MODEL STUDY OF AIRCRAFT NOISE

REVERBERATION IN A CITY STREET

by

LALIT PANDE

B. Tech., Indian Institute of Technology, Delhi
(1970)

SUBMITTED IN PARTIAL FULFILLMENT

OF THE REQUIREMENTS FOR THE

DEGREE OF

MASTER OF SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

January, 1972

Signature of Author ____________________

Department of Mechanical Engineering, January 21, 1972

Certified by ____________________

Thesis Supervisor

Accepted by ____________________

Chairman, Departmental Committee on Graduate Students

MODEL STUDY OF AIRCRAFT NOISE REVERBERATION IN A CITY STREET

by

LALIT PANDE

Submitted to the Department of Mechanical Engineering on 21 January 1972 in partial fulfillment of the requirements for the degree of Master of Science.

ABSTRACT

Experimental studies of sound propagation from a source situated above roof top level in an urban environment have indicated the amplification and shielding effects of buildings. These experiments have been supplemented by diagnostic tests with a spark source which indicate the paths of propagation and their contribution to the received sound. A criterion for reverberation in a city street due to an aircraft is developed in terms of images formed. Charts indicating the amplification or shielding of noise from low flying aircraft are presented.

Thesis Supervisor: Richard H. Lyon
Title: Professor of Mechanical Engineering

ACKNOWLEDGMENTS

I take this opportunity to thank Professor Richard H. Lyon for his ideas, patience and encouragement.

I would also like to thank Mrs. Betsy Buckley for the typing.

This work was done under contract number DOT-TSC-93 from the U.S. Department of Transportation. Thanks are due to Captain J.E. Wesler for his interest.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

CHAPTER I

INTRODUCTION

This work was initiated to study the reverberation effects in a city street from a noise source situated above the buildings. It is concerned with the development and definition of reverberation in a city street due to aircraft noise. It attains special significance in understanding the propagation of sound in an urban environment from low flying aircraft, e.g., V/STOL and helicopters.

This situation is complicated by the fact that it does not correspond either to sound propagation in a completely confined space or in a free field. Most studies of aircraft noise have concerned themselves with open-terrain conditions. They have not considered the effect of buildings - especially when the buildings are high and the altitude of the aircraft is low. Sound propagation in urban areas from sound sources placed in the street have been studied to develop outdoor sound communication systems in urban areas [1]. Reverberation effects in a city street due to a noise source at ground level have been studied to determine the spatial characteristics of the sound field [2].

The experimental study described here was, therefore, undertaken to find out the effect of buildings on the propagation of sound from aircraft to street level. Moreover, this leads to an understanding of "reverberation" in city streets. Such definitions have been developed for room acoustics and for underwater sound propagation [3,4].

An experimental study on a 1:32 scale model was undertaken. Modeling techniques have been used extensively in architectural acoustics [5]. It was particularly suitable that a model analysis be attempted in the present situation of urban noise propagation because of (a) the complexity of the problem, (b) the practical limitations on an actual field study, and (c) a situation where the calculations from a mathematical model are neither available nor easily obtained.

Two approaches have been used - a simulation study using a steady-state broad-band aerodynamic noise source, and diagnostic tests using a spark source. The transient experiments are particularly helpful in identifying propagation paths and in studying the reverberation effects in terms of images.

The use of transient sources, either spark gaps or tone bursts, is not a new concept in the study of room acoustics. It has been used in model studies [5] for impulse response tests. Schroeder [6] has shown that reverberation times can be measured by tone bursts.

To describe the reverberation effects in city streets we have used the concept of images. This has been used earlier to describe the acoustics of rooms. Mathematically the transient response of rooms can be studied either by a normal mode point of view or in terms of sources and images. Lyon [7] has described the statistics of direct and reverberant field amplitude distributions of noise in nearly hard rooms using superposition of pulses. Bolt et al [8] have studied the pulse statistics of rooms by replacing the walls by an array of images sources. This has been used to derive expressions for quantities such as reverberation time and mean free path.

Taking a directive from these works, instrumentation and data reduction techniques were developed which could be used for a model study of reverberant effects in city streets. These are described in subsequent chapters. The effect on the sound pressure field due to the presence of the buildings was isolated and led to the development of shielding and amplification effects as compared to open terrain propagation. The effect of the buildings in providing reflecting surfaces which increased the number of paths whereby sound could reach an observer, whether the source was in direct line of sight or not, was noted as an important effect and led to the concept of "reverberation".

By the application of geometrical acoustics, ray tracing was used to find the number of images formed when a source traverses a linear street at varying heights. The experimental results are correlated to the images and an objective definition for reverberation is developed. Charts for varying geometries are presented on which zones have been drawn which show the number of images that will be formed for an aircraft position relative to an observer situated at the street level. This may prove useful to urban designers and aircraft operators.

CHAPTER II

REVERBERANT SOUND FIELDS

Acoustical phenomena can be studied in terms of three elements:

(a) source,

(b) path of propagation,

(c) receiver.

The sound energy reaching a receiver is affected by the path of propagation. There are two phenomena which can substantially alter the direct sound energy field at the receiver: reflection and scattering. These have led to the distinction between the direct field and the reverberant field.

The more commonly understood concept of reverberation is that of a sound field in an enclosed space. The sound energy reaching a listener in an enclosed space consists of two parts - the direct sound and the reverberant field. By definition, a direct sound field exists until a wave from the source has undergone its first reflection.

The reverberant sound field comprises all sound waves after they have experienced their initial reflection. The reverberant field arises due to the reflections of the direct sound in an enclosed space. If the source of sound is operated continuously, the acoustic intensity at any point in the enclosure builds up to higher values than would be true if the source were operated in open space. The equilibrium value of the sound field is dependent on the absorption characteristics of the enclosure.

The name "reverberation" is also applied to a phenomena occurring in underwater sound propagation. Underwater reverberations are the combined effect of numerous scatterers in the body of water, and the scattering from waves in the surface as well as irregularities in the bottom. The effect of this reverberation is once again to alter the direct field from the source to the transducer.

Let us consider a source of sound in a room. If the sound source is started in the room, it takes a certain finite time to build up to a steady-state value. Much work has been done in the field of room acoustics and auditorium design concerning quantitative measurements of reverberation. There are two aspects in studying this problem; (a) the spatial distribution of the sound field in a room in terms of the pressure amplitude distributions in the direct and reverberant field, and (b) the temporal response of the enclosure to a transient sound.

The temporal characteristics of a room are studied in terms of the room's "reverberation time" or the response to a transient pulse. Reverberation time for a room has been defined in terms of the time (in seconds) required for the intensity to be reduced by 60 dB. This can be measured by recording the decay curve obtained after turning off a steady-state noise source which is used as an excitation signal in the enclosure. Reverberation time can also be measured using tone bursts and Schroeder [6] has shown that a simple integral over the tone burst response of the enclosure yields, in a single measurement, the ensemble average of the decay curves that would be obtained with bandpass-filtered noise as an excitation signal.

To simplify measurements and to obtain a correlation with subjective measurements other criteria have been developed. We can briefly comment on these. One is the ratio of early energy and reverberant energy which is the ratio of the energy from a short pulse or tone burst arriving within the first 50 msec after the direct sound, in proportion to the total energy.

To study the subjective characteristics of a hall Beranek [9] has studied the response of a room in terms of the time between the direct sound pulse and the first of the train of reflected sound pulses. The subjective quality of sound in a room is very much affected by the times and energy of the reflected sound. However, in determining the position of a sound source, the ear apparently makes use only of the first pulse of each train.

Mathematically, the response of rooms can be studied from a normal mode point of view; or in terms of a source and its images, essentially a ray technique. Lyon [7] has considered the direct and reverberant field amplitude distributions in nearly hard rooms by considering a point source to emit a Poisson sequence of pulses. Source statistics are reproduced in the direct field, and the reverberant field tends to normality independently of the source distribution for sufficiently reverberant spaces. Moreover, the direct and reverberation field statistics can be considered to be independent for short pulses. This has been done by studying the probability distribution of pressure amplitudes in a room theoretically and experimentally.

Bolt et al [8] have studied the transient response of rooms by replacing the walls by an array of image sources (simple images if the walls are hard, or appropriately modified if there is absorption). These image arrays are then considered statistically to derive quantities like reverberation time and mean free path. Analyzing the detailed nature of discrete reflections including interference effects, one can also obtain an average correlation between room geometry and the character of its pulse response.

Schroeder [10] has used digital computers for reverberation studies based on geometrical acoustics and by refined ray tracing techniques. This has indicated the dependence of the reverberation time on the shape of the enclosure and the distribution of the sound absorbing materials.

All this naturally leads us to believe that we should expect some reverberation effects in a city street. The characteristics can be studied in terms of images and generalized to predict the reverberation effects. Experimental studies carried out confirm these ideas.

CHAPTER III

EXPERIMENTAL STUDIES

We are interested in finding out whether there is any difference in the sound energy distribution in a city street as compared to open terrain due to reverberation. Moreover, we wish to correlate this effect with the reflections from a building.

One way of getting information about complex situations is by means of models. The propagation of sound in urban areas is a very complicated problem. If we idealize the situation, then by making measurements on a small scale we can apply the results directly to large scale situations with the aid of a simple scaling factor. The concept of modeling an urban terrain for aircraft noise has been described by Lyon et al [11]. Beside geometrical similitude, one has also to consider absorption effects.

The fundamental scaling relationship in acoustics is the ratio of sound wavelength λ to geometrical length L. Thus, if the speed of sound in the medium remains unchanged, the constancy of the ratio L/λ requires that fL be constant also. This can be easily derived from the Helmholtz equation governing the sound pressure:

$$(\nabla^2 + k^2)p = 0 \tag{1}$$

where $\nabla^2 \equiv \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$

$k = \frac{2\pi}{\lambda}$

$p = p(x,y,z)$ is the pressure at the point (x,y,z)

Forming new variables

$$x' = \frac{x}{L}$$

$$y' = \frac{y}{L}$$

$$z' = \frac{z}{L}$$

where L is a typical length, we get

$$\frac{\partial^2}{\partial x'^2} + \frac{\partial^2}{\partial y'^2} + \frac{\partial^2}{\partial z'^2} p(x',y',z')$$

$$+ (kL)^2 p(x',y',z') = 0 \qquad (2)$$

Both equations (1) and (2) will satisfy the same boundary conditions, and the wave field will remain unchanged as long as we keep $kL = \frac{2\pi L}{\lambda}$ constant.

The application of this result is that experiments on a model can be used to predict full scale effects. A 1:32 scale model was used. Since the aircraft noise energy lies mainly between 500 Hz and 4000 Hz, the model experiments are designed for experiments in the 16 KHz to 128 KHz range. The buildings were replaced by 1/2" thick plywood modules - these do not take into account the surface roughness effects, atmospheric turbulence, doors, windows, etc., which may be expected to alter the sound field distribution.

Experiments on the model were carried out with a steady-state noise source as well as a transient source. The factors to be considered in the selection of noise sources has been discussed in Ref. 11. The steady-state noise source is shown in Fig. 1. It consists of four intersecting jets through which air at 100 psi is passed. It produces a broad band noise having a spectrum level as shown in Fig. 1. The instrumentation used is shown in Fig. 2. A more detailed description of the source and selection considerations are given in Ref. 11.

The effect of the reverberant buildup due to the buildings is shown in Fig. 3a. This is an experimental record of the rms pressure in the 32 KHz octave band as received at the microphone when a steady-state noise source was traversed at a height of five feet above the ground across a linear street model configuration (Fig. 3b). Curve A corresponds to a situation where there were no objects in the path of propagation. Curve B corresponds to a situation where the sides of the street were covered with sound absorbing material. Curve C corresponds to the situation where the fuzz has been removed.

From Fig. 3a we see the difference in the sound pressure level received at the microphone under the three conditions. Curve A shows the sound pressure level under open terrain conditions. The buildings are now introduced with the streets lined with fuzz. The levels drop off as indicated in Curve B. This is the effect of imposing barriers which cut off the direct sound. The effect of reflections from the buildings is shown in Curve C. The levels in Curve C are consistently higher than in Curve B, even when there is no line of sight. This amplification effect is due to reflections and the multiple paths of propagation from source to receiver. This clearly indicates that there is a reverberant field.

To generalize the results to full scale conditions the analysis of noise levels in the model is carried out for each octave band of interest. The experiments consist of traversing the noise source over the model and measuring the sound pressure level in each octave band for an observer at street level as a function of source position.

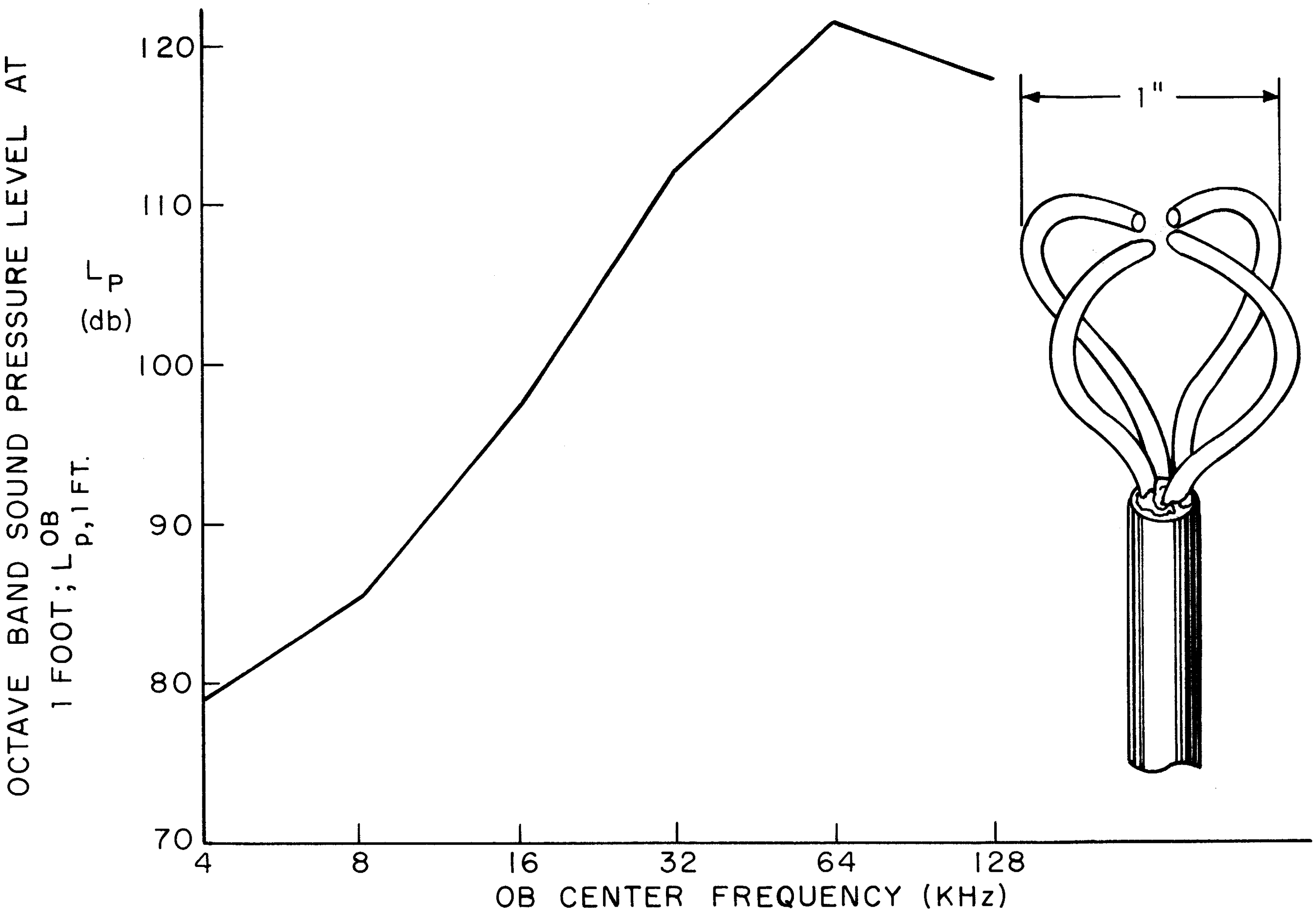


Fig. 1. Spectrum of Steady-State Broad Band Noise Source, Measured at 1 foot.

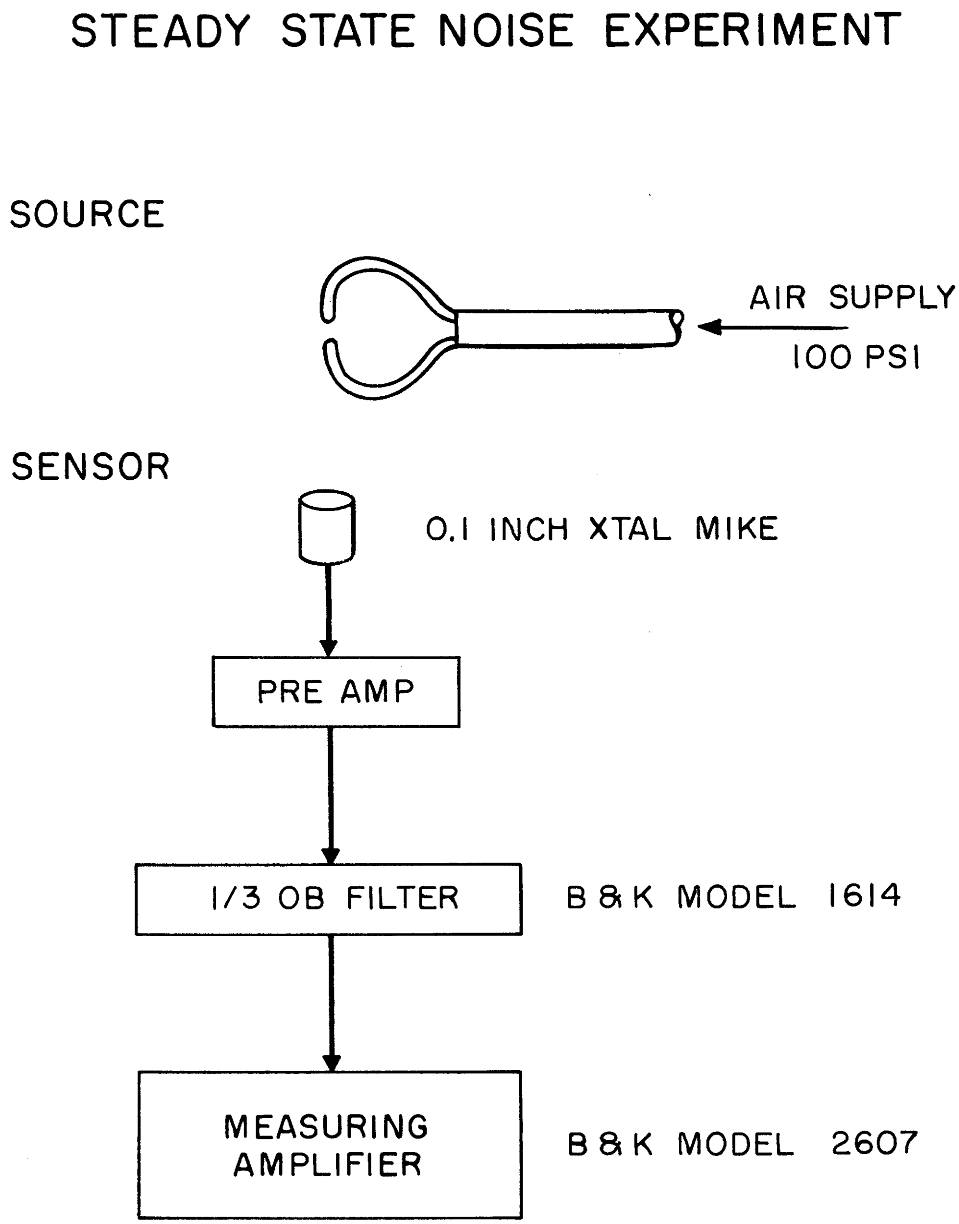


Fig. 2. Line-up of Steady-State Instrumentation

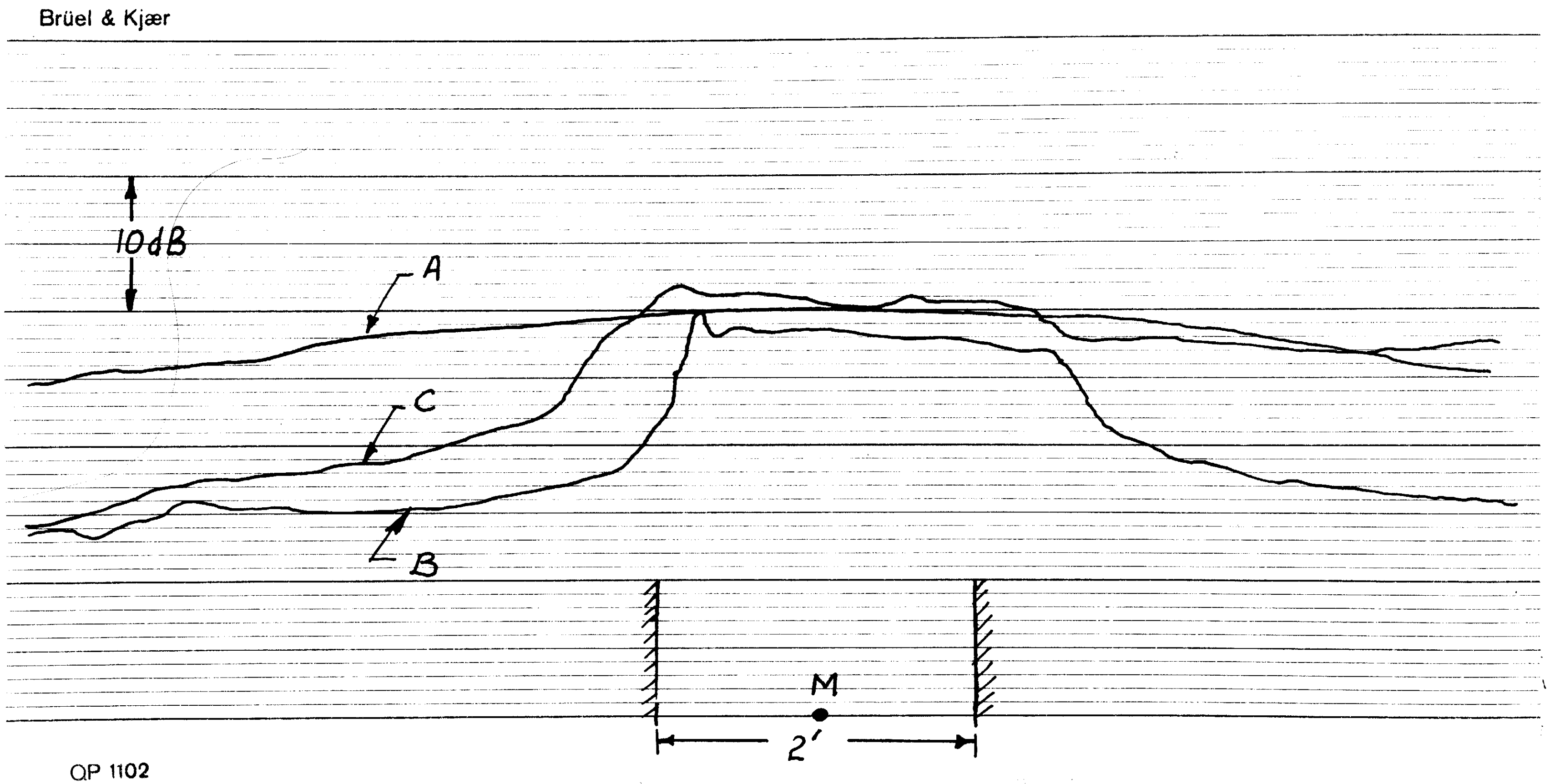
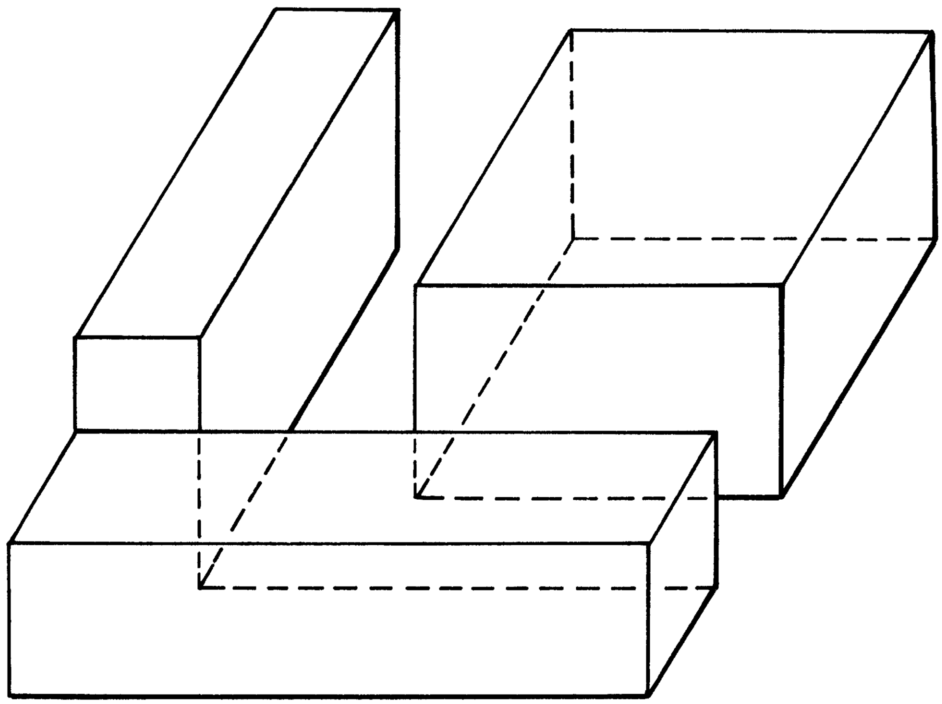
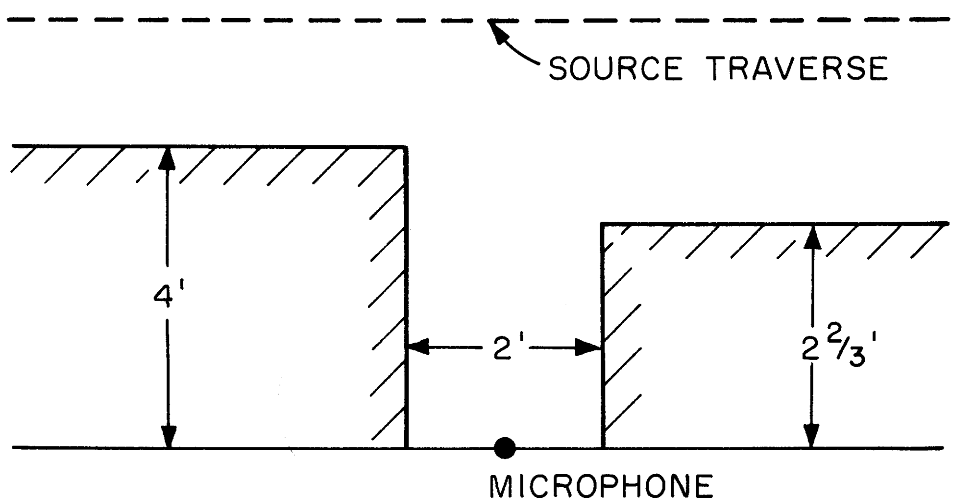


Fig. 3a. The Variation of Sound Pressure Level as a Function of Source Position for Flyover Across a Linear Street Model [rms Pressure Level in the 32 KHz OB Recorded at M]



MODEL CONFIGURATION FOR STREET
OVERFLIGHT EXPERIMENTS



LINEAR STREET

Fig. 3b

Simulating a flyover in a model experiments allows much more control over the experiment than one has in a field situation. We are able to choose a particular geometrical layout of streets and buildings along with the position of the microphone. Moreover, we can move the source at a constant desired height, and can hold it stationary at one position if necessary.

To get meaningful results and to present them in a form enabling us to compare with open terrain conditions the procedure adopted was as follows. The experimental results provide us with the sound pressure level received at the microphone for a particular source position. These levels are recorded in the different octave bands having center frequencies from 4 to 128 KHz corresponding to the full-scale frequencies 125 Hz to 4 KHz. From this data we wish to obtain the transmission gain TG due to the geometry as defined by

$$TG = L_p - L_{p(1\ ft)} + A_g + A_a$$

where A_g is $20 \log r/r_o$, r is the distance from the source in feet

$r_o = 1$ foot

A_a is atmospheric attenuation in dB

L_p is the sound pressure level in dB at the point of observation

$L_{p(1\ ft)}$ is the sound pressure level of the source measured at 1 foot in an anechoic chamber.

The calculation of TG is carried out for each octave band and combination of source receiver positions.

The spectra and levels for a helicopter flyover over open terrain are also calculated. These are based on data for helicopter vortex noise assuming isotropic radiation [12]. The equation for the overall sound pressure at 30 ft from the helicopter is taken from Ref. 12:

$$L_p^{30'} = 10 \log [6.1 A_b V_{0.7}^6] + 20 \log C_L + 126 \text{ (dB)}$$

where we have taken the blade area $A_b = 72$ ft^2, the blade speed at the 70% span position to be $V_{0.7} = 500$ ft/sec, and the blade lift coefficient to be $C_L = 0.4$. Since our scaling is 1:32, this corresponds to our band pressure levels at a distance of 1 ft. From the spectrum of vortex noise given in Ref. 12, the sound pressure level in each full scale band relative to this overall level is as follows.

Frequency (Hz)	500	1000	2000	4000
Level relative to overall (dB)	-4	-7	-9	-13

Geometric spreading is taken into account to predict levels at the microphone location assuming open terrain propagation. Atmospheric attenuation at audible frequencies for the distances involved here may be neglected.

The values of Transmission Gain (TG) are now superimposed on these levels for each octave band (with the data for the 32 KHz octave band in the model corresponding to the full scale 1 KHz octave band) and corresponding positions. Figure 4 illustrates how this is done. The solid lines show the open terrain values obtained from the helicopter noise spectrum. Superimposed on them is the TG value obtained in the model for each position.

Using these octave band levels, we have computed the perceived noise level (L_{PN}) for open terrain and for flyover across a street. The procedure for computing L_{PN} is that described in Ref. 4.

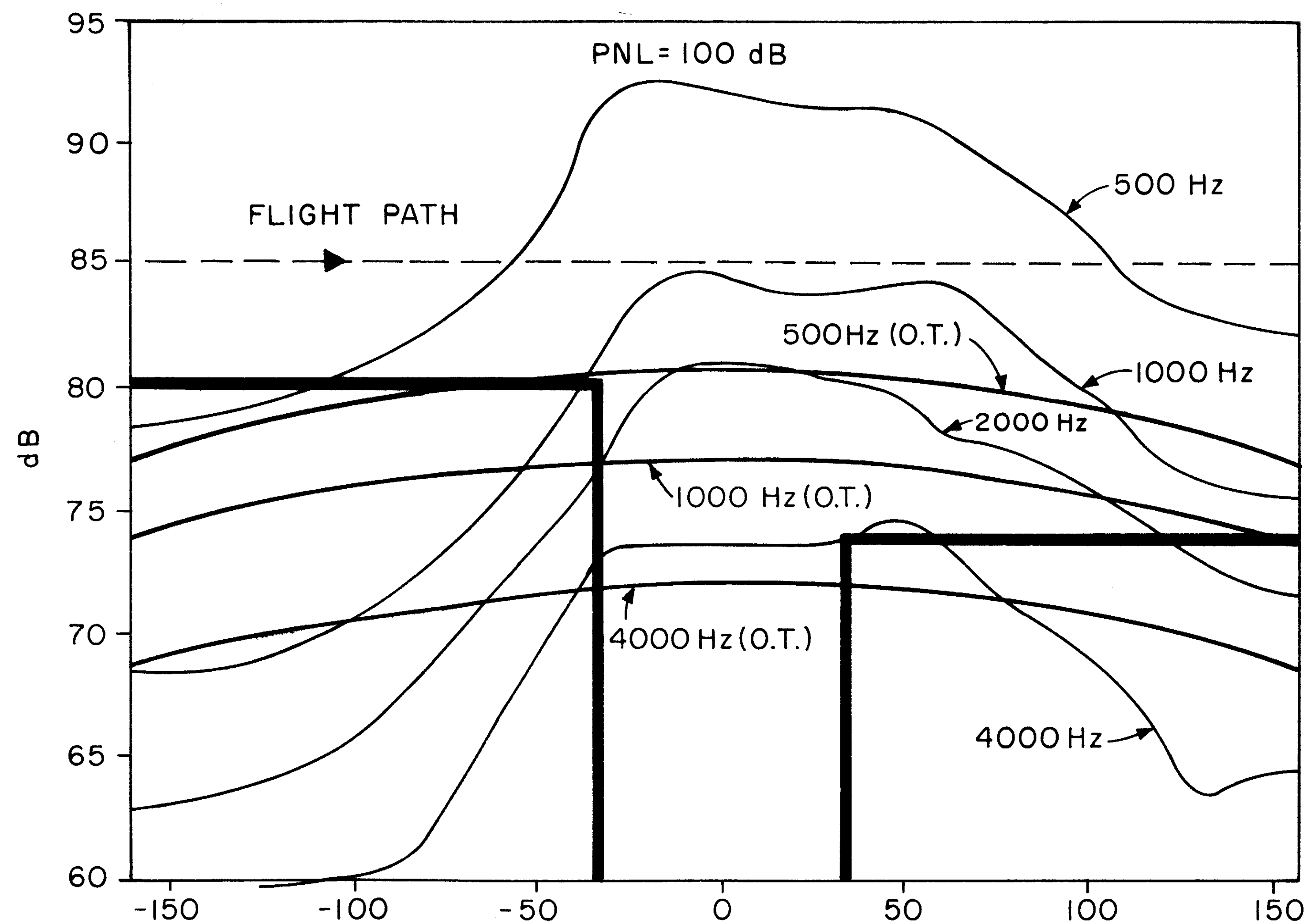


Fig. 4. Measured Band Levels and Calculated Open Terrain Band Levels for Same Flyover

The first question that arises is whether there are general differences between the "urban" noise levels and those computed for open terrain. To this end, we find from Fig. 5 that there are conditions of amplification of the noise when the levels are higher than those to be expected for an open terrain, and also there can be shielding effects when the levels are lower. Several other examples of such experiments are given in Ref. 11. They also consider the effect of a longitudinal flyover over an L-shaped street. The data reveal the reverberant buildup in a city street.

Transient Experiments

A set of transient experiments were used to find the impulse response of a linear street and to study the reflection effects. For these diagnostic tests we require a source that generates, a short, highly reproducible sound pulse with appreciable sound energy in the octave bands from 16 to 128 KHz. A spark source that meets these requirements has been developed (Fig. 6). The gap is powered from a 4-μf capacitor charged to 2 KV. To trigger the gap and to be sure that the capacitor is fully charged before it is discharges we use a trigger spark gap (EG&G GP-11B). The current that flows through the spark gap is controlled and we can obtain a constant pulse shape. The trigger module (TM-11) provides a fast rise pulse and can be used to fire the spark either manually or automatically in a repetitive mode.

A spectrum of the peak sound pressure when electronically processed as described below is shown in Fig. 7. The waveforms of the sound pulse produced when passed through a third octave filter is shown as an inset in Fig. 7. The duration of the pulse is short enough so that the differences in path lengths of a few inches may be resolved. The log rms of the fil-

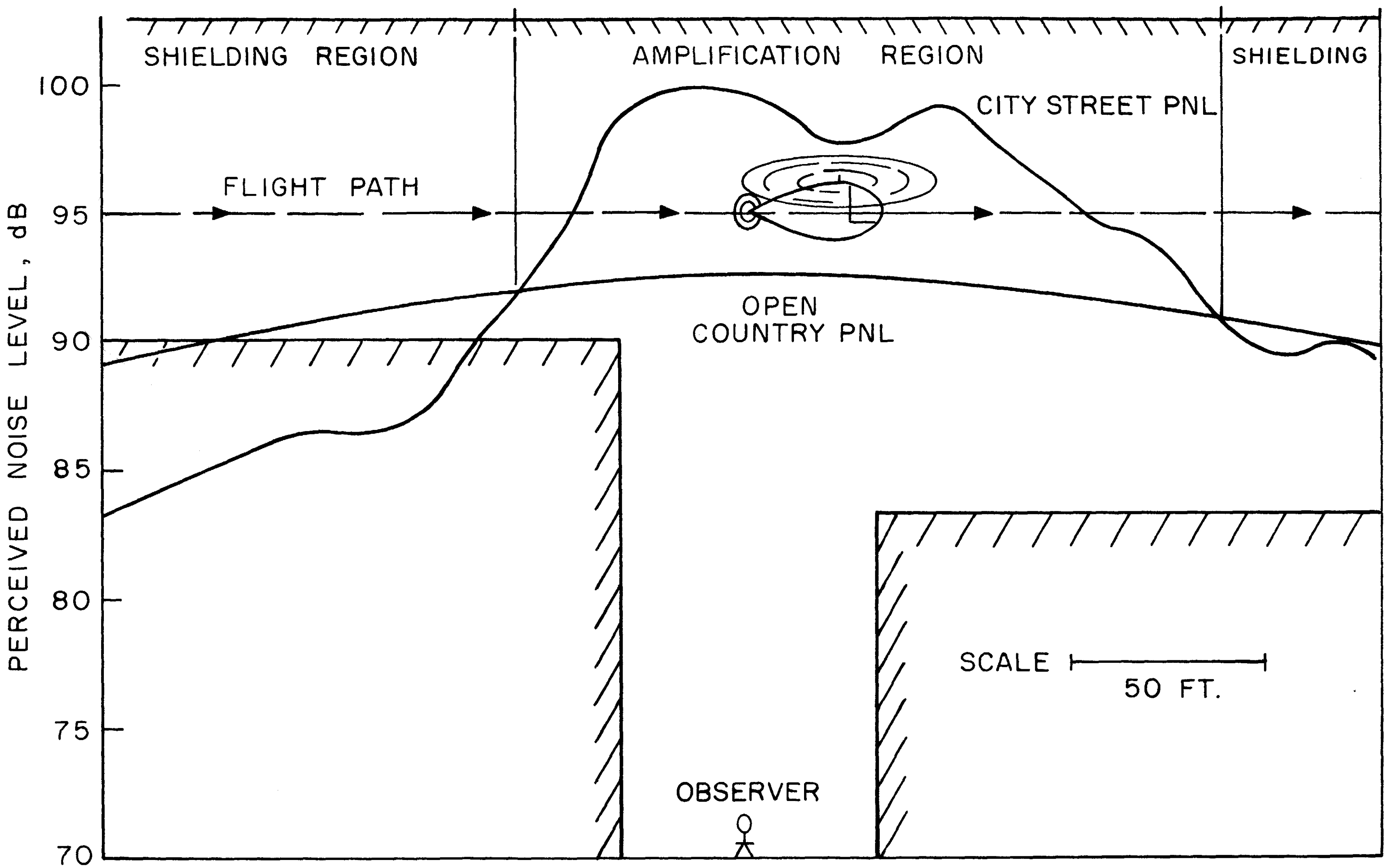


Fig. 5. The Variation of Perceived Noise Level as a Function of Source Position for Flyover Across a City Street

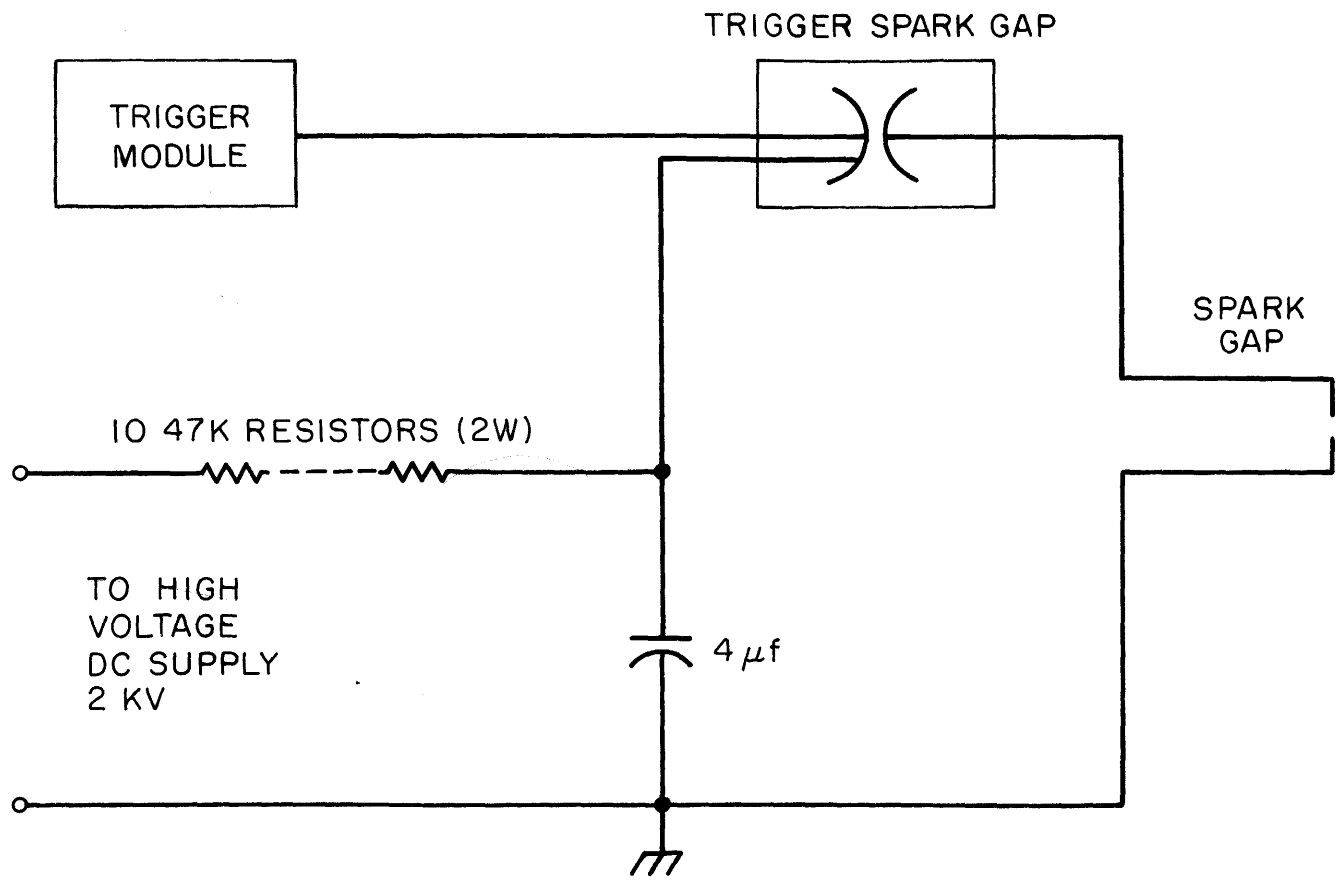


Fig. 6. Schematic of Circuit Diagram for Spark Gap Transient Sound Source

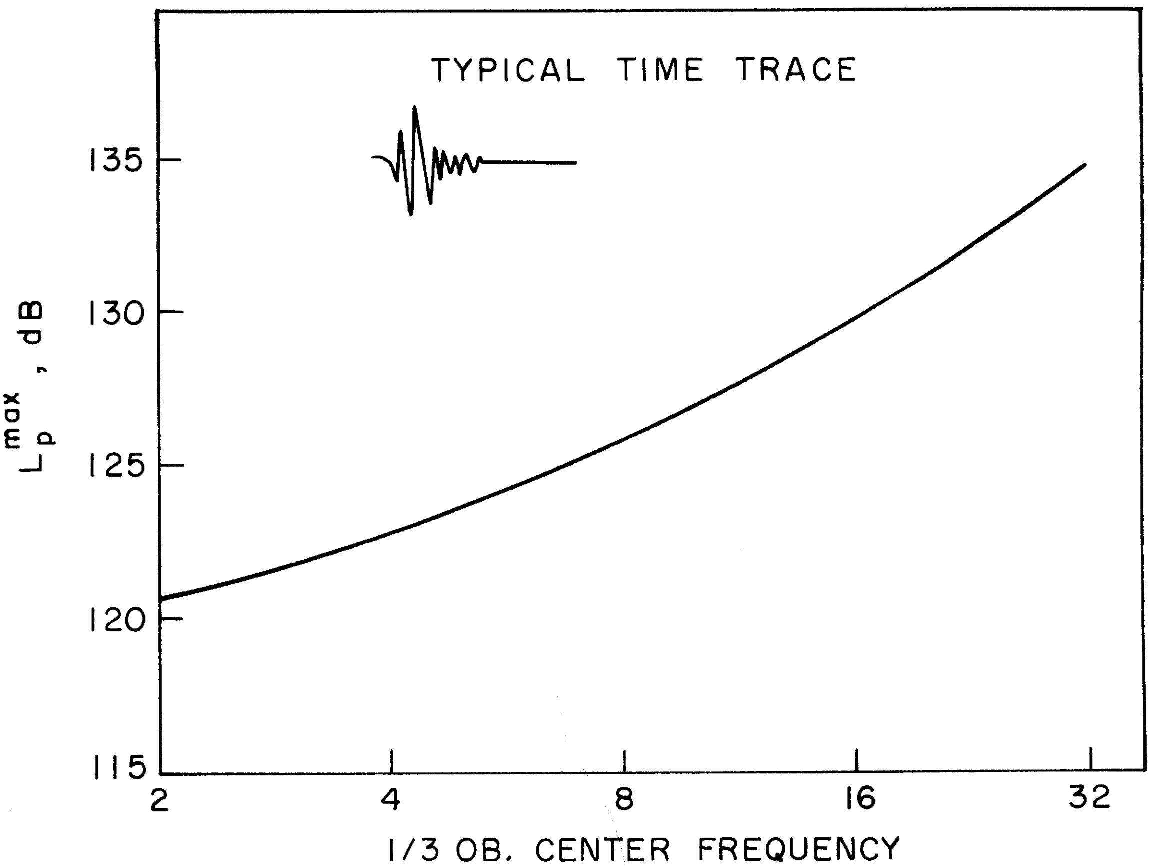


Fig. 7. Energy Spectrum of Spark Source in 1/3 Octave Bands

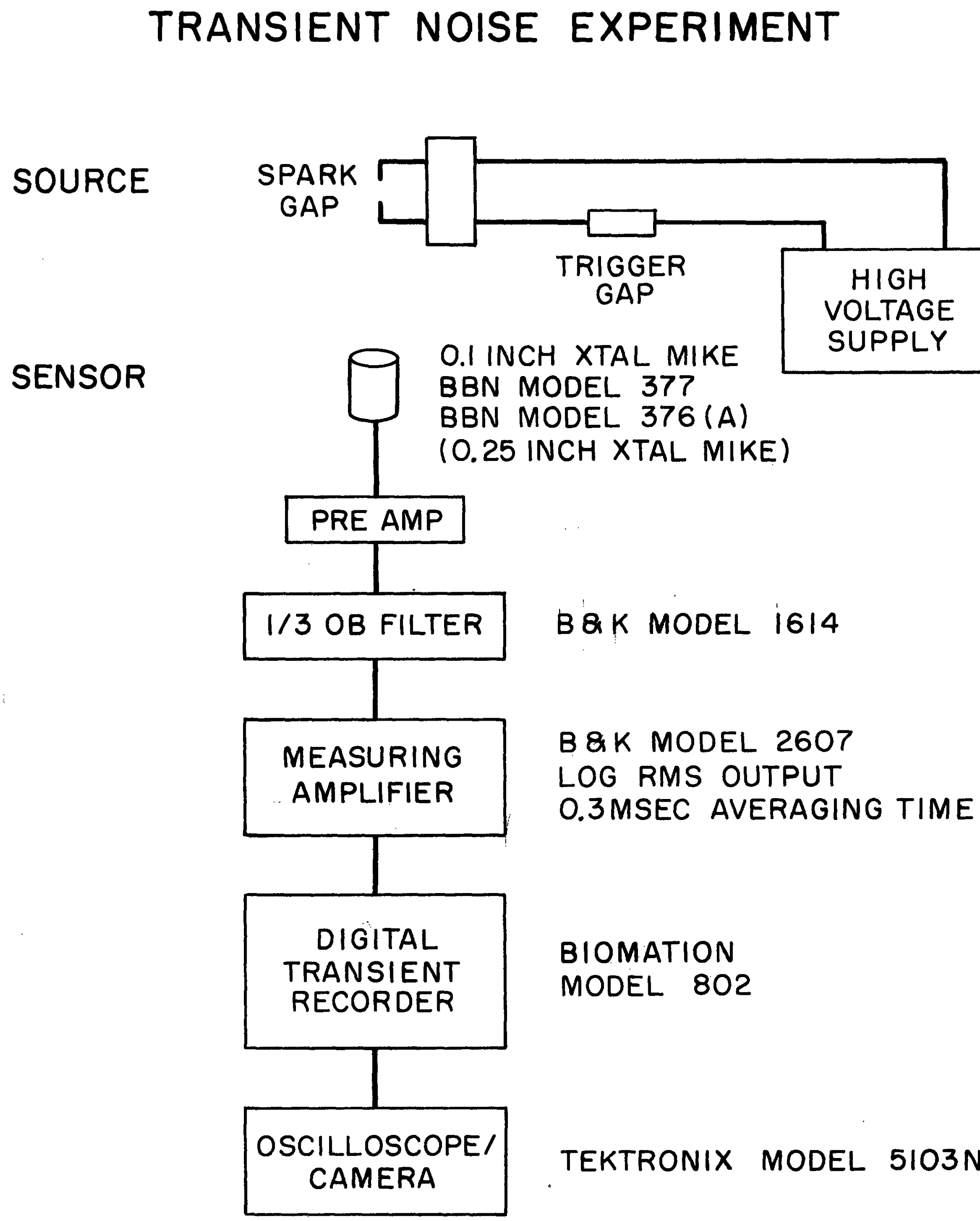


Fig. 8. Equipment Line-up for Transient Experiments

tered pressure signal is displayed and photographed from the oscilloscope face. In most cases, only the first 20 milliseconds of this signal have been recorded since this period includes the most prominent paths of propagation in terms of energy content. The oscilloscope was adjusted so that one vertical centimeter on the face represented 10 dB.

The formal derivation of the equivalence between steady-state noise and transient pulses has been used earlier for correlation of steady-state and transient experiments [11]. These indicated good agreement between the steady-state experiments and showed that we could use the temporal structure of the pulse train at the receiver to determine the paths of propagation and use the amplitudes of individual pulses to determine the relative contributions of each path to the mean square pressure at the receiver for a steady-state noise source.

The experiment was therefore designed to find the path of propagation and the reflections caused by the building surface. A linear street configuration was used and experiments carried out in 32 KHz octave band. This corresponds to the 1000 Hz octave band in full scale. The microphone was at the center of the street and the source position was varied. The time pattern of the signal was recorded under two conditions

(a) with the sides of the street lined with sound absorbing material

(b) with no sound absorbing material.

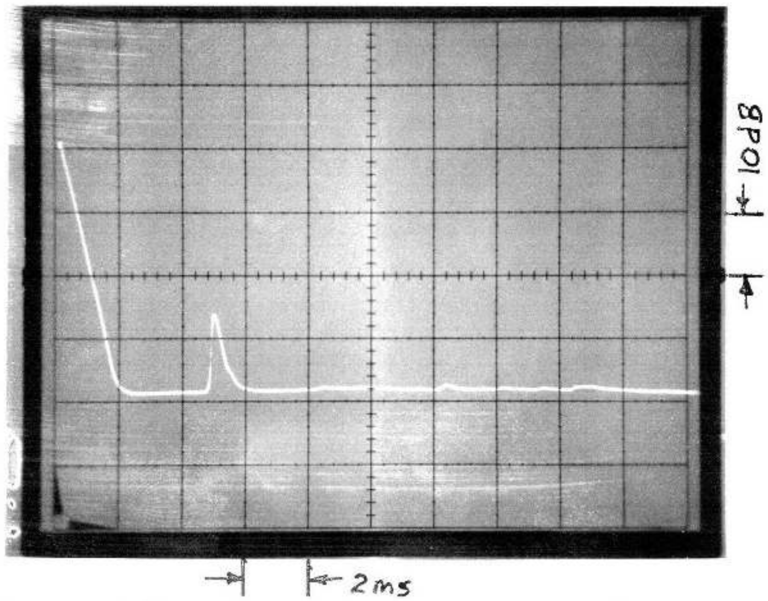
The difference between the two configurations was in the path of propagation that a sound pulse could take from source to receiver. Figures 9 to 13 clearly indicate the additional paths provided by the reflecting surface of the buildings. The positions of the source are shown in the scale drawings of Figs. 14 to 18. The results of these experiments are explained as follows. Consider Figs. 9 to 18. These show the time patterns and the scale drawing showing the various paths. The first peak in each photograph represents the direct pulse. When there is no sound absorbing material the subsequent peaks are reflected pulses. With the streets lined with fuzz the situation changes - no signal is received if there is no line of sight; and only the direct pulse is received in case of a direct line of sight - the reflections are absorbed.

Consider Fig. 9b. The first pulse arrived after a time of 4.8 msec which corresponds to a propagation distance of 5.4 ft (taking the speed of sound to be 1127 ft/sec). This corresponds to the direct distance of 5.4 ft as measured from the scale drawing Fig. 14. The second pulse corresponds to a time of 5.3 msec or a propagation distance of 5.95 ft. This corresponds to a ray emanating from image S_1 in Fig. 14. This does not appear in Fig. 9a because the fuzz lining the street has prevented the reflected ray from reaching observer O. The reverberant effect of the street is clearly indicated.

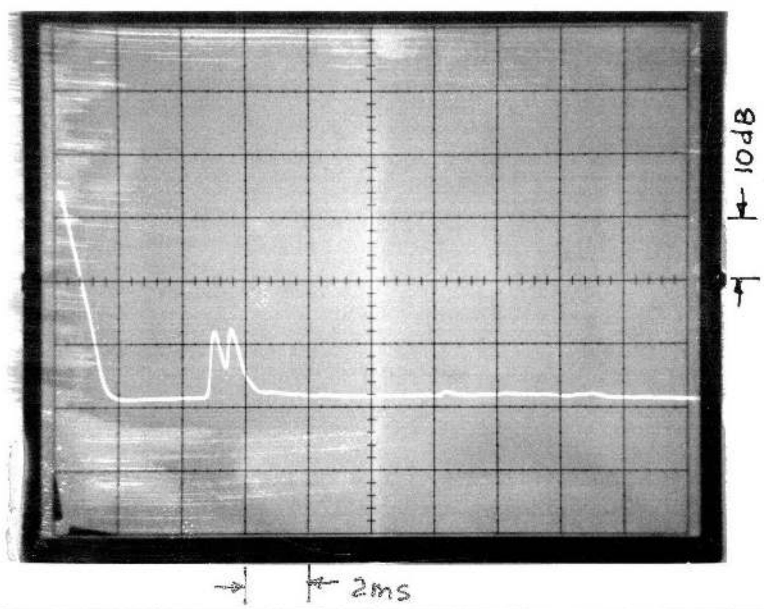
Consider now Figs. 12 and 13. These correspond to source positions such that there is no direct line of sight. They also show that the diffracted wave is very much weaker than the reflected wave. Consider Fig. 12. There is no direct line of sight and Fig. 17 indicates that there are 3 image sources. Figs 12a and 12b indicate the diffracted wave. It is the first pulse arriving at 5.4 msec and is about 6 dB below the next peak. The subsequent peaks in Fig. 12b correspond to the sound coming from the image sources.

This point is more clearly indicated in Fig. 13. The first diffracted wave coming from source position E arrives after 6 msec. From this source point four image sources can be seen by the observer which is confirmed by the result of Fig. 13b. Also, it shows that the diffracted signal is 10 dB below the reflected sound.

These results have indicated the effect of the buildings as providing image sources leading to the reverberant buildup of sound energy. The idea is generalized in the next chapter.

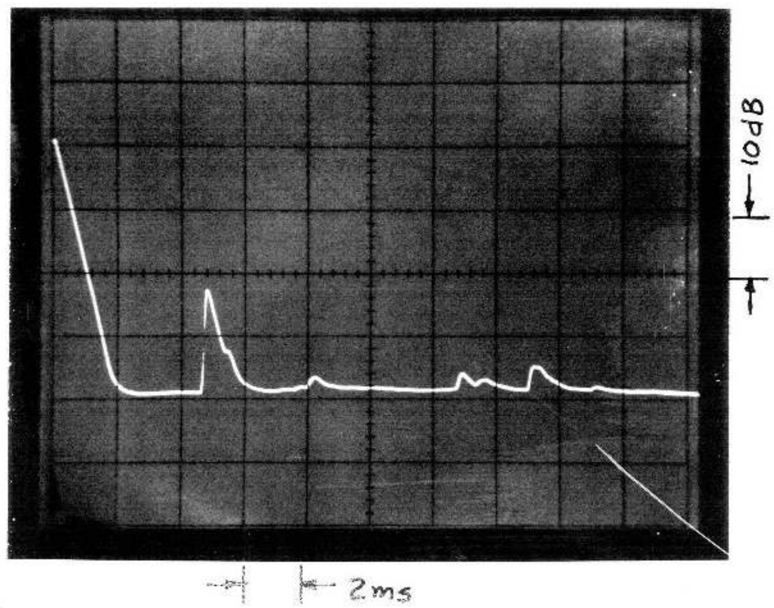


(a)

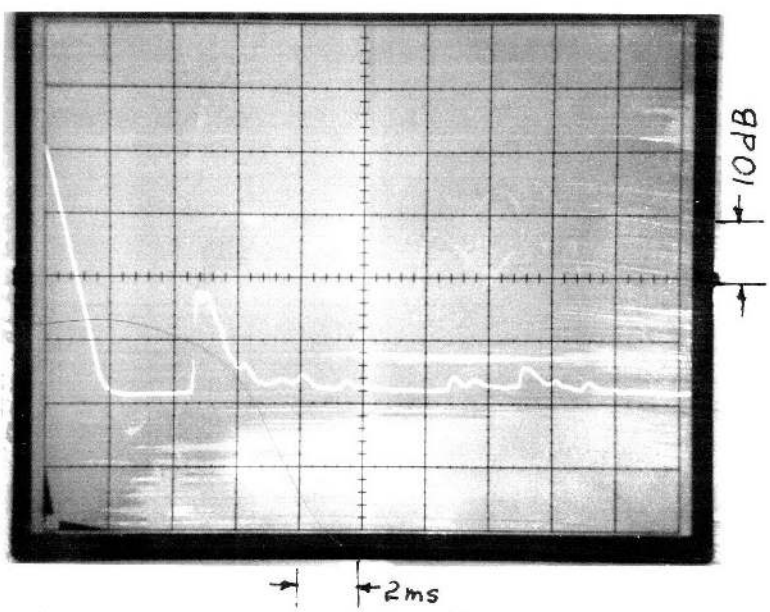


(b)

Fig. 9. Time Pattern for position A in linear street configuration [32 KHz] with (a) the sides of the street lined with sound absorbing material and (b) no sound absorbing material.

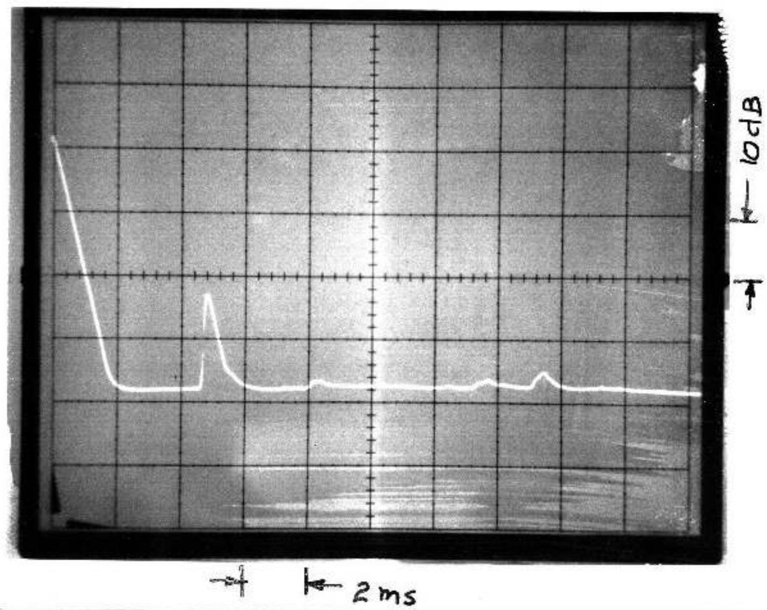


(a)

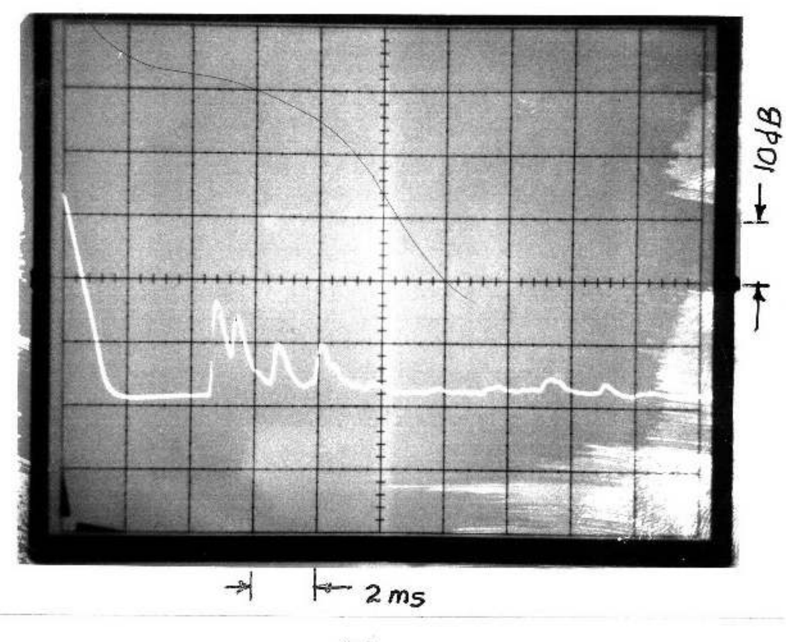


(b)

Fig. 10. Time Pattern for position B in linear street configuration [32 KHz] with (a) the sides of the street lined with sound absorbing material and (b) no sound absorbing material.

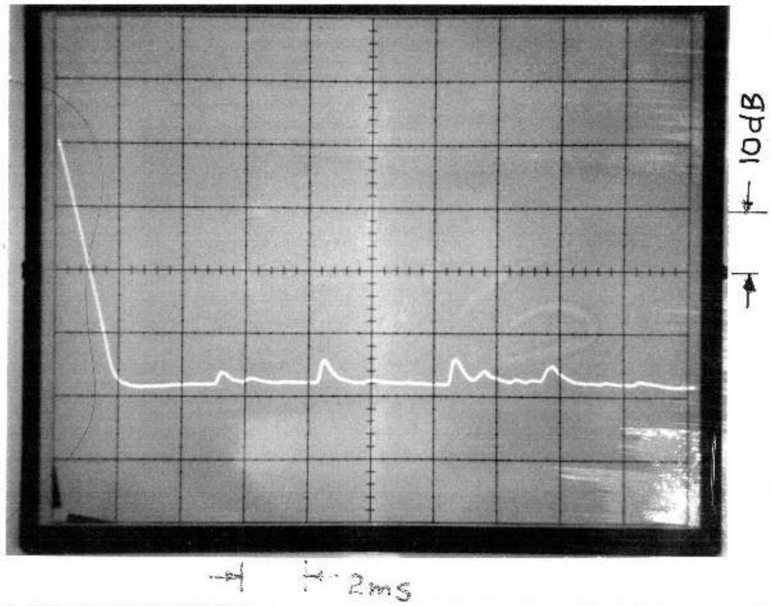


(a)

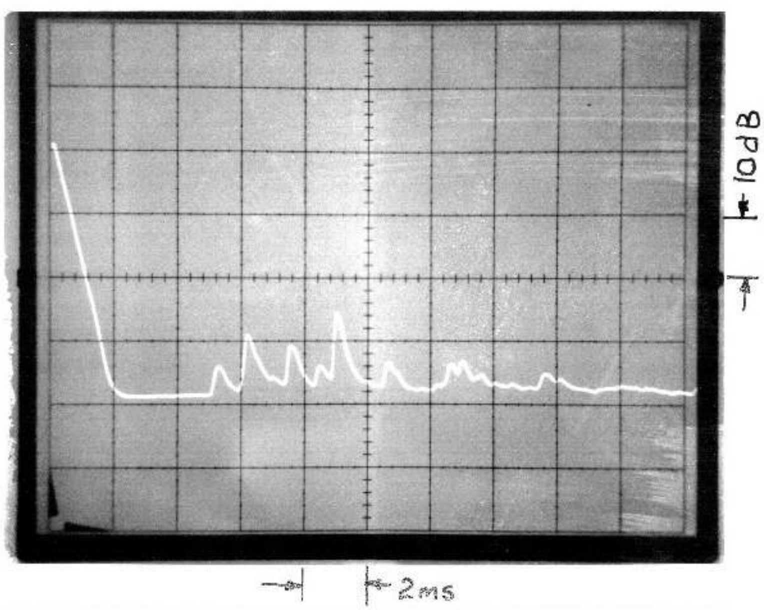


(b)

Fig. 11. Time Pattern for position C in linear street configuration [32 KHz] with (a) the sides of the street lined with sound absorbing material and (b) no sound absorbing material.

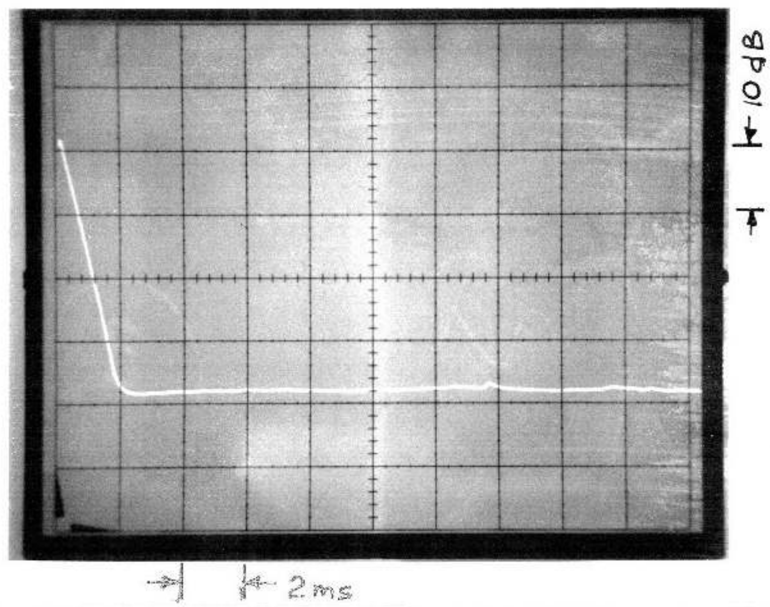


(a)

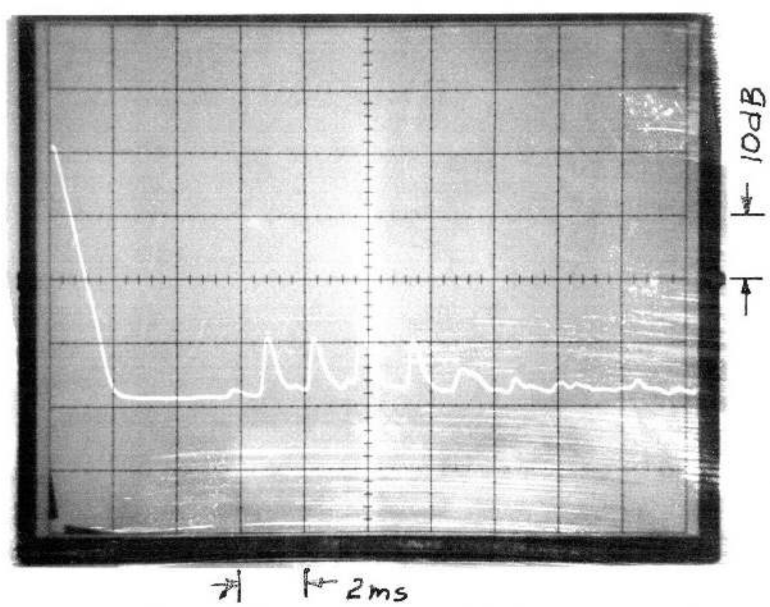


(b)

Fig. 12. Time Pattern for position **D** in linear street configuration [32 KHz] with (a) the sides of the street lined with sound absorbing material and (b) no sound absorbing material.



(a)



(b)

Fig. 13. Time Pattern for position E in linear street configuration [32 KHz] with (a) the sides of the street lined with sound absorbing material and (b) no sound absorbing material.

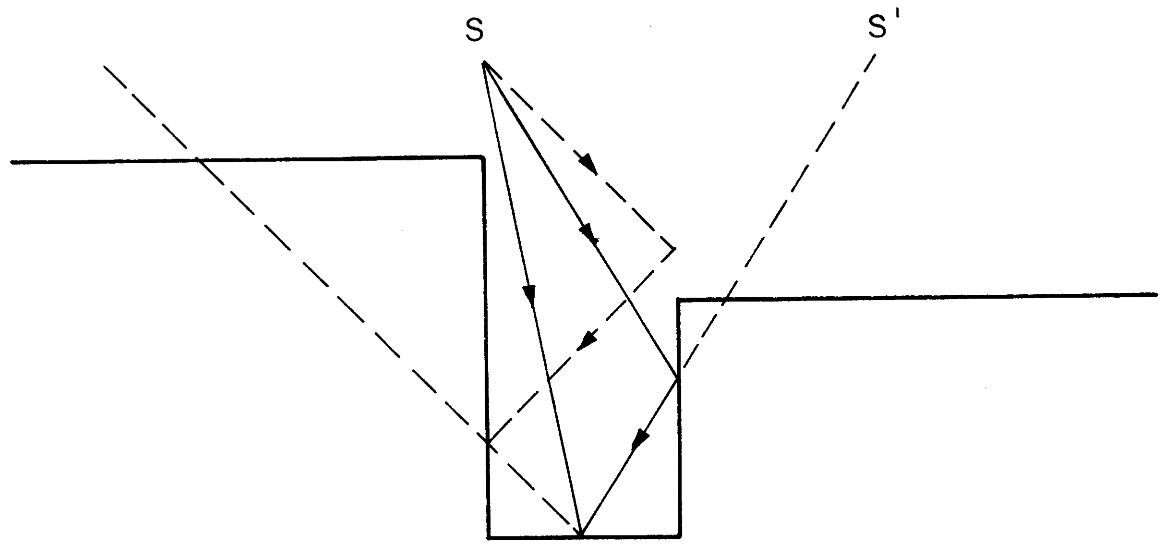


Fig. 14. Scale Drawing Showing Images Seen by Observer for a Source S at Position A [1 inch = 2 feet]

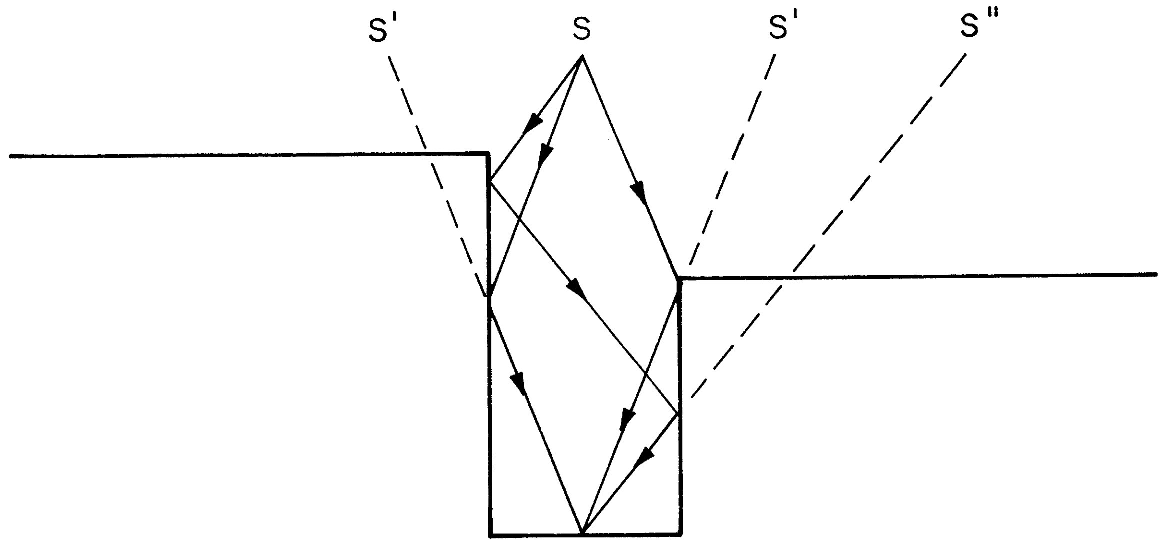


Fig. 15. Scale Drawing Showing Images Seen by Observer for Source Position B [1 inch = 2 feet]

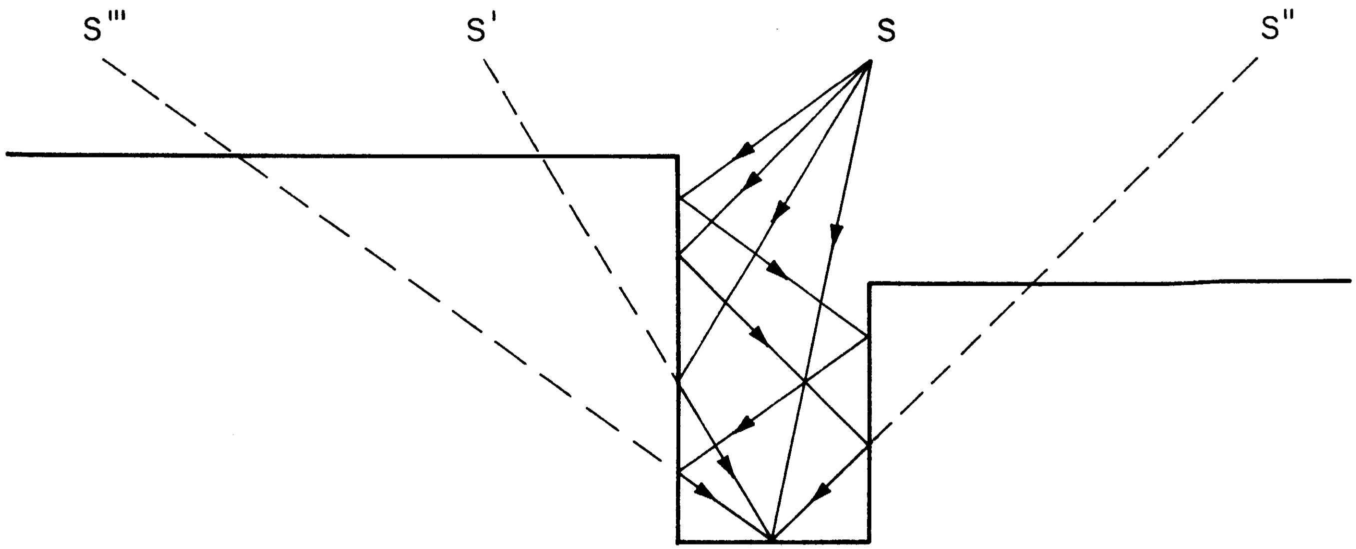


Fig. 16. Scale Drawing Showing Images Seen by Observer for Source Position C [1 inch = 2 feet]

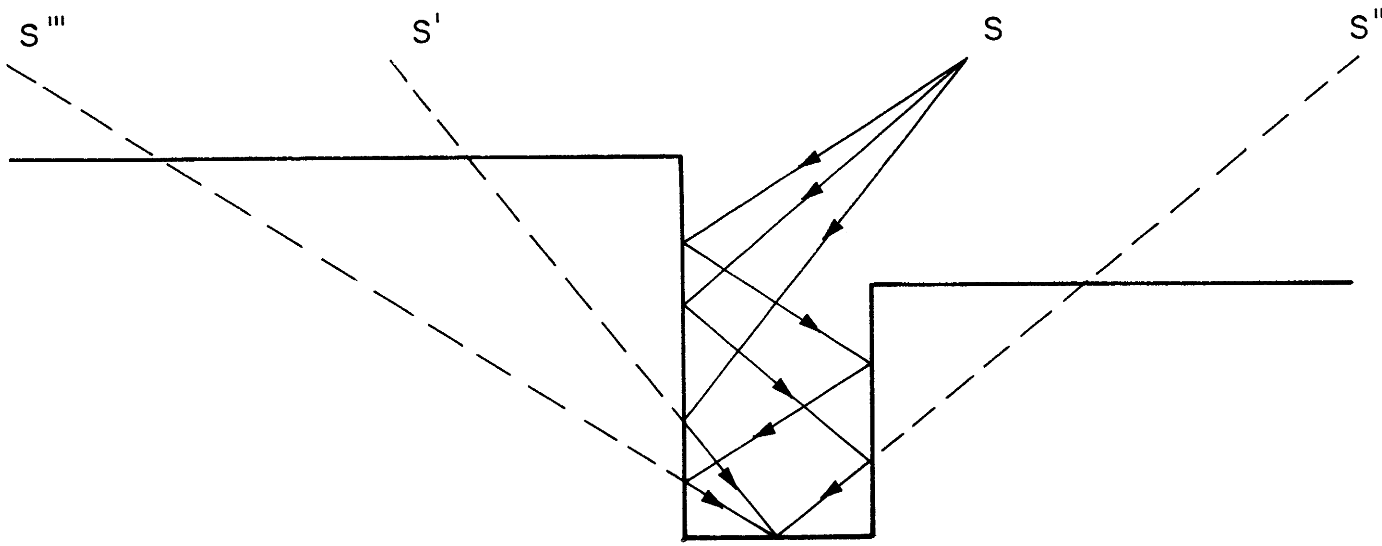


Fig. 17. Scale Drawing Showing Images Seen by Observer for Source Position D [1 inch = 2 feet]

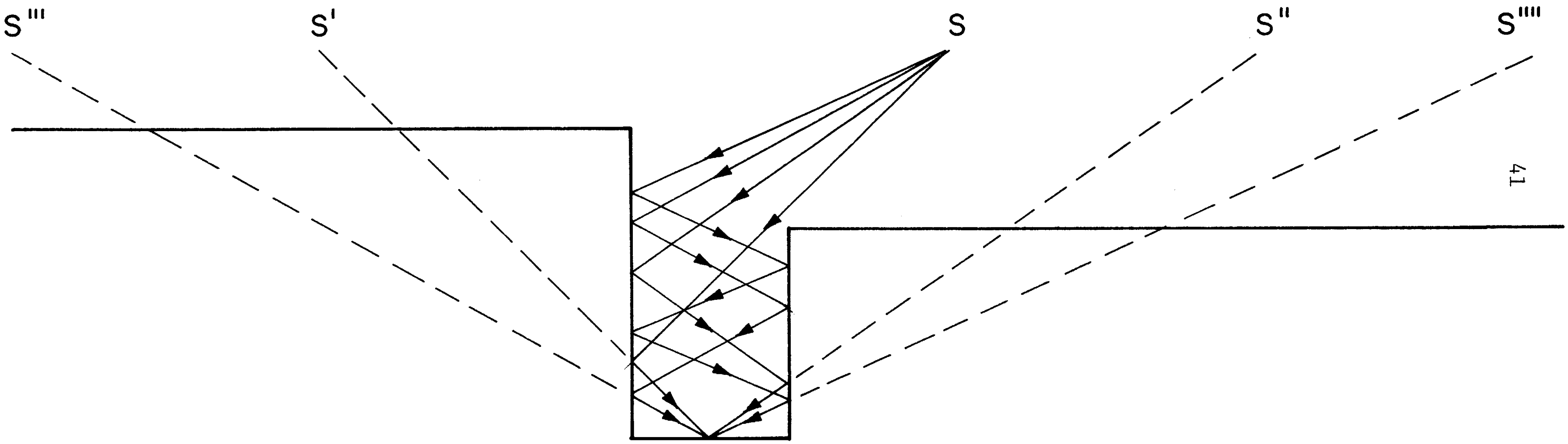


Fig. 18. Scale Drawing Showing Images Seen by Observer for Source Position E [1 inch = 2 feet]

CHAPTER IV

REVERBERATION IN A CITY STREET

Experimental investigations have confirmed the idea of a reverberant buildup of sound energy in a city street. The spatial energy characteristics are correlated with images using geometrical acoustics.

Let us consider the temporal aspect first. Figure 19 indicates three typical time patterns drawn on the same time scale. These correspond to different source-receiver positions. Figure 19a indicates that the energy at the receiver is received by discrete reflections. Figure 19b indicates a situation where most of the energy is received in a direct pulse. Figure 19c indicates a more reverberant buildup of the sound energy.

These indicate that the time scales and levels involved here are quite different from those in room acoustics, and we cannot easily relate reverberant buildup to the rate of decay in intensity of the sound. Figure 19a indicates that we can talk of a time delay between the direct and reflected pulse but this does not lead to a practical criterion. It indicates that three distinct reflections are received after the direct pulse. It is not immediately obvious how much the reverberant effect will be because the temporal pattern will also depend on the speed of the aircraft.

Figure 19c indicates that the sound energy adds up sufficiently so that the reverberant field may last for 5 msec (about 160 msec in full scale) before it decays. This situation is typical of the channel-like propagation of sound for longitudinal flyover over an L-shaped street. Such a long duration may have a substantial effect on the noise impact and speech interference for an observer in the street. However, this point is not

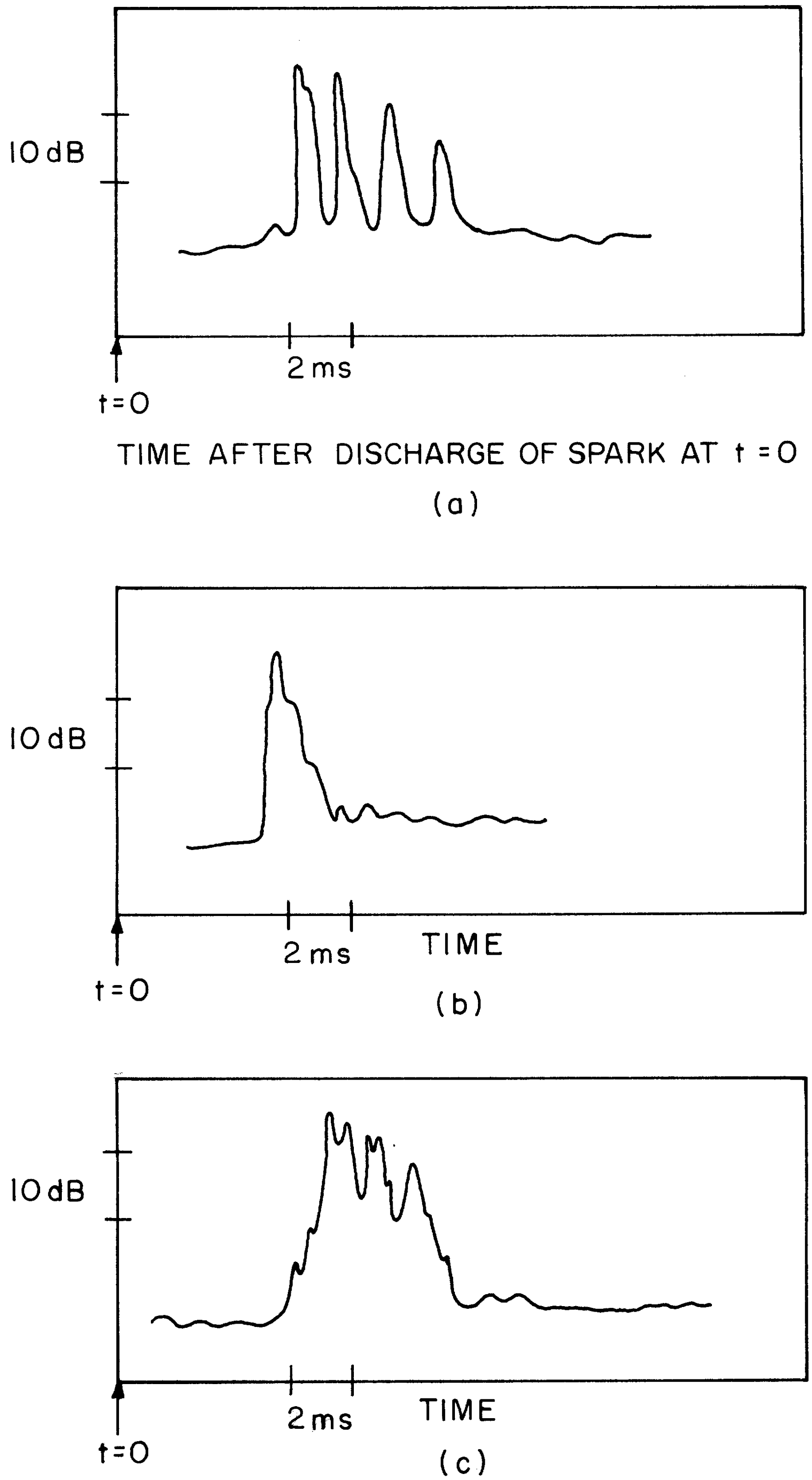


Fig. 19. Typical Time Patterns for Different Source-Receiver Positions

pursued further here because it does not immediately lead to a definition of reverberation in a city street.

As mentioned earlier, the reflected sound can be considered to be coming from image sources. The transient response of a linear street has confirmed our ideas that we could look at the reflection effects in terms of images. These images have been identified and it has also been shown that it is the first three or four reflections which contribute the bulk of the energy. Hence, a criterion that develops is the number of images from a source point seen by the observer. Since the reverberant energy is due to reflections, we can speak of the number of images that are formed by a city street for an observer in the street and a source illuminating it from above.

An enhancement of the sound energy is to be expected when the source is in a region from where there is more than one path of propagation. A shielding effect, i.e., a substantial decrease in the sound energy as compared with open terrain, occurs when the buildings obstruct the direct line of sight and the image sources are too weak. This will also be dependent on the relative geometry of the source-receiver-building configuration. Graphical constructions are presented in Figs. 21 to 24 which indicate zones showing the number of images that will be formed for a source position in that zone relative to the street and observer position.

The construction of these figures can be explained as follows. Consider a reflecting surface AB of length D as shown in Fig. 20. We are interested in finding the images seen by an observer 0, from a source situated above AB and to the right of it (see Fig. 20). An image will not be seen by 0 for two conditions: (a) if the incident ray from a source makes an angle of incidence greater than α ($\alpha = \tan^{-1} \frac{D}{x_1}$) and (b) if the incident ray makes an incident angle less than β where β is determined by CD. The shadow regions are, therefore, determined by the position of observer, height of buildings and the height of source above AB, i.e., the distance H.

The shadow zones are the regions XAP and SCY and are marked 0. Any source located outside these, i.e., located in the region PACS, will form at least one image as seen by the observer.

One additional condition is applied in labeling a zone by the number of images it will form. Let us call the images from a source S as S', S", S''' ... S^n. If two consecutive sources S^n, S^{n+1}, are not seen by 0, then the zone will be labeled as S^{n-1} images. Also, the effective images concerned are the lower order images, we are not interested in formation of higher order images. This is because the energy content of interest is only in the first few reflections, and higher order images have to travel a greater distance, so that the image strength is well below 10 dB of the source. This is an important point, because any image arriving after a sufficiently long time of the direct pulse and having an energy content 10 dB below, should not be considered as a reverberant effect.

Going back to Fig. 20, we wish to find the region such that a ray from a source located in it will reach the observer after two reflections, i.e., be reflected first by AB and then by CD before striking the observer. The limiting condition for this is that the incident angle must make an angle smaller than γ as shown in Fig. 20. Any source located in the region RACS will form two images as seen by observer 0 and is hence labeled 2.

If we now consider the region to the left of AB (region MTAX) and consider the reflection effects of CD, similar zones will be obtained.

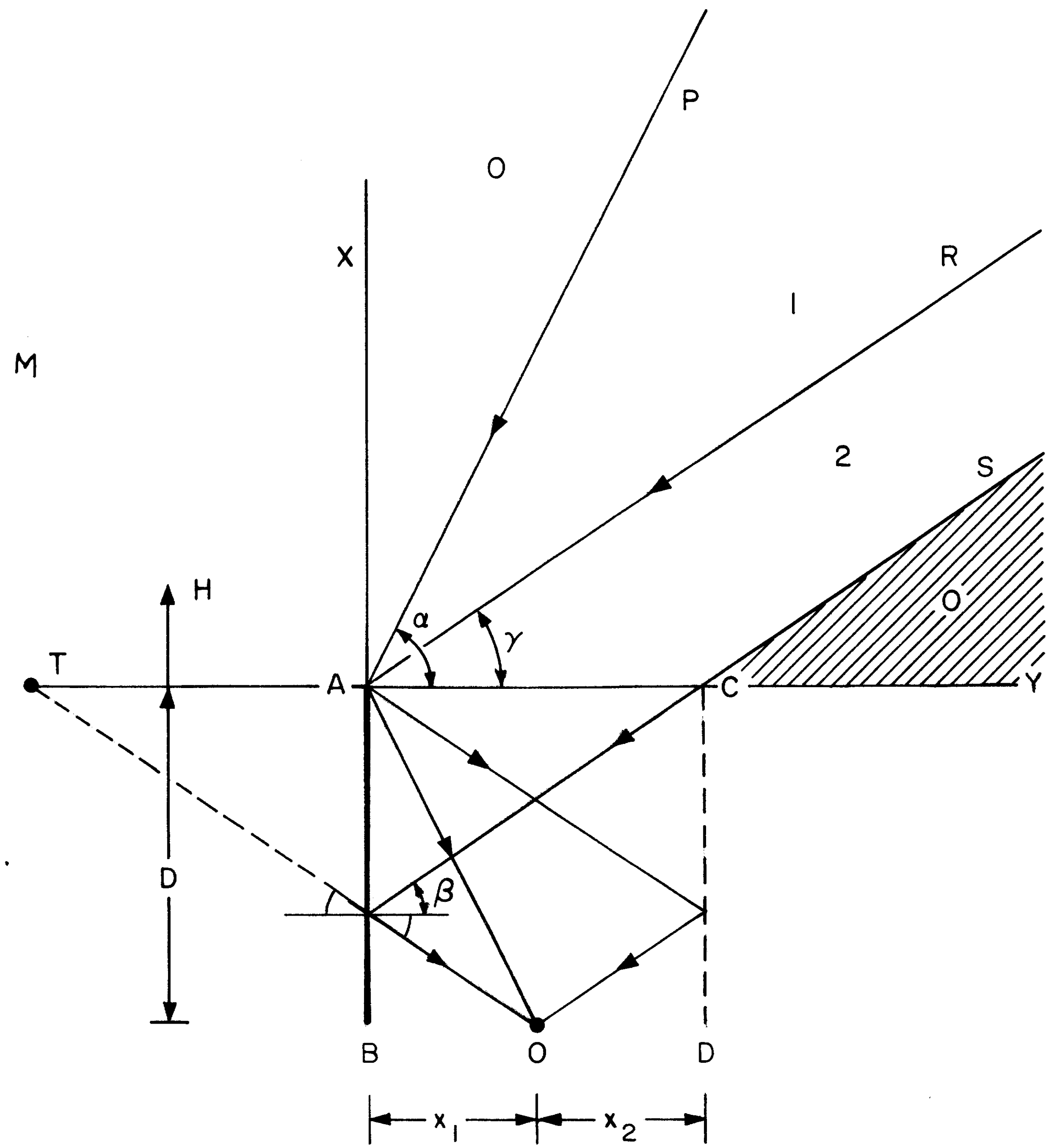


Fig. 20. Illustration of Image Formation

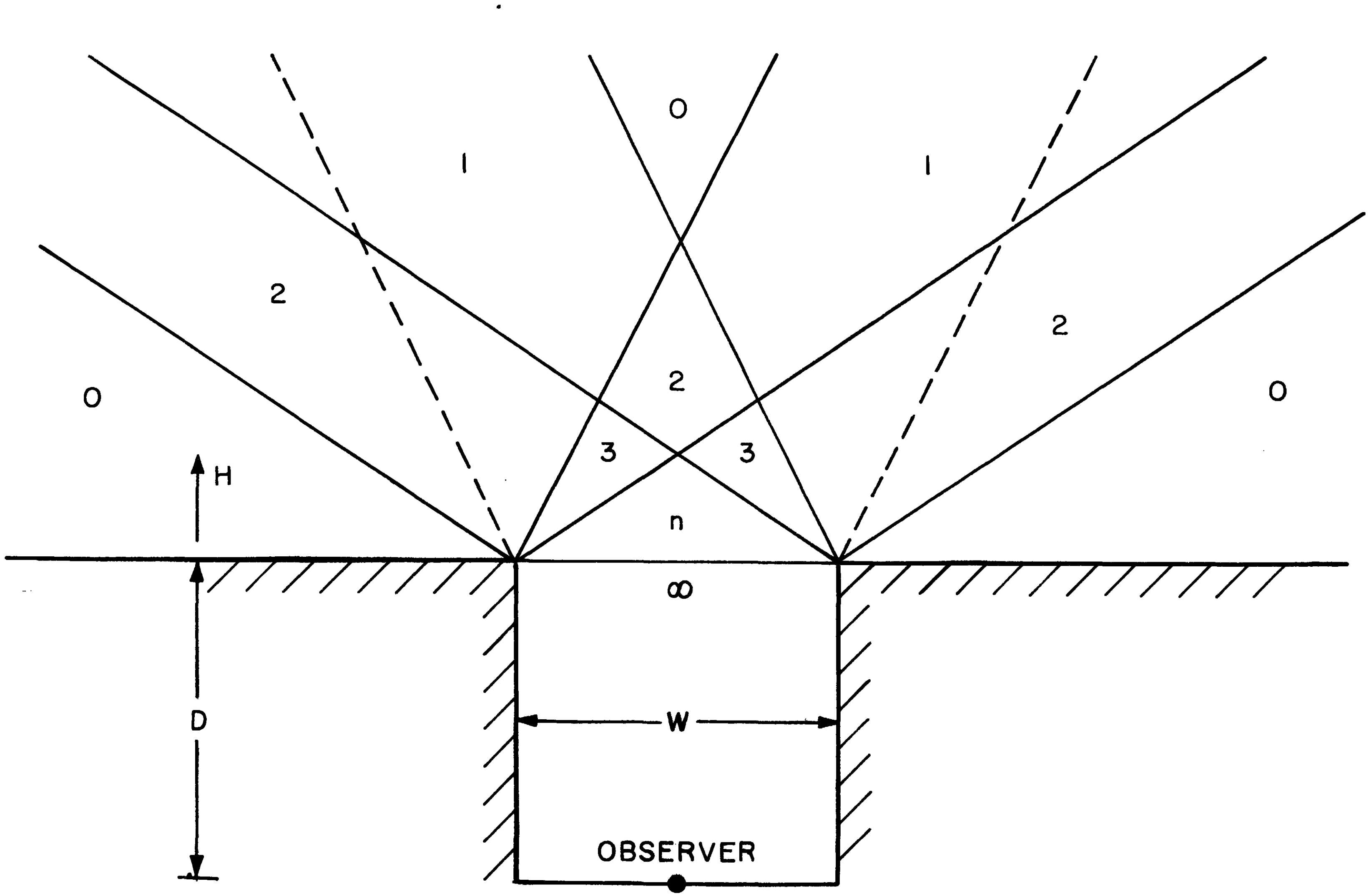


Fig. 21. Figure Indicating Zones Forming Images Seen by Observer in City Street [Dotted Lines Indicate Direct Line of Sight]

Now consider both surfaces AB and CD and a source situated anywhere in the region TAYX. If one image is formed by AB and two by CD, effectively three images will be seen by the observer (see Fig. 21). The regions are labeled accordingly. In the zone marked n, the first 4 images are seen, but the higher order images are also seen and are not separated by a gap of two as required. As the height H decreases, the number of images increases until it becomes infinite at H = 0.

The effect of asymmetry is shown in Figs. 22 to 24. The dotted lines in Figs. 21 to 24 indicate the direct line of sight. If there were no reflection effects, there would be only one source illuminating the observer in any region within the direct line of sight and no sound reaching the observer from any point outside it. However, the reflecting surfaces provide alternate paths. Zones marked 0 indicate the shadow zone from where no images will be seen by the observer. If the height of the aircraft measured from the top of the building is less than D, the number of images rapidly increases in a region whose dimensions are determined by the width W of the street, becoming infinite as the source approaches the height of the building. Figure 22 also indicates the effect of the decrease in the width of the street.

Essentially, the characteristics of the region above the higher buildings is not altered. However, multiple images can be formed from a region over the lower buildings which did not exist before. This effect is due to the extra reflecting surface exposed to a source situated over the lower buildings.

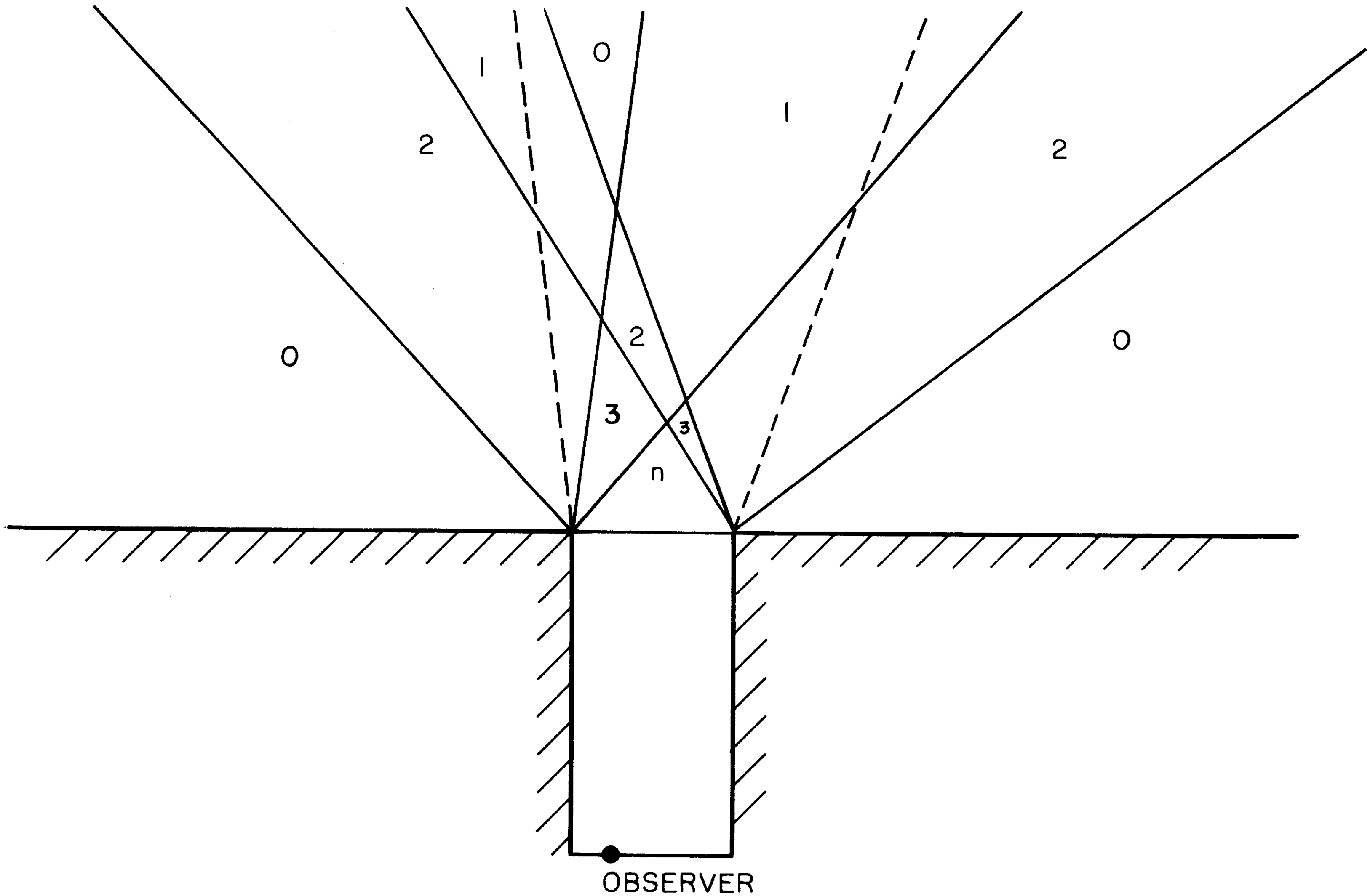


Fig. 22. Effect of Asymmetry in the Formation of Images

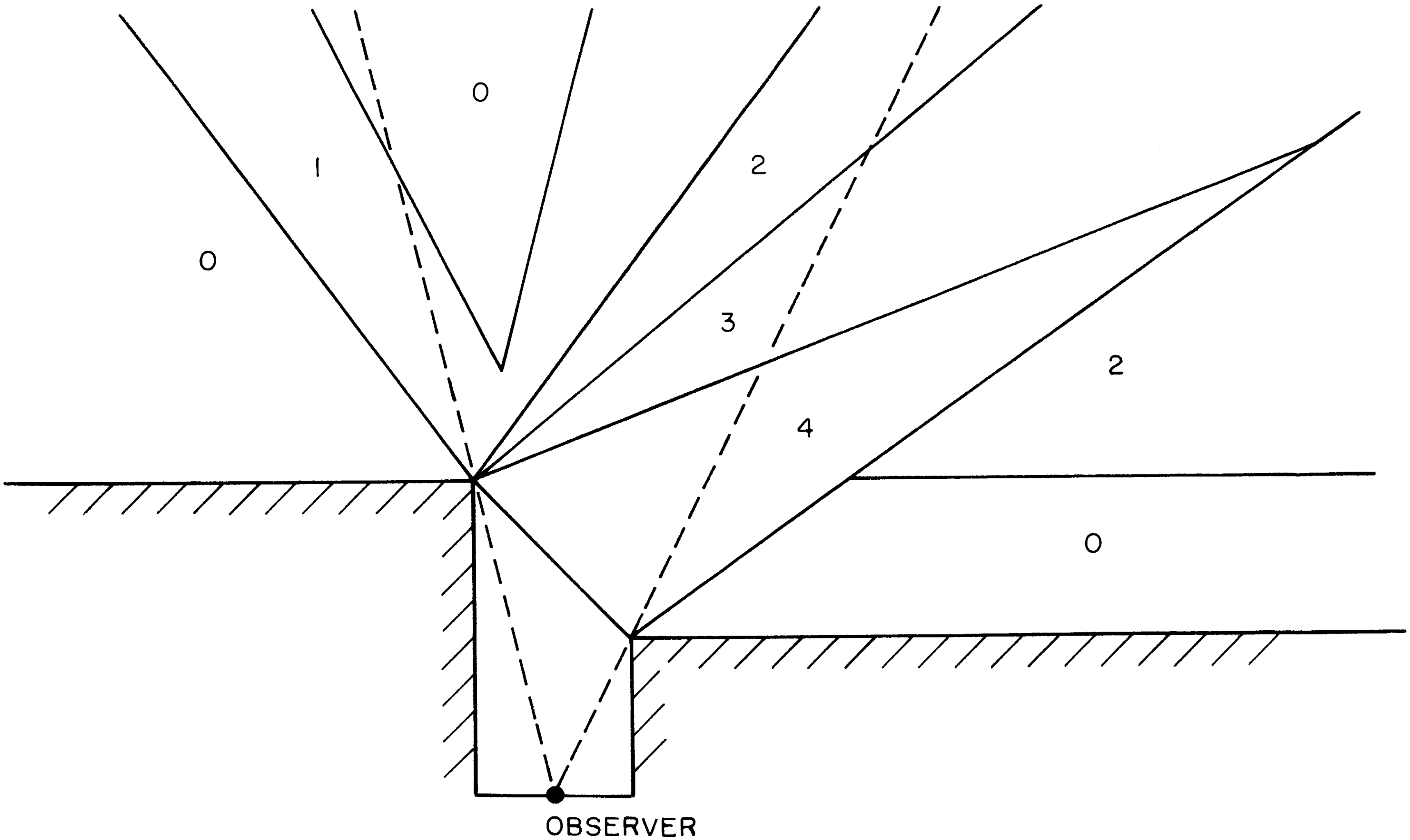


Fig. 23. Effect of Asymmetry in the Formation of Images

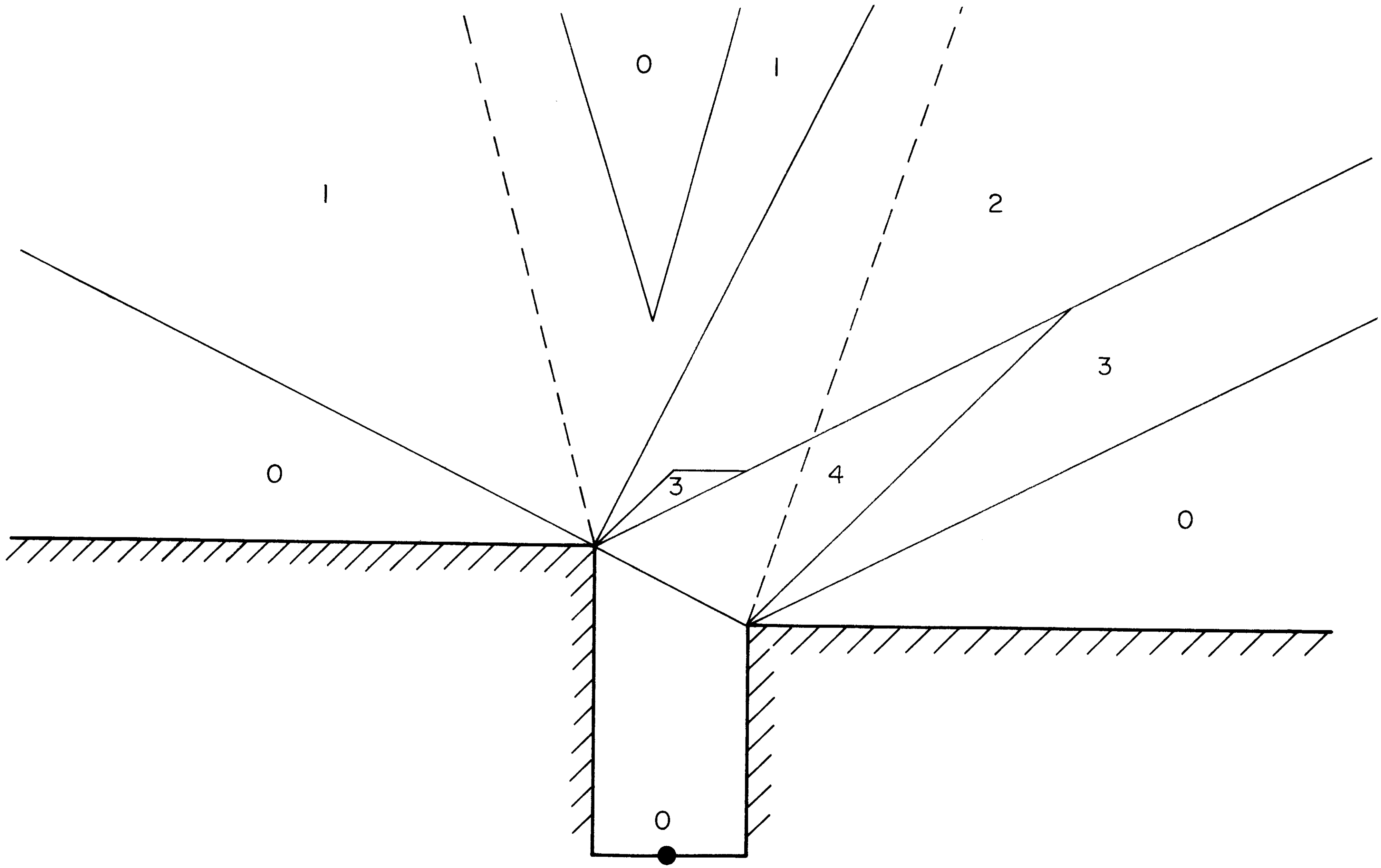


Fig. 24. Effect of Asymmetry in the Formation of Images

CHAPTER V

CONCLUSIONS AND APPLICATIONS

We have found that the sound field reaching an observer from an airborne sound source is affected by the presence of buildings. The effect on the energy distribution as compared to open terrain propagation has been defined as the reverberation effect of a city street.

The reverberation characteristics of a linear street have been studied for a source of sound situated above the buildings. The amplification and shielding effects can be explained in terms of the images that are formed from such a source with respect to an observer at street level. The model results provide a good insight into the propagation of sound from a low-flying noise source over an urban environment. This can be used to predict the effect of buildings on aircraft noise as compared to open terrain conditions.

Pulse studies have indicated the paths of propagation. These have enabled us to look at the reverberation effect in terms of images. The buildings can be replaced by an equivalent number of image sources. Also, we have found that it is the first three or four reflections which contribute most of the energy in the received signal. An energy summation has been used earlier to correlate the results for a steady-state experiment.

The understanding of reverberation in terms of the "effective" number of images to be expected for a particular source position has led to the development of charts indicating various zones. This brings out the effect of the relative position of source, receiver, and buildings.

The contribution of each image source as a 3 dB increase in the sound pressure level is modified by geometric and atmospheric attenuation. Geometric attenuation is given by 20 log r/r_o where r is the distance of propagation from source to observer and r_o is a reference distance. Atmospheric attenuation is given by 8.7 Nμ where N is the number of wavelengths from the source to receiver and μ is in nepers/wavelength. Since the sound energy from an image source has to travel a distance greater than the direct ray, attenuation effects have to be considered.

Another important conclusion relates to the distance between the noise source and the top of the building. Reverberation effects are important when this distance is small. If the distance of the noise source from the top of the building is less than the height of that building, then reverberation effects are very significant in a region whose horizontal dimension is determined by the width of the building. This is the region from where 4 or more images of the source can be seen by the observer.

Also, in the diagrams are drawn lines demarcating the direct line of sight. A shielding effect, as compared to open terrain, will be afforded by those regions which do not lie in a direct line of sight and do not form images.

For situations where the heights of the building on either side of the street are not symmetrical, the same conclusions apply. The higher buildings provide a greater shielding effect. The lower buildings do not. A recommendation that can be made is that use be made of the relative shielding effect of taller buildings. Flight paths over relatively lower buildings should be avoided.

Another important effect relates to the longitudinal flight over a city street. This refers to flights along the length of a city street.

Such a situation provides for the formation of multiple images and a channel-like propagation of the sound energy. A substantial increase in the sound pressure level occurs, as well as its duration. It is significant for an observer in that street, and for an observer at right angles and located such that there may be no direct line of sight.

The work reported here can be further improved and extended in several directions. It has provided techniques for modeling environmental noise. These could be further improved, e.g., better models to simulate an urban terrain which would mean more exact scaling in terms of geometry; a more complex and larger model; control of humidity so as to be able to model air absorption effects. These techniques can be used to study various noise problems. This may prove particularly useful to urban planners as urban areas consist of high-rise buildings with narrow streets. Reverberation effects are particularly significant here.

Not much mention has been made of the temporal characteristics, i.e., the rate at which the reverberant energy builds up. This would be important with a moving source and is worth investigating the effect of speed and height of flyover.

It would also be necessary to find the "effective" strength of an image. An image source would enhance the sound pressure level by 3 dB if it were of equal strength as the source. However, it is modified by geometric attenuation, atmospheric absorption, turbulence effects over buildings, and absorption and diffusion occurring at each reflection from a building face. This last factor has not been considered and could be significant in a practical situation.

With the current use of computer modeling, it appears as if the results presented here could be used in calculations of noise exposure for different flight paths.

Actual predictions of the noise impact on people would require psychoacoustic studies of noise exposure due to moving sources. An important question that arises is whether a short exposure to a greater energy level is less annoying than a lower energy level for a longer time.

REFERENCES

1. F.M. Weiner, C.I. Malme, C.M. Gogos "Sound Propagation in Urban Areas" J. Acoust. Soc. Am. 37 no. 4, pp 738-747, April 1965.

2. W.R. Schlatter "Sound Power Measurement in a Semi-Confined Space" S.M. Thesis, Mechanical Engineering, Massachusetts Institute of Technology, July 1971.

3. L.E. Kinsler and A.R. Frey Fundamentals of Acoustics, (John Wiley & Sons, Inc., New York, 1962).

4. L.L. Beranek Noise Reduction, (McGraw-Hill Book Co., Inc., New York, 1962).

5. "Modeling Techniques in Architectural Acoustics" Proceedings of a Symposium held at the 76th Meeting of the Acoustical Society of America, 19 November 1968, Cleveland, Ohio.

6. M.R. Schroeder "New Method of Measuring Reverberation Time" J. Acoust. Soc. Am. 37 no. 3, pp 409-412, March 1965.

7. R.H. Lyon "Direct and Reverberant Field Amplitude Distributions in Nearly Hard Rooms" J. Acoust. Soc. Am. 33 no. 12, pp 1699-1704, December 1961.

8. R.H. Bolt, P.E. Doak, P.J. Westervelt "Pulse Statistics Analysis of Room Acoustics" J. Acoust. Soc. Am. 22 no. 3, pp 328-340, May 1950.

9. L.L. Beranek Music, Acoustics and Architecture, (John Wiley & Sons, Inc., New York, 1962) pp 573-574.

10. M.R. Schroeder "Ditital Simulation of Sound Transmission in Reverberant Spaces" J. Acoust. Soc. Am. 47 no. 2 (part I) p 424-431, February 1970.

11. R.H. Lyon, L. Pande, and W.A. Kinney "Modelling of V/STOL Noise in City Streets" Summary Report DOT-TSC-93, Department of Mechanical Engineering, Massachusetts Institute of Technology, 15 November 1971.

12. J.E. Marte and D.W. Kurtz "A Review of Aerodynamic Noise and Propellers, Rotors and Lift Fans" JPL Technical Report 32-1462, pp 33-34.