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APPENDIX C

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NASA REPORT: "AUDIBILITY OF THE CENTER FUEL TANK EXPLOSION OF TWA FLIGHT 800"

(51 pages)

Audibility of the Center Fuel Tank Explosion of TWA Flight 800

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Summary

The disturbance signal generated by the explosion of the center fuel tank of TWA Flight 800 was predicted for 40 observer locations, by the Thomas program. These 40 observers account for 60 of the 83 observers provided by the NTSB. For three of these predictions the audibility of the signal was also predicted. It was determined that the predicted signal was audible for all three locations. Since the three signals for which an audibility analysis was carried out include the signal with the lowest amplitude it may be safely assumed that the signal was audible at all of the locations for which a signal was predicted.

Of the remaining observer positions provided by the NTSB, 17 fell into the shadow region, hence no signal could be predicted for these locations. The ray trace program failed to converge for 2 of the remaining 6 observer locations. The last 4 observer locations were deemed too far away from the source for a ray trace to be successful. Hence no predictions were made for these locations. However, there is no reason to suspect that there was no signal at these locations, nor that such signal was inaudible.

An alternate method of prediction was provided by ANSI Standard S2.20-1983. This method predicted peak pressure levels and positive durations in good agreement with those obtained by use of the Thomas program. Further the ANSI standard predicts that the signal at the observers for which the Thomas program could not provide a prediction are similar in magnitude to the pressure at the position that had the lowest amplitude predicted by the Thomas program. Thus it may be concluded that the disturbance was audible at these locations also.

Overview

There are three components to most acoustic predictions. First, a determination of the source; second, the path analysis, or propagation analysis; third, the receiver analysis. The source analysis determines the pressure level and time variation of the signal at the source of the disturbance. The path or propagation analysis determines the changes in the signal as it travels from the source to the receiver. The receiver analysis determines whether or not a person could have heard the disturbance, and, perhaps, whether or not the person would have found the disturbance acceptable or annoying.

The prediction of the audibility of the blast wave produced by the explosion of the center wing tank of TWA Flight 800 is also accomplished in these three stages. First, a prediction of the blast wave signature in a region of space near the explosion is made using the theory of Harold L. Brode.[1] This is the source analysis. The signature of the source is predicted at a distance from the center of the explosion sufficient to allow the application of weak shock theory[2] to transform the predicted source signature to the predicted ground signature. This is the second stage, the propagation, or path, analysis. The propagation analysis is followed by a receiver analysis. This stage of the analysis addresses the problem of determining whether or not a person can actually hear the disturbance that the analysis has predicted will be present at the observer location. In the following, each of these stages in the prediction process will be considered in turn. The discussion of both the source prediction method, and the receiver, or audibility analysis is relatively short and straightforward. The bulk of the following discussion addresses the propagation analysis since this is where the major difficulty of the prediction process occurs.

Source

The effect of an explosion is to force most of the air within a spherical region of radius R(t) into a thin shell immediately behind a shock front, also of radius R(t), and expanding at speed $V_r = \frac{dR}{dt}$ in the radial direction. Thus, the disturbance pressure, as seen by a stationary observer, increases dramatically as the shock front and the thin shell of compressed air immediately behind it starts to pass over the observer location. This dramatic increase in pressure is followed by a short time interval during which the pressure

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[1] "Numerical Solutions of Spherical Blast Waves", Harold L. Brode, Journal of Applied Physics, V. 26 #6, June 1955.

[2] "Extrapolation of Sonic Boom Pressure Signatures by the Wave form Parameter Method", Charles L. Thomas, NASA TN D-6832, June 1972.

drops from its peak value to a level below the ambient pressure, and a long time interval over which the pressure slowly returns to the ambient level, see Figure 1. One major difficulty in predicting the disturbance pressure signature on the ground is due to the large overpressure in the initial stage of the disturbance.

Most propagation analysis assumes infinitesimal pressure disturbances. This assumption allows linearization of the governing equations.[3] That is, most propagation analysis is based on equations obtained from the full governing equations by neglecting all terms that contain products of the unknown quantities. This simplifies the analysis considerably. However, this assumption is not valid for the explosion problem.

A propagation model that can be applied to the explosion problem is weak shock theory.[4] In this theory, second order products of the unknown quantities are maintained in the governing equations, although higher order products are neglected. Thus, this theory is valid for disturbances whose peak overpressure is less than one tenth of the ambient atmospheric pressure, or those which, though initially having peak overpressures slightly greater than one tenth ambient, are such that these high pressures rapidly decay to less than one tenth ambient. This is the theory used in the current analysis to transfer the source signature to the ground.

The disturbance pressure near the explosion is considerably greater than one tenth of the ambient pressure. Therefore, a model of the explosion is required that predicts the wave form at a distance from the explosion center sufficient to preclude disturbance pressures greater than one tenth of local atmospheric pressure. Just such a model is provided by the theory of reference 1. In reference 1, H. L. Brode presents the results of the numerical integration of the equations governing a spherically symmetric blast wave field. He also provides an empirical fit of the numerical data that allows the prediction of a blast wave disturbance field based upon two parameters, the ambient pressure, and the energy contained within the initial blast wave. It is assumed that the blast wave is expanding into a uniform, homogeneous, stationary medium. The explosion of Flight 800's fuel tank occurred in a nonuniform medium, and a slightly sheared flow profile. A slight generalization, allowing Brode's theory to be applied to a medium moving with a constant uniform velocity is possible through use of a

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[3] For basic acoustic theory see "Fundamentals of Acoustics", 2nd Ed., Lawrence E. Kinsler, and Austin R. Frey, John Wiley & sons, 1962.

[4] "Linear and Nonlinear Waves", G. B. Whitham, John Wiley and Sons, New York, 1974. Chapter 9, *The Propagation of Weak Shocks*, pp. 312-338. This book contains what is probably the best introduction to nonlinear propagation and weak shock theory currently available.

Lorentz transformation.[5] Even with this generalization, Brode's theory is not strictly applicable to the current problem. However, the blast wave predicted by the theory, for the ambient pressure and the energy level applicable to the current problem, reaches a peak overpressure of one tenth ambient in a propagation distance of less than 80 feet. At the altitude of the explosion the ambient pressure gradient is approximately $3.6\text{x}10^{-4}$ psi/ft., and the wind speed gradient is approximately $3.2\text{x}10^{-3}$ sec^{-1}. These gradients are sufficiently small that the error introduced by neglecting them are negligible over the propagation distance of 80 feet, and Brode's theory may be applied.

The ambient pressure at the altitude of Flight 800 at the time of the explosion is taken to be 8.6 psi. The energy of the explosion is taken as $2.9\text{x}10^{7}$ Ft-LB_f. This is equivalent to approximately 20 pounds of TNT. The calculation of this energy level is presented in Appendix A. Given these values the predicted wave form is as presented in Figure 2. This wave form occurs at approximately 80 feet from the explosion center, and is used as the input to weak shock theory, which is then applied to determine the pressure disturbance on the ground.

Propagation

The propagation is complicated by two factors; first, meteorology, and second, nonlinearity. Consider the meteorological factor. The atmosphere is in motion, and that motion, given as a wind velocity, varies in both magnitude and direction with altitude. Also, the temperature varies with altitude. It is the sound speed variation, not the temperature variation itself, that affects the propagation, but the sound speed is directly proportional to the square root of the absolute temperature. This is why temperature variation affects the propagation. The temperature effects are somewhat simpler than the wind effects, and will be discussed first. A short discussion of nonlinearity will be undertaken after completing the discussion of the meteorological factor. A third factor, neglected in the current study, is the effect of atmospheric turbulence on the received signal. Turbulence can increase or decrease the amplitude of the disturbance.[6] These excursions from the mean amplitude predicted by the analysis of this study occur randomly, with higher amplitudes as likely as lower amplitudes. Further, it is highly improbable that the

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[5] "Theoretical Acoustics," Philip M. Morse, and K. Uno Ingard, McGraw Hill, New York, 1968; pp. 721-726.

[6] "Sonic Boom Research," NASA SP-147, A. R. Seebass, Ed., April 1967, pp. 25-48, *Sonic Boom Flight Research - Some effects of Airplane Operations and the Atmosphere on Sonic Boom Signatures*, Domenic Maglieri; pp. 49-64, *Some effects of the Atmosphere on Sonic Boom*, Edward J. Kane.

effects of turbulence could change the conclusions arrived at in this report.

If the signal given in Figure 2 were to propagate through a homogeneous stationary medium to the ground according to linear theory, the signal received at the ground would be exactly the same as the source signal, except that the signal at the ground would be of lower amplitude. The amplitude at the ground would be decreased by the factor $\frac{r_0}{r}$, where r is the distance the signal has propagated, and r_0 is the distance from the point where the source amplitude is given to the actual source location, in the present case approximately 80 feet. This follows from four facts. First, acoustic propagation, that is linear propagation, essentially translates the given signal along the propagation path unchanged. That this must be so for most audible signals can be seen by noting that if the signal were to change significantly as it propagated oral communication would not be possible. Second, the propagation is along straight lines. Third, the energy of the disturbance is conserved, and that energy is being spread over a larger area as the signal propagates away from the source. In fact, in this simple example, the disturbance energy is evenly distributed over the area of the surface of a sphere of radius r, hence this area is proportional to r^2. Fourth, and finally, in a stationary homogeneous medium, the energy flux (The energy passing a given point per unit area, per unit time.) at a point in an acoustic disturbance field, subject to certain conditions that need not be discussed here, is proportional to p^2, where p is the disturbance pressure. Since energy is conserved, and the energy is spread over a larger area as r increases, the equation

$$r^2p^2 = p_0^2 r_0^2$$

where p_0 and r_0 are the pressure and distance at an initial point on the propagation path, must hold. Thus we obtain

$$p = \frac{p_0 r_0}{r}$$

and the signal is the same at the ground as at the source, although diminished in amplitude by the factor $\frac{r_0}{r}$. Thus, if the linear theory were valid, and the medium through which the blast wave from the explosion of the center wing tank of Flight 800 propagated were stationary and homogeneous, the pressure disturbance at each of the observers would be exactly the same as that given in Figure 2, multiplied by the factor $\frac{80.0}{r}$, where r is the distance from the position of Flight 800 at the time of the explosion, to any given observer, this distance given in feet.

However, as mentioned previously, the medium through which the disturbance is propagating is neither homogeneous, nor stationary. When a temperature gradient exists within a medium the sound speed varies with position. When the sound speed varies with position the sound no longer travels along straight lines. The first, and the easiest affect on the disturbance field to determine is the change in where the disturbance signal will go. A more important, yet more subtle, effect is a change in amplitude.

In order to understand this second affect, consider again the $\frac{1}{r}$ drop in pressure associated with spherical spreading losses in a homogeneous medium. The justification for this dependence on the pressure with propagation distance depended on the argument that the area of the sphere at any given radius r was proportional to r^2. Although this is true, the argument implies that the pressure at any given point in the medium depends on the behavior of the field over a large sphere through that point. Fundamentally, the field at a given point should depend only on more local factors. In fact one should be able to argue that the only global factor that can affect the field at a point is the path the disturbance has traversed, and that, beyond this, only local features of the medium and the field should be required. Consider a sphere at the source location, that is for the explosion of Flight 800's fuel tank, a sphere of radius 80 ft, centered on the position of the center of the fuel tank at the time of the explosion. On that sphere draw a circle with a small radius, for example, a radius of 1 inch, centered on the line connecting the center of the fuel tank with the observer for which we are attempting to calculate the disturbance field. Then draw a line from the source position through each point on the circle to the ground. What has been constructed is a cone shaped structure, with its apex at the source position, and its large end on the ground. This is a ray tube. By definition, the energy travels along the rays. Since our ray tube has its walls made of rays, no energy leaves the ray tube through its walls. Hence, all the energy injected at the apex of the ray tube must travel down the ray tube.[7]

The ray tube concept allows us to eliminate the large sphere from our discussion of the spherical spreading losses. We now consider a central ray passing from the source to the receiver, and a bundle of rays around the central ray. This is our ray tube. Now, for propagation in a stationary homogeneous medium, the rays are all straight lines, the ray tube area increases as r^2, and the disturbance pressure decreases as r^{-1}. However, if the medium is not homogeneous, the ray is no longer a straight line. The ray tube area now depends on the shape of each of the rays making up the ray tube walls. This is the subtle way that temperature variation

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[7] An elementary discussion of rays, ray tubes, and energy flux is given in "Studies in Mathematics, Volume XV, Calculus and Science," by Victor Twersky, SMSG, 1967, pp. 69-73.

affects the disturbance amplitude. There is one more way the temperature variation can affect the amplitude of the wave form. The energy flux at a point in the medium is actually related to the product p*u, where p is the disturbance pressure, and u is the velocity of the medium induced by the disturbance. Generally, again subject to conditions which need not be considered here, $p = \rho cu$, where ρ is the local ambient density of the medium, and c is the local sound speed of the medium. Hence we have

$p*u = \frac{p^2}{\rho c}$. It was stated earlier that the energy flux was proportional to p^2. In a homogeneous medium ρc is a constant. Thus the previous statement is true. However in an inhomogeneous medium there is the, so called, ρc correction. This correction is required for the reason given here. It is accounted for in the weak shock theory code used for the current study. There are two further corrections included in the code. Again they are factors which are multiplied by the source signal to obtain the signal at the ground. In all cases one of these factors was $1 - \varepsilon_1$ and the other $1 + \varepsilon_2$ where ε_1 and ε_2 are positive numbers very near zero. Hence the effect of these factors is negligible and they are not discussed here.

The variation in sound speed bends the rays in a way that is reasonably easy to calculate. Consider, for example, a disturbance propagating in a homogeneous, stationary medium within which the sound speed is c, and incident upon another stationary, homogeneous medium within which the sound speed is a. The situation under discussion is illustrated in Figure 3.

Let the ray in medium 1 make an angle θ with the normal to the interface separating the two media, and let the ray in medium 2 make an angle β with the normal to that interface. Then, by Snell's law, the equation relating β to θ is[8]:

$$\frac{\sin(\theta)}{\sin(\beta)} = \frac{c}{a}$$

or, solving for the unknown angle in medium 2:

$$\sin(\beta) = \frac{a \sin(\theta)}{c}$$

This equation may be used to determine the "ray path" through a temperature stratified medium. It is important to note that, although two different numbers have been used to designate the rays in medium 1 and medium 2, in actuality, there is only a single ray. One may consider two segments of the ray, that in medium 1, and that in medium 2, but there is

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[8] "Fundamentals of Acoustics", 2nd Ed., Lawrence E. Kinsler, and Austin R. Frey, John Wiley & sons, 1962, p. 143.

only a single ray. Also note that if the sound speed is the same in both regions, that is: a = c, we obtain

$$\sin(\beta) = \sin(\theta)$$

and may conclude that in a medium with a uniform sound speed the rays are straight lines.

Now, if $a > c$, that is the sound speed is greater in the second medium than in the first, $\sin(\beta) > \sin(\theta)$, hence $\beta > \theta$, (Note that both θ and β are between 0 and 90 degrees, inclusive.) and the ray has been bent toward the interface in passing from medium 1 to medium 2. Thus, if the sound speed were to decrease with altitude, that is if the temperature is lower at the flight altitude than it is on the ground, the rays will be bent away from the ground. On the other hand, if the temperature is lower on the ground than at the flight altitude, the rays will be bent toward the ground.

Rewriting the above equation in the form

$$\sin(\theta) = \frac{c \sin(\beta)}{a}$$

and letting $\sin(\beta) = 1$, that is, $\beta = 90$ degrees, which implies that the ray is parallel to the interface in medium 2, the equation

$$\sin(\theta) = \frac{c}{a}$$

is obtained. Now, for $0 \le \theta \le 90$ degrees, $0 \le \sin(\theta) \le 1$, hence the ray can become parallel to the interface in region 2 only if $a > c$, that is when the sound speed in the second medium is greater than the sound speed in the first. Since the sound speed increases with the temperature this phenomena can occur only if the temperature is higher in medium 2 than it is in medium 1. The angle of the ray in medium 1, at which the ray is parallel to the interface in medium 2, is

$$\theta_c = \mathrm{Sin}^{-1}(\frac{c}{a})$$

This angle is called the critical angle. This phenomena is of importance because, if the temperature is greater at the ground than at the flight altitude, then, for a spherical source, such as the explosion, there will be a set of rays that graze the ground. Any member of this set is called a shadow forming ray because no disturbance energy can propagate to points on the ground beyond the shadow boundary, at least in the ray theory. There are mechanisms that act to allow acoustic energy to enter the shadow region. These are not discussed here. The shadow boundary is the locus of points at which the shadow forming rays graze the ground. For a stationary, temperature stratified medium the shadow boundary will be a circle centered at the point on the ground directly below the source. Hence a single calculation of the location of the intersection of a shadow forming ray and the ground serves to provide the radius of the circle that separates the shadow region from the region within which a signal will be received. For the atmosphere given in the Meteorological Factual Report[9], this shadow boundary lies about 20 Miles from the location of the source. Therefore, a signal will reach observers within a circle centered on the ground directly below the source position, and with a radius of 20 miles. The shadow boundary for this case is presented, along with the observer positions, in Figure 4. Figure 4 clearly shows that only two observers lie within the shadow region. The prediction with the wind included considerably alters the picture, hence discussion of the effects of the wind will now be taken up.

In order to determine the effect of wind on the disturbance field consider a disturbance propagating in a homogeneous medium moving with uniform speed U in the positive x-direction, incident upon an interface separating medium 1 from a second homogeneous medium, also moving in the positive x-direction, but with speed V. As in the previous analysis the sound speed in medium 1 is c, that in medium 2 is a. The situation is illustrated in Figure 5.

Again the angle between the ray and the normal to the interface is θ in region 1, and β in region 2. The equation relating β to θ is[10]:

$$\frac{c}{\sin(\theta)} + U = \frac{a}{\sin(\beta)} + V$$

which reduces to the equation for stationary media when $U = V = 0$, as it should. Placing all known quantities on the right-hand-side gives

$$\sin(\beta) = \frac{a \sin(\theta)}{c + (U - V)\sin(\theta)}$$

Thus, it can be seen that the wind also bends the rays. Note, in fact, that the effect of the wind is to augment the sound speed in the second region by the amount $(U - V)\sin(\theta)$. This augmentation is positive in two cases. First, if $\sin(\theta)$ is greater than zero, i.e., the disturbance is propagating with the wind, and U is greater than V, that is the flow speed is greater in region 1 than in region 2. Second, if $\sin(\theta)$ is less than zero, i.e., the disturbance is propagating against the wind, and U is less than V, that is the flow speed is less in region 1 than in region 2. In these cases the ray bending due to the wind is similar to the ray bending caused by an increase in sound speed in the propagation direction.

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[9] Meteorological Factual Report, [DCA96MA070], pp. 3-4

[10] "Theoretical Acoustics," Philip M. Morse, and K. Uno Ingard, McGraw Hill, New York, 1968; pp. 708-710.

And, this augmentation is negative in two cases. First, if $\sin(\theta)$ is less than zero, i.e., the disturbance is propagating against the wind, and U is greater than V, that is the flow speed is greater in region 1 than in region 2. Second, if $\sin(\theta)$ is greater than zero, i.e., the disturbance is propagating with the wind, and U is less than V, that is the flow speed is less in region 1 than in region 2. In these cases the ray bending due to the wind is similar to the ray bending caused by an decrease in sound speed in the propagation direction.

Hence, the bending of the rays, by the wind itself, is in a different direction when the disturbance is propagating with the wind than it is if the disturbance is propagating against the wind. Another way to see this is to note that if the medium were to be moving in the negative x direction in both regions the above equation would become:

$$\sin(\beta) = \frac{a \sin(\theta)}{c - (|U| - |V|)\sin(\theta)}$$

where $|U|$ and $|V|$ represent the magnitude of the wind velocity in regions 1 and 2 respectively. Note that U and V are taken as positive in the previous equation. Therefore, the symmetry present in the temperature stratified medium is lost in a wind stratified medium.

The wind in a real atmosphere varies in both speed and direction with altitude. Thus the analysis is slightly more complex than that described here for the simple case where the wind varies only in magnitude with altitude. For a more complete analysis of sound propagation in a stratified moving medium, see "Acoustics of a Nonhomogeneous Moving Medium," by D. I. Blokhintsev.[11] The effects of the wind, like the effects of the temperature variation, include a change in the signal path, and an alteration of the amplitude of the signal through the variation of the cross-sectional area of the ray tube.

Since, near the ground, the wind speed generally increases with altitude, in a medium with no temperature gradient a disturbance propagating near the ground and with the wind is bent towards the ground, and a disturbance propagating near the ground and against the wind is bent away from the ground. The locus of the points where the shadow forming rays graze the ground is presented in Figure 6. Also shown in Figure 6 are the observer positions and the ground position of TWA Flight 800 at the time of the explosion.

The other complicating factor is the high pressure in the source wave form. Although a linear disturbance propagates essentially unchanged, a high amplitude disturbance propagates nonlinearly, which changes the form of

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[11] "Acoustics of a Nonhomogeneous Moving Medium," D. I. Blokhintsev, NACA TM 1399, 1946.

the disturbance as it propagates. In essence, the high amplitude portions of the wave form propagate faster than the low amplitude portions of the wave form. Hence, the high amplitude portions of the wave form tend to overtake those low amplitude portions that are ahead of them, and continually increase the distance, or time, between themselves and those lower amplitude portions of the wave form that are behind them. Further, the wave form undergoes a slight loss in amplitude due to nonlinear losses.

The theory used to propagate the signal from the source to the ground is weak shock theory, coupled with ray theory, also known as geometric acoustics. The discussion of this theory may be found in several references.[12] The method assumes that the geometric theory is valid. This assumption is certainly true for the problem considered here except for observers located in the shadow region. No calculations were carried out for these observers. In fact the absence of rays at observers in the shadow region precludes the calculation of the field there by the theory used in this study. The theory also neglects viscous dissipation and losses due to molecular relaxation. Both of these tend to dissipate energy, especially in regions with large gradients of the disturbance pressure. Weak shock theory, however, introduces its own dissipation. The major discrepancy between weak shock theory predictions and measurements of actual signals which are of large amplitude is that the actual signals do not reach their peak values as rapidly as the predicted signal, and the actual signal is more rounded than, or, looked at another way, is not as angular as, the predicted signal. However, corrections for these rather minor discrepancies can be applied to the predicted signal.

An alternate method to calculate the received signal is provided by ANSI Standard S2.20-1983. The method presented in this standard does not account for wind and temperature variation in the atmosphere. The results provided by this standard are discussed later in this report.[13]

Signal Prediction

The observers were given an observer number based on their distance from the source. Table I provides the NASA observer number and the corresponding NTSB observer number. A ray tracing program which accounted for winds that vary in

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[12] "Acoustics; An Introduction to Its Physical Principles and Applications," Allan D. Pierce, McGraw Hill, 1981; Chapters 8 and 11. "Linear and Nonlinear Waves", G. B. Whitham, John Wiley and Sons, New York, 1974. Chapter 9.

[13] ANSI S2.20-1983, AMERICAN NATIONAL STANDARD "Estimating Airblast Characteristics for single point Explosions in Air, With a Guide to Evaluation of Atmospheric Propagation and Effects"

both direction and magnitude with altitude, as well as variation in temperature, was used in an attempt to trace a ray from the source to each of the observers whose positions was provided to NASA. The weather data given in the National Transportation Safety Board report[14] was used for the atmospheric data. It was found that 17 of the 83 observers were in the shadow region, see Table II. No rays could be traced to these observers. Further, several of the observers were at large enough distances from the source, or close enough to the shadow boundary, to make it difficult to find a ray passing through them. In all 40 ray traces were made. Due to the fact that many positions had two or more observers, a ray was traced through the positions of 60 witnesses by these 40 ray traces, see Table III.

The wave form predicted by the theory of H. L. Brode, given in Figure 2, was used as a source to predict the signal observed at each of these 40 positions. The Thomas Code[15] was modified to propagate the signal from a stationary source, rather than a supersonic aircraft, and used to propagate this input signal to the ground.

The Thomas Code uses ray theory to determine the amplitude variation due to changes in ray tube area, and weak shock theory to account for nonlinear effects. The audibility of 3 of these 40 signals was determined. These three were: NASA observer number 2, representative of observers receiving a signal with a high peak amplitude, presented in Figure 7; the signal with the lowest peak amplitude, NASA observer numbers 72, 73, and 74, which all have the same geographic position, hence a single prediction holds for the three observers, presented in Figure 8; and a signal that could be considered as having the median peak amplitude, i.e., about as many observers had signals with higher peak amplitudes as had signals with lower peak amplitudes, NASA observer number 44 presented in Figure 9. If the lowest amplitude signal is audible it may be assumed that all of the signals are audible.

Observers in the shadow

There are at least two reasons why one cannot say that an observer in the shadow region did not hear the explosion of Flight 800's center fuel tank. First, there are mechanisms which allow acoustic energy to propagate into the shadow region. These are not accounted for in the current analysis, hence the analysis used in this study is not valid in the shadow region, and can say nothing about the audibility of the signal there. Second, and perhaps more important, a slight change in the weather data would move the shadow boundary. The observers in the shadow region with the

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[14] Meteorological Factual Report, [DCA96MA070], pp. 3-4

[15] "Extrapolation of Sonic Boom Pressure Signatures by the Wave form Parameter Method", Charles L. Thomas, NASA TN D-6832, June 1972.

weather data used for this study might not be in the shadow region if only slightly different weather data were used. As an example, none of the observers within a circle of 20 mile radius centered on the ground position of Flight 800 at the time of the explosion are in a shadow region if the wind is neglected and only the given temperature data is used. This places only the observers at the two farthest positions (NASA observer numbers 82 and 83) in the shadow region. Also, it must be remembered that the meteorological data provided to NASA represents a small fraction of that which would be required to fully characterize the atmosphere from the aircraft to each observer at the time of the explosion.

Code Verification

In order to verify that the modified code was providing reasonable results a series of tests was carried out. These may be divided into three categories. The first category consists of tests which verified that the code reproduced simple known analytical solutions. The results of these tests are presented in Appendix B. The second category verified that the level and spectra predicted by the code were reasonable estimates of the disturbance produced by a given charge of TNT. The results of this test are presented in Appendix C. The third category of tests provides a comparison of the predictions with the signal that would be predicted using ANSI Standard ANSI S2.20-1983. The results of this comparison are presented in Appendix D.

An Alternate Prediction Method: ANSI Standard ANSI S2.20-1983.

The ANSI Standard S2.20-1983, used to provide a verification of the Thomas code, provides an alternate method for predicting the pressure signal for an explosion. Beyond providing upper and lower bounds for the peak amplitude of the signal, ANSI Standard S2.20-1983 does not account for the variations of the signal introduced by the temperature and wind gradients which occur in the atmosphere as the Thomas code does. The conclusions presented in this study would be unchanged if the Standard had been used to predict the signal at each of the observers, rather than the Thomas code. The prediction of the peak amplitude of the signal by the ANSI Standard at each of the observers, including those for which no signal could be predicted by the Thomas code, can be determined through use of Figure 10. The ANSI Standard predicts a nominal peak amplitude of approximately 0.06 psf for the observer furthest from the explosion, at a lateral distance of approximately 35 miles. This is insignificantly different than the lowest peak amplitude predicted by the Thomas code for all of the observers for which a signal was predicted. The conclusions of the study may, therefore, be extended to all observer locations provided to NASA by the NTSB.

Audibility analysis

Just because a signal exists at an observer location does not imply that the receiver would detect that signal. Two questions immediately come to mind. First; Is the received signal above the threshold of hearing? That is, is the signal loud enough to be heard in the absence of the ambient background noise? This question is answered by comparing the spectra of the predicted signal with minimum audible sound pressure levels as a function of frequency for otologically normal human subjects.

Second; Is the signal above the background noise? If the ambient noise level is sufficiently high, the signal from the explosion of Flight 800's fuel tank will be hidden in the background noise. This question is answered by comparing the spectra of the predicted signal with the spectra of typical (ambient) background noise levels present in residential areas.

If the signal from the explosion of Flight 800's fuel tank is of sufficient amplitude its spectra will be above both curves, and it can be concluded that a human observer would probably have "heard the explosion". If the signal is not of sufficient amplitude, its spectra will lie below one or both of the curves at all points, and it can be concluded that a human observer would probably not have "heard the explosion".

The audibility analysis of the predicted blast wave is illustrated by means of Figure 11. The threshold of hearing[16] describes minimum audible sound pressure levels as a function of frequency for otologically normal human subjects, and is shown in Figure 11 by the curve labeled "Pure tone threshold." Also shown are typical (ambient) background noise levels present in residential areas[17]. The predicted blast wave signatures, shown in Figures 7, 8, and 9, are transformed to the frequency domain and shown in Figure 11 as one-third octave band spectra.

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[16] "Normal Equal-Loudness Contours for Pure Tones and Normal Threshold of Hearing under Free Field Listening Conditions". International Organization for Standardization, Recommendation R 226 (December 1961)

[17] "Handbook of Noise Control, 2nd Edition", Edited by Cyril M. Harris, McGraw Hill. (1979)

The method used to predict the blast signature has not accounted for several phenomena that occur as the signal propagates through the atmosphere, namely absorption due to viscosity, heat transfer, and molecular relaxation. Further the effects of scattering due to turbulence are neglected. The major result of ignoring these effects is that the predicted shock associated with the blast wave has no thickness; that is, the disturbance pressure rises from zero to its peak amplitude over a time interval of length zero. In reality, the pressure rise occurs over a time interval of some definite nonzero length, called the rise time.[18] For the current study a rise time of 5 milliseconds has been assumed. Figure 11 presents the one-third octave band spectra for the predicted signals at observers 2, 44, and 72, with a 5 millisecond rise time imposed on the predicted signal.

An alternate approach to estimating the effects of atmospheric absorption on the received signal is to take the signal predicted at the ground without attenuation, and apply attenuation to the predicted signal as if it had propagated from the source to the observer as an acoustic signal. This method accounts for some absorption twice, and should provide a conservative estimate of the signal received at the ground.

Atmospheric absorption may be calculated by the method presented in ANSI Standard S1.26-1995.[19] The results of using this method to calculate the signal at observers 2, 44, and 72 are presented in Figure 12.

It is of importance to note both of the calculations used to approximate the effects of atmospheric absorption on the waveform are approximations. However, even an exact calculation of the absorption for a nonlinear wave affects only the high frequencies. Comparison of Figures 11 and 12 shows that their is no difference in the one-third octave spectra below approximately 100 Hz. Atmospheric absorption

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[18] Basic discussion of the rise time concept may be found in, Richards, E. J. , and Mead, D. J.; "Noise and Acoustic Fatigue in Aeronautics," Chapter 12, Sonic Bangs.
Also see "Acoustics; An Introduction to Its Physical Principles and Applications," Allan D. Pierce, McGraw Hill, 1981; Chapter 11, pp. 589-593.
and: "Linear and Nonlinear Waves", G. B. Whitham, John Wiley and Sons, New York, 1974. Chapter 2, pp. 32-36.
Some of the references discuss shock thickness rather than rise time. The difference between rise time and shock thickness is one of coordinate system alone. Shock thickness is the thickness of the shock in a coordinate system in which the shock is at rest. The rise time is related to the time required for the overpressure to rise from zero to the peak value, in a coordinate system in which the shock is moving and the observer is stationary.

[19] AMERICAN NATIONAL STANDARD "**METHOD FOR CALCULATION OF THE ABSORPTION OF SOUND BY THE ATMOSPHERE**," ANSI S1.26-1995

at these low frequencies is negligible except for extremely long range propagation. Hence the conclusions of this study are independent of the model used for atmospheric absorption, as long as the model is reasonable.

One final assumption is needed in order to compute blast spectra for comparison with the threshold of hearing and the background noise levels. The hearing threshold is measured for continuous sounds and the background noise is also relatively constant with time. In contrast, the blast signature is impulsive, the most audible part of the impulse being confined to the region near the shock. For the present calculation the so-called integration time of the human hearing system has been assumed to be 70 milliseconds.

Conclusion

From inspection of Figures 11 and 12 it is clear that the blast signature greatly exceeds the hearing threshold over a wide frequency range, regardless of the assumptions used to calculate absorption losses. It is also apparent from these figures that there is a frequency range over which each of the blast spectra exceed even the "high residential ambient" condition. It is thus concluded that there is a high probability that a blast wave as described would be audible to observers 2, 44, and 72. Observer 72 had the lowest predicted amplitude. It is thus concluded that there is a high probability that a blast wave as described would be audible to observer number 72. Since this is the signal with the lowest amplitude it may safely be concluded that the blast wave was audible for all of the observers for which a prediction was made, see Table III. As mentioned previously, there is no reason to believe that the disturbance produced by the explosion of the center fuel tank of TWA Flight 800 was not audible at the remaining observer locations. Slight changes in the weather data would remove all of the observers in the shadow from the shadow. Further, those observers for which the propagation distance was great enough to make prediction difficult could also probably have heard the disturbance; the levels at observer 72 are high enough that spreading losses would be unable to attenuate the signal sufficiently for it to become inaudible in the remaining propagation distance.

Further the conclusions of this study should be valid for reasonable ranges of the energy in the initial blast wave. The audibility of the signal should be unchanged even if the initial energy is reduced. The disturbance amplitude is reasonably insensitive to initial energy, within reasonable bounds, and the amplitude of the disturbance at the observer locations could be reduced significantly without altering the conclusions.

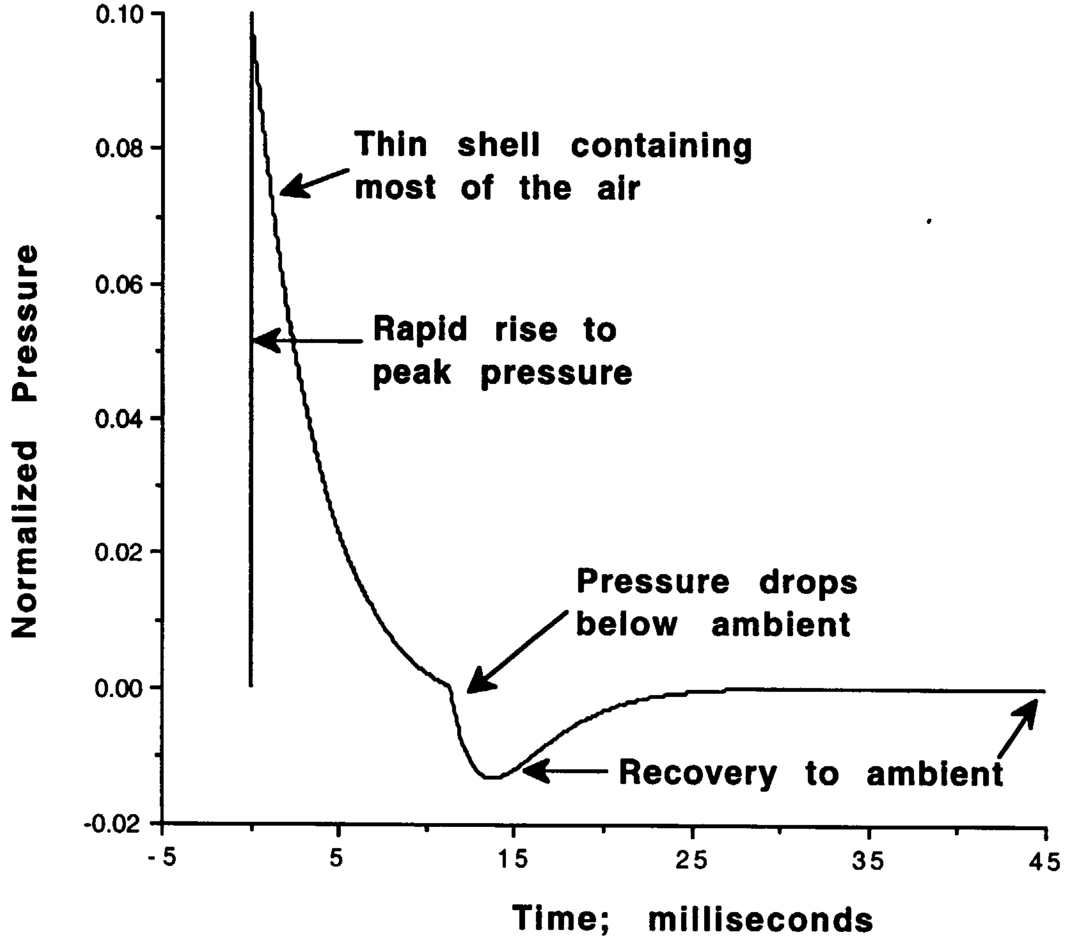

Figure 1. An idealized blast waveform showing the important characteristics. Pressure is normalized by the ambient pressure.

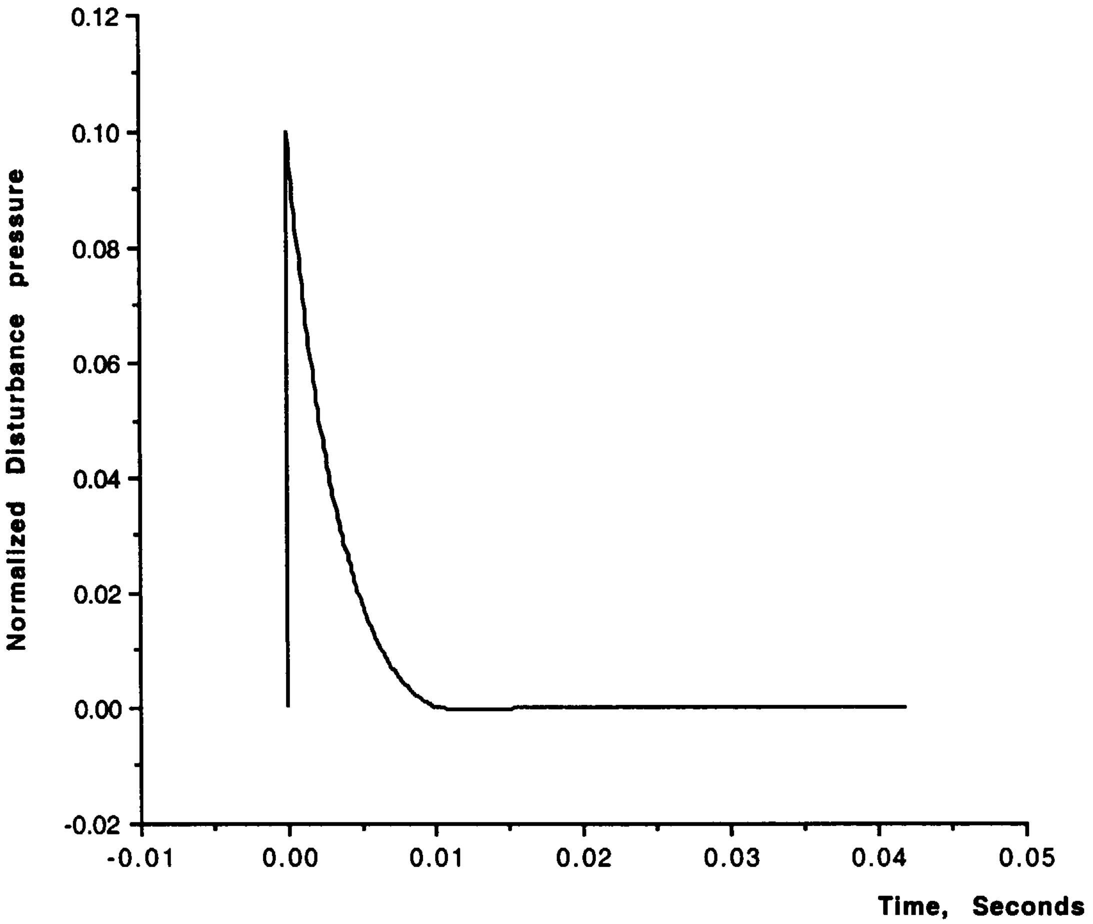

Figure 2. The pressure at the point where it is used as an initial condition for weak shock theory. Disturbance pressure is normalized by the ambient pressure.

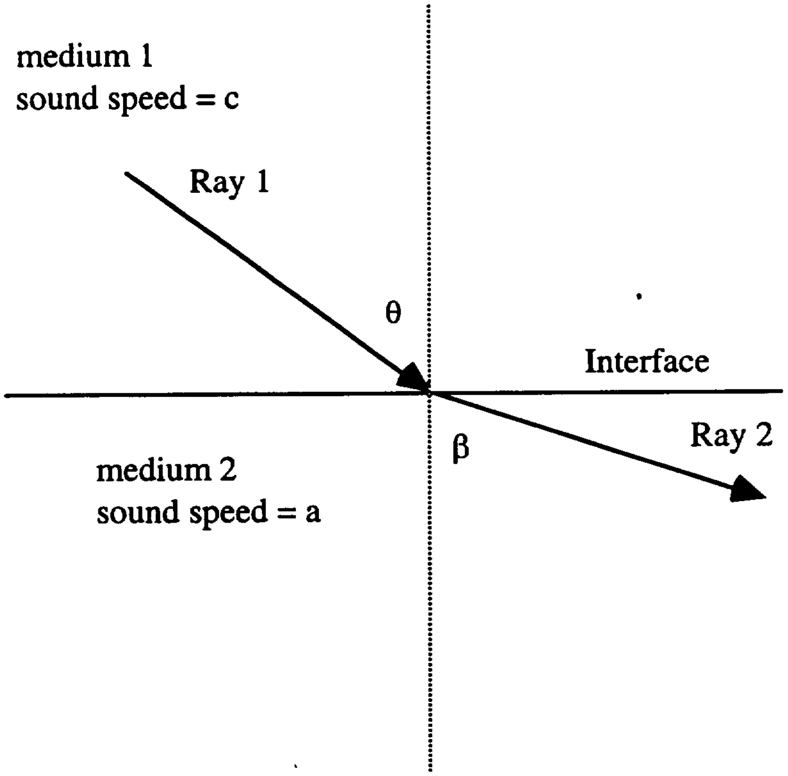

Figure 3. A disturbance propagating from a medium with sound speed c to a medium with sound speed a.

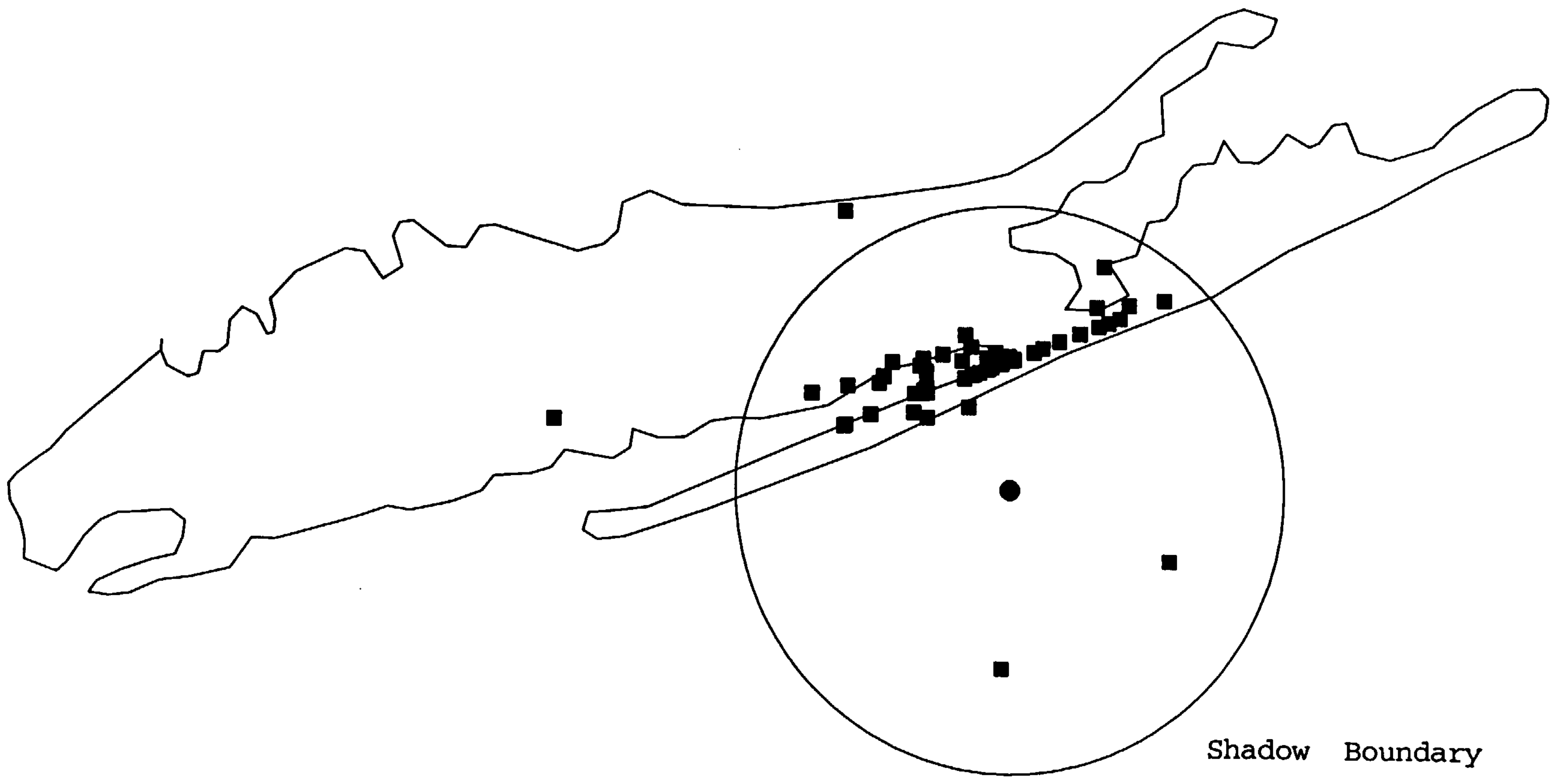

Figure 4. The shadow boundary for the temperature stratified atmosphere. Also shown are the observer locations and the ground position of Flight 800 at the time of the explosion

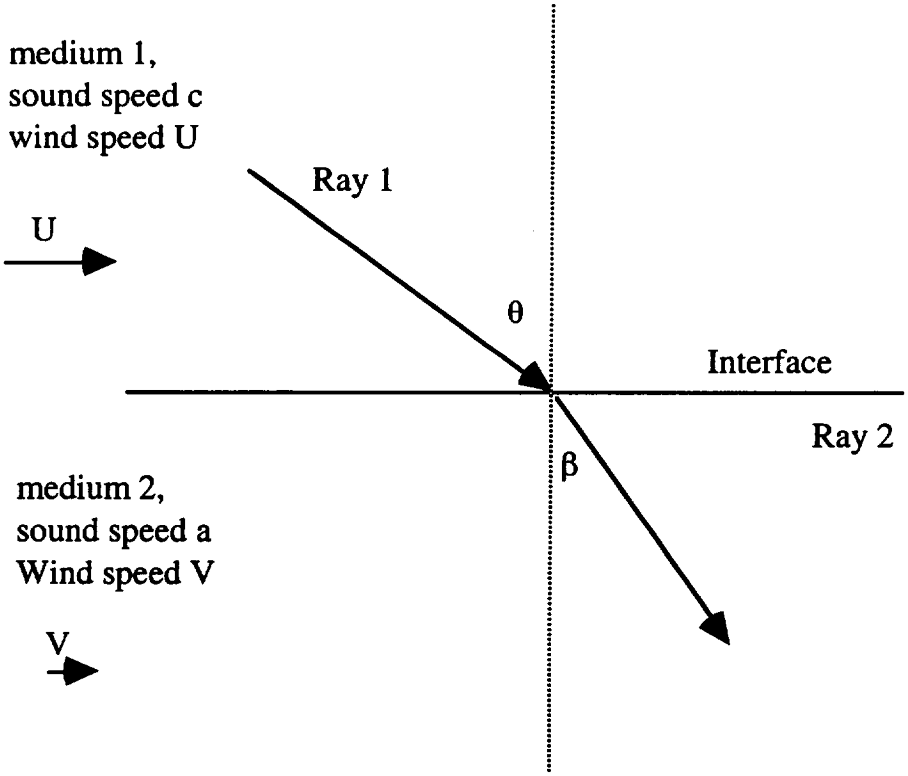

Figure 5. A disturbance propagating from a medium with sound speed c, and moving with speed U in the positive x direction, into a medium with sound speed a, moving with speed V also in the positive x direction

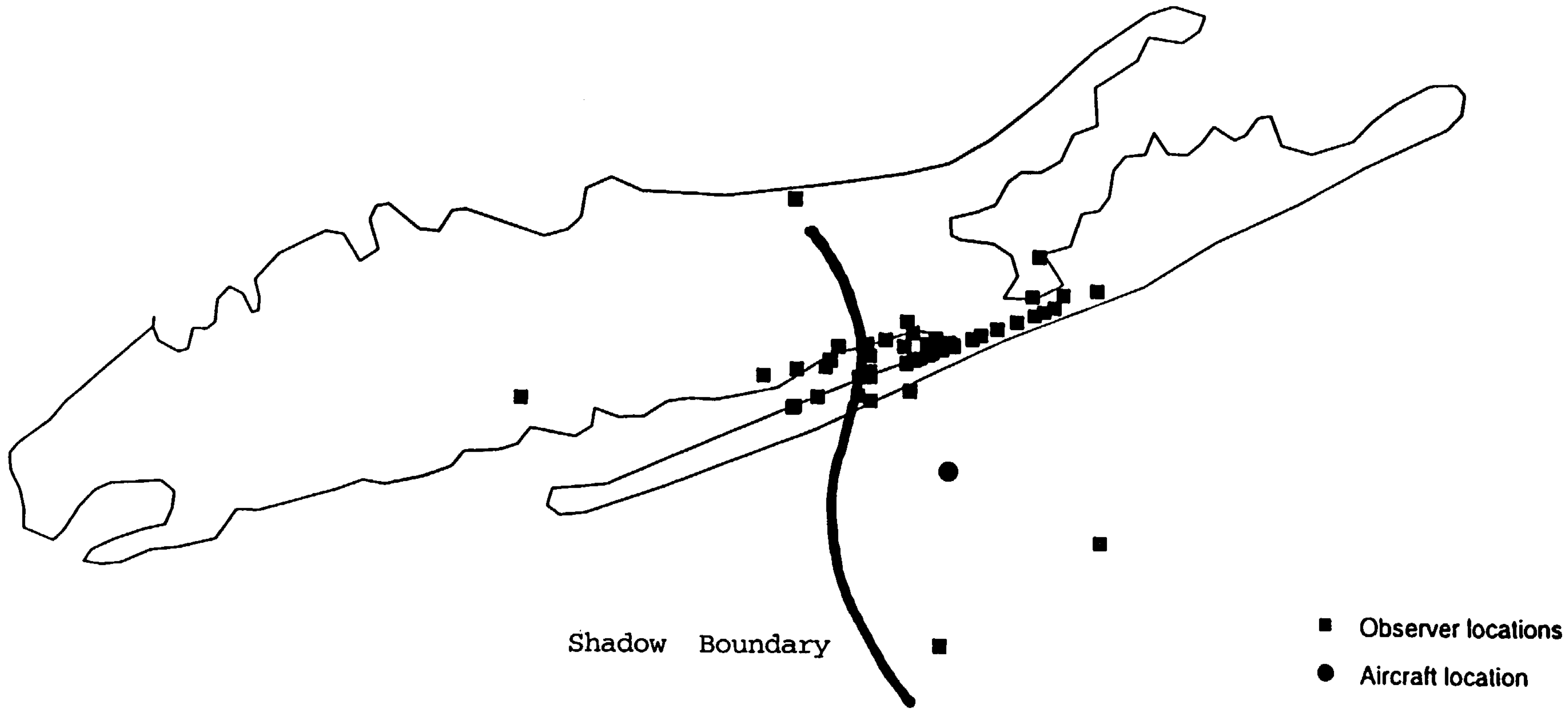

Figure 6. The shadow boundary for the wind and temperature stratified atmosphere. Also shown are the observer locations and the ground position of Flight 800 at the time of the explosion

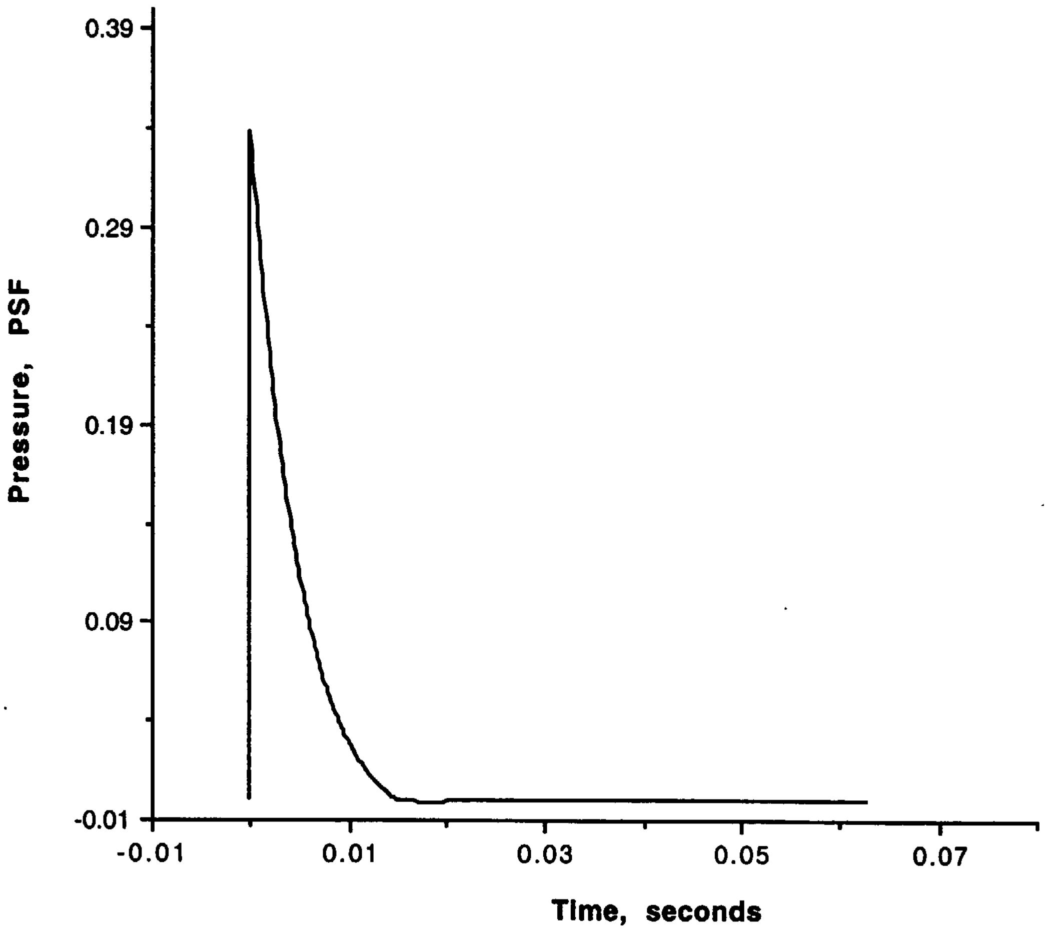

Figure 7: Waveform at observer 2

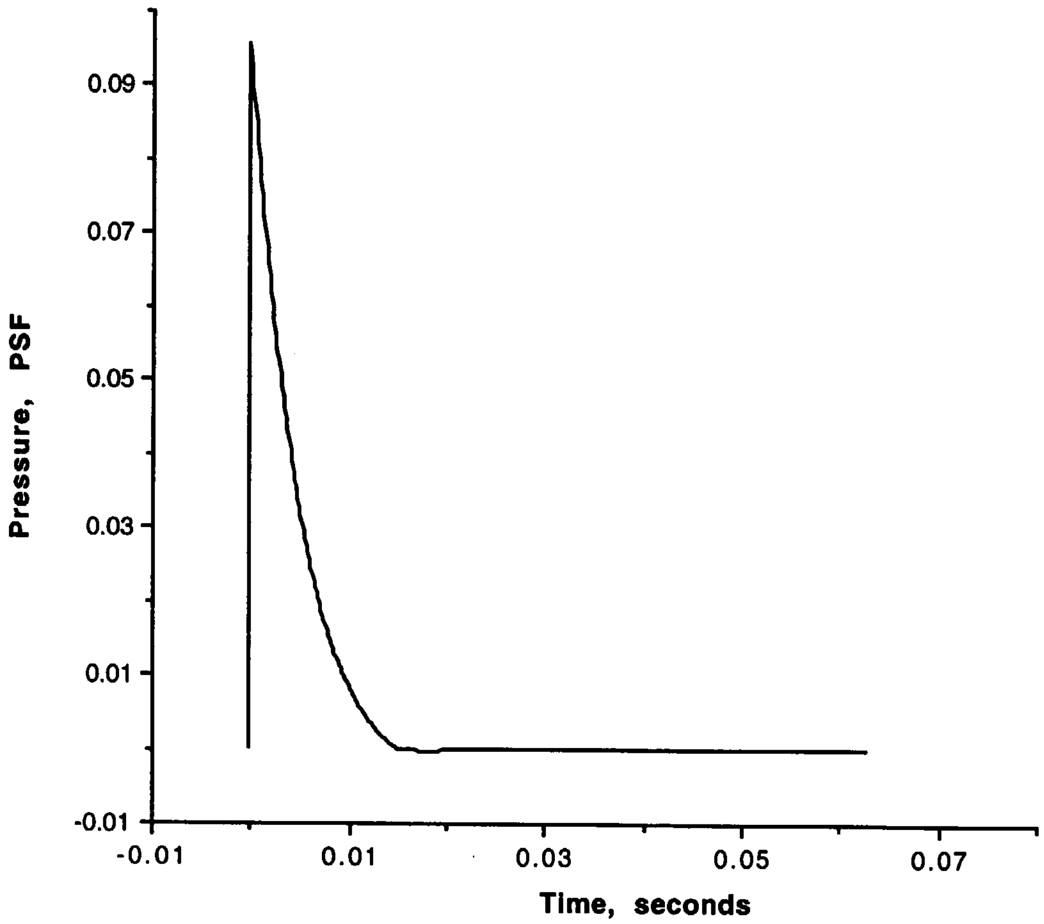

Figure 8. Waveform at observers 72, 73, and 74. These three observers were at essentially the same position.

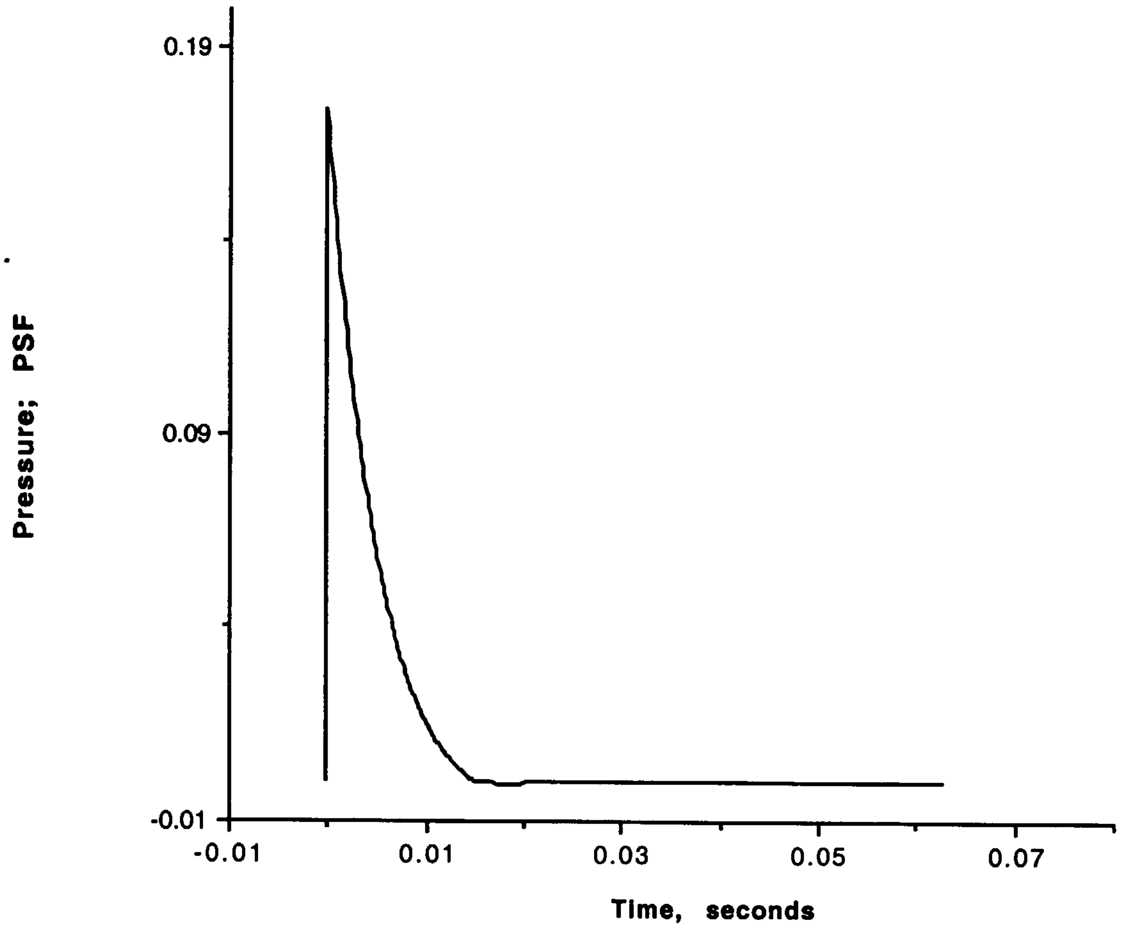

Figure 9. Waveform at Observer 44

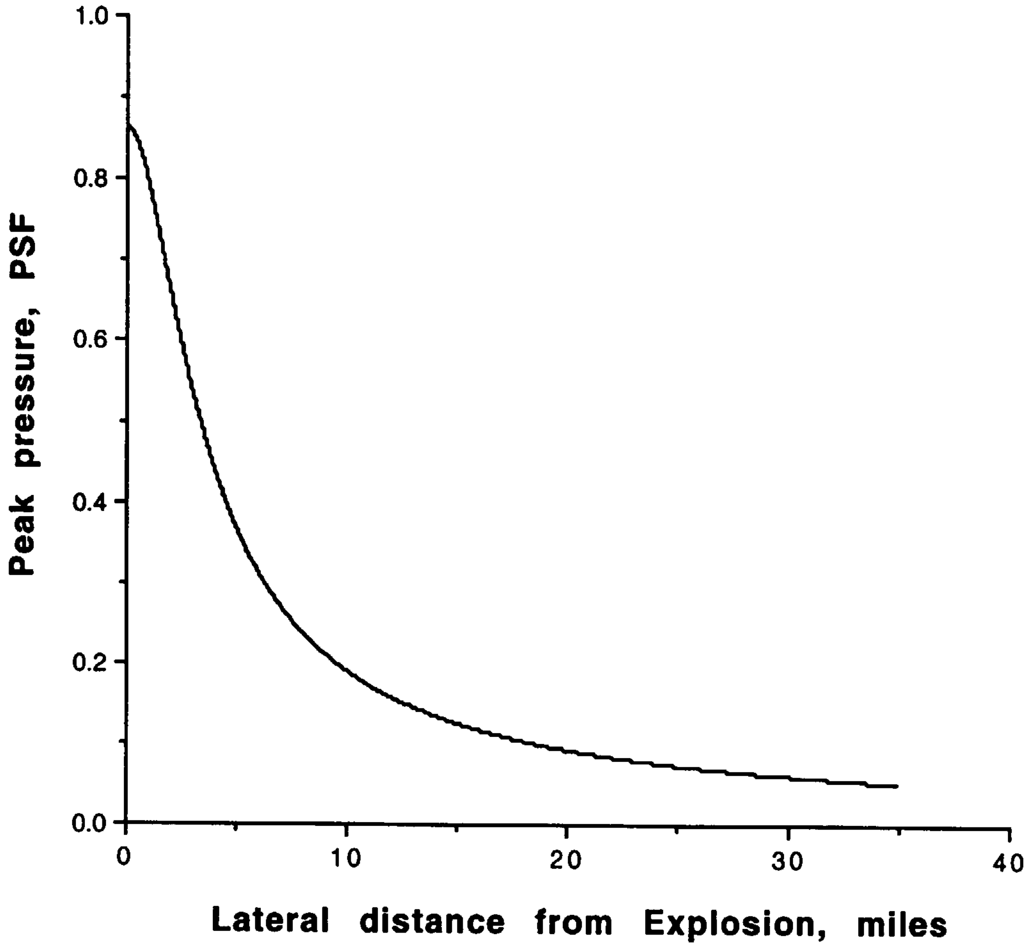

Figure 10. Peak pressure as predicted by ANSI Standard as function of lateral distance from the explosion.

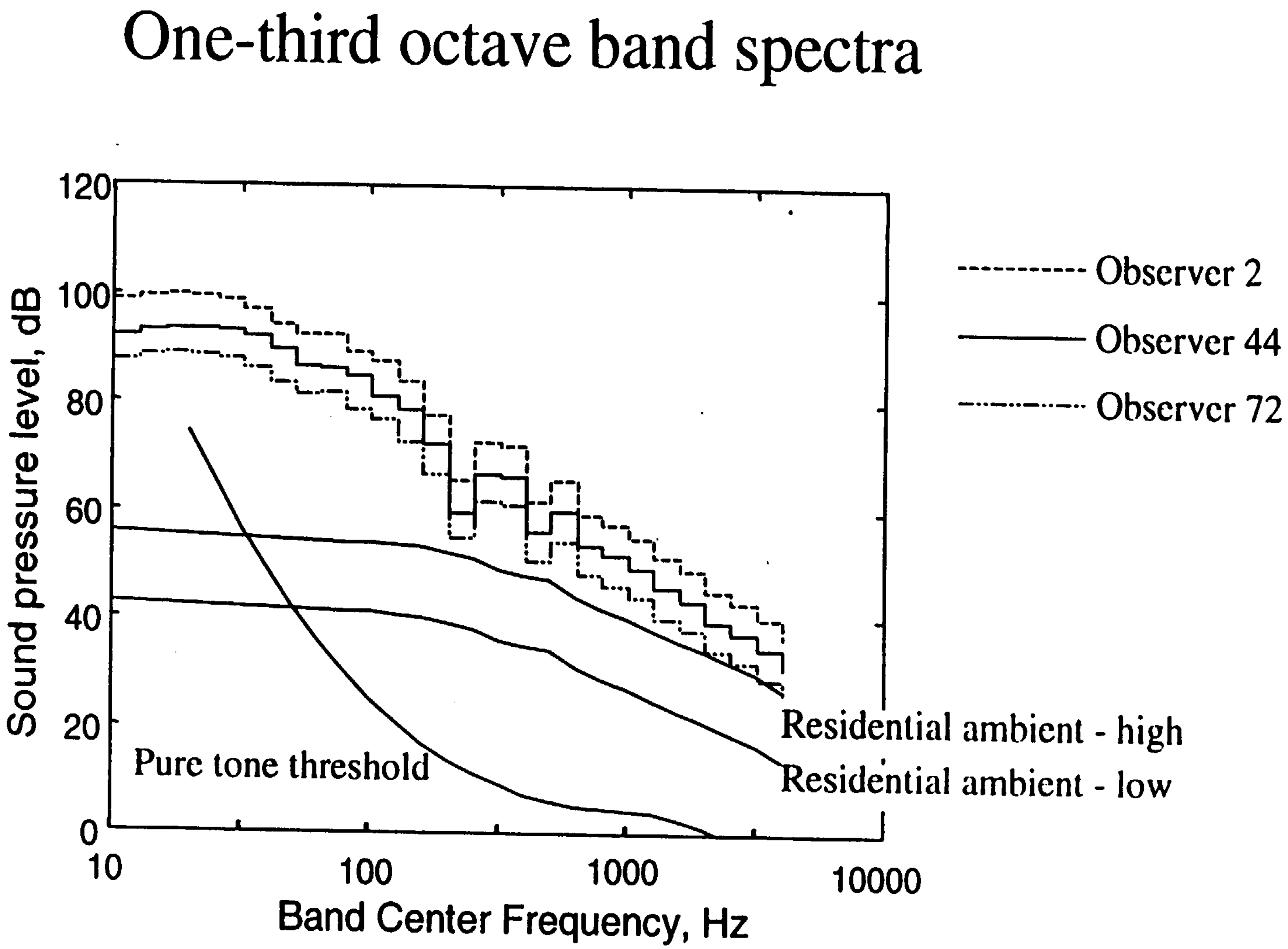

Figure 11. One-third octave band spectra for signal at observers 2, 44, and 72. Rise time assumed to be 5 milliseconds.

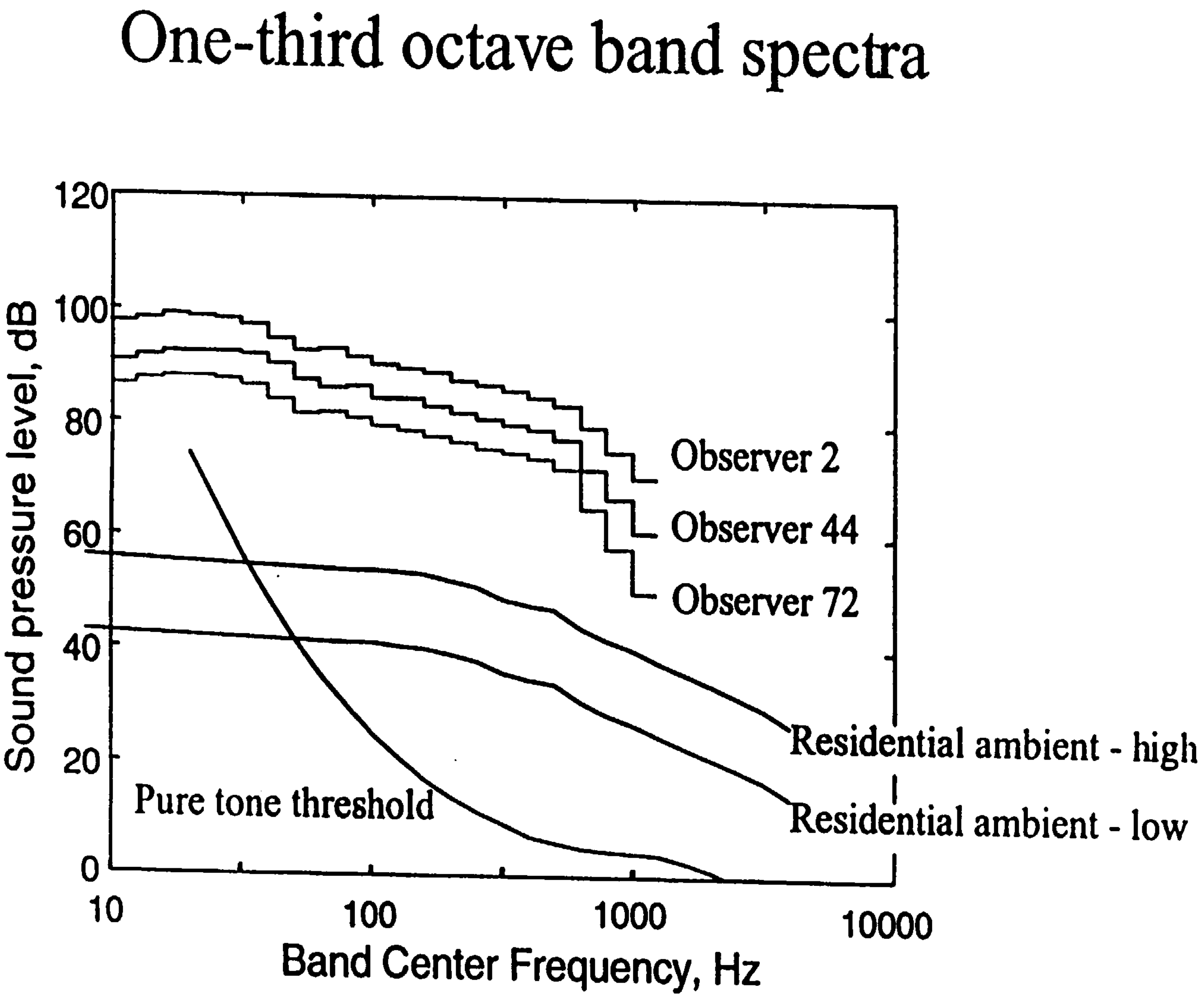

Figure 12. One-third octave band spectra for signal at observers 2, 44, and 72. Absorption calculated as if signal were propagated by linear theory.

Table I
NASA Observer Number and NTSB Observer Number

NASA observer #	NTSB observer #
1	614
2	350
3	577
4	644
5	646
6	647
7	284
8	492
9	738
10	83
11	283
12	177
13	50
14	155
15	75
16	454
17	89
18	482
19	576
20	449
21	481
22	567
23	411
24	412
25	317
26	650
27	506
28	359
29	571
30	643
31	129
32	700
33	304
34	295
35	445
36	499
37	356
38	648
39	152
40	209
41	461
42	503
43	248
44	186
45	426
46	473
47	480
48	148
49	497
50	498
51	496
52	108
53	153
54	157
55	570
56	675
57	732
58	661
59	190
60	645
61	169
62	313
63	38
64	501
65	390
66	563
67	406
68	21
69	504
70	548
71	91
72	291
73	293
74	320
75	146
76	398
77	536
78	696
79	57
80	228
81	325
82	462
83	526

Table II
Observers in the shadow region

NASA Observer Number	NTSB Observer Number
46	473
49	497
51	496
57	732
58	661
59	190
61	169
62	313
63	38
64	501
68	21
69	504
70	548
75	146
79	57
82	462
83	526

Table III
Observers for which a prediction was made

NASA observer #	NTSB observer #
1	614
2	350
3	577
4	644
5	646
6	647
7	284
8	492
9	738
10	83
11	283
12	177
13	50
14	155
15	75
16	454
17	89
18	482
19	576
20	449
21	481
22	567
23	411
24	412
25	317
26	650
27	506
28	359
29	571
30	643
31	129
32	700
33	304
34	295
35	445
36	499
37	356
39	152
40	209
41	461
42	503
43	248
44	186
45	426
47	480
48	148
50	498
52	108
53	153
54	157
55	570
56	675
60	645
65	390
66	563
67	406
71	91
72	291
73	293
74	320

Table IV
Observers which were too far from the source

NASA Observer Number	NTSB Observer Number
38	648
76	398
77	536
78	696
80	228
81	325

The ray tracing program would not converge for NASA observer numbers 38, and 76. Observer number 38 is near the shadow boundary. Observer 76 was the observer farthest away from the source for which a ray trace was attempted. Since the ray trace program failed to converge for Observer 76, no ray traces were attempted for observers 77, 78, 80, and 81, all of which are further away from the source than observer 76. All NASA observers with numbers greater than 75 would have been deemed to be too far from the source to attempt a prediction. However some appeared to be in the shadow region and are listed as in the shadow.

APPENDIX A
Calculation of the energy of the explosion

The energy in the explosion is estimated as follows. From the estimates of the fuel/air ratio in the center wing tank provided in the report "Jet A Explosion Experiments: Laboratory Testing"[1], and the estimate of the molecular weight of the fuel, and the estimate of the energy content per unit mass of fuel also contained in that report, along with an estimate of the volume of the center wing fuel tank provided in that report it is possible to obtain an estimate of the total energy available in the fuel vapor within the tank. These calculations are presented here.

<u>Relevant parameters:</u>

Fuel tank volume[2] 50. meter^3 = 1766. ft^3

Fuel air mass ratio:[3]
    Minimum 0.022
    Maximum 0.027

Average fuel tank temperature:[4]
        33.5 C
        92 F

Atmospheric pressure[5]
        8.6 psi

Energy content of the fuel:[6]
        $q = 42.8$ MJ/kg

Molecular weight of the fuel:[7]
        $W = 160$

Molecular weight of air:[8]

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[1] "Jet A Explosion Experiments: Laboratory Testing", Joseph E. Shepherd, J. Christopher Krok, and Julian J. Lee, June 6, 1997 corrected on November 21, 1997; Explosion Dynamics Laboratory Report FM97-5

[2] Ibid., p. 1

[3] Ibid. p. 56

[4] Ibid. p. 54

[5] Ibid. p. 9

[6] Ibid. p. 22

[7] Ibid. p. 22

[8] "Acoustics An Introduction to Its Physical Principles and Applications," Allan D. Pierce, McGraw Hill, 1981, p. 29

$W_a = 29$

For the purposes of the current analysis let α be the fuel air mass ratio. The analysis is as presented by Reynolds and Perkins.[9]

COMPONENT	$\frac{\text{lbm}}{\text{lbm of mixture}}$	$\frac{\text{lbm}}{\text{lb}_{\text{mole}}}$	$\frac{\text{lbmole}}{\text{lbm of mixture}}$	$\frac{\text{lbmole}}{\text{lbmole of mixture}}$
Fuel	$\frac{\alpha}{1 + \alpha}$	160	$\frac{\alpha}{160(1 + \alpha)}$	$\frac{29\alpha}{29\alpha + 160}$
Air	$\frac{1}{1 + \alpha}$	29	$\frac{1}{29(1 + \alpha)}$	$\frac{160}{29\alpha + 160}$
			$\frac{29\alpha + 160}{29*160(1 + \alpha)}$	

Column 1 of the table gives the mass of the component as a fraction of the total mass of the mixture. This is the mass ratio of the component.

Column 2 is the molecular weight of the component.

Column 3 is obtained by dividing the entry in column 1 by the entry in column 2. The final entry in column 3 is the sum of the entries in rows 1 and 2 of column 3.

The final column is obtained by dividing the entries in rows 1 and 2 of column 3 by the entry in row 3 of column 3. This is the volume fraction of the component.

The density of the mixture is given by the ideal gas law. The temperature is 92° F, or 552° R. The pressure is 8.6 psi, or 1238.4 PSF. The gas constant is the universal gas constant divided by the molecular weight of the mixture, or

$$\frac{1545}{\left[\frac{160*29\alpha}{29\alpha + 160} + \frac{29*160}{29\alpha + 160}\right]} = \frac{1545(29\alpha + 160)}{29*160(1 + \alpha)}$$

For $\alpha = 0.022$

$R = 52.34$

$\rho =$ Pressure/(R*Temperature)

$= (8.6\text{pounds/in}^2)*(144\text{in}^2/\text{ft}^2)/((52.34\text{ft-lb}_f/\text{lb}_m\text{-}^\circ\text{R})*(92 + 460)^\circ\text{R}) = 0.043\ \text{Lb}_m/\text{ft}^3$

Thus the total mass is (Volume of fuel tank)*(density of vapor) $= 1766.\text{ft}^3 * 0.043\ \text{Lb}_m/\text{ft}^3 = 75.9\text{Lb}_m$

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[9] "Engineering Thermodynamics," William C. Reynolds, and Henry C. Perkins, McGraw Hill, 1970, p. 333 - 336.

Mass of fuel is (total mass)$*[\frac{\alpha}{1 + \alpha}] = (75.9Lb_m)*[\frac{0.022}{1 + 0.022}]$

$75.9Lb_m*0.0215 = 1.63\ Lb_m$

The energy content is $\frac{42.8*10^6\ Joules}{Kg} * \frac{Kg}{2.2\ Lb_m} * \frac{cal.}{4.186\ Joules} * 1.63Lb_m \approx 7{,}600{,}000.$ calories

or (7,600,000. calories)*(778.16ft-lb_f/252 calories) ≈ 23,500,000.ft-lb_f.

or, (7,600,000. calories)*(2000 lb_m TNT/1,000,000,000 calories) ≈ 15.2 pounds of TNT;[10]

The same calculation for $\alpha = 0.027$ yields 29,000,000 Ft*Lb_f or approximately 18.8 pounds of TNT.

The difference in the energy of the explosion from minimum to maximum will yield very little difference in the disturbance field. A comparison of the predicted field at observer 20 is given in the figure.

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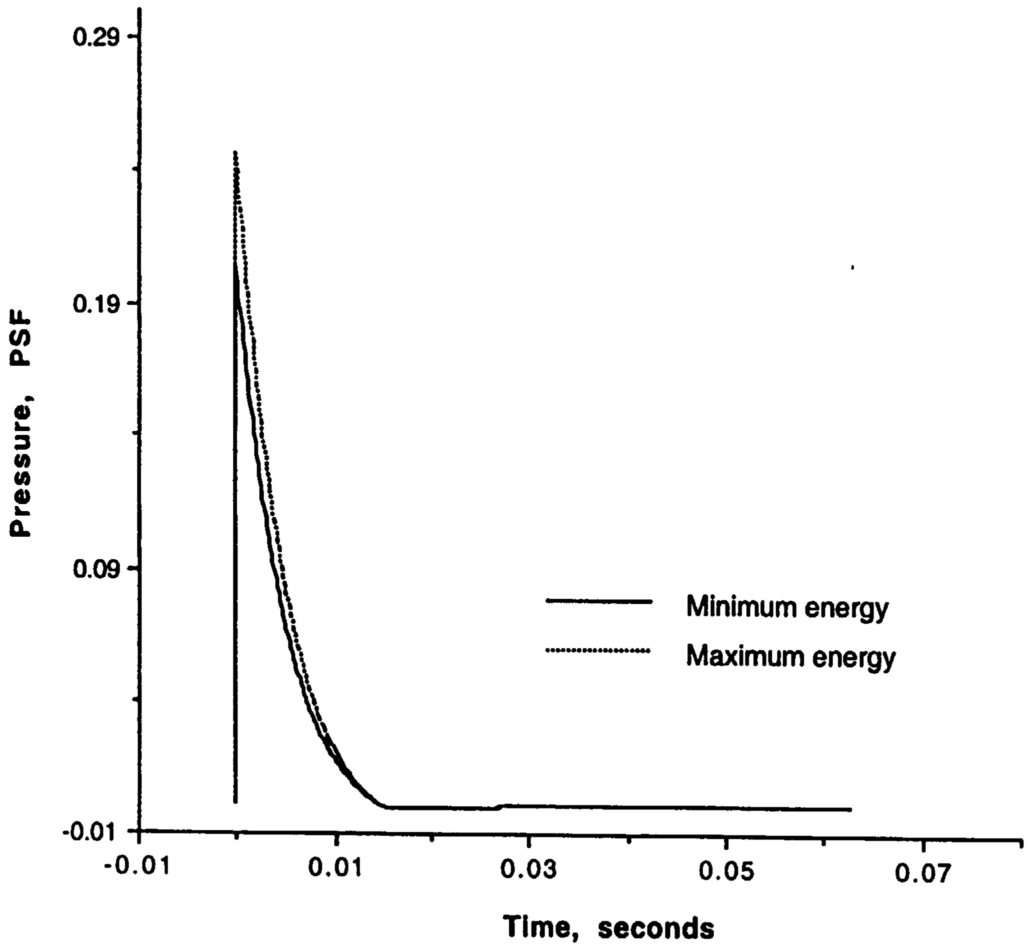
[10] For the conversion factor from calories to Tons of TNT see "The effects of NUCLEAR WEAPONS," Samuel Glasstone, Editor, United States Atomic Energy Commission, June 1957, p. 556.



Comparison of predicted waveforms at observer 20 for maximum and minimum energy in the explosion

APPENDIX B
Numerical Calculations to Verify the Propagation Routine

Several calculations were performed to verify that the propagation code was providing reasonable results. These were: a linear plane wave, a nonlinear plane wave, a linear spherical wave, and a nonlinear spherical wave, all propagated for 20 miles in a stationary homogeneous medium. The ambient pressure at the aircraft altitude is taken to be 8.6 psi, and the source amplitude is taken as one-tenth of this in all four cases. Thus the source amplitude is 0.1*8.6 psi, or 123.84 psf. In order to minimize nonlinear effects, in the three dimensional cases, and thereby check the area calculations of the ray tracing code, the source, which is presented in Figure B-1, is of long time duration. The nonlinear effects are tested, even with this physically unrealistic source, by the nonlinear plane wave case. This source is used for all cases presented in this appendix. Also, a factor of two was applied to the signal at the end of 20 miles to account for pressure doubling on reflection from the ground.

For a linear plane wave the amplitude and waveform should be unchanged after propagating the 20 miles, except for the factor of two introduced by ground reflection. Thus the amplitude for the linear plane wave should be 247.68 psf. The resulting waveform is given in Figure B-2, which may be compared with Figure 1. Note that the waveform is unchanged. The amplitude was printed out after the computer run and is what it should be. Thus the program propagates the linear plane wave successfully. This implies that the program does not introduce spurious absorption or dispersion.

The nonlinear plane wave should be reduced in amplitude as compared with the linear plane wave due to the attenuation introduced by nonlinear effects. Further, the nonlinear plane wave should be of longer duration than the linear plane wave due to the nonlinear effects. As can be seen in figure B-3 the amplitude has been reduced slightly. The linear and nonlinear plane waves, after having been propagated for 20 miles, are compared in Figure B-4, both the decrease in amplitude and the increased duration of the nonlinear wave are clearly seen.

The third test case is a linear spherical wave. Here the waveform should be unchanged in shape, but reduced by a factor of $80./(5280.0*20.0) \approx 7.6*10^{-4}$ due to spherical spreading, and increased by a factor of two due to reflection at the ground. Thus the amplitude should be $247.68*7.57575*10^{-4}$ psf ≈ 0.188 psf. As seen in Figure B-5 the waveform is essentially unchanged. Again the amplitude was printed out after the computer run and it is correct.

Finally, the results of propagating the nonlinear spherical wave over 20 miles are presented in Figure B-6. Here the results are indistinguishable from the linear spherical wave case indicating that nonlinear effects are negligible in this case, and that the ray tracing code is providing the correct ray tube area.

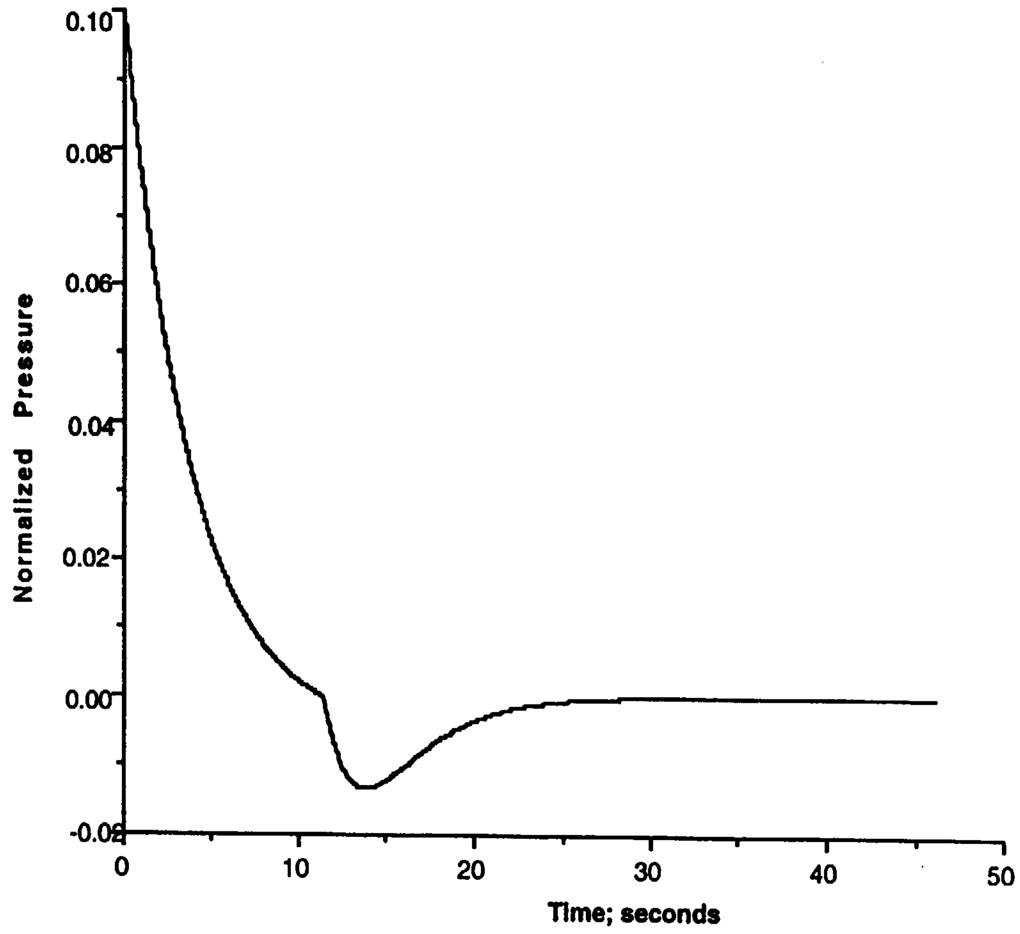


Figure B-1. The pressure at the point where it is used as an initial condition for weak shock theory. Pressure is normalized by the ambient pressure.

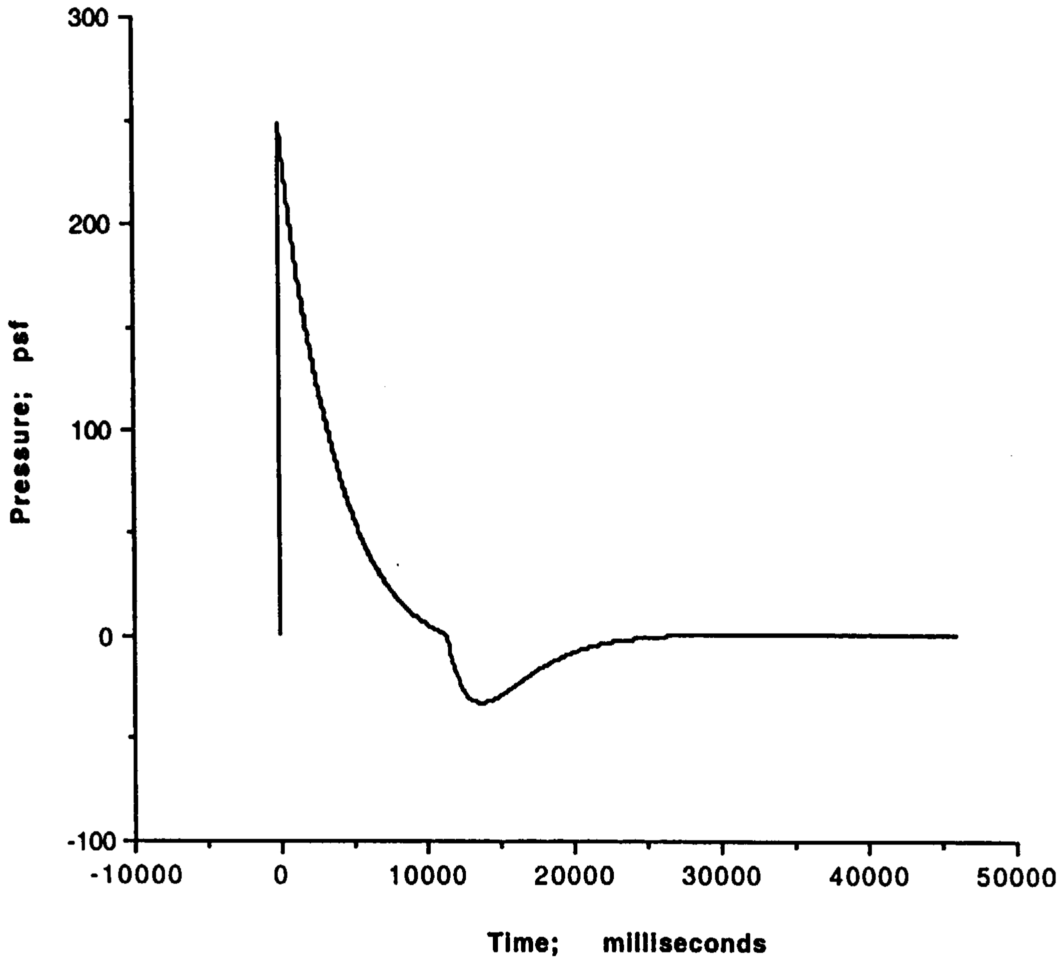


Figure B-2. Linear plane wave, propagated 20 miles, pressure doubling for reflection included.

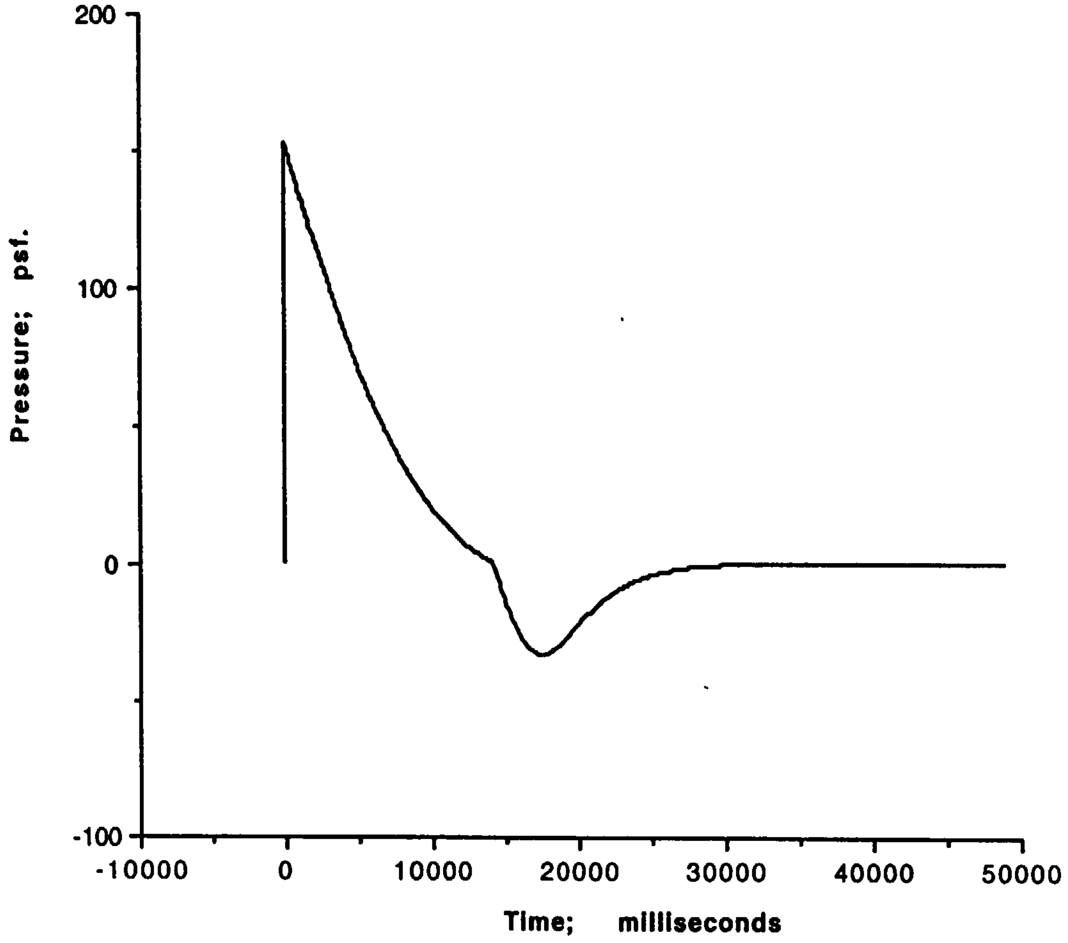


Figure B-3. Nonlinear plane wave propagated 20 miles. Pressure doubling for reflection included.

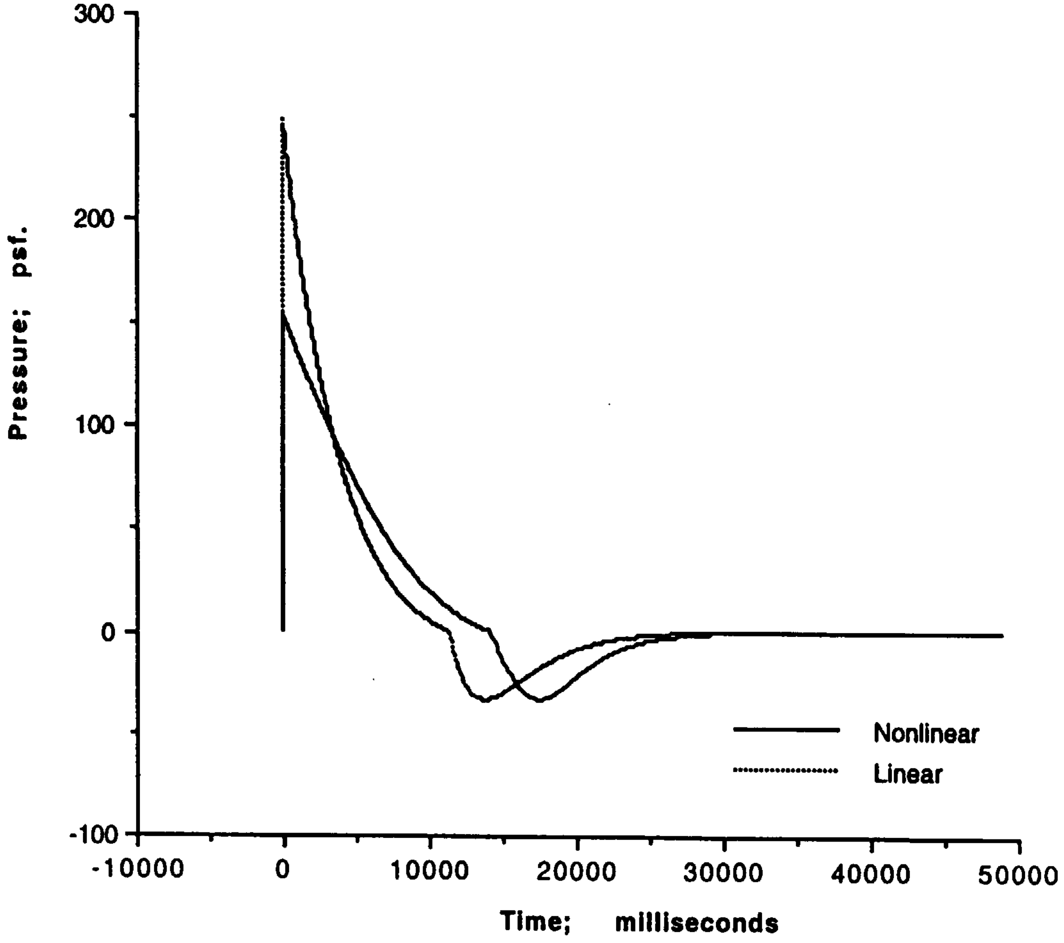


Figure B-4. Linear plane wave, Nonlinear plane wave comparison.

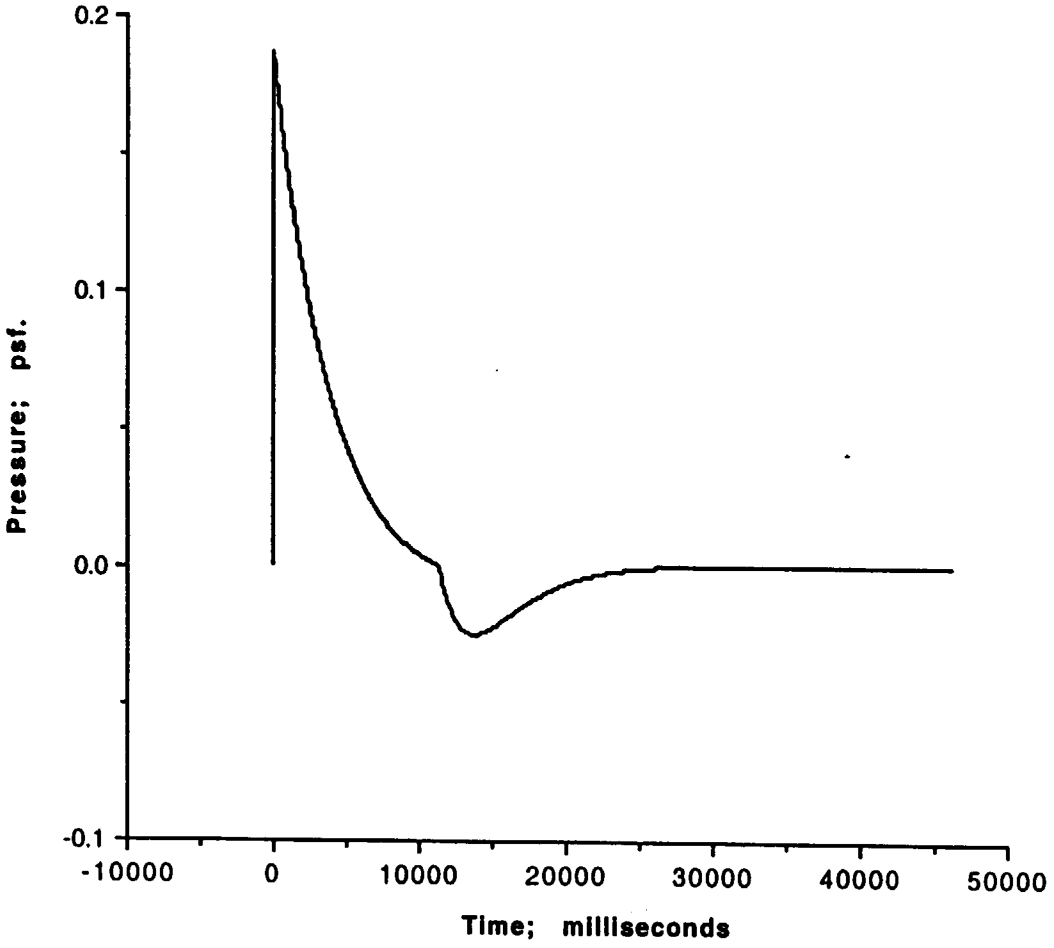


Figure B-5. Linear spherical wave propagated 20 miles. Pressure doubling for reflection included.

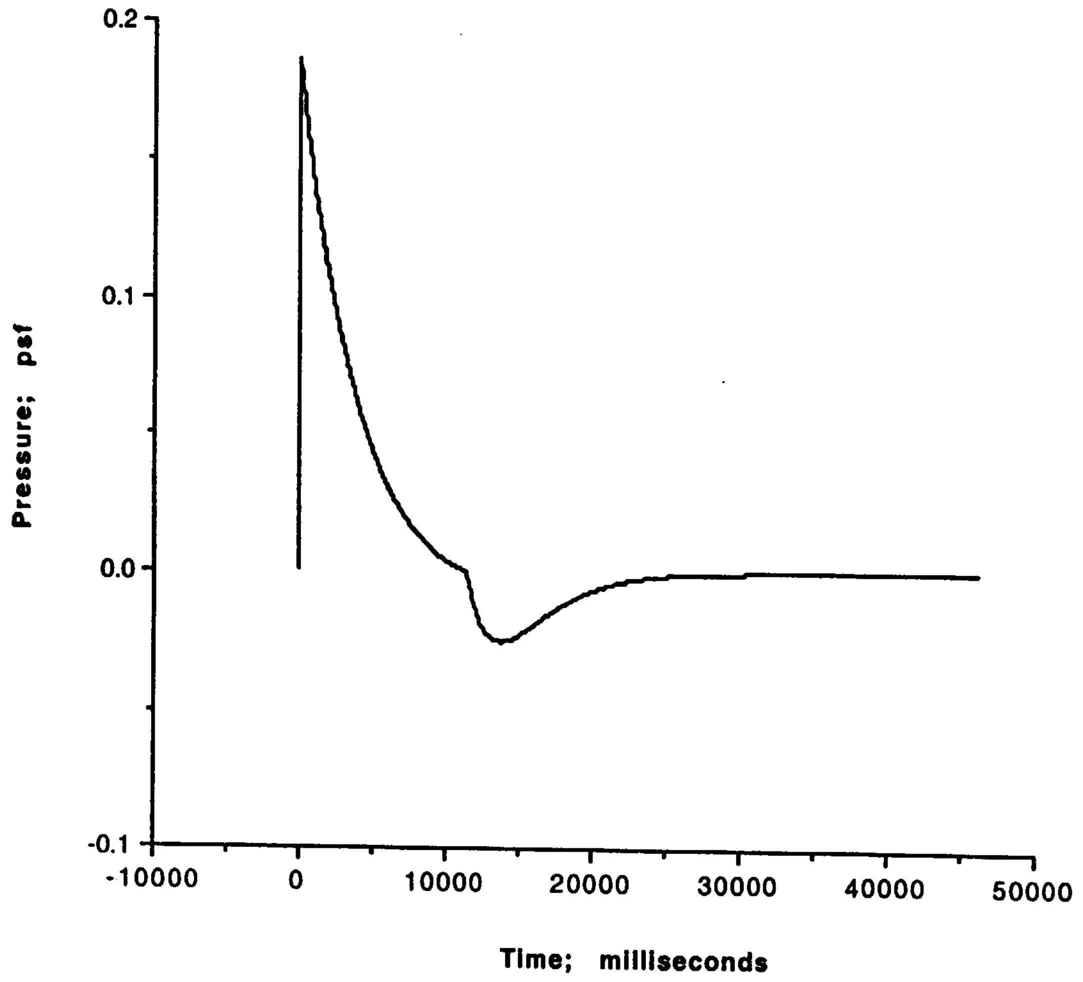


Figure B-6. Nonlinear spherical wave propagated 20 miles. Pressure doubling for reflection included.

Appendix C
Comparison of Predicted Spectra With Empirically Determined Spectra

As another check on the analysis, a comparison with measured data was desired. Conditions directly comparable with those of Flight 800 were not available. However, the spectrum for an explosion of 5 pounds of TNT was available for an observer 10 miles away from the explosion. This explosion was on the ground, as was the observer.[1]

An empirical prediction valid for air to ground propagation from the explosion of 20 pounds of TNT may be obtained from this data in several steps. First, the spectrum is corrected by adding 3 dB to account for the difference between ground to ground and air to ground propagation. Then, 6 dB more must be added, in addition to shifting the spectra down 2/3 octave to account for the change in source strength from 5 pounds of TNT to 20 pounds of TNT. Finally, a correction of 11.5 dB is added to the empirical estimate to account for the difference in averaging time used, 1 second for the empirical estimate, and 70 milliseconds for the numerically obtained theoretical prediction. The resulting spectra is presented in Figure C-1, which may be compared with the spectra given for Observer 44 in Figure C-2. Note that Observer 44 is approximately 10.2 miles from the point of the explosion. Given the nature of the corrections, and the fact that the predicted spectra includes the effects of winds, temperature gradients and other atmospheric variables not accounted for in the empirical prediction, and the variation in spectra which is introduced by various values of the rise time, the comparison must be considered quite good. Thus it may be concluded that the overall prediction provides a signal which is a reasonable prediction of the disturbance which might be provided by the explosion of Flight 800's center fuel tank.

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[1] "The statistics of Amplitude and Spectrum of Blasts Propagated in the Atmosphere," Construction Engineering Research Laboratory Report N-13, Volume II, Appendices C through E, November 1976, Schomer, Goff, and Little, Figure D-39.

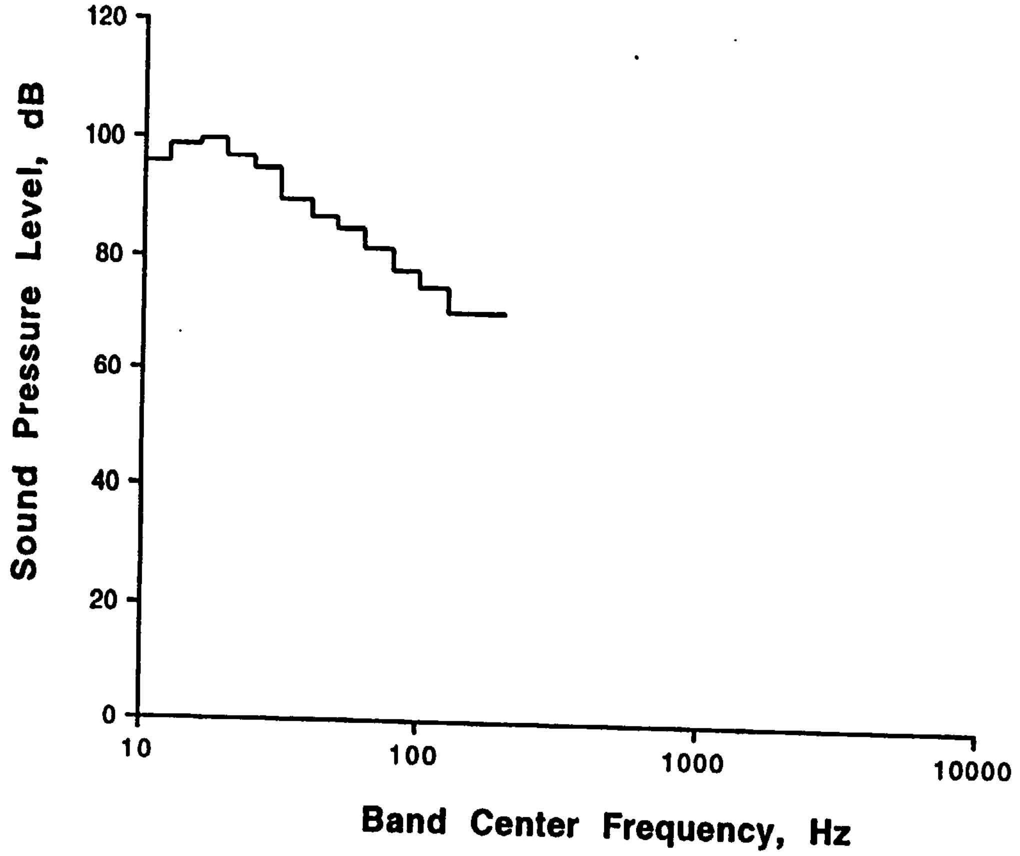

Figure C-1 Empirical prediction of 20 pound TNT blast at 10 miles, air to ground, zero gradient conditions.

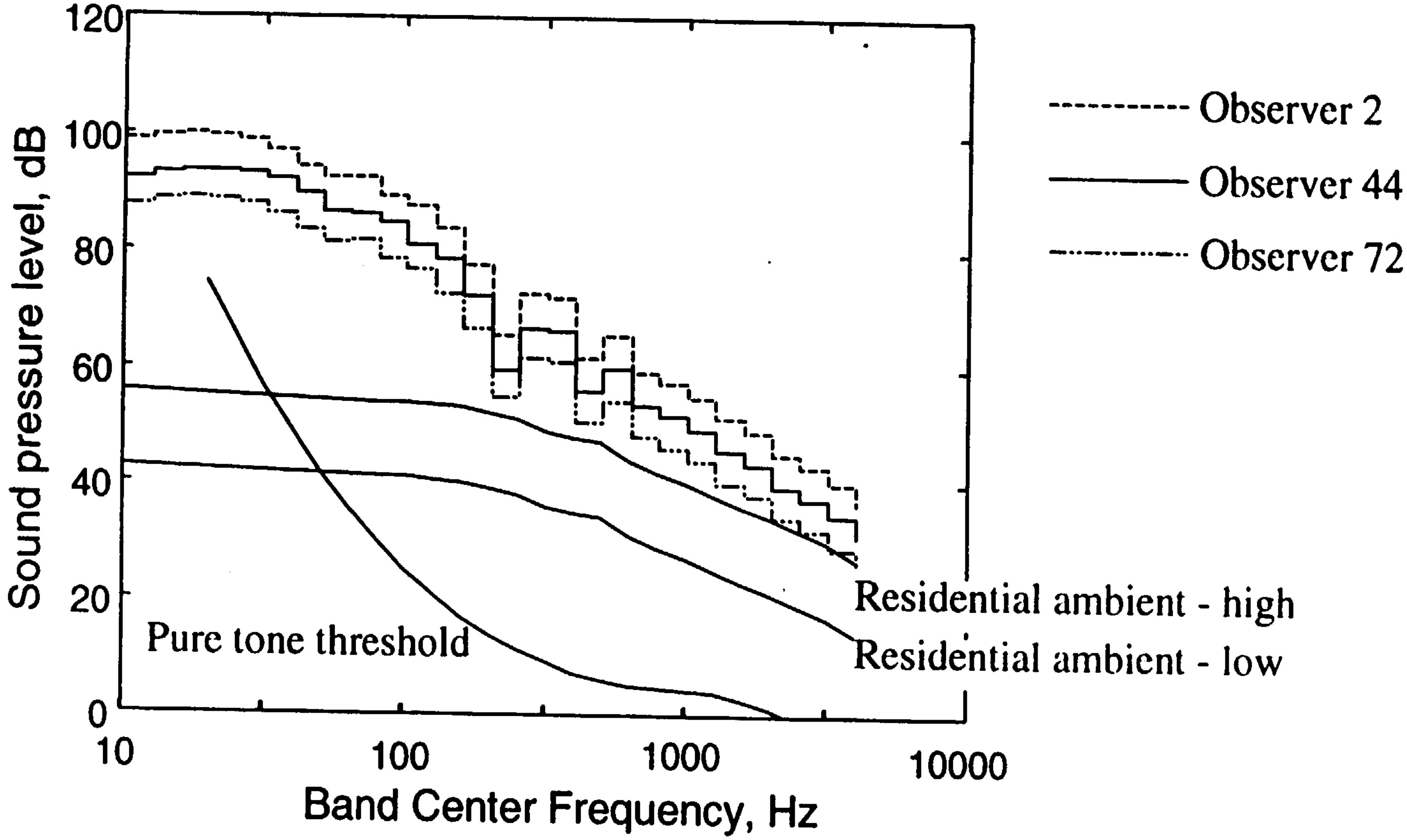
One-third octave band spectra

Figure C-2. One-third octave band spectra for signals at observers 2, 44, and 72. Rise time is 5 milliseconds.

Appendix D
Comparison of Predicted Signal With Waveforms Predicted by ANSI Standard S2.20-1983

A further check on the predictions is obtained by comparing the predicted signal's properties with those obtained by application of ANSI Standard S2.20-1983, "Estimating Airblast Characteristics for Single Point Explosions in Air, With a Guide to Evaluation of Atmospheric Propagation and Effects." The waveform predicted by the standard is identical to that presented in Figure D-1. Two characteristics of this waveform that may be used to verify the accuracy of the predictions of the Thomas code are the peak amplitude of the waveform, and the positive duration of the waveform. See Figure D-1.

Figure D-2 presents the nominal peak overpressure, as predicted by the standard. The effects of wind are given in the standard as variation around the nominal by a factor of two. The curves for the high and low peak pressure are also presented in Figure D-2. The predictions for the peak overpressure as given by the Thomas code are presented as black diamonds. Clearly the predictions fall within the range of expected values as given by the standard. The positive duration predicted by the standard is about 15 milliseconds, the same value given by the Thomas code.

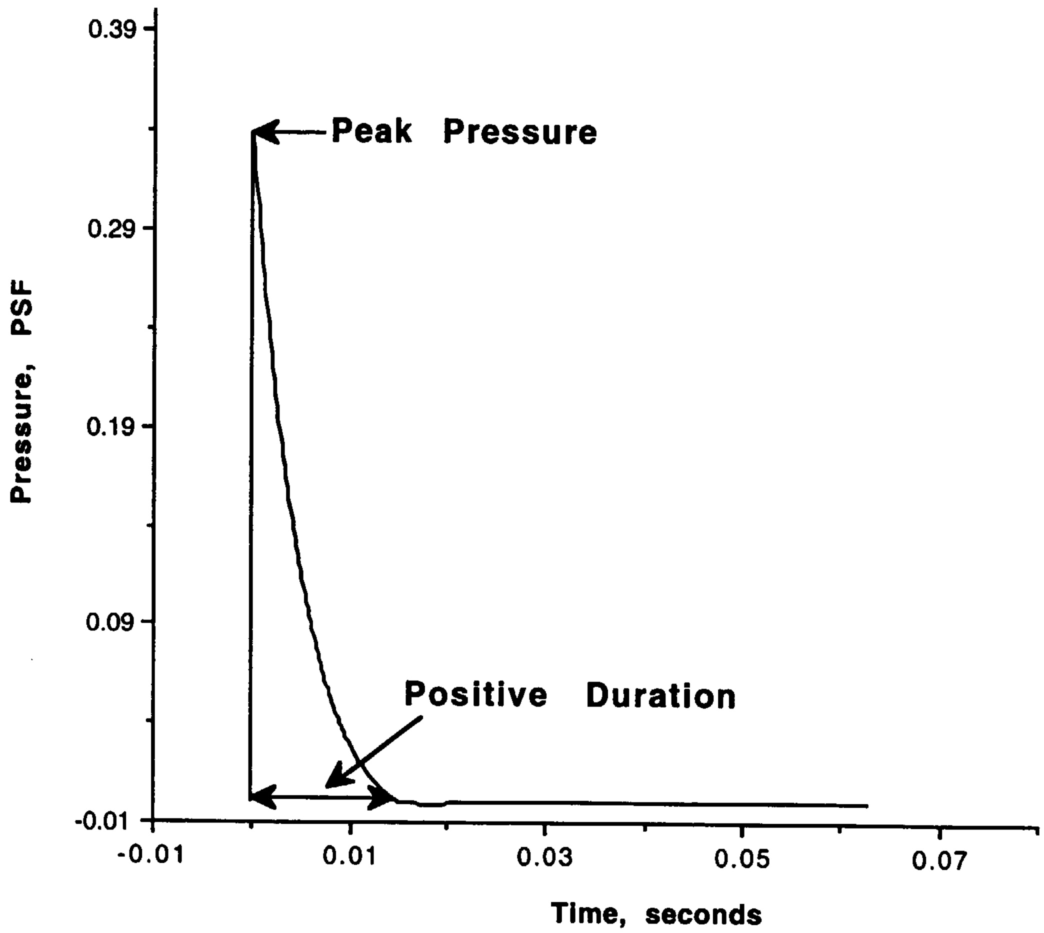

Figure D-1: Waveform at observer 2; Definition of peak amplitude and positive duration.

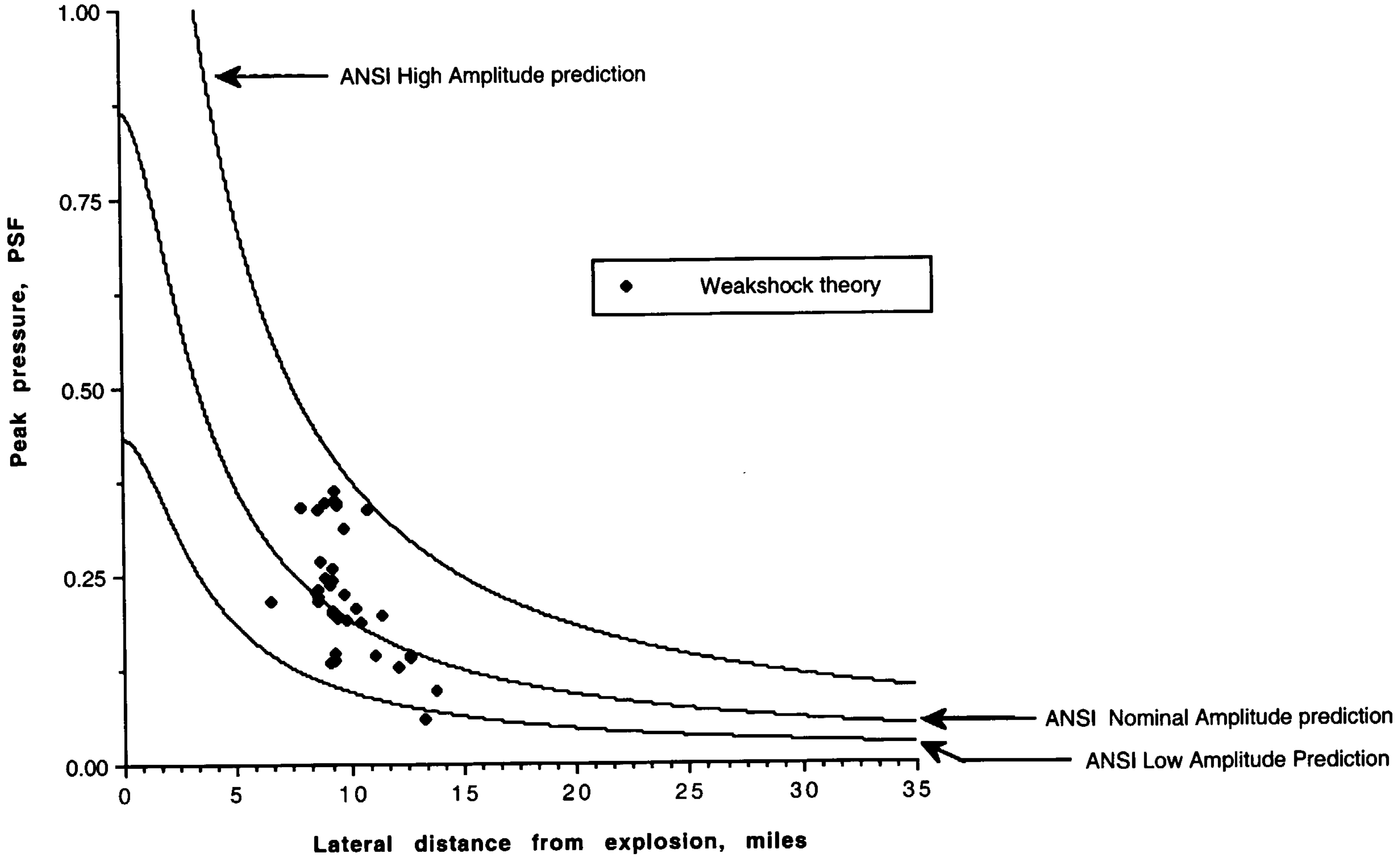

Figure D-2. Comparison: Weakshock theory and Geometric acoustics COMPARED with ANSI Standard