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Tracking a Starship launch and associated sonic booms

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On November 19, 2024, Space-X launched the sixth test flight of their Starship rocket. Measurements were made by Brigham Young University at 21 different locations around the launch pad, including two 3-meter-radius vector probes located roughly 2 km north and 2 km south of the pad. There was also an array of measurement stations near the coast ranging from 3 km south of the pad to 27 km north. Using a broadband time-correlation technique, the direction of the sound source can be determined from the vector probes. Having two vector probes potentially allows the measurement of the trajectory of the rocket as it lifts off. It was found that the small distance between the two probes limited the accuracy of the position determination when the rocket was downrange. On this launch, the super-heavy booster did not return to the launch site but was instead diverted to the Gulf of Mexico. There were two transient events that occurred after the launch which were associated with the booster-return and the hot-staging ring reentry. These sonic booms were poorly localized by the intensity probes, but well localized by the arrival times of the booms at the array of other stations.

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1. INTRODUCTION

SpaceX's Starship is the most powerful rocket, measured by thrust, ever successfully launched,[1] producing nearly twice the thrust of the Saturn V or SLS rockets.[2] This large power has generated significant interest in the acoustic impact it has on its surroundings. During SpaceX's sixth Starship launch on November 19, 2024, Brigham Young University (BYU) deployed 21 sound recording stations to characterize launch noise and Super Heavy booster return sonic booms. These stations utilized our standard Portable Units for Recording Acoustics (PUMAs) attached to microphones mounted inverted over hard ground plates and protected by windscreens.[3]

Two of these stations, located approximately two km north and south of the pad, were laid out as 3-meter-radius acoustic vector probes. Each probe consisted of four microphones: three arranged in a circle at $120°$ intervals and one at the center. In other work this arrangement has been used as an intensity probe, but since we do not calculate or use the acoustic intensity in our analysis we are calling them vector probes. By applying a time-domain cross-correlation technique, researchers can determine the sound's direction of origin.[4] Two of BYU's purposes for this measurement were to track the rocket's initial ascent and determine the directional source of sonic booms generated during the booster's landing and the hot-staging-ring reentry.

2. ACOUSTIC VECTOR PROBES

Figure 1 shows the vector probe locations, with station 3 situated 1.7 km north and station 5 located 1.9 km south of the launch pad. In the figure, these are indicated by yellow bullseye markers, while single-microphone stations are shown in red. The assumed rocket trajectory is shown as a violet line. Unlike the level, coplanar setup at station 3, the bumpy sand dunes at station 5 prevented the microphones from being laid out in a single plane. Because relative altitudes were limited to visual estimation at the time, this lack of planarity introduces additional complexity in the data analysis.

A. TRACKING THE ROCKET WITH ACOUSTIC VECTOR PROBES

The process used to track the rocket with these probes is outlined in Hart *et al.*[4] The sound is assumed to come in as a plane wave with an elevation angle θ and an azimuthal angle ϕ. This creates predictable delays between the arrival of the sound at each microphone relative to the others as a function of θ and ϕ. A cross-correlation between the all four channels is performed to find the delays between the channels. An example of the cross-correlation is shown in Figure 2. The top graph in the figure shows the signals over a one-second interval as they were recorded. The bottom graph shows the same data shifted according to the delays found by the cross-correlation. Using those delays, a least-squares fit to the model is performed to find the best θ and ϕ that fit those data. The fit to the data in this plot shows that the sound in this sample came from $\theta = 0$ and $\phi = 0$, meaning that it came from near ground level straight from the direction of the pad. This is consistent with the fact that it is measured 20 seconds after lift-off, when the rocket is just rising from the pad. Taking into account the propagation delay and the fact that the sound source is expected to be roughly 16-19 effective nozzle diameters from the bottom of the rocket,[5] the sound source was at an angle of roughly 5° above the horizontal, indistinguishable from ground level because of the insensitivity of the cosine to small angles.[4]

B. COMPARISON OF THE RESULTS TO A TRAJECTORY

Space enthusiasts scrape the telemetry data from the SpaceX livestream of every launch of Starship, which includes velocity and altitude data for the booster.[6] The altitude data can be finite-differenced to find the vertical velocity, which can be used in conjunction with the total velocity to find the downrange velocity.

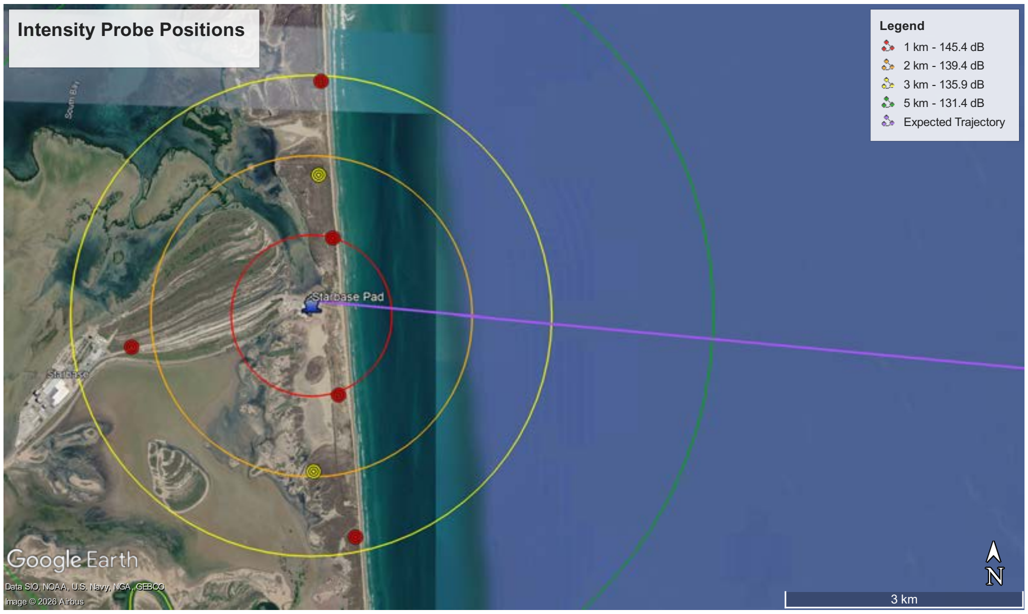

Figure 1: The positions of the two 3-m vector probes relative to the launch pad at Starbase, Texas. Station 3 is the yellow marker to the north of the launch site. Station 5 is the yellow marker to the south. The four circles are at radii of 1 km, 2 km, 3 km, and 5 km respectively. The violet line is the assumed trajectory of the launch. The red markers are other single-microphone recording stations. Map data: SIO, NOAA, US Navy, NGA, GEBCO, Image ©2026 Airbus

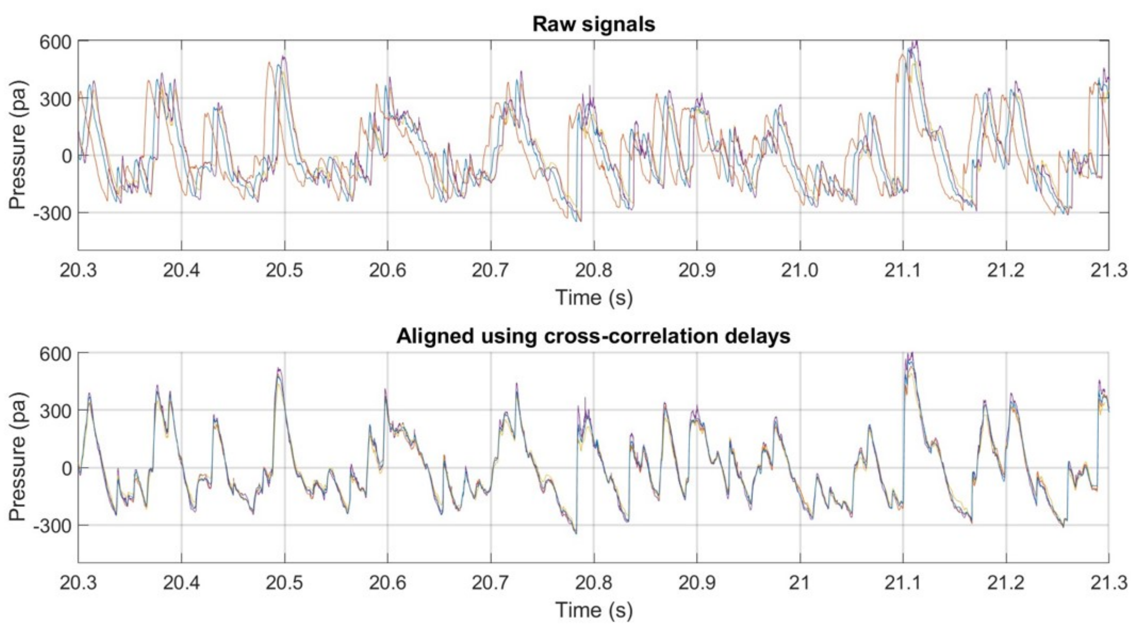

Figure 2: The top figure shows the signals as received on the four microphones of the acoustic vector probe. The bottom figure shows same figures aligned using the times derived from the one-second cross-correlation of the channels. The time delays show that this sound is coming from near ground level, straight forward from the probe. This corresponds to $\theta = \phi = 0$

Integrating that velocity gives the downrange distance. Using the assumed launch azimuth, this becomes an approximate trajectory for the rocket.

Altitude information in the trajectory of flight 6 is limited in precision at the start because in this launch the altitude was reported with only 1 km resolution. Velocity, however, was reported to 1 m/s resolution. Because of the limited altitude resolution at the beginning, the downrange distance calculation has limited accuracy until later in the trajectory.

Calculating θ and ϕ as a function of time and finding where that vector intersects the launch plane allows computation of the downrange distance and altitude of the rocket. The comparison between the trajectory and the measurement results are shown in Figure 3. This figure assumes that the rocket was traveling at a heading of 95.3° clockwise from north. Part (A) of the figure shows the comparison between estimated altitude of the rocket and the trajectory. The trajectory is shown in magenta. The altitude derived from both stations is unreliable before about 18 seconds because of the insensitivity of the cosine function to small angles ($\sim 10^\circ$ or less.)

It is necessary to compensate for the unevenness of the placement of the microphones of station 5 by assuming a tilt, but the size and direction of that tilt is uncertain. The fact that station 5 is also not co-planar introduces additional difficulties, which we did not try to mitigate in this study. Part (B) shows the comparison of the calculated downrange distance from the two probes and the trajectory. As mentioned earlier, the downrange distance of the trajectory is not reliable before about 40 seconds because of limitations from in the way it is calculated and the limited resolution of the data scraped from the livestream. Before about 10 seconds into the launch the rocket has not yet cleared the launch tower and pad effects (such as reflections and plume impingement) are also evident in the downrange data. We note that the downrange data seemed to be less affected by the non-coplanar nature of the probe at station 5 than the altitude data.

One original intention for these probes was to find the intersection of the vectors from each probe to the sound source. As can be seen in Figure 3, the results from the two probes are not fully compatible with each other. They agree in a qualitative way, but clearly they are not in good quantitative agreement. They may have agreed better if both probes had been more fully characterized in terms of microphones' positions, but that is not certain. Especially when the rocket is downrange (at distances greater than about 5 km), propagation effects and atmospheric turbulence can clearly affect the results, as seen in the unphysical fluctuations at those distances. This is likely the cause of the large fluctuations in the station 3 results in Figure 3.

3. SONIC BOOM MEASUREMENTS

Besides the launch itself, there were two other events that were of interest. After the launch, it was anticipated that the booster would return to the launch tower and be caught, as occurred with flight 5.[7] The return would create a sonic boom that was of interest. Also, as part of the stage-separation process, SpaceX used a hot-staging ring that allowed the upper stage to start its engines before stage separation. This ring was jettisoned shortly afterward and allowed to fall into the Gulf, creating a sonic boom in its descent.

On this particular launch, after the booster and ship launched, automated health checks on the launch and catch tower discovered that there was damage to critical hardware on the tower. This triggered a pre-planned divert maneuver, in which the booster was not returned to the tower, but rather was landed in the Gulf.[8]

A. THREE LATE-TIME EVENTS

As can be seen in Figure 4, there were three acoustic events visible in the signals recorded at stations near the launch pad. The plot shows signals from four stations at different distances from the launch pad, offset by 20 pa per station to visually separate the signals. The first event appears to be a burst of sound

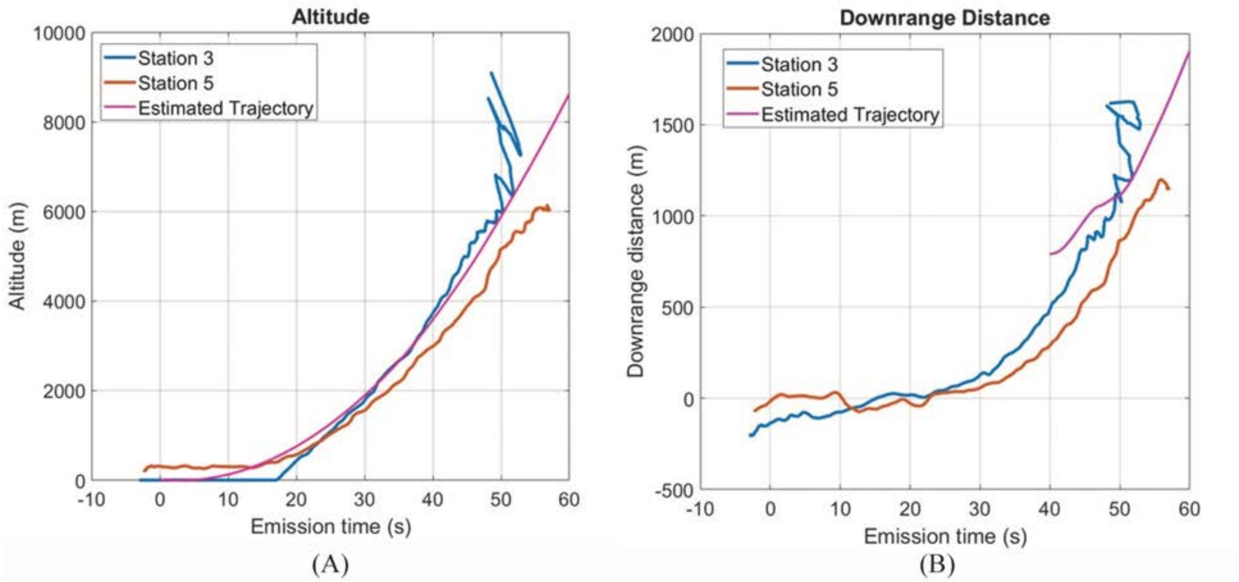

Figure 3: Both parts of this figure assume that the heading of the rocket was 95.3° clockwise from north. Part (A) of the figure shows the comparison of the altitude taken from the estimated trajectory and the results of the cross-correlation procedure using the above heading. The station 3 altitude is unreliable before about 18 seconds because of the insensitivity of the cosine function. Station 5 is also unreliable in altitude because of the fact that the vector probe is non-level by an unknown amount. Part (B) shows the estimated downrange distance for both probes, using the heading above. Because of the lack of actual downrange trajectory data, the limited resolution of the altitude data (1km), and the method necessary to calculate the downrange data, the downrange estimates are not accurate until later in the launch (after about 40 seconds).

(perhaps a venting of some equipment) at the pad. The vector probe at station 5 localized it at ground level in the direction of the pad. It appears to be shielded to the north, which is reasonable, since there are a lot of structures beyond the pad in that direction. The arrival time of that burst at the southern stations is consistent with propagation delays from the pad. The decrease in amplitude with distance is also consistent with that interpretation.

Of more interest are the second and third events in the figure. The second event is the sonic boom and landing noise of the booster as it returned under control to the Gulf. It hovered momentarily over the surface of the water before the engine was turned off and it tipped over. The third event is the sonic boom of the hot-staging ring and it has no engine noise associated with it.

Figure 5 helps identify the source of each of the booms. It shows signals measured at station 14, which is on the beach 16.6 km north of the launch pad. Part (A) shows the first boom. In it we can see the boom, followed by (and mixed with) the landing noise of the rocket. There are hints in the shape of the boom that the boom produced by the booster may have a triple-boom shape, similar to what is seen for Falcon-9 booster return sonic booms,[9] but the contamination by landing noise makes that unclear. Part (B) shows the boom from the hot-staging ring at a later time. Note that it is a simple N-wave shape and has no other noise associated with it.

B. TWO METHODS OF LOCATING THE BOOMS

There are two methods that will be attempted to locate the sources of the booster return and hot-staging ring sonic booms in this paper. The first is using the directions as determined by the two acoustic vector probes and finding the intersection of the two lines. The second is using the arrival times of the booms at

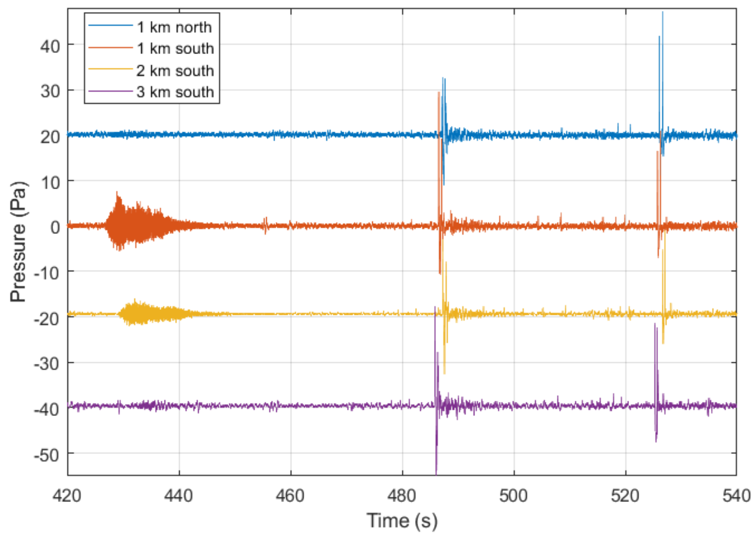

Figure 4: The late-time signals at the four stations closest to the pad. They are arranged from North to South. Each signal is offset by 20 Pa from its neighbors to visually separate the four signals. There are three distinct events that can be detected in these signals. The first is located at ground level in the direction of the pad. It appears to be shielded to the north. This is probably a gas release or similar event. The second is the sonic boom and associated landing noise of the booster as it lands in the Gulf. The third is the sonic boom produced by the hot-staging ring.

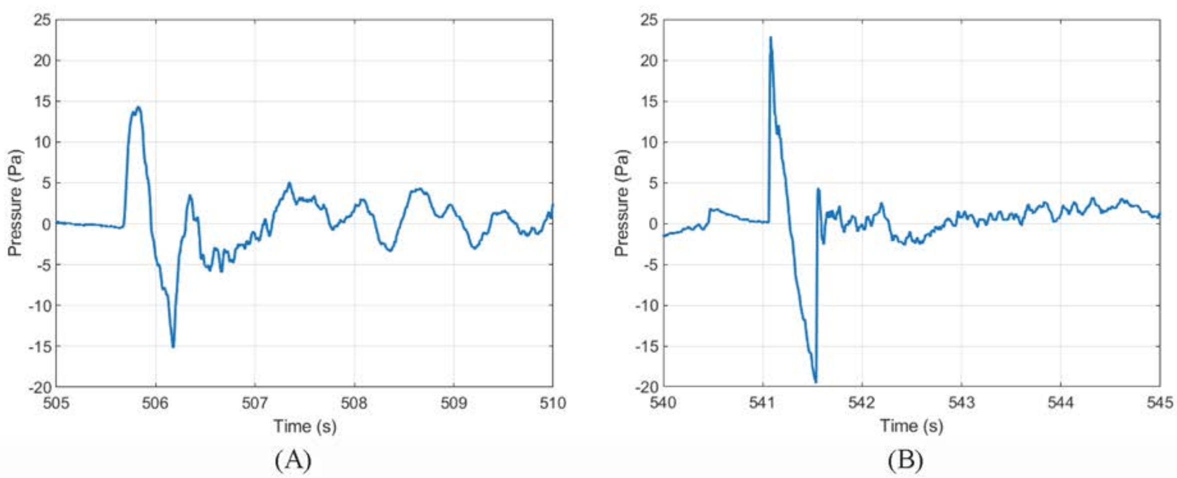

Figure 5: Both sonic booms as measured from station 14, which is located 16.6 km north of the pad on the beach. Note the landing noise after the boom in part (A) of the figure, and the relatively flat signal after the boom in part (B). There are hints of a possible triple-boom nature in part (A), but they are somewhat complicated by the presence of the landing noise signal.

all the stations to triangulate the position of emission of the booms. These two methods and their results are discussed below.

i. Locating the boom with acoustic vector probes

Since acoustic vector probes can give the direction a sound is coming from, having two vector probes allows determination of the locations where the sonic booms are produced. However, cross-correlation is not the best way to determine the delays for discrete events such as sonic booms because interference from other nearby (in time) signals can interfere with the cross-correlation results. It is best to just pick out the start of the boom on each channel and use those times to find the appropriate delays. The same least-squares fitting algorithm can be use to find the directions, θ and ϕ. The directions from the two vector probes can then be used to triangulate to the position of the boom. In this particular case, it doesn't localize the boom very well because the two probes are only four km apart and the boom is about 40 km away. The directions are therefore almost parallel, which makes the distance to their intersection point very sensitive to errors in the angles.

ii. Locating the boom using the entire array

The entire array of measurement stations was spread out over a significant area and therefore could be used to localize the sources of the booms. This analysis assumes that a sonic boom is singular event that occured at a single point in space and time, which, as discussed below, isn't accurate.

All of our stations are equipped with GPS receivers that give both the positions of the units and synchronize their recordings to within less than a millisecond. This allows an arrival-time analysis to determine the timing and position of the booms.

We used the arrival times at 17 of our 21 stations for both booms. The other four stations were not used because it was not possible to unambigously identify the booms in the recordings of those stations. They were the most distant stations and ambient noise overwhelmed the booms. Our algorithm was a least-squares fitting routine that assumed straight-line propagation from the source and fit the arrival times to the position in space (x, y, and z), the time of the event, and the average speed of sound between the source and receiver. The position was determined relative to the launch pad, with the x axis in to the east and the y axis to the north. Time is measured relative to SpaceX's definition of T_0, which is three seconds after engine ignition and is likely the release of the rocket.

C. LOCATION RESULTS

The position of the boom produced by the return of the booster is shown in Figure 6. This shows both the results from the vector probes and the station array. The green lines in the plot show the directions derived from the vector probes, which are shown as yellow bullseyes on the figure. The red ellipse on the map is an estimated error region for the intersection of the two vectors, assuming a ± 1 degree uncertainty in the vector directions. The yellow circle on the figure shows the position derived from the array timing. The cross in the center of the circle shows the estimated uncertainty of the position in the x- and y-directions. The y-direction uncertainty is much less than that in the x-direction. The elevation of the boom is not well determined. From the fits, it is between 3 and 8 km high. There is not much sensitivity to the height, though, because a height of 5 km makes very little difference to the propagation time when the horizontal distance is of the order of 35-40 km. The white star on the figure is the location of a recovery ship that SpaceX sent out the following day for unknown reasons, but which was tracked by people on the internet. While that location doesn't definitively locate the booster landing site, it is a confirmatory piece of evidence.

Figure 7 shows the estimated boom location as a magneta circle and the estimated trajectory of the booster derived from the livestream data, as mentioned earlier. This is a 3D rendering, viewed from a

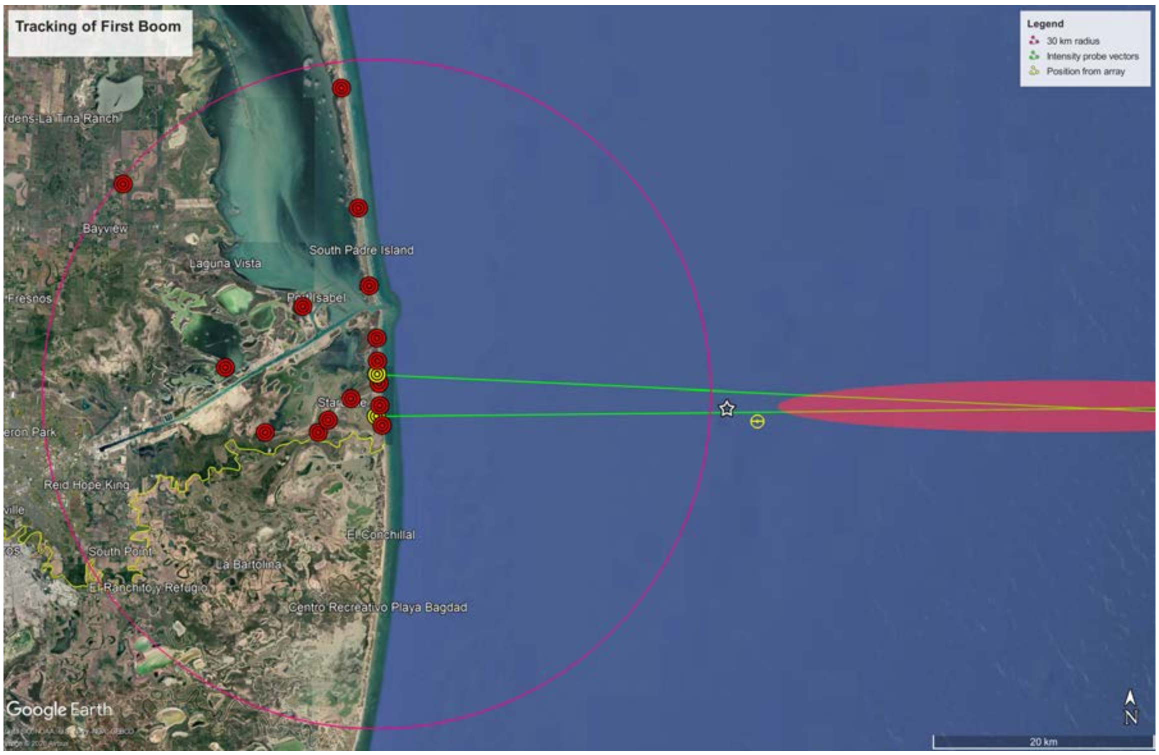

Figure 6:* *The estimated location of the booster boom derived from both the acoustic vector probes and the timing from the array. The green lines indicate the directions derived from the vector probes (shown as yellow bullseyes). The red region is an estimate of the error in that position if the directions are uncertain by about 1 degree. The center of the yellow circle is the position of the boom derived from the array of stations (shown as red bullseyes). The cross in the center of the circle shows the uncertainty in the x- and y-directions. The white star shows the estimated position of the recovery ship that SpaceX sent out the next day. Map data: SIO, NOAA, US Navy, NGA, GEBCO, Image ©2026 Airbus

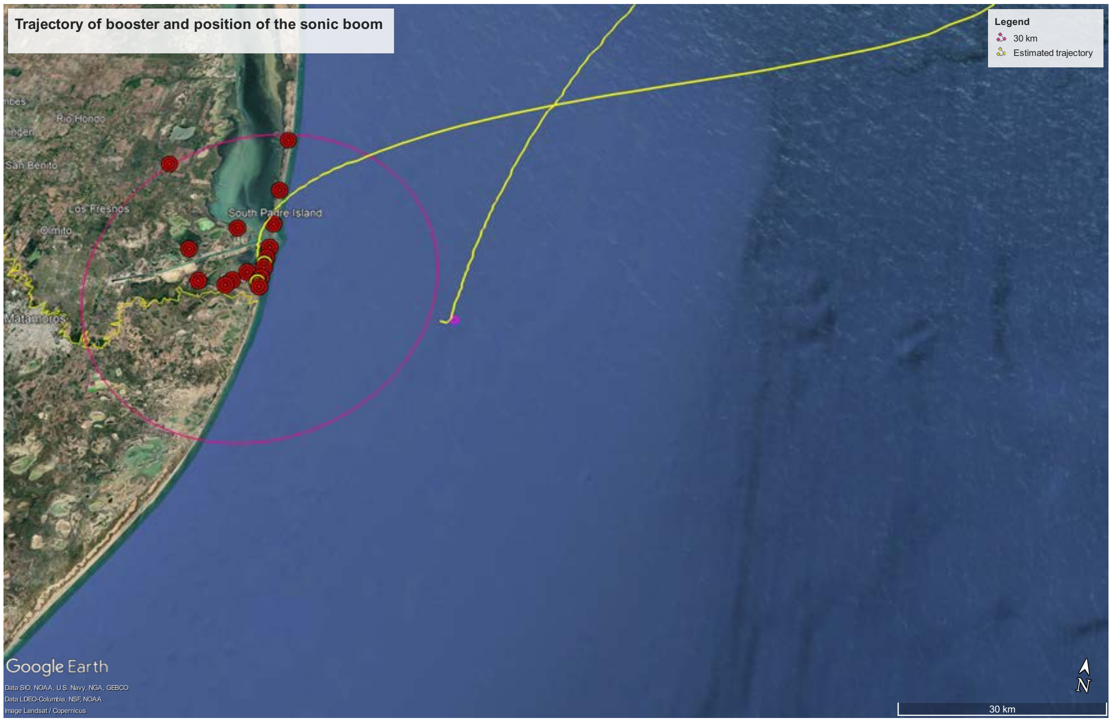

Figure 7: Location of the boom derived from the timing array and the estimated trajectory of the the booster from the livestream data. This is a 3D rendering, viewed from a location somewhat south of the launch site and looking to toward the north, so we can see the rise of the rocket as it goes east and also its return. Note that the trajectory passes close to the inferred position of the boom (magenta circle). Map data: SIO, NOAA, US Navy, NGA, GEBCO, Image ©2026 Airbus

location somewhat south of the launch site and looking to toward the north, so we can see the rise of the rocket as it goes east and also its return. Note that this trajectory comes very close to the magenta circle before it goes down to the water. This figure includes the 5 km estimated height of the boom, derived from the fit.

Figure 8 shows the same information as Figure 6 for the hot-staging ring boom. This is farther out in the Gulf than the booster boom and occurred significantly ($\sim$ 40 seconds) later. The vector probe results and the array timing results match much better in this case, but that is likely coincidence because the uncertainty is about the same.

D. EXAMINING THE ARRAY FITTING RESULTS

It appears that these data match this simple model too well. The model assumes that the boom originates at one specific time, at one height, and that the sound propagates along a straight line at a constant speed from the boom location to the receiving station. Using this model we find that it works very well. First, the predicted arrival times of the booms from the fit agree to within 0.1 seconds of the actual arrival times. Second, the time derived from the fit agrees with the appropriate time in the trajectory, when the booster is slowing down at about Mach 3. Third, the derived speed of sound (343 $\pm$ 4 m/s) is in agreement with radiosonde data for that day,[10] which ranged from 340-350 m/s, depending on the direction. And fourth, the altitude derived from the fit (3-8 km) is also consistent with the velocity of the booster as given in the trajectory.

The problem is that this simple model is not consistent with what we know about the production of reentry sonic booms.[11–13] The production of a booster-return (or any other falling object) boom is illustrated

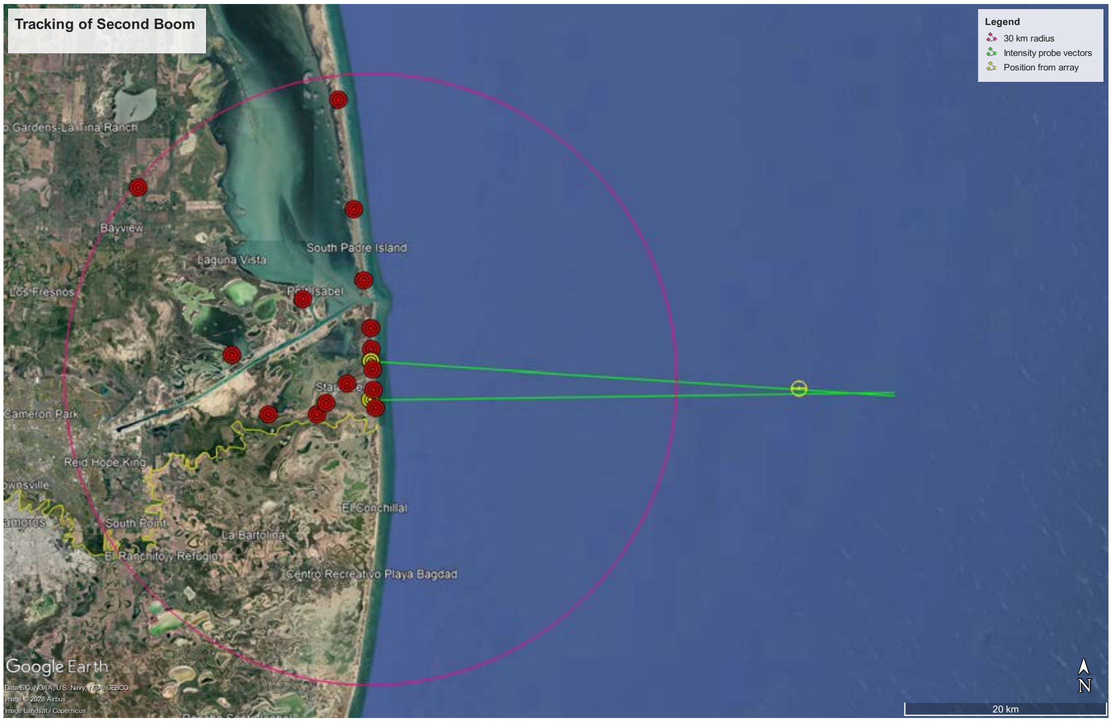

Figure 8: The estimated location of the hot-staging ring boom derived from both the acoustic vector probes and the timing from the array. The measurement stations are shown as bullseyes as before. The array and the vector probe results agree much better in this case. Map data: SIO, NOAA, US Navy, NGA, GEBCO, Image ©2026 Airbus

in Figure 9. Part (A) illustrates the first step in this process. As the booster (shown as a blue cylinder) is dropping from above at a supersonic speed, it produces a shock wave from the leading edge, as indicated by the dark blue lines. The angle of the shock cone is determined by the velocity of the object at that moment. The shock wave propagates along the brown line, perpendicular to the shock front. Part (B) shows the situation a short while later when the booster has dropped somewhat farther and also slowed down somewhat. The shock cone angle is wider, as shown by the lighter blue lines, and therefore the shock wave propagates downward at a steeper angle from the horizontal, as shown by the lighter brown lines. With this propagation pattern it will impact the ground closer to the flight path than does the part of the shock wave that originated higher in the flight path. Part (C) shows a further slowing of the object as it moves along its trajectory, with the corresponding widening of the shock cone and consequent closer impact on the ground. Finally part (D) shows when the object has slowed further and is just at Mach 1. The shock wave propagates directly downward and hits straight down below that point. The vertical distances shown in this figure are seriously compressed and are illustrative only.

Figure 9 and the above illustration indicates that the sonic boom production is smeared out over several seconds and several kilometers in height, and yet a model that assumes a single location at a single time works very well with this data. One possible explanation for why it matches so well can be built from atmospheric propagation effects. We know from the radiosonde data launched from the Brownsville airport that there was a generally upward refracting atmosphere at the time of the launch.[10] If we take refraction into account, we can imagine a scenario such as shown in Figure 10. The higher rays, emitted closer to parallel to the ground, as shown by the orange line and tan line, are refracted upward, and so never hit the ground. However near the end of the trajectory (shown by the brown line) the rays come out in a more vertical direction and so are refracted to propagate almost parallel to the ground. These then travel long distances over the water to the receiving stations. This would account for the fact that the boom appears to

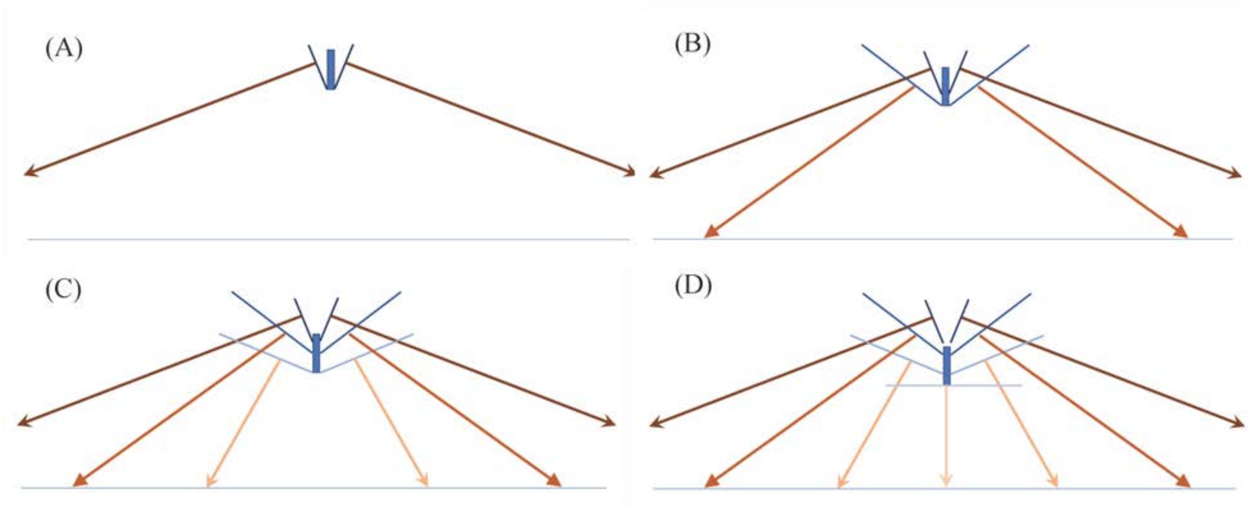

Figure 9: Production of a sonic boom from a descending and decelerating rocket booster. In part (A) the booster is at a high altitude and high Mach number. The boom shock makes a large angle relative to the movement direction of the booster and the shock propagates perpendicular to that angle, as shown in the dark brown arrows. In part (B) the booster is now lower and somewhat slower. The Mach cone has opened up somewhat and the boom travels to closer locations, as shown by the lighter brown arrows. This process continues in part (C), as shown by the lighter arrows. Finally in part (D) the booster has slowed to Mach 1 at a still lower altitude. At this altitude the boom propagates directly downward, as shown by the lightest arrow.

occur at at a single time and place - only the rays from that time and place make it to the shore. We have not yet performed the ray-tracing for this case, but a run of PCBoom for a Falcon-9 booster return at Vandenberg Space Force Base did show a similar effect.[14] This needs further investigation.

4. CONCLUSIONS

By using a time-correlation technique on the signals from a pair of 3-meter radius intensity probes, used as acoustic vector probes, the early part of the launch of Starship can be tracked with limited accuracy. The accuracy would be better if the relative positions of the probes were measured in all three dimensions instead of just x and y. The signals could then be corrected for the tilt and be more accurate. At longer distances (greater than about 5 km) it appears likely that propagation effects and turbulence affect the results, given the unphysical fluctuation of the results at those distances.

The position and timing of the sonic booms can be be measured with two different techniques. The vector probes can indicate the direction of the boom using the same time delay technique as above. The intersection of the vectors give the position of the boom. This is limited by the same uncertainties as the tracking. It also was limited by the fact that the two probes are only separated by about four kilometers and the distance to the booms was over 30-40 kilometers. That meant that the intersection point was quite uncertain because of the long lever arms and small base.

The sonic booms can also be localized by using our stations as a microphone array and using the arrival times to localize the source. The model used assumes that there is a single location that produces the boom at a single time and calculates the straight-line propagation time to each station, using the same speed of sound for all of them. The least-squares fit produces arrival times that are within 0.1 seconds of the actual arrival times. The positions of the booms are reasonable, given other evidence that we have, such as the estimated trajectory, velocity of the rocket, and the position of the recovery ship the day later.

This model actually works better than it should, given the fact that the booms are produced over a range

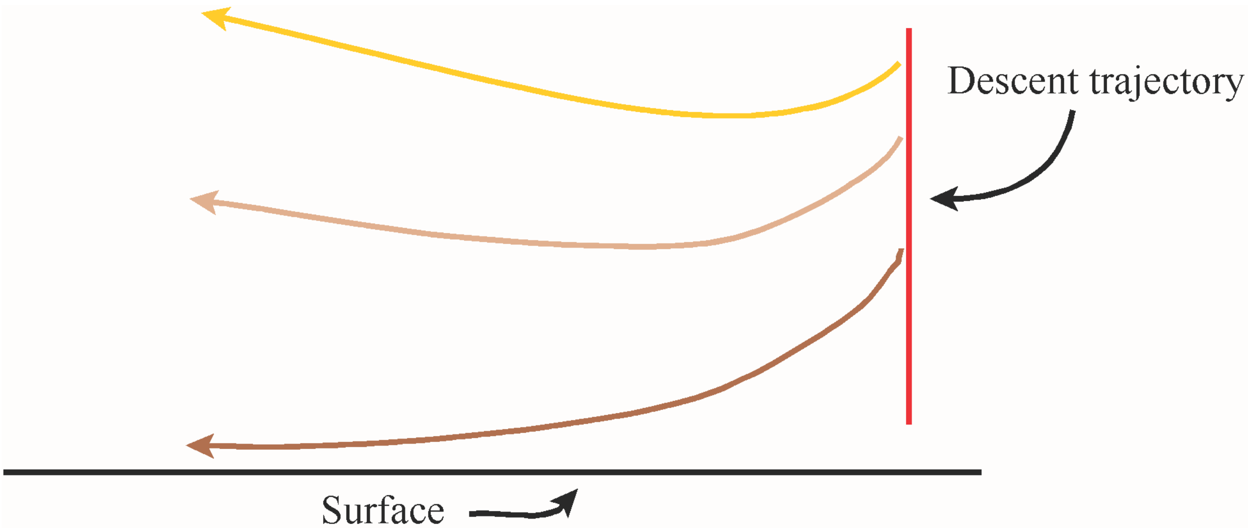

Figure 10: Potential mechanism for why the boom model fits. There was an upward refracting atmosphere at the time of the booster return. The booms emitted from the higher altitudes at higher angles to the travel direction get refracted upward, away from the ground. Eventually the booms are emitted at an angle and height that allows them to propagate parallel to the ground, where they are received by the measuring stations.

of altitudes and times. However it is possible that atmospheric refraction makes it so that all the stations actually do receive a signal corresponding to a boom from similar altitudes at the similar times.

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