A COMPUTER MODEL TO SIMULATE SUBURBAN NOISE PROPAGATION

by

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ABSTRACT

This thesis describes the workings of a two dimensional ray-tracing computer model developed to simulate sound propagation in suburban areas. Chapter 1 discusses in detail the nature of the computer code, which produces as a result the sound pressure level as a function of time at user-defined locations.

Chapter 2 compares results of this code to scale-model experiments. In general there is good agreement between the experiments and the simulation, pointing to the code's ability to predict the times of pulse arrivals at a receiver and to predict the direct sound energy quite accurately.

Chapter 3 compares computer-produced results to the analytical solutions for sound between two infinite parallel walls. For totally absorbing walls, the computer results agree with the
analytical results. For totally reflecting walls, the simulation systematically predicts lower sound pressure levels than the theory by 1.9 dB on the average.

Chapter 4 compares field-data to the simulation with excellent agreement. This indicates that the code may be applied to complex environments with good results.

Chapter 5 applies the code to study general sound propagation patterns in suburban areas. Results indicate similar patterns for both a point and a line source with the major difference lying in the ability to receive direct sound from the line source at positions where no line of sight to the point source exists. In addition, the same pattern holds for both random and regular model geometries. This indicates the ability to study suburban sound propagation by studying randomly generated house locations instead of a specific geometry.

Thesis Supervisor: Richard H. Lyon
Title: Professor, Department of Mechanical Engineering
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CHAPTER 1  DESCRIPTION OF THE COMPUTER MODEL

1.1  The Purpose of the Computer Model

The study of sound propagation in suburban areas presents many difficulties to acoustical engineers. Because of the presence of multitudes of objects to scatter, reflect, and absorb sound the analytical prediction of noise levels in a community is intractable. Computer models, scale model experiments, and field data are relied upon to describe patterns of noise intrusion. The purpose of this computer model is to predict average sound pressure levels produced in suburban-type environments given an acoustic point source radiating from a given location. Such a model makes it possible to study for example the effect of placing a major roadway near an already existing housing development. (A roadway is more accurately represented by an acoustical line source. A discussion of how to include line sources in the model is presented in Section 5.2).

Many computerized methods exist for predicting noise levels produced by vehicular sources, but none seem to be appropriate for general suburban environments, where the distances between scattering objects is large. This particular computer model was designed to be analogous to a computer model developed for studying noise levels in urban environments written by D. G. Holmes [1]. In the urban model, the space of interest was divided into many cells, each being a receiving cell, building cell, sink cell or free cell. In the sub-
urban model it is undesirable to divide the area under investigation into cells, because the cell size would need to be small in order to describe buildings accurately, while the area of the model has increased. The number of cells required would make computing size and cost prohibitive. Figure 1.1 gives an example of the type of suburban situation which may be handled by this model.

1.2 The Basic Assumptions

The computer model employs the use of acoustic ray-tracing. A source which is assumed to radiate uniformly in space emits "acoustic quanta" of a given strength in some direction. These "quanta" are followed as they impinge on scattering surfaces. To use a ray-tracing model it is necessary to make two basic assumptions:

1. The typical scale lengths in suburban environments are many times larger than the wavelengths of the sound which contributes measurably to the sound pressure level. This assumption makes possible the use of ray-tracing. All phase information is lost.

2. The noise sources being considered are broad-band with auto-correlation lengths much shorter than the typical suburban length scales. This eliminates the possibility of interference between two rays whose paths cross. The sound pressure level at any location may thus be calculated by adding the mean square sound pressures
resulting from each "quanta". In the limiting case of extremely small scattering objects, and in the case of ground reflections, it is possible that the path lengths are close enough that some correlation between them occurs. In this event, the validity of the computer model breaks down. Ground reflections are included in this model only in the sense that the input parameters of the scatterers are determined while they are on the ground that surrounds them. Specific paths which reflect from the ground are not included since the model is two dimensional in its current form.

1.3 Gross Structure of the Code

The computer code of this model consists of seven subprograms each with a set task. The programing heirarchy is shown schematically in Figure 1.2. MAIN is the main program in the code. It initializes arrays, reads in pertinent information about the area to be studied through AIN, and accepts commands relating to computing tasks. LIST summarizes the parameters assembled in MAIN. RANDOM generates locations of scatterers. In this work, two versions of RANDOM were used. The first was not random at all, but deterministic, specifying the exact locations of scattering objects. This version of RANDOM was used to get the best possible predictions of sound pressure levels and arrival times for a given environment. The second version of RANDOM generated scatterer locations randomly, assuming a uniform
FIGURE 1.2 Structure of the Computer Code
distribution of probability of locating a scatterer in space, and a uniform probability of angular orientation. The purpose of this version of RANDOM is to predict general patterns of behavior in acoustical spaces. DIST is a function subroutine called by RANDOM version two, to calculate distances between the source and receivers, and the corners of the scatterers. TRACE is the core of the computer code. It is the subprogram that generates rays and follows their motion. TRACE calculates the sound pressure levels and arrival times at each receiver location, and checks for convergence of the algorithm. OUTPUT is called at the completion of the ray-tracing to print a histogram of sound energy arriving at each receiver as a function of time. These subroutines will be described in further detail in Section 1.5.

1.4 Other Assumptions

In addition to the basic assumptions made in order to allow for the use of a ray-tracing model, several simplifying assumptions have been made in this computer model. Most of these assumptions can be easily relaxed or modified in the computer code. Some are designed to simplify the geometry, some to simplify the physics.

1.4.1 The Nature of the Scatterers

In this version of the computer model, several restrictive assumptions were made regarding the nature of the scattering objects.
Firstly, it is assumed that each scatterer may be described by a single set of acoustical parameters (absorption, reflection, scattering, and transmission coefficients) valid for all frequencies of interest and all angles of incidence. These parameters are fed into the code by the user. The frequency independence may be justified by the fact that the result sought is a single-number sound pressure level independent of frequency. This restriction could be lifted by assigning each ray a frequency based on spectrum information assigned by the user. The angular independence is included for simplicity and could be modified if desired by using a matrix of acoustical parameters.

It is assumed that all of the scatterers are identical in shape and acoustical properties. This assumption implies that there is one type of scattering object having the dominant role in the sound interaction. Further it assumes that these objects are very similar. In the study of suburban environments it is likely that the major sound barriers are houses, and that they are similar in size and acoustic behavior. If, however, the community being studied is heavily wooded, it is quite possible that neglecting the role of the foliage in sound reflection, scattering, and absorption could produce large errors. In this case, the obvious first order correction is to specify two barrier types, each with a given size, shape, and acoustic behavior. This modification is easily made in the model. Even if the area is well described by one type of
barrier, there may be cases where it is desirable to allow the barrier sizes to vary according to some probability density. This again is an easy modification of the existing model.

The scattering objects are assumed to be rectangular in shape. Most buildings have a rectangular cross-section and trees may be reasonably approximated by rectangles. The removal of this restriction would complicate the geometric calculations immensely. It is not an easy modification to make in the computer code. This assumption allows the user to totally describe the shape of all of the scatterers by specifying just two lengths.

It is assumed that the scatterers have a uniform probability of being located at any position in space and a uniform probability of angular orientation for the version of the model involving random scatterer locations. The model generates many sets of scatterer locations, averaging over the results for each set. Clearly, no community has a random structure. It is not the intent of this assumption to provide realism, but a means of predicting average patterns. A more realistic model might use other probabilistic distribution to describe the scatterer locations. This is a simple modification to the computer code.

Buildings and other scatterers contain irregularities which may be of the same order as the acoustic wavelengths. These irregularities cause additional scattering and specular reflection be-
yond that of a surface without nonuniformities. This additional scattering and reflection is assumed to be included in the scattering and reflection coefficients. Otherwise, irregularities are ignored.

It is assumed that the scattering of sound by surfaces occurs uniformly in all directions bounded by the surface angles of orientation. With very little difficulty, a more elaborative angular dependence, (Lambert's cosine law, for example), could be included if the motivation existed.

1.4.2 Assumptions Regarding the Source and Environment

It is also necessary to make assumptions regarding the nature of the source, and the relative effects of environmental factors. It is assumed that the source radiates as a point monopole. This implies that the source radiates uniformly in all directions and that the energy radiated decays as $1/r^2$, where $r$ is the distance from the source. Virtually all noise sources of interest are much too complicated acoustically to be described by a simple point source. However, in regions relatively far away from the source (more than a few wavelengths), it is a good approximation to say that the radiated power goes as $1/r^2$. The angular dependence of the sound radiation of a real source may easily be included in the computer model by assigning ray directions based on a nonuniform probability density. In many cases of interest, however, the real source
possesses little directivity.

A single number is used to represent air absorption in this model, even though air absorption is strongly dependent on frequency. In the use of the model to compare to field data, the air absorption is relatively constant over frequencies of consideration. For comparisons to scale model experiments this assumption involves averaging over a large range of values for air absorption because the frequencies used in the model are scaled into the high frequency range where air absorption varies greatly. This treatment of air absorption could be improved by specifying air absorption coefficients at many frequencies. A simple modification of the code would, for example, allow the user to specify average air absorption coefficients in each third octave band being studied. Each ray would then be assigned a frequency based on source spectrum information and attenuated appropriately.

Meteorological effects such as wind and temperature gradients in the atmosphere are neglected. A study of these effects was the topic of work done by R. DeJong [2].

1.5 Details of the Computer Model

In this section, the intimate workings of each subprogram are discussed with particular attention given to the structure of the ray-tracing algorithm of the model. A listing of the code is given
in Appendix A.

1.5.1 MAIN

The main program of the computer model forms the backbone of the computer structure. It is the part of the code that accepts all input parameters and calls all other subroutines based on four possible commands: STrart, LIsr, GO and ENd.

The STrart command begins the data initialization process. All arrays are set to zero, and input parameters are read in the following sequence:

1. XLEN - The x-length of the total area to be studied.
2. YLEN - The y-length of the total area to be studied.
3. SURF1 - One of the two lengths of the rectangular scatterers.
4. SURF2 - One of the two lengths of the rectangular scatterers.
5. SDEN - The density of scatterers per 1000 square feet.
6. ABCO - The absorption coefficient for the scatterers.
7. SCATCO - The acoustical scattering coefficient of the scatterers.
8. REFCO - The reflection coefficient of the scatterers.
9. XSRC - The x location of the sound source.
10. YSRC - The y location of the sound source.
11. SPLVL - The reference sound pressure level of the source.

12. SDIST - The distance in feet at which the source sound pressure level is SPLVL in the free-field.

13. AAB - The air absorption in units of dB/1000 ft.

14. DBTOL - The convergence criterion for the average sound pressure level at each receiver.

15. TMER - The convergence criterion for the variance in energies seen at each receiver in each set of 100 rays.

16. NMAX - The maximum number of rays which are traced for each scatterer geometry.

17. Rcvr
   (10,2) - The positions of up to 10 receivers.

With these above values defined by the user, the processing is ready to begin. The command L1st causes a call to subroutine L1st which summarizes the pertinent parameters. If changes are desired, they may be accomplished by a command of S1art which repeats the initialization procedure. The command GO instructs MAIN to relinquish program control and begin ray-tracing. Two more parameters are read in:

18. NSETS - The number of scatter configurations to be generated.
19. IOOPT - A parameter allowing the user to display the locations of the generated scatterers for a value of IOOPT of "1".

Control is then passed first to subroutine RANDOM, and then to subroutine TRACE. Upon convergence of the ray-tracing algorithm, control is returned to MAIN. START would begin an entirely new run; END ends the program.

1.5.2 RANDOM

The two versions of RANDOM used in this study accomplish the same task: they generate the locations of the scatterers and print these locations if IOOPT is "1". In the deterministic model, RANDOM is actually written by the user and merely assigns the scatterer locations to the array ALOC(200,9) by giving x and y coordinates of the four corners in ALOC(I,1) through ALOC(I,8) and in ALOC(I,9) the angle of orientation of the first corner, measured counter clockwise from horizontal and toward increasing x. In Figure 1.3, for example, ALOC(I,1) = P_1, ALOC(I,2) = P_2,
ALOC(I,3) = Q_1, ALOC(I,4) = Q_2, ALOC(I,5) = R_1, ALOC(I,6) = R_2,
ALOC(I,7) = S_1, ALOC(I,8) = S_2, and ALOC(I,9) = \theta. In the deterministic version of RANDOM, the array is assigned in any consistent fashion. If, in fact, different scatterer sizes are desired, they may simply be assigned. In the stochastic version of RANDOM, a random-number generator is used to supply the x and y coordinates.
FIGURE 1.3  Assignment of ALOC Matrix
of the first corner of each scatterer, and the angle of orientation of the scatterer. The locations of the remaining three corners are generated in a manner consistent with the angular orientation, and the side lengths SURF1 and SURF2. The restrictions on scatterer placement are: they may not overlap, they may not contain the source, and they may not contain a receiver. These conditions are ensured by finding the sum of all of the distances from the source (or receiver, or corners of another scatterer) to the corners of the scatterer by issuing a call to DIST. If that total distance is less than the total distance from any one corner of the scatterer to all other corners, than the source (or receiver, or corner of another scatterer) is at an interior point. The scatterer location is then rejected. In both versions of RANDOM, the total number of scatterers defined must be consistent with the scatterer density per 1000 square feet, SDEN, and the area XLEN times YLEN. A maximum of 200 scatterers may be used.

1.5.3 TRACE

Subroutine TRACE performs the computational task of the computer model. It is a complicated routine set up in many blocks, each with a set role. The structure is outlined in Figure 1.4.

The first loop increments for each set of 100 rays which are traced. It begins with the initialization of arrays which store data
FIGURE 1.4 Flow Chart of Subroutine Trace

- 27 -
on each set of 100 rays. This is followed by the beginning of the second loop, which commences with the initialization of parameters which change with every ray and must be reset when a new ray is traced.

The first computation occurs with the assignment of a ray angle. A random number-generator is used to generate an angle between 0 and 2\pi radians. A check is made that this angle is in the acceptable range. For a new ray, the entire range is accepted. For a scattered ray the acceptable range is given by the \pi radians representing forward scattering off of the surface. If the angle generated is unacceptable, a new one is found.

The next section of the program is designed to check if any receiver is along the ray path. This is done in the following manner: An angle \phi is defined as the angle between a path in the positive horizontal direction and the path to the receiver from the current ray location. This angle is always defined counter-clockwise. Receivers are assumed to occupy a circular area with radius of one percent of the shortest dimension of the area to be studied. This geometry ensures that the number of rays reaching a receiver is independent of the definition of the coordinate axes. Based on this geometry, the range of possible angles about \phi which would intersect the receiver is determined. As indicated in Figure 1.5, this defines an angular range \phi-d\phi to \phi+d\phi.
FIGURE 1.5  Ray Intersection with a Receiver
\[ d\phi = \sin^{-1}(r/R) \] (1.1)

Unless the angle of ray propagation is within this defined range, the ray cannot intersect the receiver. If the ray does hit the receiver, the distance to the receiver along the ray path is calculated by:

\[ D = |R \cos(\phi - \theta)| \] (1.2)

This actually calculates the distance along the ray to the point of closest approach to the receiver center, as indicated in Figure 1.5. One ray may intersect more than one receiver, in which case the contribution to each receiver is computed, but the ray may not reach one receiver twice without hitting a scattering surface between the receiver arrivals.

The next section of the subroutine determines if a scatterer is in the ray path. It does so by going through two elimination procedures applied to each scatterer. The first elimination checks to see if the scatterer is in the quadrant which contains the ray angle. If not, the scatterer is not in the ray path. The second elimination defines angles from the ray's current position to each of the scatterer's four corners. If the ray is to intersect the scatterer, the ray angle must be between at least one consecutive pair of these four angles. If this is the case, the point of intersection of the ray with the surface is calculated. This is done using two simultaneous equations, one derived from triangle similarity
and one from a right triangle relation. Referring to Figure 1.6, if the point of intersection is at \((S,T)\), then similarity says:

\[
\frac{A_1-S}{A_2-T} = \frac{S-A_3}{T-A_4}
\]  

(1.3)

With \(\theta\) the angle of ray travel

\[
\tan \theta = \frac{(T-YRAY)}{(S-XRAY)}
\]  

(1.4)

Solving gives:

\[
S = \frac{XRAY \tan \theta - YRAY + \left[\frac{(A_2A_3-A_1A_4)}{(A_3-A_1)}\right]}{\tan \theta - \frac{(A_4-A_2)}{(A_3-A_4)}}
\]  

(1.5)

\[
T = \frac{S \cdot (A_4-A_2) + A_2A_3 - A_1A_4}{A_3 - A_1}
\]  

(1.6)

The distance between the surface and the current position is calculated for each surface on the ray path. The surface corresponding to the smallest distance of travel is the surface which may actually be impinged upon. Rays may not pierce the scatterer in the current version of the model, so no scatterer may be hit twice in succession.

The subroutine now branches depending on the distance to the nearest scatterer, SCDIST, and the distance to the nearest receiver, RCDIST. If both are very large, the ray has left the system and TRACE proceeds by beginning with a new ray. If RCDIST is smaller...
FIGURE 1.6 Ray Intersection with a Scatterer
than SCDIST the ray reaches the receiver. The squared pressure is then calculated based on the reference value of the source sound pressure level.

\[ p^2 = 10^{[\text{SPLVL} - \text{ABB(DIST-SDIST)]} - 0.1} \quad p_{ref} \cdot \frac{2\pi \text{SDIST}}{100 \text{ RLEN}} \cdot \frac{\text{SDIST}}{\text{DIST}} \quad (1.7) \]

In this expression ABB is the air absorption in dB/ft, \( p_{ref} \) is the reference pressure used in calculating dB (2.0 x 10^{-5} \text{ n/m}^2), and RLEN is the diameter of the receiver. The factor \( 2\pi \text{SDIST}/100 \text{ RLEN} \) is \( 1/N \) where \( N \) is the number of rays which would arrive at a receiver at the source reference distance out of 100 rays. This factor ensures that in the free-field, the sound pressure level predicted by the computer model at SDIST feet will be SPLVL on the average. The factor SDIST/DIST corrects for the two dimensionality of the model. Since in two dimensions the rays spread as \( 1/r \) a factor that goes as \( 1/r \) must multiply the squared pressure to provide for geometric spreading as \( 1/r^2 \) analogous to three-dimensional spreading. Here DIST is the total distance the ray traveled in reaching the receiver. In other words, each ray has a certain sound energy associated with it, and this sound energy is given by the source reference level, the air absorption, and the distance traveled. To find the sound pressure level, the squared pressures are summed to give a total squared pressure, and then the log is taken.

Following the pressure calculation the ray arrival time is
calculated and information on the ray's pressure and path printed. The ray is then allowed to proceed further until it either leaves the system, is absorbed, or undergoes more than ten reflections. (The number ten was chosen as a reasonable limit beyond which the ray possesses little sound energy).

If the ray has hit a scatterer, the ray's new location is set as the intersection point \((S,T)\) and the possible scattering range is set. This version of the model assumes scattering in the forward direction uniformly in the \(\pi\) radians defined by the surface. The random number-generator is used to determine, based on the acoustical parameters of the surface, whether the ray is absorbed, scattered, reflected, or transmitted. If the ray is absorbed TRACE continues by beginning a new ray. If scattered, the process starts anew by generating a ray angle within the acceptable limits and proceeding to find the next position. If the ray is reflected, the new ray angle is determined and again, the ray continues by finding the next location. If the ray is transmitted, it is treated as if it were diffracted around the scatterer since for real scatterers in suburban areas diffraction accounts for most of what has been called transmission in this paper. The procedure used is to first determine from which two of the four corners of the scatterer the ray may continue, given that the ray's angular direction is unchanged and it may not pierce the scatterer. The corner which is closest in terms of distance along the perimeter of the scatterer is then chosen as
the ray's next position. The ray's next location is then found as described above. An example of a transmitted ray is shown in Figure 1.7. The ray may proceed from corner 2 or corner 4, but corner 2 is closest and would be chosen by the algorithm.

After 100 rays are traced the end of the second loop is reached and the subroutine begins a convergence test. The current version of the computer model determines the average sound pressure level for all the rays traced so far, and checks to see if the change from the average last calculated is within DBTOL. But it is insufficient to require the mean of a statistical distribution to converge, because the standard deviation may not converge. Hence the variance in the energy reaching each receiver in each set of 100 rays is calculated. Although this variance may not approach zero, it should approach a constant. The procedure used to check for this is to take the ratio of the variance after N sets of 100 rays to the variance after N-1 sets. If convergence is complete, this ratio is required to fall within TMER of 1.00 (i.e., 1-TMER ≤ (σ²_N/σ²_N-1) ≤ 1+TMER) as well as the sound pressure level being within DBTOL of the previous calculation. Typical values of TMER used for this study are 0.05 and 0.01. If more than one receiver is being used, all receivers must simultaneously converge. This convergence check ensures that both the mean and variance of the energy distribution converge. An example of the convergence is shown in Figure 1.8.
FIGURE 1.7 Example of Ray "Transmission"
FIGURE 1.8  Typical Program Convergence
Ray-tracing continues until convergence is obtained at which point control is returned to MAIN. If more than one scatterer configuration is to be treated, RANDOM is used to generate the next set of scatterer locations and TRACE begins anew. Upon completion of this cycle, a call to OUTPUT is issued.

1.5.4 OUTPUT

The function of subroutine OUTPUT is to print in histogram from a graph of the sound pressure level versus time for each receiver. This is intended to be compared to oscilloscope traces. The time scale is determined in MAIN based on the shortest distance from the source to the receivers. The histogram is based on data stored of the energy versus time.

1.6 Program Operation

The computer model which has been described is currently running on a 16 bit computer. Because of the many computations done, the computer program takes a relatively large amount of space and time to run. This version occupies 34k and takes a minimum of 120 seconds to run on an Interdate M80 computer. The number of receivers, and the complexity of the model affects the time needed to complete each run, but it is in general quicker to run many receivers simultaneously than to run each as a separate job. As the convergence criteria are stiffened, the run time increases by roughly the square if everything
else about the model remains constant. For the runs in this study, maximum run times of 1000 seconds were encountered. On the average, though, the tests included in the next chapters took about five minutes and considered five receivers each.

The program is coded in Fortran, and should be usable on other machines with only minor modifications.

1.7 **Future Modifications**

Some of the minor modifications which can be made to the current version of the computer model have already been discussed in Section 1.4. Besides these relatively simple modifications there are some major acoustical phenomena which the current version of the model cannot treat without modification. This model version cannot, for example, treat atmospheric phenomena such as the effect of wind, topological effects, or barrier problems. The modification of the program to include barriers of finite height, but extent long compared to the scatterers in the model is one which may be accomplished relatively easily and has great importance in the application of this model to suburban areas. The inclusion of topological effects and ground reflections amounts to changing the computer model from a two-dimensional to a three-dimensional system. The added geometric computations and data will add considerably both to the computer program's space and time of run. The effect of wind and temperature gradients may be possible to include by assigning a non-uniform
angular distribution of rays emanating from the source, allowing the source to favor the downwind directions. A more accurate treatment would again require a three-dimensional model.
2.1 The Use of Scale Modeling

Conventional mathematical procedures used for studying sound propagation are unable to take into consideration the many physical phenomena that are important in sound propagation outdoors. Sound pressure levels are, for example, a function of scatter locations, the acoustical properties of the scatterers, the air absorption, and the terrain of the environment. In order to study sound propagation outdoors the technique of scale modeling was employed. In acoustical scale modeling, a scale model of the area of interest is built, including as much detail as desired. The source frequencies are then increased by the same factor by which object lengths are decreased. The acoustical parameters of the environment must also be accurately represented in the model, so that results obtained in the scale model study may be directly applied to the real environment.

The use of scale modeling has been applied to both sound studies of auditoriums [3,4] and sound propagation outdoors [5,6,7,8]. Historically, MIT's involvement with scale modeling began with a study of the flyover noise produced in an urban area by a helicopter [9]. Model studies of urban areas continued and specialized equipment
was developed. It is the attempt of this thesis to aid in the ex-
tension of modeling techniques to study suburban areas.

The major advantage of physical modeling is the ability to
predict sound paths and sound pressure levels in areas which are too
complicated to be described theoretically. Phenomena which play a
significant role physically, such as ground reflections and dif-
fractions around buildings, may be modeled with relative ease. Scale
modeling also allows the researcher to study the effects of physical
changes by simply altering the model. In this manner, the impact of
proposed construction may be considered as well as already existing
spatial configurations. In addition, the materials needed for scale
modeling are generally inexpensive once the equipment is obtained.
The scale model studies conducted for this work used a base of plywood,
and houses of styrofoam.

There are two major disadvantages to the use of scale
modeling. Scale modeling, because of the frequencies involved, employs
specialized equipment. This equipment will be described in Section 2.2.
The initial expense of modeling is thus considerable compared to
field data or computer studies. Scale modeling techniques also do not
allow the user to separate acoustical phenomenon in the manner com-
puter programs and theoretical calculations do. For example, an
object in the scale model scatters, reflects, and diffracts sound.
Without changing the object, these effects may be impossible to identify singly.

2.1.1 How Modeling Works

Scale modeling techniques require that all of the relevant features of a physical area be appropriately scaled. This implies that in addition to constructing a detailed scale model of the environment, it is necessary to scale the sound source and microphone. Sound interactions between waves and objects depend on the ratio of the wavelength to the object size, so the frequencies of use must be scaled up by the same factor by which objects are scaled down. In addition, it is necessary to accurately reproduce the acoustical parameters of the objects. If the absorption, reflection, and scattering coefficients of all of the objects in the model match the coefficients of the real objects, the results of the scale model study may be used directly to predict results in the real area.

2.2 The Modeling Equipment

The major problem in the use of scale modeling techniques has been the development of specialized equipment to be used in model experiments. Under a grant from the National Science Foundation, MIT has been designing instrumentation for scale model experiments
[10,11]. The equipment used for this work was the system marketed by Grozier Technical Systems, Inc. with minor modifications.

2.2.1 General System Considerations

In the design of the modeling instrumentation there were several goals aimed at making the use of the equipment relatively simple, and inexpensive:

1. The system gives results directly in decibels.
2. The system does not require special facilities such as an anechoic chamber. Any large space where reflections from walls occur at times which are distinct from the times of pulse arrivals at the microphone is sufficient.
3. The system is compact and easily portable. It may be used in relatively tight quarters without much concern over reflections off of the equipment.
4. The system is sufficiently accurate to give model data consistent with full scale measurements.
5. The source is able to simulate full scale sources with dominant frequencies between 125 Hz and 4 kHz.

A decision was made to use an impulsive noise source instead of a steady-state acoustic signal. Steady-state sources have the
advantage of being easily processed by standard equipment, and more
like environmental noise. The possible sources of this type are
small loudspeakers, crystals, or air jets. However, high sound levels
are needed to maintain a sufficiently large signal to noise ratio
over lengths of several feet; ruling out the use of loudspeakers or
crystals. Loud air jets unfortunately use large amounts of compressed
air and must be run in anechoic chambers to eliminate wall reflections.

An impulsive source has the advantage of making is possible
to separate different sound paths by their arrival times. Wall re-
flections from the modeling space may be identified by their arrival
time, and then ignored, so almost any modeling space may be used.
Since the arrival times for each sound path are known, corrections
for the higher air absorption in the model can be made.

2.2.2 The System Hardware

A block diagram of the system is shown in Figure 2.1. The
system consists of a spark source, a microphone, an amplifier, the
signal processor, and a storage oscilloscope.

The impulsive noise source used is a spark, chosen for its
short duration and high frequency content. It produces an acoustic
pulse at the tip of a wand upon the triggered discharge of a high-
voltage capacitor. The wand tip is placed at the source location in the model. It is triggered remotely when a button is depressed for about two seconds and then released. Bleed resistors and "dead-man" switches render the spark generator safe for normal usage. The generator has a spark amplitude control permitting adjustments from a capacitor energy of 0.5 to 12.5 joules and a pointed wand that gives an omnidirectional pulse over approximately 94% of the solid angle. The measured strength of the sound pulses have a standard deviation of 0.5 dB, so the sparks are very repeatable. The complete spark generator outfit weighs 45.0 pounds. Newer versions of the same model are considerably lighter, weighing only 25.0 pounds.

The model studies done for this thesis work used a BBN 0.10 inch microphone. This is the smallest microphone size available commercially today, yet in a 1:80 scale model this represents a full scale microphone of 8.0 inches in diameter, which is unrealistically large. The microphone is very insensitive due to its size and thus requires a powerful source. It is also more directional than the standard 1.0 inch microphone used in field data acquisition.

The amplifier used in this study was an Ithaco 255 amplifier. The standard Grozier equipment includes a scaling amplifier with decade adjustments and an internal filter which may be disconnected if an external filter is desired.
The Waveburst Processor was used in this study both to produce a smoothed envelope of the received signal to give sound pressure level peaks, and to give an equivalent steady-state level. The latter is obtained by squaring the signal received, integrating, and taking the log. As pulses arrive their energy is thus logarithmically summed. This combined with the short time average allows for the acquisition of an overall sound pressure level, and the identification of pulses. The levels are displayed on a storage scope versus travel time. A typical trace is shown in Figure 2.2. The scope may be triggered simultaneous to the triggering of the Processor, or with a delayed signal. The latter allows the user to obtain greater resolution of sound pulse arrivals over long distances by delaying the display rather than compressing it. The potential problem of integrating the noise has been diverted by mean square averaging the noise prior to spark discharge, and subtracting it from the signal during integration. The Waveburst Processor is very light, weighing only 5.0 pounds.

2.3 The Model Configuration

For the purpose of this study a suburban-type scale model was constructed. The scaling factor of 1:80 was used in order to include a large community in a reasonably sized physical model. The base of the model was made of painted plywood, chosen more for the
ease than its ability to model grass. The houses were assumed to have sloping roofs with dimensions as indicated in Figure 2.3. They were constructed from a sheet of 3 inch thick styrofoam. As a community model, it was assumed that each house was in the center of a 3/8 acre square plot, and that each house had the same orientation in the lot. The resulting scale model is pictured in Figure 2.4. This model was chosen for its simplicity. Scale-model studies used to consider sound propagation in a specific area would use more complex models.

The source location was held fixed in the model tests, as pictured in the figure, and at a height of one inch off the plywood. This height corresponds to a full scale height of about seven feet. An example of a common community noise source with that height would be a tractor trailer. The receiver locations varied in the scale model tests, but the height remained fixed at three inches, corresponding to a full scale height of twenty feet.

It was necessary to determine the mean free path between the sound ray reflections for use in determining the acoustical parameters of the house. The mean free path between sound ray collisions is given by:

\[ \text{mfp} = \frac{A}{N_1} \] (2.1)
FIGURE 2.3 Houses Used in the Scale Model Experiments
FIGURE 2.4  Scale Model Geometry
where $A$ is the total model area, $N$ the number of scatterers, and $l$ a characteristic length of the house. Given a house with sides $L_1$ and $L_2$, a good choice for $l$ is:

$$l = \frac{2}{\pi} \int_{0}^{\pi/2} (L_1 \sin \theta + L_2 \cos \theta) d\theta = \frac{2}{\pi} (L_1 + L_2)$$  \hspace{1cm} (2.2)$$

so the mfp is:

$$\text{mfp} = \frac{\pi A}{2(1 + \frac{1}{2}) N}$$  \hspace{1cm} (2.3)$$

In the model constructed, the mfp was 79.87 inches.

2.4 Determining Acoustical Parameters for Input to the Program

The computer model developed assumes that when a sound pulse arrives at an object it may be reflected, transmitted, scattered, or absorbed. The relative frequencies of each of these occurrences are given by the reflection, transmission, scattering, and absorption coefficients of the object, each defined as the ratio of the acoustical energy undergoing the phenomenon to the total acoustical energy in the pulse. Thus, the sum of the four acoustical coefficients is unity. It was necessary to determine the parameters of the houses in the scale model tests for use in the computer model.
In addition, it was necessary to measure the air absorption of sound at least once during each day in which tests were run since the air absorption at high frequencies is strongly dependent on humidity and temperature.

2.4.1 Transmission

The acoustical phenomenon labeled "transmission" in this study is not transmission in the true acoustical sense. I have assumed that virtually none of the sound energy penetrates through the model homes. What is actually being measured is the sound energy which is diffracted around the house at edges of the house. The computer model treats transmission of a sound ray by assuming the ray moves along the house perimeter to an appropriate corner and continues propagating at the same angular direction. This is an admittedly crude model of real diffraction by an edge, where wave fronts obtain an angular direction distributed about the angular direction prior to diffraction.

I have assumed that the acoustic field in the model community is diffuse, i.e., that the sound has uniform angular distribution. In such a field, the most likely angle of incidence on a surface is 45°. The experimental set-up is pictured in Figure 2.5. The source and receiver heights were those used in the model experiments.
FIGURE 2.5 Experimental Set-Up for Measuring the Transmission Coefficient of the Model Houses
Initially, the house was removed and the sound pressure level at a distance of two mean free paths was measured. The house was then replaced midway between the source and receiver, and again the sound pressure level was measured. It is the reduction in the level which is important. The definition of a sound pressure level is:

\[ L_p = 10 \log_{10} \left( \frac{p^2}{p_{\text{ref}}^2} \right) \]  

(2.4)

and the transmission coefficient is given by:

\[ T = \frac{p_{\text{with house}}^2}{p_{\text{without house}}^2} \]  

(2.5)

Hence, if \( \Delta \) is the drop in the sound pressure level upon insertion of house, the transmission coefficient for the house is:

\[ T = 10^{-\Delta/10} \]  

(2.6)

This value of \( T \) need not be corrected for air absorption since the two paths which were compared were very close in length.

The houses used in the model experiments were cut from a large sheet of styrofoam. As a result, some of the surfaces were rough, some smooth. The transmission, absorption and reflection tests
were run for both smooth and rough styrofoam. The results were averaged based on the relative amounts of surface area: 55% rough, 45% smooth. The transmission tests for painted and unpainted styrofoam are shown in Table 2.1.

The difference between the painted and unpainted houses is very small, indicating that diffraction by a wide barrier is not strongly dependent on absorption. This agrees with Keller's theory [12].

2.4.2 Air Absorption

It was necessary to determine the air absorption coefficient for input to the computer program. This was done by assuming that the spark source may be treated as a simple point source. In the far field then, (i.e., many wavelengths from the source), the pressure drops as $r^{-1}$ so the energy decays as $r^{-2}$. This implies that if the distance between the source and receiver is doubled, the sound pressure level should drop by a factor of:

$$10 \log_{10} \left( \frac{r_2^2}{r_1^2} \right) = 10 \log_{10} 4 = 6.02 \text{ dB}$$

Tests were run with path lengths of 1.5 and 3.0 meters. The drop in the sound pressure level was noted, and it was assumed that the ex-
<table>
<thead>
<tr>
<th></th>
<th>smooth</th>
<th>rough</th>
<th>average</th>
</tr>
</thead>
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<td>0.71</td>
<td>0.72</td>
</tr>
<tr>
<td>painted</td>
<td>0.71</td>
<td>0.68</td>
<td>0.69</td>
</tr>
</tbody>
</table>

TABLE 2.1 Transmission Coefficients of the Scale Model Houses as Determined by Experiment
cess attenuation beyond six decibels was caused by air absorption. This then produced the air absorption coefficient in dB/m. On the days that the model tests were run with unpainted houses, the resulting air absorption coefficients were 1.27 dB/m and 0.50 dB/m. On the days the painted houses were employed, Figures of 1.47 dB/m and 1.07 dB/m were obtained. Considering the high frequency content of the spark, and the temperature and humidity variations, these numbers are reasonably close.

The assumption that the spark source behaves like a simple point source encounters some difficulties caused by the nonlinearity of the source. The spark is, in fact, a shock wave. In order to check the severity of the deviation from a point source, the same air absorption test as described above was run in third-octave bands using an Ithaco third-octave band filter. A wet-bulb thermometer was used to give readings on both the temperature and humidity. The resulting air absorption was compared to the data published by the Wyle Laboratories for a steady-state source [13]. The results are shown in Figure 2.6. The most significant discrepancy between the Wyle data and the data obtained from the spark source occurs at the frequencies above 63 kHz where the spectral amplitude of the spark is dropping. Although the spark source clearly deviates from a simple source, the figures obtained from the experiment with the source were used for the computer code since the program assumes a point source
Figure 2.6  Air Absorption Using the Spark Source Compared to Steady State Measurements
and was being used to compare to the scale model experiments.

2.4.3 Surface Absorption

To determine the absorption coefficient of the styrofoam a reverberation time measurement was made. The reverberation time, $\tau$, is defined as the time required for the sound pressure level in a room to decay by 60 dB. It was empirically related to the absorption coefficient of the room surface by Wallace Clement Sabine in 1895 [14]. This formula, modified to include the absorption of sound by air was employed to determine the absorption coefficient of the styrofoam used, $\alpha$.

$$\tau = \frac{55.262V}{cs\alpha + 4Vcm}$$  \hspace{1cm} (2.8)

where $V$ is the room volume, $c$ is the speed of sound in air, $s$ the room surface area and $m$ the absorption coefficient of air in units of inverse length. (The air absorption may then be written as $e^{-mr}$ where $r$ is the path length). Since the room parameters are known, if $\tau$ is measured, $\alpha$ may be calculated. It was originally intended to determine both $m$ and $\alpha$ by a series of three experiments. The first would use a cardboard box, the second a box of cardboard with one styrofoam side, the third an all styrofoam box. This would result in three simultaneous equations for $\alpha_c$, $\alpha_s$, and $m$. 

- 61 -
\[ \tau_1 = \frac{55.262V_1}{(cs_1 \alpha_C + 4V_1 \text{cm})} \]

\[ \tau_2 = \frac{55.262V_2}{(cs_2 \alpha_C + cs_2 \alpha_S + 4V_2 \text{cm})} \quad (2.9) \]

\[ \tau_3 = \frac{55.262V_3}{(cs_3 \alpha_S + 4V_3 \text{cm})} \]

These may be written in matrix form and the coefficients may be solved for provided the determinant of the matrix is not too small.

\[
\begin{bmatrix}
    cs_1 \tau_1 & 0 & 4V_1 c\tau_1 \\
    cs_2 c\tau_2 & cs_2 s\tau_2 & 4V_2 c\tau_2 \\
    0 & cs_3 s\tau_3 & 4V_3 c\tau_3
\end{bmatrix}
\begin{bmatrix}
    \alpha_C \\
    \alpha_S \\
    \text{m}
\end{bmatrix}
= 
\begin{bmatrix}
    55.262V_1 \\
    55.262V_2 \\
    55.262V_3
\end{bmatrix}
\quad (2.10)
\]

Unfortunately, Sabine's reverberation time formula only applies when the decay of the acoustical energy in the room is exponential. This requires that the enclosures be rectangular with room dimension ratios near unity. Yet this requires the matrix determinant, $4c^3 \tau_1 \tau_2 \tau_3 (V_3 s_1 s_2 s_5 - V_2 s_1 s_3 + V_1 s_2 c s_3)$, to approach zero. For the boxes used, and many dimensions were tried, the entrees in the matrix were of order $10^{-2}$ and the determinant was of order $10^{-5}$. The results were thus totally useless.

Since the above method could not produce reasonable results,
it was necessary to obtain the air absorption coefficient and the styrofoam absorption coefficient separately. The determination of the air absorption coefficient was previously explained. To convert from units of dB/m to units of inverse meters one uses the equation:

\[
- \text{absorption (dB/m)} = 10 \log_{10} e^{-m} \\
= -10 m \log_{10} e
\]  

(2.11)

This produces values of \( m \) varying from 0.292 per meter to 0.338 per meter.

The styrofoam absorption was then obtained using an all styrofoam box to measure the reverberation time, which was then substituted into Sabine's reverberation time formula. Again, since the houses each had both smooth and rough sides, it was necessary to find two absorption coefficients for the unpainted styrofoam and two for the painted styrofoam. The enclosure was constructed so that five of the sides were smooth. The top was smooth on one side, rough on the other. The reverberation time using all smooth sides produced \( \alpha_{\text{smooth}} \):

\[
\alpha_{\text{smooth}} = \frac{55.262V}{cs\tau_{\text{smooth}}} - \frac{4mV}{s}
\]  

(2.12)
Upon flipping the lid, $\alpha_{\text{rough}}$ was obtained:

$$\alpha_{\text{rough}} = \frac{55.262V}{cs_{\text{rough}}t_{\text{rough}}} - \frac{4mV}{s_{\text{rough}}} - \alpha_{\text{smooth}}$$

Figure 2.7 shows the two traces of the sound energy decay for the box of unpainted styrofoam. Table 2.2 presents the absorption coefficients for the painted and unpainted styrofoam, smooth and rough. The average is weighted by relative amounts of smooth and rough surfaces. The effect of the paint is to drastically reduce the absorptivity of the styrofoam.

2.4.4 Reflection Coefficient

The reflection coefficient of the painted and unpainted styrofoam houses were determined by firing the spark source at a distance of one mean free path from a large sheet of styrofoam oriented at an angle of 45° from the spark source. A microphone was placed at a distance of one mean free path from the styrofoam in order to record the reflected spark. The experimental set-up is pictured in Figure 2.8. The strength of the reflected spark was compared to a direct signal over two mean free path lengths to determine the reflection coefficient in much the same manner that the transmission coefficient was found:

$$R = 10^{-\Delta/10}$$
Top trace - box with rough top
Bottom trace - box with all smooth surfaces

FIGURE 2.7 Sound Energy Decay for Styrofoam Box
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<th></th>
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<th>rough</th>
<th>average</th>
</tr>
</thead>
<tbody>
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<td>0.47</td>
<td>0.40</td>
</tr>
<tr>
<td>painted</td>
<td>0.12</td>
<td>0.17</td>
<td>0.15</td>
</tr>
</tbody>
</table>

**TABLE 2.2** Absorption Coefficients of the Model Houses Determined Using Sabine's Reverberation Time Formula
FIGURE 2.8 Experimental Set-Up for Determining the Reflection Coefficient of Styrofoam
where $\Delta$ is the dB difference between the direct and reflected sound pressure levels. The reflection coefficients were determined for rough and smooth styrofoam, both painted and unpainted, and are summarized in Table 2.3. The average reflection coefficient of the styrofoam is not significantly changed upon painting. What is somewhat difficult to explain is the reduction in the reflection coefficient of the rough styrofoam upon painting. It is possible that the styrofoam painting was very nonuniform and these irregularities served to measurably increase the scattering. It is also possible that the unpainted, rough styrofoam scattered sound waves toward the microphone. The resolution of the system is such that it is impossible to separate the reflected sound energy from sound energy which is scattered toward the microphone and has an almost identical path length. The painted surface may in fact have eliminated some of this scattering, producing a smaller measured reflection coefficient.

2.4.5 Summary of Acoustical Parameters

The acoustical parameter tests described in this section were assembled to give average values for transmission, absorption, reflection, and scattering coefficients. This was done by assuming that the sound waves incident upon the model homes were either diffracted (i.e., "transmitted") or not. If the sound waves were not diffracted, they were then either reflected, absorbed or scattered.
<table>
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<th>rough</th>
<th>average</th>
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</thead>
<tbody>
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<td>0.54</td>
<td>0.54</td>
</tr>
<tr>
<td>painted</td>
<td>0.68</td>
<td>0.32</td>
<td>0.48</td>
</tr>
</tbody>
</table>

TABLE 2.3 Reflection Coefficient of Scale-Model Houses as Determined by Experiment
This explicitity divides the phenomena into two categories: sound impinging on a surface and sound diffracted around the surface. Attenuation upon diffraction is already included in the transmission coefficient by virtue of the experiment conducted to determine the transmission coefficient.

For the unpainted styrofoam, the implication is that an average of 72\% of the sound energy is transmitted. Of the remaining 28\%, 40\% is absorbed, 54\% reflected, and the remainder scattered. In other words, for the unpainted houses:

\[
\begin{align*}
\bar{T} &= 0.72 \\
\bar{a} &= 0.11 \\
\bar{R} &= 0.15 \\
\bar{S} &= 0.02
\end{align*}
\]

A similar computation for the painted styrofoam gives:

\[
\begin{align*}
\bar{T} &= 0.69 \\
\bar{a} &= 0.05 \\
\bar{R} &= 0.15 \\
\bar{S} &= 0.11
\end{align*}
\]

The net effect of painting the houses was thus to decrease the absorption and increase the apparent scattering.
2.5 Model Tests and Results

The model tests were conducted in four sets, each designed to emphasize different abilities of the computer program. The first set placed the receiver in five different locations along the center line of the model, in a line of clear view from the source. The second set placed the receiver in three locations off the center line of the model, with varying degrees of obstruction between the source and receiver locations. The third set placed the receiver in two slightly different positions near a house. The last set placed the receiver in three positions on and off the center line of the model, with and without removing a row of houses. In each case the source location was as shown in the model configuration pictured in Figure 2.4.

2.5.1 Set 1 -- On the Center Line

Positions of receivers and the source are shown in Figure 2.9. This set of tests was aimed to test the ability of the computer program to predict the time of direct sound arrival and the sound pressure level produced by the direct sound and used receiver positions 1 through 5. In all of the cases a calibration level of 80 dB at 200 ft free field was used. Results are presented in Figures 2.10 to 2.14. Each figure contains an oscilloscope
FIGURE 2.9 Receiver Positions in the Model
FIGURE 2.10 $L_p$ at Position 1 Using Unpainted and Painted Houses
FIGURE 2.11 $L_p$ at Position 2: Using Unpainted and Painted Houses
FIGURE 2.12 $L_p$ at Position 3 Using Unpainted and Painted Houses
FIGURE 2.13 $L_p$ at Position 4 Using Unpainted and Painted Houses
FIGURE 2.14 L_p at Position 5: Using Unpainted and Painted Houses
trace (solid line) with the computer result overlaid (dotted line) in the form of a histogram. The histogram peak should be compared with the area under the solid curve at that time interval. The height of each interval in the histogram was produced by the computer model. For both painted and unpainted styrofoam houses, the results indicate that the program can very accurately predict the time of pulse arrival and the level for direct sound. As expected, more reflected and scattered sound energy is observed for the painted houses.

2.5.2 Set 2 -- Off the Center Line

For this set of computer runs the receivers were located in positions along a line parallel to those in the first set, but off the center line of the model (positions 6, 7 and 8 in Figure 2.9). The intent of this test was to examine the ability of the computer program to accurately predict sound pressure levels when there is no line of sight to the source and the sound energy must arrive via reflections. The results of this test are shown in Figure 2.15 to 2.17. At receiver position 6 the majority of the sound energy arrives directly, but for the painted houses the computer model accurately predicts the time and height of at least the sound energy arriving by one reflection. For receiver position 7 the result for the unpainted houses still predicts only the earliest sound arrival while the result for the painted houses predicts both of the
FIGURE 2.15 $L_p$ at Position 6 Using Unpainted and Painted Houses
FIGURE 2.16  $L_p$ at Position 7 Using Unpainted and Painted Houses
FIGURE 2.17 $L_p$ at Position 8 Using Unpainted and Painted Houses
peaks seen, although the energy levels differ from the experimental results by about 6 dB. At receiver position 8 for both unpainted and painted houses, the computer model predicts only the earliest sound arrival. Although the results from this test are not in as close agreement with the experiments as the results from the first set, the model predicts reasonably well the sound pressure levels as a function of time. The earliest sound is predicted by the code the best.

2.5.3 Set 3 -- Shadow Region

The purpose of this set of computer runs was to test the ability of the computer model to predict the acoustical shadow region behind a house in the path of direct sound from the source. Positions 9 and 10 in Figure 2.9 were employed for this test. The results are pictured in Figures 2.18 and 2.19. For position 9, outside of the house's shadow region, the model predicts the experimental results well, especially for the case with the painted houses. At receiver position 10, inside the house's shadow region, the code still predicts quite well the scale model results. The tendency to overestimate the earliest sound energy arriving at the receiver can be explained by the size of the receiver position in the computer model. Because a ray-tracing model very quickly loses accuracy the receivers defined in the model have a diameter of two percent of the
FIGURE 2.18 $L_p$ at Position 9 Using Unpainted and Painted Houses
FIGURE 2.19  $L_p$ at Position 10 Using Unpainted and Painted Houses
smallest scale length which in this model means a diameter of 10.4 ft. In this instance, the receiver at position ten is partly out of the shadow region and picks up some direct sound, causing the over-estimation of the earliest sound energy.

2.5.4 Removing a Row of Houses

For this set of computer runs positions 1, 6 and 11 as indicated in Figure 2.9 were used. First the positions were examined for the model geometry as indicated by the figure. Then the left-most column of houses were removed. The intent was to test the ability of the program to predict small changes. Figure 2.20 shows the results for the column removal as measured as position one. They may be compared to Figure 2.10. In both the scale model experiments and in the computer results, there was little change upon the removal of the column of houses. Figure 2.21 shows the results at receiver position 6 after the removal of the houses. This may be compared to Figure 2.15 where the houses were in place in the model. As indicated by the figures, the result of removing the column of houses was to increase the direct sound energy which arrived as well as the reflected energy. The computer predictions and experiments agree well. Finally, Figure 2.22 shows the results for position 11 while Figure 2.23 shows the results for the same receiver position with the houses removed. The results for the unpainted houses show the correct
FIGURE 2.20 $L_p$ at Position 1 with the Leftmost Column of Houses Removed
FIGURE 2.21 $L_p$ at Position 6 with the Leftmost Column of Houses Removed

- 87 -
FIGURE 2.22 \( L_p \) at Position 11 Using Unpainted and Painted Houses

- 88 -
FIGURE 2.23 $L_p$ at Position 11 with the Leftmost Column of Houses Removed
shape but are at a lower level than measured experimentally. The results for the painted styrofoam show the shift in the relative importance of reflected and direct sound energy towards direct sound in the case of the removed houses. For this test the computer results are quite good.

From the results pictured and described above, one may conclude that the computer model is an effective means of predicting the results of scale model experiments. The strength of the computer predictions lies in the ability to very accurately predict the time of arrival and the level of direct sound energy. Because of computer code inaccuracies the reflected sound energy is not predicted with the same precision.
CHAPTER 3    COMPARISON TO ANALYTICAL RESULTS

The intent of this chapter is to compare analytical results for sound pressure levels to the predictions of the computer model. The geometry employed is pictured in Figure 3.1, and corresponds to the geometry used in the work done by W. R. Schlatter [15]. In the treatment by Schlatter an imaging technique was used to replace the walls within an infinite series of source images as pictured in Figure 3.2. The path between each image source and the receiver corresponds to a path in the real situation in which the number of wall reflections equals the number of image walls the image path crosses. The total sound energy reaching the receiver is the sum of the energies contained in the image paths.

The sound power level $L_w$ is given by:

$$L_w = L_p - 10 \log_{10} X - C \quad (3.1)$$

where $L_p$ is the sound pressure level, $C$ is a factor relating to air thermodynamics, and $X$ is a factor defined by the geometry of the source, and the source directivity factor. For this study, the factor $C$ was set to zero, and the source was assumed to be a point source radiating uniformly in all directions. For such a point source
FIGURE 3.1 Model Geometry for Comparison to Analytical Results
FIGURE 3.2 Imaging of a Source between two Parallel, Infinite Walls
\[ p^2 = \rho cW/4\pi r^2 = \rho cWX \]  \hspace{1cm} (3.2) \\

where \( W \) is the acoustical power of the source and \( r \) is the distance between the source and receiver.

The case of a point source may be extended to the case of many image sources by summing the contribution of each image source:

\[ p^2 = \sum_{n=-\infty}^{\infty} \rho cWR|n|/4\pi r_n^2 \]  \hspace{1cm} (3.3)

where \( R \) is the reflection coefficient of the walls, and \( r_n \) is the path length between the nth image and the receiver position. For this case then, \( X \) may be identified with:

\[ X = \sum_{n=-\infty}^{\infty} R|n|/4\pi r_n^2 \]  \hspace{1cm} (3.4)

and Equation 3.2 is still correct. This summation may be rewritten as:

\[ 4\pi X = \frac{1}{d^2+(b-a)^2} + \sum_{n=1}^{\infty} \left\{ \frac{R^n}{d^2+(nL+(-1)^n b-a)^2} \right\} \]  \hspace{1cm} (3.5)
The first term corresponds to the direct sound path and the summation contains a term for the path to the image source \( S_n \), and to the image source \( S_{-n} \). Johnson and Saunders [16] have evaluated the limit of this summation for \( R=1 \) (perfectly reflecting walls):

\[
X = \frac{1}{8L^2\delta} \left\{ \frac{\sinh(\pi\delta)}{\cosh(\pi\delta) - \cos[\frac{\pi(a-b)}{L}]} + \frac{\sinh(\pi\delta)}{\cosh(\pi\delta) + \cos[\frac{\pi(a+b)}{L}]} \right\} (3.6)
\]

where \( \delta \) is the ratio \( \frac{d}{L} \). This reduces for the case of \( b=0 \) (the source positioned on the center line) to:

\[
X = \frac{1}{4L^2\delta} \left( \frac{\sinh(2\pi\delta)}{\cosh(2\pi\delta) - \cos(2\pi\alpha)} \right) (3.7)
\]

where \( \alpha \equiv \frac{a}{L} \). The other case of interest for this study is the case of perfectly absorbing walls, \( R=0 \). Equation 3.5 reduces to the first term only:

\[
X = \frac{1}{4\pi[d^2 + (b-a)^2]} (3.8)
\]

Other cases have been studied by Schlatter, but were not employed here to compare to computer predictions.

Results for the case of perfectly absorbing walls are shown in Figure 3.3. The computer code was normalized to a sound pressure level of 30 dB at a distance of 200 feet free-field: corresponding to a
FIGURE 3.3 Comparison of Theory to Computer-Produced Results for Perfectly Absorbing Walls
sound power level of 87.0 dB. The figure gives sound pressure level versus $\delta$ for three different cases: the source and receiver on center, the receiver off-center, and both off-center. The solid lines in the figure are the analytical results, and the experimental values are noted by points. In all three cases the agreement is quite good, with maximum disagreements of 2.2 dB and average deviations of 0.7 dB.

For the perfectly reflecting walls, it was necessary to modify the analytical predictions to account for the inability of the computer model to include rays with an infinite number of reflections. For this study a limit of 10 ray reflections was set in the program. The error introduced by this truncation was evaluated by calculating the first 10 terms of the summation in Equation 3.5 and subtracting from the result in Equation 3.6. The error introduced for the cases tested was at maximum 1.5 dB. The results of the tests are shown in Figure 3.4 with the sound pressure level produced by 10 reflections graphed versus $\delta$. Three cases were examined, two with the receiver and source off-center, one with both on-center. The agreement between the computer tests and theoretical results is not as good as the perfectly absorbing wall case. The average error in the sound pressure level is 1.90 dB in the case of both the source and receiver on-center, 1.01 dB for the case of $a=47, b=22$, and 1.73 dB in the case of $a=25, b=-25$. The maximum disagreement in the three cases is 3.5 dB. In every case the model underestimated the over-
FIGURE 3.4 Comparison of Theory to Computer-Produced Results for Perfectly Reflecting Walls
all sound pressure level.

An error in this case of 2 or 3 dB is not unreasonable for two reasons. Firstly, this comparison test used infinite parallel walls, assumed to be perfectly reflecting. In fact, since the program was designed for use in a suburban environment, no case like this will be encountered. All surfaces will have finite absorption tending to emphasize the role of the direct sound which Figure 3.3 indicates the program predicts well. Secondly, the program uses a random-number generator which is, in fact, only pseudo-random. This implies that although the model should converge to the theoretical results, it should not do so to within arbitrary accuracy. Any tendency to favor certain angles can lead to errors of this magnitude. Since no absorption occurs at the walls, the expected number of ray arrivals in each set of one hundred rays depends only on the angle the image source subtends. Table 3.1 shows as an example the number of rays arriving with zero through 10 reflections for the case of both the receiver and source on-center. Comparison of the theoretical result to the actual density generated by the computer indicates that for this particular test the forward angles were not generated as often as a truly random generator would select them. Hence, the direct levels were low, causing the disagreement of the computer model with theory. This problem could be avoided by either running the program with various seeds for the random number generator, or randomly selecting the seed for the number generator during the
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**TABLE 3.1** Number of Rays Arriving with 0 to 10 Reflections for the Case of Source and Receiver on the Center Line
run. The first solution is extremely costly, and the second means that an input deck when used more than once will give different results. This is undesirable because it makes debugging of the program very difficult.

In general, the agreement between the computer predictions and the theoretical results is acceptable, with excellent agreement for the case of perfectly absorbing walls.
CHAPTER 4 COMPARISON TO FIELD DATA

This chapter compares data obtained in field measurements in a suburban community, to the predictions of the computer model. The field data was obtained from a study of noise propagation in the community surrounding Los Angeles International Airport [5] through the courtesy of Cambridge Collaborative, Inc. and R. G. Cann.

4.1 Description of the Field Data

As part of the Los Angeles International Airport study conducted in 1974, a cannon was fired in the community surrounding the proposed site of a new runway, and sound data was recorded at various locations. The relative attenuation between receiver locations was measured in third octave bands centered at 156, 312.5, 625 and 1250 Hz. Three sets of receiver positions were used along lines from the cannon location. The cannon in each case was positioned at a height of 20 feet above the ground, and the microphone at a height of 4.5 feet above the ground. For the purpose of comparison to the computer-produced predictions, only one set of microphone positions was considered. In addition, the data for the third octave band centered about 312.5 Hz was selected for study. Results for the other octave bands were not considered.
The community surrounding the runway site was a suburban area with noticeable topological variations, ground surface variations, and considerable foliage. A typical section is pictured in Figure 4.1. This figure also depicts the variation in building sizes and shapes.

4.2 Choosing the Model

The first task in modeling the community was to construct a model suitable for the computer program. In this selection many assumptions were made. The first step was to define an area of the model. This was done by allowing the line on which the receiver positions were located to be an axis of the model, and taking a model length normal to this axis which would include on the average three buildings between the receiver line axis and the model boundary. The computer code does not trace rays which travel beyond the boundary of the model. Hence it was necessary to define a model area sufficiently large to include paths of significant sound energy.

Once the model area was chosen it was necessary to model each scatterer. For this study each house was individually constructed by as many rectangular shapes as needed, and the location of each noted. The area is shown in Figure 4.2 which indicates the segmentation of each building. This portion of the model was quite accurate.

The actual area being modeled was on a gentle slope, and in
FIGURE 4.1 Typical Section of Suburban Community
FIGURE 4.2 Model Used in the Computer Program
some sections was thickly foliated. The effect of the elevation and surface variations was assumed to be relatively small for this study, and the model used for the program was flat and had a uniform surface. Had this model produced poor results, a more elaborate model with trees as well as houses could have been constructed. The elevation gradient could also have been included at least crudely by defining the model plane to be at an angle from the horizontal. The effect would be to increase distances in the model plane between objects.

4.3 Choosing Acoustical Parameters

In the work done for Chapters 2 and 3 of this thesis, the acoustical parameters of the scatterers were known because they were measured for the scale model, and assigned for comparison to analytical results. However, for almost all cases to which this program was designed to be applied, the acoustical parameters are not well known. It is then necessary to provide reasonable "guesses" for the absorption, scattering, reflection and transmission coefficients of the scatterers as well as air attenuation and any other significant effects. In a large study of a specific suburban area, these parameters would be generated and tested in the computer code in a representative area of the model. If the results produced were not satisfactory, a new set of parameters would be selected and the process iterated until the computer-produced results for that sample
area agreed well with the field data. The parameters would then be applied to study the entire model.

For this study, this procedure would undoubtedly produce excellent agreement between the field data and the computer results because only four receiver locations were used and the model requires more than enough parameters to arbitrarily fit four locations. For this particular model then, only the initial parameter selection was made, based on field studies made by others.

4.3.1 Transmission Coefficient

The transmission coefficient of the houses was obtained by the use of Fresnel theory for diffraction around an infinite barrier. The Fresnel number (FN) is defined as:

\[ FN = 2f\Delta t \]  \hspace{1cm} (4.1)

where \( f \) is the center frequency of the frequency band of interest, and \( \Delta t \) is the difference in the time to travel between source and receiver over the barrier and in the direct path. For the barrier pictured in Figure 4.3:

\[ \Delta t = \frac{r_2 - r_1}{c} \]  \hspace{1cm} (4.2)
The FN generated in this model may be related to the barrier's insertion loss by an empirically derived relation [17], where the insertion loss of a barrier is defined as:

\[
IL = 10 \log_{10} \left( \frac{p_{\text{without barrier}}^2}{p_{\text{with barrier}}^2} \right) \quad (4.3)
\]

so

\[
T = 10^{-IL/10} \quad (4.4)
\]

For this model the mean free path was found to be 87.4 ft and the average house length 28.6 ft on a side. Assuming a diffuse ray field, the house on the average presents a barrier size of 14.3 ft and the source and receiver are each 87.4 ft from the barrier. This is pictured to scale in Figure 4.4. The result corresponds to a small FN or the insertion loss for grazing incidence:

\[
IL = 5 \text{ dB} \quad (4.5)
\]

The houses in the model differ from barriers in that diffraction may occur not just at one edge on a side, but two, as pictured in Figure 4.4. Hence the energy would be doubled (raised by 3 dB) by adding diffraction from a second edge, producing a theoretical insertion loss of 2 dB and finally a transmission coefficient of:
\[ \tau = 10^{-0.2} = 0.63 \] (4.6)

4.3.2 Reflection, Absorption, and Scattering Coefficients

As in previous treatments, it was assumed that the sound energy not transmitted was either absorbed, reflected, or scattered. The absorption coefficients of wood and brick are both 0.03 [18] so for the absorption coefficient of the house \( \bar{\alpha} = 0.03 \times (1.0 - 0.63) = 0.02 \). The remaining 35% of the sound energy is either reflected or scattered. Based on work done in previous ray models for scattering from houses along city street, [19] a scattering coefficient of 25% was assumed for each surface of \( \bar{S} = 0.25 \times (1.0 - 0.63) = 0.09 \) for the houses. Thus the house acoustical parameters were guessed to be:

\[
\bar{\tau} = 0.63 \\
\bar{\alpha} = 0.02 \\
\bar{S} = 0.09 \\
\bar{R} = 0.26
\] (4.7)

4.3.3 Air and Ground Attenuation

For the frequency band considered in this model, the air absorption in dB/meter is negligible and was set to zero for this test. The ground attenuation, however, is significant in suburban
areas. Studies of the attenuation of sound produced by jet planes, by flat grassy spaces was the subject of research by W. E. Scholes and P. H. Parkin [20]. They showed that for a source height of 15 ft, a receiver height of 5 ft, and relatively little wind, the ground attenuation is approximately 6 dB per doubling of the distance from 360 to 3600 ft from the source. This experimental data corresponds well to the model situation with a source height of 20 ft and receiver height of 4.5 ft, so an extra attenuation of 6 dB per doubling of distance was used to account for ground attenuation in the computer code.

4.4 Results

The results of the comparison, using the acoustical parameters determined above for the computer program, are shown in Figure 4.5 which compares the attenuation at receiver locations beyond that of the first receiver. The computer-produced results agree amazingly well with the field data, having an average discrepancy of 1.2 dB. In view of the simplicity of the model used, the agreement between the field data and the computer results is somewhat surprising. Had the receivers not been in direct view of the source, the results would most likely not have been so close.

From these results, one can conclude that the computer
FIGURE 4.5 Comparison of Field Data to Computer Results
model which has been developed for the prediction of sound pressure levels in suburban areas can be expected to produce results which are comparable to field data.
CHAPTER 5  A PRELIMINARY STUDY OF GENERAL SOUND PROPAGATION PATTERNS IN SUBURBAN AREAS

In this chapter, the computer program previously described is used to study general sound propagation patterns for a suburban environment. Four sets of computer tests were run using a point source and using a line source for both a regular and random scatterer geometry. The intent of this study was to provide information on the amount of sound energy contained in direct and reflected paths as a function of scatterer density. This permits a comparison between the general patterns of sound propagation for line and point sources, and between random and regular geometries.

In each test the receivers were fixed at three locations in the model of dimensions 1000 x 1000 ft as indicated in Figure 5.1. The acoustical parameters determined in Chapter 4 were employed for this model. For the point source test, the source was located as shown in the figure. For the line source runs, the source extended along the dotted line. In each of the four cases, three scatterer densities were used: $SDEN = 0.0161$ (16 houses), $SDEN = 0.0641$ (64 houses), $SDEN = 0.1961$ (196 houses). The regular geometry located simulation houses with dimension of 30 x 20 ft in the center of square plots. The case for $SDEN = 0.0161$ is pictured in Figure 5.1. For the random geometry, a subroutine randomly placed the houses in the model space.

- 115 -
5.1 Point Source Results

Results for the point source tests for a regular house geometry are pictured in Figures 5.2, 5.3 and 5.4. At receiver position A, there is always line of sight to the source as the density varies and the direct sound energy dominates as expected. As the scatterer density increases the percentage of the total sound energy included in reflected paths increases, with paths of more reflections playing an increasingly more important role. This result is also as expected since as the scatter density increases the number of possible sound paths including reflections increases while the direct path is unchanged.

At receiver location B, the drop in direct sound energy is more precipitous since line of sight does not exist for the case of SDEN = .1961. Again, as the density increases, the role of paths with three or more reflections increases.

At receiver location C, there is no line of sight to the source for any of the three densities: hence no direct sound. At this position, the role of paths with one, two, three, and more than three reflections is clearly shown. For low density paths of one and two reflections dominate, but as the house density increases, the paths of three or more reflections dominate. In general, if
FIGURE 5.1 Model of Suburban Area
FIGURE 5.2  Point Source, Regular Geometry Position A
FIGURE 5.3 Point Source, Regular Geometry Position B
tests were run at many densities one would expect to see the role of paths with a given number of reflections increase and begin to drop while the role of paths with one more reflection begins to rise.

The results at the same locations for a random scatterer geometry are shown in Figures 5.5, 5.6 and 5.7. At position A, the same general pattern is seen as for the regular case with one important exception: the direct sound energy drops precipitously because line of sight to the source does not exist at the two higher densities. This loss of direct sound shows up in the drop in the overall sound pressure level at the two top densities from a regular to a random geometry as indicated by Table 5.1. The general pattern of paths with greater than three reflections coming to dominate for high densities is followed.

At receiver position B a similar situation exists, with direct sound dropping off very quickly. The overall sound pressure levels, however, agree quite well as shown by Table 5.1.

At position C, the random geometry allows for line of sight at the lowest density, causing a somewhat higher overall sound pressure level than the regular case. In addition, for the random case, paths of two reflections dominate at the high density and in
FIGURE 5.5 Point Source, Random Geometry Position A
FIGURE 5.6 Point Source, Random Geometry  Position B
FIGURE 5.7 Point Source, Random Geometry Position C
<table>
<thead>
<tr>
<th>Position</th>
<th>SDEN = 0.0161</th>
<th>SDEN = 0.0641</th>
<th>SDEN = 0.1961</th>
</tr>
</thead>
<tbody>
<tr>
<td>Areg</td>
<td>73.7</td>
<td>74.5</td>
<td>76.2</td>
</tr>
<tr>
<td>Aran</td>
<td>73.4</td>
<td>69.5</td>
<td>69.3</td>
</tr>
<tr>
<td>Breg</td>
<td>69.7</td>
<td>69.4</td>
<td>64.4</td>
</tr>
<tr>
<td>Bran</td>
<td>68.5</td>
<td>67.3</td>
<td>64.6</td>
</tr>
<tr>
<td>Creg</td>
<td>60.6</td>
<td>54.4</td>
<td>40.1</td>
</tr>
<tr>
<td>Cran</td>
<td>60.0</td>
<td>56.0</td>
<td>57.8</td>
</tr>
</tbody>
</table>

**TABLE 5.1** Simulated Sound Pressure Levels Using a Point Source
the regular case, paths of more than three reflections dominate. Since on the average the fewer the number of reflections the shorter the path length, the paths of two reflections have more energy than those with three reflections. Hence the higher sound pressure level for SDEN = .1961, random geometry.

In general, both for random and regular scatterer geometries, the direct sound dominates and the contribution of paths with three or more reflections rises sharply as density increases. Although differences in random and regular geometry results do exist, they agree fairly well in the prediction of sound pressure levels at receivers.

5.2 Line Source Study

Tests were run using the computer model to simulate a line source for random and regular scatterer geometries analogous to those used for the point source tests. This entailed first modifying then running the code.

5.2.1 Modification to Simulate Line Source

For this study, it was necessary to modify two small portions of the logic in subroutine TRACE: the definition of the ray starting location and the determination of the energy of the ray. The origin
of the ray was found by setting $x = 0$ and generating $y$ with a ran-
dom number generator assuming a uniform probability of beginning at
any $y$ in the interval from 0 to $L$. (See Figure 5.1).

The energy adjustment for a line source involved redefining
the normalization coefficient. If $P$ is the probability of begin-
ning the ray at a position $y$ along the line, then:

$$\int_{0}^{L} Pdy = 1$$

(5.1)

And since a uniform probability is assumed, $P$ is constant so:

$$P = 1/L$$

(5.2)

For a point source, the number of rays in each set of 100 which would
be expected to reach the receiver in the free field is given by:

$$N = 100 \frac{RLEN}{2\pi} \text{SDIST}$$

(5.3)

where RLEN is the receiver diameter and SDIST is the distance from
the source to the receiver:

$$\text{SDIST} = \sqrt{(x-R_x)^2 + (y-R_y)^2}$$

(5.4)
Hence \( x \) and \( y \) are source coordinates, \( R_x \) and \( R_y \) receiver coordinates. For the line source \( x-R_x \), is constant, \( C \), but \( y-R_y \) varies. The total number of rays expected to arrive at the receiver out of 100 rays generated is:

\[
N_{TOT} = \int_{0}^{L} PN(y)dy
\]

where \( N(y) \) is given by Equation 5.3. Hence:

\[
N_{TOT} = \frac{100 \, RLEN}{2\pi L} \int_{0}^{L} \frac{1}{\sqrt{c^2 + (y-R_y)^2}} \, dy
\]

\[
= \frac{100 \, RLEN}{2\pi L} \left\{ 10 \log \left( L-R_y + \sqrt{c^2 + (L-R_y)^2} \right) - 10 \log \left( -R_y + \sqrt{c^2 + R_y^2} \right) \right\}
\]

This normalization if applied to find the square pressure of each ray:

\[
p^2 = p_{\text{point source}}^2 \cdot \frac{1}{L} \left\{ 10 \log \left( L-R_y + \sqrt{c^2 + (L-R_y)^2} \right) - 10 \log \left( -R_y + \sqrt{c^2 + R_y^2} \right) \right\}
\]

With this normalization, a line of sources, each of which is of the
strength of the point source in Section 5.1, was generated.

5.2.2 Results

With the above modifications the code was run to simulate a line source in both a random and regular scatterer environment. Results for the regular geometry are shown in Figures 5.8, 5.9 and 5.10. At receiver location A, the dominant sound energy is direct sound except for SDEN = 0.0641 where the first reflection dominates. The fact that sound having undergone one reflection plays a larger role for this case than that of the point source is not surprising because the line source allows for many more paths with one reflection. As the density increases, more paths with reflections exist but the energy contribution for each decreases rapidly as the path length increases. Hence direct sound will again dominate.

At location B, the same general pattern is seen, but with less disparity in the amount of sound energy contributed by the direct path and by one reflection. The percent of direct sound does not continue to fall quickly as density increases as it did in the point source case because line of sight to at least a portion of the line still exists.

At receiver location C, a similar pattern is observed except that the direct sound contribution does in this case continue drop-
FIGURE 5.8 Line Source, Regular Geometry Position A
FIGURE 5.9 Line Source, Regular Geometry Position B
FIGURE 5.10 Line Source, Regular Geometry Position C
ping as the density increases. Because this receiver location is near to the end of the line source, it is more likely than for the other receivers that the line of sight to the line source will be blocked. This case, however, when compared to the analogous point source case (Figure 5.4) shows remarkable similarity. In both cases as density increases the paths with more than three reflections dominate and other paths tend to contribute almost nothing.

The results for the random geometry are pictured in Figures 5.11, 5.12 and 5.13. As in the regular case, at SDEN = 0.0161 and 0.0641 the direct sound and sound from paths of one reflection dominate, but a SDEN = .1961 the two differ. For the random geometry, the direct sound does not dominate, line of sight not existing, and the paths with many reflections are dominant. Table 5.2 shows the close agreement at the lower frequencies. Comparing this case to the analogous case for the point source, (Figure 5.5) shows excellent agreement in pattern at each density.

Location B, again is similar to the regular geometry line source case (Figure 5.9) except in the drop in direct sound at high densities. Table 5.2 indicates that even at SDEN = .1961 the overall predicted sound pressure levels agree fairly well. Compared to the analogous point source case (Figure 5.6), there is for the line source proportionately more sound contained in paths of fewer re-
FIGURE 5.11 Line Source, Random Geometry Position A
FIGURE 5.12 Line Source, Random Geometry Position B
FIGURE 5.13  Line Source, Random Geometry  Position C
flections. Considering the fact that more such paths exist in the line source case, this is not surprising.

Finally at location C, the direct sound is dominant except at SDEN = .1961 where sound having undergone three reflections is larger. In both the regular geometry line source case and the analogous point source case (Figure 5.7) the percentage of direct sound decayed more quickly while sound from one reflection played a larger role. This discrepancy is indicated by the difference in overall sound pressure levels for the regular and random geometries in Table 5.2 and SDEN = .1961.

5.3 Conclusions

Based on the results discussed in Sections 5.1 and 5.2, it is possible to address the question of the difference in the general pattern of sound propagation in a suburban area for a line and a point source. The results indicate that the major difference lies in the ability to receive direct sound. The general drop-off of direct sound followed by a rise in importance of the sound having undergone many reflections is seen. For a point source, as the scatterer density increases paths of 3 or more reflections dominate, in general, at microphone positions where direct sound is not received. This implies that increasing the absorption coefficient
<table>
<thead>
<tr>
<th>Position</th>
<th>SDEN = 0.0141</th>
<th>SDEN = 0.0641</th>
<th>SDEN = 0.1961</th>
</tr>
</thead>
<tbody>
<tr>
<td>A reg</td>
<td>99.2</td>
<td>95.9</td>
<td>93.6</td>
</tr>
<tr>
<td>A ran</td>
<td>98.4</td>
<td>95.8</td>
<td>90.0</td>
</tr>
<tr>
<td>B reg</td>
<td>100.3</td>
<td>98.9</td>
<td>96.6</td>
</tr>
<tr>
<td>B ran</td>
<td>100.7</td>
<td>100.2</td>
<td>95.8</td>
</tr>
<tr>
<td>C reg</td>
<td>96.6</td>
<td>93.5</td>
<td>84.1</td>
</tr>
<tr>
<td>C ran</td>
<td>95.3</td>
<td>94.2</td>
<td>92.8</td>
</tr>
</tbody>
</table>

TABLE 5.2  Simulated Sound Pressure Levels Using a Line Source
of the scatterer surfaces could be an effective means of reducing noise propagation. For a line source, relatively more sound energy is included in paths with fewer reflections, so increasing the surface absorption coefficient would probably not reduce the noise intrusion significantly.

In addition, it is possible to say with certainty that the study of suburban noise propagation may be accomplished by studying random geometries rather than a specific model of a community. The results in Sections 5.1 and 5.2 indicated that the random geometry produced results with good agreement with a regular geometry. The times of pulse arrival are not in agreement, but the general patterns are. If the program were to iterate over many randomly generated locations, the comparison would likely be even closer.
CHAPTER 6 SUMMARY AND CONCLUSIONS

A computer model has been developed to study sound propagation in suburban communities. The model consists of a two dimensional ray-tracing code simulating the travel of sound rays in a three dimensional environment. The model treats a point source and includes surface absorption, reflection, and scattering, and an elementary form of diffraction around scattering objects. In addition, air and ground attenuation are included in the current version of the code, and a line source version has been tested. The program predicts sound pressure levels at receivers as well as the time of pulse arrivals.

The computer-produced results of the model have been compared to scale-model experiments (Chapter 2), analytical results (Chapter 3), and field data (Chapter 4) with good agreement. The scale-model experiments indicated that the code can quite accurately predict the times of pulse arrivals and the sound energy contained in direct sound. The prediction of reflected sound is good, but not in as close agreement with the experiments as the direct sound result. Even shadow regions behind buildings are forecast fairly well.

The comparison to analytical results again indicated the
ability of the program to accurately predict direct sound and pointed to a possible weakness in the code's lack of accuracy when used to simulate sound between highly reflective, parallel walls. This condition, however, would never arise upon normal usage of the code.

The field data comparison pointed out the ability to predict extremely well the results obtained in outdoor sound propagation in suburban environments with a very simple model and guesses for acoustical parameters.

Having shown the strengths and weaknesses of the model, Chapter 5 applied the program to a preliminary study of sound propagation patterns in suburban areas. The general pattern observed held for both a point and line source, but most important was that this pattern of sound propagation extended to both very regular and random geometries. The implication is that a study of suburban noise propagation may be accomplished by considering the results of several sets of random positions of scatterers. In addition, the study indicated that added absorption on scatterer surfaces might be a useful means of reducing the sound energy propagating in a densely packed community for a point source. For a line source, this method would probably not produce significant results.
In the future, this model may be modified to include barriers, topology and atmospheric effects, to allow for the simulation of almost any suburban area. The simplifying assumptions that were made regarding the acoustical phenomena can be relaxed and the model's realism improved.
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IMPLICIT INTEGER*2 (I-N)
INTEGER*2 SRFLAG
REAL*4 ITIME
COMMON/RESLTS/ESUM(10),HSCALE(10),RMFP,ITIME(10,15),ISTART(10)
COMMON/SPACE/XLEN,YLEN,SURF1,SURF2,SDEN
COMMON/PARAM/RCVR(10,2),ABCO,SCATCO,REFCO,XSRC,YSRC,SPLVL,SDIST,
    * DBTOL,TMER,AAB,NMAX
COMMON/LOCATE/ALOC(200,9),NSCAT
COMMON/TOTAL/SPL(10)
    DIMENSION IC(9)
DATA C/1128.,/
DATA IC/'ST','WA','SO','SC','ER','LI','RE','GO','EN'/

THE COMMANDS "CLEAR", "BUILD", "SINKS", "MAP", AND "ALL" HAVE BEEN
ELIMINATED FROM THE CODE. VALID COMMANDS ARE "START", "WALLS",
"SOURCE", "SCALE", "ERROR", "LIST", "GO", "END", AND "RECEIVER".

JFLAG=0
NFLAG=0
DO 1 I=1,10
    SPL(I)=0.
1 CONTINUE
WRITE(5,10)
10 FORMAT(* START*)

C*****COMMAND DECODER (LABEL 20)*****

REQUEST COMMAND

20 WRITE(5,30)
30 FORMAT(2H *)
JFLAG=JFLAG+1
READ(8,40) ICX
40 FORMAT(5A2)

DECIDE COMMAND

45 DO 50 K=1,9
   IF(IC(K) .EQ. ICX) GO TO 70
50 CONTINUE

COMMAND NOT UNDERSTOOD. ISSUE QUERY AND TRY AGAIN

WRITE(5,60)
60 FORMAT(2H 7)
GO TO 45

BRANCH STATEMENT

70 GO TO (100,300,400,500,600,700,800,900,1000),K

*START ROUTINE (LABEL 100)*

START OBTAINS PARAMETERS OF THE SPACE TO BE TREATED: SDEN,XLEN
YLEN,SURF1,AND SURF2. CONTROL IS THEN SUCCESSIVELY TRANSFERRED
TO THE SCATTERER LOCATION GENERATOR, 'WALLS','SOURCE','SCALE',
'ERROR', AND 'RECEIVER' BEFORE CONTROL IS RETURNED TO THE USER.

100 WRITE (5,110)
110 FORMAT(' XLEN =')
CALL AIN(XLEN,0.0,10000.0)
WRITE(5,120)
120 FORMAT(' YLEN =')
CALL AIN(YLEN,0.0,10000.0)

AIN IS A SUBPGM WHICH READS VALUES SUPPLIED BY THE USER AND
ASSIGNS THEM TO THE FIRST ARGUMENT, PROVIDED THE VALUE IS BETWEEN THE SECOND AND THIRD ARGUMENTS.

WRITE(5,130)
130 FORMAT(' SURF1 =')
CALL AIN(SURF1,0.0,100.0)
WRITE(5,140)
140 FORMAT(' SURF2 =')
CALL AIN(SURF2,0.0,100.0)
145 WRITE(5,150)
150 FORMAT(' SDEN =')
AMXDEN=10000./(SURF1*SURF2*3.)
CALL AIN(SDEN,0.0,AMXDEN)

C***** WALLS ROUTINE (LABEL 300) *****

300 WRITE(5,310)
310 FORMAT(' **WALLS */* ABCO =')
CALL AIN(ABCO,0.0,1.0)
WRITE(5,320)
320 FORMAT(' SCATCO =')
SCATMX=1.001-ABCO
CALL AIN(SCATCO,0.0,SCATMX)
WRITE(5,330)
330 FORMAT(' REFCO =')
REFMX= 1.002-SCATCO -ABCO
CALL AIN(REFCO,0.0,REFMX)
IF (JFLAG .GT. 1) GO TO 20

C***** SOURCE ROUTINE (LABEL 400) *****

THE SOURCE ROUTINE ALLOWS THE USER TO DEFINE THE SOURCE LOCATION WHICH NEED NOT BE IN THE AREA DEFINED BY XLEN AND YLEN. IF THE SOURCE IS OUTSIDE THE AREA DEFINED BY XLEN AND YLEN NO SCATTERING OF THE SOUND OCCURS UNTIL IT ENTERS THE AREA

400 SRFLAG=0
WRITE(5,410)
410 FORMAT(* **SOURCE*/' XSRC =')
       READ (9,420) XSRC
420 FORMAT(F10.3)
       WRITE(5,425) XSRC
425 FORMAT(I1,F10.4)
       WRITE(5,430)
430 FORMAT(* YSRC =')
       READ(8,420) YSRC
       WRITE(5,425) YSRC
       IF ((YSRC .GE. 0.) .AND. (XSRC .LE. XLEN)) GO TO 500
       IF ((YSRC .GE. 0.) .AND. (YSRC .LE. YLEN)) GO TO 500
440 FORMAT(* SOURCE OUTSIDE SCATTERING AREA*/' TO RELOCATE SOURCE TYPE
       * "1", TO CONTINUE TYPE"0"*/)
       READ(8,450) I
450 FORMAT(I1)
       IF (I .EQ. 1) GO TO 400
       SRFLAG=1
       IF (JFLAG .GT. 1) GO TO 20

C
C***** SCALE ROUTINE (LABEL 500) *****
C    IN THIS SECTION OF THE PGM THE USER SUPPLIES INFORMATION REGARDING
C    THE SOUND PRESSURE LEVEL OF THE SOURCE, SPLVL
C
500 WRITE(5,510)
510 FORMAT(* **SCALE*/' SPLVL =')
       CALL AIN(SPLVL, -1000.0, 1000.0)
       WRITE(5,520)
520 FORMAT(* SDIST =')
       CALL AIN(SDIST, 0.01, 1000.0)

C    AIR ABSORPTION IN DB REDUCTION PER THOUSAND FEET
C
530 FORMAT(* AIR ABSORPTION*/' AAB =')
530
CALL AIN(AAB,0.0,55000.0)
AAB=AAB*.001
IF (JFLAG .GT. 1) GO TO 20

C
C***** ERROR ROUTINE (LABEL 600) *****
C THIS SECTION OF THE PGM READS TOLERANCE VALUES OF SPL RESULTS,
C AND ARRIVAL TIME RESULTS.
C
600 WRITE(5,610)
610 FORMAT(* **ERROR*/ DPTOL =')
   CALL AIN(DPTOL,0.1,5.0)
   WRITE(5,620)
620 FORMAT(* TMR =')
   CALL AIN(TMR,0.01,1.0)
625 WRITE(5,630)
630 FORMAT(* NMAX =')
   READ(8,640) NMAX
640 FORMAT(I5)
   WRITE(5,645) NMAX
645 FORMAT(1X,I5)
   IF((NMAX .LT. 100) .OR. (NMAX .GT. 32767)) GO TO 650
   IF (JFLAG -2) 800,20,20
650 WRITE(5,660)
660 FORMAT(* ?*)
   GO TO 625
C
C***** LIST ROUTINE (LABEL 700) *****
C THIS CALLS SUBROUTINE LIST WHICH SUMMARIZES THE PARAMETERS READ IN.
C
700 CALL LIST
   GO TO 20
C
C***** RECEIVERS (LABEL 800) *****
C THIS SECTION OF THE PGM READS IN THE X AND Y COORDINATES OF UP
C TO 10 USER SPECIFIED LOCATIONS AT WHICH THE SPL AND ARRIVAL TIMES
WILL BE CALCULATED.

800 WRITE(5,810)
810 FORMAT(* RECEIVER LOCATIONS*/* X-COORD THEN Y-COORD IN F10.3,F10.3
* . ONE SET PER LINE.*/* TO SIGNIFY END OF LIST TYPE "-1.0"
) DO 830 M=1,10
MM=M-1
840 READ (8,820) RCVR(M,1),RCVR(M,2)
WRITE(5,843) RCVR(M,1),RCVR(M,2)
843 FORMAT(1X,2F10.3)
820 FORMAT(2F10.3)
IF (RCVR(M,1) .LT. 0.) GO TO 840
IF(((RCVR(M,1).GT.XLEN).OR.(RCVR(M,2).GT.YLEN)).OR.(RCVR(M,2).LT.
* 0.)) GO TO 842
830 CONTINUE
840 IF(M .EQ. 1) GO TO 841
WRITE(5,850) MM
850 FORMAT (* THERE ARE*,1X,I3,1X,*RECEIVERS*)
DO 870 L=1,MM
T=SQRT((XSRC-RCVR(L,1))**2 + (YSRC-RCVR(L,2))**2 )
HScale(L)=T/C
ASUB=1.
RMDR=AMOD(HScale(L),10.)
IF(RMDR .GE. 3.16228) ASUB=ASUB+1.
HScale(L)=10.**(AINT(ALOG10(HScale(L)))-ASUB)
ISTART(L) = T/(C*HScale(L))
870 CONTINUE
GO TO 20
841 WRITE(5,843)
843 FORMAT(* SPECIFY AT LEAST 1 LOCATION*)
GO TO 842

C***** GO ROUTINE (LABEL 900) *****
C THIS PORTION OF THE PGM RELEASES CONTROL TO THE SURPDM WHICH
C TRACES SOUND RAYS USING A MONTECARLO TECHNIQUE.
C
900 WRITE(5,910)
910 FORMAT(' ** GO ROUTINE')
905 WRITE(5,915)
915 FORMAT(' NSETS =')
READ(8,920) NSETS
920 FORMAT(I5)
WRITE(5,925) NSETS
IF ((NSETS .LT. 1) .OR. (NSETS .GT. 32767))
* GO TO 905
WRITE(5,2201)
2201 FORMAT(' I/O OPTION. FOR SCATTERER LOCATIONS TYPE "1"')
925 FORMAT(1X,I5)
READ (8,2202) IOOPT
2202 FORMAT(I1)
DC 930 I=1,NSETS
C**** SCATTERER LOCATION GENERATOR (LABEL 200) ****
C THIS SECTION OF THE PGM GENERATES LOCATIONS AND ORIENTATIONS FOR THE
SCATTERERS ASUMING UNIFORM PROBABILITIES FOR THE SCATTERER
LOCATION AND ORIENTATION.
AREA =XLEN*YLEN
NSCAT = AREA*SDEN*1.E-3 + .5
IF (NSCAT .LT. 1) GO TO 200
IF (NSCAT .GT. 200) GO TO 205
GO TO 220
200 WRITE(5,210)
210 FORMAT(' SDEN TOO SMALL')
GO TO 145
205 WRITE(5,215)
215 FORMAT(' SDEN TOO LARGE')
GO TO 145
220 CALL RANDOM(IOOPT,NFLAG)
RMFP = 3.14159/(SDEN * 2. * (SURF1 + SURF2))
CALL TRACE(NFLAG,NM)
NFLAG=NFLAG+1
930 CONTINUE
CALL OUTPUT(NM)

C
C**** PROGRAM END (LABEL 1000) ****
1000 STOP
END
SUBROUTINE AIN(A,ALOW,AHIGH)
*********** ***********

C
C AIN IS A SERVICE ROUTINE WHICH ACCEPTS A SINGLE REAL VARIABLE FROM THE USER. THE VARIABLE A, IS REJECTED UNLESS IT LIES IN THE RANGE (ALOW,AHIGH). A MUST BE SUPPLIED IN F10.4 FORMAT.
C
C IMPLICIT INTEGER*2 (I-N)
C
10 READ (8 ,20) A
   WRITE(5,21) A
   21 FORMAT(1X,F10.4)
   20 FORMAT(F10.4)
   IF (A.LT.ALOW.OR.A.GT.AHIGH) GO TO 15
   RETURN
15 WRITE (5 ,30)
   30 FORMAT(2H ?)
   GO TO 10
SUBROUTINE LIST
IMPLICIT INTEGER*2 (I-N)
COMMON/SPACE/XLEN,YLEN,SURF1,SURF2,SDEN
COMMON/PARAM/RCVR(10,2),ABCO,SCATCO,REFCO,XSRC,YSRC,SPLVL,SDIST,
* DBTOL,ARTMER,ABB,NMAX
WRITE(5,10) XLEN,YLEN,SURF1,SURF2,SDEN
10 FORMAT(1H1,'AREA AND SCATTERER PARAMETERS'/XLENGTH = ',2X,F10.3,
* 10X,'YLENGTH = ',2X,F10.3/' SURFACE 1 = ',F10.3,2X,'SURFACE 2 = ',
% F10.3/' DENSITY OF SCATTERERS PFR THOUSAND SQ. FT. = ',F10.3/)
WRITE(5,20) ABCO,SCATCO,REFCO
20 FORMAT(1H1,'SURFACE PARAMETERS'/ABSORPTION COEFFICIENT = ',F10.3,
* 2X,'SCATTERING COEFFICIENT = ',F10.3/1X,'REFLECTION COEFFICIENT = 
* ,F10.3/)
WRITE(5,30) XSRC,YSRC,SPLVL,SDIST
30 FORMAT(1H1,'SOURCE PARAMETERS'/X COORDINATE = ',F10.3,2X,'Y COORDINA 
% TE = ',F10.3/ ' SOURCE SPL = ',F10.3,2X,'AT',1X,F10.3,1X,'FEET'/)
WRITE(5,40) DBTOL,ARTMER
40 FORMAT('ERROR PARAMETERS'/DB ERROR FOR SPL = ',F10.3/1X,'PER CEN 
* T ERROR FOR ARRIVAL TIME = ',F10.3/)
WRITE(5,50) AAB
50 FORMAT('AIR ABSORPTION IN DB PER FOOT = ',1PE10.3/1H1)
RETURN
END
SUBROUTINE RANDOM(IOOPT,NFLAG)
IMPLICIT INTEGER*2 (I-N)
COMMON/PARAM/RKVR(10,2),ABC0,SCATCO,REFCO,YSRC,YSRC,SPLVL,SDIST,
* DBTOL,ARTMER,AAB,NMAX
COMMON/LOCATE/ALOC(200,9),NSCAT
COMMON/SPACE/XLEN,YLEN,SURF1,SURF2,SDEN

THIS VERSION DESIGNED FOR REFLECTION STUDY
THIS VERSION OF RANDOM IS STOCHASTIC IN NATURE

NH=XLEN*YLEN*1.E-3*SDEN
AH=XLEN*YLEN/FLOAT(NH)
SIDE=QRSR(AH)
EX1=(SIDE-SURF1)*.5
EX2=(SIDE-SURF2)*.5
N1=XLEN/SIDE+.5
N2=YLEN/SIDE+.5
K=1
DO 20 I=1,N1
DO 10 J=1,N2
ALOC(K,1)=FLOAT(I-1)*SIDE+EX1
ALOC(K,2)=FLOAT(J-1)*SIDE+EX2+SURF2
ALOC(K,3)=ALOC(K,1)+SURF1
ALOC(K,4)=ALOC(K,2)
ALOC(K,5)=ALOC(K,3)
ALOC(K,6)=ALOC(K,2)-SURF2
ALOC(K,7)=ALOC(K,1)
ALOC(K,8)=ALOC(K,6)
ALOC(K,9)=0.
10 K=K+1
20 CONTINUE
K=K-1
PUT NH,AH,SIDE,EX1,EX2,N1,N2
RETURN
SUBROUTINE RANDOM(IOOPT,NFLAG)
IMPLICIT INTEGER*2 (I-N)
COMMON/PARAM/Rcvr(10,2),ARCO,SCATCO,REFCO,YSRC,YSRC,SPLVL,SDIST,*
                DBTOL,ARTmax,AAB,NMAX
COMMON/LOCATE/ALOC(200,9),NSCAT
COMMON/SPACE/XLEN,YLEN,SURF1,SURF2,SDEN

C
C
C
C

     THIS PROGRAM IS DESIGNED FOR USE WITH THE FIELD DATA TEST

N=0
DO 10 I=1,200
10 ALOC(I,9)=0.
DO 20 I=1,200
READ(8,30)(ALOC(I,J),J=1,8)
20 N=N+1
30 FORMAT(6F6.0)
   IF(ALOC(I,1) .LE. 0.) GO TO 40
40 WRITE(5,50)((ALOC(I,J),I=1,N),J=1,8)
50 FORMAT(1X,8F7.0/)
RETURN
END
SUBROUTINE RANDOM(IOOPT,NFLAG)  
IMPLICIT INTEGER*2 (I-N)  
COMMON/PARAM/RCCVR(10,2),ABCO,SCATCO,REFCO,XSRC,YSRC,SPRLVL,SDIST,  
* DBTOL,ARTMER,AAB,NMAX  
COMMON/LOCATE/ALOC(200,9),NSCAT  
COMMON/SPACE/XLEN,YLEN,SURF1,SURF2,SDEN  

C
C
C THIS PROGRAM IS DESIGNED FOR USE WITH THE SET OF EXPERIMENTS BEUNG
C RUN IN THE AV LAB. IT IS NOT RANDOM IN NATURE BUT DETERMINISTIC.
C
A1 = 195. - 5*SURF1  
DO 10 I=1,4  
A = A1  
B = 65. - 5*SURF2 + FLOAT(I-1)*130.  
DO 20 K=1,5  
NM = (I-1)*5 + K  
ALOC(NM,1) = A  
ALOC(NM,2) = B  
ALOC(NM,3) = A + SURF1  
ALOC(NM,4) = B  
ALOC(NM,5) = A + SURF1  
ALOC(NM,6) = B + SURF2  
ALOC(NM,7) = A  
ALOC(NM,8) = B + SURF2  
ALOC(NM,9) = 0.  
20 A = A + 130.  
10 CONTINUE  
IF(IOOPT.LE.0) GO TO 210  
DO 200 I=1,NSCAT  
WRITE(5,220) (ALOC(I,J), J=1,9)  
220 FORMAT(1X,9F10.3)  
200 CONTINUE  
210 RETURN  
END
FUNCTION DIST(I,LI,KK,M)
IMPLICIT INTEGER*2 (I-H)
COMMON/PARAM/RCVR(10,2),ABC0,SCATCO,REFCO,XSRC,YSRC,SPLVL,SDIST,
* DBT0L,ARTMER,AAB,NMAX
COMMON/LOCATE/ALOC(200,9),NSCAT
GO TO (10,20,30),LI
10 DIST1=SQR((RCVR(KK,1)-ALOC(I,1))**2 +(RCVR(KK,2)-ALOC(I,2))**2)
DIST2=SQR((RCVR(KK,1)-ALOC(I,3))**2 +(RCVR(KK,2)-ALOC(I,4))**2)
DIST3=SQR((RCVR(KK,1)-ALOC(I,5))**2 +(RCVR(KK,2)-ALOC(I,6))**2)
DIST4=SQR((RCVR(KK,1)-ALOC(I,7))**2 +(RCVR(KK,2)-ALOC(I,8))**2)
GO TO 40
20 DIST1=SQR((XSRC-ALOC(I,1))**2 +(YSRC-ALOC(I,2))**2)
DIST2=SQR((XSRC-ALOC(I,3))**2 +(YSRC-ALOC(I,4))**2)
DIST3=SQR((XSRC-ALOC(I,5))**2 +(YSRC-ALOC(I,6))**2)
DIST4=SQR((XSRC-ALOC(I,7))**2 +(YSRC-ALOC(I,8))**2)
GO TO 40
30 DIST1=SQR((ALOC(I,M)-ALOC(KK,1))**2+(ALOC(I,M+1)-ALOC(KK,2))**2)
DIST2=SQR((ALOC(I,M)-ALOC(KK,3))**2+(ALOC(I,M+1)-ALOC(KK,4))**2)
DIST3=SQR((ALOC(I,M)-ALOC(KK,5))**2+(ALOC(I,M+1)-ALOC(KK,6))**2)
DIST4=SQR((ALOC(I,M)-ALOC(KK,7))**2+(ALOC(I,M+1)-ALOC(KK,8))**2)
GO TO 40
40 DIST=DIST1+DIST2+DIST3+DIST4
RETURN
END
SUBROUTINE TRACE (NFLAG, NM)

THIS SUBPGM TRACES THE SOUND RAYS TO DETERMINE SPL'S AND
ARRIVAL TIMES

INTEGER*2 RFLAG
IMPLICIT INTEGER*2 (I-N)
REAL*4 ITIME
COMMON/SPACE/XLEN, YLEN, SURF1, SURF2, SDEN
COMMON/PARAM/RCVR(10, 2), ABCO, SCATCO, REFCO, XSRC, YSRC, SPLVL, SDIST,
* DBTOL, TMER, AAB, NMAX
COMMON/TOTAL/SPL(10)
COMMON/RESULT/ESUM(10), HSCALE(10), RMFP, ITIME(10, 15), ISTART(10)
COMMON/LOCATE/ALOC(200, 9), NSCAT
DIMENSION PHI(5), S(800), T(800)
DIMENSION MMEHRY(2, 10), SEN(10), SESQ(10)
DIMENSION VAR(10), VARI(10)
DATA PI, PREF, C/3.141593, 2.E-5, 1128. /

CUTOFF VALUES FOR ABSORPTION AND SCATTERING

IF(NFLAG .LE. 0) IRAN=32767
NM=0
AWALL=ABCO+SCATCO
BWall=AWALL+REFCO
RRAD=.02*XLEN
IF(YLEN .LT. XLEN) RRAD=.02*YLEN
RLEN=2.*RRAD
ECHN=10.*((SPLVL*1.)*2.*PI*SDIST/(100.*PLEN))
DO 12 I=1, 10
DO 11 J=1, 15
11 ITIME(I, J)=0
SEN(I)=0.
VARL(I)=1.E10
VAR(I)=1.E10
12 SESQ(I) =0.

C MAIN ITERATION LOOPS
C
DO 800 N=100,NMAX,100
C
INITIALIZATION
C
DO 10 I=1,10
10 ESUM(I)=0.
NRO=0
NSO=0
DO 700 I=1,100
XRAY=XSRC
YRAY=YSRC
KRN=5
GO TO 100
14 YRAY=0.+1000.*YRAN
DIST=0.
MEMFLG=0

C START A NEW RAY
C GET A RAY ANGLE
C
AMIN1=0.
AMIN2=0.
AMAX1=2.*PI
AMAX2=AMAX1
KRN=-1

C RANDOM NUMBER GENERATOR. KRN=-1 FOR ANGLE, KRN=1 FOR NUMBER
C FROM 0 TO 1.
C
100 IRAN=899*IRAN+3
YRAN=1.525879E-05*FLOAT(IRAN)+.5
IF(KRAN.EQ.5) GO TO 14
IF(KRAN.GT.0) GO TO 630
ANGLE=2.*PI*YRAN
IF((ANGLE.GE. AMIN1).AND.(ANGLE.LE. AMAX1)) GO TO 105
IF((ANGLE.GE. AMIN2).AND.(ANGLE.LE. AMAX2)) GO TO 105
GO TO 100
105 SINE=SIN(ANGLE)
COSINE=COS(ANGLE)
TANCT=TAN(ANGLE)

DETERMINE NEXT RAY LOCATION

DO WE HIT A RECEIVER POSITION (PLUS OR MINUS 1FT) ALONG
THE RAY LINE?

195 RCDIST=1.E10
DO 200 I=1,10
IF (RCVR(I,1).LT.0.) GO TO 205
IF(ABS(RCVR(I,1)-XRAY).LT.1.E-2) GO TO 1954
GAMMA=ATAN((RCVR(I,2)-YRAY)/(RCVR(I,1)-XRAY))
IF((GAMMA.GT.0.).AND.(RCVR(I,2).LT. YRAY)) GAMMA=GAMMA+PI
IF((GAMMA.LT.0.).AND.(RCVR(I,1).LT. XRAY)) GAMMA=GAMMA+PI
IF(GAMMA.LT.0.) GAMMA=2.*PI+GAMMA
GO TO 1955
1954 IF(RCVR(I,2).LT. YRAY) GAMMA=PI*.5
IF(RCVR(I,2).GE. YRAY) GAMMA=1.5*PI
1955 R=SQR((XRAY-RCVR(I,1))**2+(YRAY-RCVR(I,2))**2)
IF(R.LT. RRAD) GO TO 200
DANG=ASIN(RPAD/R)
ANG1=GAMMA-DANG
ANG2=GAMMA+DANG
IF(ANG1.LT.0.) GO TO 1951
IF(ANG2.CT.2.*PI) GO TO 1952
IF((ANGLE.LT. ANG1).OR.(ANGLE.GT. ANG2))GO TO 200
GO TO 1953
1951 ANG1=2.*PI+ANG1
  IF((ANGLE .GT. ANG2) .AND. (ANGLE .LT. ANG1)) GO TO 200
  GO TO 1953
1952 ANG2=ANG2-2.*PI
  IF((ANGLE .GT. ANG2) .AND. (ANGLE .LT. ANG1)) GO TO 200
1953 D=R*COS(GAMMA-ANGLE)
  D=ABS(D)
  IF(RCDIST .LE. D) GO TO 200
  XX=XRAY+D*COS(ANGLE)
  YY=YRAY+D*SIN(ANGLE)
  RCDIST=D
  RFLAG=I
  200 CONTINUE

C
C    DO WE INTERSECT A SCATTERING SURFACE?
C
205 DO 215 I=1,800
  S(I)=-1.
215 T(I)=-1.
  SCDIST=1.E10
  DO 600 I=1,NSCAT
     XSCAT=0
     IF(I.EQ.IJ) GO TO 600
     IF(COSIN)300,340,320
300 DO 310 J=1,7,2
     IF(ALOC(I,J) .LT. XRAY) GO TO 340
310 CONTINUE
     GO TO 600
320 DO 330 J=1,7,2
     IF(ALOC(I,J) .GT. XRAY) GO TO 340
330 CONTINUE
     GO TO 600
340 IF (SINC)350,390,370
350 DO 360 J=2,8,2
IF(ALOC(I,J) .LT. YRAY) GO TO 390
360 CONTINUE
GO TO 600
370 DO 380 J=2,8,2
IF(ALOC(I,J) .GT. YRAY) GO TO 390
380 CONTINUE
GO TO 600

C
UNLESS THE RAY HAS PASSED THE SIN, COS, TESTS IT IS ELIMINATED.
THE NEXT TEST IS FOR ANGLE OF SURFACE IN CORRECT RANGE.

C
390 LL=0
3 DO 400 J=1,7,2
LL=LL+1
B=ALOC(I,J) -XRAY
IF(ABS(B) .LE. 1.E-2) GO TO 600
PHI(LL)=ATAN((ALOC(I,J+1)-YRAY)/B)
IF((ALOC(I,J) .LT. XRAY) .AND. (ALOC(I,J+1) .LT. YRAY)) PHI(LL)
* = PHI(LL)+PI
IF(PHI(LL) .LT. 0.) PHI(LL)=2.*PI+PHI(LL)
IF((ALOC(I,J) .LT. XRAY) .AND. (ALOC(I,J+1) .GT. YRAY)) PHI(LL)
* = PHI(LL)-PI
400 CONTINUE

C
PHI(5)=PHI(1)

C
THE ABOVE DEFINED ANGLES FROM THE CURRENT LOCATION TO THE
REMAINING SCATTERING SURFACES. A CHECK IS NOW CONDUCTED.

C
DO 430 J=1,4
440 DPHI=PHI(J) - PHI(J+1)
   IF (ABS(DPHI) .GT. PI) GO TO 441
   IF (DPHI 440,440,450
   440 IF((PHI(J+1) .GE. ANGLE) .AND. (PHI(J) .LE. ANGLE)) GO TO 460
   450 IF((PHI(J) .GE. ANGLE) .AND. (PHI(J+1) .LE. ANGLE)) GO TO 460
GO TO 430
441 IF(DPHI) 442,442,443
442 IF((PHI(J+1) .LE. ANGLE).AND.(2.*PI .GE. ANGLE))GO TO 460
   IF((0. .LE. ANGLE).AND.((PHI(J) .GE. ANGLE))GO TO 460
   GO TO 430
443 IF((PHI(J) .LE. ANGLE).AND.(2.*PI .GE. ANGLE))GO TO 460
   IF((0. .LE. ANGLE).AND.((PHI(J+1) .GE. ANGLE)) GO TO 460
C     IF SURFACE IS REJECTED LOOP CONTINUES. ACCEPTED SURFACES ARE
C     PROCESSED IN LABELS 460 TO 490
C
430 CONTINUE
   GO TO 600
460 J1 = 2*J-1
   IF (J1 .GT. 5) GO TO 461
   J2=J1+1
   J3=J2+1
   J4=J3+1
   GO TO 462
461 J2=J1+1
   J3=1
   J4=2
462 II=4*(I-1) + J
   IF(ABS(ALOC(I,J1)-ALOC(I,J3)) .LT. 1.E-05) GO TO 470
   FAC1=XRAY*TANGT-YRAY+(ALOC(I,J2)*ALOC(I,J3)-ALOC(I,J1)*ALOC(I,J4))/
   /* ( ALOC(I,J3)-ALOC(I,J1) )
      FAC2= (TANGT-(ALOC(I,J4)-ALOC(I,J2))/(ALOC(I,J3)-ALOC(I,J1)))
      S(II)=FAC1/FAC2
      T(II)=(S(II)-XRAY)*TANGT+YRAY
   GO TO 480
470 FAC1=(XRAY+(ALOC(I,J2)*ALOC(I,J3)-ALOC(I,J1)*ALOC(I,J4))/(ALOC(I,J
   *4)-ALOC(I,J2)))*TANGT-YRAY
   FAC2=(ALOC(I,J3)-ALOC(I,J1))*TANGT/(ALOC(I,J4)-ALOC(I,J2))-1.
   T(II)=FAC1/FAC2
   S(II)=(T(II)-YRAY)/TANGT +XRAY
480 IF(ABS(XRAY -S(II)).LT.1.E-10) GO TO 4810
R = SQRT((XRAY - S(II))**2 + (YRAY - T(II))**2 )
GO TO 4820

4810 R = ABS(YY - T(II))
4820 IF (R .GT. SCDIST) GO TO 430
     IF (INDR .GT. 0) GO TO 492
     IF (ABS(R) .LE. 1.E-2) GO TO 600

492 LSCAT=II
     IND1=J
     IND2=I
     SCDIST=R
     JSCAT=J1
     GO TO 430

600 CONTINUE

CHECK TO SEE IF RAY LEFT SYSTEM

IF((SCDIST .GE. 1.E9) .AND. (RCDIST .GE. 1.E9)) GO TO 700
IF(RCDIST - SCDIST) 640, 640, 620

RAY HAS HIT SCATTERER

620 DIST = SCDIST + DIST
     NSO = NSO + 1
     XRAY = S(LSCAT)
     YRAY = T(LSCAT)
     IF (MEMFLG .GE. 10) GO TO 700
     MEMFLG = MEMFLG + 1
     MEMRY (1, MEMFLG) = IND2
     MEMRY (2, MEMFLG) = IND1

CALCULATING POSSIBLE SCATTERING RANGE

J = (JSCAT + 1) / 2
I = (LSCAT - J) / 4 + 1
TL = ALOC(I, 9)
GO TO (481,482,483,484),J

481 AMAX=TL
        AMIN=AMAX-PI
        IF(AMIN .LT. 0.) GO TO 485
        GO TO 486

482 AMAX=TL+.5*PI
        TL=TL+PI*.5
        AMIN=AMAX-PI
        IF(AMIN .LT. 0.) GO TO 485
        GO TO 486

483 AMIN=TL
        AMAX=AMIN +PI
        GO TO 486

484 AMIN=TL+.5*PI
        TL=TL+PI*.5
        AMAX=AMIN+PI
        IF(AMAX .GT. 2.*PI) GO TO 487
        GO TO 486

485 AMIN1=2.*PI +AMIN
        AMAX1=2.*PI
        AMIN2=0.
        AMAX2=AMAX
        GO TO 490

486 AMIN1=AMIN
        AMIN2=AMIN
        AMAX1= AMAX
        AMAX2= AMAX
        GO TO 490

487 AMIN1= AMIN
        AMAX1= 2.*PI
        AMIN2= 0.
        AMAX2= AMAX-2.*PI

490 KRON=1
        GO TO 100

630 IF(YRAN .LT. ABCD) GO TO 700
IF (YRAN .LT. AWALL) GO TO 660
IF (YRAN .LT. BNAIL) GO TO 670
A1 = ALOC(IND2,9)
A2 = A1 + PI*.5
A3 = A1 + PI
IF( A3 .GT. 2.*PI) A3 = A3-2.*PI
A4 = A3 + PI*.5
IF(A4 .GT. 2.*PI) A4 = A4-2.*PI
JQ = 2*IND1 - 1
NJ = JQ + 2
IF (NJ .EQ. 9) NJ=1
DI1= SQRT((XRAY-ALOC(IND2,JQ))**2 +(YRAY-ALOC(IND2,JQ+1))**2)
DI2= SQRT((XRAY-ALOC(IND2,NJ))**2 +(YRAY-ALOC(IND2,NJ+1))**2)
GO TO ( 631,632,633,634),IND1

C H I T A  1,2 TO 3,4 SURFACE
C
631 IF(ANGLE-A2) 6311,6312,6313
6311 DI1= DI1+SURF2
    IF (DI1-DI2) 701,701,702
6312 DI1=DI1+SURF2
    DI2 = DI2+SURF2
    IF(DI1-DI2) 701,701,703
6313 DI2=DI2+SURF2
    IF(DI1-DI2) 704,704,703

C H I T A  3,4 TO 5,6 SURFACE
C
632 IF(ANGLE-A3) 6321,6322,6323
6321 DI1=DI1+SUFRF1
    IF(DI1-DI2) 704,704,703
6322 DI1= DI1+SURF1
    DI2= DI2+SURF1
    IF(DI1-DI2) 704,704,706
6323 DI2= DI2+SURF1
IF(DI1-DI2) 707,707,706

C
C HIT A 5,6 TO 7,8 SURFACE
C
633 IF(ANGLE - A3) 6331,6332,6333
6331 DI1 = DI1 + SURF2
   IF ( DI1-DI2) 707,707,706
6332 DI1 = DI1 + SURF2
   DI2 = DI2 + SURF2
   IF(DI1-DI2) 707,707,705
6333 DI2 = DI2 + SURF2
   IF(DI1-DI2) 708,708,705

C
C HIT A 7,8 TO 1,2 SURFACE
634 IF(ANGLE-A4) 6341,6341,6342
6341 IF(ANGLE-A1) 6342,63411,63412
63411 DI1 = DI1 + SURF1
   DI1 = DI1 + SURF1
   IF(DI1-DI2) 708,708,702
63412 DI2 = DI2 + SURF1
   IF(DI1-DI2) 701,701,702
6342 DI1 = DI1 + SURF1
   IF(DI1-DI2) 708,708,705

701 XRAY = ALOC(IND2,7)
   YRAY = ALOC(IND2,8)
   DIST = DIST + DI1
   GO TO 195
702 XRAY = ALOC(IND2,3)
   YRAY = ALOC(IND2,4)
   DIST = DIST + DI2
   GO TO 195
703 XRAY = ALOC(IND2,5)
   YRAY = ALOC(IND2,6)
   DIST = DIST + DI2
   GO TO 195
704  XRAY=ALOC(IND2,1)
     YRAY=ALOC(IND2,2)
     DIST=DIST+DI1
     GO TO 195
705  XRAY=ALOC(IND2,1)
     YRAY=ALOC(IND2,2)
     DIST=DIST+DI2
     GO TO 195
706  XRAY=ALOC(IND2,7)
     YRAY=ALOC(IND2,8)
     DIST=DIST+DI2
     GO TO 195
707  XRAY=ALOC(IND2,3)
     YRAY=ALOC(IND2,4)
     DIST=DIST+DI1
     GO TO 195
708  XRAY=ALOC(IND2,5)
     YRAY=ALOC(IND2,6)
     DIST=DIST+DI1
     GO TO 195
660  KRAW=-1
     IJ=I
     JI=J
     GO TO 100
670  ANGLE=2.*TL-ANGLE
     IF(ANGLE .LT.0.) ANGLE =2.*PI+ ANGLE
     IF(ANGLE .GT. 2.*PI) ANGLE=ANGLE-2.*PI
     COSIN=COS(ANGLE)
     SINE=SIN(ANGLE)
     TANGT=TAN(ANGLE)
     IJ=I
     JI=J
     GO TO 195
C
C     RAY IS AT RECEIVER.  CALCULATE PRESSURE THEN GET THE NEXT RAY
640 DIST=DIST+RCDIST
NRO=NRO+1
XRAY=XX
YRAY=YY
AD=1000.-RCVR(RFLAG,2)+SQRT((100.-RCVR(RFLAG,2))**2+RCVR(RFLAG,1)**2)
AE=-RCVR(RFLAG,2)+SQRT(RCVR(RFLAG,2)**2+RCVR(RFLAG,1)**2)
AG=ALOG(AD)-ALOG(AE)
FACTOR=1000./AG
IF(DIST.GT.350.) FACTOR=(SDIST/(DIST-350.))**2*FACTOR
PP=ECON*10.**(AAB*(DIST-SDIST)**1)*SDIST/DIST*FACTOR
ESUM(RFLAG)=ESUM(RFLAG)+PP
WRITE(5,6407) RFLAG,DIST,PP.

6407 FORMAT(1X,'AT RECEIVER NO. ',I3,2X,'A RAY WHICH HAS TRAVELED ',
* F10.3,2X,'CONtributes ENERGY ',1PE10.3)

CALCULATE ARRIVAL TIMES

ARTME=DIST/C
IF(MEMFLG) 6411,4141,6413

6413 DO 6410 LL=1,MEMFLG
WRITE(5,6412) MEMRY(1,LL),MEMRY(2,LL)
6412 FORMAT(1X,'REFLECTED ON SCATTERER',2X,I3,4X,'SURFACE NO.',2X,I3)
6410 CONTINUE

6411 AK=FLOAT(ISTART(RFLAG))*HSCALE(RFLAG)
DO 6408 LL=1,15
AK1 = AK-.25*HSCALE(RFLAG)
AK2 = AK+.25*HSCALE(RFLAG)
IF((ARTME.GE. AK1) .AND. (ARTME.LT. AK2)) GO TO 6409
AK = AK + .5*HSCALE(RFLAG)
6408 CONTINUE
GO TO 195
6409 ITIME(RFLAG,LL)=ITIME(RFLAG,LL)+PP
GO TO 195
GET A NEW RAY

700 CONTINUE

CONVERGENCE TEST

WRITE(5,6666)NSO,NRO

6666 FORMAT(/"CONVERGENCE CHECK/
* /10X,'NO. OF SCATTERING EVENTS = ',I7/
* 10X,'NO. OF ARRIVALS AT RECEIVER = ',I7)
ICFLAG=0
N=N+1
DO 900 J=1,10
IF(RCVR(J,1) .LT.0.) GO TO 940
SEN(J)= (FLOAT(NM-1)*SEN(J)+ESUM(J))/FLOAT(NM)
SESQ(J)= (FLOAT(NM-1)*SESQ(J)+ESUM(J)*ESUM(J))/FLOAT(NM)
IF(SEN(J) .LE. 0.) GO TO 910
TEMP=SPL(J)
SPL(J)=10.4*LOG10(SEN(J))
VAR(J)= (SESQ(J)-SEN(J)*SEN(J))/(SEN(J)*SEN(J))
CCHK=VARL(J)/VAR(J)
IF((CCHK.LT.(1.-TMEP)).OR.(CCHK.GT.(1.+TMEP)))ICFLAG=1
IF(ABS(TEMP-SPL(J)).GT. DBTOL)ICFLAG=1
GO TO 930
SPL(J)=0.
VAR(J)=0.
CCHK=0.
ICFLAG=1
930 WRITE(5,9001) J,SPL(J),CCHK
9001 FORMAT(10,3/RECEIVER NO.,I3,'SOUND PRESSURE LEVEL ',
*F10.3,5X,'DE VARIANCE',F10.3) 
VARL(J)=VAR(J)
DO 920 JJ=1,15
IF(ITIME(J,JJ).LE. 0.) GO TO 920

ITIME(J,JJ)=ITIME(J,JJ)/FLOAT(NM)
TLVL=10.*ALOG10(ITIME(J,JJ))
WRITE(5,9301) JJ,TLVL

9301 FORMAT(5X,'INTERVAL NO. ',I3,2X,'SPL = ',F10.3)
ITIME(J,JJ)=ITIME(J,JJ)*FLOAT(NM)
920 CONTINUE
900 CONTINUE
940 WRITE(5,942)
942 FORMAT(/,/,/,/
PUT SPL
IF(N .EQ. 100) GO TO 800
IF(ICFLAG .GT. 0) GO TO 800

CONVERGENCE IS COMPLETE IF WE GO TO LABEL 810

GO TO 810
800 CONTINUE
810 RETURN
END
SUBROUTINE OUTPUT (NM)
IMPLICIT INTEGER*2 (I-N)
REAL*4 MAX, ITIME
COMMON/RESULT/ESUM(10), HSCALE(10), RMFP, ITIME(10, 15), ISTART(10)
COMMON/PARAM/RCVR(10, 2), ABCO, SCATCO, REFEO, XSRC, YSRC, SPLVL, SDIST,
* DBTOL, TMER, AAB, NMAX
COMMON/TOTAL/SPL(10)
DIMENSION SYM(2), SPACE(15), INUM(8)
DATA SYM/******/
FIND MAXIMUM SPL

MAX=0.
DO 40 J=1, 10
IF(RCVR(J, 1) .LT. 0.) GO TO 50
DO 41 JJ=1, 15
ITIME(J, JJ)=ITIME(J, JJ)/FLOAT(NM)
IF(ITIME(J, JJ) .LE. 0.) GO TO 5
ITIME(J, JJ) = 10.*ALOG10(ITIME(J, JJ))
GO TO 6
5 ITIME(J, JJ)=0.
6 IF(ITIME(J, JJ) .GT. MAX) MAX=ITIME(J, JJ)
41 CONTINUE
JPLUS=0
MAX=INT(MAX+.5)
IF(MAX .EQ. 0.) GO TO 43
VSCALE =1.
IF(MAX .GT. 50.) VSCALE=5.
IF(MAX/VSCALE .LT. 10.) JPLUS=4
NEXT=(50.-MAX/VSCALE*FLOAT(JPLUS+1))*5.
WRITE(5, 11)
11 FORMAT(1H1)
WRITE(5, 51) RCVR(J, 1), RCVR(J, 2), SPL(J)
51 FORMAT(' LOCATION (X,Y) OF RECEIVER', 2F10.3/* SPL OF RECEIVER', F10
* 3/
   DO 20 K=1,NEXTR,2
20 WRITE(5,21)
   FORMAT(/(/)
   WRITE(5,90)
90 FORMAT(' SOUN D PRESSURE LEVEL VERSUS TIME(SEC S)')
   R=MAX
33 DO 30 K=1,15
   IF(ITIME(J,K).GE. MAX) GO TO 31
   SPACE(K)=SYM(2)
   GO TO 30
31 SPACE(K)=SYM(1)
30 CONTINUE
   WRITE(5 ,32) R,( SPACE(K),K=1,15)
32 FORMAT('F5.2',15A4)
   Z=JPLUS+1
   MAX=MAX-1./Z*VSCALE
   R=MAX
   IF(MAX.GT.0.) GO TO 33
   DO 54 JJ=1,8
54 INUM(JJ) = ISTART(J) + (JJ-1)
   WRITE(5 ,34) (INUM(K),K=1,8),VSCALE,HSCALF(J)
34 FORMAT(8X,1HI,16(4H-II-)/9X,8(I3,5X)//4X,'VERTICAL SCALE TIMES ''
 ,1PE10.3/4X,'HORIZONTAL SCALE TIMES ''F10.3/1H!)'
   GO TO 40
43 WRITE(5 ,44)
44 FORMAT('NO PULSES ARRIVED')
40 CONTINUE
50 RETURN
 END