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Sonic Boom Focal Zones from Tactical Aircraft Maneuvers

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A study has been conducted of the focal zone "superbooms" associated with tactical maneuvers of military supersonic aircraft. Focal-zone footprints were computed for 21 tactical maneuvers: two for the SR-71 aircraft during acceleration, and 19 for fighters engaged in air combat maneuver (ACM) training. These footprints provide quantitative results which may be used for environmental planning and were the primary objective of this study. A significant observation from these footprints is that focus factors and footprint areas for high-*g* fighter maneuvers are substantially smaller than those for gentle maneuvers associated with larger aircraft.

I. Introduction

A CONCERN in the analysis of sonic booms is that certain maneuvers can lead to geometrical focal zones where ray acoustic theory is singular and high-amplitude superbooms can occur. Focus booms have been experimentally observed[1,2] and there is good theoretical understanding of the mechanisms involved.[3,4] This understanding has been incorporated into a computational methodology,[5] which has been formally applied to the environmental assessment of focus booms from Space Shuttle launch.[6] In recent environmental assessments of sonic booms from air combat maneuver (ACM) training in military operating areas, focal zones have generally been treated in a qualitative manner. Typically, the measurement results of Ref. 1 are cited, noting that focal zones are "small" or "rare" and that booms are amplified by a "focus factor" of up to 5–9 times relative to carpet booms. This description leaves considerable uncertainty as to the actual magnitude of impact which might be expected in these areas. Additionally, there was a need for a simple method to estimate the magnitude and location of focal zones, to aid in the planning of particular supersonic operations.

A study was therefore conducted to apply quantitative knowledge of sonic-boom focusing to tactical maneuvers performed by USAF aircraft. The study consisted of three phases: 1) identification of conditions which could cause focusing[7]; 2) validation of the methodology of Ref. 5 by comparison to available flight-test data[8]; and 3) calculation of focus boom footprints for a representative sample of maneuvers.[9] In this article, we first discuss (Sec. II) sonic boom focus conditions and prediction of focal zone geometry and signatures. Charts of nominal focus conditions are presented. Section III contains a discussion of supersonic training maneuvers and identification of specific maneuvers which can cause focusing. Section IV presents typical focal zone footprints for these maneuvers.

II. Sonic Boom Focusing

A. Focusing Ray Geometries

Focusing is associated with acceleration, turns (horizontal or vertical), or other maneuvers which lead to convex wavefronts and converging ray geometry. Figure 1 illustrates the ray geometry associated with in-plane focusing due to acceleration. The focus is along the caustic surface which is formed by the envelope of rays. Along the caustic, differentially separated rays cross, leading to zero ray tube area and a singularity in the ray-tube area. There is a focal region within a narrow volume centered on the caustic surface. Within that volume, boom signatures are distorted, as will be discussed in Sec. II.B. The focal zone of practical interest is where the caustic surface intersects the ground. Figure 2 is a three-dimensional sketch, analogous to Fig. 1, showing the forward-facing crescent shape of an acceleration focal zone. The focal zone is generated once at the particular location where the caustic intersects the ground. Down-track of this location, the usual sonic boom "carpet" is swept out along the ground by the boom pattern moving with the aircraft. (The word "carpet" was originally used as a description of the area receiving

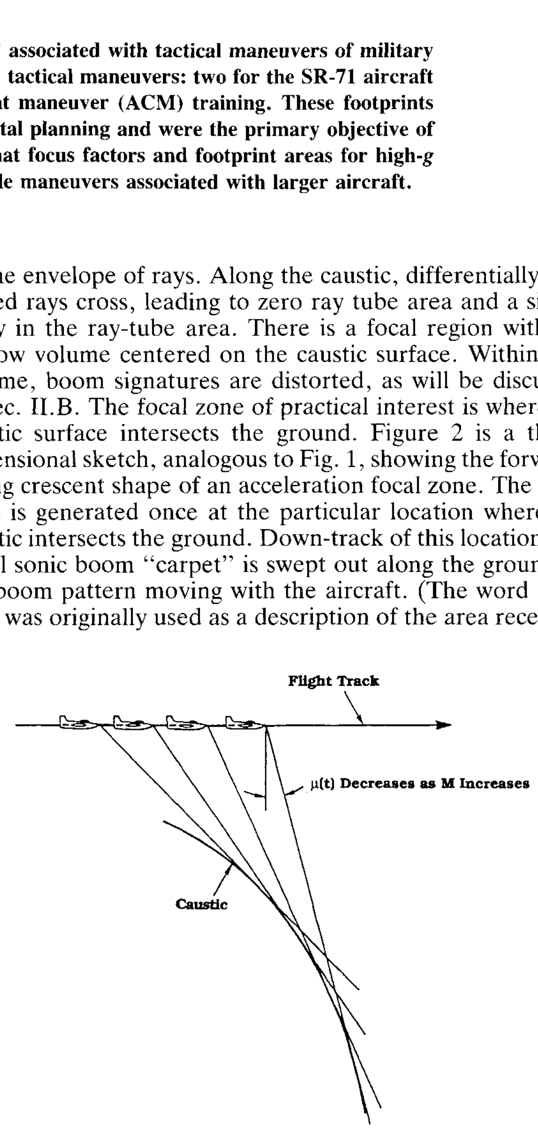

Fig. 1 Sonic boom focal zone (caustic) geometry due to acceleration.

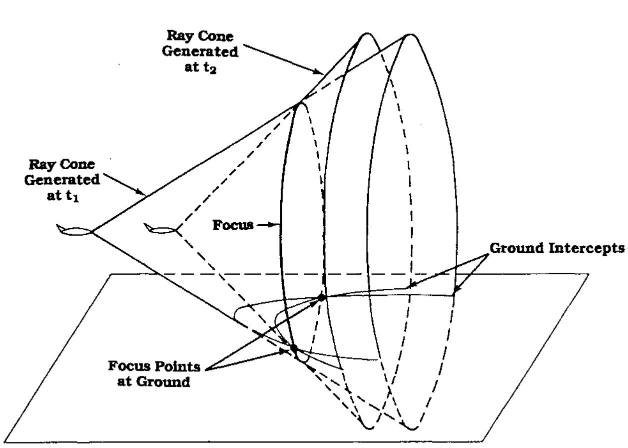

Fig. 2 Acceleration focus in three dimensions.

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sonic boom from sustained supersonic cruise; the term "carpet boom" has since come to be used to denote nonfocused booms associated with steady or near-steady flight.)

Figure 3 is a sketch of in-plane focusing due to a steady turn. The focal zone is a circle concentric with the flight path. Due to the forward projection of sonic boom relative to aircraft position, the focus circle can actually be outside the flight-track circle. Reference 10 contains an excellent illustration of a steady turn caustic surface, and Ref. 1 contains additional illustrations of ground focus geometries.

Figures 1–3 illustrate focal zones associated with a smooth caustic. This corresponds to a simple focus, as defined in Ref. 5. The focal zone theory developed in Ref. 5 applies to any simple focus, including sonic cutoff and the maneuvers sketched in Figs. 1–3. Higher-order types of focus exist, and one higher-order type (the cusped "superfocus") has been measured in the transition from steady level flight to a steady level turn.[1] Maneuvers considered in the current study generated only simple foci.

It can be seen from Figs. 1–3 that any converging ray situation will inevitably lead to a focus. What matters is whether that focus occurs near the ground. If it is sufficiently far below the ground (i.e., rays intercept the ground well before the focus would have occurred), then there is an ordinary nonfocused boom at the ground. If it is sufficiently far above the ground, then the ground receives a "postfocus" boom which is substantially attenuated due to its passage through the caustic. Ray convergence depends on the strength of the aircraft's maneuver. Whether rays with a particular convergence focus at the ground depends on distance to the ground. Figure 4 illustrates various combinations of acceleration and altitude. Figure 4 represents conditions which occur instantaneously during a maneuver and is not in itself a complete description. Comparing Figs. 1, 2, and 4, it is seen that various portions of a given focusing maneuver can have at-ground, above-ground, and below-ground focus conditions. The criteria of whether there will be a ground focal zone for a given maneuver is whether the maneuver passes through a ground focus condition (i.e., whether the caustic intersects the ground). Identification of focus maneuvers consists of assessing whether this threshold has been attained.

A screening model was prepared which would identify whether a particular flight condition or maneuver crossed the focus threshold.[7] This model utilized ray acoustics, testing for vanishing ray tube area, similar to the method used in Ref. 10. Parametric studies were made to determine focus threshold conditions as a function of maneuver strength (i.e., acceleration or turn rate) at various altitudes, attitudes, and Mach numbers. It was found that the dependence of focus threshold on altitude and maneuver strength approximately reduced to a single parameter, altitude times maneuver strength.

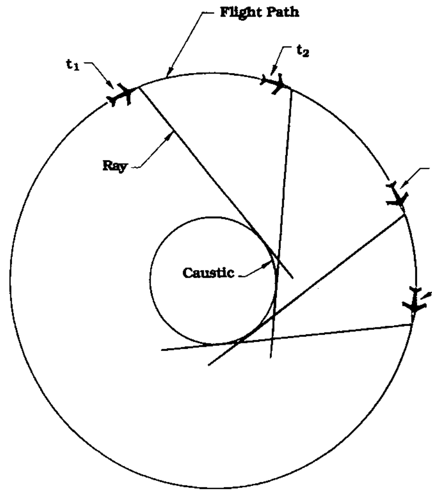

Fig. 3 Caustic geometry for a steady turn.

Figures 5 and 6 show the results of these calculations in the form of focus condition charts for acceleration in level and diving flight and for level turns. These charts define focus condition theshold; relative to a threshold condition, ground focus will occur for higher acceleration, higher altitude, or lower Mach number.

Figures 5 and 6 show that focusing is a low supersonic Mach number phenomenon. Note that both figures quantify focus threshold in terms of acceleration (linear acceleration or turn rate) and altitude. At higher altitudes, focus can occur for lower acceleration. It is obvious from the sketch in Fig. 1 that any acceleration to supersonic speed which ultimately generates a carpet boom will have a focal zone at the initial boundary of the boom footprint; Fig. 5 shows the Mach number associated with this initial boundary Focus due to turning

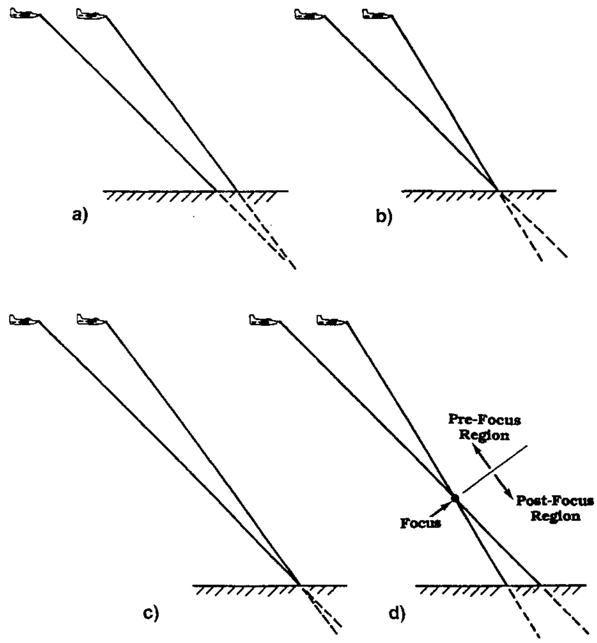

Fig. 4 Converging rays for small and large acceleration, low and high altitude: a) Small acceleration, low altitude, "focus below ground"; b) large acceleration, low altitude, "focus at ground"; c) small acceleration, high altitude, "focus at ground"; and d) large acceleration, high altitude, "focus above ground."

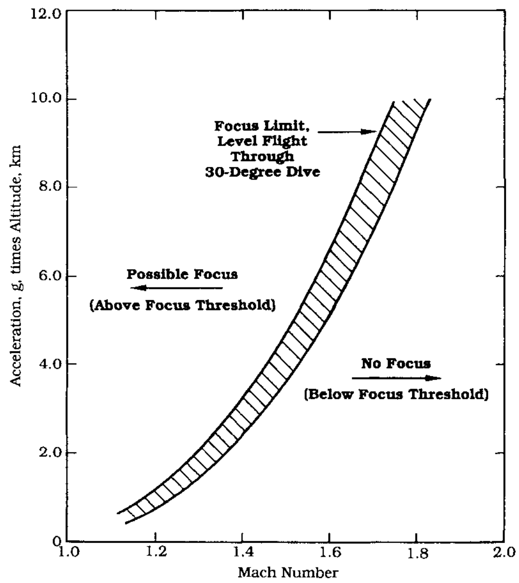

Fig. 5 Focus threshold condition, acceleration in level and diving flight.

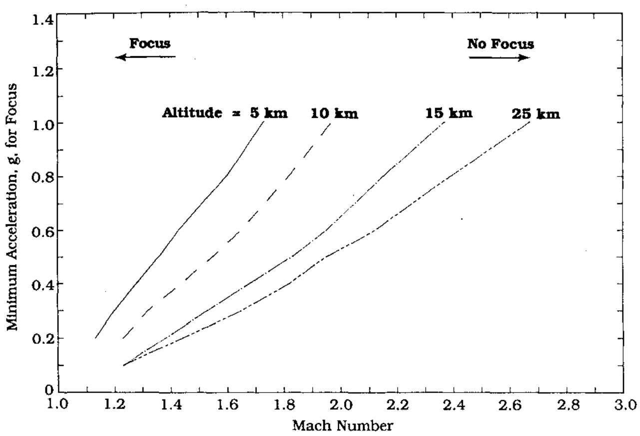

Fig. 6 Focus threshold condition, steady level turns.

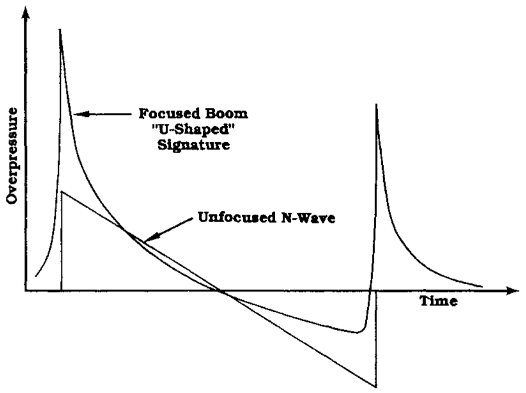

Fig. 7 Focused and unfocused boom signatures.

is not inevitable but has a threshold quantified by Fig. 6. When the nature of tactical maneuvers is considered (Sec. III), focusing is seen to occur under two conditions: 1) during the initial acceleration to supersonic speeds, forming a boundary to the carpet boom region; and 2) during high-*g* turns while still at low supersonic Mach number.

B. Signatures at Focus

At a focus, where ray acoustic theory is singular, a combination of diffraction and nonlinear effects causes sonic boom signatures to have finite amplitude, although their shape is distorted. Figure 7 illustrates a nonfocus *N*-wave and the distorted "*U*-wave" typically seen at a focus. Guiraud[3] wrote the governing equations and derived a similarity scaling law. If a focused signature shape is available for some condition, then Guiraud's similitude allows its application to any smooth caustic focus. A numerical focus solution by Gill and Seebass,[4] when applied by way of Guiraud's similitude, is in excellent agreement with available flight test[1] and laboratory[11] focus data. This procedure has been added to an existing NASA sonic boom program.[12] The modified program (described in Ref. 5) was updated for use in this study and demonstrated to be in good agreement with Ref. 1 data.[8] The current version of the program is denoted "FOBOOM."

Focal zones are actually somewhat more complicated than suggested above. Flight test data for turn[1] and sonic cutoff[2] focal zones exhibit maximum focus signatures as described above. Away from the maximum these data show an incident *N*-wave and a reflected *U*-wave. The reflected (or postfocus) *U*-wave is somewhat more symmetric than the focused *U*-wave shown in Fig. 7. The focus *U*-wave can be viewed, at least qualitatively, as the superposition of these two waves. The Gill-Seebass analysis provides solutions for the entire focal zone, not just the maximum at the caustic. In the model employed here, only the maximum focus signature is considered and applied over the full region which the scaling law considers to be the focal zone. This is a conservative approach, which will tend to overestimate the magnitude of focus effects.

When discussing *N*-wave sonic booms it is common to discuss amplitude in terms of the peak overpressure. This custom has carried over to focused booms, and it is common to discuss focus amplification in terms of a focus factor, the ratio of peak focus overpressure to that of the nearby carpet boom. The current study adopts this convention, and results are presented in terms of peak over pressures. Examination of Fig. 7 suggests that this is a worst-case definition of focus factor. A definition based on impulse or on *C*-weighted sound exposure level (recommended in Ref. 13 for assessment of annoyance), would certainly yield a lower ratio for a given situation. The current presentation of results in terms of peak overpressure is, therefore, conservative, in that a focused *U*-wave of given overpressure would probably have less adverse impact than an *N*-wave of equal overpressure.

III. Supersonic Tactical Maneuvers

Four aircraft were specified for analysis: 1) SR-71, 2) F-4, 3) F-15, and 4) F-16. Supersonic operations for these aircraft fall into two decidedly different categories. The SR-71 engages in sustained supersonic flight with relatively few maneuvers and the fighter aircraft become supersonic for brief periods during ACM training.

Tracking data for a number of SR-71 training missions were reviewed. It was found that the only focusing maneuver for this aircraft is its initial acceleration to supersonic speed at a rate of about 0.1 *g* and an altitude of slightly over 30,000 ft. Depending on fuel load, this maneuver can be in level flight or in a 1- to 3-deg dive. Following this initial acceleration (referred to as a "dipsy" if a dive is required), the aircraft enters a steady climb to its cruise condition. All subsequent maneuvers (heading changes, pitch-over at the start and end of cruise) are well below focus threshold.

Two focusing maneuver conditions were analyzed for the SR-71: 1) 0.1-*g* acceleration at slightly above 30,000 ft in level flight; and 2) in a 3-deg dive. These bracket the range of actual focusing conditions.

Maximum maneuver performance of fighter aircraft occurs at subsonic speeds, so that supersonic speeds are usually attained during energy addition prior to engagement, and during break at the end of an engagement. The acceleration-to-supersonic phases generally occur at full throttle and in a straight line, either level or diving. Mach number rarely exceeds 1.25. During an engagement, turns are usually carried out at maximum allowable *g*-loads. Focus conditions for such turns tend to be at relatively low supersonic Mach numbers, at which point the aircraft is decelerating (typically at idle power) back to subsonic speed. There are two generic focusing maneuvers to consider: 1) linear acceleration (level or diving) at full throttle; and 2) maximum-*g* turns while decelerating at idle power. These maneuvers occur over an altitude range of 10,000–45,000 ft above ground level.

A set of maneuvers, presented in Tables 1 and 2, was defined which brackets the range of potentially focusing maneuvers.[7] These maneuvers were selected in conjunction with the focus condition charts (Figs. 5 and 6) and the performance

Table 1 Focus maneuvers: fighter energy addition[a]

Initial altitude, ft AGL[b]	Dive angle, deg 0	10	20	30
45,000	●	○	○	○
30,000	○	○	○	●
15,000	○	●	○	
10,000	●			

[a]Full throttle, constant angle, from M = 1.0–1.25.
[b]Above ground level
○Define breadth of focus boom occurrence.
●Intermediate maneuvers to cover range.

Table 2 Focus maneuvers: fighter turn

Altitude, ft AGL[b]	Plane of turn[a] 90 deg	45 deg	0 deg	−45 deg	−90 deg
10,000	—	●	●		
15,000	—	○	○	○	
30,000	—	○	●	○	●
45,000	—	—	○	○	○

[a]0 deg = level; 90 deg = pull-up; −90 deg = pushover.
[b]Above ground level.

characteristics of the three fighter aircraft being considered. Drag polars and engine performance charts were obtained for the three aircraft and trajectories computed for each maneuver. The maneuvers used were highly simplified. Acceleration was at full throttle, in a straight line at constant dive angle. Turns were at idle power, constant *g*-load, and within a plane (i.e., no spirals). These simplified maneuvers were adopted in the spirit that each was effectively tangent to the actual maneuver during the brief period during which focusing would occur.

IV. Focal Zone Footprints

Focal zone footprints were computed, using FOBOOM, for the two SR-71 maneuvers and the eight primary fighter maneuvers shown in Tables 1 and 2. Some of the primary fighter maneuvers did not result in focal zones for all three fighter aircraft, so footprints were computed for some alternate maneuvers to cover the range. A total of 21 footprints were generated. Figures 8–10 show three typical results.[9] Each footprint shows the ground track of the maneuver (oriented with flight direction toward the top of the figure), three overpressure contours (one somewhat above carpet boom, one that is two to three times carpet boom, and one near the maximum overpressure), and summary information. The charts are designed so that an environmental planner can overlay them on a map on which an expected trajectory has been plotted, and/or use the summary information to estimate the probability of exposure.

As reproduced in this article, only the lowest overpressure contour values (3.5 psf in Fig. 8, 6 psf in Fig. 9, and 5 psf in Fig. 10) are clearly visible. Higher pressure contours can be seen within these outermost contours as a doubling or thickening of a portion of the lines. Even at larger scales the maximum focus contours are often thinner than line thickness. The outermost contours may be used as a guide to the location of the focal zone, and quantitative impact based on the computed summary information.

Tables 3 and 4 present summary information for all computed fighter maneuvers. Two computed acceleration focus conditions are identified in Table 3 as having no focus at the ground. The "no-focus" case for the F-4 (level acceleration at 45,000 ft) represents a maneuver outside of that aircraft's performance envelope. The no-focus case for the F-15 (30-deg dive from 30,000 ft) does actually have a ground focus, but this occurs at a Mach number greater than 1.25. In a real maneuver, the acceleration phase would have ended well before this, and the ground focus would be associated with a much more complex situation involving the transition to deceleration and turn. It was felt that the remaining conditions (which were computed adequately) bracketed the cases of interest.

In Fig. 8, the focusing part of the maneuver lasts 22 s, with Mach number going from 1.176 to 1.241. Each contour has a forward-facing crescent shape, as expected from Fig. 3. The 3.5 psf contour is represented by the upper and lower curves which span the width of the figure. The 6 psf contour is the pair of curves just above the lower 3.5 psf contour which span about half the width of the figure. The 9 psf contour is barely visible at the center of the footprint, within the 6 psf contour. The legend in the lower left corner of the figure shows the carpet boom overpressure and the area within each of the

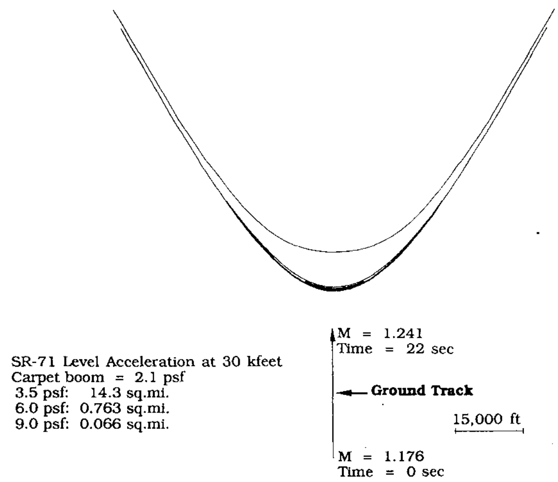

Fig. 8 Focal zone footprint, SR-71 level acceleration at 30,000 ft.

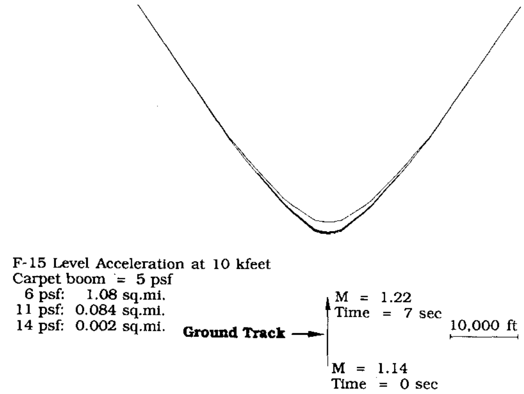

Fig. 9 Focal zone footprint, F-15 level acceleration at 10,000 ft.

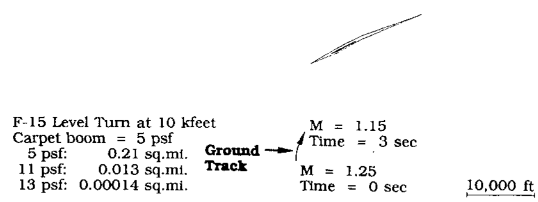

Fig. 10 Focal zone footprint, F-15 decelerating level turn at 10,000 ft.

plotted contours. The maximum focus factor for this maneuver is slightly less than 5, which agrees well with the flight test data of Ref. 1. The relatively small areas involved should be noted.

Figure 9 shows a similar footprint for an accelerating F-15. Note that the areas involved are much smaller (even when the altitude difference is considered) and that the focus factor is somewhat less than three. This is typical of a trend that higher acceleration rates resulted in smaller, lower amplitude focal zones. These differences are clearly related to the higher accelerations of the fighters which were up to an order of magnitude greater than the acceleration of the SR-71 and the Ref. 1 flight tests. The smaller focus amplification factor follows from the scaling law of Ref. 3: higher acceleration increases the curvature of the focus geometry, enhancing diffraction effects which limit amplification. The smaller area is partly a consequence of this lower amplification, plus the fact that at high acceleration the focus condition is passed through more quickly and simply exists for a much shorter period of time. This trend may be seen in Table 3, where focus factors for fighter acceleration are typically two to three, and focus footprint areas are typically a fraction (often a very small fraction) of a square mile.

Table 3 Focal zone areas for fighter acceleration[a]

Aircraft type	10,000 ft,[b] level		15,000 ft, 10-deg dive		30,000 ft, 30-deg dive		45,000 ft, level	
	p	*A*	*p*	*A*	*p*	*A*	*p*	*A*
F-4	7	1.8	7	0.70	5	0.45	No focus at ground (see text)	
	11	0.26	11	0.12	11	0.005		
	16	0.16	16	0.003				
F-15	6	1.1	6	1.45	No focus at ground (see text)		2	1.26
	11	0.08	11	0.23			5	0.33
	16	0.002	16	0.055				
F-16	5	1.0	5	0.43	4	0.36	2	1.28
	11	0.023	11	0.0045	8	0.005	4	0.218

[a]Area A (square miles) within contours of pressure *p* (psf). The lowest pressure contour for each aircraft and maneuver represents the limit of pressure exceeding the carpet or enhanced carpet boom. As noted in the text, the areas are narrow crescent-shaped regions.
[b]Altitudes are above ground level (AGL).

Table 4 Focal zone areas for fighter turns[a]

Aircraft type	10,000 ft,[b] 0 deg		15,000 ft, 0 deg		30,000 ft, 0 deg		45,000 ft, 45 deg	
	p	*A*	*p*	*A*	*p*	*A*	*p*	*A*
F-4	5	0.36	Not calculated		2.4	0.78	2.4	0.65
	11	0.0003			6	0.001	4.8	0.006
							7	0.0005
F-15	5	0.21	4.1	0.2	2.4	0.75	Not calculated	
	11	0.013	8.2	0.043	3.0	0.13		
	13	0.00014						
F-16	4	0.241	3.3	0.15	1.9	0.346	Not calculated	
	8	0.016	6.6	0.003	3.0	0.025		

[a]See footnote, Table 3. Pressure outside of the focal zone for turns had a tendency to be significantly lower than carpet booms.
[b]Nominal altitude above ground, and plane of turn. A plane of 0 deg is a level turn; 45 deg is a diving turn, midway between a level turn and an outside loop.

Another interesting observation about initial acceleration focusing is that the initial boundary of the entire sonic boom footprint lies along the focus line and is associated with a higher Mach number than would be expected from simple consideration of cutoff Mach number. This is the consequence of lower Mach numbers being associated with "above-the-ground" focusing. For a brief supersonic event, this results in a substantially smaller total footprint than would be obtained by estimating carpet boom at some average Mach number.

Figure 10 shows a typical decelerating-turn focal zone. The focal zone is an arc which is concentric with the arc formed by the flight path, as sketched in Fig. 2. In this case, the focus arc lies to the outside of the flight path arc. The focus has a finite length because of the transient nature of the maneuver: it begins when Mach number becomes low enough for a focus to exist, and ends as cutoff Mach number is approached. The deceleration aspect of this maneuver has a strong defocusing effect, therefore, reducing the size of the footprint. Comparison of Tables 3 and 4 show that the focal zone associated with this type of supersonic turn is much smaller than that of the acceleration maneuver which preceded it.

V. Conclusions

Sonic boom focal zone footpints have been computed for a range of tactical maneuvers of the SR-71, F-4, F-15, and F-16. Charts have been prepared which identify focusing maneuver conditions. A graphical set of footprints, suitable for use by planners, has been prepared for a number of representative maneuvers. A tabulation of maximum focus overpressures and areas within various overpressures has been prepared. Focus factor for the SR-71 acceleration maneuver is about 5, while focus factors for fighter maneuvers are in the range of 2–3. There is a clear trend that stronger maneuvers (i.e., higher acceleration rates) result in focal zones with lower focus factor and smaller footprint area than gentler focusing maneuvers.

Acknowledgments

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