

Analyzing Sonic Boom Footprints of Military Jets

Author

Andy S. Rogers, Senior Analyst, AOT, Inc.

Testing and training exercises involving supersonic U.S. military aircraft can produce sonic booms. By using ArcView and PCBoom3, the U.S. Air Force's sonic boom modeling tool, the effects of sonic booms in a particular environment can be studied. We have currently partially integrated PCBoom into ArcView, with a view to full integration of sonic boom modeling into a GIS to follow. The current implementation allows users to ingest either actual flight data or design flights. Using real flight data helps review past supersonic impacts. Creating model flights allows the user to predict future impacts, and determine how they may be reduced. Using this modeling capability, coupled with ground reference data, we are performing a parametric study that will be the basis for an interactive flight planning tool.

Analyzing Sonic Boom Footprints of Military Jets with GIS

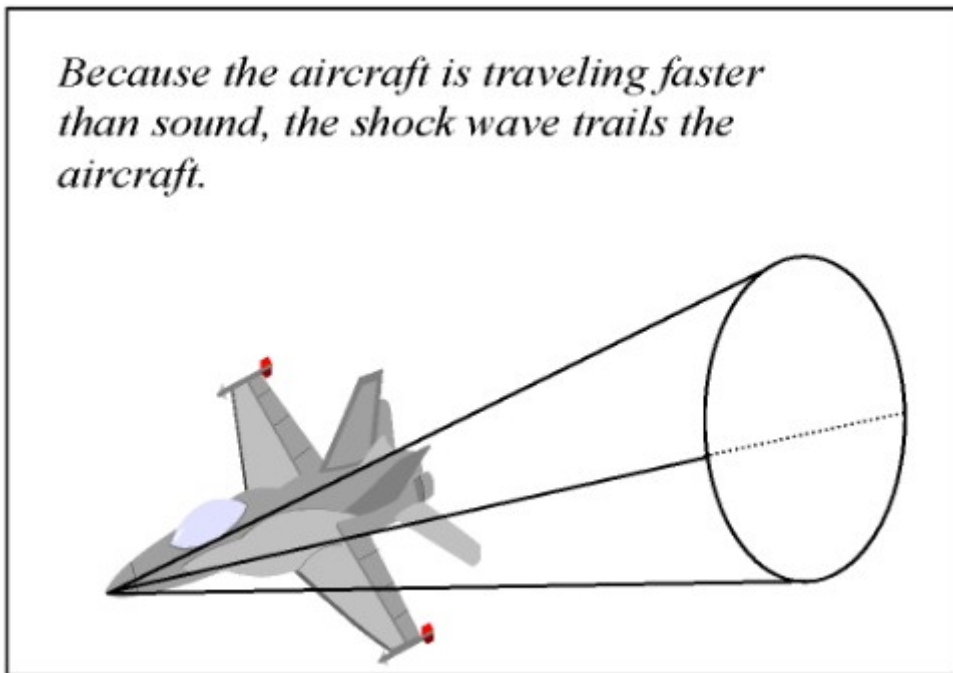
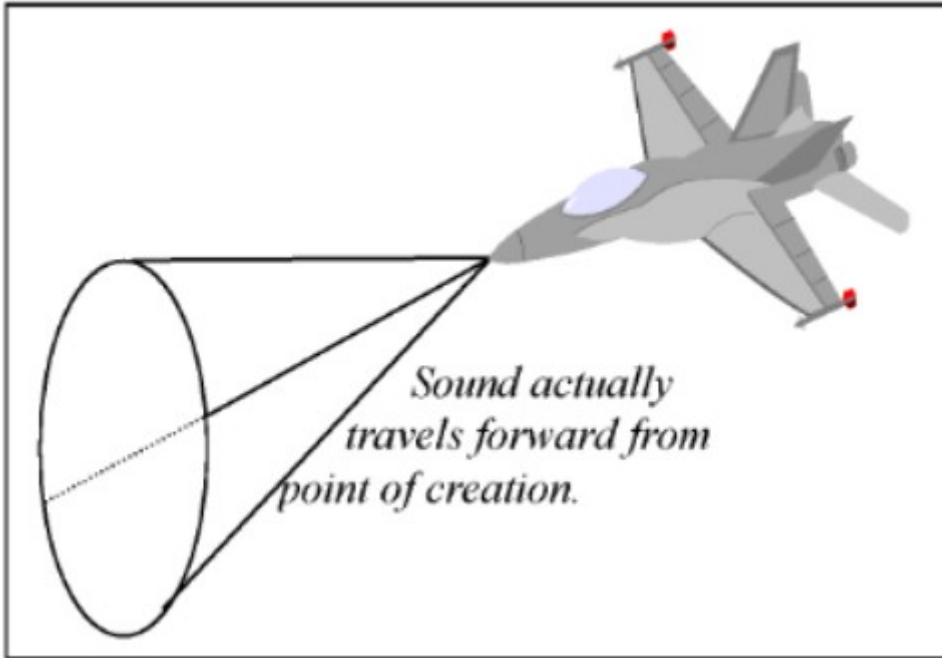
Background

Sonic booms generated by high-performance aircraft are a source of noise for communities near supersonic flight corridors and the Navy and Air Force are often required to expend money and manpower to deal with damage claims. The purpose of this study is to facilitate understanding of sonic boom phenomena and the development of possible alternative flight patterns to reduce sonic boom impacts to a community near a military installation where supersonic jets are flown. This must be done without jeopardizing pilot safety or constraining research, development, testing and evaluation (RDT&E) or training exercises. To respond proactively to these issues, the Navy has decided to undertake various measures to help understand and predict the effects of its supersonic operations. The goals of this parametric study project are to show how changes in various flight parameters, weather parameters and geographic parameters affect the impacts of supersonic operations. The results of this study should be useful in flight planning to reduce sonic boom impacts. The general method is to use PCBoom to calculate sonic boom footprints for model flights that are based on actual operations at Naval Air Station Patuxent River (NAS PAX). These model flights have been altered by varying the altitudes, flight path angles (FPA), weather conditions and other parameters listed below. Each model footprint is then converted to a GIS format and displayed in ArcView to make visual comparisons possible.

1.1 Sonic Booms: A Brief Primer

All objects moving through the air create pressure waves as the air in front of them is compressed. Sonic booms are generated when an aircraft moves faster than the speed of sound and begins to outrun its own bow pressure wave. This creates a shock wave that spreads forward from the point of its creation (Figure 1). Because the aircraft that created the shock wave is moving faster than the speed of sound in air, the wave will appear, to trail the aircraft (Figure 2). The cone formed by waves trailing the aircraft is called the Mach cone. The boom is formed where there are major pressure points, which generally correspond to the front and tail sections of an aircraft. The boom generally has two spikes with a drop in pressure between them forming an N-wave (Figure 3). For military aircraft of the size of an

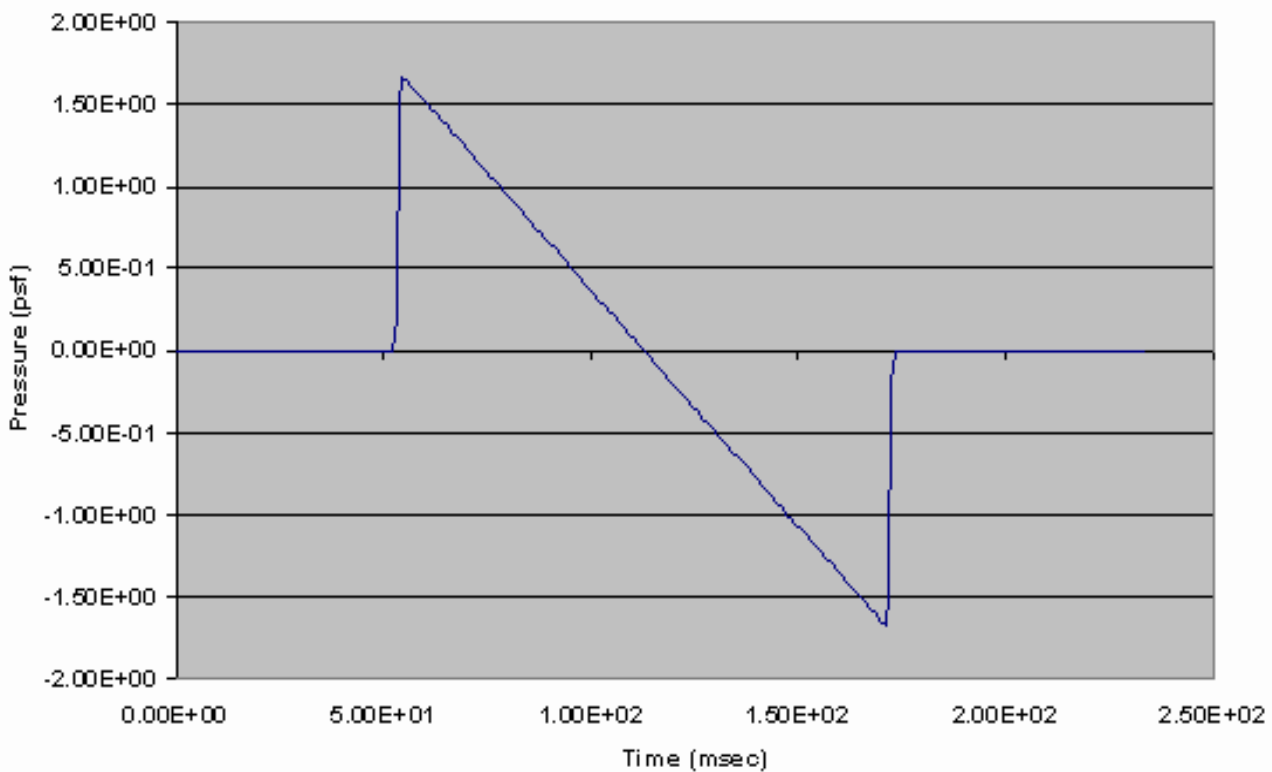
F/A-18 E/F, the time between these two peaks is about 1/10 of a second, too short for the ear to detect. However, for the Space Shuttles, which are 122 feet long, the two spikes are about ½ second apart and are heard as two distinct booms. Under other circumstances a "u" shaped wave is formed (Figure 3). The sonic boom heard on the ground is only one portion of a circular shockwave (Figure 4). This type of boom is referred to as a "carpet boom". It spreads broadly across the surface beneath the aircraft. In general, the carpet will be one mile wide for every thousand feet of altitude of the aircraft. Therefore, a carpet boom generated at 50,000 feet above ground level will be approximately 50 miles wide. It is important to remember that, as shown in Figure 4, the boom always strikes the ground forward of the point at which it is created.



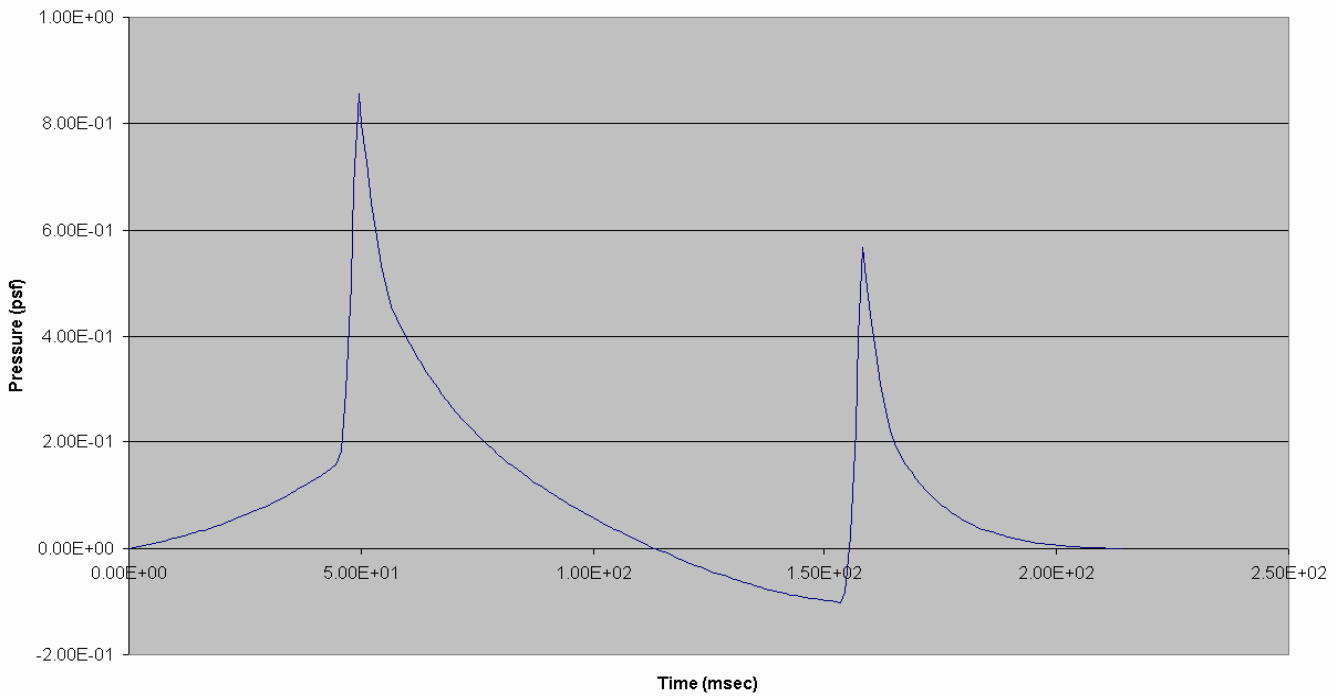
The strength of the sonic boom is affected by various factors including the size and weight of the aircraft, speed, altitude, angle of attack, and atmospheric effects. Maneuvers also affect the strength of a boom.

Any change in the aircraft's velocity can either focus or diffuse the boom. This includes acceleration, deceleration, changing flight path angle (FPA), or heading. In general, lifting the nose of the aircraft will diffuse a boom, dropping the nose will focus it. Acceleration will focus the boom, deceleration will weaken it. Any change in horizontal direction will focus the boom along a track to the outside of the flight path. A focused boom (Figure 5) occurs when two or more wavefronts, originating at different times from the aircraft, coincide exactly. Sonic booms are simply a rapid change in air pressure, and booms normally heard are about the same change in air pressure as experienced in traveling a few floors in an elevator. Modern supersonic aircraft in normal operating conditions generate peak overpressures varying from less than one pound to about 10 pounds per square foot for a carpet boom. Focused booms may have peak overpressures two to five times as large. Areas of focused booms are typically very small areas when compared to the area exposed to the rest of the sonic boom.

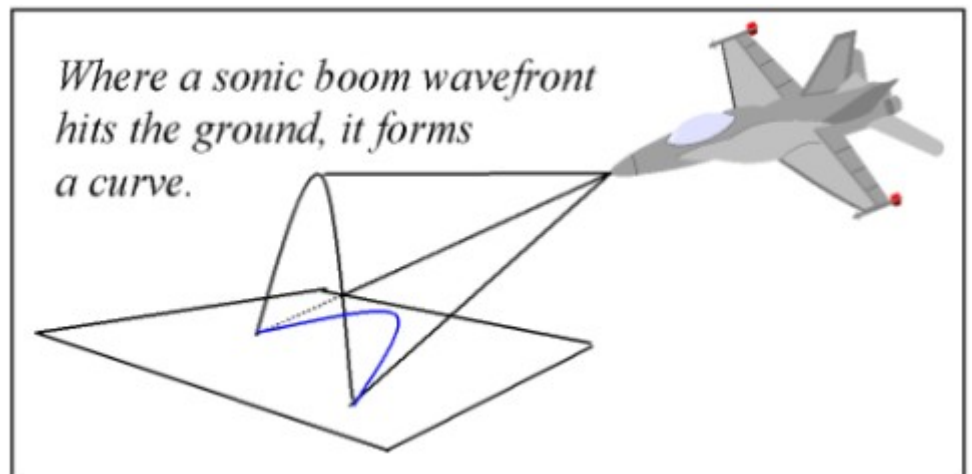
N-Wave (Carpet Boom)

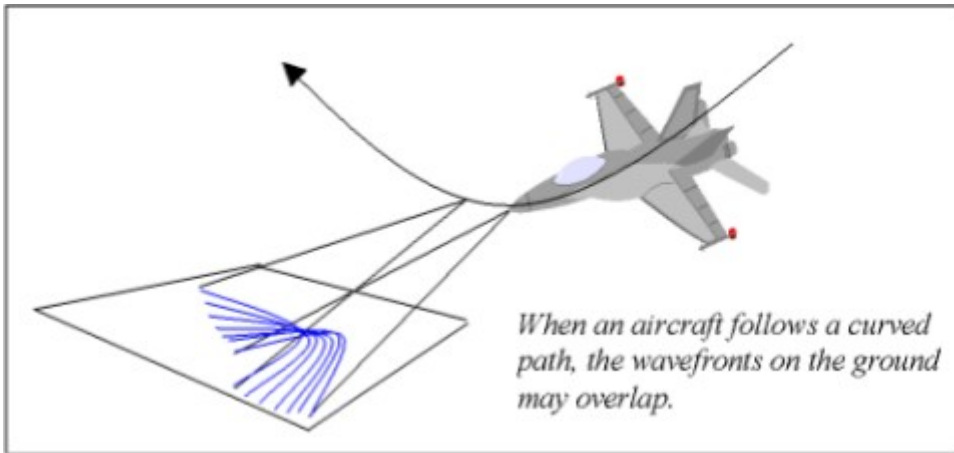


U-Wave (Focused Boom)



Sonic booms are measured in pounds per square foot of overpressure (psf). Overpressure is the increase over normal atmospheric pressure (2,116 psf). One pound of overpressure would not be expected to produce damage to structures. Sonic booms may cause minor damage such as shattered glass but structurally sound buildings should not suffer damages from overpressures less than 16 psf. Sonic boom exposure to communities typically does not exceed two psf. Some public reaction could be expected between 1.5 and 2 pounds. Rare minor damage may occur with 2 to 5 pounds overpressure. The strongest sonic boom ever recorded was 144 pounds per square foot and it did not cause injury to the researchers who were exposed. The boom was produced by an F-4 flying just above the speed of sound, at an altitude of 100 feet.





Sonic boom energy is concentrated in the 0.1 to 100 Hz frequency range and duration typically are about 500 milliseconds, varying on the size of the aircraft.

1.2 An Introduction to PCBoom

PCBoom is a single-event sonic boom prediction tool designed to meet the sonic boom prediction needs of the USAF. This model uses full ray tracing propagation theory and includes the effects of aircraft maneuvers, non-standard atmospheric profiles, and winds. Calculations include focused superbooms when they occur. Input parameters are flexible to allow general supersonic maneuvers. The program accepts user-defined F functions, and has F functions built in for current USAF aircraft. The model predicts the location and waveforms of sonic booms on the ground. PCBoom actually calculates the sonic boom along rays, thereby generating a set of points on the ground where the rays intersect the ground surface. The points are organized by time step (when a given wave originates at the aircraft) and angular distance around the ray cone. We have bypassed PCBoom's display module and directly display the points the model calculates using a GIS package (Figure 6) rather than using the contour lines produced by PCBoom. PCBoom assumes homogeneity in both horizontal dimensions for both the atmosphere and the ground surface. We have begun to test it in the Chesapeake Bay area, and it has been tested over land before.

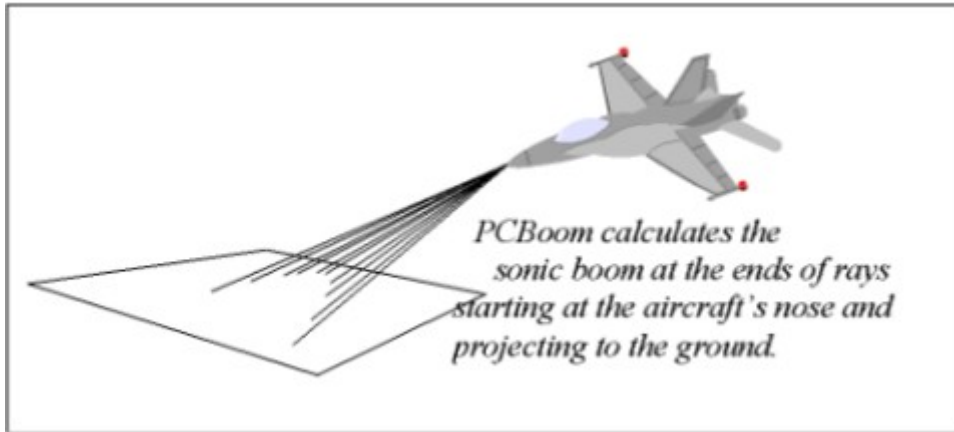
1.2.1 Models in PCBoom

PCBoom3 requires several inputs to calculate a sonic boom model. These include an aircraft model, a maneuver, an atmospheric model, and ground surface height.

1.2.2 Aircraft Models

PCBoom comes pre-loaded with several aircraft models. Among these are an F-14, an F/A-18 C, and generic models designated as "fixed-wing fighter", "large fighter", and various others. Because the F/A-18 E/F is not included in the listed models we used (REF Downing, pers.comm, 2/16) the "fixed wing fighter" choice under "user defined" on the aircraft menu, and entered the values for length and weight

of the aircraft. This model was also recommended for the F-15, F16 and JSF.



1.2.3 Maneuver Modeling.

PCBoom does not provide the means of creating maneuver models. They were created using Excel spreadsheets and fitted to PCBoom input specifications using a separate program packaged with PCBoom (traj2trj). Maneuvers in this project are designed based on desired g-force in the turns, maximum allowable g-forces in acceleration, deceleration and turns, rate of g onset, and other requirements of the flight. For instance, weapons separation flights are designed to be performed at 45-degree and 60-degree flight path angles (FPA). The FPA is the angular separation between the flight path and the horizontal and is negative when the aircraft is diving.

1.2.3.1 Creating Maneuver Models

Maneuver models were created using Excel spreadsheets. Model inputs include aircraft type, maximum Mach, minimum Mach, the time for acceleration and deceleration, starting position (x,y,z), heading, upper and lower altitude bounds and maximum rates of change of FPA and heading. The data form also provides checks on the g-forces and other factors as required. A flight model can be fitted to actual requirements by defining the total g from acceleration and maneuvering, and adjusting the left-hand parameters until the g's have the desired values.

1.2.3.2 Atmospheric Modeling

PCBoom has its own interface for entering atmospheric models. However, this requires individually typing every value. Atmospheric models in this work were created using an Excel spreadsheet in which the atmospheric data could be cut and pasted. Due to the stringent input requirements of PCBoom, any error in the format of this file, including extraneous spaces and other unidentifiable errors can cause PCBoom to fail with unintelligible errors. Worse still, certain errors allow PCBoom to appear to operate correctly while producing data that is seriously in error. This happens most noticeably when there is no wind in the profile, but PCBoom produces footprints that are skewed as though there is a wind. To eliminate these errors, the atmospheric models had to be slightly hand-edited.

1.3 ArcView Adaptations

The technological task here is to integrate a variety of spatial and non-spatial data, in different formats, and the means for creating them into a relatively simple-to-use package. This work so far has been developmental in that it demonstrates the possibility of good integration and incorporates some

integration. To make the system work, we used ArcView 3.2's GUI as the integration tool. This was done by adding buttons that initiate Excel spreadsheets and the PCBoom program. The native interfaces for these programs were used to enter data into them. Eventually, this will be mostly automated so that the data flows from one program to another without the user having to use all the interfaces. PCBoom puts its data out in contour lines. However, there are issues with these lines, besides the fact that they cross, they must be converted into another mapping program's format and then to shapefiles before they can be imported into ArcView. This causes a loss of data and a lot of work. We altered PCBoom to write out the points it calculates for the ends of the rays with latitude, longitude and several key attributes. The data can be directly imported into ArcView using tables and then made into an "event theme". The flight tracks are also generated as a series of points with latitude and longitude and other attributes, which can similarly be imported into ArcView.

1.4 Parameters

To perform this study, it is necessary to identify the parameters that affect the intensity, placement or dispersion of the sonic boom. These parameters are broken up into three general categories - flight characteristics, atmospheric characteristics and geographic characteristics. These are discussed in the following sections.

2 Flight Characteristics

Flight characteristics are determined by the test or training exercise being flown, existing laws, controlled airspaces and standard operating procedures (SOP). Therefore, to a certain degree, these elements are inflexible. However, it is essential to this study that all flight parameters be tested over a wide range of values to determine what impact, if any, changes in the flight parameters have on the sonic boom footprint. Flight characteristics include flight path angle (FPA), Mach, Angle of Attack (AOA), thrust, g, altitude, and aircraft type, which affects aircraft parameters such as length, thrust, weight and other characteristics. Supersonic aircraft fly under varying conditions of Mach, altitude, and g's pulled in a turn. Some of these characteristics, along with different aircraft types are examined in this section.

2.1 Aircraft Type

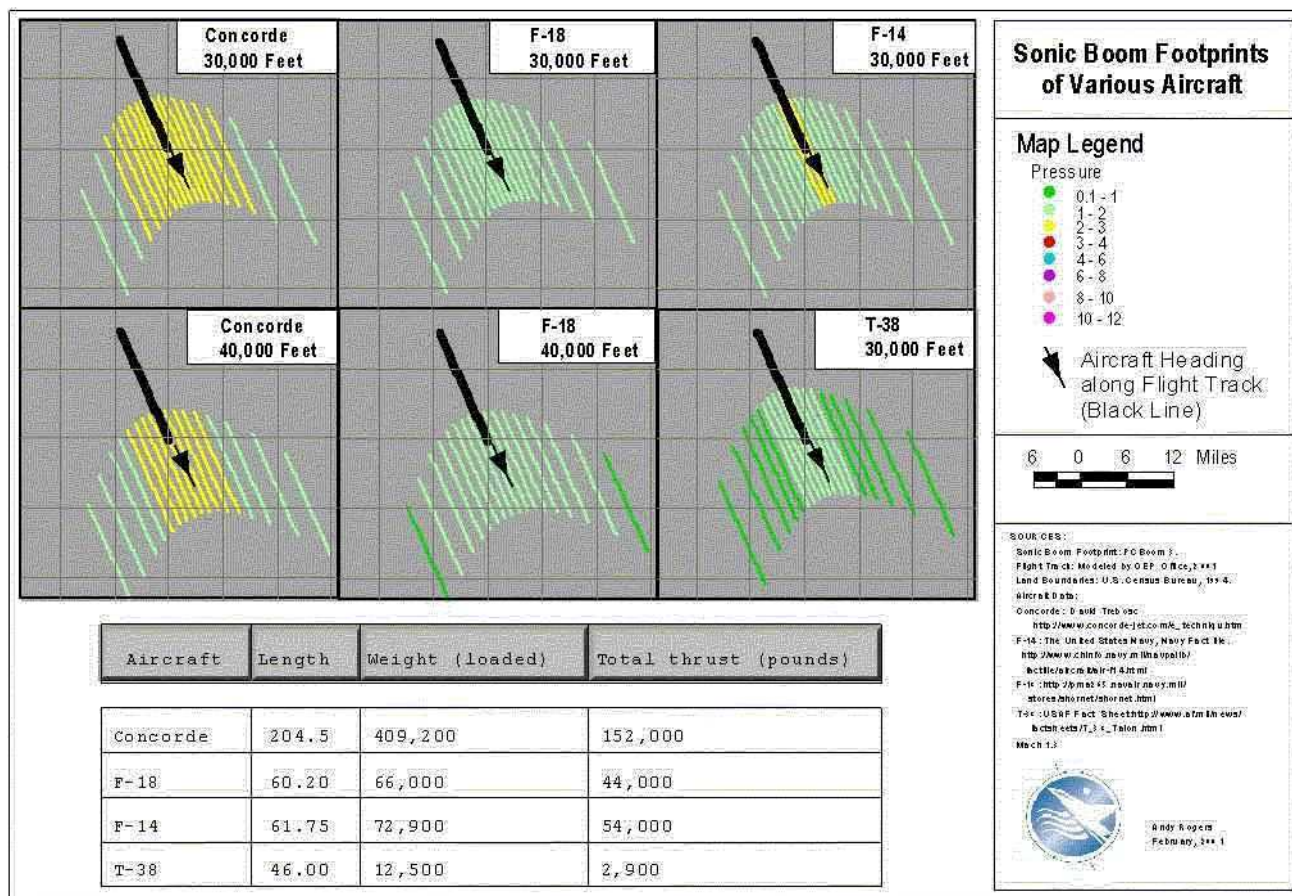
The principal supersonic aircraft examined here is the F/A-18 E/F. The T-38 and F-14 are also examined briefly. The aircraft type has a significant impact on the sonic boom. Size is a major factor, as can be seen in the tables in Figure 7. The Concorde, included here just for reference, makes a huge boom at 30,000 feet compared to any aircraft used at NAS PAX. At 40,000 feet, it is still louder than the small military jets. The T-38, on the other hand, makes a barely noticeable boom, not exceeding one psf even directly under the flight path.

2.2 Mach Number

Mach is the speed of sound in a given medium. Maximum Mach is used as a parameter, because both the Mach and the acceleration required to achieve a given Mach number effect the sonic boom. The effect of Mach number on the footprint is subtler). Neither aircraft at 1.1 Mach is predicted to make an audible boom. At Mach 1.2 or above the F/A-18 E/F produces a boom of approximately two psf. The strength of this boom does not increase, as was expected. However, the width of the carpet expands, achieving a level of 1-2 psf up to 8 miles off the flight track. The T-38 boom footprints are similar, although because the aircraft is smaller, the boom is weaker.

2.3 Altitude

Regulations stipulate that all supersonic flights in the CTR occur at or above 30,000 feet except when the test specifications require a lower altitude. This occurs primarily when supersonic weapons separation testing is occurring.



The sonic boom strength is closely related to the altitude (Figure 9). The shock wave dissipates according to the inverse-square law, which explains the general shape of the graph (Figure 14).

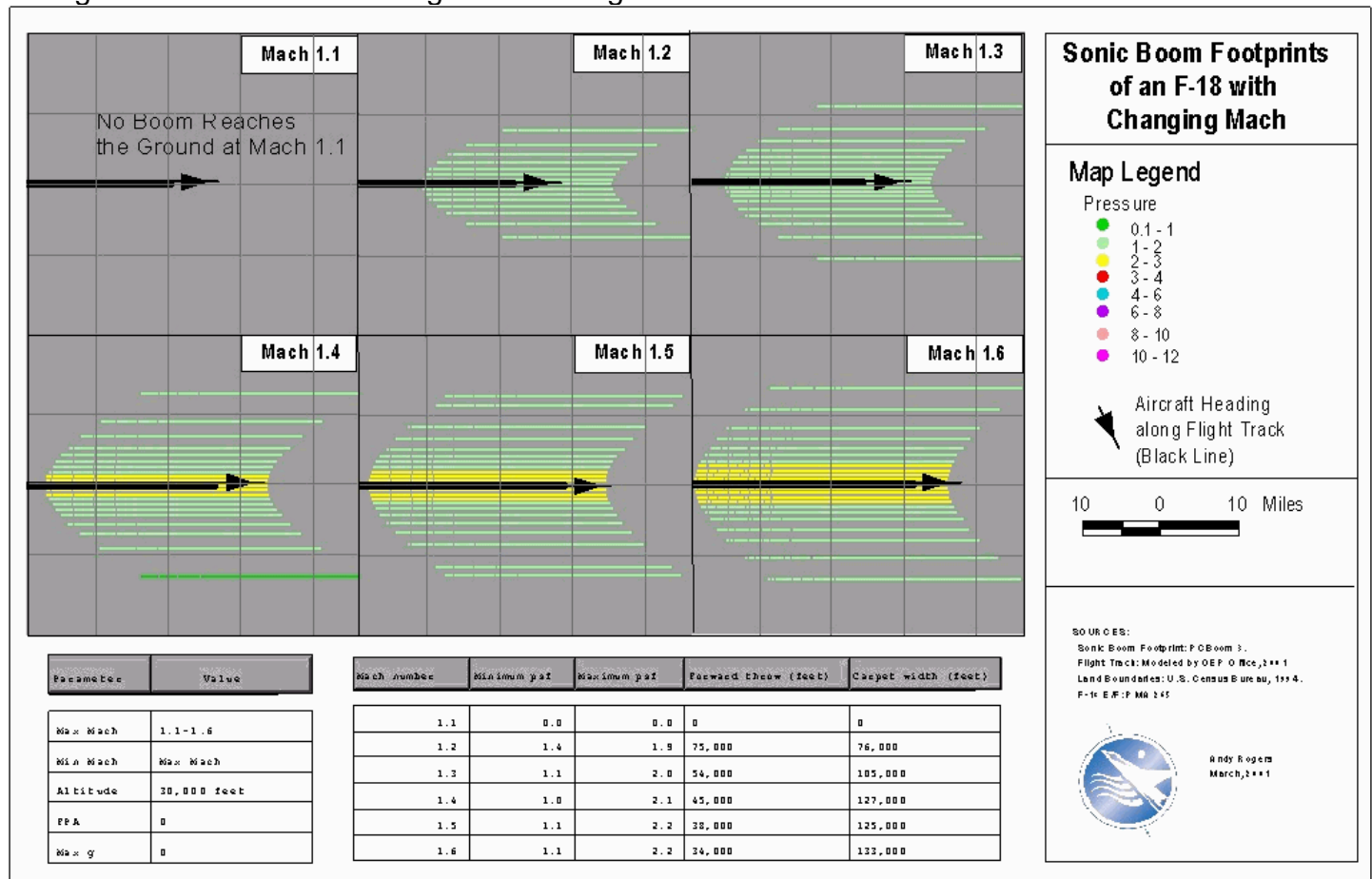
2.4 Acceleration

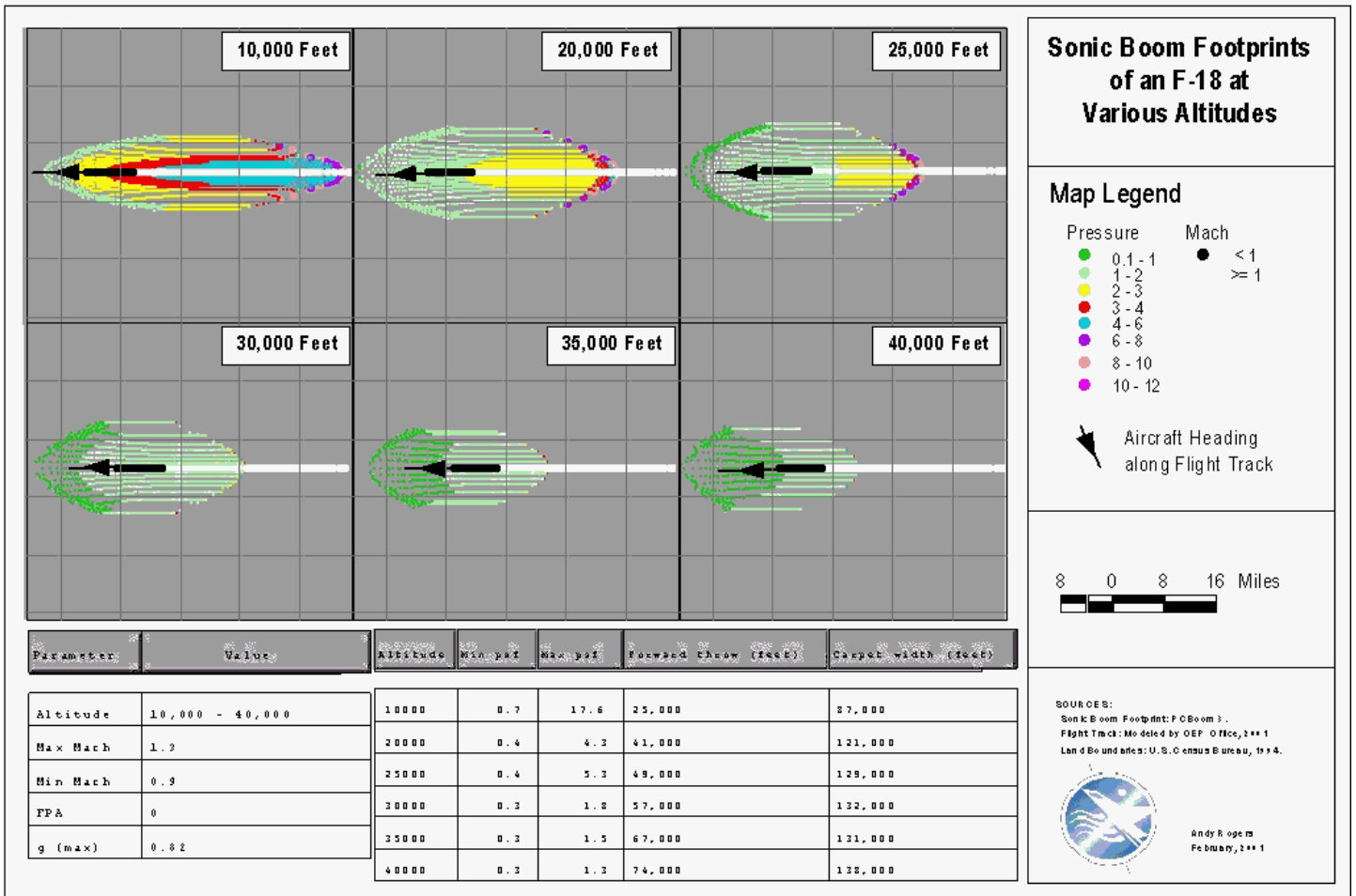
There is no accompanying graph to show the impacts of linear acceleration. However, the Mach number graph) was done at constant speed (just a slice in time of a total flight) while the altitude graph (Figure 9) shows the entire supersonic portion of the flight, including the acceleration and deceleration phase. By comparing these two sets of graphs, it can be seen that level acceleration causes a focussing of the boom at the back edge of the boom. At 10,000 feet AGL the F/A-18 E/F's boom reaches 10-12 psf. There is a portion of the flight in which the psf level is constant along the flight track. When the aircraft decelerates, the boom weakens and dissipates until it is just a single point at the leading edge (Figure 9).

2.5 Weapons Separations

FPA is calculated as: $\arcsin(D\text{Altitude}/D\text{Dist})$ where DAltitude is the change in altitude and DDist is the total distance traveled in space. Weapons separations are complex maneuvers done in two patterns for testing purposes. In one, the aircraft delivers the weapon while at an FPA of 60 degrees, in the other,

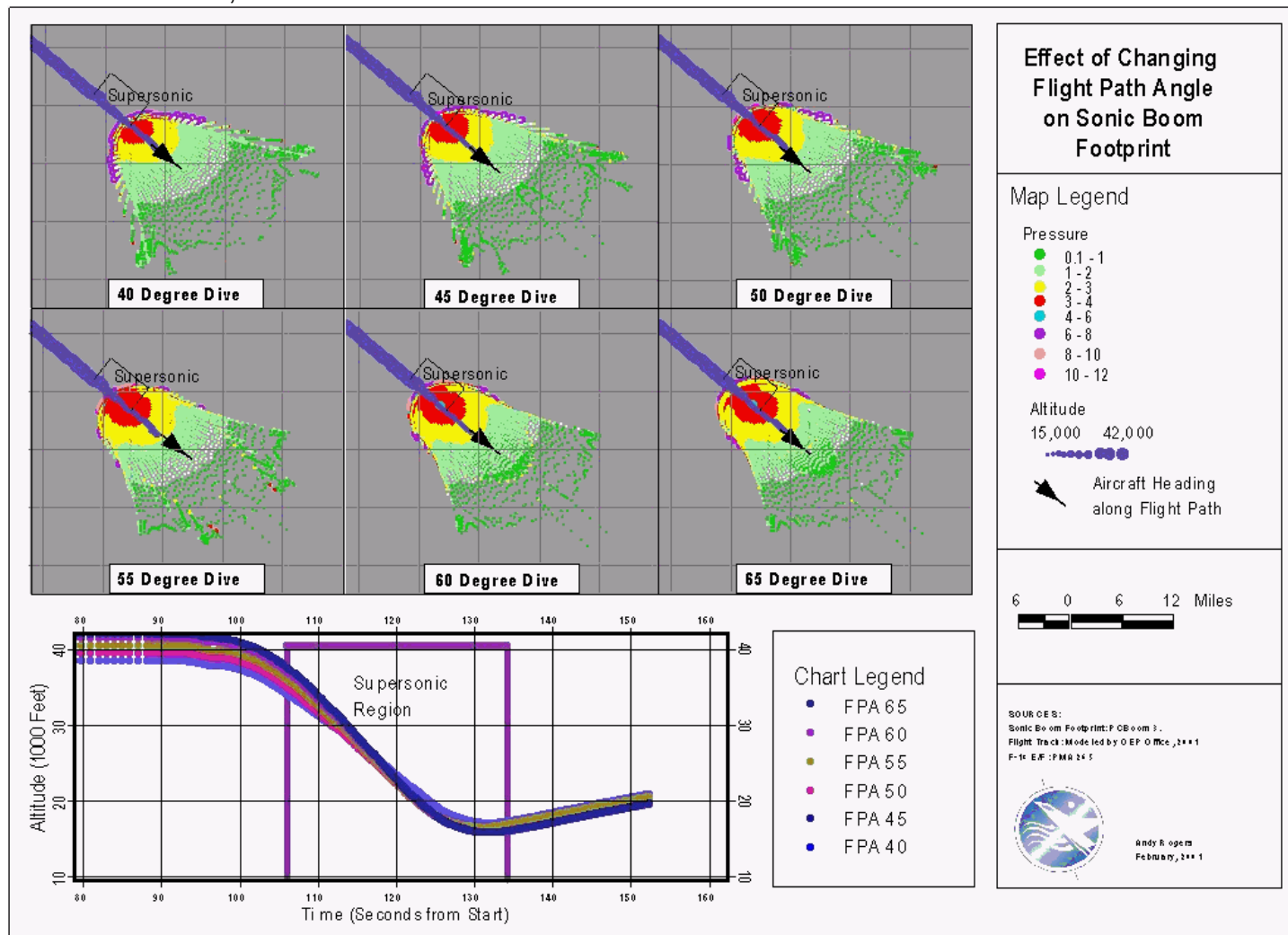
the weapon is delivered in a 45-degree dive. For 45-degree FPA, the pilot typically rolls in at about 35,000 feet and 0.97 Mach. He will roll inverted, pull 3 g's for approximately 3 seconds to get to -45 FPA and then right the aircraft again. He should reach the target release speed at approximately 30,000 feet and hold that speed until the release point at approximately 18,000 feet. He then slows and pulls out. The expected tolerances on this are about +/- ten knots on the airspeed, +/- 0.02 Mach, + 0.1 g, - 0.2 g, +/- 5 degrees on the FPA, + 1,000 feet for the release altitude, +/- 2 degrees for the heading. The flights are modeled primarily as variable FPA flights in this section. Because changing the FPA requires changes in other variables as well, the altitude of achieving maximum Mach was held constant and the pull out altitude was held constant. This required changes in the starting altitude and changes to the rate of change of FPA to achieve the minimum altitude. Starting altitudes ranged from 37,500 to 42,000 feet. The flight path used is an actual test flight performed on 11/1/2000, which was digitally smoothed and straightened. The standard procedure is to recover back to subsonic speed by pulling g's in a change of FPA from descending to ascending.





Changes in the flight path angle have a complex impact on the sonic boom footprint because they necessarily involve changes in the altitude of the maneuvers. However, as the FPA increases, the forward throw decreases (Figure 10). This shifts the impact by shifting the whole footprint back along the flight track. The steeper angle also reduces the spread. Changes in the recovery portion of the flight are quite distinct between the 45-degree dive and the 60-degree dive. For the 45-degree FPA, there is no difference between the three footprints. For the 60 degree FPA, there is a huge difference, but only if the aircraft stays in the dive until it has become subsonic. However, in this particular scenario, it puts the

aircraft down to 5,000 feet AGL.



3 Atmospheric Characteristics

3.1 Background

Atmospheric temperature and wind profiles affect the way sound is transmitted through the atmosphere. Strong temperature gradients and inversion layers contribute to the scattering of sonic booms and wind can move and alter the shape of the footprint. The angle between the wind and aircraft flight path will also affect the shape and location of the footprint. All of these factors change seasonally. The temperature of the atmosphere changes with altitude. In a standard atmosphere the temperature decreases with increasing altitude within the altitudes of interest to this study. Occasionally, there are temperature inversions, where the temperature increases with increasing altitude. To understand the changes in the sonic boom footprints it is necessary to understand what happens to a sound wave as it moves through the air. The speed of sound is temperature dependent. A sound wave is refracted as it passes through various temperature regimes. Sound travels more slowly in the cooler atmosphere and the sound speed drops as the sound passes through an inversion layer. Wind also has a major effect on the sound. The wind essentially moves the sound with it as it moves the air. Atmospheric wind profiles for this area show that the wind in this area tends to be from the west, and is virtually never from the east.

3.2 Maneuvers with Atmospheric Effects

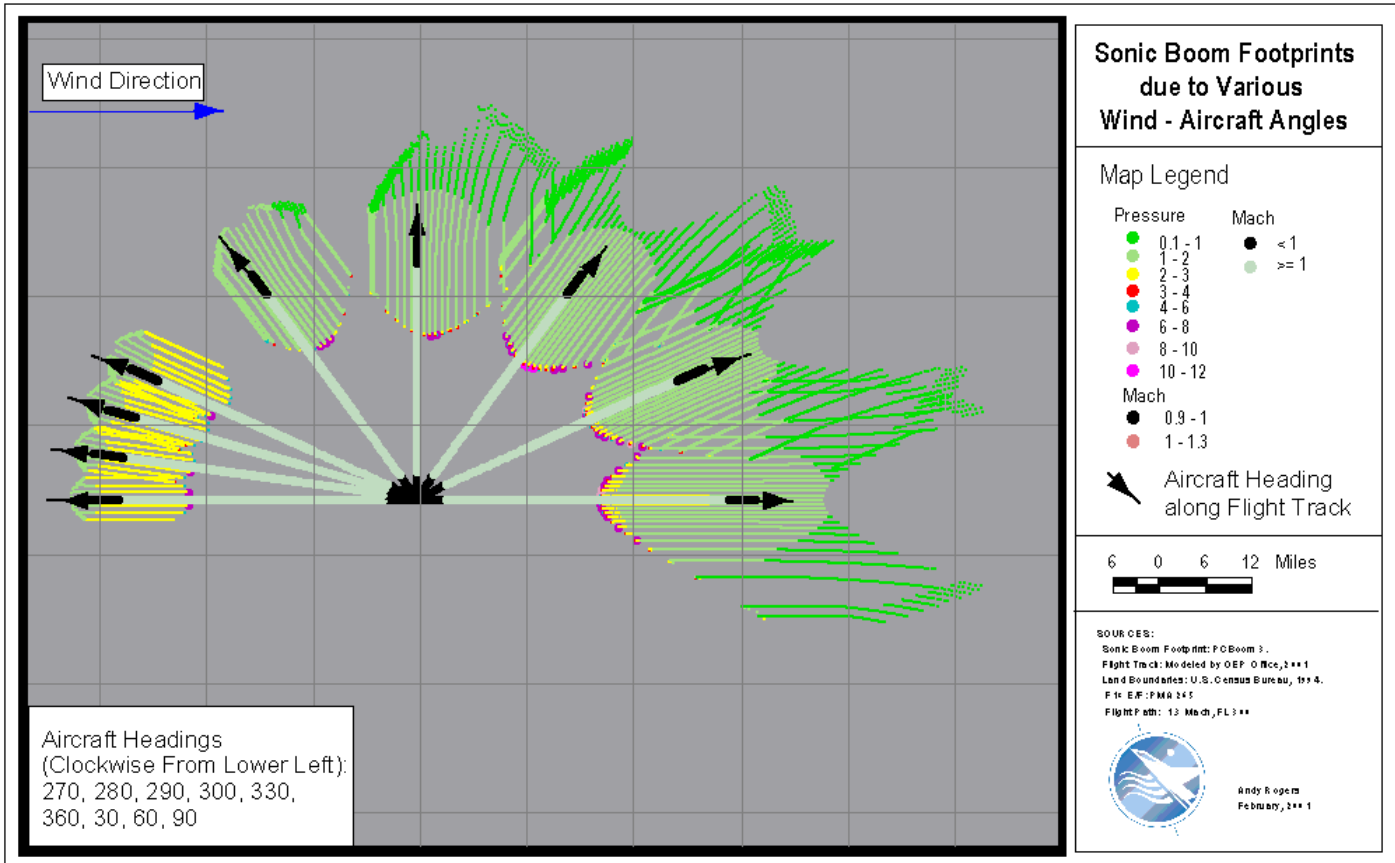
The only maneuvers modeled in this section are straight, level flights. The variables are the atmosphere and the angular separation between the prevailing wind and the aircraft's heading.

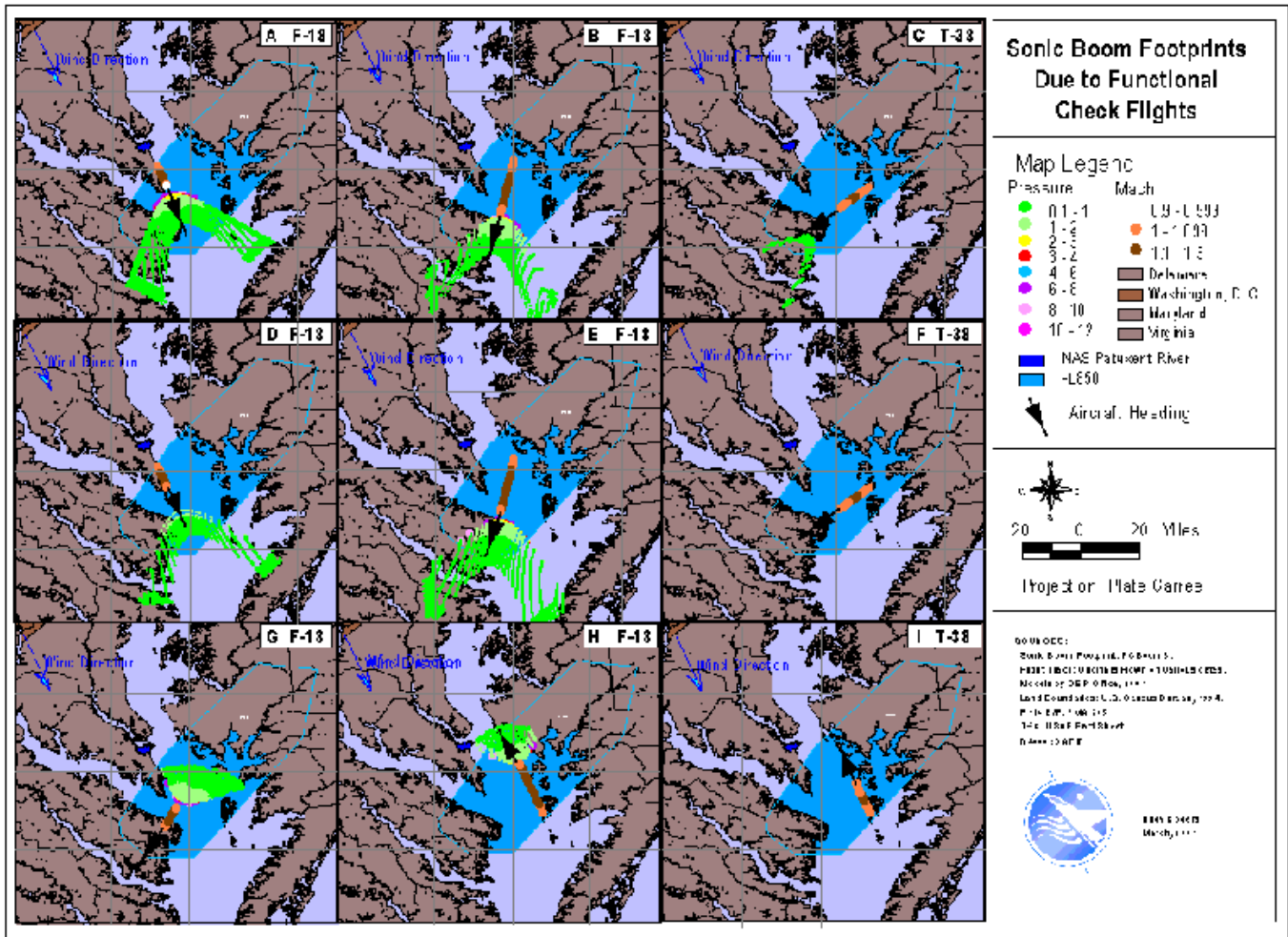
3.3 Atmospheric Temperature Profiles

The footprints in Figure 11 are arranged so that the altitude and strength of the inversion layer increase from top to bottom and the temperature at the ground increases from upper left to lower right. These are real atmospheric profiles, so the progression is not perfect. Close examination of the atmospheric profiles is necessary to understand the effects seen here. However, the footprints are noticeably larger at the top where the inversions are strongest. One thing is clear from the footprints, different atmospheric conditions cause large changes in the sonic boom footprint.

3.4 Aircraft - Wind Angle Interactions

The interaction of the aircraft's motion and the wind speed also affects the sonic boom footprint (Figure 12). The progression of the nine footprints shows that the wind foreshortens the footprint when the aircraft is headed directly into the wind. As the aircraft heading - wind angle decreases from 180 to 0, the back edge of the footprint is displaced toward the aircraft and the leading edge is displaced downwind. This lengthens the footprint in both directions. The focussing along the back edge of the footprint is stronger when the aircraft has a tail wind. Due to the spreading caused by the wind, the rest of the boom footprint loses intensity when the aircraft is flying in the same direction as the wind blowing.





4 Geographic Characteristics

Ultimately, understanding how all these factors affect the sonic boom is only of interest when it can be used to determine how sonic booms will affect the population in the range area. With the understanding of the other factors listed above, the key geographic aspects of a flight are the location and heading of the flight.

4.1.1 Functional Check Flights

Functional Check Flights (FCF's) shown here are derived from actual FCF's flown in the CTR. The data available for these flights comprises start and end positions in three dimensions and maximum Mach, so a number assumptions were necessary. It is assumed that the reported starting and ending locations were given when the aircraft accelerated from subsonic to transonic (i.e., reached Mach 1) or decelerated from transonic to subsonic. Appropriate time for acceleration was allowed to achieve the maximum Mach. For the F/A-18 E/F approximately 0.2 g maximum acceleration was used; for the T-38 a maximum acceleration of 0.1 g was assumed. Error! Reference source not found. are actual flights. The two panels beneath each actual flight represent possible alterations that could have been made to reduce sonic boom impacts on the ground. The sonic booms from the two F/A-18 flights Error! Reference source not found.) are affected by rotating the flight path with respect to the wind and by changing the altitudes. Raising the altitudes seems to have the effect mainly of spreading the boom.

Changing the aircraft heading and flight location does impact where the boom lands. However, for the T-38, when the altitude is raised, or when the aircraft is turned straight into the wind, the boom disappears altogether.

5 Conclusion

It has been the commonly accepted wisdom that T-38's flying above 30,000 feet do not make an audible sonic boom on the ground. The models shown here demonstrate that that is not always true. These results also show which parameters can be altered to minimize sonic boom impacts and which parameters are of little value.

Acknowledgments:

Efforts have been made to include input from a variety of stakeholders such as range safety, NAS Patuxent River Meteorology and Oceanography (METOC) Detachment, Naval STRIKE Aircraft Test Squadron (Strike), and the U.S. Naval Test Pilot School (TPS). By including their input we have captured the types of operations done at NAS PAX to use as the basis for flight models.