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Abstract

A combined ray tracing/radiosity method for propagation of sonic booms was developed. The method was developed modularly so that complexity can be added and the radiosity part of the model can be turned off. The method is a high frequency approximation and models the shocks of the sonic boom most accurately. The model was compared to an image theory and a stochastic ray tracing model to validate its overall accuracy. This validation showed good agreement.

The model was then used to simulate environments that were measured during the 2009 Sonic Booms On Big Structures (SonicBOBS) NASA experiment on Edwards AirForce Base. These environments were used for further validation to determine the accuracy when applied to a realistic sonic boom events. The Environmental Management (EM) building, a single building with surface irregularities, was examined. Façade features, diffusion and surface absorption were varied to determine their impact. The EM building showed good comparison to the measured data. The model was then used to simulate an environment with multiple buildings. This did not show good agreement between the simulated and measured data even for microphones that were not affected by the presence of additional buildings. The reason for this is the location of the multiple building environment on the edge of the boom carpet. It is concluded that the ray tracing/radiosity method is not valid for locations near the edge of the carpet. With these limitations in mind this model can successfully used to propagate sonic booms around buildings. The impact of absorption was shown to be minimal for a single building. The loss of energy to diffuse reflections reduced the amount of specularly reflected energy significantly. The complexity of the façade features did not improve the accuracy of the results enough to warrant the additional computation time and memory required.

The method was then applied to an urban canyon environment. The perceived loudness (PLdB) on the sidewalk, the shape of the signal, and the pressure loading
on the building wall were all examined. It was found that the PLdB increases as much as 7 dB from an environment with no buildings. While this increases the impact on people it does not drastically increase the impact over a single building environment. The PLdB can also be zero if it falls in a shadow zone. There was no observable trend between the parameters varied, building height, canyon width, initial boom elevation angle and azimuthal angle and the sound level. Varying diffusion did have a significant effect on both the signal shape and the PLdB on the sidewalk. Diffusion could significantly reduce the impact on people at the ground level.
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<td>Percent Error of the peak values of the direct and reflected boom event at CC for all simulations as compared to the measured data for the simple environment for the fifth boom event.</td>
</tr>
<tr>
<td>5.9</td>
<td>Percent Error of the peak values of the direct and reflected boom event at CC for all simulations as compared to the measured data for the fifth boom event.</td>
</tr>
<tr>
<td>6.1</td>
<td>Octave band values for the acoustically hard absorption coefficients.</td>
</tr>
</tbody>
</table>
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Introduction

1.1 Context of Problem

At the time of writing, super sonic flight over the United States is banned. This ban was instituted in 1973 by the FAA due to the negative effect of the aircraft noise on communities on the flight path. The aircraft noise of super sonic aircraft, referred to as ‘Sonic Booms’, was banned during a time when awareness of aircraft noise all over the country was increasing. In the 1960s, a variety of states passed legislation limiting the noise from aircraft. Most of these laws were focused on the noise around airports. In 1973, the U.S. Supreme court case American Airlines v. Hempstead ruled that the aircraft and its noise were subject to regulation from the same body. This ruling granted regulation to the federal government, overturned the current state regulations, leading to the ban on overland supersonic flight [1]. The supersonic flight over land bans are in place in several other countries as well.

In the three in a half decades since this legislation, a significant body of research has been done to reduce the impact on communities from supersonic flight by developing a way to shape the sonic booms. The original shape of a sonic boom was a time signature that resembled a capital N or an N-wave. The research has shown that it is possible to shape the sonic boom by changing the shape of the plane. There are now several proposed boom shapes for consideration. The next major step in the research is to determine how these shaped booms propagate in and around buildings. A significant body of work exists that analyzes the
community response to the original N-waves and the shaped sonic booms. The next hurdle is to determine the effect of sonic booms in and around buildings. The environment outside of buildings and multiple building environments need to be examined in order to determine the effect in an urban environment. The effect of the sonic booms on buildings must be understood so that the responses of the building and the sound field inside the building can be understood. These will all combine to determine the impact on communities in a realistic living situation.

1.2 Research Question

This study aims to study the sound field around buildings. In particular, the following questions is put forth to be answered by this work:

What is the impact of urban environments and their features such as diffusion, absorption, and surface irregularities on the sound field created by sonic booms as modeled by a combined ray-tracing and radiosity method?

This is done by creating simulations of environments similar to the buildings involved in the 2009 Sonic Booms on Big Structures (SonicBOBS) experiment performed by NASA in September 2009. These simulations are compared to the recorded data to determine the accuracy of the combined ray-tracing and radiosity method. Diffusion, absorption and surface irregularities are varied to determine their impact. Once the comparison to data has been analyzed, more environments can be modeled to determine the effect of sonic booms on multiple urban configurations. This can be done using the parameters and accuracy determined in the comparison to the measured data.

1.3 Structure of Thesis

This document is structured to be thorough and complete and this first chapter outlines the structure of the document.

Chapter 2 will provide some theoretical and historical background about the concepts and methods useful in investigating this subject. This includes an ex-
planation of sonic booms, urban sound propagation, and various computational methods.

Chapter 3 describes the methods utilized to do this work in more detail. It provides an in depth description of both ray tracing techniques and radiosity. It then provides a rigorous validation varying all relevant parameters to ensure that the technique is behaving as expected.

Chapter 4 provides a detailed description of the single building environment that was measured in the 2009 SonicBOBS experiment. Both a simple and a complex building configuration are analyzed, as well as a variety of absorption coefficients and diffusion coefficients. These simulations are then compared to the measured data to determine the ability of the simulation to accurately model the sound field in the single building environment.

Chapter 5 provides a detailed description of a multiple building environment. The museum building that was measured in the 2009 SonicBOBS experiment is used for comparison. Both a simple and complex building environment are examined, as well as various absorption and diffusion coefficients.

Chapter 6 describes the urban environment simulations. Two different environments were modeled: a single urban canyon and a four way intersection. Some environmental parameters were varied including building height, building width, initial boom elevation angle, initial boom azimuthal angle and diffusion to determine the overall effect.

Chapter 7 provides some general conclusions regarding the work discussed in this document. Suggestions for future work are given in this chapter as well.

The appendices give all of the code and a description of how to implement the code. The implementation of the code provides an example environment.
Chapter 2

Background

2.1 Introduction

In order to understand the propagation of sonic booms in an urban landscape one must first understand what both sonic booms and urban landscapes are. Often urban landscapes are simplified into something called an urban canyon which is a simplified geometry with no gaps between the buildings. In this chapter these two topics and a few of the tools which have been developed to deal with them will be explored.

The literature review will show that there are many different ways to propagate sound, especially in a large urban environment. In this chapter, some background about the methods chosen for this work will be given.

2.2 Sonic Booms

Sonic booms are a phenomenon that occur when objects travels faster than the speed of sound. Each object has a series of shockwaves associated with it once it travels faster than the local sound speed. These shockwaves are directly related to the shape of the projectile. A simple projectile such as a bullet usually has a signature with a bow shock and tail shock associated with the front and back ends of the projectile. As the object shape becomes more complicated the signature near the object also becomes more complicated. Near the object, sound travels
non-linearly which results in the shockwaves moving in relationship to each other and the shocks merging and steepening. Over a long distance this non-linear propagation yeilds a simplified signature with a bow shock and a tail shock. This resulting signature is referred to as an N-wave and is shown in Figure 2.1. The

![Figure 2.1. An idealized sonic boom or N-wave.](image)

signature featured here is an idealized N-wave. This is non-physical and has a very small rise time, or the time it takes for the pressure to reach the peak level from zero pressure.

By the time the signature from an aircraft is measured at the ground, it has traveled thousands of feet through a variety of atmospheric conditions. It may encounter turbulence, and other atmospheric effects which may alter the shape of the resulting signature. In addition, the shape and size of the aircraft will affect the resulting N-wave in ways such as the duration of the signature, the strength of the shocks, and the rise time. Figure 2.2 shows some examples of sonic booms measured on the ground from aircraft. This data was taken from the sonic booms
Figure 2.2. Sonic booms measured at Edwards Air Force Base during the 2009 SonicBOBS experiment.

The shockwaves emerge from the aircraft in a conical shape. This presents as a hyperbolic shape when the boom intersects the ground and a significant amount of the energy is propagated upward. This is illustrated in Figure 2.3. The energy that reaches the ground is called the sonic boom ‘carpet’. The carpet is divided into the primary and secondary boom carpet. The primary boom carpet is the area where the direct energy from the underside of the aircraft reaches the ground. The secondary boom carpet is the area where the energy that comes off the top of the aircraft reaches the ground due to bending in the atmosphere from certain atmospheric conditions. The secondary carpet is often much quieter than the primary boom carpet because it travels a substantially longer distance. It is often not audible and is predominantly low frequency as the higher frequencies are attenuated during propagation. Because of the low frequency content it is possible for the secondary booms to create some building response. The carpet shape can vary depending on the flight track of the aircraft and the atmospheric conditions.

In some instances something called a ‘focus boom’ can occur. This is a phe-
nomenon that occurs when the aircraft changes direction or speed. It causes the signatures to be focused at a particular point or line. This causes the boom to be much louder on the ground. The appearance of focus booms occur on something called a caustic. A caustic is a line that traces the locations where the rays from the aircraft will come together. Figure 2.4 shows a caustic from an accelerating aircraft. The focus boom is not only louder than a normal sonic boom but it also has a different signature shape. It is something referred to as a U-shaped signature. Although sonic booms have a very complicated non-linear propagation that extends from the flight altitude to the ground, this work considers the sonic booms once they are very close to the ground compared to their initial height. Due to this propagation distance and over the lengths considered all booms in this work are considered to propagate linearly [2].

2.2.1 Metrics

In order to better quantify sonic booms a variety of metrics have been developed. A lot of these metrics are centered around the reaction of humans to sonic booms. Various characteristics of the sonic boom were examined to determine the impact of
Figure 2.4. A caustic resulting from the acceleration of an aircraft. 

each characteristic on the human response. The characteristics that were examined were duration of boom, overpressure, and rise time. At first, sonic booms were characterized by using overpressure alone. However, it was soon evident that other factors contributed significantly to the human response such as rise time and duration. May and Sohn proposed a metric that included all of these characteristics called ‘perceived loudness level’. This metric does not include any of the psychoacoustic loudness level curves like some of the more complicated metrics.

Another commonly used metric is the Sound Exposure Level (SEL). This is a common metric that is applied to transient sounds including but not limited to sonic booms. In the typical application of this metric, when the energy of the signal is within 10 dB of the peak sound pressure level the energy is summed over time. This can be problematic in the case of sonic booms because it may include several components but not the entire sonic boom event. Some research has modified this to sum the energy over the boom event to ensure that all of the boom event was
included in the metric [1]. This energy summation is often done in the frequency domain. Frequency weightings can be applied to this metric. The most common weighting is A-weighting but C-weighting is also used in the case of sonic booms since the majority of the energy is in the lower frequencies.

Another frequently used metric is called Steven’s MkVII Perceived Level or more commonly, PLdB [5]. This is the metric most commonly used by NASA. PLdB is found by using the 1/3rd octave band spectrum that is converted to sones. The total perceived loudness is determined using lookup tables developed by Beranek in 1988 [6]. This total perceived loudness is then converted to PLdB using a different look up table. This metric is specific to aircraft noise but a more universal metric called perceived noise level, PNL is calculated the same way using a slightly different weighting.

Another metric specifically related to a psychoacoustics model is ‘Loudness’. This is not to be confused with ‘perceived loudness’. The major unique feature in Loudness is applying filters that mimic the inner ear and the outer ear. Newer versions of the Loudness metric also have filters that account for frequency masking. Though the earlier Loudness metric was for steady state sounds it has been adapted to include transient sounds as well.

Figure 2.5. A comparison between a normal N-wave and a focused U-wave [2].
2.2.2 Low Amplitude Booms

Recently, supersonic transport has become much more feasible than at the time of the first attempt at a supersonic aircraft in the 1950s. At the time when the US, the Soviet Union, and Europe were all racing to complete a supersonic transport, the research surrounding sonic booms was extensive. However, it was shown that the levels of the sonic booms were considered unacceptable by the population at large. Though Europe succeeded in completing a commercial supersonic transport called the Concorde, supersonic flight over land was prohibited, restricting supersonic flight to transoceanic flights. If overland supersonic flight was deemed acceptable then operating commercial supersonic aircraft would be much more economically feasible.

The strength and duration of the sonic boom is directly related to the shape of the aircraft and can be predicted to a first linear approximation by using something called an F function given by equation 2.1

\[ F(x) = \frac{1}{2\pi} \int_0^x \frac{A''(\xi)}{(x-\xi)^{1/2}} d\xi \]  (2.1)

where \( A''(\xi) \) is the cross-sectional area of the body of the projectile and \( \xi \) the distance from the nose of the projectile. With a very simple shape that does not change in cross section, this equation is moderately difficult, however, with something as complex as an aircraft it is almost impossible without significant computational assistance. In fact, until recently, the computation power required to solve this equation for various shapes was extremely prohibitive. It made designing an aircraft to minimize the impact of the sonic boom nearly impossible. However with advances in computing, it has become possible to design aircraft that have a lower signature. These ‘low boom’ aircraft have signatures with a smaller over-pressure and longer rise time. It is thought that this will reduce the impact on the people exposed to the booms and allow supersonic flight over land.

2.2.3 Interaction with Structures

The consideration of sonic booms interacting with structures has been a concern since supersonic flight became potentially viable. Because of the amount of low
energy and the pressure changes at the front and tail shocks, sonic booms can have a significant impact on structures. Not only do the sonic booms interact with the structures but the signatures inside a structure are markedly different than outside and can cause very different reactions from the individuals exposed.

In order for supersonic flight to be a viable mode of transportation, the impact on the people exposed to sonic booms must be minimal. It is important to study both the impact on structures and the impact on the people exposed to sonic booms inside.

NASA and the U.S. Air Force have seen that communities exposed to conventional sonic booms have a large number of complaints pertaining to structure damage. The most frequent kind of damage reported was plaster cracks, approximately 40% of the total complaints. The second most common kind of damage was broken windows, at 30%. Other complaints such as masonry cracks, broken tile and mirrors, broken bric-a-brac, and damaged appliances were reported with less occurrence. The occurrence of damage is often correlated with the peak over-pressure, which is the amplitude of the bow shock. Because the fundamental response of most buildings is usually lower in frequency, approximately 10 to 30 Hz, the low frequency content of the boom is often just as important as the initial impulse [2].

To be able to predict the effect sonic booms will have on buildings, a number of studies have been done trying to model the building response. Slutsky and Arnold tried to predict the acoustic response indoors from an external sonic boom. They developed a system transfer function that allowed them to predict the interior levels based on the external function. They included the effect of open and closed windows in their calculations. They also compared their transfer functions to scale models which showed good agreement [9]. Martini and Garrelick attempted to model the response of a window in a 3-D enclosure. Windows are often a weak point in a structure so it is important to understand how the signature effects a window. They modeled the window using a Finite Element/Boundary Element (FE/BE) model [10]. Clarkson and Hayes gave a simple model of building response using a single-degree-of-freedom model of a structure. It was assumed that this will give a simple prediction of a window vibrating in its fundamental mode. This model was then used as a basis to build a more complicated model. Then Clarkson and
Hayes used this theoretical predictions to try and determine when damage would occur. This was done by examining situations where buildings were exposed to sonic booms and reported damage as a result [11]. Garrellick and Martini attempted to use data collected on a building that was exposed to sonic booms or impulsive noise to predict damage to a structure. They instrumented a building and then measured the response when the building was subjected to the shock-wave from a cannon shot. These results were also compared to flyover data for the same structure [12].

In order to study the response of people inside buildings a great number of subjective response tests have been conducted. McCurdy et al conducted a test that placed a sonic boom simulator in peoples’ homes. The people were then exposed to a variety of boom signatures. The participants then filled out a survey that assessed their perception of the boom signature. A variety of parameters were correlated with annoyance including age, occupation, spouse, number of household members and children [13]. Leatherwood et al outlined three significant groups of perception studies conducted by NASA. The first kind of study was conducted through a sonic boom simulator. The simulator allows for the environment to be strictly controlled, i.e. no extraneous noise to influence the sound field, however it does not allow for a very realistic environment for testing. When people will be exposed to real sonic booms they will be in their own home, surrounded by their own belongings and this may impact their responses to exposure. Filters were applied to sonic booms in order to produce signatures that would be heard indoors. The second type of study was conducted in the subjects homes and the signatures were played through loud speakers. This allows less control over the actual signature heard due to the differences between homes, the setups and background noises. The third type of study that was outlined was field tests. These studies examined peoples’ responses to booms off reflective surfaces. Often when people are located outside when a sonic boom reaches the ground they are located next to a reflective surface such as a building. These types of situations are extremely hard to control due to external factors. Even the source cannot be fully controlled because it is an inflight aircraft and unexpected things may occur. In these studies the effects of low booms was also considered [14].

Sutherland, Kryter, and Czech examined past and present information about
subjective responses to sonic booms and building vibration. They concluded that in previous studies people were most annoyed by building vibration or rattle from sonic booms. However, recent studies have shown that the startle response from the shocks was found most disturbing. These studies have shown that the low booms did not reduce the building response and the best way to reduce rattle was to reduce the peak over-pressure [15].

2.3 Urban Sound Propagation

This section will give some background on urban sound propagation and some studies that have been performed to try and predict the sound field in urban environments. There are two general ways to calculate sound distributions in urban landscapes, microscale and macroscale. Microscale urban sound predictions are usually for a small or medium scale environment such as a single street or an urban square. Macroscale sound predictions involve a much larger scale environment and the prediction methods usually involve statistical methods and simplified algorithms. Microscale modeling has commonly been done using image source methods, ray tracing, radiosity, transport theory, equivalent source method, or empirical formulae. These methods encompass a wide variety of phenomena including diffuse reflections, specular reflections, high and low frequency ranges and diffraction. Macroscale modeling is often done with commercially available software such as CadnaA [16], fluidyn-dB[17], Synoise [18], IMMI [19], LimA [20], Mithra [21], Noisemap [22], and SoundPLAN [23]. These often include simplified formulae that can include or exclude various parameters such as source characteristics, geometrical divergence, atmospheric absorption, ground effects, screening effects, reflections and meteorological correction. This method is often less accurate but can be easily applied to a significantly larger area [24]. Measurements and scale models have also been used to improve the understanding of sound in urban canyons [25, 26, 27].

The work in this study will be done using microscale techniques. This review will focus on those techniques and previous studies that use them. In order to simplify some of the environments encountered in large cities something called an ‘urban canyon’ or a ‘street canyon’ is used. Another simplification of an urban environment is the urban square where the access openings are considered small.
enough to be neglected. Cross streets are modeled in a similar manner. The geometries of these simplified models are shown in Figure 2.6.

![Figure 2.6. Simplified geometry used in urban sound propagation. (a) an urban canyon configuration (b) a cross street configuration (c) an urban square configuration](image)

### 2.3.1 Previous Studies

Numerous studies have been carried out in order to accurately predict the sound levels in urban streets and squares. A variety of methods have been used and this section will outline some of the work that has been done and the methods used. The methods discussed are image source theory, radiosity and combined methods. There are many other methods such as transport theory [28] or the equivalent source method [29] but for the sake of brevity the focus will be constrained.

#### 2.3.1.1 Image Theory

Image theory is a popular method of predicting sound in urban environments. Lu and Li used image theory to propagate sound in narrow street canyons that were 10 meters wide or less. The results of their model was then compared to measurements
taken in an indoor scale model and in an outdoor street canyon [30]. The results compared reasonably well. Image theory was used by Kang to model specular reflections. These results were then compared to diffuse reflections calculated by a radiosity method [31]. Ismail and Oldham studied the noise from low flying subsonic aircraft in an urban canyon using image source theory. The effects of flight altitude, building height and canyon width were compared [32]. Donovan studied sound propagation in urban spaces using image theory. He included a surface scattering component to the imaging theory to include the scattered reflections [33]. Walerian et al used a computer simulation program called PROP5 which propagates the sound using image theory. It also has other corrections in order to calculate diffraction and other aspects that image theory does not include [34, 35, 36, 37].

2.3.1.2 Radiosity

Radiosity is another technique that is used to propagate sound in urban environments. It is not as widely used because it is traditionally used to propagate diffuse reflections. Jian Kang of the University of Sheffield has been very active using radiosity to model urban environments. He used radiosity to compare diffuse boundaries to geometrically reflecting boundaries. Radiosity was used for the diffuse reflections [31]. Kang then used radiosity in a later paper where he examined the effect of parameters such as height, absorption, vegetation, gaps between buildings, etc. on the noise level in an urban environment. Again the application of radiosity was for purely diffuse reflections [38]. He also used radiosity to model the sound field in urban squares [39]. Kang used radiosity to perform a parametric study for urban canyons comparing various absorption coefficient configurations in a cross street. He studied the effect on the overall sound pressure level in the street with the source and the cross street. The effect of changing the geometry such as staggering the streets and changing the canyon width and height was also examined [40]. There have been studies that adapted radiosity to perform specular reflections as well as diffuse reflections. However, they are not specifically applied to urban canyon propagation [31].
2.3.1.3 Combined Methods

Often a single method of propagation is not sufficient to model the sound in an environment so two methods are combined to broaden the relevance of the model. Onaga and Rindel combined the image source method and radiosity. This used the image theory for the specular reflections and the radiosity for the diffuse reflections. A variety of absorption coefficients and scattering coefficients were examined to determine the impact on the overall sound field in urban canyons [42]. Meng developed a combined ray tracing and radiosity method for modeling urban canyons. Comparison to other methods and measured data showed the results to be accurate [43].

2.4 Computational Methods

Numerous computational methods have been developed to propagate sound. It is important that a few of the relevant methods are discussed to give context to this work. Each method has limitations, and the goal of the work needs to be carefully considered when determining which computational method to choose. Three main methods were considered for this work: beam tracing, ray tracing, and radiosity. Some previous studies related to these methods are presented in this section.

2.4.1 Ray Tracing

Ray tracing is commonly used in a variety of applications even outside the scope of acoustics, particularly in optics. Within acoustics, ray tracing is often used in ocean acoustic sound propagation, long distance propagation in the atmosphere, and room acoustics. In ocean acoustics and atmospheric propagation the rays are often curved due to a changing speed of sound. A complete derivation of ray tracing for curved rays is given by Jensen et al in Chapter 3 of his book Computational Ocean Acoustics. Two dimensional and three dimensional ray tracing is discussed as well as reflections from porous media. The main focus of his work is strongly related to ocean acoustics [44].

In room acoustics, the rays are usually straight because the changes in the sound speed are assumed to be negligible. Room acoustics utilizes a very similar
algorithm to optics for this reason. In 1985, Andrej Kulowski published a comprehensive ray tracing technique that allowed for complicated geometries to be accurately modeled by ray tracing with acceptable computation times \[45\]. Ray tracing has been used in room acoustics for many different geometrical configurations and to predict a number of metrics. Hodgson and Wong adapted a ray model to predict speech intelligibility in classrooms. The model was found to have good agreement with the diffuse model for highly diffuse configurations \[46\]. Yang utilized a ray tracing technique to propagate sound in long enclosures such as a hallway or train station. Speech intelligibility and reverberation time were examined. The correction for late reflections called the reverberation tail compensation was examined and found to be useful in calculating reverberation time in a diffuse field \[47\]. Kuttruff uses a combined ray tracing and image theory model to create time waveforms for auralization \[48\]. Schroeder also uses ray tracing to determine the response and reverberation time of a concert hall for the purposes of auralization \[49\]. Krokstad et al used ray tracing to determine the room response in concert halls. They focused on early reflections and the overall temporal distribution of the sound space \[50\]. Krokstad also provided an overview of experience with ray tracing including the spatial, temporal, and directional distributions of the acoustic energy. The study outlines fifteen years of successful implementation of ray tracing techniques with a variety of geometries \[51\].

Ray tracing often addresses specular reflections but can overlook the diffuse reflections. Several studies have been done to include diffuse reflections in a ray tracing algorithm. Vorlander discusses a method of including diffuse reflections using a stochastic or randomized ray tracing method. This method scatters the sound by generating a random direction for the sound to go every time it is reflected diffusely by a surface \[52\]. Vorlander also developed a combined ray tracing/image theory method to reduce computation time for determining the sound field in rooms. This method quickly eliminates the images that are not visible by the receiver using ray theory and then continues the propagation using the image source method. This quickly yields the impulse response of an enclosed space \[53\]. Embrechts discusses a similar method of including diffuse reflections in a ray-tracing algorithm using a randomized ray algorithm. Due to the dependency on frequency of the scattering, he has developed a model to reduce computation time.
by combining the frequency bands into a single calculation [54]. Embrechts also did work in the initial source distribution of rays. He used a monte carlo simulation to determine the rays to be “shot” from the initial source. This allowed fewer rays to be shot and still accurately represent the distribution. The method was compared to measured sound pressure levels and reverberation times and showed good agreement [55]. Wayman and Vanyo used a randomized ray tracing algorithm to model sound fields in an enclosure. The results were compared with the Eyring equation and some experimental results with good agreement [56].

2.4.2 Beam Tracing

Beam tracing is very similar to ray tracing. The main difference is that beam tracing follows a ray with a finite cross section. Studies have varied the cross section and distributions to address a variety of situations. Drumm and Lam developed an adaptive beam tracing algorithm where the cross section is determined by the reflecting surface. This allows for very complex geometries. Radiosity is used to include the diffuse reflections in this method [57]. Porter and Bucker used a gaussian beam tracing algorithm to compute sound fields in the ocean. This followed a single ray at the center with the amplitude tapering off with distance. This yields a beam with a gaussian distribution [58]. Farina used a triangular cross section beam in his pyramid tracing algorithm for outdoor sound propagation. The model was compared to outdoor measurements and showed good agreement [59]. Farina also used the same pyramid beam tracing and modified it to include diffuse reflections [60]. Lewers used a combined beam tracing and radiant exchange or radiosity computer model to model room acoustics. The beams of triangular cross section propagate the specular energy and the radiosity method propagates the diffuse energy [61]. Fortune developed a topological beam tracing algorithm. This improved on the algorithm for determining the visible areas to the source. Because of the decreased computation time a more complex environment can be employed [62]. Summers et al developed a cone tracing method, a beam with a circular cross section, to model coupled rooms. They included a tail correction to model the later reflections [63]. Funkhouser et al considered a beam tracing model where the source and receiver could move within the environment. This was done by
pre-calculating any environment dependent variables. This significantly decreased the computation time\cite{64}. Dalenback uses an approximate cone tracing algorithm that includes diffuse reflections. This is accomplished by splitting the cone when it interacts with the surface\cite{65}.

Wareing and Hodgson developed a combined beam tracing and transfer matrix method. This allowed for complex surface absorption coefficients. The transfer matrix method was very computationally intensive \cite{66}.

### 2.4.3 Radiosity

Radiosity is a method of energy exchange first employed by physicists to model heat exchange. It has been called many things including the bulk energy transfer method or radiative transfer method. It has been used in optics, computer graphics, and thermal engineering. For acoustics, radiosity is derived from a geometrical acoustics approach and therefore has the same high frequency limitation that ray tracing and image theory both have.

Muehleisen has worked extensively in radiosity for modeling sound fields in rooms. He has created a simplified radiosity method to determine the diffuse steady state sound field in a room. This method can be implemented using only a spreadsheet or a simple hand calculation \cite{67}. He extended this model in a paper with Beamer to include more complex geometries. It provides a closed form matrix solution of the radiosity equations. When comparing to the diffuse field theory the results showed good agreement \cite{68}. He also used the steady state diffuse radiosity to compare the speech to noise ratios in an office conference room \cite{68}. Korany et al created a combined image theory and radiosity method to model partially diffuse reflections. The results showed good reverberation time agreement with the Sabine and Eyring equation methods \cite{69}.

### 2.5 Summary

After examining the literature discussed above I have made the decision to focus on a combined ray tracing and radiosity method. I chose this method because it gives me a significant amount of flexibility in order to address the question put forth in
Section 1.2. Ray tracing allows me to include very complicated geometries with relatively small surface irregularities without a significant increase in computation time. Because beam tracing has an increasing cross section along the beam, small surface irregularities can be overlooked by the beams with larger cross sections.

By incorporating radiosity into the model it allows me to include diffuse reflections. It is an improvement over stochastic ray tracing because with a statistical method, a significant increase in the number of rays is required to increase the accuracy. Because ray tracing and radiosity are both geometric acoustics approximations they have similar assumptions and are valid in the same frequency ranges. This makes them ideal for use as a combined method.

A high frequency approximation was chosen because of the structure of the sonic boom. Most of the audible energy in a sonic boom is present in the shockwaves. This is where most of the high frequency energy is present so it would follow that the high frequency would be of interest in an urban environment. For the purposes of this work, the focus going forward will be on the ray tracing and radiosity methods.
Chapter 3

Description of Method and Validation

3.1 Introduction

This section discusses the modeling method chosen, the basic structure of the code and the methods of initial validation. Ray tracing and radiosity are the two methods that have been combined. They will be discussed separately for simplicity and then the combined method will be introduced. Section 3.2 will give a mathematical derivation of ray tracing. A description of the source used in this model will be given. In addition, the normalization of the signal will be described. It should be mentioned again at the outset that all the methods utilized assume a constant speed of sound c, yielding only straight rays.

3.2 Ray Tracing

3.2.1 Mathematical Derivation

There are three important things that are needed to propagate sound correctly. These things are the trajectory of the sound waves, the phase as the sound is propagated, and the amplitude as the ray travels with distance. This derivation follows that of Jensen [44].

If the wave equation is separable in time and space then deriving the ray equa-
tions starts with the Helmholtz equation in cartesian coordinates given in equation 3.1

\[ \nabla^2 p + \frac{\omega^2}{c^2(\vec{x})} p = 0 \] (3.1)

For the moment the speed of sound varies with vector position \( \vec{x} \). In order to determine the ray equations a solution in the following form is sought,

\[ p(\vec{x}) = e^{i\omega \tau(\vec{x})} \sum_{j=0}^{\infty} \frac{A_j(\vec{x})}{(i\omega)^j}. \] (3.2)

This solution is defined as the ray series. Taking the first and second derivatives of the solution the following equation can then be written.

\[ \nabla^2 p = e^{i\omega \tau(\vec{x})} \left\{ [ -\omega^2 |\nabla \tau|^2 + i\omega \nabla^2 \tau ] \sum_{j=0}^{\infty} \frac{A_j}{(i\omega)^j} + 2i\omega \nabla \tau \sum_{j=0}^{\infty} \frac{\nabla A_j}{(i\omega)^j} + \sum_{j=0}^{\infty} \frac{\nabla^2 A_j}{(i\omega)^j} \right\} \] (3.3)

Substituting equation 3.3 into the Helmholtz equation and equating like terms yield a series of equations that describe the propagation of rays. The \( O(\omega^2) \) equation is called the Eikonal equation and is given by

\[ |\nabla \tau|^2 = c^{-2}(\vec{x}) \] (3.4)

The remaining equations in the infinite series are for the amplitude, \( A_j(\vec{x}) \) and are known as the transport equations. These equations are related to the amplitude associated with the ray and are given in the form:

\[ O(\omega) : \quad 2\nabla \tau \cdot \nabla A_0 + (\nabla^2 \tau) A_0 = 0 \] (3.5)
\[ O(\omega^{1-j}) : \quad 2\nabla \tau \cdot \nabla A_j + (\nabla^2 \tau) A_j = -\nabla^2 A_{j-1}, j = 1, 2, \ldots \] (3.6)

### 3.2.1.1 Trajectory

At this point, the Eikonal equation can be solved which will determine the trajectory of the rays. This is done by assuming that there are rays that travel perpendicular to the wavefronts. These wavefronts can be described as curves of
constant phase, \( \tau(x, y, z) \). These rays describe a new coordinate system. Using the fact that the ray path travels perpendicular to the wavefronts the ray trajectory can be described as

\[
\frac{d\vec{x}}{ds} = c \nabla \tau
\]  

(3.7)

where \( s \) is the distance along the ray path. If equation [3.7] is differentiated by \( s(x, y, z) \) considering only the x component of \( \tau \) one has:

\[
\frac{d}{ds} \left( \frac{1}{c} \frac{d\vec{x}}{ds} \right) = \frac{d}{ds} \left( \frac{\partial \tau}{\partial x} \right) = \frac{\partial^2 \tau}{\partial x^2} \frac{\partial x}{\partial s} + \frac{\partial^2 \tau}{\partial x \partial y} \frac{\partial y}{\partial s} + \frac{\partial^2 \tau}{\partial x \partial z} \frac{\partial z}{\partial s} = \frac{\partial^2 \tau}{\partial x \partial y} \left( c \frac{\partial \tau}{\partial y} \right) + \frac{\partial^2 \tau}{\partial x \partial z} \left( c \frac{\partial \tau}{\partial z} \right) = \frac{c}{2} \frac{\partial}{\partial x} \left( \frac{\partial^2 \tau}{\partial x^2} + \frac{\partial^2 \tau}{\partial y^2} + \frac{\partial^2 \tau}{\partial z^2} \right)
\]

(3.8)

(3.9)

(3.10)

This derivation can be followed considering each cartesian coordinate. Along with equation [3.4] this can be simplified to a vector equation for paths that the rays take.

\[
\frac{d}{ds} \left( \frac{1}{c} \frac{d\vec{x}}{ds} \right) = \frac{-1}{c^2} \nabla c
\]

(3.11)

In cartesian coordinates this can be expressed as the system of equations

\[
\frac{dx}{ds} = c \xi(s) \quad \frac{d\xi}{ds} = \frac{-1}{c^2} \frac{dc}{dx}
\]

(3.12)

\[
\frac{dy}{ds} = c \eta(s) \quad \frac{d\eta}{ds} = \frac{-1}{c^2} \frac{dc}{dy}
\]

(3.13)

\[
\frac{dz}{ds} = c \zeta(s) \quad \frac{d\zeta}{ds} = \frac{-1}{c^2} \frac{dc}{dz}
\]

(3.14)

For the purposes of this study the speed of sound will be assumed to be constant over the range. This means that equations [3.12] [3.13] and [3.14] can be rewritten as
\[
\begin{align*}
\frac{dx}{ds} &= c\xi(s) & \frac{d\xi}{ds} &= 0 \\
\frac{dy}{ds} &= c\eta(s) & \frac{d\eta}{ds} &= 0 \\
\frac{dz}{ds} &= c\zeta(s) & \frac{d\zeta}{ds} &= 0
\end{align*}
\] (3.15)

Using a finite difference approximation the ray equations can be written as a vector equation

\[
\begin{pmatrix}
x_{final} \\
y_{final} \\
z_{final}
\end{pmatrix} = \begin{pmatrix}
x_{initial} \\
y_{initial} \\
z_{initial}
\end{pmatrix} + h \begin{pmatrix}
d_x \\
d_y \\
d_z
\end{pmatrix}
\] (3.18)

where \(h\) is a small spatial step along the ray path, \(s\), and \(\vec{d}\) is the direction vector of \((c\xi, c\eta, c\zeta)\). With this vector equation and the initial conditions of the ray, the ray path can be determined.

The \(x\), \(y\), and \(z\) initial conditions correspond to the location of the source. For this study, the source is a plane wave that corresponds to an incoming boom. The entire plane of the boom cannot be used, so instead a section of the boom plane large enough to cover the entire environment is used. Once the finite section of plane is determined, it is sampled at regular intervals. Each of the sampled points is an initial location of a ray. This configuration is different than for traditional ray tracing. In traditional ray tracing the initial source is often a point source with rays being launched in all directions.

\(\xi\), \(\eta\), and \(\zeta\) are related to the initial direction of the ray. For this study this is dependent on the elevation and azimuthal approach angle of the boom. If \(\theta\) is defined as the elevation angle measured down from the \(z\) axis, and \(\phi\) is defined as measured counter clockwise from the \(x\) axis the direction vector can be written as:

\[
d = \begin{pmatrix}
\cos(\phi) \sin(\theta) \\
\sin(\phi) \sin(\theta) \\
\cos(\theta)
\end{pmatrix}
\] (3.19)
3.2.1.2 Amplitude

The transport equation is related to the amplitude along the ray. The transport equation is given as

\[ 2\nabla \tau \cdot \nabla A_0 + (\nabla^2 \tau) A_0 = 0 \] (3.20)

Using equation [3.7], the transport equation can be written as

\[ \frac{2}{c} \frac{d\vec{x}}{ds} \cdot \nabla A_0 + (\nabla^2 \tau) A_0 = 0 \] (3.21)

The second term in this equation, \( \nabla^2 \tau \) can be rewritten as

\[ \nabla^2 \tau = \nabla \cdot \nabla \tau = \nabla \cdot \frac{d\vec{x}}{ds} \] (3.22)

This says the amplitude is dependent on the divergence of the ray trajectory. Due to the plane wave source used in this study there is no divergence between the rays. The only change in the amplitude has to do with the absorption due to the air, and surface absorption when a ray interacts with a surface. The amplitude is therefore given by

\[ A_{\text{final}} = A_{\text{initial}} e^{-m(h(1 - \alpha))} \] (3.23)

where \( m \) is the absorption coefficient of air and \( \alpha \) is the absorption coefficient of a surface.

3.2.1.2.1 Normalization The rays that are being propagated with these equations have no cross section, however the receiver has a finite cross section. For this study, it was chosen for the receivers to have a spherical shape. For a graphical representation see Figure [3.1].

If the uniform spacing of the rays is less than the diameter of the sphere then multiple rays will intersect with the sphere. This will artificially increase the amplitude recorded at the receiver. In order to correct for this a normalization factor is introduced. The normalization factor is a function of the ray spacing and the radius of the receiver. The normalization factor is given by:
Figure 3.1. Graphic representation of a ray/receiver interaction. The rays have no cross sectional area, but the spherical receiver does have a finite area.

\[ N = \frac{\pi r^2}{\text{spacing}^2} \]  \hspace{1cm} (3.24)

This normalization factor takes the largest cross section of the receiver and multiplies it by the number of rays per square meter. If the amplitude at the receiver is divided by the normalization factor it corrects the amplitude as if only a single ray would hit in that cross sectional area.

### 3.2.1.3 Phase

The last important aspect to be considered is the phase. The phase can be determined by looking at the Eikonal equation.

Starting with the Eikonal equation

\[ |\nabla \tau|^2 = \nabla \tau \cdot \nabla \tau = \frac{1}{c^2} \]  \hspace{1cm} (3.25)

The equation can then be rewritten using equation 3.7

\[ \nabla \tau \cdot \frac{1}{c} \frac{d\vec{x}}{ds} = \frac{1}{c^2} \]  \hspace{1cm} (3.26)

\( d\vec{x}/ds \) has a value of unity and the equation can be rewritten

\[ \frac{d\tau}{ds} = \frac{1}{c} \]  \hspace{1cm} (3.27)

To solve for the phase, \( \gamma \), equation 3.27 is integrated with respect to the ray path, \( s \), to give
τ(s_{final}) - τ(s_{initial}) = \int_{s_{initial}}^{s_{final}} \frac{1}{c(s)} ds \quad (3.28)

For this study, \( c \) is a constant so the equation (3.32) can be simplified to

\[ \tau(s_{final}) - \tau(s_{initial}) = \frac{h}{c} \quad (3.29) \]

where \( h \) is the step size along \( s \). \( \tau \) in the above equations has the units of time. In order to determine the phase we need to consider the form \( e^{i\gamma} \) where \( \gamma \) is phase. Now, equation (3.29) can be written

\[ e^{i\omega(\tau(s_{final})-\tau(s_{initial}))} = e^{i(h\omega/c)} = e^{i2\pi h/\lambda} \quad (3.30) \]

where \( \lambda \) is the wavelength. We can then determine that the phase, \( \gamma \), reduces to

\[ \gamma = \frac{2\pi h}{\lambda} \quad (3.31) \]

which yields the phase equation

\[ \gamma_{final} = \gamma_{initial} + \frac{2\pi h}{\lambda} \quad (3.32) \]

This equation determines the phase, equation (3.18) determines the ray trajectory and (3.23) determines the amplitude. These are the three major components needed to effectively propagate sound.

### 3.2.1.4 Ray/Surface Interaction

An important aspect of this study is the environment in which the rays propagate which requires that the rays interact with surfaces. When dealing with buildings the three interactions that are most commonly used and that will be discussed here are ray/plane, ray/box, and ray/polygon interactions.

#### 3.2.1.4.1 Ray/Plane Interaction

The first step in the Ray/Plane interaction is to accurately define the plane. The standard equation for a plane is
\[ Ax + By + Cz + D = 0 \]
where \[ A^2 + B^2 + C^2 = 1 \] (3.33)

The vector \((A, B, C)\) is the normal of the plane, \(P_n\). If the initial position of the ray, \(R_0 = (X_0, Y_0, Z_0)\), and the direction of the ray, \(R_d = (X_d, Y_d, Z_d)\), are considered, an algorithm can be created to test if the ray intersects the plane. It is assumed that \(R_f\) is the location where the ray intersects the plane. \(R_f\) can be given by \(R_f = R_0 + lR_d\) where \(l\) is the distance to the plane. \(R_f\) is on the plane if it satisfies the equation

\[
A \cdot R_f + B \cdot R_f + C \cdot R_f = 0 \quad (3.34)
\]

\[
A \cdot (X_0 + X_d \cdot l) + B \cdot (Y_0 + Y_d \cdot l) + C \cdot (Z_0 + Z_d \cdot l) + D = 0 \quad (3.35)
\]

This equation is then solved for \(l\) to determine the distance to the plane. This yields the equation:

\[
l = \frac{v_0}{v_d} = \frac{-(P_n \cdot R_0 + D)}{P_n \cdot R_d} = \frac{-(AX_0 + BY_0 + CZ_0 + D)}{AX_d + BY_d + CZ_d} \quad (3.36)
\]

If \(l < 0\) then the ray does not intersect the plane. If \(l > 0\) then the ray intersects the plane and \(l\) is the distance to that intersection. In order to determine if the ray will intersect the plane first calculate the dot product

\[
v_d = P_n \cdot R_d = AX_d + BY_d + CZ_d \quad (3.37)
\]

If \(v_d = 0\) then the ray is parallel to the plane and it will not intersect the plane. If \(v_d > 0\) then the normal of the plane is pointing away from the ray and there is no need to proceed. If \(v_d < 0\) then proceed with equation 3.36 to determine the distance to intersection.

### 3.2.1.4.2 Ray/Polygon Interaction

In the event that there are irregular building façades or façade features the need for a ray/polygon interaction is required. It allows for a much more complex building geometry. The ray/polygon
interaction is based on the ray/plane intersection. The general idea behind determining if a point is in a polygon is to draw a line from that point, if it intersects a segment from the polygon an odd number of times then the point is inside the polygon. If the line intersects an even number of segments from the polygon then the point it outside the polygon. A diagram to illustrate this is shown in figure 3.2.

![Figure 3.2](image)

**Figure 3.2.** This figure shows the test to determine if a point is inside the polygon. Inside is shown here as the shaded area. An even number of intersections shows the point to be outside and an odd number of intersections shows the point to be inside [70].

The first step in the mathematical algorithm to determine the ray/polygon interaction is to determine the intersection point on the plane that the polygon is in. This is done by first determining if the ray hits the plane. Then the point can be determined by propagating the ray the distance \( l \). The intersection can then be determined given the intersection point \( R_f \), the vertex points of the polygon \( G_1, G_2, ..., G_n \) and the plane equation, \( P \).

The normal of the plane \( P_n \) is examined and the dominant coordinate is iden-
ified. The dominant coordinate is the maximum of the absolute value of the components of \( P_n \). Once this coordinate is identified than that coordinate is neglected. For example, if \( P_n = (3, -5, 4) \) the Y coordinate is identified as the dominant coordinate and all Y coordinates in the vertex points and the intersection point are neglected. Then the coordinate system is translated to the intersection point as the origin. This is done by subtracting the intersection point from the vertex points and a new polygon is identified. Now the vertices are redefined

\[
G'_1 = (U_a, V_a) \\
G'_2 = (U_{a+1}, V_{a+1}) \\
\vdots \\
G'_n = (U_n, V_n)
\]  

The number of crossings, \( NC \), is set to zero. A sign holder, \( SH \), is identified. The first sign holder is set to \(-1\) if \( V_a < 0 \) and is set to \( 1 \) if \( V_a \geq 0 \). For each edge of the polygon the next sign holder, \( NSH \), is identified as \(-1\) if \( V_{a+1} < 0 \) and is set to \( 1 \) if \( V_{a+1} \geq 0 \).

If \( SH = NSH \) then there is no crossing and the next segment of the polygon should be examined. If \( SH \neq NSH \) proceed to check the other coordinate direction. If \( U_a \) is positive and \( U_{a+1} \) is positive then \( NC = NC + 1 \). Otherwise if \( U_a \) is positive or if \( U_{a+1} \) is positive than it is possible that the line will cross the edge and the \( U \) axis intersection must be computed. If \( U_a - V_a \times (U_{a+1} - U_a)/(V_{a+1} - V_a) > 0 \) then the line must cross and \( NC = NC + 1 \). If \( NC \) is odd then the point is inside the polygon and the ray intersects with the polygon with a distance \( l \).

### 3.2.1.4.3 Ray/Box Interaction

The first thing that needs to be done in order to determine the intersection with a box is to define the box. The box is defined by the closest point, \( B_1 \) and the farthest point, \( B_2 \). Initial values of the near distance and far distance are initially set arbitrarily large at \( l_{\text{near}} = -\infty \) and \( l_{\text{far}} = +\infty \). The following process should be repeated for each pair of parallel planes but is shown here for the \( X \) plane where \( X_d \) is the \( X \) direction of the ray and \( X_O \) is the \( X \) coordinate of the ray origin.
If $X_d$ is equal to zero then the ray is parallel to the planes and must be between the edges of the box. If $X_O < B_1$ or if $X_O > B_2$ then the ray does not intersect the box. If the ray is in between the points then the ray intersects with the box. If the ray is not parallel to the plane then calculate the distances, $l_1$ and $l_2$, from the origin to the planes using the equations:

$$l_1 = \frac{B_1 - X_O}{X_d} \quad (3.39)$$
$$l_2 = \frac{B_2 - X_O}{X_d} \quad (3.40)$$

If $l_1 > l_2$ then swap $l_1$ and $l_2$. Then, if $l_1 > l_{\text{near}}$ then $l_{\text{near}} = l_1$ and if $l_2 < l_{\text{far}}$ then $l_{\text{far}} = l_2$. If $l_{\text{near}} > l_{\text{far}}$ the box is not hit or if the $l_{\text{far}} < 0$ the ray originates behind the box. At this point the algorithm is complete, and if the box is not missed then the ray intersects the box at a distance $l_{\text{near}}$.

3.2.1.4.4 Reflection Once it has been determined that a ray will hit a surface the ray must be reflected. This consists of a slight loss in amplitude, due to the absorption of the surface, and a change in direction as the ray is reflected. The loss of amplitude is a factor of $(1 - \alpha)$ where $\alpha$ is the absorption coefficient of the surface. The change in direction is slightly more involved. For a perfectly specular reflection the angle of incidence should be equal to the angle of reflection. Figure 3.3 shows the incident and reflected wave when a ray is specularly reflected from a surface.

In order to determine the new direction vector the following equation is used.

$$\vec{r} = \vec{d} + 2\vec{\alpha} = \vec{d} + 2\frac{\vec{d} \cdot \vec{n}}{|\vec{n}|^2} \vec{n} \quad (3.41)$$

where $\vec{\alpha}$ is the distance from the ground to end point of the ray shown in figure 3.3 and $\vec{n}$ is the normal of the reflecting surface. Once this direction vector has been changed the ray continues on in the $\vec{r}$ direction until another obstacle is encountered.
Figure 3.3. Illustration of a ray reflecting from a surface. $\theta_I$ is the incident angle and $\theta_R$ is the angle of reflection [71].

3.2.2 Validation

In order to validate the ray tracing code it was compared to a simple image theory simulation. The source for the image theory comparison was a source very far away from the receiver. The environment for the test is a large square building with rigid walls and sides measuring 20 meters. The incoming boom has an elevation angle of $\theta = 135^\circ$ and an azimuthal angle of $\phi = 0^\circ$. Figure 3.4 shows the setup for this validation run.
For simplicity, a sinusoidal pulse was used as an input signal. The pulse is a single cycle of a 500 Hz sine wave with an amplitude of 1 Pa. Figure 3.5 shows a close-up of the input signal. The total signal was 0.5 seconds long in order to encompass all reflections.

![Figure 3.4. Validation simulation environment](image)

Figure 3.4. Validation simulation environment

![Figure 3.5. Input signal used in the validation.](image)

Figure 3.5. Input signal used in the validation.
3.2.2.1 Image Theory

In order to fully understand the comparison a brief description of image theory will be given, for a more complete description see Pierce Chapter 6 [72]. Image theory assumes a high frequency approximation in the same way that ray tracing does. They are both based on geometrical acoustics.

A point source located at the origin creates a pressure field of

\[ p_i = \frac{A}{r} e^{i(\omega t - kx)} \]  

(3.42)

In the simulated environment, when there are surfaces where the pressure would reflect, an image of the source is created. This is a theoretical source of equal strength that is reflected from the original about the surface boundary. For the environment described above for validation there is one source with three image sources. A two-dimensional cross section of the environment that shows all of the images is shown in Figure 3.6

![Figure 3.6](image)

**Figure 3.6.** Representation of the method of images. \( R \) is the location of the receiver, \( S_0 \) is the location of the source, and \( S_1, S_2, \) and \( S_3 \) are the image sources for the various reflections.

Each of the sources has the pressure field identified in equation (3.42). To deter-
mine the pressure at the receiver identified in Figure 3.6 the pressure fields from all the images are added at that location. For this comparison, absorption by air is neglected and all surfaces are considered to be rigid with no surface absorption. Spherical spreading is also neglected in the image theory case because the source is in the far field so the $1/r$ spreading term may be omitted.

### 3.2.2.2 Comparison

In order to be vigorous in the validation several parameters were varied to determine the effect. The first parameter that was varied was the receiver location. The receiver was originally located at 1.5 meters above the ground on the incident side of the building in the center of the wall. This was chosen in order to simulate an observer standing in front of the building. The comparison between the first receiver location and an image theory simulation is shown in Figure 3.7. The ray tracing simulation shows good agreement with the image theory simulation. Two alternate receiver locations were chosen. The first was a location significantly far away, specifically above the $45^\circ$ line intersection with the building/ground corner. The comparison between the second receiver location and an image theory simulation is shown in Figure 3.8. This figure also shows good agreement. The third location was slightly displaced in each direction by 0.0125 meters which corresponds to half of the spacing of the input rays. The comparison between the third receiver location and an image theory simulation is shown in figure 3.9. The third pulse also shows good agreement. Each of these simulations were run with a receiver radius of 0.125 meters and an initial ray spacing of 0.025 meters. The accuracy of the arrival time does not change as the receiver location is changed. The amplitude has a slight discrepancy at all three locations which changes slightly as the receiver location changes. The average discrepancy in the four pulses amplitude at location 1 is 0.0825 Pa or 8.25% error. The average discrepancy across the four pulses at location 2 is 0.086 Pa or 8.6% error. The average discrepancy in the four pulses amplitude at location 3 is 0.0521 Pa or 5.2% error. The small change in this has to do with the discrete nature of the input. As the receiver moves, a slightly different number of rays intersect with the receiver. As the number of rays increases this error decreases.

The next parameter that was varied was the radius of the receiver. Because of
Figure 3.7. Receiver location (7.0, 20.0, 1.5) ray tracing comparison with image theory

the fact that ray tracing needs a finite receiver size, the size of the receiver plays
a part in the final simulated sound field. The receiver was varied from 0.03125 to
0.5 meter radius. Figure 3.10 shows the comparison of each of the various receiver
sizes as well as the image theory simulation.

This figure shows that the larger receiver sizes are less accurate. Because of the
larger volume that the rays can hit there is a spreading of the pulse. The amplitude
of the pulse is less, but the duration of the pulse is longer. This basically means
that the amplitude is getting spread over a larger time period because the rays are
traveling different distances to different points in the receiver. This phenomenon
is greatly reduced as the size of the receiver goes down. Figure 3.11 shows an
enlarged graph of the initial pulse. The pulse with a radius of 0.5 meters is the most
exaggerated of this effect only reaching an amplitude of 0.6 but with a duration of
0.003 seconds instead of the correct 0.002 seconds. This shows that with a radius
of 0.125 meters or less approximates the duration of the pulse well. This is valid
for a frequency of 500 Hz or the frequency of the pulse. As the frequency increases
the size of the receiver should decrease. The frequency to which the radius should
Figure 3.8. Receiver location (8.5, 20.0, 3.0) ray tracing comparison with image theory

$$f = \frac{c}{r}$$  \hspace{1cm} (3.43)

where \( r \) is the radius and \( c \) is the speed of sound. For this particular example and for most of this work this frequency is about 2500 Hz. This is suitable for a sonic boom because the majority of the energy is low frequency. It should be noted that the initial spacing of the rays remains the same as the radius changes so the number of rays that hits each receiver is less. This will affect the amplitude and is the next examined parameter.

The radius then was held constant while the initial ray spacing was varied. Figure 3.12 shows a variety of spacings compared to the image theory method. It is shown that the arrival time and duration is not affected as the spacing changes. The amplitude is affected. This has to do with the normalization factor. As the normalization factor increases the accuracy of the amplitude increases. Figure 3.13 shows that a spacing of 0.0625 meters or less gives a good agreement with the image theory simulation.
The next parameter that was examined was the sampling frequency. Sampling frequencies of 2000 Hz, 4000 Hz, 5000 Hz, 10000 Hz, 15000 Hz, and 20000 Hz were utilized. Figure 3.14 shows that the arrival time and amplitude are good for all the frequencies but 2000 Hz. The pulse with a sampling frequency of 2000 Hz was not simulated well. Figure 3.15 shows a close up of the direct pulse with the varied frequencies. This shows that the simulations of the pulse get increasingly better with increased sampling frequency. Anything above 2000 Hz gives a reasonable approximation of the pulse.

Each of the these validation models took about 1080 minutes of computation time. This was run on a Mac OS X 2 x 2.26 Quad-Core Intel Xeon Computer with 24 GB of memory. Up to 15 instances were run at the same time on this machine. The biggest factor in the computation time was the initial ray spacing. Table 3.1 shows the initial spacing versus the computation time.

Figure 3.9. Receiver location (7.0125, 20.0125, 1.5125) ray tracing comparison with image theory
Validation of Ray Trace Radius Size

![Graph showing sound field with various receiver sizes](image.png)

**Figure 3.10.** Receiver size was varied. This figure shows the sound field from receivers with radii of 0.5, 0.25, 0.125, 0.0625, and 0.03125 meters.

**Table 3.1.** Computation time for various initial spacing

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<thead>
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<th>Initial Spacing (m)</th>
<th>Computation Time (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>8</td>
</tr>
<tr>
<td>0.125</td>
<td>40</td>
</tr>
<tr>
<td>0.0625</td>
<td>168</td>
</tr>
<tr>
<td>0.03125</td>
<td>683</td>
</tr>
<tr>
<td>0.015625</td>
<td>1577</td>
</tr>
</tbody>
</table>

### 3.3 Radiosity

Radiosity is used in this study to add the effects of diffuse reflections. It has been called a variety of things such as radiation balance, radiation exchange or radiant interchange[24]. When radiosity is applied to acoustics it is also a geometric acoustics approximation, which means that the method is only valid for high frequencies. There are four distinct steps in radiosity. The first is to create the environment geometry. The next is to determine the source and environment interaction. Then the diffuse reflections are calculated and finally the sound level is determined at
the receiver. This section will describe each of these steps and how they were implemented in this study.

### 3.3.1 Creating the Environment

In order to create the environment geometry all structures and areas of ground of interest must be split into patches. In order to do this all of the planes in the environment need to be identified. Figure 3.16 shows the planes for a simple building geometry. In Kang’s previous work with radiosity in urban environments each dimension was uniform because he was dealing with urban canyons [24]. The same basic principles apply here but the environment must be broken into smaller planes and then meshed into patches. This increases the number of patches, but it is a logical conclusion because there are also many more edges in these environments.

In order to mesh each of the planes into patches a geometric series is employed. The geometric series is used to create the length of the patch in that dimension. The series allows the patches to go from smaller at the edge, to larger in the middle.
Validation of Ray Trace Boom Spacing

Figure 3.12. Initial spacing was varied. This figure shows the sound field from initial spacings of 0.25, 0.125, 0.0625, 0.03125, and 0.015625 meters.

and then smaller again as they approach the far edge. To create an array of the lengths of the patches, $dd_m$, in a particular direction, the following series is used

$$dd_m = k_m q_y^{m-1} \left( 1 \leq m \leq \frac{N_Y}{2} \right)$$

(3.44)

$$dd_m = k_m q_y^{N_Y-m} \left( \frac{N_Y}{2} < m \leq N_Y \right).$$

(3.45)

where $q_y$ is the ratio between two adjacent patches, $N_Y$ is number of patches which must be an even number and $k_m$ is given by the expression

$$k_m = \frac{W}{2} \frac{1 - q_y}{1 - q_y^{N_Y/2}}$$

(3.46)

As the patches get closer to the edges they get smaller. This increases the accuracy while reducing the computation time.
Figure 3.13. This figure shows a close up of the direct pulse when the initial spacing was varied.

3.3.1.1 Form Factors

The form factor is a value that determines the percentage of energy that leaves one patch and travels to another. An illustration of the form factor geometry is shown in Figure 3.17. This is calculated using the equation[69]

\[ F_{1 \rightarrow 2} = \frac{\cos(\theta_1) \cos(\theta_2)}{\pi S_{12}^2} \Delta A_2 \]  \hspace{1cm} (3.47)

3.3.2 Initial Patch Energy

In the traditional radiosity method a point source is distributed to all of the patches. This is done by using the solid angle to determine the fraction of energy reaching each patch. Because this is a combined ray tracing method, the initial patch energy is determined by the number of rays that hit the patch. The initial ray tracing is performed, and anytime the ray hits a surface a percentage of the energy is stored in that patch and the ray continues on. This percentage of
Validation of Ray Trace Sampling Frequency

![Graph showing sound field with varying sampling frequencies](image)

**Figure 3.14.** Sampling frequency was varied. This figure shows the sound field from receivers with a sampling frequency of 2,000, 4,000, 5,000, 10,000, 15,000, 20,000 Hz.

energy is determined by the diffusion coefficient, $d$.

### 3.3.3 Patch Energy Exchange

Once the amount of energy initially stored in the patches is determined, the energy must be exchanged between patches. This step calculates higher order diffuse reflections. The number of reflections included is given by the parameter $k$. This becomes very important when there are multiple structures involved and the diffuse reflections will have a greater impact. The $k$th order patches are only dependent on the form factor and the $(k - 1)$ order patches. The patch energy exchange for a particular patch is calculated by summing all the energy from the other patches of the previous order. This calculation is given by the equation:

$$G_k(t)_{l,m} = \sum_{l' = 1}^{N_x} \sum_{n' = 1}^{N_z} AG(l',n',l,m)A_{k-1}\left( t - \frac{d(l',n',l,m)}{c} \right)_{l',n'}$$
Validation of Ray Trace Sampling Frequency Zoom In

Figure 3.15. This figure shows a close up of the direct pulse when the sampling frequency was varied.

Figure 3.16. The planes of a single building environment. Notice the ground plane must be subdivided

\[
+ \sum_{l'=1}^{N_z} \sum_{n'=1}^{N_z} BG_{(l',n'),(l,m)} B_{k-1} \left( t - \frac{d_{(l',n'),(l,m)}}{c} \right)_{l',n'} \quad \text{with} \quad \left( t - \frac{d_{(l',n'),(l,m)}}{c} \right)_{l',n'} \geq 0
\]

(3.48)

This calculation is done for every patch and for each order of \( k > 1 \) [24].
3.3.4 Receiver-Patch Exchange

The energy at the receiver is a sum of the energy of all the patches at the receiver. This is given by

\[ E_k(t)_G = \sum_{l=1}^{N_x} \sum_{m=1}^{N_y} \left[ \frac{G_k \left( t - \frac{R_{l,m}}{c} \right)_{(l,m)}}{\pi \ast R_{(l,m)}^2} \cos(\xi_{l,m}) \right] e^{-MR_{l,m}} \text{where} \left( t - \frac{R_{l,m}}{c} \geq 0 \right) \]

(3.49)

where \( \xi_{l,m} \) is the angle between the normal of the patch and the line between the patch and receiver, and \( R_{l,m} \) is the mean length between the patch and the receiver. This can be approximated by the length between the center of the patch and the receiver but for the purpose of this work a more accurate approximation is used. This approximation is given by subdividing the patch and then calculating the average distance between the subdivisions and the receiver. This calculation is given by
\[ R_{l,m} = \frac{1}{N_l N_m N_n} \sum_{i=1}^{N_l} \sum_{j=1}^{N_m} \sum_{k=1}^{N_n} \left[ d_l - \frac{1}{2} dd_l + \frac{dd_l}{N_l} (i - \frac{1}{2}) - R_x \right]^2 + \left[ d_m - \frac{1}{2} dd_m + \frac{dd_m}{N_m} (j - \frac{1}{2}) - R_y \right]^2 + \left[ d_n - \frac{1}{2} dd_n + \frac{dd_n}{N_n} (k - \frac{1}{2}) - R_z \right]^2 \right]^{1/2} \] (3.50)

3.3.5 Validation

To validate this combined ray tracing radiosity method, a comparison was done with a stochastic ray tracing method. A variety of parameters were examined and compared. For this simulation, the same environment was used as in the ray tracing validation. A diffusion coefficient of 0.2 was used for all the simulations. It was not expected that any of the simulations will match the stochastic ray tracing exactly because the radiosity method is a deterministic method, and stochastic ray tracing is a statistical method. However the amplitude of the signal should be on the same order.

3.3.5.1 Stochastic Ray Tracing

Stochastic ray tracing was used to validate the combined ray tracing and radiosity method. This method is very similar to the ray tracing method described in section 3.2. The difference occurs when a ray intersects with a surface. Every time a ray hits a surface a random number is generated. When this number is above the diffusion coefficient, the ray is reflected specularly as described in equation 3.41. If the random number is below the diffusion coefficient then the ray is reflected diffusely. This is done by creating two random numbers, \( z_1 \) and \( z_2 \). These become the new azimuthal and elevation angles. These new angles are given by

\[ \theta = \arccos \sqrt{z_1} \] (3.51)
\[ \phi = 2\pi z_2 \] (3.52)

This yields a scattering according to Lambert’s law which is a cosine distribution.
Lambert’s law is given by

\[
    w(\theta)d\Omega = \frac{1}{\pi} \cos \theta d\Omega
\]  

(3.53)

Because the stochastic ray tracing is a statistical method, to increase the accuracy
the number of rays must be significantly increased.

### 3.3.5.2 Comparison

In order to be vigorous in the validation a variety of parameters were examined to
determine their effect on the resulting sound field simulation. The parameters that
were examined were patch number, ratios of patch number, \( q \), and the number of
diffuse reflections, \( k \). The first parameter that we examined was the patch number.
The planes shown in Figure 3.16 were used. Each of these planes was divided into
a certain number of patches, namely \( N_x \times N_y \) patches in the \( xy \)-plane. When
varying the patch numbers the \( N_x, N_y, \) and \( N_z \) where all varied uniformly. This
would mean that the patch number is changed the same amount in each direction.
If a plane originally had \( N_x = 10 \) and \( N_y = 10 \) it yields a plane with 100 patches.
However, if the patch number is doubled than the plane would have \( N_x = 20 \) and
\( N_y = 20 \) it yields a plane with 4 times the number of patches with 400 patches.
The patch numbers examined were 2, 4, 8, 10, 16, and 32. For these simulations
\( k = 1 \) and \( q = 2 \). Figure 3.18 shows that varying patch numbers compared to
the stochastic ray tracing code. The direct and reflective pulses show very good
agreement with the stochastic ray tracing method. There is very little difference
between the amplitude of the pulses, and the arrival times are all very similar. The
pulses appear to lose the same amount of energy to the diffuse reflections. The
differences are only evident in the diffuse reflections. When the number of patches
are 2 or 4, the amplitude of the diffuse energy is slightly smaller. However once
the number of patches were 8 or above, the amplitude levels out. The differences
are very subtle, and all of the runs showed good agreement with the stochastic
ray tracing. The computation time is drastically affected by the increase in the
number of patches. Table 3.2 shows the computation time compared to the patch
number. It is obvious that as the patch number increases the computation time
increases substantially so the number should be kept as low as possible while still
Table 3.2. Computation time for various patch numbers

<table>
<thead>
<tr>
<th>Patch Number</th>
<th>Computation Time (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>999</td>
</tr>
<tr>
<td>4</td>
<td>1221</td>
</tr>
<tr>
<td>8</td>
<td>2248</td>
</tr>
<tr>
<td>10</td>
<td>3045</td>
</tr>
<tr>
<td>16</td>
<td>7722</td>
</tr>
<tr>
<td>32</td>
<td>78794</td>
</tr>
</tbody>
</table>

The number of patches has varied from 2,4,8,10,16 and 32.

The next parameter that was examined was the ratio of the patches or the $q$ parameter. This describes the length ratio of two adjacent patches. Again this parameter was changed uniformly in each of the $x$, $y$, and $z$ directions. The $q$ values considered were 1.25, 1.5, 2.0, 2.5, 3.0, and 5.0. For these simulations the number of patches was 10 and $k = 1$. It is shown in Figure 3.20 that as each reflection is observed a percentage of the energy is lost into the diffuse reflections. This is seen by the decreasing amplitude in the large pulses, and the presence of small perturbations occurring after the first reflection. The amplitudes of the
large pulses seem to be in good agreement for all values of $q$ and seem to be reducing in the same fashion as the stochastic simulation. The diffuse energy has a different result. This can be better seen in the enlarged figure of the diffuse energy shown in Figure 3.21. When $q$ is as low as 1.25 and 1.5, the amplitude of the diffuse reflections is almost a factor of 10 greater than for the stochastic simulation. While it is not expected that the simulations will be identical, it is expected that they will agree to within an order of magnitude. As $q$ gets larger, 2.0, the simulations are starting to agree much better. The amplitude is reducing in the radiosity method and shows relatively good agreement. When $q$ is 2.5 or greater, the perturbations seem to be on the same order of magnitude and do not appear to change in magnitude significantly as $q$ increases.

The third parameter that was varied was $k$. This is the parameter that indicates how many diffuse reflections are considered. Figure 3.22 shows that there is very little variation between the various values for $k$. Only when the figure is enlarged and there is a focus on later reflections as seen in figure 3.23 are slight differences evident. There is very little difference between values of $k$ for a single building.
Figure 3.20. The parameter $q$ has the values 1.25, 1.5, 2.0, 2.5, 3.0, and 5.0.

Figure 3.21. A close up view of the results from a varied $q$ parameter.

configuration. It is expected that geometries with multiple buildings will have greater contributions from second or third order reflections.

3.4 Summary

The ray tracing technique shows good agreement with image theory. The validation showed that the radius of the receiver needs to be 0.125 meters or smaller. A normalization of 12.56 is also required. Radiosity showed good agreement with
Figure 3.22. The parameter $k$ has the values 1, 2, 3 and 5 stochastic ray tracing when $q$ is 2.5 or greater. This shows that the combined ray tracing/radiosity method that was created in this study propagates sound well around a building. The next step is to compare a sonic boom simulated with this method with measured data for further validation. This was done for both a single building and a multiple building environment and is discussed in chapters 4 and 5.
Figure 3.23. A close up view of the results from a varied \( k \) parameter.
In order to determine how well the model compares to measured data, a single building geometry was examined. Several features of this building were looked at in detail to determine the importance of these features on the comparison. The three features that are examined for a simple building geometry are the building façade features, the absorption coefficient of the building surfaces, and the diffusion coefficient of the building surfaces. This chapter will discuss the layout of the building geometry, the input boom signal, and compare the resulting simulations with the measured data.

4.1 Description of Environment

The environment for this simulation is modeled from the Environmental Management (EM) building that was used in the 2009 Sonic Booms on Big Structures (SonicBOBS) experiment. This was used because it was a large box-like building relatively far away from other structures. An aerial view of the building is shown in Figure 4.1. It can be seen in this figure that the building is not perfectly square in floor plan. The entrance and loading dock are protruding and recessed respectively. It is important to know how much including these features affects the overall sound field. There are four important aspects in this model: the input signal, the building complexity, the coefficients, and the receivers.
4.1.1 Input Signal

In the 2009 SonicBOBS experiment, two aircraft flew multiple times over the environment for a total of 24 booms of varying over-pressure. For this study all 24 booms were examined for the EM building to determine which yielded the cleanest signal at various receivers. A few booms were identified as good results and these were then narrowed down to a single boom to use for this study. Although a variety of these booms could be used considering time and effort in the simulation and analysis, it was reasonable to use a single input boom. Table 4.1 shows the recorded booms with the over-pressure measured by the BADS apparatus at the EM Building. There was a significant amount of wind during the experiment which had an effect on the quality of the resulting measurements. Therefore each boom
Table 4.1. Sonic Booms from the 2009 SonicBOBS experiment at Edwards Air Force Base Environmental Management Building.

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Flight #</th>
<th>Pass #</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>852</td>
<td>1207</td>
<td>1</td>
<td>Very Good</td>
</tr>
<tr>
<td>852</td>
<td>1207</td>
<td>2</td>
<td>No Good</td>
</tr>
<tr>
<td>852</td>
<td>1207</td>
<td>3</td>
<td>Very Good</td>
</tr>
<tr>
<td>843</td>
<td>1207</td>
<td>2</td>
<td>OK</td>
</tr>
<tr>
<td>852</td>
<td>1207</td>
<td>4</td>
<td>Good</td>
</tr>
<tr>
<td>843</td>
<td>1207</td>
<td>3</td>
<td>Good</td>
</tr>
<tr>
<td>852</td>
<td>1207</td>
<td>5</td>
<td>No Good</td>
</tr>
<tr>
<td>843</td>
<td>1207</td>
<td>4</td>
<td>No Good</td>
</tr>
<tr>
<td>852</td>
<td>1207</td>
<td>6</td>
<td>Good</td>
</tr>
<tr>
<td>843</td>
<td>1207</td>
<td>5</td>
<td>Good</td>
</tr>
<tr>
<td>843</td>
<td>1207</td>
<td>6</td>
<td>Good</td>
</tr>
<tr>
<td>843</td>
<td>1207</td>
<td>7</td>
<td>Good</td>
</tr>
<tr>
<td>843</td>
<td>1208</td>
<td>1</td>
<td>Very Good</td>
</tr>
<tr>
<td>852</td>
<td>1208</td>
<td>1</td>
<td>No Good</td>
</tr>
<tr>
<td>843</td>
<td>1208</td>
<td>2</td>
<td>Good</td>
</tr>
<tr>
<td>852</td>
<td>1208</td>
<td>2</td>
<td>OK</td>
</tr>
<tr>
<td>843</td>
<td>1208</td>
<td>3</td>
<td>Very Good</td>
</tr>
<tr>
<td>852</td>
<td>1208</td>
<td>3</td>
<td>Good</td>
</tr>
<tr>
<td>843</td>
<td>1208</td>
<td>4</td>
<td>Good</td>
</tr>
<tr>
<td>852</td>
<td>1208</td>
<td>4</td>
<td>Very Good</td>
</tr>
<tr>
<td>843</td>
<td>1208</td>
<td>5</td>
<td>Good</td>
</tr>
<tr>
<td>852</td>
<td>1208</td>
<td>5</td>
<td>No Good</td>
</tr>
<tr>
<td>843</td>
<td>1208</td>
<td>6</td>
<td>No Good</td>
</tr>
<tr>
<td>843</td>
<td>1208</td>
<td>7</td>
<td>OK</td>
</tr>
</tbody>
</table>

was examined and rated on the clarity of the signal above the background noise. The ratings were No Good, OK, Good and Very Good. These ratings were based on a visual inspection of the far field microphone. The rating was deemed Very Good if the far field signal could be clearly identified above the background noise and was not distorted significantly by atmospheric or other effects.

From this data the first boom was used as an input to the simulation. The input signal that was taken from the far field microphone. The far field microphone is shown in Figure 4.1 at the bottom of the figure and is identified as EM37 by NASA. Figure 4.2 shows the input signal to be used in the simulation. This was created by looking at the measurement and isolating the boom, taking about 0.025 seconds
before the front shock and including the measurement until amplitude returns to zero after the rear shock. This microphone was positioned about 55 meters away from the building.

![Graph](image.png)

**Figure 4.2.** Signal from EM37 to be used as the input to simulation

The next characteristic of the input signal is the initial location of the input plane and the initial angles. The initial angles were calculated by PC Boom or determined by the BADS Data. For this experiment the results from these methods were inconclusive so further verification was done with the information from the microphones. Two microphones in the same ground plane were examined as well as two microphones in the same xy plane. The vertical time delay was then examined to determine the angles. First the microphones at different elevations were analyzed. Several pairs of microphones were examined for redundancy. The microphones that were examined were EM19 and EM29, EM20 and EM30, and EM21 and EM31. The time delay differences are given in Table 4.2. This gives an average elevation angle of 6.62° which is slightly different than the PC Boom elevation angle calculated at the EM building of 8.4° or the measured BADS angle of 14.7°. Therefore, the elevation angle of 6.62° was used in the simulation.

Next the azimuthal angle needs to be determined. This is done with three pairs of microphones at the same elevation, EM17 and EM18, EM19 and EM21, and
EM 20 and EM21. The same procedure was followed for these microphones, and the time delay and angles are shown in Table 4.3. This gives an average of 197° which is inconsistent with the 264° calculated by the PCBoom program. Therefore the azimuthal angle of 197° was used for the simulation.

The initial location of the plane is generally arbitrary. The only requirement is that it is large enough that it encompasses the environment of interest. This includes being far enough away that the ground reflection will reach the top of the building. The position was determined using the angles of the incoming plane. The plane needed to be at least 80 meters away from the incident edge of the building. It needed to be 70 meters wide and 25 meters high. This will encompass the entire building. Another essential parameter to be considered for the input boom is the spacing of the rays. This was set at 0.035 meters because of the findings of the validation runs shown in section 3.2.2. The sampling frequency is dependent on the capability of the microphone for this simulation which is given for all the microphones in the single building geometry as 24000 Hz.

4.1.2 Environment Parameters

Several overall environmental parameters must be set in order to define some general environmental parameters. These include sound speed which is essential in calculating the propagation. This is based on other parameters such as temperature that was taken by the weather station present at the site. The temperature at the site during the first boom was recorded at 302 K or approximately 84° fahren-

<table>
<thead>
<tr>
<th>Microphone pair</th>
<th>Time Delay</th>
<th>Estimated Elevation Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM19 and EM29</td>
<td>0.0023</td>
<td>5.5</td>
</tr>
<tr>
<td>EM20 and EM30</td>
<td>0.0015</td>
<td>3.6</td>
</tr>
<tr>
<td>EM21 and EM31</td>
<td>0.0045</td>
<td>10.8</td>
</tr>
</tbody>
</table>

**Table 4.3. Time delay for horizontal microphone pairs.**

<table>
<thead>
<tr>
<th>Microphone pair</th>
<th>Time Delay</th>
<th>Estimated Elevation Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM17 and EM18</td>
<td>0.051</td>
<td>201</td>
</tr>
<tr>
<td>EM19 and EM21</td>
<td>-0.0158</td>
<td>197</td>
</tr>
<tr>
<td>EM20 and EM21</td>
<td>-0.008</td>
<td>194</td>
</tr>
</tbody>
</table>
Table 4.4. Octave band values for the absorption coefficient of the ground plane.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>63 Hz</th>
<th>125 Hz</th>
<th>250 Hz</th>
<th>500 Hz</th>
<th>1 kHz</th>
<th>2 kHz</th>
<th>4 kHz</th>
<th>8 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.03</td>
<td>0.03</td>
</tr>
</tbody>
</table>

heit. This yields a speed of sound of 349 meters per second. A relative humidity of 20% and an ambient pressure of 1.0 atm is assumed. The ground plane is assumed to be flat, acoustically hard with a height of 0 meters for all simulations. Acoustically hard in this situation is equivalent to painted concrete. The octave spectrum for absorption coefficients for the ground is shown in Table 4.4. The ground is also considered to be non-diffuse.

### 4.1.3 Building Characteristics

For this study several different characteristics of the building were considered. The first is the geometry of the building, the second is the absorption coefficient of the building and the third is the diffusion coefficient. Each of these parameters will be discussed in this section as well as the motivation behind the values chosen. A sample geometry file is shown in the Appendix B.3.

#### 4.1.3.1 Building Geometry

The building geometry has two different configurations. The first is a simple representation of the building as a single box with no façade irregularities. The second is a much more complex version of the building with the façade irregularities present in the physical building.

##### 4.1.3.1.1 Simple Single Building Geometry

The simple building geometry is a single large box with the dimensions of the largest dimensions of the EM Building. This does not include the entranceway or the loading dock irregularities. The simple geometry is shown in Figure 4.3 with the dimensions.

##### 4.1.3.1.2 Complex Single Building Geometry

The complex building geometry is as close to the original EM building geometry as possible. The entryway and loading dock were included as well as two small ledges that go around the
building. The complex geometry is shown in Figure 4.4. The dimensions are shown in Figure 4.5 with a plan view and an elevation view to show the detail.  

4.1.4 Absorption Coefficients

Absorption coefficients were varied in order to determine how much they effect the resulting sound field. This will determine how accurate the absorption coefficient needs to be in order to accurately recreate the environment to be modeled. Four different absorption coefficient coefficients were used. The first is that the entire building is acoustically hard. The absorption coefficient for unpainted poured concrete was used. The second was a average of absorption coefficients. In this case, two surfaces were considered. There was a significant amount of glass for windows and concrete for the building. The surface area of each of these components was calculated and an average absorption coefficient was created. A surface area of 948.21 m$^2$ for glass was used and a surface area of 2568.15 m$^2$ for concrete was used. In the third situation, the areas that were windows in the original buildings had the absorption coefficient of glass and the other areas have a coefficient of concrete. The last coefficient was an all soft case. The coefficient of fiberglass
batting was used. This last case was mostly a contrast case to compare with the all hard coefficient case. Table 4.5 shows the relevant absorption coefficients.
Table 4.5. Octave band values for the absorption coefficient of the building [71, 74].

<table>
<thead>
<tr>
<th>Material</th>
<th>63 Hz</th>
<th>125 Hz</th>
<th>250 Hz</th>
<th>500 Hz</th>
<th>1 kHz</th>
<th>2 kHz</th>
<th>4 kHz</th>
<th>8 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Glass</td>
<td>0.55</td>
<td>0.55</td>
<td>0.25</td>
<td>0.18</td>
<td>0.12</td>
<td>0.07</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Average</td>
<td>0.156</td>
<td>0.156</td>
<td>0.075</td>
<td>0.063</td>
<td>0.047</td>
<td>0.033</td>
<td>0.033</td>
<td>0.033</td>
</tr>
<tr>
<td>Absorptive</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td>0.97</td>
<td>0.97</td>
</tr>
</tbody>
</table>

4.1.5 Diffusion Coefficients

Five different diffusion coefficients were chosen to observe the changes of the overall sound field from the amount of diffuse energy. The diffusion coefficient was assumed to be constant along all frequencies. This was assumed because looking at some diffusion coefficient measurements, the diffusion coefficient seems to level off as the frequencies go higher [75, 71]. Since this is a high frequency model it was assumed that the diffusion coefficient could be assumed constant. In addition, there is a lot of variation in diffusion coefficient measurements and most of the measurements that are taken are for constructed diffusers to add on to existing materials. Since this study is interested in the material itself no data was available. The five coefficients that were considered were 0%, 10%, 20%, 50%, and 100%. The code can be easily modified to include a diffusion coefficient that varies with frequency.

4.1.6 Microphone Locations

In order to determine the effect of the sound field and to compare to the measured data several microphones were chosen for comparison. The microphones needed to be placed in the simulation at equivalent locations for a relevant comparison to measured data. The microphones identified in Figure 4.1 as EM17, EM18, EM19 and EM29 were chosen as the comparison microphones. These microphones were chosen because they represent the microphones that will determine the pressure field directly in front of the building at the ground and the roof (EM19 and EM29), and microphones a distance away but still significantly affected by the presence of the building (EM17 and EM18). Figure 4.6 shows the microphone positions with the simple geometry. There were no microphone locations behind the building that were not in the shadow zone which is the reason for microphones only at the front of the building.
Figure 4.6. Microphone Locations around the simple building geometry. Compare with Figure 4.1

4.2 Comparison to Data

In order to compare the data to the simulated sound fields several parameters need to be identified that are crucial to creating an accurate sonic boom. As discussed in section 2.2.1 the characteristics that were identified as crucial to human response are duration of boom, over-pressure and rise time. In this environment, only the high frequency energy is examined. Since both low and high frequencies must be included to model rise time, only overpressure and duration will be compared. Each observed boom will be treated separately. This means that if there is a distinct incident boom and a distinct reflected boom each of these events will be compared. In order to obtain these values an algorithm was developed which will be described in section 4.2.2

4.2.1 High Pass Filter

The first thing to consider in this situation is that the combined ray tracing/radiosity method is a high frequency approximation. In order to account for future work
the high pass filter developed by Cho was utilized [76]. This filter is part of a high and low pass filter pair that will be used in conjunction with a finite difference time domain method to create a hybrid method. The hybrid method will be valid for both the high frequency and low frequency energy. A basic description of these filters is given here but for a more complete description, please refer to Cho’s paper [76]. The following section will discuss the frequencies where the method is valid. This will form the basis for determining the crossover frequencies.

4.2.1.1 Frequency Range

The ray tracing and radiosity theory are both a geometric acoustic approximation. This means that the method is valid for high frequencies. In order to determine at what frequency the results should be filtered, the simulated data was compared to the measured data at a variety of microphones for a variety of input booms. The frequency range will be related to the dimensions of the environment so it is expected that the complex environment would have a different frequency range than the simple environment. While none of simulated runs match the measured data exactly, a general idea of the magnitudes can be compared and with several samples a good idea of the valid frequency range can be determined.

The first frequency spectrum comparison is the first boom event which is analyzed in the rest of this chapter. Microphones EM17, EM18, and EM19 were all compared with the measured data for both the simple and complex environments. These comparisons are shown in Figures 4.7, 4.8, and 4.9 respectively.

For the first boom event that was measured at EM17, the complex and simple environments’ frequency spectra are almost identical. The simulated and measured data seems to come into agreement at approximately 40 Hz. For the comparison with EM18 there is significant difference between the complex environment and the simple environment. The simple environment seems to coincide with the measured data at about 40 Hz and above. The complex environment seems to match up with the measured data at around 150 Hz. For the EM19 microphone the simple simulation shows good agreement at approximately 40 Hz and above. The complex simulation shows good agreement at about 150 Hz and above.

The second comparison is the third boom event. Microphones EM17, EM18, and EM19 were all compared with the measured data for both the simple and
**Figure 4.7.** Comparison for Boom 1 in the frequency domain between simple simulated, complex simulated and measured data for microphone EM17.

**Figure 4.8.** Comparison for Boom 1 in the frequency domain between simple simulated, complex simulated and measured data for microphone EM18.
complex environments. These comparisons are shown in Figures 4.10, 4.11 and 4.12, respectively.

For the third boom event that was measured at EM17, the complex and simple environments show a significant difference in their frequency spectra. The simulated simple environment and the measured data seem to come into agreement at approximately 50 Hz. The complex environment shows good agreement for 70 Hz and above. For the comparison with EM18 there is significant difference between the complex environment and the simple environment. The simple environment seems to coincide with the measured data at about 60 Hz and above. The complex environment seems to match up with the measured data at around 90 Hz. For the EM19 microphone the simple simulation shows good agreement at approximately 50 Hz and above. The complex simulation shows good agreement at about 400 Hz and above.

The last comparison is the thirteenth boom event. Microphones EM17, EM18, and EM19 were all compared with the measured data for both the simple and complex environments. These comparisons are shown in Figures 4.13, 4.14 and 4.15, respectively.
**Figure 4.10.** Comparison for Boom 3 in the frequency domain between simple simulated, complex simulated and measured data for microphone EM17.

**Figure 4.11.** Comparison for Boom 3 in the frequency domain between simple simulated, complex simulated and measured data for microphone EM18.
Figure 4.12. Comparison for Boom 3 in the frequency domain between simple simulated, complex simulated and measured data for microphone EM19.

Figure 4.13. Comparison for Boom 13 in the frequency domain between simple simulated, complex simulated and measured data for microphone EM17.
**Figure 4.14.** Comparison for Boom 13 in the frequency domain between simple simulated, complex simulated and measured data for microphone EM18.

**Figure 4.15.** Comparison for Boom 13 in the frequency domain between simple simulated, complex simulated and measured data for microphone EM19.
For the thirteenth boom event measured at EM17 the complex and simple environments have almost identical frequency spectra. The simulated and the measured data seems to coincide at 50 Hz. For the comparison with EM18 there is significant difference between the complex environment and the simple environment. The simple environment seems to coincide with the measured data at about 40 Hz and above. The complex environment seems to match up with the measured data at around 100 Hz. For the EM19 microphone the simple simulation shows good agreement at approximately 200 Hz and above. The complex simulation shows good agreement at about 200 Hz and above.

Averaging all these observations it can be concluded that the simple geometry shows good agreement at 63 Hz and above. Considering the above observations the complex environment seems to be in good agreement at 139 Hz and above. For the sake of comparison, a single filter frequency will be used by both the simple and the complex environments. The lowest frequency that should be considered is 150 Hz and this is used as the crossover frequency for the filter.

The filter is created with the MATLAB \texttt{firpm} function. This function creates a linear-phase Finite Impulse Response (FIR) filter using the Parks-McClellan algorithm with an order, $N_{\text{filt}}$, and amplitude, $a$. For the filter in this study $N_{\text{filt}} = 2000$ and $a = 1$ for frequencies above the crossover frequency and $a = 0$ for the frequencies below the crossover frequency. The biggest fault in this filter is something referred to as an \textit{equiripple} effect. This creates ripples in the filter and consequently in the filtered signal. The filter used in these simulations and it’s pair is shown in Figure 4.16.
Figure 4.16. Filter pair designed for these simulations.


4.2.2 Algorithm for Comparison

Each simulation will be compared to the measured data from the SonicBOBS 2009 experiment. Three parameters were considered: arrival time, over pressure, and duration. In addition the overall shape of the boom was examined to determine how well the simulations predict the shape of the measured boom. The shape of the signature is an subjective description but the other three parameters are determined quantitatively. The algorithm for determining these parameters is described in this section.

Each boom event is considered separately. If a direct and reflected boom event occur at two distinct times at a single receiver then they will be considered individually. The first step is to determine the time delay. There is an arbitrary time delay between the measured and the simulated data. The important arrival times are the relative times between the first boom event and subsequent boom events. Therefore the arrival time of the first boom event for each microphone is adjusted to align with the first measured boom event at that microphone location. This is done by cross correlating the input signal with both the measured data and the simulated data. The difference between the time delay between measurement locations indicates the error in the arrival time between microphones.

Next the peak values of the first boom event are found. These values are different than for the traditional sonic boom overpressure because of the high pass frequency filter. There are four important numbers to examine for each boom event. These would be the positive and negative front shock peaks and the positive and negative back shock peaks. The positive peak is the local maxima. The negative peak is the largest negative number before the positive peak. Usually this negative number is a local minima. However, when several reflections overlap this is not necessarily the case. This method was adopted for the sake of consistency.

Then the duration is calculated. This is done by determining the time difference between the arrival of the front and back positive peak values. If this is the only event in the signal than the focus can proceed to the diffuse reflections, however, if there are additional boom events than more analysis is needed. The first boom event must be subtracted from the signal. This is done so that in the event that the reflections overlap, the events can be separated as much as possible. Both the measured and simulated signals have twice the input signal subtracted from the
first event. Then this procedure is repeated for as many events as are present in the signal.

The diffuse reflections need to be considered. This is done by examining the energy in the signal. First the pressure is squared. Then the energy is averaged every 0.05 seconds. This is done in order to be able to compare a manageable amount of numbers while still utilizing all the data.

For each microphone 20 different simulations were run. Each of these runs are examined in this section. Each microphone will be examined individually, and a best fit simulation is determined. NOTE: the following subsections give very detailed observations about individual boom events. The casual reader may wish to immediately skip to Section 4.2.7 for a discussion of these results.

### 4.2.3 Microphone EM17

#### 4.2.3.1 Overall Shape

The overall shape of each simulation compared to the measured data needs to be examined. Simulations for each combination of parameters were performed for each microphone location. For ease of comparison the simulations have been grouped according to the amount of diffusion. Figure [4.17](#) shows the shape of the 0% diffuse reflections compared to the measured data. The overall shape looks very similar although there are some obvious differences. The boom events seem to arrive at the same time and the amplitude is at the same order of magnitude.

Figures [4.18](#), [4.19](#) and [4.20](#) show the close up on the individual shocks in the signal. The first event in Figure [4.18](#) shows very good agreement. There are very small differences between the different absorption coefficients for this shock. There is also no difference between the complex and simple geometries.

Figure [4.19](#) shows the second shock agreement. This is an overlapping of the tail shock of one boom event and the front shock of the reflected boom event. While the overall amplitude tracks rather well there is some definite differences in the overall shape. The all soft case is missing any reflected wave which does not track very well with the shape. Some of the discrepancies in this case can be accounted for by a time shift where that the reflected wave would arrive earlier. The complex and simple geometries show no differences in shape for this event.
Figure 4.17. Comparison between 0% diffusion simulations for EM17.

Figure 4.18. Comparison between 0% diffusion simulations for EM17 first shock event.
Figure 4.19. Comparison between 0% diffusion simulations for EM17 second shock event.

Figure 4.20 shows the third shock. With a slight time shift the measured and simulated data would match better in shape. The complex and simple geometries show no differences in shape for this event.

Figure 4.21 shows the shape of the 10% diffuse simulations compared to the measured data. The overall shape looks very similar although there are some obvious differences. The boom events seem to arrive at the same time and the amplitude is at the same order of magnitude.

Figures 4.22, 4.23, and 4.24 show the close up on the individual shocks in the signal. The first event in Figure 4.22 shows very good agreement. There are only very small differences between the different absorption coefficients for this shock. The simple and complex geometries show no differences in shape for this event.

Figure 4.23 shows the second shock agreement. This is an overlapping of the tail shock of one boom event and the front shock of the reflected boom event. While the overall amplitude tracks rather well, there is some definite differences in the overall shape. The all soft case is missing any reflected wave which does not track very well with the shape. Some of the discrepancies in this case can be corrected
Figure 4.20. Comparison between 0% diffusion simulations for EM17 third shock event.

Figure 4.21. Comparison between 10% diffusion simulations for EM17.
Figure 4.22. Comparison between 10% diffusion simulations for EM17 first shock event. by a time shift where the measured boom reflected wave arrives later than the simulated reflection. The complex and simple geometries show no differences in shape for this event.

Figure 4.24 shows the third shock. Again with a slight time shift in the reflected wave the measured and simulated data would match better in shape.

Figure 4.25 shows the shape of the 20% diffuse simulations compared to the measured data. The overall shape looks very similar although there are some obvious differences. The boom events appear to arrive at the same time and the amplitude is at the same order of magnitude.

Figures 4.26, 4.27, and 4.28 show the close up on the individual shocks in the signal. The first event in Figure 4.26 shows very good agreement. There are only very small differences between the different absorption coefficients for this shock. The complex and simple geometries show no differences in shape for this event.

Figure 4.27 shows the second shock agreement. This is an overlapping of the tail shock of one boom event and the front shock of the reflected boom event. While the overall amplitude tracks rather well there are some definite differences
Figure 4.23. Comparison between 10% diffusion simulations for EM17 second shock event.

in the overall shape. The all soft case is missing any reflected wave which does not track very well with the measured shape. Some of the discrepancies in this case can be corrected by a time shift so that the reflected wave would arrive earlier. The complex and simple geometries show no differences in shape for this event.

Figure 4.28 shows the third shock. Again with a slight time shift in the reflected wave the measured and simulated data would match better in shape. The complex and simple geometries show no differences in shape for this event.

Figure 4.29 shows the shape of the signal compared to the measured data. The overall shape looks very similar though there are some obvious differences. The boom events seem to arrive at the same time and the amplitude is at the same order of magnitude.

Figures 4.30, 4.31, and 4.32 show the close up on the individual shocks in the signal. The first event in Figure 4.30 shows very good agreement. There are only very small differences between the different absorption coefficients for this shock. The complex and simple geometries show no differences in shape for this event.

Figure 4.31 shows the second shock agreement. This is an overlapping of the
Figure 4.24. Comparison between 10% diffusion simulations for EM17 third shock event.

Figure 4.25. Comparison between 20% diffusion simulations for EM17.
**Figure 4.26.** Comparison between 20% diffusion simulations for EM17 first shock event.

**Figure 4.27.** Comparison between 20% diffusion simulations for EM17 second shock event.
**Figure 4.28.** Comparison between 20% diffusion simulations for EM17 third shock event.

**Figure 4.29.** Comparison between 50% diffusion simulations for EM17.
Figure 4.30. Comparison between 50% diffusion simulations for EM17 first shock event.

While the overall amplitude tracks rather well there is some definite differences in the overall shape. The all soft case is missing any reflected wave which does not track very well with the measured shape. Some of the discrepancies in this case can be corrected by a time shift so that the reflected wave would arrive earlier. The complex and simple geometries show no differences in shape for this event.

Figure 4.32 shows the third shock. With a slight time shift the measured and simulated data would match better in shape. The complex and simple geometries show no differences in shape for this event.

Figure 4.33 shows the shape of the signal 100% compared to the measured data. There is no reflected pulse which significantly alters the overall shape of the signature and no longer has good agreement.

Figures 4.34, 4.35, and 4.36 show the close up on the individual shocks in the signal. The first event in Figure 4.34 shows very good agreement. This is due to the fact that the first shock is only the incident and ground reflected energy. There are only very small differences between the different absorption coefficients for this
Figure 4.31. Comparison between 50% diffusion simulations for EM17 second shock event.

shock. The complex and simple geometries show no differences in shape for this event.

Figure 4.35 shows the second shock agreement. The back shock is well modeled however there is no specularly reflected wave in this case, and it does not show good agreement in this shape. The complex and simple geometries show no differences in shape for this event.

Figure 4.36 shows the third shock. There is no third shock in the simulated data so it does not show good agreement. The complex and simple geometries show no differences in shape for this event.

4.2.3.2 Direct Boom

4.2.3.2.1 Time Delay Since the first boom for EM17 is the first boom event to be recorded the time delay is not considered. All subsequent delays are relative to this arrival.
**Figure 4.32.** Comparison between 50% diffusion simulations for EM17 third shock event.

**Figure 4.33.** Comparison between 100% diffusion simulations for EM17.
Figure 4.34. Comparison between 100% diffusion simulations for EM17 first shock event.

4.2.3.2.2 Duration The duration of the first boom event was calculated. Table 4.6 presents the percent error of the duration when compared with the measured data. There is less than one percent error and the model is considered to predict this aspect well.

4.2.3.2.3 Peak Values The peak values are examined next. Table 4.7 presents the percent error of all the simulations when they are compared to the measured data for the simple environment. The positive front peak is about 19% error and the negative front peak is at 16% error. The positive back peak is about 35% error while the negative back peak is between 0.5% and 9% error.

Table 4.8 presents the percent error of all the simulations when they are compared to the measured data for the complex environment. There is no significant difference between the simple environment peak numbers and the complex environment peak numbers.
**Figure 4.35.** Comparison between 100% diffusion simulations for EM17 second shock event.

**Table 4.6.** Percent Error of the duration of the first boom events for all simulations as compared to the measured data for the first boom event at EM17.

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Figure 4.36. Comparison between 100% diffusion simulations for EM17 third shock event.
Table 4.7. Percent Error of the peak values of the first boom event at EM17 for all simulations as compared to the measured data

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Table 4.8. Percent Error of the peak values of the first boom event at EM17 for the complex environment for all simulations as compared to the measured data

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<td>-16.0</td>
<td>-16.0</td>
<td>-16.0</td>
<td>-16.0</td>
</tr>
<tr>
<td>Peak Back +</td>
<td>-20.3</td>
<td>-20.3</td>
<td>-20.3</td>
<td>-20.2</td>
<td>-20.2</td>
</tr>
<tr>
<td>Peak Back -</td>
<td>0.65</td>
<td>0.64</td>
<td>0.64</td>
<td>0.61</td>
<td>0.58</td>
</tr>
</tbody>
</table>
Table 4.9. Percent Error of the duration of the second boom events for all simulations as compared to the measured data for the second boom event at EM17.

**SIMPLE ENVIRONMENT**

<table>
<thead>
<tr>
<th>Diffusion</th>
<th>Absorption Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All Hard</td>
</tr>
<tr>
<td>0%</td>
<td>0.13</td>
</tr>
<tr>
<td>10%</td>
<td>0.13</td>
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<td>20%</td>
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</tr>
<tr>
<td>50%</td>
<td>0.13</td>
</tr>
<tr>
<td>100%</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**COMPLEX ENVIRONMENT**

<table>
<thead>
<tr>
<th>Diffusion</th>
<th>Absorption Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All Hard</td>
</tr>
<tr>
<td>0%</td>
<td>0.13</td>
</tr>
<tr>
<td>10%</td>
<td>0.13</td>
</tr>
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<td>20%</td>
<td>0.13</td>
</tr>
<tr>
<td>50%</td>
<td>0.13</td>
</tr>
<tr>
<td>100%</td>
<td>N/A</td>
</tr>
</tbody>
</table>

4.2.3.3 Reflected Boom

4.2.3.3.1 Time Delay The second event has a time delay of 0.0021 seconds. This is the same for each simulation.

4.2.3.3.2 Duration The duration of the first boom event was calculated. Table 4.9 presents the percent error of the duration when compared with the measured data. Since there is no reflected boom event for the all soft case and the 100% diffusion case these are listed as N/A. For the remaining simulations the percent error is less than one percent which shows good agreement.

4.2.3.3.3 Peak Values The peak values are examined next. Table 4.10 presents the percent error of all the second boom event simulations when they are compared to the measured data for the simple environment. Table 4.11 presents the percent error of all the simulations when they are compared to the measured data for the complex environment. There is no significant difference between the simple and the complex environment values. The positive front peak has between about 1% and 50% error and the negative front peak has about 2% and 95% error. The
Table 4.10. Percent Error of the peak values of the second boom event for the simple environment at EM17 for all simulations as compared to the measured data

<table>
<thead>
<tr>
<th>Diffusion</th>
<th>0 %</th>
<th>10 %</th>
<th>20 %</th>
<th>50 %</th>
<th>100 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Front +</td>
<td>16.1</td>
<td>4.53</td>
<td>-7.2</td>
<td>-42.0</td>
<td>N/A</td>
</tr>
<tr>
<td>Peak Front -</td>
<td>94.6</td>
<td>75.3</td>
<td>55.9</td>
<td>-2.1</td>
<td>N/A</td>
</tr>
<tr>
<td>Peak Back +</td>
<td>8.6</td>
<td>-2.24</td>
<td>-13.1</td>
<td>45.6</td>
<td>N/A</td>
</tr>
<tr>
<td>Peak Back -</td>
<td>97.3</td>
<td>77.6</td>
<td>57.8</td>
<td>-1.42</td>
<td>N/A</td>
</tr>
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<table>
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<th>20 %</th>
<th>50 %</th>
<th>100 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Front +</td>
<td>-1.06</td>
<td>-11.0</td>
<td>-20.9</td>
<td>-50.6</td>
<td>N/A</td>
</tr>
<tr>
<td>Peak Front -</td>
<td>66.1</td>
<td>49.6</td>
<td>33.1</td>
<td>-16.4</td>
<td>N/A</td>
</tr>
<tr>
<td>Peak Back +</td>
<td>-7.4</td>
<td>-16.6</td>
<td>-25.9</td>
<td>-53.6</td>
<td>N/A</td>
</tr>
<tr>
<td>Peak Back -</td>
<td>68.2</td>
<td>51.3</td>
<td>34.5</td>
<td>-16.0</td>
<td>N/A</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Diffusion</th>
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<th>10 %</th>
<th>20 %</th>
<th>50 %</th>
<th>100 %</th>
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</thead>
<tbody>
<tr>
<td>Peak Front +</td>
<td>16.1</td>
<td>4.46</td>
<td>-7.16</td>
<td>-42.0</td>
<td>N/A</td>
</tr>
<tr>
<td>Peak Front -</td>
<td>94.6</td>
<td>75.3</td>
<td>55.9</td>
<td>-2.17</td>
<td>N/A</td>
</tr>
<tr>
<td>Peak Back +</td>
<td>8.6</td>
<td>-2.24</td>
<td>-13.1</td>
<td>-45.6</td>
<td>N/A</td>
</tr>
<tr>
<td>Peak Back -</td>
<td>97.3</td>
<td>77.6</td>
<td>57.8</td>
<td>-1.43</td>
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<table>
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<th>50 %</th>
<th>100 %</th>
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</thead>
<tbody>
<tr>
<td>Peak Front +</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Peak Front -</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Peak Back +</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Peak Back -</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

positive back peak has about 2% and 53% error while the negative back peak has between 1% and 97% error.

4.2.3.3.4 Diffuse Reflections These simulations are grouped by absorption coefficients. This was done so that as the diffusion coefficient increases, the change in pressure value can be observed. It is expected that the contribution from diffuse reflections will be present after the reflected booms. Figure 4.37 shows the root mean squared (RMS) pressure when compared to the measured RMS pressure for the all hard case. The figure shows the difference between the measured and
Table 4.11. Percent Error of the peak values of the second boom event for the complex environment at EM17 for all simulations as compared to the measured data

### ALL HARD ABSORPTION

<table>
<thead>
<tr>
<th>Diffusion</th>
<th>0 %</th>
<th>10 %</th>
<th>20 %</th>
<th>50 %</th>
<th>100 %</th>
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</thead>
<tbody>
<tr>
<td>Peak Front +</td>
<td>16.07</td>
<td>4.46</td>
<td>-7.16</td>
<td>-42.02</td>
<td>N/A</td>
</tr>
<tr>
<td>Peak Front -</td>
<td>94.62</td>
<td>75.25</td>
<td>55.89</td>
<td>-2.19</td>
<td>N/A</td>
</tr>
<tr>
<td>Peak Back +</td>
<td>8.6</td>
<td>-2.24</td>
<td>-13.09</td>
<td>45.62</td>
<td>N/A</td>
</tr>
<tr>
<td>Peak Back -</td>
<td>97.29</td>
<td>77.54</td>
<td>57.8</td>
<td>-1.46</td>
<td>N/A</td>
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### AVERAGE ABSORPTION

<table>
<thead>
<tr>
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<th>100 %</th>
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<tr>
<td>Peak Front +</td>
<td>-1.06</td>
<td>-10.97</td>
<td>-20.87</td>
<td>-50.59</td>
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<tr>
<td>Peak Front -</td>
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<td>33.04</td>
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<tr>
<td>Peak Back +</td>
<td>-7.4</td>
<td>-16.64</td>
<td>-25.89</td>
<td>-53.62</td>
<td>N/A</td>
</tr>
<tr>
<td>Peak Back -</td>
<td>68.17</td>
<td>51.33</td>
<td>34.49</td>
<td>-16.03</td>
<td>N/A</td>
</tr>
</tbody>
</table>

### COMPLEX ABSORPTION

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<th>20 %</th>
<th>50 %</th>
<th>100 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Front +</td>
<td>16.07</td>
<td>4.46</td>
<td>-7.16</td>
<td>-42.02</td>
<td>N/A</td>
</tr>
<tr>
<td>Peak Front -</td>
<td>94.62</td>
<td>75.25</td>
<td>55.9</td>
<td>-2.19</td>
<td>N/A</td>
</tr>
<tr>
<td>Peak Back +</td>
<td>8.6</td>
<td>-2.25</td>
<td>-13.09</td>
<td>-45.63</td>
<td>N/A</td>
</tr>
<tr>
<td>Peak Back -</td>
<td>97.29</td>
<td>77.55</td>
<td>57.80</td>
<td>-1.45</td>
<td>N/A</td>
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</tbody>
</table>

### ALL SOFT ABSORPTION

<table>
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<tr>
<th>Diffusion</th>
<th>0 %</th>
<th>10 %</th>
<th>20 %</th>
<th>50 %</th>
<th>100 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Front +</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Peak Front -</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Peak Back +</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Peak Back -</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Simulated pressures. Other than the pressure present in the boom event there is no observable difference between the measured and simulated signals. Only the signal after the reflected boom is shown here.

Figure 4.38 shows the RMS pressure when compared to the measured data for the average case. Other than the pressure present in the boom event there is minimal difference between the different signals. Only the pressures after the reflected boom is shown here.

Figure 4.39 shows the RMS pressure when compared to the measured data for the complex case. Other than the pressure present in the boom event there is
minimal difference between the different signals. Only the signal after the reflected boom is shown here.

Figure 4.40 shows the RMS pressure when compared to the measured data for the all soft case. Other than the pressure present in the boom event there is no observable difference between the different signals. Only the signal after the reflected boom is shown here.

4.2.3.3.5 Best Fit

Considering all the parameters discussed here the best fit simulations are the all hard 50% diffusion case and the complex 50% diffusion case. For both the simple environment and the complex environment case the agreement was comparable. The simulations with no reflection are not considered because the shape of the signal is incorrect.
4.2.4 Microphone EM18

4.2.4.1 Overall Shape

The simulations have been grouped according to the amount of diffusion. Figure 4.41 shows the shape of the 0% diffusion simulations compared to the measured data. The overall shape does not match the measured data as well as the EM17 microphone. The shock events do seem to happen at approximately the correct time. However, the amplitude is significantly over predicted by the model. For this microphone we do see a significant difference between the complex environment and the simple environment.

Figures 4.42, 4.43, 4.44, and 4.45 show the close up on the individual shocks in the signal. The first event in Figure 4.42 shows acceptable agreement. The amplitude is over predicted but the overall shape matches well.

Figure 4.43 shows the second shock agreement. This is the front shock of the reflected boom event. There are two distinct peaks from the complex and the simple environments. The same peaks in the measured data are present in some
fashion in the simulated data but do not match the exact shape. The simple geometry matches the shape slightly better than the complex geometry.

Figure 4.44 shows the third shock. The simulation matches very well in shape except that the amplitude is over predicted.

Figure 4.45 shows the fourth shock. This is the tail shock of the reflected wave. The same observations made for the second shock event still apply for this shock.

Figure 4.46 shows the shape of the 10% diffuse simulations compared to the measured data. The overall shape does not match the measured data as well as the EM17 microphone. The shock events do seem to happen at approximately the correct time. However, the amplitude is significantly over predicted. For this microphone we do see a significant difference between the complex environment and the simple environment.

Figures 4.47, 4.48, 4.49, and 4.50 show the close up on the individual shocks in the signal. The first event in Figure 4.47 shows acceptable agreement. The amplitude is over predicted but the shape of the signal matches well.

Figure 4.48 shows the second shock agreement. This is the front shock of the
Figure 4.40. RMS pressure in the All Soft Case simulation as compared to the measured data.

Figure 4.41. Comparison between 0% diffusion simulations for EM18.
Figure 4.42. Comparison between 0% diffusion simulations for EM18 first shock event.

Figure 4.43. Comparison between 0% diffusion simulations for EM18 second shock event.
**Figure 4.44.** Comparison between 0% diffusion simulations for EM18 third shock event.

**Figure 4.45.** Comparison between 0% diffusion simulations for EM18 fourth shock event.
**Figure 4.46.** Comparison between 10% diffusion simulations for EM18.

**Figure 4.47.** Comparison between 10% diffusion simulations for EM18 first shock event.
reflected boom event. There are two distinct peaks from the complex and the simple environments. The measured data shape has some interesting characteristics including multiple decreasing peaks that are irregular in shape. These peaks are present in some fashion in the simulated data but do not match the exact shape. The simple geometry matches the shape slightly better than the complex geometry.

Figure 4.48. Comparison between 10% diffusion simulations for EM18 second shock event.

Figure 4.49 shows the third shock. The shape of this shock matches well with the measured data although the amplitude is over predicted.
Figure 4.49. Comparison between 10% diffusion simulations for EM18 third shock event.
Figure 4.50 shows the fourth shock. This is the tail shock of the reflected wave. The same observations made for the second shock event still apply for this shock.

**Figure 4.50.** Comparison between 10% diffusion simulations for EM18 fourth shock event.

Figure 4.51 shows the shape of the 20% diffuse simulations compared to the measured data. The overall shape does not match the measured data as well as EM17 does. The shock events do seem to happen at approximately the correct time. However, the amplitude is substantially over predicted. For this microphone we do see a significant difference between the complex environment and the simple environment.

Figures 4.52, 4.53, 4.54, and 4.55 show the close up on the individual shocks in the signal. The first event in Figure 4.52 shows acceptable agreement. The amplitude is over predicted but the overall shape matches well.

Figure 4.53 shows the second shock agreement. This is the front shock of the reflected boom event. There are two distinct peaks from the complex and the simple environments. These peaks present in the measured data are present in some fashion in the simulated data but do not match the exact shape. The simple geometry matches the shape slightly better than the complex geometry.
Figure 4.51. Comparison between 20% diffusion simulations for EM18.

Figure 4.52. Comparison between 20% diffusion simulations for EM18 first shock event.
Figure 4.53. Comparison between 20% diffusion simulations for EM18 second shock event.

Figure 4.54 shows the third shock. The amplitude is under predicted but the overall shape matches well.

Figure 4.55 shows the fourth shock. This is the tail shock of the reflected wave. The same observations made for the second shock event still apply for this shock.

Figure 4.56 shows the shape of the 50% diffuse simulations compared to the measured data. The overall shape does not match the measured data as well as the EM17 microphone. The shock events do seem to happen at approximately the correct time. The direct amplitude is substantially over predicted, however, the reflected amplitude is on the same order of magnitude. For this microphone we do see a significant difference between the complex environment and the simple environment.

Figures 4.57, 4.58, 4.59, and 4.60 show the close up on the individual shocks in the signal. The first event in Figure 4.57 shows acceptable agreement. The amplitude is over predicted but the overall shape is well modeled.

Figure 4.58 shows the second shock agreement. This is the front shock of the reflected boom event. There are two distinct peaks from the complex and
the simple environments. The multiple peaks in the measured data are present in some fashion in the simulated data but do not match the exact shape. Both environments show relatively good agreement in shape.

Figure 4.59 shows the third shock. The shape of this shock is well modeled although the amplitude is over predicted.

Figure 4.60 shows the fourth shock. This is the tail shock of the reflected wave. The same observations made for the second shock event still apply for this shock.

Figure 4.61 shows the shape of the 100% diffuse simulations compared to the measured data. There is no reflected pulse which significantly alters the overall shape of the signature and no longer has good agreement.

Figures 4.62, 4.63, 4.64, and 4.45 show the close up on the individual shocks in the signal. The first event in Figure 4.62 shows acceptable agreement. The amplitude is over predicted but the overall shape is well modeled.

Figure 4.63 shows the second shock agreement. There is no reflected shock which does not agree with the measured data.

Figure 4.64 shows the third shock. The shape is well modeled but the amplitude
Figure 4.55. Comparison between 20% diffusion simulations for EM18 fourth shock event.

Figure 4.56. Comparison between 50% diffusion simulations for EM18.
Figure 4.57. Comparison between 50% diffusion simulations for EM18 first shock event.

Figure 4.58. Comparison between 50% diffusion simulations for EM18 second shock event.
EM18 Comparison of Simulated and Measured Data for 50% Diffusion Event 3

Figure 4.59. Comparison between 50% diffusion simulations for EM18 third shock event.

is over predicted.

Figure 4.65 shows the fourth shock. There is no reflected shock so the simulated data does not agree well with the measured data.

4.2.4.2 Direct Boom

4.2.4.2.1 Time Delay The time delay for the first boom event was 0.0017 seconds.

4.2.4.2.2 Duration The duration of the first boom event was calculated to be 0% error for each simulation.

4.2.4.2.3 Peak Values The peak values are examined next. Table 4.12 presents the percent error of all the simulations for the simple environment when they are compared to the measured data. Table 4.13 presents the percent error of all the simulations for the complex environment when they are compared to the measured data. The simple and complex environment show only slight differences for the
Figure 4.60. Comparison between 50% diffusion simulations for EM18 fourth shock event.

Figure 4.61. Comparison between 100% diffusion simulations for EM18.
peak values. The positive front peak has between 152% and 160% error and the negative front peak has between 75% and 85% error. The positive back peak has between approximately 118% and 129% error while the negative back peak has between 79% and 93% error. These errors are very high and do not show good agreement for either the complex or the simple environment.

4.2.4.3 Reflected Boom

4.2.4.3.1 Time Delay The second boom event had a different time delay for the complex environment versus the simple environment. The simple environment has a time delay of 0.0071 seconds. The complex environment has a time delay of 0.0124 seconds.

4.2.4.3.2 Duration The duration of the first boom event was calculated. The percent error in the duration for all simulations was 0.13% which shows good agreement with the measured data.
4.2.4.3.3 Peak Values  The peak values are examined next. Table 4.14 presents the percent error of all the simulations when they are compared to the measured data for the simple environment. Table 4.15 presents the percent error of all the simulations when they are compared to the measured data for the complex environment. The simple and complex environments show significant differences in these values. The positive front peak ranges from about 0% and 119% error and the negative front peak has about 0% and 336% error. The positive back peak has about 1% and 103% error while the negative back peak has between 3% and 371% error. These ranges are very large and show that the absorption coefficients have a significant effect on this location. Some of the simulations show very good agreement while others do not.

4.2.4.3.4 Diffuse Reflections  These simulations are grouped by absorption coefficients. This was done so that as the diffusion coefficient increases, the change in pressure can be observed. Figure 4.66 shows the simulated RMS pressure when compared to the measured RMS pressure for the all hard case. This is the difference...
between the pressures in the measured signal and the simulated signal. Other than the amplitude in the boom event there is very little difference between the different diffusion coefficients.

Figure 4.67 shows the RMS pressure when compared to the measured data for the average case. Other than the pressure differences in the boom event there is very little difference between the different diffusion coefficients.

Figure 4.68 shows the RMS pressure when compared to the measured data for the complex absorption case. Other than the pressure differences in the boom event there is very little difference between the different diffusion coefficients.

Figure 4.69 shows the RMS pressure when compared to the measured data for the all soft case. Other than the pressure differences in the boom event there is very little difference between the different diffusion coefficients.

4.2.4.3.5 Best Fit Considering all the parameters discussed here the best fit simulations are the complex absorption case with 50% diffusion. The simple environment seemed to have a better overall shape.
Figure 4.65. Comparison between 100% diffusion simulations for EM18 fourth shock event.
Table 4.12. Percent Error of the peak values of the first boom event at EM18 for all simulations of the simple environment as compared to the measured data

**ALL HARD ABSORPTION**

<table>
<thead>
<tr>
<th>Diffusion</th>
<th>0 %</th>
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<th>20 %</th>
<th>50 %</th>
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<tr>
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<td>154</td>
<td>155</td>
<td>156</td>
<td>158</td>
<td>161</td>
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<tr>
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<td>85.7</td>
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<td>83.6</td>
<td>80.5</td>
<td>75.4</td>
</tr>
<tr>
<td>Peak Back +</td>
<td>120</td>
<td>121</td>
<td>122</td>
<td>125</td>
<td>130</td>
</tr>
<tr>
<td>Peak Back -</td>
<td>93.9</td>
<td>92.5</td>
<td>91.0</td>
<td>86.8</td>
<td>79.8</td>
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**AVERAGE ABSORPTION**

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<th>Diffusion</th>
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<th>10 %</th>
<th>20 %</th>
<th>50 %</th>
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<td>157</td>
<td>156</td>
<td>158</td>
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<td>123</td>
<td>125</td>
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</tr>
<tr>
<td>Peak Back -</td>
<td>92.0</td>
<td>90.8</td>
<td>86.6</td>
<td>86.0</td>
<td>80.0</td>
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**COMPLEX ABSORPTION**

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**ALL SOFT ABSORPTION**

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Table 4.13. Percent Error of the peak values of the first boom event at EM18 for all simulations of the complex environment as compared to the measured data

### ALL HARD ABSORPTION

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### AVERAGE ABSORPTION

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### COMPLEX ABSORPTION

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<tr>
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### ALL SOFT ABSORPTION

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<td>81.38</td>
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</table>
Table 4.14. Percent Error of the peak values of the second boom event at EM18 for all simulations as compared to the measured data for the simple environment.

<table>
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<tr>
<td>Peak Front +</td>
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<td>71.2</td>
<td>6.79</td>
<td>N/A</td>
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<tr>
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<td>282</td>
<td>240</td>
<td>112</td>
<td>N/A</td>
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<tr>
<td>Peak Back +</td>
<td>97.6</td>
<td>77.9</td>
<td>58.1</td>
<td>1.20</td>
<td>N/A</td>
</tr>
<tr>
<td>Peak Back -</td>
<td>359</td>
<td>313</td>
<td>267</td>
<td>129</td>
<td>N/A</td>
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<table>
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<td>190</td>
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<tr>
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<td>-15.7</td>
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<td>212</td>
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<tr>
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<td>N/A</td>
<td>N/A</td>
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<tr>
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<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
<td>Peak Back +</td>
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<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
<td>Peak Back -</td>
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<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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Table 4.15. Percent Error of the peak values of the second boom event at EM18 for all simulations as compared to the measured data for the complex environment.

**ALL HARD ABSORPTION**

<table>
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<th>Diffusion</th>
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<td>9.82</td>
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<td>293</td>
<td>250</td>
<td>119</td>
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<td>82.9</td>
<td>62.6</td>
<td>1.80</td>
<td>N/A</td>
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<tr>
<td>Peak Back -</td>
<td>371</td>
<td>324</td>
<td>277</td>
<td>135</td>
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**AVERAGE ABSORPTION**

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<tbody>
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<td>87.4</td>
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<td>-13.2</td>
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**COMPLEX ABSORPTION**

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**ALL SOFT ABSORPTION**

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<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<td>N/A</td>
<td>N/A</td>
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<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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</table>
Figure 4.66. RMS pressure in the all hard case simulation as compared to the measured data.
**Figure 4.67.** RMS pressure in the average absorption case simulation as compared to the measured data.
Figure 4.68. RMS pressure in the complex absorption case simulation as compared to the measured data.
Figure 4.69. RMS pressure in the all soft case simulation as compared to the measured data.
4.2.5 Microphone EM19

4.2.5.1 Overall Shape

The simulations have been grouped according to the amount of diffusion. Figure 4.70 shows the shape of the 0% diffuse simulations compared to the measured data. The shock events happen at approximately the correct time and the amplitude is relatively close to the measured data. For this microphone there is a noticeable difference between the complex and simple environments.

![EM19 Comparison of Simulated and Measured Data for 0% Diffusion](image)

**Figure 4.70.** Comparison between 0% diffusion simulations for EM19.

Figures 4.71 and 4.72 show the close up on the individual shocks in the signal. The first event in Figure 4.71 shows good agreement. The overall shape is well predicted. There are noticeable differences between the simple and complex environments but these are mostly in the amplitude rather than the shape.

Figure 4.72 shows the second shock agreement. The shape shows good agreement.

Figure 4.73 shows the shape of the 10% diffuse simulations compared to the measured data. The shock events happen at approximately the correct time and
**Figure 4.71.** Comparison between 0% diffusion simulations for EM19 first shock event.

**Figure 4.72.** Comparison between 0% diffusion simulations for EM19 second shock event.
the amplitude is relatively close to the measured data. For this microphone there is a noticeable difference between the complex and simple environments.

Figures 4.74 and 4.75 show the close up on the individual shocks in the signal. The first event in Figure 4.74 shows good agreement. The overall shape is well predicted. There are noticeable differences between the simple and complex environment but these are mostly in the amplitude rather than the shape.

Figure 4.75 shows the second shock agreement. The shape shows good agreement.

Figure 4.76 shows the shape of the 20% diffuse simulations compared to the measured data. The shock events happen at approximately the correct time and the amplitude is relatively close to the measured data. For this microphone there is a noticeable difference between the complex and simple environments.

Figures 4.77 and 4.78 show the close up on the individual shocks in the signal. The first event in Figure 4.77 shows good agreement. The overall shape is well predicted. There are noticeable differences between the simple and complex environments but these are mostly in the amplitude rather than the shape.
Figure 4.74. Comparison between 10% diffusion simulations for EM19 first shock event.

Figure 4.75. Comparison between 10% diffusion simulations for EM19 second shock event.
Figure 4.76. Comparison between 20% diffusion simulations for EM19.

Figure 4.77. Comparison between 20% diffusion simulations for EM19 first shock event.
Figure 4.78 shows the second shock agreement. The shape shows good agreement.

![EM19 Comparison of Simulated and Measured Data for 20% Diffusion Event 2](image)

**Figure 4.78.** Comparison between 20% diffusion simulations for EM19 second shock event.

Figure 4.79 shows the shape of the 50% diffuse simulations compared to the measured data. The shock events happen at approximately the correct time and the amplitude is relatively close to the measured data. For this microphone there is a noticeable difference between the complex and simple environments.

Figures 4.80 and 4.81 show the close up on the individual shocks in the signal. The first event in Figure 4.80 shows very good agreement. The overall shape is well predicted. There are noticeable differences between the simple and complex environments but these are mostly in the amplitude rather than the shape.

Figure 4.81 shows the second shock agreement. The shape shows good agreement.

Figure 4.82 shows the shape of the 100% diffuse simulations compared to the measured data. While there is no reflected energy, the simulated data still matches well with the measured data.
Figure 4.79. Comparison between 50% diffusion simulations for EM19.

Figure 4.80. Comparison between 50% diffusion simulations for EM19 first shock event.
Figure 4.81. Comparison between 50% diffusion simulations for EM19 second shock event.

Figure 4.82. Comparison between 100% diffusion simulations for EM19.
Figures 4.83 and 4.84 show the close up on the individual shocks in the signal. The first event in Figure 4.83 shows good agreement. There is no observable difference between the simple environment and the complex environment.

![EM19 Comparison of Simulated and Measured Data for 100% Diffusion Event 1](image)

**Figure 4.83.** Comparison between 100% diffusion simulations for EM19 first shock event.

Figure 4.84 shows the second shock agreement. It shows good agreement with the measured data.

### 4.2.5.2 Direct Boom

#### 4.2.5.2.1 Time Delay

This boom event has a time delay of 0.0019 seconds.

#### 4.2.5.2.2 Duration

The duration of the first boom event was calculated. Table 4.16 presents the percent error of the duration when compared with the measured data. The duration has a small percent error not more than 1.13% which shows good agreement.

#### 4.2.5.2.3 Peak Values

The peak values are examined next. Table 4.17 presents the percent error of all the simulations when they are compared to the measured
**Figure 4.84.** Comparison between 100% diffusion simulations for EM19 second shock event.

**Table 4.16.** Percent Error of the duration of the boom events for all simulations as compared to the measured data for the at EM19.

**SIMPLE ENVIRONMENT**

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<th>Absorption Coefficient</th>
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**COMPLEX ENVIRONMENT**

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Table 4.17. Percent Error of the peak values of the first boom event at EM19 for all simulations as compared to the measured data for the simple environment.

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<tr>
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<td>-6.66</td>
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<td>50 %</td>
<td>100 %</td>
</tr>
<tr>
<td>Peak Front +</td>
<td>29.1</td>
<td>23.3</td>
<td>17.9</td>
<td>4.14</td>
<td>-6.66</td>
</tr>
<tr>
<td>Peak Front -</td>
<td>96.7</td>
<td>88.6</td>
<td>80.8</td>
<td>58.6</td>
<td>27.2</td>
</tr>
<tr>
<td>Peak Back +</td>
<td>39.4</td>
<td>32.1</td>
<td>25.6</td>
<td>7.94</td>
<td>-4.25</td>
</tr>
<tr>
<td>Peak Back -</td>
<td>115</td>
<td>106</td>
<td>97.8</td>
<td>73.5</td>
<td>39.0</td>
</tr>
<tr>
<td></td>
<td>0 %</td>
<td>10 %</td>
<td>20 %</td>
<td>50 %</td>
<td>100 %</td>
</tr>
<tr>
<td>Peak Front +</td>
<td>5.44</td>
<td>3.41</td>
<td>1.48</td>
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<td>-6.66</td>
</tr>
<tr>
<td>Peak Front -</td>
<td>60.9</td>
<td>57.2</td>
<td>53.4</td>
<td>42.9</td>
<td>27.2</td>
</tr>
<tr>
<td>Peak Back +</td>
<td>9.57</td>
<td>6.91</td>
<td>4.47</td>
<td>-1.20</td>
<td>-4.26</td>
</tr>
<tr>
<td>Peak Back -</td>
<td>76.0</td>
<td>72.0</td>
<td>67.9</td>
<td>56.3</td>
<td>39.0</td>
</tr>
<tr>
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<td>10 %</td>
<td>20 %</td>
<td>50 %</td>
<td>100 %</td>
</tr>
<tr>
<td>Peak Front +</td>
<td>-6.60</td>
<td>-6.61</td>
<td>-6.61</td>
<td>-6.63</td>
<td>-6.67</td>
</tr>
<tr>
<td>Peak Front -</td>
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<td>27.8</td>
<td>27.7</td>
<td>27.5</td>
<td>27.2</td>
</tr>
<tr>
<td>Peak Back +</td>
<td>-4.31</td>
<td>-4.31</td>
<td>-4.31</td>
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<td>-4.29</td>
</tr>
<tr>
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<td>39.8</td>
<td>39.7</td>
<td>39.6</td>
<td>39.4</td>
<td>39.1</td>
</tr>
</tbody>
</table>

A simple and complex environments show some differences in these values. The positive front peak ranges from about 0% and 40% error and the negative front peak has about 0% and 111% error. The positive back peak has about 1% and 52% error while the negative back peak has between 39% and 130% error.

4.2.5.2.4 Diffuse Reflections These simulations are grouped by absorption coefficients. This was done so that as the diffusion coefficient increases, the change
Table 4.18. Percent Error of the peak values of the first boom event at EM19 for all simulations as compared to the measured data for the complex environment.

<table>
<thead>
<tr>
<th>ALL HARD ABSORPTION</th>
<th>Diffusion</th>
<th>0 %</th>
<th>10 %</th>
<th>20 %</th>
<th>50 %</th>
<th>100 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Front +</td>
<td>17.9</td>
<td>8.8</td>
<td>0.69</td>
<td>-2.24</td>
<td>-6.68</td>
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<tr>
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<td>51.6</td>
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<td>26.7</td>
<td></td>
</tr>
<tr>
<td>Peak Back +</td>
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<td>10.3</td>
<td>2.02</td>
<td>-0.52</td>
<td>-4.08</td>
<td></td>
</tr>
<tr>
<td>Peak Back -</td>
<td>75.5</td>
<td>71.8</td>
<td>68.1</td>
<td>57.0</td>
<td>38.5</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>AVERAGE ABSORPTION</th>
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<th>10 %</th>
<th>20 %</th>
<th>50 %</th>
<th>100 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Front +</td>
<td>4.42</td>
<td>0.37</td>
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<td>-6.68</td>
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<tr>
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<tr>
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<td>0.93</td>
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<td>-4.11</td>
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<tr>
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<td>67.0</td>
<td>63.8</td>
<td>54.3</td>
<td>38.5</td>
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<table>
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<th>10 %</th>
<th>20 %</th>
<th>50 %</th>
<th>100 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Front +</td>
<td>-2.67</td>
<td>-3.12</td>
<td>-3.52</td>
<td>-4.70</td>
<td>-6.67</td>
<td></td>
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<td>34.0</td>
<td>26.9</td>
<td></td>
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<tr>
<td>Peak Back +</td>
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<td>-1.34</td>
<td>-1.69</td>
<td>-2.70</td>
<td>-4.18</td>
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</tr>
<tr>
<td>Peak Back -</td>
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<td>54.0</td>
<td>52.3</td>
<td>47.2</td>
<td>38.8</td>
<td></td>
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</tbody>
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<table>
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<tr>
<th>ALL SOFT ABSORPTION</th>
<th>Diffusion</th>
<th>0 %</th>
<th>10 %</th>
<th>20 %</th>
<th>50 %</th>
<th>100 %</th>
</tr>
</thead>
<tbody>
<tr>
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<td>-6.58</td>
<td>-6.59</td>
<td>-6.60</td>
<td>-6.62</td>
<td>-6.67</td>
<td></td>
</tr>
<tr>
<td>Peak Front -</td>
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<td>27.3</td>
<td>27.3</td>
<td>27.2</td>
<td>27.0</td>
<td></td>
</tr>
<tr>
<td>Peak Back +</td>
<td>-4.22</td>
<td>-4.23</td>
<td>-4.24</td>
<td>-4.26</td>
<td>-4.29</td>
<td></td>
</tr>
<tr>
<td>Peak Back -</td>
<td>39.5</td>
<td>39.4</td>
<td>39.4</td>
<td>39.3</td>
<td>39.1</td>
<td></td>
</tr>
</tbody>
</table>

in pressure can be observed. Figure 4.85 shows the simulated RMS pressure when compared to the measured RMS pressure data for the all hard case. The figure shows the difference between the RMS pressure in the measured signal and the simulated signal. Other than the pressure difference in the boom event there is very little difference between the different diffusion coefficients.

Figure 4.86 shows the RMS pressure for the average absorption case when compared to the measured data. Other than the pressure differences in the boom event there is very little difference between the different diffusion coefficients.

Figure 4.87 shows the simulated RMS pressure for the complex absorption case
Figure 4.85. RMS pressure in the all hard case simulation as compared to the measured data.

when compared to the measured data. Other than the pressure differences in the boom event there is very little difference between the different diffusion coefficients.

Figure 4.88 shows the simulated RMS pressure for the all soft case when compared to the measured data. There is no observable difference between the different diffusion coefficients.

4.2.5.2.5 Best Fit Considering all the parameters discussed here the best fit simulations are the 100% Diffusion case as well as the all soft cases. Both the simple and the complex environments have a similar accuracy. Basically this states that the fit is best with only a ground reflection. Because this case is a non-physical case the next best comparison will be considered. The second best fit for this is the 50% diffuse case with a complex absorption. The complex environment has a slightly better fit than the simple environment case.
Figure 4.86. RMS pressure in the average absorption case simulation as compared to the measured data.

4.2.6 Microphone EM29

4.2.6.1 Overall Shape

The simulations have been grouped according to the amount of diffusion. Figure 4.89 shows the shape of the 0% diffuse simulations compared to the measured data. The shock events happen at approximately the correct time and the amplitude is relatively close to the measured data. For this microphone there is no noticeable difference between the complex and simple environments.

Figures 4.90 and 4.91 show the close up on the individual shocks in the signal. The first event in Figure 4.90 shows good agreement. The overall shape is well predicted.

Figure 4.91 shows the second shock agreement. The shape shows modest agreement.

Figure 4.92 shows the shape of the 10% diffuse simulations compared to the measured data. The shock events happen at approximately the correct time and the amplitude is relatively close to the measured data. For this microphone there
Figure 4.87. RMS pressure in the complex absorption case simulation as compared to the measured data.

is no noticeable difference between the complex and simple environments.

Figures 4.93 and 4.94 show the close up on the individual shocks in the signal. The first event in Figure 4.93 shows good agreement. The overall shape is well predicted.

Figure 4.94 shows the second shock agreement. The shape shows good agreement.

Figure 4.95 shows the shape of the 20% diffuse simulations compared to the measured data. The shock events happen at approximately the correct time and the amplitude is relatively close to the measured data. For this microphone there is no noticeable difference between the complex and simple environments.

Figures 4.96 and 4.97 show the close up on the individual shocks in the signal. The first event in Figure 4.96 shows good agreement. The overall shape is well predicted.

Figure 4.97 shows the second shock agreement. The shape shows good agreement.

Figure 4.98 shows the shape of the 50% diffuse simulations compared to the
Figure 4.88. RMS pressure in the all soft case simulation as compared to the measured data.

Figure 4.89. Comparison between 0% diffusion simulations for EM29.
**Figure 4.90.** Comparison between 0% diffusion simulations for EM29 first shock event.

**Figure 4.91.** Comparison between 0% diffusion simulations for EM29 second shock event.
Figure 4.92. Comparison between 10% diffusion simulations for EM29.

Figure 4.93. Comparison between 10% diffusion simulations for EM29 first shock event.
**Figure 4.94.** Comparison between 10% diffusion simulations for EM29 second shock event.

**Figure 4.95.** Comparison between 20% diffusion simulations for EM29.
Figure 4.96. Comparison between 20% diffusion simulations for EM29 first shock event.

Figure 4.97. Comparison between 20% diffusion simulations for EM29 second shock event.
measured data. The shock events happen at approximately the correct time and the amplitude is relatively close to the measured data. For this microphone there is no noticeable difference between the complex and simple environments.

**Figure 4.98.** Comparison between 50% diffusion simulations for EM29.

Figures 4.99 and 4.100 show the close up on the individual shocks in the signal. The first event in Figure 4.99 shows very good agreement. The overall shape is very well predicted.

Figure 4.100 shows the second shock agreement. The shape shows good agreement.

Figure 4.101 shows the shape of the 100% diffuse simulations compared to the measured data. While there is no reflected energy, the simulated data still matches well with the measured data.

Figures 4.102 and 4.103 show the close up on the individual shocks in the signal. The first event in Figure 4.102 shows good agreement.

Figure 4.103 shows the second shock agreement. It shows good agreement with the measured data.
Figure 4.99. Comparison between 50% diffusion simulations for EM29 first shock event.

Figure 4.100. Comparison between 50% diffusion simulations for EM29 second shock event.
Figure 4.101. Comparison between 100% diffusion simulations for EM29.

Figure 4.102. Comparison between 100% diffusion simulations for EM29 first shock event.
Figure 4.103. Comparison between 100% diffusion simulations for EM29 second shock event.

4.2.6.2 Direct and Reflected Boom

4.2.6.2.1 Time Delay
The time delay for this boom is 0.0009 seconds.

4.2.6.2.2 Duration
The duration of the first boom event was calculated. Table 4.19 presents the percent error of the duration when compared with the measured data. The duration has a small percent error all less than 1%.

4.2.6.2.3 Peak Values
The peak values are examined next. Table 4.20 presents the percent error of all the simulations when they are compared to the measured data for the simple environment. Table 4.21 presents the percent error of all the simulations when they are compared to the measured data for the complex environment. The simple and complex environments show some differences in these values. The positive front peak ranges from about 0% and -38% error and the negative front peak has about -17% and -51% error. The positive back peak has about -2% and -43% error while the negative back peak has between -13% and
Table 4.19. Percent Error of the duration of the boom events for all simulations as compared to the measured data for the at EM29.

<table>
<thead>
<tr>
<th>Diffusion</th>
<th>Absorption Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All Hard</td>
</tr>
<tr>
<td>0%</td>
<td>0.13</td>
</tr>
<tr>
<td>10%</td>
<td>0.13</td>
</tr>
<tr>
<td>20%</td>
<td>0.13</td>
</tr>
<tr>
<td>50%</td>
<td>0.2</td>
</tr>
<tr>
<td>100%</td>
<td>0.07</td>
</tr>
</tbody>
</table>

-49% error.

4.2.6.2.4 Diffuse Reflections These simulations are grouped by absorption coefficients. This was done so that as the diffusion coefficient increases, the change in pressure can be observed. Figure 4.104 shows the simulated RMS pressure for the all hard absorption case when compared to the RMS pressure for the measured data. Other than the pressure differences in the boom event there is very little difference between the different diffusion coefficients.

Figure 4.105 shows the RMS pressure for the average absorption case when compared to the measured data. Other than the pressure difference in the boom event there is very little observable difference between the different diffusion coefficients.

Figure 4.106 shows the RMS pressure for the complex absorption case when compared to the measured data. Other than the pressure difference in the boom event there is very little difference between the different diffusion coefficients.

Figure 4.107 shows the RMS pressure for the all soft absorption case when compared to the measured pressure data. There is no observable difference between
Table 4.20. Percent Error of the peak values of the first boom event at EM29 for all simulations as compared to the measured data for the simple environment.

**ALL HARD ABSORPTION**

<table>
<thead>
<tr>
<th>Diffusion</th>
<th>0 %</th>
<th>10 %</th>
<th>20 %</th>
<th>50 %</th>
<th>100 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Front +</td>
<td>0.71</td>
<td>-4.95</td>
<td>-10.4</td>
<td>-24.5</td>
<td>-38.1</td>
</tr>
<tr>
<td>Peak Front -</td>
<td>-17.2</td>
<td>-21.1</td>
<td>-25.0</td>
<td>-35.9</td>
<td>-51.8</td>
</tr>
<tr>
<td>Peak Back +</td>
<td>-2.23</td>
<td>-7.60</td>
<td>-12.9</td>
<td>-27.9</td>
<td>-43.4</td>
</tr>
<tr>
<td>Peak Back -</td>
<td>-13.7</td>
<td>-17.8</td>
<td>-21.8</td>
<td>-33.2</td>
<td>-49.9</td>
</tr>
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</table>

**AVERAGE ABSORPTION**

<table>
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<th>20 %</th>
<th>50 %</th>
<th>100 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Front +</td>
<td>-7.55</td>
<td>-12.1</td>
<td>-16.3</td>
<td>-27.4</td>
<td>-38.2</td>
</tr>
<tr>
<td>Peak Front -</td>
<td>-23.0</td>
<td>-26.2</td>
<td>-29.4</td>
<td>-38.5</td>
<td>-51.8</td>
</tr>
<tr>
<td>Peak Back +</td>
<td>-10.1</td>
<td>-14.6</td>
<td>-19.0</td>
<td>-31.3</td>
<td>-43.4</td>
</tr>
<tr>
<td>Peak Back -</td>
<td>-19.7</td>
<td>-23.0</td>
<td>-26.4</td>
<td>-35.9</td>
<td>-49.9</td>
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</table>

**COMPLEX ABSORPTION**

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<tbody>
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<td>-4.95</td>
<td>-10.4</td>
<td>-24.5</td>
<td>-38.2</td>
</tr>
<tr>
<td>Peak Front -</td>
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<td>-21.1</td>
<td>-25.0</td>
<td>-35.9</td>
<td>-51.8</td>
</tr>
<tr>
<td>Peak Back +</td>
<td>-2.23</td>
<td>-7.60</td>
<td>-12.9</td>
<td>-27.9</td>
<td>-43.5</td>
</tr>
<tr>
<td>Peak Back -</td>
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<td>-17.8</td>
<td>-21.8</td>
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<td>-49.8</td>
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**ALL SOFT ABSORPTION**

<table>
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<th>20 %</th>
<th>50 %</th>
<th>100 %</th>
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<tr>
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<td>-43.4</td>
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</tbody>
</table>

the different diffusion coefficients.

4.2.6.2.5 **Best Fit** Considering all the parameters discussed here the best fit simulations are the 0% diffusion case with the all hard or complex absorption. Both the simple and the complex environments have a similar accuracy.
Table 4.21. Percent Error of the peak values of the first boom event at EM29 for all simulations as compared to the measured data for the complex environment.

<table>
<thead>
<tr>
<th></th>
<th>Diffusion</th>
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<th>20 %</th>
<th>50 %</th>
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<td>-21.8</td>
<td>-33.2</td>
<td>-49.8</td>
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<table>
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<th>20 %</th>
<th>50 %</th>
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<tr>
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<tr>
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<td>-14.6</td>
<td>-19.0</td>
<td>-31.3</td>
<td>-43.5</td>
<td></td>
</tr>
<tr>
<td>Peak Back -</td>
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<td>-26.4</td>
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<td>-49.8</td>
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<table>
<thead>
<tr>
<th></th>
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<th>0 %</th>
<th>10 %</th>
<th>20 %</th>
<th>50 %</th>
<th>100 %</th>
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<tbody>
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<tr>
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<td>-21.1</td>
<td>-24.9</td>
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<td>-7.60</td>
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<td>-43.5</td>
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<tr>
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<td>-21.8</td>
<td>-33.2</td>
<td>-49.8</td>
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<th>20 %</th>
<th>50 %</th>
<th>100 %</th>
</tr>
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<td>-38.1</td>
<td>-38.1</td>
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<td>-49.6</td>
<td>-49.7</td>
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<td></td>
</tr>
</tbody>
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4.2.7 Discussion
Overall, the simulation predicted the measured data well. There are a few discrepancies that should be discussed. For each simulation, there was a slight time delay in some of the arrival times. This can come from a variety of factors. The first is the slight discrepancy between the model geometry and the actual environment geometry. While there was great care in making the model geometry realistic there were things that could differ enough to impact the resulting sound field. One of the
reasons for the time delay could be a slight displacement of the microphone location. The time delay corresponds to about 0.5 meters in microphone displacement. This is a reasonable amount of error for a microphone location. Another reason for this error could be the slight terrain changes around the EM building. They are small but particularly for the farther microphones could be significant. Another reason for this difference could be very small variations in the arrival angles. The angles are hard to measure accurately and even a very small difference between the simulated and measured data could result in the time delay observed for these simulations.

The next feature that has some discrepancies is the amplitude. For most of the simulations the amplitude is significantly over predicted. The best fit for all microphones but EM29 was the 50% diffuse case. Because of the lack of energy from the actual diffuse reflections, this indicates that the energy is going somewhere else. If the energy is, in fact, diffuse then the majority of the energy is being directed upward away from the receivers. Another explanation for the additional energy is that the walls have a significant transmission into the building that is
Figure 4.105. RMS pressure in the average absorption case simulation as compared to the measured data.

not being accounted for. Either of these situations can be accounted for by a more significant absorption coefficient. This will provide the same results with a significantly reduced computation time. Some additional study needs to be done to determine how much greater the absorption coefficient should be.

The last feature that should be discussed is the complexity of the environment. While there are visual differences at some of the microphones, the accuracy of the results does not necessarily get better with an increase in model complexity. The increased complexity increases computation time. Without radiosity the computation time for both simple and complex environments is comparable. However once radiosity is included, the computation time for the complex environment went up significantly more than for the simple environment. With all these factors included, one may conclude that the façade features do not need to be included.

In the next chapter, the museum environment from the 2009 SonicBOBS experiment is discussed. The museum environment has two buildings in proximity to each other. This environment is examined to determine the model accuracy when multiple buildings are included. The comparison between simulations and
Figure 4.106. RMS pressure in the complex absorption case simulation as compared to the measured data.

measured data will be examined in detail as they were in this chapter.
Figure 4.107. RMS pressure in the All Soft Case simulation as compared to the measured data.
A second environment that incorporated multiple buildings was simulated to compare with the measured data. The same features were examined for this configuration as for the previous simulation to determine the effects of these parameters on a multiple building environment. These three features are the facade features, the absorption coefficient of the building, and the diffusion coefficient of the building. This chapter will discuss the layout of the buildings, the input boom signal, and compare the resulting simulations with the measured data. The comparison between the simulated and measured data was not as accurate as for the EM building in chapter 4. Therefore, only a few samples of the simulations are shown for this chapter. The proposed reasons why the agreement is not as good for this environment are discussed at length.

5.1 Description of Environment

The environment for this simulation is modeled from the museum building and a small, side building number 5296 next to the museum located on Edwards AirForce Base. These buildings were measured in the 2009 SonicBOBS experiment. This set of buildings was used to determine the effect of more than one building on the sound field. An aerial view of the building is shown in Figure 5.1. In this figure several large pieces of equipment around the two buildings are visible. The larger vintage and aircraft and helicopters around the museum are expected to be far enough away from the microphones that the effect will be minimal. However,
the equipment in between the buildings is large enough and close enough to the microphones that they may have an effect on the measured sound field. These pieces of equipment include pieces of aircraft, tanks, and large metal rooms. They were not included in the model and this may negatively affect the comparison. The four important aspects of this model are: the input signal, the building complexity, the simulation coefficients and the receiver locations.

![Aerial View of Museum Buildings](image)

**Figure 5.1.** Aerial View of Museum Buildings. The scale of this figure is approximately 200 m x 175 m

### 5.1.1 Input Signal

The 2009 SonicBOBS experiment supplied the boom events discussed in this section. The same 24 booms from two aircraft discussed in section 4.1.1 were recorded at the museum. However, the BADS unit that measures the arrival times and determines the arrival angles did not register a boom event for the first 12 booms or
Table 5.1. Sonic Booms from the 2009 SonicBOBS experiment at Edwards Airforce Base museum buildings

<table>
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<th>Flight #</th>
<th>Pass #</th>
<th>Rating</th>
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<td>1208</td>
<td>1</td>
<td>Unusable</td>
</tr>
<tr>
<td>852</td>
<td>1208</td>
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</tr>
<tr>
<td>843</td>
<td>1208</td>
<td>6</td>
<td>OK</td>
</tr>
<tr>
<td>843</td>
<td>1208</td>
<td>7</td>
<td>Unusable</td>
</tr>
</tbody>
</table>

boom 22, so these were disregarded. Since there are no elevated microphones it was not possible to determine the angles by examining arrival times in the same manner as the EM building arrival angles were calculated. Several of the measured angles were recorded as a negative elevation angle which is a non-physical result. Booms 20, 23 and 24 all had negative elevation angles and were disregarded. The remaining booms are examined to determine the condition of the input boom to ensure that the boom event was significantly above the background noise and had minimal distortion. Each boom was rated using Unusable, OK, Good, and Very Good. Table 5.1 shows the booms measured by the BADS unit at the museum building and their ratings.

From the booms considered in Table 5.1 the third and fifth booms were used as inputs to the simulation. The input signals were taken from the far field microphone indicated at the top of Figure 5.1 as CA. Figure 5.2 shows the input signals to be used in the simulation. These were created by examining the measurements and isolating the boom, taking about 0.018 seconds before the front shock and including the measurement until the amplitude returned to zero after the rear shock. Microphone CA is approximately 30 meters to the north of the buildings.

The next characteristic of the input signal is the initial location of the input plane and initial angles. The initial angles were taken from the measured data from the BADS unit at the museum building. For the third boom event, aircraft 842 flight 1208 and pass number 2, the elevation angle was measured as 18.9° down
Figure 5.2. The third and fifth boom event recorded at CA to be used as the input to simulation from the horizontal. The azimuthal angle was 266.5° from north. For boom 5, the elevation angle was measured as 19.6° down from the horizontal and an azimuthal of 267.6° from north.

The input plane for the simulation is placed in order to ensure that the entire museum area was covered. The plane was placed far enough back to ensure that the ground reflections reach the top of the building. This position was determined using the incoming angles. The plane needed to be at least 28 meters away from the incident corner of the building. It needed to be 80 meters wide and 35 meters high. The ray spacing was set at 0.035 meters because of the findings of the validation runs shown in section 3.2.2. The sampling frequency is dependent on the capability of the microphones for this simulation which is 24000 Hz.
Table 5.2. Octave band values for the absorption coefficient of the ground plane.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>63 Hz</th>
<th>125 Hz</th>
<th>250 Hz</th>
<th>500 Hz</th>
<th>1 kHz</th>
<th>2 kHz</th>
<th>4 kHz</th>
<th>8 kHz</th>
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</thead>
<tbody>
<tr>
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<td>0.01</td>
<td>0.01</td>
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<td>0.02</td>
<td>0.02</td>
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<td>0.03</td>
</tr>
</tbody>
</table>

5.1.2 Environment Parameters

Several overall environmental parameters must be set in order to define some general characteristics. These include sound speed which is essential to propagate the rays. The sound speed is based on other parameters such as temperature, relative humidity and ambient pressure. The temperature taken by a weather station at the site during the third boom event was 306 kelvin or approximately 91.1° fahrenheit. A relative humidity of 20% and an ambient pressure of 1.0 atm is assumed. This yields a sound speed of 351 meters per second. The ground plane is assumed to be flat, acoustically hard with a height of 0 meters for all simulations. Acoustically hard in this case is equivalent to painted concrete. The octave spectrum for absorption coefficients for the ground is shown in Table 5.2. The ground is also considered to be non-diffuse.

5.1.3 Building Characteristics

For this study several different characteristics of the building were considered. The first is the geometry of the building, the second is the absorption coefficient of the building and the third is the diffusion coefficient. Each of these parameters will be discussed in this section as well as the motivation behind the values chosen.

5.1.3.1 Building Geometry

Two geometries were considered for this environment. As seen in Figure 5.1, the two buildings are at an oblique angle to each other. In addition, the roof is slightly pitched on both buildings. In order to simplify the geometry, the buildings were modeled as parallel with flat roofs. A schematic and elevation view of this geometry is shown in Figure 5.3. There is a small concrete block wall that connects the two buildings on the south side.

The more complex building geometry tries to model the buildings as accurately as possible. This means that the angle between the two buildings was modeled
Figure 5.3. (a) shows the schematic layout of the simple geometry environment (b) shows the elevation layout of the simple geometry environment. Two buildings and an interconnecting wall are included.

as it appears in the aerial pictures. The pitched roof is included in the more complicated model of this environment. A schematic and elevation view of the complex geometry is shown in Figure 5.4.

5.1.3.2 Absorption Coefficients

Absorption coefficients were varied in order to determine how much they affect the resulting sound field. This will determine how accurate the absorption coefficient needs to be in order to accurately recreate the environment to be modeled. Both of the buildings are made of the same corrugated metal material. Therefore the absorption coefficient is uniform over all the building surfaces. Several different absorption coefficients were identified in order to provide a variety of coefficients for comparison. A concrete or acoustically hard case is the first coefficient to be
considered. This is expected to be the most similar absorption coefficient to the metal sheets. A wood panel was considered for a slightly more absorptive case. A material called Sound Blox, an absorptive concrete, was used. The last case to be considered is a totally absorptive material case. The four absorption coefficients used in these simulations are shown in Table 5.3.
5.1.3.3 Diffusion Coefficients

Five different diffusion coefficients were chosen to observe the changes of the overall sound field from the amount of diffuse reflections. The diffusion coefficient was assumed to be constant along all frequencies as explained in section 4.1.5. The five coefficients considered were 0%, 10%, 20%, 50%, and 100%.

5.1.3.4 Microphone Locations

Several microphones were chosen for comparison. The microphones chosen were identified by NASA as CC, CG, CI, and CH [73]. A microphone on the incident side of the building (CC), is chosen as well as three microphones between the buildings (CG, CI, and CH). These microphones are identified on Figure 5.1. It should be noted here that microphone CI and CH are both inside the building for the simple geometry and are therefore not considered. This is indicative that for some microphones the simple geometry is completely inappropriate.

5.2 Comparison to Data

The same algorithm discussed in section 4.2 was used to compare the museum simulations to the measured data. The data must be high pass filtered as well. The frequency spectra of several microphones for several different boom events are examined to determine the appropriate frequency range for these buildings. This section will then describe the museum simulations and accuracy compared to the measured data.

5.2.1 Frequency Response

The first comparison is for the third boom event. Microphones CC and CG were compared with the measured data for both the simple and complex environments. These comparisons are shown in Figures 5.5 and 5.6 respectively.

For the third boom event at CC, the complex and simple environments’ frequency spectra are almost identical. The simulated and measured data seems to come into agreement at approximately 10 Hz. There is some discrepancy in the
higher frequencies of the frequency spectrum for this microphone which makes determining a firm cutoff a bit difficult. The discrepancies will be discussed in more detail in the following sections. For the comparison with CG there is also very little difference between the simple and complex simulations. The simulation seems to match up with the measured data at around 10 Hz.

The second comparison is for the fifth boom event. Microphones CC and CG were compared with the measured data for both the simple and complex environments. These comparisons are shown in Figures 5.7 and 5.8 respectively.

For the fifth boom event considered at CC, the complex and simple environments’ frequency spectra are almost identical. The simulated and measured data seems to come into agreement at approximately 25 Hz. There is some discrepancy in the higher frequencies of the frequency spectrum for this microphone which makes determining a firm cutoff difficult. The discrepancies will be discussed in more detail in the following sections. For the comparison with CG in Figure 5.8 a
Figure 5.6. Comparison for Boom 3 in the frequency domain between simple simulated, complex simulated and measured data for microphone CG.

difference between the simple and complex simulations is evident. Both simulations seem to match up with the measured data at around 150 Hz.

The third comparison is for the seventh boom event. Microphones CC was compared with the measured data for both the simple and complex environments. This comparison is shown in Figure 5.9. The angle of approach for this boom event is very shallow at only 3.7° which means that CG is in the shadow of the museum building.

For the seventh boom event considered at CC, the complex and simple environments’ frequency spectra are almost identical. The simulated and measured data seem to come into agreement at approximately 25 Hz. The agreement between the simulated and the measured data for this boom event does not have a particularly good agreement in general.

Each of the museum environment simulations seem to match up to the measured data around 25 Hz except for the boom 5 Microphone CG comparison in Figure
Figure 5.7. Comparison for Boom 5 in the frequency domain between simple simulated, complex simulated and measured data for microphone CC.

which matches around 150 Hz. To take a conservative approach 150 Hz was taken as the high pass frequency below which the ray trace method is questionable. This was chosen not only because it was the most conservative comparison of the museum microphones but because it was comparable to the EM building high pass frequency discussed in section 4.2.1.1. The overall dimensions of the museum building are on the same order as those used in the EM building, and so it is reasonable to assume that a similar high pass filter frequency would be appropriate for the museum environment as well.

5.2.2 Boom Event 3 Microphone CC

Microphone CC was on the incident side of the museum building receiving a direct sonic boom, a ground reflection and reflections of the front of the building. It is expected that the comparison here would have a similar accuracy to the microphones
examined for the Environmental Management building. This section examines the 0% diffuse case and the 100% diffuse case using the same algorithm for comparison described in section 4.2.2.

### 5.2.2.1 Overall Waveform Shape

The overall shape of each simulation compared to the measured data needs to be examined. Simulations for each combination of parameters were performed for this microphone. For the sake of examination the simulations have been grouped according to coefficient of diffusion.

Figure 5.10 shows the waveform shape with 0% diffuse reflections compared to the measured data. The overall shape of the simulations do not match the measured data very well. In addition, the amplitude is substantially overpredicted.

Figures 5.11 and 5.12 show the close up on the individual shocks in the signal to get a better idea of how the shape of the signals compare. The first event in
Figure 5.9. Comparison for Boom 7 in the frequency domain between simple simulated, complex simulated and measured data for microphone CC.

Figure 5.11 shows moderate agreement. The amplitude is still overpredicted by the simulation.

Figure 5.12 shows the second shock to have moderate agreement. The amplitude is still substantially overpredicted by the simulation.

Because the totally specular case significantly overpredicts the amplitude the other extreme case of totally diffuse was examined for comparison. Figure 5.13 shows the shape of the 100% diffusion simulations compared to the measured data. The overall shape of the simulated pressure signal does not show good agreement with the measured data. This simulation does not include any reflected energy and this simulation overpredicts the amplitude.

Figures 5.14 and 5.15 show a close-up on the individual shocks in the signal. The first shock event in Figure 5.14 shows moderate agreement. The amplitude is overpredicted by the simulation.

Figure 5.15 shows the second shock to have moderate agreement. The ampli-
Figure 5.10. Third boom event comparison between 0% diffusion simulations for CC.

Figure 5.11. Third boom event comparison between 0% diffusion simulations for CC, first shock event.
The poor comparison of overall waveform shape was clearly shown in this section. The next section will provide quantitative comparisons for this boom event.

5.2.2.2 Direct and Reflected Boom

5.2.2.2.1 Time Delay Since the first boom for CC is the first boom event to be recorded for this environment the time delay is not considered. All subsequent delays are relative to this arrival.

5.2.2.2.2 Duration The duration of the third boom event recorded at Microphone CC was calculated. Table 5.4 presents the percent error of the duration when compared with the measured data. There is less than one percent error, and the model is considered to predict this aspect well.

5.2.2.2.3 Peak Values The peak values are examined next. Table 5.5 presents the percent error of all the simulations when they are compared to the measured
Figure 5.13. Third boom event comparison between 100% diffusion simulations for CC.

Table 5.4. Percent Error of the duration of the third boom event for all simulations as compared to the measured data for the third boom event at CC.

**SIMPLE ENVIRONMENT**

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<td>-0.022</td>
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</tr>
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**COMPLEX ENVIRONMENT**

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</table>
Figure 5.14. Third boom comparison between 100% diffusion simulations for CC, first shock event.

data for the simple environment. Each amplitude is well over 200% error.

Table 5.6 presents the percent error of all the simulations when they are compared to the measured data for the complex environment. There are only very small differences between the simple environment peak numbers and the complex environment peak numbers. Both environments show poor agreement with the measured data.
Third Boom Event CC Comparison of Simulated and Measured Data for 100% Diffusion Event 2

Figure 5.15. Third boom comparison between 100% diffusion simulations for CC second shock event.
Table 5.5. Percent Error of the peak values of the direct and reflected boom event at CC for all simulations as compared to the measured data for the third boom event.

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</table>
Table 5.6. Percent Error of the peak values of the direct and reflected boom event at CC for all simulations as compared to the measured data for the third boom event.

**ALL HARD ABSORPTION**

<table>
<thead>
<tr>
<th>Diffusion</th>
<th>0 %</th>
<th>10 %</th>
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**WOOD PANEL ABSORPTION**

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**SOUND BLOX ABSORPTION**

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**ALL SOFT ABSORPTION**

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<td>219</td>
<td>219</td>
<td>219</td>
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<td>210</td>
<td>210</td>
<td>210</td>
<td>209</td>
<td>208</td>
</tr>
</tbody>
</table>
To determine if the problem with the simulation is unique to the boom event or if it is universal to the environment another boom event was examined. When choosing the boom for the second simulation in addition to the criteria used to rate the booms, the general presence of pressure doubling between the far field microphone and the microphone directly next to the building was looked for. The fifth recorded boom event was chosen for this reason.

5.2.3 Boom Event 5 Microphone CC

Again, microphone CC was on the incident side of the museum building receiving a direct sonic boom, a ground reflection and reflections from the front of the building. It is expected that the comparison here would have a similar accuracy to the microphones examined for the Environmental Management building assuming that the simulation problems were unique to the third boom event. Because of the multiple peaks at the shock events it was difficult to determine the positive and negative peak values for this comparison. The first major peak of the measured data was used as the positive front peak even if it was not the highest peak. For the simulated data the value of the peak closest to the arrival time of the measured peak was used. Aside from these differences, the same algorithm for comparison discussed in Section 4.2.2 was used to compare the simulations to the measured data. Only the 0% and 100% diffusion simulations were shown because the comparison to the measured data still showed significant problems.

5.2.3.1 Overall Waveform Shape

The overall shape of each simulation compared to the measured data needs to be examined. Simulations for each combination of parameters were performed for this microphone. For the sake of examination the simulations have been grouped according to the amount of diffusion.

Figure 5.16 shows the waveform shape of the 0% diffuse reflections compared to the measured data. The overall shape of the simulations show moderate agreement but the shocks are significantly underpredicted.

Figures 5.17 and 5.18 show the close up on the individual shocks in the signal to get a better idea of how the shape of the signals compare. The first event in
Figure 5.16. Fifth boom event comparison between 0% diffusion simulations for CC.

Figure 5.17 shows the disagreement in the shock event clearly.

Figure 5.18 shows the second shock agreement. A similar disagreement between the measured signal and the simulations is shown.

Figure 5.19 shows the shape of the 100% diffusion simulations compared to the measured data. The overall shape of the simulated pressure signal shows poor agreement with the measured data particularly for the all hard and wood paneled cases.

Figures 5.20 and 5.21 show a close-up on the individual shocks in the signal. The first shock event in Figure 5.20 clearly shows the discrepancies in the shape of the shock event.

Figure 5.21 shows the second shock agreement. A similar disagreement between the measured signal and the simulations is shown.

The poor comparison of overall waveform shape was clearly shown in this section. The next section will provide quantitative comparisons for this boom event.
Figure 5.17. Fifth boom event comparison between 0% diffusion simulations for CC, first shock event.

5.2.3.2 Direct and Reflected Boom

5.2.3.2.1 Time Delay  Since the first boom for CC is the first boom event to be recorded for this environment the time delay is not considered. All subsequent delays are relative to this arrival.

5.2.3.2.2 Duration  The duration of the fifth boom event recorded at microphone CC was calculated. Table 5.7 presents the percent error of the duration when compared with the measured data. There is less than one percent error and the model is considered to predict this aspect well.

5.2.3.2.3 Peak Values  The peak values are examined next. Table 5.8 presents the percent error of all the simulations when they are compared to the measured data for the simple environment.

Table 5.9 presents the percent error of all the simulations when they are compared to the measured data for the complex environment. There are only very
Figure 5.18. Fifth boom event comparison between 0% diffusion simulations for CC, second shock event.

Figure 5.19. Fifth boom event comparison between 100% diffusion simulations for CC.
**Figure 5.20.** Fifth boom comparison between 100% diffusion simulations for CC, first shock event.

**Table 5.7.** Percent Error of the duration of the fifth boom event for all simulations as compared to the measured data at CC.

<table>
<thead>
<tr>
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<th>Absorption Coefficient</th>
</tr>
</thead>
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<td></td>
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<tr>
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<td>-0.05</td>
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<tr>
<td>10%</td>
<td>-0.05</td>
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<tr>
<td>50%</td>
<td>0.03</td>
</tr>
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</table>

<table>
<thead>
<tr>
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<th>Absorption Coefficient</th>
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<td></td>
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<td>100%</td>
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</table>
Figure 5.21. Fifth boom comparison between 100% diffusion simulations for CC, second shock event.

small differences between the simple environment peak numbers and the complex environment peak numbers.

The percent error observed for the amplitude shows that the amplitude is consistently under-predicted. The errors are all under 100% which shows a better agreement with the measured data than the third boom event. However all of the amplitude errors are between 50% and 85% which is considered to be, at best, a mediocre agreement.

5.2.4 Discussion

At this point enough of this environment has been examined to draw the conclusion that the model is not accurately simulating the measured data. The location of the microphone examined in this section should not be affected by the presence of multiple buildings. It would be expected that for this microphone the agreement would be comparable to the EM building if all of the other factors were the same.

Examining the factors that are different and may cause substantial differences in
Table 5.8. Percent Error of the peak values of the direct and reflected boom event at CC for all simulations as compared to the measured data for the simple environment for the fifth boom event.

**ALL HARD ABSORPTION**

<table>
<thead>
<tr>
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**WOOD PANEL ABSORPTION**

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**SOUND BLOX ABSORPTION**

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**ALL SOFT ABSORPTION**

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the sound field will determine some further limitations of this model. The biggest difference between the environments is their location on the boom carpet. The EM building is more centrally located on the carpet while the museum is located near the edge of the carpet for most of the boom events. In fact, the physical location of the environment was the reason that about half of the booms were not recorded at all. At the edge of the carpet the signature tends to change from the shape observed on the ground track [2]. The recorded signature at the museum building has very little high frequency energy. Because the ray-trace model is a
Table 5.9. Percent Error of the peak values of the direct and reflected boom event at CC for all simulations as compared to the measured data for the fifth boom event.

### ALL HARD ABSORPTION

<table>
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### WOOD PANEL ABSORPTION

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### SOUND BLOX ABSORPTION

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### ALL SOFT ABSORPTION

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</table>

For boom 3, the signature measured at the far field microphone, used here as the input, does not have half the pressure of the measured microphone in front of the building. Even in the high frequency portion of the input boom, the expected doubling of pressure due to the reflections off the building is not observed. This may be indicative of some local atmospheric effects causing additional attenuation. Looking more closely at the amplitude predictions, even the completely absorptive case yields a 200% overprediction of the amplitude which means that the energy high frequency approximation this will significantly affect the results.
is being attenuated by more than the assumed air absorption, surface absorption, or diffusion.

The overall shape of the third boom event did not match well with the measured data. When zooming in on the shock events themselves however the shocks, while not perfect showed a moderate agreement.

To determine if the discrepancies were limited to the third boom event or if other boom events with slightly different atmospheric conditions and locations along the carpet might yield more acceptable results, the fifth boom event was examined. As a quick check, the far field microphone pressure for the remaining boom events was compared to the incident microphone pressure to see if there was evidence of pressure doubling near the wall. The best boom event that showed this as well as meeting the other criteria was boom event 5.

The overall waveform shape of the fifth boom event showed slightly better agreement than the third boom event particularly for the 0% diffusion case. When zooming in on the individual shock events, the overall shape did not match well. The measured data showed amplitude values significantly higher than the simulated values for this boom. The amplitude was consistently underpredicted by values ranging from about 50% to 85%. This shows a slightly better agreement than the third boom event but overall the comparison is still poor. In this boom event the presence of high frequency energy is very small which also negatively affects the results for this simulation due to the high frequency approximation.

The most likely explanation for the discrepancies with the museum environment is the physical location of the environment on the boom carpet. Because the museum is at the edge of the carpet the boom no longer behaves consistently. This close to the carpet edge, the arrival angle is much harder to determine and may change significantly with location. The shape of the boom is also significantly changed at the edge of the carpet and contains less high frequency content. In conclusion, this environment has demonstrated that the model does not accurately predict the sound field when located at the edge of the carpet and all future use of this model should be limited to environments closer to the ground track.

Another likely culprit that may be contributing to the inaccuracy of this comparison would be strong local atmospheric effects. These atmospheric effects may be the reason for the varying amplitudes between the far field microphone and
the incident side of the building microphone. It may be possible in the future to augment this code to include more detailed atmospheric conditions, particularly in situations when meteorological data is well known. In its current form, however, the atmosphere is assumed to be homogeneous with a constant temperature profile and with no wind over the distances propagated. Obviously this is not usually the case but for mild weather conditions this can be assumed. When the local atmospheric effects start to increase, particularly wind speed, these effects play a more crucial role.

In chapter 6, sonic boom propagation in an urban canyon will be examined. For the following environments, no measured data is available. However, a number of parameters were examined to determine the effect on the overall sound field.
In order to determine the effect of that an urban environment has on the sound field created by a sonic boom, a variety of urban environments are compared to an environment without buildings. Several features were examined in detail including elevation angle of the boom, azimuthal angle of the boom, diffusion, height of the buildings, and width of the canyons. This chapter will discuss the arrangements of the different environments, the input boom signal and the resulting sound field compared to an environment without buildings. It is important to note when examining these simulations that diffraction is not currently present in the model. This may significantly affect the results when included and will make the lower frequencies much more accurate as well. Cho is currently working on a hybrid model to include diffraction in the lower frequencies \[76\]. Lind is also working on a different model to include high frequency diffraction. This model also has potential for diffraction to be included at a later date.

6.1 Description of Environment

The environments in this chapter were taken to resemble real world urban environments. Two environments in particular are examined in detail. A simplified version of an urban street is used as well as a four way intersection. The versions of these are simplified because they show no differences in the building sizes along a city block and shows no separation between each of the buildings. They are modeled as a single building the size of a block. Figure \[6.1\] shows the simulation
environments. The length of 76 meters was chosen for the length of the canyon. This was a reasonable size for a simulation while still being a large enough environment to accurately simulate a city block. Sizes of canyons in places like New York’s financial district were examined to determine an appropriate size. Figure 6.2 shows a Google Earth satellite image of this area. The small yellow line measures 42 meters which would be the smallest urban canyon that is of the order of both simulation geometries created. There are several parameters to be examined: diffusion, azimuthal arrival angle, elevation arrival angle, building height, and canyon width.

Figure 6.1. Environments considered for this chapter. Environment 1 is the single city block environment. Environment 2 is the four way intersection environment. Approximate microphone locations are denoted.
6.1.1 Input Signal

These simulations utilized the same input wave as was used for the Environmental Management Building in Chapter 4. This boom was used because it was a realistic boom with a substantial amount of high frequency energy. An important characteristic of the input signal is the arrival direction. In order to determine the effect of various arrival angles this parameter was varied. The elevation angles were 20° and 40° down from the horizontal. The azimuthal angle varied from 0° to 45° to 90°. For the 4 way intersection, both the 0° and 90° are the same because the environment is symmetrical so only one of these angles was considered. The initial ray spacing is 0.06 meters. The input signal is shown in Figure 6.2. The sampling
Table 6.1. Octave band values for the acoustically hard absorption coefficients.

<table>
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<th>125 Hz</th>
<th>250 Hz</th>
<th>500 Hz</th>
<th>1 kHz</th>
<th>2 kHz</th>
<th>4 kHz</th>
<th>8 kHz</th>
</tr>
</thead>
<tbody>
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<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.03</td>
<td>0.03</td>
</tr>
</tbody>
</table>

There are several parameters that were consistent throughout the environment. The atmospheric pressure was standard at 1 atm. The temperature is 20° Celsius and there is 20% relative humidity. The speed of sound was assumed to be 343.0 meters per second. Each of these parameters were considered to be standard atmosphere and temperature. The ground plane is still considered to be flat and acoustically hard with a height of 0 meters for each of the simulations. The ground is also considered to have 0% diffuse reflections. Each of the buildings was assumed to be acoustically hard. The absorption coefficients used were comparable to painted concrete and are given by Table 6.1.

6.1.3 Variables

Several parameters were varied to determine the effect on the sound level. Two parameters that were varied were the direction angles of the incoming boom. Two elevation angles were considered, 20° and 40°, measured down from the horizontal. Three azimuthal angles were considered, 0°, 45°, and 90°. These are measured so that 90° is oriented along the urban canyon and 0° is perpendicular to the canyon. The height of the buildings was also varied. Four heights of 3 meters, 6 meters, 12 meters and 24 meters were considered. These heights were chosen to model a one story building, a two story building, a four story building and an eight story building, with one story being 3 meters. The width of the canyon was also varied. The widths of 5.5 meters, 9 meters, and 16 meters were chosen to model a single lane of traffic, two lanes of traffic and four lanes of traffic with a one meter wide sidewalk on each side. The last variable that was considered was the diffusion. The diffusion coefficient was 0 or 0.50. These values were chosen to determine the
difference between the sound field without diffusion and 50% diffusion which was the most accurate result when examining the EM building in chapter 4.

### 6.1.4 Frequency Range

The metric used for comparison in this chapter is PLdB. This requires that the signals are not high-pass filtered as they were in previous chapters. For the taller buildings, 12 meter and 24 meter, the ray-trace method will be accurate due to the large dimensions, except at the lowest frequencies. There may be additional inaccuracy for the lower height buildings due to the high frequency approximation of the model.

### 6.2 Single City Block

The first environment to examine is the single city block or the urban canyon. There are several interesting elements that will be discussed in this section to describe the sound levels in the canyon. There are three particular areas of interest: The shapes of the signals, the PLdB at ear height on the sidewalks, and the pressure loading on the walls.

#### 6.2.1 Signal Shapes

Due to the linear nature of the propagation method the shape does not change significantly when only specular reflections are included. The arrival times of the various reflections and amplitudes are the biggest variables in the shape for the specular only runs. To demonstrate the differences in the shapes for each variable a few sample signatures are shown here. The signatures are taken from a microphone on the far sidewalk 15 meters along the canyon at ear height or Microphone A and a microphone directly in the center of the canyon on the far sidewalk at ear height referred to as Microphone B. See Figure 6.1 for these locations. Figure 6.3 shows the signal shape for Microphone A for all heights with a width of 5.5 meters, an azimuthal angle of $0^\circ$, an elevation angle of $40^\circ$ and 0% diffusion. Figure 6.4 shows the signal shapes for Microphone B with the same parameters. The biggest differences between the various heights are the arrival times and the
amplitudes. The arrival times of the different reflections within each signature are not different enough from each other to be visible. Notice that the Microphone A and Microphone B signals are identical.

The wide range of amplitudes seen in Figure 6.3 and 6.4 and in additional figures to follow is due to the number of reflections composing the received signals. As the number of included reflections increases, the superposition of the multiple signals increases the overall received amplitude. This is further discussed in section 6.2.2.

![Graph](image)

**Figure 6.3.** Comparison of the Microphone A signal shape for all heights with a width of 5.5 m, an azimuthal angle of 0°, an elevation angle of 40° and 0% diffusion.

Figure 6.5 shows the signal shape for Microphone A for all widths with a height of 12 m, an azimuthal angle of 0, an elevation angle of 40° and 0% diffusion. Figure 6.6 shows the signal shapes for Microphone B with the same parameters. The amplitudes of these signatures are very different. Obviously, the microphone for the canyon with a width of 9 meters is in a shadow zone. Having strong shadow
zones is expected for a model without diffraction. A very slight indication of the arrival times between the different reflections is visible in the canyon width of 16 meters. The Microphone A and Microphone B signals are identical.

Figure 6.7 shows the signal shape for Microphone A for both elevation angles with a height of 12 meters, an azimuthal angle of 0°, a width of 5.5 meters and 0% diffusion. Figure 6.8 shows the signal shapes for Microphone B with the same parameters. The biggest difference between these signals are the amplitudes and the arrival times of the booms. The arrival times of the different reflections are not observable in the signals. The Microphone A and Microphone B signals appear to be identical.

Figure 6.9 shows the signal shape for Microphone A for all azimuthal angles with a height of 12 meters, an elevation angle of 40°, a width of 5.5 meters and 0% diffusion. Figure 6.10 shows the signal shapes for Microphone B with the same
Figure 6.5. Comparison of the Microphone A signal shape for all widths with a height of 12 m, an azimuthal angle of 0°, an elevation angle of 40° and 0% diffusion.

parameters. The biggest differences between these signals are the arrival times of the booms and amplitudes. There is a visible difference in arrival time of the different reflections within the signal for the 90° azimuthal angle. The Microphone A and Microphone B signals are identical.

The received signals including diffuse reflections show a significant change in shape. To demonstrate the changes in shape with all variables the same signals included in Figures 6.3 - 6.10 are also examined for 50% diffusion. Figure 6.11 shows the signal shape for Microphone A for all heights with a width of 5.5 m, an azimuthal angle of 0°, an elevation angle of 40° and 50% diffusion. Figure 6.12 shows the signal shapes for Microphone B with the same parameters. The shape for the height of 6 meters shows a significant change in the shape of the signal with the end shock being sharpened and the center slope flattening out. The other signatures still look like N waves with some mild rounding. The height of 24 meters
Figure 6.6. Comparison of the Microphone B signal shape for all widths with a height of 12 m, an azimuthal angle of 0°, an elevation angle of 40° and 0% diffusion.

shows that the N wave is almost completely reduced. Microphone B shows very similar signal shapes. There are observable differences especially in the 6 meter height case where the Microphone B signal is very different than the Microphone A case.

Figure 6.13 shows the signal shape for Microphone A for all widths with a height of 12 meters, an azimuthal angle of 0°, an elevation angle of 40° and 50% diffusion. Figure 6.14 shows the signal shapes for Microphone B with the same parameters. The shapes here are significantly different than the input waveform. Particularly the canyon width of 9 meters is extremely different. This is because there are no specular reflections recorded at the microphone. All of the signal results from diffuse reflections. The other canyon width produce signals with shapes that still resemble N-waves however the shape is visibly changed with significantly smaller amplitudes. Microphones A and B show visible differences between each of the
Figure 6.7. Comparison of the Microphone A signal shape for both elevation angles with a height of 12 meters, a width of 5.5 meters, an azimuthal angle of 0° and 0% diffusion.

signal shapes, most noticeably in the case for the canyon width of 9 meters.

Figure 6.15 shows the signal shape for Microphone A for both elevation angles with a height of 12 meters, an azimuthal angle of 0°, a width of 5.5 meters and 50% diffusion. Figure 6.16 shows the signal shapes for Microphone B with the same parameters. The elevation angle of 20° does not register very much of a signal for either microphone. The elevation angle of 40° does show an N-wave of a smaller amplitude than the specular reflections. The signals for Microphone A and Microphone B are very similar.

Figure 6.17 shows the signal shape for Microphone A for all azimuthal angles with a height of 12 meters, an elevation angle of 40°, a width of 5.5 meters and 50% diffusion. Figure 6.18 shows the signal shapes for Microphone B with the same parameters. There is no change in shape for the 90° case however the 45° case
has a significant reduction in amplitude. The shape for the 45° azimuthal angle is significantly different than an N wave with significant flattening in the tail end of the pressure between the shocks.

There is a striking difference between the 0% diffusion and the 50% diffusion cases. To compare them more closely Figure 6.19 shows both the diffusion cases for Microphone A with a height of 12 meters, a width of 5.5 meters, an elevation of 40°, and an azimuthal angle of 0°. Figure 6.20 shows both the diffusion cases for Microphone B with a height of 12 meters, a width of 5.5 meters, an elevation of 40 meters, and an azimuthal angle of 0°. The amplitudes of these signals are very different. The amplitude is much smaller for the 50% diffusion case. There also appears to be a longer rise time for the diffusion case. This is because with 0% diffusion substantial specular reflections are reaching the receivers. With the

Figure 6.8. Comparison of the Microphone B signal shape for both elevation angles with a height of 12 meters, a width of 5.5 meters, an azimuthal angle of 0° and 0% diffusion.
50% diffusion on each reflection the amplitude of the specular reflections reaching the receivers is greatly reduced.

Figure 6.9. Comparison of the Microphone A signal shape for all azimuthal angles with a height of 12 meters, a width of 5.5 meters, an elevation angle of 40° and 0% diffusion.
Figure 6.10. Comparison of the Microphone B signal shape for all azimuthal angles with a height of 12 meters, a width of 5.5 meters, an elevation angle of 40° and 0% diffusion.
Figure 6.11. Comparison of the Microphone A signal shape for all heights with a width of 5.5 m, an azimuthal angle of 0°, an elevation angle of 40° and 50% diffusion.
Figure 6.12. Comparison of the Microphone B signal shape for all heights with a width of 5.5 m, an azimuthal angle of 0°, an elevation angle of 40° and 50% diffusion.
Figure 6.13. Comparison of the Microphone A signal shape for all widths with a height of 12 m, an azimuthal angle of 0°, an elevation angle of 40° and 50% diffusion.
Figure 6.14. Comparison of the Microphone B signal shape for all widths with a height of 12 m, an azimuthal angle of 0°, an elevation angle of 40° and 50% diffusion.
Figure 6.15. Comparison of the Microphone A signal shape for both elevation angles with a height of 12 meters, a width of 5.5 meters, an azimuthal angle of 0° and 50% diffusion.
Figure 6.16. Comparison of the Microphone B signal shape for both elevation angles with a height of 12 meters, a width of 5.5 meters, an azimuthal angle of 0° and 50% diffusion.
Figure 6.17. Comparison of the Microphone A signal shape for all azimuthal angles with a height of 12 meters, a width of 5.5 meters, an elevation angle of 40° and 50% diffusion.
Figure 6.18. Comparison of the Microphone B signal shape for all azimuthal angles with a height of 12 meters, a width of 5.5 meters, an elevation angle of 40° and 50% diffusion.
Figure 6.19. Comparison of the Microphone A signal shape between 0% and 50% diffusion with a height of 12 meters, a width of 5.5 meters, an elevation angle of 40° and an azimuthal angle of 0°.
Figure 6.20. Comparison of the Microphone B signal shape between 0% and 50% diffusion with a height of 12 meters, a width of 5.5 meters, an elevation angle of 40° and an azimuthal angle of 0°.
6.2.2 Sidewalks

The next area of interest is the hearing height on the sidewalk. Currently PLdB is the most widely used measure of annoyance for sonic booms in America so this was the metric used to examine this area. The current psychoacoustic metrics are discussed in detail in section 2.2.1. There are a few interesting features to discuss for these sidewalks. The first thing to discuss is that the sound level is does not increase drastically with the increase in height of the canyon. The sound only records between 1 and 4 reflections. This is dependent on the height, the width and the arrival angles of boom. Figures 6.21, 6.22, 6.23, and 6.24 show the ray trace into the canyons for all heights. For the three meter canyon in Figure 6.21 there are four reflections recorded at the receiver. In Figure 6.22 the receiver only sees one reflection. In Figure 6.23 only three reflections are seen at the receiver. In Figure 6.24 four reflections are seen by the receiver. These figures show that even as the height increases there is not necessarily an increase in the sound levels at the sidewalk. In other locations along the walls there are also very distinct shadow zones where no sound is recorded at all. Again, these shadow zones appear because diffraction is not included in the present model. The PLdB at the far sidewalk for specular reflections varies from 0 dB to 94 dB. Without buildings the PLdB is about 89 dB. This shows that the buildings can add to the PLdB about 5 dB or can shield the areas completely. The near sidewalk shows similar results.

Figure 6.21. A ray trace of a 3 m canyon with an azimuthal angle of 0°, an elevation angle of 40°, and a width of 5.5 meters. The white dot is the location of the sidewalk receivers.

Another interesting thing to note is a boom with a 90° azimuthal angle or a boom that travels down the canyon is the same as a boom propagated without buildings. The 0° azimuthal angle is uniform across the entire length of the canyon. The 45° azimuthal angle gives a pattern that alternates between zero and a higher number for the specular reflection case. Figure 6.25 shows the ray trace for the
Figure 6.22. A ray trace of a 6 m canyon with an azimuthal angle of 0°, an elevation angle of 40°, and a width of 5.5 meters. The white dot is the location of the sidewalk receivers.

Figure 6.23. A ray trace of a 12 m canyon with an azimuthal angle of 0°, an elevation angle of 40°, and a width of 5.5 meters. The white dot is the location of the sidewalk receivers.

45° azimuthal angle. This shows the situation where the elevation angle is 0° to better illustrate the cause of the pattern. The pattern of hits and shadow zones is illustrated very well by this figure. There are some slight differences between this figure example and the actual simulations which have a different elevation angle.

Figure 6.26 shows the PLdB along the length of the canyon. As the height increases the pattern becomes more obvious. This is due to the downward elevation angle. The sound from above can reach the receivers more easily for the shorter buildings. Figure 6.27 shows the near sidewalk PLdB along the canyon. The near sidewalk shows the same pattern along the canyon but with a spatially complementary sound level pattern.

Another important feature to discuss about the sidewalk PLdB levels is the
Figure 6.24. A ray trace of a 24 m canyon with an azimuthal angle of 0°, an elevation angle of 40°, and a width of 5.5 meters. The white dot is the location of the sidewalk receivers.

pattern of the diffuse energy values along the sidewalk. Figure 6.28 compares the non-diffuse to the diffuse energy example. There is a clear constructive and destructive pattern in the diffuse energy that is not present in specular reflection case. This has to do with the symmetry of the environment and the distribution of the diffuse energy. These factors provide a situation where the phase can add or subtract pressures. Figure 6.29 shows a similar pattern for the near sidewalk. There is some variation on the sound levels in addition to the constructive and destructive pattern. This has to do with the non-zero radius of the receiver and the digital nature of the sampling of the initial boom. As the normalization factor discussed in section 3.2.1.2.1 gets bigger these variations become smaller.

Figure 6.30 shows all heights for a canyon width of 5.5 meters, an azimuthal angle of 0°, and an elevation angle of 40°. The constructive and destructive pattern along the canyon is still present though it is more obvious for some heights than
Figure 6.25. A ray trace for the 45° to demonstrate the pattern shown in the sound levels. Notice the periodic shadow zones in this top down view.

for others. Figure 6.31 shows similar patterns on the near sidewalk. The edges of the canyon seem to have higher sound levels than the center for several heights. This is generally ignored for this work because the simulation is less accurate near the edges of the building due to a lack of diffraction. There does not appear to be an overall trend in the sound level related to the height.

Figure 6.32 shows all azimuthal angles for a canyon height of 12 meters, a canyon width of 5.5 meters, and an elevation angle of 40°. The sound levels for the azimuthal angles of 0° and 45° are significantly below the PLdB for an environment with no buildings, a consistent PLdB of 89 dB. Azimuthal angle of 90° is the same as an environment without buildings. Notice that the dip in the sound level for the 45° azimuthal angle case is still present but it does not go all the way to zero and it is much less pronounced than for the purely specular case. Figure 6.33 shows
Figure 6.26. PLdB values along the far sidewalk of the canyon for the 45° azimuthal angle to demonstrate the pattern shown in the sound levels. Notice the pattern becomes more obvious as the height increases.

A similar pattern on the near sidewalk. The azimuthal angle of 0° shows a strong constructive and destructive pattern.

Figure 6.34 shows both elevation angles for a canyon height of 12 meters, a canyon width of 5.5 meters, and an azimuthal angle of 0° for the far sidewalk. The sound levels are significantly below that of an environment without buildings. The elevation angle of 20° gives particularly low values of only about 50 PLdB. The 20° case has an observable pattern along the length of the sidewalk. The pattern is much more prominent than in the 40° case. Figure 6.35 shows a similar pattern on the near sidewalk but with the 40° case having a much more prominent pattern.

Figure 6.36 shows all heights for a canyon width of 5.5 meters, an azimuthal angle of 45° and an elevation angle of 40°. Notice that the pattern seen for specular reflections in Figure 6.26 is not nearly as well defined in the diffusion case shown.
Figure 6.27. PLdB values along the near canyon for the 45° azimuthal angle to demonstrate the pattern shown in the sound levels. Notice the pattern becomes more obvious as the height increases.

here. The shadow zones are no longer going all the way to zero. Figure 6.37 demonstrates this for the near sidewalk.
Figure 6.28. Comparison of PLdB values along the far sidewalk for the 6 meter high, 5.5 meters wide, 0° azimuthal angle and elevation angle of 40° for both diffusion cases.
Figure 6.29. Comparison of PLdB values along the near sidewalk for the 6 meter high, 5.5 meters wide, 0° azimuthal angle and elevation angle of 40° for both diffusion cases.
Figure 6.30. Comparison of PLeqdB values along the far sidewalk for all heights, canyon width of 5.5 meters, azimuthal angle of 0° and elevation angle of 40°.
Figure 6.31. Comparison of PLdB values along the near sidewalk for all heights, canyon width of 5.5 meters, azimuthal angle of 0° and elevation angle of 40°.
Figure 6.32. Comparison of PLdB values along the far sidewalk for all azimuthal angles for a height of 12 meters, canyon width of 5.5 meters, and elevation angle of 40°.
Figure 6.33. Comparison of PLdB values along the near sidewalk for all azimuthal angles for a height of 12 meters, canyon width of 5.5 meters, and elevation angle of 40°.
Figure 6.34. Comparison of PLdB values along the far sidewalk for both elevation angles for a height of 12 meters, canyon width of 5.5 meters, and azimuthal angle of 0°.
Figure 6.35. Comparison of PLdB values along the near sidewalk for both elevation angles for a height of 12 meters, canyon width of 5.5 meters, and azimuthal angle of 0°.
Figure 6.36. Comparison of PLdB values along the far sidewalk for all heights for a canyon width of 5.5 meters, an azimuthal angle of 45° and an elevation angle of 40°.
Figure 6.37. Comparison of PLdB values along the near sidewalk for all heights for a canyon width of 5.5 meters, an azimuthal angle of 45° and an elevation angle of 40°.
6.2.3 Wall

The last important feature to discuss is the pressure loading on the walls. Two building heights, 6 meters and 24 meters are examined in this section. Each wall area shown here has a figure showing only the peak pressure at each receiver as well as an embedded animation that shows the pressure loading over time. Only the far wall is examined in this section because the near wall showed very similar results.

Figures 6.38, 6.39, 6.40, and 6.41 show the pressure loading for a 6 meter high building. Each of these figures assumes an elevation angle of 20° and a width of 5.5 meters. Figure 6.38 shows the pressure for specular reflections with an azimuthal angle of 0°. This figure shows some areas of slightly lower sound levels but overall a uniform pressure loading on the building. Figure 6.39 shows the pressure for specular reflections with an azimuthal angle of 45°. This figure shows the pattern of the 45° azimuthal angle clearly. Notice the stark shadow zone for the 45° case. Figure 6.40 shows the diffuse reflection result with an azimuthal angle of 0°. The maximum levels are much lower here than with only specular reflections. Figure 6.41 shows the diffuse reflection result with an azimuthal angle of 45°. These figures show that the stark shadow zones are blurred significantly. The overall sound level is much lower than for the specular reflection cases.

Figures 6.42, 6.43, 6.44 and 6.45 show the pressure loading for a 24 meter high building. Each figure assumes an elevation angle of 20° and a width of 5.5 meters. Figure 6.42 shows the pressure for specular reflections with an azimuthal angle of 0°. This figure shows a regular pattern traveling down the canyon. The pressure is reduced as it travels to the bottom of the canyon due to the absorption of the building surfaces. Figure 6.43 shows the pressure for specular reflections with an azimuthal angle of 45°. The stark shadow zones are shown very clearly here. The pattern observed on the sidewalk is extended into 2 dimensions here. Figure 6.44 shows the diffuse reflections with an azimuthal angle of 0°. Figure 6.45 shows the diffuse reflection result with an azimuthal angle of 45°. These figures show that the stark shadow zones are blurred significantly. The pressure loading is also less than for the purely specular cases.
Figure 6.38. Peak pressures along the far wall of a six meter tall building with an azimuthal angle of $0^\circ$ and an elevation of $20^\circ$ and a width of 5.5 meters with only specular reflections. To activate the animation click on the figure. The animation runs from 0.1 seconds to 0.75 seconds and then loops.

Figure 6.39. Peak pressures along the far wall of a six meter tall building with an azimuthal angle of $45^\circ$ and an elevation of $20^\circ$ and a width of 5.5 meters with only specular reflections. To activate the animation click on the figure. The animation runs from 0.1 seconds to 0.75 seconds and then loops.
Figure 6.40. Peak pressures along the far wall of a six meter tall building with an azimuthal angle of 0° and an elevation of 20° and a width of 5.5 meters with 50% diffusion. To activate the animation click on the figure. The animation runs from 0.1 seconds to 0.75 seconds and then loops.

Figure 6.41. Peak pressures along the far wall of a six meter tall building with an azimuthal angle of 45° and an elevation of 20° and a width of 5.5 meters with 50% diffusion. To activate the animation click on the figure. The animation runs from 0.1 seconds to 0.75 seconds and then loops.
Figure 6.42. Peak pressures along the far wall of a 24 meter tall building with an azimuthal angle of 0° and an elevation of 20° and a width of 5.5 meters with only specular reflections. To activate the animation click on the figure. The animation runs from 0.1 seconds to 0.75 seconds and then loops.

Figure 6.43. Peak pressures along the far wall of a 24 meter tall building with an azimuthal angle of 45° and an elevation of 20° and a width of 5.5 meters with only specular reflections. To activate the animation click on the figure. The animation runs from 0.1 seconds to 0.75 seconds and then loops.
Figure 6.44. Peak pressures along the far wall of a 24 meter tall building with an azimuthal angle of 0° and an elevation of 20° and a width of 5.5 meters with 50% diffusion. To activate the animation click on the figure. The animation runs from 0.1 seconds to 0.75 seconds and then loops.

Figure 6.45. Peak pressures along the far wall of a 24 meter tall building with an azimuthal angle of 45° and an elevation of 20° and a width of 5.5 meters with 50% diffusion. To activate the animation click on the figure. The animation runs from 0.1 seconds to 0.75 seconds and then loops.
6.3 Four Way Intersection

The second environment to examine is the four way intersection. There are several interesting elements that will be discussed in this section to describe the sound levels in the canyon. There are three particular areas of interest: The shapes of the signals, the PLdB at ear height on the sidewalks and the pressure loading on the walls. Only the canyon that is perpendicular with the direction of the boom is examined. Due to the symmetry of the environment only azimuthal angles of 0° and 45° are considered. The buildings in this case are 30 meters wide. This means that the canyon is only 65.5 meters long for the 5.5 meter width. For the 16 meter width it is comparable to the single canyon length of 76 meters long.

6.3.1 Signal Shapes

Due to the linear nature of the propagation method the shape does not change significantly when only specular reflections are included. The arrival times of the various reflections and amplitudes vary considerably for the specular only runs. To demonstrate the differences in the signal shapes for each variable a few sample signatures are shown here. The signatures are taken from a microphone on the far sidewalk 15 meters along the canyon at ear height referred to as Microphone A and a microphone directly in the center of the canyon on the far sidewalk at ear height referred to as Microphone B. These microphone locations were shown in Figure 6.1. Figure 6.46 shows the signal shape for Microphone A for all heights with a width of 5.5 meters, an azimuthal angle of 0°, an elevation angle of 40° and 0% diffusion. Figure 6.47 shows the signal shapes for Microphone B with the same parameters. The biggest differences between the various heights are the arrival times of the booms and the amplitudes. The arrival times of the different reflections are not different enough from each other to be visible in the signatures for Microphone A. For Microphone B the ground reflection arrival time is distinctly seen in the signature. Microphone A and Microphone B are visibly different. This is because Microphone B is in the middle of the intersection so there are no reflections from the buildings at this location.

Figure 6.48 shows the signal shape for Microphone A for all widths with a height of 12 meters, an azimuthal angle of 0°, an elevation angle of 40° and 0%
**Figure 6.46.** Comparison of the Microphone A signal shape for all heights with a width of 5.5 meters, an azimuthal angle of 0°, an elevation angle of 40° and 0% diffusion. The Microphone A signals look very similar to the full canyon. The canyon width of 9 meters is still in a shadow zone. Microphone B shows that all widths show two reflections. The arrival times of the two reflections are evident in each of the Microphone B signatures.

Figure 6.49 shows the signal shapes for Microphone B with the same parameters. Microphone A signals look very similar to the full canyon. The canyon width of 9 meters is still in a shadow zone. Microphone B shows that all widths show two reflections. The arrival times of the two reflections are evident in each of the Microphone B signatures.

Figure 6.50 shows the signal shape for Microphone A for both elevation angles with a height of 12 meters, an azimuthal angle of 0°, a width of 5.5 meters and 0% diffusion. Figure 6.51 shows the signal shapes for Microphone B with the same parameters. Both elevation angles give results very similar to the signatures for the single canyon. Microphone B only records two arrivals. The 40° signals shows the ground reflection clearly. However, the 20° does not show the reflection.

Figure 6.52 shows the signal shape for Microphone A for both azimuthal angles with a height of 12 m, an elevation angle of 40, a width of 5.5 meters and 0% diffusion.
Figure 6.47. Comparison of the Microphone B signal shape for all heights with a width of 5.5 meters, an azimuthal angle of $0^\circ$, an elevation angle of $40^\circ$ and 0% diffusion. Figure 6.53 shows the signal shapes for Microphone B with the same parameters. The $0^\circ$ azimuthal angle shows a high amplitude while the $45^\circ$ azimuthal angle only shows a very small amplitude. Microphone B shows that there are two reflections for the $0^\circ$ azimuthal angle with an obvious difference in arrival time. The $45^\circ$ azimuthal angle however only shows one reflection because the ground reflection is blocked by the buildings in this case.

The signals including diffuse signals show a significant change in the shape of the signature. To demonstrate the changes in shape with all variables the same signals included in Figures 6.46 - 6.53 are discussed for 50% diffusion. Figure 6.54 shows the signal shape for Microphone A for all heights with a width of 5.5 meters, an azimuthal angle of $0^\circ$, an elevation angle of $40^\circ$ and 50% diffusion. Figure 6.55 shows the signal shapes for Microphone B with the same parameters. There are significant changes in the Microphone A signatures. The height of 24 shows
almost no signature at all. The 6 meter height building signature has changed significantly from an N-wave signal. The 12 meter height building has a flattening of the area between the shocks. The 3 meter high building shows the least change in the signature but the rise time is obviously changed even for this signature. Microphone B shows no change in the signatures because Microphone B is in the intersection and less diffusion is encountered.

Figure 6.48 shows the signal shape for Microphone A for all widths with a height of 12 meters, an azimuthal angle of 0°, an elevation angle of 40° and 0% diffusion. Figure 6.56 shows the signal shape for Microphone B for all widths with a height of 12 meters, an azimuthal angle of 0°, an elevation angle of 40° and 50% diffusion. Figure 6.57 shows the signal shapes for Microphone B with the same parameters. The width of 9 meters for Microphone A shows the largest change in signal because it has no specular energy in the signature. There are visible differences in each of the other widths as well. Microphone B shows no changes in the signature.
Figure 6.49. Comparison of the Microphone B signal shape for all widths with a height of 12 meters, an azimuthal angle of 0°, an elevation angle of 40° and 0% diffusion.

Figure 6.58 shows the signal shape for Microphone A for both elevation angles with a height of 12 meters, an azimuthal angle of 0°, a width of 5.5 meters and 50% diffusion. Figure 6.59 shows the signal shapes for Microphone B with the same parameters. The 20° elevation angle has almost no signal at all because of the reduction from phase adding deconstructively. There is also significant reduction and rounding in the 40° elevation signal. Microphone B shows minimal differences in the signatures from the purely specular case.

Figure 6.60 shows the signal shape for Microphone A for both azimuthal angles with a height of 12 meters, an elevation angle of 40, a width of 5.5 meters and 50% diffusion. Figure 6.61 shows the signal shapes for Microphone B with the same parameters. The azimuthal angle of 45° shows a significantly altered signal with a significant reduction in the pressure.

There is a striking difference between the 0% diffusion and the 50% diffusion
Figure 6.50. Comparison of the Microphone A signal shape for both elevation angles with a height of 12 meters, a width of 5.5 meters, an azimuthal angle of 0° and 0% diffusion.

To compare them more closely Figure 6.62 shows both the diffusion cases for Microphone A with a height of 12 meters, a width of 5.5 meters, an elevation of 40°, and an azimuthal angle of 0°. The differences between these signals is striking. The amplitude is much smaller for the 50% diffusion case. There also appears to be some rounding of the shocks in the diffusion case which increases the rise time. Figure 6.63 shows both the diffusion cases for Microphone B with a height of 12 meters, a width of 5.5 meters, an elevation of 40°, and an azimuthal angle of 0°. The signals are very similar at this location though there is a small amount of increased pressure in the 50% diffusion case.
Figure 6.51. Comparison of the Microphone B signal shape for both elevation angles with a height of 12 meters, a width of 5.5 meters, an azimuthal angle of 0° and 0% diffusion.
Figure 6.52. Comparison of the Microphone A signal shape for all azimuthal angles with a height of 12 meters, a width of 5.5 meters, an elevation angle of 40° and 0% diffusion.
Figure 6.53. Comparison of the Microphone B signal shape for all azimuthal angles with a height of 12 meters, a width of 5.5 meters, an elevation angle of 40° and 0% diffusion.
Figure 6.54. Comparison of the Microphone A signal shape for all heights with a width of 5.5 meters, an azimuthal angle of 0°, an elevation angle of 40° and 50% diffusion.
Figure 6.55. Comparison of the Microphone B signal shape for all heights with a width of 5.5 meters, an azimuthal angle of 0°, an elevation angle of 40° and 50% diffusion.
Figure 6.56. Comparison of the Microphone A signal shape for all widths with a height of 12 meters, an azimuthal angle of 0°, an elevation angle of 40° and 50% diffusion.
Figure 6.57. Comparison of the Microphone B signal shape for all widths with a height of 12 meters, an azimuthal angle of 0°, an elevation angle of 40° and 50% diffusion.
Figure 6.58. Comparison of the Microphone A signal shape for both elevation angles with a height of 12 meters, a width of 5.5 meters, an azimuthal angle of 0° and 50% diffusion.
Figure 6.59. Comparison of the Microphone B signal shape for both elevation angles with a height of 12 meters, a width of 5.5 meters, an azimuthal angle of $0^\circ$ and 50% diffusion.
Figure 6.60. Comparison of the Microphone A signal shape for both azimuthal angles with a height of 12 meters, a width of 5.5 meters, an elevation angle of 40° and 50% diffusion.
Figure 6.61. Comparison of the Microphone B signal shape for both azimuthal angles with a height of 12 meters, a width of 5.5 meters, an elevation angle of 40° and 50% diffusion.
Figure 6.62. Comparison of the Microphone A signal shape between 0% and 50% diffusion with a height of 12 meters, a width of 5.5 meters, an elevation angle of 40° and an azimuthal angle of 0°.
Figure 6.63. Comparison of the Microphone B signal shape between 0% and 50% diffusion with a height of 12 meters, a width of 5.5 meters, an elevation angle of 40° and an azimuthal angle of 0°.
6.3.2 Sidewalks

The next location to examine is the hearing height on the sidewalk. Currently PLdB is the most widely used measure of annoyance for sonic booms in America so this was the metric use to examine this area. There are a few interesting features to discuss for these sidewalks. The first thing to discuss is that the sound level does not increase drastically as the parameters are varied. As with the single city block geometry the receiver only records between 0 and 4 reflections. The biggest difference in this intersection geometry is the gap between the buildings. This is obvious in the sound levels along the canyons. Where the receivers only record 2 reflections in other locations along the canyons this gap in the buildings is less obvious.

The 45° azimuthal angle still gives a regular pattern along the sidewalk. The intersection in the middle of the buildings allows the pattern to continue further down the sidewalk.

Figure 6.64 shows the PLdB along the length of the canyon. As the height increases the pattern becomes more obvious. This is due to the downward elevation angle. The sound from above can reach the receivers more easily for the shorter buildings. Figure 6.65 shows the near sidewalk PLdB along the canyon. The near sidewalk shows a similar pattern along the canyon which is complementary spatially.

Another important feature to discuss about the sidewalk noise levels is the pattern of the diffuse energy PLdB values along the sidewalk. Figure 6.66 compares the 0% diffusion to the 50% diffuse example. There is a destructive and constructive pattern along each building with an obvious 'break' where the intersection occurs. Figure 6.67 shows a similar pattern for the near sidewalk.

Figure 6.68 shows all heights for a canyon width of 5.5 meters, an azimuthal angle of 0°, and an elevation angle of 40°. The 'break' for the intersection is very obvious in this example. In the far sidewalk there appears to be a trend (as the height gets greater the sound level goes down) however this is not a universal occurrence. This is seen in the near sidewalk example in Figure 6.69. Here the sound level is the same for 12 meter and 25 meter heights.

Figure 6.70 shows both azimuthal angles for a canyon height of 12 meters, a canyon width of 5.5 meters, and an elevation angle of 40°. The break in the
Figure 6.64. PLdB values along the far sidewalk of the canyon for the 45° azimuthal angle to demonstrate the pattern shown in the sound levels. Notice the pattern becomes more obvious as the height increases.

buildings is evident in the 0° azimuthal angle case. The 45° azimuthal angle shows the pattern discussed earlier. However, the break in the buildings do create an additional pattern for the second building. Figure 6.71 shows a similar pattern on the near sidewalk.

Figure 6.72 shows both elevation angles for a canyon height of 12 meters, a canyon width of 5.5 meters, and an azimuthal angle of 0°. Again the clear 'break' at the intersection is very obvious in these examples. The sound levels outside the intersection are lower because these areas are shadowed by the buildings. Figure 6.73 shows a similar pattern on the near sidewalk.

Figure 6.74 shows all heights for a canyon width of 5.5 meters, an azimuthal angle of 45° and an elevation angle of 40°. Notice that the pattern seen in Figure 6.64 for the specular case is not nearly as well defined in this figure for the diffusion
Figure 6.65. PLdB values along the near canyon for the 45° azimuthal angle to demonstrate the pattern shown in the sound levels. Notice the pattern becomes more obvious as the height increases.

case. Figure 6.75 demonstrates this for the near sidewalk.
Figure 6.66. Comparison of PLdB values along the far sidewalk for 12 meters high, 5.5 meters wide 0° azimuthal angle and elevation angle of 40° for both diffusion cases.
Figure 6.67. Comparison of PLdB values along the near sidewalk for 12 meters high, 5.5 meters wide, 0° azimuthal angle and elevation angle of 40° for both diffusion cases.
Figure 6.68. Comparison of PLdB values along the far sidewalk for all heights, canyon width of 5.5 meters, azimuthal angle of 0° and elevation angle of 40°.
Figure 6.69. Comparison of PLdB values along the near sidewalk for all heights, canyon width of 5.5 meters, azimuthal angle of 0° and elevation angle of 40°.
Figure 6.70. Comparison of PLdB values along the far sidewalk for both azimuthal angles, a height of 12 meters, canyon width of 5.5 meters, and an elevation angle of 40°.
Figure 6.71. Comparison of PLdB values along the near sidewalk for both azimuthal angles, a height of 12 meters, canyon width of 5.5 meters, and an elevation angle of 40°.
Figure 6.72. Comparison of PLdB values along the far sidewalk for both elevation angles, a height of 12 meters, canyon width of 5.5 meters, and an azimuthal angle of 0°.
Figure 6.73. Comparison of PLdB values along the near sidewalk for both elevation angles, a height of 12 meters, canyon width of 5.5 meters, and an azimuthal angle of $0^\circ$. 
Figure 6.74. Comparison of PLdB values along the far sidewalk for all heights, a canyon width of 5.5 meters, an azimuthal angle of 45° and an elevation angle of 40°.
Figure 6.75. Comparison of PLdB values along the near sidewalk for all heights, a canyon width of 5.5 meters, an azimuthal angle of 45° and an elevation angle of 40°.
6.3.3 Wall

The last important feature to discuss for the intersection is the pressure loading on the walls. Two building heights, 6 meters and 24 meters are examined in this section. Each wall area shown here has a figure showing only the peak pressure at each receiver as well as an embedded animation that shows the pressure loading over time. Only the far wall is examined in this section because the near wall showed very similar results. A single plane is examined that includes the break in the buildings.

Figures 6.76, 6.77, 6.78 and 6.79 show the pressure loading for a 6 meter high building. Each figure has an elevation angle of 20° and a width of 5.5 meters. Figure 6.76 shows the pressure for specular reflections with an azimuthal angle of 0°. This shows a uniform distribution of the pressure on the buildings with almost no indication of where the intersection is. Figure 6.77 shows the pressure for specular reflections with an azimuthal angle of 45°. Notice the stark shadow zones in this figure. The pattern is obvious in this figure with additional shadow zones on the far building. Figure 6.78 shows the diffuse reflections with an azimuthal angle of 0°. Figure 6.79 shows the diffuse reflections with an azimuthal angle of 45°. These figures show that the stark shadow zones are blurred significantly. Overall the sound levels are much lower. The gap in the buildings is evident in these figures as well.

Figures 6.80, 6.81, 6.82, and 6.83 show the pressure loading for a 24 meter high building. Each figure has an elevation angle of 20° and a width of 5.5 meters. Figure 6.80 shows the pressure for specular reflections with an azimuthal angle of 0°. This shows a pattern as the sound travels into the canyon with areas of lower maximum pressures. Figure 6.81 shows the pressure for specular reflections with an azimuthal angle of 45°. The stark shadow zones are still evident just over a larger area. Both of these azimuthal angles show regular patterns of peaks and valleys in the sound levels. The location of the intersection is evident in the sound levels. Figure 6.82 shows the 50% diffusion case with an azimuthal angle of 0°. Figure 6.83 shows the 50% diffusion case with an azimuthal angle of 45°. These figures show that the stark shadow zones are blurred significantly. Overall the pressure loading is smaller for these simulations than for the specular reflection cases. The gap in the buildings is evident in these figures as well.
Figure 6.76. Peak pressures along the far wall of a six meter tall intersection with an azimuthal angle of 0° and an elevation of 20° and a width of 5.5 meters with only specular reflections. To activate the animation click on the figure. The animation runs from 0.1 seconds to 0.75 seconds and then loops.

Figure 6.77. Peak pressures along the far wall of a six meter tall intersection with an azimuthal angle of 45° and an elevation of 20° and a width of 5.5 meters with only specular reflections. To activate the animation click on the figure. The animation runs from 0.1 seconds to 0.75 seconds and then loops.
Figure 6.78. Peak pressures along the far wall of a six meter tall intersection with an azimuthal angle of 0°, an elevation of 20° and a width of 5.5 meters with 50% diffusion. To activate the animation click on the figure. The animation runs from 0.1 seconds to 0.75 seconds and then loops.

Figure 6.79. Peak pressures along the far wall of a six meter tall intersection with an azimuthal angle of 45°, and an elevation of 20° and a width of 5.5 meters with 50% diffusion. To activate the animation click on the figure. The animation runs from 0.1 seconds to 0.75 seconds and then loops.
Figure 6.80. Peak pressures along the far wall of a 24 meter tall intersection with an azimuthal angle of 0°, an elevation of 20° and a width of 5.5 meters with only specular reflections. To activate the animation click on the figure. The animation runs from 0.1 seconds to 0.75 seconds and then loops.

Figure 6.81. Peak pressures along the far wall of a 24 meter tall intersection with an azimuthal angle of 45°, an elevation of 20° and a width of 5.5 meters with only specular reflections. To activate the animation click on the figure. The animation runs from 0.1 seconds to 0.75 seconds and then loops.
Figure 6.82. Peak pressures along the far wall of a 24 meter tall intersection with an azimuthal angle of 0°, an elevation of 20° and a width of 5.5 meters with 50% diffusion. To activate the animation click on the figure. The animation runs from 0.1 seconds to 0.75 seconds and then loops.

Figure 6.83. Peak pressures along the far wall of a 24 meter tall intersection with an azimuthal angle of 45°, an elevation of 20° and a width of 5.5 meters with 50% diffusion. To activate the animation click on the figure. The animation runs from 0.1 seconds to 0.75 seconds and then loops.
6.4 Discussion

From all these individual examples, and from other calculations not presented here, we infer some key points about the propagation of sonic booms in urban environments. The first main result to come from this work is that the ability to do this simulation is possible. Literature review has not revealed any studies that have done this type of environment for sonic booms. Another major result is that although the model does not include diffraction, the magnitude of the effects of building geometry can be estimated.

Including diffusion in these simulations significantly changed the shape of the signal. This is very different than the simulations for single buildings or even for the museum building where the buildings were not very close to each other. This leads to the conclusion that the effect of diffusion increases as the buildings get closer together and the height increases.

Both environments showed that there were areas where the amplitude was greater than an environment without buildings. However there were also areas of shadow zones where the amplitude was lower than the environment without buildings. In addition, when diffusion was included the amplitude in the specular reflections that reach the ear level microphones is significantly reduced.

The single city block and the four way intersection show very similar properties. The biggest change in the sound levels comes when the azimuthal angle changes. For 0° azimuthal angle the break in the buildings is obvious in the sound levels. For the 45° azimuthal angle there is a significant increase in the pattern of shadow zones and recorded energy due to the break in the buildings allowing some additional energy into the canyon.

Another important conclusion is that there was no observable trend related to the varied parameters, height, width, azimuthal angle, elevation angle, and diffusion coefficient. Each of these conclusions provide important insight into the behavior of sonic booms. This may aide in the determining of flight paths or to the ability to mitigate noise problems if they arise. These signatures can also be used as the input into transmission models to determine sound levels inside buildings.
Chapter 7

Summary and Conclusions

The research question set forth at the start of this work was:

What is the impact of urban environments and their features such as diffusion, absorption, and surface irregularities on the sound field created by sonic booms as modeled by a combined ray-tracing and radiosity method?

The first step was to create the combined ray tracing and radiosity method. This was then validated first by image theory and then by stochastic ray tracing. The model was additionally validated using the NASA SonicBOBS 2009 test data. The comparison between the measured and simulated sound field showed that this model effectively modeled sonic booms around buildings. This model can be effectively used to predict how the high frequency component of sonic booms behave around buildings. There are a few limitations related to this model that should be kept in mind when applying it. The more complex the environment or fine the surface features become, the smaller the frequency range the model accurately simulates. This model does not include diffraction. It is based on a homogenous atmosphere so situations where the temperature profile is extreme or where high winds are an issue will not be accurately simulated. This model is also not accurate at the edges of the carpet.

The absorption coefficients of the building were varied in chapter [3]. There was very little effect on the final signal from the absorption coefficient of the building.
It was shown that for common building materials that the effect of absorption materials was minimal. The only observable effect was when there was a discontinuity in the absorption coefficient between two materials. This configuration did show small differences as the microphone location was changed.

The diffusion coefficient was also varied. This factor gave the single biggest effect on the resulting sound field. The diffuse reflections themselves showed a minimal impact on the sound field for a single building. However a significant difference in the specular reflection amplitude is observed. For a single building, this reduction in energy can either be accounted for by including the radiosity part in this model or artificially increasing the absorption coefficient of the building. In situations where there are multiple buildings located close together the diffuse reflections have an even larger impact. They showed a substantial change in the shape of the signal as well as the amplitude of the specular reflections. As the buildings get taller, the diffusion reduces the sound levels at the ground significantly. The signals are also rounded when diffusion is included in the model versus just specular reflections.

The surface irregularities (façades) were also considered to determine their effect on the surrounding sound field. Simulations were run with complicated geometrical features both included and ignored. It was found that directly next to the building surface irregularities can have observable effects on the sound field. This is mostly observable in the arrival times of the reflections. This is evident because in these simulations the microphone locations were kept steady and the wall shape changed. As the receivers move farther away from the buildings the effect becomes smaller.

Lastly, the presence of the buildings themselves were examined using the urban canyon simulations. While having buildings present did affect the sound levels they did not necessarily raise the sound levels. PLdB with buildings could be found as much as 7 dB higher than an environment without buildings but could also provide shadow zones in many places where the sound level was reduced to a level significantly below the PLdB when there were no buildings present. When diffuse reflections were included, the shadow zones are partially filled in. However, the absence of diffraction in this model makes it difficult to assess this effect. The urban canyons did systematically increase the number of reflections because the
sound was bounced between the canyon walls. However, the number of reflections at each receiver is only between zero and four.

The presence of urban canyons can increase the sound levels but these levels are not any more than the levels present around a single building. With the presence of diffusion the sound levels are consistently lower than purely specular reflections. The taller the buildings are the more the diffuse reflections will decrease the sound levels at the ground.

7.1 Utilizing Conclusions

There are several ways that the information in this document can be utilized in future sonic boom research as well as additional applicable studies involving urban environments. The most important feature of this work is the model. This model can be applied to any environment and though the computational and memory usage will increase as the environment is expanded, the model can be expanded to fit any environment with any amount of complexity.

The second most important conclusion coming from this work is that the diffusion has a significant impact on urban environments. This conclusion can be utilized to mitigate noise from sources such as sonic booms or other large area shockwaves for the people at the ground level around buildings. For example, an architect could design building façades in high air traffic areas with highly diffuse surfaces in order to reduce sound levels at the ground. These surfaces could include anything from decretive carvings to irregularly spaced columns, anything that creates a three dimensional pattern to scatter sound. In addition, it also draws attention to the requirement for diffusion to be included in future models. When there are multiple buildings in an environment this work shows that diffusion can not be ignored to create an accurate model. It also leads to the requirement for more detailed examination of how much diffusion is present in typical building constructions.

These conclusion can give guidelines for the user of this model and other similar models to make judgements about what factors need to be included in a particular environment. The importance of absorption, diffusion, and surface features can be assessed based on the structure of the environment, the materials, and the location
of the microphones. This work shows that there is no need to include some of the features and they only serve to increase the complexity and probability for mistakes.

7.2 Future Work

The work provided in this document gives detailed descriptions of each of these components to the overall question that was put forth at the beginning of this document, however, there is further exploration that can be done to improve and expand the work accomplished here.

The first things that can be done to extend this work is to improve the model. Currently one of the model’s biggest weaknesses is the length of time it takes to complete a single run. The run time can be greatly decreased by the parallelization of the code. This could be further enhanced using a GPU. Ray tracing lends itself to be parallelized and GPU’s are particularly suited to doing these kinds of calculations very fast.

Adding diffraction to this code would also be beneficial. It would make the areas at the edges of the buildings more accurate and the code would be much more robust as a propagation model. It would help with the unrealistically sharp shadow zones that are created by the pure specular part of this code.

Other situations can be examined using this model as well. Using real city maps to propagate into larger and more complicated geometries could be done to determine the ability of this model to accurately predict sound levels in a more macroscopic capacity. This model can predict any kind of sound from a source above the buildings. This could lead to the study of a variety of other aircraft sources that include some high frequency component to the noise.

It would be helpful to have outdoor measurements to compare to the urban canyon simulations. Perhaps in the future, measurements in an actual city could be made to validate the outputs of this type of simulation. Trying to determine the most reasonable methods for reducing the noise effectively would be very useful. This would allow potential problem areas to be treated most effectively and economically.

While this work supports the conclusions drawn here this work can be built on
to expand to a broader application. The code may be expanded or modified to apply to different sources and these conclusions can be validated for other situations. The conclusions can also be further verified by varying other parameters, environmental characterizations, or source characteristics and observing the changes in the sound field.

Finally, indoor noise is a significant concern when sonic booms are propagated into urban environments. This code could easily be converted to propagate the sonic boom noise within the buildings. These simulations could be compared against some of the measured data that has been collected by NASA using residential and commercial buildings.
Code Documentation

A.1 Project Description and Background

This document is part of the NASA cooperative agreement number NNX07AN55A entitled 'Low boom sonic boom coupled diffraction around and transmission through individual and aggregated building structures'. The indoor response to sonic booms is considered crucial to understanding the acceptability of super sonic flight. Fully exploring the indoor response requires the ability to accurately simulate a variety of indoor signatures. The first thing required to do this is the pressure loading on the building. Once an accurate method for determining the pressure loading has been created a transmission model must be used to propagate the pressure through the building structure to create an internal pressure field. The goals of this project are (a.) to provide an improved understanding of the temporally and spatially dependent pressure loads on single and aggregated buildings induced by incident low-boom sonic booms, and (b.) to provide input information needed to do the outdoor-indoor transmission problem correctly. This particular document is presented to facilitate using the method for the high frequency portion of the pressure loading on buildings. This program uses a combined ray tracing and radiosity method to do this propagation. Setting up the environment, compiling the code and running the code are all described here.

In order to run this code several files are needed:

- RayTrace.f
• Functions.f
• RadiosityFunctions.f
• Parameter.f
• BuildingGeometry.f
• ReceiverFile.f
• Input.txt

And if diffuse reflections are desired:

• PatchingGeometry.f

Each of these files will be described in detail in this section.

A.2 General Code Description

This code is written in gfortran which is a Fortran 95/2003/2008 compiler developed by the GNU Fortran project. To obtain this code or learn more about the compiler the official homepage is at the url http://gcc.gnu.org/fortran/ [78]. In addition to the gfortran compiler, fftw is utilized in this code to perform Fourier transforms and inverse Fourier transforms. This library and more information about the fftw algorithm can be found at http://www.fftw.org/ [79]. The code can be run on a unix PC with very little CPU power. The memory required is dependent on the complexity of the environment and on the use of radiosity.

A.3 RayTrace.f

This file is the main propagation file and should only be altered to include the correct supplementary files. All files should be included using the statement:

INCLUDE ‘Filename.f’

The building geometry file should be included in the section with the comment
Include Structure Geometry”. The receiver file should be included in the section under the comment “Create a receiver array”. The Parameter file also needs to be included after the comment “Initialize all environmental Parameters”. And lastly the radiosity file should be included where desired under the comment section “Mesh the patches for the environment. Include a Patching File.” This is the only information in the RayTrace.f file that should every be changed unless changes to the propagation method are desired.

A.4 Functions.f and RadiosityFunctions.f

These files never need to be changed in order to run the simulations. They do however need to be compiled and linked in order for the code to run correctly.

A.5 Input.f

The input file is required to run the simulations. This file is simply the pressure values over the length of the signal. For the simulations related to the SonicBOBS experiment a MATLAB script has been included that can create an input file from the data as well as a sample input file. The MATLAB script is a simple file that will create a sample input file once the data has been read into MATLAB. Reading the data into MATLAB is done with a simple load command for data already converted to .MAT files (Museum data) or with the ExampleRead.m file supplied by NASA for the raw data. Once the data is loaded, the script can be run to export the input file. The signal can be created as long as desired by specifying the InitialSample and the FinalSample values. These values are the index of the data array where the desired section of the signal is located. For the majority of these simulations a signal length of between 0.5 seconds and 0.75 seconds was sufficient however the signal length should be long enough to accommodate the entire propagation distance. The input file can also be generated by a variety of other methods as long as it is a list of pressures in pascals in an ASCII format.
A.6 Parameter.f

The parameter file defines the important characteristics of the environment and the input boom. The input file name is defined here. The sample frequency of this input file is identified as $Fs$ in the parameter file. The environmental parameters are identified in the parameter file. The required environmental parameters are: speed of sound ($\text{soundspeed}$), atmospheric pressure ($ps$), temperature ($\text{Temp}$), and relative humidity ($hr$). The radius of the receivers is identified here. Next the parameters that describe the initial boom location and direction are identified. $X_{\text{initial}}$, $y_{\text{initial}}$ and $z_{\text{initial}}$ identifies the point where the initial boom plane is located. $x_{\text{min}}$, $x_{\text{max}}$, $y_{\text{min}}$, $y_{\text{max}}$, $z_{\text{min}}$, and $z_{\text{max}}$ describe the scope of the initial plane. This identifies the width and height of the plane and should be large enough to encompass the entire relevant geometry. $\Theta$ and $\phi$ describes the direction of the initial plane. $\Theta$ is the elevation angle measured down from the z axis. $\Phi$ is the azimuthal angle measured clockwise from the x axis. The only constraint in this initial plane is that the boom direction must be traveling predominantly in the x direction. $\text{IMAX}$ and $h$ are parameters related to the ray tracing code. $\text{IMAX}$ is the maximum number of steps along each ray. $h$ is the step length along a ray, this is set high because the rays are straight. The step length is cut shorter by the algorithm if the ray intersects with a surface within the length of $h$. The name of the output file is then identified. The output file must not exist already otherwise the program will fail when it tries to create the file. The output file name should be less than 30 characters long.

Next the absorption of the building surfaces and ground are defined. If the absorption does not change along the building then there is only one absorption plane. This code can vary the absorption with height and the number of variations along that height is identified by $\text{absorbplanes}$. If complex absorption is equal to 1 then the absorption will vary with height. It can accommodate up to four different absorption planes. The heights at which the absorption planes change are also identified here. It is assumed that the building starts at the ground at a height of 0 meters. The absorption of the ground is also identified here. All absorption coefficients are given in octave bands from 63 Hz to 8000 Hz. All of the allocate statements that are shown in this file are extremely important to be included in
other parameter files. To include only specular reflections radiosity must be set to 0.

A.7 BuildingGeometry.f

The second file that needs to be included is a geometry file. This sets up the geometry for the ray tracing portion of the simulation. An example of a geometry file is shown in section A.14. The face normals are defined first. This should include all relevant normals for each plane in the environment. The environment can be described in a variety of ways. The first method is using a series of boxes. Each box is identified by the closest point and the farthest point. Any number of boxes can be used and the number of boxes is given by the value boxnumber. The surface can also be given as a series of squares and triangles. These squares and triangles would be a series of polygons that make up a building and can be used if the building has an irregular shape. These polygons are defined by the vertex points and each of these points are given by the BuildingPoints array. Any number of points can be used and is defined by PointNumbers. Then the number of triangles and the number of squares are defined by TriangleNumber and SquareNumber respectively. Then each of the triangles and squares are defined by identifying the building points that make up each polygon and the normal of the plane of the polygon. In TriangleArray, the first number is the index of the FaceNormals array that corresponds to the appropriate plane normal. The next three numbers are the indices of the BuildingPoints array which mark the vertices of the triangle. For SquareArray, the first number is the index of the corresponding normal identified in the FaceNormals array. The next four numbers are the indices that correspond to the points from BuildingPoints that identify the vertices of the squares. Polybuilding is the number of buildings made up of individual polygons. Triangle is the number of triangles in each building. Squares is the number of squares in each building. Finally, the TriangleSequence and SquareSequence values are identified. These identify which squares and triangles correspond to which buildings. Each of the allocate statements are essential to be included in similar geometry files. If there are no triangles or squares than TriangleNumber and SquareNumber should be set to 0. Most environments can be
described by a series of boxes however more complicated buildings can be created with a series of triangles and squares. Each of the buildings should be a closed shape with all normals pointing outward.

A.8 ReceiverFile.f

The next file that needs to be included is the receiver file. An example receiver file is shown in section A.15. There are two ways to create receivers. The first is to just identify certain receiver points. This means arraysize must be manually set to the number of point receivers. Then ReceiverArray should be manually set to each receiver point. The other way to create an array is to create a grid of receiver points. This is shown in the example file. $X_{\text{min}}, y_{\text{min}}, z_{\text{min}}, x_{\text{max}}, y_{\text{max}},$ and $z_{\text{max}}$ describe the scope of the receiver plane. Two of these parameters must always be equal and the other two describe the width and length of the plane. receiverA, receiverB, receiverC, and receiverD describe the coefficients of the plane equation given by

$$Ax + By + Cz + D = 0.$$ (A.1)

Planenum determines the number of receiver planes. Each of these should be defined for each plane of receivers. The current program can accommodate up to 7 receiver planes however there should be consideration for the amount of memory required for large numbers of receivers. Each plane should be named by planename1, planename2 or planename3 etc. Step determines how far apart the centers of the receiver are. The next section of the example file should be included for each receiver file that includes a plane of receivers. Arraysize is the final size of the array. If there are multiple arrays then arraysize should be the addition of each individual array size (arraysize1, arraysize2, arraysize3 etc.) value. Then for each plane of receivers grid should be called. Then receiverarray should have all of the individual receiver planes combined into one array.
A.9 Including Radiosity

These three files are all that are needed to run the simulation without radiosity. If diffuse reflections are desired a few more things are needed. The first thing that must be done is that radiosity must be set to 1 in the parameter file. In addition, the percent of diffuse energy should also be set. This should be a number between 0 and 1 that determines the amount of energy that is reflected diffusely. This is also set in the parameter file.

A.9.1 PatchingFile.f

Even the most simple of these files is quite complicated. Each plane must be patched individually using a geometric sum. This requires that each plane that is near an edge must be patched separately. The first thing to do is split each direction, x, y and z, into sections where each section starts and ends at an edge. An example of this is shown in Figure A.1. An example patching file is shown in section A.16.

![Figure A.1. The planes of a single building environment. Notice the ground plane must be subdivided.](image)

The first thing that needs to be done is to identify the locations in each direction where an edge occurs. The number of edge locations is given by PatchNox, PatchNoy, and PatchNoz in the respective directions. Then xlim, ylim, and zlimit are arrays of all the different locations where an edge occurs in each direction. Nx, Ny, and Nz are arrays that define the number of patches between each edge location. Qx, Qy, and Qz are all the ratio of the lengths of the patches in each direction. The value for q should be at least 2.5.
Next the total number of patches needs to be calculated. Each plane has a length and width and with each of these dimensions a number of patches is associated. Therefore the number of patches for each width multiplied by the number of patches for each length for each plane added together will yield the total number of patches for the environment. This method is shown in the example file however this can also just be set to an integer value if desired. Then you keep on going for each plane several parameters need to be determined. The first is increment which should continue to increase for each plane. It is set to one for the first plane then set to the value of $Q$ for each subsequent plane. Then the slope and intercept for the top and bottom line of each plane are defined. This allows for a trapezoid type shape for more complicated geometries. $Slope$ and $b$ are for the bottom line, and $slope1$ and $b1$ are for the top line. Tempsize should be created by multiplying the number of patches in the two directions of the plane. Then the patches should be created in each direction by calling PATCHESSHORT for each direction. The arguments of this function are the lower limit of the plane, then the upper limit of the plane, the number of patches in this direction, the ratio of the patch lengths and the array that the lengths will be stored in. Then create the array of patches for each plane by calling CREATEPATCHARRAY. CREATEPATCHARRAY has many arguments. The first two are the arrays with the patch lengths, then the number of patches in each direction, then the limits in each direction of the plane including the direction that is the same along each direction. Then patcharraytemp which is the array where the patch array will be stored. Then $slope$, $b$, $slope1$, $b1$, count which is a temporary value, and the vector from FaceNormals that corresponds to the normal vector of the plane. Once this is complete there is a loop that needs to put the temporary patch array into the patcharray with all the planes This will take up the first six numbers in the array. Then for the seventh, eighth, ninth, and tenth values need to determined. Seven and eight should be set to zero because they will eventually hold the diffuse energy stored in the patch. The ninth value is the number of the plane and the tenth value is the index for the FaceNormal array that corresponds to the normal of the plane. These steps should be done for each plane until all the planes have been patched.

Then the form factors for each of the planes must be calculated. This is the
percentage of energy that reaches from one patch to another. The first thing is to
determine whether the plane is on the ground or part of a building. If the plane
is on the ground, the second value in formfactors is set to 1.0 and if it is on the
building it is set to 2.0. For each plane “sees” another plane, form factors are
created. When a plane “sees” another plane some fraction of the plane has a direct
line of sight to some part of the other plane. This requires that the planes are not
coplanar, and that one plane is not behind the others. This is determined by an
if statement shown in the example file. For each situation where this is true call
PERPFORMFACTOR to create a form factor between the planes. If this doesn’t
occur then formfactors values one and three should be set to zero. This creates all
required features of the environment.

A.10 Compiling

Once the geometry is set up and all the files are included in RayTrace.f the files
need to be compiled, linked and ran. To compile the files use the following com-
mands in a unix command terminal.

\texttt{gfortran -c RayTrace.f}
\texttt{gfortran -c Functions.f}
\texttt{gfortran -c RadiosityFunctions.f}

This will create three files: RayTrace.o, Functions.o, and RadiosityFunctions.o.
These files then need to be linked along with the fftw libraries. Make sure that the
fftw.h file is in the same directory as the code files so that all of the functions are
recognized. Then the files can be linked with the command

\texttt{gfortran RayTrace.o Functions.o RadiosityFunctions.o -lfftw3 -o RayTrace}

This will create an executable file RayTrace, which can be ran in a unix terminal
as well with the command

\texttt{./RayTrace}
This will create a ‘.dat’ file that can be read by TecPlot. Average run time for this
varies significantly depending on the complexity of the environment, inclusion of
diffuse reflections, size of environment etc. The run times vary from about 1 day
to 2 weeks. It is an ASCII file with some header information, receiver locations
and pressure in pascals. The tecplot file can be loaded into tecplot and set up to
be visualized as needed. For example, a point source receiver file can be read in
and the scatter option can be turned on to view the spacial locations of each of
the receivers. Each individual receiver can then be traced in time as desired using
tecplot. In addition a MATLAB file to parse the file and put receivers into a single
array is included. This is useful when the data needs post processing in addition
to visualization.

\section*{A.11 Code Extension}

This code can be expanded to include other environments and environmental fea-
tures. This method can be extended to propagate sound indoors. Two features
need to be carefully examined in order to do this. The first is that the boom needs
to be carefully defined within the building. The plane should be completely inside
the building. The environment could be set up the same way however the normals
of each surface should be pointed into the building. There are a few built in checks
within the code that checks to ensure that a receiver is not inside the building
and that the rays have not permeated into the buildings. This is usually done by
checking normals of the surfaces with the location and direction of the ray. These
would have to be reconfigured to account for rays inside structures.

In addition the code can be changed to propagate in an environment with a
varying sound speed. This would be done by adding a function in the $Functions. f$
file that changed $soundspeed$. Then for each step this function would be called to
redefine $soundspeed$ rather than it remaining constant.
A.12 Input MATLAB Script

InitialSample=117000;
FinalSample=135000;
SampFreq=24000;
T=1/SampFreq;
NFFT=24000;
t=(0:NFFT-1)*T;
size=FinalSample-InitialSample+1
input=CalibratedMikeData(InitialSample:FinalSample,9)*47.880259
%input=CalibratedOverpressure(InitialSample:FinalSample,2)*47.880259
%input=ResponseChannelData2(InitialSample:FinalSample);
input1=zeros(1,NFFT);
input1(1:size)=input;
figure
plot(input)
dlmwrite('/Volumes/Mercury/MuseBoom7RecCI.txt',input,'\n')

A.13 Parameter File Example

INPUTFILE=" inputNASABOOM1.txt ">
Fs=24000.0
soundspeed=348.537
ps=1.0
Temp=302.182778
hr=20.0
radius=.15
xinitial=145.0
yinitial=35.0
zinitial=0.0
xmin=-1
ymin=30.0
zmin=0.0
xmax=-1
ymax=100.0
zmax=25.0
theta=1.6863372
phi=3.44458181
boomspacing=.035
IMAX=75
h=10.0
absorbplanes=1
OUTPUTFILE='NASABoom1_0Diff_1Alpha.dat'
allocate(tempalphabuilding(absorbplanes,8))
C Turn on complex absorption
complexabsorption=0
C Enter an array for absorption of Alpha Building octave bands between 63 and 8000
if(complexabsorption.eq.1)then
  tempalphabuilding(1,1:8)=(/0.55,0.55,0.25,0.18,0.12,0.07,0.04,0.03/)
  tempalphabuilding(2,1:8)=(/0.01,0.01,0.01,0.02,0.02,0.03,0.03,0.03/)
  tempalphabuilding(3,1:8)=(/0.55,0.55,0.25,0.18,0.12,0.07,0.04,0.03/)
  tempalphabuilding(4,1:8)=(/0.01,0.01,0.01,0.02,0.02,0.03,0.03,0.03/)
  height1=2.7
  height2=4.191
  height3=6.6802
elseif(complexabsorption.eq.0)then
  tempalphabuilding(1,1:8)=(/0.01,0.01,0.01,0.02,0.02,0.03,0.03,0.03/)
  endif
C Enter an array for absorption of alpha ground octave bands between 63 and 8000
tempalphaground=(*0.01,0.01,0.01,0.02,0.02,0.02,0.03,0.03/)

C Turn Radiosity on or off. This will include diffuse reflections
radiosity=0

C what percentage of the energy is reflected diffusely between 0,1
percentdiffuse=0.1

A.14  Geometry Files

Boxnumber=1
allocate(Boxarraynear(boxnumber,3))
allocate(Boxarrayfar(boxnumber,3))
Boxarraynear(1,1:3)=(-40.1274551,10.0,0.0/)
boxarrayfar(1,1:3)=(-60.643706,10.1524,1.9812/)
PointNumbers=20
allocate(BuildingPoints(PointNumbers,3))
BuildingPoints(1,1:3)=(-10.0,10.0,0.0/)
BuildingPoints(2,1:3)=(-10.0,10.0,6.54/)
BuildingPoints(3,1:3)=(-40.127455,10.0,0.0/)
BuildingPoints(4,1:3)=(-40.127455,10.0,6.54/)
BuildingPoints(5,1:3)=(-40.127455,47.2043806,0.0/)
BuildingPoints(6,1:3)=(-40.127455,47.2043806,6.54/)
BuildingPoints(7,1:3)=(-10.0,47.2043806,0.0/)
BuildingPoints(8,1:3)=(-10.0,47.2043806,6.54/)
BuildingPoints(9,1:3)=(-25.0634275,10.0,7.479/)
BuildingPoints(10,1:3)=(-25.0634275,47.2043806,7.479/)
BuildingPoints(11,1:3)=(-58.6461508,12.760544,0.0/)
BuildingPoints(12,1:3)=(-58.6461508,12.760544,4.51928571/)
BuildingPoints(13,1:3)=(-68.2141525,5.55150414,0.0/)
BuildingPoints(14,1:3)=(-68.2141525,5.55150414,4.51928571/)
BuildingPoints(15,1:3)=(-81.7541508,23.511504,0.0/)
BuildingPoints(16,1:3)=(-81.7541508,23.511504,4.51928571/)
BuildingPoints(17,1:3)=(-72.1861508,30.720504,0.0/)
BuildingPoints(18,1:3)=(-72.1861508,30.720504,4.51928571/)
BuildingPoints(19,1:3)=(-63.364406,9.07505125,6.66/)
BuildingPoints(20,1:3)=(-76.970443,27.116376,6.66/)
TriangleNumber=4
allocate(Trianglearray(TriangleNumber,4))
Trianglearray(1,1:4)=(/1,2,4,9/)
Trianglearray(2,1:4)=(/2,6,8,10/)
Trianglearray(3,1:4)=(/9,12,14,19/)
Trianglearray(4,1:4)=(/11,16,18,20/)
SquareNumber=12
allocate(SquareArray(SquareNumber,5))
SquareArray(1,1:5)=(/3,7,8,1,2/)
SquareArray(2,1:5)=(/1,1,2,3,4/)
SquareArray(3,1:5)=(/4,3,4,5,6/)
SquareArray(4,1:5)=(/2,7,8,5,6/)
SquareArray(5,1:5)=(/5,4,6,10,9/)
SquareArray(6,1:5)=(/6,8,2,9,10/)
SquareArray(7,1:5)=(/8,17,18,11,12/)
SquareArray(8,1:5)=(/9,11,12,13,14/)
SquareArray(9,1:5)=(/10,13,14,15,16/)
SquareArray(10,1:5)=(/11,15,16,17,18/)
SquareArray(11,1:5)=(/12,16,14,19,20/)
SquareArray(12,1:5)=(/13,19,20,18,12/)
Triangles=2
Squares=6
allocate(TriangleSequence(PolyBuilding,Triangles))
TriangleSequence(1,1:2)=(/1,2/)
TriangleSequence(2,1:2)=(/3,4/)
allocate(SquareSequence(PolyBuilding,Squares))
SquareSequence(1,1:6)=(/1,2,3,4,5,6/)
SquareSequence(2,1:6)=(/7,8,9,10,11,12/)
FaceNormalNo=13
allocate(FaceNormals(FaceNormalNo,3))
FaceNormals(1,1:3)=(/0.0,-1.0,0.0/)
FaceNormals(2,1:3)=(/0.0,1.0,0.0/)
FaceNormals(3,1:3)=(/1.0,0.0,0.0/)
FaceNormals(4,1:3)=(-1.0,0.0,0.0/)
FaceNormals(5,1:3)=(/0.062216,0.0,.9980627/)
FaceNormals(6,1:3)=(/-.062216,0.0,.9980627/)
FaceNormals(7,1:3)=(/0.0,0.0,1.0/)
FaceNormals(8,1:3)=(/.7985,.6020,0.0/)
FaceNormals(9,1:3)=(/-.7985,.6020,0.0/)
FaceNormals(10,1:3)=(/-.7985,-.6020,0.0/)
FaceNormals(11,1:3)=(/.6018,.7987,0.0/)
FaceNormals(12,1:3)=(/-.6018,.7987,0.0/)
FaceNormals(13,1:3)=(/.2685,.2025,.9417/)
FaceNormals(13,1:3)=(/-.2685,.2025,.9417/)

A.15 Receiver File

xmin=-5.0D0
ymin=-1.0D0
zmin=0.0D0
xmax=80.0D0
ymax=-1.0D0
zmax=20.0D0
receiverA=0.0D0
receiverB=1.0D0
receiverC=0.0D0
receiverD=27.5D0
planenum=1
planename1='Cross Section'
step=1.0
if (xmin.eq.xmax) then
arraysize1=\text{int}\left(\frac{\text{ymax}-\text{ymin}}{\text{step}}\right) * \text{int}\left(\frac{\text{zmax}-\text{zmin}}{\text{step}}\right)

\text{elseif}(\text{ymin} .eq. \text{ymax}) \text{ then }
arraysize1=\text{int}\left(\frac{\text{xmax}-\text{xmin}}{\text{step}}\right) * \text{int}\left(\frac{\text{zmax}-\text{zmin}}{\text{step}}\right)

\text{elseif}(\text{zmin} .eq. \text{zmax}) \text{ then }
arraysize1=\text{int}\left(\frac{\text{ymax}-\text{ymin}}{\text{step}}\right) * \text{int}\left(\frac{\text{xmax}-\text{xmin}}{\text{step}}\right)

\text{endif}
arraysize=arraysize1
allocate(receiverarray1(arraysize1,3))

call \text{Grid}(\text{radius},\text{receiverA},\text{receiverB},\text{receiverC},\text{receiverD},\text{xmin},
* \text{ymin},\text{zmin},\text{ymax},\text{zmax},\text{receiverarray1},\text{arraysize1},\text{sizex1},
* \text{sizey1},\text{sizez1},\text{step})
sizex=sizex1
sizey=sizey1
sizez=sizez1
allocate(receiverarray(arraysize,3))
do 31 \text{I}=1,\text{arraysize}
if (\text{I} .le. \text{arraysize1}) \text{then }
receiverarray(\text{I},1)=\text{receiverarray1}(\text{I},1)
receiverarray(\text{I},2)=\text{receiverarray1}(\text{I},2)
receiverarray(\text{I},3)=\text{receiverarray1}(\text{I},3)
\text{endif}
31 \text{ CONTINUE}
print*, 'created receiver array', arraysize

\textbf{A.16 Patching File}

PatchNox=4
allocate(xlimit(PatchNox))
allocate(Nx(patchNox-1))
xlimit(1)=0.0
xlimit(2)=10.0
xlimit(3)=64.4322
xlimit(4)=100.0

Nx(1)=10
Nx(2)=10
Nx(3)=10

qx=3.0

PatchNoy=4
allocate(ylimit(PatchNoy))
allocate(Ny(PatchNoy-1))

ylimit(1)=0.0
ylimit(2)=10.0
ylimit(3)=46.9316
ylimit(4)=60.0

Ny(1)=10
Ny(2)=10
Ny(3)=10

qy=3.0

PatchNoz=2
allocate(zlimit(PatchNoz))
allocate(Nz(PatchNoz-1))

zlimit(1)=0.0
zlimit(2)=8.2423
Nz(1)=10

qz=3.0

PatchNo=Nx(1)*Ny(1)+Nx(2)*Ny(1)+Nx(3)*Ny(1)+Nx(1)*Ny(2)+Nx(2)*
* Ny(2)+Nx(3)*Ny(2)+Nx(1)*Ny(3)+Nx(2)*Ny(3)+Nx(3)*Ny(3)+2*Nx(2)
* *Nz(1)+2*Ny(2)*Nz(1)

allocate(patcharray(PatchNo,sizeffttwo,10))
allocate(formfactors(PatchNo,PatchNo,3))

patcharray=0.0
C This creates a patches for the Building.
increment=1
slope=0
slope1=0
tempsize=Nx(1)*Ny(1)
allocate(ddx1(Nx(1)))
allocate(ddy1(Ny(1)))
allocate(patcharraytemp(tempsize,6))
b=ylimit(2)
b1=ylimit(1)
CALL PATCHESSHORT(xlimit(1),xlimit(2),Nx(1),qx,ddx1)
CALL PATCHESSHORT(ylimit(1),ylimit(2),Ny(1),qy,ddy1)
CALL CREATEPATCHARRAY(ddx1,ddy1,Nx(1),Ny(1),xlimit(1),xlimit(2)
* ,ylimit(1),ylimit(2),zlimit(1),zlimit(1),patcharraytemp,slope
* ,b,slope1,b1,count,FaceNormals(5,1:3))
DO 101 Q=increment,increment+tempsize-1
   DO 102 W=1,sizeffttwo
      patcharray(Q,W,1)=patcharraytemp(Q-increment+1,1)
      patcharray(Q,W,2)=patcharraytemp(Q-increment+1,2)
patcharray(Q,W,3) = patcharraytemp(Q-increment+1,3)
patcharray(Q,W,4) = patcharraytemp(Q-increment+1,4)
patcharray(Q,W,5) = patcharraytemp(Q-increment+1,5)
patcharray(Q,W,6) = patcharraytemp(Q-increment+1,6)
patcharray(Q,W,7) = 0.0
patcharray(Q,W,8) = 0.0
patcharray(Q,W,9) = 1.0
patcharray(Q,W,10) = 5.0

CONTINUE

increment = Q
tempsize = Nx(2) * Ny(1)
deallocate(ddx1)
deallocate(ddy1)
deallocate(patcharraytemp)

allocate(ddx1(Nx(2)))
allocate(ddy1(Ny(1)))
allocate(patcharraytemp(tempsize,6))
b = ylimit(2)
b1 = ylimit(1)
CALL PATCHESHORT(xlimit(2), xlimit(3), Nx(2), qx, ddx1)
CALL PATCHESHORT(ylimit(1), ylimit(2), Ny(1), qy, ddy1)
CALL CREATEPATCHARRAY(ddx1, ddy1, Nx(2), Ny(1), xlimit(2), xlimit(3),
* ylimit(1), ylimit(2), zlimit(1), zlimit(1), patcharraytemp, slope,
* b, slope1, b1, count, FaceNormals(5, 1:3))
DO 103 Q = increment, increment + tempsize - 1
    DO 104 W = 1, sizeffttwo
    patcharray(Q,W,1) = patcharraytemp(Q-increment+1,1)
    patcharray(Q,W,2) = patcharraytemp(Q-increment+1,2)
    patcharray(Q,W,3) = patcharraytemp(Q-increment+1,3)
    patcharray(Q,W,4) = patcharraytemp(Q-increment+1,4)
    patcharray(Q,W,5) = patcharraytemp(Q-increment+1,5)
    CONTINUE
patcharray(Q,W,6)=patcharraytemp(Q-increment+1,6)
patcharray(Q,W,7)=0.0
patcharray(Q,W,8)=0.0
patcharray(Q,W,9)=2.0
patcharray(Q,W,10)=5.0
104 CONTINUE
103 CONTINUE
deallocation(ddx1)
deallocate(ddy1)
increment=Q
tempsize=Nx(3)*Ny(1)
deallocate(patcharraytemp)
allocate(ddx1(Nx(3)))
allocate(ddy1(Ny(1)))
allocate(patcharraytemp(tempsize,6))
b=ylimit(2)
b1=ylimit(1)
CALL PATCHESHORT(xlimit(3),xlimit(4),Nx(3),qx,ddx1)
CALL PATCHESHORT(ylimit(1),ylimit(2),Ny(1),qy,ddy1)
CALL CREATEPATCHARRAY(ddx1,ddy1,Nx(3),Ny(1),xlimit(3),xlimit(4),
                        ylimit(1),ylimit(2),zlimit(1),zlimit(1),patcharraytemp,slope,
                        b,slope1,b1,count,FaceNormals(5,1:3))
DO 105 Q=increment,increment+tempsize-1
  DO 106 W=1,sizeffttwo
    patcharray(Q,W,1)=patcharraytemp(Q-increment+1,1)
    patcharray(Q,W,2)=patcharraytemp(Q-increment+1,2)
    patcharray(Q,W,3)=patcharraytemp(Q-increment+1,3)
    patcharray(Q,W,4)=patcharraytemp(Q-increment+1,4)
    patcharray(Q,W,5)=patcharraytemp(Q-increment+1,5)
    patcharray(Q,W,6)=patcharraytemp(Q-increment+1,6)
    patcharray(Q,W,7)=0.0
    patcharray(Q,W,8)=0.0
    patcharray(Q,W,9)=3.0
patcharray(Q,W,10)=5.0
106 CONTINUE
105 CONTINUE
deallocate(ddx1)
deallocate(ddy1)
increment=Q
tempsize=Nx(1)*Ny(2)
deallocate(patcharraytemp)
allocate(ddx1(Nx(1)))
allocate(ddy1(Ny(2)))
allocate(patcharraytemp(tempsize,6))
b=ylimit(3)
b1=ylimit(2)
CALL PATCHESHORT(xlimit(1),xlimit(2),Nx(1),qx,ddx1)
CALL PATCHESHORT(ylimit(2),ylimit(3),Ny(2),qy,ddy1)
CALL CREATEPATCHARRAY(ddx1,ddy1,Nx(1),Ny(2),xlimit(1),xlimit(2),
* ylimit(2),ylimit(3),zlimit(1),zlimit(1),patcharraytemp,slope,
* b,slope1,b1,count,FaceNormals(5,1:3))
DO 107 Q=increment,increment+tempsize-1
  DO 108 W=1,sizefftwo
    patcharray(Q,W,1)=patcharraytemp(Q-increment+1,1)
    patcharray(Q,W,2)=patcharraytemp(Q-increment+1,2)
    patcharray(Q,W,3)=patcharraytemp(Q-increment+1,3)
    patcharray(Q,W,4)=patcharraytemp(Q-increment+1,4)
    patcharray(Q,W,5)=patcharraytemp(Q-increment+1,5)
    patcharray(Q,W,6)=patcharraytemp(Q-increment+1,6)
    patcharray(Q,W,7)=0.0
    patcharray(Q,W,8)=0.0
    patcharray(Q,W,9)=4.0
    patcharray(Q,W,10)=5.0
108 CONTINUE
107 CONTINUE
deallocate(ddx1)
deallocate(ddy1)
increment=Q
tempsize=Nx(3)*Ny(2)
deallocate(patcharraytemp)
allocate(ddx1(Nx(3)))
allocate(ddy1(Ny(2)))
allocate(patcharraytemp(tempsize,6))
b=ylimit(3)
b1=ylimit(2)
CALL PATCHESHORT(xlimit(3),xlimit(4),Nx(3),qx,ddx1)
CALL PATCHESHORT(ylimit(2),ylimit(3),Ny(2),qy,ddy1)
CALL CREATEPATCHARRAY(ddx1,ddy1,Nx(3),Ny(2),xlimit(3),xlimit(4)
* ,ylimit(2),ylimit(3),zlimit(1),0.0,patcharraytemp,slope,b,
* slope1,b1,count,FaceNormals(5,1:3))
DO 109 Q=increment,increment+tempsize-1
   DO 110 W=1,sizeffttwo
      patcharray(Q,W,1)=patcharraytemp(Q-increment+1,1)
      patcharray(Q,W,2)=patcharraytemp(Q-increment+1,2)
      patcharray(Q,W,3)=patcharraytemp(Q-increment+1,3)
      patcharray(Q,W,4)=patcharraytemp(Q-increment+1,4)
      patcharray(Q,W,5)=patcharraytemp(Q-increment+1,5)
      patcharray(Q,W,6)=patcharraytemp(Q-increment+1,6)
      patcharray(Q,W,7)=0.0
      patcharray(Q,W,8)=0.0
      patcharray(Q,W,9)=5.0
      patcharray(Q,W,10)=5.0
  110 CONTINUE
109 CONTINUE
deallocate(ddx1)
deallocate(ddy1)
increment=Q
tempsize=Nx(1)*Ny(3)
deallocate(patcharraytemp)
allocate(patcharraytemp(tempsize,6))
b=ylimit(4)
b1=ylimit(3)
allocation(ddx1(Nx(1)))
allocation(ddy1(Ny(3)))
CALL PATCHESHORT(xlimit(1),xlimit(2),Nx(1),qx,ddx1)
CALL PATCHESHORT(ylimit(3),ylimit(4),Ny(3),qy,ddy1)
CALL CREATEPATCHARRAY(ddx1,ddy1,Nx(1),Ny(3),xlimit(1),xlimit(2),
* ylimit(3),ylimit(4),zlimit(1),zlimit(1),patcharraytemp,slope
* ,b,slope1,b1,count,FaceNormals(5,1:3))
DO 111 Q=increment,increment+tempsize-1
  DO 112 W=1,sizeffttwo
    patcharray(Q,W,1)=patcharraytemp(Q-increment+1,1)
    patcharray(Q,W,2)=patcharraytemp(Q-increment+1,2)
    patcharray(Q,W,3)=patcharraytemp(Q-increment+1,3)
    patcharray(Q,W,4)=patcharraytemp(Q-increment+1,4)
    patcharray(Q,W,5)=patcharraytemp(Q-increment+1,5)
    patcharray(Q,W,6)=patcharraytemp(Q-increment+1,6)
    patcharray(Q,W,7)=0.0
    patcharray(Q,W,8)=0.0
    patcharray(Q,W,9)=6.0
    patcharray(Q,W,10)=5.0
  112 CONTINUE
111 CONTINUE
dealallocate(ddx1)
deallocate(ddy1)
increment=Q
tempsize=Nx(2)*Ny(3)
deallocate(patcharraytemp)
allocation(ddx1(Nx(2)))
allocation(ddy1(Ny(3)))
allocation(patcharraytemp(tempsize,6))
b=ylimit(4)
b1=ylimit(3)
CALL PATCHESHORT(xlimit(2),xlimit(3),Nx(2),qx,ddx1)
CALL PATCHESHORT(ylimit(3),ylimit(4),Ny(3),qy,ddy1)
CALL CREATEPATCHARRAY(ddx1,ddy1,Nx(2),Ny(3),xlimit(2),xlimit(3),
  ylimit(3),ylimit(4),zlimit(1),zlimit(1),patcharraytemp,slope,
  b,slope1,b1,count,FaceNormals(5,1:3))
DO 113 Q=increment,increment+tempsize-1
  DO 114 W=1,sizeffttwo
    patcharray(Q,W,1)=patcharraytemp(Q-increment+1,1)
    patcharray(Q,W,2)=patcharraytemp(Q-increment+1,2)
    patcharray(Q,W,3)=patcharraytemp(Q-increment+1,3)
    patcharray(Q,W,4)=patcharraytemp(Q-increment+1,4)
    patcharray(Q,W,5)=patcharraytemp(Q-increment+1,5)
    patcharray(Q,W,6)=patcharraytemp(Q-increment+1,6)
    patcharray(Q,W,7)=0.0
    patcharray(Q,W,8)=0.0
    patcharray(Q,W,9)=7.0
    patcharray(Q,W,10)=5.0
  114 CONTINUE
113 CONTINUE
  deallocate(ddx1)
  deallocate(ddy1)
  increment=Q
  tempsize=Nx(3)*Ny(3)
  deallocate(patcharraytemp)
  allocate(ddx1(Nx(3)))
  allocate(ddy1(Ny(3)))
  allocate(patcharraytemp(tempsize,6))
  b=ylimit(4)
  b1=ylimit(3)
CALL PATCHESHORT(xlimit(3),xlimit(4),Nx(3),qx,ddx1)
CALL PATCHESHORT(ylimit(3),ylimit(4),Ny(3),qy,ddy1)
CALL CREATEPATCHARRAY(ddx1,ddy1,Nx(3),Ny(3),xlimit(3),xlimit(4),
* ylimit(3),ylimit(4),zlimit(1),zlimit(1),patcharraytemp,slope,
* b,slope1,b1,count,FaceNormals(5,1:3))

DO 115 Q=increment,increment+tempsize-1
  DO 116 W=1,sizeffttwo
    patcharray(Q,W,1)=patcharraytemp(Q-increment+1,1)
    patcharray(Q,W,2)=patcharraytemp(Q-increment+1,2)
    patcharray(Q,W,3)=patcharraytemp(Q-increment+1,3)
    patcharray(Q,W,4)=patcharraytemp(Q-increment+1,4)
    patcharray(Q,W,5)=patcharraytemp(Q-increment+1,5)
    patcharray(Q,W,6)=patcharraytemp(Q-increment+1,6)
    patcharray(Q,W,7)=0.0
    patcharray(Q,W,8)=0.0
    patcharray(Q,W,9)=8.0
    patcharray(Q,W,10)=5.0
  116 CONTINUE
  115 CONTINUE

deallocate(ddx1)
deallocate(ddy1)
increment=Q
tempsize=Nx(2)*Nz(1)
deallocate(patcharraytemp)
allocate(ddx1(Nx(2)))
allocate(ddz1(Nz(1)))
allocate(patcharraytemp(tempsize,6))
b=zlimit(2)
b1=zlimit(1)
CALL PATCHESHORT(xlimit(2),xlimit(3),Nx(2),qx,ddx1)
CALL PATCHESHORT(zlimit(1),zlimit(2),Nz(1),qz,ddz1)
CALL CREATEPATCHARRAY(ddx1,ddz1,Nx(2),Nz(1),xlimit(2),xlimit(3),
  * ylimit(2),ylimit(2),zlimit(1),zlimit(2),patcharraytemp,slope
  * ,b,slope1,b1,count,FaceNormals(4,1:3))
DO 117 Q=increment,increment+tempsize-1
  DO 118 W=1,sizeffttwo
patcharray(Q,W,1)=patcharraytemp(Q-increment+1,1)
patcharray(Q,W,2)=patcharraytemp(Q-increment+1,2)
patcharray(Q,W,3)=patcharraytemp(Q-increment+1,3)
patcharray(Q,W,4)=patcharraytemp(Q-increment+1,4)
patcharray(Q,W,5)=patcharraytemp(Q-increment+1,5)
patcharray(Q,W,6)=patcharraytemp(Q-increment+1,6)
patcharray(Q,W,7)=0.0
patcharray(Q,W,8)=0.0
patcharray(Q,W,9)=9.0
patcharray(Q,W,10)=4.0

118   CONTINUE
117   CONTINUE
   deallocate(ddx1)
   deallocate(ddz1)
   increment=Q
   tempsize=Nx(2)*Nz(1)
   deallocate(patcharraytemp)
   allocate(ddx1(Nx(2)))
   allocate(ddz1(Nz(1)))
   allocate(patcharraytemp(tempsize,6))
   b=zlimit(2)
   b1=zlimit(1)
   CALL PATCHESHORT(xlimit(2),xlimit(3),Nx(2),qx,ddx1)
   CALL PATCHESHORT(zlimit(1),zlimit(2),Nz(1),qz,ddz1)
   CALL CREATEPATCHARRAY(ddx1,ddz1,Nx(2),Nz(1),xlimit(2),xlimit(3),
*   ylimit(3),ylimit(3),zlimit(1),zlimit(2),patcharraytemp,slope,
*   b,slope1,b1,count,FaceNormals(2,1:3))
DO 119 Q=increment,increment+tempsize-1
   DO 120 W=1,sizefttwo
      patcharray(Q,W,1)=patcharraytemp(Q-increment+1,1)
      patcharray(Q,W,2)=patcharraytemp(Q-increment+1,2)
      patcharray(Q,W,3)=patcharraytemp(Q-increment+1,3)
      patcharray(Q,W,4)=patcharraytemp(Q-increment+1,4)
patcharray(Q,W,5)=patcharraytemp(Q-increment+1,5)
patcharray(Q,W,6)=patcharraytemp(Q-increment+1,6)
patcharray(Q,W,7)=0.0
patcharray(Q,W,8)=0.0
patcharray(Q,W,9)=10.0
patcharray(Q,W,10)=2.0
120 CONTINUE
119 CONTINUE
disable(ddx1)
disable(ddz1)
increment=Q
tempsize=Ny(2)*Nz(1)
disable(patcharraytemp)
allocate(ddy1(Ny(2)))
allocate(ddz1(Nz(1)))
allocate(patcharraytemp(tempsize,6))
b=zlimit(2)
b1=zlimit(1)
CALL PATCHESHORT(ylimit(2),ylimit(3),Ny(2),qy,ddy1)
CALL PATCHESHORT(zlimit(1),zlimit(2),Nz(1),qz,ddz1)
CALL CREATEPATCHARRAY(ddy1,ddz1,Ny(2),Nz(1),xlimit(2),xlimit(2),
* ylimit(2),ylimit(3),zlimit(1),zlimit(2),patcharraytemp,slope
* ,b,slope1,b1,count,FaceNormals(1,1:3))
DO 121 Q=increment,increment+tempsize-1
  DO 122 W=1,sizefftwtwo
    patcharray(Q,W,1)=patcharraytemp(Q-increment+1,1)
    patcharray(Q,W,2)=patcharraytemp(Q-increment+1,2)
    patcharray(Q,W,3)=patcharraytemp(Q-increment+1,3)
    patcharray(Q,W,4)=patcharraytemp(Q-increment+1,4)
    patcharray(Q,W,5)=patcharraytemp(Q-increment+1,5)
    patcharray(Q,W,6)=patcharraytemp(Q-increment+1,6)
    patcharray(Q,W,7)=0.0
    patcharray(Q,W,8)=0.0
patcharray(Q,W,9)=11.0
patcharray(Q,W,10)=1.0
122 CONTINUE
121 CONTINUE
deallocate(ddy1)
deallocate(ddz1)
increment=Q
tempsize=Ny(2)*Nz(1)
deallocate(patcharraytemp)
allocate(ddy1(Ny(2)))
allocate(ddz1(Nz(1)))
allocation(patcharraytemp(tempsize,6))
b=zlimit(2)
b1=zlimit(1)
CALL PATCHESSHORT(ylimit(2),ylimit(3),Ny(2),qy,ddy1)
CALL PATCHESSHORT(zlimit(1),zlimit(2),Nz(1),qz,ddz1)
CALL CREATEPATCHARRAY(ddy1,ddz1,Ny(2),Nz(1),xlimit(3),xlimit(3),
* ylimit(2),ylimit(3),zlimit(1),zlimit(2),patcharraytemp,slope,
* b,slope1,b1,count,FaceNormals(3,1:3))
DO 123 Q=increment,increment+tempsize-1
  DO 124 W=1,sizeffttwo
    patcharray(Q,W,1)=patcharraytemp(Q-increment+1,1)
    patcharray(Q,W,2)=patcharraytemp(Q-increment+1,2)
    patcharray(Q,W,3)=patcharraytemp(Q-increment+1,3)
    patcharray(Q,W,4)=patcharraytemp(Q-increment+1,4)
    patcharray(Q,W,5)=patcharraytemp(Q-increment+1,5)
    patcharray(Q,W,6)=patcharraytemp(Q-increment+1,6)
    patcharray(Q,W,7)=0.0
    patcharray(Q,W,8)=0.0
    patcharray(Q,W,9)=12.0
    patcharray(Q,W,10)=3.0
  124 CONTINUE
123 CONTINUE
deallocate(ddy1)
deleate(ddz1)
increment=Q
tempsize=Ny(2)*Nx(2)
deleate(patcharraytemp)
allocate(ddx1(Nx(2)))
alocate(ddy1(Ny(2)))
alocate(patcharraytemp(tempsize,6))
b=ylimit(3)
b1=ylimit(2)
CALL PATECHSHORT(xlimit(2),xlimit(3),Nx(2),qx,ddx1)
CALL PATECHSHORT(ylimit(2),ylimit(3),Ny(2),qy,ddy1)
CALL CREATEPATCHARRAY(ddx1,ddy1,Nx(2),Ny(2),xlimit(2),xlimit(3),
*  ylimit(2),ylimit(3),zlimit(2),zlimit(2),patcharraytemp,slope,
*  b,slope1,b1,count,FaceNormals(5,1:3))
DO 125 Q=increment,increment+tempsize-1
  DO 126 W=1,sizeffttwo
    patcharray(Q,W,1)=patcharraytemp(Q-increment+1,1)
    patcharray(Q,W,2)=patcharraytemp(Q-increment+1,2)
    patcharray(Q,W,3)=patcharraytemp(Q-increment+1,3)
    patcharray(Q,W,4)=patcharraytemp(Q-increment+1,4)
    patcharray(Q,W,5)=patcharraytemp(Q-increment+1,5)
    patcharray(Q,W,6)=patcharraytemp(Q-increment+1,6)
    patcharray(Q,W,7)=0.0
    patcharray(Q,W,8)=0.0
    patcharray(Q,W,9)=13.0
    patcharray(Q,W,10)=5.0
  126 CONTINUE
125 CONTINUE
  deallocate(ddx1)
  deallocate(ddy1)
  deallocate(patcharraytemp)
DO 127 Q=1,PatchNo
DO 128 W=1, PatchNo
  if (patcharray(W,1,9).eq.1.0.or.patcharray(W,1,9).eq.2.0
  * .or.patcharray(W,1,9).eq.3.0.or.patcharray(W,1,9).eq.4.0
  * .or.patcharray(W,1,9).eq.5.0.or.patcharray(W,1,9).eq.6.0
  * .or.patcharray(W,1,9).eq.7.0.or.
  * patcharray(W,1,9).eq.8.0) then
    formfactors(Q,W,2)=1.0
  endif
  if (patcharray(W,1,9).eq.9.0.or.patcharray(W,1,9).eq.10.0
  * .or.patcharray(W,1,9).eq.11.0.or.patcharray(W,1,9).eq.12.0
  * .or.patcharray(W,1,9).eq.13.0)
  * then
    formfactors(Q,W,2)=2.0
  endif
  if (patcharray(Q,1,9).eq.1.0.and.(patcharray(W,1,9).eq.8.0
  * .or.patcharray(W,1,9).eq.9.0.or.patcharray(W,1,9).eq.12.0
  * .or.patcharray(W,1,9).eq.13.0.or.
  * patcharray(W,1,9).eq.14.0.or.patcharray(W,1,9).eq.15.0)) then
    CALL PERPFORMFACTOR(patcharray,PatchNo,sizeffttwo,
                           formfactors,Q,W,PI,FaceNormals,FaceNormalNo)
  elseif (patcharray(Q,1,9).eq.2.0.and.(patcharray(W,1,9)
  * .eq.12.0)) then
    CALL PERPFORMFACTOR(patcharray,PatchNo,sizeffttwo,
                           formfactors,Q,W,PI,FaceNormals,FaceNormalNo)
  elseif (patcharray(Q,1,9).eq.3.0.and.(patcharray(W,1,9)
  * .eq.13.0.or.patcharray(W,1,9).eq.14.0)) then
    CALL PERPFORMFACTOR(patcharray,PatchNo,sizeffttwo,
                           formfactors,Q,W,PI,FaceNormals,FaceNormalNo)
  elseif (patcharray(Q,1,9).eq.4.0.and.(patcharray(W,1,9)
  * .eq.15.0)) then
    CALL PERPFORMFACTOR(patcharray,PatchNo,sizeffttwo,
                           formfactors,Q,W,PI,FaceNormals,FaceNormalNo)
elseif(patcharray(Q,1,9).eq.5.0.and.(patcharray(W,1,9).
* eq.10.0.or.patcharray(W,1,9).eq.11.0.or.
* patcharray(W,1,9).eq.12.0.or.patcharray(W,1,9).
* eq.13.0.or.patcharray(W,1,9).eq.14.0.or.
* patcharray(W,1,9).eq.15.0))then
    CALL PERPFORMFACTOR(patcharray,PatchNo,sizeffttwo,
* formfactors,Q,W,PI,FaceNormals,FaceNormalNo)
elseif(patcharray(Q,1,9).eq.8.0.and.(patcharray(W,1,9).
* eq.1.0))then
    CALL PERPFORMFACTOR(patcharray,PatchNo,sizeffttwo,
* formfactors,Q,W,PI,FaceNormals,FaceNormalNo)
elseif(patcharray(Q,1,9).eq.9.0.and.(patcharray(W,1,9).
* eq.1.0))then
    CALL PERPFORMFACTOR(patcharray,PatchNo,sizeffttwo,
* formfactors,Q,W,PI,FaceNormals,FaceNormalNo)
elseif(patcharray(Q,1,9).eq.10.0.and.(patcharray(W,1,9).
* eq.5.0))then
    CALL PERPFORMFACTOR(patcharray,PatchNo,sizeffttwo,
* formfactors,Q,W,PI,FaceNormals,FaceNormalNo)
elseif(patcharray(Q,1,9).eq.11.0.and.(patcharray(W,1,9).
* eq.5.0))then
    CALL PERPFORMFACTOR(patcharray,PatchNo,sizeffttwo,
* formfactors,Q,W,PI,FaceNormals,FaceNormalNo)
elseif(patcharray(Q,1,9).eq.12.0.and.(patcharray(W,1,9).
* eq.1.0.or.patcharray(W,1,9).eq.2.0.or.
* patcharray(W,1,9).eq.5.0))then
    CALL PERPFORMFACTOR(patcharray,PatchNo,sizeffttwo,
* formfactors,Q,W,PI,FaceNormals,FaceNormalNo)
elseif(patcharray(Q,1,9).eq.13.0.and.(patcharray(W,1,9).
* eq.1.0.or.patcharray(W,1,9).eq.3.0.or.
* patcharray(W,1,9).eq.14.0(or.patcharray(W,1,9).
* eq.14.0))then
    CALL PERPFORMFACTOR(patcharray,PatchNo,sizeffttwo,
elseif(patcharray(Q,1,9).eq.14.0.and.(patcharray(W,1,9).eq.1.0.or.patcharray(W,1,9).eq.3.0.or.
patcharray(W,1,9).eq.5.0.or.patcharray(W,1,9).eq.13.0))then
CALL PERPFORMFACTOR(patcharray,PatchNo,sizeffttwo,
formfactors,Q,W,PI,FaceNorms,FaceNormalNo)
elseif(patcharray(Q,1,9).eq.15.0.and.(patcharray(W,1,9).eq.1.0.or.patcharray(W,1,9).eq.4.0.or.
patcharray(W,1,9).eq.5.0))then
CALL PERPFORMFACTOR(patcharray,PatchNo,sizeffttwo,
formfactors,Q,W,PI,FaceNorms,FaceNormalNo)
else
formfactors(Q,W,1)=0.0
formfactors(Q,W,3)=0.0
endif
128 CONTINUE
127 CONTINUE
print*,'Calculated form factors'
Appendix B

Code

B.1 Main Program

PROGRAM RayTrace
C Kimberly Riegel created this program to propagate sonic booms around
C large structures, and to graduate. It is a ray tracing model that
C will include specular and diffuse reflections. It will print out the
C sound field at ear height, at relevent microphone locations, and at
C the building walls. It will read in the fft of a sonic boom signiture.

C Initialize all Variables

C Initialize all parameter variables

INTEGER sum,absorbplanes
INTEGER tmp4
real soundspeed, lambda,freq,length,ps, Temp, hr
real Fs, tempalphaground(8)
real PI,HUGE,m,percentdiffuse,tmpsum
PARAMETER (PI=3.14159265358979323846,HUGE=1000000.0)
COMPLEX XJ

C Initialize all geometry parameters
real slope, b,slope1,b1
INTEGER boxnumber,TriangleNumber,SquareNumber,PointNumbers
INteGER TrinGles, Squares, PolyBuilding,FaceNormalNo,behind

C Initialize phase propagation variables

real phasefinal

C Initialize variables for complex absorptions

integer complexabsorption
real height1, height2, height3

C Initialize Amplitude propagation variables
real ampfinal,normalization,normal(3)

C Initialize Distance and Direction propagation variables

real Vinitial(3),Vecip1(3),veci(3),r(3),F(3),h
real Finitial(3),dx

C Initialize iterators and counters

INTEGER increment
INTEGER IMAX,I,Q,P,ray,RAYMAX,W,S,K,count,j,D

C Initialize receiver variables

real radius,radius2,receiverpoint(3),receiverpoint2(3)
real xmin,ymin,zmin,xmax,ymax,zmax
real dxreceiver,tempreceiver,receivercheck
real receiverA,receiverB,receiverC,receiverD
real lastreceiver(3)
real lastreceiver2(3), checkdirection(3), OC(3), OCLength
Integer receiverhit, doublehit, hitcount, arraysize, arraysize1
integer arraysize2, arraysize3, arraysize4, arraysize5, arraysize6
Integer arraysize7, planenum
real xspace, yspace, zspace

C Initialize Ground Variables

real nground(3), groundheight, GROUNDABC(3), GROUND
double precision GROUNDVD, GROUNDVO, dxground1, GROUNDN(3)
double precision Ftemp(3), vecitemp(3), vecip1temp(3)
real dxground
integer groundhit

C Initialize initial array variables

real PLANEABC(4), yinitial, xinitial, zinitial, area, corr
real theta, phi, ninitial, xiinitial, zetainitial
real boomspacing

C Initialize initial signal variables

INTEGER sizefft
INTEGER*8 plan

C Initialize Misc Variables

real temp1, temp1, temp2, temp3, temp2, temp3, temp2, temp3, twopi, twopih
integer sizefft two
real twopidx, PIRlm2, dot1
double complex temp2, temp3, temp4, dot
CHARACTER*20 FILENAME
CHARACTER*30 INPUTFILE, OUTPUTFILE

C Initialize Building Variables

real nbuilding(3), nbox(3), dxbuilding, dxnear, dxfar
integer buildinghit, hit, planehit, whichbox

C Initialize output variables

real timestep, time1, time, timelength, time2
integer sizex, sizey, sizez
integer sizex1, sizey1, sizez1, sizex2, sizey2, sizez2
integer sizex3, sizey3, sizez3, sizex4, sizey4, sizez4
integer sizex5, sizey5, sizez5, sizex6, sizey6, sizez6
integer sizex7, sizey7, sizez7
character*20 planename1, planename2, planename3, planename4
character*20 planename5, planename6, planename7

C Initialize Radiosity Variables

integer radiosity, PatchNo, tempsize, KMAX, Npatch
real diffusion, cosgamma, cosdeltagamma, nu, Rlm, patcharea
real cosxilm, Patchlength, RadFinitial(3), radF(3), diffusionground
double complex Ek, vec3(3)
double precision qx, qz, qy
real minx, maxx, miny, maxy, minz, maxz
integer PatchNox, PatchNoy, PatchNoz
real qx1, qx2, qx3, qx4, qy1, qy2, qy3, qy4, qz1, dlnlm
real dl, dm, dlprime, dnprime, ddm, knu, alpha

C Initialize all dynamic Arrays

integer, allocatable::Nx(:)
integer, allocatable::Ny(:)
integer, allocatable::Nz(:)
real, allocatable::airabsorb(:)
double precision, allocatable::xlimit(:)
double precision, allocatable::ylimit(:)
double precision, allocatable::zlimit(:)
real, allocatable::ampinitial(:)
real, allocatable::phaseinitial(:)
real, allocatable::alphabuilding(:, :)
real, allocatable::timearray(:)
real, allocatable::inputarray(:, :)
double complex, allocatable::outputsignal(:)
double precision, allocatable::inputsignal(:)
real, allocatable::outputarray1(:, :)
real, allocatable::dhoutputarray1(:, :)
real, allocatable::boomarray(:, :)
real, allocatable::receiverarray(:, :)
real, allocatable::receiverarray1(:, :)
real, allocatable::receiverarray2(:, :)
real, allocatable::receiverarray3(:, :)
real, allocatable::receiverarray4(:, :)
real, allocatable::receiverarray5(:, :)
real, allocatable::receiverarray6(:, :)
real, allocatable::receiverarray7(:, :)
real, allocatable::temparray(:, :, :)
real, allocatable::timetemparray(:, :, :)
double precision, allocatable::ddx1(:)
double precision, allocatable::ddy1(:)
double precision, allocatable::ddz1(:)
real, allocatable::patcharray(:, :, :)
real, allocatable::patcharray1(:, :, :)
double precision, allocatable::patcharraytemp(:, :)
real, allocatable::formfactors(:, :);
double complex, allocatable::Gk(:, :)
double complex, allocatable::Gkminus1(:, :)
real, allocatable::alphaground(:)
real, allocatable::alphanothing(:)
real, allocatable::boxarraynear(:, :)
real, allocatable::boxarrayfar(:, :)
real, allocatable::BuildingPoints(:, :)
real, allocatable::TriangleArray(:, :)
real, allocatable::SquareArray(:, :)
Integer, allocatable::TriangleSequence(:, :)
Integer, allocatable::SquareSequence(:, :)
double precision, allocatable::FaceNormals(:, :)
real, allocatable::tempalphabuilding(:, :)

C Assign initial values to variables. These will change depending on
C circumstances.
C Must initialize a few constants in order to utilize fftw

INCLUDE 'fftw3.f'
C Include Parameter file
   INCLUDE 'Parameterfile.f'

C Include Structure Geometry

   INCLUDE 'BuildingGeometry.f'

C Initialize counters and calculations that will be done repetitively
   XJ=(0.0,1.0)
   radius2=radius**2
   twopi=2.0*PI
   S=1
   K=0
   raysum=0
OPEN(UNIT=5,file=INPUTFILE)
print*, INPUTFILE

C Count the number of elements in the input file

11 Read(5,*,END=12)temp1
  K=K+1
  Go TO 11

C allocate the correct size to the signal and fft arrays

12 allocate(inputsignal(K))
    allocate(outputsignal(K/2+1))
    allocate(inputarray(K/2,3))
    close(5)

C Read in the input signal
OPEN(UNIT=5,file=INPUTFILE)
DO 30 W=1,K
  Read(5,*,END=5)inputsignal(W)
  S=S+1
30 CONTINUE

C Take the fft of the input signal with fftw
5  sizefft=K
    sizeffttwo=sizefft/2.0
    call dftw_plan_dft_r2c_1d(plan,sizefft, inputsignal, outputsignal
    * , FFTW_ESTIMATE)
    call dftw_execute_dft_r2c(plan, inputsignal, outputsignal)
    call dftw_destroy_plan(plan)
    allocate(timearray(sizefft))
    allocate(ampinitial(sizeffttwo))
    allocate(phaseinitial(sizeffttwo))
C Create initial signal
allocate(airabsorb(sizeffttwo))
DO 13 K=1, sizeffttwo
   inputarray(K,1)=(K)*Fs/2*1/(sizeffttwo)
   inputarray(K,2)=abs(outputsignal(K+1)/sizefft)
   inputarray(K,3)=ATAN2(imagpart(outputsignal(K+1)/sizefft),
*      realpart(outputsignal(K+1)/sizefft))
   airabsorb(K)=ABSORPTION(ps,inputarray(K,1),hr,Temp)
13 CONTINUE
DO 14 K=1, sizefft
   timearray(K)=(K-1)*1/Fs
14 CONTINUE
deallocate(outputsignal)
deallocate(inputsignal)
C Set initial values

Vinitial=(/xinitial,yinitial,zinitial/)
xiinitial=COS(phi)*sin(theta)
ninitial=SIN(phi)*sin(theta)
zetainitial=cos(theta)
length=sqrt(xiinitial*xiinitial+ninitial*ninitial+zetainitial*
*      zetainitial)
Finitial=(/xiinitial,ninitial,zetainitial/)
print*, Finitial
tmp=(Finitial(1)*Vinitial(1)+Finitial(2)*Vinitial(2)+Finitial(3)*
*      Vinitial(3))
PLANEABC=(/Finitial(1),Finitial(2),Finitial(3),tmp/)
C Create initial boom array

yspace=boomspacing*abs(cos(phi))
zspace=boomspacing*abs(sin(theta))
if (xmin.eq.xmax) then
RAYMAX=int((ymax-ymin)/yspace)*int((zmax-zmin)/zspace)
elseif(ymin.eq.ymax)then
    RAYMAX=int((xmax-xmin)/xspace)*int((zmax-zmin)/zspace)
elseif(zmin.eq.zmax) then
    RAYMAX=int((ymax-ymin)/yspace)*int((xmax-xmin)/xspace)
endif
allocate(boomarray(RAYMAX,3))
PRINT*, RAYMAX
print*, 'created boom array'

C Create a receiver array, include a receiver file.
allocate(alphanothing(sizeffttwo))
alphanothing=0.0
INCLUDE 'ReceiverEarlevel.f'
sum=0

C deallocate temparray receiver arrays
deallocate(receiverarray1)
if (planenum.ge.2) deallocate(receiverarray2)
if (planenum.ge.3) deallocate(receiverarray3)
if (planenum.ge.4) deallocate(receiverarray4)
if (planenum.ge.5) deallocate(receiverarray5)
if (planenum.ge.6) deallocate(receiverarray6)
if (planenum.ge.7) deallocate(receiverarray7)

C initialize normalization factor
normalization=(PI*radius2)/(boomspacing*boomspacing)
allocate(temparray(arraysize,sizeffttwo,6))
allocate(timetemparray(arraysize,sizefft,5))
DO 18 D=1, arraysize
    DO 15 W=1, sizeffttwo
        temparray(D,W,1)=receiverarray(D,1)
        temparray(D,W,2)=receiverarray(D,2)
        temparray(D,W,3)=receiverarray(D,3)
        temparray(D,W,4)=inputarray(W,1)
        temparray(D,W,5)=0.0
        temparray(D,W,6)=0.0
    CONTINUE
15 CONTINUE
18 CONTINUE

C Define ground plane

groundheight=0.000000000
GROUNDABC=(/0.000000000,0.000000000,1.00000000/)  
GROUNDD=-groundheight
nground=(/0.0,0.0,1.0/)  
allocate(alphaground(sizeffttwo))

C Allocate absorption coefficients for each surface for each frequency

DO 17 D=1, sizeffttwo
    if(inputarray(D,1).ge.0.0.or.inputarray(D,1).lt.88.0)then
        alphaground(D)=tempalphaground(1)
    elseif(inputarray(D,1).ge.88.0.or.inputarray(D,1).lt.177.0)then
        alphaground(D)=tempalphaground(2)
    elseif(inputarray(D,1).ge.177.0.or.inputarray(D,1).lt.355.0)then
        alphaground(D)=tempalphaground(3)
    elseif(inputarray(D,1).ge.355.0.or.inputarray(D,1).lt.710.0)then
        alphaground(D)=tempalphaground(4)

elseif(inputarray(D,1).ge.710.0.or.inputarray(D,1).lt.1420.0) *
* then
  alphaground(D)=tempalphaground(5)
elseif(inputarray(D,1).ge.1420.0.or.inputarray(D,1).lt.2840.0) *
* then
  alphaground(D)=tempalphaground(6)
elseif(inputarray(D,1).ge.2840.0.or.inputarray(D,1).lt.5680.0) *
* then
  alphaground(D)=tempalphaground(7)
elseif(inputarray(D,1).ge.5680.0.or.inputarray(D,1).lt. inputarray(sizeffttwo,1))then
  alphaground(D)=tempalphaground(8)
endif

17 CONTINUE
allocate(alphabuilding(absorbplanes,sizeffttwo))
DO 9 W=1,absorbplanes
  DO 8 D=1, sizeffttwo
    if(inputarray(D,1).ge.0.0.or.inputarray(D,1).lt.88.0)then
      alphabuilding(W,D)=tempalphabuilding(W,1)
    elseif(inputarray(D,1).ge.88.0.or.inputarray(D,1).lt.177.0) *
    * then
      alphabuilding(W,D)=tempalphabuilding(W,2)
    elseif(inputarray(D,1).ge.177.0.or.inputarray(D,1).lt.355.0) *
    * then
      alphabuilding(W,D)=tempalphabuilding(W,3)
    elseif(inputarray(D,1).ge.355.0.or.inputarray(D,1).lt.710.0) *
    * then
      alphabuilding(W,D)=tempalphabuilding(W,4)
    elseif(inputarray(D,1).ge.710.0.or.inputarray(D,1).lt.1420.0)then
      alphabuilding(W,D)=tempalphabuilding(W,5)
    elseif(inputarray(D,1).ge.1420.0.or.inputarray(D,1).lt.2840.0)then
      alphabuilding(W,D)=tempalphabuilding(W,6)
    elseif(inputarray(D,1).ge.2840.0.or.inputarray(D,1).lt.5680.0)then
      alphabuilding(W,D)=tempalphabuilding(W,7)
    elseif(inputarray(D,1).ge.5680.0.or.inputarray(D,1).lt.7100.0)then
      alphabuilding(W,D)=tempalphabuilding(W,8)
    endif
  8 CONTINUE
9 CONTINUE
alphabuilding(W,D) = tempalphabuilding(W,6)
elseif(inputarray(D,1).ge.2840.0.or.inputarray(D,1).lt.5680.0)
  then
  alphabuilding(W,D) = tempalphabuilding(W,7)
elseif(inputarray(D,1).ge.5680.0.or.inputarray(D,1).lt.inputarray(sizeffttwo,1))
  then
  alphabuilding(W,D) = tempalphabuilding(W,8)
endif
8 CONTINUE
9 CONTINUE

C Mesh the patches for the environment. Include patching file.
if(radiosity.eq.1) then
  INCLUDE 'SingleBuildingGeometry.f'
  diffusion = percentdiffuse
diffusionground = 0.0
else
diffusion = 0.0
diffusionground = 0.0
endif
 count = 0
print *, 'normalization', normalization
C Loop through the intial ray locations
DO 40 ray = 1, RAYMAX, 1
  hitcount = 0
tmpsum = 0.0
doublehit = 0
DO 24 W = 1, sizeffttwo
  ampinitial(W) = inputarray(W,2)/normalization
  phaseinitial(W) = inputarray(W,3)
24 CONTINUE
Vinitial = (/ BOOMARRAY(ray,1), BOOMARRAY(ray,2),
  * BOOMARRAY(ray,3)/)
if (h.lt.2*radius) then
  print*, 'h is less than 2r'
  Call abort
endif
F=Finitial
veci=Vinitial
C Making small steps along the ray path. For each step we should return,
C location, phase and amplitude
  DO 10 I=1,IMAX,1
    dxreceiver=HUGE
    C Find the closest sphere and store that as the distance
    DO 16 Q=1,arraysize,1
      CALL SPHERECHECK(receiverarray(Q,1:3),
       * radius2,F,veci,tempreceiver)
      if(receiverhit.ge.1) then
        if(lastreceiver(1).eq.receiverarray(Q,1).and.
         * lastreceiver(2).eq.receiverarray(Q,2).and.
         * lastreceiver(3).eq.receiverarray(Q,3))then
          tempreceiver=HUGE
        endif
        if(F(1).eq.checkdirection(1).and.F(2).eq.
         * checkdirection(2).and.F(3).eq.
         * checkdirection(3))then
          OC(1)=receiverarray(Q,1)-veci(1)
          OC(2)=receiverarray(Q,2)-veci(2)
          OC(3)=receiverarray(Q,3)-veci(3)
          OCLength=OC(1)*OC(1)+OC(2)*OC(2)+OC(3)*OC(3)
          if(OCLength.lt.radius2)then
            tempreceiver=HUGE
          endif
        endif
      endif
    endif
  endif
if(receiverhit.ge.2)then
if(lastreceiver2(1).eq.receiverarray(Q,1).and. lastreceiver2(2).eq.receiverarray(Q,2).and. lastreceiver2(3).eq.receiverarray(Q,3))then tempreceiver=HUGE endif endif

if (tempreceiver.lt.dxreceiver)then dxreceiver=tempreceiver receiverpoint(1)=receiverarray(Q,1) receiverpoint(2)=receiverarray(Q,2) receiverpoint(3)=receiverarray(Q,3) elseif (tempreceiver.eq.dxreceiver.and. tempreceiver.ne.HUGE)then receivercheck=tempreceiver if(receiverarray(Q,1).eq.receiverpoint(1).and. receiverarray(Q,2).eq.receiverpoint(2).and. receiverarray(Q,3).eq.receiverpoint(3))then doublehit=0 else receiverpoint2(1)=receiverarray(Q,1) receiverpoint2(2)=receiverarray(Q,2) receiverpoint2(3)=receiverarray(Q,3) doublehit=1 endif endif

16 CONTINUE

C Check Intersection with ground plane

GROUNDN=GroundABC Ftemp=F vecitemp=veci

GROUNDVD=GROUNDn(1)*Ftemp(1)+GROUNDN(2)*Ftemp(2)+GROUNDN(3)*Ftemp(3)

if (groundhit.eq.1) then
dxground=huge
elseif (GROUNDVD.ne.0.0) then
    GROUNDVO=((GROUNDn(1)*vecitemp(1)+GROUNDn(2)*vecitemp(2)+
*       GROUNDn(3)*vecitemp(3))+GROUNDD)
    dxground1=(-1.0D0)*GROUNDVO*(1.0D0)/GROUNDVD
    dxground=dxground1
    Vecip1=veci+dxground*F
    Vecip1temp=vecitemp+dxground1*Ftemp
    tmp=(GROUNDabc(1)*Vecip1(1)+GROUNDabc(2)*Vecip1(2)+
*       GROUNDabc(3)*Vecip1(3)+GROUNDD)
    tmp=(GROUNDn(1)*Vecip1temp(1)+GROUNDn(2)*Vecip1temp(2)+
*       GROUNDn(3)*Vecip1temp(3)+GROUNDD)
    if (dxground.lt.0.0) dxground=HUGE
    else
        dxground=huge
    endif

C Check intersection with building
    dxbuilding=HUGE
    if(buildinghit.eq.1) then
        dxbuilding=huge
    else
        hit=0
        planehit=0
    endif

C Check intersection with Boxes
    DO 28 Q=1,boxnumber,1
        CALL BOX(boxarraynear(Q,1:3), Boxarrayfar(Q,1:3)
*       ,Veci,F,dxnear, dxfar, hit, planehit)
        if (dxnear.lt.dxbuilding)then
            dxbuilding=dxnear
            Vecip1=veci+dxbuilding*F
            whichbox=Q
            CALL PLANE(Vecip1, boxarraynear(whichbox,1:3),
*                     boxarrayfar(whichbox,1:3), planehit, nbox)
endif

28 CONTINUE

C Check intersection with Triangles
if(TriangleNumber.gt.0)then
   DO 32 Q=1,TriangleNumber,1
      CALL Polygon(veci,F,Q,3,TriangleNumber,PointNumbers
                   ,Trianglearray,BuildingPoints,normal,
                   * FaceNormalNo,FaceNormals,dxnear,behind)
      if (dxnear.lt.dxbuilding)then
         dxbuilding=dxnear
         nbox=normal
         whichbox=Q
      endif
   32 CONTINUE
endif

C Check intersection with Squares
if(SquareNumber.gt.0)then
   DO 33 Q=1,SquareNumber,1
      CALL Polygon(veci,F,Q,4,SquareNumber,PointNumbers,
                   ,SquareArray,BuildingPoints,normal,FaceNormalNo
                   ,SquareNormals,dxnear,behind)
      if (dxnear.lt.dxbuilding)then
         dxbuilding=dxnear
         nbox=normal
         whichbox=Q
      endif
   33 CONTINUE
endif
endif

buildinghit=0
receiverhit=0
groundhit=0

C Check to see if ray hits within step size
if (dxreceiver.lt.h.or.dxground.lt.h.or.dxbuilding.lt.h)  
  * then  
  dx=MIN(dxreceiver,dxground,dxbuilding)  
  tmpsum=tmpsum+dx
C if the ray hits a receiver, store in an array. If the ray hits twice
C Create two arrays to store in.
  if (dx.eq.dxreceiver) then  
    sum=sum+1  
    Vecip1=veci+dx*F  
    veci=Vecip1  
    receiverhit=1  
    checkdirection=F
  endif
  if(doublehit.eq.1)then  
    receiverhit=2  
  endif
  hitcount=hitcount+1
  print*, 'hit receiver',sum,tmpsum
DO 20 W=1, sizeffttwo
  m=airabsorb(W)
  lambda=soundspeed/inputarray(W,1)
  phasefinal=phaseinitial(W)-(twopi*dx)/lambda
  ampfinal=ampinitial(W)*(1-alphanothing(W))*
    * exp(-m*dx)
  ampinitial(W)=ampfinal
  phaseinitial(W)=mod(phasefinal,twopi)
  if (phaseinitial(W).GT.PI) then  
    phaseinitial(W)=phaseinitial(W)-twopi  
  endif
  if(doublehit.eq.1)then  
    if(receivercheck.eq.dx)then  
      if(W.eq.1)allocate(outputarray1(*
        sizeffttwo,6))
if(W.eq.1)allocate(dhoutputarray1(sizeffttwo,6))
outputarray1(W,1)=inputarray(W,1)
outputarray1(W,2)=receiverpoint(1)
outputarray1(W,3)=receiverpoint(2)
outputarray1(W,4)=receiverpoint(3)
outputarray1(W,5)=ampinitial(W)/2.0
outputarray1(W,6)=phaseinitial(W)
dhoutputarray1(W,1)=inputarray(W,1)
dhoutputarray1(W,2)=receiverpoint2(1)
dhoutputarray1(W,3)=receiverpoint2(2)
dhoutputarray1(W,4)=receiverpoint2(3)
dhoutputarray1(W,5)=ampinitial(W)/2.0
dhoutputarray1(W,6)=phaseinitial(W)
lastreceiver(1)=receiverpoint(1)
lastreceiver(2)=receiverpoint(2)
lastreceiver(3)=receiverpoint(3)
lastreceiver2(1)=receiverpoint2(1)
lastreceiver2(2)=receiverpoint2(2)
lastreceiver2(3)=receiverpoint2(3)
endif
else
if(W.eq.1)allocate(outputarray1(sizeffttwo,6))
outputarray1(W,1)=inputarray(W,1)
outputarray1(W,2)=receiverpoint(1)
outputarray1(W,3)=receiverpoint(2)
outputarray1(W,4)=receiverpoint(3)
outputarray1(W,5)=ampinitial(W)
outputarray1(W,6)=phaseinitial(W)
lastreceiver(1)=receiverpoint(1)
lastreceiver(2)=receiverpoint(2)
lastreceiver(3)=receiverpoint(3)
endif
CONTINUE
Call receiverHITFUNC(sizefft, outputarray1, 
* arraysize, temparray)
if (doublehit.eq.1) then
  call receiverHITFUNC(sizefft, dhoutputarray1, 
* arraysize, temparray)
  count=count+1
endif
count=count+1
deallocate(outputarray1)
if(doublehit.eq.1)then
  deallocate(dhoutputarray1)
endif
endif
C If the ray hits the ground then bounce off the ground and continue
if (abs(dx-dxground).lt.10.0**(-13.0)) then
  Vecip1=veci+dxground*F
  tmp=(GROUNDabc(1)*Vecip1(1)+GROUNDabc(2)*Vecip1(2)+ 
  * GROUNDabc(3)*Vecip1(3)+GROUNDD)
  if(tmp.ne.GROUNDD) Vecip1(3)=0.0
  print*, 'hit ground'
  veci=Vecip1
  dot1=(F(1)*nground(1)+F(2)*nground(2)+F(3)*nground(3))
  n2=(nground(1)*nground(1)+nground(2)*nground(2)+ 
  * nground(3)*nground(3))
  r=F-2.0*(dot1/n2)*nground
  length=sqrt(r(1)*r(1)+r(2)*r(2)+r(3)*r(3))
  F=/(r(1),r(2),r(3)/)
  groundhit=1
  twopidx=twopi*dxground
C Loop through all the frequencies
DO 21 W=1, sizeffttwo
  m=airabsorb(W)
lambda = soundspeed / inputarray(W, 1)
phasefinal = phaseinitial(W) - (twopidx) / lambda
ampfinal = ampinitial(W) * (1.0 - alphaground(W))
* *(1.0 - diffusionground) * exp(-m * dxground)
phaseinitial(W) = mod(phasefinal, twoopi)
if (phaseinitial(W). GT. PI) then
    phaseinitial(W) = phaseinitial(W) - twopi
endif
if (radiosity.eq.1.and.(diffusionground.ne.0.0))
    then
        DO 25 Q=1,PatchNo
            if (formfactors(1,Q,2).eq.1)then
                if (veci(1).le.(patcharray(Q,W,1)+0.5*
patcharray(Q,W,4)).and. veci(1).ge.
* (patcharray(Q,W,1)-0.5*patcharray
* (Q,W,4)))then
                    if (veci(2).le.(patcharray(Q,W,2)+0.5
* *patcharray(Q,W,5)).and. veci(2)
* .ge.(patcharray(Q,W,2)-0.5*
* patcharray(Q,W,5)))then
                        if (veci(3).le.(patcharray(Q,W,3)+
* 0.5*patcharray(Q,W,6)).and.
* veci(3).ge.(patcharray(Q,W,3
* )-0.5*patcharray(Q,W,6)))
* then
                           temp2 = cmplx(abs(patcharray
* (Q,W,7)) * exp(XJ*patcharray(Q,W,8)))
        temp3 = cmplx(abs(ampinitial(W) *
* (1.0 - alphaground(W)) *
* diffusionground * exp(-m*
* dxground)) * exp(XJ*
* phasefinal))
temp4 = temp2 + temp3
patcharray(Q,W,7) = abs(temp4)
patcharray(Q,W,8) = ATAN2(
  imagpart(temp4), realpart
  temp4)
GOTO 25
endif
endif
endif
endif
25 CONTINUE
endif
ampinitial(W) = ampfinal
21 CONTINUE
endif
C if the ray hits the building then change the direction and continue
if (dx.eq.dxbuilding) then
  Vecip1 = veci + dx*F
  veci = Vecip1
  print*, 'hit building'
  n2 = (nbox(1)*nbox(1)+nbox(2)*nbox(2)+nbox(3)*nbox(3))
  nbuilding = nbox/sqrt(n2)
  dot1 = (F(1)*nbuilding(1) + F(2)*nbuilding(2) + F(3)*
  nbuilding(3))
  r = F - 2.0*(dot1/n2)*nbuilding
  length = sqrt(r(1)*r(1) + r(2)*r(2) + r(3)*r(3))
  F = (/r(1), r(2), r(3)/)
  buildinghit = 1
  twopidx = twopi*dx
DO 22 W = 1, sizeffttwo
  if (complexabsorption.eq.1) then
    if (absorbplanes.eq.2) then
      if (veci(3).gt.0.0.and.veci(3).le.height1) then
alpha=alphabuilding(1,W)

elseif(veci(3).gt.height1.and.veci(3).le.height2)then
  alpha=alphabuilding(2,W)
endif
donendif

if(absorbplanes.eq.3)then
  if(veci(3).gt.height2.and.veci(3).le.height3)then
    alpha=alphabuilding(3,W)
  endif
endif
donendif

if(absorbplanes.eq.4)then
  if(veci(3).gt.height3)then
    alpha=alphabuilding(4,W)
  endif
endif
donendif
else
  alpha=alphabuilding(1,W)
donendif

m=airabsorb(W)

lambda=soundspeed/inputarray(W,1)

phasefinal=phaseinitial(W)-(twopidx)/lambda

ampfinal=ampinitial(W)*(1.0-alpha)*
  (1.0-diffusion)*exp(-m*dx)

phaseinitial(W)=mod(phasefinal,twopi)

if (phaseinitial(W).GT.PI) then
  phaseinitial(W)=phaseinitial(W)-twopi
endif

if(radiosity.eq.1)then
  C Loop through all patches if radiosity is turned on.
  DO 29 Q=1,PatchNo
    if (formfactors(1,Q,2).eq.2.0)then
if((veci(1).le.(patcharray(Q,W,1)+0.5*patcharray(Q,W,4))).and.(veci(1).ge.(patcharray(Q,W,1)-0.5*patcharray(Q,W,4))))then
  if((veci(2).le.(patcharray(Q,W,2)+0.5*patcharray(Q,W,5))).and.(veci(2).ge.(patcharray(Q,W,2)-0.5*patcharray(Q,W,5))))then
    if((veci(3).le.(patcharray(Q,W,3)+0.5*patcharray(Q,W,6))).and.(veci(3).ge.(patcharray(Q,W,3)-0.5*patcharray(Q,W,6))))then
      temp2=cmplx(abs(patcharray(Q,W,7))*exp(XJ*patcharray(Q,W,8)))
      temp3=abs(ampinitial(W)*(1.0-alpha)*diffusion*exp(-m*dx))*exp(XJ*phaseinitial(W))
      temp4=temp2+temp3
      patcharray(Q,W,7)=abs(temp4)
      patcharray(Q,W,8)=ATAN2(imagpart(temp4),realpart(temp4))
      GOTO 27
    endif
  endif
endif
27 CONTINUE
endif
29 CONTINUE
endif
ampinitial(W) = ampfinal

22    CONTINUE
endif
else
C If there was no interaction with buildings then proceed with one step.
tmpsum = tmpsum + h
Vecip1 = veci + (h) * F
veci = Vecip1
twopih = twopi * h
DO 23 W = 1, sizefttwo
C Loop through all frequencies.
m = airabsorb(W)
lambda = soundspeed / inputarray(W, 1)
phasefinal = phaseinitial(W) - (twopih) / lambda
ampfinal = ampinitial(W) * (1 - alphanothing(W)) * 
         exp(-m * h)
ampinitial(W) = ampfinal
phaseinitial(W) = mod(phasefinal, twopi)
if (phaseinitial(W).GT.PI) then
    phaseinitial(W) = phaseinitial(W) - twopi
endif
23    CONTINUE
endif
10    CONTINUE
      print*, 'finished ray', ray
40    CONTINUE
C Once all rays are complete. Deallocate all arrays that are no longer needed
deallocate(boomarray)
deallocate(receiverarray)
deallocate(ampinitial)
deallocate(phaseinitial)
allocation(Gk(PatchNo, sizefttwo))
allocation(Gkminus1(PatchNo, sizefttwo))
if (radiosity.eq.1) then
C If radiosity is turned on then do the energy exchange.
   KMAX=3
   Npatch=10
   DO 53 K=1,KMAX
   DO 55 D=1,PatchNo
      DO 54 W=1,sizeffttwo
         if (K.eq.1) then
            Gk(D,W)=cmplx(abs(patcharray(D,W,7))
            )*exp(XJ*patcharray(D,W,8))
         else
            Gkminus1(D,W)=Gk(D,W)
         end if
         DO 56 I=1,PatchNo
            if (I.eq.1) then
               Gk(D,W)=0.0
            else
               if (formfactors(D,I,2).eq.1.0) then
                  alpha=alphaground(W)
               elseif (formfactors(D,I,2).eq.2.0) then
                  if (complexabsorption.eq.1) then
                     if (absorbplanes.eq.2) then
                        if (patcharray(I,1,3).gt.0.0.and.
                        * patcharray(I,1,3).le.height1) then
                           alpha=alphabuilding(1,W)
                        elseif (patcharray(I,1,3).gt.height1
                        * .and.patcharray(I,1,3).le.
                        * height2) then
                           alpha=alphabuilding(2,W)
                        endif
                     endif
                  endif
               endif
            endif
         end if
         end if
      end DO
   end DO
end DO

* height3)then
  alpha=alphabuilding(3,W)
endif
endif
endif
if(absorbplanes.eq.4)then
  if(patcharray(I,1,3).gt.height3)
    * then
    alpha=alphabuilding(4,W)
  endif
  endif
else
  alpha=alphabuilding(1,W)
endif
endif
m=airabsorb(W)
temp2=(1-alpha)*exp(-m*formfactors(D,I,3))*
  formfactors(D,I,1)*Gkminus1(D,W)*exp(-XJ*twopi*inputarray(W,1)*formfactors
  (D,I,3)/soundspeed)
Gk(D,W)=Gk(D,W)+temp2
endif
56 CONTINUE
endif
54 CONTINUE
print*, 'finished patch', D, 'of', PatchNo
55 CONTINUE
print*, arraysize,PatchNo,sizefft
C Do energy exchange with other receivers
DO 50 D=1,arraysize
  DO 51 Q=1,PatchNo
    Rlm=0.0
    DO 58 I=1,Npatch
      DO 59 J=1,Npatch
DO 60 S=1,Npatch

            tmp1=((patcharray(Q,1,1)-.5*patcharray(Q,1,4)+(patcharray(Q,1,4)/Npatch)*(I-.5))-temparray(D,1,1))*((patcharray(Q,1,1)-.5*patcharray(Q,1,4)+(patcharray(Q,1,4)/Npatch)*(I-.5))-temparray(D,1,1))
            tmp2=((patcharray(Q,1,2)-.5*patcharray(Q,1,5)+(patcharray(Q,1,5)/Npatch)*(J-.5))-temparray(D,1,2))*((patcharray(Q,1,2)-.5*patcharray(Q,1,5)+(patcharray(Q,1,5)/Npatch)*(J-.5))-temparray(D,1,2))
            tmp3=((patcharray(Q,1,3)-.5*patcharray(Q,1,6)+(patcharray(Q,1,6)/Npatch)*(S-.5))-temparray(D,1,3))*((patcharray(Q,1,3)-.5*patcharray(Q,1,6)+(patcharray(Q,1,6)/Npatch)*(S-.5))-temparray(D,1,3))
            Rlm=Rlm+1.0/(NPatch*Npatch*Npatch)*sqrt(tmp1+tmp2+tmp3)

60 Continue
59 CONTINUE
58 CONTINUE

Patchlength=sqrt(((patcharray(Q,1,1)-temparray(D,1,1))*(patcharray(Q,1,1)-temparray(D,1,1)))+((patcharray(Q,1,2)-temparray(D,1,2))*(patcharray(Q,1,2)-temparray(D,1,2)))+((patcharray(Q,1,3)-temparray(D,1,3))*(patcharray(Q,1,3)-temparray(D,1,3))))

Finitial(1)=(patcharray(Q,1,1)-temparray(D,1,1))
Finitial(2)=(patcharray(Q,1,2)-temparray(D,1,2))
Finitial(3)=(patcharray(Q,1,3)-temparray(D,1,3))
F=(/Finitial(1)/Rlm,Finitial(2)/Rlm,Finitial(3)/Rlm/)
dxbuilding=HUGE
C Check to see that the receiver is visible by patches.
DO 57 I=1,boxnumber,1
    CALL BOX(boxarraynear(I,1:3),
    *    Boxarrayfar(I,1:3),temparray(D,1,1:3),
    *    F,dxnear,dxfar,hit, planehit)
    if (dxnear.lt.dxbuilding)then
        dxbuilding=dxnear
    endif
    if (((temparray(D,1,1).gt.boxarraynear(I,1)
    *       .and.temparray(D,1,2).gt.boxarraynear(I,2)
    *       .and.temparray(D,1,3).gt.boxarraynear(I,3))
    *       .and.(temparray(D,1,1).lt.boxarrayfar(I,1)
    *       .and.temparray(D,1,2).lt.boxarrayfar(I,2)
    *       .and.temparray(D,1,3).lt.boxarrayfar(I,3)))
    *       then
        dxbuilding=-1.0
    endif
57  CONTINUE
if(TriangleNumber.gt.0)then
    DO 67 I=1,TriangleNumber,1
        call Polygon(temparray(D,1,1:3),F,I,3,
        *       TriangleNumber,PointNumbers,Trianglearray,
        *       BuildingPoints,normal,FaceNormalNo,
        *       FaceNormals,dxnear,behind)
        if (dxnear.lt.dxbuilding)then
            dxbuilding=dxnear
        endif
67  CONTINUE
endif
if(SquareNumber.gt.0)then
    DO 68 I=1,SquareNumber,1
        call Polygon(temparray(D,1,1:3),F,I,4,
        *        SquareNumber,PointNumbers,SquareArray,
* BuildingPoints, normal, FaceNormalNo,
* FaceNormals, dxnear, behind)
if (dxnear < dxbuilding) then
    dxbuilding = dxnear
endif

68 CONTINUE
endif
if (PolyBuilding > 0) then
    DO 69 I = 1, PolyBuilding
    C Check that the receivers are not inside the building
    CALL INSIDECHECK(temparray(D, 1, 1:3),
* BuildingPoints, PointNumbers, F, Trianglearray
* , SquareArray, TriangleNumber, SquareNumber,
* TriangleSequence, SquareSequence, Triangles,
* Squares, PolyBuilding, I, inside, FaceNormalNo,
* FaceNormals)
    if (inside .eq. 1) then
        dxbuilding = -1.0
    endif
    69 CONTINUE
endif
vec3 = FaceNormals(int(patcharray(Q, 1, 10)), 1:3)
PIRlm2 = PI * Rlm * Rlm
DO 52 W = 1, sizeffttwo
    if (Gk(Q, W) .ne. 0.0) then
        if (dxbuilding < Patchlength) then
            Ek = 0.0
        elseif (dxbuilding .ge. Patchlength) then
            length = sqrt(vec3(1) * vec3(1) +
* vec3(2) * vec3(2) + vec3(3) * vec3(3))
            cosxilm = (vec3(1) * F(1) + vec3(2) * F(2) + vec3(3) *
* F(3)) / (Rlm * length)
            m = airabsorb(W)
        else
            Ek = 0.0
        endif
    endif
52 CONTINUE
\[ \begin{align*}
E_k &= \exp(-m*R_{lm})*((\cos(x_{ilm}*G_k(Q,W))*\exp(-XJ*twopi*inputarray(W,1)*R_{lm}/\text{soundspeed}))/
\pi R_{lm}^2) \\
\text{endif}
\end{align*} \]

\[ \begin{align*}
temp2 &= \text{cmplx}(abs(temparray(D,W,5))*\exp(XJ*temparray(D,W,6))) \\
temp3 &= E_k + temp2 \\
temparray(D,W,5) &= \text{ABS}(temp3) \\
temparray(D,W,6) &= \text{ATAN2}(\text{imagpart}(temp3),\text{realpart}(temp3)) \\
\text{endif}
\end{align*} \]

52 \hspace{1em} \text{CONTINUE}

51 \hspace{1em} \text{CONTINUE}

\begin{verbatim}
print*, 'finished receiver', D, 'of', arraysize
50 \hspace{1em} \text{CONTINUE}
53 \hspace{1em} \text{CONTINUE}
\end{verbatim}

\text{endif}

C \hspace{1em} \text{Reconstruct the time signal}

\begin{verbatim}
CALL TIMERECONSTRUCT(sizefft, timearray, arraysize, temparray, timetemparray)
\end{verbatim}

C \hspace{1em} \text{Write out time signatures for each receiver.}

\begin{verbatim}
OPEN(UNIT=20,file=OUTPUTFILE,status='new')
true=Header(20)
if(planenum.ge.1)then
  DO 61 W=1, sizefft
    true=TimeHeader(20, timetemparray(1,W,4), sizex1, sizey1, sizez1, planename1)
    DO 62 D=1, arraysize1
      WRITE(20,* timetemparray(D,W,1:3),timetemparray(D,W,5))
    62 CONTINUE
  print*, 'finished time', timetemparray(1,W,4)
  61 CONTINUE
\end{verbatim}

\text{endif}
if(planenum.ge.2)then
   DO 63 W=1, sizefft
      true=TimeHeader(20,timetemparray(1,W,4),
      * sizex2,sizey2,sizez2,planename2)
      DO 64 D=arraysize1+1, arraysize1+arraysize2
         write(20,*) timetemparray(D,W,1:3),timetemparray(D,W,5)
   64 CONTINUE
   63 CONTINUE
endif
if(planenum.ge.3)then
   DO 65 W=1, sizefft
      true=TimeHeader(20,timetemparray(1,W,4),
      * sizex3,sizey3,sizez3,planename3)
      DO 66 D=arraysize1+arraysize2+1,arraysize1+arraysize2+
      * arraysize3
         write(20,*) timetemparray(D,W,1:3),timetemparray(D,W,5)
   66 CONTINUE
   65 CONTINUE
endif
if(planenum.ge.4)then
   DO 70 W=1, sizefft
      true=TimeHeader(20,timetemparray(1,W,4),
      * sizex4,sizey4,sizez4,planename4)
      DO 71 D=arraysize1+arraysize2+arraysize3+1, arraysize1+
      * arraysize2+arraysize3+arraysize4
         write(20,*) timetemparray(D,W,1:3),timetemparray(D,W,5)
   71 CONTINUE
   70 CONTINUE
endif
if(planenum.ge.5)then
   DO 72 W=1, sizefft
      true=TimeHeader(20,timetemparray(1,W,4),
      * sizex5,sizey5,sizez5,planename5)
DO 73 D=arraysize1+arraysize2+arraysize3+arraysize4+1,
* arraysize1+arraysize2+arraysize3+arraysize4+arraysize5
write(20,*) timetemparray(D,W,1:3),timetemparray(D,W,5)
73 CONTINUE
72 CONTINUE
endif
if(planenum.ge.6)then
    DO 74 W=1, sizefft
        true=TimeHeader(20,timetemparray(1,W,4),
* sizex6,sizey6,sizez6,planename6)
        DO 75 D=arraysize1+arraysize2+arraysize3+arraysize4+
* arraysize5+1,arraysize1+arraysize2+arraysize3+
* arraysize4+arraysize5+arraysize6
        write(20,*) timetemparray(D,W,1:3),timetemparray(D,W,5)
    75 CONTINUE
    74 CONTINUE
endif
if(planenum.ge.7)then
    DO 76 W=1, sizefft
        true=TimeHeader(20,timetemparray(1,W,4),
* sizex7,sizey7,sizez7,planename7)
        DO 77 D=arraysize1+arraysize2+arraysize3+arraysize4+
* arraysize5+arraysize6+1,arraysize1+arraysize2+
* arraysize3+arraysize4+arraysize5+arraysize6+arraysize7
        write(20,*) timetemparray(D,W,1:3),timetemparray(D,W,5)
    77 CONTINUE
    76 CONTINUE
endif
close(20)
END
B.2 Additional Functions

B.2.1 Functions

B.2.1.1 ABSORPTION

REAL FUNCTION ABSORPTION(ps,freq,hr,Temp)

C This function computes the air absorption for a given frequency, ambient pressure, relative humidity and temperature.

C Define all variables and reference values
REAL ps0, ps, freq, hr, Temp, T0, T01, F, FrN, FrO
ps0=1.0
hr=20.0
T0=293.15
T01=273.16
F=freq/ps

C Compute all relevant parameters
psat=ps0*10**(-6.8346*(T01/Temp)**1.261+4.6151)
h=ps0*(hr/ps)*(psat/ps0)
FrN=1/ps0*(T0/Temp)**(1/2)*(9+280*h*exp(-4.17*((T0/Temp)**(1/3)-1)))*
* exp(-4.17*((T0/Temp)**(1/3)-1)))
FrO=1/ps0*(24+4.04*10**4*h*((.02+h)/(.391+h)));
term1=0.01275*(exp(-2239.1/Temp)/(FrO+F**2/FrO));
term2=0.1068*(exp(-3352/Temp)/(FrN+F**2/FrN));
ABSORPTION=ps0*F**2*((1.84*10**(-11.0)*(Temp/T0)**(0.5)*ps0)+
* (Temp/T0)**(-5.0/2.0)*(term1+term2))
RETURN
END
B.2.1.2 TIMERECONSTRUCT

SUBROUTINE TIMERECONSTRUCT(sizefft, timearray, arraysize, temparray, 
   * timetemparray)

C This Function computes the timesignal from a given fft. It writes the 
C time signal out to a file.

C Define all variables

INTEGER sizefft, D, arraysize, W
DOUBLE COMPLEX tempfft(sizefft/2+1)
REAL timearray(sizefft)
COMPLEX XJ
INTEGER*8 invplan
DOUBLE PRECISION timesignal(sizefft)
REAL temparray(arraysize, sizefft/2, 6)
REAL timetemparray(arraysize, sizefft/2, 5)

INCLUDE 'fftw3.f'
XJ=(0,1)

print*, 'timereconstruct has been called'
DO 35 D=1, arraysize
   DO 36 W=1, sizefft
      timetemparray(D,W,1)=temparray(D,1,1)
      timetemparray(D,W,2)=temparray(D,1,2)
      timetemparray(D,W,3)=temparray(D,1,3)
      timetemparray(D,W,4)=timearray(W)
      timetemparray(D,W,5)=0.0
   CONTINUE
   CONTINUE
   print*, 'timetemparray has been initialized'
C Create the complex array to feed into the inverse fft function
DO 37 D=1, arraysize
   if (temparray(D,1,5).eq.0.0) then
      DO 40 W=1,sizefft
         timetemparray(D,W,5)=0.0
      40 CONTINUE
   else
      DO 38 W=1,sizefft/2+1
         if (W.eq.1) then
            tempfft(W)=cmplx(0.0)
         else
            tempfft(W)=cmplx(abs(temparray(D,W-1,5))*exp(XJ*temparray(D,W-1,6)))
         endif
      38 CONTINUE
      print*, 'created temparray'
      C use fftw to compute the inverse fft.
      call dfftw_plan_dft_c2r_1d(invplan,sizefft,tempfft,
         * timesignal, FFTW_ESTIMATE)
      call dfftw_execute(invplan, tempfft, timesignal)
      call dfftw_destroy_plan(invplan)
      print*, 'created time signature'
      DO 39 W=1,sizefft
         timetemparray(D,W,5)=timesignal(W)
      39 CONTINUE
   endif
37 CONTINUE
return
end

B.2.1.3 RECEIVERHITFUNC

SUBROUTINE RECEIVERHITFUNC(sizefft,outputarray,arraysize,
   * temparray)
This Function computes the timesignal from a given fft. It writes the time signal out to a file.

Define all variables

INTEGER sizefft,D,arraysize,W
REAL outputarray(sizefft/2,7)
REAL temparray(arraysize,sizefft/2,6)
DOUBLE COMPLEX temp1, temp2, temp3
COMPLEX XJ
XJ=(0,1)

Add new pressures to existing pressures in temparray

First Look for the correct location.

DO 40 D=1, arraysize
   if (outputarray(1,2).eq.temparray(D,1,1).and.
      * outputarray(1,3).eq.temparray(D,1,2).and.
      * outputarray(1,4).eq.temparray(D,1,3))then
   DO 41 W=1, sizefft/2
      temp1=cmplx(abs(temparray(D,W,5))*exp(XJ*
      * temparray(D,W,6)))
      temp2=cmplx(abs(outputarray(W,5))*exp(XJ*
      * outputarray(W,6)))
      temp3=temp1+temp2
      temparray(D,W,5)=abs(temp3)
      temparray(D,W,6)=ATAN2(imagpart(temp3),realpart(temp3))
   CONTINUE
endif

40 CONTINUE

return

end

B.2.1.4 HEADER

INTEGER FUNCTION Header(fileid)

C this function prints the header for the tecplot data

INTEGER fileid
Write(fileid,*) ’TITLE = ”Pressure at earlevel”’
Write(fileid,*) ’VARIABLES = ”X[m]” ”Y[m]” ”Z[m]” ”P[psf]”’
Write(fileid,*) ’TEXT’
Write(fileid,*) ’CS=FRAME’
Write(fileid,*) ’X=71.9660948264,Y=82.9866270431’
Write(fileid,*) ’C=BLACK’
Write(fileid,*) ’S=LOCAL’
Write(fileid,*) ’HU=POINT’
Write(fileid,*) ’LS=1 AN=MIDCENTER’
Write(fileid,*) ’BX=Filled BXM=60 LT=0.1 BXO=BLACK BXF=WHITE’
Write(fileid,*) ’F=HELV’
Write(fileid,*) ’H=20 A=0’
Write(fileid,*) ’MFC=””’
Write(fileid,*) ’CLIPPING=CLIPTOVIEWPORT’
Write(fileid,*) ’T=”Time = &(SOLUTIONTIME%4f)”’

Header=0

return

end
B.2.1.5 TIMEHEADER

INTEGER FUNCTION TimeHeader(fileid, time, sizex, sizey, sizez,
*   planename)

C this function prints the header between each time step.

INTEGER fileid, sizex, sizey, sizez
REAL time
CHARACTER*20 planename
Write(fileid,*) 'ZONE', ' T=', planename, ''
Write(fileid,*) 'STRANDID=1, SOLUTIONTIME=', time
Write(fileid,*) 'I=', sizex, 'J=', sizey, 'K=', sizez,
*   'ZONETYPE=Ordered'
Write(fileid,*) 'DATAPACKING=POINT'
Write(fileid,*) 'DT=(SINGLE SINGLE SINGLE SINGLE )'
header=0
return
end

B.2.1.6 GRID

SUBROUTINE Grid(radius, A, B, C, D, xmin, ymin, zmin, xmax, ymax, zmax,
*   receiverarray, arraysize, sizex, sizey, sizez, step)

C This function creates an equally spaced grid of size step apart

REAL radius, A, B, C, D, xmin, ymin, zmin, xmax, ymax, zmax, step
INTEGER i, j, sizex, sizey, sizez
INTEGER count, arraysize
REAL receiverarray(arraysize, 3), s
s = step / radius
if(xmin.eq.xmax)then
count=1
DO 1 i=1,int((zmax-zmin)/step),1
   DO 2 j=1,int((ymax-ymin)/(step)),1
      receiverarray(count,1)=(D-B*(ymin+(s*j+(1-s))*radius)-
       C*(zmin+(s*i+(1-s))*radius))/A
      receiverarray(count,2)=ymin+(s*j+(1-s))*radius
      receiverarray(count,3)=zmin+(s*i+(1-s))*radius
      count=count+1
   2 CONTINUE
   1 CONTINUE
sizex=int((ymax-ymin)/(step))
sizey=int((zmax-zmin)/step)
sizez=1
endif
if(ymin.eq.xmax)then
   count=1
   DO 3 i=1,int((xmax-xmin)/(step)),1
      DO 4 j=1,int((zmax-zmin)/(step)),1
         receiverarray(count,1)=xmin+(s*i+(1-s))*radius
         receiverarray(count,2)=(D-A*(xmin+(s*i+(1-s))*radius)-
          C*(zmin+(s*j+(1-s))*radius))/B
         receiverarray(count,3)=zmin+(s*j+(1-s))*radius
         count=count+1
      4 CONTINUE
   3 CONTINUE
   sizex=int((zmax-zmin)/step)
sizey=int((xmax-xmin)/(step))
sizez=1
endif
if(zmin.eq.zmax)then
   count=1
   DO 5 i=1,int((xmax-xmin)/(step)),1
      Do 6 j=1,int((ymax-ymin)/(step)),1
         C*Z
receiverarray(count,1)=xmin+(s*i+(1-s))*radius
receiverarray(count,2)=ymin+(s*j+(1-s))*radius
receiverarray(count,3)=(D-A*(xmin+(s*i+(1-s))*radius)-
  * B*(ymin+(s*j+(1-s))*radius))/C
  count=count+1

6  Continue
5 CONTINUE
  sizex=int((ymax-ymin)/(step))
  sizey=int((xmax-xmin)/step)
  sizez=1
endif
Return
END

B.2.1.7 INITIALGRID

SUBROUTINE InitialGrid(radius,A,B,C,D,theta,phi,xmin,ymin,zmin,
  * xmax,ymax,zmax,receiverarray, arraysize,sizex,sizey,sizez)

C This function creates an equally spaced grid of size step apart

REAL xmin,ymin,zmin,xmax,ymax,zmax
INTEGER i,j,sizex,sizey,sizez
INTEGER count,arraysize
REAL receiverarray(arraysize,3)
REAL A,B,C,D
REAL xspace, yspace,zspace
REAL theta, phi,radius
REAL lengthx, lengthy, lengthz
REAL vectorx(3), vectory(3), vectorz(3), initial(3)
  yspace=radius*abs(cos(phi))
  zspace=radius*abs(sin(theta))
if(xmin.eq.xmax)then
count=1
DO 1 i=1,int((zmax-zmin)/zspace),1
   DO 2 j=1,int((ymax-ymin)/(yspace)),1
      receiverarray(count,1)=(D-B*(ymin+j*yspace)-
      * C*(zmin+i*zspace))/A
      receiverarray(count,2)=ymin+j*yspace
      receiverarray(count,3)=zmin+i*zspace
      count=count+1
   2   CONTINUE
1   CONTINUE
sizex=int((ymax-ymin)/(yspace))
sizey=int((zmax-zmin)/zspace)
sizez=1
dendif
if(ymin.eq.ymax)then
   count=1
   DO 3 i=1,int((xmax-xmin)/(xspace)),1
      DO 4 j=1,int((zmax-zmin)/(zspace)),1
         receiverarray(count,1)=xmin+i*xspace
         receiverarray(count,2)=(D-A*(xmin+i*xspace)-
         * C*(zmin+j*zspace))/B
         receiverarray(count,3)=zmin+j*zspace
         count=count+1
      4  CONTINUE
3   CONTINUE
sizex=int((zmax-zmin)/zspace)
sizey=int((xmax-xmin)/(xspace))
sizez=1
dendif
if(zmin.eq.zmax)then
   count=1
   DO 5 i=1,int((xmax-xmin)/(xspace)),1
      DO 6 j=1,int((ymax-ymin)/(yspace)),1
         receiverarray(count,1)=(D-B*(ymin+j*yspace)-
         * C*(zmin+i*zspace))/A
         receiverarray(count,2)=ymin+j*yspace
         receiverarray(count,3)=zmin+i*zspace
         count=count+1
      6  CONTINUE
5   CONTINUE

receiverarray(count,1)=xmin+i*xspace
receiverarray(count,2)=ymin+j*yspace
receiverarray(count,3)=(D-A*(xmin+i*xspace)-
  B*(ymin+j*yspace))/C
  count=count+1

6   Continue
5   CONTINUE
  sizex=int((xmax-xmin)/(xspace))
  sizey=int((ymax-ymin)/yspace)
  sizez=1
endif
Return
END

B.2.1.8 SPHERECHECK

SUBROUTINE SPHERECHECK(Sc,Sr2,F,veci,dx)

C This function performs a check whether a ray hits a sphere. If
C it does hit the function returns the distance to the sphere
REAL Sr2,dx,dx0,dx1
REAL F(3),veci(3),Sc(3), OC(3), L2oc,tca, t2hc, dir(3)
REAL A,B,C,D
REAL HUGE
HUGE=1000000.0
OC(1)=Sc(1)-veci(1)
OC(2)=Sc(2)-veci(2)
OC(3)=Sc(3)-veci(3)
L2OC=dot_product(OC,OC)
tca=dot_product(OC,F)
t2hc=Sr2-L2OC+tca**2
if(L2oc.lt.Sr2) then
  dx=HUGE

elseif(tca.lt.0.0)then
    dx=HUGE
elseif(t2hc.lt.0.0)then
    dx=HUGE
else
    dx=tca-sqrt(t2hc)
endif
RETURN
END

B.2.1.9 CROSS

SUBROUTINE CROSS(A, B, normal)

C This function calculates a cross product of A and B and returns
C normal

REAL A(3), B(3), normal(3)
REAL length
normal(1)=A(2)*B(3)-A(3)*B(2)
normal(2)=A(3)*B(1)-A(1)*B(3)
normal(3)=A(1)*B(2)-A(2)*B(1)
length=sqrt(normal(1)**2.0+normal(2)**2+normal(3)**2)
if (length.ne.0.0)then
    normal=normal/length
endif
end

B.2.1.10 POLYGON

SUBROUTINE POLYGON(Vecip1,F,Q,size,Number,PointNumbers,PolyArray *
* ,BuildingPoints,normal,FaceNormalNo,FaceNormals,dxbuilding,
REAL Vecip1(3), normal(3), d, F(3), HUGE, odd
REAL PolyArray(Number, size+1), t, Vd, V0, G(size, 2)
REAL BuildingPoints(PointNumbers, 3), maximum
REAL intersection(3), dxbuilding, tempA, tempB, tempC
HUGE = 1000000.0
NC = 0
behind = 0
normal(1) = FaceNormals(int(PolyArray(Q, 1)), 1)
normal(2) = FaceNormals(int(PolyArray(Q, 1)), 2)
normal(3) = FaceNormals(int(PolyArray(Q, 1)), 3)
d = dot_product(normal, BuildingPoints(int(PolyArray(Q, 2)), 1:3))
Vd = dot_product(normal, F)
if (Vd.ge.0.0) then
  dxbuilding = HUGE
  GOTO 7
endif
V0 = -(dot_product(normal, Vecip1) + D)
t = V0/Vd
if (t.lt.0.0) then
  dxbuilding = HUGE
  behind = 1
  GOTO 7
endif
intersection(1) = Vecip1(1) + F(1)*t
intersection(2) = Vecip1(2) + F(2)*t
intersection(3) = Vecip1(3) + F(3)*t
maximum = max(abs(normal(1)), abs(normal(2)), abs(normal(3)))
if (maximum.eq.abs(normal(1))) then
  DO 8 P = 1, size
    G(P, 1:2) = (/intersection(2) - BuildingPoints(int(PolyArray(Q, 2)), 1:3))
* 1+P),2),intersection(3)-BuildingPoints(int(PolyArray(Q
* ,1+P)),3)/)
8 CONTINUE
elseif(maximum.eq.abs(normal(2)))then
   DO 9 P=1,size
      G(P,1:2)=(/intersection(1)-BuildingPoints(int(PolyArray(Q,
* 1+P)),1),intersection(3)-BuildingPoints(int(PolyArray(Q
* ,1+P)),3)/)
9 CONTINUE
elseif(maximum.eq.abs(normal(3)))then
   DO 10 P=1,size
      G(P,1:2)=(/intersection(1)-BuildingPoints(int(PolyArray(Q,
* 1+P)),1),intersection(2)-BuildingPoints(int(PolyArray(Q
* ,1+P)),2)/)
10 CONTINUE
endif
   DO 11 P=1,size
      if(P.eq.size)then
         if(G(P,2).lt.0.0)then
            SH=-1
         else
            SH=1
         endif
      else
         if(G(P,2).lt.0.0)then
            SH=-1
         else
            SH=1
         endif
      endif
   else
      if(G(P,2).lt.0.0)then
         SH=-1
      else
         SH=1
      endif
   endif
   endif
endif
if(G(P+1,2).lt.0.0)then
  NSH=-1
else
  NSH=1
endif
endif
if(SH.ne.NSH)then
  if(P.eq.size)then
    if(G(P,1).gt.0.0.and.G(1,1).gt.0.0)then
      NC=NC+1
    elseif(G(P,1).gt.0.0.or.G(1,1).gt.0.0)then
      IF((G(P,1)-(G(P,2)*(G(P+1,1)-G(P,1))/(G(P+1,2)-G(P,2)))
*  
      ))).GT.0.0)THEN
      NC=NC+1
    endif
  endif
else
  if(G(P,1).gt.0.0.and.G(P+1,1).gt.0.0)then
    NC=NC+1
  elseif(G(P,1).gt.0.0.or.G(P+1,1).gt.0.0)then
    IF((G(P,1)-(G(P,2)*(G(P+1,1)-G(P,1))/(G(P+1,2)-G(P,2)))
*  
    ))).GT.0.0)THEN
    NC=NC+1
  endif
endif
endif
endif
endif
11 CONTINUE
odd=MOD(NC,2)
if(odd.eq.0)then
  dxbuilding=HUGE
elseif(odd.eq.1)then
SUBROUTINE INSIDECHECK(point,BuildingPoints,PointNumbers,F,*
  TriangleArray,SquareArray,TriangleNumber,SquareNumber,*
  TriangleSequence,SquareSequence,Triangles,Squares,*
  PolyBuilding,inside)

INTEGER pointnumbers,TriangleNumber,SquareNumber,Triangles,Squares
INTEGER P,behind,inside,PolyBuilding
REAL point(3),F(3),normal(3),dxnear
REAL BuildingPoints(PointNumbers,3)
REAL TriangleArray(TriangleNumber,6)
REAL SquareArray(SquareNumber,7)
INTEGER SquareSequence(PolyBuilding,Squares)
INTEGER TriangleSequence(PolyBuilding,Triangles)
inside=1
DO 8 P=1,Triangles
   call Polygon(point,F,TriangleSequence(P,1:2),3,TriangleNumber,*
    PointNumbers,TriangleArray,BuildingPoints,normal,*
    FaceNormalNo,FaceNormals,dxnear,behind)
   if(behind.eq.0)then
      inside=0
      GOTO 10
   endif
8 CONTINUE
DO 9 P=1,Squares
   call Polygon(point,F,SquareSequence(P,1:6),4,SquareNumber,*
    PointNumbers,SquareArray,BuildingPoints,normal,*
* FaceNormalNo,FaceNormals,dxnear,behind)
if(behind.eq.0)then
  inside=0
  GOTO 10
endif
9  CONTINUE
10  CONTINUE
END

B.2.1.12  PLAN

SUBROUTINE PLAN(Vecip1, B1, B2, planehit,nbox)

C This function calculates the normal at the hitpoint of a box.

real nbox(3),Point1(3)
real Vecip1(3), B1(3), B2(3),Point3(3), Point2(3)
integer planehit
if (planehit.eq.1) then
  if(Vecip1(1).eq.B1(1)) then
    Point2=(/B1(1),B1(2),B2(3)/)
    Point3=(/B1(1),B2(2),B1(3)/)
  call CROSS((Point2-B1),(Point3-B1),nbox)
  endif
endif
if (planehit.eq.2) then
  if(Vecip1(2).eq.B1(2)) then
    Point2=(/B2(1),B1(2),B1(3)/)
  endif
endif
endf
if (planehit.eq.2) then
  if(Vecip1(2).eq.B1(2)) then
    Point2=(/B2(1),B1(2),B1(3)/)
  endif
endif
Point3=(/B1(1), B1(2), B2(3)/)
call CROSS((Point2-B1),(Point3-B1),nbox)
elseif(Vecip1(2).eq.B2(2))then
Point1=(/B1(1),B2(2),B1(1)/)
Point2=(/B1(1),B2(2),B2(3)/)
Point3=(/B2(1),B2(2),B1(3)/)
call CROSS((Point2-Point1),(Point3-Point1),nbox)
endif
endif
if(planehit.eq.3) then
if(Vecip1(3).eq.B1(3)) then
Point2=(/B2(1),B1(2),B1(3)/)
Point3=(/B1(1), B2(2), B1(3)/)
call CROSS((Point3-B1),(Point2-B1),nbox)
elseif(Vecip1(3).eq.B2(3))then
Point2=(/B1(1),B2(2),B2(3)/)
Point3=(/B2(1),B1(2),B2(3)/)
call CROSS((Point2-B2),(Point3-B2),nbox)
endif
endif
end

B.2.1.13 BOX

SUBROUTINE BOX(B1,B2,Vecip1,F,dxnear, dxfar, hit,planehit)

C This function checks to see if the ray hits a box. It determines which
C plane the ray hits

REAL T1X, T2X, T1Y, T2Y, T1Z, T2Z, tmp
REAL B1(3), B2(3),tempF(3)
REAL Vecip1(3), F(3), HUGE,dxnear, dxfar
INTEGER hit, planehit, tmphit
hit=5  
HUGE=1000000.0  
dxnear=-HUGE  
dxfar=HUGE  
tempF=F  
C print*, tempF  
   if ((F(1).eq.0.0) .or. (F(2).eq.0.0) .or. (F(3).eq.0.0)) then  
      if (F(1).eq.0.0) then  
         if ((vecip1(1).lt.B1(1)) .or. (vecip1(1).gt.B2(1))) then  
            hit=0  
            dxnear=HUGE  
            GO TO 100  
         endif  
      endif  
      if (F(2).eq.0.0) then  
         if ((vecip1(2).lt.B1(2)) .or. (vecip1(2).gt.B2(2))) then  
            hit=0  
            dxnear=HUGE  
            GO TO 100  
         endif  
      endif  
      if (F(3).eq.0.0) then  
         if ((vecip1(3).lt.B1(3)) .or. (vecip1(3).gt.B2(3))) then  
            hit=0  
            dxnear=HUGE  
            GO TO 100  
         endif  
      endif  
   endif  
   if (hit.ne.0) then  
      if (F(1).eq.0) tempF(1)=1.0  
      if (F(2).eq.0) tempF(2)=1.0  
      if (F(3).eq.0) tempF(3)=1.0  
   endif
if(F(1).ne.0.0) then
    T1X=(B1(1)-Vecip1(1))/tempF(1)
    T2X=(B2(1)-Vecip1(1))/tempF(1)
If (T1X.gt.T2X) then
    tmp=T1X
    T1X=T2X
    T2X=tmp
endif
if(T1X.gt.dxnear) dxnear=T1X
if(T2X.lt.dxfar) dxfar=T2X
if (dxnear.GT.dxfar) then
    hit=0
    dxnear=huge
    go to 100
elseif (dxfar.lt.0.0) then
    hit=0
    dxnear=huge
    goto 100
endif
endif
if(F(2).ne.0.0) then
    T1Y=(B1(2)-Vecip1(2))/tempF(2)
    T2Y=(B2(2)-Vecip1(2))/tempF(2)
print*, 'T1Y,T2Y',T1Y,T2Y
If (T1Y.GT.T2Y) then
    tmp=T1Y
    T1Y=T2Y
    T2Y=tmp
endif
if (T1Y.GT.dxnear) dxnear=T1Y
if (T2Y.LT.dxfar) dxfar=T2Y
if (dxnear.GT.dxfar) then
    hit=0
dxnear=huge
goto 100
elseif (dxfar.LT.0.0) then
    hit=0
dxnear=huge
    goto 100
endif
eendif
if(F(3).ne.0.0)then
    T1Z=(B1(3)-Vecip1(3))/tempF(3)
    T2Z=(B2(3)-Vecip1(3))/tempF(3)
    If (T1Z.GT.T2Z) then
        tmp=T1Z
        T1Z=T2Z
        T2Z=tmp
    endif
    if (T1Z.GT.dxnear) dxnear=T1Z
    if (T2Z.LT.dxfar) dxfar=T2Z
    if (dxnear.GT.dxfar) then
        hit=0
        dxnear=huge
        goto 100
    endif
endif
if (hit.ne.0) then
if (dxnear.LT.dxfar) then
    hit=1
    if (dxnear.EQ.T1X) planehit=1
    if (dxnear.EQ.T1Y) planehit=2
    if (dxnear.EQ.T1Z) planehit=3
endif
endif
endif

100 CONTINUE

return

end

B.2.2 Radiosity Functions

B.2.2.1 PATCHESSHORT

SUBROUTINE PATCHESSHORT(min,max,N,q,dd)

INTEGER N,m
REAL dd(N), min, max
REAL k(N)
REAL W,q

W=max-min

C For box 1 we mesh the x direction
DO 1 m=1, N
    k(m)=W/2.0*(1-q)/(1-q**(N/2))
    if (m.le.(N/2))then
        dd(m)=k(m)*q**(m-1)
    elseif(m.le.N.and.m.gt.(N/2))then
        dd(m)=k(m)*q**(N-m)
    endif
1 CONTINUE

END
B.2.2.2 CREATEPATCHARRAY

SUBROUTINE CREATEPATCHARRAY(ddm, ddl, Nm, Nl, x1, x2
*y1, y2, z1, z2, patcharray, slope, b, slope1, b1, count, normal)

INTEGER Nm, Nl, count
REAL ddm(Nm), ddl(Nl), patcharray(Nm*Nl, 6), x1, y1, x2, y2, z1, z2
REAL temp1(3), temp2(3), temp3(3), vec1(3), vec2(3), normal(3)
REAL vec3(3), x, y, z, slope, b, d, ddz, ddy, ddx, zcenter, xcenter, ycenter
REAL slope1, b1
d=-x1*normal(1)-y1*normal(2)-z1*normal(3)
if (z1.eq.z2) then
  count=1
  print*, 'ZPLANE', Nl, Nm, x1, y1, z1
  DO 2 l=1, Nl
    DO 3 m=1, Nm
      x=x1-0.5*ddm(m)+SUM(ddm(1:m))
      y=y1-0.5*ddl(l)+SUM(ddl(1:l))
      z=(-d-normal(1)*x-normal(2)*y)/normal(3)
      if (m.eq.1) then
        zcenter=z
      endif
      if (l.eq.1) then
        ddz=z-z1
      else
        ddz=0.5*(z-zcenter)
      endif
      if (y>=(slope*x+b).or.(y<=(slope1*x+b1)) then
        GOTO 3
      endif
      patcharray(count,1)=x
      patcharray(count,2)=y
patcharray(count,3)=z
patcharray(count,4)=ddm(m)
patcharray(count,5)=ddl(l)
patcharray(count,6)=ddz
count=count+1

3 CONTINUE
2 CONTINUE
elseif(y1.eq.y2)then
  count=1
  print*, 'YPLANE',Nl, Nm, x1, y1, z1
DO 4 l=1, Nl
  DO 5 m=1, Nm
    x=x1-0.5*ddm(m)+SUM(ddm(1:m))
    z=z1-.5*ddl(l)+SUM(ddl(1:l))
    y=(-d-normal(1)*x-normal(3)*z)/normal(2)
    if(m.eq.1)then
      ycenter=y
    endif
    if(l.eq.1)then
      ddy=y-y1
    else
      ddy=0.5*(y-ycenter)
    endif
    if(z.gt.slope*x+b.or.z.lt.slope1*x+b1)then
      GOTO 5
    endif
  patcharray(count,1)=x
  patcharray(count,2)=y
  patcharray(count,3)=z
  patcharray(count,4)=ddm(m)
  patcharray(count,5)=ddy
  patcharray(count,6)=ddl(l)
  count=count+1
elseif(x1.eq.x2)then
  count=1
  print*, 'XPLANE', Nl, Nm, x1, y1, z1
  DO 6 l=1, Nl
    DO 7 m=1, Nm
      y=y1-.5*ddm(m)+SUM(ddm(1:m))
      z=z1-.5*ddl(l)+SUM(ddl(1:l))
      x=(-d-normal(3)*z-normal(2)*y)/normal(1)
      if(m.eq.1)then
        xcenter=x
      endif
      if(l.eq.1)then
        ddx=x-x1
      else
        ddx=0.5*(x-xcenter)
      endif
      if(z.gt.slope*y+b.or.z.lt.slope1*y+b1)then
        GOTO 7
      endif
      patcharray(count,1)=x
      patcharray(count,2)=y
      patcharray(count,3)=z
      patcharray(count,4)=ddx
      patcharray(count,5)=ddm(m)
      patcharray(count,6)=ddl(l)
      count=count+1
  7 CONTINUE
  6 CONTINUE
endif
END
B.2.2.3 PERFORMFACTOR

SUBROUTINE PERFORMFACTOR(patcharray, PatchNo, sizefft, formfactors, *
   Q, W, PI)

INTEGER PatchNo, sizefft, Q, W, I
REAL patcharray(PatchNo, sizefft/2, 9)
REAL formfactors(PatchNo, PatchNo, 3), dlnlm, nu
REAL dl, ddl, dm, ddm, dlprime, dnprime, cosgamma, cosdeltagamma
REAL PI

if(patcharray(Q,1,4).eq.0.0)then
   if(patcharray(W,1,4).eq.0.0)then
      dl=patcharray(Q,1,3)
      ddl=patcharray(Q,1,6)
      dm=patcharray(Q,1,2)
      ddm=patcharray(Q,1,5)
      dlprime=patcharray(W,1,3)
      dnprime=patcharray(W,1,2)
      if(dl.eq.dlprime)then
         knu=-1.0
      else
         knu=1.0
      endif
      cosgamma=(dm-.5*ddm)/SQRT((dl-dlprime)**2+(dm-.5*ddm)**2+dnprime**2)
      cosdeltagamma=(dm+.5*ddm)/SQRT((dl-dlprime)**2+(dm+.5*ddm)**2+dnprime**2)
      nu=ABS(ATAN(abs((dl-.5*ddl-dlprime)/dnprime))-knu*ATAN(ABS((dl+.5*ddl-dlprime)/dnprime)))
      dlnlm=sqrt((patcharray(Q,1,1)-patcharray(W,1,1))**2+(patcharray(Q,1,2)-patcharray(W,1,2))**2+(patcharray(Q,1,3)-patcharray(W,1,3))**2)
      formfactors(Q, W, 1)=1/(2*PI)*ABS(cosgamma**2-cosdeltagamma**2)*nu
formfactors(Q,W,3)=dlnlm
elseif(patcharray(W,1,5).eq.0.0)then
    dl=patcharray(Q,1,3)
ddl=patcharray(Q,1,6)
dm=patcharray(Q,1,2)
ddm=patcharray(Q,1,5)
dlprime=patcharray(W,1,3)
dnprime=patcharray(W,1,1)
if(dl.eq.dlprime)then
    knu=-1.0
else
    knu=1.0
endif
endif

\[ \cos\gamma = \frac{dm - 0.5 \cdot ddm}{\sqrt{(dl-dlprime)^2 + (dm-0.5 \cdot ddm)^2 + dnprime^2}} \]
\[ \cos\delta\gamma = \frac{dm + 0.5 \cdot ddm}{\sqrt{(dl-dlprime)^2 + (dm+0.5 \cdot ddm)^2 + dnprime^2}} \]

\[ \nu = \left| \tan^{-1}\left( \frac{dl - 0.5 \cdot ddl - dlprime}{dnprime} \right) \right| - \knu \cdot \tan^{-1}\left( \left| \frac{dl + 0.5 \cdot ddl - dlprime}{dnprime} \right| \right) \]

\[ \text{dlnlm} = \sqrt{(patcharray(Q,1,1)-patcharray(W,1,1))^2 + (patcharray(Q,1,2)-patcharray(W,1,2))^2 + (patcharray(Q,1,3)-patcharray(W,1,3))^2} \]

\[ \text{formfactors}(Q,W,3) = \frac{1}{2\pi} \cdot \left| \cos\gamma^2 - \cos\delta\gamma^2 \right| \cdot \nu \]

elseif(Patcharray(W,1,6).eq.0.0)then
    dl=patcharray(Q,1,2)
ddl=patcharray(Q,1,5)
dm=patcharray(Q,1,3)
ddm=patcharray(Q,1,6)
dlprime=patcharray(W,1,2)
dnprime=patcharray(W,1,2)
if(dl.eq.dlprime)then

knu=-1.0
else
    knu=1.0
endif

cosgamma=(dm-.5*ddm)/SQRT((dl-dlprime)**2+(dm-.5*ddm)**2+dnprime**2)
cosdeltagamma=(dm+.5*ddm)/SQRT((dl-dlprime)**2+(dm+.5*ddm)**2+dnprime**2)
nu=ABS(ATAN(abs((dl-.5*ddl-dlprime)/dnprime))-knu*ATAN(abs((dl+.5*ddl-dlprime)/dnprime)))
dlnlm=sqrt((patcharray(Q,1,1)-patcharray(W,1,1))**2+(patcharray(Q,1,2)-patcharray(W,1,2))**2+(patcharray(Q,1,3)-patcharray(W,1,3))**2)
formfactors(Q,W,1)=1/(2*PI)*ABS(cosgamma**2-cosdeltagamma**2)*nu
formfactors(Q,W,3)=dlnlm
endif

elseif(patcharray(Q,1,5).eq.0.0)then
    if(patcharray(W,1,4).eq.0.0)then
        dl=patcharray(Q,1,3)
        ddl=patcharray(Q,1,6)
        dm=patcharray(Q,1,1)
        ddm=patcharray(Q,1,4)
        dlprime=patcharray(W,1,3)
        dnprime=patcharray(W,1,2)
        if(dl.eq.dlprime)then
            knu=-1.0
        else
            knu=1.0
        endif
        cosgamma=(dm-.5*ddm)/SQRT((dl-dlprime)**2+(dm-.5*ddm)**2+dnprime**2)
cosdeltagamma=(dm+.5*ddm)/SQRT((dl-dlprime)**2+(dm+.5*ddm)**2+dnprime**2)
    endif
    endif
endif
\[ \frac{.5 \cdot \text{ddm}^2 + \text{dnprime}^2}{(\text{patcharray}(Q,1,1) - \text{patcharray}(W,1,1))^2 + (\text{patcharray}(Q,1,2) - \text{patcharray}(W,1,2))^2 + (\text{patcharray}(Q,1,3) - \text{patcharray}(W,1,3))^2} \]

\[ \text{nu} = \text{ABS(ATAN(abs((dl-.5 \cdot \text{ddl}\cdot \text{dlprime})/\text{dnprime})) - \text{knu} \cdot \text{ATAN(abs((dl+.5 \cdot \text{ddl}\cdot \text{dlprime})/\text{dnprime}))})} \]

\[ \text{dlmln} = \sqrt{((\text{patcharray}(Q,1,1) - \text{patcharray}(W,1,1))^2 + (\text{patcharray}(Q,1,2) - \text{patcharray}(W,1,2))^2 + (\text{patcharray}(Q,1,3) - \text{patcharray}(W,1,3))^2)} \]

\[ \text{formfactors}(Q,W,1) = \frac{1}{2 \cdot \pi} \cdot \text{ABS(cosgamma}^2 - \text{cosdeltagamma}^2) \cdot \text{nu} \]

\[ \text{formfactors}(Q,W,3) = \text{dlmln} \]

\[ \text{elseif(patcharray}(W,1,5) = 0.0) \text{then} \]

\[ \text{dl} = \text{patcharray}(Q,1,1) \]
\[ \text{ddl} = \text{patcharray}(Q,1,4) \]
\[ \text{dm} = \text{patcharray}(Q,1,3) \]
\[ \text{ddm} = \text{patcharray}(Q,1,6) \]
\[ \text{dlprime} = \text{patcharray}(W,1,1) \]
\[ \text{dnprime} = \text{patcharray}(W,1,3) \]

\[ \text{if(dl.eq.dlprime)then} \]
\[ \quad \text{knu} = -1.0 \]
\[ \text{else} \]
\[ \quad \text{knu} = 1.0 \]
\[ \text{endif} \]

\[ \text{cosgamma} = (\text{dm} - 0.5 \cdot \text{ddm}) / \sqrt{(\text{dl} - \text{dlprime})^2 + (\text{dm} - 0.5 \cdot \text{ddm})^2 + \text{dnprime}^2} \]

\[ \text{cosdeltagamma} = (\text{dm} + 0.5 \cdot \text{ddm}) / \sqrt{(\text{dl} - \text{dlprime})^2 + (\text{dm} + 0.5 \cdot \text{ddm})^2 + \text{dnprime}^2} \]

\[ \text{nu} = \text{ABS(ATAN(abs((dl-.5 \cdot \text{ddl} \cdot \text{dlprime})/\text{dnprime})) - \text{knu} \cdot \text{ATAN(abs((dl+.5 \cdot \text{ddl} \cdot \text{dlprime})/\text{dnprime}))})} \]

\[ \text{dlmln} = \sqrt{((\text{patcharray}(Q,1,1) - \text{patcharray}(W,1,1))^2 + (\text{patcharray}(Q,1,2) - \text{patcharray}(W,1,2))^2 + (\text{patcharray}(Q,1,3) - \text{patcharray}(W,1,3))^2)} \]

\[ \text{formfactors}(Q,W,1) = 1/(2 \cdot PI) \]

\[ \text{else} \]
\[ \quad \text{ABS(cosgamma}^2 - \text{cosdeltagamma}^2) \cdot \text{nu} \]
\[ \text{formfactors}(Q,W,3) = \text{dlmln} \]
elseif(Patcharray(W,1,6).eq.0.0)then
    dl=patcharray(Q,1,1)
    ddl=patcharray(Q,1,4)
    dm=patcharray(Q,1,3)
    ddm=patcharray(Q,1,6)
    dlprime=patcharray(W,1,1)
    dnprime=patcharray(W,1,2)
    if(dl.eq.dlprime)then
        knu=-1.0
    else
        knu=1.0
    endif
    cosgamma=(dm-.5*ddm)/SQRT((dl-dlprime)**2+(dm-.5*ddm)**2+dnprime**2)
    cosdeltagamma=(dm+.5*ddm)/SQRT((dl-dlprime)**2+(dm+.5*ddm)**2+dnprime**2)
    nu=ABS(ATAN(abs((dl-.5*ddl-dlprime)/dnprime))-knu*ATAN(abs((dl+.5*ddl-dlprime)/dnprime)))-
    dlnlm=sqrt((patcharray(Q,1,1)-patcharray(W,1,1))**2+(patcharray(Q,1,2)-patcharray(W,1,2))**2+(patcharray(Q,1,3)-patcharray(W,1,3))**2)
    formfactors(Q,W,1)=1/(2*PI)*
    formfactors(Q,W,3)=dlnlm
endif
elseif(patcharray(Q,1,6).eq.0.0)then
    if(patcharray(W,1,4).eq.0.0)then
        dl=patcharray(Q,1,2)
        ddl=patcharray(Q,1,5)
        dm=patcharray(Q,1,1)
        ddm=patcharray(Q,1,4)
        dlprime=patcharray(W,1,2)
        dnprime=patcharray(W,1,3)
    else
        if(patcharray(W,1,6).eq.0.0)then
            dl=patcharray(Q,1,1)
            ddl=patcharray(Q,1,4)
            dm=patcharray(Q,1,3)
            ddm=patcharray(Q,1,6)
            dlprime=patcharray(W,1,1)
            dnprime=patcharray(W,1,2)
            if(dl.eq.dlprime)then
                knu=-1.0
            else
                knu=1.0
            endif
            cosgamma=(dm-.5*ddm)/SQRT((dl-dlprime)**2+(dm-.5*ddm)**2+dnprime**2)
            cosdeltagamma=(dm+.5*ddm)/SQRT((dl-dlprime)**2+(dm+.5*ddm)**2+dnprime**2)
            nu=ABS(ATAN(abs((dl-.5*ddl-dlprime)/dnprime))-knu*ATAN(abs((dl+.5*ddl-dlprime)/dnprime)))-
            dlnlm=sqrt((patcharray(Q,1,1)-patcharray(W,1,1))**2+(patcharray(Q,1,2)-patcharray(W,1,2))**2+(patcharray(Q,1,3)-patcharray(W,1,3))**2)
            formfactors(Q,W,1)=1/(2*PI)*
            formfactors(Q,W,3)=dlnlm
        endif
    endif
endif
else
    if(patcharray(W,1,4).eq.0.0)then
        dl=patcharray(Q,1,2)
        ddl=patcharray(Q,1,5)
        dm=patcharray(Q,1,1)
        ddm=patcharray(Q,1,4)
        dlprime=patcharray(W,1,2)
        dnprime=patcharray(W,1,3)
    else
        if(patcharray(W,1,6).eq.0.0)then
            dl=patcharray(Q,1,1)
            ddl=patcharray(Q,1,4)
            dm=patcharray(Q,1,3)
            ddm=patcharray(Q,1,6)
            dlprime=patcharray(W,1,1)
            dnprime=patcharray(W,1,2)
            if(dl.eq.dlprime)then
                knu=-1.0
            else
                knu=1.0
            endif
            cosgamma=(dm-.5*ddm)/SQRT((dl-dlprime)**2+(dm-.5*ddm)**2+dnprime**2)
            cosdeltagamma=(dm+.5*ddm)/SQRT((dl-dlprime)**2+(dm+.5*ddm)**2+dnprime**2)
            nu=ABS(ATAN(abs((dl-.5*ddl-dlprime)/dnprime))-knu*ATAN(abs((dl+.5*ddl-dlprime)/dnprime)))-
            dlnlm=sqrt((patcharray(Q,1,1)-patcharray(W,1,1))**2+(patcharray(Q,1,2)-patcharray(W,1,2))**2+(patcharray(Q,1,3)-patcharray(W,1,3))**2)
            formfactors(Q,W,1)=1/(2*PI)*
            formfactors(Q,W,3)=dlnlm
if(dl.eq.dlprime) then  
  knu=-1.0  
else  
  knu=1.0  
endif  

cosgamma=(dm-.5*ddm)/SQRT((dl-dlprime)**2+(dm-.5*ddm)**2+dnprime**2)  
cosdeltagamma=(dm+.5*ddm)/SQRT((dl-dlprime)**2+(dm+.5*ddm)**2+dnprime**2)  

nu=ABS(ATAN(abs((dl-.5*ddl-dlprime)/dnprime))-knu*ATAN(abs((dl+.5*ddl-dlprime)/dnprime))))  

dlnlm=sqrt((patcharray(Q,1,1)-patcharray(W,1,1))**2+(patcharray(Q,1,2)-patcharray(W,1,2))**2+(patcharray(Q,1,3)-patcharray(W,1,3))**2)  

formfactors(Q,W,1)=1/(2*PI)*ABS(cosgamma**2-cosdeltagamma**2)*nu  
formfactors(Q,W,3)=dlnlm  
elseif(patcharray(W,1,5).eq.0.0)then  
  dl=patcharray(Q,1,1)  
  ddl=patcharray(Q,1,4)  
  dm=patcharray(Q,1,2)  
  ddm=patcharray(Q,1,5)  
  dlprime=patcharray(W,1,1)  
  dnprime=patcharray(W,1,3)  
  if(dl.eq.dlprime) then  
    knu=-1.0  
else  
    knu=1.0  
endif  

cosgamma=(dm-.5*ddm)/SQRT((dl-dlprime)**2+(dm-.5*ddm)**2+dnprime**2)  
cosdeltagamma=(dm+.5*ddm)/SQRT((dl-dlprime)**2+(dm+.5*ddm)**2+dnprime**2)
nu=ABS(ATAN(abs((dl-.5*ddl-dlprime)/dnprime))-knu*ATAN(abs((
   dl+.5*ddl-dlprime)/dnprime))))
dlnlm=sqrt((patcharray(Q,1,1)-patcharray(W,1,1))**2+
   (patcharray(Q,1,2)-patcharray(W,1,2))**2+
   (patcharray(Q,1,3)-patcharray(W,1,3))**2)
formfactors(Q,W,1)=1/(2.0*PI)*
   ABS(cosgamma**2-cosdeltagamma**2)*nu
formfactors(Q,W,3)=dlnlm
elseif(Patcharray(W,1,6).eq.0.0)then
   dl=patcharray(Q,1,2)
   ddl=patcharray(Q,1,5)
   dm=patcharray(Q,1,1)
   ddm=patcharray(Q,1,4)
   dlprime=patcharray(W,1,2)
   dnprime=patcharray(W,1,1)
   if(dl.eq.dlprime)then
      knu=-1.0
   else
      knu=1.0
   endif
   cosgamma=(dm-.5*ddm)/SQRT((dl-dlprime)**2+(dm-.5*ddm)**2+dnprime**2)
   cosdeltagamma=(dm+.5*ddm)/SQRT((dl-dlprime)**2+(dm+.5*ddm)**2+dnprime**2)
   nu=ABS(ATAN(abs((dl-.5*ddl-dlprime)/dnprime))-knu*ATAN(abs((
      dl+.5*ddl-dlprime)/dnprime))))
   dlnlm=sqrt((patcharray(Q,1,1)-patcharray(W,1,1))**2+
      (patcharray(Q,1,2)-patcharray(W,1,2))**2+
      (patcharray(Q,1,3)-patcharray(W,1,3))**2)
   formfactors(Q,W,1)=1/(2*PI)*
      ABS(cosgamma**2-cosdeltagamma**2)*nu
   formfactors(Q,W,3)=dlnlm
endif
B.3 Sample Geometry Files

B.3.1 Geometry File

FaceNormalNo=5
allocate(FaceNormals(FaceNormalNo,3))
FaceNormals(1,1:3)=(-1,0,0/)
FaceNormals(2,1:3)=(0,1,0/)
FaceNormals(3,1:3)=(1,0,0/)
FaceNormals(4,1:3)=(0,-1,0/)
FaceNormals(5,1:3)=(0,0,1/)

Boxnumber=1
allocate(Boxarraynear(boxnumber,3))
allocate(Boxarrayfar(boxnumber,3))
Boxarraynear(1,1:3)=(10,10,0/)
boxarrayfar(1,1:3)=(64.4322,46.9316,8.2423/)
TriangleNumber=0
SquareNumber=0
PolyBuilding=0

B.3.2 Radiosity Patch File

PatchNox=4
allocate(xlimit(PatchNox))
allocate(Nx(patchNox-1))

xlimit(1)=0.0
xlimit(2)=boxarraynear(1,1)
xlimit(3)=boxarrayfar(1,1)
xlimit(4)=100.0

Nx(1)=10
Nx(2)=10
Nx(3)=10

qx=1.2

PatchNoy=4
allocate(ylimit(PatchNoy))
allocate(Ny(PatchNoy-1))

ylimit(1)=0.0
ylimit(2)=boxarraynear(1,2)
ylimit(3)=boxarrayfar(1,2)
ylimit(4)=60.0

Ny(1)=10
Ny(2)=10
Ny(3)=10

qy=1.2

PatchNoz=2
allocate(zlimit(PatchNoz))
allocate(Nz(PatchNoz-1))

zlimit(1)=boxarraynear(1,3)
zlimit(2)=boxarrayfar(1,3)

Nz(1)=10
qz=1.2

PatchNo=Nx(1)*Ny(1)+Nx(2)*Ny(1)+Nx(3)*Ny(1)+Nx(1)*Ny(2)+Nx(2)*Ny(2)+Nx(3)*Ny(2)+Nx(1)*Ny(3)+Nx(2)*Ny(3)+Nx(3)*Ny(3)+2*Nx(2)*Nz(1)

allocate(patcharray(PatchNo,sizeffttwo,10))
allocate(formfactors(PatchNo,PatchNo,3))

patcharray=0.0

C This creates patches for the Building.
increment=1
slope=0
slope1=0
tempsize=Nx(1)*Ny(1)
allocate(ddx1(Nx(1)))
allocate(ddy1(Ny(1)))
allocate(patcharraytemp(Nx(1)*Ny(1),6))
b=ylimit(2)
b1=ylimit(1)
CALL PATCHESHORT(xlimit(1),xlimit(2),Nx(1),qx,ddx1)
CALL PATCHESHORT(ylimit(1),ylimit(2),Ny(1),qy,ddy1)
CALL CREATEPATCHARRAY(ddx1,ddy1,Nx(1),Ny(1),xlimit(1),xlimit(2),ylimit(1),ylimit(2),0.0,0.0,patcharraytemp,slope,b,slope1,b1,count,FaceNormals(5,1:3))
DO 101 Q=increment,increment+tempsize-1
   DO 102 W=1,sizeffttwo
      patcharray(Q,W,1)=patcharraytemp(Q-increment+1,1)
      patcharray(Q,W,2)=patcharraytemp(Q-increment+1,2)
      patcharray(Q,W,3)=patcharraytemp(Q-increment+1,3)
      patcharray(Q,W,4)=patcharraytemp(Q-increment+1,4)
      patcharray(Q,W,5)=patcharraytemp(Q-increment+1,5)
      patcharray(Q,W,6)=patcharraytemp(Q-increment+1,6)
   END DO 102
patcharray(Q,W,7)=0.0
patcharray(Q,W,8)=0.0
patcharray(Q,W,9)=1.0
patcharray(Q,W,10)=5.0

102 CONTINUE
101 CONTINUE

increment=Q
tempsize=Nx(2)*Ny(1)
deallocate(ddx1)
deallocate(ddy1)
deallocate(patcharraytemp)
allocate(ddx1(Nx(2)))
allocate(ddy1(Ny(1)))
allocate(patcharraytemp(Nx(2)*Ny(1),6))
b=ylimit(2)
b1=ylimit(1)
CALL PATCHESHORT(xlimit(2),xlimit(3),Nx(2),qx,ddx1)
CALL PATCHESHORT(ylimit(1),ylimit(2),Ny(1),qy,ddy1)
CALL CREATEPATCHARRAY(ddx1,ddy1,Nx(2),Ny(1),xlimit(2),xlimit(3),
*       ylimit(1),ylimit(2),0,0,0,0,patcharraytemp,slope,b,slope1,b1,
*       count,FaceNormals(5,1:3))
DO 103 Q=increment,increment+tempsize-1
   DO 104 W=1,sizeffttwo
         patcharray(Q,W,1)=patcharraytemp(Q-increment+1,1)
         patcharray(Q,W,2)=patcharraytemp(Q-increment+1,2)
         patcharray(Q,W,3)=patcharraytemp(Q-increment+1,3)
         patcharray(Q,W,4)=patcharraytemp(Q-increment+1,4)
         patcharray(Q,W,5)=patcharraytemp(Q-increment+1,5)
         patcharray(Q,W,6)=patcharraytemp(Q-increment+1,6)
         patcharray(Q,W,7)=0.0
         patcharray(Q,W,8)=0.0
         patcharray(Q,W,9)=2.0
         patcharray(Q,W,10)=5.0
   104 CONTINUE
   103 CONTINUE
deallocate(ddx1)
deallocate(ddy1)
increment=Q
tempsize=Nx(3)*Ny(1)
deallocate(patcharraytemp)
alocate(ddx1(Nx(3)))
alocate(ddy1(Ny(1)))
alocate(patcharraytemp(Nx(3)*Ny(1),6))
b=ylimit(2)
b1=ylimit(1)
       CALL PATCHESSHORT(xlimit(3),xlimit(4),Nx(3),qx,ddx1)
       CALL PATCHESSHORT(ylimit(1),ylimit(2),Ny(1),qy,ddy1)
       CALL CREATEPATCHARRAY(ddx1,ddy1,Nx(3),Ny(1),xlimit(3),xlimit(4),
       *  ylimit(1),ylimit(2),0.0,0.0,patcharraytemp,slope,b,slope1,b1,
       *  count,FaceNormals(5,1:3))
DO 105 Q=increment,increment+tempsize-1
   DO 106 W=1,sizefttwo
      patcharray(Q,W,1)=patcharraytemp(Q-increment+1,1)
      patcharray(Q,W,2)=patcharraytemp(Q-increment+1,2)
      patcharray(Q,W,3)=patcharraytemp(Q-increment+1,3)
      patcharray(Q,W,4)=patcharraytemp(Q-increment+1,4)
      patcharray(Q,W,5)=patcharraytemp(Q-increment+1,5)
      patcharray(Q,W,6)=patcharraytemp(Q-increment+1,6)
      patcharray(Q,W,7)=0.0
      patcharray(Q,W,8)=0.0
      patcharray(Q,W,9)=3.0
      patcharray(Q,W,10)=5.0
106    CONTINUE
105    CONTINUE
       deallocate(ddx1)
       deallocate(ddy1)
increment = Q
tempsize = Nx(1) * Ny(2)
deallocate(patcharraytemp)
allocate(ddx1(Nx(1)))
allocate(ddy1(Ny(2)))
allocate(patcharraytemp(Nx(1) * Ny(2), 6))
b = ylimit(3)
b1 = ylimit(2)
CALL PATCHESHORT(xlimit(1), xlimit(2), Nx(1), qx, ddx1)
CALL PATCHESHORT(ylimit(2), ylimit(3), Ny(2), qy, ddy1)
CALL CREATEPATCHARRAY(ddx1, ddy1, Nx(1), Ny(2), xlimit(1), xlimit(2),
* ylimit(2), ylimit(3), 0.0, 0.0, 0.0, patcharraytemp, slope, b, slope1, b1,
* count, FaceNormals(5, 1:3))
DO 107 Q = increment, increment + tempsize - 1
   DO 108 W = 1, sizefftwo
      patcharray(Q, W, 1) = patcharraytemp(Q - increment + 1, 1)
      patcharray(Q, W, 2) = patcharraytemp(Q - increment + 1, 2)
      patcharray(Q, W, 3) = patcharraytemp(Q - increment + 1, 3)
      patcharray(Q, W, 4) = patcharraytemp(Q - increment + 1, 4)
      patcharray(Q, W, 5) = patcharraytemp(Q - increment + 1, 5)
      patcharray(Q, W, 6) = patcharraytemp(Q - increment + 1, 6)
      patcharray(Q, W, 7) = 0.0
      patcharray(Q, W, 8) = 0.0
      patcharray(Q, W, 9) = 4.0
      patcharray(Q, W, 10) = 5.0
   CONTINUE
108 CONTINUE
107 CONTINUE
deallocate(ddx1)
deallocate(ddy1)
increment = Q
tempsize = Nx(3) * Ny(2)
deallocate(patcharraytemp)
allocate(ddx1(Nx(3)))
allocate(ddy1(Ny(2)))
allocate(patcharraytemp(Nx(3)*Ny(2),6))
b=ylimit(3)
b1=ylimit(2)
CALL PATCHESSHORT(xlimit(3),xlimit(4),Nx(3),qx,ddx1)
CALL PATCHESSHORT(ylimit(2),ylimit(3),Ny(2),qy,ddy1)
CALL CREATEPATCHARRAY(ddx1,ddy1,Nx(3),Ny(2),xlimit(3),xlimit(4)
* ,ylimit(2),ylimit(3),0.0,0.0,patcharraytemp,slope,b,slope1,b1
* ,count,FaceNormals(5,1:3))
DO 109 Q=increment,increment+tempsize-1
  DO 110 W=1,sizeffttwo
    patcharray(Q,W,1)=patcharraytemp(Q-increment+1,1)
    patcharray(Q,W,2)=patcharraytemp(Q-increment+1,2)
    patcharray(Q,W,3)=patcharraytemp(Q-increment+1,3)
    patcharray(Q,W,4)=patcharraytemp(Q-increment+1,4)
    patcharray(Q,W,5)=patcharraytemp(Q-increment+1,5)
    patcharray(Q,W,6)=patcharraytemp(Q-increment+1,6)
    patcharray(Q,W,7)=0.0
    patcharray(Q,W,8)=0.0
    patcharray(Q,W,9)=5.0
    patcharray(Q,W,10)=5.0
  110 CONTINUE
109 CONTINUE

deallocate(ddx1)
dallocate(ddy1)
increment=Q
tempsize=Nx(1)*Ny(3)
deallocate(patcharraytemp)
allocate(patcharraytemp(Nx(1)*Ny(3),6))
b=ylimit(4)
b1=ylimit(3)
allocate(ddx1(Nx(1)))
allocate(ddy1(Ny(3))))
CALL PATCHESHORT(xlimit(1),xlimit(2),Nx(1),qx,ddx1)
CALL PATCHESHORT(ylimit(3),ylimit(4),Ny(3),qy,ddy1)
CALL CREATEPATCHARRAY(ddx1,ddy1,Nx(1),Ny(3),xlimit(1),xlimit(2),
  ylimit(3),ylimit(4),0.0,0.0,patcharraytemp,slope,b,slope1,b1,
  count,FaceNormals(5,1:3))
DO 111 Q=increment,increment+tempsize-1
  DO 112 W=1,sizefttwo
    patcharray(Q,W,1)=patcharraytemp(Q-increment+1,1)
    patcharray(Q,W,2)=patcharraytemp(Q-increment+1,2)
    patcharray(Q,W,3)=patcharraytemp(Q-increment+1,3)
    patcharray(Q,W,4)=patcharraytemp(Q-increment+1,4)
    patcharray(Q,W,5)=patcharraytemp(Q-increment+1,5)
    patcharray(Q,W,6)=patcharraytemp(Q-increment+1,6)
    patcharray(Q,W,7)=0.0
    patcharray(Q,W,8)=0.0
    patcharray(Q,W,9)=6.0
    patcharray(Q,W,10)=5.0
  112 CONTINUE
111 CONTINUE
allocate(ddx1)
deallocate(ddy1)
increment=Q
tempsize=Nx(2)*Ny(3)
deallocate(patcharraytemp)
allocate(ddx1(Nx(2)))
allocate(ddy1(Ny(3)))
allocate(patcharraytemp(Nx(2)*Ny(3),6))
b=ylimit(4)
b1=ylimit(3)
CALL PATCHESHORT(xlimit(2),xlimit(3),Nx(2),qx,ddx1)
CALL PATCHESHORT(ylimit(3),ylimit(4),Ny(3),qy,ddy1)
CALL CREATEPATCHARRAY(ddx1,ddy1,Nx(2),Ny(3),xlimit(2),xlimit(3),
  ylimit(3),ylimit(4),0.0,0.0,patcharraytemp,slope,b,slope1,b1,
* count,FaceNormals(5,1:3))
DO 113 Q=increment,increment+tempsize-1
  DO 114 W=1,sizeffttwo
    patcharray(Q,W,1)=patcharraytemp(Q-increment+1,1)
    patcharray(Q,W,2)=patcharraytemp(Q-increment+1,2)
    patcharray(Q,W,3)=patcharraytemp(Q-increment+1,3)
    patcharray(Q,W,4)=patcharraytemp(Q-increment+1,4)
    patcharray(Q,W,5)=patcharraytemp(Q-increment+1,5)
    patcharray(Q,W,6)=patcharraytemp(Q-increment+1,6)
    patcharray(Q,W,7)=0.0
    patcharray(Q,W,8)=0.0
    patcharray(Q,W,9)=7.0
    patcharray(Q,W,10)=5.0
  114 CONTINUE
113 CONTINUE
  deallocate(ddx1)
  deallocate(ddy1)
  increment=Q
  tempsize=Nx(3)*Ny(3)
  deallocate(patcharraytemp)
  allocate(ddx1(Nx(3)))
  allocate(ddy1(Ny(3)))
  allocate(patcharraytemp(Nx(3)*Ny(3),6))
  b=ylimit(4)
  b1=ylimit(3)
  CALL PATCHESSHORT(xlimit(3),xlimit(4),Nx(3),qx,ddx1)
  CALL PATCHESSHORT(ylimit(3),ylimit(4),Ny(3),qy,ddy1)
  CALL CREATEPATCHARRAY(ddx1,ddy1,Nx(3),Ny(3),xlimit(3),xlimit(4),
    * ylimit(3),ylimit(4),0.0,0.0,patcharraytemp,slope,b,slope1,b1,
    * count,FaceNormals(5,1:3))
  DO 115 Q=increment,increment+tempsize-1
    DO 116 W=1,sizeffttwo
      patcharray(Q,W,1)=patcharraytemp(Q-increment+1,1)
patcharray(Q,W,2)=patcharraytemp(Q-increment+1,2)
patcharray(Q,W,3)=patcharraytemp(Q-increment+1,3)
patcharray(Q,W,4)=patcharraytemp(Q-increment+1,4)
patcharray(Q,W,5)=patcharraytemp(Q-increment+1,5)
patcharray(Q,W,6)=patcharraytemp(Q-increment+1,6)
patcharray(Q,W,7)=0.0
patcharray(Q,W,8)=0.0
patcharray(Q,W,9)=8.0
patcharray(Q,W,10)=5.0

CONTINUE

increment=Q
tempsize=Nx(2)*Nz(1)
deallocate(patcharraytemp)
allocate(ddx1(Nx(2)))
allocate(ddz1(Nz(1)))
allocate(patcharraytemp(Nx(2)*Nz(1),6))
b=zlimit(2)
b1=zlimit(1)

CALL PATCHESHORT(xlimit(2),xlimit(3),Nx(2),qx,ddx1)
CALL PATCHESHORT(zlimit(1),zlimit(2),Nz(1),qz,ddz1)
CALL CREATEPATCHARRAY(ddx1,ddz1,Nx(2),Nz(1),xlimit(2),xlimit(3),
ylimit(2),ylimit(2),zlimit(1),zlimit(2),patcharraytemp,slope,
b,slope1,b1,count,FaceNormals(4,1:3))

DO 117 Q=increment,increment+tempsize-1
  DO 118 W=1,sizeffttwo
    patcharray(Q,W,1)=patcharraytemp(Q-increment+1,1)
    patcharray(Q,W,2)=patcharraytemp(Q-increment+1,2)
    patcharray(Q,W,3)=patcharraytemp(Q-increment+1,3)
    patcharray(Q,W,4)=patcharraytemp(Q-increment+1,4)
    patcharray(Q,W,5)=patcharraytemp(Q-increment+1,5)
  END

CONTINUE

deallocate(ddx1)
deallocate(ddy1)
increment=Q
tempsize=Nx(2)*Nz(1)
deallocate(patcharraytemp)
allocate(ddx1(Nx(2)))
allocate(ddz1(Nz(1)))
allocate(patcharraytemp(Nx(2)*Nz(1),6))
b=zlimit(2)
b1=zlimit(1)

CALL PATCHESHORT(xlimit(2),xlimit(3),Nx(2),qx,ddx1)
CALL PATCHESHORT(zlimit(1),zlimit(2),Nz(1),qz,ddz1)
CALL CREATEPATCHARRAY(ddx1,ddz1,Nx(2),Nz(1),xlimit(2),xlimit(3),
ylimit(2),ylimit(2),zlimit(1),zlimit(2),patcharraytemp,slope,
b,slope1,b1,count,FaceNormals(4,1:3))

DO 117 Q=increment,increment+tempsize-1
  DO 118 W=1,sizeffttwo
    patcharray(Q,W,1)=patcharraytemp(Q-increment+1,1)
    patcharray(Q,W,2)=patcharraytemp(Q-increment+1,2)
    patcharray(Q,W,3)=patcharraytemp(Q-increment+1,3)
    patcharray(Q,W,4)=patcharraytemp(Q-increment+1,4)
    patcharray(Q,W,5)=patcharraytemp(Q-increment+1,5)
\[
\begin{align*}
\text{patcharray}(Q,W,6) &= \text{patcharraytemp}(Q-\text{increment}+1,6) \\
\text{patcharray}(Q,W,7) &= 0.0 \\
\text{patcharray}(Q,W,8) &= 0.0 \\
\text{patcharray}(Q,W,9) &= 9.0 \\
\text{patcharray}(Q,W,10) &= 4.0 \\
118 &\text{ CONTINUE} \\
117 &\text{ CONTINUE} \\
deallocate(ddx1) \\
deallocate(ddz1) \\
\text{increment} &= Q \\
\text{tempsize} &= Nx(2) * Nz(1) \\
deallocate(patcharraytemp) \\
allocate(ddx1(Nx(2))) \\
allocate(ddz1(Nz(1))) \\
allocate(patcharraytemp(Nx(2) * Nz(1), 6)) \\
b &= \text{zlimit}(2) \\
b1 &= \text{zlimit}(1) \\
\text{CALL PATCHESHORT}(xlimit(2),xlimit(3),Nx(2),qx,ddx1) \\
\text{CALL PATCHESHORT}(zlimit(1),zlimit(2),Nz(1),qz,ddz1) \\
\text{CALL CREATEPATCHARRAY}(ddx1,ddz1,Nx(2),Nz(1),xlimit(2),xlimit(3), \\
\quad ylimit(3),ylimit(3),zlimit(1),zlimit(2),\text{patcharraytemp},\text{slope}, \\
\quad b,\text{slope1},b1,\text{count},\text{FaceNormals}(2,1:3)) \\
\text{DO} 119 Q = \text{increment},\text{increment} + \text{tempsize} - 1 \\
\text{DO} 120 W = 1,\text{sizefftwo} \\
\text{patcharray}(Q,W,1) &= \text{patcharraytemp}(Q-\text{increment}+1,1) \\
\text{patcharray}(Q,W,2) &= \text{patcharraytemp}(Q-\text{increment}+1,2) \\
\text{patcharray}(Q,W,3) &= \text{patcharraytemp}(Q-\text{increment}+1,3) \\
\text{patcharray}(Q,W,4) &= \text{patcharraytemp}(Q-\text{increment}+1,4) \\
\text{patcharray}(Q,W,5) &= \text{patcharraytemp}(Q-\text{increment}+1,5) \\
\text{patcharray}(Q,W,6) &= \text{patcharraytemp}(Q-\text{increment}+1,6) \\
\text{patcharray}(Q,W,7) &= 0.0 \\
\text{patcharray}(Q,W,8) &= 0.0 \\
\text{patcharray}(Q,W,9) &= 10.0
\end{align*}
\]
patcharray(Q,W,10)=2.0

CONTINUE

increment=Q
tempsize=Ny(2)*Nz(1)
deallocate(patcharraytemp)
allocate(ddy1(Ny(2)))
allocate(ddz1(Nz(1)))
allocate(patcharraytemp(Ny(2)*Nz(1),6))
b=zlimit(2)
b1=zlimit(1)
CALL PATCHESSHORT(ylimit(2),ylimit(3),Ny(2),qy,ddy1)
CALL PATCHESSHORT(zlimit(1),zlimit(2),Nz(1),qz,ddz1)
CALL CREATEPATCHARRAY(ddy1,ddz1,Ny(2),Nz(1),xlimit(2),xlimit(2),
* ylimit(2),ylimit(3),zlimit(1),zlimit(2),patcharraytemp,slope
* b,slope1,b1,count,FaceNormals(1,1:3))
DO 121 Q=increment,increment+tempsize-1
  DO 122 W=1,sizeffttwo
    patcharray(Q,W,1)=patcharraytemp(Q-increment+1,1)
    patcharray(Q,W,2)=patcharraytemp(Q-increment+1,2)
    patcharray(Q,W,3)=patcharraytemp(Q-increment+1,3)
    patcharray(Q,W,4)=patcharraytemp(Q-increment+1,4)
    patcharray(Q,W,5)=patcharraytemp(Q-increment+1,5)
    patcharray(Q,W,6)=patcharraytemp(Q-increment+1,6)
    patcharray(Q,W,7)=0.0
    patcharray(Q,W,8)=0.0
    patcharray(Q,W,9)=11.0
    patcharray(Q,W,10)=1.0
  CONTINUE

122 CONTINUE

121 CONTINUE

deallocate(ddy1)
deallocate(ddz1)
increment=Q
tempsize=Ny(2)*Nz(1)
deallocate(patcharraytemp)
allocate(ddy1(Ny(2)))
allocate(ddz1(Nz(1)))
allocate(patcharraytemp(Ny(2)*Nz(1),6))
b=zlimit(2)
b1=zlimit(1)
CALL PATCHESHORT(ylimit(2),ylimit(3),Ny(2),qy,ddy1)
CALL PATCHESHORT(zlimit(1),zlimit(2),Nz(1),qz,ddz1)
CALL CREATEPATCHARRAY(ddy1,ddz1,Ny(2),Nz(1),xlim(3),xlim(3),
* ylimit(2),ylimit(3),xlim(1),xlim(2),patcharraytemp,slope,
* b,slope1,b1,count,FaceNormals(3,1:3))
DO 123 Q=increment,increment+tempsize-1
   DO 124 W=sizeffttwo
      patcharray(Q,W,1)=patcharraytemp(Q-increment+1,1)
      patcharray(Q,W,2)=patcharraytemp(Q-increment+1,2)
      patcharray(Q,W,3)=patcharraytemp(Q-increment+1,3)
      patcharray(Q,W,4)=patcharraytemp(Q-increment+1,4)
      patcharray(Q,W,5)=patcharraytemp(Q-increment+1,5)
      patcharray(Q,W,6)=patcharraytemp(Q-increment+1,6)
      patcharray(Q,W,7)=0.0
      patcharray(Q,W,8)=0.0
      patcharray(Q,W,9)=12.0
      patcharray(Q,W,10)=3.0
   124 CONTINUE
123 CONTINUE
   deallocate(ddy1)
   deallocate(ddz1)
   increment=Q
tempsize=Ny(2)*Nx(2)
deallocate(patcharraytemp)
allocate(ddx1(Nx(2)))
allocate(ddy1(Ny(2)))
allocate(patcharraytemp(Ny(2)*Nx(2),6))
b=ylimit(3)
b1=ylimit(2)
CALL PATCHESHORT(xlimit(2),xlimit(3),Nx(2),qx,ddx1)
CALL PATCHESHORT(ylimit(2),ylimit(3),Ny(2),qy,ddy1)
CALL CREATEPATCHARRAY(ddx1,ddy1,Nx(2),Ny(2),xlimit(2),xlimit(3),
  ylimit(2),ylimit(3),zlimit(2),zlimit(2),patcharraytemp,slope,
  b,slope1,b1,count,FaceNormals(5,1:3))
DO 125 Q=increment,increment+tempsize-1
  DO 126 W=1,sizefttwo
    patcharray(Q,W,1)=patcharraytemp(Q-increment+1,1)
    patcharray(Q,W,2)=patcharraytemp(Q-increment+1,2)
    patcharray(Q,W,3)=patcharraytemp(Q-increment+1,3)
    patcharray(Q,W,4)=patcharraytemp(Q-increment+1,4)
    patcharray(Q,W,5)=patcharraytemp(Q-increment+1,5)
    patcharray(Q,W,6)=patcharraytemp(Q-increment+1,6)
    patcharray(Q,W,7)=0.0
    patcharray(Q,W,8)=0.0
    patcharray(Q,W,9)=13.0
    patcharray(Q,W,10)=5.0
  CONTINUE 126
CONTINUE 125
allocate(ddx1)
deallocate(ddy1)
deallocate(patcharraytemp)
DO 127 Q=1,PatchNo
  DO 128 W=1, PatchNo
    if (patcharray(W,1,9).eq.1.0.or.patcharray(W,1,9).eq.2.0
        .or.patcharray(W,1,9).eq.3.0.or.patcharray(W,1,9).eq.4.0.
        or.patcharray(W,1,9).eq.5.0.or.patcharray(W,1,9).eq.
        .eq.6.0.or.patcharray(W,1,9).eq.7.0.or.
* patcharray(W,1,9).eq.8.0) then
  formfactors(Q,W,2) = 1.0
endif
if (patcharray(W,1,9).eq.9.0.or.patcharray(W,1,9).eq.10.0 or
*    .or.patcharray(W,1,9).eq.11.0.or.patcharray(W,1,9).eq.
*    12.0.or.patcharray(W,1,9).eq.13.0)
*    then
  formfactors(Q,W,2) = 2.0
endif
if(patcharray(Q,1,9).eq.1.0.and.(patcharray(W,1,9).eq.
*    9.0.or.patcharray(W,1,9).eq.11.0)) then
  CALL PERFPERFORMFACTOR(patcharray,PatchNo,sizefft,
*    formfactors,Q,W,PI)
elseif(patcharray(Q,1,9).eq.2.0.and.(patcharray(W,1,9)
*    .eq.9.0)) then
  CALL PERFPERFORMFACTOR(patcharray,PatchNo,sizefft,
*    formfactors,Q,W,PI)
elseif(patcharray(Q,1,9).eq.3.0.and.(patcharray(W,1,9)
*    .eq.9.0.or.patcharray(W,1,9).eq.12.0)) then
  CALL PERFPERFORMFACTOR(patcharray,PatchNo,sizefft,
*    formfactors,Q,W,PI)
elseif(patcharray(Q,1,9).eq.4.0.and.(patcharray(W,1,9)
*    .eq.11.0)) then
  CALL PERFPERFORMFACTOR(patcharray,PatchNo,sizefft,
*    formfactors,Q,W,PI)
elseif(patcharray(Q,1,9).eq.5.0.and.(patcharray(W,1,9)
*    .eq.12.0)) then
  CALL PERFPERFORMFACTOR(patcharray,PatchNo,sizefft,
*    formfactors,Q,W,PI)
elseif(patcharray(Q,1,9).eq.6.0.and.(patcharray(W,1,9)
*    .eq.10.0.or.patcharray(W,1,9).eq.11.0)) then
  CALL PERFPERFORMFACTOR(patcharray,PatchNo,sizefft,
*    formfactors,Q,W,PI)
elseif(patcharray(Q,1,9).eq.7.0.and.(patcharray(W,1,9)
* .eq.10.0))then
    CALL PERPFORMFACTOR(patcharray,PatchNo,sizefft,
* formfactors,Q,W,PI)
elseif(patcharray(Q,1,9).eq.8.0.and.(patcharray(W,1,9)
* .eq.10.0.or.patcharray(W,1,9).eq.12.0))then
    CALL PERPFORMFACTOR(patcharray,PatchNo,sizefft,
* formfactors,Q,W,PI)
elseif(patcharray(Q,1,9).eq.9.0.and.(patcharray(W,1,9)
* .eq.1.0.or.patcharray(W,1,9).eq.2.0.or.
* patcharray(W,1,9).eq.3.0))then
    CALL PERPFORMFACTOR(patcharray,PatchNo,sizefft,
* formfactors,Q,W,PI)
elseif(patcharray(Q,1,9).eq.10.0.and.(patcharray(W,1,9)
* .eq.6.0.or.patcharray(W,1,9).eq.7.0.or.
* patcharray(W,1,9).eq.8.0))then
    CALL PERPFORMFACTOR(patcharray,PatchNo,sizefft,
* formfactors,Q,W,PI)
elseif(patcharray(Q,1,9).eq.11.0.and.(patcharray(W,1,9)
* .eq.1.0.or.patcharray(W,1,9).eq.4.0.or.
* patcharray(W,1,9).eq.5.0))then
    CALL PERPFORMFACTOR(patcharray,PatchNo,sizefft,
* formfactors,Q,W,PI)
elseif(patcharray(Q,1,9).eq.12.0.and.(patcharray(W,1,9)
* .eq.3.0.or.patcharray(W,1,9).eq.5.0.or.
* patcharray(W,1,9).eq.8.0))then
    CALL PERPFORMFACTOR(patcharray,PatchNo,sizefft,
* formfactors,Q,W,PI)
else
    formfactors(Q,W,1)=0.0
    formfactors(Q,W,3)=0.0
endif
CONTINUE

print*, 'Calculated form factors'
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Vita

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Work Experience

Pennsylvania State University 8/2009-Present
  Research Assistant and PhD Work with Dr. Victor Sparrow

CSTI Acoustics 7/2006-7/2011
  Consultant in Acoustics with Robert D. Bruce

  Research Assistant, M. Eng. with William D. Mark

Education

Pennsylvania State University 2005-2011
  PhD in Acoustics, Fall 2011 (Pending)

Vassar College 2002-2004
  Major in Physics, Senior thesis related to cosmic microwave background
  Concentration in Music, Senior research - equal temperament and its influence
  Concentration in Math

Regis College 2000-2002
  Major in Math
  Concentration in Music and Computer Science
  Transferred end of sophomore year due to discontinuation of major

Professional Societies

Member of Acoustical Society of America
Member of Institute of Noise Control Engineering
The Council for Accreditation in Occupational Hearing Conservation (CAOHC)
Co-Chair for working group on Animal Housing Measurements

Presentations

Seattle (2011) - “Determining the importance of building features in sonic boom simulation and comparison to measured data”

Baltimore (2010) - “A combined ray tracing and radiosity method for propagation and diffraction of sonic booms in urban landscapes”

Portland (2009) - “Sonic boom propagation into urban landscapes: Preliminary study”


Miami (2008) - “The presence of infrasound in our everyday life”

INTERNOISE in Ottawa (2009) - “Ultrasound in the Home and Workplace”