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A SUMMARY OF RESULTS ON SONIC-BOOM PRESSURE-SIGNATURE VARIATIONS ASSOCIATED WITH ATMOSPHERIC CONDITIONS

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A SUMMARY OF RESULTS ON SONIC-BOOM PRESSURE-SIGNATURE VARIATIONS ASSOCIATED WITH ATMOSPHERIC CONDITIONS*

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SUMMARY

This report reviews the most pertinent information obtained in recent years relating to atmospheric effects on the sonic boom and, in particular, includes some results of various flight programs. These atmospheric effects are complex, and a statistical approach appears necessary. The statistics of peak pressures follows approximately a log normal distribution, a result that is indicated by existing theory for pure (sinusoidal) sound. A tabular summary of the flight data gives the standard deviations of pressure peaks relative to nominal calculated values of the mean. Information is included on observed variations of sonic-boom signatures for different types and sizes of airplanes. Measurements indicate that wavelike spatial patterns exist in which peaked and rounded waves may alternate and vary with time. Such variations are shown to be induced by the atmosphere rather than by effects of airplane unsteady motion. The spectral content of some ideal and some measured pressure signatures is exhibited and discussed with reference to peakedness or roundness of the wave.

INTRODUCTION

Acceptance by the general public of supersonic transports will depend in great measure on the characteristics of their sonic booms. (See ref. 1.) These characteristics are affected by several factors which depend on (a) design, (b) operations, and (c) environment or atmospheric conditions. Design factors such as weight, size, lift, and volume distributions and operation factors such as altitude, Mach number, and flight path may be accounted for, or even predicted, by existing theoretical methods which have been closely verified under controlled conditions, such as in a supersonic wind tunnel.

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*This report includes material presented in a paper by the authors entitled "Variability of Sonic Boom Pressure Signatures Associated With Atmospheric Conditions" which was presented at the International Association of Meteorology and Atmospheric Physics, XIV General Assembly of the International Union of Geodesy and Geophysics, Lucerne, Switzerland, Sept. 25-Oct. 7, 1967.

However, the effects of environment or atmospheric conditions, such as wind, temperature, and pressure gradients and turbulence, like the prediction of weather itself remain probabilistic or statistical in nature.

The chief objective of this report is to exhibit, summarize, and discuss some of these atmospheric effects including the findings of several flight studies. A certain background of analytical and experimental information is also briefly included to provide a more meaningful framework for the statistical information. For convenience, references 2 and 3 are referred to for much of the detailed bibliography and for certain background material.

SYMBOLS

The millibar as a unit in this report is equivalent to 100 newtons per meter^2.

h	airplane flight altitude above mean sea level, feet (kilometers)
I_o	impulse of positive phase of sonic-boom ground pressure signature, pounds-seconds/foot^2 (millibars-seconds)
K_r	ground reflection factor (for perfect reflectory surface K_r has a value of 2.0)
M	Mach number
$\bar{p}$	reference pressure, sometimes defined herein as $\sqrt{p_a p_g}$, pounds/foot^2 (millibars)
p_a	ambient pressure at altitude, pounds/foot^2 (millibars)
p_g	ambient pressure at ground level, pounds/foot^2 (millibars)
Δp	sonic-boom overpressure, pounds/foot^2 (millibars)
Δp_o	maximum pressure rise across bow shock wave at ground level, pounds/foot^2 (millibars)
S	separation distance between microphones, feet (meters)
T	period of N-wave signature, seconds

t time

σ standard deviation

$\sigma_{\Delta p_o}$ standard deviation of overpressure differences, pounds/foot^2 (millibars)

τ rise time of N-wave, seconds

ω frequency, hertz

Subscripts:

calc calculated

meas measured

ANALYTICAL CONSIDERATIONS

Prediction of sonic-boom characteristics have been based on theoretical methods in which idealized atmospheres are assumed. For example, in his basic work on the flow fields of bodies of revolution, Whitham assumed a uniform atmosphere. Randall employed a correction factor to account for an isothermal hydrostatic (exponential) atmosphere. (This factor $\sqrt{p_a p_g}$ which involves ambient pressure at the airplane p_a and the pressure at the ground p_g is related to the work of Lamb on the vertical propagation of sound.) The formula

$$\Delta p = \frac{K_r \bar{p}(M^2 - 1)^{1/8}\left(I_{V+L}\right)}{h^{3/4}}$$

indicates a calculation process for the overpressure Δp along the ground track of the airplane based on this theory (where I_{V+L} refers to an integration which depends on the volume and lift distributions).

Effects of a layered or stratified atmosphere with arbitrary steady or slowly varying winds and temperatures were studied by Palmer, Friedman, Kane, and Sigalla. This work, which was also pursued by Swedish workers Dressler and Fredholm, makes direct use of classical concepts of geometrical (ray) acoustics and permits comparison of results for a nonstandard atmosphere with those for the standard atmosphere (ref. 3). It also leads to means for predicting effects of maneuvers and explains in large measure the focusing and channeling of energy of acoustical signals.

The general theory of the scattering of sound in the atmosphere may be based on a form of the local wave equation and indicates that variations in the local speed of sound and in the local convection velocity of the sound field are responsible for the modulating effects of turbulence and temperature fluctuations on the distortion of the pressure signatures of the aircraft. The task of calculation of the modulating effects of wind turbulence and temperature spottiness is a most difficult one, since not only are these calculations highly complex in themselves but also the basic data required are extremely difficult to determine or even to assess. The variability in peak pressures for sonic booms, although significant, is much less than that attributed to ground-to-ground sound propagation of explosives over similar distances. However, many investigators have made partial contributions to various aspects of the scattering of sound and shock waves due to turbulence, starting with A. M. Obukhov. (An account of his work and of other Russian investigators dealing with sinusoidal sound waves is given in the comprehensive book by Tatarski, ref. 4.) Only a few other names are mentioned here: Lighthill, Ribner, Palmer (ref. 5), and Müller and Matschat (ref. 6). A brief résumé of reference 6 follows.

Müller and Matschat treat the scattering of sound by a single vortex as a classical boundary value problem and apply these results to scattering by turbulence. They develop expressions for changes in amplitude and phase, or in scattering energy, as a function of several parameters. The parameters employed are (a) ratio of mean velocity of turbulence to ambient sound speed, (b) characteristic length represented by the mean radius of the scattering vortices (for a single vortex, this is the radius of the outer edge beyond which potential flow is assumed), (c) properties of the turbulence, for example, whether isotropic and homogeneous, (d) frequency and directionality of the incident sound waves, and (e) length of the sound path in the turbulent medium. Their results, which were confirmed experimentally with ultrasonic sound by Schmidt (ref. 7), indicate that for large vortices relative to sound wavelength the scattered energy is proportional to the volume of turbulence, characteristic length, intensity of sound, and frequency squared. For smaller vortices the proportionality approaches the fifth power of the frequency. The overall behavior for isotropic and for nonisotropic turbulence was not greatly different. Schmidt also showed that by passing the sound through a wake vortex street the frequency was clearly modulated by the wake pattern of vortices. It is of interest to mention that the linear treatment of reference 6 corresponds to Lighthill's for weak shocks and that Lighthill points out the important nonlinear effect that occurs after the passage through turbulence, when parts of the wave catch up with the shock front and are reformed.

Despite such encouraging analytical efforts, relevant statistical predictions for sonic booms at present seem to depend mainly on measurements from airplane flights. It is convenient, in general, to normalize the measured data in relation to a nominal overpressure calculated by a relation such as that previously indicated. A scheme for calculating these nominal overpressures including complete signature shapes has been programed for computing machines and is given in reference 8.

SONIC-BOOM EXPOSURES

Characteristics of Pressure Signatures

In figure 1 is shown schematically the overall ground pressure pattern of a supersonic transport for both the transition to supersonic flight by acceleration through the transonic regions and level cruise. Also included is a representative pressure signature. Among the signature characteristics that have been identified as having special significance, several stand out, as indicated in the figure: overpressure Δp, positive impulse I_O, bow-wave rise time τ, and duration of N-wave T. In addition, the spectral content is of significance. It has been shown, for example, that the psychological startle factor is associated with the steepness of the pressure rise, namely, the rise time τ.

Certain characteristics of the sonic-boom pressure signatures have not been fully assessed as to their importance. There are those characteristics that influence subjective human factors, and the effects are different when the observer is outdoors or indoors or when indoors whether windows or doors are open. Then, there are characteristics that affect the overall response of buildings or dwellings, or structural components or windows, or bric-a-brac. To indicate the differences associated with outdoor and indoor stimuli, figure 2 is presented. The top trace is a sample outdoor pressure

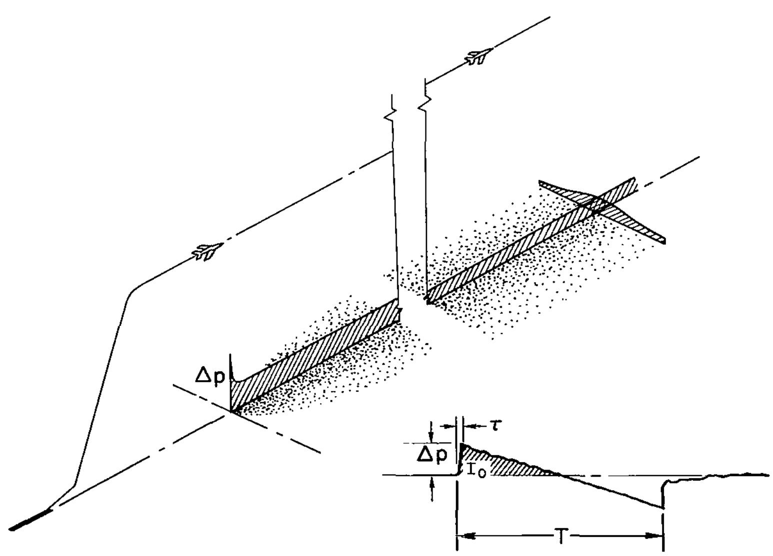


Figure 1.- Sonic-boom ground-pressure patterns and signature characteristics. (From ref. 2.)

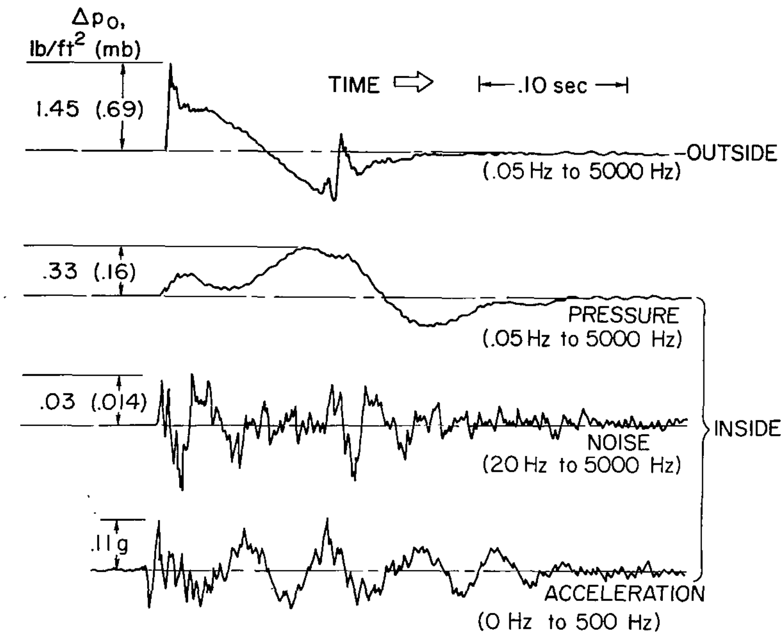


Figure 2.- Outside and inside exposure stimuli due to sonic booms. (From ref. 2.)

exposure. The three bottom traces represent corresponding indoor-exposure stimuli. The topmost trace of these three represents the overall pressure variation inside the building, the middle trace is the audible portion of this signal, and the bottom trace is the vibratory signal resulting from floor accelerations. Wide differences in the temporal characteristics of these stimuli are seen to exist for the given outdoor pressure signature.

Spectral Considerations

Development of spectra of some pressure signatures can be useful since they contain information of significance with respect to response factors, whether human or structural. Although the effect of spectral information is obvious in a general way, it has not been analyzed in detail. On the other hand, the interaction of the spectrum and turbulence and the modification of the spectrum by turbulence are also of considerable interest and relevant to the variability and distortion of the pressure signature as actually measured. An amplitude squared – or so-called energy – spectrum of an ideal N-wave is indicated in figure 3 for a short-duration wave (T = 0.04 sec) and a long-duration wave (T = 0.4 sec). An envelope may be drawn to the peaks having a slope of 6 dB per octave; the relative loudness of the boom is associated with this slope for the higher frequency range. It is noted that even for the short-duration wave there is a large contribution from subaudible frequencies. In contrast to the characteristics of the ideal N-wave, figure 4 shows mathematical spectra for a short rise time τ/T of 0.01

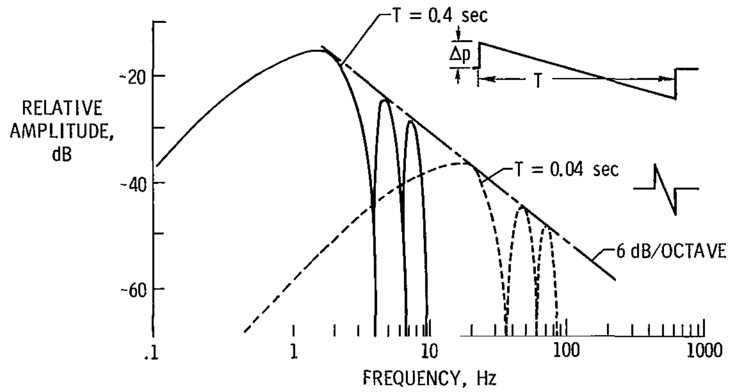


Figure 3.- Effects of time duration on the energy spectra of N-waves having the same rise time. (From ref. 2.)

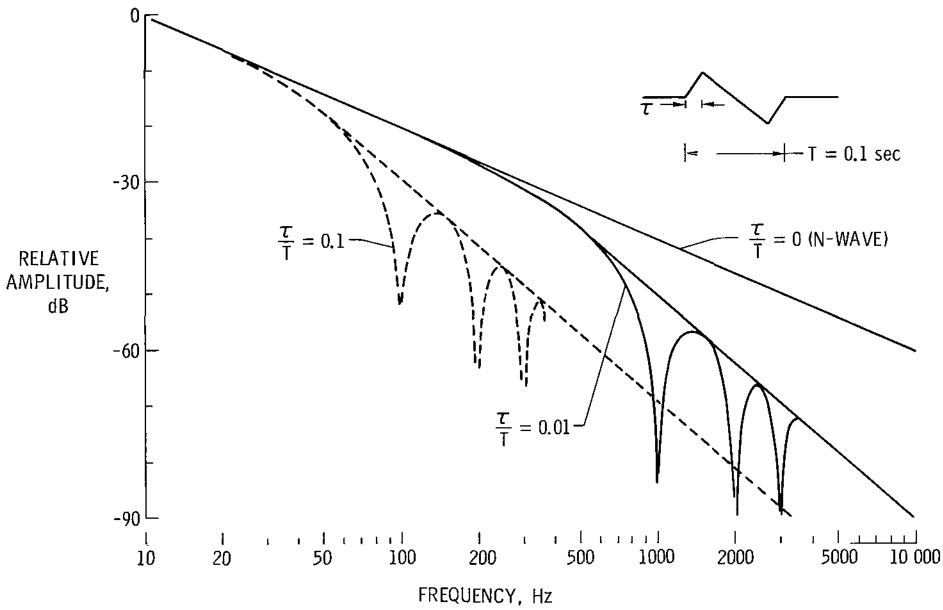
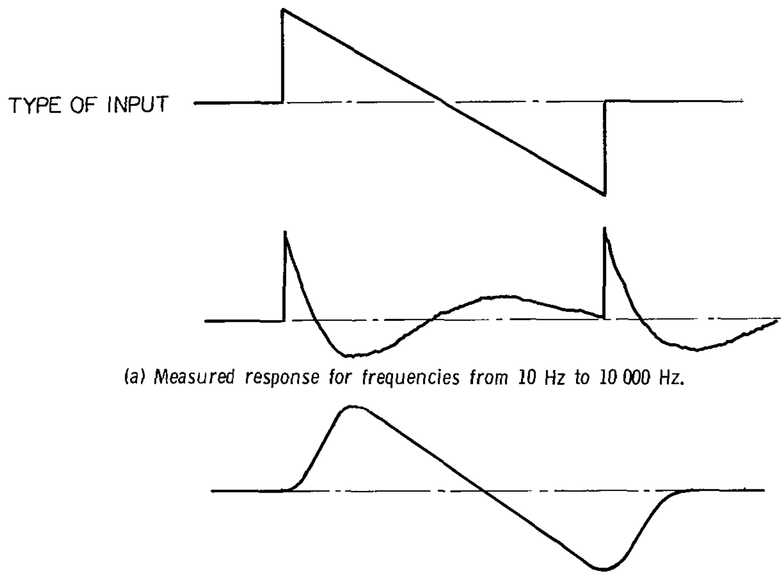


Figure 4.- Effects of rise time on the energy spectra of N-waves having the same time duration.

and a longer rise time τ/T of 0.1. The relative amplitudes at the higher frequencies are less for the longer rise time and, thus, the loudness factors are reduced. Phase plots were also obtained, but these are not reproduced herein.

Additional insight into sonic booms and into the frequency response requirements of the measuring instruments is obtained by applying various filtering techniques to the analog signal of the N-wave. Shown in figure 5 are two typical results: (a) filtering so that frequencies below 10 Hz are not measured and (b) filtering out all frequencies above 30 Hz. The amplitude is not changed very much, but whereas filtering out the high frequencies yields a rounded N-wave, filtering out the low frequencies gives a sharp rise



(a) Measured response for frequencies from 10 Hz to 10 000 Hz.

(b) Measured response for frequencies from 0 Hz to 30 Hz.

Figure 5.- Effects of filtering low or high frequencies on a sonic-boom pressure signature having a time duration T of 0.15 second. (From ref. 2.)

and a distorted wave. Thus, the high frequencies seem dominant in defining the rapid compressions of the N-wave, and the lower frequencies appear dominant in defining the expansion. However, filtering out high frequencies to obtain rounded signatures is not necessary, since these signatures may also be obtained by a shifting of the phases of the high-frequency components.

MEASURED DATA

Wave Shapes

An indication of the measured variations in wave shapes at ground level is given in figure 6 for airplanes of three different sizes. The associated durations are approximately 0.1, 0.2, and 0.3 sec. These signatures generally fall in several classes:

(a) Normal representing signatures closely resembling theoretically calculated N-waves

(b) Peaked representing signatures wherein the pressure peak is amplified relative to the basic N-wave

(c) Rounded representing signatures with longer rise times and lower peaks than the N-wave

Combinations and variations of these signatures also occur.

It is known that near the airplane the pressure signature is quite complex, regardless of atmospheric effects, and that with increased distance the nonlinear characteristics of the propagation process in quiescent atmosphere tend to simplify the signature and to produce the N-wave signature. Figure 7 shows results of probe flights of the flow field of the XB-70 airplane flying at $M = 1.5$ and at an altitude of 37 000 ft (11.28 km), made by an F-104 airplane at various separation distances. The detailed geometry of the airplane is reflected in the near-field signatures both above and below the airplane. Of particular interest is the signature at ground level which indicates that for an altitude of 37 000 ft the far-field N-wave is not fully achieved for this large airplane, rather a hybrid-type near-field signature exists.

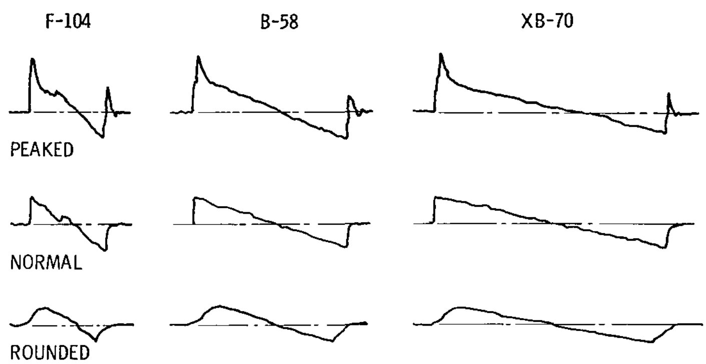


Figure 6.- Variation of measured sonic-boom pressure signatures at ground level for small, medium, and large airplanes in steady level flight. (From ref. 1.)

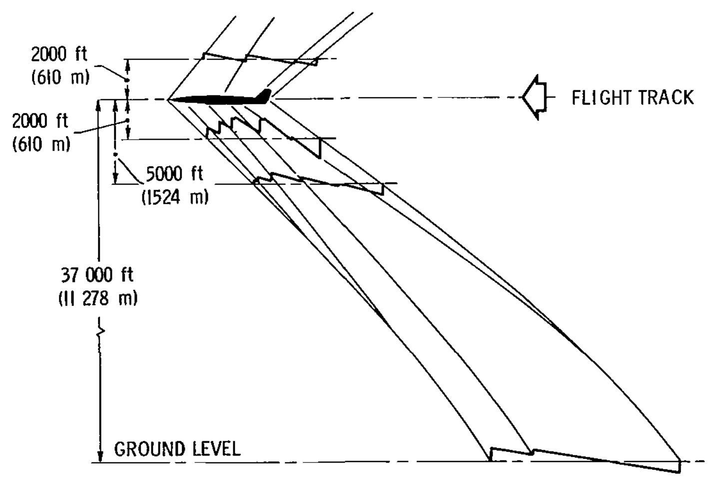


Figure 7.- Diagram comparing the signatures measured in close proximity to the XB-70 airplane in flight with a ground signature for the same flight conditions. (From ref. 1.)

Atmospheric Turbulence

Perhaps the most detailed study of meteorological effects on the sonic boom, based on analysis of NASA data obtained prior to the summer of 1964, was given by Kane and Palmer (ref. 3). In general, subsequent investigations have confirmed many of their conclusions. This study is amplified with additional data and discussion.

In recent years, much information on the local structure of the atmosphere has been assembled. (See, for example, ref. 9.) It is known that characteristic lengths of turbulence in the lower atmosphere below 1000 to 2000 ft (or about 305 to 610 m) depend on height above terrain. It is also believed that much of the distortion of sonic-boom pressure signatures due to turbulence may occur at the lower altitudes. An interesting detailed view of the vortex structure near the ground is afforded by figure 8 (from ref. 10), which shows equal velocity contours, or isotachs, obtained from measurements taken during 25 sec of gusty weather. The horizontal section shows the isotachs obtained from measurements taken at eight stations along an array of 50-ft (15.2 m) poles equally spaced over a linear distance of 420 ft (128 m). The vertical section shows the isotachs obtained from measurements taken at five equally spaced stations up a 250-ft-high (76.2 m) tower. In each section, the ordinate represents distance along the array or up the tower, and the abscissa is time. During the sampling period the average wind traversed a distance of over 1000 ft (304.8 m).

Turbulence in the upper atmosphere has been probed by instrumented airplanes (ref. 11). Typical results of measurement for moderate turbulence are shown in figure 9 as the variation of power spectral density of vertical velocity with wave number (1/wave length). The dashed extension to the measurements follows the theoretically indicated

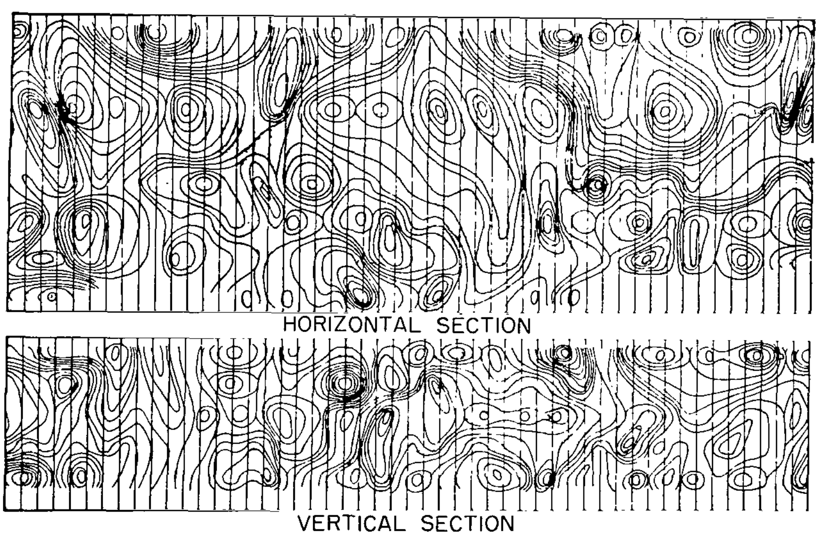


Figure 8.- Gust structure near the ground as revealed by isovelocity contours. (From ref. 10.)

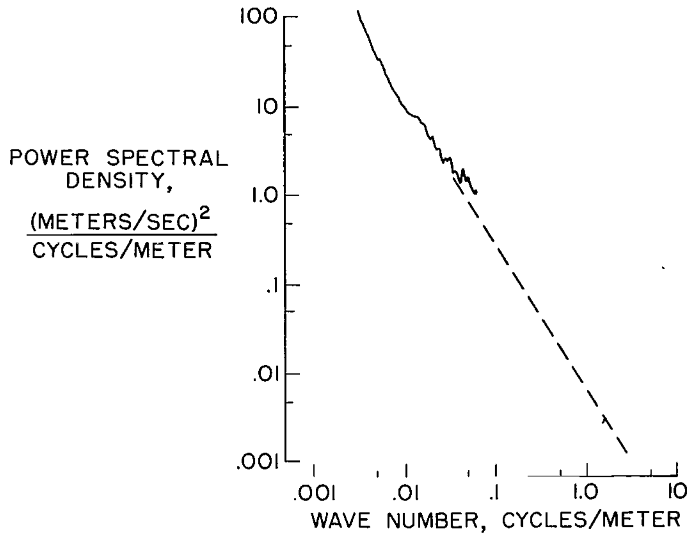


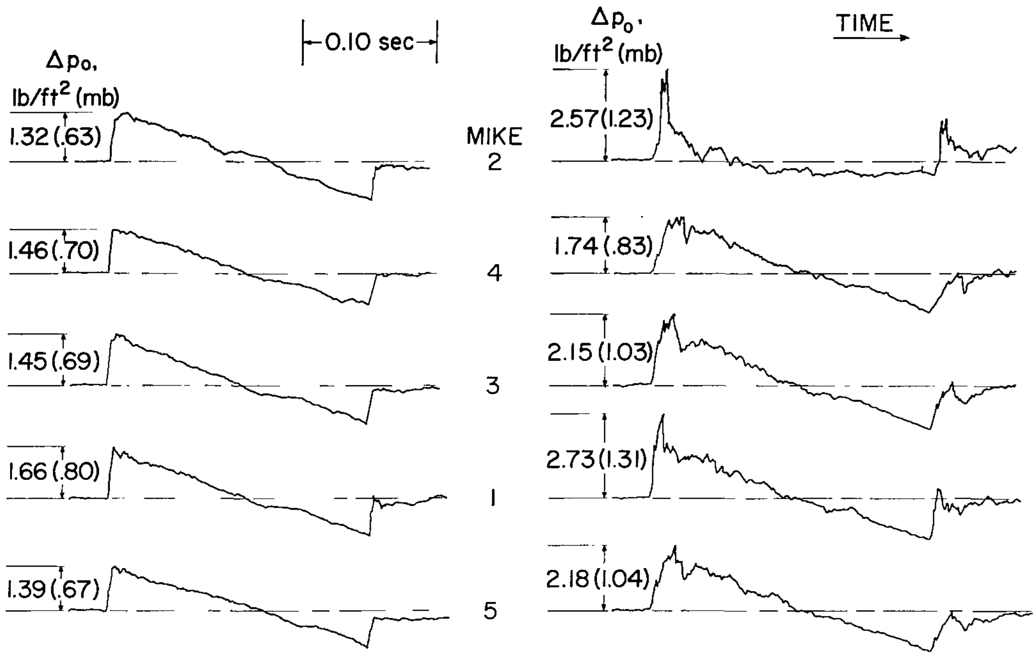
Figure 9.- A spectrum of atmospheric turbulence. (From ref. 11.)

5/3 power of the wave number. The shape of this curve tends to be relatively invariant, while the amplitude is a function of the severity of the turbulence. The curve shows the distribution of power in the various wavelengths and the area under the curve yields the total power. This same type of figure can also apply approximately near the ground with relatively less power in the longer wavelengths. From its spectral distribution, as indicated in figure 3, it may be noted that a sonic-boom pressure signature of 0.3-to-0.4-sec duration covers acoustic wavelengths that range from about 1000 m to fractions of a meter. Thus, the interaction of the pressure signature and the turbulence occurs over the entire spectrum shown and includes acoustic wavelengths less than and greater than the characteristic vortex sizes.

Sonic-Boom Pressure

Measured sonic-boom pressure signatures for two flights of the same airplane type are shown in figure 10. The pressure signatures on the right were obtained when surface winds were about 28 knots (14.4 m/sec) and rather gusty, and those on the left were obtained for much lower wind velocities. These signatures were obtained at one station by microphones separated by only 100 ft (30.48 m) in a cross arrangement. However, as indicated in reference 12, similar variations indicating wave-shape distortion on the one hand and lack of distortion on the other hand were measured over a 150-sq-mile (388.5 km^2) area during the same two flights.

Measurements have shown that in a stable atmosphere with little turbulence the classical N-wave signature tends to occur. Figure 11 shows the temperature profiles as measured at Edwards Air Force Base, California, during the early morning and during



(a) Low wind velocities.

(b) High wind velocities (gusty).

Figure 10.- Time histories of sonic-boom overpressure showing wave-shape variations between microphones for two flights of a B-58 airplane on different days. (From ref. 12.)

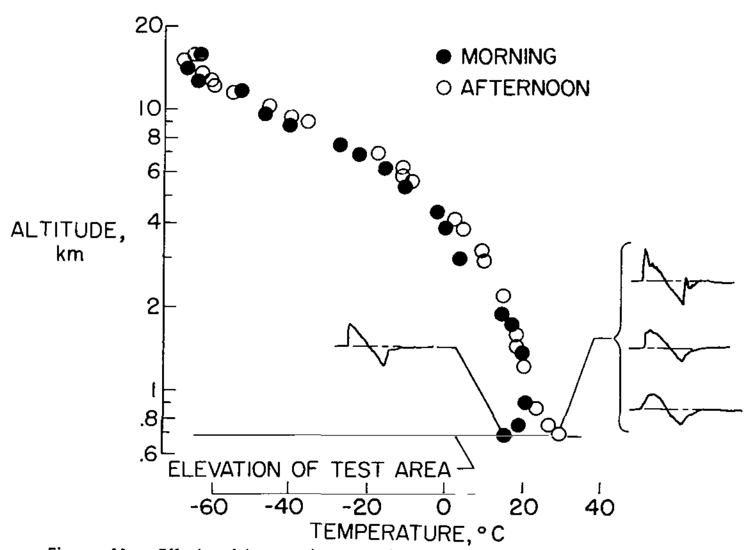


Figure 11.- Effects of temperature profiles including an inversion on measured sonic-boom pressure signatures. (From ref. 2.)

the afternoon, with the associated measured pressure signatures indicated. The morning inversion leads to a normal N-wave signature, whereas the afternoon convectivity associated with the heating of the lower atmosphere or temperature spottiness yields distorted N-wave signatures.

The lateral spread of the sonic-boom pressure variations is shown in figure 12. Refraction of the shock waves by the atmosphere results in a cut-off phenomenon indicated by vertical dashed lines in the figure. The trend from peaked to rounded signature with increasing lateral distance is indicated by the sketches. The ray path distances may be of the order of 20 to 50 miles (32 to 80 km). A discussion of the lateral spread phenomenon and associated measurements is given in reference 13.

Additional information on measured and calculated lateral spread of the pressure variations for the XB-70 airplane is presented in figure 13. Figure 13 shows a definite lateral cut-off distance; for a 37 000-ft (11.28 km) altitude the width is about 35 miles (56 km), and for a 60 000-ft (18.3 km) altitude it is about 60 miles (96 km). As indicated by the calculations, the measured pressures are generally a maximum along the track and decrease with an increase in lateral distance.

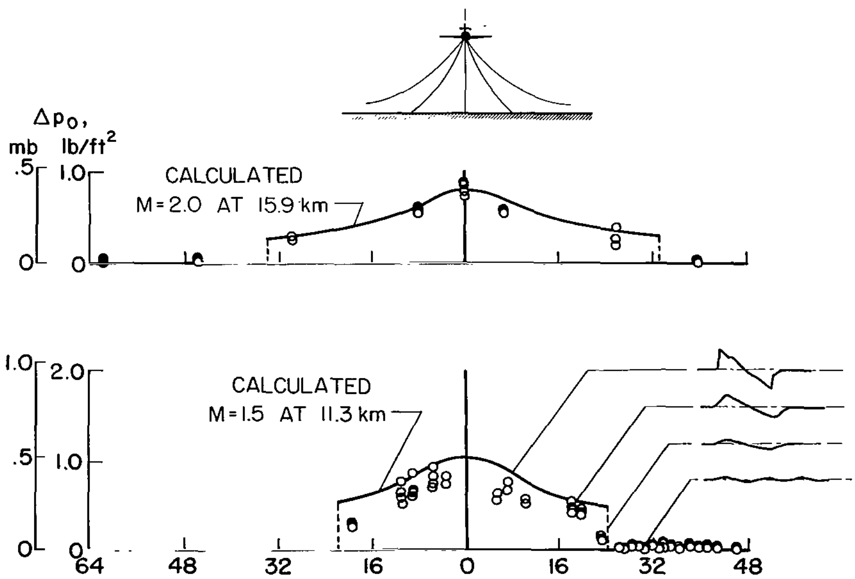


Figure 12.- Measured lateral spread patterns for a fighter airplane at two different altitudes. (From ref. 2.)

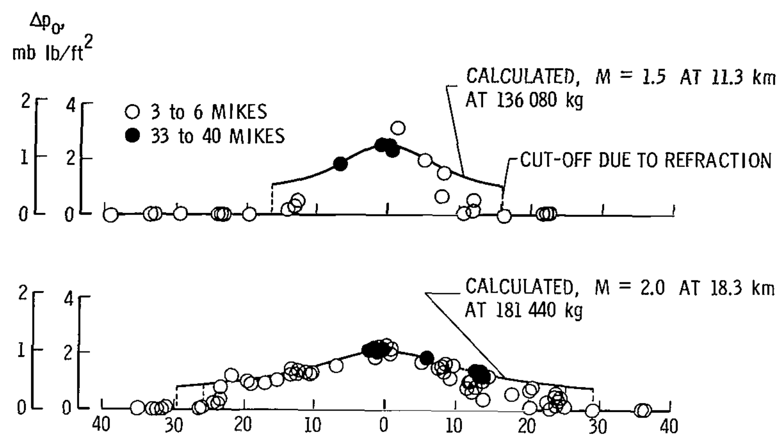


Figure 13.- Sonic-boom overpressures for the XB-70 airplane as a function of lateral distance for two different flight conditions. (From ref. 1.)

Statistics of Pressure Peaks

A number of flight programs during which routine measurement of sonic-boom signatures was made with carefully calibrated pressure instrumentation have been conducted and reported. The most extensive of these was a 6-month flight program at Oklahoma City (ref. 14). However, only fragmentary observations were made of associated weather conditions. The investigation demonstrated that wide variations in the signature types were associated with dynamics of the atmosphere; moreover, the distributions of pressure peaks appeared to follow approximately a log normal probability curve – that is, if the pressure peaks are plotted as log pressure or in decibels, an approximately Gaussian or normal distribution occurs. Also shown by this study was the result that the impulse also followed such a distribution law, although it has smaller variance or standard deviation. The approximate theory for scattering of sound (monochromatic waves) by turbulence also yields a normal distribution for the logarithm of the amplitude. (See ref. 4.) The theory indicates that given certain sufficient information about the structure of turbulence, a calculation of the variance cf the distribution of peaks for sonic booms may be feasible. Palmer (ref. 5) has already made some preliminary estimates in this regard.

Flight programs have been conducted in several geographical areas in the United States. Figure 14 is a composite of data obtained along the ground track for one type of airplane in operations in these several areas (ref. 12). The inset represents the histogram of the data. The temperatures ranged from 3^{o} to 95^{o} F (-16^{o} to 35^{o} C), with quiescent as well as turbulent conditions and calm and gusty winds. On this type of plot for the cumulative probability the $\pm\sigma$ conditions (where σ is the standard deviation) lie between probability values of 0.16 and 0.84, and this range would include more than 68.3 percent of the data; the $\pm 2\sigma$ conditions lie between probability values of 0.023 and 0.977, and this range would include 95.5 percent of the data. Figure 15, included for comparison, shows the similar distribution for the positive impulse and indicates smaller variance.

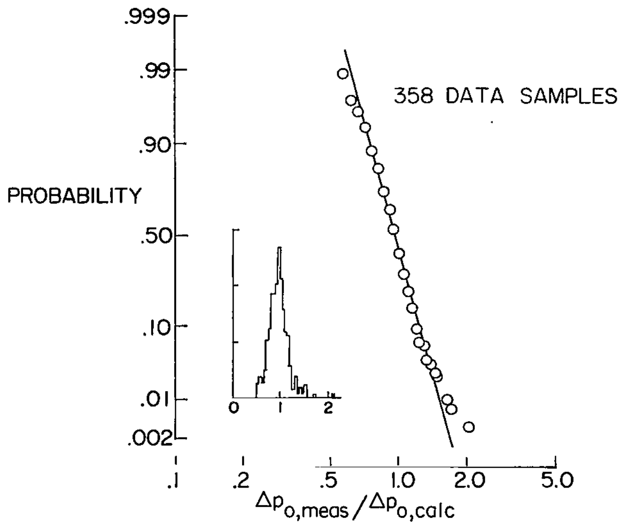


Figure 14.- Probability of exceeding a given value of the ratio of measured to calculated overpressures for a B-58 airplane as obtained during measurements in the areas of Chicago, Illinois; Edwards Air Force Base, California; St. Louis, Missouri; and Oklahoma City, Oklahoma. (From ref. 12.)

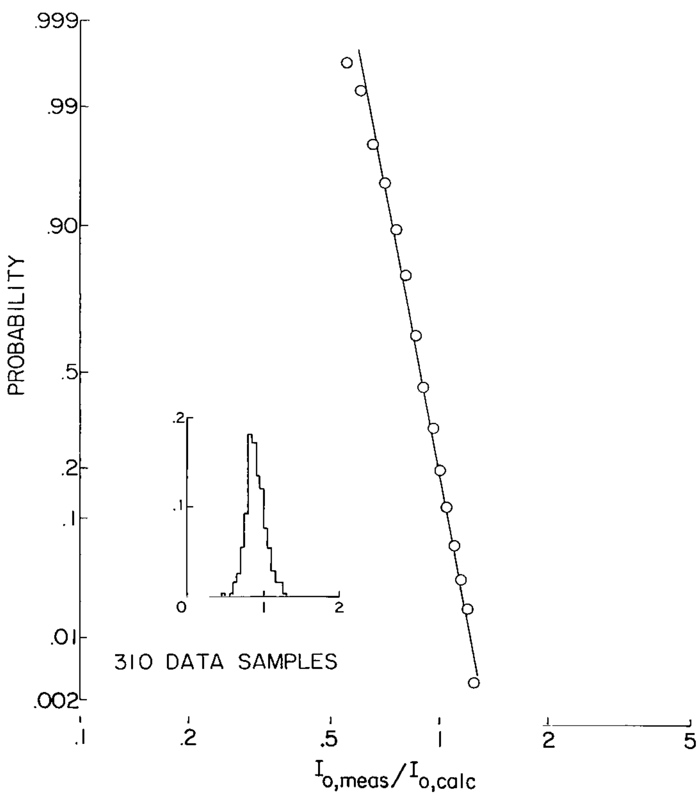


Figure 15.- Probability of exceeding a given value of the ratio of measured to calculated positive impulse for a B-58 airplane as obtained during measurements in the areas of Chicago, Illinois; Edwards Air Force Base, California; St. Louis, Missouri; and Oklahoma City, Oklahoma. (From ref. 12.)

The most recent of several flight programs was performed during 1966 and 1967 at Edwards Air Force Base, California, with several types of airplanes including the XB-70. Some preliminary data are given in reference 1; other data remain to be published. Some of the data taken with the XB-70 airplane are shown in figure 16; the data were obtained during the winter and during the summer. The winter data fall very closely on a normal distribution curve with small variance. The summer data are associated with greater convective activity in the atmosphere and only roughly follow a normal distribution.

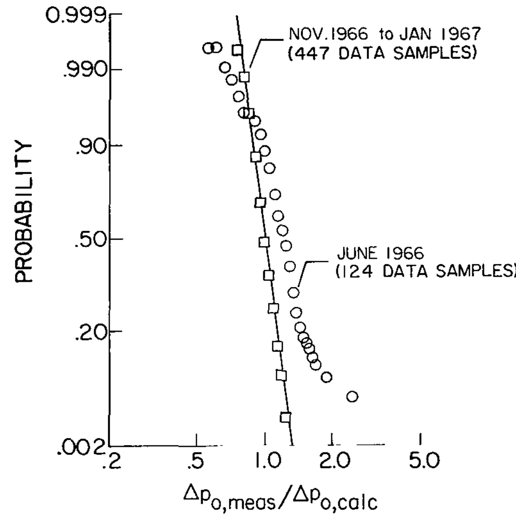


Figure 16.- Probability of exceeding given values of the ratios of measured to calculated ground overpressures for the XB-70 airplane for two different time periods. (From ref. 1.)

Table I provides a convenient summary of some of the results of several flight programs (refs. 12 to 15). Presented are the ratios of the mean values measured to the nominal values calculated. The ratios of the ranges of $\pm 1\sigma$ and $\pm 2\sigma$ relative to the mean of the pressure ratio are also given.

TABLE I.- STATISTICAL VARIATIONS OF SONIC-BOOM OVERPRESSURES

Test site	Time period	Range of –		Mean of $\frac{\Delta p_{o,meas}}{\Delta p_{o,calc}}$	Ratios relative to mean for range of –			Number data samples
		Mach no.	Altitude, km		$\pm 1\sigma$	$\pm 2\sigma$	$\pm 3\sigma$	
Oklahoma City 1	Feb. to Apr. 1964	1.3 to 2.0	6.4 to 12.5	[a]0.825	0.76 to 1.30	0.58 to 1.70	0.45 to 2.21	652
[b]3				[a]1.04	.73 to 1.37	.53 to 1.86	.39 to 2.55	654
[c]4				[a].96	.67 to 1.51	.45 to 2.23	.30 to 3.31	637
Oklahoma City 1	May to July 1964	1.2 to 1.6	8.5 to 14.0	[a].925	.75 to 1.34	.56 to 1.78	.42 to 2.37	549
[b]3				[a]1.20	.74 to 1.35	.56 to 1.92	.42 to 2.37	554
[c]4				[a]1.38	.68 to 1.49	.46 to 2.39	.31 to 3.23	548
Edwards AFB	Nov. 1966 to Jan. 1967	1.3	9.4	[d].855	.78 to 1.28	.61 to 1.64	.47 to 2.11	1378
Chicago	Jan. to Mar. 1965	1.2 to 1.66	11.6 to 14.6	[d].92	.77 to 1.29	.60 to 1.67	.46 to 2.15	191
Edwards AFB	Sept. to Oct. 1961	1.5 to 2.0	9.4 to 21.3	[d]1.035	.90 to 1.11	.81 to 1.23	.73 to 1.36	135
Combined (fig. 14)		1.2 to 2.0	9.4 to 21.3	[d].942	.82 to 1.24	.67 to 1.53	.54 to 1.87	358
Edwards AFB	Nov. 1966 to Jan. 1967	1.5 to 2.5	11.3 to 18.3	[d]1.00	.91 to 1.10	.82 to 1.22	.74 to 1.36	447
Edwards AFB	Nov. 1966 to Jan. 1967	3.0	21.3+	[d].98	.86 to 1.16	.74 to 1.34	.64 to 1.56	578

[a]Nominal overpressure calculated for isothermal atmosphere.
[b]5-mile offset from flight track.
[c]10-mile offset from flight track.
[d]Nominal overpressure calculated for standard atmosphere.

(These ratios may be regarded as corresponding to a chosen mean pressure ratio of unity.) The $\pm 3\sigma$ values as extrapolated are also presented and represent 99.7 percent of the data. This latter result is only suggestive and, as mentioned in reference 3, these extreme values may be conservative. The pressure measurements were made under the flight track, except where the lateral distance is noted. The largest variability in the ratio factors occurs at the farthest lateral distances and for the lowest supersonic Mach numbers where ray paths in the atmosphere are longest. However, the nominal calculated values are generally lower at the lateral positions because of the greater distances. The numerical factor of the mean overpressure for the $\pm 2\sigma$ range of ground-track data varies from a maximum of 1.78 (Oklahoma City data) to a minimum of 1.22 (Edwards winter data). It should be noted that the Edwards summer data in figure 16, not shown in the table, also yield a maximum factor of approximately 1.8. The data in the table cover a wide range of Mach numbers; in particular, data at $M = 3$ obtained at Edwards Air Force Base are included.

In conjunction with the XB-70 flights a number of accompanying flights of B-58 and F-104 airplanes were made. The Mach number and altitude ranges covered were from $M = 1.5$ to 2.5 and $h = 11.3$ to about 18 km for the XB-70 airplane, $M = 1.5$ to 1.65 and $h = 9.7$ to 12.2 km for the B-58 airplane, and $M = 1.3$ to 1.4 and $h = 5.2$ to 6.3 km for the F-104 airplane. The nominal calculated overpressure for all these airplanes was about 1 millibar. The data in figure 17 for the three airplanes were obtained in late morning flights from November 1966 to January 1967, when generally small turbulence and convectivity occurred. Despite the differences in airplane operating conditions and

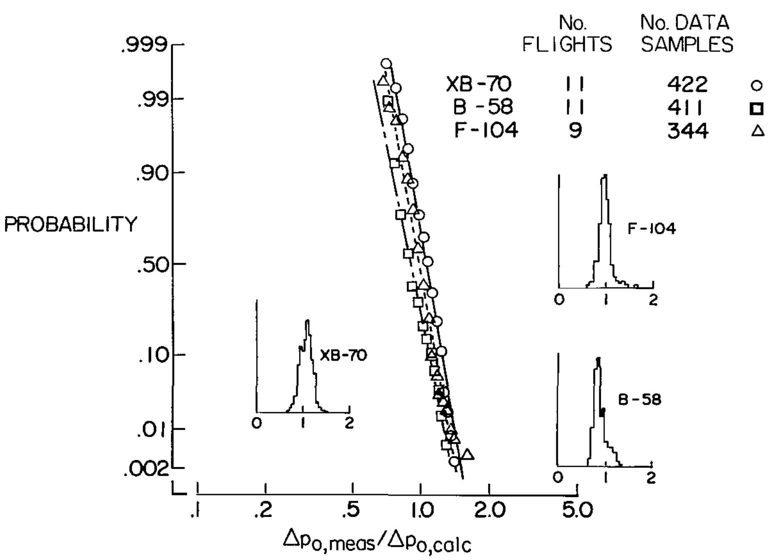


Figure 17.- Probability of exceeding a given value of the ratio of measured to calculated ground overpressures along flight track for XB-70, B-58, and F-104 airplanes. (Time intervals of flights of three airplanes varied from about 2 to 5 minutes.)

signature durations (fig. 8), a strikingly similar probability distribution pattern for the three airplanes appears.

Variations in Rise Time

Also of interest is the variation in bow-wave rise time τ (defined in fig. 1 and the sketch in fig. 18) since it has been suggested (ref. 2) that this quantity is important from a subjective reaction standpoint. The data of the histograms of the figure have been normalized on the horizontal scale to indicate the rise time per unit overpressure (the reciprocal of this ratio being an indication of the rate of onset of pressure). The data of figure 18 are for a B-58 airplane at an altitude of approximately 42 000 ft (12.8 km) and a Mach number of about 1.65 for measurement made along the flight track. These flight conditions result in a calculated nominal overpressure of 2.35 lb/ft^2 (1.13 mb). The two histograms of the figure relate to the same measured data but result from different interpretations of that data. With reference to the signature sketch in the figure, the solid-line histogram is based on the rise time to the largest overpressure and the dash-line histogram is based on the rise time associated with the first peak in the pressure signature even though it may not be the largest peak. This latter definition of rise time per

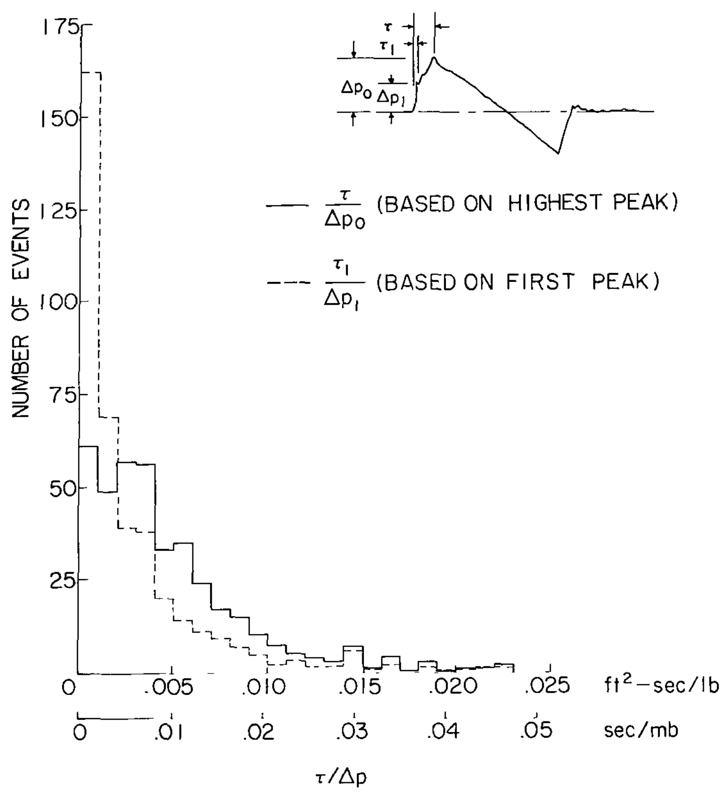


Figure 18.- Variations of bow-wave rise time per unit overpressure for the B-58 airplane at a Mach number of about 1.65 and an altitude of 42 000 feet (12.8 km). (From ref. 1, with corrections.)

unit pressure is a commonly accepted one. In either histogram considerable variations in rise times are encountered regardless of the manner in which rise time is defined. It should be noted that rise times of less than a millisecond are commonly encountered for the initial peak of the wave. Zepler and Harel in reference 16 conclude that the rise time has a very significant effect on loudness, and it would therefore follow that the statistics of the rise times of the pressure signatures is important.

Evaluation of Effects of Airplane Motion

Measurements of sonic-boom signatures on the ground may be affected by variations in the airplane operating conditions as well as by atmospheric conditions. An experiment was performed in an attempt to evaluate the effects on measured signatures of perturbations of the airplane about its nominal flight path. In order to accomplish this study the test setup of figure 19 was used. The airplane was flown at a given altitude and Mach number and on a given heading directly over and along a 6200-ft long (1.888 km) array of 40 microphones. The airplane which was specially instrumented to record its motions was flown both in steady level flight and in "porpoising" flight. All flights were accomplished at an altitude of 35 000 ft (10.65 km) and a Mach number of 1.5 with an F-106 airplane. For porpoising flight the pilot caused the airplane to deviate from the nominal flight track by cycling the controls to produce a $\pm 0.5g$ ($1g = 9.80665\ m/sec^2$) normal acceleration at the center of gravity of the airplane. These induced motions have

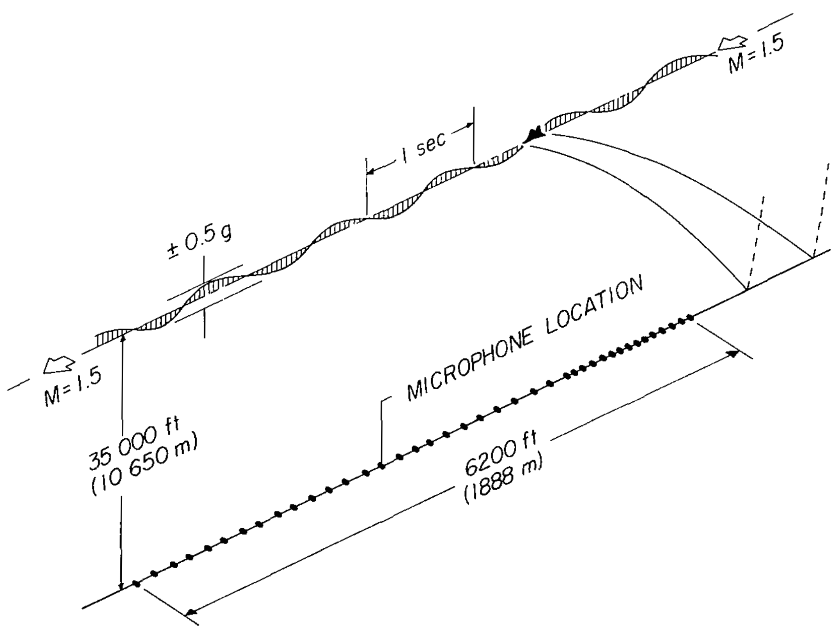


Figure 19.- Schematic diagram of test arrangements in the Edwards Air Force Base, California, area for evaluating the effects of airplane motions on sonic-boom pressure signatures at the ground. (From ref. 1.)

a period of about 1 second and thus the wavelengths of the motion were about 1600 ft (488 m) for these particular flight conditions.

Ground overpressure measurements for the two types of flights are shown in figure 20. The data for three steady flights and for four porpoising flights were obtained from individual microphones at various stations along the ground track, as indicated schematically in figure 19. Figure 20 indicates that approximately the same ranges of overpressure were measured for each of the flight conditions. Furthermore, an inspection of the data of figure 20 shows the occurrence of variations of the overpressures for both flight conditions. Such variations have been documented during this and other flight research programs (ref. 1). It is significant to note, however, that variations which occur during the steady flights have wavelengths that may vary considerably. Since it is believed that the porpoising flight condition might produce a variation of overpressure at a preferred wavelength on the ground, the data of all the flights were analyzed in such a manner as to accentuate this effect if it existed. These results are shown in figure 21.

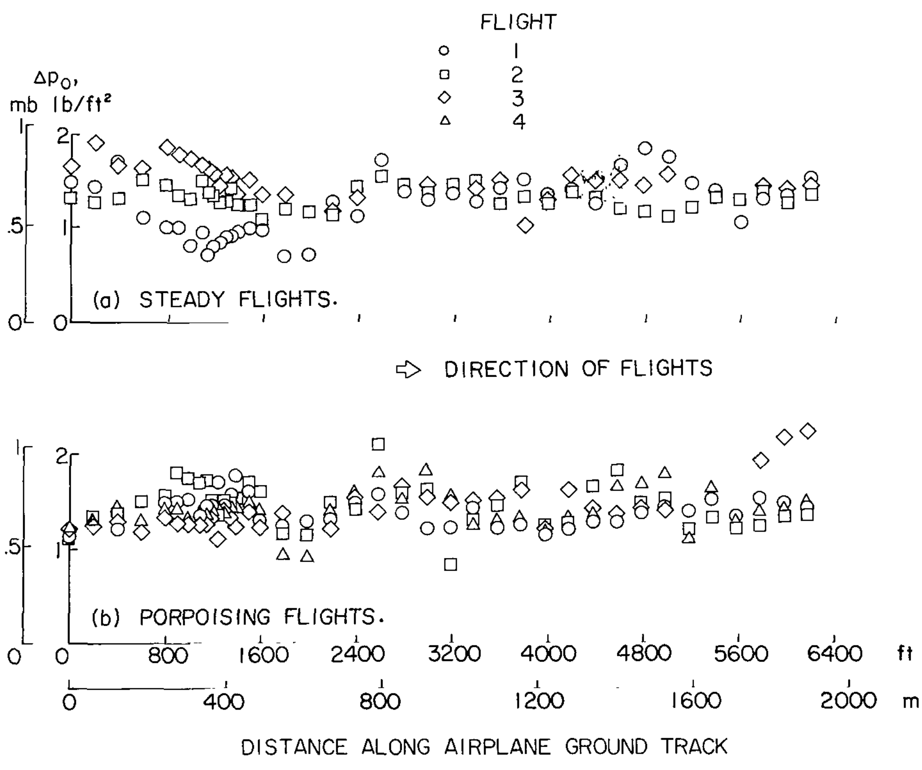
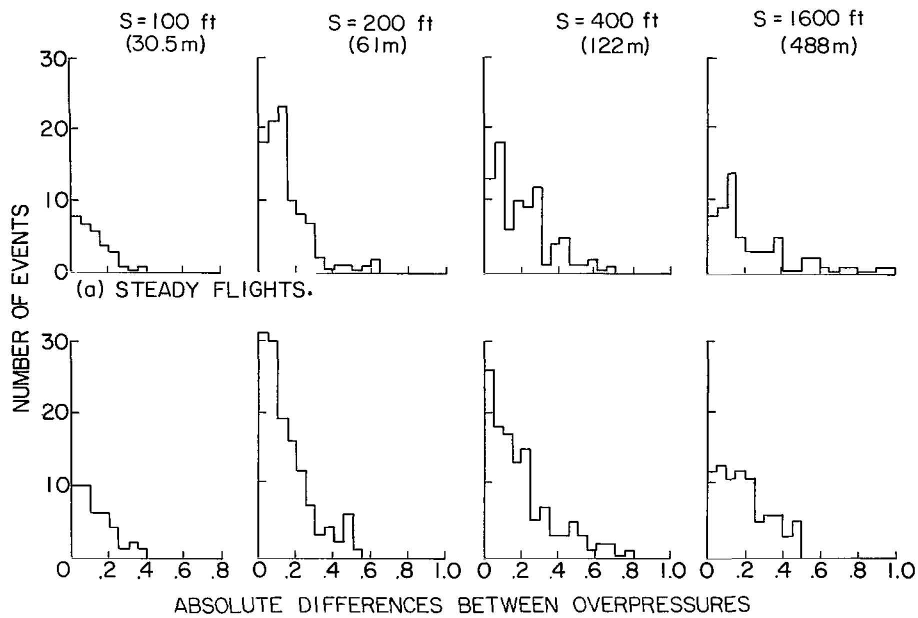


Figure 20.- Measured peak overpressures at several stations along the ground for both steady and porpoising flights of an F-106 airplane at an altitude of 35 000 feet (10 650 m) and a Mach number of 1.5. (From ref. 1.)



(b) PORPOISING FLIGHTS.

Figure 21.- Histograms of the absolute values of the differences between peak overpressures at points separated by distances from 100 to 1600 feet (30.5 to 488 m) for both steady and porpoising flights. (From ref. 1.)

The individual histograms of figure 21 represent variations in the absolute values of the differences in the overpressures measured at pairs of points which are separated by distances from 100 to 1600 ft (30.5 to 488 m). If the effects of the porpoising airplane motion show up in the data on the ground, it is reasonable to expect that smaller differences in overpressures would be obtained at some separation distances than at others. No conclusions regarding significant differences in trends for the steady and porpoising flight data may be drawn from this figure. However, a better definition of the trends of the variations shown in figure 21 may be obtained from figure 22.

In figure 22 the quantity $\sigma_{\Delta p_o}$, which is the root-mean-square overpressure difference, is plotted as a function of separation distance for the distances for which data are available. The curve of figure 22 seems to represent generally the variation of $\sigma_{\Delta p_o}$ with distance for both steady and porpoising flights. Both sets of data are seen to increase monotonically with separation distance. Such a result strongly suggests that perturbations about the flight track of the order of those illustrated in figure 19 do not show up in the data propagated to the ground from high altitude. It is thus believed that the variations discussed previously in this paper are due mainly to atmospheric effects and should not be attributed to effects of aircraft motion.

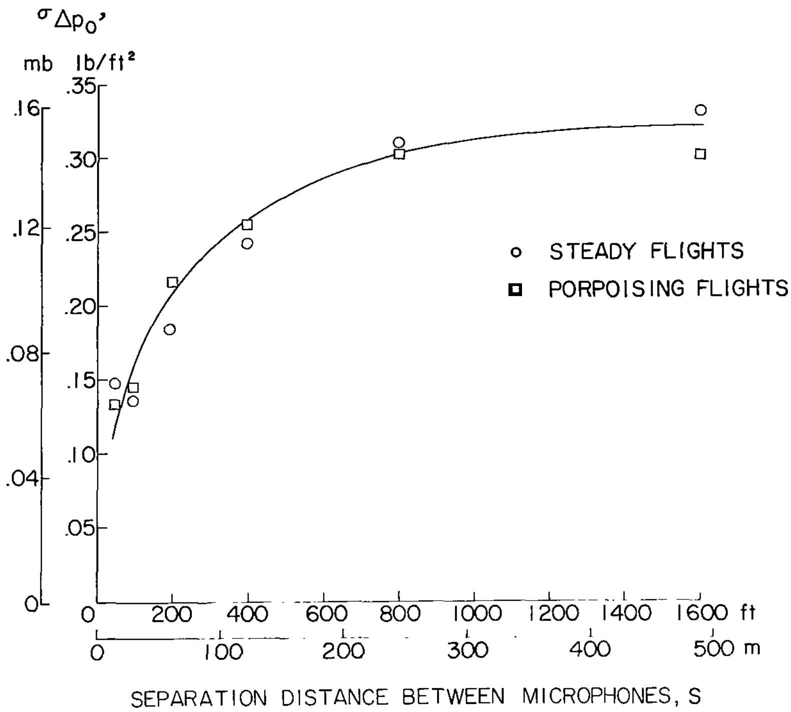


Figure 22.- Root-mean-square differences in overpressures as a function of separation distance for both steady and porpoising flights. (From ref. 1.)

Propagation Studies in the Lower Atmosphere

Several special studies have been made to try to identify atmospheric conditions particularly effective in modulating the pressure signatures. The flow field produced by an airplane for a number of flights at a Mach number of 1.5 at an altitude of 40 000 ft (12.2 km) was probed at an altitude of 2000 ft (610 m) by an instrumented blimp. The results of these studies are illustrated in figure 23 and indicate that the incident signature was undistorted, but both the ground signature and the reflected signature at the blimp showed distortion. From these studies, it appears that the 2000-ft (610 m) surface boundary layer was the effective agent. Previous studies have also suggested that turbulence in the lower layers of the atmosphere was most effective in signature distortion. On the other hand, other measurements with the blimp have indicated distortion of the incident wave; this indicates that higher altitude conditions were responsible for the distortion. It is known that patches of turbulence several thousand feet thick may occur throughout the troposphere. After passing through high altitude turbulence, the shock wave can still readily re-form its structure; whereas, near the ground the wave is generally weak and more readily scattered, and there is insufficient time to re-form.

An interesting tower experiment is indicated in figure 24. Incident and reflected waves were measured by microphones on the ground and on a 250-ft-high (76.2 m) tower. The generating airplanes were flown at an altitude of 40 000 ft (12.2 km) and at a Mach

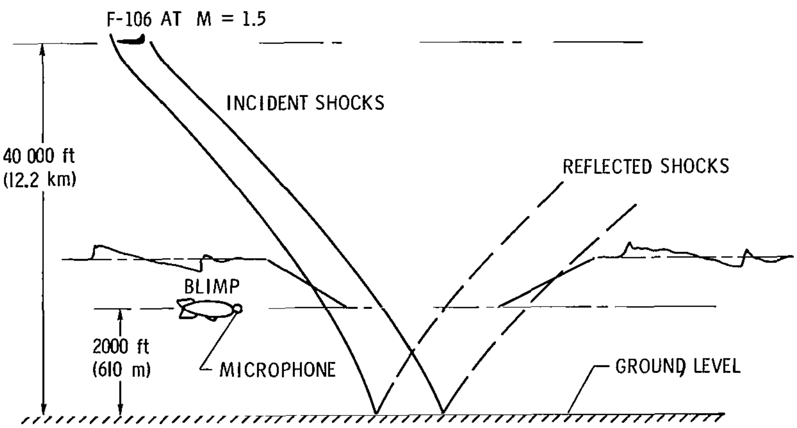


Figure 23.- Schematic diagram of test arrangements at Edwards, California, for evaluating atmospheric effects on sonic-boom wave propagation in the lower layer (2000-ft depth) of the atmosphere. Generating airplane was an F-106 at a 40 000-foot (12.2 km) altitude and a Mach number of 1.5. (From ref. 1.)

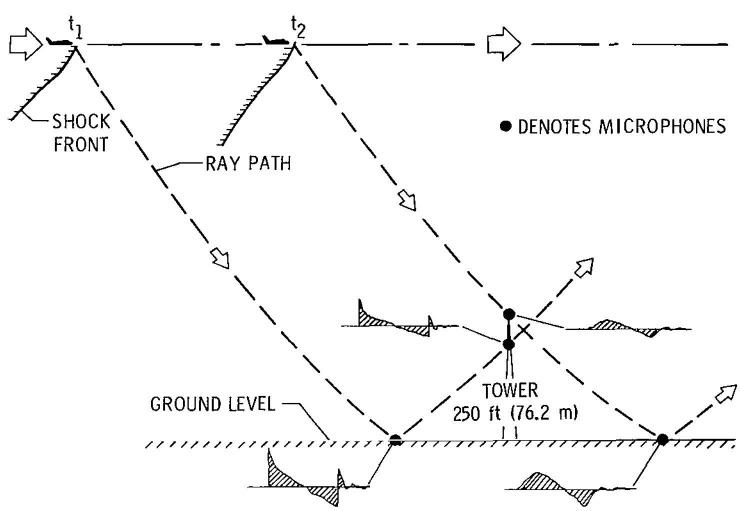


Figure 24.- Schematic diagram of test setup at the NASA Wallops Station, Virginia, for evaluating atmospheric effects on sonic-boom wave propagation in the surface layer (250-ft depth) of the atmosphere. Generating airplane was an F-106 at a 40 000-foot (12.2 km) altitude and a Mach number of 1.2. (From ref. 1.)

number of 1.2 for a variety of weather conditions. The objective of the studies was to correlate the sonic-boom measurements with meteorological data obtained on the instrumented tower. When wave-form distortion existed, similar wave shapes occurred at the ground surface and at the tower for both incident and reflected waves. Thus, the same signature distortion occurred along a given ray path from the airplane, and in these studies the atmosphere below 250 ft (76.2 m) was not significantly modifying the distortion.

In one of the recent studies with the F-104 airplane, an 8000-ft horizontal (2.44 km) range instrumented with many microphones was employed. The pressures were measured at about 40 stations along the range. Figure 25 shows some results for the overpressures, which indicate a remarkable wavelike pattern. Apparently long waves in the atmosphere of the order of 10^3 meters are influencing the pattern of the results. Experimental results suggest that this is a moving pattern and that the approximate Gaussian distribution pattern for the overpressures would exist at each station. A gradual change along the range from peaked to rounded signature is apparent. The measured positive impulse also shows a wavelike pattern, but considerably reduced in variance.

The mechanism of the apparent embedding of the local pattern of turbulence within a systematic larger pattern is not understood. It is of interest to examine the spectra of two signatures, one having a peaked and the other a rounded wave shape as indicated in figures 25 and 26. The stations for these measured signatures were 600 ft (183 m) apart. Shown in figure 26 are the calculated amplitude-squared, or energy, spectra of the signatures. Phase plots were also obtained but are not reproduced herein. Only relatively small changes occur in the envelopes of the amplitudes, despite the large change in signatures. As indicated previously in the discussion of figures 4 and 5, differences between peaked and rounded signatures may be reflected in the presence or absence of high frequencies in the associated spectra. For the wave shapes and spectra of figure 26, the higher frequencies are apparent for both signatures; but calculations of the relative phases showed that the lower frequencies of the spectra appear well correlated and coherent, whereas for the higher frequencies the relative phases of the two waves tend to become random. The general theory of sound scattering also indicates reduced

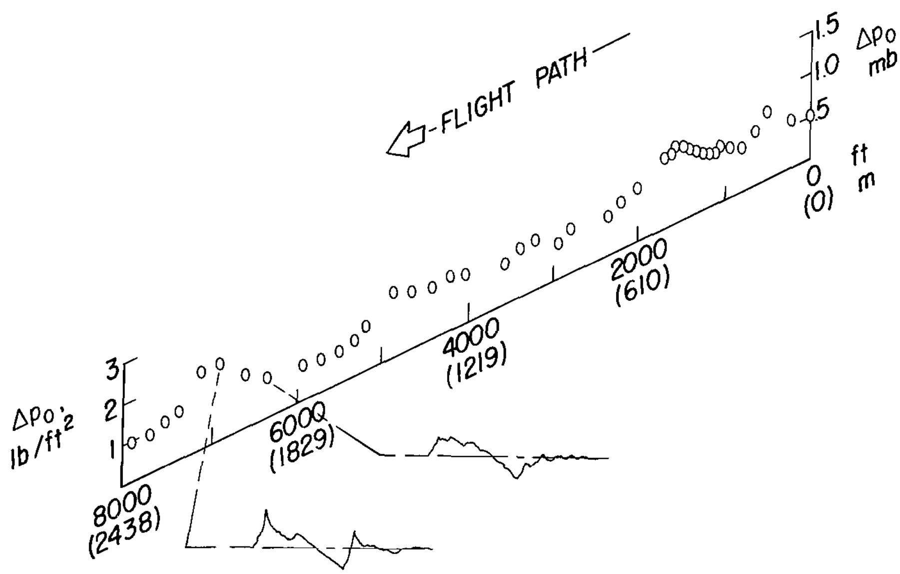


Figure 25.- Overpressure as a function of distance on the ground track for an F-104 airplane in steady flight at a Mach number of 1.3 and an altitude of 30 500 feet (9.340 km), and sample signatures.

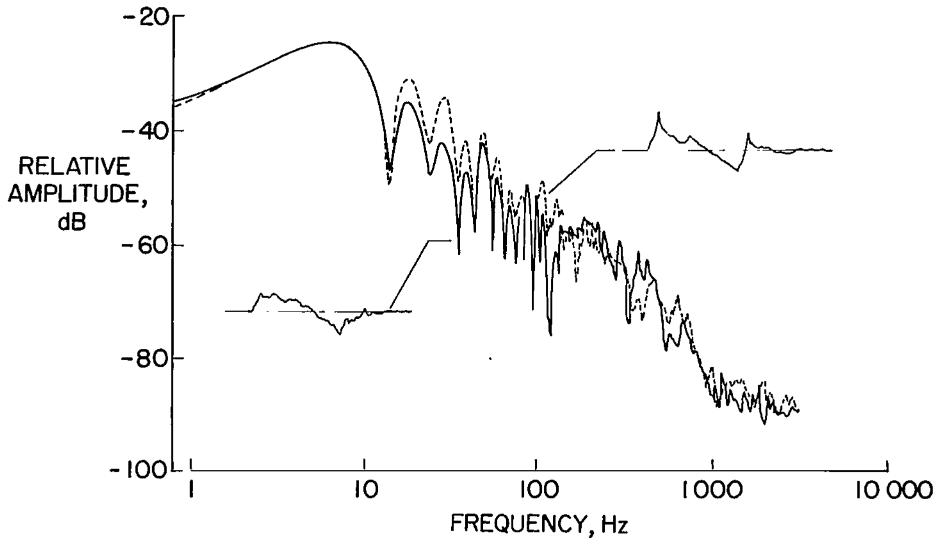


Figure 26.- Energy spectra for the two different shapes of sonic-boom pressure signatures in figure 25. Relative amplitude is given by $10 \log_{10}|f(\omega)|^2$ dB.

coherence of sound waves and increased fluctuations in phase with increase in frequency. Thus, it is suggested that the turbulence scattering leads to a phase scrambling process taking place for the higher frequencies.

CONCLUDING REMARKS

A review has been presented of information obtained in recent years about atmospheric effects on the sonic boom and, in particular, has included some results of various flight programs. These atmospheric effects are complex, and a statistical approach appears necessary. The statistics of peak pressures follows approximately a log normal distribution, a result that is indicated by existing theory for pure (sinusoidal) sound. A tabular summary of the flight data gives the standard deviations of pressure peaks relative to nominal calculated values of the mean. Information is included on observed variations of sonic-boom signatures for different types and sizes of airplanes. Measurements indicate that wavelike spatial patterns exist in which peaked and rounded waves may alternate and vary with time. Such variations are shown to be induced by the atmosphere rather than by effects of airplane unsteady motion. The spectral content of some ideal and some measured pressure signatures is exhibited and discussed with reference to peakedness or roundness of the wave.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., February 16, 1968,
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