

Simulation and Regression Modeling of NASA's X-59 Low-Boom Carpets Across America

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NASA's X-59 aircraft is predicted to produce a significantly quieter cruise sonic boom than traditional N-wave-producing aircraft. A propagation simulation study was undertaken to quantify loudness levels, exposure size, and variability of the X-59's low-boom carpet using realistic atmospheric profiles across the contiguous United States of America (CONUS). Near-field pressure data of the X-59 in supersonic cruise from NASA's fully unstructured Navier-Stokes three-dimensional (known as FUN3D) computational fluid dynamics code were propagated using NASA's PCBoom code, which solves an enhanced Burgers equation along acoustic rays. Atmospheric profiles from the National Oceanic and Atmospheric Administration's Climate Forecast System Version 2 database were used for propagation at 138 locations across the CONUS. Carpets at each location were generated for aircraft headings in the four cardinal directions. Over one million X-59 carpets were generated in total. The effects of the heading, season, geography, and climate zone on boom levels and exposure size are presented. Multiple linear regression models were developed to estimate carpet width and loudness metrics across the CONUS. These results inform regulators and mission planners on expected variations in boom levels and carpet extent from atmospheric variations. Understanding potential carpet variability is important when planning community noise surveys using the X-59.

Nomenclature

CW	=	carpet width
P	=	freestream pressure
δp	=	acoustic pressure

I. Introduction

THE International Civil Aviation Organization (ICAO) and its members are investigating the possibility of overturning the prohibition on supersonic flight over land, which has been in place for over 45 years [1]. To provide community response data to support this rule change, the National Aeronautics and Space Administration (NASA) has contracted Lockheed Martin to build the X-59 low-boom flight demonstration aircraft [2]. The X-59 has a design cruise Mach number of 1.4 and a flight altitude of 16,459 m (54,000 ft). The aircraft will be flown over several communities, and community members will provide feedback on their perception of the shaped sonic booms [3]. Participant responses versus boom level will be used to create dose-response curves. The dose-response curves will be provided to the ICAO to aid in determining the noise limit in a potential future supersonic aircraft certification standard.

A community's exposure to a sonic boom is generally quantified using the geometric carpet width (CW) and a noise metric. Six sonic boom metrics are under consideration to be used for supersonic aircraft noise certification. These metrics have been previously shown to correlate well with human perception of sonic booms [4]. These are A-, B-, D-, and E-weighted Sound Exposure Level, Stevens' Mark VII Perceived Level (PL), and Indoor Sonic Boom Annoyance Predictor (ISBAP) [5–9].

The geometric sonic boom CW for a given isopemp (which is sound that reaches the ground, which is generated at a particular instant at the source) is defined as the flight-path-perpendicular distance between the ground arrival positions of the lateral cutoff rays on either side of the aircraft that initially propagate downward toward the ground. For example, consider the isopemp (blue dashed line) generated by an aircraft when it was located at the origin in Fig. 1 (left). The aircraft had a heading of $\theta_{AC} = 30$ deg. The lateral cutoff rays landed at (x_1, y_1) and (x_2, y_2) , shown as red circles, where x_n is the distance from the aircraft to the east and y_n is the distance from the aircraft to the north, as shown in Fig. 1 (left). The geometric CW can be calculated using the following steps:

1) Convert the aircraft heading θ_{AC} to the mathematical heading θ_m (aircraft headings are typically defined as degrees clockwise from the north, and the mathematical heading is defined as degrees counter-clockwise from the east):

$$\theta_m = \begin{cases} 90 \text{ deg} - \theta_{AC}, & \text{for } 0 \text{ deg} \leq \theta_{AC} \leq 90 \text{ deg} \\ 90 \text{ deg} - \theta_{AC} + 360 \text{ deg}, & \text{for } \theta_{AC} > 90 \text{ deg} \end{cases}$$

2) Rotate the ray landing positions on the isopemp to align with the x' axis [Fig. 1 (right)]:

$$\begin{bmatrix} x'_n \\ y'_n \end{bmatrix} = \begin{bmatrix} \cos(-\theta_m) & -\sin(-\theta_m) \\ \sin(-\theta_m) & \cos(-\theta_m) \end{bmatrix} \begin{bmatrix} x_n \\ y_n \end{bmatrix}$$

3) Compute the carpet width:

$$CW = y'_1 - y'_2$$

This simplifies to

$$CW = (x_2 - x_1) \sin \theta_m + (y_1 - y_2) \cos \theta_m$$

The black dashed line in Fig. 1 with a length of

$$\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} = \sqrt{(x'_1 - x'_2)^2 + (y'_1 - y'_2)^2}$$

is not the CW because it is not perpendicular to the flight track due to carpet asymmetry from wind. A metric-based CW can also be defined

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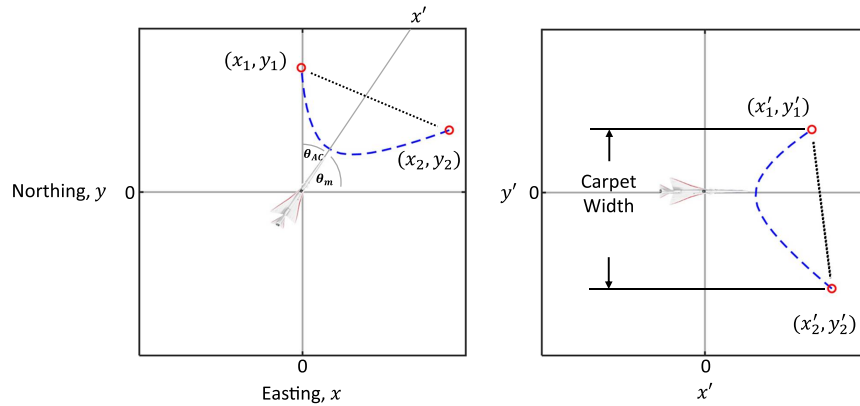


Fig. 1 Top-down view of the geometric CW definition unrotated (left) and rotated for CW computation (right).

as the fraction of the carpet that exceeds a threshold metric value (e.g., $PL > 55$ dB) multiplied by the geometric CW.

Boom carpet sizes and noise levels are affected by the atmospheric profile through which the boom propagates [10–12]. There has been considerable study of this in the literature with various aircraft, locations, and fidelity [13–19]. Understanding the expected sizes, levels, and variability in these quantities is important for several aspects of X-59 community test planning. First, the X-59 community tests will use a planned noise exposure schedule that consists of a desired exposure size and metric levels. The results from this work can inform the strategy and expected achievability of this schedule. Second, the X-59 flight tests will occur in a variety of regions and seasons. Trends in the exposure level and size due to prevailing atmospheric conditions can aid in determining when and where to perform flight tests. Finally, variability due to the aircraft heading relative to atmospheric conditions will aid in flight trajectory planning at the test sites.

From a noise regulation standpoint, it is desirable to set a supersonic en route noise limit that is globally applicable. Understanding regional variability in exposure size and level is important to ensure a noise limit will be effective worldwide.

The contiguous United States of America (USA) has a diverse set of climate zones. The definition of the climate zones in this work was taken from the U.S. Department of Energy's Building America Best Practices documentation, which incorporates surface temperature trends and precipitation trends [20]. Figure 2 shows the seven climate zones in the contiguous USA, which are hot-humid, mixed-humid, hot-dry, mixed-dry, cold, very-cold, and marine. Building and housing construction differ across climate zones, which may cause differences in indoor exposure and perception for the same outdoor

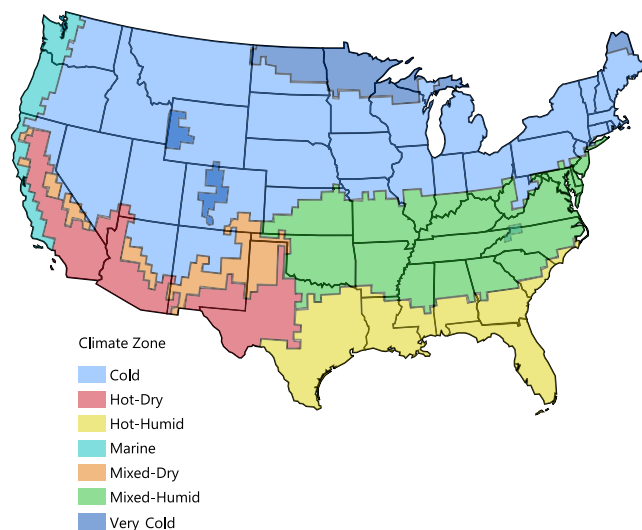


Fig. 2 USA climate zones.

exposure levels. The statistics of boom carpet size and level are investigated in each of these climate zones in the current work.

This work presents simulations of the X-59's shaped sonic boom propagated through five years of realistic atmospheric profiles at 138 locations across the contiguous USA. The effects of local ground elevation, climate zone, aircraft heading, and astronomical season on sonic boom CW and sonic boom noise metrics (e.g., PL) are investigated, and statistical models are developed. The paper begins with a description of the tools used to generate and propagate the boom, the atmospheric database, and a design of experiments approach. The results of the paper quantify the means and variability of the CW and sonic boom noise metrics of the X-59 in its supersonic cruise condition across the country.

II. Approach and Methods

To determine trends in the X-59 sonic boom CW, boom noise metric levels, and their variability, X-59 steady level cruise near-field pressure data were propagated through more than 250,000 realistic atmospheric profiles from 138 locations across the USA at the four cardinal aircraft headings. Over one million X-59 sonic boom carpets were generated. Ground boom levels were computed across the width of each carpet at points uniformly spaced 3.2 km (2 statute miles) apart, but this paper will mainly focus on the undertrack data. Results from propagation at the 138 locations were used to fit statistical models using multiple linear regression to evaluate the effects of latitude, longitude, ground elevation, heading, season, and climate zone.

A. PCBoom Propagation Code

NASA's PCBoom 6.7.1 code was used to perform the propagation simulations [21–23]. PCBoom solves an enhanced Burgers equation along acoustic rays. This simulation study was made possible using an updated version of PCBoom that computes ground waveforms several orders of magnitude faster than previous versions. The code takes as inputs the aircraft near-field pressure data, atmospheric profile data, aircraft trajectory data, desired acoustic emission angles, and the local ground elevation. Ground waveforms and their locations are output at each emission angle, assuming a constant ground reflection factor of 1.9. The effects of atmospheric turbulence on the sonic boom waveforms are not considered in this work. On average, turbulence reduces the strength and loudness of sonic booms. However, due to its stochastic nature, it is possible that turbulence can increase the strength and loudness in some locations [24–28]. It will be important to account for this increase in loudness when assessing supersonic aircraft noise over land and its impact on communities.

A lateral ground resolution of two statute miles (3.2 km) was achieved by operating PCBoom in a three-step process. Step one was to find the lateral cutoff ray emission angles. Step two was to ray trace 100 angularly uniform rays out to the lateral cutoff angle and interpolate the lateral landing position vs emission angle curve to find the emission angles that would land every 2 miles. Step three was to propagate those emission angles using the Burgers module. Using

this approach, 99.5% of the over 18 million emitted rays in this dataset landed within 0.02 miles (32 m) of the desired lateral position.

B. Atmospheric Profile Database Preparation

Five years of atmospheric profiles were selected from the National Oceanic and Atmospheric Administration Climate Forecast System Version 2 (CFSv2) database from July 2013 to June 2018 [29]. Atmospheric profiles in this database are available every 6 h at 0.5 by 0.5° latitude/longitude resolution. The CFSv2 atmospheric profile static variables applicable for this work are latitude, longitude, and ground elevation. The altitude-dependent variables are temperature, u-wind, v-wind, relative humidity, and pressure, which are available on 37 isobaric surfaces from 1000 to 1 mbar. For the 54,000 ft (16,459 m) flight altitude of the X-59, roughly 25 of these isobaric surfaces exist between the aircraft and the ground, depending on a location's elevation and ambient pressure behavior.

Occasionally, the 1000 mbar surface was above the ground elevation, which meant no data were available between that isobaric surface and the ground level. In these cases, the profile was supplemented with +1 h forecast data at ground elevation, a 2 m altitude, and a 10 m altitude because those were the closest available data in time. The profile data are generally preferred over the forecast products unless profile data are not available near the surface. Usage of the forecast data was not expected to significantly affect the signatures because it constitutes less than 1% of the propagation distance. Offtrack booms could be more affected by usage of the forecast data because these booms travel through the lower atmosphere for a longer time period.

C. X-59 Near-Field Pressure Data

The X-59 (C609 design) near-field pressure data were generated using NASA's fully unstructured Navier-Stokes three-dimensional (FUN3D) computational fluid dynamics (CFD) code as part of a separate study [14,30]. The near-field data were computed on a cylinder with 2° azimuthal resolution and at a distance of $R/L = 3$, where R is the radius of the CFD cylinder and L is the aircraft length. The CFD cylinder's axial resolution is 6.8 cm. The near-field was computed for the X-59 in its cruise condition, which is steady, level flight at Mach 1.4 at 54,000 ft (16,459 m). Thus, all the ground boom results shown in this paper are from the X-59 in its design cruise condition. Because perfect cruise is assumed, the ground booms resulting from the propagation of near-field pressure signatures generated at a single instance in time represent the entire perfect cruise carpet.

The geometric altitude of the aircraft is held constant for the propagation simulations conducted in this work. Because the macroscopic atmospheric profiles' isobars change at this altitude, the conditions at which near-field CFD data were generated do not exactly match the macroscopic atmospheric conditions of the realistic

profiles. This is a source of variability that is not accounted for in this paper, and its impact is left for future work.

Zeros were added to the front and rear of the cylinder to both ensure the shocks did not escape the domain due to nonlinear stretching along the propagation path and create a ramp at the rear of the cylinder to bring it back to the freestream pressure value, as shown in the left plot of Fig. 3. The near-field pressure data at 0 deg (undertrack, black line), 30 deg, 60 deg, and 90 deg (out the wing) are shown. Red portions are points that were added to the cylinder. The right plot shows the ground signatures of the 0 and 30 deg rays after propagation through a standard atmosphere. The sound speed profile prevents the 60 and 90 deg ray from reaching the ground. The PL values of the ground signatures are shown in the legend.

During propagation, the near-field data closest to the desired emission angle were used. For example, if the emission angle of 31.5 deg was requested, the near-field data at 32 deg were propagated along the 31.5 deg ray path. The cylinder data are fairly smooth at this 2 deg resolution, but some variability in the offtrack loudness can be attributed to propagating data from the nearest 2 deg emission angle rather than the requested emission angle.

D. Design of Experiments Approach

A design of experiments approach was used to determine both the spatial resolution of the propagation locations across the USA and the temporal resolution of the atmospheric profiles.

Computational constraints indicated that simulating propagation at 150 locations through four atmospheric profiles per day for five years was an upper bound on the resolution that could be achieved. Propagation locations were selected using the fast flexible space-filling design, which is an approach commonly used in computer experiments to achieve good spatial coverage properties while providing the flexibility to define nonregular design regions [31]. To quantify the impact of propagating to only 150 locations, two spatial resolutions containing 450 and 150 locations were evaluated. The 450-point resolution corresponded to approximately 60 km separation distance between locations, whereas the 150-point resolution had an approximately 200 km separation distance between locations. These will be referred to as "fine" and "coarse" spatial resolution. The locations for the coarse spatial resolution were a subset of the locations for the fine spatial resolutions.

Fine and coarse temporal resolutions of the atmospheric data were also studied to evaluate the impact of time-of-day variations on the booms. To evaluate the temporal resolution, the X-59 boom was propagated at the four cardinal aircraft headings through a subset of the coarse and fine locations (34 out of the 450 and 10 out of the 150) in the northeast USA. The fine temporal resolution corresponded to four atmospheres per day and per location, whereas the coarse temporal resolution used one atmosphere per day and per location.

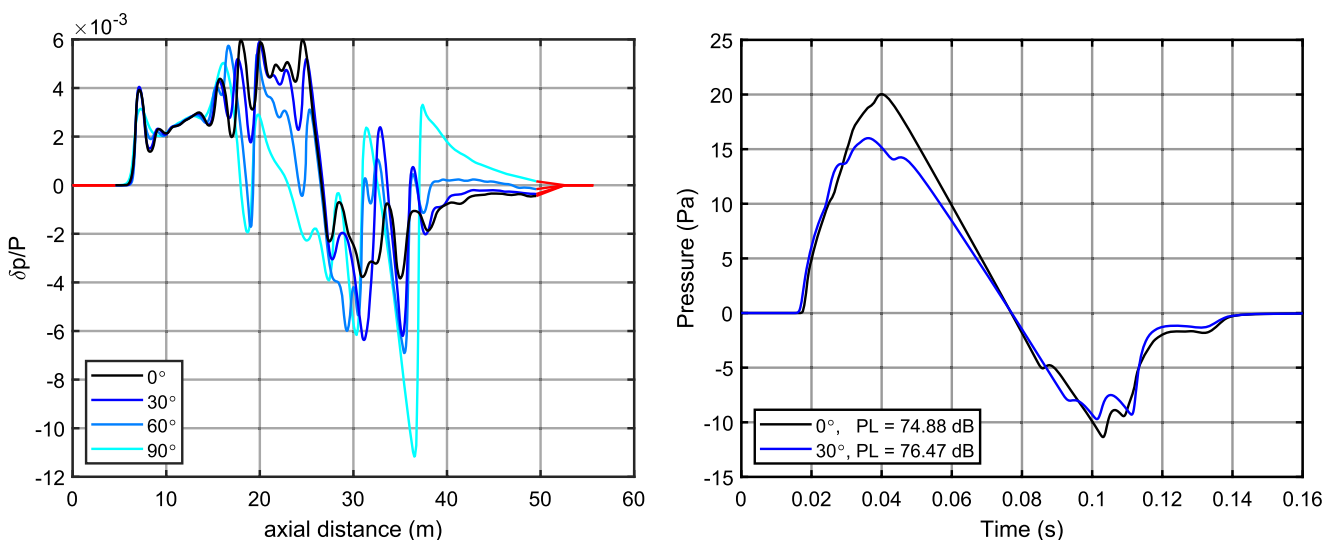


Fig. 3 Scaled X-59 near-field pressure (left) and ground signatures after propagation through a standard atmosphere (right).

The northeast USA was chosen because it has some seasonal variability, and it will likely contain future supersonic routes.

A bootstrap forest analysis was performed with the latitude, longitude, year, month, day, time of day, aircraft heading, ground elevation, season, and climate zone as predictors of the undertrack PL and CW at each location in the subset [32]. A bootstrap forest is an analysis method that is based on decision trees to partition the data. The bootstrap forest models the relationship between the predictors and the response variables by averaging across many decision trees: each of which is fit to a random (bootstrap) sample of the data. A bootstrap forest is useful for identifying potential predictors of a response. In this study, it was used to identify if the aforementioned predictors contributed to the CW and PL. It also provided an assessment of the relative contribution of each of these predictors. The bootstrap forest analysis results were similar, regardless of the temporal and spatial resolutions, with the contribution of each predictor changing little, whether there were 150 vs. 450 locations or one vs. four atmospheric profiles per day. The time of day was found to be the predictor with the least contribution to the undertrack PL and CW. Additionally, the mean and standard deviation of the PL and CW were robust to changes in the resolutions. Therefore, the coarse temporal and spatial resolutions were determined to be adequate for a countrywide simulation.

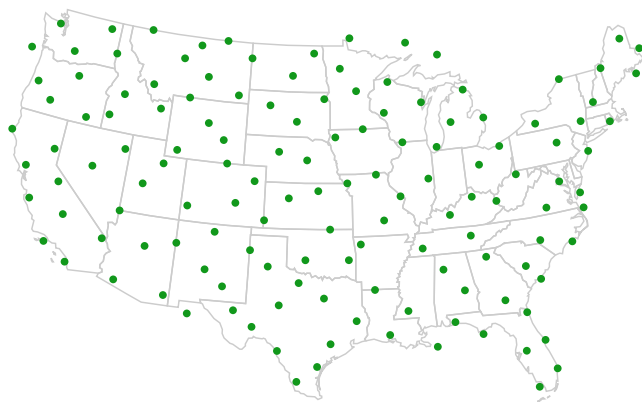


Fig. 4 X-59 propagation simulation locations.

The final resolution was chosen to include 138 locations across the USA with one atmospheric profile per day and per location at 1800 hrs Coordinated Universal Time. This time was chosen because it is the closest time to midday over the USA (between 1000 and 1600 hrs local time, depending on the location and time of year). Twelve of the original 150 locations were removed because they were over the ocean or too far outside the borders of the contiguous USA. Four locations outside of the contiguous USA were adjusted slightly to be closer to the borders. The final locations are shown in Fig. 4.

E. Multiple Linear Regression Models

Multiple linear regression was used to develop individual statistical models for estimating the mean and variability of each of the undertrack loudness metrics and the CW across the USA [33]. Regression analysis is a statistical technique for modeling the relationship between a response metric and one or more predictor variables. These models were developed from the predicted propagation data collected at the 138 locations as described in Sec. II.D. The models are used to provide estimates of the CW and loudness metrics at locations in the contiguous USA beyond the 138 propagation locations without significant computational cost. The regression models only include inputs that are available during community test planning (latitude, longitude, ground elevation, heading, season, and climate zone) and do not require atmospheric profile data. Results from the multiple linear regression models are discussed in Sec. III.B.3.

III. Results

A. Aggregate Results for the Entire USA

Figure 5 shows peak-normalized histograms of the undertrack levels of the six metrics for the 138 propagation locations, including results at all headings and all seasons. The dashed line in each histogram shows the metric value corresponding to a standard atmosphere. Note that the standard atmosphere used here consists of standard temperature and pressure profiles (from ICAO Document 7488) [34]; an example relative humidity profile (from ISO 9613-1:1993 Annex C) [35]; and a ground elevation of 0 km, which is generally lower than the ground elevations of the simulation locations. The median ground elevation of the 138 locations is 0.42 km. Each subplot has a 20 dB range. The majority of the undertrack levels

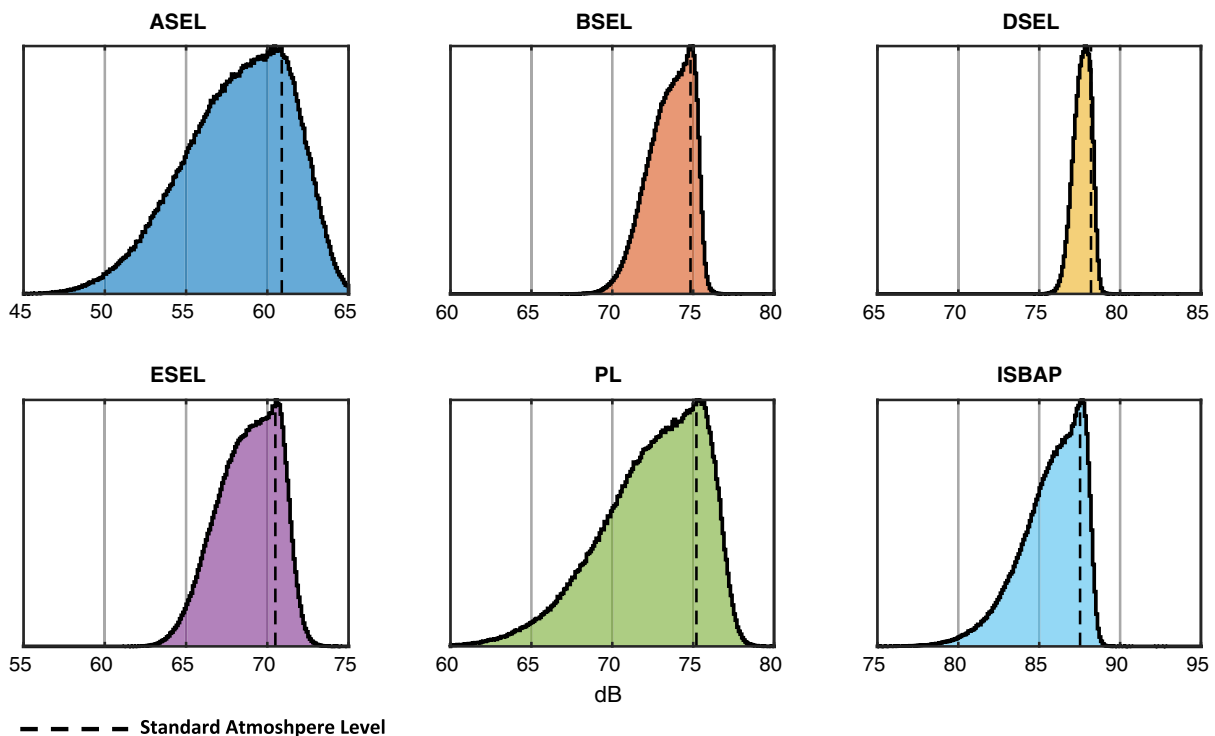


Fig. 5 Peak-normalized histograms of X-59 sonic boom perception metrics undertrack for all locations, seasons, and headings.

is lower than the level computed using the standard atmosphere. The D-weighted Sound Exposure Level (DSEL) has the narrowest distribution, indicating large-scale atmospheric effects affect it the least, followed by the B-weighted Sound Exposure Level (BSEL), the ISBAP, the E-weighted Sound Exposure Level (ESEL), the PL, and the A-weighted Sound Exposure Level (ASEL). From a certification standpoint, a preferred metric may be one that is least affected by the atmosphere. In this case, the DSEL, BSEL, ISBAP, and ESEL have considerably narrower distributions and smaller standard deviations than the PL and ASEL.

Figure 6 shows a violin plot of the X-59 booms every 3.2 km (2 miles) laterally out to 64.4 km (40 miles). The violins show the peak-normalized probability density of the PL at each lateral position. Wider portions of the violins indicate more observations of a given PL value at that lateral position. The black dots show the median PL value at each lateral position. The solid black line shows the standard day prediction. It is encouraging that the X-59 boom levels are predicted to be lower than the standard day for the majority of the carpets because the aircraft was designed to produce a quiet sonic boom using a standard atmosphere. This indicates that realistic atmospheres typically work to reduce the X-59 boom loudness. However, there are still apparent cases where the macroscopic atmosphere increases the loudness of the X-59 booms.

Figure 7 shows the CW probability density function (PDF) of all generated X-59 sonic boom carpets for all headings, seasons, and locations. The black dashed line is the CW for a standard atmosphere. This version of PCBoom has a hundredths-place precision limitation in emission angle, which causes the predicted CW to be underestimated in general. This precision limitation will be relaxed in future PCBoom releases.

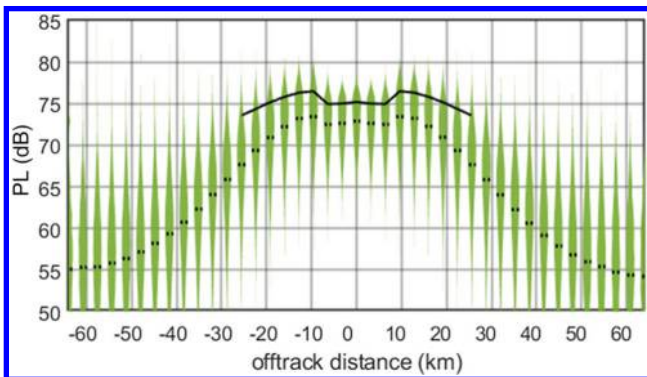


Fig. 6 PL distributions (green violins) of X-59 low booms observed every 3.2 km (2 miles).

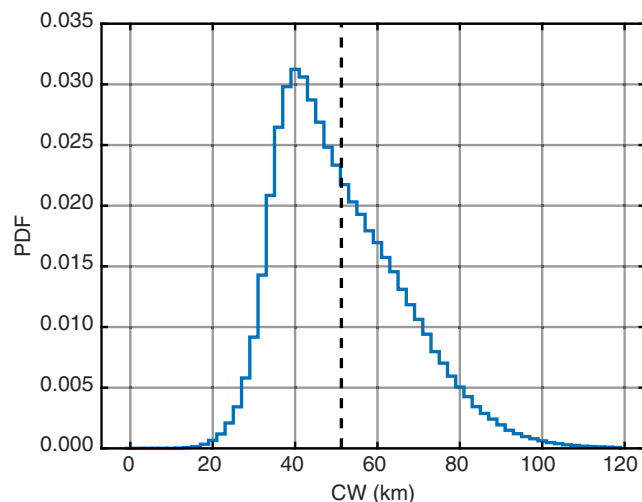


Fig. 7 Probability density function of X-59 sonic boom CW for all locations, seasons, and headings.

Although Fig. 7 shows the CW based on geometric considerations, the metric CW is also of interest. To compute the metric CW, the levels of each boom carpet were linearly interpolated to a uniform ground spacing of 161 m (0.1 miles). The sum of each 0.1 mile fraction of the carpet that exceeded a metric value threshold was used as the metric CW. The metric CW for various threshold values is shown in Fig. 8. For example, the red line shows the PDF of the portions of carpets with a PL greater than 55 dB. The right plot is a zoomed-in portion of the left plot. The dashed black line shows the geometric CW of a standard atmosphere. The blue line shows the geometric CW for all carpets (i.e., $PL > -\infty$) for comparison to the metric-based CW. The metric CW is always less than or equal to the geometric CW. When the metric threshold is $PL > 70$ dB, a sizeable peak appears in the CW PDF at 0 km, which indicates that many of the boom carpets are predicted to be less than 70 dB across their entire extent.

1. Effects of Heading and Season in Aggregate

The histograms in Fig. 9 show the effects of both the heading and season on the geometric CW [56 carpets with CWs greater than 160 km (0.006% of those observed) are not shown to improve plot legibility]. In general, west-heading carpets are the narrowest, and east-heading carpets are the widest; this is due in part to the eastward-moving jet stream over the USA. Carpets also tend to be wider in the winter than in summer. This may be in part due to the temperature lapse rate decrease that occurs in the winter, allowing more acoustic rays to reach the ground. The opposite is true for the summer months.

The effects of the heading and season on the X-59's undertrack PL are shown in Fig. 10. The heading seems to only have a minor effect, with east heading having the highest undertrack PL and the west heading having the lowest. The season also has only a minor effect, with slightly higher PL values most likely during the winter. For all headings and seasons, the undertrack PL distribution is centered at approximately 72 dB.

2. Effects of Climate Zone in Aggregate

The undertrack PL for different climate zones and seasons is shown as a violin plot in Fig. 11, and the blue solid line shows the median PL. Seasonal trends can be seen in three zone sets: 1) cold, very-cold, and marine; 2) hot-dry and hot-humid; and 3) mixed-dry and mixed-humid. These groupings have similar latitude ranges. Grouping 1 has the lowest median undertrack PL during the summer and the highest in the fall and winter. Grouping 2 has the lowest median undertrack PL during the fall and the highest median undertrack PL in the summer. Grouping 3 has the lowest median undertrack PL during the fall and a higher median undertrack PL in the spring and winter. The undertrack PL values for the cold and very-cold climate zones were typically the highest.

These climate zones are defined by near-surface properties (e.g., wet-bulb temperature and heating degree days) and annual precipitation. The upper atmosphere where most of the X-59 low-boom propagation occurs is not considered in the definition of these zones. The climate zone results are useful when considering differences in housing construction. For example, a person who frequently has open windows or needs less home insulation in a particular climate zone may be more annoyed by a boom with a given outdoor PL than someone who rarely has open windows or has a more heavily insulated residence in another climate zone.

Figure 12 shows the geometric CWs for different climate zones as a violin plot for various seasons, and the blue solid line shows the median [56 carpets with CWs greater than 160 km (0.006% of those observed) are not shown to improve plot legibility]. The CW of the hot-dry, hot-humid, and mixed-dry regions are typically the smallest. With the exception of the marine climate zone, the CWs are especially narrow in the summer. The marine climate zone's median CW changes minimally with season.

B. Geographical Results

1. Geographical Results in Aggregate

Figure 13 shows the means (color) and standard deviations (dot size) in undertrack PL values at each location and for all headings and

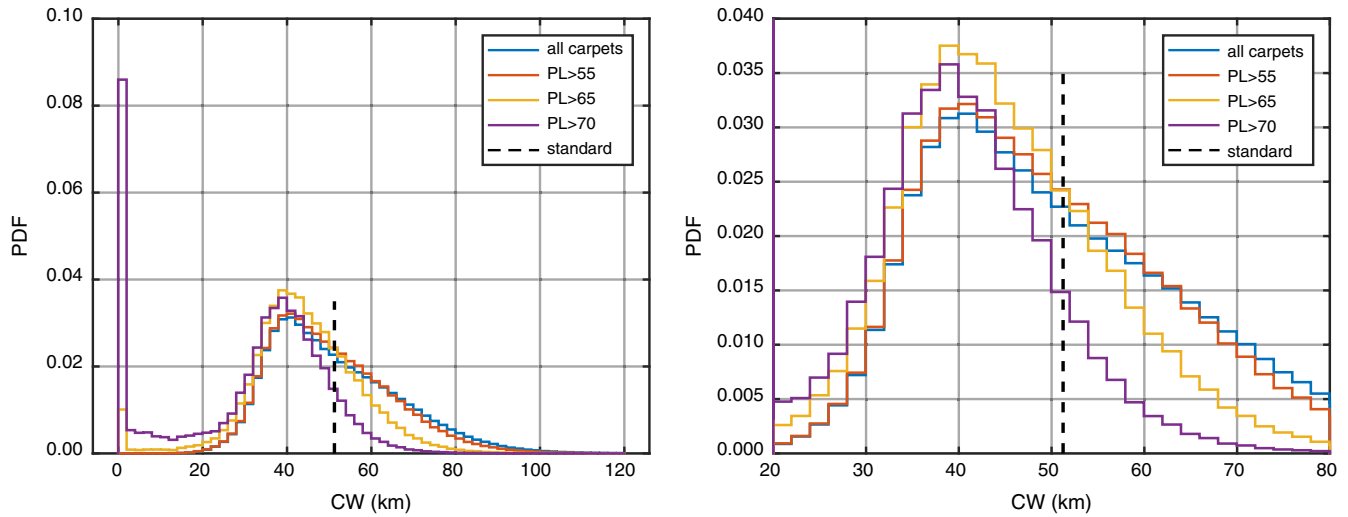


Fig. 8 X-59 sonic boom metric CW for various PL thresholds for all locations, seasons, and headings.

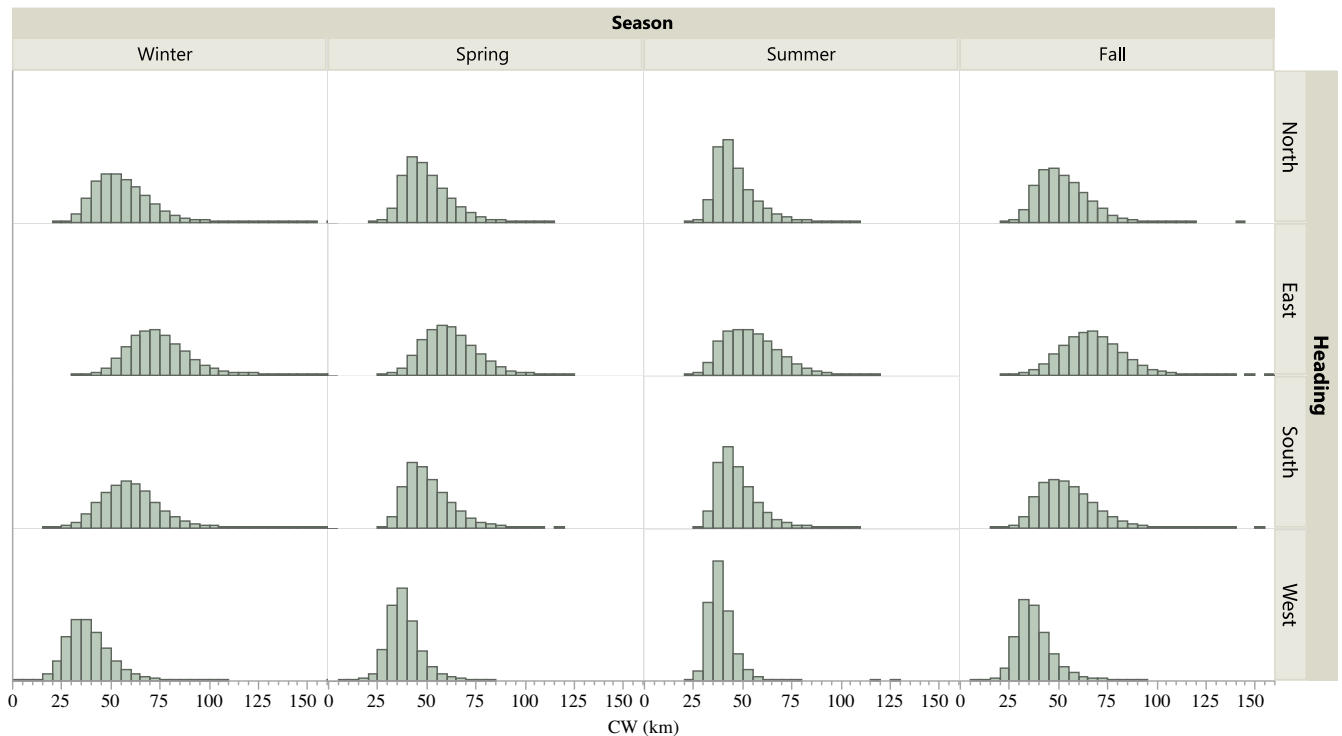


Fig. 9 Histograms showing the effects of seasons and headings on X-59 CW.

seasons in the simulation study. The mean undertrack PL varies by about 7 dB, depending on the location. The standard deviation in the undertrack PL ranges from 1.5 to 4.25 dB. Higher latitudes tend to have higher undertrack PL values, and there are especially high average PL values over the Rocky Mountains. Locations closer to the coast typically have lower mean undertrack PL values but higher standard deviations.

Figure 14 shows the means (color) and standard deviations (dot size) of geometric CWs at each simulation location. The mean CW ranged from 41.8 to 61.2 km (26 to 38 miles). The standard deviation ranged from 11.3 to 17.7 km (7 to 11 miles). Sonic boom carpets are typically wider at higher latitudes and are more variable in the north-east portion of the USA, due in part to the relatively strong jet stream in that region.

2. Geographical Results Separated by Season and Heading

Figure 15 shows the means (color) and standard deviations (dot size) of undertrack PL values at the 138 propagation locations

separated by season (columns) and aircraft heading (rows). Changes in the heading have little effect on the mean undertrack PL. However, the southern region has slightly lower mean undertrack PL values (~ 1 dB) when flying west than when flying east. The standard deviation in undertrack PL is also slightly higher (~ 0.5 dB) when flying west as compared to east. The inland locations have almost no changes in the means and standard deviations of the undertrack PL values due to heading. Differences in the means and standard deviations of undertrack PL values due to season are more obvious. The mean undertrack PL is higher during the summer than the winter for the south central and southeastern USA. The midwest region near Ohio has the opposite trend in mean undertrack PL, but it is not as drastic. The undertrack PL standard deviation is largest in the fall and winter and smallest in the summer. Although not presented here, the other sonic boom metrics from Fig. 5 have similar trends but different decibel ranges for the mean and standard deviation of the undertrack level. The PL and ASEL vary the most, and the BSEL and DSEL vary the least. Thus, the PL variability trends can be considered an upper

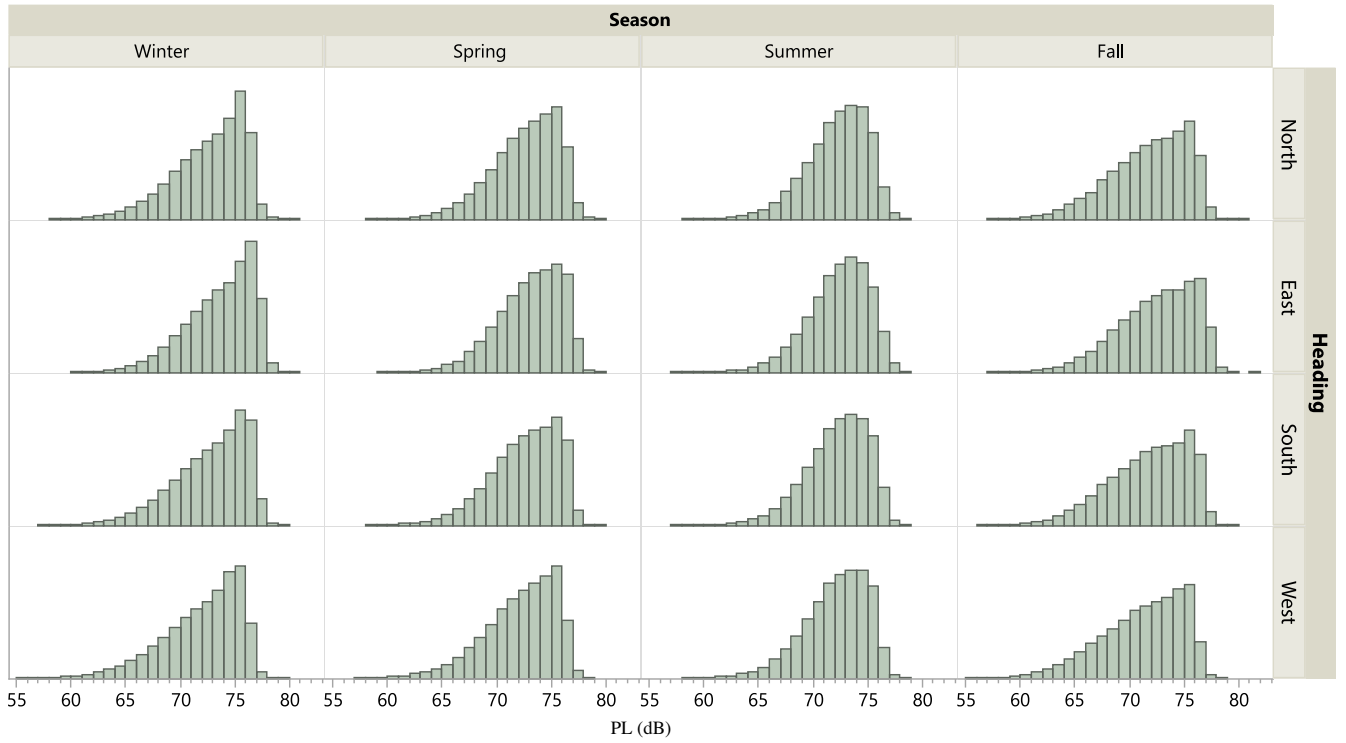


Fig. 10 Histograms showing the effects of seasons and headings on X-59 undertrack perceived level.

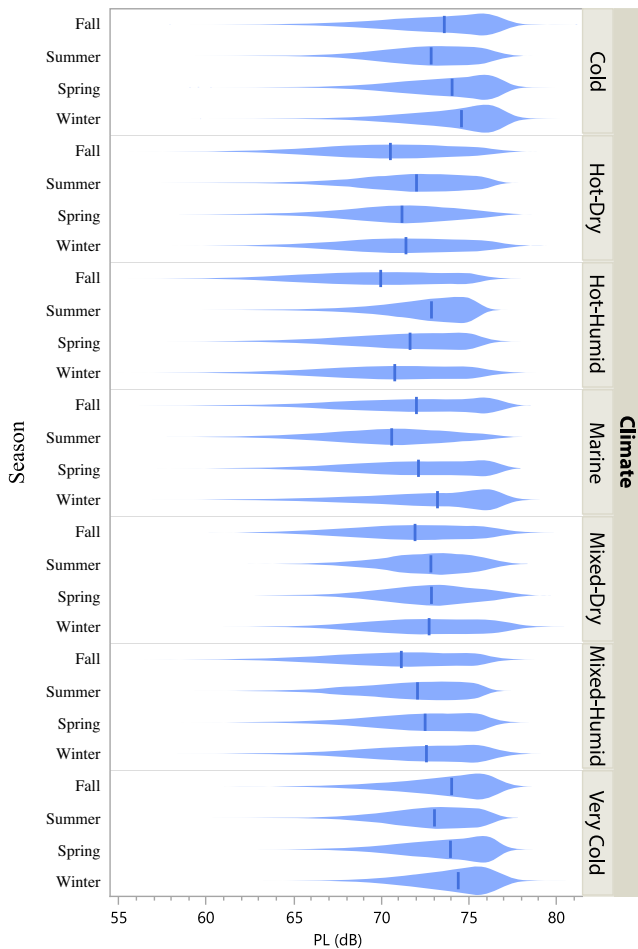


Fig. 11 Violin PDFs of X-59 undertrack PL in the contiguous USA climate zones.

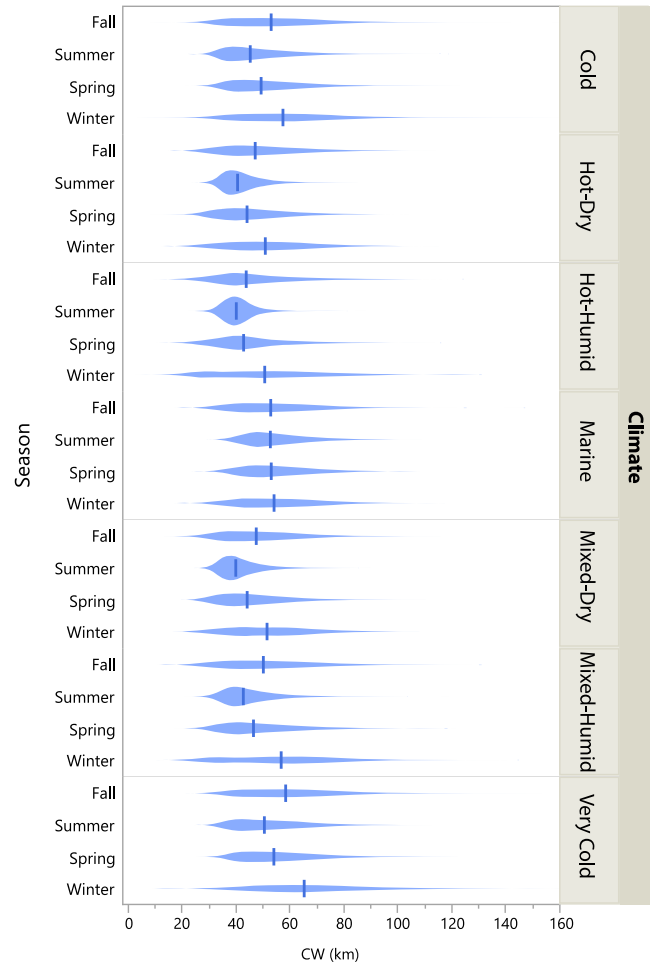


Fig. 12 Violin PDFs of X-59 geometric CWs in the contiguous USA climate zones.

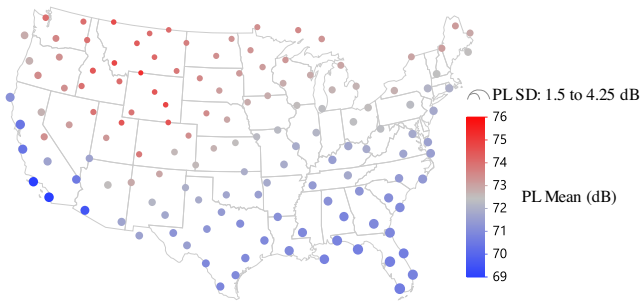


Fig. 13 Mean and standard deviation of undertrack PL at each simulation location.

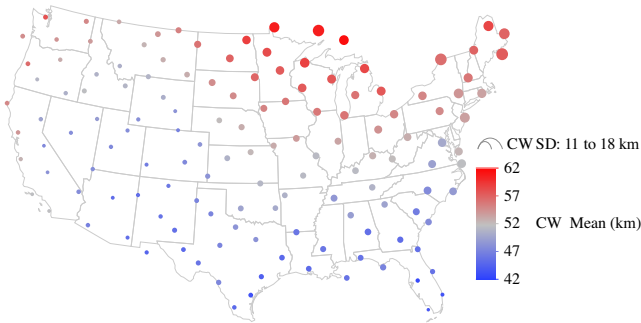


Fig. 14 Mean and standard deviation of geometric CWs at each simulation location.

bound for macroscopic atmospheric effects on the X-59’s shaped sonic boom.

Figure 16 shows the means (color) and standard deviations (dot size) of geometric CWs at the 138 propagation locations separated by season and heading. Changes in heading have a significant effect on CWs. East headings have the widest carpets, likely due to the prevailing tailwind; and west headings have the narrowest carpets due to the prevailing headwind. The mean CW is typically highest in the winter and lowest in the summer, although the magnitude of this

effect is heading dependent and latitude dependent. The effects of the seasonal jet stream in the northeast portion of the USA are apparent, causing larger and more variable carpets during the fall and winter.

It is interesting to note that even though the carpets are narrower when heading west, the mean undertrack PL was not higher. Thus, a narrower carpet does not necessarily indicate a louder carpet. It simply means less sound is reaching the ground, and not that the sound energy is being encapsulated in a smaller region.

3. Multiple Linear Regression Model Results

Multiple linear regression models were developed to estimate the mean and variability of the CW and loudness metrics as a function of latitude, longitude, ground elevation, heading, season, and climate zones. These models only include predictors that are available at the test planning stage, and they do not require atmospheric profile data. The adjusted coefficient of determination R^2_{adj} , which is a measure of the amount of variability in the data that is explained by the model, was used to evaluate the overall adequacy of the regression models. Values of R^2_{adj} ranged from 0.55 to 0.80 for the models, with models for the metric means having higher values than for the metric standard deviations. This was expected due to the large amount of variability in the atmospheric profile data at each location, and models with lower values of R^2_{adj} still showed clear trends, which provide useful insights for planning X-59 community noise surveys. Contour maps were generated to provide visualization of the regression model results across the USA and are shown in Figs. 17–20. The mean and standard deviation (SD) of the undertrack PL or CW are plotted separately; thus, the color indicates the quantity of interest in these figures.

Figure 17 shows the mean undertrack PL across the contiguous USA predicted by the statistical model. The highest mean undertrack PL is in the mountainous region in the western portion of the USA. Overall, the mean undertrack PL is highest in the winter and lowest in the summer and fall. East headings typically have higher PL than west headings, with north and south headings lying in between.

Figure 18 shows the standard deviation of undertrack PL values predicted by the statistical model. The highest variability in the undertrack PL (4 dB) occurs during fall in the southeastern portion

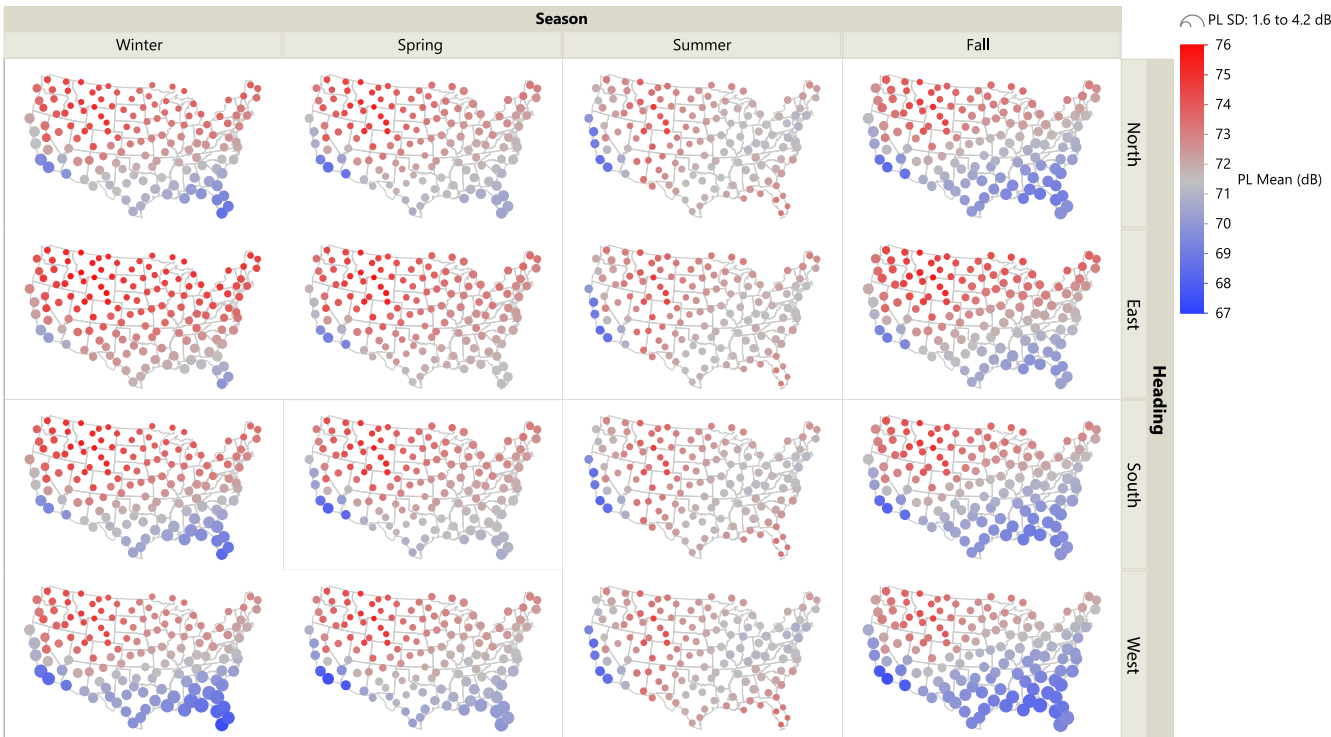


Fig. 15 Mean and standard deviation of undertrack PL at each location separated by season and heading.

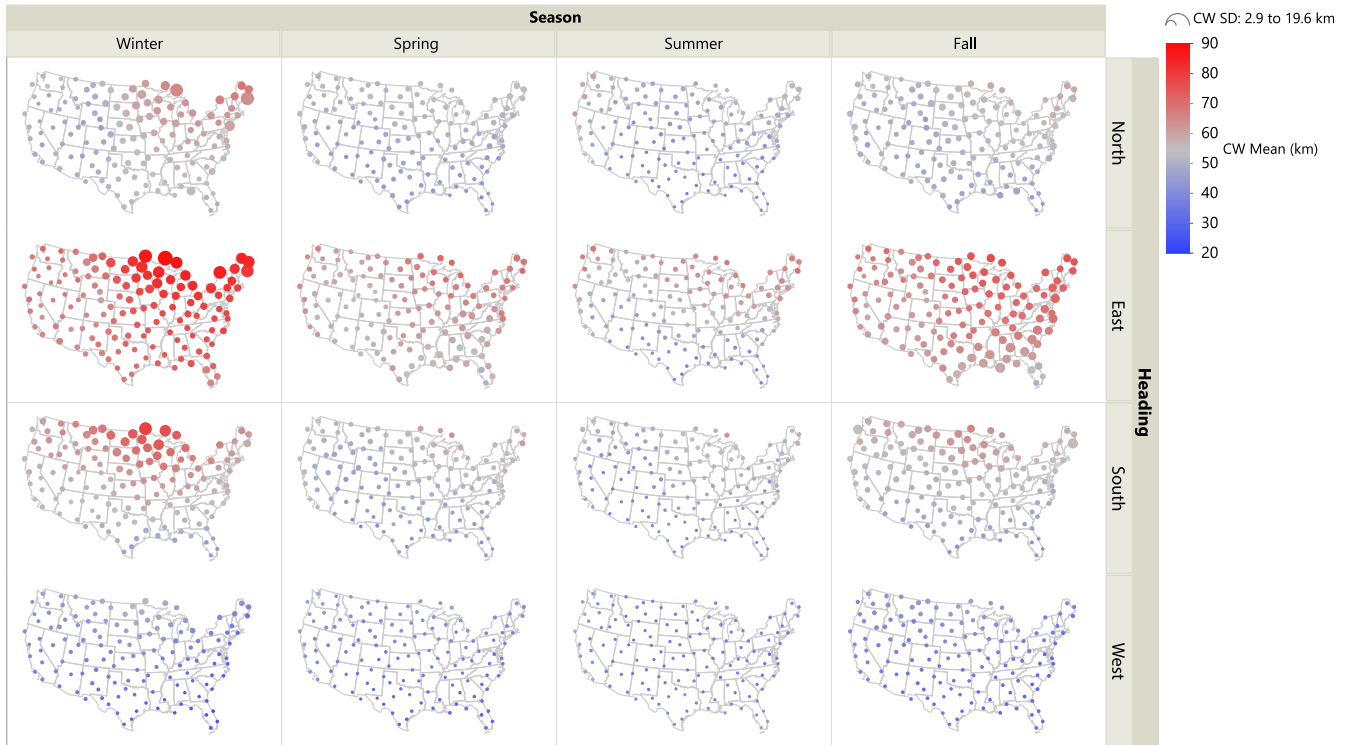


Fig. 16 Mean and standard deviation of geometric CW at each location separated by season and heading.

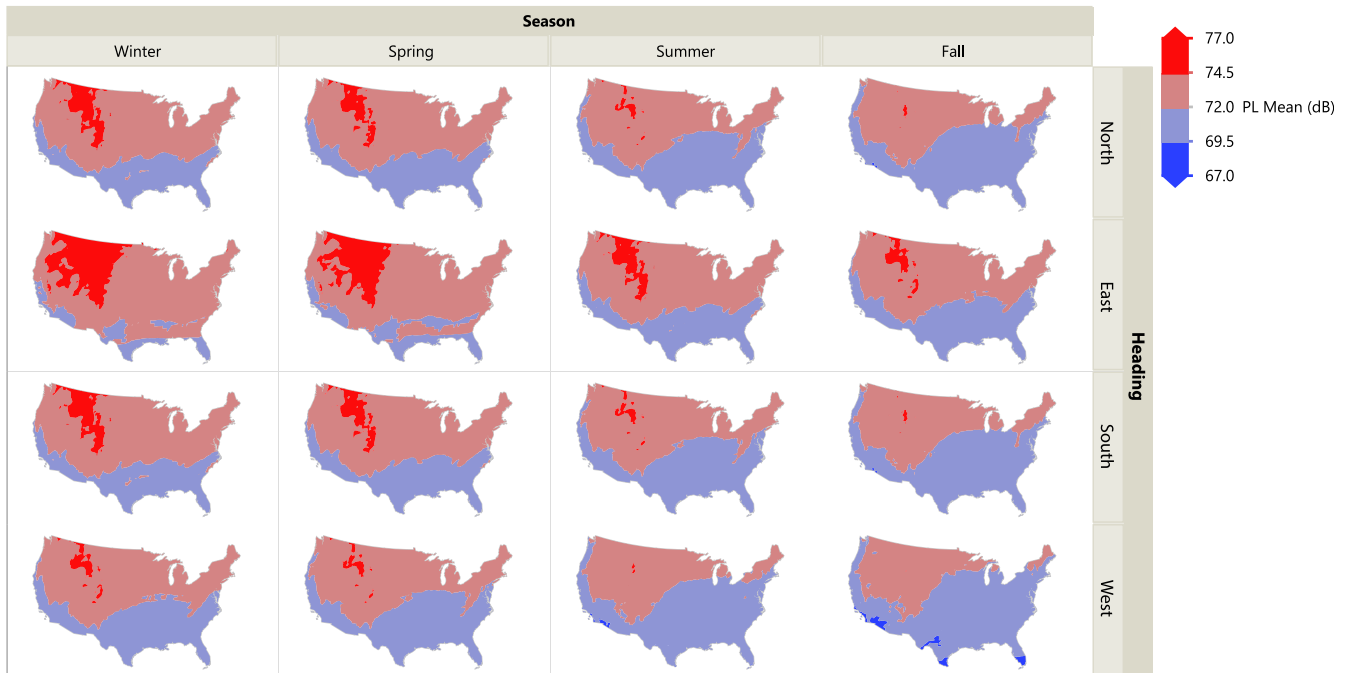


Fig. 17 Mean undertrack PL contours from multiple linear regression model separated by season and heading.

of the USA, with the west heading being especially variable. Higher variability in level at a particular location could make achieving the desired exposure level more difficult during X-59 community noise surveys (the same aircraft configuration results in a different level each day, and so the configuration of the aircraft would need to be adjusted more frequently). In general, the east heading is predicted to have the lowest variability in undertrack PL across the country. The mountainous western portion of the country and higher latitudes also have lower variability.

Figure 19 shows the mean geometric CW predicted by the statistical model. Seasonally, the CWs are highest in the winter and lowest in the summer. Higher latitudes typically have larger CWs. Carpets with east headings are typically largest, and west headings are the narrowest.

Figure 20 shows the standard deviation of CWs predicted by the statistical model. The trends in CW variability are similar to the trends in the mean CW, with higher CW variability during the winter and at higher latitudes. East headings have the largest variability in CW, and west headings typically have the lowest variability.

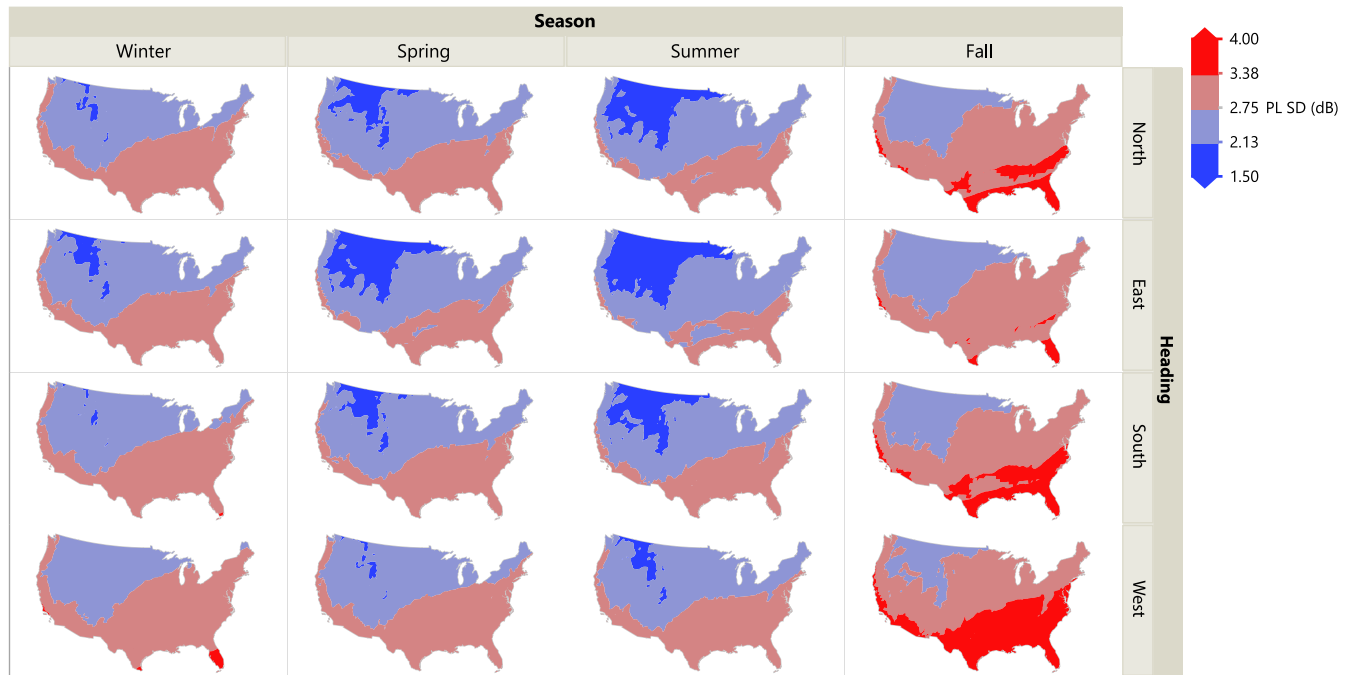


Fig. 18 SDs of undertrack PL contours from multiple linear regression model separated by season and heading.

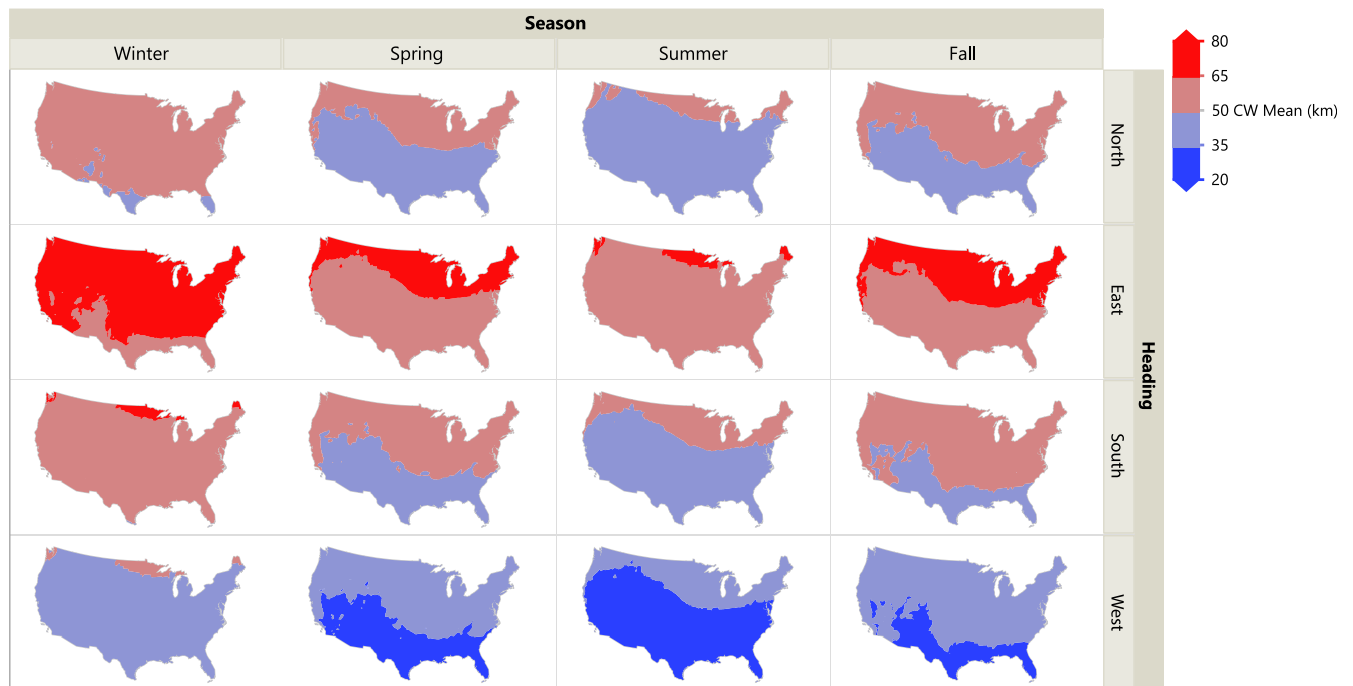


Fig. 19 Mean geometric CW contours from multiple linear regression model separated by season and heading.

IV. Conclusions

The predictions of near-field pressure data for NASA's X-59 vehicle at design cruise conditions were propagated at the four cardinal aircraft headings using PCBoom 6.7.1 through more than 250,000 realistic atmospheres from the CFSv2 database across the contiguous USA. Over one million X-59 carpets were generated at a 3.2 km (2 mile) lateral resolution at 138 locations within the contiguous United States of America and separated by roughly 200 km. Multiple linear regression models were developed; and the effects of the heading, climate, and season on the boom metric level, carpet width, and standard deviation of these values were evaluated.

The results indicate that sonic booms will, on average, be louder at higher latitudes in colder climates. The range of mean PL values

across the USA was 7 dB. Locations near the coast had lower mean undertrack PL values but higher standard deviations. In general, sonic booms from the X-59 were predicted to be a few decibels louder on the PL scale during winter months and when flying eastward. The boom levels across the carpet in realistic atmospheres were typically lower by about 3 dB on the PL scale than the boom levels from a standard atmosphere (ICAO 7488 temperature and pressure with ISO 9613-1:1993 Annex C humidity), and they typically had a smaller CW by a few kilometers unless flying eastward. If predictions using this standard atmosphere definition were used for certification, the actual levels and CWs for typical atmospheres would be lower than the certification level. Sonic boom CWs will also be greater and more variable in the higher latitudes, especially in the northeast due to the



Fig. 20 SDs of CW contours from multiple linear regression model separated by season and heading.

seasonal jet stream. The mean CWs across the country ranged from about 42 to 62 km. Seasonal trends in CWs were similar for the climate zones studied here, except for the marine climate zone, where CWs had little variability with season. It was observed that narrower carpets do not necessarily result in louder carpets, and thus are not concentrating acoustic energy in a smaller region. The metric threshold CW was also described to provide insight into the carpet extent exceeding a given loudness level. The metric threshold CW could be favorable over geometric CWs if low booms beneath a certain level were virtually unnoticeable.

Distributions of undertrack levels of six sonic boom metrics were compared. The PL and ASEL were found to vary more than the other four metrics (BSEL, DSEL, ESEL, and ISBAP). Because all six metrics have been shown to correlate well with human perception of sonic booms, a metric with the least variability may be preferred for future supersonic aircraft noise certification. However, most of the results were shown in PL because the X-59 was designed using this metric. There are similar trends in results for the other metrics; because the PL is the most sensitive of these metrics, it can be considered an upper bound of variability that is expected for the X-59 low booms.

Future work may include repeating this study with other aircraft configurations and atmospheric model databases. Additional analyses may also include identifying specific atmospheric profile characteristics that have the greatest impact on the metric level and CW. The effect of assuming a constant geometric altitude and a single CFD solution for the propagation simulation inputs would also be interesting to study in the future. Finally, future work to fully characterize the overland noise would require assessment of the effects of atmospheric turbulence.

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