A,max}$ 115 dBA contour associated with New Glenn operations at LC-36 are presented in Figure 18 through Figure 20. The 115 dBA noise contours for New Glenn launch and static fire operations are both within the boundaries of CCSFS. Additionally, people in the community will reach less than 5% of their daily noise dose when exposed to noise from a single New Glenn launch operation from LC-36 and less than 1% of their daily noise dose when exposed to noise from a single New Glenn first stage or second stage static fire test at LC-36. Thus, the potential for impacts to people in the community with regards to hearing conservation is negligible.

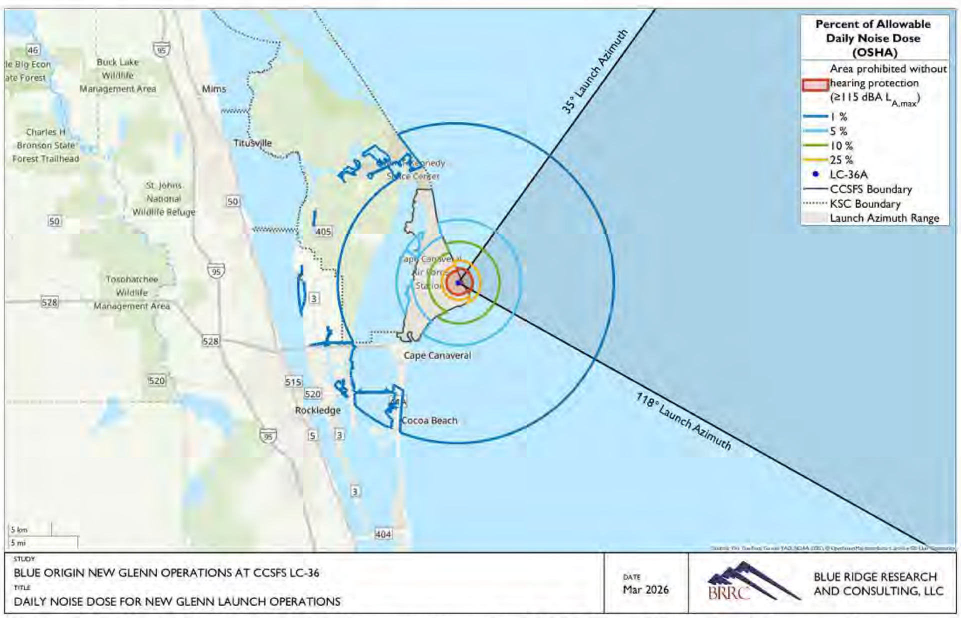

Figure 18. Allowable daily noise dose contours for LC-36 New Glenn launch operations.

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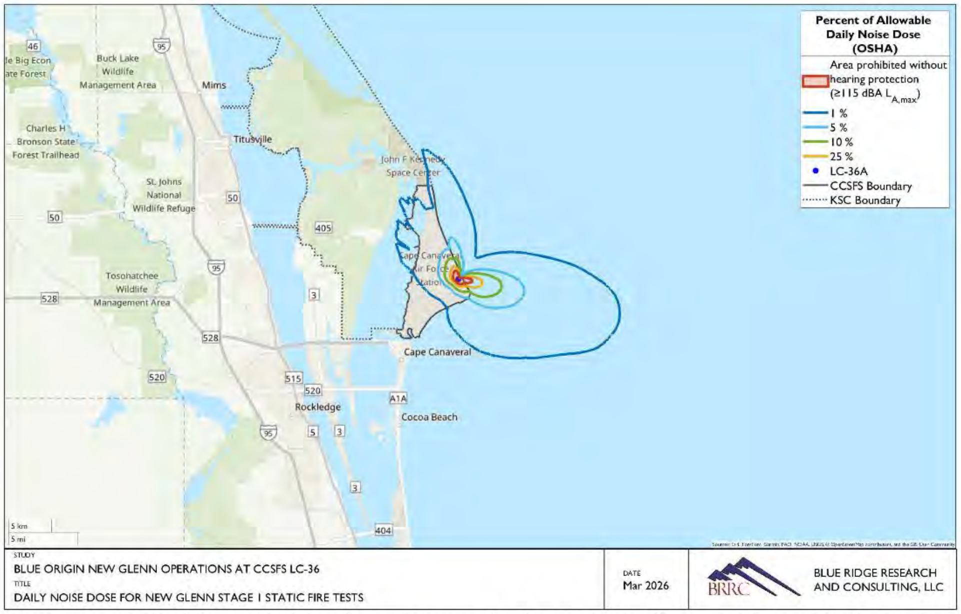

Figure 19. Allowable daily noise dose contours for LC-36 New Glenn stage 1 static fire tests.

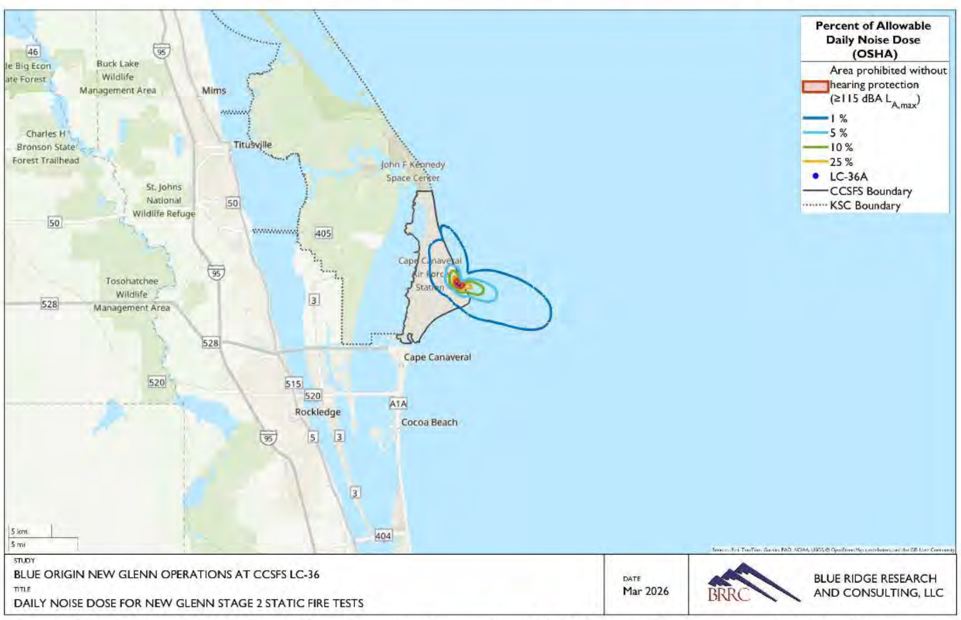

Figure 20. Allowable daily noise dose contours for LC-36 New Glenn stage 2 static fire tests.

3.2.3 Sleep Disturbance

Sleep disturbance is a major concern for communities exposed to launch vehicle noise at night. 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 rocket 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 mainly focused on predicting the probability of awakening during nighttime operations.

The probability that a person of average sensitivity to awakening will be awakened by a noise event is calculated using the ANSI Noise Standard, ANSI S12.9-2008/Part 6 [7]. This ANSI Standard was developed from field studies of behavioral awakening primarily in homes near airports subject to routine jet aircraft operations, not rocket operations. Furthermore, in 2018 ANSI made the decision to rescind the standard based partly on "the relatively small and non-representative corpus of field observations of noise-induced behavioral awakening available for analysis." However, 1050.1 Desk Reference [2] specifies that the number of awakenings may be calculated using this ANSI Standard. Thus, although there are no established criteria for evaluating sleep disturbance from rocket noise, the calculation of the probability of awakening is presented as a tentative criterion when comparing the effects of different operational alternatives.

Figure 21 through Figure 23 present the probability of awakening contours for New Glenn launch operations and static fire tests. The probability of people awakening in the neighboring communities is calculated to be less than 6% for a single New Glenn launch operation and less than 4% for a New Glenn first stage or second stage static fire test.

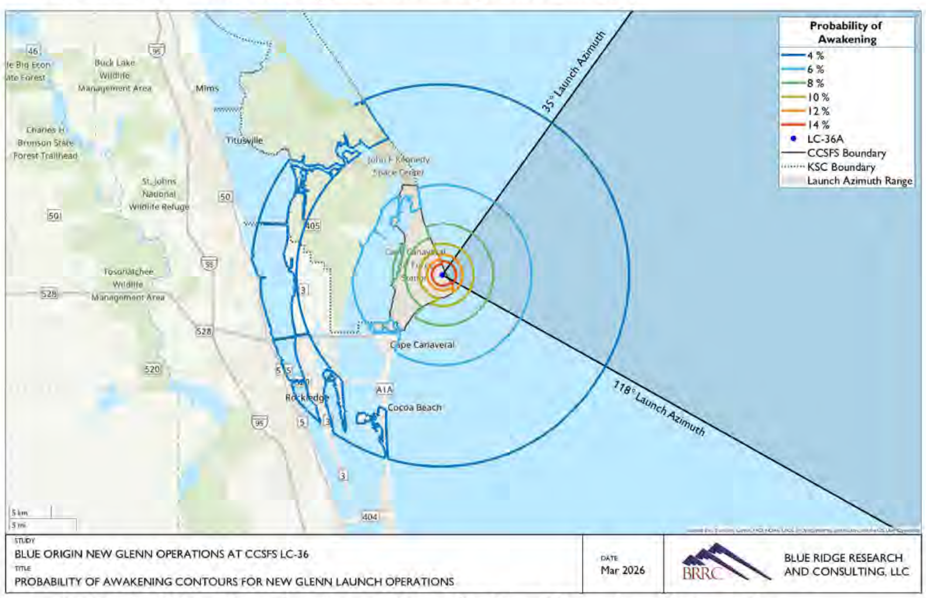

Figure 21. Probability of awakening contours for New Glenn launch operations.

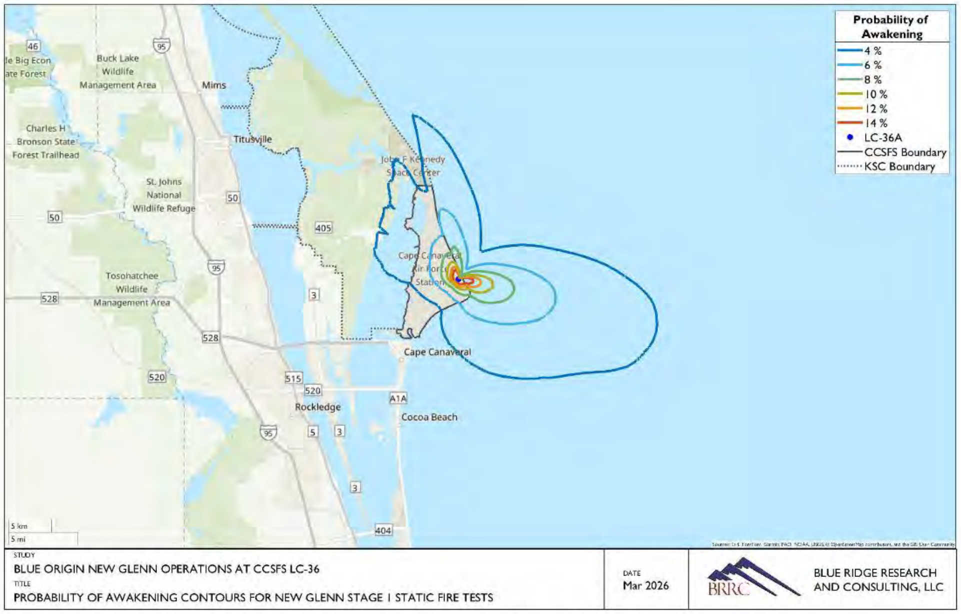

Figure 22. Probability of awakening contours for New Glenn first stage static fire tests.

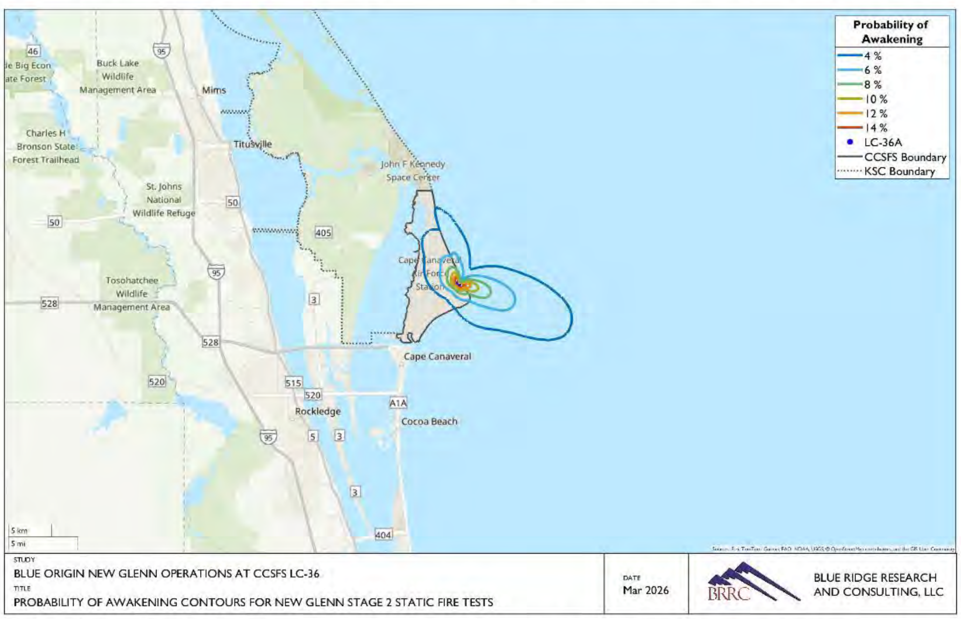

Figure 23. Probability of awakening contours for New Glenn second stage static fire tests.

3.2.4 Speech Interference

Speech interference from noise is a primary cause of annoyance for communities. Disruption of routine activities such as conversation leads to frustration and annoyance. One measure of speech comprehension is sentence intelligibility: the percent of sentences spoken and understood. This might be important for people 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 sentence intelligibility of 95% for two people standing outside, approximately 3 feet (1 meter) apart [8].

The modeled time above 66 dBA contours associated with New Glenn operations at LC-36 are presented in Figure 24 through Figure 26. People may experience levels above 66 dBA in the neighboring communities for durations ranging from 0 to 145 seconds for a single New Glenn launch operation and up to 30 seconds for a New Glenn first stage or second stage static fire test (equal to the duration of the static fire test). Note, the noise contours represent the time above 66 dBA for a receptor outdoors. A receptor indoors (i.e., in their home, office, or classroom) would be exposed to levels above 66 dBA for less time than presented in Figure 24 through Figure 26.

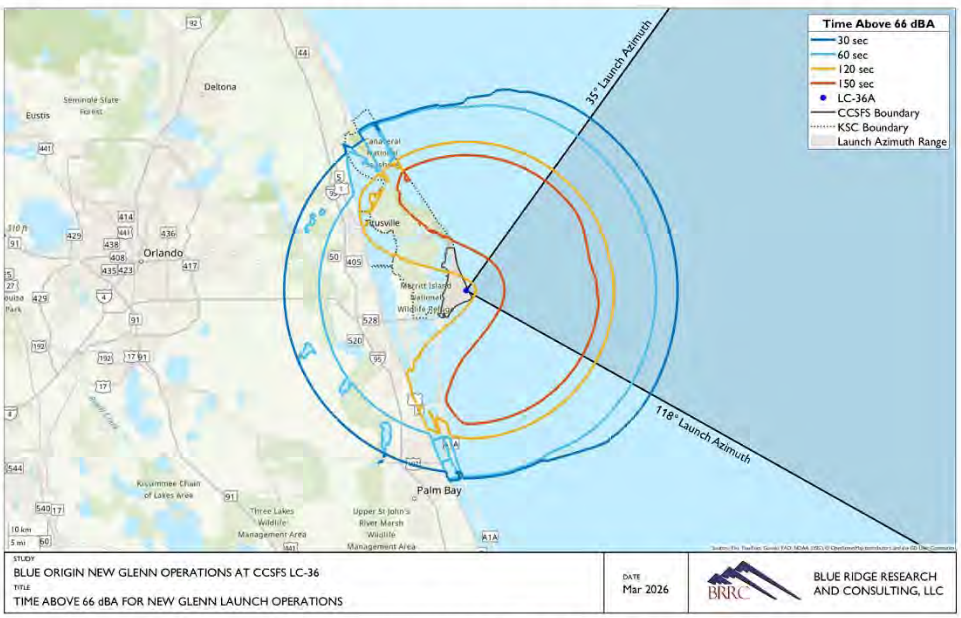

Figure 24. Time above 66 dBA contours for LC-36 New Glenn launch operations.

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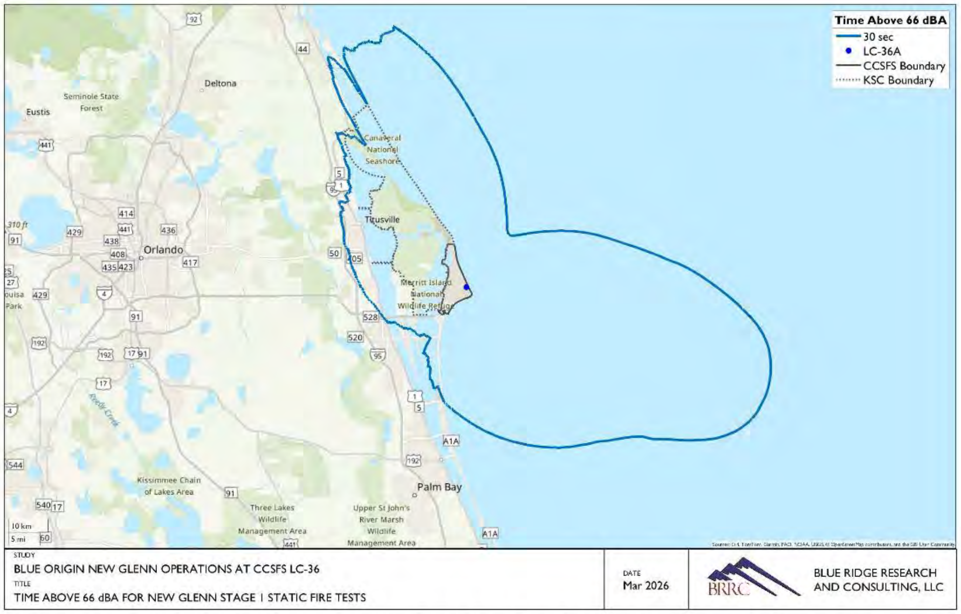

Figure 25. Time above 66 dBA contours for LC-36 New Glenn first stage static fire tests.

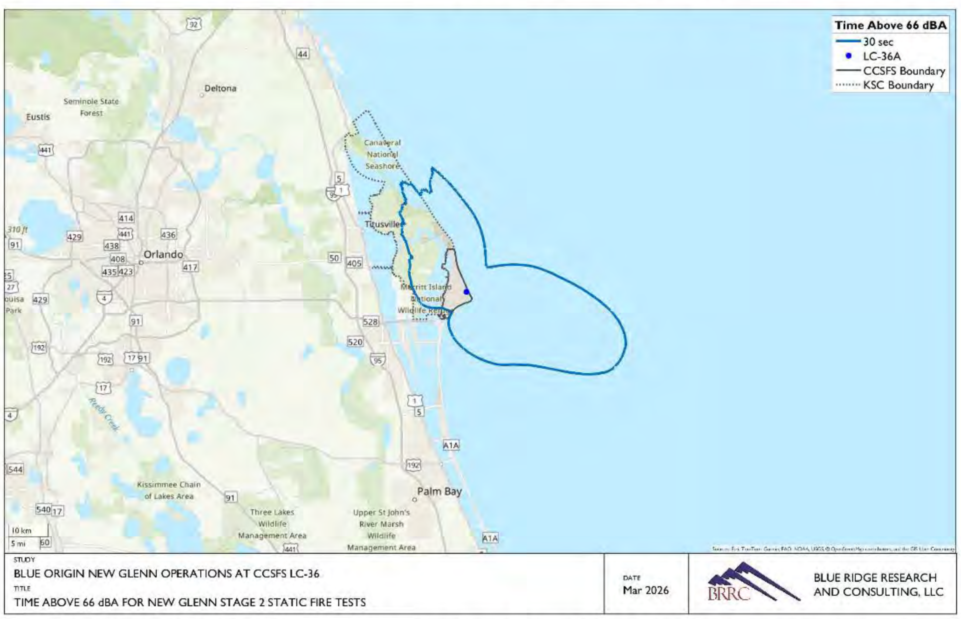

Figure 26. Time above 66 dBA contours for LC-36 New Glenn second stage static fire tests.

3.2.5 Noise-Induced Vibration Effects on Structures

Windows are typically the most sensitive components of a structure to launch vehicle noise. Infrequently, plastered walls and ceilings may also be affected. The potential for damage to a structure depends on the incident sound, the condition and material of the structural element, and installation of each element.

A NASA technical memo [9] concluded that the probability of structural damage is proportional to the intensity of the low frequency sound. The memo estimated that one in 100 households exposed to an average continuous sound level of 120 dB and one in 1,000 households exposed to 111 dB filed structural damage claims. These values form the basis for using L_{max} thresholds of 120 and 111 dB as conservative indicators of potential risk for damage claims. This metric reflects the likelihood of claims being submitted, not the occurrence, type, severity, or verification of actual structural damage.

The contours associated with 1:1,000 damage claims (111 dB) and 1:100 damage claims (120 dB) for LC-36 New Glenn operations are presented in Figure 27 through Figure 29. For New Glenn launch operations, the 1:100 damage claims contour does not encompass any land outside CCSFS, but the 1:1,000 damage claims contours encompass land outside CCSFS including Merritt Island, Cape Canaveral, and Cocoa Beach. For New Glenn first stage or second stage static fire tests, the 1:100 and 1:1,000 damage claims contours do not encompass any land outside CCSFS.

The L_{max} value of 130 dB is used to further assess potential impacts to structures based on a report from the National Research Council which states that one may conservatively consider all sound lasting more than one second with levels exceeding 130 dB (unweighted) as potentially damaging to structures [10]. The 130 dB L_{max} contours from New Glenn operations do not include any land area outside CCSFS.

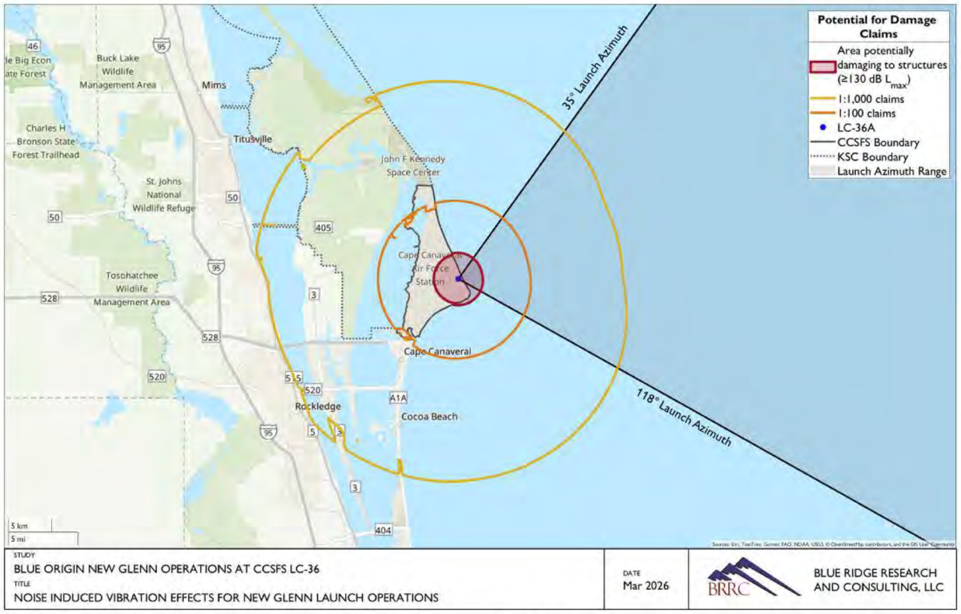

Figure 27. Potential for damage claims contours for LC-36 New Glenn launch operations.

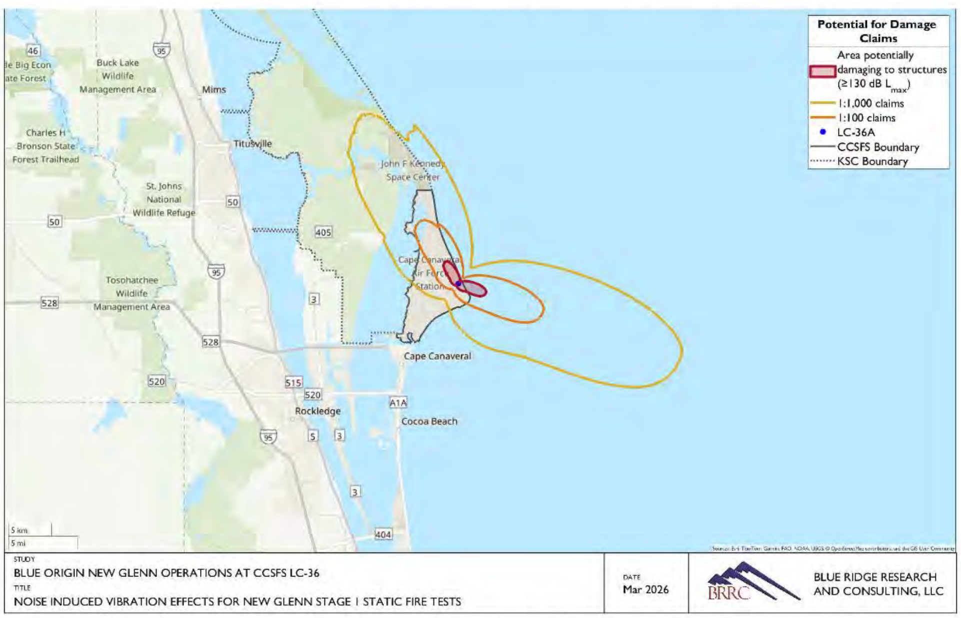

Figure 28. Potential for damage claims contours for LC-36 New Glenn stage 1 static fire tests.

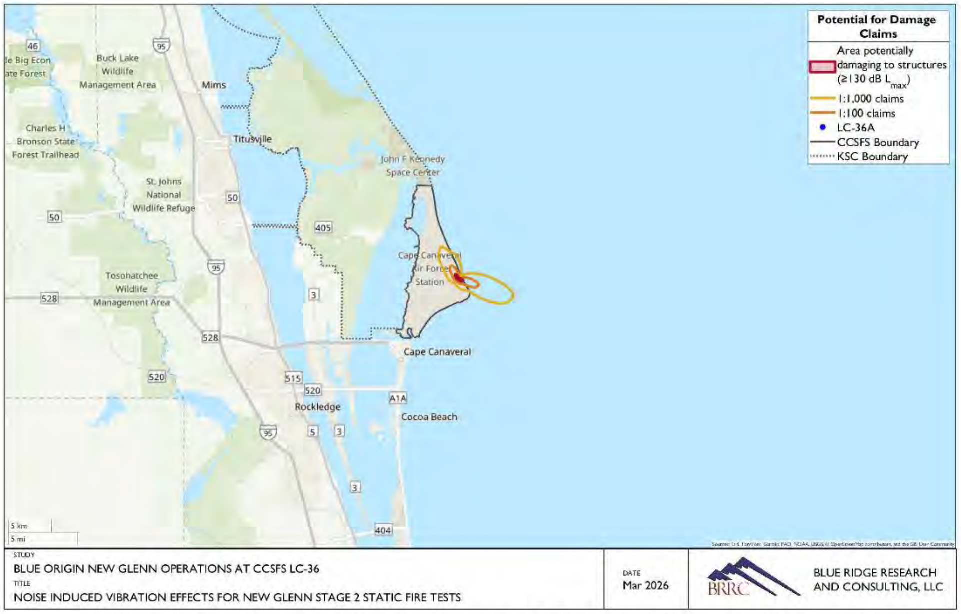

Figure 29. Potential for damage claims contours for LC-36 New Glenn stage 2 static fire tests.

4 SONIC BOOM STUDY RESULTS

Sonic booms generated by New Glenn launch operations from LC-36 were modeled using PCBoom (see Appendix B.2). The modeled peak overpressure levels of sonic booms from New Glenn launch operations are described in Section 4.1. The potential sonic boom effects from New Glenn launch operations are discussed in Section 4.2 with respect to annoyance, hearing conservation, physiological effects, and structural damage.

4.1 Sonic Boom Peak Overpressure Levels

The location and intensity of the sonic boom footprint produced by New Glenn launch and landing operations will be highly dependent on the vehicle configuration, trajectory, and atmospheric conditions at the time of flight. Figure 30 presents the modeled launch and landing sonic boom peak overpressure contours at 0.25, 0.5, 1, 2, 4, and 8 psf for an eastern launch azimuth using an average annual CCSFS atmospheric profile without winds [11]. A summary of the modeled results is detailed below.

The New Glenn launch is modeled to generate sonic booms with a narrow, forward-facing crescent shaped focal region. The focus boom region is generated when the vehicle continuously accelerates and pitches downward as it ascends. As the vehicle continues to ascend, the sonic boom levels decrease, and the crescent shape becomes slightly longer and wider. The 1 psf contour begins approximately 47 miles downrange from LC-36 and is 128 miles wide. The modeled maximum peak overpressures (up to 10 psf) occur within this focal region and are highly dependent on the mission trajectory and the atmospheric profile at the time of launch.

The New Glenn's first stage landing is modeled to generate sonic booms that begin approximately 53 miles up range of the sea-based landing platform with a wide low level sonic boom as the vehicle descends below 280,000 feet and ends when the vehicle's speed becomes subsonic at an altitude of approximately 19,000 feet. The landing sonic boom contours become narrower and increase in amplitude as the vehicle descends closer to the landing platform. The 1 psf contour begins approximately 33 miles up range from the landing platform and is approximately 81 miles wide. Figure 30 presents the peak overpressure contours up to 8 psf, although higher peak overpressure levels up to 14 psf are modeled to occur over smaller areas within the 8 psf contour.

Figure 31 illustrates the launch and landing sonic boom contours at the extents of the launch azimuth range (35° to 118°) and range of potential landing platform locations in the Atlantic Ocean (300 – 500 nautical miles downrange). Figure 31 shows the area potentially exposed to peak overpressures greater than 0.25 psf from New Glenn launch and landing operations within these ranges.

The launch and landing sonic boom contours greater than 1 psf are modeled (without wind) to occur entirely over the Atlantic Ocean. However, low level sonic booms (< 1 psf) are modeled to reach land areas for the most northern or southern launch azimuths. For example, missions launching on the 35 degree launch azimuth and landing closer to the 500 nautical mile range expose North Carolina's Outer Banks to low level sonic booms. Additionally, missions launching on the 118 degree launch azimuth expose southern Florida and/or the Bahamas to low level sonic booms.

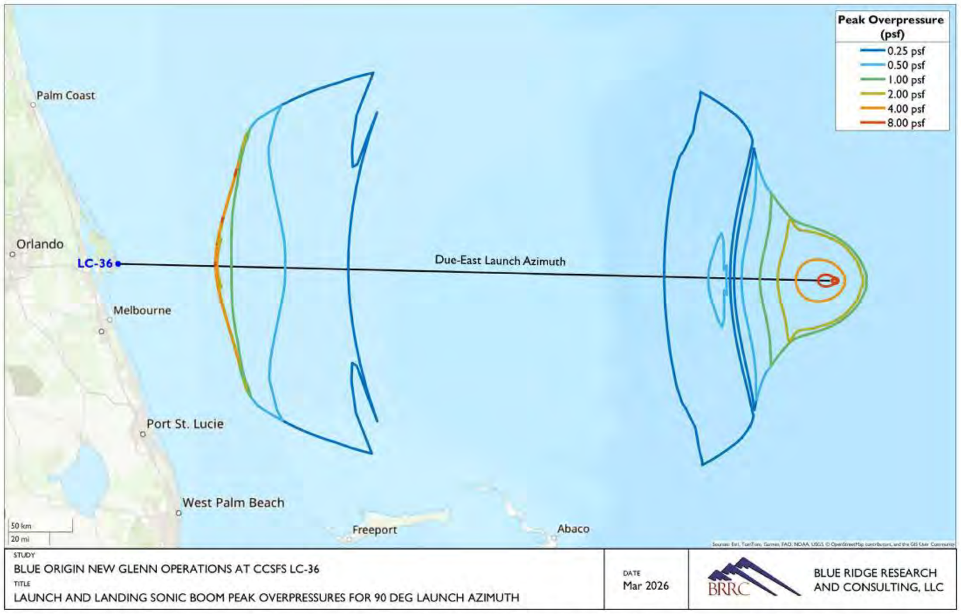

Figure 30. Sonic boom peak overpressure contours for New Glenn due-east launch.

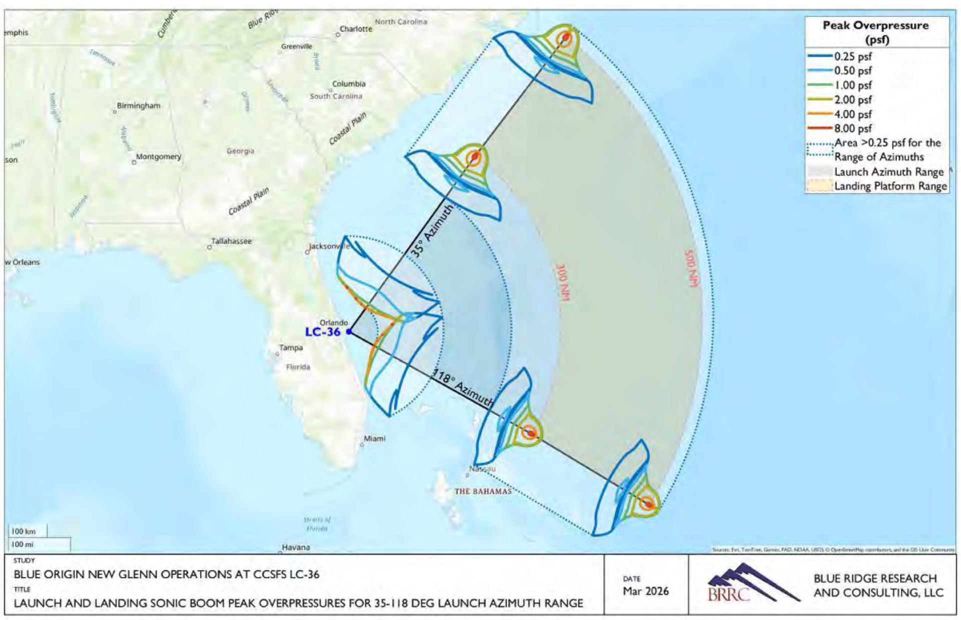

Figure 31. Sonic boom peak overpressure contours for launches between 35°-118° azimuths.

The sonic boom contours displayed in Figure 30 and Figure 31 were modeled using an average annual CCSFS atmospheric profile without winds. However, the sonic booms produced by New Glenn operations will be highly dependent on the atmospheric conditions at the time of flight. To illustrate the potential variability due to atmospheric conditions, the sonic boom contours were modeled for the northernmost landing (35° and 500 NM downrange) and southernmost launch (118°) using up to 24 additional atmospheric scenarios: 12 monthly average profiles with mean wind speeds, and 12 monthly average profiles with high wind speeds (i.e., mean plus two standard deviations wind speeds). Figure 32 and Figure 33 present contour comparisons between the sonic boom results using an annual average atmospheric profile (dark green) versus the monthly average atmospheric profiles (light green) for 1 psf peak overpressure levels. The results demonstrate that over the modeled range of atmospheric conditions, the peak overpressure levels on the mainland are predicted to be less than 1 psf.

Figure 32. Monthly variation in 1 psf peak overpressure contours for 35° and 500 NM landing.

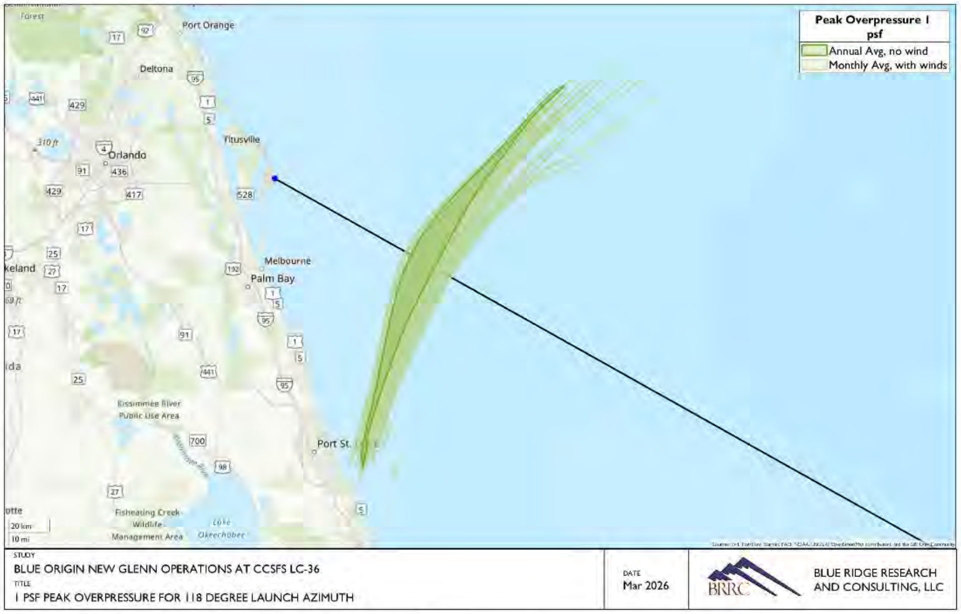

Figure 33. Monthly variation in 1 psf peak overpressure contours for 118° launch.

4.2 Sonic Boom Effects

The modeled sonic booms generated by New Glenn launch and landing operations from LC-36 are presented with respect to four noise effects: annoyance, hearing conservation, physiological effects, and structural damage.

4.2.1 Annoyance

FAA uses C-weighted DNL (CDNL) to assess potential impacts resulting from impulsive noise sources such as sonic booms. CDNL integrates the 10 dB adjustment to events during acoustical nighttime, respectively, and exposures to CDNL 60 dBC are considered significant per its relationship with dose-dependent community annoyance.

CDNL is used to evaluate the potential for long-term community annoyance by quantifying the cumulative exposure of individuals to sonic booms and is therefore applied only to land areas where people reside. Launch and landing sonic booms that reach land are modeled to be less than 1 psf and only occur for the most northern and southern azimuths. Even under a conservative scenario in which all 50 launches occur at one azimuth and 25 occur at night, the resulting CDNL would not exceed ~51 dBC, which is less than the significance threshold of 60 dBC for impulsive noise sources.

4.2.2 Noise-Induced Hearing Impairment

NIOSH [5] and OSHA [4] state that impulsive or impact noise levels should not exceed 140 dB peak sound pressure level, which equates to a sonic boom peak overpressure level of approximately 4 psf. The modeled New Glenn launch operations from CCSFS may generate peak overpressure levels greater than 4 psf over the Atlantic Ocean. However, the area exposed to levels greater than 4 psf are extremely small and unlikely to occur in the same location over multiple launches. Peak overpressure levels greater than 4 psf are not predicted to occur on land in the United States or the Bahamas.

4.2.3 Physiological Effects

The unexpected, loud impulsive noise of sonic booms tends to cause a startle effect in people. However, when people are exposed to impulsive noises with similar characteristics on a regular basis, they tend to become conditioned to the stimulus and no longer display the startle reaction. Low-level sonic booms (<1 psf) may reach land for the most northern or southern launch azimuths, potentially affecting North Carolina's Outer Banks, southern Florida, or the Bahamas. People exposed to these booms may exhibit a range of behavioral responses (see Table 5), from no startle response at levels below 0.3 psf to startle reactions with body movements at levels above 0.6 psf.

4.2.4 Noise-Induced Vibration Effects on Structures

The potential for damage from sonic booms is generally confined to brittle objects, such as glass, plaster, roofs, and bric-a-brac, or structural elements that are in ill-repair. A large degree of variability exists in damage types and amounts, and much of the potential for damage depends on the sonic boom overpressure and the pre-existing condition of a structure. Generally, the potential for damage to well-maintained structures from sonic boom overpressures less than 2 psf is unlikely [12, 13]. Peak overpressure levels greater than 2 psf are not predicted to occur on land in the United States or the Bahamas.

5 SUMMARY

This report documents the noise and sonic boom study performed to support Blue Origin's environmental review of their New Glenn operations at CCSFS LC-36.

Propulsion Noise Results

The discussion of potential propulsion noise impacts from New Glenn launch, landing, and static fire operations from LC-36 is summarized.

- **Annoyance:** The cumulative DNL 65 dBA contour is used to identify significant noise impacts resulting from the propulsion noise generated by New Glenn operations at LC-36. The area identified within the 65 dBA contour for cumulative noise does not encompass land outside of the boundary of CCSFS, and, thus, no residences are impacted.
- **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. The entire land area encompassed by the 115 dBA New Glenn noise contours is within CCSFS boundaries. Additionally, people in the community will reach less than 5% of their daily noise dose when exposed to noise from a single New Glenn launch and less than 1% when exposed to noise from a single first or second stage static fire operation. Thus, the potential for impacts to people in the community with regards to hearing conservation is negligible.
- **Sleep Disturbance:** Although there are no established criteria for evaluating sleep disturbance from rocket noise, the calculation of the probability of awakening is presented as a tentative criterion when comparing the effects of different operational alternatives. The probability of people awakening in off-base communities is calculated to be less than 6% for a single New Glenn launch operation and less than 4% for a single New Glenn first or second stage static fire test.
- **Speech Interference:** Levels must remain below 66 dBA to maintain a sentence intelligibility of 95% for two people standing outside, approximately 3 feet (1 meter) apart. People may experience levels above 66 dBA in off-base communities for durations up to 145 seconds for a single New Glenn launch operation and up to the 30 second duration of a New Glenn first or second stage static fire test.
- **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. The 1:100 damage claims contours do not encompass any land outside of CCSFS boundaries. The 1:1,000 damage claims contour from New Glenn launches encompass area outside CCSFS including Merritt Island, Cape Canaveral, and Cocoa Beach. The L_{max} 130 dB threshold is used to further assess potential impacts to structures where levels exceeding 130 dB are conservatively considered potentially damaging to structures. The 130 dB L_{max} contours from New Glenn operations do not include any land area outside CCSFS.

Sonic Boom Results

The discussion of potential sonic boom impacts from New Glenn launch operations from LC-36 is summarized.

- **Annoyance:** For the projected operation tempo of 50 annual launches, the C-weighted DNL is less than the significance threshold of 60 dBC for impulsive noise sources. Thus, the New Glenn launch operations do not pose a significant impact with regards to human annoyance.
- **Hearing Conservation:** NIOSH and OSHA state that impulsive noise levels should not exceed 140 dB peak sound pressure level, which equates to a sonic boom peak overpressure level of approximately 4 psf. Sonic booms from New Glenn launch operations may exceed 4 psf in small areas over the Atlantic Ocean, but are not predicted to occur on land in the United States or the Bahamas.
- **Physiological Effects:** People that experience sonic booms from New Glenn launch operations from CCSFS may exhibit a range of behavioral effects, from no startle response (for levels less than 0.3 psf) to a startle response with body movements (for levels greater than 0.6 psf).
- **Structural Damage:** Generally, the potential for damage to well-maintained structures from sonic boom overpressures less than 2 psf is unlikely. Peak overpressure levels greater than 2 psf are not predicted to occur on land in the United States or the Bahamas.

APPENDIX A NOISE APPENDIX

This appendix gives an overview of the basics of sound, noise metrics, and noise effects.

A.1 Basics 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 [14].

- **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.

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 [15].

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 [14]. 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" [16].

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 [17].

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 34, are adequate to quantify most environmental noises. A-weighting puts emphasis on the 1,000 to 6,000 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.

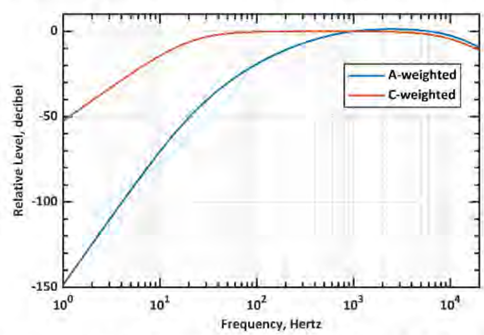

Figure 34. Frequency adjustments for A-weighting and C-weighting. [18]

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 (See A.2).

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 [19] is shown in Figure 35. 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 35) are averages over extended periods [20]. Per the United States 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 36. For example, thunder overpressure resulting from lightning strikes at a distance of one kilometer (0.6 miles) is estimated to be near two psf, which is equivalent to 134 dB [21].

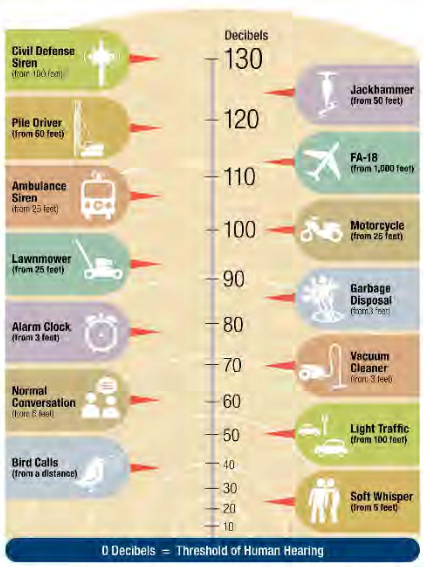

Figure 35. Typical A-weighted levels of common sounds. [22]

Figure 36. Typical impulsive event levels. [21]

A.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.

Maximum Sound Level

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.

Sound Exposure Level

Sound exposure level (SEL) 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.

Day-Night Average Sound Level and Community Noise Equivalent Level

Day-Night Average Sound Level (DNL) is a cumulative metric that accounts for the SEL of 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. Legislation in the state of California uses the Community Noise Equivalent Level (CNEL), a variant of the DNL. In addition to the 10 dB (i.e. 10 times weighting) adjustment during the acoustical nighttime period, the CNEL includes a ~4.8 dB adjustment (i.e. 3 times weighting) to events during the acoustical evening period (7:00 PM to 10:00 PM) to account for decreased community noise during this period. DNL and CNEL do not represent a level heard at any given time but represent long term exposure to noise.

Time Above

The Time Above (TA) metric is the total time that the A-weighted noise level is at or above a threshold. Combined with the threshold level (L), it is denoted as TAL. TA can be calculated for a single event or a specific time period of interest. TA is a supplemental metric that is used to help understand noise exposure.

Daily Noise Dose

The percentage daily noise dose is a measure of the sound exposure normalized to an 8-hour workday, where 100% represents the maximum allowable daily dose.

Probability of Awakening

The percentage probability of awakening is a measure that a person of average sensitivity to awakening will be awakened by a single noise event.

Peak Overpressure

For impulsive sounds, the true instantaneous peak sound pressure level (L_{pk}), 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.

A.3 Noise Effects

A variety of acoustic metrics can be used to describe how noise from commercial space operations affects communities and the environment. Metrics can describe the effect of an individual operation (single event) or the cumulative noise of multiple events over a long time. A comprehensive listing of acoustical terminology and definitions is available in the American National Standards Institute's (ANSI) "Acoustical Terminology" standard (ANSI S1.1-2013).

The Day Night Average Sound Level (DNL) is the FAA's primary noise metric to quantify the cumulative exposure of individuals to noise from aviation activities [1]. Despite the differences between aviation and commercial space vehicle noise, DNL is the required metric to quantify cumulative exposure to noise from commercial space transportation activities. However, the DNL metric may not fully describe the noise experienced during a commercial space noise event, and the use of supplemental noise metrics is recommended. Legislation in the state of California uses the Community Noise Equivalent Level (CNEL), a variant of the DNL.

The metrics and effects relevant to propulsion noise and sonic booms from commercial space operations are presented in Sections A.3.1 and A.3.2, respectively. The noise effects described in the following sections are associated with the effects on people and structures.

A.3.1 Propulsion Noise Metrics and Effects

Table 3 presents metrics and associated effects relevant to the analysis of propulsion noise from commercial space operations. The associated effects referenced in Table 3 are discussed in more detail in the following sections.

In addition to the FAA's primary noise metric, DNL, Table 3 provides supplemental metrics that are used to evaluate potential impacts to people and structures. The maximum sound level metrics are particularly useful in improving the public's understanding of exceptionally loud commercial space event(s). Maximum sound level metrics are used to evaluate the potential for noise-induced hearing impairment and vibration effects on structures. Additionally, A-weighted Sound Exposure Level (SEL), percent allowable daily noise dose, probability of awakening, and time above at threshold level (TAL) are used to describe the potential noise impact from rocket operations but do not have specific criteria associated with them.

Table 3. Metrics for propulsion noise analysis.

Metric	Description	Effect	Level
Day-Night Average Sound Level (DNL)	A cumulative (A-weighted) metric that accounts for all noise events in a 24-hour period.	Annoyance	65 dBA Ref. [1]
Community Noise Equivalent Level (CNEL)	A cumulative (A-weighted) metric that accounts for all noise events in a 24-hour period.	Annoyance	65 dBA Ref. [1]
Maximum A-weighted Sound Level ($L_{A,max}$)	A single-event metric that describes the highest A-weighted sound level during an event in which the sound changes with time.	Hearing Impairment	115 dBA Ref. [4]
Maximum Unweighted Sound Pressure Level (L_{max})	A single-event metric that describes the highest unweighted sound pressure level during an event in which the sound changes with time.	Vibration on Structures	111 dB 120 dB Ref. [9] 130 dB Ref. [10]
A-weighted Sound Exposure Level (SEL)	A single-event metric that accounts for the noise level and duration of the event, referenced to a standard duration of one second.	[Used to Calculate DNL/CNEL and Probability of Awakening]	--
Percent Allowable Daily Noise Dose	A single-event metric that describes the sound exposure normalized to an 8-hour working day, expressed as a percentage of the allowable daily noise dose.	Hearing Impairment	--
Probability of Awakening	A single-event metric that describes the probability that a person will be awakened.	Sleep Disturbance	--
Time Above a Threshold Level (TAL)	A time-based metric that gives the duration, in seconds, for which rocket noise exeeds a specified A-weighted sound level during a given period.	Speech Interference	--

Annoyance

DNL is based on long-term cumulative noise exposure and has been found to correlate with long-term community annoyance for regularly occurring events including aircraft, rail, and road noise [23, 24]. Noise studies used in the development of the DNL metric did not include rockets, which can have significant low-frequency noise energy and are historically irregularly occurring events. Thus, the suitability of DNL for rocket noise events is uncertain [25]. Additionally, 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"[1]. However, DNL is the most widely accepted metric to estimate the potential changes in long-term community annoyance.

Yearly DNL is the FAA's primary noise metric to quantify the cumulative exposure of individuals to noise from aviation activities. The Community Noise Equivalent Level (CNEL) may be used in lieu of DNL for FAA actions in California. FAA Order 1050.1G [1] defines the FAA's significance threshold for noise. An action is considered significant if it would increase noise in a noise-sensitive area by DNL 1.5 dBA or more and the resulting noise exposure level is at least DNL 65 dBA. For example, an increase from DNL 63.5 dBA to 65 dBA is considered a significant impact. The threshold levels for DNL are the same for CNEL.

Noise-Induced Hearing Impairment

U.S. government agencies provide guidelines on permissible noise exposure limits to unprotected human hearing. These 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 federal agencies have set exposure limits on non-impulsive noise levels, including the Occupational Safety and Health Administration (OSHA) [4], National Institute for Occupational Safety and Health (NIOSH) [5], and the Department of Defense (DoD) Occupational Hearing Conservation Program [6]. The most conservative of these upper noise level limits is the OSHA standard, which specifies that exposure to continuous steady-state noise is limited to a maximum of 115 dBA. At 115 dBA, the allowable exposure duration is 15 minutes for OSHA and 28 seconds for NIOSH and DoD. $L_{A,max}$ can be used to identify potential locations where hearing protection should be considered for rocket operations.

In addition to the maximum exposure limits, OSHA standards also specify a daily noise dose based on the SEL which accounts for the energy over the duration of the event(s). Although the daily noise dose metric was established to protect workers against NIHL, the results can also help contextualize the noise exposure in the community. The level of exposure is typically calculated in terms of a daily noise dose, which is a function of the sound exposure normalized to an 8-hour workday. For example, a person will reach 100% of their daily noise dose after 15 minutes of exposure to 115 dBA. A person will also reach 100% of their daily noise dose after 8 hours of exposure to 90 dBA.

Sleep Disturbance

Sleep disturbance is a major concern for communities exposed to launch vehicle noise at night. 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 mainly focused on predicting the probability of awakening during the night from nighttime operations.

The probability that a person of average sensitivity to awakening will be awakened by a single noise event is calculated using the ANSI Noise Standard, ANSI S12.9-2008/Part 6 [7]. Note, the ANSI Noise Standard was developed from field studies of behavioral awakening primarily in homes near airports subject to routine jet aircraft operations, not rocket operations. Furthermore, in 2018 ANSI made the decision to rescind the standard based partly on "the relatively small and non-representative corpus of field observations of noise-induced behavioral awakening available for analysis." However, the 1050.1 Desk Reference [2] specifies that the number of awakenings may be calculated using this ANSI Noise Standard. Thus, although there are no established criteria for evaluating sleep disturbance from rocket noise, the calculation of the probability of awakening is presented as a tentative criterion when comparing the effects of different operational alternatives.

Speech Interference

Speech interference from noise is a primary cause of annoyance for communities. Disruption of routine activities such as conversation leads to frustration and annoyance. One measure of speech comprehension is sentence intelligibility, the percent of sentences spoken and understood. This might be important for people 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 sentence intelligibility of 95% for two people standing outside, approximately 3 feet (1 meter) apart [8].

Noise-Induced Vibration Effects on Structures

Windows are typically the most sensitive components of a structure to launch vehicle noise. Infrequently, plastered walls and ceilings may also be affected. The potential for damage to a structure depends on the incident sound, the condition and material of the structural element, and installation of each element. A report from the National Research Council on the "Guidelines for Preparing Environmental Impact Statements on Noise" [10] 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 National Aeronautics and Space Administration (NASA) technical memo [9] concluded that the probability of structural damage is proportional to the intensity of the low frequency sound. The conclusions were 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 memo found that the estimated number of damage claims is one in 100 households exposed to an average continuous sound level of 120 dB (unweighted) and one in 1,000 households exposed to 111 dB (unweighted).

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 rocket engine 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 [9] damage claim criteria represent 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.

A.3.2 Sonic Boom Metrics and Effects

Table 4 presents metrics and associated effects relevant to the analysis of sonic booms from commercial space operations. The associated effects referenced in Table 4 are discussed in more detail in the following sections.

In addition to the FAA's primary noise metric for sonic booms, C-weighted DNL (CDNL), Table 4 provides supplemental metrics that can be used to evaluate potential impacts to people, and structures. The peak overpressure is particularly useful in improving the public's understanding of the impulsive sonic boom event(s). The peak overpressure is used to evaluate the potential for noise-induced hearing impairment and vibration effects on structures.

Table 4. Metrics for sonic boom analysis.

Metric	Description	Effect	Level
C-weighted Day-Night Average Sound Level (CDNL)	A cumulative (C-weighted) metric that accounts for all noise events in a 24-hour period. (A.2)	Annoyance	60 dBC [26]
C-weighted Community Noise Equivalent Level (CNEL)	A cumulative (C-weighted) metric that accounts for all noise events in a 24-hour period. (A.2)	Annoyance	60 dBC [26]
Peak Overpressure	A single-event metric that describes the highest instantaneous sound pressure level, characterized for sonic booms by the front shock wave. (A.2)	Physiological Effects	
		Hearing Impairment	140 dB (4 psf) [5]
		Vibration on Structures	2 psf [12, 13]

Annoyance

Similar to propulsion noise, DNL is the FAA's primary noise metric to quantify the cumulative exposure of individuals to sonic booms. However, for impulsive noise sources with significant low frequency content such as sonic booms, C-weighted DNL (CDNL) is preferred over A-weighted DNL [2]. In terms of percentage of people who are highly annoyed, DNL 65 dBA is equivalent to CDNL 60 dBC [26]. The C-weighted Community Noise Equivalent Level (CNEL) may be used in lieu of CDNL for FAA actions in California.

Physiological Effects

The unexpected, loud impulsive noise of sonic booms tends to cause a startle effect in people. However, when people are exposed to impulsive noises with similar characteristics on a regular basis, they tend to become conditioned to the stimulus and no longer display the startle reaction. The physiological effects of single sonic booms on humans [27] can be grouped as presented in Table 5.

Table 5. Physiological effects of a single sonic booms on humans. [27]

Overpressure	Behavioral effects
< 0.3 psf	Orienting, but no startle response; eyeblink response in 10% of subjects; no arm/hand movement.
0.6–2.3 psf	Mixed pattern of orienting/startle responses; eyeblink in about half of subjects; arm/hand movements in about a fourth of subjects, but not gross bodily movements.
2.7–6.5 psf	Predominant pattern of startle responses; eyeblink response in 90 percent of subjects; arm/hand movements in more than 50 percent of subjects with gross body flexion in about a fourth of subjects.

Noise-Induced Hearing Impairment

Multiple U.S. government agencies provide guidelines on permissible noise exposure limits for impulsive noise such as sonic booms. NIOSH [5] and OSHA [4] state that impulsive or impact noise levels should not exceed 140 dB peak sound pressure level, which equates to a sonic boom peak overpressure level of approximately 4 psf.

Noise-Induced Vibration Effects on Structures

The potential for damage from sonic booms is generally confined to brittle objects, such as glass, plaster, roofs, and bric-a-brac. Table 6 provides a summary of potential damage to conventional structures at various overpressures. Additionally, Table 6 describes example impulsive events for each level range. A large degree of variability exists in damage types and amounts, and much of the potential for damage depends on the sonic boom overpressure and the pre-existing condition of a structure. Generally, the potential for damage to well-maintained structures from sonic boom overpressures less than 2 psf is unlikely [12, 13]. The probability of the potential for damage to well-maintained structures by overpressures less than 4 psf is low (see Table 6) and increases for levels greater than 4 psf. Ground motion resulting from sonic boom is rare and is considerably below structural damage thresholds accepted by the United States Bureau of Mines and other agencies.

Table 6. Possible damage to structures from sonic booms. [12]

Nominal level	Damage Type	Item Affected
0.5 – 2 psf *piledriver at construction site*	Glass	Extension of existing cracks; potential for failure for glass panes in bad repair; failure potential for existing good glass panes is less than 1 out of 10,000 at 2 psf.
	Ceiling Plaster	Fine cracks; extension of existing cracks; mostly from fragile areas.
	Wall Plaster	Fine cracks; extension of existing cracks (less than in ceilings); over doorframes; between some plasterboards; mostly fragile areas.
	Roof	Older roofs may have slippage of existing loose tiles/slates; sometimes new cracking of old slates at nail hole; New and modern roofs are rarely affected.
	Bric-a-brac	Those carefully balanced or on edges can fall; fine glass, such as large goblets, can fall and break.
2 – 4 psf *cap gun/ firecracker near ear*	Glass	Failures show that would have been difficult to forecast in terms of their existing localized condition. Nominally in good condition.
	Ceiling Plaster	Estimated rate of cracking ranges from less than 1 out of 5,000 (2 psf) to 1 out of 625 (4 psf).
	Wall Plaster	Estimated rate of cracking ranges from less than 1 out of 10,000 (2 psf) to 1 out of 1,000 (4 psf).
	Roof	Potential for nail-peg failure if eroded.
	Bric-a-brac	Increased risk of tipping or falling objects.
4 – 10 psf *handgun at shooter's ear*	Glass	Regular failures within a large population of well-installed glass (1 out 50 (10 psf) to 500 (4 psf)); Failure potential in industrial and greenhouses glass panes.
	Ceiling Plaster	Estimated rate of cracking ranges from 1 out of 625 (4 psf) to 1 out of 10 (10 psf). Potential for partial ceiling collapse of good plaster; complete collapse of very new, incompletely cured, or very old plaster.
	Wall Plaster	Estimated rate of cracking ranges from less than 1 out of 1,000 (4 psf) to 1 out of 50 (10 psf). Measurable movement of inside ("party") walls at 10 psf.
	Roof	Regular failures within a large population of nominally good slate, slurry-wash; some chance of failures in tiles on modern roofs; light roofs (bungalow) or large area can move bodily.
	Bric-a-brac	Increased risk of tipping of falling objects

Table 6. Possible damage to structures from sonic booms. [12] (continued)

Nominal level	Damage Type	Item Affected
> 10 psf *fireworks display from viewing stand*	Glass	Some good glass will fail regularly (great than 1 out of 10) to sonic booms and at an increase rate when the wavefront is normal to the glass panel. Glass with existing faults could shatter and fly. Large window frames move.
	Ceiling Plaster	Plasterboards displaced by nail popping.
	Wall Plaster	Most plaster affected. Internal party walls can move even if carrying fittings such as hand basins or taps; secondary damage due to water leakage.
	Roof	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; rarely domestic chimneys dislodged if not in good condition.
	Bric-a-brac	Some nominally secure items can fall, e.g., large pictures, especially if fixed to party walls.

APPENDIX B MODELING METHODS

An overview of the propulsion noise and sonic boom modeling methodologies used in this noise study are presented in Section B.1 and B.2, respectively.

B.1 Propulsion Noise Modeling

Rocket propulsion systems, including solid-propellant motors and liquid-propellant engines, produce high-amplitude, broadband noise. Most of this 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.

RUMBLE 4.1, the Rocket Propulsion Noise and Emissions Simulation Model, developed by Blue Ridge Research and Consulting, LLC (BRRC), is used to predict the noise associated with the proposed operations. The RUMBLE model has been validated and accepted by regulatory agencies (i.e., USSF, FAA, NASA, Transport Canada, and UK's Civil Aviation Authority) for use in over 35 environmental studies to describe the noise environment in communities surrounding rocket facilities. In 2025, BRRC completed a validation study of RUMBLE under FAA AST funding [8], confirming the model's performance across key metrics for 11 measured events, spanning a range of rocket payload classes, propellent types, and environments.

The core components of the model are visualized in Figure 37 and are described in the following subsections.

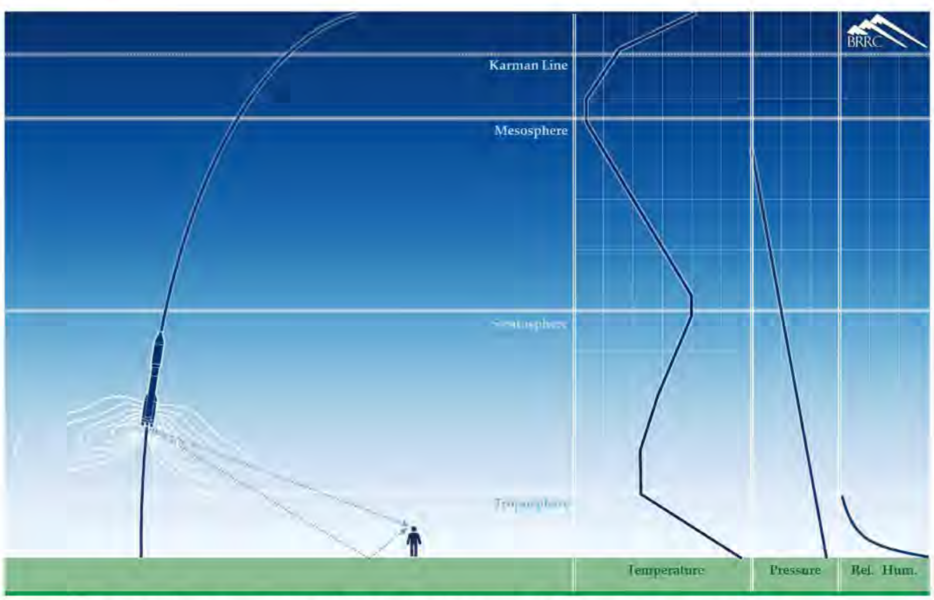

Figure 37. Conceptual overview of rocket noise prediction model methodology.

B.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 vehicle's total sound power based on its total thrust, exhaust velocity, and the engine/motor's acoustic efficiency. BRRC's 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 is assumed to be 0.4% for single-core rockets and 0.2% for rocket configurations that have multiple-cores or boosters. 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, 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 [30-33]. 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 the directivity of rockets [34]. These directivity indices (DI) incorporate a larger range of frequencies and angles than previously available data. Subsequently, improvements were made to the formulation of the NASA DI [35] 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 and 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.

B.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 rocket propulsion noise model components are calculated based on the specific geometry between source (vehicle trajectory point) to receiver (grid point). The position of the 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 [36-39] were used to create a composite atmospheric profile for altitudes up to 66 miles. 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 [40] as they travel through the medium. These nonlinear effects are counter to the effect of atmospheric absorption [41, 42]. However, recent research shows that nonlinear propagation effects change the perception of the received sound [43-49], but the standard acoustical metrics are not strongly influenced by nonlinear effects [50, 51]. 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 37. 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 [52, 53] when estimating the received noise. The model assumes a five-foot receiver height and a variable ground impedance to account for grass (soft) or water (hard) ground surfaces. To account for the random fluctuations of wind and temperature on the direct and reflected wave, the effect of atmospheric turbulence is also included [52, 54].

B.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. If a range of launch azimuths is being considered, the received noise represents the highest metric level generated from any launch azimuth within that range. For example, the noise metric level at a single receiver is modeled for every possible launch azimuth within the specified range, and the maximum of the range of levels is stored for the single receiver. This process is repeated for each receiver in the defined grid, and noise metric contours are developed from the grid of receivers.

B.1.4 Model Validation

Validation of the rocket noise model RUMBLE was performed through comparisons to field measurements. RUMBLE was used to predict noise exposure based on trajectory and atmospheric data specific to each location and event in the measured dataset. The dataset uses BRRC's database of noise measurements collected between 2017 and 2023. This dataset includes data from ten rocket missions across six unique rockets. The rockets range from medium to super heavy class. The dataset also represents various engine configurations used in modern rockets, including single-core, three-core, and single-core rockets with solid rocket boosters. The combination of rocket missions and measurement sensors yielded 239 data points, ranging from 0.2 to 21.4 km from the launch pad. Comparisons of modeled output were performed for all unique measurement data points (including measurements out to 21.4 km) for which the rocket event was clearly observed.

Figure 38 compares the RUMBLE predictions with the field measurements for all launch events. The maximum sound level metrics are presented in the top row, and the exposure-based metrics are presented in the bottom row. The unweighted, A-weighted, and C-weighted levels are presented in the left, middle, and right columns, respectively. Each of the 200+ data points represent a unique sensor location and height for one event. The color of the markers indicates the distance of the sensor from the launch pad. The black diagonal dashed lines indicate perfect agreement between the predictions and measurements, and the shaded areas represent ±5 dB. Points above and to the left of the diagonal dashed lines indicate that RUMBLE overestimates the noise metric level relative to the measured data. Points below and to the right of the diagonal dashed lines indicate that RUMBLE underestimates the noise metric level. Figure 38 shows that most data points lie within ±5 dB.

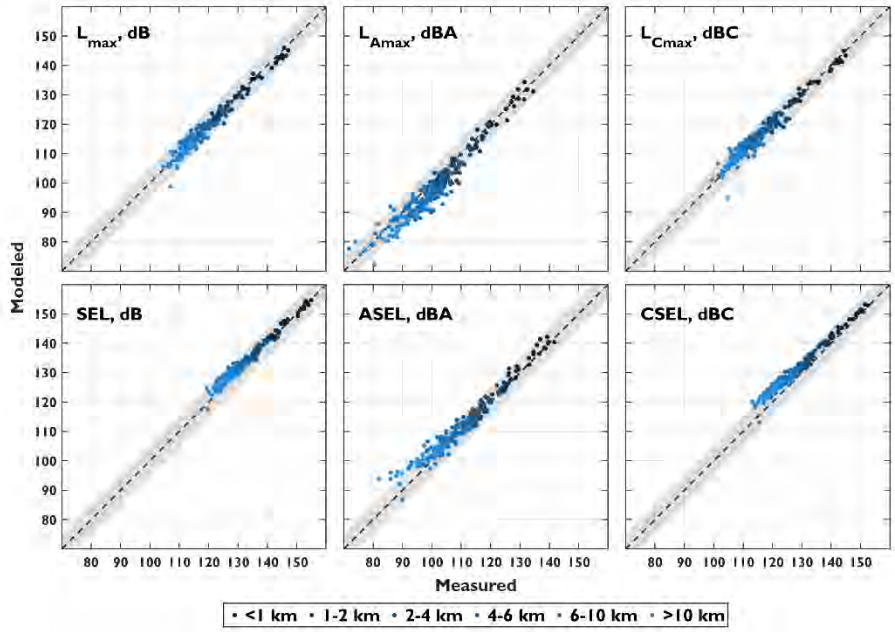

Figure 38. Metric comparison between RUMBLE predictions and launch field measurements.

While Figure 38 presents a comparison between the measured and modeled levels, the validation focused on the difference between those levels (i.e., the modeled level minus the measured level) to quantify the model's accuracy. Table 7 lists the median difference between the RUMBLE predictions and measured launch data for each noise metric. Positive differences indicate that RUMBLE overestimates the noise metric level relative to the measurement. Negative differences indicate RUMBLE underestimates the noise metric level. Table 7 demonstrates that the median differences are within ±2.9 dB, which is smaller than the observed variation in the measured data.

Table 7. Median differences (RUMBLE – Measured) for launch events.

ΔL_{max}	ΔL_{Amax}	ΔL_{Cmax}	ΔSEL	ΔASEL	ΔCSEL
-0.5 dB	-2.7 dBA	0.6 dBC	1.2 dB	1.1 dBA	2.9 dBC

Figure 39 presents a box plot of the differences between modeled and measured levels to illustrate the statistical distribution of the data. The median differences presented in Table 7 are represented in the box plot by the central horizontal mark in each box. The box represents the interquartile range, which includes the middle 50% of the data, where the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The boxes show that the middle

50% of the data is within ±2.0 dB of the median. The whiskers extend to the most extreme data points not considered outliers[1]. Scatter plots of the data points are also shown, where the width of each scatter represents the distribution density.

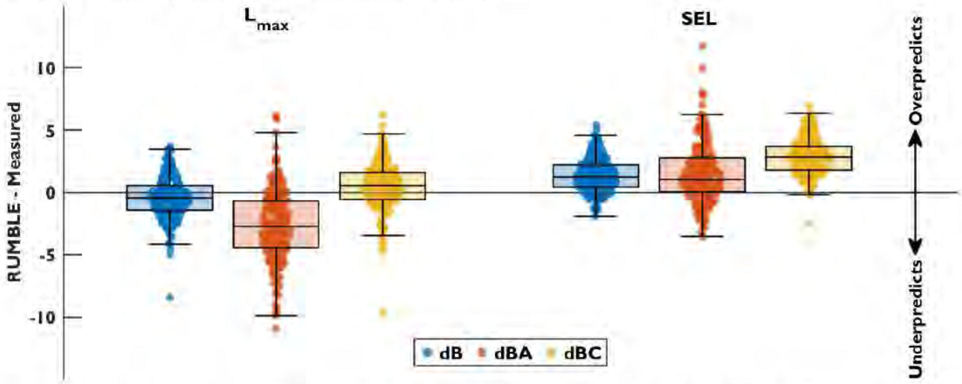

Figure 39. Box plots of the differences (RUMBLE – Measured) for all field measurements.

The model validation confirmed that RUMBLE accurately predicts noise from rockets across a wide range of thrust levels and engine configurations. While RUMBLE performed slightly better for distances less than 6 km from the launch pad, it still provided accurate predictions for distances greater than 6 km. Finally, the model's performance was consistent across all measurement heights.

[1] Data points are outliers if they are greater than $q_3 + w \times (q_3 - q_1)$ or less than $q_1 + w \times (q_3 - q_1)$, where w is the multiplier whisker, and q_1 and q_3 are the 25th and 75th percentiles of the sample data, respectively.

B.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 B.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 B.2.2.

B.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 40 shows the generation and evolution of a sonic boom N-wave under the vehicle.

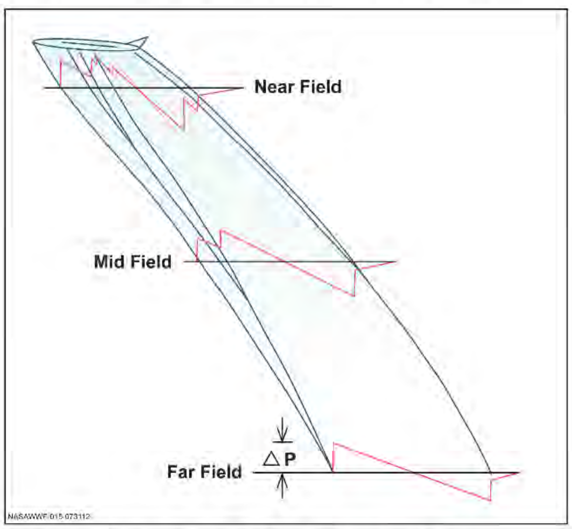

Figure 40. Sonic boom generation and evolution to N-wave. [55]

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 41 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."

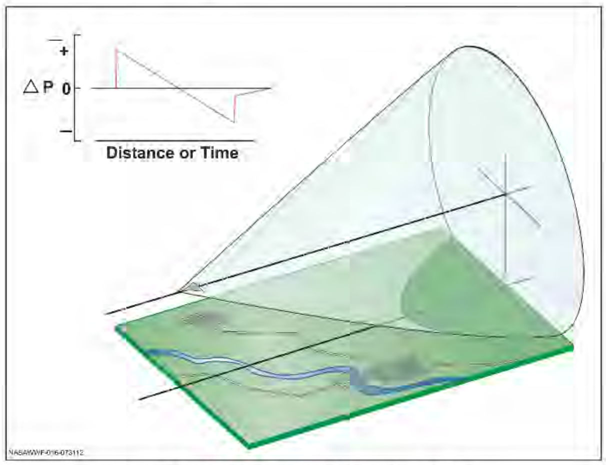

Figure 41. Sonic boom carpet for a vehicle in steady flight. [56]

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 [57]. Both perspectives are shown in Figure 42. The difference in wave versus ray perspectives is described for level, climbing, and diving flight, in the PCBoom Sonic Boom Model User Guide [57]:

> 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 42] 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."

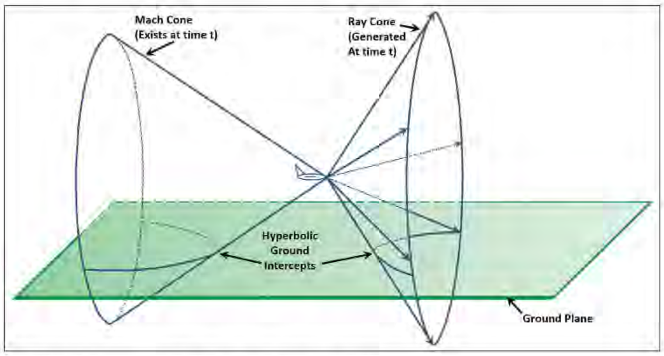

Figure 42. Mach cone vs ray cone viewpoints.

Figure 41 and Figure 42 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 42. For a vehicle climbing at an angle steeper than the ray cone half angle, such as in the left image of Figure 43, 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 43, 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.

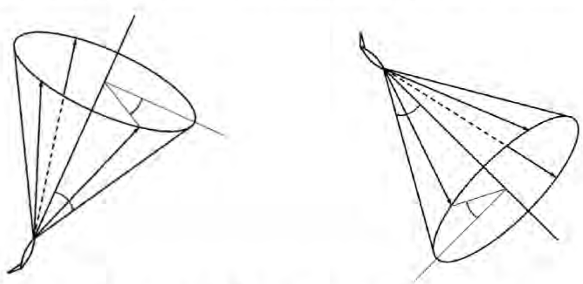

Figure 43. Ray cone in climbing (left) and diving (right) flight.

B.2.2 PCBoom

The single-event prediction model, PCBoom 6.7b [58-60], 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 [39].

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Appendix D Air Emissions Report

Blue Ridge Research and Consulting, LLC

BRRC Report 25-19 (Final)

Emissions Study for Blue Origin New Glenn Operations at CCSFS LC-36

19 December 2025 (Rev 3, 23 February 2026)

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1 INTRODUCTION

This report documents the air emissions from the operations of Blue Origin's New Glenn launch vehicle from Cape Canaveral Space Force Station (CCSFS) Launch Complex 36 (LC-36). Blue Origin plans to conduct up to 50 launches and landings of New Glenn per year. Prior to each launch, Blue Origin may perform static fire tests of New Glenn's stage 1 and stage 2 engines. The first stage of New Glenn (Figure 1) is powered by seven BE-4 liquid oxygen (LOX) and methane (LNG) engines with a combined mass flow rate of 6,575 kilograms per second. The second stage of New Glenn is powered by two BE-3U LOX and liquid hydrogen (LH2) engines with a combined mass flow rate of 440 kilograms per second.

Figure 1. New Glenn on the launch pad at LC-36 (Credit: Michael James)

This emissions study describes the mass of pollutants generated on an annual basis by Blue Origin New Glenn operations at LC-36. The emissions inventories were computed using BRRC's Rocket Noise and Emissions Simulation Model (RUMBLE) [1]. RUMBLE's emissions modeling methods were developed under the Transportation Research Board (TRB) Airport Cooperative Research Program (ACRP) Project 02-85 and are summarized in Appendix A. For a more detailed description of RUMBLE's formulations, see the TRB ACRP Web-Only Document 51: Commercial Space Vehicle Emissions Modeling [2], published by the National Academies Press. In accordance with the Federal Aviation Administration (FAA) regulations [3], the emissions inventory results provide a quantitative, project-specific indication of the magnitude of the proposed operations' potential air quality impact.

The following sections of this report are outlined below.

- Section 2 describes the proposed Blue Origin New Glenn operations;
- Section 3 presents the emissions modeling results; and
- Appendix A describes the general methodology of the emissions modeling.

2 NEW GLENN OPERATIONS

New Glenn is a heavy-lift launch vehicle designed and manufactured by Blue Origin. Blue Origin plans to launch their New Glenn rocket from LC-36 as illustrated in Figure 2.

Figure 2. A sample New Glenn mission profile. (Credit: Blue Origin)

Table 1 presents the proposed New Glenn operations at LC-36. Blue Origin plans to launch their New Glenn rocket from LC-36 up to 50 times per year. After stage separation, New Glenn's first stage will land on a landing platform in the Atlantic Ocean between 300 and 500 nautical miles downrange from the launch site. In addition to 50 annual launch and landing operations, Blue Origin plans to conduct up to 50 static fire operations of New Glenn's stage 1 and stage 2 engines.

Table 1. Proposed New Glenn LC-36 operations.

Event	Description	Annual Operations
Launch	Easterly launch from LC-36	50
Landing	Landing on platform in the ocean	50
S1 Static Fire	Up to 30 second burn of 7 engines	50
S2 Static Fire	Up to 30 second burn of 2 engines	50

Table 2 presents the engine modeling data for New Glenn. The first stage of New Glenn is powered by seven BE-4 LOX/LNG engines with a combined mass flow rate of 6,575 kilograms per second. The second stage of New Glenn is powered by two BE-3U LOX/LH2 engines with a combined mass flow rate of 440 kilograms per second. Note, the emissions modeling uses the time varying mass flow rate profile from the provided launch and landing trajectories.

Table 2. Modeling parameters for New Glenn.

Engine	Propellant	Mass Flow Rate
Stage 1	Liquid Oxygen (LOX) + Liquid Natural Gas (LNG)	6,575 kg/s (939 kg/s x Qty. 7 BE-4 engines)
Stage 2	Liquid Oxygen (LOX) + Liquid Hydrogen (LH2)	440 kg/s (220 kg/s x Qty. 2 BE-3U)

3 RESULTS

The emissions results are presented in the form of emissions inventories, which enumerate the masses of the various pollutants emitted as a result of the proposed operations. In accordance with FAA guidance [3-5] and the Clean Air Act, the emissions inventories present the relevant criteria air pollutants, hazardous air pollutants (HAPs), and greenhouse gases that could be emitted in each atmospheric layer from the proposed New Glenn operations at LC-36. While the model uses the best available literature to produce first-order, altitude-dependent emissions estimates, current predictions are subject to uncertainty. Dedicated field measurements are needed to reduce uncertainty and improve future emissions estimates.

Table 3 and Table 4 present the duration, propellant burned, and pollutant mass emitted for each operation type (i.e., launch, landing, and static fires) on a per-event and per-year basis, respectively. The pollutant masses are reported in US tons (2,000 lbm) for each atmospheric layer: troposphere below the mixing height (3,000 feet), troposphere above the mixing height, stratosphere, and mesosphere. The amount of each pollutant emitted into each atmospheric layer is directly related to the amount of propellant burned in each layer. For example, static fire tests are confined to the troposphere below 3,000 feet, while the launch and landing operations emit pollutants in all layers. The total pollutant mass exceeds the propellant mass because the heated plume reacts with the surrounding air, which adds the mass of molecules from the surrounding air to the pollutants.

The specific pollutant species emitted depend on the type of rocket propellant.

- **New Glenn's first stage uses LOX/methane BE-4 engines,** which power the stage 1 static fires, the launch through most of the mesosphere, and the landings. For hydrocarbon fueled engines like the BE-4, carbon dioxide (CO_2) and water vapor (H_2O) are the pollutants emitted in the greatest quantities because they are the products of complete combustion between oxygen and the rocket propellant. However, the combustion process in a rocket engine is typically incomplete. Carbon monoxide (CO) and a small amount of black carbon (BC) are emitted due to incomplete combustion inside the rocket engine. BC, commonly known as soot, is the only significant source of particulate matter (PM) emitted by liquid rocket engines. Particulate matter is classified by its diameter: PM_{10} describes particles that are 10 micrometers and smaller, and $PM_{2.5}$ describes particles that are 2.5 micrometers and smaller. Prior research has shown that BC particles emitted by liquid rocket engines are smaller than 2.5 micrometers [6]. Thus, BC emissions are classified as particulate matter in both the PM_{10} and $PM_{2.5}$ size categories. Furthermore, nitrogen oxides (NO_x) are emitted due to afterburning between the extremely high-temperature exhaust plume and nitrogen from the surrounding air.
- **New Glenn's second stage uses LOX/LH2 BE-3U engines**, which power the stage 2 static fires and the post-stage-separation ascent near the upper mesosphere. Like the BE-4 engines, the BE-3U's emit H_2O and NO_x. However, as LOX/LH2 does not contain carbon, the BE-3U engines do not emit CO, CO_2, or BC.

The amount of each pollutant emitted varies with altitude due to altitude-dependent chemical processes.

- At low altitudes, CO is nearly completely oxidized to CO_2 by reactions with oxygen molecules from the surrounding air. However, the rate of oxidation decreases at higher altitudes because fewer oxygen molecules are present in the lower-density air. Thus, the amount of CO increases as altitude increases. Similarly, BC is nearly completely oxidized to CO and CO_2 at low altitudes, but the amount of BC also increases at higher altitudes due to decreasing oxidation.
- Conversely, since NO_x is formed by afterburning between the high-temperature exhaust plume and nitrogen from the surrounding air, NO_x production decreases with altitude because fewer nitrogen molecules are present in the lower-density air.

No alumina (Al_2O_3) or chlorine species (Cl_x) are emitted because the propellants do not include aluminum or chlorine compounds (typical of solid rocket motors). Sulfur dioxide (SO_2) emissions are negligible because sulfur impurities occur in extremely low concentrations in rocket propellants. Additionally, volatile organic compounds (VOCs) are not typically emitted by launch vehicles. For these reasons, Al_2O_3, Cl_x, SO_2, and VOCs are not included in the emissions inventories below.

Table 3 presents the duration, propellant burned, and pollutant mass emitted for each operation type (i.e., launch, landing, and static fires) on a per-event basis.

Table 3. Duration, propellant burn, and pollutant mass per event by New Glenn operation.

	Duration	Propellant	Annual Pollutant Mass, US tons per event					
	seconds	US tons	CO_2	H_2O	CO	NO_x	PM_{10}	$PM_{2.5}$
Stage 1 Static Fire ***(7 x LOX/methane BE-4 engines)***								
Troposphere Below 3,000 feet	30	217	142	116	0.04	1.4	0.04	0.04
Troposphere Above 3,000 feet	--	--	--	--	--	--	--	--
Stratosphere	--	--	--	--	--	--	--	--
Mesosphere	--	--	--	--	--	--	--	--
Total	30	217	142	116	0.04	1.4	0.04	0.04
Stage 2 Static Fire ***(2 x LOX/LH2 BE-3U engines)***								
Troposphere Below 3,000 feet	30	15	--	22	--	0.48	--	--
Troposphere Above 3,000 feet	--	--	--	--	--	--	--	--
Stratosphere	--	--	--	--	--	--	--	--
Mesosphere	--	--	--	--	--	--	--	--
Total	30	15	--	22	--	0.48	--	--
Launch								
Troposphere Below 3,000 feet	26	191	124	102	0.04	1.1	0.04	0.04
Troposphere Above 3,000 feet	49	354	230	189	0.25	0.87	0.07	0.07
Stratosphere	72	517	328	276	5.2	0.04	0.84	0.84
Mesosphere	33	201	99	107	20	< 0.01	1.00	1.00
Total	180	1,263	782	675	26	2.0	1.9	1.9
Landing								
Troposphere Below 3,000 feet	20	23	15	12	< 0.01	0.14	< 0.01	< 0.01
Troposphere Above 3,000 feet	6.9	10	6.6	5.4	<0.01	0.05	< 0.01	< 0.01
Stratosphere	5.2	4.3	2.5	2.3	0.15	< 0.01	0.02	0.02
Mesosphere	19	45	24	24	3.4	< 0.01	0.23	0.23
Total	51	82	48	44	3.6	0.18	0.25	0.25

Notes: CO_2 = carbon dioxide, H_2O = water vapor, CO = carbon monoxide, NO_x = nitrogen oxides, PM_{10} and $PM_{2.5}$ = particulate matter with a diameter of less than or equal to 10 microns and 2.5 microns, respectively.
The table does not include the pollutants SO_2, VOCs, Al_2O_3, and Cl_2 as their mass is either negligible or zero.

Table 4 presents the duration, propellant burned, and pollutant mass emitted per year in each atmospheric layer by multiplying the estimates presented in Table 3 by 50, the number of annual operations.

Table 4. Duration, propellant burn, and pollutant mass per year by New Glenn operation.

	Duration seconds	Propellant US tons	Annual Pollutant Mass, US tons per year					
			CO_2	H_2O	CO	NO_x	PM_{10}	$PM_{2.5}$
Stage 1 Static Fire ***(7 x LOX/methane BE-4 engines)***								
Troposphere Below 3,000 feet	1,500	10,872	7,078	5,816	2.2	69	2.2	2.2
Troposphere Above 3,000 feet	--	--	--	--	--	--	--	--
Stratosphere	--	--	--	--	--	--	--	--
Mesosphere	--	--	--	--	--	--	--	--
Total	1,500	10,872	7,078	5,816	2.2	69	2.2	2.2
Stage 2 Static Fire ***(2 x LOX/LH2 BE-3U engines)***								
Troposphere Below 3,000 feet	1,500	726	--	1,082	--	24	--	--
Troposphere Above 3,000 feet	--	--	--	--	--	--	--	--
Stratosphere	--	--	--	--	--	--	--	--
Mesosphere	--	--	--	--	--	--	--	--
Total	1,500	726	--	1,082	--	24	--	--
Launch								
Troposphere Below 3,000 feet	1,317	9,545	6,213	5,105	2.2	57	1.9	1.9
Troposphere Above 3,000 feet	2,444	17,714	11,518	9,475	32	44	3.5	3.5
Stratosphere	3,576	25,843	16,422	13,823	261	1.8	42	42
Mesosphere	1,663	10,027	4,928	5,364	1,020	<0.01	50	50
Total	9,000	63,129	39,081	33,767	1,296	102	97	97
Landing								
Troposphere Below 3,000 feet	1,003	1,139	741	609	0.26	6.8	0.23	0.23
Troposphere Above 3,000 feet	347	508	331	272	0.17	2.2	0.10	0.10
Stratosphere	259	213	127	114	7.4	<0.01	1.1	1.1
Mesosphere	941	2,255	1,200	1,206	171	<0.01	11	11
Total	2,550	4,114	2,399	2,201	179	9.0	13	13

Notes: CO_2 = carbon dioxide, H_2O = water vapor, CO = carbon monoxide, NO_x = nitrogen oxides, PM_{10} and $PM_{2.5}$ = particulate matter with a diameter of less than or equal to 10 microns and 2.5 microns, respectively.
The table does not include the pollutants SO_2, VOCs, Al_2O_3, and Cl_2 as their mass is either negligible or zero.

Table 5 and Figure 3 present a summary of the pollutant mass emitted per year in each atmospheric layer from New Glenn operations at LC-36 by summing the estimates presented in Table 4 across all operations.

Table 5. Annual pollutant mass in US tons emitted by New Glenn operations including 50 launches, landings, stage 1 static fire tests, and stage 2 static fire tests.

	Annual Pollutant Mass, US tons per year					
Atmospheric Layer	CO_2	H_2O	CO	NO_x	PM_{10}	$PM_{2.5}$
Troposphere Below 3,000 feet	14,033	12,612	4.6	157	4.3	4.3
Troposphere Above 3,000 feet	11,848	9,747	13	46	3.6	3.6
Stratosphere	16,549	13,937	269	1.8	43	43
Mesosphere	6,128	6,569	1,191	< 0.01	61	61
Total	48,558	42,865	1,477	204	112	112

Notes: CO_2 = carbon dioxide, H_2O = water vapor, CO = carbon monoxide, NO_x = nitrogen oxides, PM_{10} and $PM_{2.5}$ = particulate matter with a diameter of less than or equal to 10 microns and 2.5 microns, respectively.
The table does not include the pollutants SO_2, VOCs, Al_2O_3, and Cl_2 as their mass is either negligible or zero.

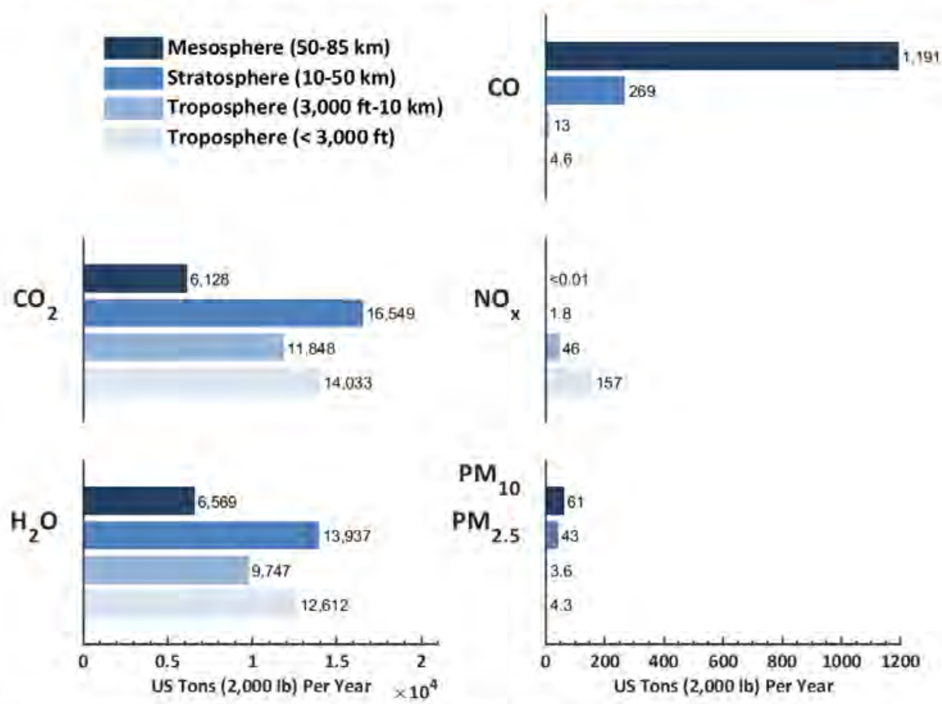

Figure 3. Annual pollutant mass in US tons per year emitted by New Glenn operations including 50 launches, landings, stage 1 static fire tests, and stage 2 static fire tests.

APPENDIX A EMISSIONS MODELING

RUMBLE 4.2, the Launch Vehicle Noise and Emissions Simulation Model developed by Blue Ridge Research and Consulting, LLC (BRRC), was the model used to predict the emissions associated with the proposed operations. Development of the RUMBLE emissions model was funded by FAA under Airport Cooperative Research Program (ACRP) Project 02-85 [2], administered by the Transportation Research Board (TRB), a unit of the National Academies of Sciences, Engineering, and Medicine. The RUMBLE emissions modeling methodology was developed to produce accurate emissions estimates relevant to environmental analysis of commercial space operations. The model is applicable to inflight and static operations of vertical and horizontal launch vehicles.

A.1 Emissions Background

Launch vehicle propulsion systems, such as liquid-propellant rocket engines and solid rocket motors, produce emissions through a series of chemical reactions, as shown in Figure 4. First, combustion occurs between the fuel and oxidizer inside the rocket engine. Next, the combustion products expand and accelerate through the nozzle, where additional chemical reactions may occur. Finally, the chemical species in the high-temperature exhaust plume may continue to react with each other and the surrounding air in a process called afterburning.

The combustion products present at the nozzle exit plane are called the *primary emissions* of the rocket engine. The products formed by afterburning and other reactions in the high-temperature exhaust plume are referred to as *secondary emissions*. The chemical species emitted into the atmosphere after the rocket has passed by and the exhaust plume has cooled to the ambient temperature include contributions from both the primary and secondary emissions. RUMBLE is designed to estimate these *final emissions* since they are the chemical species that the vehicle ultimately emits into the atmosphere.

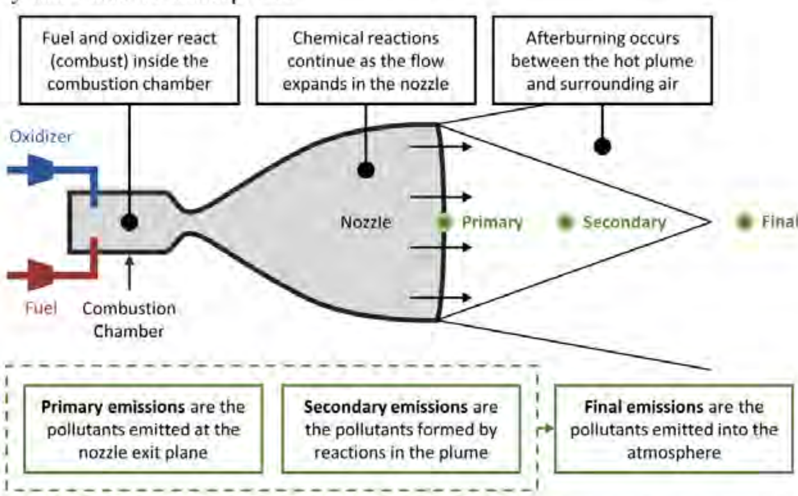

Figure 4. Diagram of the chemical processes in a rocket engine that produce the primary, secondary, and final emissions.

A.2 Emissions Modeling Methodology

The RUMBLE emissions model calculates the mass of each pollutant emitted by commercial space operations. The calculations are first performed at the most detailed level (i.e. individual trajectory segment), and the results are aggregated to produce the propellant burn report and emissions inventory.

First, the propellant mass burned by a single engine during an individual trajectory segment is calculated by

$$\begin{bmatrix}\text{Propellant}\\ \text{Mass}\end{bmatrix} = \begin{bmatrix}\text{Propellant}\\ \text{Mass Flow Rate}\end{bmatrix} \times \begin{bmatrix}\text{Segment}\\ \text{Duration}\end{bmatrix}$$

where the duration of the trajectory segment is the time between successive points in the trajectory.

Next, the mass of each pollutant emitted by a single engine during an individual trajectory segment is calculated by

$$\begin{bmatrix}\text{Pollutant}\\ \text{Mass}\end{bmatrix} = \begin{bmatrix}\text{Emissions}\\ \text{Index}\end{bmatrix} \times \begin{bmatrix}\text{Propellant}\\ \text{Mass}\end{bmatrix}$$

The emissions indices are the factors that relate the amount of propellant burned to the amount of each pollutant emitted by the engine. Emissions indices are discussed in more detail in Section A.3.

The main output of the RUMBLE emissions model is the emissions inventory. The emissions inventory enumerates the masses of the various pollutants emitted as a result of commercial space operations. RUMBLE aggregates the detailed pollutant mass calculations over the number of engines, trajectory segments, and operations to compute the total amount of each pollutant emitted. In accordance with FAA guidelines, RUMBLE reports the emissions inventory in the troposphere below and above the mixing height (3,000 feet), the stratosphere, and the mesosphere.

A.3 Emissions Indices

RUMBLE uses emissions indices to estimate the total amounts of the various pollutants emitted by space vehicles. Emissions indices are the factors that relate the amount of propellant burned to the amount of each pollutant emitted by a rocket engine. The emissions index for a specific pollutant reports the outcome of the complex series of chemical reactions that occur within the rocket engine and exhaust plume as a single number.

Primary Emissions Indices

The primary emissions are the chemical species present at the nozzle exit plane due to processes that occur inside the rocket engine. The primary emissions indices were predicted using the computer program Chemical Equilibrium with Applications (CEA) [7, 8]. CEA was developed at the NASA Glenn Research Center for the purpose of calculating the chemical equilibrium composition and thermodynamic properties of any chemical system.

A key application of CEA is the prediction of theoretical rocket engine performance and emissions. To predict rocket engine emissions, CEA requires the propellant (fuel and oxidizer) species, mixture ratio, combustion chamber pressure, and nozzle area ratio as input parameters.

Using these vehicle-specific input parameters, CEA performs calculations at several locations inside the rocket engine, including the combustion chamber, throat, and nozzle exit plane. The results at each location include the chemical composition, which is reported in terms of mole fractions or mass fractions of the combustion products. The mass fractions at the nozzle exit plane are directly proportional to the primary emissions indices.

Final Emissions Indices

However, the primary emissions indices at the nozzle exit plane are not the final emissions indices used in the emissions model. The chemical species in the high-temperature exhaust plume outside the rocket engine may continue to react with each other and with the surrounding air to produce secondary emissions. These secondary emissions modify and add to the final pollutant species that the rocket ultimately emits into the atmosphere. The formation of secondary emissions in the exhaust plume is a complex process involving finite-rate chemical kinetics, non-isentropic shocks and expansion waves, and turbulent dispersion. Prior studies have shown that the formation of secondary emissions depends most strongly on the chemical composition of the rocket exhaust plume and the altitude. Estimates for the secondary emissions from commercial space vehicles were developed under ACRP Project 02-85 [2]. RUMBLE implements these estimates to calculate the final emissions indices based on the primary emissions indices computed by CEA and the altitude from the nominal trajectory.

RUMBLE 4.2 incorporates updated NO_x and CO formulations for LOX/methane engines that more accurately capture their formation in the troposphere below 3,000 ft. These improvements are based on high-fidelity plume-chemistry modeling for the SpaceX Raptor engine [9, 10], which provides secondary emissions that are representative of methane-fueled systems. Earlier versions of the model relied on secondary emissions relationships developed for LH_2 and RP-1 fueled engines, whose combustion chemistry, exhaust composition, and afterburning characteristics differ from those of methane-fueled engines. The methane-specific NO_x and CO secondary emissions indices introduced in RUMBLE 4.2 ensure the model continues to use the best available literature to produce first-order emissions estimates. However, these predictions remain subject to uncertainty, and dedicated field measurements are needed to reduce that uncertainty and improve future emissions estimates for NO_x and CO, as well as the other pollutants.

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