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UNITED STATES AIR FORCE

Sonic Boom

PREFACE

In the past few years, several field tests have been conducted to measure sonic booms and their effects on structures and people. These same tests have been carried out in a variety of weather conditions with several aircraft being operated at different heights and speeds.

Because there are important meteorological effects on shock wave propagation, weather officers should become acquainted with some of the terminology and the physical principles of weather effects on sonic boom propagation.

Calculation of shock wave patterns covering many square miles is an exceedingly complex operation which involves several parameters other than weather data. Sonic booms caused by either aircraft or missiles are influenced by size, shape, speed, trajectory, etc. The use of equations to combine the effects of such a large number of variables can only give results in terms of simplified conditions. Actual measurements made in

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field tests show a rather broad range of values surrounding those derived from mathematical calculation. In this report, no attempt will be made to present the mathematical treatments required by those who calculate expected sonic booms with the aid of electronic computers.

Current knowledge of the effect of weather parameters on sonic boom has been gained primarily from limited atmospheric measurement made near the time and location of planned sonic boom tests. At present, meteorologists are being asked to examine and help explain the rather wide variability in the observed sonic boom pressures being measured. In the future, they may be asked to advise on appropriate altitudes for transition from sub-sonic to super-sonic speeds which will create safe and tolerable sonic booms at ground level near the flight path.

I gratefully acknowledge the assistance of staff personnel at Hq 6th Weather Wing, Andrews AFB (LtCol L.C. Garvin, LtCol F.S. Shay, Major W.D. Kleis and Capt L.C. Johnson) who provided reference material and served as advisors. The Langley Research Center of the National Aeronautics and Space Administration has generously furnished copies of reports and photographs.

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1. Physical Characteristics of Sound

Any vibrating object surrounded by an elastic medium will produce compressional waves in that medium. These waves travel outward as alternate compressions and expansions (See Figure 1).

a. Sound waves may exist whether or not they are received by an ear. This is physical sound. The physicist is concerned with sound waves, their production, their translational movement and their physical effects on objects including the ear. Sound waves are not up and down gravitational waves as in water, but pulsations of higher and lower pressure.

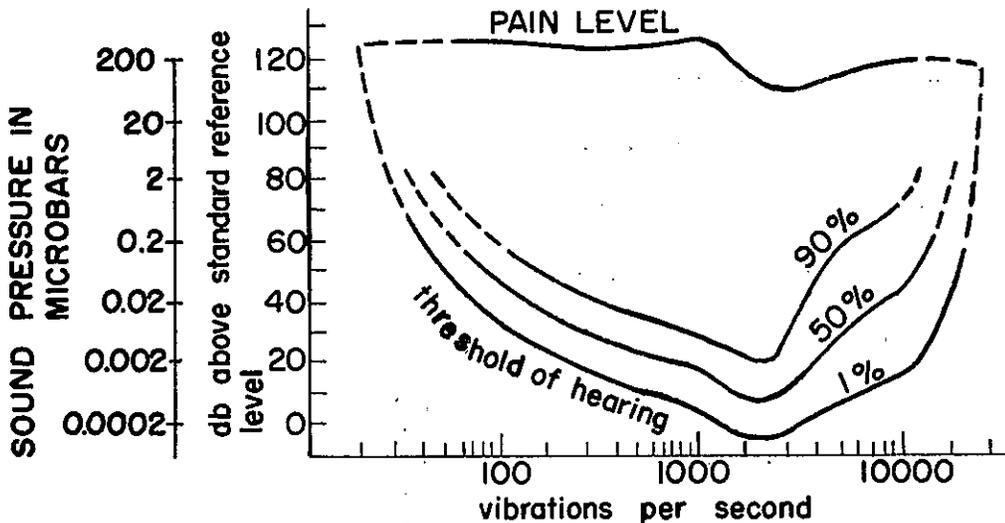
b. Most human ears can sense pressure disturbances as low as .0005 pounds per square foot (psf). Very loud noises produce rapid pressure disturbances with overpressures of one pound or more psf. Louder noise can be sustained without actual damage to the eardrum but would cause annoyance. Eardrums have been known to burst at a sudden pressure change of around 40 psf. By comparison, the steady undisturbed pressure of one atmosphere at sea level is 2,116 psf. The level of sound perception is not entirely a function of the overpressure. Fletcher [1] has shown that human hearing is limited to sound which travels in the frequency range



Figure 1. Schematic pattern of sound propagation in two dimensions showing compression and expansion portions of the outward moving wave.

between 20 and 20,000 cycles per second. See Figure 2. The zero loudness line for older people is somewhat higher than that shown in Figure 2. Threshold levels for both sound perception and a "feeling" of sound depend on the frequency.

c. For convenience in the mechanical measurement of sound, engineers have established an arbitrary scale which measures sound in decibels (db).



from "Speech and Hearing in Communication" by Harvey Fletcher
 c D'Van Nostrand Co. Inc., 1953.

Figure 2. Auditory area between threshold of feeling and threshold of hearing.

The sound of conversational speech has an intensity of about 50 db at a distance of a few feet. Traffic at a busy intersection will produce about 70 db. Inside a boiler factory the noise level can attain 110 db. An overpressure corresponding to 1 lb psf is equal to 128 db. The scale in Fig 2 shows the comparative relationship between decibels and the fundamental scale of pressure in dynes per square centimeter. See Table I (Nilsestuen and Edelstein[2]) for decibel values of 108 and higher with

their corresponding scale of overpressures in lb/ft^2 .

Table I. Comparable Effects of Shock Noise Phenomena

<u>P</u> <u>lb/ft²</u>	<u>Decibels</u>	<u>Physiological</u> <u>Reaction</u>	<u>Physical</u> <u>Phenomenon</u>
0.1-0.3	108-118	Not Objectionable	Barely audible explosion
0.3-1.0	118-128	Tolerable	Distant explosion or thunder
1.0-3.0	128-138	Objectionable	Close thunder, some window damage
3.0-10.0	138-148	Objectionable	Damage to large plate glass windows
10.0-30.0	148-158	Objectionable	Damage to small barracks-type windows

d. The intensity of a sound wave is defined as the amount of energy which crosses a unit area in unit time. The wave front of a spherical sound wave as it advances is a sphere of increasing area. The intensity of a sound wave varies inversely as the square of the distance from the source.

e. The speed of sound in the troposphere has very little dependence on pressure or density. Humidity introduces a small correction which can be accounted for by using virtual temperature. For all practical purposes, any temperature scale has a corresponding velocity of sound scale. At 0°C the speed of sound in the air is 331 mps, 1087 fps, or 741 mph. At moderate temperatures, the rate of change is approximately 2 feet per second for each degree centigrade. Table II gives a metric scale of sound speeds for air temperatures between -70° and $+50^{\circ}\text{C}$ (Berry, et al [3]).

Table II. Velocity of Sound in Dry Air
(Metric Units)

Temp °C	Velocity mps	Temp °C	Velocity mps
-70	286	0	331
-60	292	10	337
-50	299	20	342
-40	306	30	348
-30	312	40	354
-20	319	50	360
-10	325		

Table III shows the scale of sound speeds in British units at heights to 35,000 feet of a Standard Atmosphere (Power [4]).

Table III. Velocity of Sound in Dry Air
(British Units)

Alt ft	Press. P in. Hg	Temp °F	Velocity knots	Velocity ft/sec
0	29.92	+59.0	661.7	1116.4
5000	24.90	+41.2	650.3	1087.1
10000	20.58	+23.3	638.6	1077.4
15000	16.89	+ 5.5	626.7	1057.4
20000	13.75	-12.3	614.6	1036.1
25000	11.10	-30.2	602.2	1016.1
30000	8.885	-48.0	589.5	994.8
35000	7.041	-65.8	576.6	973.1

The temperature profile in Figure 3 is taken from a radiosonde record used in a field test program at Edwards AFB in 1961. (Hubbard, et al[5]). The corresponding profile of sound speeds is shown on the right side of the figure.

f. The deflection from a straight path suffered by a ray of sound passing through a medium which produces a velocity gradient is known as refraction. Since the speed of sound varies with temperature, the path

of a sound ray is "bent" toward colder air as it moves through any non-homogeneous temperature field. The path of emanating sound waves bends upward when temperatures decrease with height. Conversely, when colder air lies near the earth's surface, as with a strong temperature inversion, the "bending" will be downward. The contrast is shown in Fig 4.

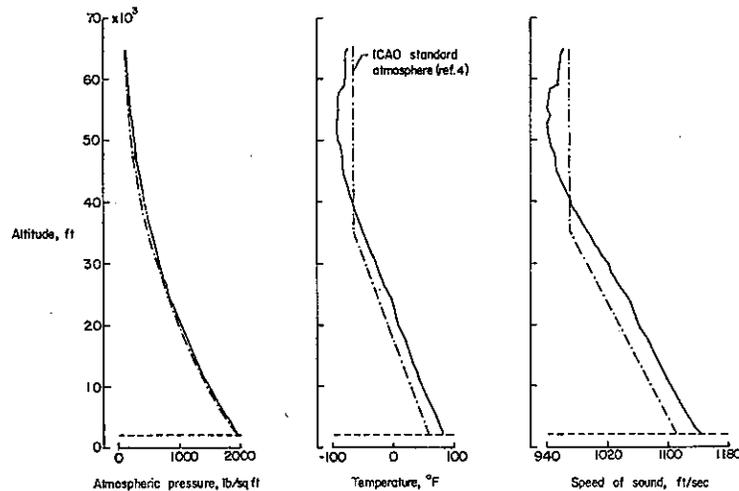


Figure 3. Sample results from atmospheric soundings taken during test flights 27 and 28, Edwards AFB, Calif., October 1961.

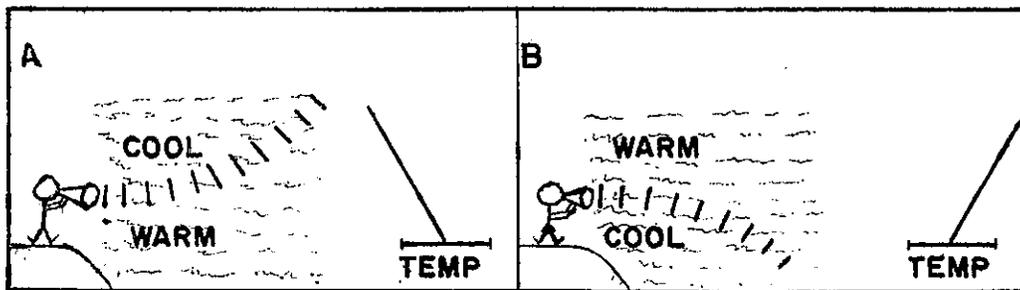


Figure 4. Relationships of temperature gradient to sound propagation.
 A. Sound waves are bent (refracted) upward by cool air above warm air.
 B. Sound waves are bent downward by layer of warm air above cool.

g. Wind speed gradients also cause refraction. Wind velocity profiles resolved into components parallel to and perpendicular to the airplane flight path used in tests 27 and 28 (See Figure 3) are shown in Figure 5 (Hubbard, et al [5]). By superposing of direct addition or subtraction to the sound speed profile in Figure 3, specific sound velocity profiles could be drawn for the four cardinal directions related to the flight path. Thus, the ray paths of sound in each direction would undergo varying influences of refraction.

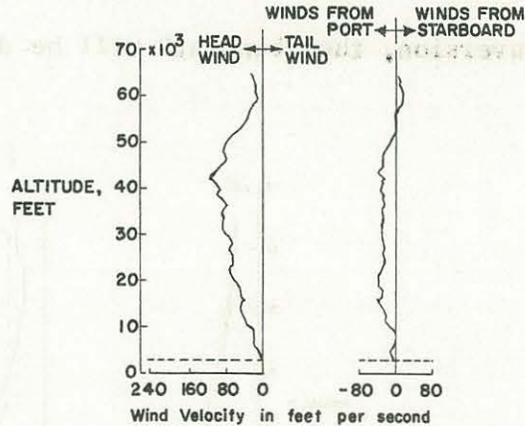


Figure 5. Sample wind velocity profile resolved into components parallel to and perpendicular to the flight direction of the airplane. Data for same flight as in Figure 3.

h. Sound waves moving in one medium can be reflected from the face of another medium. Echoes are a common illustration of this phenomenon. Near a reflecting surface, sound waves moving toward the reflecting surface will be reinforced by others returning from the reflecting surface to produce a net intensity of nearly double that of the arriving waves.

i. Sound waves may undergo interference. The compressional parts of one set of waves can arrive at the same time as the expansional

parts of another set of similar waves. They will thus neutralize each other and produce nearly uniform pressure at a particular sensing point. It is also possible for two or more sets of similar sound waves to reinforce each other and cause focusing. If they arrive in phase with each other at one point, they increase the net difference between the compressional portion and expansional portion of the combined wave.

j. The total sound perceptible at any one time and place is the resultant total of a tremendously large family of sound waves coming from sources both far and near. The very faint wave motions from distant sources will tend to neutralize or reinforce the more intense wave motion coming from nearby sources.

k. Ducting of sound waves takes place when ray paths are restricted to limited movement due to temperature gradients and reflecting surfaces. A strong low level temperature inversion is conducive to ducting.

2. Sound from Fixed Sources

Sound emanating high above the ground from a single fixed source completely immersed in an isothermal atmosphere would propagate outward in a spherical pattern. A high level rocket explosion comes close to being this type of source. However, the temperature profile is not likely to be isothermal but will have decreasing temperatures with in-

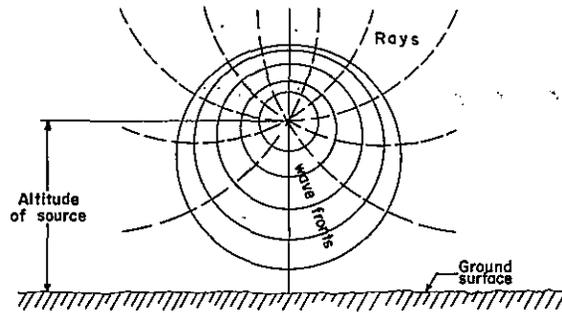


Figure 6. Rays and wave fronts for a point disturbance in a non-isothermal atmosphere.

creasing height in the troposphere. Figure 6 portrays various ray paths of sound from a point source well above the ground in a cross sectional slice through the atmosphere. The bending of the rays in this case is caused by the temperature decreasing with height.

a. Sound emanating from a single fixed source on the ground can only propagate outward through the atmosphere in a dome shaped pattern resembling a hemisphere. The various parts of Figure 7 illustrate the influences of atmospheric conditions on the propagation from ground blast sites [7].

(1) In the event of the very rare circumstance of a blast occurring when the atmosphere is perfectly still and isothermal, the velocity of sound in all directions will be equal. The wave front will be hemispherical with the sound waves extending radially from the blast

site. See Figure 7A. In the ray paths of sound near the ground, energy is absorbed by the many obstructions encountered such as trees, buildings, roofs, terrain, etc. There are also attenuation losses as sound travels greater distances through the air.

(2) If the air temperature decreases with altitude, there is a corresponding decrease in sound velocity and the sound rays are bent upward. See Figure 7B.

(3) If the weather conditions (temperature and wind velocity) are such that a greater sound velocity in any direction occurs above the earth's surface, then a sound inversion exists. In this case, parts of the sound wave may be returned to the ground by refraction and when added to other sound rays will produce loud noise at the points of return. Figure 7C shows the patterns resulting when temperature alone increases with height. Figure 7D shows the pattern of sound propagation with a positive wind gradient with height. Large sound returns are recorded down wind from the blast site.

(4) In rare instances, wind speeds decrease with height near the ground and may combine with the temperature gradient to produce notable sound returns upwind from the blast site. See Figure 7E.

(5) From this discussion, it can be seen that different atmospheric conditions result in a variety of sound-speed patterns. This becomes very complex with multiple changes of either temperature or wind. In Figure 7F an inversion of both temperature and sound speed are assumed at some height above the ground. Under such conditions, a zone of relatively little noise exists near the blasting location and

loud noise disturbances occur at points where bundles of rays return together.

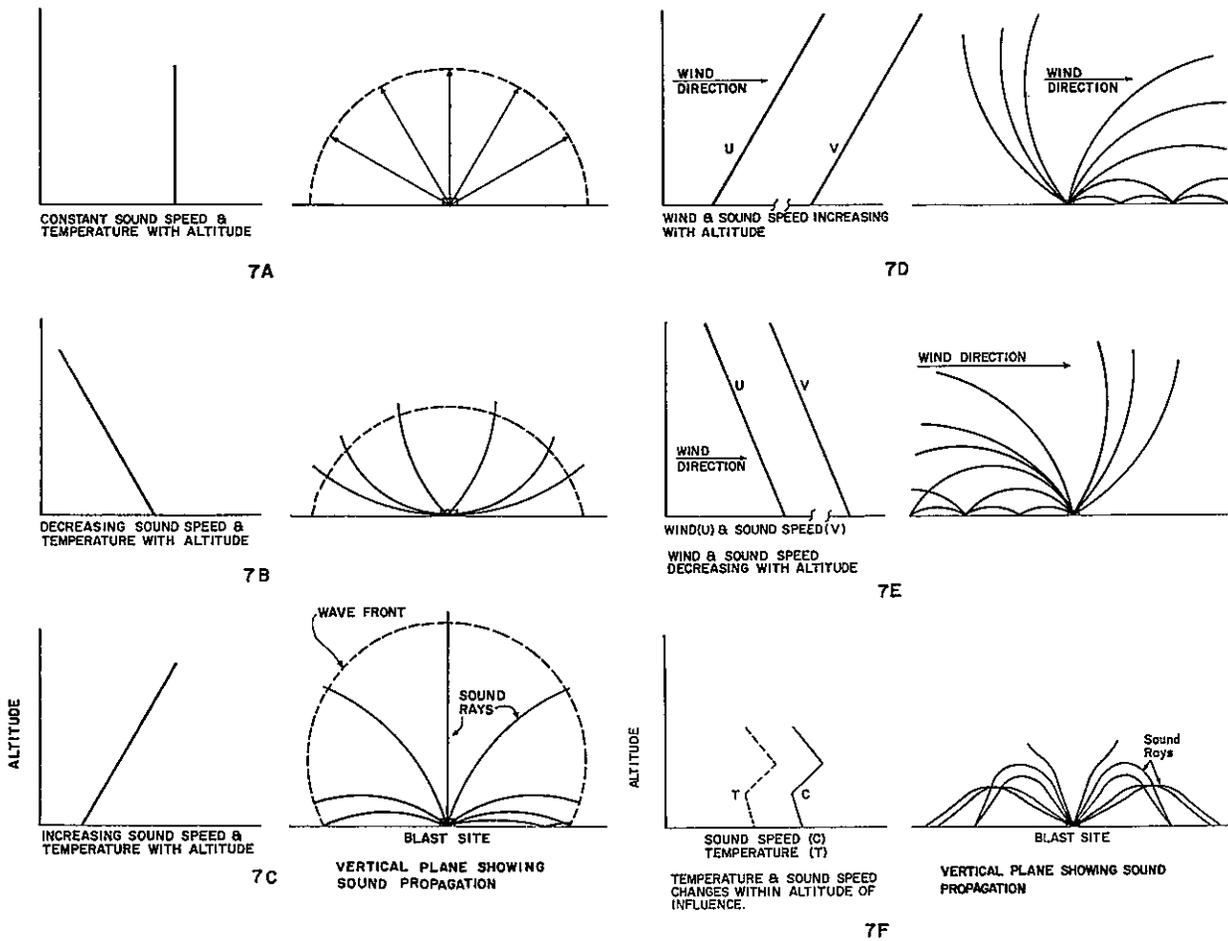


Figure 7. Atmospheric influences on sound propagation from ground blast sites.

b. Intense shock waves can be generated by large explosions. The explosion disturbs the air so rapidly that it builds a very large pressure increase (overpressure) in the compressional part of a giant type sound wave.

While the action in the explosion itself may take place at speeds greater than the speed of sound to build the shock wave the propagation of this shock wave, as it moves away from the explosion area, is at the speed of sound. The intensity of this wave undergoes attenuation as it moves farther and farther from the source: See Figure 8.

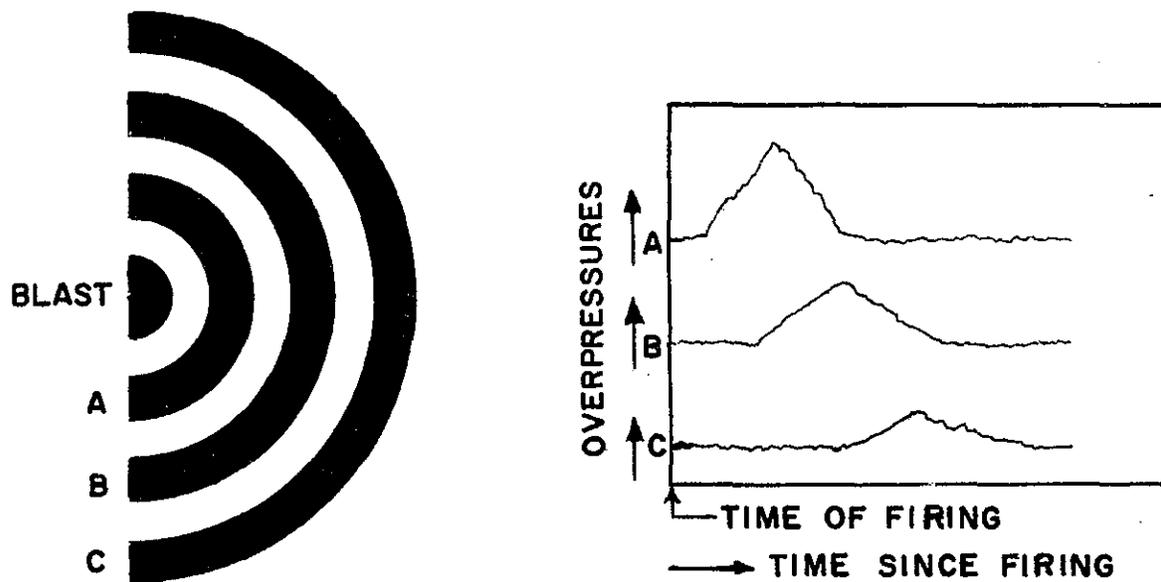


Figure 8. Comparative intensity and shock wave signatures at increasing distances from a ground explosion.

c. A low level temperature inversion keeps a certain portion of outward propagating sound energy from a ground based blast confined to the zone of the atmosphere between the ground and the top of the inversion. This zone permits ducting of sound waves. Sound rays emanating along low angles are bent back to earth where they in turn are reflected

back to the atmosphere at corresponding low angles and the process repeats itself. When two or more ray paths reach a given point at the same time, they produce a focusing of sound. Fig 9 shows a sample vertical cross section of the ray path of sound moving away from a source at 5° , 10° and 15° respectively (Reed [8]). By limiting consideration to these three angles only, it is easy to see that a variable pattern of resulting sound measurements could be made along any ground path away from the sound source. The intensity of the sound arriving 15,000 feet away from

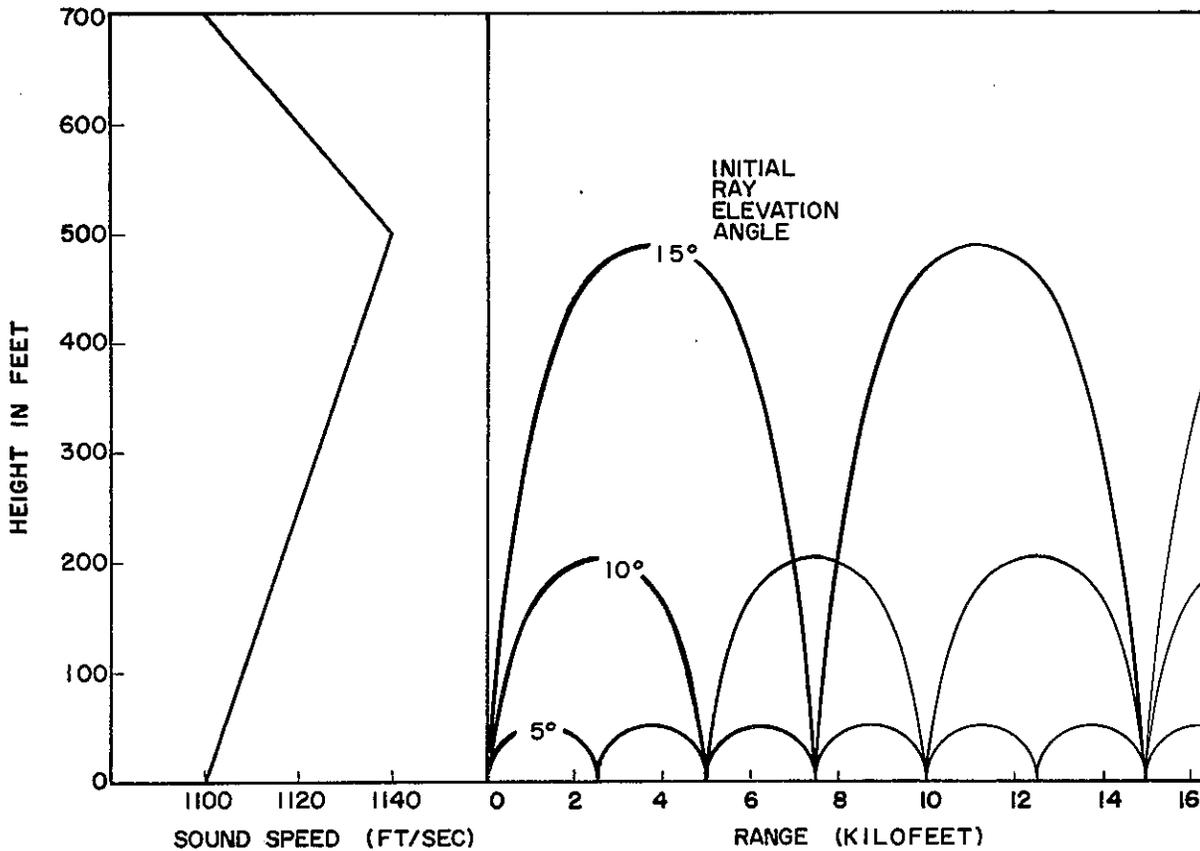


Figure 9. Sound ray propagation combined with inversion ducting.

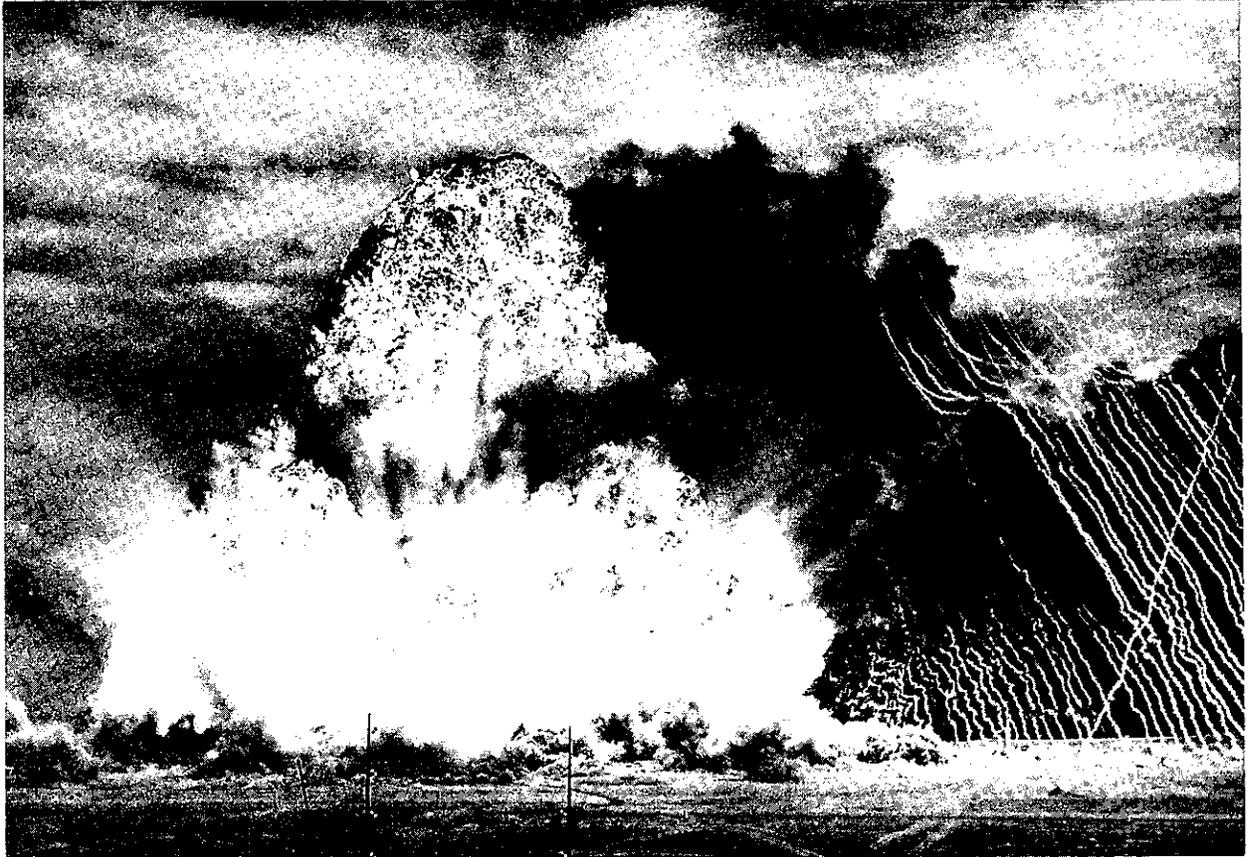


Figure 10. Controlled explosion of 500 tons TNT at Suffield, Alberta, Canada, on 17 July 1964. Official photo, Suffield Experimental Station, Defense Research Board of Canada.

the source will result from combination of the 6th return of the 5° ray angle, the 3d return of the 10° ray angle and the 2d return of the 15° ray angle. Due to attenuation, the total sound may be much less than at 7,500 feet where only two ray paths were coincident but it would be stronger than the sound at 12,500 feet.

d. There have been many historical accounts of long distance paths of sound connected with explosions of various kinds. The audibility at several hundred miles from the source with intervening quiet zones involves sound ray paths which move back and forth between the earth and layers of increasing temperature with height well above the troposphere. The Defense Research Board of Canada at their Suffield Experiment Station in Alberta Province have conducted a series of controlled tests using various sized charges of TNT. (Gilbert [9]). At 1058 MST on July 17, 1964, they exploded 500 tons of TNT. See Figure 10. The vertical lines at the right hand side of the picture are trails produced by smoke rockets fired immediately prior to the explosion to determine the progress of the shock wave. The services of some 750 voluntary trained observers were enlisted to report on the audibility of the explosion at distances exceeding 400 miles.

(1) Using a limited amount of upper atmosphere wind and temperature soundings made on July 17th plus data from the U.S. Standard Atmosphere, 1962 [10]., Gilbert [9] prepared the temperature profile shown in Figure 11. He used this profile to estimate sound paths moving away from the explosion.

(2) Computations of areas of possible audibility based on the

current observations of winds and temperature showed very close agreement with the areas of reported audibility, see Fig 12. There were three kinds of possible audibility areas revealed by these computations:

(a) A limited area some 30 miles to the east of the source, and a corresponding area at twice the distance, due to refraction in the troposphere from a layer at an altitude of about 2 miles where

there was an increase of wind speed with height.

(b) A zone to the west at a distance of some 150 miles, and corresponding areas at twice and three times the distance, due to refraction from the upper stratosphere between altitudes of about 20 to 35 miles.

(c) A zone some 300 miles to the east due to refraction from the lower ionosphere between altitudes of about 60 and 75 miles. The areas of possible audibility have been plotted in Figure 12 for comparison with the areas of observed audibility. The paths followed by typical sound rays resulting in the three different kinds of possible audibility areas are shown in diagrammatic form in Figure 13.

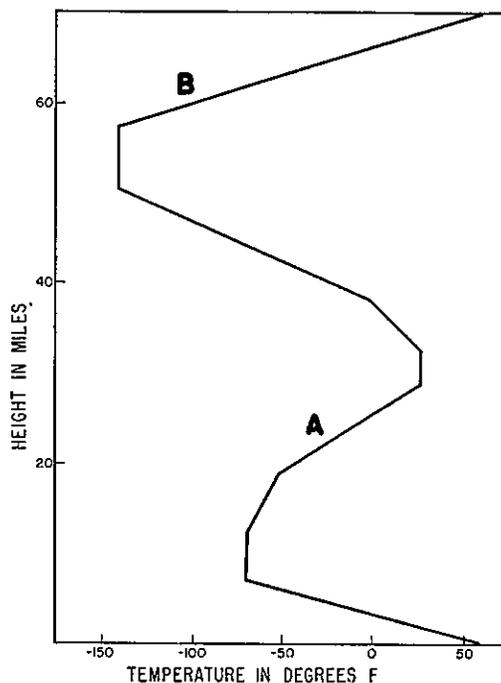


Figure 11. Temperature profile (based on Standard Atmosphere). Layers A and B are characterized by an increase of temperature with height and could therefore act as refracting layers for the long-range transmission of sound.

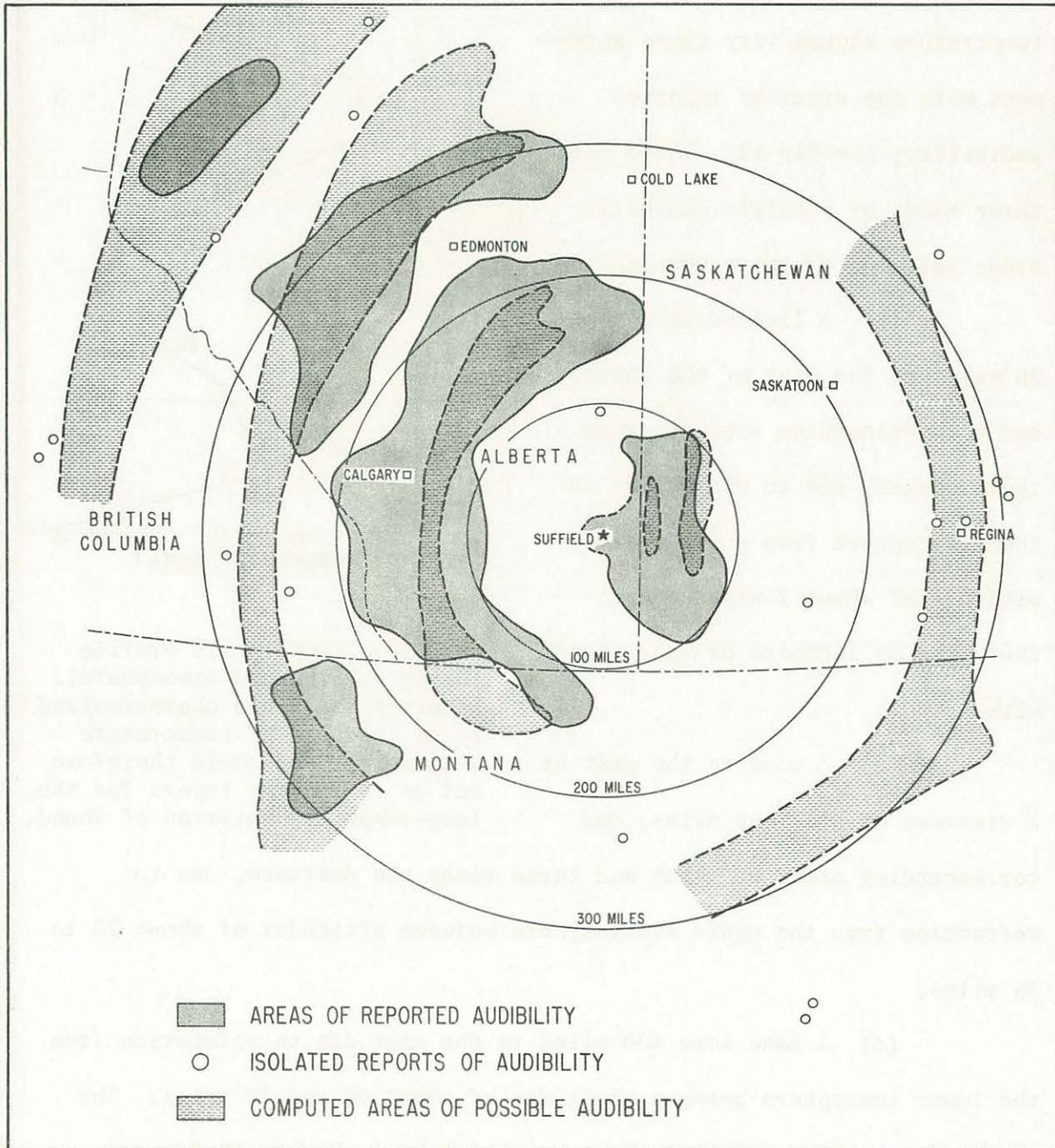


Figure 12. Observed audibility pattern associated with 500 ton explosion of TNT.

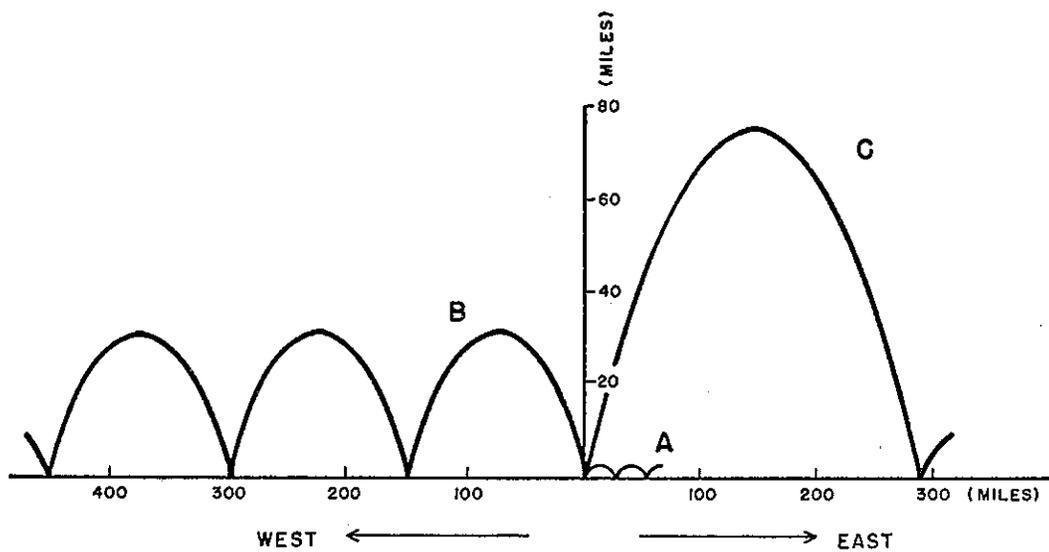


Figure 13. Paths of typical sound rays, vertical scale exaggerated.
 A-tropospheric ray; B-stratospheric ray; C-ionospheric ray.

3. Sound From Moving Sources

Many of the common sounds registered on living ears come from moving sound sources. Most of these relate to sources which are moving primarily in the horizontal plane at subsonic speeds. Cars, trains, buses, police sirens, low flying aircraft, all have their distinctive sounds. Experienced listeners can often identify the type of aircraft flying over head by the uniqueness of the sound being produced. Generally speaking, the loudness depends to a great extent on the size of the moving object, and the amount of air disturbance it creates. For large objects with irregular configurations, a "roar type" sound is created as air disturbances are generated in a wide band of wave lengths and frequencies.

a. Acoustical observations of a moving source emitting sound at a constant frequency show that its pitch appears higher when the source is approaching the listener, and lower when the distance between the source and the listener is increasing. This is known as the Doppler effect. The acoustical Doppler effect deals with cases of relative motion between the listener and the source, and includes the effect of the motion of the medium itself relative to both the source and the listener. A sound source moving toward the listener produces an effect of shortening the wave length because of a crowding of the waves. However, each wave, even though apparently shortened, arrives at the ear before the next one does.

b. When there is an explosion which causes air to be disturbed at speeds greater than the speed of sound, a shock wave is created. This shock wave is produced by the super-posing of multiple waves into a compound wave having a very high overpressure (the sharp jump in pressure

above the undisturbed pressure of the medium prior to the arrival of compressional portions of any sound wave).

(1) The firing of a high powered gun or cannon produces an explosion at the point of firing which can produce a shock wave. This shock wave propagates away from the point of firing. The projectile fired from the gun will move through the air at supersonic speeds and create its respective shock wave signature which spreads outward from the projectile path. Finally, if the projectile itself explodes at some point of impact or at a prearranged time before impact another shock wave is created and propagates outward from that explosion point.

c. The photograph (Fig 14) shows a test model of a supersonic aircraft in a wind tunnel being operated at supersonic speed. (Maglieri and Carlson [11]). This clearly depicts both a bow wave portion emanating from near the head of the model and a tail wave portion from a zone near the tail. The pressure signature of the shock wave as it passes any point along its propagation path resembles a capital letter N (See Fig 15). On recording paper moving from right to left and time accumulating from left to right the signature is made up of three identifiable portions. The first part is an almost instantaneous large

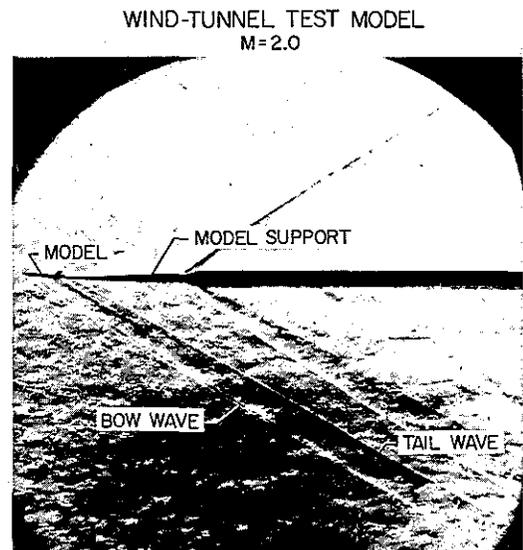


Figure 14. Profile of a wind-tunnel test of a model aircraft at Mach 2.0.

increase in pressure above the pre-shock quiet level. The second portion is a gradual decrease in pressure over a longer time span than the initial increase. This time span is directly related to the actual physical length of the projectile and the distance from its path at which the measurement is being made. The decrease in pressure continues to a point somewhat below the original undisturbed pressure. The third portion is an abrupt increase in pressure from the lowest point as a pressure level near the original undisturbed state is resumed.

NATURE OF THE PROBLEM

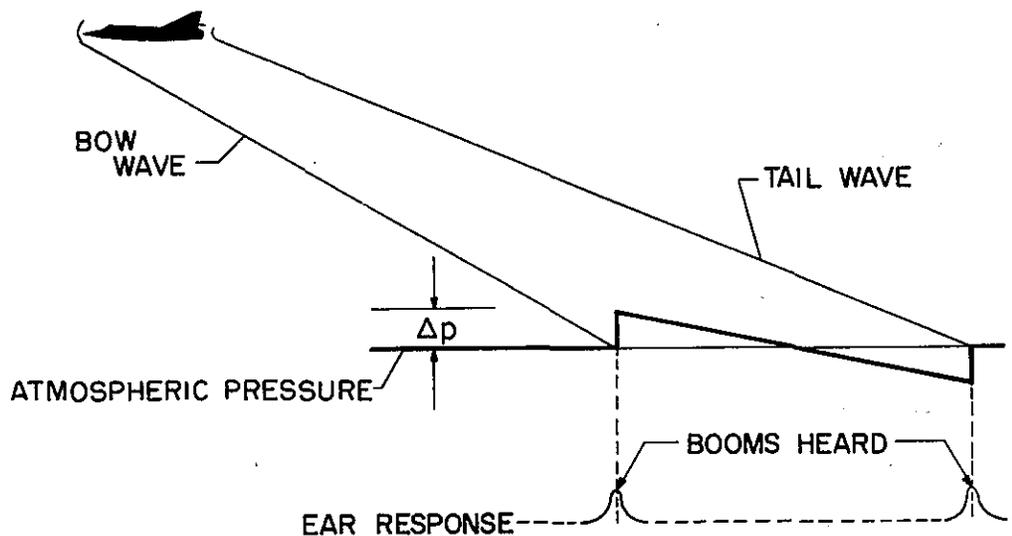


Figure 15. Schematic diagram for a field test condition of supersonic flight.

(1) Although recording equipment currently used in measuring sound can record very minute pressure changes along an extremely fast time scale, the human ear has a limited response time. Most people

cannot separate the bow and the tail portions of a shock wave if they both occur within a time period of less than one tenth of one second (100 milli seconds).

(2) When the shock waves emanating from the bow and tail of a supersonic aircraft pass by a listener on the ground he experiences, if outdoors, something which usually sounds like two heavy-duty rifle shots fired in quick succession. This sound is commonly called a "sonic boom." If the listener is inside his house, the sound will not be as sharp but will continue for a longer time due to reverberation and structural vibra-

tion, see Figure 16. (Nixon and Hubbard [12]). Pearson and Kryter [13] have developed techniques for reproducing sonic boom sound sequences to compare with other familiar sounds to test human reaction. Since the general public is found both inside and outside of buildings, attempts were made to simulate both conditions. The boom one would experience outdoors is essentially an N-shaped wave ranging in duration from 75 to 300 milliseconds (Maglieri et al [14]) (Maglieri and Hubbard [15]) with the shorter durations being those produced by military fighter aircraft, and the longer durations produced by bombers and the forthcoming supersonic transport.

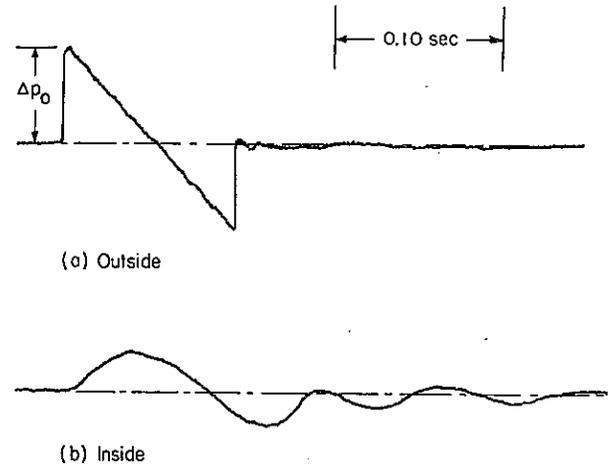


Figure 16. Tracings of F-106 sonic boom pressure signature recorded outside and inside a building.

The duration of the N-wave outside the building (from which they obtained F.M. recordings) was approximately 100 milliseconds. However, the sounds produced inside could be heard for upwards of one second.

d. There is a noticeable contrast between the compound family of shock waves produced in the immediate surroundings of an irregular shaped aircraft moving at supersonic speed and the more or less regular N-wave recorded at the ground several miles from the flight path. This has led to a need to consider the "Near Field" and "Far Field" pressure patterns (Parrott [16]) see Fig 17. In the near field there are several shock waves, each having its own cause in the compound disturbance produced by fuselage, wings, motors, tail section, etc. As these compound waves move farther from the source, they coalesce (Whitham[17]) and move outward into the major outward edges of the bow and tail sections of the far field N-wave.

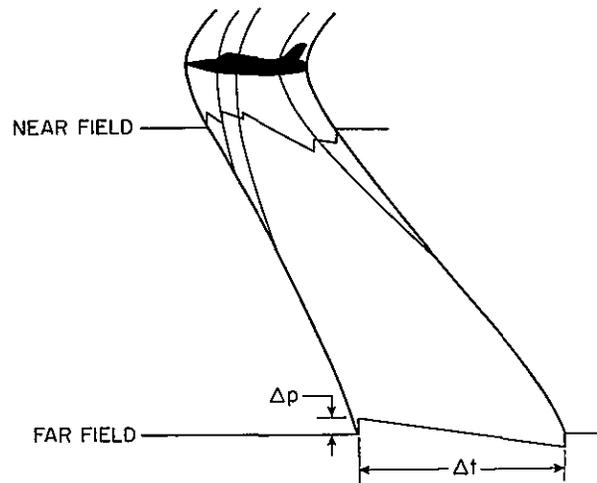


Figure 17. Typical pressure signatures of sonic boom in near field and far field.

(1) This coalescence and outward movement acts to strengthen the intensity of the overpressure at the forward edge of the N-wave (bow wave) and the peak of the low extreme just prior to the return-to-normal-pressure (tail wave). However, this peaking tendency is counteracted by attenuation of the entire wave plus the tendency for the N-wave

to spread outward and flatten as it moves farther and farther from the source. Figure 18 shows this spreading with increasing distance in the sample tracings produced by fighter and bomber aircraft at various altitudes. (Hubbard and Maglieri [18]).

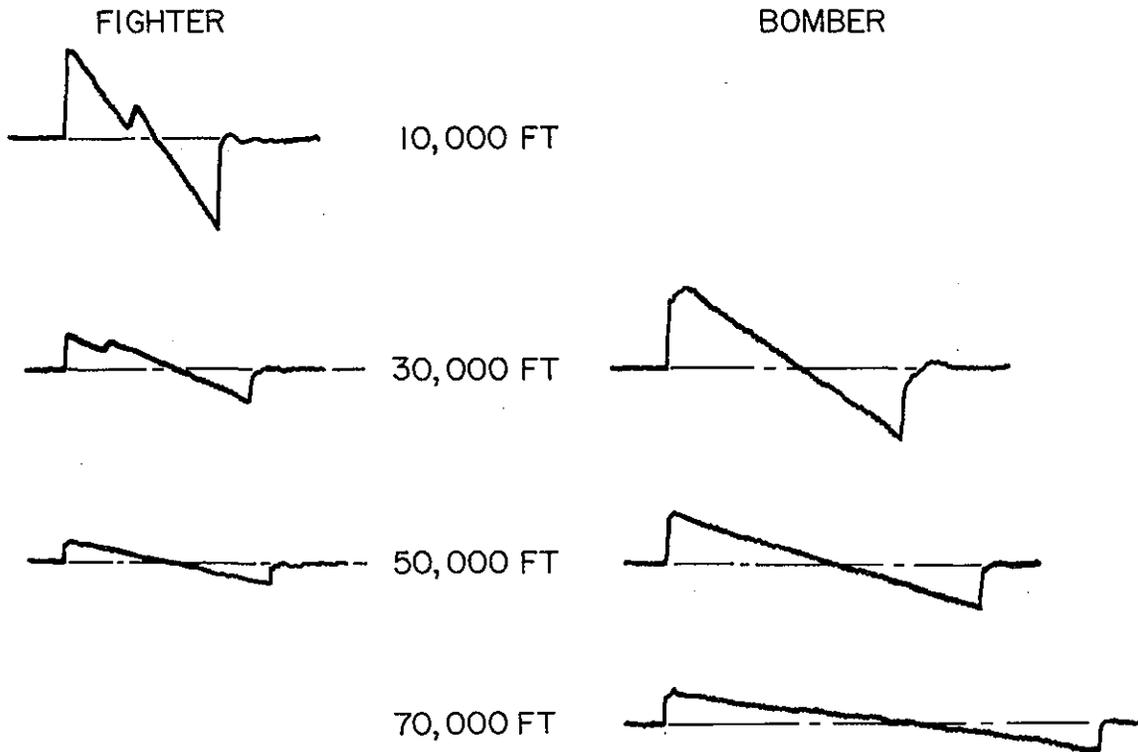


Figure 18. Measured shock-wave ground-pressure signature for various altitudes for both fighter and bomber aircraft in steady flight in the Mach number range 1.2 to 2.0.

e. There are many variables which bear on the production and spread of sonic booms. Table IV presents a list of the more notable factors.

Table IV. Sonic Boom Variables

Aircraft Mach Number	Attitude of Aircraft
Aircraft Fineness Ratio	Temperature Gradient
Aircraft Length	Wind Gradient
Aircraft Altitude	Wind Direction
Distance	Atmospheric Losses
Pressure	Aircraft Flight Path
Location Max Thickness	Ground Reflectivity
Aircraft Lift Carried	

f. Consider for the moment the typical spread of a sonic boom from an aircraft moving along a horizontal path at supersonic speed. The basic pattern for a point source was shown in Figure 6. The pattern for a moving source is in the form of a modified cone. The portion of the cone of greatest importance is that which reaches the ground. Figure 19 shows a three dimensional view of the ground locus along which the shock wave originating from one position P, of the flight path strikes the ground. Also inferred is the similar spread of rays from other points, P', P'', along the flight path. (Lansing [19]). As aircraft follow higher and higher paths in the atmosphere they have the potential for spreading sonic boom patterns along wider and wider belts at the earth's surface. However, both refraction and attenuation limit the extent of the noticeable sonic boom effects. For altitudes greater than 50,000 feet, lateral spreads of 20 or more miles on either side of the flight path can be expected.

g. When aircraft barely exceed the speed of sound at the cooler temperatures in the upper portion of the troposphere, the sonic boom which they generate at that level has a speed of propagation which is less than the speed of sound in the warmer air near the ground.

To produce a sonic boom at the ground under standard atmospheric conditions, an aircraft at 35,000 ft needs to fly at a Mach number of approximately 1.2. This is the cut-off Mach number for that particular elevation and atmospheric condition. Flights conducted at lower speeds will not produce sonic booms at the ground. Two notable variables strongly affect the shock wave intensities reaching the ground and corresponding cut-off Mach numbers. The first is the flight path angle (Power [4]), (Nixon and Hubbard [12]), (Kane and Palmer [20]), and the second is the wind. (Power [4]), (Kane and Palmer [20]), (Reed [21]). The influences of these two factors are illustrated in part b and c in Figure 20.

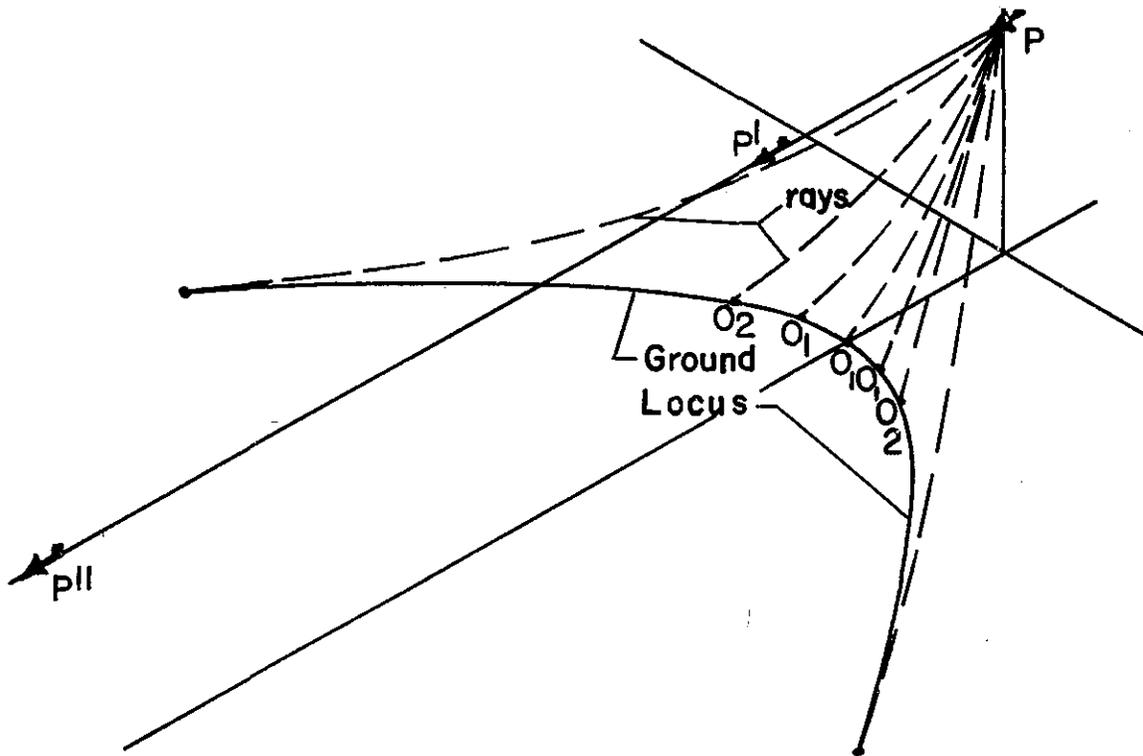


Figure 19. Three-dimensional view of the ground locus of spreading shock wave from a single point of a flight path.

h. Several extensive field projects have been carried out to measure the sonic boom intensities at the ground produced by various sized aircraft at different altitudes and coincident weather conditions.

From a series of 76 supersonic flights (known as BONGO) over St. Louis using a B-58 bomber and an F-106 fighter at elevations generally above 40,000 feet it was learned that the overpressures of sonic booms at the ground ranged from 1 to 3 lbs. per square foot directly below the flight path and for several miles on either side of the ground track (Nixon and Hubbard [12]). Figure 21 summarizes the measurements made at a large number of ground observing points including reactions of the public, at distances up to 16 miles from the ground track.

i. During the period between February 3 and July 30, 1964, 1225 supersonic flights were conducted over Oklahoma City. Altitudes ranged

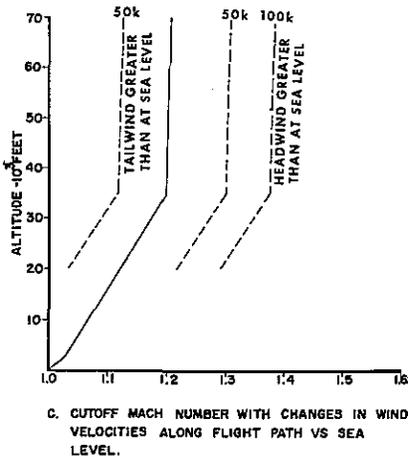
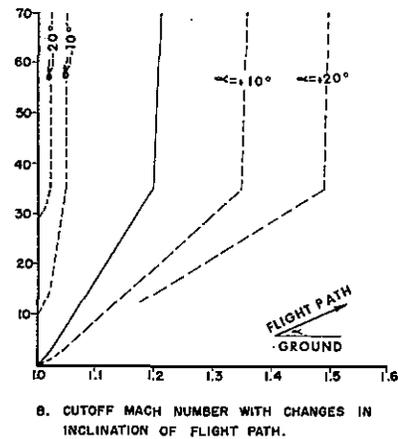
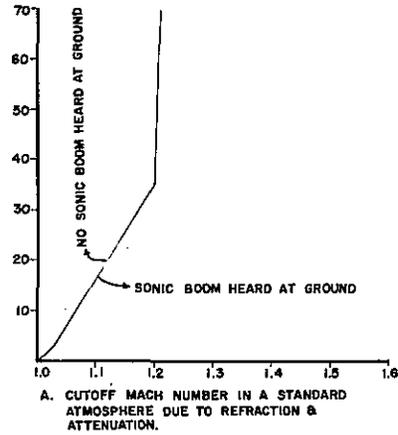


Figure 20. The influences of flight path angle and atmospheric conditions on cut-off Mach numbers.

from 21,000 to 50,000 feet and speeds ranged from Mach 1.2 to Mach 2.0.

Overpressures of 3 lb/sq ft or greater were measured many times at distances of both 5 and 10 miles to one side of the ground track (Hilton, et al [22]). The conclusion included a statement that one percent of the measured overpressures equaled or exceeded the predicted values by a factor of about 1.5 to 3.0 depending on the distance relative to the ground

track; the larger factor was associated with the larger distances and with the lower predicted value. In an independent summary of results relating weather factors to the collected data, Kane and Palmer [20] found that the important scattering parameters are the angle of the path of propagation of the shock wave and the time of day as related to the turbulent intensity near the ground.

j. From an analysis of data from multiple supersonic flights in both the United States and England, Warren [23] states that for supersonic aircraft flying at altitudes above 50,000 feet we must expect that on 1% of occasions the sonic boom pressure jump will be greater than the mean value by a factor of 1.85.

(1) The amount and intensity of sound generated by an aircraft moving at supersonic speed in non-turbulent air is assumed to be

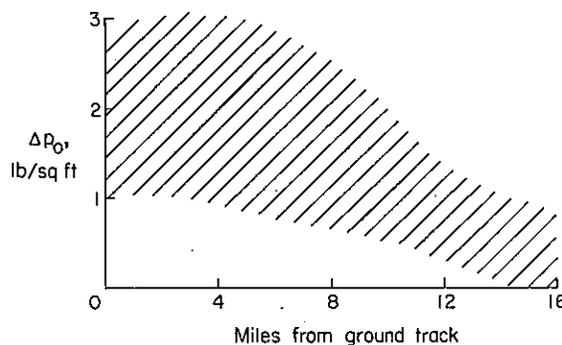


Figure 21. The estimated ranges of sonic boom overpressure as a function of distance from ground track for BONGO flights.

nearly constant over fairly long distances. However, measurements of sonic booms at the ground can show variations in relatively short distances. The seven sonic boom signatures (Hubbard, et al [5]) shown in Figure 22 were obtained from seven separate microphones all placed within one square foot of space near the ground. All microphones recorded nearly identical sound patterns. In another field test, (Hubbard and Maglieri [18]) a comparison was made between the records of five microphones placed side by side to calibrate the similarity of their recording capacity. These matched microphones were then spaced 200 feet apart and recorded the five sharply variable measurements shown in Figure 23 during the flight of a fighter aircraft. The scale of the ground pressure pattern variation is compatible with the predicted scale of turbulence in the lower atmosphere. The convective motion near the ground may account for a large fraction of this variability.

k. Intensities of sonic booms can be increased appreciably by different aircraft maneuvers. Even when these maneuvers are conducted at altitudes above 30,000 feet they can be executed in such a manner as to increase sharply the overpressures at the ground. Tests have been made to measure the ground shock patterns resulting from the following aircraft maneuvers; pushover-dive-pullout, longitudinal acceleration, pullup-climb-pushover, and circular turn. (Lansing and Maglieri [24]) (Maglieri and Lansing [25]).

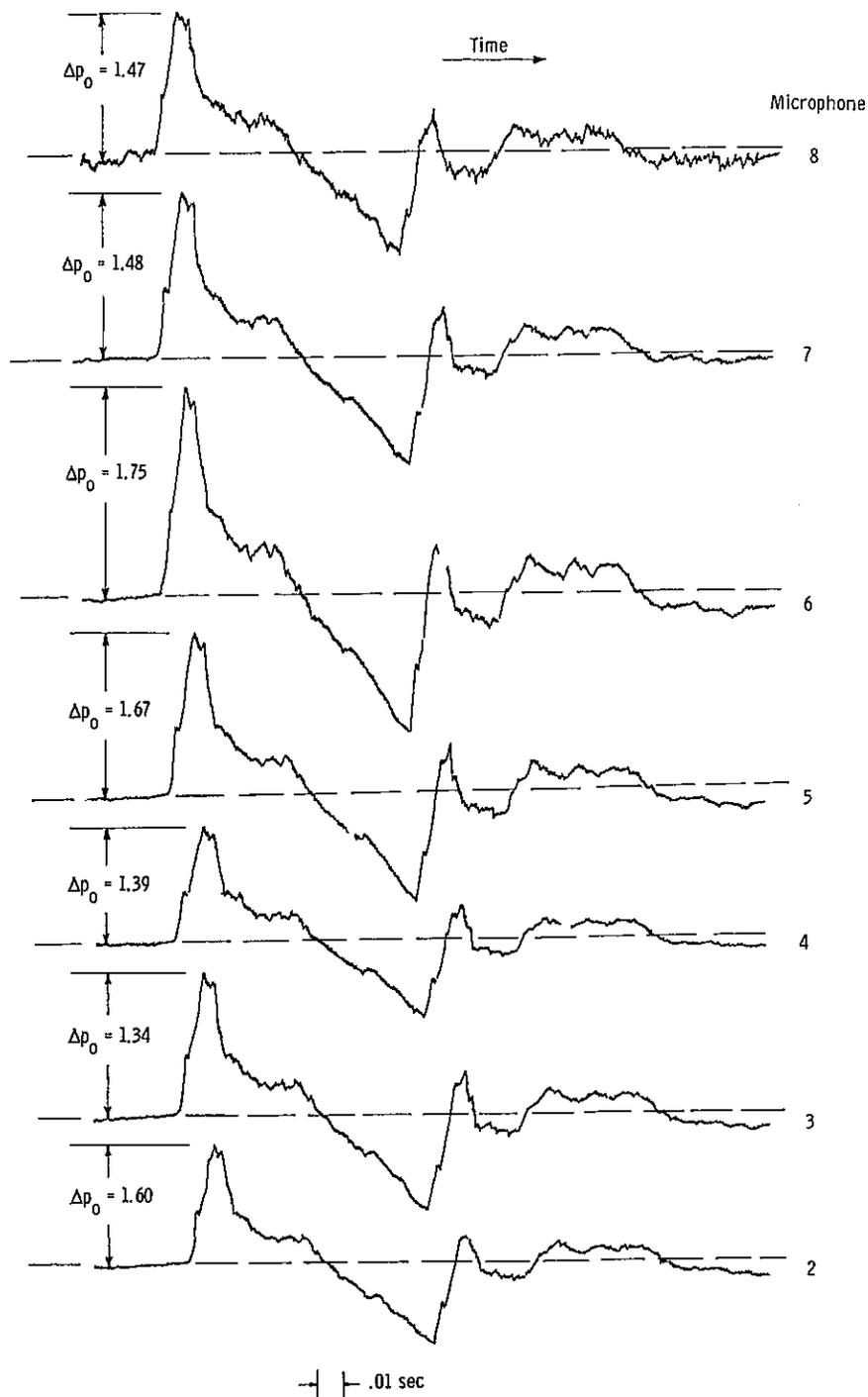


Figure 22. Sonic boom pressure signatures for a fighter airplane at an altitude of 41,200 feet and a Mach number of 1.52 from seven different microphones grouped within a 1-square-foot area on the ground. (Values of P_0 are expressed in pounds per square foot).

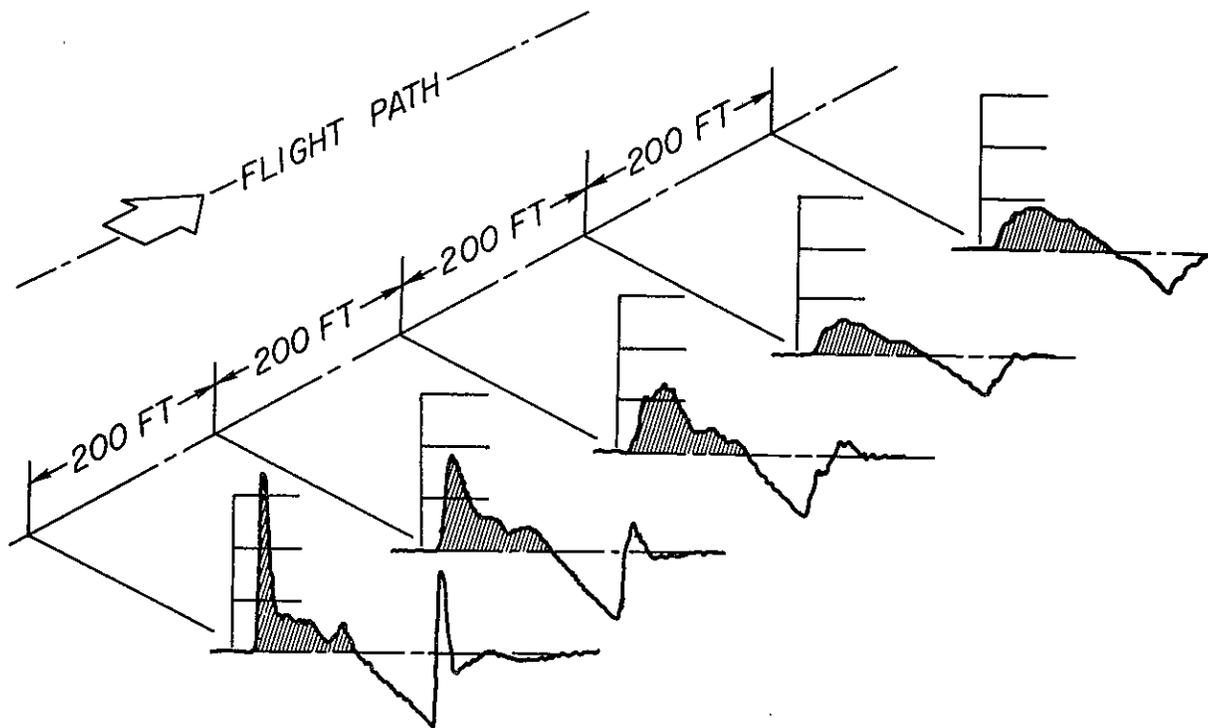


Figure 23. Measured sonic boom pressure signatures at several points on the ground track of a fighter aircraft in steady-level flight at Mach number 1.5 and an altitude of 29,000 feet, showing effects of the atmosphere.

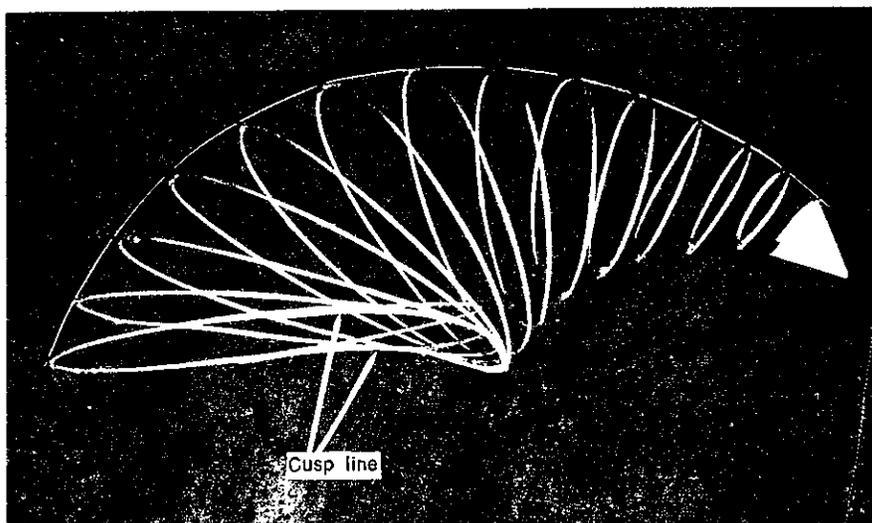


Figure 24. Wire model depicting cusp line and representation characteristic lines of shock envelope resulting from a planar turn flight maneuver.

1. The super-posing of shock waves coming from different parts of a planar turn develop a cusp line at the ground, see Figure 24. (Barger [26]). The relative values of overpressures for routine military flight maneuvers are shown in Fig 25. (Hubbard and Maglieri [18]) (Mayes and Edge [27]).

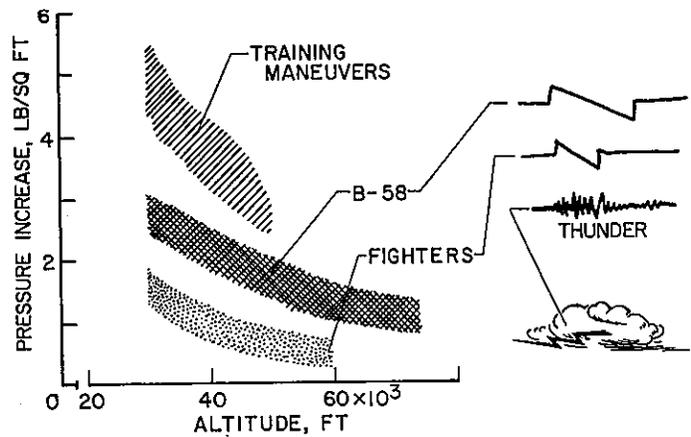


Figure 25. Sonic boom exposure levels for routine military flight operations.

4. Sound from Rockets

With the advent of large rockets, there is a corresponding concern for the sonic boom which may be created in areas surrounding the launch sites. Fortunately, for earth bound man and the structures he builds, much of the energy in the sonic booms generated by vertically accelerating rockets is directed toward the upper atmosphere. The measurement of any shock wave from that portion of flight in which the rocket becomes supersonic is difficult. For nearly all locations it will arrive coincident with the roar type noise that spreads outward from the launch site region. Nearly all of the noise generated from the launch site is sub-sonic at the point of origin. The multiplicity of ray paths for sound generated by the ascending rocket produces a rather lengthy loud noise at any fixed point surrounding the launching. Figure 26 shows the record of comparative noise in terms of decibels at three separate distances from the launch site -- 14,000, 24,700 and 79,600 feet. (Wilhold, et al [28]). These measurements were made in connection with the launch of a Saturn 1A which produced 1.32 million pounds of thrust. From tests made to date, it appears that sonic booms generated from ascending large rockets will have smaller overpressures than the present family of supersonic aircraft can generate by carrying out certain maneuvers. Prediction equations have been developed for use in estimating the intensity and spread of sound to be expected from the larger moving rocket sources that will be used in future space exploration.

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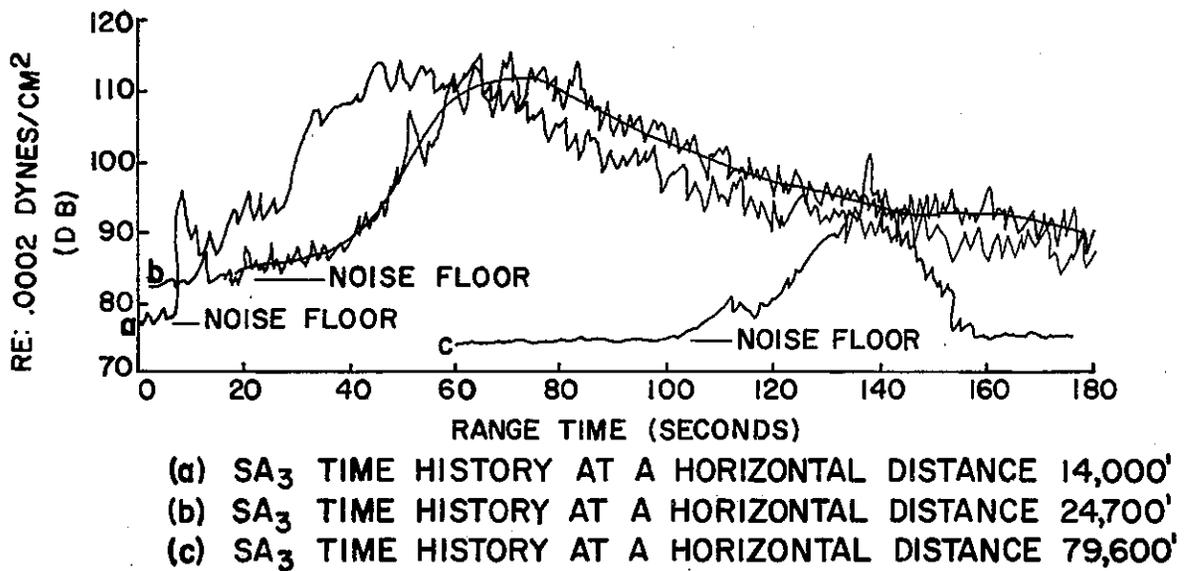


Figure 26. Relative intensities and timing of sound produced by the launch of a Saturn 1A missile.

5. Response Phenomena

Both structures and living creatures respond in varying ways to pressure patterns of sonic booms. Various investigations have been made to determine corresponding building vibrations, ground vibrations, responses of other aircraft, and responses of people exposed to sonic booms.

a. Several building response studies have shown that the natural vibration modes of each primary structural element of a building has its own response pattern when excited by a sonic boom. Most of the vibration responses have frequencies ranging between 5 and 30 cps. The strain responses of three individual components of the primary structure are shown in Figure 27. (Mayes and Edge [27]). Such strain levels are low in amplitude compared with the design loads of the building. The classification of over 3,000 complaint cases in Air Force files (Hubbard and Maglieri [18]) (Mayes and Edge [27]), is shown in Figure 28. Plaster cracks, the type of damage reported most frequently, were mentioned in 43 per cent of the complaints. It should be noted that such damage as is reported to have been caused by sonic booms may also result from many other causes such as normal living activities, weathering, degradation of materials, settling, road traffic, etc.

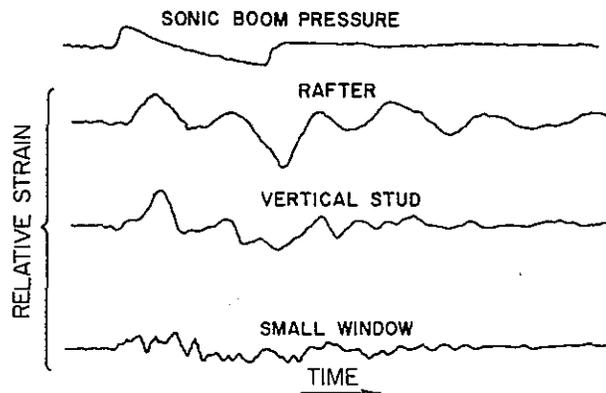


Figure 27. Sample strain-time histories for components of a building exposed to sonic boom produced by bomber aircraft.

b. One case of severe damage to a large structure took place at Ottawa, Canada when a loss of approximately \$300,000 was inflicted on a nearly completed air terminal building (Ramsay [29]). In this instance, a fighter aircraft had flown above the runway below 1,000 feet at supersonic speed and was climbing and accelerating in an upward turn in the vicinity of the building. Damage to glass, curtain walls, suspended ceilings and roofing was extensive, but the structural steel frame was said to be unaffected by the boom.

c. The orientation of any building with reference to the aircraft flight tracks will permit variation in the acoustical response that can be measured in different parts of the building. Diffraction effects due to building size and shape will produce load variations.

d. From tests of the influences of sonic booms on the surface layers of the earth beneath the flight path, the following conclusions have been reached. Measured accelerations are consistently greater in the direction of flight and are consistently lowest in the direction perpendicular to the flight direction (Hubbard and Maglieri [18]).

The highest value of acceleration measured did not exceed 0.03g which is

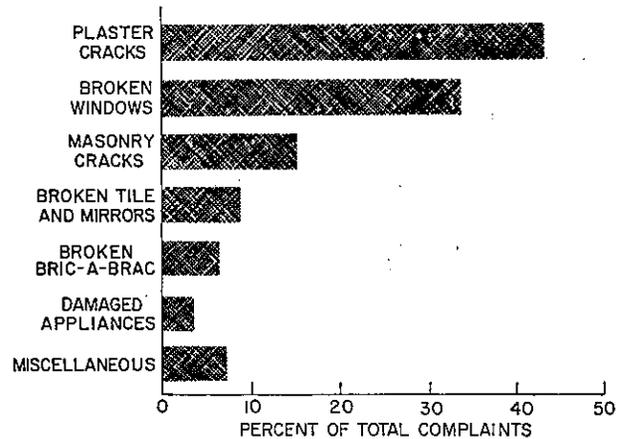


Figure 28. Classification of about 3000 complaints due to sonic booms as recorded in Air Force files. (The damage reported in the complaints was not necessarily validated).

lower than accelerations associated with the onset of earthquake damage.

e. There has been some concern about possible adverse effects of some shock waves on other aircraft in flight, particularly small aircraft. From flight tests it has been shown that the highest level of acceleration measured did not exceed .3g. (Hubbard and Maglieri [18]) (Power [30]) (Maglieri and Morris [31]). Sonic boom induced accelerations were

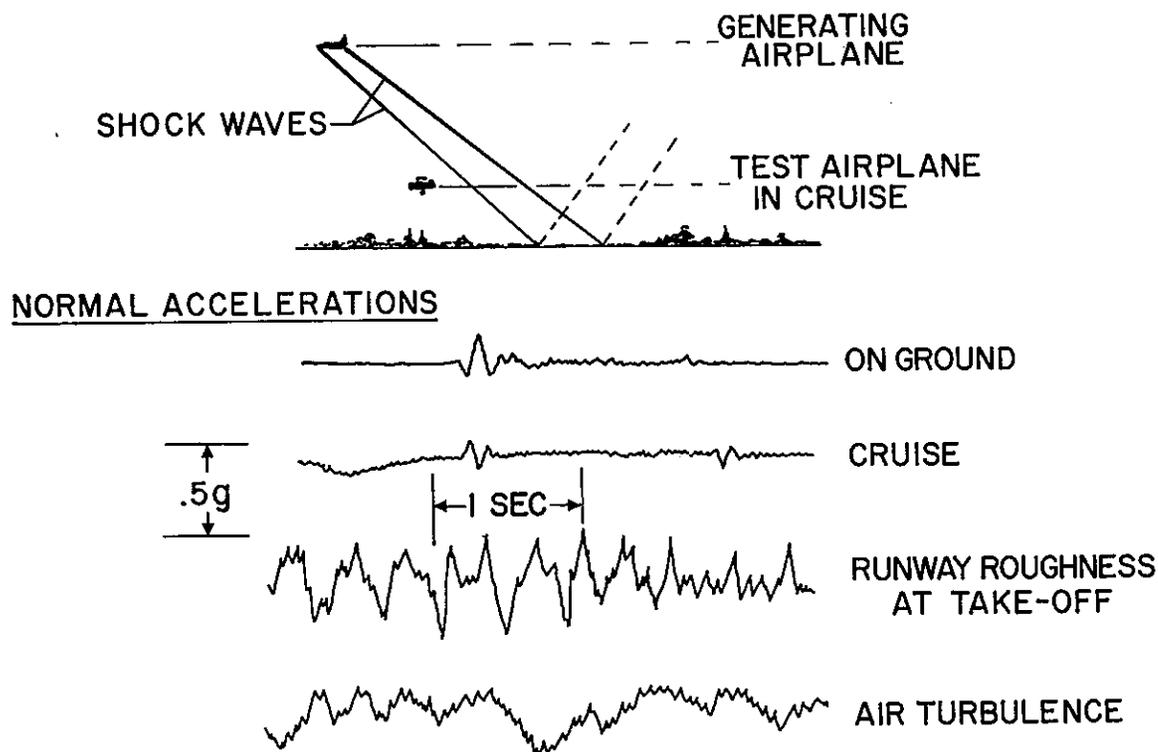


Figure 29. Measured normal accelerations of a light airplane exposed to sonic booms while on the ground and in flight.

judged to be small by comparison with those induced by such commonly encountered phenomena as runway roughness and moderate air turbulence (See Fig 29). Observations made of the pilots in the test aircraft showed them blinking their eyes as the sonic boom reached them. Otherwise they reported no personal effect.

f. Two supersonic flight test series have been conducted over extended periods of time in the vicinity of large cities. During 1961 and 1962, 66 supersonic flights were carried out over St. Louis. In 1964 about 1225 supersonic flights were made over Oklahoma City. Although there were many complaints of annoyance, there were no adverse physiological effects. (Nixon and Hubbard [12]) (Hilton, et al [22]). In the St. Louis study, over 2000 interviews were conducted to determine human response. About 35 percent were annoyed by the flights, but only a fraction of 1 percent actually filed a formal complaint.

g. As a part of project "LITTLE BOOM", an experiment was carried out to determine what injuries, if any, would be inflicted on personnel due to intense sonic boom exposure. (Maglieri et al, [32]). During this project, approximately 50 people of varying backgrounds were exposed to peak overpressures up to about 100 lb/sq ft. Such values are considered to be about 10 times as intense as any that would be generated in routine operations. No direct injury resulted from repeated intense exposure during these experiments.

6. Sound Forecasting Problems

Forecasting of the composite sonic boom intensity pattern along the ground for any specific flight is highly conjectural. Mathematical equations can be used effectively to calculate an estimated general pattern that will result from a yet unbuilt aircraft having a particular size and shape and certain specified flight characteristics. However, data from field tests have shown that from one flight to the next, using the same aircraft at the same speed, direction and weight, overpressure measurements varied in amplitude over a considerable range. These variations may be due to such factors as small variations in aircraft flight conditions, small variations due to measuring techniques and instrument inaccuracies, or variations due to weather. Weather effects are judged to be dominant. Wind patterns and profiles can account for much of the change in the geographic areas that will be most affected by sonic booms. Fluctuations in the temperature profile account for changes in the sound ray path patterns which carry the shock wave energy away from the source. The combinations of multiple ray paths to a series of points on the ground help increase wide variability over short distances. Convective processes in the lower few hundred feet permit ducting of sound rays to further increase variability. Thus it is advantageous to describe forecast ground path measurements of sonic boom responses as covering a range of values for any point or segment of the total path of influence of a superconic flight.

a. With present knowledge of sonic boom characteristics, meteorologists can probably best serve operational personnel by advising

them only in a general way regarding expected sonic boom patterns related to any particular weather situation.

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