Medium Frequency Radio Propagation in Urban Settings

by

Jessica Forbess

Submitted to the Department of Electrical Engineering and Computer Science in partial fulfillment of the requirements for the degree of Master of Engineering in Electrical Engineering and Computer Science at the MASSACHUSETTS INSTITUTE OF TECHNOLOGY February 2000

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Abstract

Radionavigation by measuring the carrier phase of amplitude modulated (AM) broadcast radio waves has potentially one-meter accuracy, and the added ability to navigate within buildings. However, electrically conducting structures such as buildings and utility lines may degrade this accuracy. Version 4 of the Numerical Electromagnetics Code (NEC-4) has been used to simulate a number of such structures to determine and understand their effects, both indoors and out.

The phase observed one meter above ground outside a building, even very nearby, is not significantly perturbed by these buildings.

Outdoor networks of underground and overhead conductors perturb the phase observed at one meter above ground, typically by the equivalent of one-meter in position, but occasionally by tens of meters. The resulting navigational errors can be avoided by observing signals from multiple transmitters at different locations and with different frequencies.

Inside a building, the phase can be significantly perturbed, but the simulation results suggest several ways of minimizing indoor navigational errors. First, I find that in the three meters inside the wall facing the transmitter, the phase is typically perturbed by about one radian of phase. Second, severe phase perturbations occur in the lower stories of a multistory building, and in the basement or crawlspace under a building, where signal attenuation may exceed 40 to 50 dB. Therefore, the reliability of the AM carrier-phase method inside buildings seems likely to be improved by rejecting or down-weighting phase observations of highly attenuated signals. Third, better positional accuracy appears obtainable at the higher frequency end of the AM broadcast band, in the neighborhood of 1.5 MHz.

Changing the electrical connection between the building frame and the ground may have significant effects on the phase perturbations on the lower floors. Unfortunately, building codes and standards governing this connection seem to be lacking.

Thesis Supervisor: Charles C. Counselman III
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Contour map of the attenuation (dB) of the $z$-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a four-story building, sampled at $z = 8.5$ meters, one meter above the third floor. The interval between contours is 0.7 dB.  

Three-dimensional contour map of the attenuation (dB) of the $z$-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a four-story building, sampled at $z = 8.5$ meters, one meter above the third floor. The interval between contours is 0.7 dB.  

Three-dimensional contour map of the phase of the $z$-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a four-story building, sampled at $x = 15.5$ meters, with $0.3 < z < 10.3$ meters. The interval between contours is 0.4 meters in height ($z$), rather than distance ($x$ and $y$), as in previous figures.  

Three-dimensional contour map of the attenuation (dB) of the $z$-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a four-story building, sampled at $x = 15.5$ meters, with $0.3 < z < 10.3$ meters. The interval between contours is 0.4 meters in height ($z$), rather than distance ($x$ and $y$), as in previous figures.  

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Three-dimensional contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a four-story building, sampled at $x = 27.5$ meters, with $0.3 \leq z \leq 10.3$ meters. The interval between contours is 0.4 meters in height ($z$), rather than distance ($x$ and $y$), as in previous figures.

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Contour map of the phase of the z-component of the electric field \( (E_z) \) of a 1.5 MHz transmitted signal, around a network of connected underground pipes and overhead wires with the transmitter at \( y = 9000 \) meters, sampled at \( z = 0.9 \) meters. The interval between contours is 12 degrees, or six meters.

Three-dimensional contour map of the phase of the z-component of the electric field \( (E_z) \) of a 1.5 MHz transmitted signal, around a network of connected underground pipes and overhead wires with the transmitter at \( y = 9000 \) meters, sampled at \( z = 0.9 \) meters. The interval between contours is 12 degrees, or six meters.
Chapter 1

Introduction

Navigation has been an important skill for as long as humanity has existed, and the current decades are no exception. The launching of the Global Positioning System (GPS) paired with the expansion of the mobile electronics market has popularized that particular technology, and more and more applications are being developed for every possible circumstance. These varied scenarios push the limitations of GPS, and other methods may be required to avoid its weaknesses.

One such method involves measuring the phases of the carrier waves received at an unknown position from existing amplitude modulated (AM) broadcast radio stations, and comparing them with the phases from the same wave at a known position to determine the unknown position. This method has been suggested in the past, but it is difficult to find in the literature much information about the perturbations that an urban environment imposes on the wave.

The purpose of this thesis is to examine the perturbations imposed by a series of structures, including a number of buildings of different forms, and evaluate the utility of the AM radio band for radionavigation.

1.1 System Overview

An AM radio signal propagates through the air at approximately the speed of light. Therefore, measurements made at different distances from a source will show a
phase difference in the same signal, proportional to the differences in distance between each point of measurement and the source. By comparing the phase differences between one known position and one unknown position for multiple sources in different directions, the unknown position may be determined, though perhaps with an integer-wavelength ambiguity. In order to navigate, one must resolve this ambiguity with comparisons from multiple transmitter locations and frequencies.

Duffet-Smith [1] has shown that measuring the phase difference is possible to a useful degree of accuracy in theory, because the signal-to-noise ratio of broadcast quality radio signals is quite high. However, accurately modeling signal propagation in a complex environment is difficult.

The simplest model assumes that the medium of propagation is uniform, and that there are no reflectors or scatterers, which is certainly not the case. In a somewhat more complex version of the real world, the AM radio signal reaches a receiver via two paths, the ground-wave and the skywave. The ground-wave travels along the ground, guided by the ground-air interface, and has a fairly stable and predictable travel time. The skywave path is reflected from the ionosphere, which is variable in height, yielding a travel time that is variable and cannot be used in the calculation of phase delay. Another radionavigation system, Loran-C, [5] uses a signal designed to easily separate the two components. Loran-C signals are transmitted in short bursts, so that the arrival of the signal traveling along one path can be separated from the arrival of a signal along another path. Because AM radio transmission is continuous, this convenient feature is not available to us. In order to ensure that the ground wave is dominant, the path must be kept short.

The travel time of the ground-wave has been analyzed with many different models, beginning with Sommerfeld and Norton [3] who first quantified the phenomenon, first with a flat earth approximation, followed by multiple homogeneous spherical earth models, and continuing in complexity by modeling multiple surface conductivities. I have modeled certain characteristics of urban environments that may affect radiated signals. These characteristics include grids of underground pipes, grids of overhead wires, and buildings with steel framing.
These conductors change the character of the "waveguide" that the ground-wave follows, and therefore will change the wave's characteristics as well.

I have quantified these effects, and found that the perturbations outside of most buildings are small enough that this method of radionavigation is feasible even in close proximity to a number of buildings. In addition, outdoor networks of underground and overhead conductors impose only a small perturbation on signals observed at one meter above ground, and it appears that navigation errors can be avoided by making observations of signals from multiple transmitters at different locations and frequencies.

Inside buildings, the phase was significantly perturbed, and a few observations may provide the key to using this method indoors. First, the wall facing the transmitter experiences a perturbation on the order of one radian of phase within about the first three meters inside. Second, severe phase perturbations occur in the lower stories of a multistory building, and in the basement or crawlspace under a building, where signal attenuation may exceed 40 – 50 dB.

Other observations include the realization that changing the connection between the conducting building frame and ground may have significant effects on the phase perturbations on the lower floors, Unfortunately, there is little data on what this connection is in practice. Also, the reliability of the AM carrier-phase method inside buildings will likely be improved by rejecting phase observations of signals having an attenuation exceeding 40 – 50 dB. Finally, better positional accuracy may be obtained with higher frequency signals, in the neighborhood of 1.5 MHz.

1.2 Motivation

There are many radionavigation methods currently in use, and the addition of a new system requires some justification. The weaknesses of two current prominent systems are discussed below and addressed by the proposed AM broadcast radio system.
1.2.1 Current Navigation Methods

Global Positioning System  The most popular current technology for radionavigation is GPS [2], which is a system of twenty-four satellites, transmitting time signals which are used to determine the position and velocity of the individual. This system has many strengths, including its small uncertainty, which for civilian users is usually less than 100 meters horizontally and 156 meters vertically. This uncertainty can be reduced by using differential techniques, and certain methods have achieved a relative-positioning uncertainties smaller than one centimeter. Another strength of GPS is its ability to determine vertical position, a feature which no system based on ground-waves is yet able to provide.

However, GPS has a number of weaknesses, most notably the lack of coverage indoors. Due to the high frequencies of GPS signals, most buildings and substances like thick foliage and water are impenetrable. This makes it difficult to use GPS seamlessly in most urban settings, even for outside use only, as satellites may be blocked from view by tall buildings. This stumbling block is one of the greatest motivations to develop an alternative method for a certain set of potential users.

Another serious problem with GPS is the weakness of the signal. These signals are easily interfered with, intentionally or not. Depending on the signals in a life-critical situation is not advisable. In particular, as satellite-based mobile telephones become common, the bands around the GPS frequency will become more and more congested, providing more and more interference.

Loran-C  Loran-C is a ground-based radionavigation method, in fairly wide use around the world in the fields of marine and aviation navigation. It is similar to our proposed method, but has its own infrastructure, limiting it to certain parts of the globe. The Loran system has higher strength signals, compared to GPS, and is not as vulnerable to interference. It can penetrate buildings as well, due to its lower frequency. However, because of its long wavelength, it is much less precise, with an accuracy of roughly one kilometer.

The major limitations of Loran-C are due to its lack of diversity. Because it op-
erates on only one frequency, the propagation characteristics of the ground-wave cannot be explored through varying the frequency. The distribution of Loran-C transmitters is also limited. An area like Boston is covered by only approximately four Loran-C transmitters, which again limits the parameters used in the ground-wave propagation characteristic.

1.2.2 Proposed AM broadcast radio

The choice of the broadcast AM radio band came from certain criteria stemming from the weaknesses of the previously mentioned methods. Low frequencies would provide a signal that would penetrate indoors, and a significant range of frequencies and a diverse and numerous set of fairly powerful transmitters would be useful for wide coverage and more precise location. These characteristics fit the broadcast AM radio band perfectly.

The lower frequencies used in AM radio signals penetrate buildings fairly well. This feature could allow navigation inside, provided the phase perturbation within buildings is not significantly larger than that outside. Other methods of indoor position tracking are being developed, such as the Locust at the Media Lab, [7] but a method that can work seamlessly indoors and out is much more powerful, and can be used by people who move from building to building on a regular basis.

Another strength is the use of an already existing infrastructure of signals. Though the current methods of radionavigation have already installed infrastructures, there is maintenance, which is often not cheap, and the GPS infrastructure is still being deployed, at a cost of roughly $200 million per satellite.

The great diversity of frequencies and transmitter locations is the other strength of this system. The frequencies range from about 500 kHz to 1.5 MHz, and the number of transmitters in an area like Greater Boston is approximately thirty. Ideally, this will allow one to vary the frequency or location of the transmitter that is sampled, and better identify the environment through which the signal is propagating, and reduce the error in the propagation model, thereby reducing the error
in the estimate of the position.

The AM radio signals are also far more robust than those of the GPS system. Interference is not an issue due to the high power of the transmitters commonly used.

In addition, using multiple navigation techniques is prudent in any critical application, in case of one failing, or as an accuracy check.

1.3 Methods

To evaluate the characteristics of phase within urban environments, a number of simulations were performed. Typically consisting of a transmitting antenna and a building in free space over a lossy dielectric, the simulations were performed using Numerical Electromagnetics Code [6]. This software was designed to model the electromagnetic response of antennae and scatterers and their environments. It solves Maxwell’s equations and matches boundary conditions by finite element methods. Particularly of use to this project was its ability to represent a divided space, an upper half composed of free space or air, and a lower half composed of lossy dielectric. The environment could also include conducting wires or surfaces either elevated or buried, which allowed easy simulation of pipes and wires.
Chapter 2

Overview

An overview of the individual structures included in the simulations is presented before discussing the results. All of the phase perturbations presented are actually the difference between a particular simulation and a baseline simulation. The baseline consists of the antenna radiating through free space with a lossy dielectric ground below $z = 0$ meters with $\epsilon / \epsilon_0 = 5$ and $\sigma = 0.001$ S/m, which is representative of the New England terrain.

Most of the figures presented show the phase of the $z$ component of the electric field. The phase is truncated to remain between positive 180 degrees and negative 180 degrees. A few figures show the attenuation of the $z$ component of the electric field in order to examine apparent singularities in the phase perturbation.

Figure 2-1 shows a typical setup for a simulation, though it is not to scale. The antenna is placed far out along the positive $x$ axis, at nine kilometers. The dotted lines indicate wires below ground. Both the building and the antenna are sunken. Most of the simulations include one building, with three horizontal planes, like the one shown here. The lowest plane will be referred to as the basement, despite the fact that it is filled in with ground, and therefore is not actually a space that can be entered. The space between $z = 0$ meters and the next horizontal plane will be referred to as the crawlspace. The space between the middle horizontal plane and the roof will be referred to as the first floor. In buildings with more horizontal planes, the floors above the first floor will be named appropriately.
2.1 Structures

The simulated transmitting antenna is a simple base-fed vertical monopole with four buried radials, as shown in Figure 2-2. The height of the monopole (125 meters) was chosen to provide a reasonable admittance for signals between 0.5 MHz and 1.5 MHz. The radius of the conducting "wire" is 0.25 meters. The four radials are placed one meter below the boundary between ground and free space. In practice, more radials are used for greater efficiency, but for simulation four is sufficient.

As shown in Figure 2-3, the simplest building is two floors high, with the bottom horizontal plane buried 1.5 meters in the ground, forming a basement that is full of ground, and a crawlspace between the ground and the middle horizontal plane. The height of the floors varies from three meters to five meters in separate simulations. The basement is located at $z = -1.5$ meters, the first floor at $z = 1.5$ meters, and the roof at $z = 4.5$ meters in a building with three-meter-high stories. The vertical "wires" forming the outside walls are spaced at one meter intervals, and have a radius of 0.1 meter. Inside, there are more vertical "wires" also spaced at one meter intervals, outlining rooms that are three meters by three meters. All
Figure 2-2: Antenna structure in simulation

of the horizontal planes in the building except for the basement floor are modeled as conducting surfaces, by creating a mesh with "wires" of the appropriate radius of 0.159 meters, as specified in the NEC User's Guide [6]. The footprint of the building is nine meters by twenty-one meters.

Additional buildings have four floors.

The grids of underground pipes and overhead wires shown in Figure 2-4 have the same configuration, though the underground pipes have a larger radius of 0.1 meters, while the overhead wires have a radius of 0.025 meters. The main length of
each network is 300 meters, and runs parallel to the y-axis. with five shorter spurs of 90 meters each, running off in the positive x direction. Each spur has a number of nine-meter connections, theoretically to a house.

The grids were simulated individually and together. When the grids were simulated together, the pipes and wires were connected at each "house" as shown in Figure 2-5 to replicate the practice in modern construction of connecting electrical ground to the water pipe running into the house. Figure 2-5 shows the two networks running directly over one another, but simulations were also performed with the two systems offset a few meters in the y direction.
Figure 2-5: Connected pipe and wire structure in simulation
Chapter 3

Discussion

This section presents and discusses the relevant data from the numerous simulations run over the course of this project. Most of the figures presented show the phase of the z component of the electric field. The phase is truncated to remain between positive 180 degrees and negative 180 degrees. All of the phase perturbations presented are actually the difference between a particular simulation and a baseline simulation. A number of figures show the attenuation of the z-component of the electric field in order to examine apparent singularities in the phase perturbation. The attenuation is measured in decibels, and referenced to $2 \times 10^{-6}$ volts/meter, the approximate field strength in the absence of the building.

The z-component was chosen for observation primarily because almost all AM band transmitters are vertically polarized, and it is therefore the strongest component. In addition, it will be the simplest to obtain in the real world, using a simple whip antenna, which can be found on many cars. The choice of electric field was also determined for the pragmatic reason that it is more likely to be sampled in experiments.

The transmitting antenna is placed far out along the positive x-axis, at nine kilometers, and the structures are placed near the origin. Both the building and the antenna are sunken, with parts of the structures below ground. Most of the simulations include one building, with three horizontal planes, like the one shown in Figure 2-3. The lowest plane will be referred to as the basement, despite the
fact that it is filled in with ground, and therefore is not actually a space that can be entered. The space between \( z = 0 \) meters and the next horizontal plane will be referred to as the crawlspace. The space between the middle horizontal plane and the roof will be referred to as the first floor. In buildings with more horizontal planes, the floors above the first floor will be named appropriately.

### 3.1 Baseline

The baseline simulation consists of the transmitting antenna radiating in a space consisting of vacuum in the upper infinite half-space, and a lossy dielectric ground below \( z = 0 \) meters. The ground parameters used are \( \varepsilon / \varepsilon_0 = 5 \) and \( \sigma = 0.001 \text{ S/m} \), which are typical parameters for New England soil. The antenna is located at \( x = 9000 \) meters, as it is in almost all simulations.

In Figure 3-1, the equally spaced lines of the contour map show that the phase of the \( z \)-component of the electric field varies essentially linearly in vacuum over a lossy ground. A slight arc is observable in the contours, particularly at the edges of the figure, as the wave is actually radiating radially from the antenna, but these observations are distant enough from the source to generally approximate the radiation as a plane wave traveling parallel to the \( x \)-axis, particularly for simulations over a much smaller area. In this figure, the sampling has been done from the origin \( (x = 0, y = 0 \) meters) to \( x = 250 \) meters, \( y = 350 \) meters. Most other figures will focus on a smaller corner near the origin, within the bounds of \( x = 50 \) meters, \( y = 50 \) meters. This figure shows data sampled at \( z = 2.5 \) meters above ground.

In vacuum, over a fairly poor ground, the phase of a signal with frequency of 1.5 MHz linearly varies about two degrees per meter. The interval between contours in Figure 3-1 is approximately 14 degrees, or seven meters. Additionally, there is a darker line at approximately \( x = 60 \) meters, and the contour labels show that the phase wraps around from 180 degrees to -180 degrees at this location.

The samples in this figure were taken at \( z = 2.5 \) meters, which is one meter above the first floor in the standard building. One meter above the floor will be
Figure 3-1: Contour map of the phase of the z-component of the electric field $E_z$ of a 1.5 MHz transmitted signal, from a baseline simulation, sampled at $z = 2.5$ meters. The interval between contours is 14 degrees, or seven meters.

the standard sampling height inside buildings, and will be paired with sampling at $z = 1$ meter, for observations outside buildings.

In Figure 3-2 the phase wrapping is much more obvious, as is the linear change over distance, though this is a figure including exactly the same data as the previous figure. Both of these methods of graphing can be useful to highlight certain characteristics, and both will be used throughout this thesis.
Figure 3-2: Three-dimensional contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, from a baseline simulation, sampled at $z = 2.5$ meters. The interval between contours is 14 degrees, or seven meters.
Figure 3-3: Contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, from a baseline simulation, sampled at $z = 2.5$ meters. The interval between contours is $6 \times 10^{-3}$ decibels.

Figures 3-3 and 3-4 show the attenuation of the z-component of the electric field in a baseline simulation. Unsurprisingly, the attenuation varies approximately linearly with distance, and is inversely proportional to the distance from the transmitting antenna. The interval between contours is $6 \times 10^{-3}$ decibels.
Figure 3-4: Three-dimensional contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, from a baseline simulation, sampled at $z = 2.5$ meters. The interval between contours is $6 \times 10^{-3}$ decibels.
3.2 Buildings

The simplest test building is a two-story structure with three horizontal planes. The lowest plane will be referred to as the basement, despite the fact that it is filled in with ground, and therefore is not actually a space that can be entered. The space between \( z = 0 \) meters and the next horizontal plane will be referred to as the crawlspace. The space between the middle horizontal plane and the roof will be referred to as the first floor. In buildings with more horizontal planes, the floors above the first floor will be named appropriately.

The standard building will be described as having its "front" wall as the one closest to the antenna, parallel to the y-axis. Generally, this is located at \( x = 36 \) meters, and the antenna is out at \( x = 9000 \) meters. The "back" wall is at \( x = 15 \) meters, and the side walls run parallel to the x-axis, at \( y = 15 \) meters and \( y = 6 \) meters. A detailed picture of the building's structure can be seen in Section 2.1. The figures presented in this chapter show the phase after subtracting the baseline phase, and therefore the resulting contours are those caused by the presence of the building.

In Figure 3-5 the contour labels indicate that most of the building sees a mild perturbation with a maximum of approximately eight degrees (equivalent to four meters) just inside the back wall. The front wall has a larger perturbation, however, and a better idea of its magnitude can be determined in Figure 3-6, by noting its minimum peak occurs between -25 and -30 degrees, or the equivalent of about -15 meters. The minimum points also fall within the building, and are centered in two of the three meter by three meter rooms at the front of the building. The interval between contours is 1.5 degrees, or about 0.75 meters. The front-back asymmetry is to be expected, because in the ground-wave mode of propagation that is occurring here, the electric field is not vertical but has a significant component in the direction of propagation, in this case along the x-axis, toward \(-x\). In fact, because the oncoming wavefronts are facing slightly downward, the top of the building can intercept E-field lines that should have reached the front wall, causing the more
extreme perturbations commonly seen there.

Figures 3-5 and 3-6 show data sampled at $z = 2.5$ meters, which is exactly one meter above the first floor.

Figures 3-7 and 3-8 show data sampled at $z = 1$ meter above ground, which is a reasonable height to assume as a typical operating height at points outside the building. The interval between contours is 14 degrees, or seven meters. There is no perturbation outside of the building at this level, which is very different from the samples at $z = 2.5$ meters. Inside the building there is more variation from the previous sample, as there is a complete phase wraparound, where the phase increases above 180 degrees, and is mapped to negative 180 degrees. However, these sampling points fall in the crawlspace under the first floor, and so may not be a problem in "usable" spaces. The reason for the more drastic perturbation within the crawlspace may be that because the E-field is concentrated at the top of the building (a long, skinny conductor), it is reduced outside the building near the ground, and there is less to propagate through the windows of the lower levels. This variation will be discussed with further figures.
Figure 3-5: Contour map of the phase of the $z$-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, sampled at $z = 2.5$ meters around the standard building. The interval between contours is 1.5 degrees, or 0.75 meters.
Figure 3-6: Three-dimensional contour map of the phase of the z-component of the electric field \((E_z)\) of a 1.5 MHz transmitted signal, sampled at \(z = 2.5\) meters around the standard building. The interval between contours is 1.5 degrees, or 0.75 meters.
Figure 3-7: Contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, sampled at $z = 1.0$ meters around the standard building. The interval between contours is 14 degrees, or seven meters.
Figure 3-8: Three-dimensional contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, sampled at $z = 1.0$ meters around the standard building. The interval between contours is 14 degrees, or seven meters.
Figure 3-9: Contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, sampled at $z = 2.5$ meters around the standard building. The interval between contours is 3.3 dB.

Figures 3-9 and 3-10 show the attenuation of the z-component of the electric field around the standard building, sampled at $z = 2.5$ meters. The minimum peak of -50 dB is located at the intersection of two internal walls. In fact, all of the circular closed loop contours fall at the intersection of two internal walls, where the phase perturbation is at a minimum. The diamond contours in the middle are higher, and fall within the interior rooms.

Figures 3-11 and 3-12 show the attenuation of $E_z$, sampled at $z = 1$ meter. The maximum attenuation seen in the building is approximately -60 dB, in the middle of the building. The attenuation contours do not correspond significantly to the phase perturbation contours.
Figure 3-10: Three-dimensional contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, sampled at $z = 2.5$ meters around the standard building. The interval between contours is 3.3 dB.
Figure 3-11: Contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, sampled at $z = 1.0$ meters around the standard building. The interval between contours is 4.4 dB.
Figure 3-12: Three-dimensional contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, sampled at $z = 1.0$ meters around the standard building. The interval between contours is 4.4 dB.
3.2.1 Phase changing over varying sampling heights

The previous figures demonstrated that phase perturbation varies with the height at which it is sampled. Figures 3-13 and 3-14 show data sampled at \( z = 2.3 \) meters, which is slightly closer to the horizontal plane at \( z = 1.5 \) forming the first floor, but still within the same story. The shape of the contours is similar to that sampled at \( z = 2.5 \) meters, but the amplitudes have changed fairly significantly. Notably, the minimum at the front wall is now between -60 and -70 degrees (-30 and -35 meters), rather than -30 degrees (-15 meters). The interval between contours has changed to about twice that of the figures sampled at \( z = 2.5 \) meters, which is three degrees, or 1.5 meters between lines. This washes out the number of contours across most of the building in order to see the larger minimum. One should note that the maximum peak of 7.6 degrees, at \( x = 15 \) meters, is still approximately the same as that in the samples at \( z = 2.5 \) meters.

When the phase is sampled at a height greater than 2.5 meters (but still within the first floor), Figures 3-15 and 3-16 show that the front wall minimum at \( x = 36 \) meters diminishes from -27 degrees (-14.5 meters) to approximately -12 degrees (-6 meters). The interval between contours is 0.8 degrees, or 0.4 meters. This is approximately twice as fine as the figures of samples at \( z = 2.5 \) meters, and looks more complex as a result, but it should be noted that the maximum at \( x = 15 \) meters is still only 7.5 degrees. The lack of variation in the maximum peak and contour levels indicates that reasonable deviations from \( z = 1 \) meter should not affect navigation.

Another way to examine the variation of phase over \( z \) is to plot a "slice" of data that is constant over \( x \) rather than \( z \), as in Figures 3-17, 3-19, 3-21, 3-23, and 3-25. These sets of data were taken at four meter intervals from \( x = 15.5 \) meters (just inside the back of the building) to \( x = 31.5 \) meters (4.5 meters inside the front of the building), spanning the inside. Each contour line is approximately 0.2 meters in \( z \). The figures show that the least perturbation occurs above \( z = 1.5 \) meters, which is at the floor level of the first floor. Above this point, the perturbation is
Figure 3-13: Contour map of the phase of the z-component of the electric field \((E_z)\) of a 1.5 MHz transmitted signal, sampled at \(z = 2.3\) meters around the standard building. The interval between contours is three degrees, or 1.5 meters.

mostly gone, except for the slices at \(x = 15.5\) meters and \(x = 31.5\) meters in Figures 3-17 and 3-25, which show some perturbation below the ceiling, which is at \(z = 4.5\) meters. Below \(z = 1.5\) meters, in the crawlspace, the perturbation varies as much as \(\pm 150\) degrees.

Figures 3-18, 3-20, 3-22, 3-24, and 3-26 show the attenuation of the same “slices” of \(x\). At \(x = 15.5\) meters, the spikes of phase perturbation at \(z = 3.4\) meters and above seem to be correlated with similar peaks in the attenuation at the same height. The peaks are in the range between -20 and -30 dB. Later slices show peaks of that attenuation that do not correspond to peaks in phase perturbation, suggesting that there is another variable to consider.
Figure 3-14: Three-dimensional contour map of the phase of the $z$-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, sampled at $z = 2.3$ meters around the standard building. The interval between contours is three degrees, or 1.5 meters.
Figure 3-15: Contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, sampled at $z = 2.7$ meters around the standard building. The interval between contours is 0.8 degrees, or 0.4 meters.
Figure 3-16: Three-dimensional contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, sampled at $z = 2.7$ meters around the standard building. The interval between contours is 0.8 degrees, or 0.4 meters.
Figure 3-17: Three-dimensional contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a standard building, sampled at $x = 15.5$ meters, with $0.3 \leq z \leq 4.9$ meters. The interval between contours is 0.2 meters in height ($z$), rather than distance ($x$ and $y$), as in previous figures.
Figure 3-18: Three-dimensional contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a standard building, sampled at $x = 15.5$ meters, with $0.3 \leq z \leq 4.9$ meters. The interval between contours is 0.2 meters in height ($z$), rather than distance ($x$ and $y$), as in previous figures.
Figure 3-19: Three-dimensional contour map of the phase of the z-component of the electric field \( E_z \) of a 1.5 MHz transmitted signal, around a standard building, sampled at \( x = 19.5 \) meters, with \( 0.3 \leq z \leq 4.9 \) meters. The interval between contours is 0.2 meters in height (z), rather than distance (x and y), as in previous figures.
Figure 3-20: Three-dimensional contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a standard building, sampled at $x = 19.5$ meters, with $0.3 \leq z \leq 4.9$ meters. The interval between contours is 0.2 meters in height ($z$), rather than distance ($x$ and $y$), as in previous figures.
Figure 3-21: Three-dimensional contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a standard building, sampled at $x = 23.5$ meters, with $0.3 \leq z \leq 4.9$ meters. The interval between contours is 0.2 meters in height ($z$), rather than distance ($x$ and $y$), as in previous figures.
Figure 3-22: Three-dimensional contour map of the attenuation (dB) of the $z$-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a standard building, sampled at $x = 23.5$ meters, with $0.3 \leq z \leq 4.9$ meters. The interval between contours is 0.2 meters in height ($z$), rather than distance ($x$ and $y$), as in previous figures.
Figure 3-23: Three-dimensional contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a standard building, sampled at $x = 27.5$ meters, with $0.3 \leq z \leq 4.9$ meters. The interval between contours is 0.2 meters in height ($z$), rather than distance ($x$ and $y$), as in previous figures.
Figure 3-24: Three-dimensional contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a standard building, sampled at $x = 27.5$ meters, with $0.3 \leq z \leq 4.9$ meters. The interval between contours is 0.2 meters in height ($z$), rather than distance ($x$ and $y$), as in previous figures.
Figure 3-25: Three-dimensional contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a standard building, sampled at $x = 31.5$ meters, with $0.3 \leq z \leq 4.9$ meters. The interval between contours is 0.2 meters in height ($z$), rather than distance ($x$ and $y$), as in previous figures.
Figure 3-26: Three-dimensional contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a standard building, sampled at $x = 31.5$ meters, with $0.3 \leq z \leq 4.9$ meters. The interval between contours is 0.2 meters in height ($z$), rather than distance ($x$ and $y$), as in previous figures.
3.2.2 Phase changing with varying transmitter frequency

The next sets of data were taken while the antenna was transmitting at different frequencies. Figures 3-27 and 3-28 show the phase when the carrier frequency is 0.5 MHz. The shape of the perturbation is similar to that of the perturbation at 1.5 MHz. There is a sharp minimum at the front wall at \( x = 36 \) meters, of approximately -40 degrees, or equivalently, -66.7 meters, since about 0.6 degrees equals one meter at 0.5 MHz. There is also a maximum near the back wall at \( x = 15 \) meters, of about -8 degrees, or -13 meters. These peaks are about fifty percent larger in meters than those when the carrier frequency is 1.5 MHz.

Figures 3-29 and 3-30 aren’t as easy to generalize about. Here 1.2 degrees is the equivalent of one meter, at 1.0 MHz. The maximum height of 13 degrees is equivalent to 10 meters, and the minimum peak of -25 degrees is -20 meters. Translating...
Figure 3-28: Three-dimensional contour map of the phase of the z-component of the electric field \( E_z \) of a 0.5 MHz transmitted signal, around a standard building, sampled at \( z = 2.5 \) meters. The interval between contours is 1.4 degrees, or 2.3 meters.

From degrees into equivalent meters, it appears that the higher frequency stations are preferable, as the phase perturbations are similar for different transmitting frequencies, and the higher frequencies provide a better resolution of meters per degree.
Figure 3-29: Contour map of the phase of the z-component of the electric field ($E_z$) of a 1.0 MHz transmitted signal, around a standard building, sampled at $z = 2.5$ meters. The interval between contours is 1.7 degrees, or 1.4 meters.
Figure 3-30: Three-dimensional contour map of the phase of the z-component of the electric field ($E_z$) of a 1.0 MHz transmitted signal, around a standard building, sampled at $z = 2.5$ meters. The interval between contours is 1.7 degrees, or 1.4 meters.
3.2.3 Phase changing with varying building floor heights

Figures 3-31 and 3-32 show the phase sampled around a building similar to the standard, but with floors that are four meters high. The front wall is at $x = 36$ meters, and the back wall is at $x = 15$ meters. The side walls run along $y = 15$ meters and $y = 6$ meters. There are still only two floors, and the bottommost is also partly submerged in the ground. Because the floor height is four meters, the lowest horizontal plane, the basement, is two meters below ground, so that the crawlspace is half as high as one story. The first floor starts at $z = 2$ meters.

The first sample is taken at $z = 2.9$ meters, which is 0.9 meters above the first floor level, similar to sampling at $z = 2.4$ meters in the standard building. Explanations for the points in Figures 3-31 and 3-32 have not yet been found. Figure 3-33 shows the attenuation around the building. There are points where the attenuation drops below -60 dB, which correspond to the singularities in Figure 3-31. In fact, comparing Figure 3-31 to Figure 3-33, one can see that the sharp drop-off in the phase in the middle of the building in Figure 3-31 corresponds to the contours at approximately -40 dB in Figure 3-33.

Figures 3-34 and 3-35 show the phase at $z = 1$ meter, and are similar to those previous taken at this height. The most useful information that can be gathered is that the perturbation doesn’t extend beyond the borders of the building.
Figure 3-31: Contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a building with a floor height of four meters, sampled at $z = 2.9$ meters, 0.9 meters above the first floor. The interval between contours is 14 degrees, or seven meters.
Figure 3-32: Three-dimensional contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a building with a floor height of four meters, sampled at $z = 2.9$ meters, 0.9 meters above the first floor. The interval between contours is 14 degrees, or seven meters.
Figure 3-33: Contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a building with a floor height of four meters, sampled at $z = 2.9$ meters, 0.9 meters above the first floor. The interval between contours is 5.4 dB.
Figure 3-34: Contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a building with a floor height of four meters, sampled at $z = 1.0$ meters. The interval between contours is 14 degrees, or seven meters.
Figure 3-35: Three-dimensional contour map of the phase of the z-component of the electric field \( E_z \) of a 1.5 MHz transmitted signal, around a building with a floor height of four meters, sampled at \( z = 1.0 \) meters. The interval between contours is 14 degrees, or seven meters.
Figures 3-36 and 3-37 show the phase sampled around a building similar to the standard with floors that are five meters high. The first data is sampled at $z = 3.5$ meters, which is one meter above the first floor level, similar to sampling at $z = 2.5$ meters in the standard building.

The most significant feature of the phase perturbation in this building was also seen in the previous building with four-meter-high stories. The sharp drop-off in the middle of the building, which falls along the line of interior walls at $y = 12$ meters and $y = 9$ meters. The attenuation in Figure 3-38 has a corresponding ring of contours that are approximately -50 dB.

Figures 3-39 and 3-40 show the phase at $z = 1$ meter, and again, show only that there is little perturbation outside the structure at $z = 1$ meter.

The most significant observation from these figures is the recognition that building structure will significantly affect the variation of the phase within the building. This makes it much more unlikely that this method will be useful for navigation within buildings. However, the plots of attenuation indicate that there is a threshold below which erroneous phase measurements may be disregarded, and above which, the phase will be within an acceptable degree of uncertainty.
Figure 3-36: Contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a building with a floor height of five meters, sampled at $z = 3.5$ meters, one meter above the first floor. The interval between contours is 14 degrees, or seven meters.
Figure 3-37: Three-dimensional contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a building with a floor height of five meters, sampled at $z = 3.5$ meters, one meter above the first floor. The interval between contours is 14 degrees, or seven meters.
Figure 3-38: Contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a building with a floor height of 7.4 meters, sampled at $z = 2.9$ meters, 0.9 meters above the first floor. The interval between contours is 4.2 dB.
Figure 3-39: Contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a building with a floor height of five meters, sampled at $z = 1.0$ meters. The interval between contours is 14 degrees, or seven meters.
Figure 3-40: Three-dimensional contour map of the phase of the $z$-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a building with a floor height of five meters, sampled at $z = 1.0$ meters. The interval between contours is 14 degrees, or seven meters.
3.2.4 Phase within a building with the first floor close to ground level

Figures 3-41 and 3-42 show the phase at $z = 1.1$ meters in a building exactly like those of the first figures, but more deeply sunken in the ground, so that the middle floor is 0.1 meters above ground level. The most striking feature in the perturbation is the pair of sharp peaks just inside the back corners of the building, at $x = 16$ meters. However, looking at Figures 3-43 and 3-44, it is apparent that the peaks are simply artifacts of wrapping around the phase to limit it to being between 180 and -180 degrees. Figures 3-41 and 3-42 were plotted with the phase wraparound in effect, such that if any data were less than -180 degrees, that point had 360 degrees added to it so that it would be between -180 and 180 degrees. Figures 3-43 and 3-44 were not limited to being between -180 and 180 degrees, and do not have the peaks.

Interestingly, the perturbations around this building extend beyond the boundaries of the building, which is similar to Figures 3-5 and 3-6, the standard building, sampled at $z = 2.5$ meters. Figures 3-7 and 3-8 show the samples taken at $z = 1$ meter around the standard building. The perturbation doesn’t extend beyond the borders of the building.

The attenuation of this building also extends far beyond its borders, as shown in Figures 3-45 and 3-46.
Figure 3-41: Contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, *around a standard building with the basement submerged 2.9 meters into the ground*. The data was sampled at $z = 1.1$ meters, one meter above the first floor. The interval between contours is 14 degrees, or seven meters.
Figure 3-42: Three-dimensional contour map of the phase of the $z$-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, *around a building with the basement submerged 2.9 meters into the ground*. The data was sampled at $z = 1.1$ meters, one meter above the first floor. The interval between contours is 14 degrees, or seven meters.
Figure 3-43: Contour map of the phase of the z-component of the electric field \((E_z)\) of a 1.5 MHz transmitted signal, around a building with the basement submerged 2.9 meters into the ground. The data was sampled at \(z = 1.1\) meters, one meter above the first floor. This data was not wrapped to lie between -180 and 180 degrees. The interval between contours is 14 degrees, or seven meters.
Figure 3-44: Three-dimensional contour map of the phase of the z-component of the electric field \( (E_z) \) of a 1.5 MHz transmitted signal, around a building with the basement submerged 2.9 meters into the ground. The data was sampled at \( z = 1.1 \) meters, one meter above the first floor. This data was not wrapped to lie between -180 and 180 degrees. The interval between contours is 14 degrees, or seven meters.
Figure 3-45: Contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a building with the basement submerged 2.9 meters into the ground. The data was sampled at $z = 1.1$ meters, one meter above the first floor. The interval between contours is 2 dB.
Figure 3-46: Three-dimensional contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a building with the basement submerged 2.9 meters into the ground. The data was sampled at $z = 1.1$ meters, one meter above the first floor. The interval between contours is 2 dB.
Figure 3-47: Three-dimensional contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a building with the basement submerged 2.9 meters into the ground, sampled at $x = 15.5$ meters, with $0.3 \leq z \leq 4.7$ meters. The interval between contours is 0.2 meters in height ($z$), rather than distance ($x$ and $y$), as in previous figures.

Figures 3-47, 3-49, 3-51, 3-53, and 3-55 provide a view of data that sampled over one $x$ coordinate, while $z$ is varied. Each figure shows a “slice” of $x$, taken at four-meter intervals from $x = 15.5$ meters to $x = 31.5$ meters. The perturbation appears to lessen at about $z = 3$ meters in each case, and to remain fairly small above that point, with some exceptions at $x = 27.5$ meters and $x = 31.5$ meters. The point $z = 3$ meters is just below the ceiling.

Figures 3-48, 3-50, 3-52, 3-54, and 3-56 show the attenuation over the same set of constant $x$ positions. However, there is little correlation between peaks in attenuation, and peaks in phase perturbation. In addition, $E_z$ is never very attenuated, so attempting to use a threshold for the strength of the signal will not change the phase measurements.
Figure 3-48: Three-dimensional contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a building with the basement submerged 2.9 meters into the ground, sampled at $x = 15.5$ meters, with $0.3 \leq z \leq 4.7$ meters. The interval between contours is 0.2 meters in height ($z$), rather than distance ($x$ and $y$), as in previous figures.
Figure 3-49: Three-dimensional contour map of the phase of the $z$-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a building with the basement submerged 2.9 meters into the ground, sampled at $x = 19.5$ meters, with $0.3 \leq z \leq 4.7$ meters. The interval between contours is 0.2 meters in height ($z$), rather than distance ($x$ and $y$), as in previous figures.
Figure 3-50: Three-dimensional contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a building with the basement submerged 2.9 meters into the ground, sampled at $x = 19.5$ meters, with $0.3 \leq z \leq 4.7$ meters. The interval between contours is 0.2 meters in height ($z$), rather than distance ($x$ and $y$), as in previous figures.
Figure 3-51: Three-dimensional contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a building with the basement submerged 2.9 meters into the ground, sampled at $x = 23.5$ meters, with $0.3 \leq z \leq 4.7$ meters. The interval between contours is 0.2 meters in height ($z$), rather than distance ($x$ and $y$), as in previous figures.
Figure 3-52: Three-dimensional contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a building with the basement submerged 2.9 meters into the ground, sampled at $x = 23.5$ meters, with $0.3 \leq z \leq 4.7$ meters. The interval between contours is 0.2 meters in height ($z$), rather than distance ($x$ and $y$), as in previous figures.
Figure 3-53: Three-dimensional contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a building with the basement submerged 2.9 meters into the ground, sampled at $x = 27.5$ meters, with $0.3 \leq z \leq 4.7$ meters. The interval between contours is 0.2 meters in height ($z$), rather than distance ($x$ and $y$), as in previous figures.
Figure 3-54: Three-dimensional contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a building with the basement submerged 2.9 meters into the ground, sampled at $x = 27.5$ meters, with $0.3 \leq z \leq 4.7$ meters. The interval between contours is 0.2 meters in height ($z$), rather than distance ($x$ and $y$), as in previous figures.
Figure 3-55: Three-dimensional contour map of the phase of the $z$-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a building with the basement submerged 2.9 meters into the ground, sampled at $x = 31.5$ meters, with $0.3 \leq z \leq 10.3$ meters. The interval between contours is 0.2 meters in height ($z$), rather than distance ($x$ and $y$), as in previous figures.
Figure 3-56: Three-dimensional contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a building with the basement submerged 2.9 meters into the ground, sampled at $x = 31.5$ meters, with $0.3 \leq z \leq 4.7$ meters. The interval between contours is 0.2 meters in height ($z$), rather than distance ($x$ and $y$), as in previous figures.
Figure 3-57: Contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a standard building with the basement floating one meter above the ground. The data was sampled at $z = 5$ meters, one meter above the first floor. The interval between contours is 5 degrees, or 2.5 meters.

3.2.5 Phase around a building at different depths in the ground

The building in Figures 3-57 and 3-58 is actually hovering a meter above ground, in order to distance it from any connection to ground. As the sunken building seemed to produce more phase perturbations, it was prudent to check if less contact with the ground might produce fewer phase perturbations. As can be seen in the following figures, the result is a set of perturbations very similar to those found in the standard building at $z = 2.5$ meters.

The building in Figures 3-59 and 3-60 has a basement level only 0.1 meters in the ground, in order to minimize its connection to ground. The result is a set of perturbations again very similar to those found in the standard building at $z = 2.5$ meters.

The building in Figures 3-61 and 3-62 has a basement level at 0.5 meters below
Figure 3-58: Three-dimensional contour map of the phase of the $z$-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a building with the basement floating one meter above the ground. The data was sampled at $z = 5$ meters, one meter above the first floor. The interval between contours is 5 degrees, or 2.5 meters.

ground. As can be seen in the following figures, the result is a set of perturbations somewhat similar to those found in the standard building at $z = 2.5$ meters, but with a few oddities that echo the attenuation pattern. In fact, comparing the attenuation contour plots (Figure 3-63) of the building that is only sunken 0.1 meters into the ground with the attenuation plots for this building (Figure 3-64) indicate that the attenuation crosses the tentative threshold of -45 dB when the building is sunken 0.5 meters.

This pattern of greater perturbation with greater depth in the ground indicates that a building with a frame that is well connected to ground may have a much larger perturbation than a similar building that is not. The large perturbation may be a result of current flowing from ground into the building frame, and interacting with the E- and H-fields of the transmitted wave. More research is needed to clarify this phenomenon.
Figure 3-59: Contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a standard building with the basement only 0.1 meters below ground. The data was sampled at $z = 3.9$ meters, one meter above the first floor. The interval between contours is 2.5 degrees, or 1.2 meters.
Figure 3-60: Three-dimensional contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, *around a building with the basement only 0.1 meters below ground*. The data was sampled at $z = 3.9$ meters, one meter above the first floor. The interval between contours is 2.5 degrees, or 1.2 meters.
Figure 3-61: Contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a standard building with the basement 0.5 meters below ground. The data was sampled at $z = 3.5$ meters, one meter above the first floor. The interval between contours is 7 degrees, or 3.5 meters.
Figure 3-62: Three-dimensional contour map of the phase of the $z$-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a building with the basement 0.5 meters below ground. The data was sampled at $z = 3.5$ meters, one meter above the first floor. The interval between contours is 7 degrees, or 3.5 meters.
Figure 3-63: Contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a building with the basement 0.1 meters below ground, sampled at $z = 3.9$ meters, one meter above the first floor. The interval between contours is 3 dB.
Figure 3-64: Contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a building with the basement 0.5 meters below ground, sampled at $z = 3.5$ meters, one meter above the first floor. The interval between contours is 4 dB.
3.2.6 Phase around multiple buildings

Figures 3-65 and 3-66 show two standard two-story buildings, with the front walls at $x = 36$ meters, the back walls at $x = 15$ meters, and the side walls for the lower building along $y = 6$ meters and $y = 15$ meters. The side walls for the top building run along $y = 20$ meters and $y = 29$ meters. These figures show a reasonable amount of perturbation overlapping between the buildings, though the perturbation within the building does resemble the perturbation of a single building.

At the height of $z = 1$ meter, the perturbation outside each building is much more restrained in comparison to the samples taken at $z = 2.5$ meters, as is shown in Figures 3-69 and 3-70. The contour in the front is very minimal, though the smaller pockets on the bordering walls are of a significant size to reach a level of unacceptable uncertainty.

Figures 3-67 and 3-68 show the attenuation of $E_z$, which is, again, very similar to that of one standard building.
Figure 3-65: Contour map of the phase of the z-component of the electric field $(E_z)$ of a 1.5 MHz transmitted signal, around a pair of standard two-story buildings, sampled at $z = 2.5$ meters, one meter above the first floor. The interval between contours is 1.4 degrees, or 0.7 meters.
Figure 3-66: Three-dimensional contour map of the phase of the $z$-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a pair of standard two-story buildings, sampled at $z = 2.5$ meters, one meter above the first floor. The interval between contours is 1.4 degrees, or 0.7 meters.
Figure 3-67: Contour map of the attenuation (dB) of the z-component of the electric field \( E_z \) of a 1.5 MHz transmitted signal, around a pair of standard two-story buildings, sampled at \( z = 2.5 \) meters, one meter above the first floor. The interval between contours is 2.3 dB.
Figure 3-68: Three-dimensional contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a pair of standard two-story buildings, sampled at $z = 2.5$ meters, one meter above the first floor. The interval between contours is 2.3 dB.
Figure 3-69: Contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a pair of standard two-story buildings, sampled at $z = 1.0$ meters. The interval between contours is 14 degrees, or seven meters.
Figure 3-70: Three-dimensional contour map of the phase of the z-component of the electric field \( E_z \) of a 1.5 MHz transmitted signal, around a pair of standard two-story buildings, sampled at \( z = 1.0 \) meters. The interval between contours is 14 degrees, or seven meters.
3.2.7 Phase within a building with multiple floors

The figures discussed in this section show the phase perturbation around a building with four stories. The building has the same footprint as the standard building, and each floor is still three meters in height, with the basement submerged 1.5 meters, as in the previous figures.

Figures 3-71 and 3-72 show the phase sampled at \( z = 2.5 \) meters, as usual, one meter above the first floor of the standard building. The most notable difference is the appearance of a “shadow” behind the building, and the lack of any perturbation beyond the boundaries of the building, which was noticeable on the previous buildings at this height. The minimum peak along the front wall is also significantly lower, and extends farther back into the building. The large peak in the middle is a curious feature, but it can be explained by looking at a similar set of figures that have not had the phase wrapped around to limit it to be between -180 and 180 degrees. Figures 3-73 and 3-74 show data that was allowed to range outside of -180 and 180 degrees. There are no apparent peaks, indicating that the peak in the previous figures was simply an artificial result of the phase wrapping.

Figures 3-75 and 3-76 show the attenuation of \( E_z \). The center of the building has a minimum of -83 dB, which corresponds to the very low phases in Figure 3-73. Again, monitoring the attenuation as a threshold for valid phase readings is in order. This extreme attenuation is the result of the E-field being concentrated at the top of the building (a long, skinny conductor). The E-field outside the building close to the ground is reduced, and less will penetrate the building through the windows in the lower stories. Jumping ahead to examine Figures 3-85 and 3-86, the gain of the E-field at the top of the building is apparent, even in the middle of the top floor.

Figures 3-77 and 3-78 show a similar picture to those of other buildings sampled at \( z = 1 \) meter, except for the slight “shadow” at the back of the building.

The figures showing the phase at \( z = 5.5 \) meters (Figures 3-79 and 3-80) and \( z = 8.5 \) meters (Figures 3-83 and 3-84) show a phase perturbation much more
similar to those of the simplest buildings. The minimum peaks in phase along the front wall are -30 degrees or more, and the maximum peaks along the back wall are 8 degrees or less, which is similar to those in the standard building.

Figures 3-81 and 3-82 show the attenuation of $E_z$, sampled at $z = 5.5$ meters. These figures are very similar to those sampled at $z = 2.5$ meters around the standard building, shown in Figures 3-9 and 3-10, both in the shape of the contours and the level of attenuation.

Figures 3-85 and 3-86 show the attenuation of $E_z$, sampled at $z = 8.5$ meters. These figures are significantly different from the previous samples at $z = 5.5$ meters. The attenuation is actually positive gain, resulting from a concentration of the E-field at the top of the building (a long, skinny conductor).
Figure 3-72: Three-dimensional contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a four-story building, sampled at $z = 2.5$ meters, one meter above the first floor. The interval between contours is 14 degrees, or seven meters.
Figure 3-73: Contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, *around a four-story building*. The data was sampled at $z = 2.5$ meters, one meter above the first floor. *This data was not wrapped to lie between -180 and 180 degrees*. The interval between contours is eight degrees, or four meters.
Figure 3-74: Three-dimensional contour map of the phase of the z-component of the electric field \( E_z \) of a 1.5 MHz transmitted signal, around a four-story building. The data was sampled at \( z = 2.5 \) meters, one meter above the first floor. This data was not wrapped to lie between -180 and 180 degrees. The interval between contours is eight degrees, or four meters.
Figure 3-75: Contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a four-story building, sampled at $z = 2.5$ meters, one meter above the first floor. The interval between contours is 5.5 dB.
Figure 3-76: Three-dimensional contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a four-story building, sampled at $z = 2.5$ meters, one meter above the first floor. The interval between contours is 5.5 dB.
Figure 3-77: Contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a four-story building, sampled at $z = 1.0$ meters. The interval between contours is 14 degrees, or seven meters.
Figure 3-78: Three-dimensional contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a four-story building, sampled at $z = 1.0$ meters. The interval between contours is 14 degrees, or seven meters.
Figure 3-79: Contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a four-story building, sampled at $z = 5.5$ meters, one meter above the second floor. The interval between contours is 1.2 degrees, or 0.6 meters.
Figure 3-80: Three-dimensional contour map of the phase of the z-component of the electric field \( E_z \) of a 1.5 MHz transmitted signal, around a four-story building, sampled at \( z = 5.5 \) meters, one meter above the second floor. The interval between contours is 1.2 degrees, or 0.6 meters.
Figure 3-81: Contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a four-story building, sampled at $z = 5.5$ meters, one meter above the second floor. The interval between contours is 3 dB.
Figure 3-82: Three-dimensional contour map of the attenuation (dB) of the $z$-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a four-story building, sampled at $z = 5.5$ meters, one meter above the second floor. The interval between contours is 3 dB.
Figure 3-83: Contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a four-story building, sampled at $z = 8.5$ meters, one meter above the third floor. The interval between contours is 0.8 degrees, or 0.4 meters.
Figure 3-84: Three-dimensional contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a four-story building, sampled at $z = 8.5$ meters, one meter above the third floor. The interval between contours is 0.8 degrees, or 0.4 meters.
Figure 3-85: Contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a four-story building, sampled at $z = 8.5$ meters, one meter above the third floor. The interval between contours is 0.7 dB.
Figure 3-86: Three-dimensional contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a four-story building, sampled at $z = 8.5$ meters, one meter above the third floor. The interval between contours is 0.7 dB.
Figure 3-87: Three-dimensional contour map of the phase of the z-component of the electric field (Ez) of a 1.5 MHz transmitted signal, around a four-story building, sampled at x = 15.5 meters, with 0.3 ≤ z ≤ 10.3 meters. The interval between contours is 0.4 meters in height (z), rather than distance (x and y), as in previous figures.

Data "slices" were taken as well, along the same x coordinates as in the standard building. Every four meters from x = 15.5 meters to x = 31.5 meters, data was collected across a range of z coordinates, and are shown in Figures 3-87, 3-89, 3-91, 3-93, and 3-95.

The perturbation is generally minimal above z = 5 meters, with the exception of the first "slice" at x = 15.5 meters, which has a few bumps at about z = 7 meters, just under the ceiling of the third floor.

Figures 3-88, 3-90, 3-92, 3-94, and 3-96 show the attenuation of Ez, and there is a corresponding drop in attenuation to -30 dB at about z = 5 meters.
Figure 3-88: Three-dimensional contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a four-story building, sampled at $x = 15.5$ meters, with $0.3 \leq z \leq 10.3$ meters. The interval between contours is 0.4 meters in height ($z$), rather than distance ($x$ and $y$), as in previous figures.
Figure 3-89: Three-dimensional contour map of the phase of the z-component of the electric field (Ez) of a 1.5 MHz transmitted signal, around a four-story building, sampled at x = 19.5 meters, with 0.3 ≤ z ≤ 10.3 meters. The interval between contours is 0.4 meters in height (z), rather than distance (x and y), as in previous figures.
Figure 3-90: Three-dimensional contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a four-story building, sampled at $x = 19.5$ meters, with $0.3 \leq z \leq 10.3$ meters. The interval between contours is 0.4 meters in height ($z$), rather than distance ($x$ and $y$), as in previous figures.
Figure 3-91: Three-dimensional contour map of the phase of the z-component of the electric field \(E_z\) of a 1.5 MHz transmitted signal, around a four-story building, sampled at \(x = 23.5\) meters, with \(0.3 \leq z \leq 10.3\) meters. The interval between contours is 0.4 meters in height \((z)\), rather than distance \((x\) and \(y)\), as in previous figures.
Figure 3-92: Three-dimensional contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a four-story building, sampled at $x = 23.5$ meters, with $0.3 \leq z \leq 10.3$ meters. The interval between contours is 0.4 meters in height ($z$), rather than distance ($x$ and $y$), as in previous figures.
Figure 3-93: Three-dimensional contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a four-story building, sampled at $x = 27.5$ meters, with $0.3 \leq z \leq 10.3$ meters. The interval between contours is 0.4 meters in height ($z$), rather than distance ($x$ and $y$), as in previous figures.
Figure 3-94: Three-dimensional contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a four-story building, sampled at $x = 27.5$ meters, with $0.3 \leq z \leq 10.3$ meters. The interval between contours is 0.4 meters in height ($z$), rather than distance ($x$ and $y$), as in previous figures.
Figure 3-95: Three-dimensional contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a four-story building, sampled at $x = 31.5$ meters, with $0.3 \leq z \leq 10.3$ meters. The interval between contours is 0.4 meters in height ($z$), rather than distance ($x$ and $y$), as in previous figures.
Figure 3-96: Three-dimensional contour map of the attenuation (dB) of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a four-story building, sampled at $x = 31.5$ meters, with $0.3 \leq z \leq 10.3$ meters. The interval between contours is 0.4 meters in height ($z$), rather than distance ($x$ and $y$), as in previous figures.
3.3 Networks of conducting lines

Buildings are not the only large structures in the urban landscape. Water pipes and electrical wires stretch across cities and between them, and are also often made of conducting material.

The network of pipes simulated for these figures consists of a 300-meter-long main line running parallel to the y-axis at $x = 0$ meters. Every 60 meters, there is a 90-meter-long side spur running parallel to the positive x-axis, the first one at $y = 0$ meters, the second at $y = 60$ meters, and so on, until the last one at $y = 300$ meters. Each side spur has a nine-meter-long line every five meters running parallel to the y-axis, on alternating sides of the spur. These simulate the connections to individual houses. A diagram for the network can be found in Section 2.1. The network is submerged three meters underground. The transmitting antenna is placed at $x = 9000$ meters.

Figures 3-97 and 3-98 show the phase measured at $z = 0.9$ meters, over a network of pipes. These pipes have a radius of 0.1 meters, and those in Figures 3-99 and 3-100 have a radius of 0.5 meters. The perturbation seen in Figures 3-97 and 3-98 has a maximum at about 5 degrees, and a minimum at about -5 degrees, both of which are found at the endpoints of the network. Near the center of the network, the perturbation is within $\pm 2$ degrees, or one meter.

The radius of the pipe makes very little difference. Figures 3-99 and 3-100 show a maximum of about 7 degrees, and a minimum of about -7 degrees, and an overall form similar to the network with a radius of 0.1 meters.
Figure 3-97: Contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, over a network of underground pipes with a radius of 0.1 meters, sampled at $z = 0.9$ meters. The interval between contours is 0.4 degrees, or 0.2 meters.
Figure 3-98: Three-dimensional contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, over a network of underground pipes with a radius of 0.1 meters, sampled at $z = 0.9$ meters. The interval between contours is 0.4 degrees, or 0.2 meters.
Figure 3-99: Contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, over a network of underground pipes with a radius of 0.5 meters, sampled at $z = 0.9$ meters. The interval between contours is 0.6 degrees, or 0.3 meters.
Figure 3-100: Three-dimensional contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, over a network of underground pipes with a radius of 0.5 meters, sampled at $z = 0.9$ meters. The interval between contours is 0.6 degrees, or 0.3 meters.
3.3.1 Connected grids

Figures 3-101 and 3-102 show data sampled from around a network of underground pipes, each with a radius of 0.1 meters which is connected to a network of overhead wires, each with a radius of 0.025 meters. The two networks run in the same pattern as described in the previous section, with the pipes submerged three meters underground, and the overhead wires running five meters above ground. The two networks are connected at each "house," which are at the end of each of the shortest, nine-meter-long lines.

When the pipes are connected to overhead electrical wires, the perturbation along the main line at $x = 0$ meters is increased, though the perturbation at the endpoints at $x = 90$ meters is about the same at 6 degrees. The peak along the main line at $x = 0$ meters is a rather high 53 degrees, but the rest of the space beyond $x = 25$ meters is under 10 degrees. Beyond $x = 100$ meters, the perturbation is only about 0.5 degrees, but there is no structure that far out to cause perturbations, as the network of pipes and wires only extends to $x = 90$ meters.

Figures 3-103 and 3-104 show the same network of pipes and wires, but the antenna has been placed nine kilometers up the y-axis, rather than along the x-axis. This eliminates most of the perturbations along the main line at $x = 0$ meters, and at the endpoints at $x = 90$ meters. Those discontinuities still remaining occur at the point where the phase wraps around, and for some reason isn't cancelled when the baseline measurements are subtracted.
Figure 3-101: Contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a network of connected underground pipes and overhead wires, sampled at $z = 0.9$ meters. The peak values along the y-axis are approximately 53 degrees. The interval between contours is 2.8 degrees, or 1.4 meters.
Figure 3-102: Three-dimensional contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a network of connected underground pipes and overhead wires, sampled at $z = 0.9$ meters. The interval between contours is 2.8 degrees, or 1.4 meters.
Figure 3-103: Contour map of the phase of the z-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a network of connected underground pipes and overhead wires with the transmitter at $y = 9000$ meters, sampled at $z = 0.9$ meters. The interval between contours is 12 degrees, or six meters.
Figure 3-104: Three-dimensional contour map of the phase of the $z$-component of the electric field ($E_z$) of a 1.5 MHz transmitted signal, around a network of connected underground pipes and overhead wires with the transmitter at $y = 9000$ meters, sampled at $z = 0.9$ meters. The interval between contours is 12 degrees, or six meters.
Chapter 4

Conclusions

First, the results from the discussion are summarized before drawing conclusions. The standard building does cause perturbations in the phase, and the perturbations vary as the structure of the building varies. This can make navigation using the phase of an AM radio signal difficult. However, the perturbations are mostly minimal outside the buildings, and, with enough data, including taking into account the attenuation of the signal, navigation within buildings may even be possible.

4.1 Summary of building data

The first perturbation variation to be examined was the variation over different heights in and around the building. Around what is the convenient height for measurement, one meter above the floor, the perturbation had a constant form, with a large minimum peak along the front wall, and a smaller maximum peak along the back wall, but the peaks varied in size, with greater perturbations occurring closer to the floor, and lessening as the sampling points approached the ceiling. The front-back asymmetry became evident while considering this data, and the asymmetry may be an exploitable feature, if appropriately placed antenna can be sampled.

In later sections examining the four-story and sunken buildings, it is observed
that the perturbation is, in general, smaller as the data is sampled nearer to the ceiling, though there are some exceptions.

One of the most difficult sets of buildings to generalize about was the set with varying floor heights. Here the problems of phase wraparounds creating artificial peaks masked other observations. Pairing the attenuation of the signal with the phase perturbation indicates that there exists a threshold for the strength of the signal below which the phase is not valid. This threshold falls around -40 dB.

The building with the basement submerged more deeply in the ground was also difficult to generalize about. There were artificial peaks from phase wraparounds. The perturbations at a meter above the first floor were large and unlike those found in the standard building. Examining a few “slices” along the x-axis, it was apparent that the perturbation was fairly large until very close to the ceiling.

Examining buildings with different basement depths indicated that buildings with more connection to ground caused greater phase perturbation.

Once the effects of changing individual characteristics of a single building were established, simulations involving two standard buildings, side by side, were examined. There was little additional perturbation in these simulations.

Simulating a building with multiple floors, it became evident that higher points in buildings see less perturbation. The second and third floors of a four-story building (where the third floor is the top floor) had a similar appearance to the first floor of a standard building — minimal perturbation — while the first floor of the four-story building showed a great deal of perturbation, similar to that in buildings with higher ceilings.

4.2 Summary of network data

The other type of structure under examination was the network of pipes or wires that pervades the urban landscape. First, a simple network of underground pipes was examined. The perturbation was both rather limited in the amplitude of its peaks, being within ±8 degrees, and the peaks only fell at the endpoints of the
network.

When the pipes were connected to overhead wires, the peak at one of the end-points — along the main line — increased dramatically to about 40 degrees, but a simulation with the transmitting antenna along the axis parallel to the main line, rather than perpendicular to it, eliminated the perturbation completely. This can be useful for navigation purposes, by comparing the signals from antennae 90 degrees apart.

4.3 Overall conclusions

My findings can be broken down as follows: Outdoor networks of underground and overhead conductors impose a small perturbation on signals observed at one meter above ground, but it appears that navigation errors can be avoided by making observations of signals from multiple transmitters at different locations and different frequencies. The phase observed at one meter above ground outside of buildings, even very nearby, was not significantly perturbed by these buildings.

Inside buildings, the phase was significantly perturbed, and a few observations may provide the key to using this method indoors. First, the wall facing the transmitter experiences a perturbation on the order of one radian of phase within about the first three meters inside. Second, severe phase perturbations occur in the lower stories of a multistory building, and in the basement or crawlspace under a building, where signal attenuation may exceed 40 – 50 dB.

Other observations include the realization that changing the connection between the conducting building frame and ground may have significant effects on the phase perturbations on the lower floors, Unfortunately, there is little data on what this connection is in practice. Also, the reliability of the AM carrier-phase method inside buildings will likely be improved by rejecting phase observations of signals having an attenuation exceeding 40 – 50 dB. Finally, better positional accuracy may be obtained with higher frequency signals, in the neighborhood of 1.5 MHz.
4.4 Suggestions for future research

In addition, a building frame with a substantial connection to ground generally caused a greater phase perturbation. The electrical connection between a building frame and ground was a fact that was taken for granted when performing these simulations. Conversations with building inspectors and architects indicate that there isn’t necessarily a regulated connection in most cities. Investigations should be made to determine whether most buildings fall into a particular category — well-connected to ground, not connected at all, or intermittently connected at different points in the frame.
References


