STARSHIP ROCKET NOISE ASSESSMENT FOR FLIGHT AND TEST OPERATIONS AT THE BOCA CHICA LAUNCH FACILITY

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1 Introduction

Noise levels have been estimated for SpaceX's Starship rocket which is currently under development. Starship, which has a length of 180 feet and a diameter of 9 meters, will be mated with a Super Heavy Booster rocket (length of 207 feet) to form the Starship/Super Heavy Launch Vehicle intended to provide long-duration cargo- and passenger-carrying capability. Both vehicles have vertical take-off and landing (VTOL) capability and are reusable. This study was conducted to estimate noise levels from future Starship and booster launches, landings, and static fire tests of these vehicles at the Boca Chica Launch Facility in Texas.

The Starship would use six Raptor engines that each provide sea-level thrust of about 478 Klbf; three engines would be used for suborbital liftoffs and landings (hops) and static fire tests and three engines would be used in space. The Super Heavy Booster would use thirty-seven Raptor engines that each provide sea-level thrust of about 375 Klbf. Starship launches, landings, and static fire tests are planned to occur at the Boca Chica Launch Facility as are booster landings and static fire tests. Starship and booster landings are also planned to occur at a downrange site (drone ship) located several hundred miles from the coast in the Gulf of Mexico. This assessment was conducted to estimate the single event and cumulative noise levels in the vicinity of the Boca Chica Launch Facility and downrange landing site due to these rocket operations.

SpaceX provided the following data for noise modeling:

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

Noise levels were estimated for Starship and Super Heavy Booster flight and static test operations conducted at the Boca Chica and downrange sites using Wyle's RNOISE model. RNOISE[1,2] is a far-field (distances beyond several hundred feet) community noise model for launch noise assessment.

In the following sections of this report, a description of rocket noise fundamentals is provided in Section 2 followed by estimated single event noise levels for Starship orbital and suborbital launches (Section 3), Starship and Super Heavy Booster landings (Section 4), and static fire tests for both vehicles (Section 5). Section 6 presents cumulative noise level estimates at the Boca Chica Launch Facility for two projected operation scenarios involving future launches, landings, and static fire tests; for each scenario, 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 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.

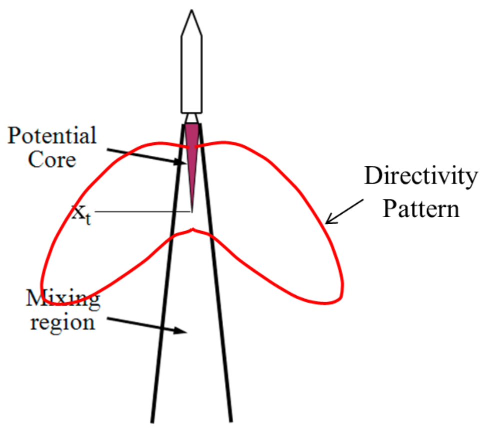

Figure 1. Rocket Noise Source

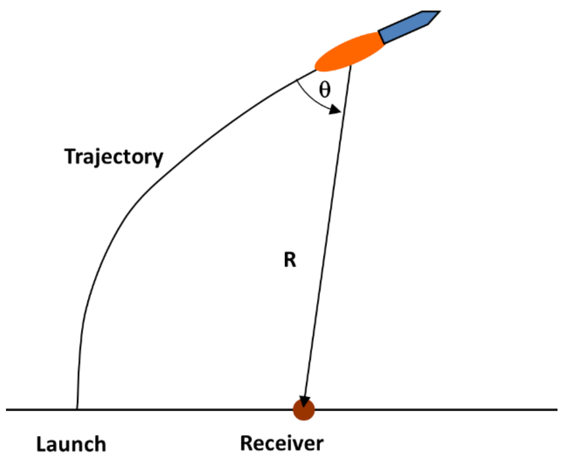

Figure 2. Modeling Rocket Noise at the Ground

Figure 2 is a sketch of far field rocket noise as treated by RNOISE. The vehicle 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] and atmospheric absorption of sound.[8] 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. 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 Noise Metrics

FAA Order 1050.1F 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 level, for individual events;
- OASPL or L_{max}, the maximum overall sound pressure level, for individual events; and
- One third octave spectra at sensitive receptors.

As mentioned, DNL is necessary for policy. The next two metrics (L_{Amax} and SEL) are A-weighted and provide a measure of the impact of individual events. 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. The last two metrics, OASPL and spectra, may be needed to assess potential damage to structures and adverse reaction of species whose hearing response is different from that of humans. Reported levels are A-weighted unless otherwise noted.

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. The L_{Amax} metric indicates the maximum sound level occurring for a fraction of a second. Slowly varying or steady sounds are generally integrated over a period of one second. The maximum sound level is important in judging the interference caused by a noise event with conversation, TV or radio listening, sleep, or other common activities. Although it provides some measure of the intrusiveness of the event, it does not completely describe the total event, because it does not include the period that the sound is heard.

SEL is a composite metric that represents both the intensity 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 net impact of the entire acoustic 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. SEL is a logarithmic measure of the total acoustic energy transmitted to the listener during the event. 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}.

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 OASPL contours for single event noise assessment (Sections 3 through 5) and DNL contours to assess the cumulative noise for two different scenarios involving projected annual operations of each event (Section 6).

3 Launch Noise Levels

3.1 Starship Orbital Launches at the Boca Chica Launch Facility

RNOISE was used to estimate the L_{Amax}, and SEL contours for Starship orbital launches at the Boca Chica Launch Facility using trajectory data, from liftoff to stage separation, provided by SpaceX in file 'Starship_Boca_RTLS_ROTATED_80_12.ASC'. 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 (vehicle with payload) mated with 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. Ground areas were modeled as acoustically soft, and water acoustically hard. Ground effect was based on a weighted average over the propagation path. As will be shown in the resulting noise contour maps (Figures 3 through 6), 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 acoustically hard water and acoustically soft ground. The launch pad location at Boca Chica is indicated in the map legends as is the Padre Island National Seashore. All maps depicting noise contours for operations at Boca Chica also show the nearby cities of Brownsville, Harlingen, and Raymondville, TX.

The L_{Amax} 90 dB through 140 dB contours shown in Figures 3 and 4 represent the maximum levels estimated for each Starship orbital launch at Boca Chica; Figure 4 shows these contours using a zoomed in map scale to better show the extent of the noise exposure relative to cities located around the Boca Chica Launch Facility. The higher L_{Amax} contours (100 – 140 dB) are located within about 7 miles of the Boca Chica Launch Facility; the 100 dB contour extends into parts of South Padre Island and 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 Harlingen 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 on-shore or off-shore 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 each Starship orbital launch at Boca Chica 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 100 dB SEL contour is expected to extend west into Brownsville and the 90 dB SEL contour to extend even further west and north into Harlingen and Raymondville.

Starship orbital launch events are the loudest single events of all the flight and test operations assessed in this modeling study. Accordingly, orbital launch single event noise levels are related to guidelines for hearing conservation and potential for structural damage in the following two sections, respectively.

3.1.1 Hearing Conservation

An estimate of the areas, in the vicinity of Starship orbital launches, where a hearing conservation program should apply was made using guidelines on permissible noise exposure limits from the Occupational Safety and Health Administration (OSHA)[9]. These OSHA 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 sound level of 115 dBA (slow response) for a duration of 0.25 hours or less. Since 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, this L_{Amax} 115 dB guideline can be used as a conservative limit for hearing conservation. Figure 4 shows that noise levels (L_{Amax}) are less than OSHA's 115 dBA upper noise limit guideline at distances greater than approximately 2.3 miles from the launch pad.

3.1.2 Structural Damage Potential

The potential for structural damage due to Starship orbital launch events is assessed using the potential for structural damage claims. An applicable study of structural damage claims from rocket static firing tests indicates that, based on Maximum Unweighted Sound Level (L_{max}), approximately one damage claim will result per 100 households exposed at 120 dB and one damage claim per 1,000 households exposed at 111 dB[10]. The L_{max} 110 dB through 150 dB contours estimated for Starship orbital launch events are shown in Figures 7 and 8 (zoomed in) including the L_{max} 111 dB and 120 dB contours used for damage claim assessment. Starship orbital launch events are estimated to generate L_{max} of 120 dB approximately eight miles from the launch pad (Figure 8); the 120 dB contour would be north of Port Isabel and approximately four miles north of the southernmost point of South Padre Island. The 111 dB contour would extend approximately 19 miles from the launch pad and encompass Port Isabel, Laguna Vista, the southernmost 15 miles of South Padre Island, and the easternmost areas of Brownsville.

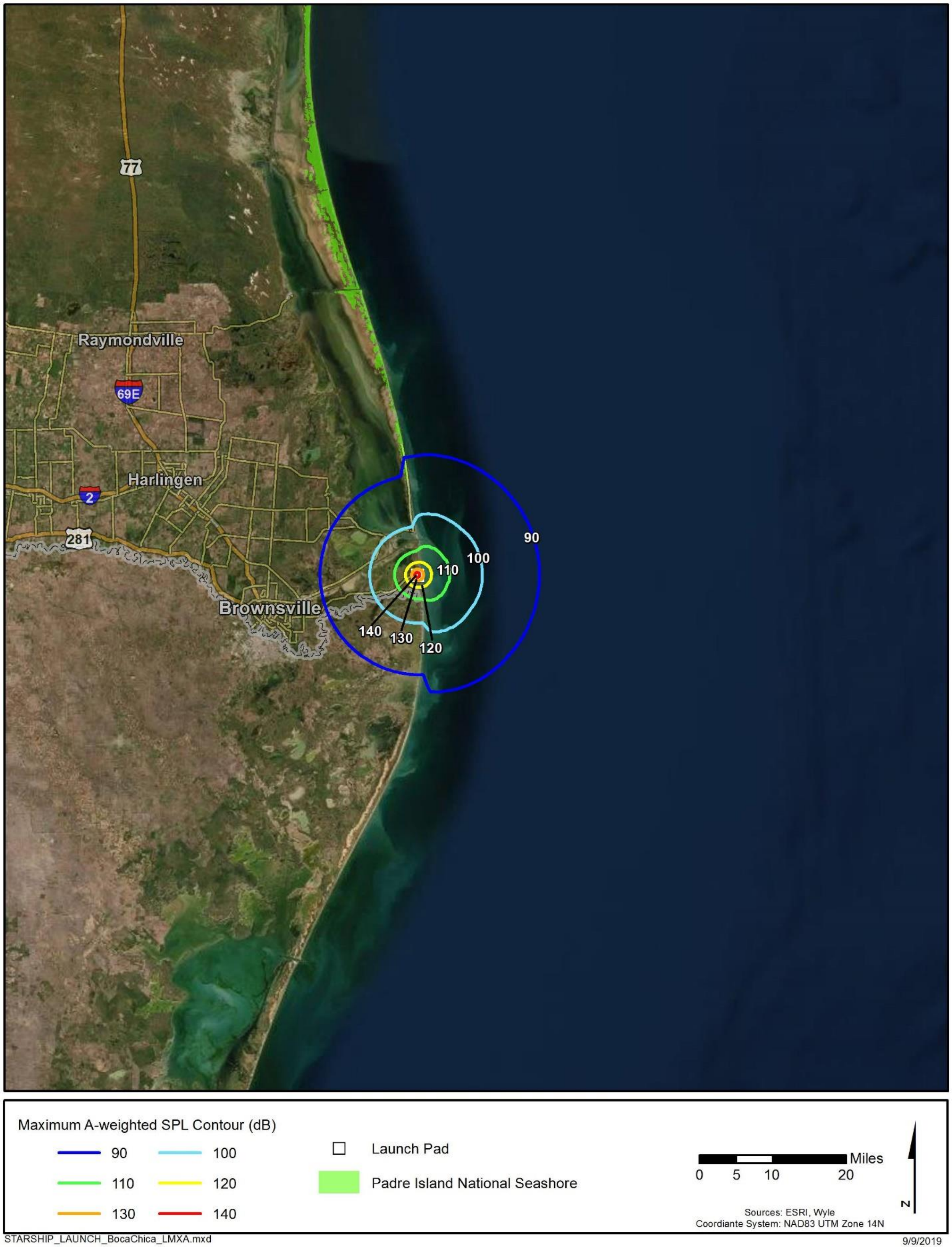

Figure 3. Starship Orbital Launch from Boca Chica: Maximum A-Weighted Sound Levels

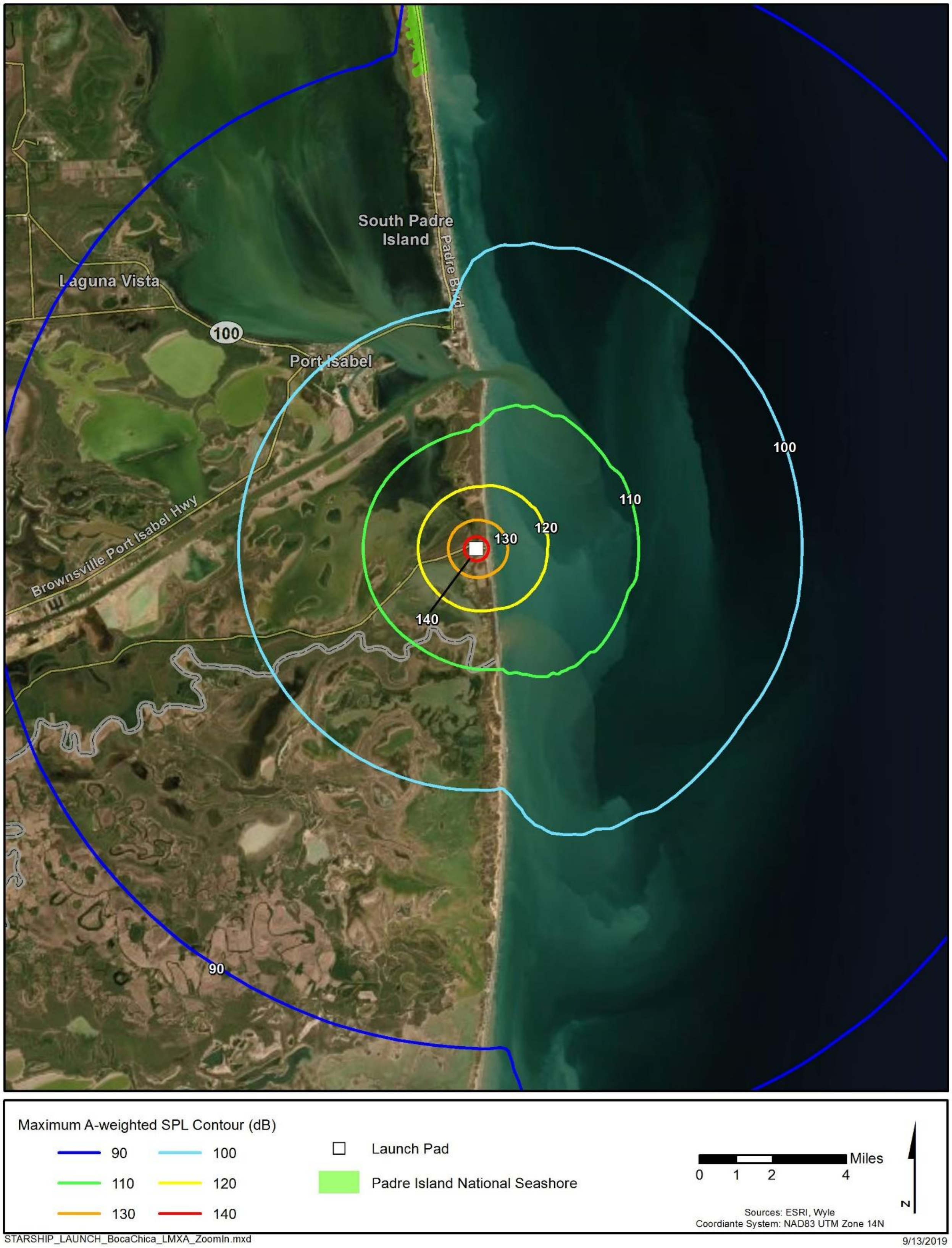

Figure 4. Starship Orbital Launch from Boca Chica: Maximum A-Weighted Sound Levels (Zoom In)

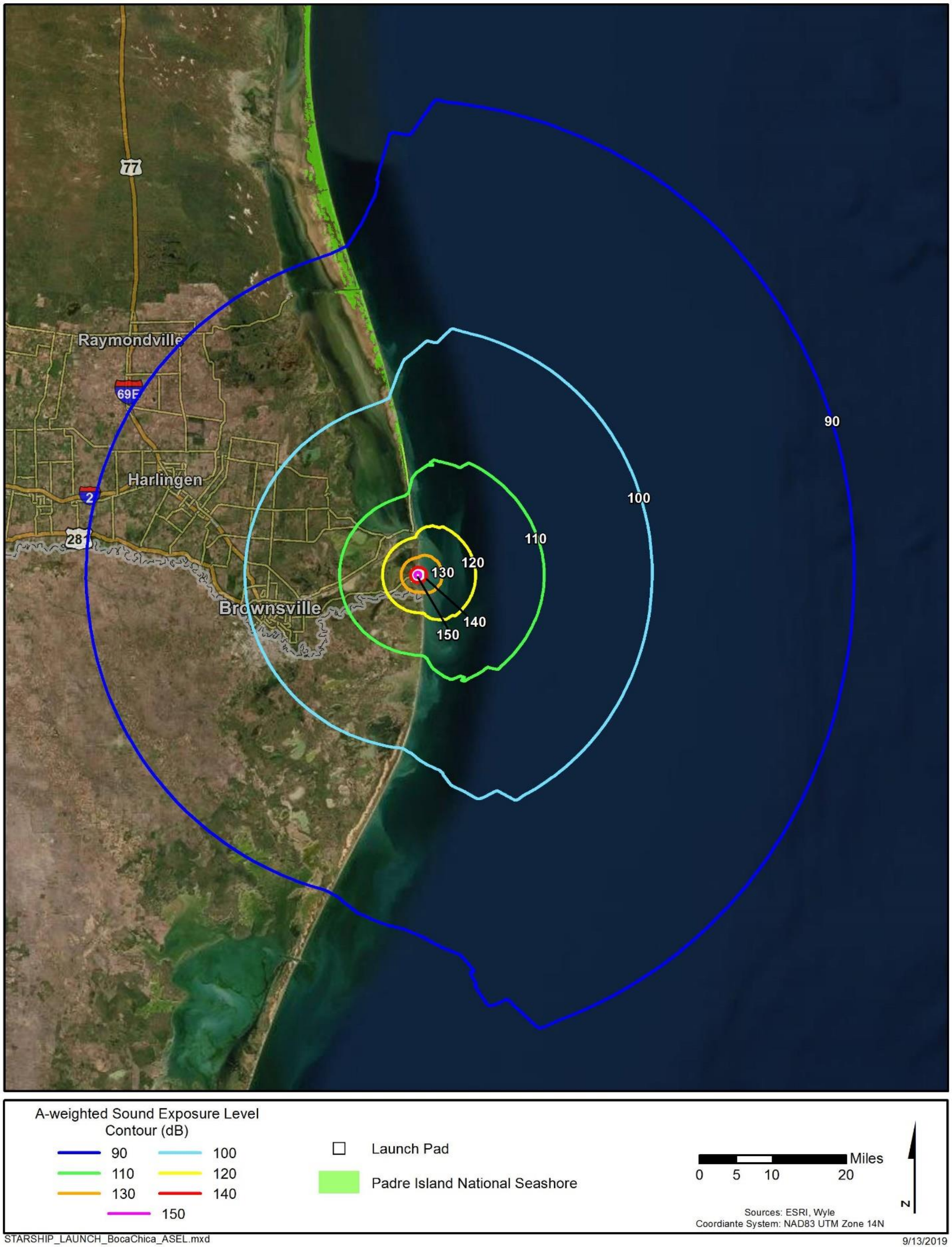

Figure 5. Starship Orbital Launch from Boca Chica: Sound Exposure Levels

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

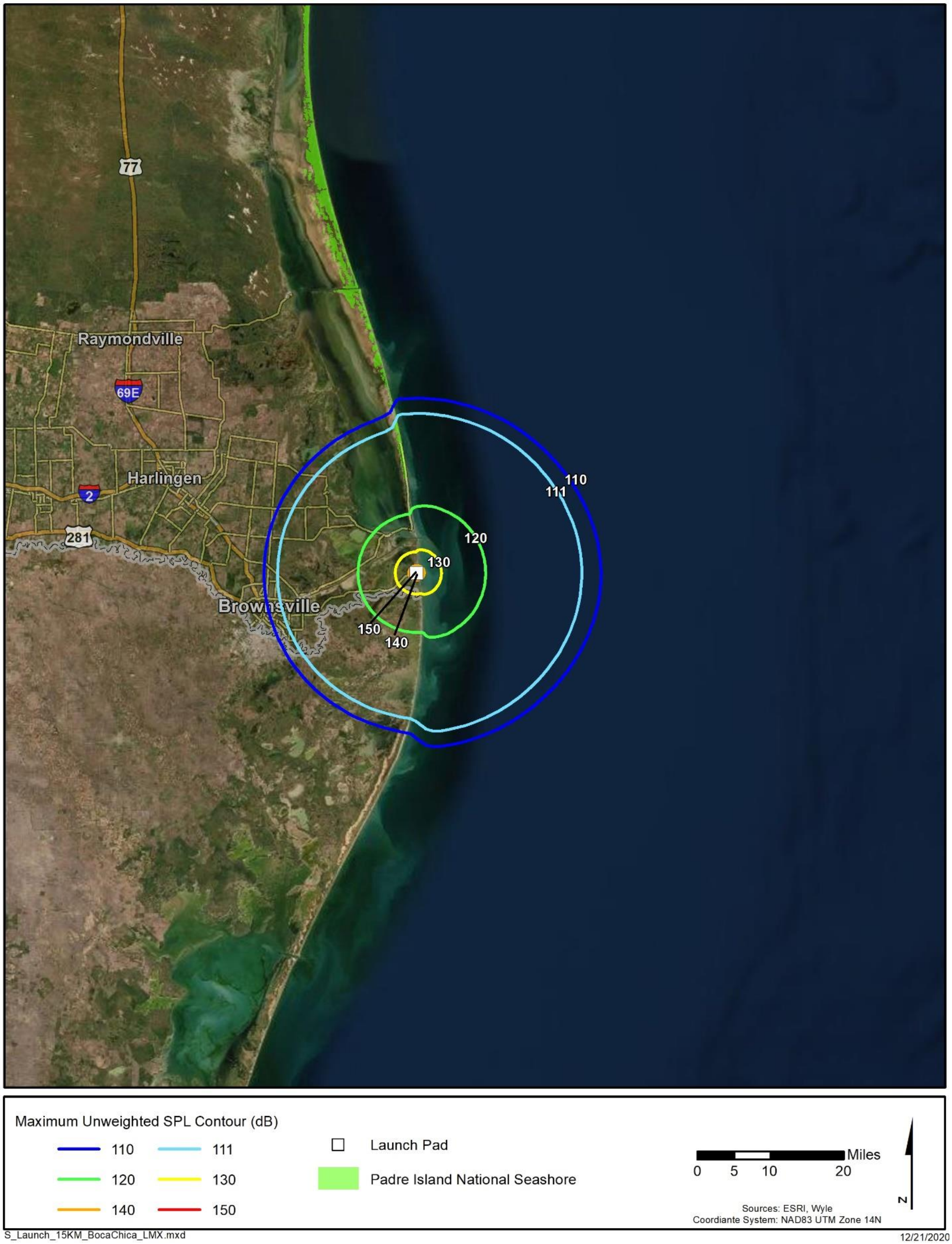

Figure 7. Starship Orbital Launch from Boca Chica: Maximum Unweighted Sound Levels

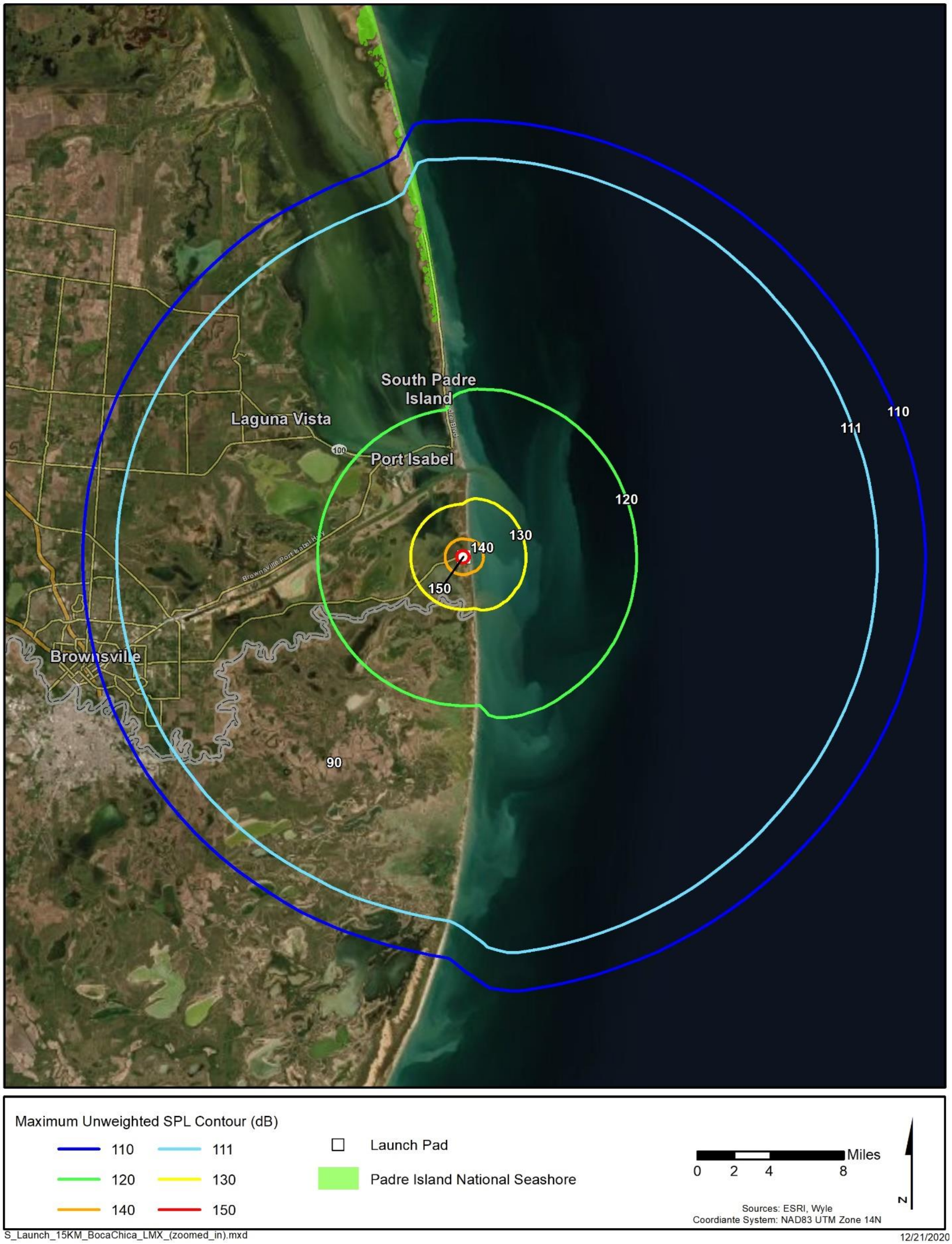

Figure 8. Starship Orbital Launch from Boca Chica: Maximum Unweighted Sound Levels (Zoom In)

3.2 Starship Suborbital Launches at the Boca Chica Launch Facility

RNOISE was used to estimate the L_{Amax}, and SEL contours for Starship suborbital launches at the Boca Chica Launch Facility using trajectory data, from liftoff to stage separation, provided by SpaceX in file 'STARSHIP_15KM_7775A4FD_80_12.ASC'. 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. Starship suborbital launches are conducted with the Starship vehicle without the booster. RNOISE computations were conducted as described in section 3.1.

The L_{Amax} 90 dB through 140 dB contours shown in Figures 9 and 10 represent the maximum levels estimated for each Starship suborbital launch at Boca Chica; Figure 10 shows these contours using a zoomed in map scale to better show the extent of the noise exposure relative to cities located around the Boca Chica Launch Facility. The higher L_{Amax} contours (100 – 140 dB) are in unpopulated areas surrounding the Boca Chica Launch Facility. The 90 dB contour extends into Port Isabel as shown in Figure 10. If a Starship launch occurs during the day, when background levels are in the 50 dB to 60 dB range, residents of Port Isabel 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 on-shore or off-shore breeze may also strongly influence noise levels in the surrounding communities.

Estimated SEL contour levels of 90 dB through 150 dB, in 10 dB increments, are shown in Figures 11 and 12 for each Starship suborbital launch at Boca Chica with Figure 12 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 11, the 100 dB SEL contour extends west into Laguna Vista and the 90 dB SEL contour extends even further west into Brownsville.

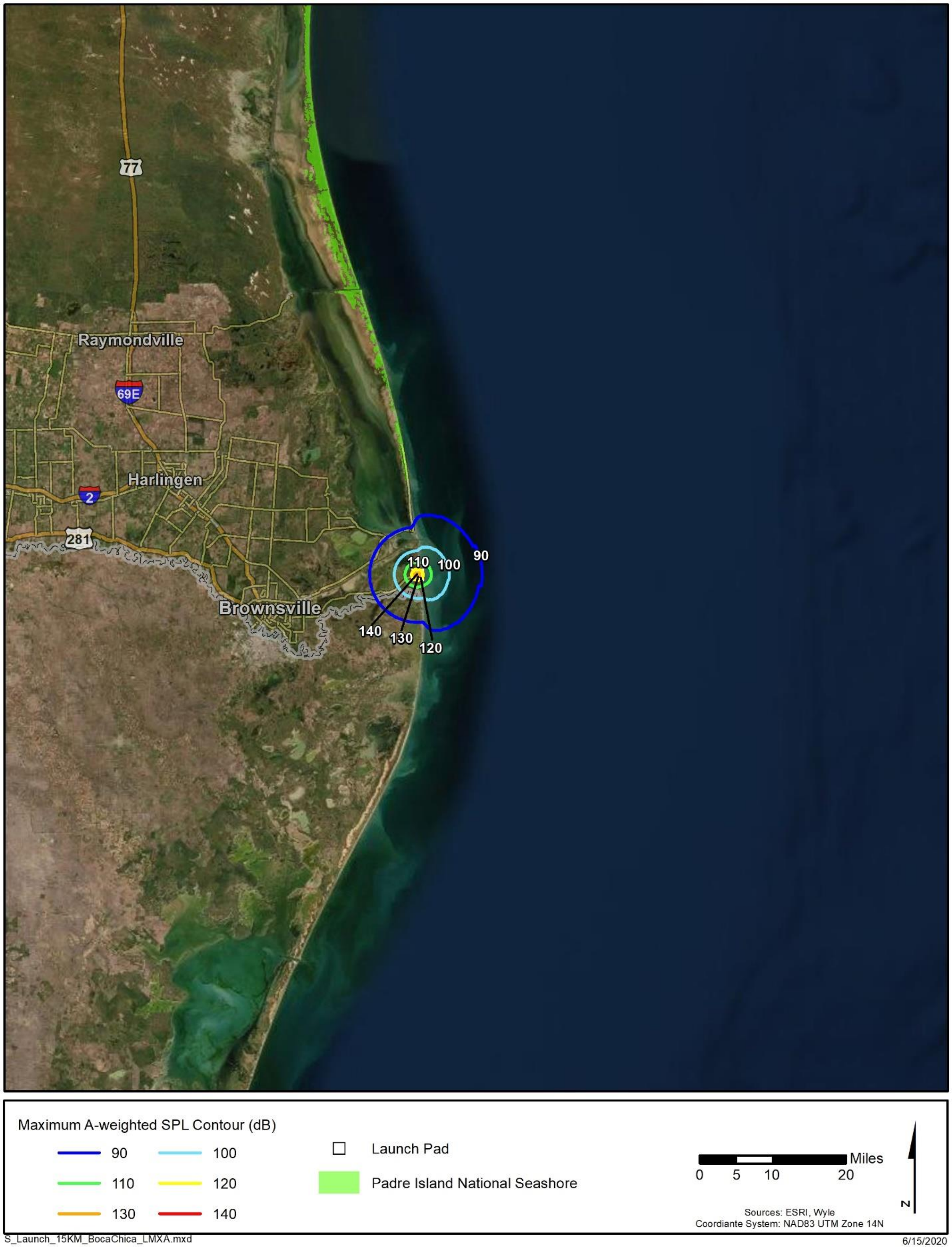

Figure 9. Starship Suborbital Launch from Boca Chica: Maximum A-Weighted Sound Levels

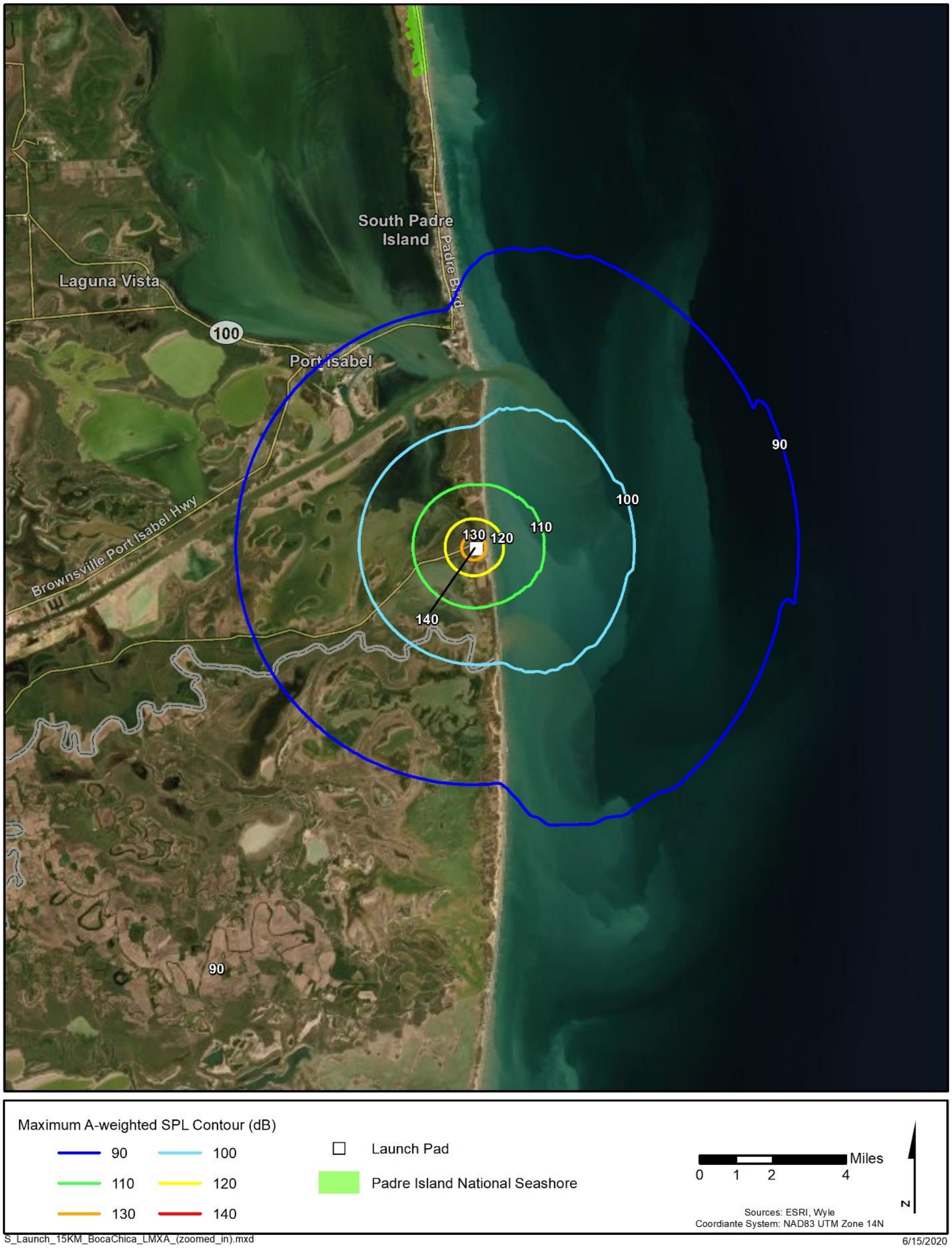

Figure 10. Starship Suborbital Launch from Boca Chica: Maximum A-Weighted Sound Levels (Zoom In)

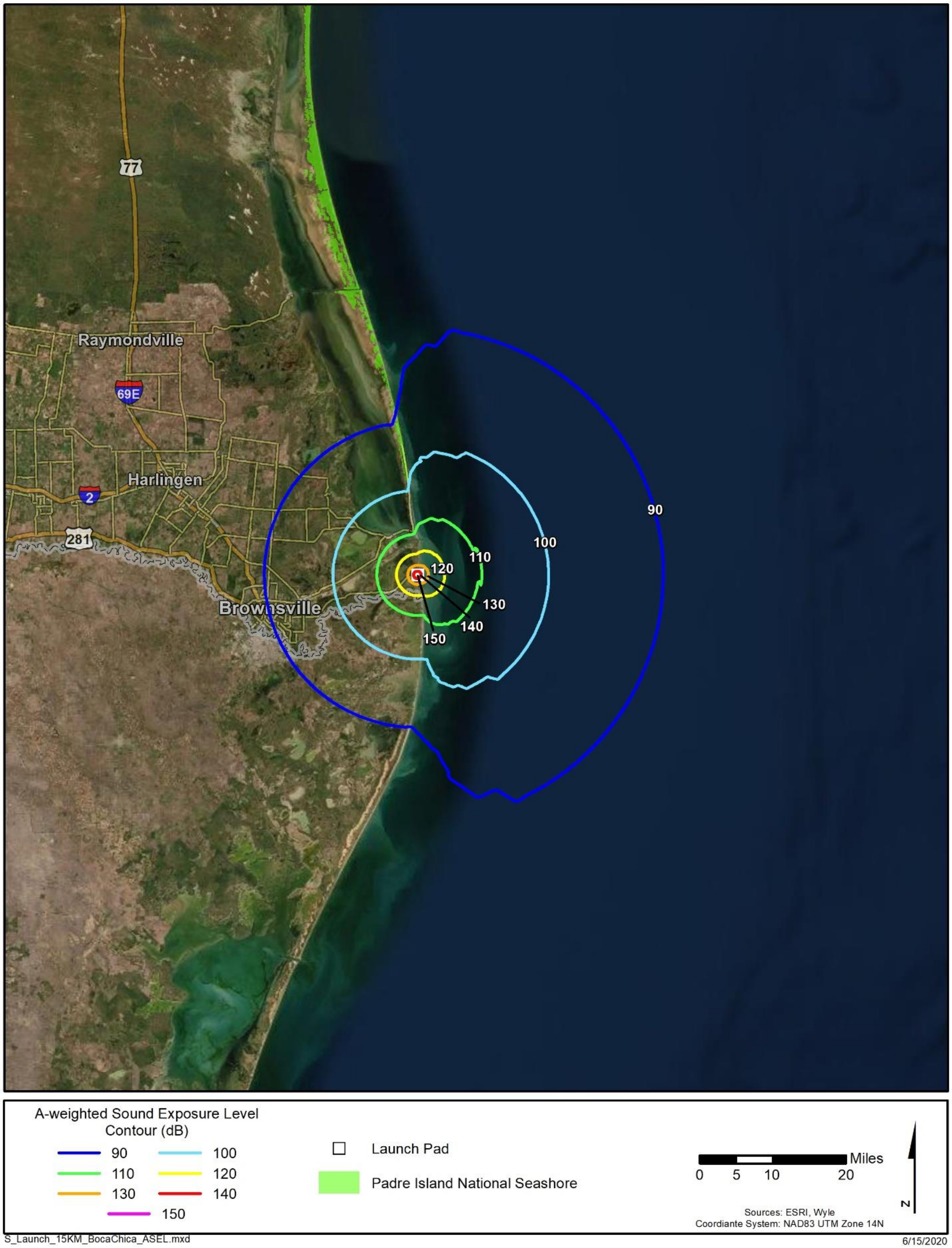

Figure 11. Starship Suborbital Launch from Boca Chica: Sound Exposure Levels

Figure 12. Starship Suborbital Launch from Boca Chica: Sound Exposure Levels (Zoom In)

4 Reentry/Landing Noise Levels

4.1 Starship Orbital Reentry/Landings at Boca Chica and the Downrange Site

RNOISE was used to estimate the L_{Amax}, and SEL contours for Starship orbital reentry/landings at Boca Chica and the downrange landing site located about 400 miles east of Boca Chica, in the Gulf of Mexico. The Starship orbital reentry and landing trajectory was provided by SpaceX in file 'Starship_Boca_Chica_Landing_80_12.ASC '. L_{Amax} contours indicate the maximum sound level at each location over the duration of the landing where engine thrust varies according to the reentry/descent thrust schedule provided. Starship landings involve the Starship vehicle without the 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. Ground areas were modeled as acoustically soft, and water acoustically hard. Ground effect was based on a weighted average over the propagation path. The L_{Amax} contours for the Starship landing at Boca Chica are shown in Figure 13. Similarly, the SEL contours for the Starship landing are shown in Figure 14. The landing pad location at Boca Chica and landing trajectory are indicated in the map legends as is the Padre Island National Seashore. In Figure 13 the 90 dB L_{Amax} contour is about 5 miles from the Boca Chica landing site in mostly unpopulated areas except Port Isabel and the southern part of South Padre Island. Residents of Brownsville may notice levels above 60 dB L_{Amax} especially for nighttime landing events. Compared with the Starship orbital launch noise levels reported in Section 3, Starship orbital reentry/landing noise levels are considerably lower due to the much lower total engine thrust used for landing operations.

Figures 15 and 16 show the L_{Amax} and SEL contours, respectively, estimated for Starship landings at the downrange site (drone ship in the Gulf of Mexico). The Starship downrange landings are planned to occur several hundred miles offshore, therefore noise from these events is not expected to be noticed by residents along the coast.

The next section presents single event noise levels for Starship suborbital flight landings at the Boca Chica landing site.

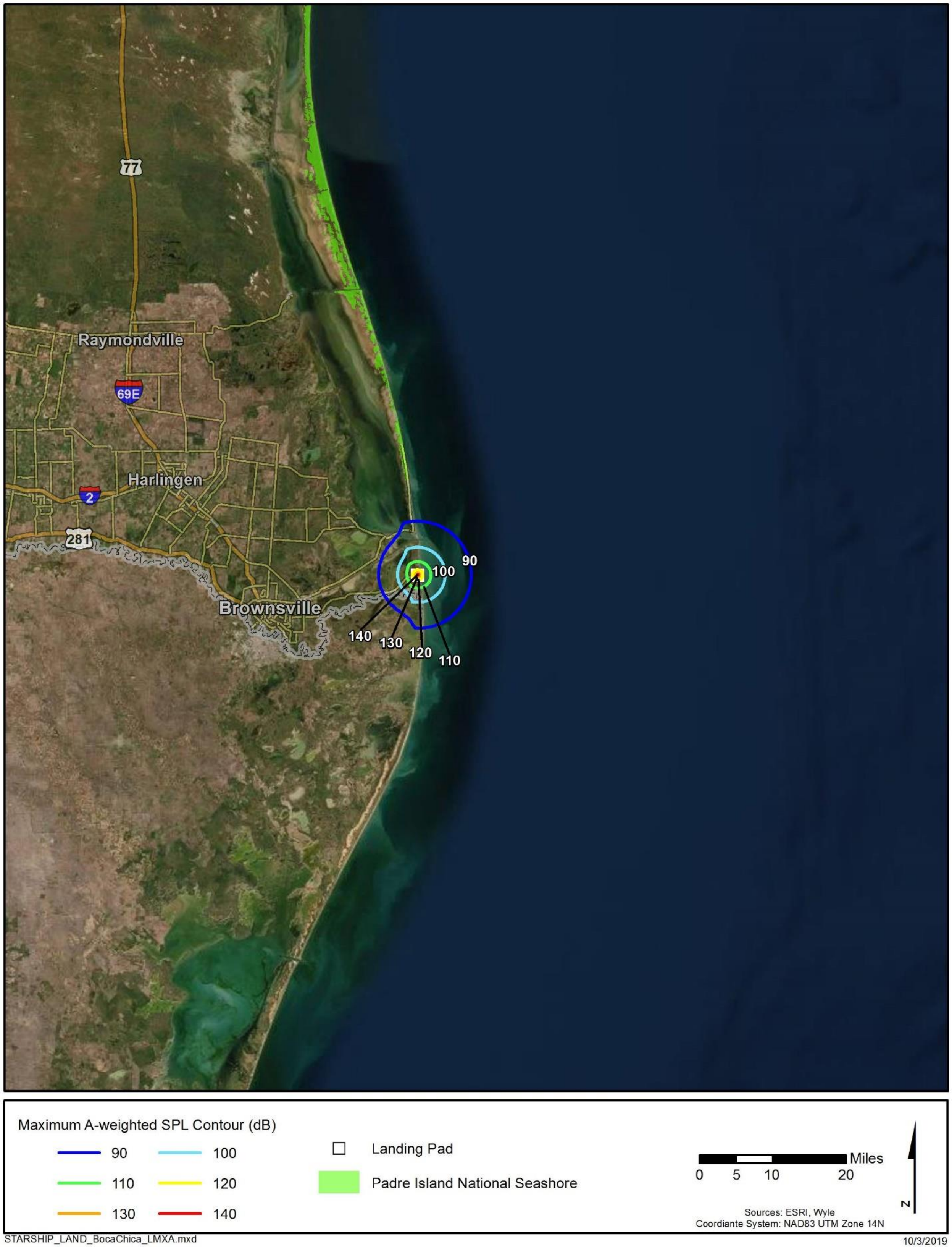

Figure 13. Starship Landing at Boca Chica: Maximum A-Weighted Sound Levels

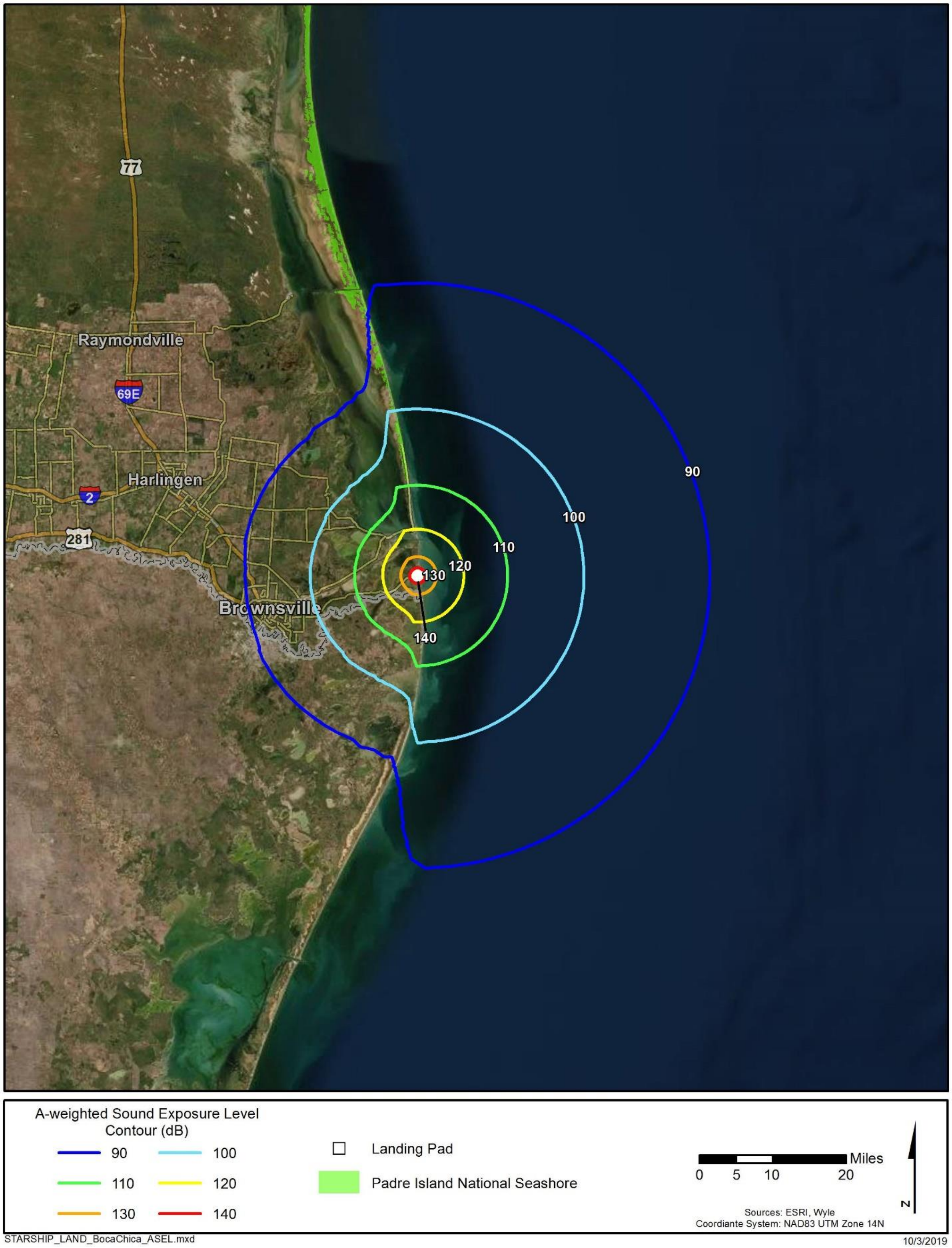

Figure 14. Starship Landing at Boca Chica: Sound Exposure Levels

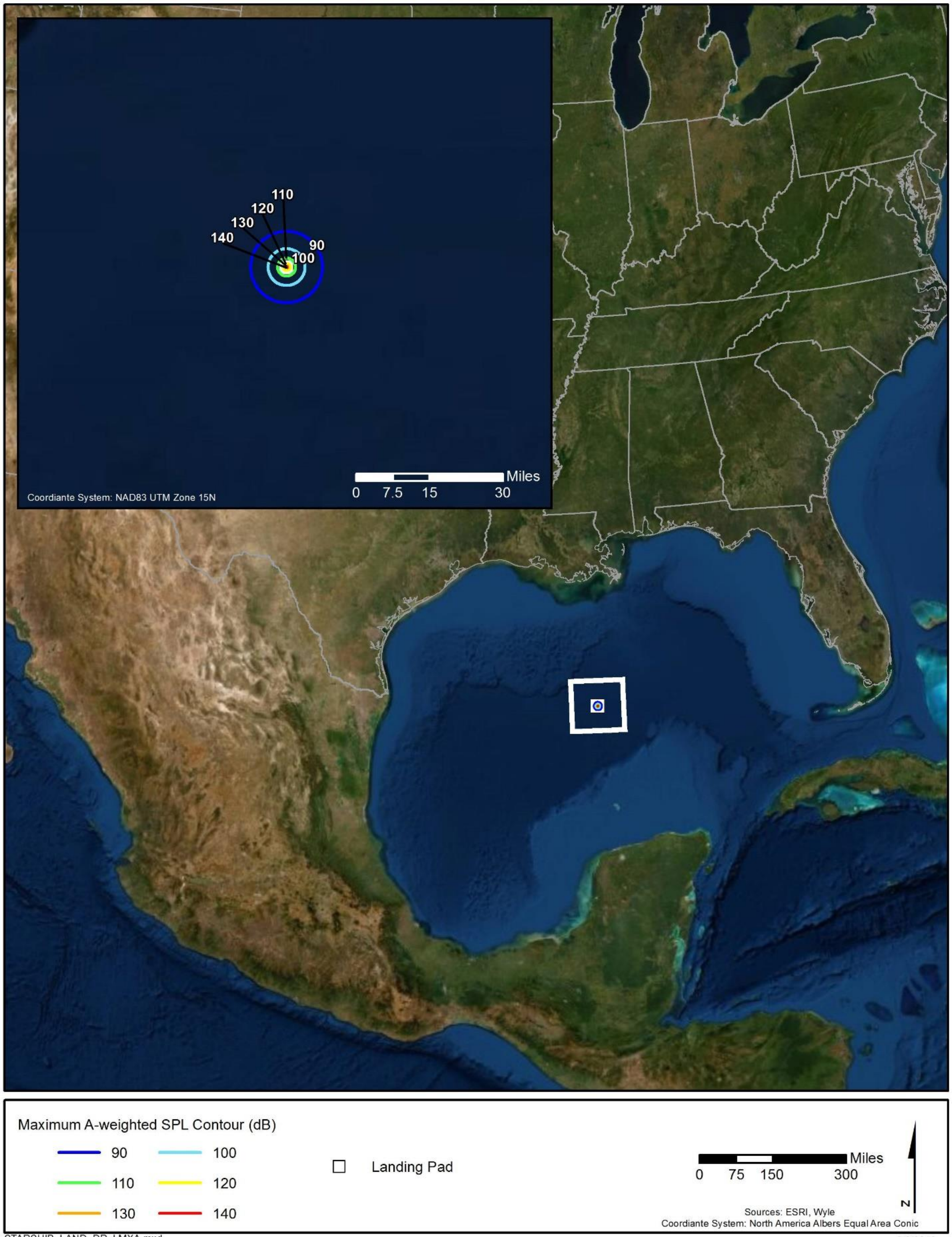

Figure 15. Starship Landing at the Downrange Site: Maximum A-Weighted Sound Levels

Figure 16. Starship Landing at the Downrange Site: Sound Exposure Levels

4.2 Starship Suborbital Flight Landings at Boca Chica

RNOISE was used to estimate the L_{Amax}, and SEL contours for Starship suborbital flight landings at Boca Chica. The Starship suborbital flight trajectory was provided by SpaceX in file 'STARSHIP_15KM_7775A4FD_80_12.ASC'. L_{Amax} contours indicate the maximum sound level at each location over the duration of the landing where engine thrust varies according to the reentry/descent thrust schedule provided. Starship suborbital flight landings involve the Starship vehicle without the booster.

RNOISE computations were performed as noted in Section 4.1. Ground areas were modeled as acoustically soft, and water acoustically hard. Ground effect was based on a weighted average over the propagation path. The L_{Amax} contours for the Starship suborbital flight landing at Boca Chica are shown in Figure 17 and in Figure 18 using a zoomed in map scale. The landing pad location at Boca Chica and landing trajectory are indicated in the map legends as is the Padre Island National Seashore. In Figure 18 the 90 dB L_{Amax} contour is about 5 miles from the Boca Chica landing site in mostly unpopulated areas except Port Isabel and the southern part of South Padre Island. Residents of Brownsville may notice levels above 60 dB L_{Amax} especially for nighttime landing events. Compared with the Starship suborbital launch noise levels presented in Section 3, Starship suborbital flight landing noise levels are considerably lower due to the lower total engine thrust used for landing operations and the altitudes at which landing thrust is applied. Similarly, the SEL contours for the Starship suborbital flight landing are shown in Figures 19 and 20.

The next section presents single event noise levels for Super Heavy Booster landings at the Boca Chica and Downrange landing sites.

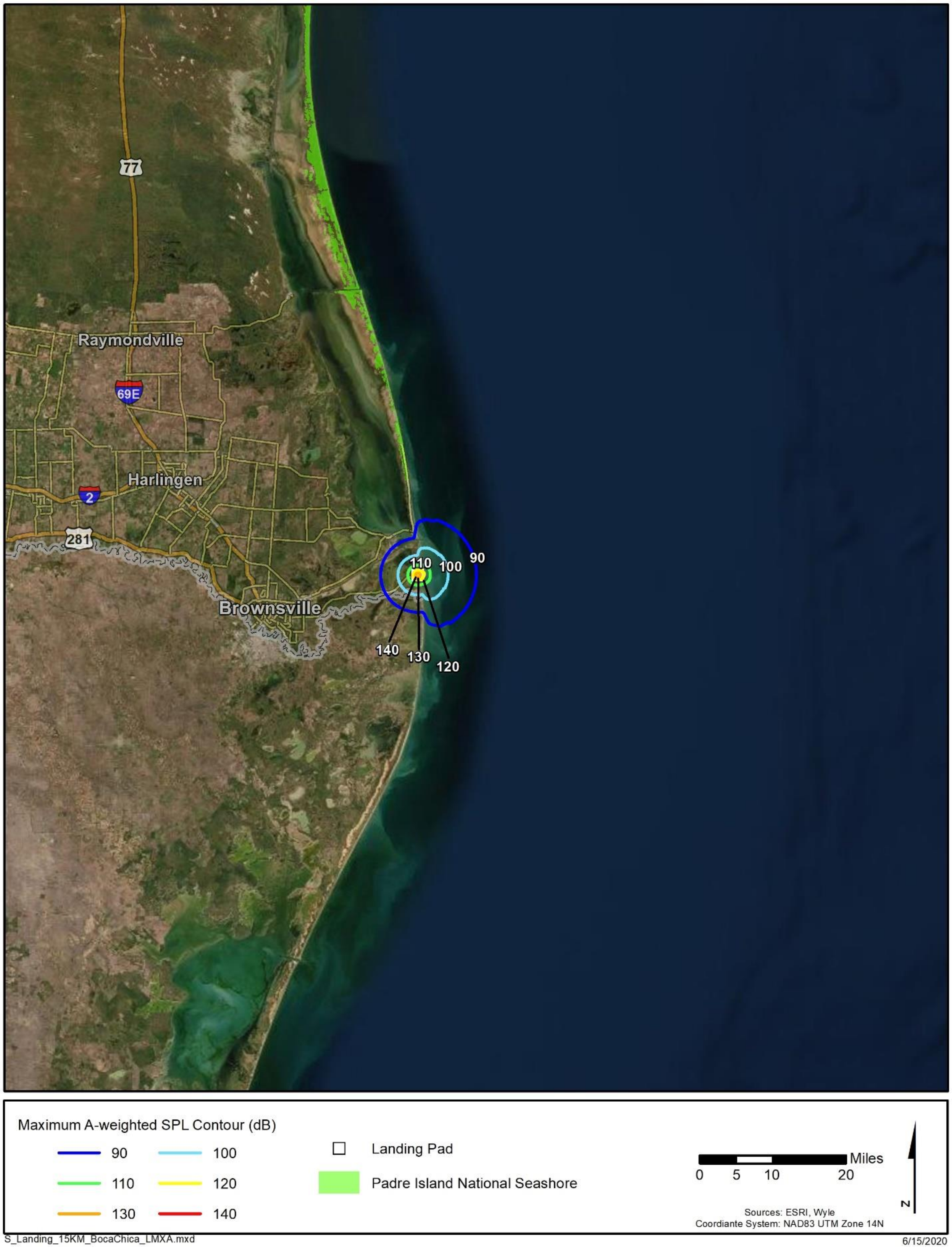

Figure 17. Starship Suborbital Flight Landing at Boca Chica: Maximum A-Weighted Sound Levels

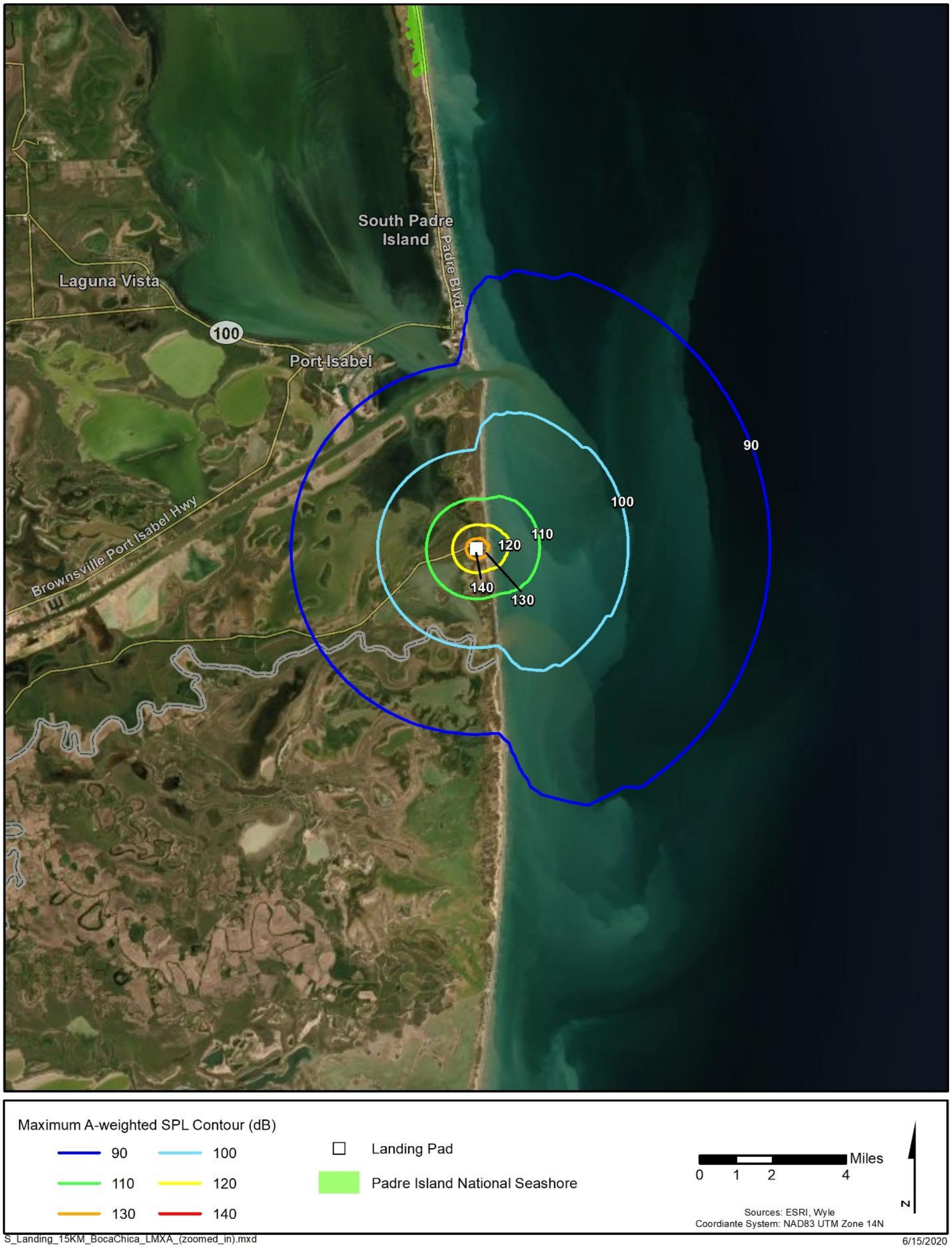

Figure 18. Starship Suborbital Flight Landing at Boca Chica: Maximum A-Weighted Sound Levels (Zoom In)

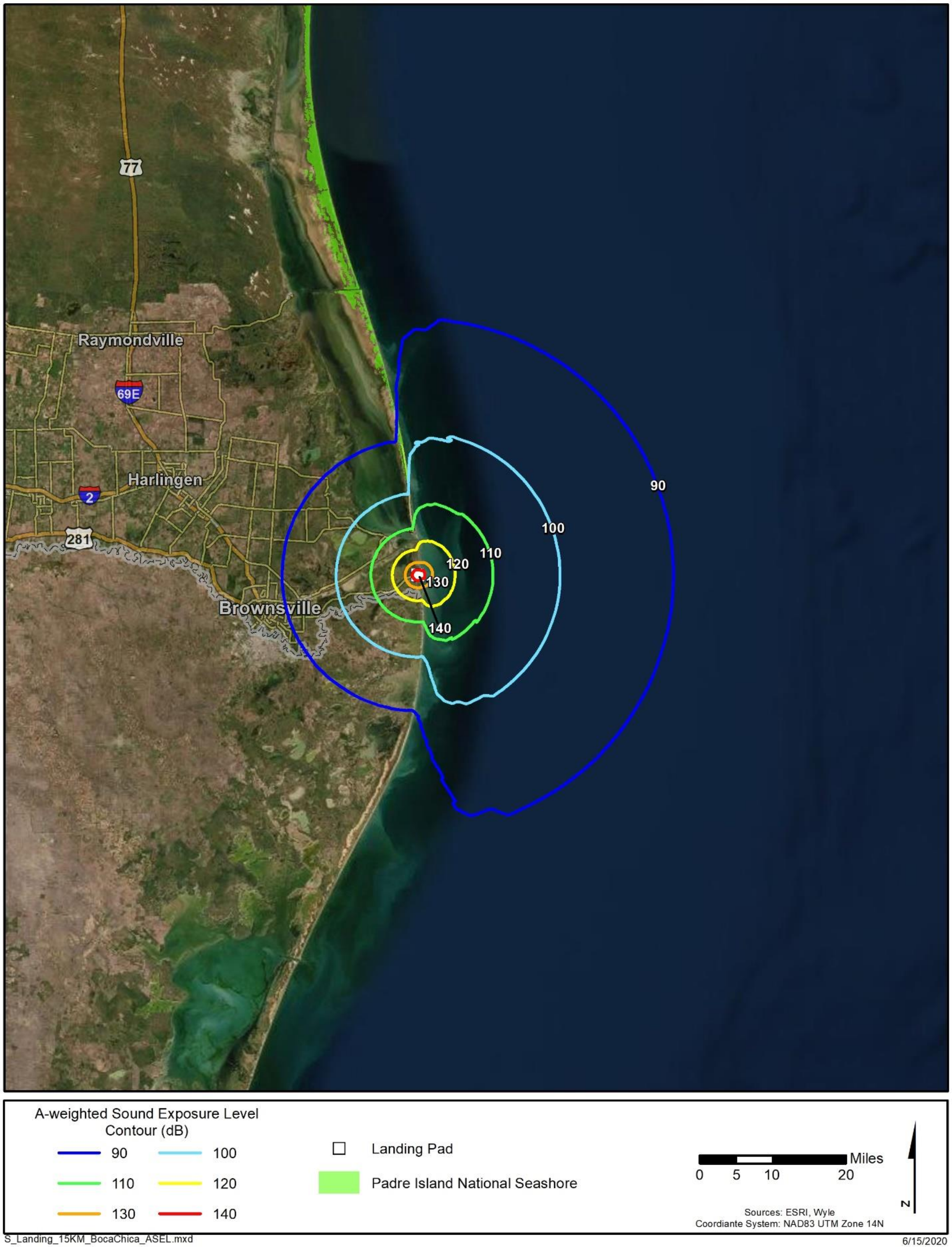

Figure 19. Starship Suborbital Flight Landing at Boca Chica: Sound Exposure Levels

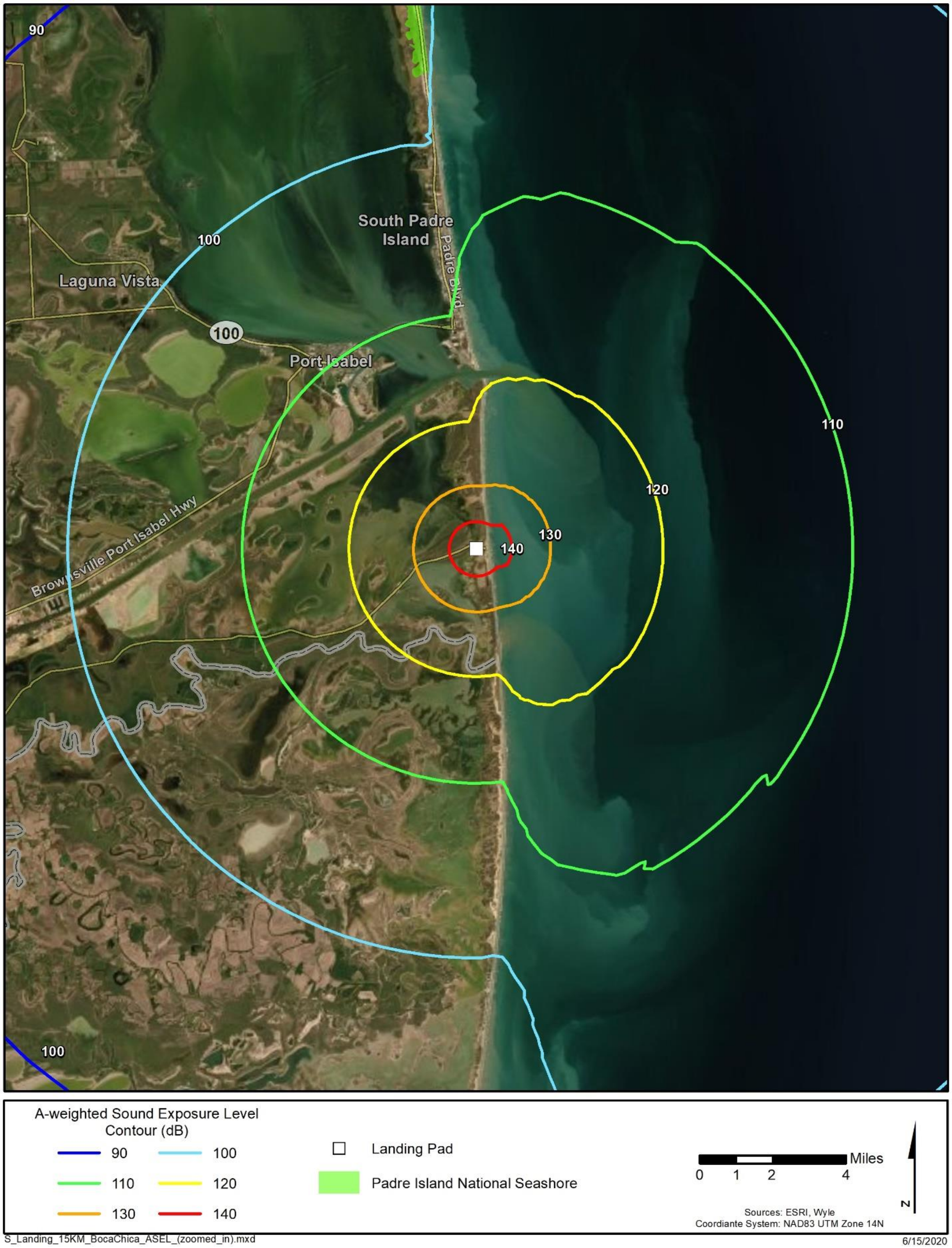

Figure 20. Starship Suborbital Flight Landing at Boca Chica: Sound Exposure Levels (Zoom In)

4.3 Super Heavy Booster Landings at Boca Chica and the Downrange Site

RNOISE was used to estimate the L_{Amax}, and SEL contours for Super Heavy Booster landings at the Boca Chica and downrange landing sites. The Super Heavy Booster descent/landing trajectory for Boca Chica was provided in file 'Super_Heavy_Boca_RTLS_ROTATED_80_12.ASC' and the landing trajectory for the downrange site was provided in file 'Super_Heavy_Boca_Downrange_ROTATED_80_12.ASC'. L_{Amax} contours indicate the maximum sound level at each location over the duration of the landing where engine thrust varies according to the reentry/descent thrust schedule provided.

RNOISE computations were performed as noted previously in Section 3. Ground areas were modeled as acoustically soft, and water acoustically hard. Ground effect was based on a weighted average over the propagation path. The L_{Amax} contours for the Super Heavy Booster landing at Boca Chica are shown in Figure 21 and in Figure 22 (using a zoomed in map scale). Similarly, the SEL contours for the Super Heavy Booster landing at Boca Chica are shown in Figures 23 and 24 (using a zoomed in map scale). In Figure 21 the 90 dB L_{Amax} contour is about 7 miles from the Boca Chica landing site and in unpopulated areas. Residents of Brownsville may hear booster landing events above 60 dB, particularly nighttime landings.

Figures 25 and 26 show L_{Amax} and SEL contours, respectively, for Super Heavy Booster landings at the downrange landing site; inset maps show the contours using a zoomed in scale. In these figures, the drone ship location is identified in the main map legend as the landing pad. The Super Heavy booster downrange landings are planned to occur several hundred miles offshore, therefore noise from these events is not expected to be noticed by residents along the coast.

Section 5 presents the estimated noise levels for Starship and Super Heavy Booster static fire tests that are planned to be conducted at the Boca Chica Launch Facility.

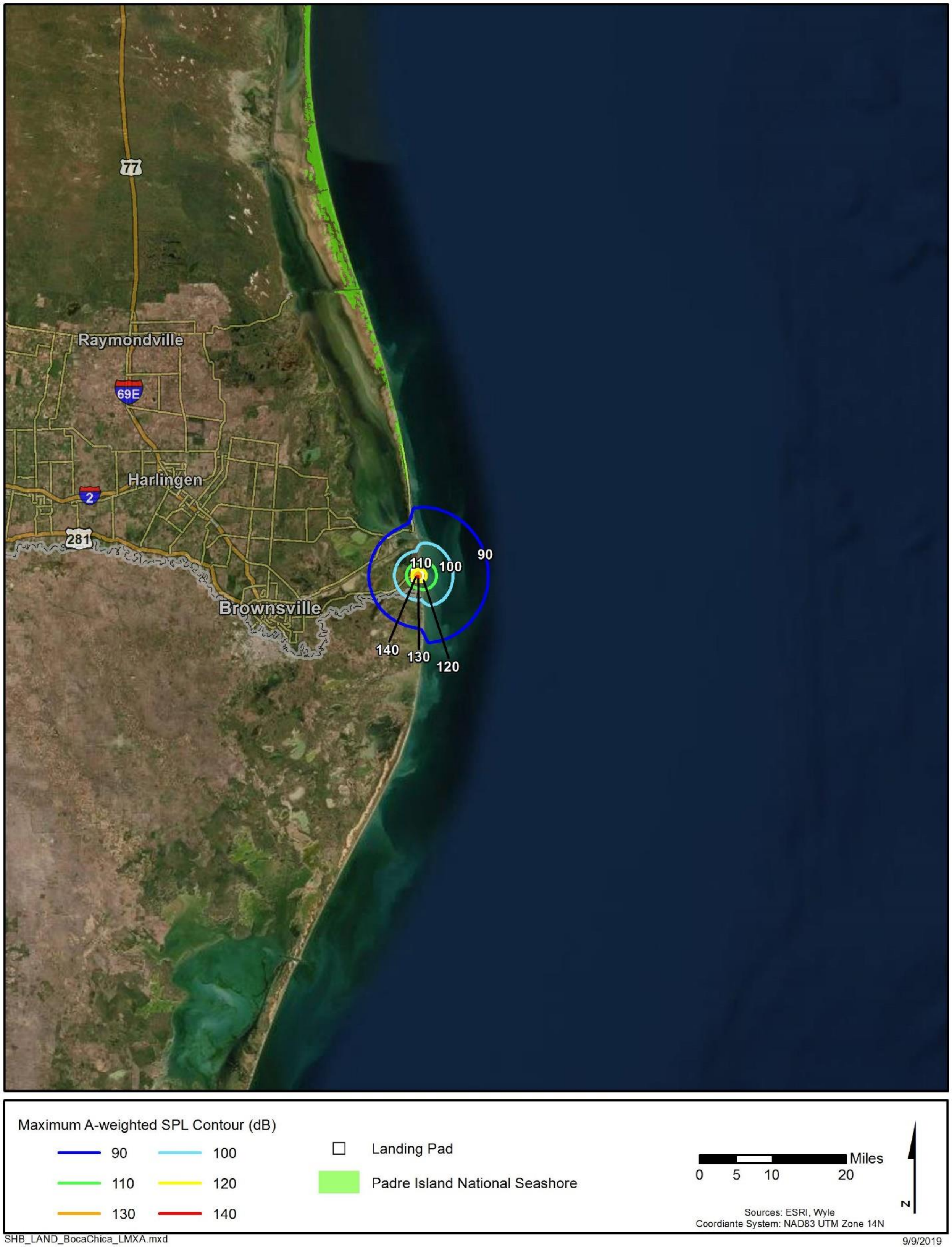

Figure 21. Super Heavy Booster Landing at Boca Chica: Maximum A-Weighted Sound Levels

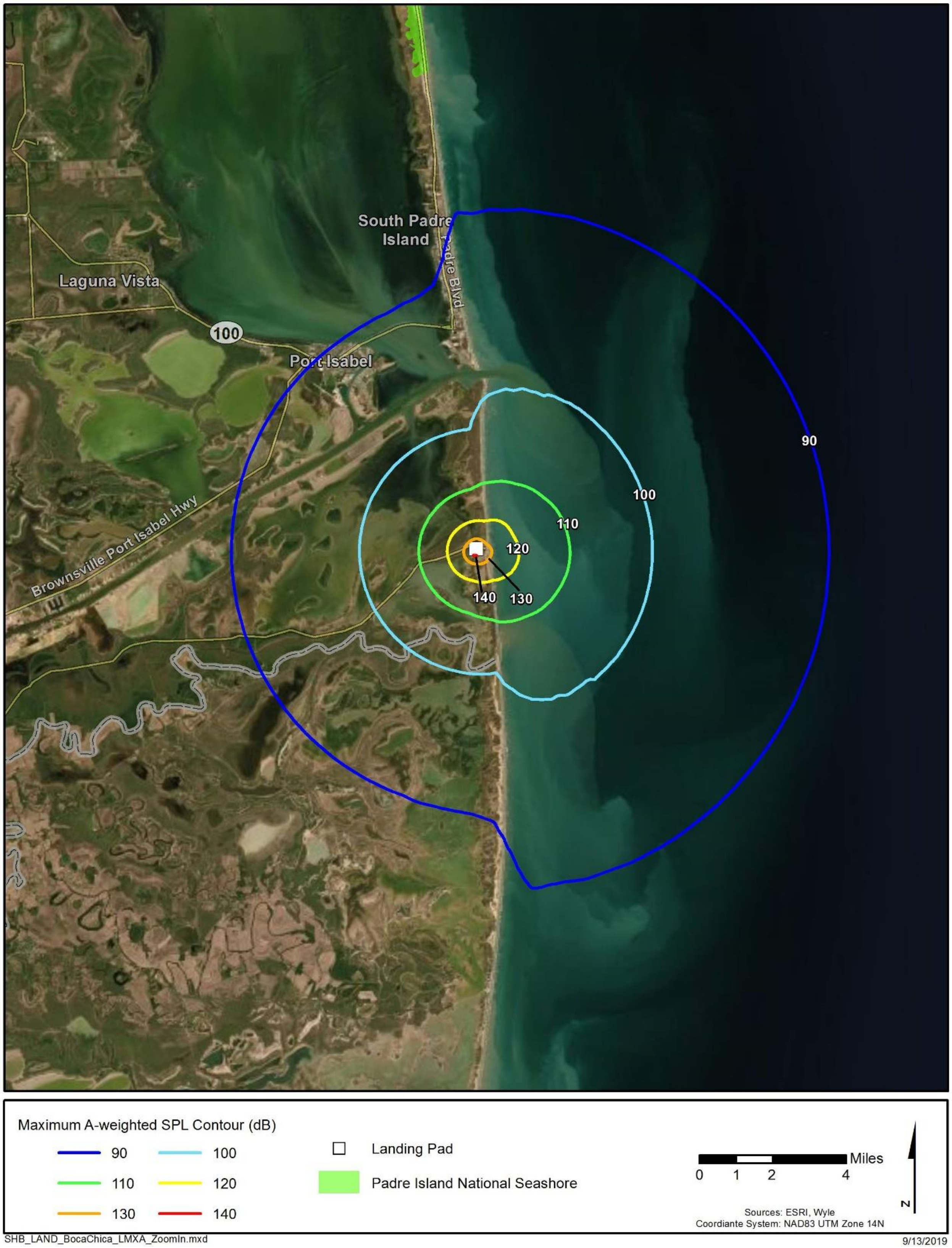

Figure 22. Super Heavy Booster Landing at Boca Chica: Maximum A-Weighted Sound Levels (Zoom In)

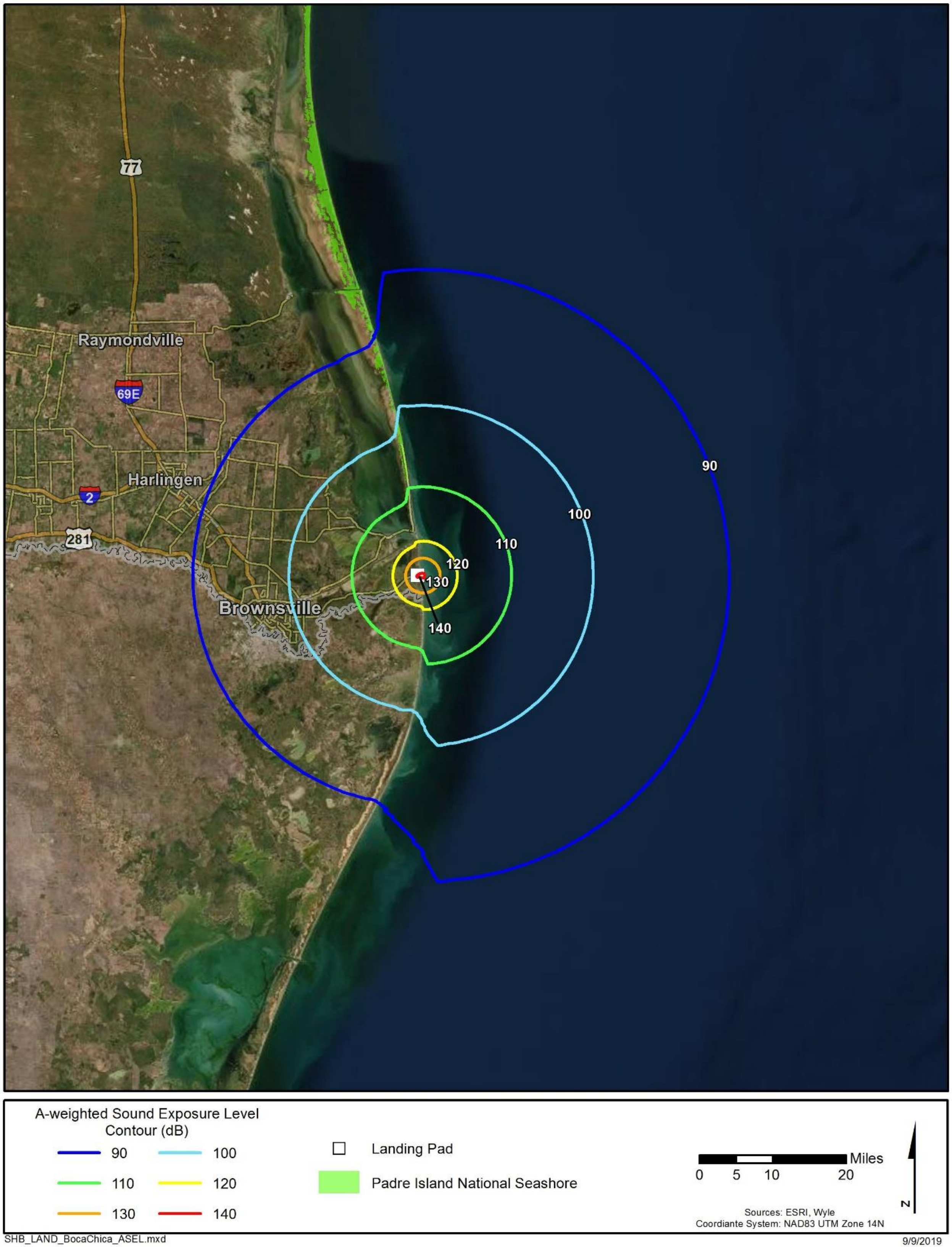

Figure 23. Super Heavy Booster Landing at Boca Chica: Sound Exposure Levels

Figure 24. Super Heavy Booster Landing at Boca Chica: Sound Exposure Levels (Zoom in)

Figure 25. Super Heavy Booster Landing at the Downrange Site: Maximum A-Weighted Sound Levels

Figure 26. Super Heavy Booster Landing at the Downrange Site: Sound Exposure Levels

5 Static Fire Test Noise Levels

5.1 Starship Static Fire Tests at Boca Chica

Starship static fire tests are planned to occur at the Boca Chica Launch Facility where 3 engines, that each generate 478 Klbs of thrust at sea level, will be fired for 60 seconds. Figures 27 and 28 show the estimated L_{Amax} and SEL contours, respectively, for the Starship static fire test. The L_{Amax} 90 dB contour extends about 2.5 miles west of the test site while the SEL 90 dB contour extends about 7 miles west of the test site. To the east of the test site, these contours extend much farther out due to modeling sound propagation over water compared with propagation over land to the west. Residents of Brownsville may hear Starship static test events above 60 dB, and particularly at night, if onshore wind conditions favor sound propagation to the west.

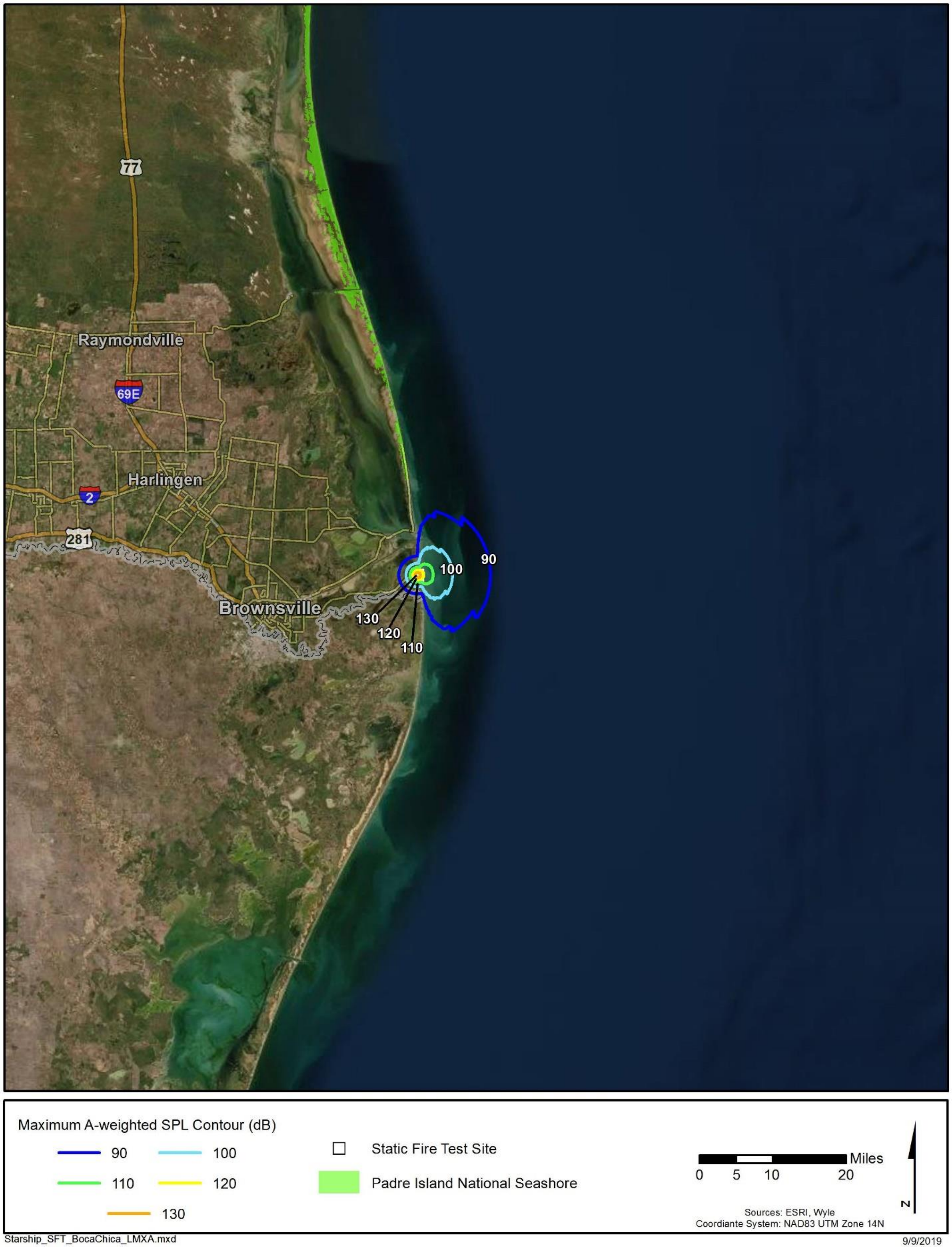

Figure 27. Starship Static Fire Test at Boca Chica: Maximum A-Weighted Sound Levels

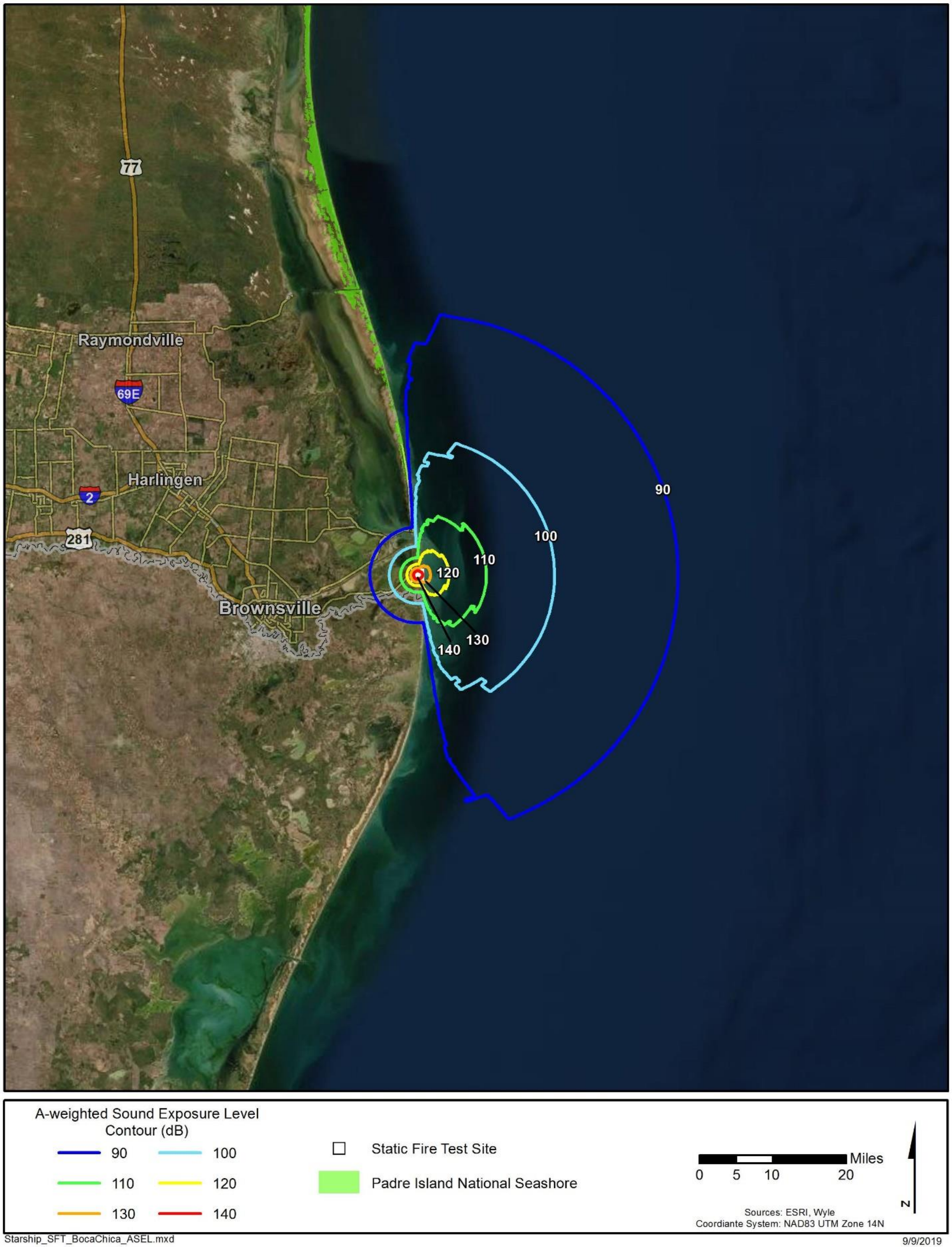

Figure 28. Starship Static Fire Test at Boca Chica: Sound Exposure Levels

5.2 Super Heavy Booster Static Fire Tests at Boca Chica

Super Heavy Booster static fire tests are planned to occur at the Boca Chica Launch Facility where all 37 engines, that each generate 375 Klbs of thrust at sea level, will be fired for 60 seconds. Figures 29 and 30 show the estimated L_{Amax} and SEL contours, respectively, for the Super Heavy Booster static fire test. The L_{Amax} 90 dB contour extends about 4 miles west of the test site while the SEL 90 dB contour extends about 10 miles west of the test site. To the east of the test site, these contours extend much farther out due to modeling sound propagation over water compared with propagation over land to the west. Residents of Brownsville may hear Super Heavy Booster static test events above 60 dB, and particularly at night, if onshore wind conditions favor sound propagation to the west.

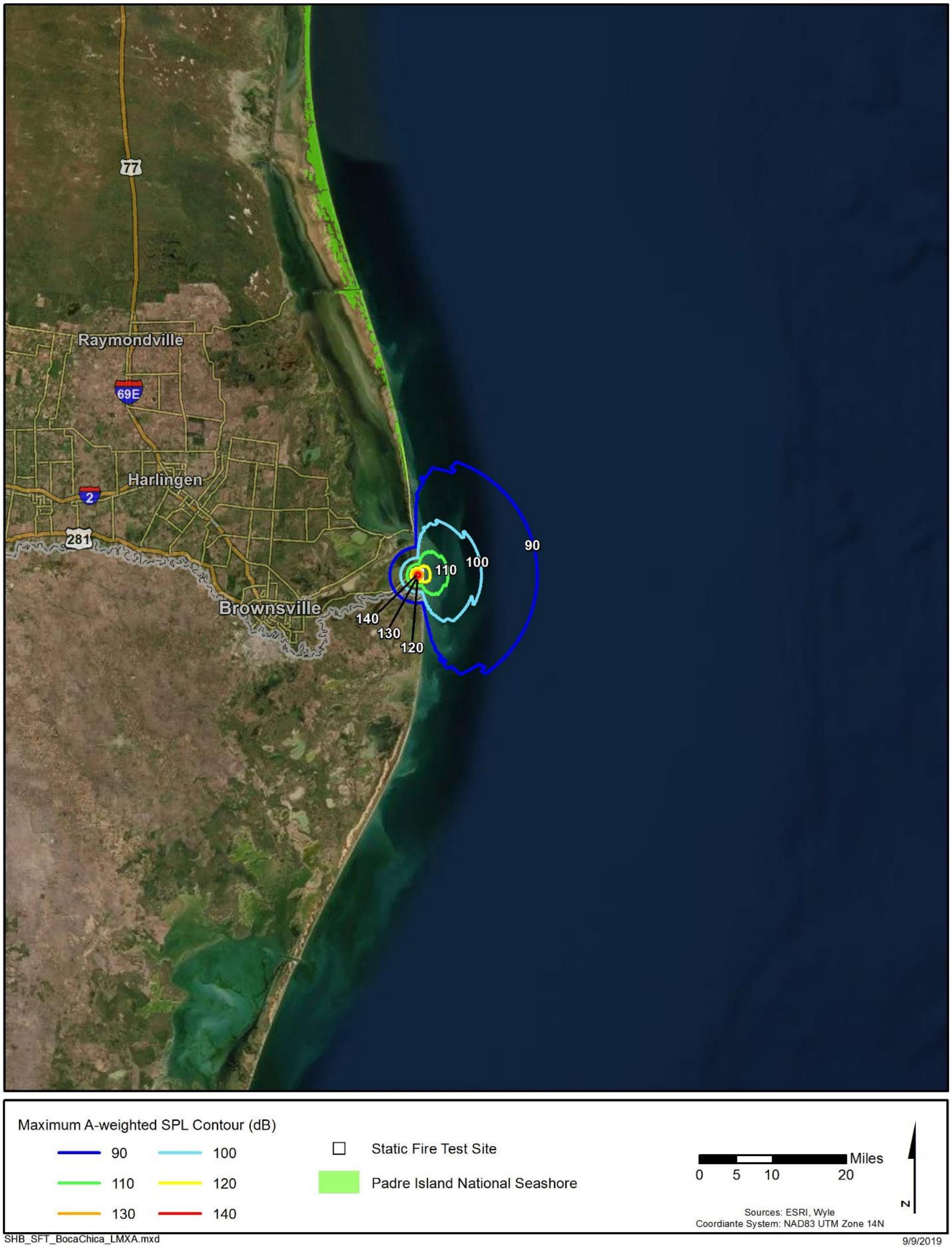

Figure 29. Super Heavy Booster Static Fire Test at Boca Chica: Maximum A-Weighted Sound Levels

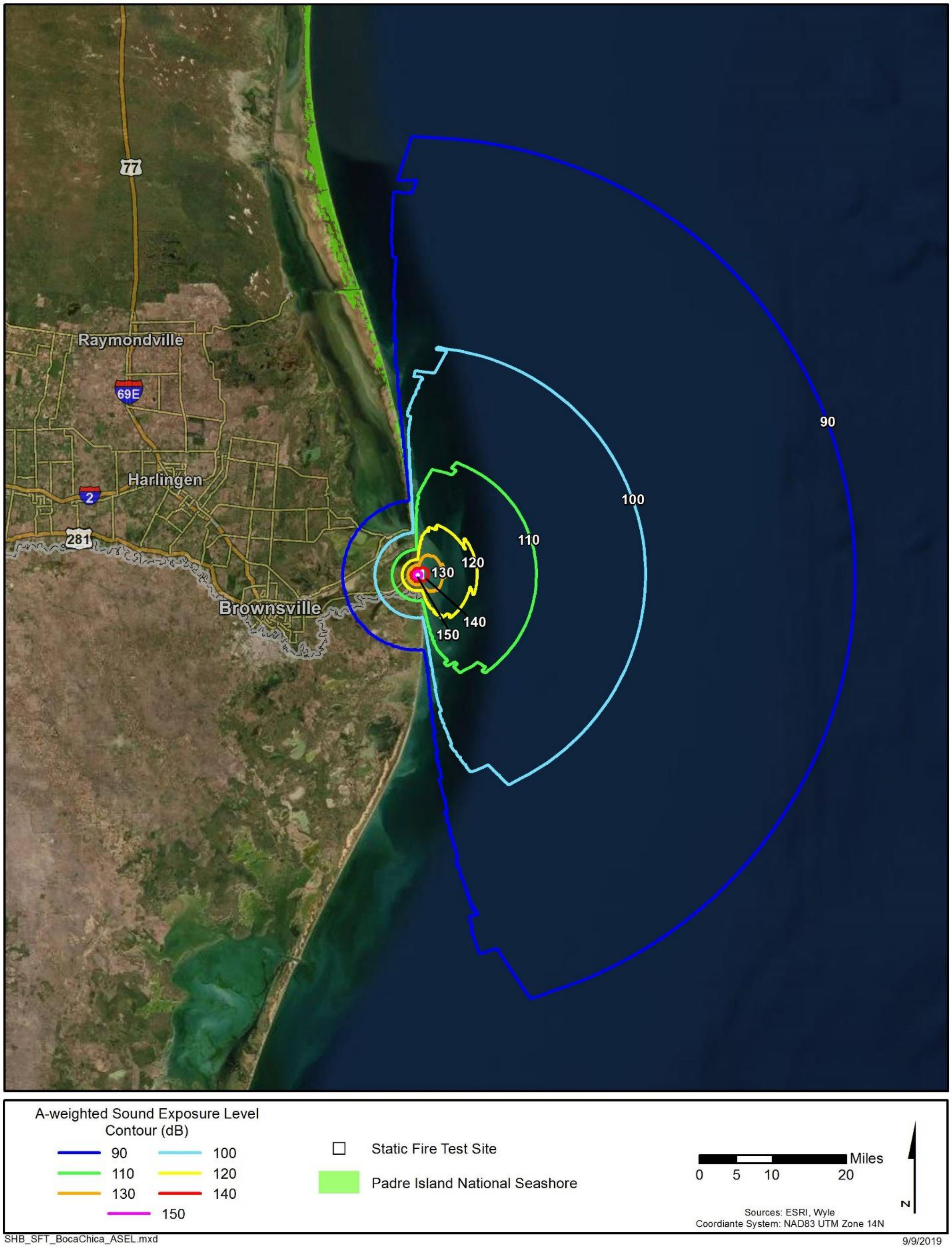

Figure 30. Super Heavy Booster Static Fire Test at Boca Chica: Sound Exposure Levels

6 Cumulative Noise Levels for Starship and Super Heavy Booster Operations

6.1 Projected Launch, Landing, and Static Fire Tests at Boca Chica

Cumulative noise levels were estimated, using DNL, for projected launch, landing, and static fire test operations at the Boca Chica Launch Facility. These estimates were made for each operation type (e.g. Starship orbital launches or Starship static fires) and results indicate that none of the operation types alone are expected to cause adverse community noise exposure using the 65 DNL contour for assessment purposes. However, when cumulative noise is assessed for certain combinations of these operation types, then adverse community noise exposure is possible in some of the populated areas in the vicinity of the Boca Chica Launch Facility.

Two scenarios were analyzed for different combinations of projected launch, landing, and static fire operations that are expected to fulfill mission and test requirements at the Boca Chica Launch Facility. In this modeling analysis, certain operations were held constant and other operations were varied with the objective of maximizing either launch or test operations while ensuring that overall community noise exposure was within acceptable limits. The resultant annual operations determined for each scenario are as follows.

<u>Operations Scenario 1</u>

- 10 Super Heavy static fires
- 5 Super Heavy orbital launches
- 5 Super Heavy landings
- 14 Starship static fires
- 5 Starship suborbital launches
- 10 Starship landings

The estimated DNL contours in the vicinity of the Boca Chica Launch Facility for the combined annual operations of scenario 1, using an operations split of 80% daytime and 20% nighttime, are shown in Figure 31. For these combined Starship and Super Heavy Booster operations, it can be seen from Figure 31 that the 65 DNL contour is located entirely in areas that are unpopulated.

Operations scenario 1 maximized Super Heavy orbital launch and landing and Starship landing operations (flight operations) whereas operations scenario 2 maximized Starship static fires and suborbital launches (test operations).

<u>Operations Scenario 2</u>

- 10 Super Heavy static fires

- 3 Super Heavy orbital launches
- 0 Super Heavy landings
- 35 Starship static fires
- 20 Starship suborbital launches
- 23 Starship landings

The DNL contours shown in Figure 32 are a cumulative noise estimate for all projected Scenario 2 annual operations at the Boca Chica Launch Facility. Like the results for operations scenario 1, the 65 DNL contour for the combined operations of scenario 2 is entirely located in unpopulated areas.

In summary, SpaceX is planning to conduct flight operations and testing of the Starship and Super Heavy Booster vehicles at the Boca Chica Launch Facility (TX) and downrange landing site. Noise from individual launch, landing, and static fire test events is expected to be heard by people in the surrounding communities, including Brownsville, Laguna Vista, Port Isabel, and South Padre Island. But, 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. Cumulative noise in these surrounding communities, whether from multiple events of a single operation type as defined in projected operations scenarios 1 and 2 or from all these individual events combined, is estimated to be below levels associated with adverse noise exposure.

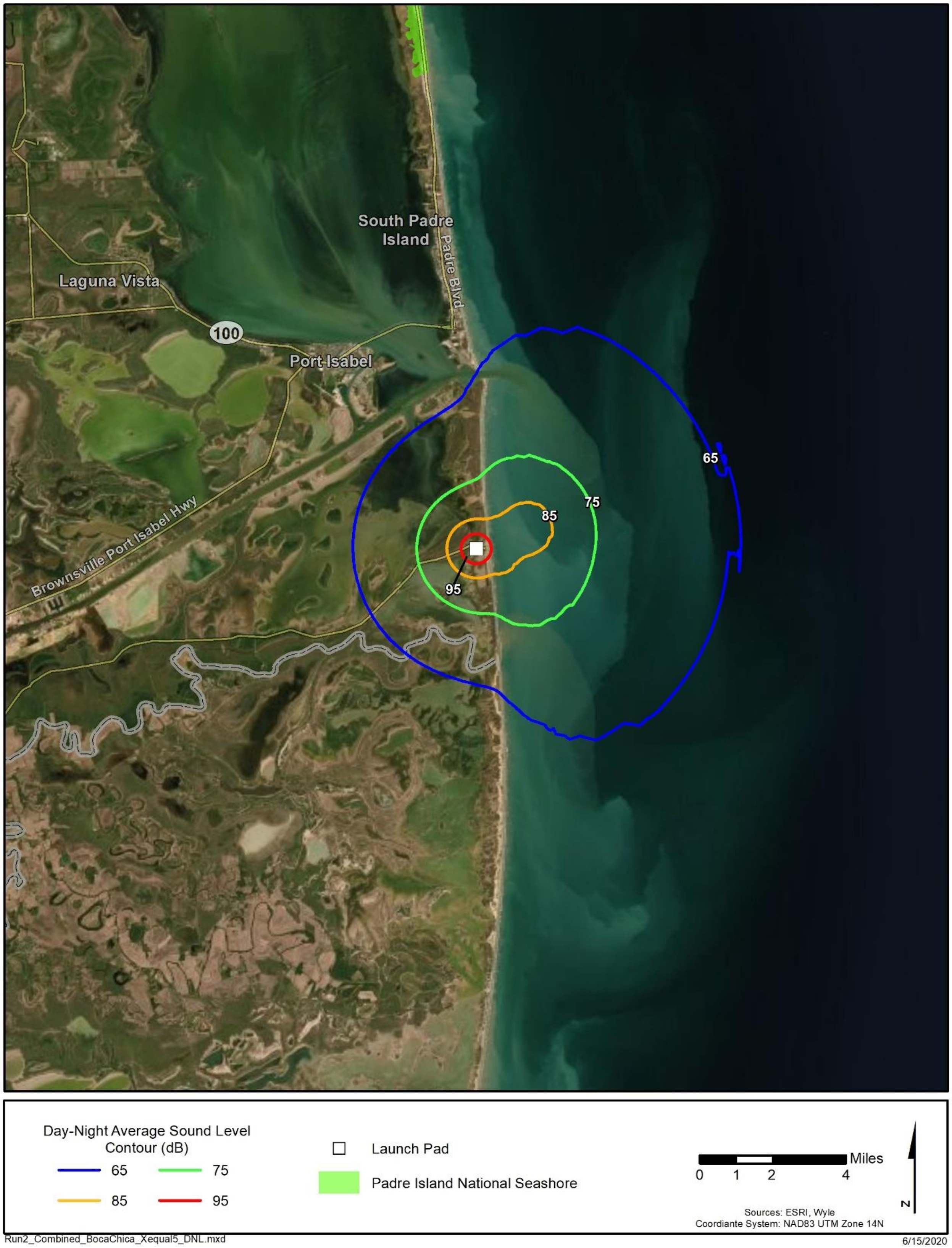

Figure 31. Starship and Booster Scenario 1 Combined Operations: DNL Contours

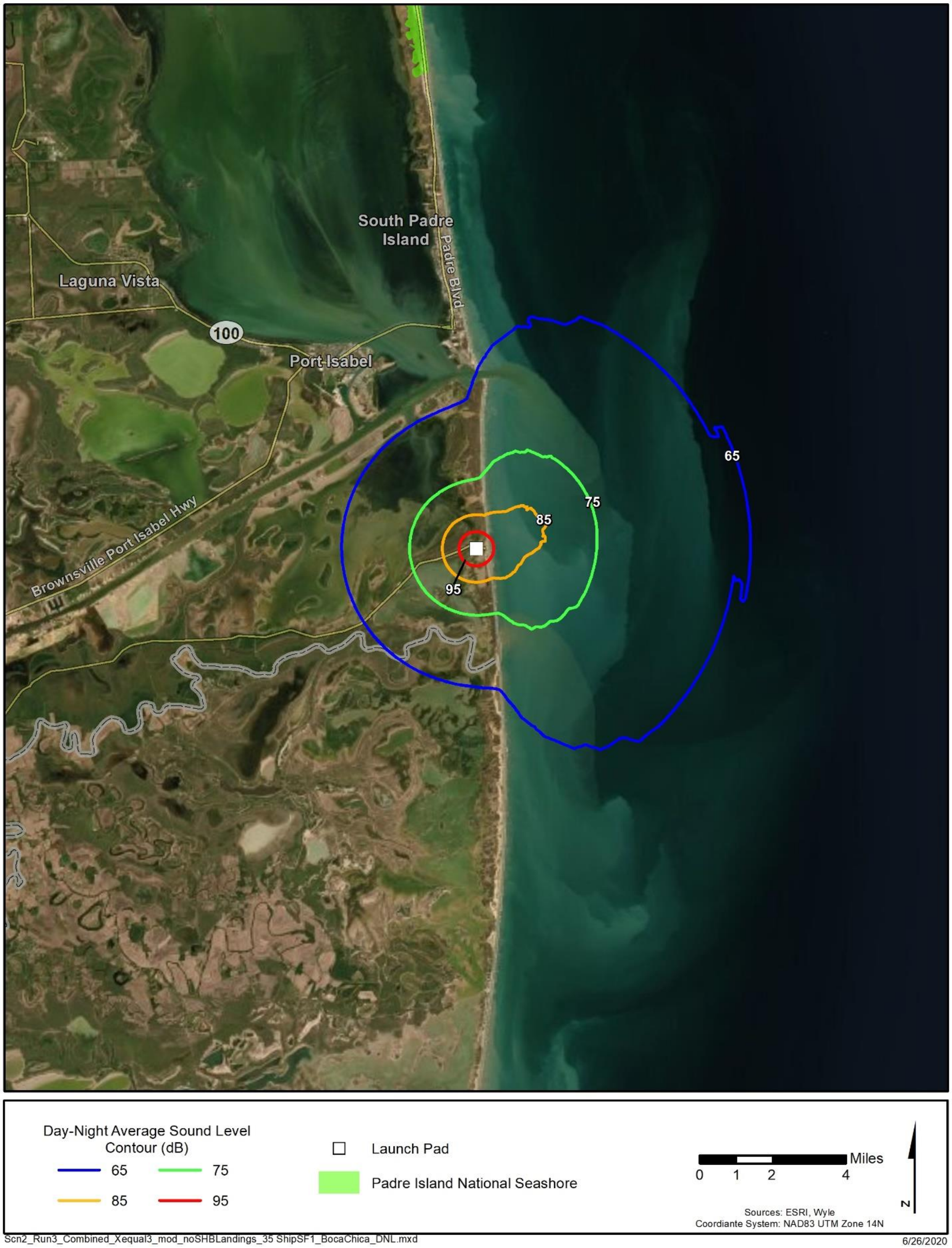

Figure 32. Starship and Booster Scenario 2 Combined Operations: DNL Contours

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MEMORANDUM **August 11, 2020**

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.

An 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*. 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 expected to result from Super Heavy and Starship landings. SpaceX is proposing to use PCBOOM, an FAA-approved model, for predicting sonic booms from landings.

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, 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.

For the second stage Starship vehicle, SpaceX estimated a shape factor of 0.2 based on the NASA-1122 sonic boom reference. This shape factor estimation was derived over a range of large angles of attack, consistent with the vehicle's planned flight profile. Because boom profiles predicted using this estimated shape factor are bounded by those produced using the PCBOOM database for the Shuttle orbiter, SpaceX has chosen to provide sonic boom predictions for the Starship second stage using the Shuttle orbiter parameters.

The Starship second stage vehicle shares several key reentry profile characteristics with the Falcon 9 first stage when returning to land. Most notably, both stages are long, slender vehicles that travel through supersonic speeds at low angles of attack with engines facing into the flow. SpaceX is leveraging these similarities to estimate the appropriate shape factor for the Starship second stage vehicle. The Falcon 9 first stage shape factor of 0.035 was derived by anchoring measured data across ten flights to sonic boom modeling with the Carlson method. SpaceX is utilizing a shape factor of 0.07, or twice as large as the Falcon 9 first stage, from comparisons of shock wave strength in the near-field from CFD analysis of the Super Heavy and Falcon 9 first stage vehicles.

SpaceX Sonic Boom Data and Modeling

Previous work on predicting and measuring sonic boom magnitudes with the return to land of the Falcon 9 first stage has shown that a simplified model, grounded in measured data, has improved capability for general prediction over PCBOOM, unless specific flight atmospheric conditions are utilized. Until data can be collected for sonic booms during Starship and Super Heavy return, SpaceX is leveraging generic analysis with PCBOOM to predict bounding ground overpressures.

Figure 1 shows the SpaceX modeled overpressure predictions for a Starship land landing. The levels range from 1.2 psf to approximately 2.2 psf, with the highest levels on land at 2 psf.

The boom footprint for Figure 2 shows the SpaceX modeled overpressure predictions for a Super Heavy land landing. The levels range from 2.5 psf to approximately 15 psf at the landing pad.

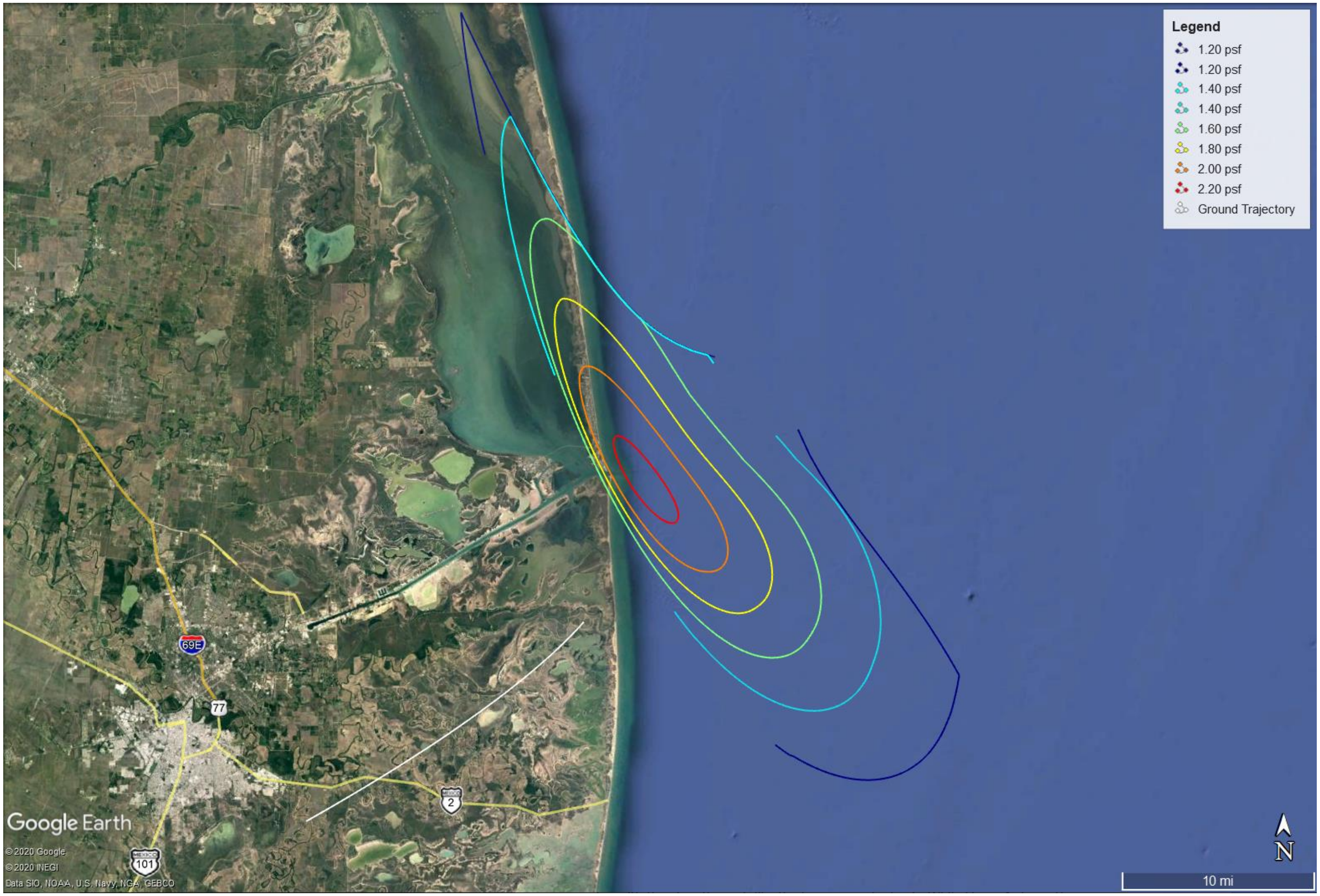

Figure 1: Starship Sonic Boom Levels for Reentry/Landing at Boca Chica, TX

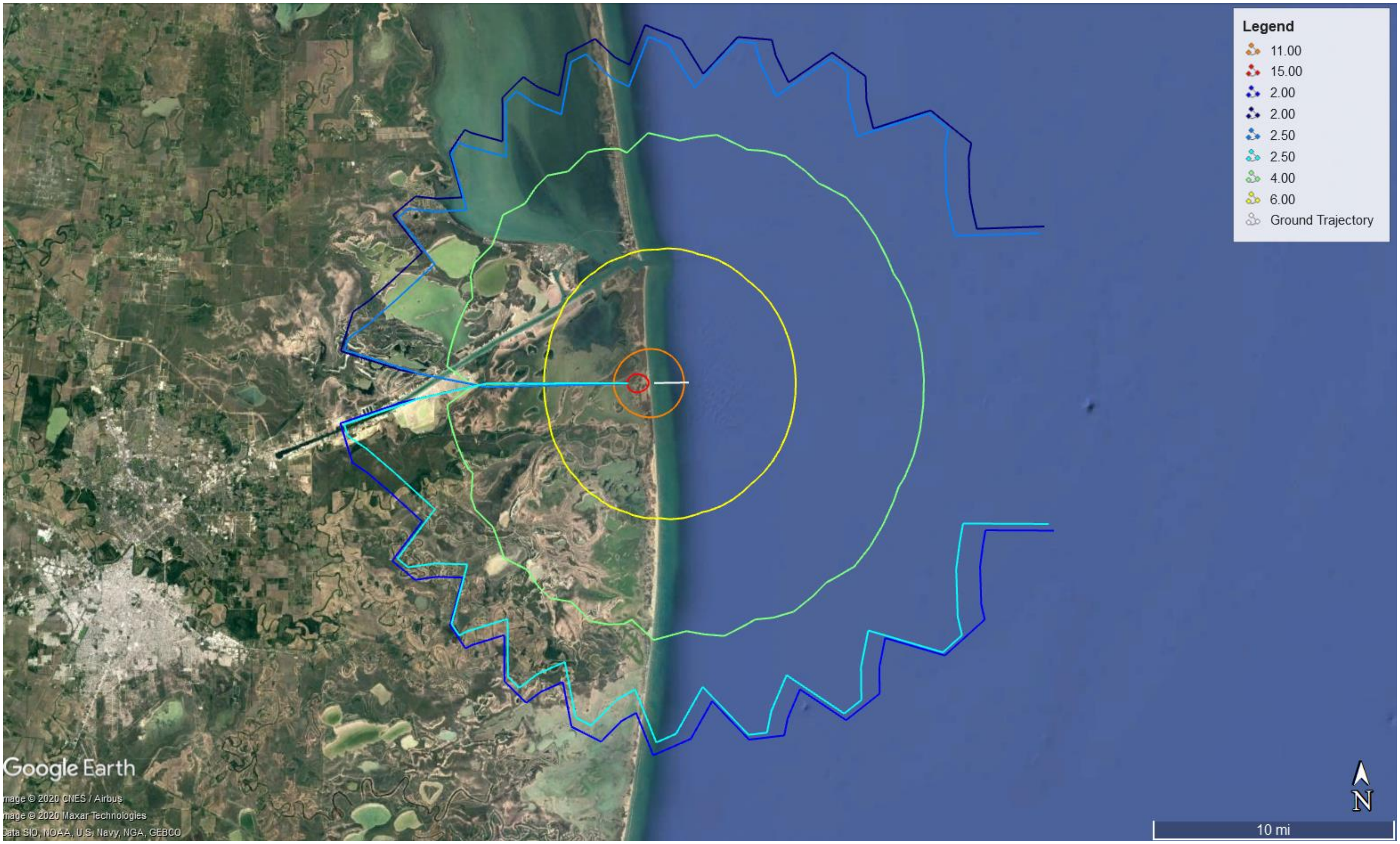

Figure 2: Super Heavy Sonic Boom Levels for Reentry/Landing at Boca Chica, TX