APPENDIX B

Noise Assessment

STARSHIP ROCKET NOISE ASSESSMENT FOR FLIGHT AND TEST OPERATIONS AT SPACEX LAUNCH FACILITY (STARBASE)

TN 23-05

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Prepared for:

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Executive Summary

Space Exploration Technologies Corporation (SpaceX) is planning to conduct flight operations and testing of the Starship and Super Heavy Booster vehicles at Starbase in Boca Chica, TX. To support environmental studies for FAA launch licensing, KBR, Inc. conducted this noise modeling study to estimate the single event and cumulative noise levels in the vicinity of Starbase from future Starship launches, Ship and booster landings, and Ship and booster static fire tests.

The RNOISE model, which computes far field noise levels in the community, was used to estimate rocket noise from Starship flight and test operations at Starbase. SpaceX provided the operations data required to conduct noise modeling of the individual flight and test events, including orbital launch and booster landing trajectories, engine operating data, and static fire test parameters. Cumulative noise was estimated for a future projected operations scenario involving 25 annual operations of each flight event plus 6 Ship static tests and 5 booster static tests.

Conclusions are that rocket noise from individual launch, landing, and static fire test events are expected to be heard by people in the communities surrounding Starbase, primarily South Padre Island to the north and Port Isabel, Laguna Vista, Brownsville, and Los Fresnos to the west. However, due to the levels and expected frequency of events, these individual noise events are not expected to cause general annoyance or pose health concerns, though noise complaints may occur. A future projected annual operation scenario at Starbase involving 25 annual operations of each flight event, plus additional static tests, is estimated to generate cumulative noise levels in residential areas that are below levels associated with adverse noise exposure (i.e., below the FAA's Day-Night Average Sound Level (DNL) 65 dBA threshold). Recent criterial used to assess the potential for structural damage indicates that no damage is expected from Starship launches or any of the other Ship or booster operations that generate lower noise levels than launches (i.e., the 134 dB L_{max} contour for all Starship flight and test operations is within Starbase property, such that no damage is expected to occur to structures off-base).

1 Introduction

Space Exploration Technologies Corporation (SpaceX) plans to conduct flight and ground tests of their Starship rocket at SpaceX Launch Facility (Starbase) in Boca Chica, Texas. KBR, Inc. has estimated noise levels for the Starship which is currently under development. Starship, which has a length of seventy meters and a diameter of nine meters, will be attached to a Super Heavy Booster rocket (length of eighty meters) to form the Starship Launch Vehicle intended to provide long-duration cargo- and passenger-carrying capability. Both vehicles have vertical take-off and landing (VTOL) capability and are fully reusable. The Starship would use nine Raptor engines that each provide sea-level thrust of about 3.19 Meganewtons (MN) during flight operations and static fire tests. The Super Heavy Booster would use thirty-five Raptor engines that each provide sea-level thrust of about 2.94 MN during launch and static fire tests.

This study was conducted to estimate single event and cumulative noise levels from future Starship and booster launches, Ship and booster landings, and static fire tests of both vehicles at Starbase. SpaceX provided the following data for noise modeling:

- Orbital launch trajectory for the Starship from liftoff to stage separation.
- Raptor engine operating data and nominal ascent thrust profile.
- Ship and Super Heavy Booster reentry and descent/landing trajectories from separation to landing with descent thrust profiles.
- Static fire test parameters for the Ship and Super Heavy Booster.
- Projected annual launch, landing, and static fire test operations at Starbase.

Noise levels for Starship and Super Heavy Booster flight and static test operations were estimated using the RNOISE model. RNOISE[1,2] is a far-field (distances beyond several hundred feet) community noise model for rocket noise assessment.

The following sections of this report provide a description of rocket noise fundamentals (Section 2) followed by estimated single event noise levels for Starship orbital launches (Section 3), Ship and Super Heavy Booster landings (Section 4), and static fire tests for both vehicles (Section 5). Section 6 presents a cumulative noise level estimate at Starbase for a projected annual operation scenarios involving future launches, landings, and static fire tests; cumulative noise is assessed for all projected operations combined.

2 Rocket Noise Background and Metrics

2.1 Background

Rockets generate significant noise from the combustion process and turbulent mixing of the exhaust flow with the surrounding air. Figure 1 is a sketch of rocket noise. There is a supersonic potential core of exhaust flow, surrounded by a mixing region. Noise is generated in this flow. It is directional, with the highest noise levels at an angle of 40 to 50 degrees from the direction of the exhaust flow. The fundamentals of predicting rocket noise were established by Wilhold et al.[3] for moving rockets and by Eldred et al.[4] for static firing. Sutherland[5] refined modeling of rocket source noise, improving its consistency relative to jet noise theory. Based on those fundamentals, Wyle has developed the PAD model for near field rocket noise[6] and the RNOISE model for far field noise in the community. RNOISE was used for the current analysis.

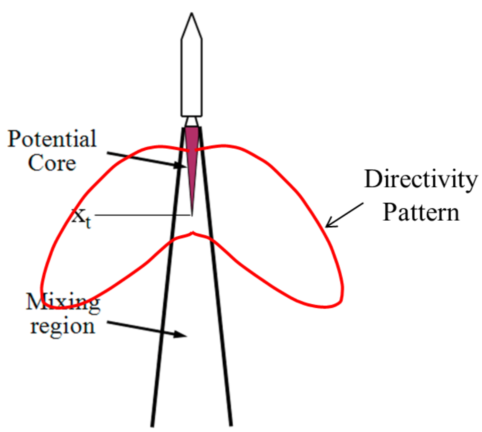

Figure 1. Rocket Noise Source

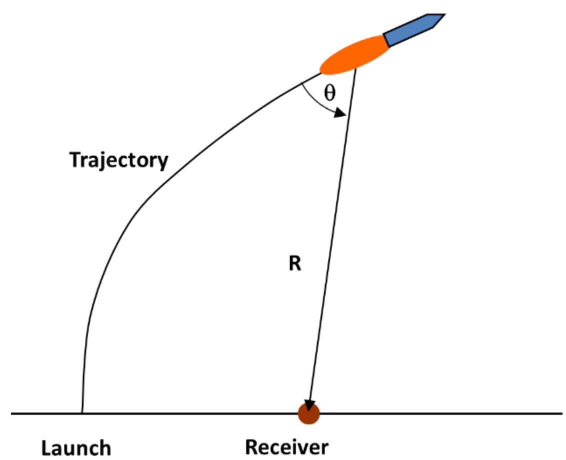

Figure 2. Modeling Rocket Noise at the Ground

Figure 2 is a sketch of far field rocket noise as treated by RNOISE. The vehicle's position and attitude are known from the trajectory. Rocket noise source characteristics are known from the engine properties, with thrust and exhaust velocity being the most important parameters. The emission angle and distance to the receiver are known from the flight path and receiver position. Noise at the ground is computed accounting for distance, ground impedance,[7] atmospheric absorption of sound,[8] and uniform ground elevation. RNOISE propagates the full spectrum to the ground, accounting for Doppler shift from vehicle motion. It is a time simulation model, computing the noise at individual points or on a regular grid for every time point in the trajectory. Propagation time from the vehicle to the receiver is accounted for, yielding a spectral time history at the ground (including a range of frequencies from 1 Hz to 16 kHz). A variety of noise metrics can be computed from the full calculated noise field and the metrics commonly used to assess rocket noise are described in the following section.

2.2 Rocket Noise Metrics and Assessment Criteria

2.2.1 Noise Metrics

FAA Order 1050.1F[9] specifies Day-Night Average Sound Level (DNL) as the standard metric for community noise impact analysis, but also specifies that other supplemental metrics may be used as appropriate for the circumstances. DNL is appropriate for continuous noise sources, such as airport noise and road traffic noise. The noise metrics used for rocket noise analysis are:

- DNL, as defined by FAA Order 1050.1F;
- SEL, the Sound Exposure Level, for individual events;
- L_{Amax}, the maximum A-weighted overall sound pressure level (OASPL), for individual events;
- L_{max}, the maximum unweighted OASPL, for individual events; and
- One third octave spectra at certain sensitive receptors.

As mentioned, DNL is necessary for policy. The next three metrics provide a measure of the impact of individual events; SEL and L_{Amax} are A-weighted and L_{max} is un-weighted. Loud individual events can pose a hearing damage hazard to people and can also cause adverse reactions by animals. Adverse animal reactions can include flight, nest abandonment, and interference with reproductive activities. L_{max} along with spectra, may be needed to assess potential damage to structures and adverse reaction of species whose hearing response is not like that of humans.

L_{Amax} is appropriate for community noise assessment of a single event, such as a rocket launch or static fire test. This metric represents the highest A-weighted integrated sound level for the event in which the sound level changes value with time. Slowly varying or steady sounds are generally integrated over a period of one second. L_{Amax} is important in judging the interference caused by a noise event with conversation, TV listening, sleep, or other common activities. Similarly, L_{max} is the highest unweighted integrated sound level for the event, used to assess the potential for structural damage. Although A-weighted maximum sound level provides some measure of the intrusiveness of the event, it does not completely describe the total event, because it does not include the duration that the sound is heard.

SEL is a composite metric that represents both the level of a sound and its duration. Individual time-varying noise events (e.g., aircraft overflights) have two main characteristics: a sound level that changes throughout the event and a period during which the event is heard. SEL provides a measure of the total acoustic energy transmitted to the listener during the event, but it does not directly represent the sound level heard at any given time. For example, during an aircraft flyover, SEL would include both the maximum noise level and the lower noise levels produced during onset and recess periods of the overflight. Mathematically, it represents the sound level of a constant sound that would, in one second, generate the same acoustic energy as the actual time-varying noise event. For a rocket launch, SEL is expected to be greater than L_{Amax}.

2.2.2 Noise Assessment Guidelines

Land Use Compatibility Guidelines for Cumulative Noise Exposure

As previously mentioned, DNL represents the average sound level for annual average daily aircraft events which are used to assess cumulative noise exposure. FAA's published 14 Code of Federal Regulations (CFR) Part 150 defines land use compatibility guidelines for aviation noise exposure that are also applicable to rocket noise exposure. These guidelines consider land use compatibility for different uses over a range of DNL noise exposure levels, including the adoption of DNL 65 dBA as the limit for residential land use compatibility.

Hearing Conservation

Occupational Safety and Health Administration (OSHA)[10] guidelines are to protect human hearing from long-term, continuous exposures to high noise levels and aid in the prevention of noise-induced hearing loss (NIHL). OSHA's permissible daily noise exposure limits include a L_{Amax} of 115 dBA (slow response) for a duration of 0.25 hours or less. This is the criteria used in this study to evaluate areas around launch, landing, and static fire test sites that would require implementing a hearing conservation program, i.e., areas within the L_{Amax} 115 dBA contour. This level was chosen as a conservative indicator of when a hearing conservation program should be implemented since all proposed flight and test operations, individually or together, are not expected to exceed 0.25 hours in duration on any given day.

Structural Damage Potential

The potential for structural damage due to launch, landing, and static fire test events is assessed using the conclusions from a recent, applicable study to ascertain whether range activities (i.e., test, evaluation, demilitarization, and training activities of items such as weapons systems, ordinance, and munitions) would cause structural damage. The study concluded that structural damage becomes improbable below 140 dB [Maximum Un-weighted or linear Sound Level (L_{max})]. No glass or plaster damage is expected below 140 dB and no damage is expected below 134 dB[11].

Estimated noise results for Starship and Super Heavy booster launch, landing, and static fire test events are presented in the following sections. These results include L_{Amax}, SEL, and L_{max} contours for single event noise assessment over the study area (Sections 3 through 5) and DNL contours to assess the cumulative noise for a scenario involving projected annual operations of each type of event (Section 6).

3 Orbital Launch Noise Levels

3.1 Starship Orbital Launches at Starbase

RNOISE was used to estimate the L_{Amax}, SEL, and L_{max} contours for a Starship orbital launch at Starbase using trajectory data, from liftoff to stage separation, provided by SpaceX in file 'Starship_Boca_RTLS_ROTATED_80_12.ASC' with an uprated maximum total thrust of approximately 23 MM lbf (35 engines x 2.94 MN per engine). The L_{Amax} contours indicate the maximum sound level at each location over the duration of the launch where engine thrust varies according to the ascent thrust profile provided. For orbital launches, the Starship launch vehicle is comprised of the Starship (second stage vehicle with payload) and the Super Heavy Booster.

RNOISE computations were done using a radial grid consisting of 128 azimuths and 100 intervals out to 500,000 feet from the launch point. Land areas were modeled using a single ground impedance value estimated from the most common ground cover type in the vicinity of Boca Chica, TX and offshore water areas modeled as acoustically hard. Ground effect was based on a weighted average over the propagation path. As shown in the resulting noise contour maps (Figures 3 through 8), the shape of the innermost contours is approximately circular. The shape of the outermost contours is due to rocket noise directivity and the difference between the ground impedance values used for onshore and offshore areas. The launch pad location at Starbase is indicated in the map legend as is the Padre Island National Seashore. All maps depicting noise contours for operations at Starbase also show the nearby cities of Port Isabel, Laguna Vista, and Brownsville, TX.

Throughout this report, different map scales are used as appropriate to show the extent of the noise contours. The L_{Amax} 90 dB through 140 dB contours shown in Figures 3 and 4 represent the maximum levels estimated for a Starship orbital launch at Starbase; Figure 4 shows these contours using the zoomed in map scale to better show the extent of the noise exposure relative to cities close to Starbase. The higher L_{Amax} contours (100 – 140 dB) are located within about 8 miles of Starbase; the 100 dB contour extends into South Padre Island beyond Port Isabel. The 90 dB contour extends into Laguna Vista and eastern parts of Brownsville. If a Starship orbital launch occurs during the day, when background levels are in the 50 dB to 60 dB range, residents of Brownsville and Los Fresnos may notice launch noise levels above 70 dB and up to 90 dB. If the same launch occurs during the night, when background levels are lower than during the day (e.g., below 40 dB to 50 dB range), these residents may notice launch noise levels that exceed 60 dB. A prevailing onshore or offshore breeze may also strongly influence noise levels in these communities.

Estimated SEL contour levels of 90 dB through 150 dB, in 10 dB increments, are shown in Figures 5 and 6 for a Starship orbital launch at Starbase with Figure 6 showing a zoomed in map scale. As mentioned previously, SEL is an integrated metric and is expected to be greater than the L_{Amax} because the launch event is up to several minutes in duration whereas the maximum sound level (L_{Amax}) occurs instantaneously. In Figure 5, the 90 dB SEL contour would extend west of Brownsville and Los Fresnos.

Orbital launch events are the loudest single events of all the flight and test operations assessed in this modeling study. Starship orbital launch single event noise levels are related to guidelines for hearing conservation and potential for structural damage as follows.

An estimate of the areas, in the vicinity of Starship orbital launches, where a hearing conservation program should apply was made using OSHA's permissible daily noise exposure limit of 115 dBA (slow response) for a duration of 0.25 hours or less. Figure 4 shows that noise levels (L_{Amax}) are less than OSHA's 115 dBA upper noise limit guideline at distances greater than approximately 3 miles from the launch pad (i.e., hearing conservation should apply within 3 miles from the launch pad). Starship orbital launch noise events will last a few minutes at most, at a single location, with the highest noise levels occurring for less than a minute such that OSHA's 115 dBA daily noise exposure limit is not expected to be exceeded.

The potential for structural damage due to Starship orbital launch events is assessed using the criteria described in Section 2.2.2. Applying these criteria indicates that no damage is expected from Starship launches or any of the other flight and test operations that generate lower noise levels than launches. The 134 dB Maximum Unweighted Sound Level (L_{max}) contour for Starship orbital launch, located in between the 130 dB and 140 dB contours shown in Figure 7, is within 1.5 miles from the launch pad, such that damage is not expected to occur beyond the Starbase property line. This is expected for all Starship (Ship) and Booster flight and test operations described herein.

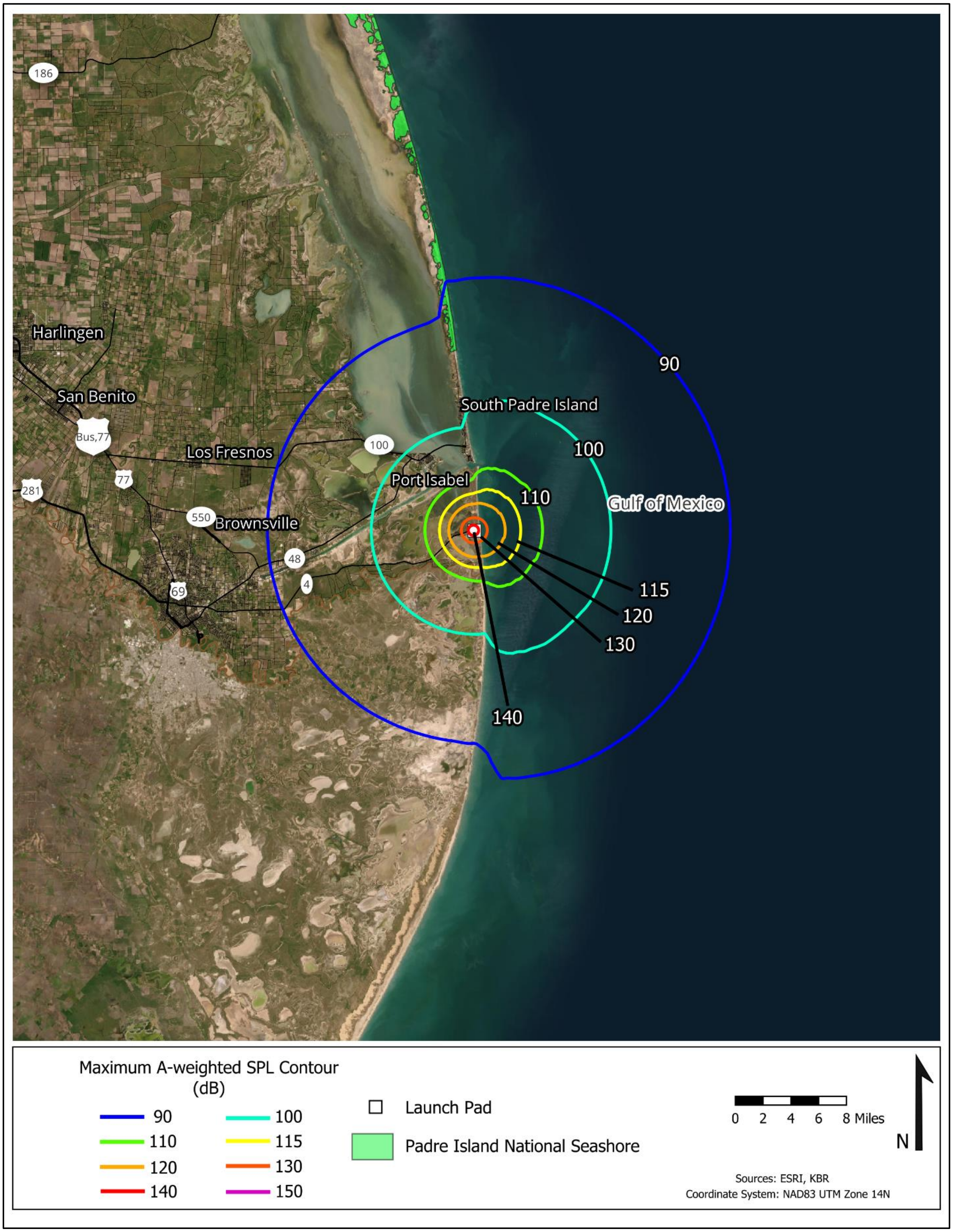

Figure 3. Starship Orbital Launch from Starbase: Maximum A-Weighted Sound Levels

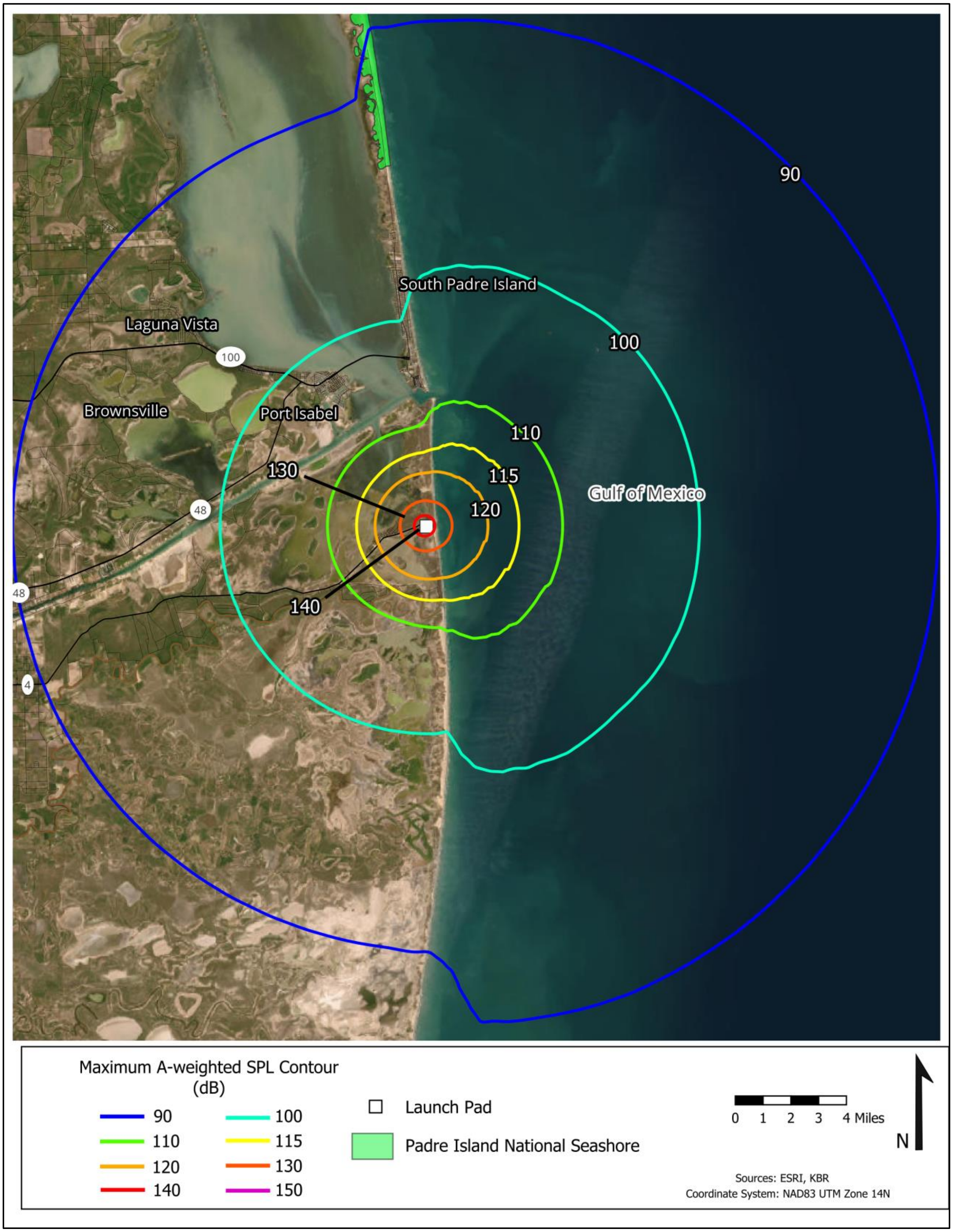

Figure 4. Starship Orbital Launch from Starbase: Maximum A-Weighted Sound Levels (Zoom In)

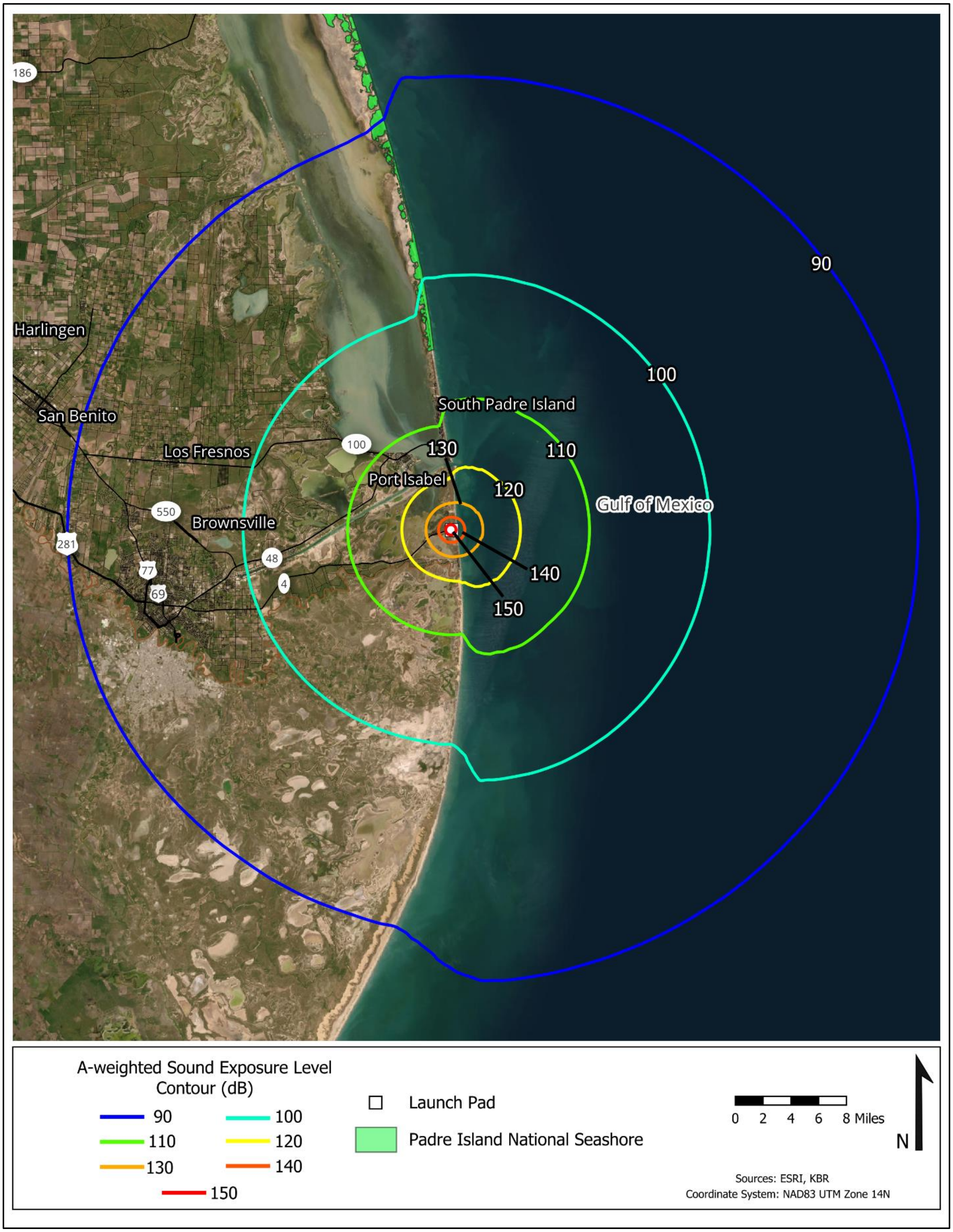

Figure 5. Starship Orbital Launch from Starbase: Sound Exposure Levels

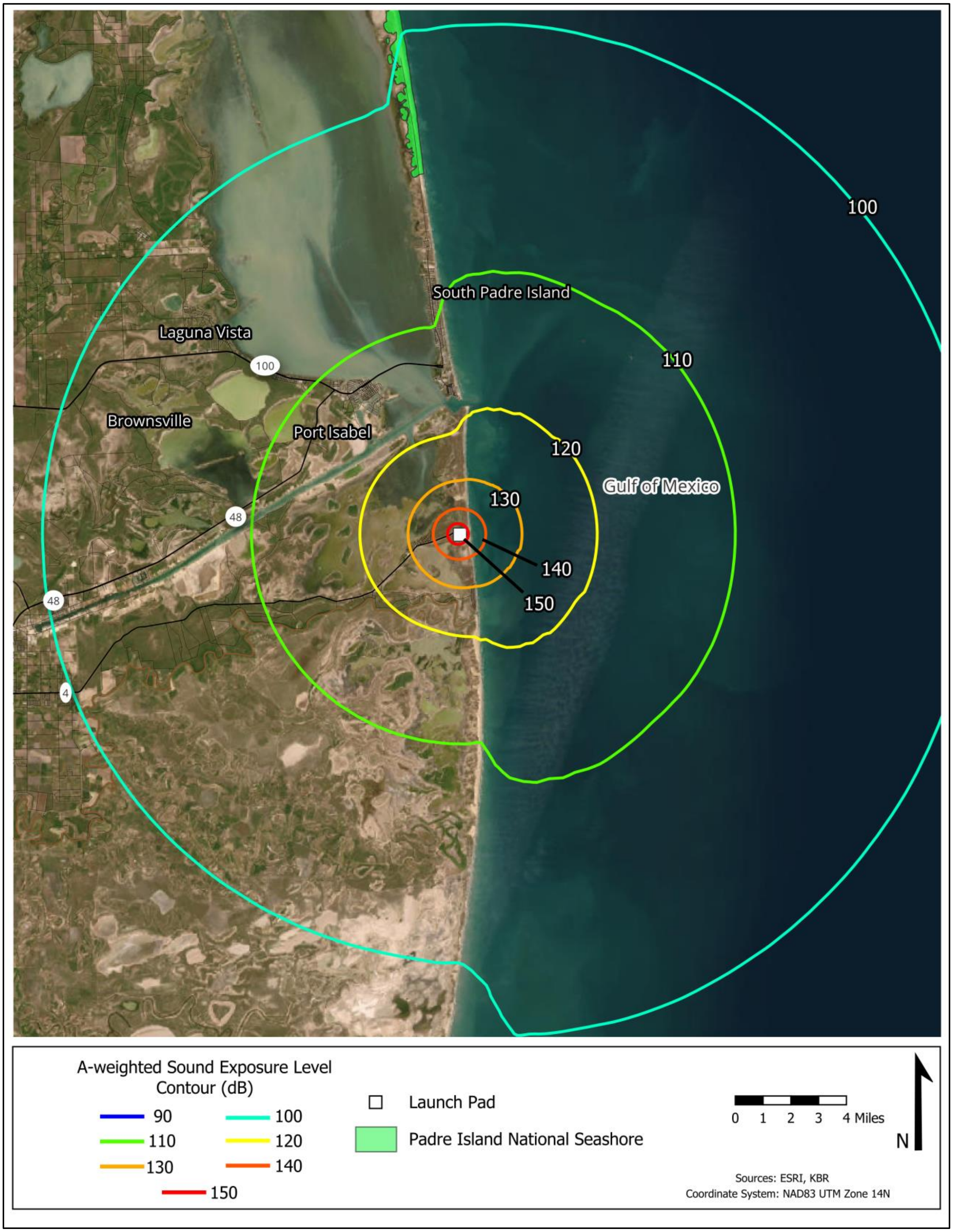

Figure 6. Starship Orbital Launch from Starbase: Sound Exposure Levels (Zoom In)

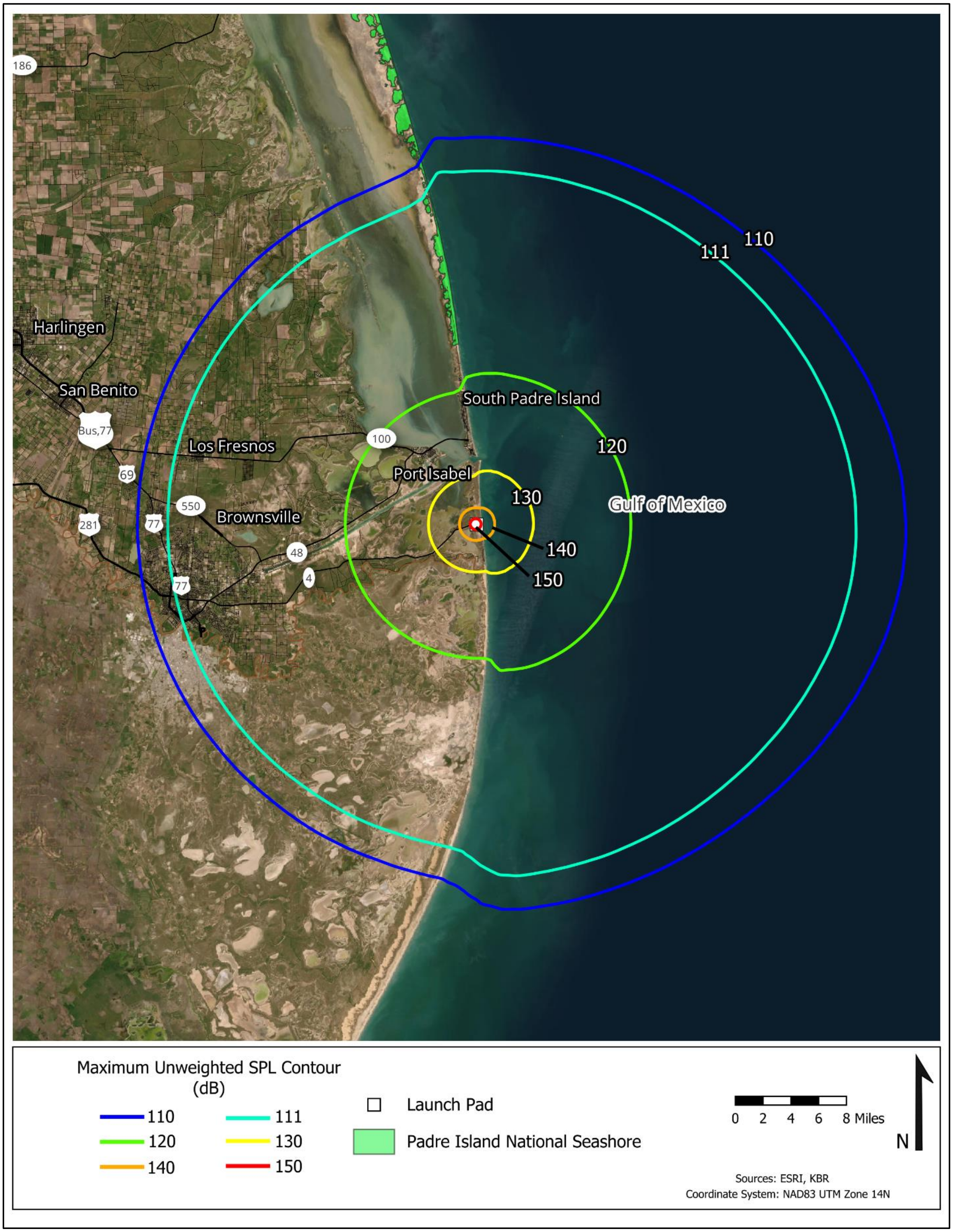

Figure 7. Starship Orbital Launch from Starbase: Maximum Unweighted Sound Levels

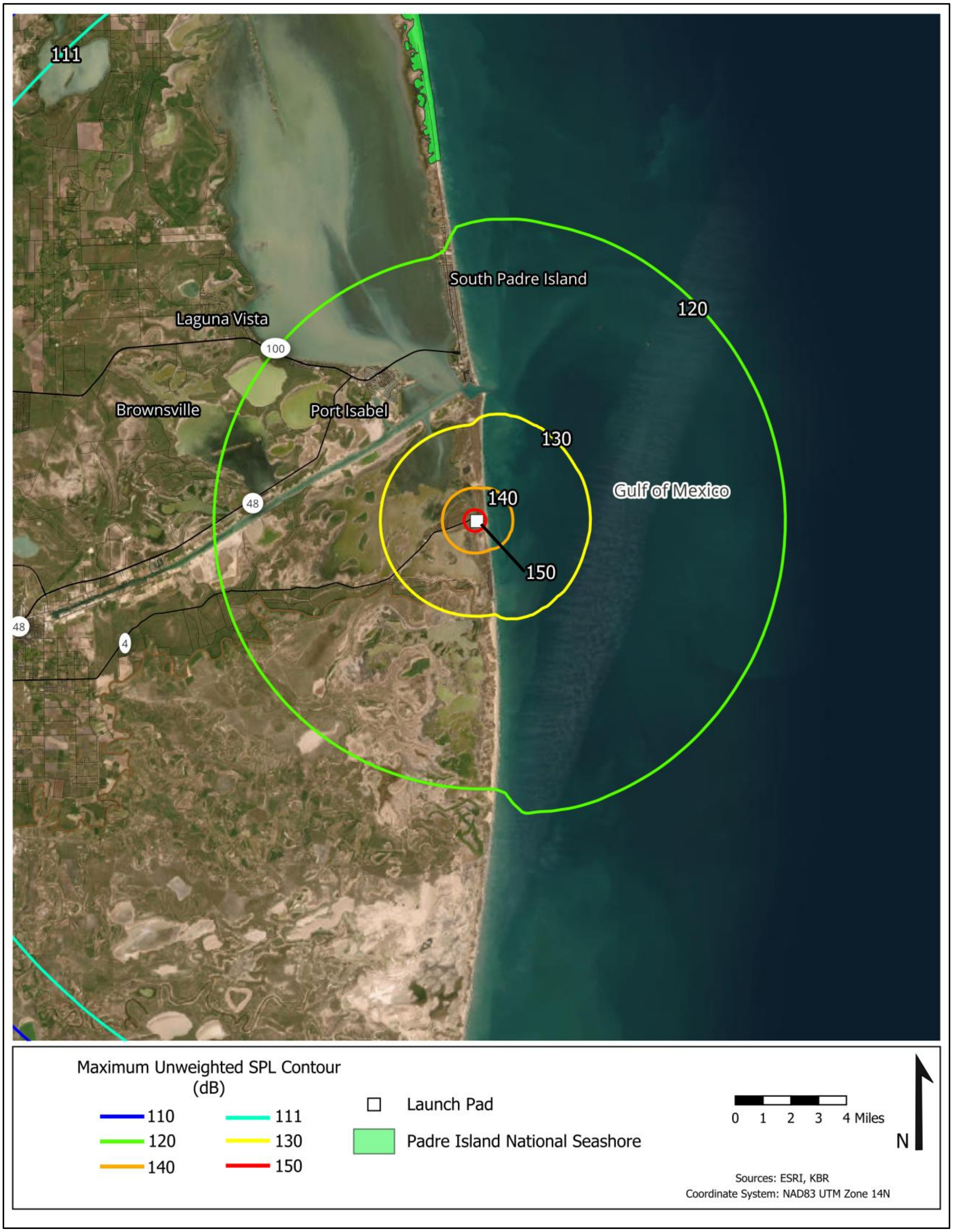

Figure 8. Starship Orbital Launch from Starbase: Maximum Unweighted Sound Levels (Zoom In)

4 Descent/Landing Noise Levels

4.1 Starship Landings at Starbase

RNOISE was used to estimate the L_{Amax}, SEL, and L_{max} contours for a Starship landing at the Starbase landing site. The Starship descent/landing trajectory was provided by SpaceX in file 'Starship_Boca_Chica_Landing_80_12.ASC' with uprated total maximum thrust of about 1.19 MM lbf.

RNOISE computations were performed as noted previously in Section 3. The L_{Amax}, SEL, and L_{max} contours for a Starship landing at Starbase are shown in Figures 9 through 11, respectively (using a zoomed in map scale). In Figure 9 the 90 dB L_{Amax} contour is about 6 miles from the Starbase landing site. Residents of Port Isabel may hear Starship landing events above 60 dB, particularly nighttime landings. The 115 dB L_{Amax} contour, which is used as a conservative limit for hearing conservation, is located approximately 1 mile from the landing pad.

The 134 dB L_{max} contour used to assess the potential for structural damage, located between the 130 dB and 140 dB contours in Figure 11, is approximately 0.5 miles from the landing pad and within Starbase property.

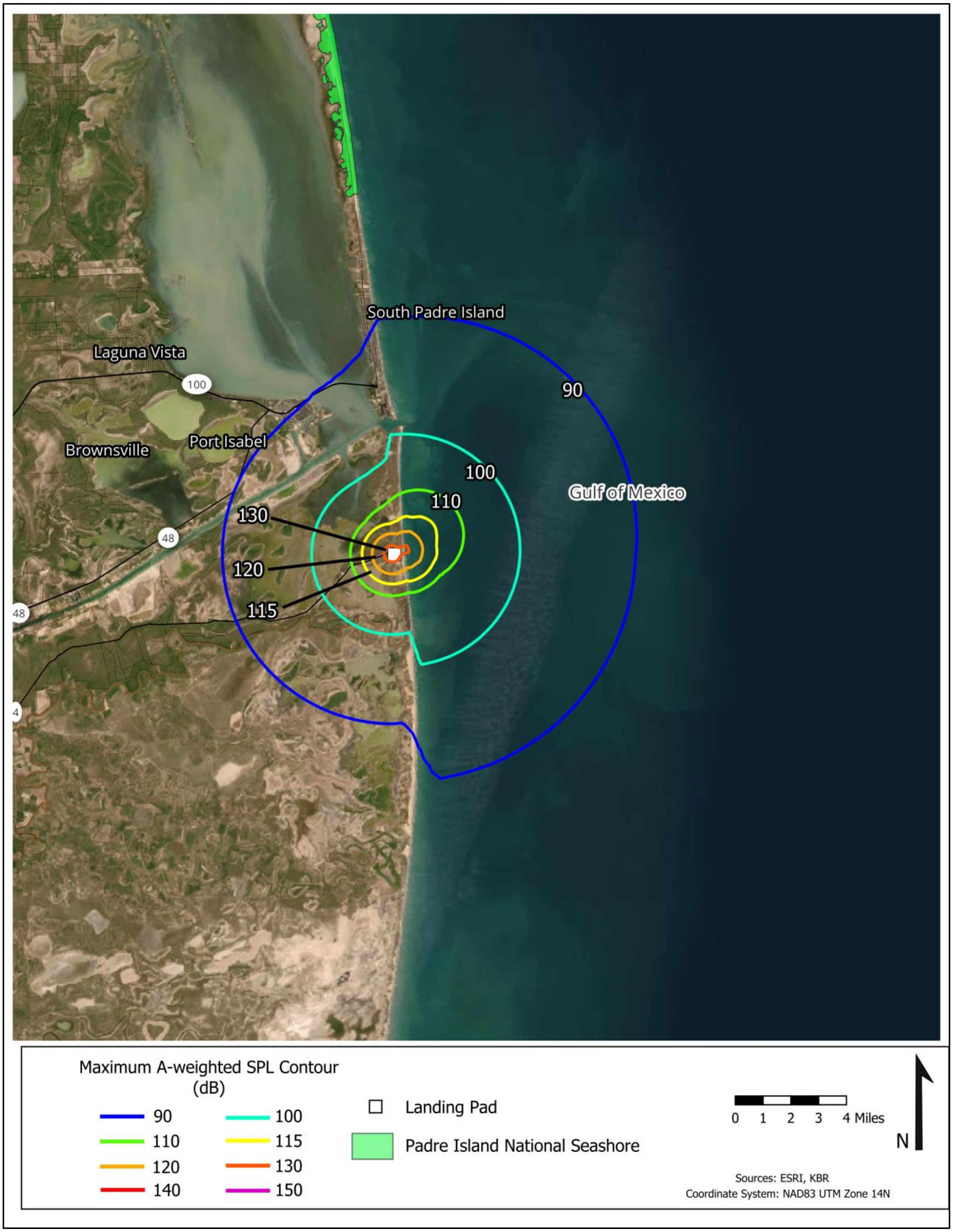

Figure 9. Starship Landing at Starbase: Maximum A-Weighted Sound Levels

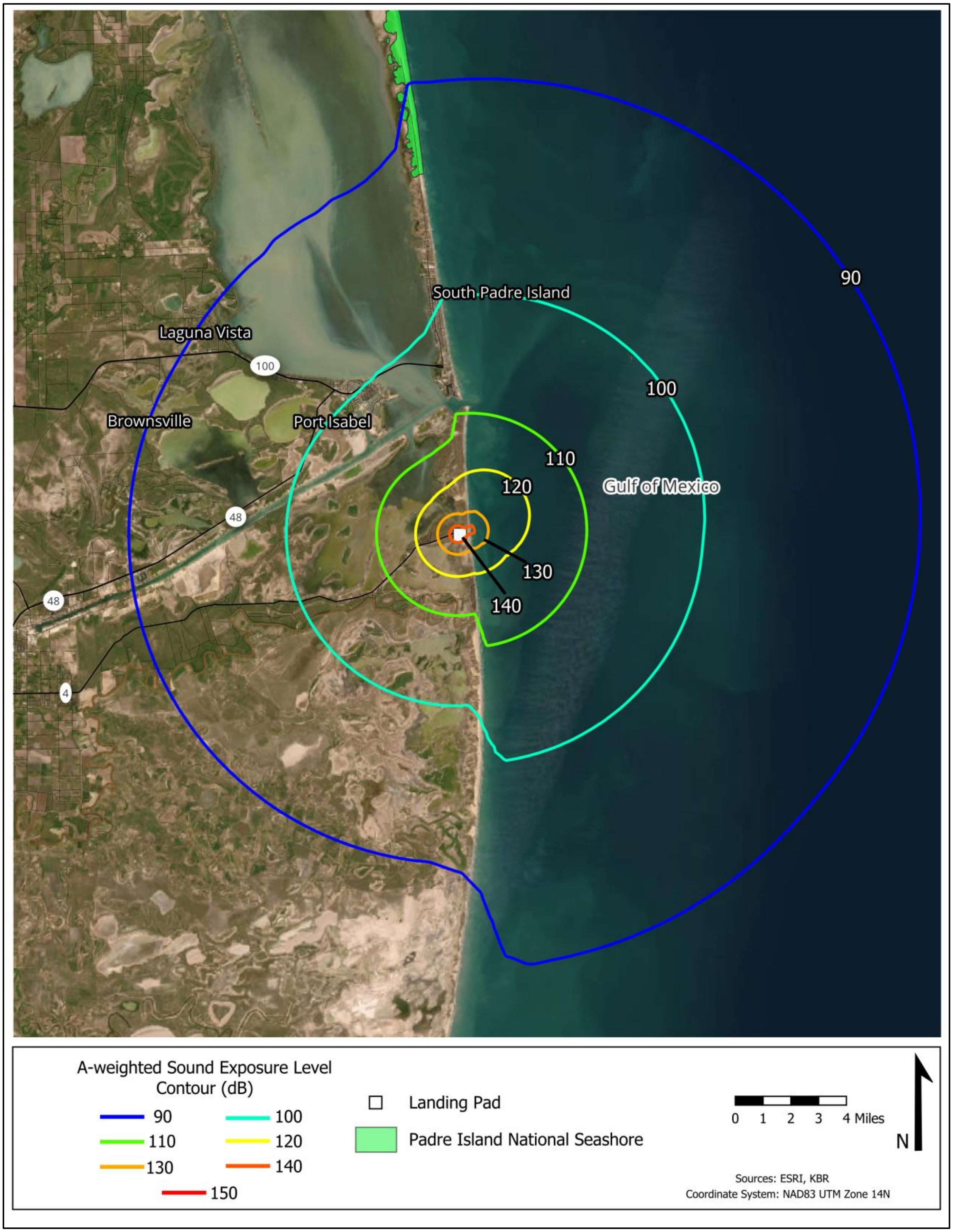

Figure 10. Starship Landing at Starbase: Sound Exposure Levels

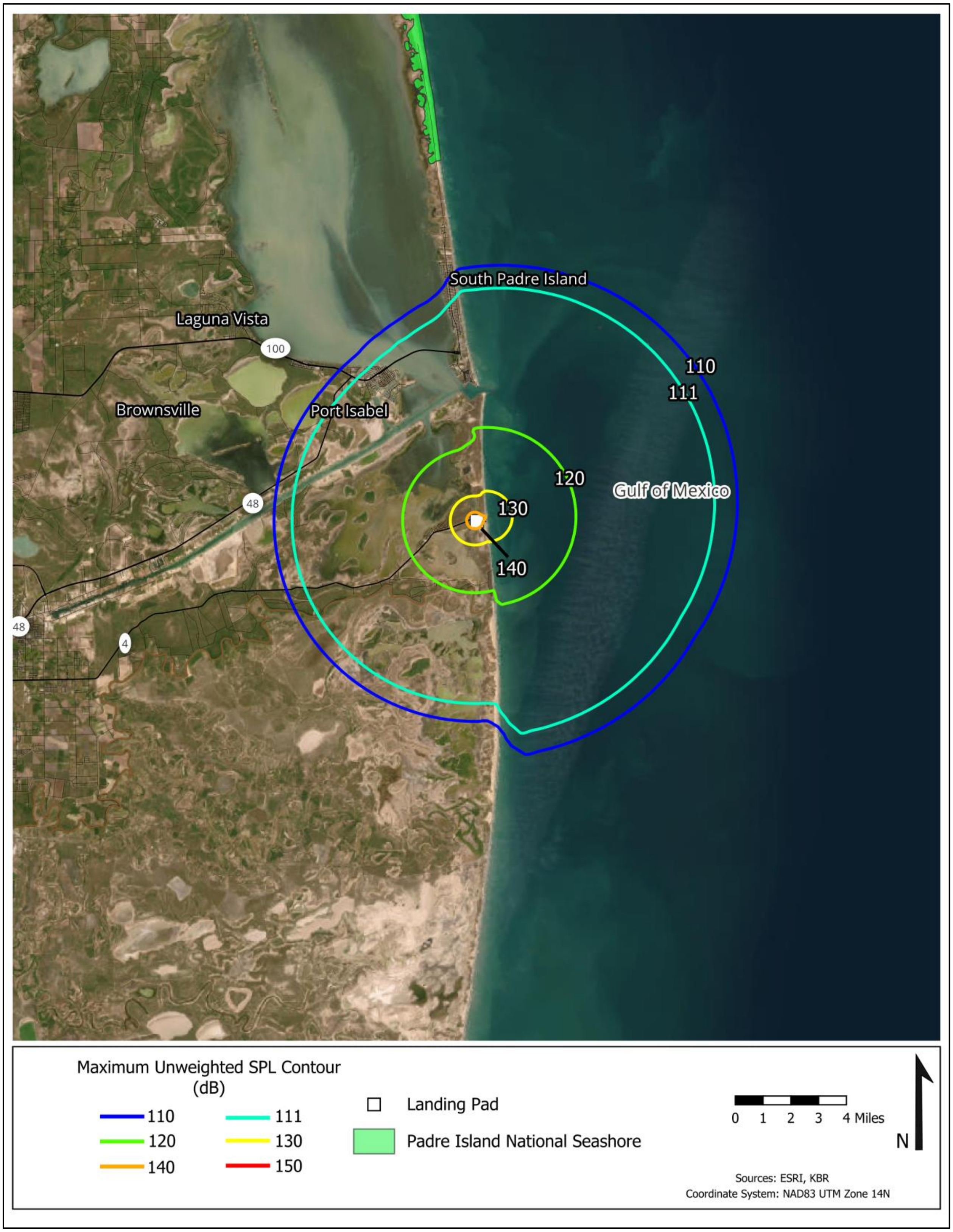

Figure 11. Starship Landing at Starbase: Maximum Unweighted Sound Levels

4.2 Super Heavy Booster Landings at Starbase

RNOISE was used to estimate the L_{Amax}, SEL, and L_{max} contours for a Super Heavy Booster landing at the Starbase landing site. The Super Heavy Booster descent/landing trajectory was provided by SpaceX in file 'Super_Heavy_Boca_RTLS_ROTATED_80_12.ASC' with uprated maximum thrust of about 3.31 MM lbf (5 engines x 2.94 MN per engine).

RNOISE computations were performed as noted previously in Section 3. The L_{Amax}, SEL, and L_{max} contours for a Super Heavy Booster landing at Starbase are shown in Figures 12 through 14, respectively (using a zoomed in map scale). In Figure 12 the 90 dB L_{Amax} contour is about 8 miles from the Starbase landing site. Residents of Port Isabel and eastern Brownsville may hear booster landing events above 60 dB, particularly nighttime landings. The 115 dB L_{Amax} contour, which is used as a conservative limit for hearing conservation, is located approximately 1.5 miles from the landing pad.

The 134 dB L_{max} contour used to assess the potential for structural damage, located between the 130 dB and 140 dB contours in Figure 14, is less than 1 mile from the landing pad and within Starbase property.

Section 5 presents the estimated noise levels for Starship and Super Heavy Booster static fire tests to be conducted at Starbase.

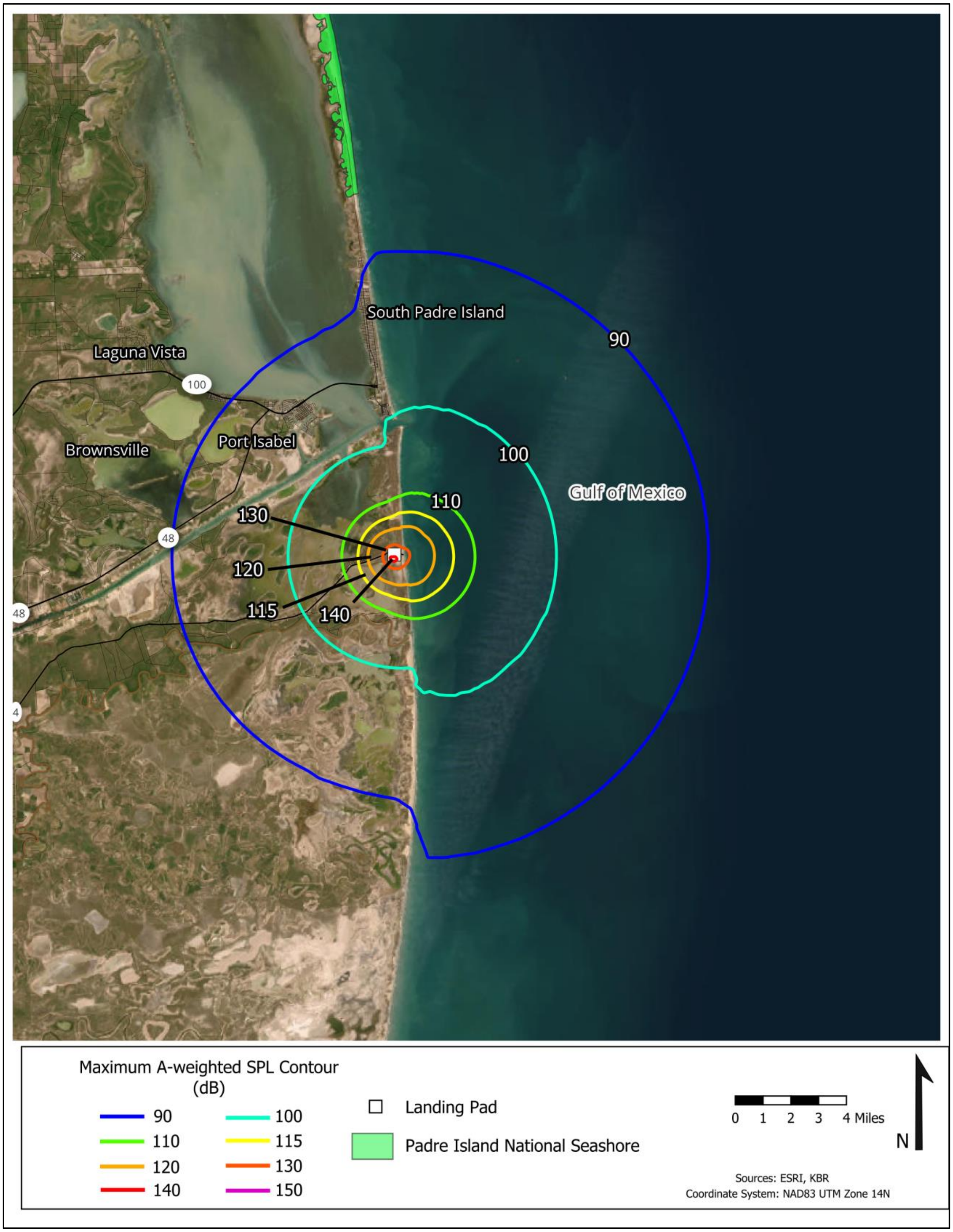

Figure 12. Super Heavy Booster Landing at Starbase: Maximum A-Weighted Sound Levels

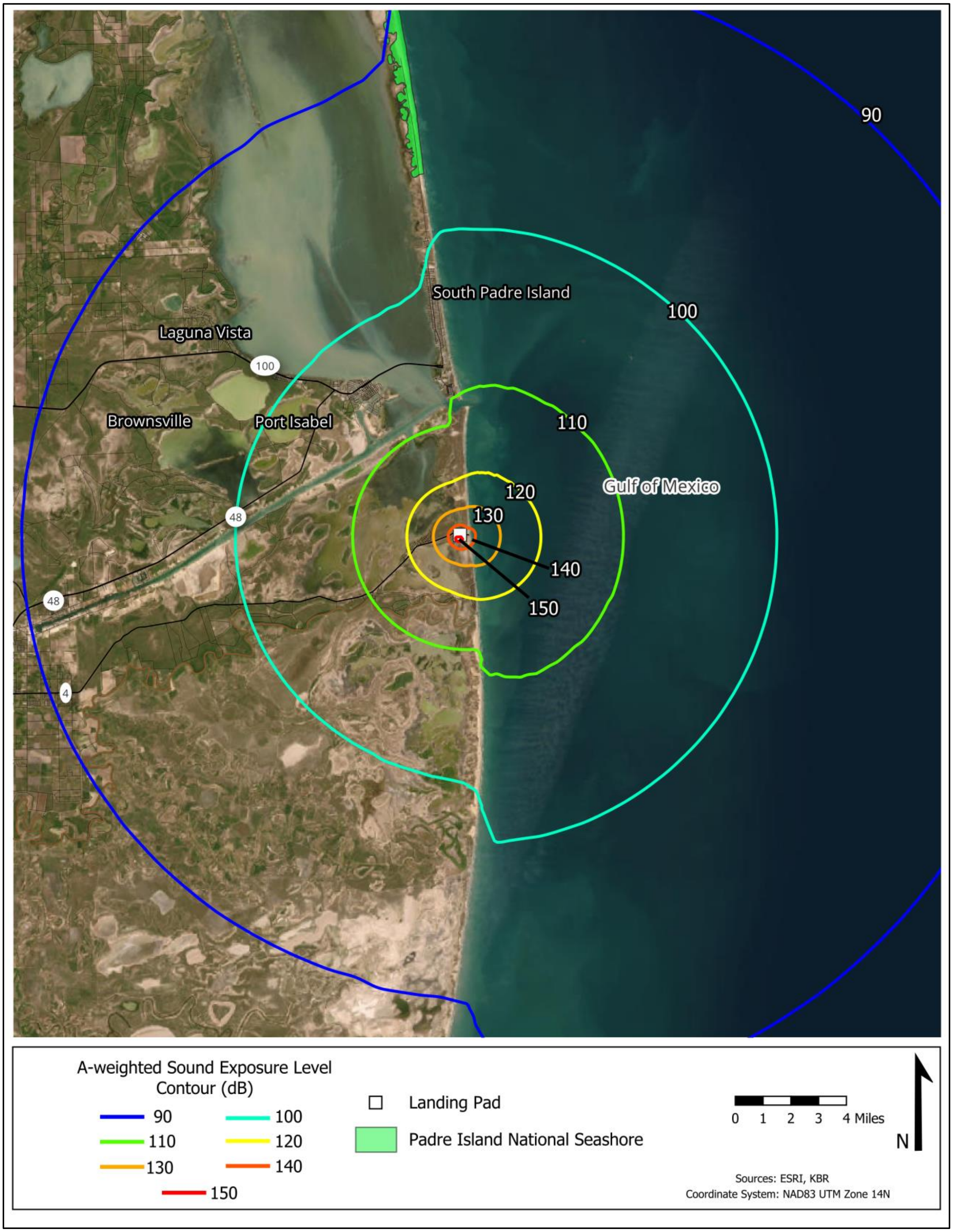

Figure 13. Super Heavy Booster Landing at Starbase: Sound Exposure Levels

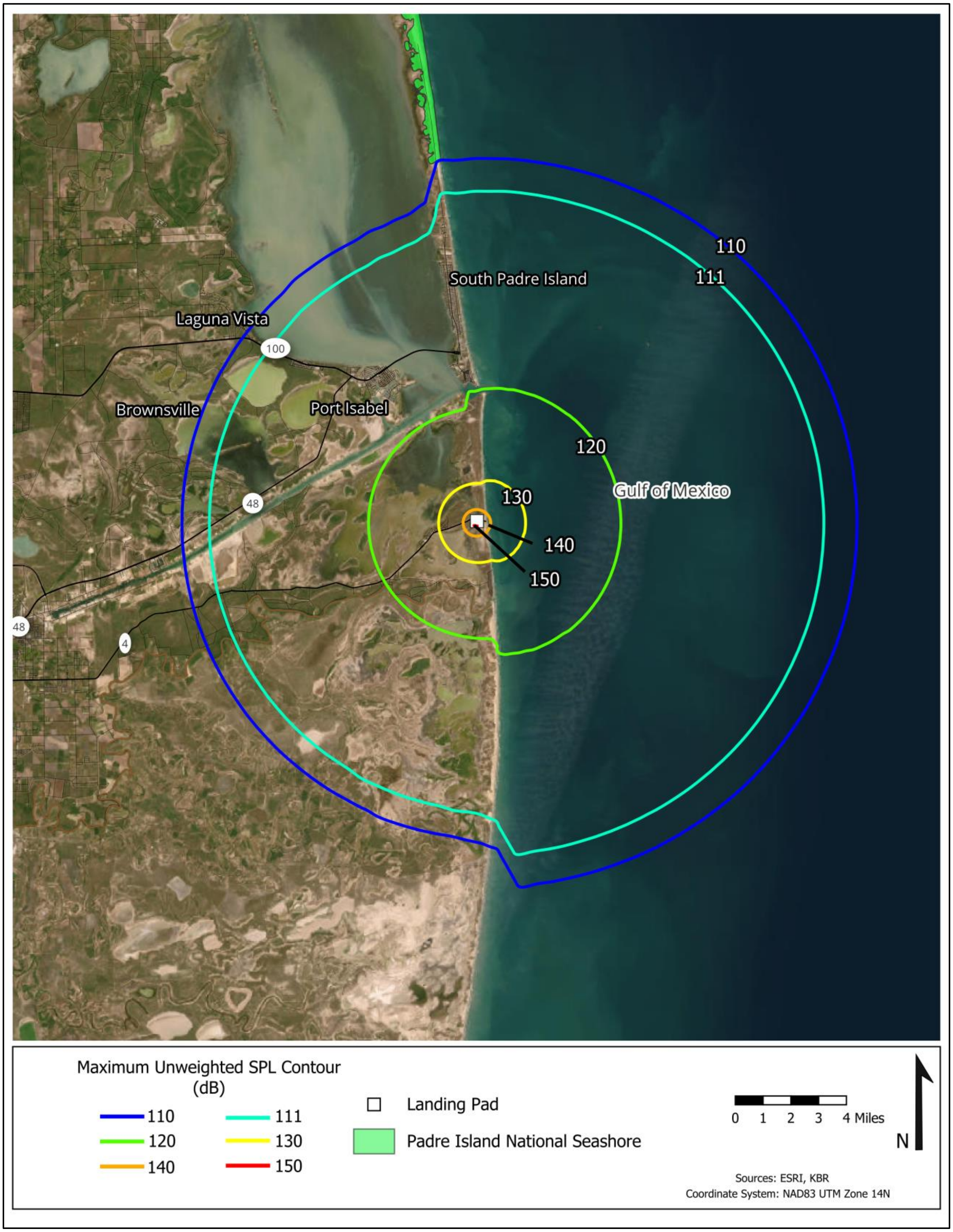

Figure 14. Super Heavy Booster Landing at Starbase: Maximum Unweighted Sound Levels

5 Static Fire Test Noise Levels

5.1 Ship Static Fire Tests at Starbase

Starship static fire tests are planned to occur at Starbase where nine engines, that each generate 3.19 MN of thrust at sea level, will be fired 6 times annually for 15 seconds per test event (average duration). RNOISE computations were performed as noted previously in Section 3. The L_{Amax}, SEL, and L_{max} contours for a Starship static fire test at Starbase are shown in Figures 15 through 17, respectively (using a zoomed in map scale).

The L_{Amax} 90 dB contour in Figure 15 extends about 3 miles west of the test site. Residents of Port Isabel may hear Starship static test events above 60 dB, and particularly if onshore wind conditions favor sound propagation to the west. The 115 dB L_{Amax} contour, which is used as a conservative limit for hearing conservation, is located approximately 1 mile from the static test site.

The 134 dB L_{max} contour used to assess the potential for structural damage, located between the 130 dB and 140 dB contours in Figure 17, is less than 1 mile from the test site and within Starbase property.

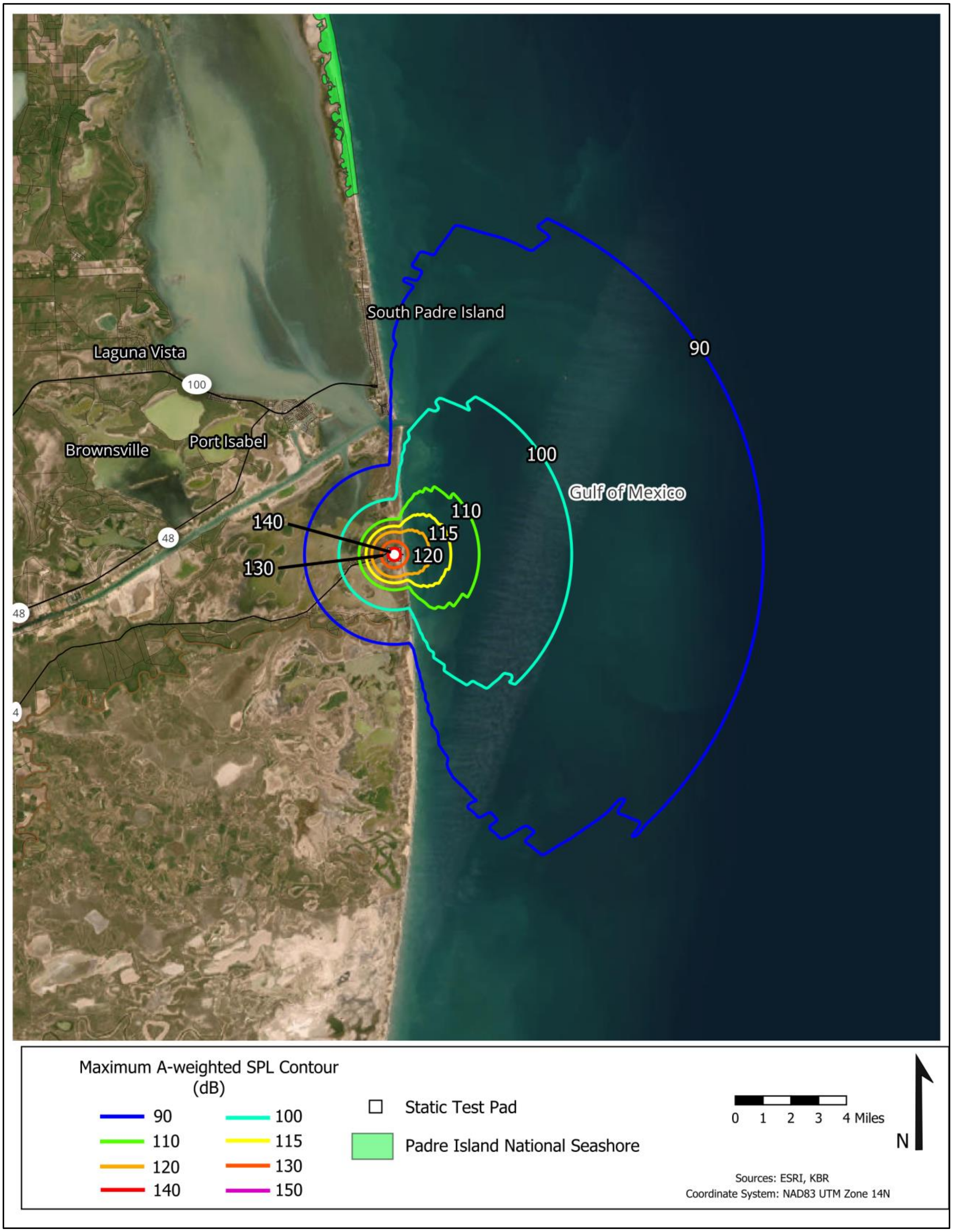

Figure 15. Starship Static Fire Test at Starbase: Maximum A-Weighted Sound Levels

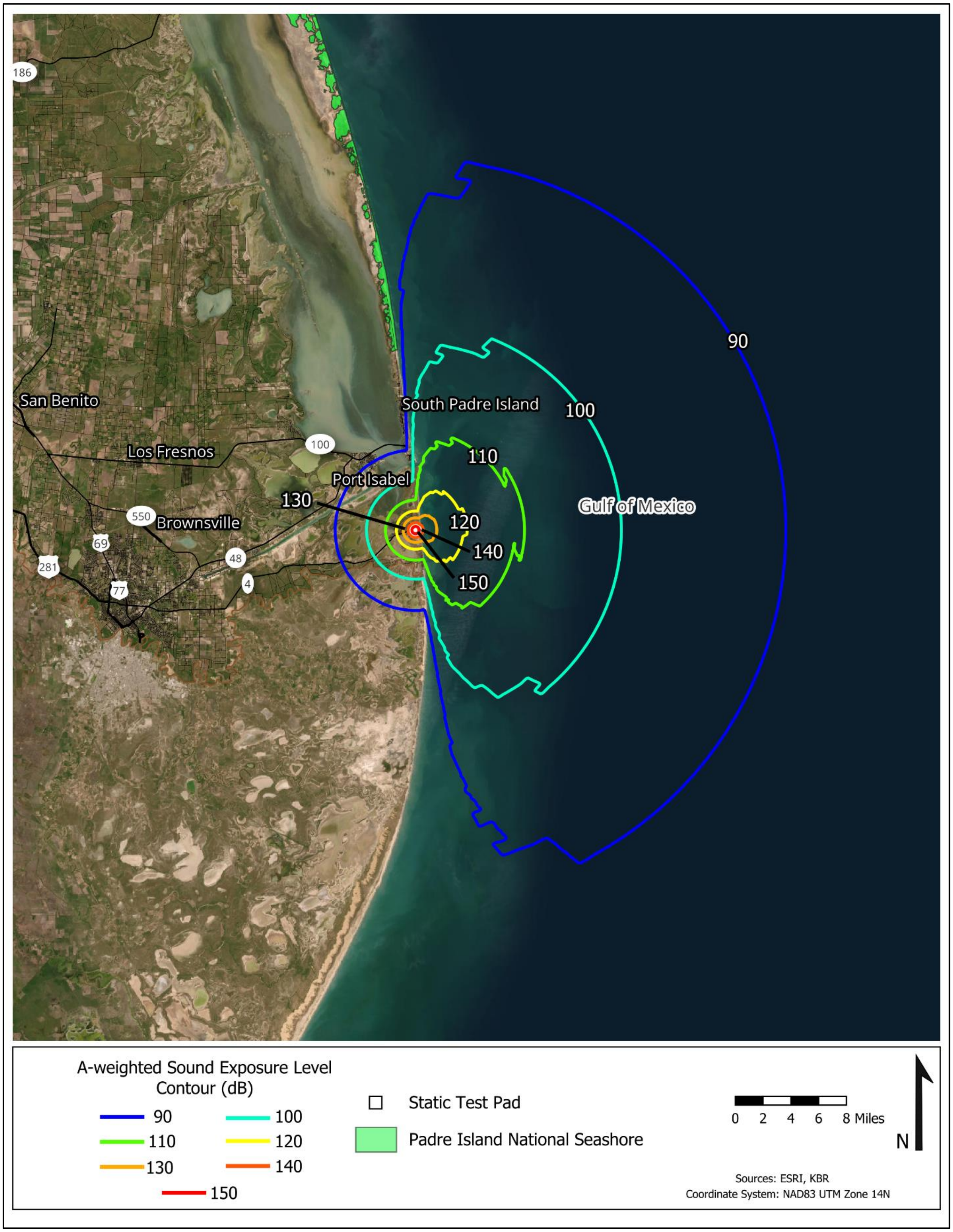

Figure 16. Starship Static Fire Test at Starbase: Sound Exposure Levels

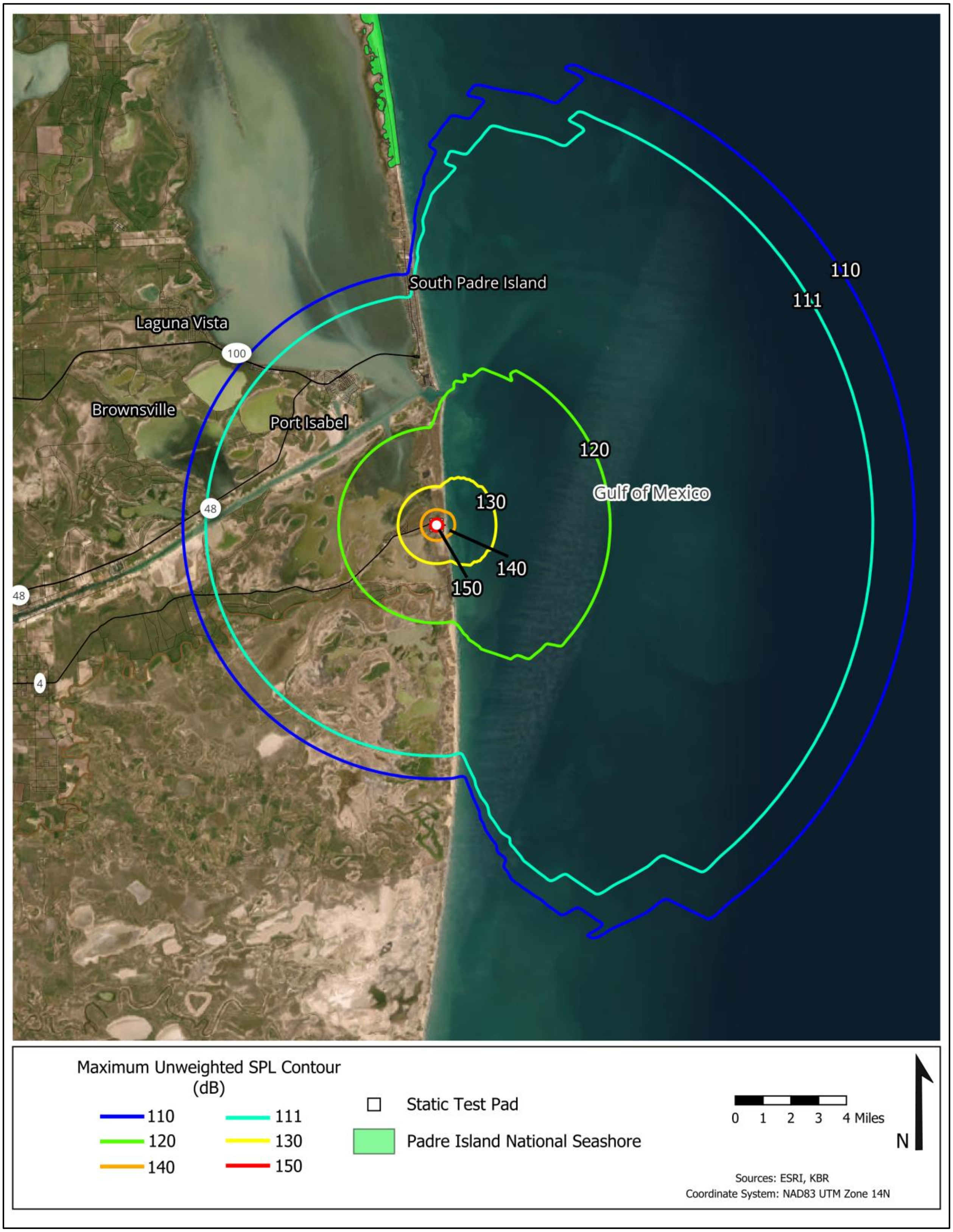

Figure 17. Starship Static Fire Test at Starbase: Maximum Unweighted Sound Levels

5.2 Super Heavy Booster Static Fire Tests at Starbase

Super Heavy Booster static fire tests are planned to occur at Starbase where thirty-five engines, that each generate 2.94 MN of thrust at sea level, will be fired 5 times annually for 15 seconds per test event (average duration). RNOISE computations were performed as noted previously in Section 3. The L_{Amax}, SEL, and L_{max} contours for a booster static fire test at Starbase are shown in Figures 18 through 20, respectively.

The L_{Amax} 90 dB contour in Figure 18 extends about 4 miles west of the test site. Residents of Port Isabel may hear booster static test events above 60 dB, and particularly at night and if onshore wind conditions favor sound propagation to the west. The 115 dB L_{Amax} contour, which is used as a conservative limit for hearing conservation, is located approximately 1.2 miles from the static test site.

The 134 dB L_{max} contour used to assess the potential for structural damage, located between the 130 dB and 140 dB contours in Figure 20, is approximately 1.5 miles from the test site and within Starbase property.

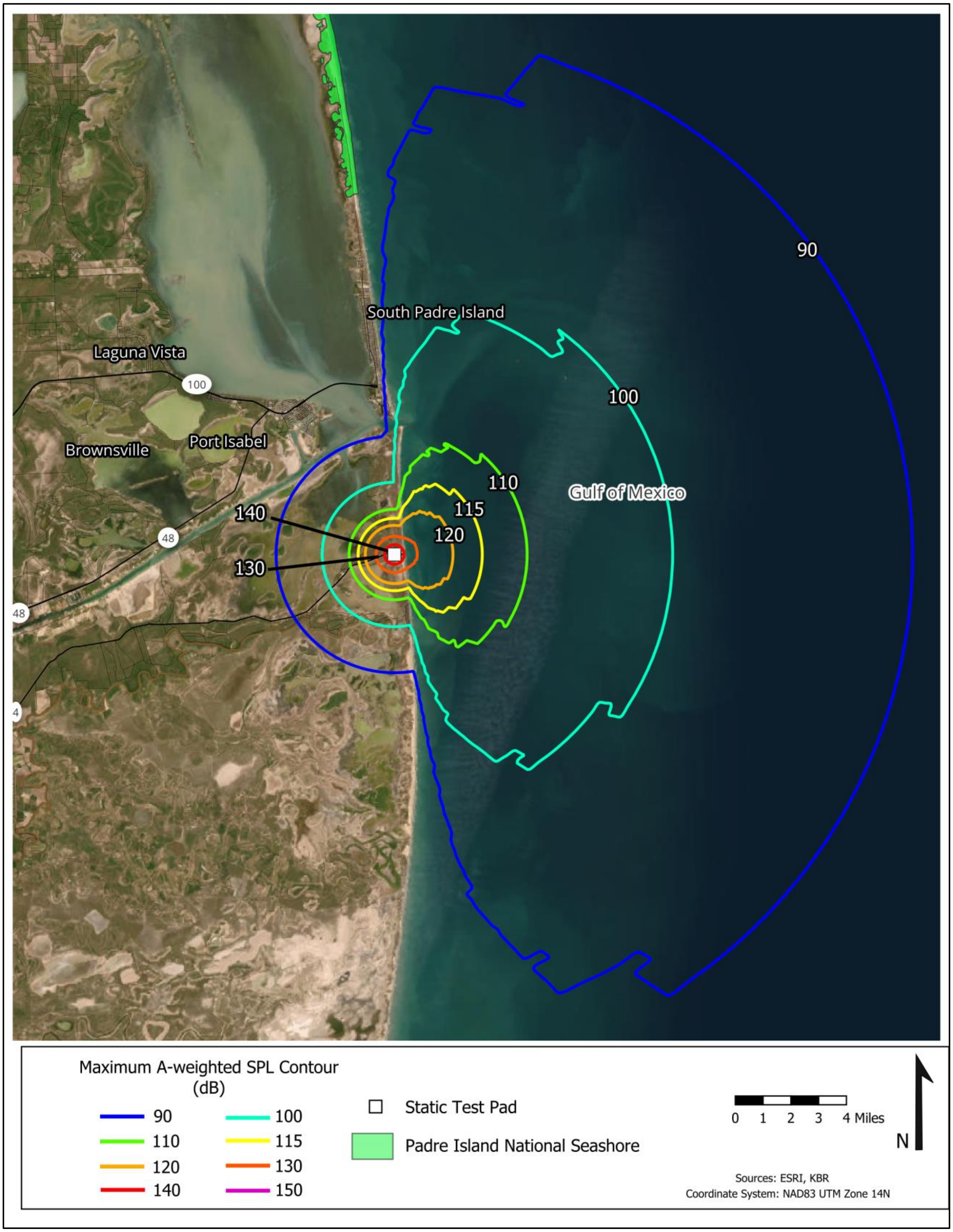

Figure 18. Super Heavy Booster Static Fire Test at Starbase: Maximum A-Weighted Sound Levels

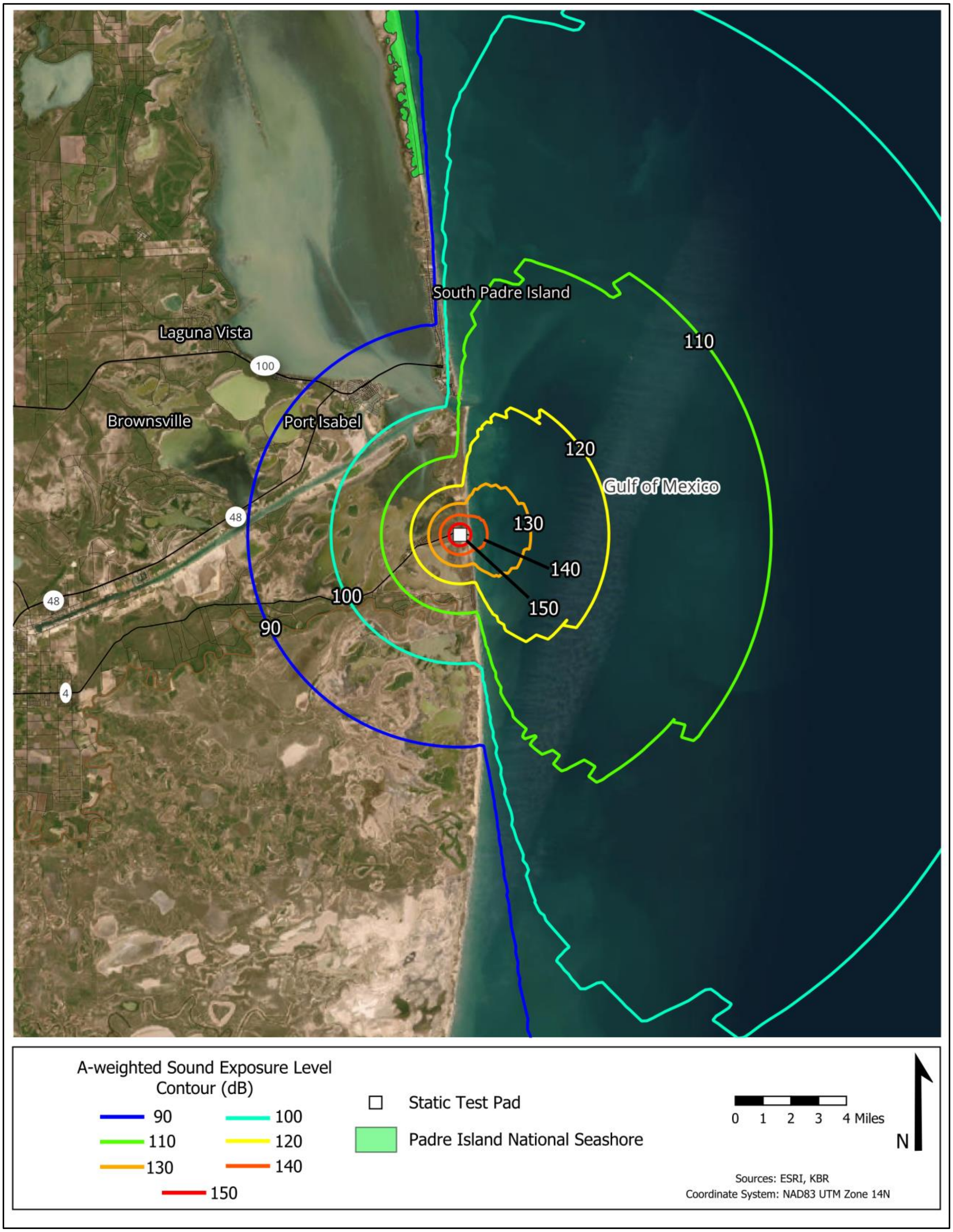

Figure 19. Super Heavy Booster Static Fire Test at Starbase: Sound Exposure Levels

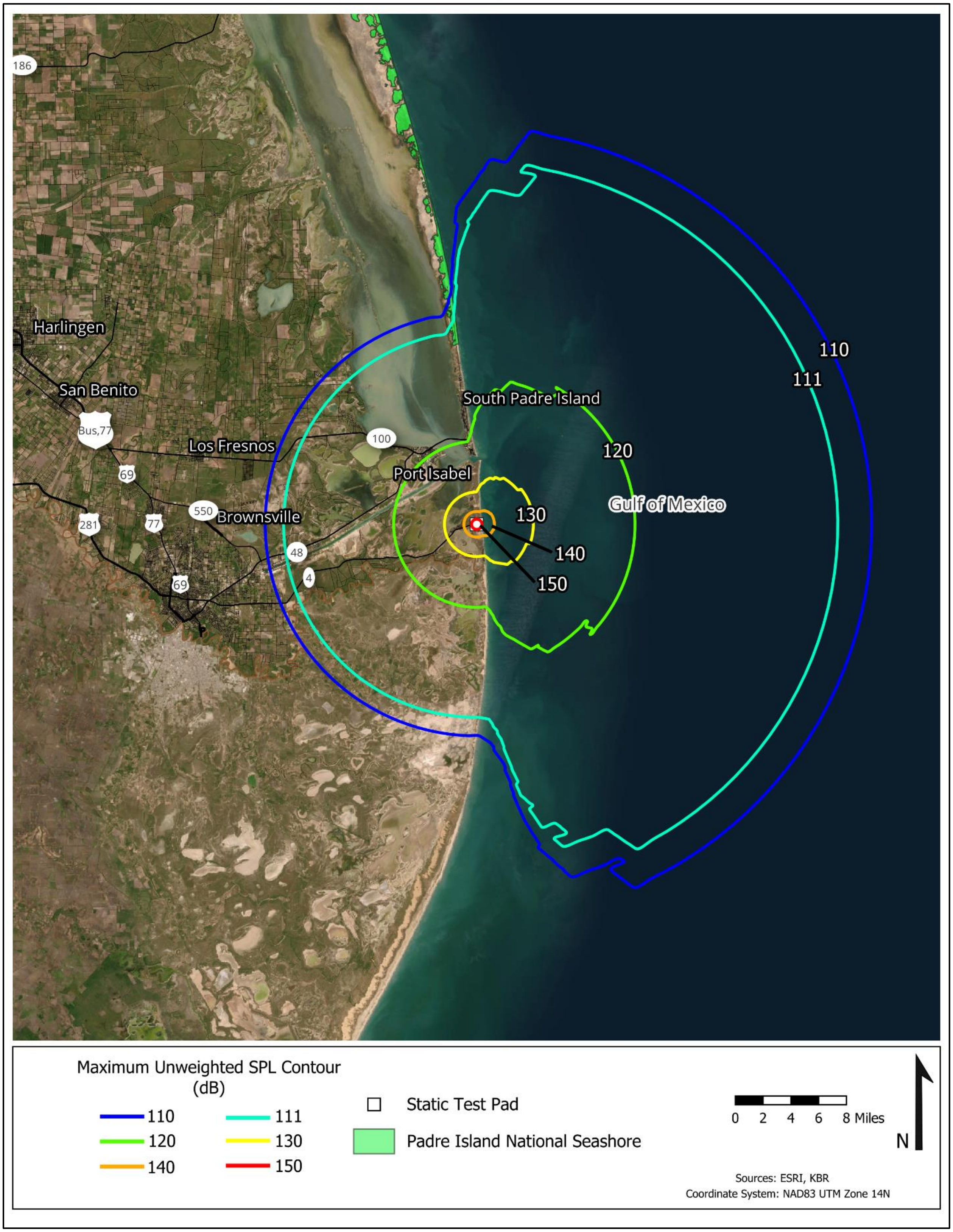

Figure 20. Super Heavy Booster Static Fire Test at Starbase: Maximum Unweighted Sound Levels

6 Cumulative Noise Levels for Projected Starship Flight and Test Operations

6.1 Projected Launch, Landing, and Static Fire Tests at Starbase

Cumulative noise levels were estimated for a future projected operations scenario involving twenty-five launches and landings of both vehicles plus additional static fire tests of both vehicles at Starbase as follows:

(25) Annual Operations Scenario

- 25 Starship and Booster orbital launches (22 daytime / 3 Nighttime)
- 25 Super Heavy Booster landings (22 daytime / 3 Nighttime offshore)
- 25 Starship landings (22 daytime / 3 Nighttime offshore)
- 5 Super Heavy Booster static fire tests (5 daytime / 0 Nighttime)
- 6 Starship static fire tests (6 daytime / 0 Nighttime)

The DNL contours shown in Figure 21 are a cumulative noise estimate for these projected annual operations at Starbase. These operations include 22 daytime launches and landings of both vehicles and up to 3 nighttime launches and offshore landings plus the static fire tests of both vehicles. Note that the 3 nighttime launches from Starbase were included in the DNL estimate, whereas the nighttime landings that would occur at an offshore landing site were not included in the DNL estimate. Overland, the DNL 65 contour extends approximately 3 to 3.5 miles from Starbase to the north, west and south, in unpopulated areas. This projected operations scenario is expected to fulfill mission and test requirements for the Starship without causing adverse noise exposure in any of the communities near Starbase.

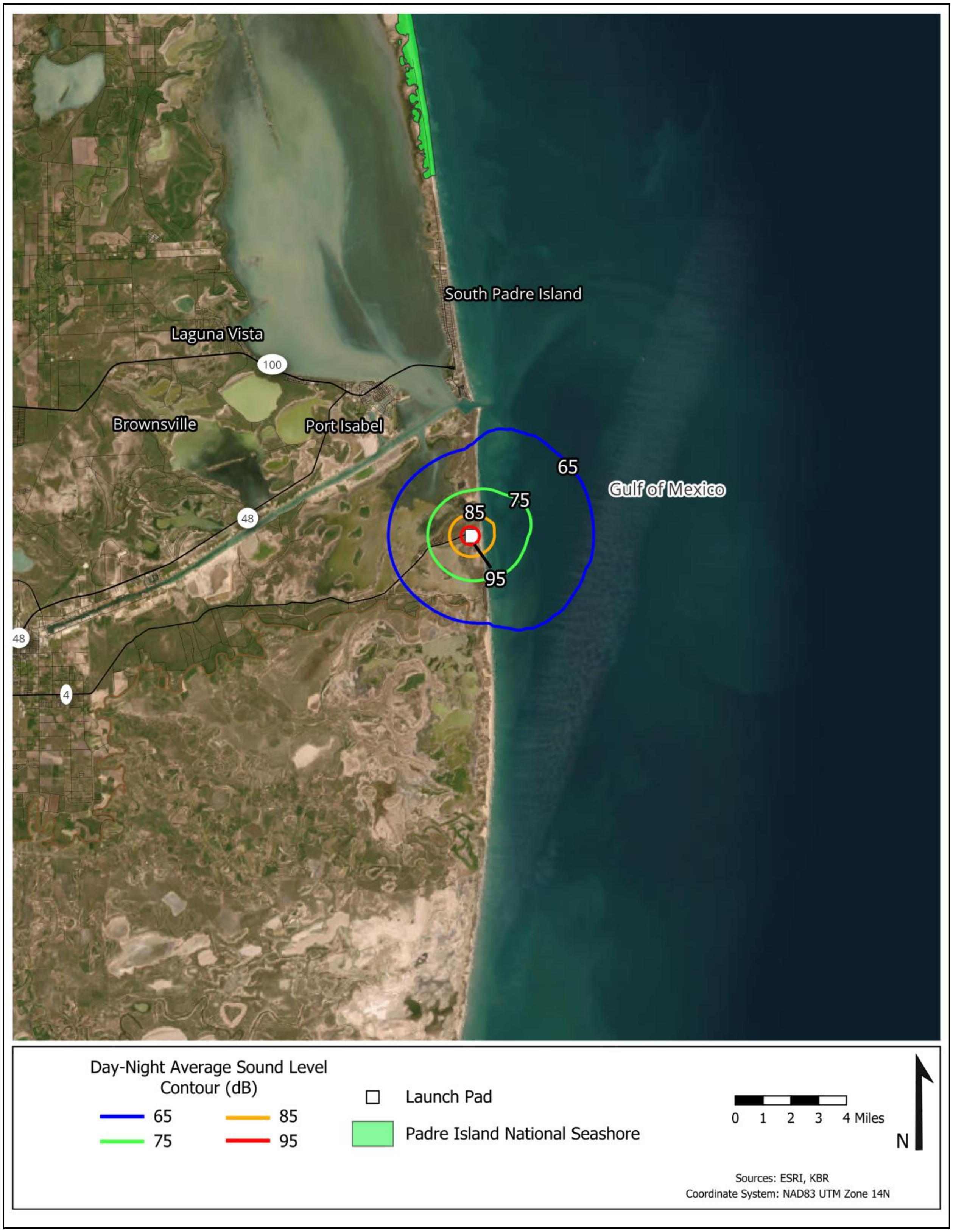

Figure 21. Starship and Booster 25 Annual Operations Scenario: DNL Contours

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MEMORANDUM **September 6, 2024**

TO: Federal Aviation Administration, Office of Commercial Space Transportation

FROM: Space Exploration Technologies

SUBJECT: Sonic Boom Analysis

Space Exploration Technologies (SpaceX) is proposing to launch its Starship/Super Heavy launch vehicle from the SpaceX Boca Chica Launch Site. Each Starship/Super Heavy launch would include a boost-back and immediate landing of the first stage Super Heavy booster and a landing of the second stage Starship. Super Heavy and Starship would each land vertically on the pad.

A tiered Environmental Assessment (EA) is being prepared for the Proposed Action. The EA is being prepared in accordance with the National Environmental Policy Act (NEPA) of 1969, as amended (42 U.S.C. 4321 et seq.), Council on Environmental Quality NEPA-implementing regulations (40 CFR Parts 1500 to 1508), and FAA Order 1050.1F, Environmental Impacts: *Policies and Procedures*. SpaceX is proposing to increase the cadence of the Starship/Super Heavy launch program at the Boca Chica vertical launch area in Cameron County, Texas to up to 25 annual launches and 50 total annual landings (25 of the Starship and 25 of the Super Heavy), and make vehicle and operational upgrades (see Section 2.1 of the EA). Of the 25 annual launches, up to 3 launches would occur during night-time hours (defined as 7:00 pm to 7:00 am), however the 3 nighttime landings would occur offshore. There would be up to 22 daytime only landings of Super Heavy and up to 22 daytime only landings of Starship at the Vertical Launch Area. In accordance with FAA Order 1050.1F, if a project involves commercial space launch vehicles reaching supersonic speeds, the potential for sonic boom impacts should be discussed. A sonic boom is the sound associated with the shock waves created by a vehicle traveling through the air faster than the speed of sound. A sonic boom trace is an impulsive event that lasts for less than 300 milliseconds. A sonic boom is generated during vehicle ascent, but it would not impact land areas. A sonic boom would also be generated during orbital Starship/Super Heavy launches and Starship and Super Heavy landings as the vehicle approaches the landing location. SpaceX used PCBOOM to estimate single event sonic boom levels during Starship and Super Heavy descent. Sonic boom modeling contours are approximate and actual exposure at any particular location or time during a sonic boom event can vary depending on a number of different atmospheric, physical, and operational parameters.

Assumed Operations and Vehicle Definition

For all operations included in the increased launch cadence assessment, a "return to launch site" (RTLS) trajectory is assumed, where both stages return to the Boca Chica launch site. As a result, the sonic boom generation on ground and populated areas is maximized, since offshore landings for the first stage strictly reduce the sonic boom footprint on land and offshore landings for the second stage will not be conducted with overflight regions that produce sonic booms over South Texas.

The Super Heavy (first stage) reenters the atmosphere from a moderate altitude (approximately 100 km) with a steep flight path angle, oriented engines first, and with a shallow pitch, oriented roughly 25 degrees from vertical during the supersonic portion of flight. The reentry trajectory is shown in Figure 1. This trajectory is similar to the Falcon first stage booster approach and produces a sonic boom that can make landfall from flight conditions ranging from Mach 1 to Mach 4. The contours of constant sonic boom overpressure magnitude that intersect with land tend to form nearly concentric circles or ellipses because of this steep, targeted descent.

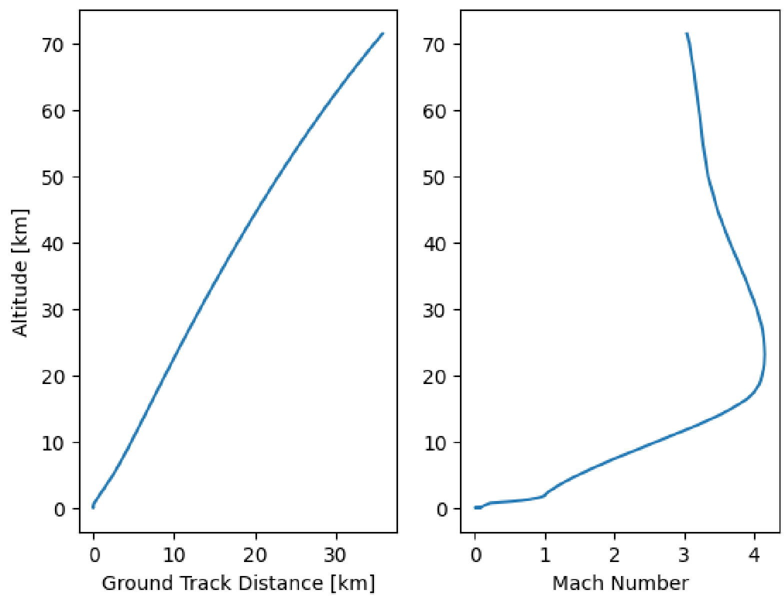

Figure 1: A nominal return trajectory for first stage

The Starship (second stage) reenters the atmosphere from orbital velocity and altitudes with a shallow flight path angle until subsonic speeds, oriented with a large cross-sectional area exposed to the flow – a high vehicle pitch. This is similar to the reentry of the STS Orbiter Shuttle, with the distinction of a transition to a much steeper flight path angle in the subsonic regime with during which there is little modulation of crossrange or downrange ground track. The net result of this flight plan is the potential for a "carpet" of perceptible sonic booms along the ground track in supersonic flight depending on the trajectory's altitude. The final portion of descent may also produce sonic booms that intersect with the ground past the landing site given the pointing and velocity vector of the vehicle.

The assumed heading for return of the first stage is 268-345 degrees clockwise from north. While flight trajectories may vary the return inclination in the future, this has limited impact on the sonic boom levels experienced by most communities surrounding Boca Chica. Due to the steep flight path angle of the first stage reentry, the sonic boom footprint consists of nearly concentric circles. Within 10 kilometers of the landing site, more asymmetry is produced by trajectory heading than by the prevailing wind speed. Non-concentric sonic boom footprints are expected at lower magnitudes (below 3 psf) and reach the longest distances from the landing site in a direction normal to the ground track. As a result, a steeper inclination RTLS trajectory maximizes the area of Brownsville that is exposed to at least 2 psf sonic booms in the model results presented for this EA.

The assumed heading for return of the second stage ranges from 22-158 degrees clockwise from north, both ascending and descending ground tracks. This variation has the effect of creating many over-land regions that could be exposed to sonic booms around the vehicle's ground track. A singular case for 68 degrees approach heading is shown, and a secondary illustration sweeping the potential sonic boom magnitudes in a continuous arc through 22-158 degrees is also shown. The secondary illustration is non-physical of any single RTLS trajectory of the second stage.

Sonic Boom Modeling Approach

SpaceX has derived initial predictions for sonic boom magnitudes and contours during return of both stages of the Starship/Super Heavy launch vehicle using the industry standard PCBoom software. Primary inputs used with PCBoom are the planned flight trajectories for return to land, a shape factor of each stage (including variation with vehicle pitch where significant), and each stage's length and weight. PCBoom was run utilizing the Carlson mode of calculation, with a simple N-wave shaped, F-function for originating shock waves from the supersonic flight of the vehicle. The provided sonic boom contours are augmented where past experience suggests deficiencies with the PCBoom v6.6 prediction capability, primarily the extent of ground track carpet produced by the reentering second stage.

While a simplified version of near-field shock strength is used in the Carlson mode, PCBoom completes a ray tracing propagation solution for intersection of the generated shock front with sea level. For this to be accurate, data for wind velocity, temperature, static pressure, and humidity as it varies by altitude must be provided. Of these, the sonic boom magnitudes on land are most significantly affected by wind velocities. Historical wind data is available from Global Forecasting System past predictions and some limited weather balloon data. A single, consistent wind profile vs altitude based on median Brownsville winds is assumed for the entire region. It should be noted that significant variation can be expected in the prevailing winds on seasonal to daily timescales, which could alter the intensity of the sonic boom at different locations. The extreme and average winds are shown in Figure 2. The temperature profile used is a representative profile collected immediately before Flight Test 4 of Starship/Super Heavy, which is generally more representative of the subtropical oceanic climate of south Texas than the "Standard Atmosphere". A constant humidity of 80% is assumed.

For the first stage vehicle, SpaceX estimated a shape factor of $K_s = 0.154$ based on the NASA-1122 sonic boom reference and methodology and validated this value with measurements collected from buoys during Flight Test 4. This shape factor estimation was derived over a range of vehicle pitch angles during reentry, consistent with the vehicle's planned future flight profiles. A bounding vehicle length of 80 meters is assumed.

For the second stage vehicle, SpaceX estimated a shape factor of $K_s = 0.3$ based on the NASA-1122 sonic boom reference and methodology. This shape factor estimation was derived over a range of angles of attack, consistent with the vehicle's planned future flight profiles. A bounding vehicle length of 70 meters is assumed. Because second stage boom contours on ground are expected to be wide and have more variability from choice of approach heading, a zero-wind profile is used in prediction of the second stage sonic booms on ground.

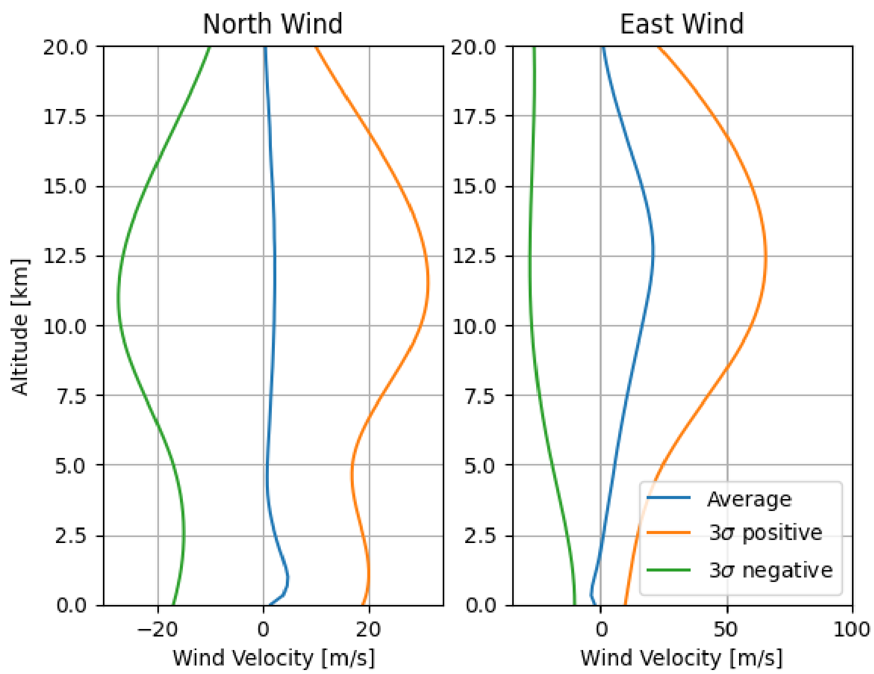

Figure 2: Wind speed averages and extrema used in each cardinal direction. Positive valued velocity is blowing toward the title direction

Secondary, or "over the top", sonic booms are not predicted in this set of nominal environmental assessment results. Certain combinations of temperature profiles versus altitude and winds aloft could produce sufficient atmospheric refraction that sonic booms could be heard at further distances than presented here. The resulting sonic booms would be weak in magnitude and expected to only be heard by those listening for it, or in particularly low noise floor environments – below levels of significance.

<u>Sonic Boom Overpressure Interpretation and Thresholds</u>

A vehicle traveling supersonic, or faster than the local speed of sound, produces a shock wave field around the vehicle. This shock wave propagates away from the vehicle and can intersect with the ground. The sonic boom sensed on the ground or by an observer is characterized by its overpressure magnitude, or the peak pressure caused by the shock front's arrival. This peak pressure is most often measured and quoted in terms of pounds per square foot, or psf. Acceptable levels of sonic boom exposure are not well standardized, in large part because audible levels and general annoyance associated with high exposure frequency are well below overpressures that are likely to cause damage. There are no defined thresholds for human annoyance, and annoyance is likely to increase with loudness of the booms. Additionally, surveys of residents have found that startle, rattle, and vibrations and the possibility of damage to be the most disturbing aspects of sonic booms (Maglieri et al. 2014). Direct human health and safety is not at risk, with evidence of human exposure in tests up to 144 psf with no adverse consequences (Benson 2013, Maglieri et al. 2014, Nixon 1968, Maglieri 1966). A study of the long-term effects of exposures to sonic booms from supersonic military flight operations on human health conducted on residents of Nevada between 1969 to 1983 found no convincing evidence to prove the existence of adverse health effects due to sonic booms (Sutherland and Plotkin 1986, Anton-Guirdis et al. 1986). A set of literature references for both auditory and damage likelihood thresholds is provided here, and a discussion of threshold levels that SpaceX proposes using to assess the areas of exposure. Different sources provide varying guidance or results for what overpressure magnitudes induce structural damage or what the typical community response is to sonic boom exposure.

Sonic booms of 0.5 psf and higher are expected to be generally audible, with booms of lower magnitude requiring an expectation of arrival or a very low noise floor environment to be heard. A sonic boom overpressure of at least 1.0 psf is even more certain to be noticed and is used to define the action area associated with potential environmental impacts (FAA 2022). The next notable threshold of 2.0 psf is used to indicate a level which is typical for supersonic aircraft fly overs, which could be heard by communities and cause noise complaint and annoyance when experienced at high frequency exposure rates (multiple times per day)(Maglieri et al. 2014). Numerous studies have determined that no credible damage to structures or windows is expected at 2.0 psf (Fenton 2016, Benson 2013, White 1972, NOAA 2019). For sonic booms, at approximately 2 psf, there is a 1/10,000 probability of breakage for a large window, and at approximately 4 psf, there is a 1/10,000 probability of breakage for a small window (USACE 1989). The next threshold presented is 6.0 psf, where community awareness of the event, and audibility is effectively guaranteed. However, a survey of the most recent literature indicates this magnitude is still extremely unlikely to cause damage (Benson 2013, NOAA 2019). Laboratory and field testing shows that pre-damaged or poor condition windows could possibly exhibit progression of damage (e.g. pre-existing crack growth) over multiple exposures to this magnitude of boom (Higgins 1965). At 10.0 psf the likelihood of superficial (plaster, bric a brac) damage and window damage becomes more plausible but is generally still expected to be very low probability and predominantly due to poor existing conditions such as pre-cracked, pre-stressed, older and weakened, or poorly mounted windows (Benson 2013, White 1972, Fenton 2016, Maglieri et al. 2014). Finally, SpaceX presents sonic boom exposures up to 21 psf, if any exists for a proposed vehicle operation. This represents a threshold where prevailing literature indicates window breakage becomes possible for standard condition windows, though the prediction of specific window breakage still depends on size, age, orientation, surrounding structure, and other effects (NOAA 2019, Maglieri et al. 2014). The areas that would be exposed to this level are generally limited and would be evacuated during launch and when reentering vehicles may fly supersonic at the lowest altitude before landing

SpaceX Sonic Boom Results

Starship/Super Heavy Orbital Launches

A sonic boom would be generated during vehicle ascent, but it would not impact land areas.

First Stage (Super Heavy Booster) Landing

Figure 4 presents the PCBoom modeled sonic boom contours for a bounding set of first stage RTLS trajectories, with return heading 268, 272, and 345 degrees. Contours of constant magnitude exposure level for 1, 2, 4, 6, 10, 15, and 21 psf are shown, consistent with the described thresholds for sonic boom exposure. Figure 3 presents the results for the 268 degree trajectory by showing the isopemps or lines of intersection with the ground of the shock front produced at a given Mach number in flight. Ground intersection is predicted from Mach 4.1 to Mach 1. The first stage reentry does produce isopemps along its ground track, which take on a shallow hyperbolic shape until a low Mach number and altitude combination allows for both sides of the Mach cone to intersect with the ground and produce a predicted circular exposure area just downrange of the landing site. Overpressure magnitudes of greater than 21 psf, where damage to windows could occur, is confined to restricted access areas during a launch. Overpressure events of 15 psf and 21 psf in areas located within the area where only SpaceX personnel are allowed during launches public hard checkpoint[1]. Boca Chica Village is within the public hard checkpoint, which is evacuated during launch/landing activities. The predicted overpressure for the area surrounding the public hard checkpoint indicate overpressure events up to 15 psf, with contours extending just beyond the U.S. / Mexico Border[2]. Predicted overpressure levels at the southern portion of South Padre Island and Port Isabel, Tarpon Bend, as well as northeast regions of Tamaulipas, Mexico would be expected to reach 10 psf. The 6 psf sonic boom contour is predicted to extend approximately 10 miles from the launchpad, and encompass portions of South Padre Island, all of Port Isabel, Laguna Heights, and portions of Laguna Vista. Portions of northeastern Tamaulipas, Mexico, including La Burrita and El Conchillal, would also be encompassed in the 6 psf sonic boom contour. The 4 psf boom contour is expected to extend approximately 15 miles from the launchpad, and would encompass northern portions of South Padre Island, Laguna Vista, eastern portions of Brownsville, and La Bartolina and El Huisachal in Tamaulipas, Mexico. The 2 psf sonic boom contour is predicted to extend approximately 28 miles, and would overlap Laguna Atascosa, Los Fresnos, Brownsville; and in Mexico, Matamoros and San José. The 1 psf sonic boom contour is predicted to extend approximately 27 miles, and would impact Rio Hondo, San Benito, as well as Santa Adelaida, La Venada, and San José in Mexico.

[1] The public hard checkpoint is located at State Highway 4 and Richardson Avenue. Only SpaceX personnel and FAA launch support personnel are able to pass this checkpoint.

[2] Because the FAA is required to analyze transboundary impacts, areas in Mexico are also considered in the analysis.

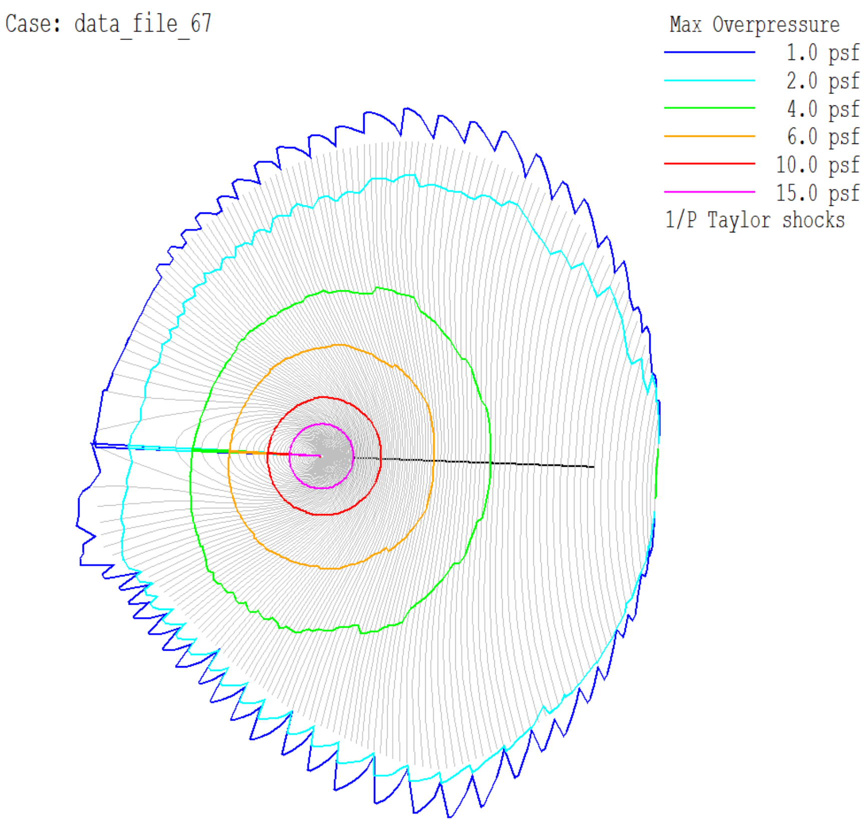

Figure 3: PCBoom v6.6 Pressure contours and isopemps for the 268 degree Super Heavy RTLS trajectory

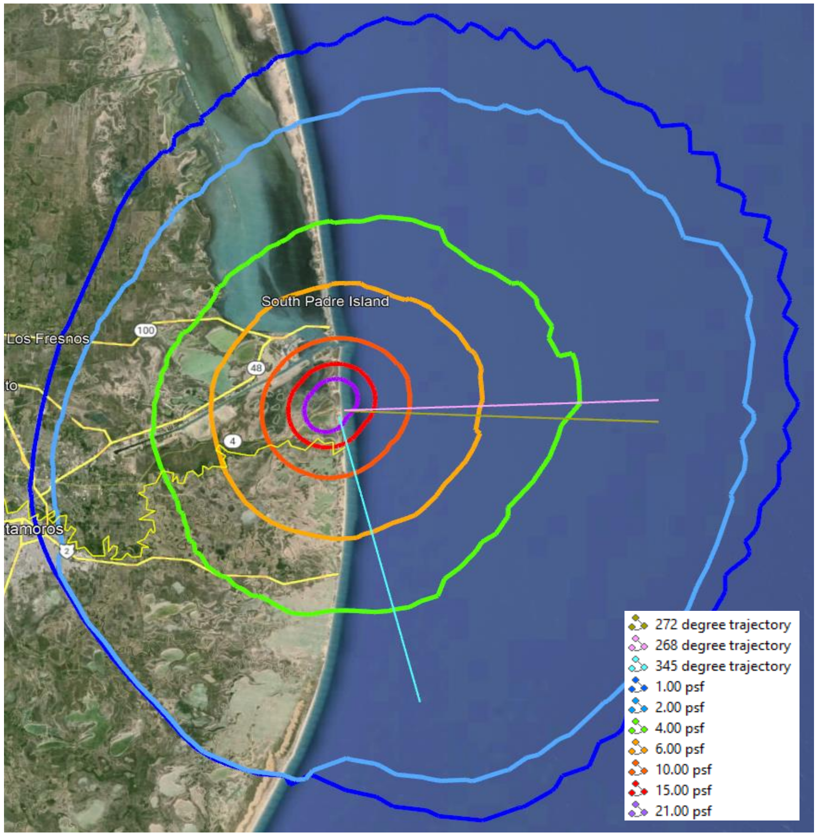

Figure 4: PCBoom v6.6 Pressure contours for a nominal Super Heavy RTLS at 1, 2, 4, 6, 10, 15, and 21 psf, overlayed with a map. The white line indicates the supersonic portion of the Super Heavy trajectory.

Second Stage (Starship) Landing

Figure 5 presents the PCBoom modeled sonic boom contours for the second stage RTLS trajectory. Contours of constant magnitude exposure level for 1.0 and 2.0 psf are shown, consistent with the described thresholds for sonic boom exposure and the maximum predicted on-ground overpressure. Additional contours of 0.7, 1.25, 1.5, 2.5 psf are shown because the peak magnitude of sonic boom on land that will be produced by the second stage is significantly lower than the first stage on an RTLS trajectory. This is the result of the significantly higher altitude at which the second stage reaches a subsonic velocity, and the much shallower flight path angle of the vehicle through supersonic flight. Figure 6 presents the same model results by showing the isopemps or lines of intersection with the ground for the shock front produced at a given Mach number in flight. The first isopemp line is generated from Mach 7.5. The incomplete 1.5 and 1.25 psf contours are a result of granularity in simulated Mach numbers through the vehicle’s deceleration. The ground track shown ends as the vehicle transitions to subsonic flight. The simulated lateral cutoff is approximately 35 km on either side of the ground track, and PCBoom predicts all sonic booms to intersect with the ground downrange of the landing site.

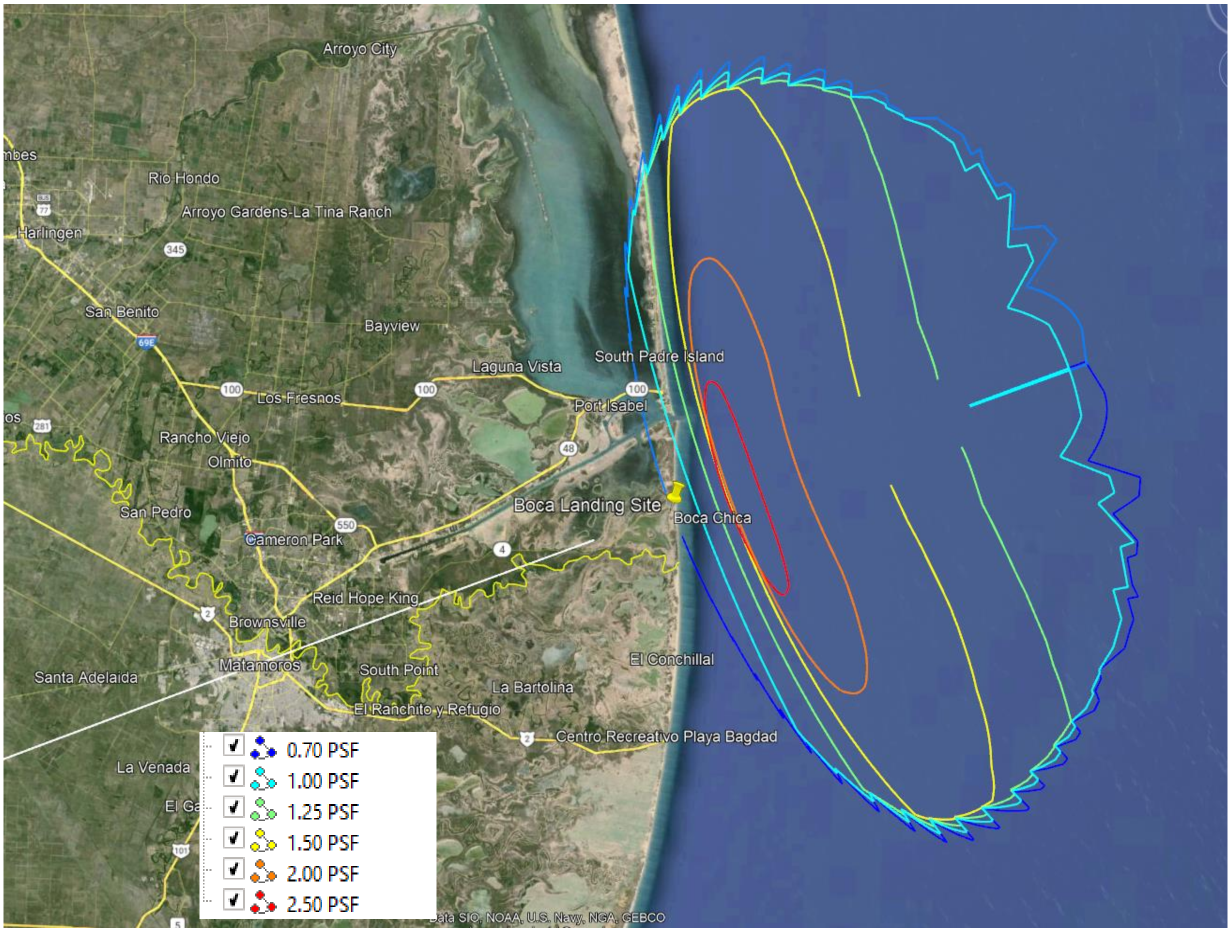

Figure 5: PCBoom v6.6 Pressure contours, Second Stage RTLS for 68 degree heading

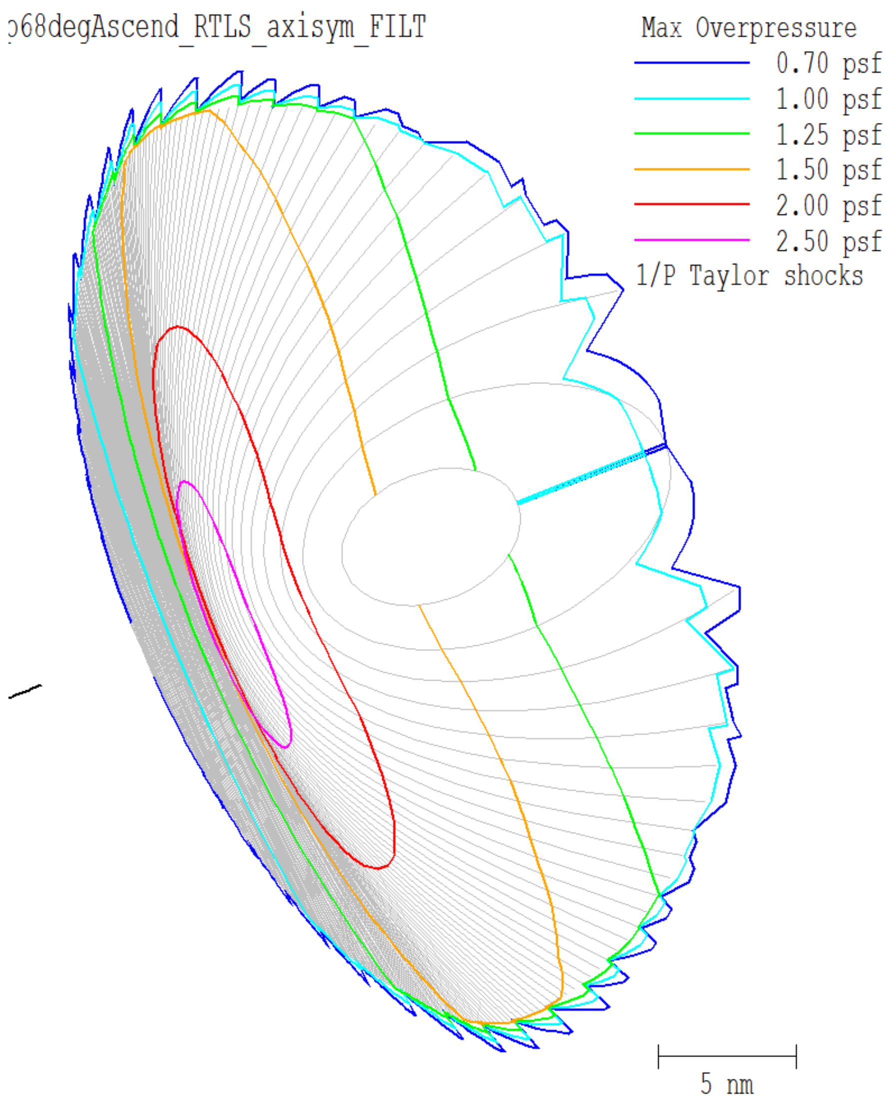

Figure 6: Second stage overpressure contours with Mach based isopemps for 68 degree heading RTLS trajectory

Notably, the predicted ground intersection of sonic booms is almost entirely downrange of the landing site and has limited intersection around the ground track. Historical precedent of measured sonic booms on the Shuttle orbiter and a comparison of vehicle size and typical entry trajectory can be used to infer the following expectations for second stage entry. The second stage is likely to produce sonic booms along its ground track for some lateral extent during supersonic flight up to 50 km of altitude and Mach number of 10. The lateral extent of a low-level sonic boom carpet can be expected to reach up to 150 km of width around the ground track, in addition to the higher magnitude localized boom near and slightly downrange of the landing site. An approximate

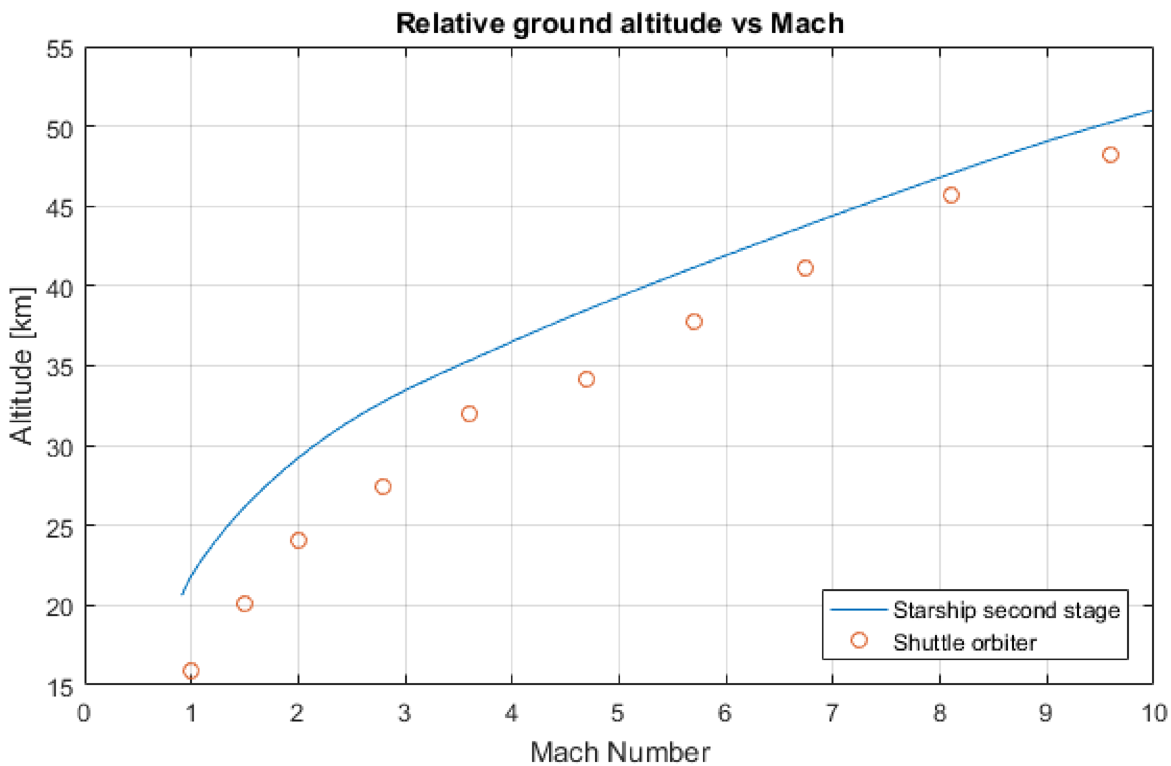

Figure 7: Approximate comparison of second stage RTLS descent trajectory and Shuttle Orbiter

comparison of the second stage and Shuttle orbiter trajectory in terms of altitude vs Mach is shown in Figure 7 (Maglieri, Domenic, et. al. 2011). As a result, the direct PCBoom v6.6 results are not believed to be complete.

According to *Quieting the boom: the shaped sonic boom demonstrator and the quest for quiet supersonic flight,* a simplified approach for calculating sonic boom magnitudes on land for low flight path angle overflight of aircraft, with evidence of extensibility to orbital reentry vehicles (Benson. 2013). This model is implemented and used to augment the ground track sonic boom generation predicted for the second stage. The results are in better alignment with the Shuttle's overflight sonic boom magnitudes considering that the Starship second stage is slightly larger, but also flies at a higher altitude for all supersonic Mach numbers. The augmented contours for a single 68 degree ascending approach heading case are shown in Figures 8 and 9. The pinched behavior near the landing site is not believed to be physical, and ground track contours likely transition more smoothly to the lobe beyond the landing site. This modeling artifact is mitigated by the swept heading angle results, which effectively rotate the ground track carpet through this pinched zone. The augmented approach is swept across the range of approach headings from 22-158 degrees is shown in Figures 10 and 11 with the overlay of the single 68 degree case as an illustration of the additional conservatism assumed by sweeping the approach heading.

The augmented results show sonic booms up to 2 psf on land within 20 km of the landing site. Depending on vehicle heading, this could include area that encompasses populated regions of South Padre Island, Port Isabel, and northeast portions of Tamaulipas, Mexico. Sonic booms of up to 4 psf could reach sea level within 10 km of the landing site, and for many heading angles be entirely offshore, but for steep approaches and on shore wind conditions, could be sensed in South Padre. Sonic booms up to 1 psf could be heard up to 40 km from the landing site, typically only at that distance if within 10km of the approaching vehicle's ground track. Thus, for specific heading angles sonic booms of 1 psf are predicted to extend approximately 24 miles, and may be heard in Brownsville, Matamoros, South Padre, Port Isabel, Laguna Heights, Laguna Vista, Los Fresnos, and other South Texas communities, as well as El Huisachal and Rancho Santa Isabel in Mexico. Beyond this distance, sonic booms are expected to be below 1 psf, at which point they will be heard by individuals anticipating their arrival or in a low noise floor environment but are otherwise not expected to be of significance.

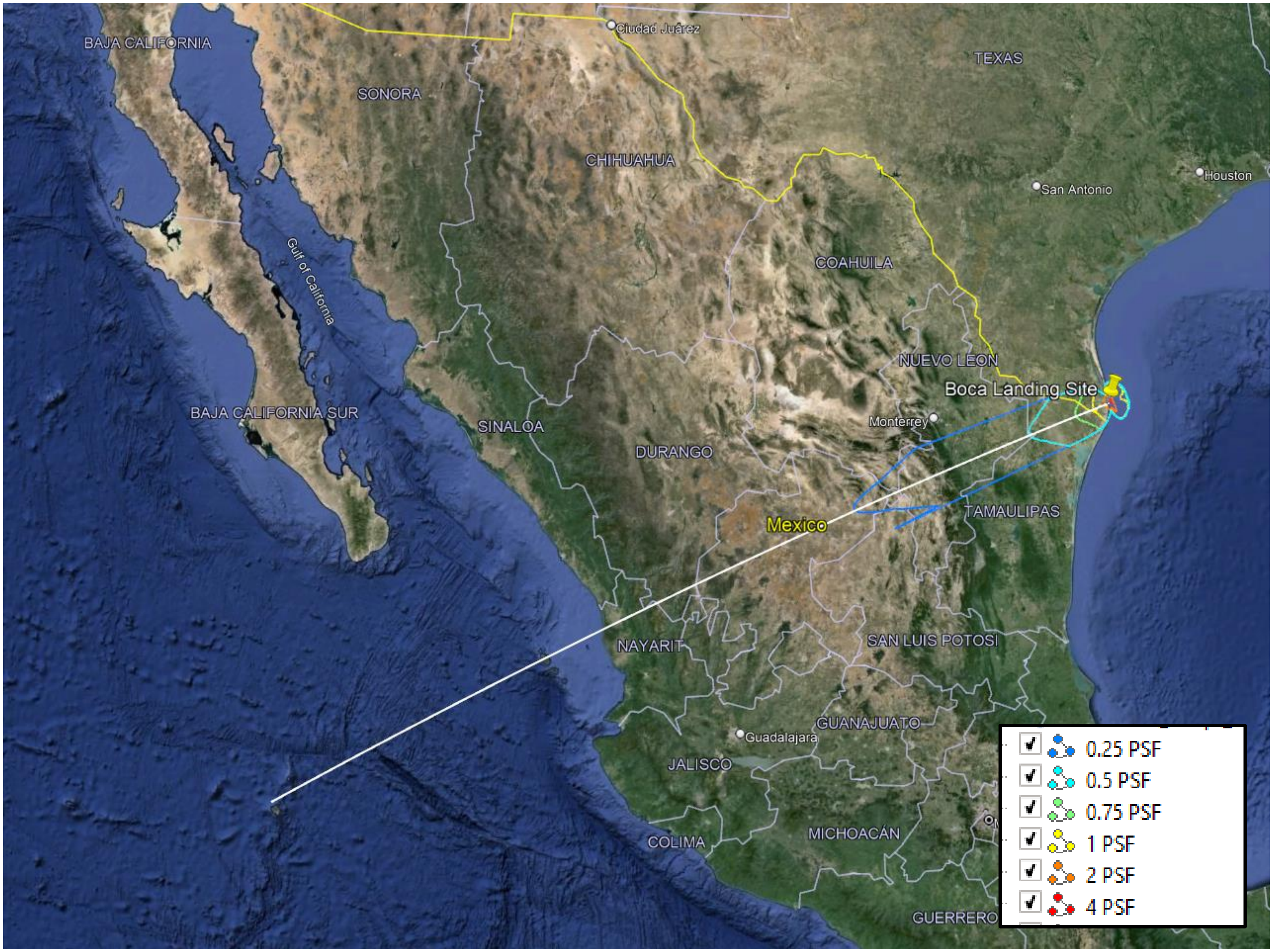

Figure 8: Starship second stage RTLS with 68 degree heading, augmented PCBoom + 1122 Ground Track Prediction

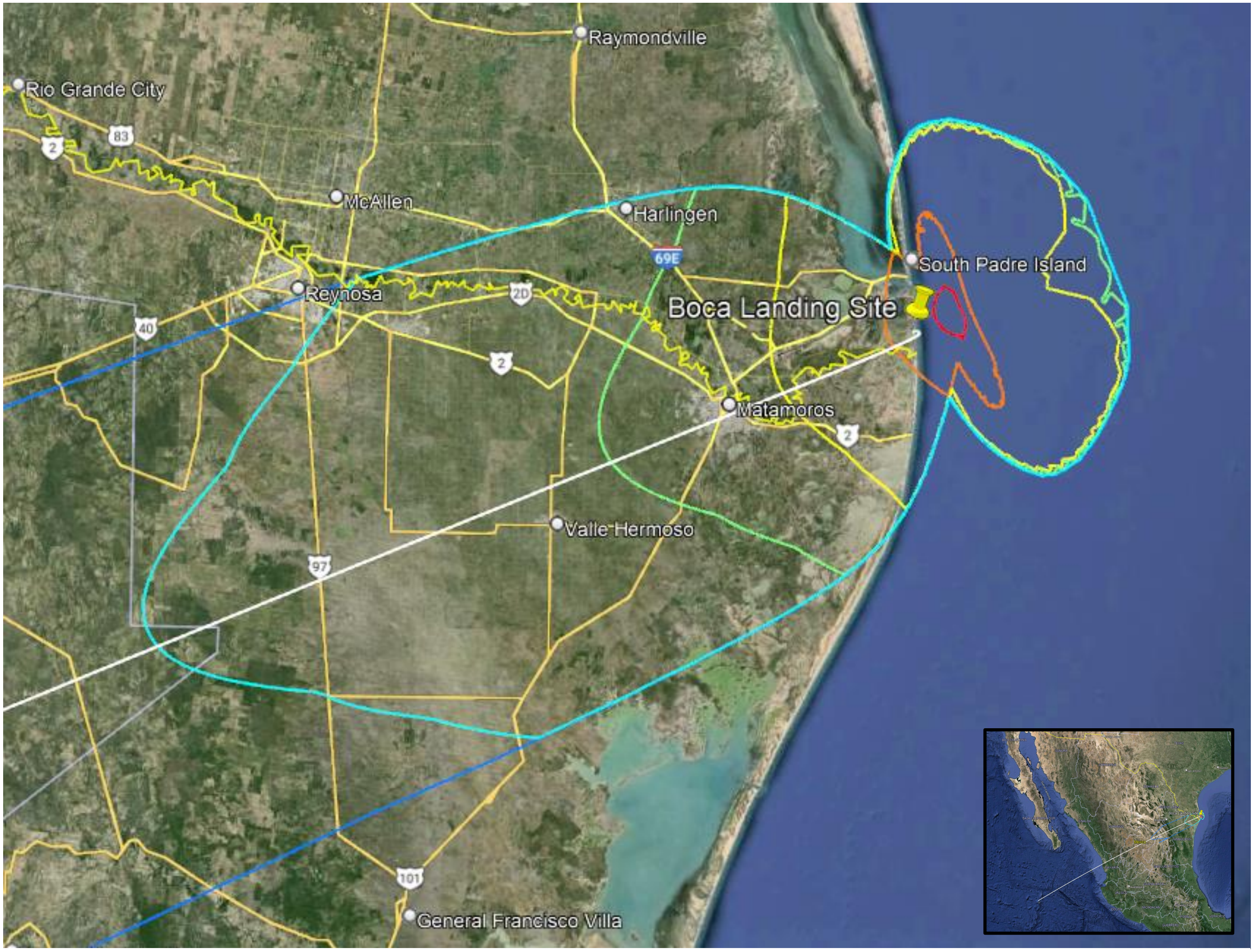

Figure 9: Starship second stage RTLS with 68 degree heading, augmented PCBoom + 1122 Ground Track Prediction (ZOOM)

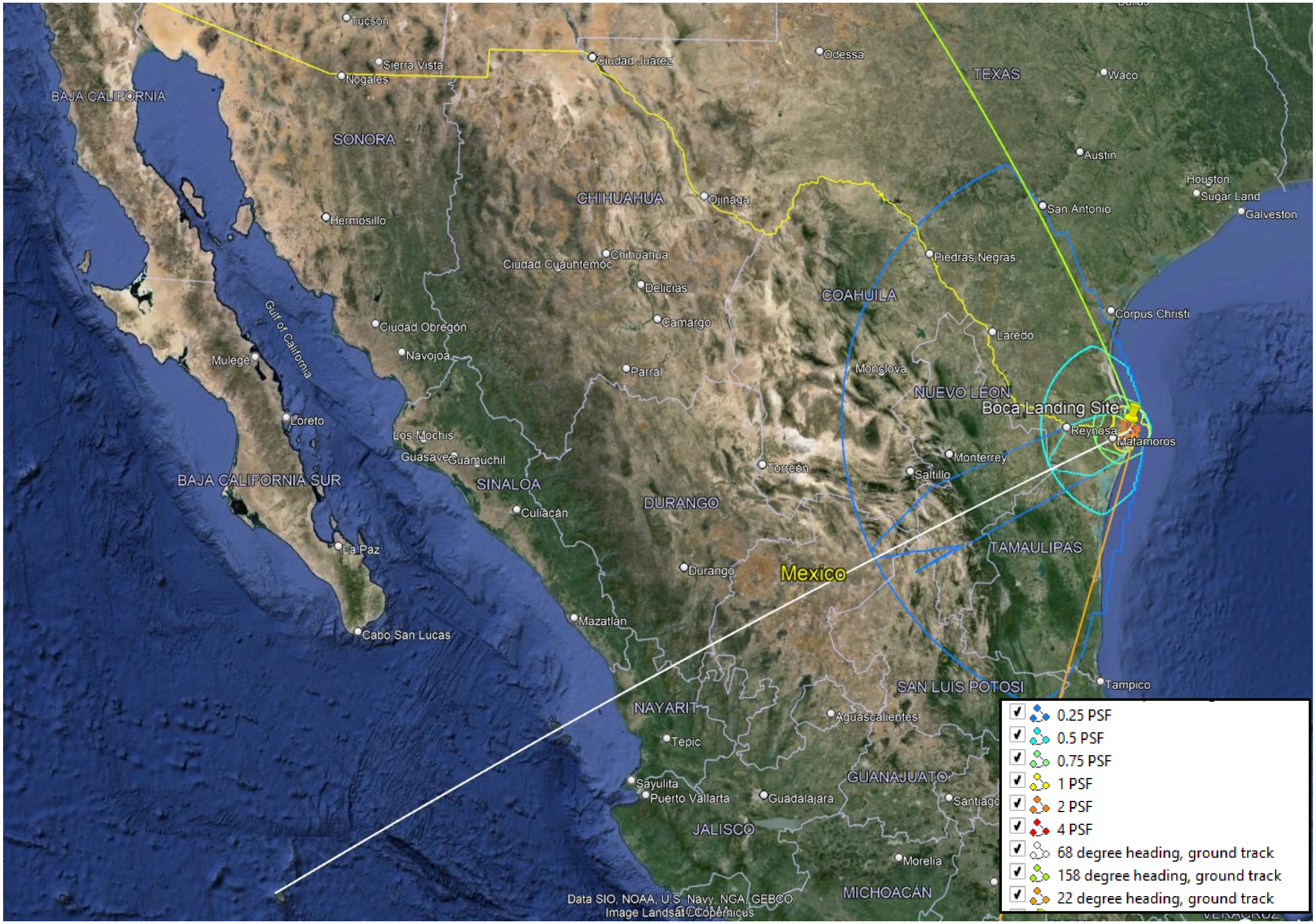

Figure 10: Starship second stage RTLS with swept heading from 22-158 degrees, augmented PCBoom + 1122 Ground Track Prediction

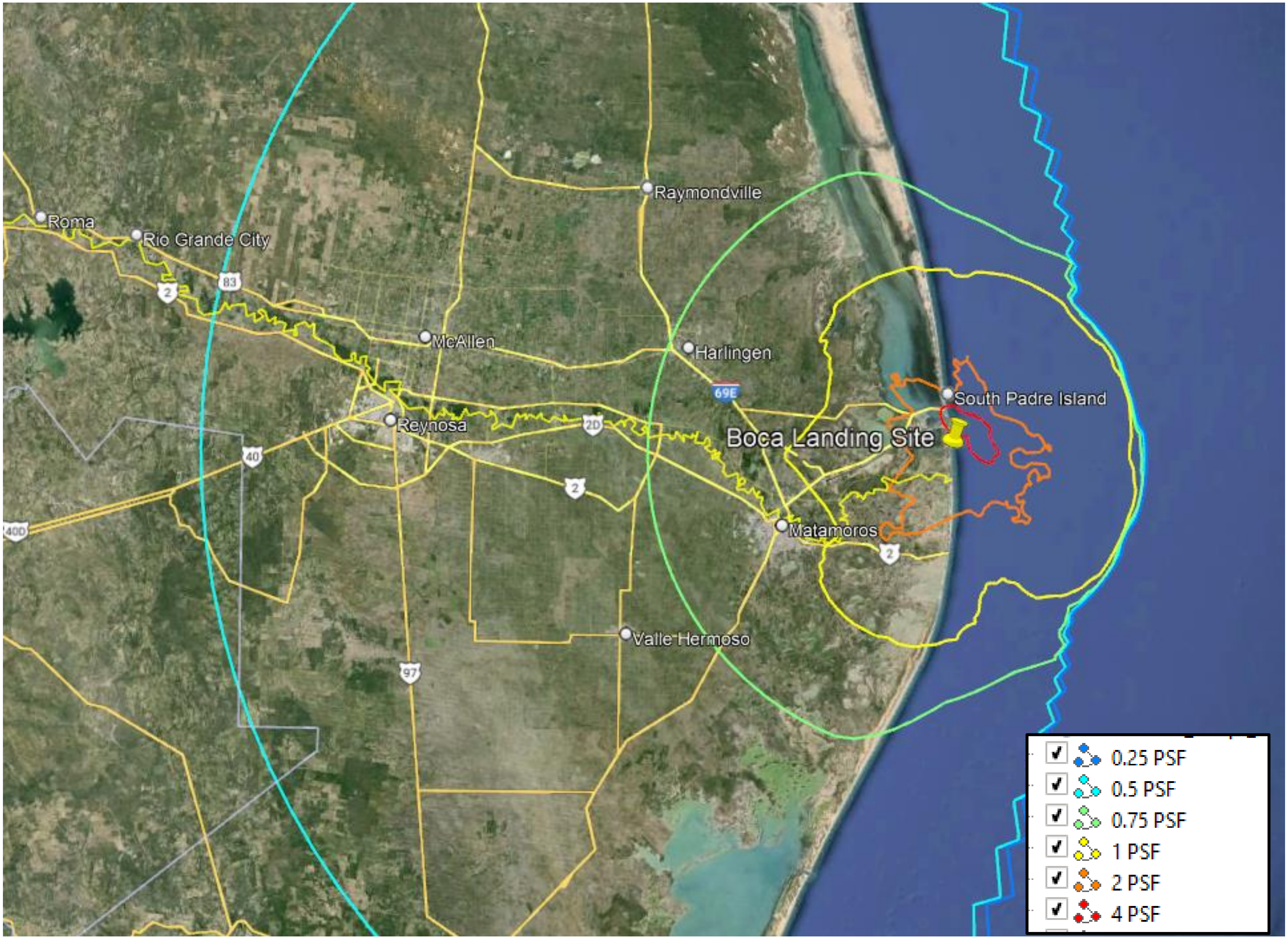

Figure 11: Starship second stage RTLS with swept heading from 22-158 degrees, augmented PCBoom + 1122 Ground Track Prediction (ZOOM)

In addition to presenting and evaluating sonic boom noise contours in terms of psf using PCBOOM, sonic boom noise contours were converted to a C-weighted day-night average noise level (CDNL). Noise exposure from sonic booms that exceeds the significance threshold of C-weighted day-night average noise level (CDNL) 60 dBC for impulsive noise sources (equivalent to DNL 65 dBA) is a significant impact (FAA 2020, FAA 2022). To determine the significance of sonic boom exposure on surrounding communities, the FAA converted psf data to CDNL. The FAA uses CDNL to assess cumulative annoyance from impulsive noise like sonic booms, while using other metrics to evaluate hearing loss and other noise-related health effects (FAA 2024). Given unique characteristics of commercial space operations, the FAA's guidance recommends that other supplemental noise metrics may also be used in conjunction with DNL "to describe and assess noise effects for commercial space operations" (FAA 2024). The FAA does not use these supplemental metrics to make decisions. Rather, the FAA has established a system of noise measurement that comprises a single, core decision-making metric, the A-weighted DNL. Under FAA Order 1050.1F, significant noise impacts would occur if the Proposed Action would increase noise by DNL 1.5 dB or more for a noise sensitive area that is exposed to noise at or above the DNL 65 dBA noise contour, or that will be exposed at or above the DNL 65 dB level due to a DNL 1.5 dB or greater increase in noise exposure, when compared to the No Action alternative for the same timeframe. FAA's NEPA implementing policies and procedures did not exempt commercial space transportation from this threshold. Until the FAA revises its noise policy, all actions including commercial space transportation actions, are subject to this metric and significance threshold.[3]

The CDNL contours were calculated using 44 total booms (22 daytime Super Heavy Booms, 22 daytime Starship booms), booster return trajectories included 268, 272 and 345 degree headings, and yearly average wind profile. The CDNL curves presented are bounding for the three trajectories.

[3] The FAA determined that changes in transportation use, public expectations, and technology warrant a review of its civil aviation noise policy. On January 13, 2021, the FAA published in the Federal Register a notice entitled, "*Review of FAA Aircraft Noise Policy and Research Efforts: Request for Input on Research Activities to Inform Aircraft Noise Policy"*,86 FR 2722, which described the FAA's noise research portfolio and a first of its kind nationally scoped survey that updated FAA's understanding of the dose-response relationship between exposure to aircraft noise and community annoyance (Neighborhood Environmental Survey or NES). FAA also requested input on the FAA's research activities that would inform the FAA's noise policy and would inform the future direction of the FAA noise research portfolio. The NES showed that a higher percentage of people were "highly annoyed" by aircraft noise across all levels of noise exposure that were studied. In addition to setting forth the FAA noise policy and research efforts, this Notice described the results of research into the societal benefits and costs of noise mitigation measures. On May 1, 2023, the FAA published in the Federal Register a notice entitled "*Request for Comments on the Federal Aviation Administration's Review of the Civil Aviation Noise Policy, Notice of Public Meeting.*" In this notice, the FAA announced that it intends to consider how changes to the FAA civil aviation noise policy may better inform agency decisions and the types of impacts FAA considers in making decisions (e.g., community annoyance, certain types of adverse health impacts highly correlated with aviation noise exposure). The FAA requested suggestions of potential improvements to how the FAA analyzes, explains, and presents changes in exposure to civil aviation noise. 88 FR 26641. In this notice, the FAA specifically sought public comments on whether it should establish noise thresholds for low-frequency events, such as those associated with the launch and reentry of commercial space transportation vehicles authorized by the FAA Office of Commercial Space Transportation, which metrics should be used to establish these noise thresholds, and the appropriate noise exposure level to define the threshold of significant noise impacts. As part of this policy review, FAA is also examining the body of scientific and economic literature to understand how aviation noise correlates with annoyance as well as environmental, economic, and health impacts. The FAA is also evaluating whether any of these impacts are statistically significant and the metrics that may be best suited to disclose them. Until this policy development process is concluded, the FAA will continue to rely on DNL to make decisions regarding the significance of potential noise impacts.

Figure 12 Cumulative Day-Night Average Sound Levels for the Proposed Action

As Figure 12 shows, the 60 dB CDNL contour extends approximately 5 miles from the VLA. No noise-sensitive areas are located within the 60 dB CDNL contour. There are no noise-sensitive areas within the 60 dB CDNL, therefore there would be no significant noise impacts under the FAA's current 60 dB CDNL significance threshold.

As described in the 2022 PEA, SpaceX will implement their public notification plan to educate the public and announce when a launch or landing event would occur. Announcements of upcoming Starship/Super Heavy launches and landings would serve to warn people about these noise events. The plan would involve issuing statements to news outlets and law enforcement so that when noise is heard, the public would understand what has occurred. Sonic booms from Starship landings could occur days or weeks after the launch mission however, these booms are substantially less noisy than Super Heavy landings.

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