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Design and Development of Conformal Automobile Antennas Using Numerical Modeling and Experimental Techniques

DISSERTATION

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy in the Graduate School of The Ohio State University

By

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* * * * *

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ABSTRACT

This dissertation presents techniques for the design, development, and analysis of conformal automobile antennas. Numerical modeling and experimental techniques used in the development of on-glass vehicle antennas are presented. Antennas for various mobile applications developed using those tools are also presented.

A discussion of several applications for mobile antennas is first presented. The design parameters and specifications for mobile antennas used in five specific applications (AM/FM radio, cellular telephone, GPS system, and vehicle radar) are then presented. The parameters discussed include bandwidth, impedance, pattern, polarization, system efficiency, and signal propagation environment.

An overview of some of the experimental techniques developed and used is given. The techniques include range-type measurements (impedance, pattern, and polarization) and mobile-measurement type systems.

Numerical modeling techniques were developed to analyze on-glass automobile antennas in various frequency bands. The method of moments and the UTD techniques were used. The modeling results are compared to measurements.

The development and analysis of on-glass automobile antennas for AM/FM radio, cellular telephone, GPS navigation systems, and collision-avoidance radar are presented. A discussion of the antenna-vehicle interaction and its effect on the radiation pattern and polarization of the antenna is presented. The advantages of antenna
diversity systems and antenna arrays are discussed. A study of FM antenna diversity is discussed. The advantages of multi-use antennas are also presented. A study of a dual use (cellular/GPS) on-glass antenna is discussed.
I dedicate this dissertation to my parents as a small token for all the love and support they have always given me.
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CHAPTER 1

INTRODUCTION

This dissertation presents a study in the design and development of conformal automobile antennas. The goals of the study were to device theoretical and experimental technique for the design and testing of conformal antennas, to apply these techniques to study the antenna-vehicle interactions, to develop guidelines or design parameters for automobile antennas. and to use these techniques and guidelines to design and develop new conformal antenna concepts for various mobile applications.

In this Chapter we present general applications for mobile antennas and describe some of the design and analysis tools that are currently used. In each of the following chapters we describe antennas for a particular mobile application. The different applications that will be covered are AM/FM broadcast radio (Chapter 2), cellular telephone (Chapter 3), GPS navigation (Chapter 4), and automotive collision-avoidance radar (Chapter 6). (Antennas that combine the dual-use functionality of cellular and GPS will be described in Chapter 5.) Those five applications represent the different electromagnetic environments that characterize most mobile antenna systems. Each chapter will describe the design parameters and specifications for the antennas as well as the numerical and experimental techniques used in the development of these antennas. Automobile antennas that were designed, tested and implemented will
also be presented. The summary and the conclusions of the research work are given in Chapter 7.

1.1 Applications for Mobile Antennas

The electromagnetic spectrum has become a valuable resource world wide. The frequency spectrum is controlled by government agencies and world organizations who license the spectrum's usage. A significant portion of the spectrum is licensed for applications developed specifically for mobile users. Advances in electronics and communication systems have made the equipment needed by the mobile users more affordable.

Automobile users form a large portion of the mobile community. In addition to the existing applications, new ones are constantly immuring. Figure 1.1 shows a drawing of some of the most popular antennas already available on commercial automobiles. The following is a list of some of the applications that are currently available for the automobile users and some of the current research interests in the electromagnetic mobile field.

- **Radio**: AM/FM analog transmissions are still the most popular. New forms of radio transmissions include digital and direct broadcasts from satellites (DBS) [1].

- **Television**: It covers a large bandwidth in the VHF and UHF bands. New direct satellite broadcasts are also becoming popular.

- **Telephone**: Analog and digital cellular systems are already very common for voice and data transmissions [2, 3]. Microcellular systems for personal
communications networks (PCN) might be the next generation of mobile telephones [4, 5].

- **Navigation**: The Global Positioning System (GPS) is becoming popular with automobile users and is being used with mapping systems [6].

- **Remote Keyless Entry**: Most luxury automobiles allow the user to activate several vehicle functions (open doors, turn alarm on, etc.) remotely using a radio frequency signal from a key-chain transmitter.

- **Paging systems**: The new trends in paging systems is for national or even worldwide coverage using satellite transmissions.
- **Radio Toll Booth**: Systems already exist for automatic vehicle identification (AVI) and payments at unmanned toll booths [7].

- **ITS**: The new highway systems may need to interact with automobiles using Radar and other communication systems.

- **Amateur Radio**

- **Citizens Band (CB) radio**

  Automobile antennas are needed for all of the above applications. In most cases, a specific antenna is needed for each application. As the number of applications increases the number of antennas on automobiles will increase [8]. The trend for new automobile antennas is to be conformal to the vehicle body [9]. Conformal antennas improve the esthetics of the vehicle, reduce wind noise and drag, and are subjected to less damage and vandalism. Conformal antennas also practically allow the installation of multiple antennas on a vehicle for use with a diversity system.

1.2 **On-Glass Antennas**

On-glass antennas are currently the most popular conformal automobile antennas [10, 11, 12]. On-glass antennas have several advantages over other mobile antennas. Some of those advantages are listed below.

- **Conformal**: They have all the advantages of conformal antennas. In some cases, they could be made invisible in the optical region of the spectrum.

- **Isolated**: They are located on a large non-conducting structure that is isolated from the metallic vehicle body.
• **Existing technology:** In most cases, antennas can be printed on the glass using existing silk-screening technologies.

• **Structural integrity:** Antennas on the glass do not require modifications to the vehicle body that could compromise the vehicle’s structural integrity.

Some of the limitations of on-glass antennas are listed below.

• **Limited Space:** Antennas must be placed on fixed glass fixtures, usually the front (windshield), back (backlite), or side (sidelite).

• **May impede vision:** Antennas, especially on the windshield, must not present a visible obstruction.

• **Part of the glass:** The antenna gets replaced with the glass.

In this dissertation we will present design and analysis tools that can be used in the general development of automobile antennas. However, we will specifically discuss the development of new on-glass antenna concepts that are conformal or invisible. The discussion of conformal automobile antennas in the published literature is very limited, and most of the significant published works have been sited in this dissertation. There is, however, a large number of patents about conformal automobile antennas that are issued each year. We have collected more than one hundred US-patents dealing with on-glass automobile antennas. Most of these patents discuss AM/FM antennas, but a few more recent patents discuss cellular antennas as well. Patents tend to present the design details of the antenna but give very little information about the performance of the antenna. Therefore, the patent literature
does not serve as a good reference for this dissertation. Patents were used mainly for identifying the types of antennas that have already been investigated or developed.

1.3 Design and Analysis Tools

To develop mobile antennas, certain design and analysis tools must be used. We have developed and used several different techniques for designing and testing mobile antennas. These techniques can be used with conformal as well as non-conformal antennas. We have used them successfully in designing on-glass antennas for various applications [13]. In the following sections we will summarize the theoretical and experimental techniques that could be used in the antenna design and analysis process.

1.3.1 Theoretical and Numerical Models

One approach to study antennas is to calculate their characteristics theoretically. For complex antenna structures and geometries, such as mobile antennas, the theoretical solutions most often must be solved numerically. There exists several numerical techniques that could be used to model the mobile antennas. Some of the techniques that could be effective are the method of moments (MoM), the uniform geometrical theory of diffraction (UTD), the finite element methods, and the finite difference methods. We have used the MoM and UTD to model automobile antennas for AM, FM, cellular, GPS, and radar applications. In the following chapters we will describe the details of modeling antennas for each of those applications.

Numerical techniques have several advantages. Some of those advantages are listed below.
• **Convenient:** Analysis and calculation can be performed with minimal cost and tools (usually just a computer).

• **Effective:** Models can usually predict antenna performance accurately compared to measurements.

• **Flexible:** The geometry and the parameters of the computer models can be easily modified for analysis.

• **Complete:** All the essential characteristics of the antennas (impedance, gain pattern, and polarization) can be calculated.

Numerical techniques also have some limitations, as listed below.

• **Complex:** The model may become complex for complicated antenna structures such as automobile antennas.

• **Long start-up times:** Setting up the initial models and verifying their accuracy may be time consuming.

• **Not comprehensive:** A single model may not be effective for all applications. Several models (or hybrid models) may be needed.

**Overview of Numerical Modeling Techniques**

The two numerical techniques that we used for our modeling are the Method of Moments (MoM) and the Uniform Geometrical Theory of Diffraction (UTD). The MoM is considered a low frequency technique while UTD is a high frequency technique.
The MoM is a technique for solving the matrix form of the Electric Field Integral Equation (EFIE) for the current modes on the body [14].

\[ [Z]I = V \]

\[ V = \text{Source (known)} \]

\[ I = \text{Current mode coefficients (unknown)} \]

\[ Z = \text{Impedance matrix (calculated)} \]

Once the current is calculated, other parameters of interest (such as the input impedance and gain pattern) can be calculated. The number of current modes (and elements in the \([Z]\) matrix) required to model a given body accurately increases with increasing frequency. Also, for a given frequency, the number of modes required to model a body is higher the larger the size of that body. The computer processing time increases as the square or the cube of the number of modes. Therefore, theoretically the MoM can be used at any frequency, but in practice, the technique is inefficient for electrically large bodies (body sizes of several wavelengths). We used the MoM for modeling vehicle antennas in the AM radio band (vehicle \(\approx \lambda/100\)), in the FM radio band (vehicle \(\approx \lambda\)), and in the cellular telephone band (vehicle \(\approx 10\lambda\)). For frequencies above 1 GHz (just above the cellular band) the MoM becomes inefficient at modeling an antenna on a full-body vehicle.

We used two different general purpose MoM programs for our modeling. The first one was the Electromagnetic Surface Patch Code version IV (ESP4) written by professor E.H. Newman at The Ohio State University ElectroScience laboratory [15]. ESP4 calculates the gain pattern of the antenna for both azimuth and elevation.
cuts, and also the input impedance of the antenna. ESP4 allows the body to be constructed either as a thin wire structure, a perfect electric conducting (PEC) or dielectric plate structure, or a combination of thin wires and plates. The wire and plate current modes are modeled using piecewise-sinusoidal wire and surface-patch dipoles, respectively. Wires are attached to plates using a special attachment mode. For our FM and cellular models we used the ESP4 plate model for the vehicle body and we used plates and thin wires for the antennas. The advantage of using plates to model a vehicle is that the plate model represents a vehicle body more accurately than a wire-grid model. In the AM frequency band the vehicle is very small in terms of wavelength (≈ λ/100). The surface-patch plate model was not designed to have dipole modes shorter than λ/10 and, therefore, is not expected to produce an accurate AM model. The wire-grid model, however, is sufficient in representing the vehicle body at such low frequencies. Also, we were interested in looking at the current flow on the vehicle body in the AM band. Displaying the current is much simpler for a wire-grid model then for a plate model. Although ESP4 allows the model to be represented as a wire-grid, numerical problems (that cause asymmetric results) can arise in the computations as the wire-grid body becomes small in terms of wavelength. In [16], this asymmetry is attributed to the computation of non-physical asymmetric fields, for electrically short wires, in the original Richmond code [17] (which ESP4 uses for thin-wire calculations). A small modification to the basic Richmond code is suggested (a bridge-current formulation) and is shown to solve these numerical errors. In [18], Balmain and Tilston describe a new general purpose multiradius-wire MoM program that includes the above modification. This program (MBCPF164)
allows only wires to be used in the models. We used the MBCPF164 code to model the wire-grid vehicle in the AM frequency band.

The UTD is an asymptotic high frequency technique for approximating the integral relations that govern the electromagnetic behavior of antennas and scatterers. For the approximations to be accurate, the components of the model body should be approximately larger than a quarter wavelength ($\lambda/4$). UTD can be used to model vehicle antennas at cellular frequencies and higher ($\lambda/4$ @ FM=0.75 meter; @ Cellular=0.08 meter).

We used a general purpose UTD code (the NEC-BSC) written under the supervision of Dr. R.J. Marhefka at The Ohio State University ElectroScience laboratory [19]. We used the NEC-BSC (Numerical Electromagnetic Code - Basic Scattering Code) on the vehicle cellular antenna models to compare the results with those of ESP4. Vehicles in the cellular frequency band can be modeled using either the MoM code or the UTD code. An antenna in NEC-BSC is modeled as a basic source element (uniform electric current distribution, annular magnetic ring current distribution, etc.) with a given excitation current. For vehicle antennas, we use MoM to find the excitation current on the model antenna and then use that in the NEC-BSC antenna-plus-vehicle model. To find the excitation current using MoM one would use only the antenna and its surrounding geometry (a few wavelengths around the antenna) since at high frequencies the antenna current distribution is determined mainly by the local surrounding geometry. In some cases it may be difficult to model a vehicle antenna accurately using NEC-BSC, especially if the details of the antenna geometry are important, which may be the case in the cellular band. In that case, the antenna-without-vehicle pattern (obtained using MoM) could be synthesized in
NEC-BSC using the basic source elements. The calculated UTD pattern would then show the effect of the vehicle on the antenna. At high frequencies, the location of the antenna on the vehicle becomes more critical than its detailed geometry. It is at those frequencies that the MoM becomes inefficient and UTD has more advantages. UTD, which is essentially a ray tracing technique, allows individual rays to be turned on and off (for example rays that bounce off the hood or trunk could be turned off). This feature allows the user to more easily find a location for the antenna that meets certain design criteria.

There exist other numerical electromagnetic techniques. Some of those include Finite Element Methods (FEM), Finite Difference Methods (FDM), Boundary Element Method (BEM), Boundary Integral Moments (BIM), and time domain methods. The above techniques are not very efficient at modeling an antenna on a vehicle with the radiation occurring in a 3-dimensional space. It is believed that using the MoM and UTD techniques is the most efficient method for modeling vehicle antennas.

1.3.2 Experimental Techniques

In many cases, theoretical models of antennas are either not accurate or not efficient. For those situations, the design process of the antennas must be carried out using experimental techniques. The paper design of the antenna could be made based on general antenna theory or experience, and then verified experimentally. This process can be repeated iteratively until the design meets the specifications. Even if an antenna design was completed using numerical techniques, experimental measurements are still needed to verify its overall performance.
Scale Model Range Measurements

One method of measuring antenna characteristics is to use scale-down models of the antennas. Scaling down the geometry of the antenna produces the same results as the full scale antenna if the test frequency and the antenna conductivity are scaled up accordingly (see page 733 in [20]). Some of the advantages of using scale models are the following:

- **Convenient**: Measurements can be performed indoors.

- **Quick**: The vehicles and the antennas can be built and modified very easily and quickly compared to full scale vehicles.

- **Cost effective**: The cost of the range equipment, scaled-down vehicles and antennas is lower than full scale testing.

- **Complete**: Impedance, gain pattern, and polarization characteristics of the antennas can be measured.

Scale model testing, however, has limitations which include the following:

- **Need accurate models**: If the vehicle size is in the resonance region of the antenna (such as for FM antennas), then the scale models must be accurate replicas of the full size vehicles.

- **Conductivity scaling**: Antennas typically use high conductivity materials (silver, copper, etc.). Scaling the conductivity to a higher value for the scaled-down antennas may not be possible. This limitation may also affect modeling the effect of water or salt (or other lossy materials) on the scaled-down antenna.
• **Ground effect**: Scale models are typically tested either in free space or over conducting ground planes. The effect of the earth on ground vehicles is not taken into account and may be an important factor.

Scale model testing is used extensively in compact range (anechoic chamber) type measurements, where the antenna model is placed on a rotating pedestal and gain pattern measurements are made. This technique has been used to characterize antennas on aircrafts and ships. We have previously used scale models to study conformal antennas on vehicles [21]. From that study we concluded that scale models may not be accurate in representing the performance of the resonant-type vehicle antennas (such as the FM radio antenna). The scale models may be more accurate at frequencies where the vehicle body becomes electrically large (cellular or GPS). At AM-radio frequencies, the vehicle is electrically small and the impedance of the vehicle antenna becomes the parameter of interest. Scale models, however, may not be very effective at predicting the impedance characteristics of an AM vehicle antenna. Full scale measurements will probably be needed for AM antennas. Therefore, scale model testing may not be very effective for AM/FM vehicle antennas. For higher frequency-band applications, scale models become more useful for antenna measurements.

**Full Scale Range Measurements**

Full scale measurements use the actual size antennas. Full scale automobile measurements characterize the antenna performance more accurately than scale-down measurements. To fully characterize the antenna, its impedance, gain pattern and
polarization must be measured. Some of the advantages of using full size antennas in range measurements are listed below.

- **Accurate models**: The antenna being characterized is the one that will actually be used.

- **Ground effect**: Measurements are usually performed over the earth ground, thus taking into account any effect the earth may have on the results.

- **Complete**: The antennas can be completely characterized by measuring their impedance, gain pattern, and polarization.

Full scale testing also has its costs and limitations, some of which are listed below.

- **Requires large area**: Far-field spherical ranges typically require a large area (especially for antennas operating at less than 1 GHz). The ranges are usually outdoors and subjected to the weather conditions.

- **Costly**: The cost of full scale antennas and vehicle is typically high (compared to scale models).

- **Time consuming**: Building and modifying full scale antennas, especially on vehicles, can be time consuming.

In the following chapters we will describe in more detail the full scale measurement systems that we used for testing the automobile antennas.

**On-Road Measurements**

The automobile antenna test range provides valuable engineering data: antenna pattern and polarization. The test range, however, can not accurately predict how
the automobile antenna would behave in the “real world”, using “real world” signals. The signal an automobile antenna receives when it is on the road may not be well characterized. The polarization, the angle of arrival, and the signal strength at the antenna may not be well known. The signal multipath environment that the antenna operates in may also not be well known. Research has been conducted in order to better understand the signal characteristics and environment [4, 5, 22, 23, 24, 25, 26, 27].

The above research appears to indicate that the signal environment is complex and may be difficult to duplicate or model in the test range. One way of testing the vehicle antenna performance, in the same environment as it would be subjected to on the road, is to use a mobile measurement system. Mobile instrumentation can be placed in the vehicle as it is driven on the road. The off-the-air signal that the antenna receives during the measurements would then be the same type of signal it receives during actual use (in this type of measurement the received signal is the one of interest). To accurately characterize the antenna performance, the mobile instrumentation must measure the signal parameters that the actual receiver (a car radio for example) would use (typically the signal strength). RF laboratory instruments usually have an input impedance of 50Ω. Actual mobile receivers may have different input impedance values. In order to more accurately represent the behavior of the antenna in the mobile environment, the input impedance of the mobile instrumentation should match that of the receiver. One effective way of achieving that is by using the actual receiver as the mobile instrumentation. The receiver may need to be modified in order to output the signal parameters needed to assess the antenna performance.
The mobile measurement system is typically used to compare the performance of an experimental vehicle antenna to that of a standard reference vehicle antenna. Two types of measurements can be made using the mobile system. The antenna azimuth pattern can be obtained by driving the vehicle in a circle. Also, the performance of the antenna in different environments (urban, rural, etc.) can be measured by driving the vehicle on the road while recording the received signal at the antenna.

The mobile measurement system has several advantages, as discussed above. A summary of those advantages is given below.

- **Accurate representation of the signal**: It uses off-the-air signals.
- **Accurate instrumentation impedance**: It uses the actual commercial instruments.

The measurement system also has several limitations, some of which are listed below.

- **Very specific**: A different system is needed for each application.
- **No absolute levels**: Need to compare antenna performance to a reference antenna.
- **Time consuming**: Mobile measurements typically take more time than range measurements.
- **Not always predictable**: Off-the-air signals may vary unpredictably. Need to properly calibrate the data before comparison of antennas.

At the ElectroScience Laboratory, we have built and used three particular mobile measurement systems. One system is for AM/FM radio antennas, one is for cellular
antennas and another system is for GPS antennas. These systems will be described in more detail in the following chapters.

1.4 Summary of Work

In the next chapter we describe the development of on-glass AM/FM antennas. We discuss design parameters of the antennas as well as the numerical modeling techniques that were used to model these on-glass antennas. Full-scale range type measurement systems and mobile systems used in testing these antennas are also presented. We then present several AM/FM antenna design concepts that were developed using these numerical and experimental techniques. We demonstrate how a windshield film antenna and a backlight heater-grid can be designed to be effective AM/FM antennas. We also discuss the multipath problem for FM signals and show how diversity systems and on-glass antennas can be used to reduce the effect of multipath.

In Chapter 3 we describe the development of on-glass cellular antennas. We describe the design parameters of the cellular antenna, and we extend the numerical modeling techniques that were discussed in Chapter 2 into the high frequency-band range. We also discuss how a mobile measurement can be performed to assess the on-glass cellular antenna performance. We also study the antenna-vehicle interactions and discuss how they may limit the performance of on-glass cellular antennas. We then present experimental results from the development of two on-glass cellular antenna concepts: an annular slot and a roof-line loop antenna. We discuss the limitations of these antennas and present alternative antenna concepts including antenna arrays and diversity systems.
In Chapter 4 we describe the development of on-glass GPS antennas. We give an overview of the GPS system and discuss the design parameters of GPS antennas. We also describe the numerical modeling techniques that were used to model the GPS antenna in the presence of the vehicle. A mobile measurement system that uses satellite signals to characterize the performance of GPS antennas on vehicles is described. We also describe how a single patch antenna behind the automobile glass can be used effectively as a GPS antenna. We discuss the limitations of this antenna and present an alternative patch array design.

In Chapter 5 we discuss a new dual-use on-glass antenna design that can be used for cellular and GPS applications. We demonstrate theoretically how that antenna can be used successfully for both applications. We then present alternative designs that may be easier to implement on the automobile glass. We show numerical modeling results and experimental results for these alternative designs and discuss the limitations of these antennas.

In Chapter 6 we describe the development of on-glass collision avoidance radar antennas. We give an overview of collision avoidance radar systems and discuss the design parameters of automotive radar antennas. We also present a feasibility study for placing lane-changing radar antennas on the automobile glass. Theoretical, numerical and experimental techniques were used in the study. We discuss the use of backlite end-fire antennas and show how the effect of the glass and the interference from the vehicle body limit the effectiveness of these antennas. Then we discuss the effectiveness of a lane-changing radar antenna on the sidelite of the vehicle.

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In this chapter we describe the development of on-glass AM/FM antennas. In section 2.1 we discuss the design parameters of the AM radio antennas and the FM radio antennas. In section 2.2 we describe the numerical modeling techniques that were used to model the on-glass AM/FM antennas. The full-scale range type measurement systems and the mobile systems are presented in section 2.3. Finally, in section 2.4 we present several AM/FM antenna design concepts that were developed using the numerical and experimental techniques. We also discuss FM diversity systems and antennas.

2.1 Design Parameters

In this section we will discuss the design parameters and specifications for AM and FM mobile antennas. These design parameters can also be applied to other antenna systems that have the same characteristics as the AM and FM antennas. The main characteristic of the AM antenna is that it is an electrically small (low frequency) antenna. The FM antenna is a resonant antenna receiving a terrestrial signal. Other automotive systems that use antennas similar to the FM antenna are television and remote keyless entry systems.
2.1.1 Broadcast Radio: AM Frequency Band

The AM radio U.S. frequency band covers the frequencies 540–1630 KHz (555–184 meter wavelength). The bandwidth ratio used is 100% around the center frequency. The signal transmitted is a vertically polarized ground wave (at night the sky wave becomes dominant).

Any mobile AM antenna will be very short electrically (length less than a hundredth of a wavelength). Such antennas behave as hertzian dipoles ($l \leq \lambda/50$). A hertzian dipole radiates energy omnidirectionally in azimuth and has a very low radiation resistance [28]. A short dipole of length $l$ and radius $a$, for example, has an input impedance given by $Z_{in} = R_{in} + jX_{in}$ where,

$$R_{in} = R_r = \frac{80\pi^2}{l^2} \left(\frac{l}{\lambda}\right)^2$$

$$X_{in} = -120 \frac{\ln\left(\frac{l}{a}\right) - 1}{\tan\left(\frac{2\pi l}{\lambda}\right)}.$$  \hspace{1cm} (2.1)

For an automobile antenna, the above equations predict that the impedance of the AM antenna will be $Z_{in} \approx -j10,000\Omega$ (at 1 MHz). Therefore the antenna can be modeled as a capacitor $C_a \approx 16pF$.

The transmission line connecting the AM antenna to the radio is also very short electrically. Transmission lines much shorter than a wavelength behave as shunt capacitors (the transmission line lumped-load model). The capacitance of a coaxial cable is given by the following [29]:

$$C_c = \frac{120\pi\varepsilon_0\sqrt{\varepsilon_r}}{Z_0} l$$  \hspace{1cm} (2.3)

where, $\varepsilon_0 = 8.85 \times 10^{-12}F/m$, $\varepsilon_r$ is the dielectric constant inside the cable, $Z_0$ is the characteristic impedance of the cable, and $l$ is the length of the cable. A coaxial
An AM automobile antenna connected to the radio by a coaxial cable can be represented by the equivalent circuit of Figure 2.1. The antenna, which is usually an electrically isolated conducting structure fed counterpoised with the vehicle body, is replaced by its equivalent capacitance. The cable is similarly replaced by its equivalent shunt-capacitance. The AM radio has traditionally been designed to have a capacitive front-end with a high input impedance (essentially a voltage probe measuring the differential voltage across the cable terminals). The resulting equivalent circuit is a voltage divider circuit. In order to maximize the power transfer to the radio, either the capacitance of the antenna must be increased, or the capacitance of the cable must be decreased. To increase the antenna capacitance, the effective height of the antenna must be made larger. A conformal antenna on the automobile
has a limited effective height because of the limited physical dimensions of the automobile. To decrease the capacitance of the cable, the length of the cable must be made shorter and the characteristic impedance of the cable must be made larger.

Another factor that influences the power received at the radio is the strength of the AM signal at the antenna terminals. Since the AM signal is usually a ground wave, the energy in the signal varies with distance above the earth. Our measurements have shown that the location of an AM antenna on an automobile affects its received power level, with antennas located higher above the earth receiving the stronger signals. Note, however, that the location of the antenna does not affect the received signal power as significantly as does the size of the antenna. Moving a 75cm long monopole antenna from the trunk lid to the roof-top of an automobile increases the received signal power level by 3dB. Doubling the length of the monopole antenna increases the power level by approximately 8dB.

In summary, an automobile AM antenna must be designed to be an electrically isolated structure fed against the vehicle body. The effective height of the antenna must be made large. The radiation pattern of the antenna will be omnidirectional independent of the specific antenna used. To maximize the power transfer to the radio, the antenna cable must be made short and must have a high characteristic impedance. Cables with characteristic impedances from 75Ω to 125Ω are typically used. The length of the cable is usually determined by the distance between the antenna and the radio. Currently, the most popular AM/FM automobile antenna is the whip antenna (an FM-tuned quarter wavelength monopole fed against the vehicle body). Conformal antennas (such as the on-glass heater-grid antenna) can be designed to have larger effective heights than the whip and, therefore, they can be
Figure 2.2: The concept AM automobile antenna that uses the full vehicle body as a monopole and the earth as a ground plane.

more efficient AM antennas. Our measurements have shown that the AM antenna element must be on the outside of the vehicle body for the antenna system to be efficient. Moving the antenna from the plane of the windshield to inside the passenger compartment, even by only 10cm, reduces its efficiency significantly (due to the Faraday cage effect). One of the most efficient AM automobile antennas that we have tested uses the vehicle body as a monopole element and the earth as the ground plane. This concept is shown on the left in Figure 2.2. Note that the tires provide the vehicle with sufficient isolation from the ground at AM frequencies. A more practical implementation of this concept is shown on the right in Figure 2.2. In this implementation the outer conductor of the cable is grounded to the vehicle body and the center conductor is connected to the earth. Tests on this antenna show that it is approximately 10dB more efficient than the standard whip antenna. In practice, the center conductor of the cable can be connected to a metallic plate or strip that lies underneath the vehicle just above the earth surface.
2.1.2 Broadcast Radio: FM Frequency Band

Several considerations have to be made when designing an automobile FM antenna. Some of the issues that must be considered are discussed below.

Antenna Design parameters

- **Frequency.** The FM radio U.S. frequency band covers the frequencies 88–108 MHz (3.4–2.75 meter wavelength). The bandwidth ratio used is approximately 20% around the center frequency. A typical automobile is on the order of a wavelength in size in the FM band. Therefore, the vehicle body is a resonant structure at FM frequencies and must be considered as part of the automobile FM antenna.

- **Impedance.** Automobile radios typically have front-end receivers with an input impedance between 50Ω and 100Ω. The radios are designed as such because the popular whip antenna typically has an impedance in that range. The cable used to connect the FM antenna to the radio typically has a characteristic impedance ranging from 75Ω to 125Ω (see section 2.1.1). If a conformal FM antenna is designed to have an impedance between 50Ω and 100Ω across the FM band, the corresponding mismatch loss due to cable and radio reflections will be small. A broadband matching network can be used if the antenna structure has an impedance that deviates greatly from 50Ω.

- **Pattern.** Experimental and statistical studies have shown that commercial radio propagation yields a uniform angular density in azimuth and a Gaussian distribution in elevation [23]. The mean and variance of the elevation
distributions vary depending on the regional environmental conditions. The above studies show that most of the radio signal energy is concentrated in elevation angles less than 20°. In certain urban environments, signals could have elevation angles as high as 50°. As a result, FM automobile antennas must be designed to have an omnidirectional azimuth pattern free of nulls. Typically, the FM antennas should be designed to be smaller than a wavelength. Larger structures tend to develop multiple current nodes that produce nulls in the pattern. The FM automobile antenna should also be designed to have a directional gain pattern in elevation in order to receive signals coming in at elevation angles lower than 50°. The signal strength received by the antenna with a smaller directive gain in elevation will be lower than that of the antenna with high directivity at the low elevation angles [24]. The gain of the antenna at elevation angles higher than 50° will mainly add to the noise level of the system.

- **Polarization.** Originally, U.S. commercial FM stations broadcast horizontally polarized signals. On automobiles, however, the vertically-mounted whip antenna was the most popular FM antenna. In order to increase the reception efficiency of those automobile antennas, the Federal Communications Commission (FCC), in the 1960’s, permitted the FM stations to transmit circular polarization [30]. Transmitting with circular polarization produces a signal with equal energy in the vertical and horizontal polarization vector. Such an arrangement allows both the horizontally polarized (HP) antennas (mainly stationary) and the vertically polarized (VP) antennas (on mobile vehicles) to efficiently receive the FM signal. Using a 45° slant linear polarization also produces a signal with
equal energy in the VP and HP components. So currently, most U.S. commercial FM stations broadcast circularly polarized (CP) signals or 45° slant signals. Therefore, a linearly polarized VP or HP automobile antenna would ideally receive equal energy signals. However, the horizontal component of the signal will be greatly attenuated near the ground. Therefore, at large distances from the transmitting tower the FM signal will be mainly vertically polarized. Near the transmitting towers (in downtown regions) the signal polarization may not be well defined due to the propagation and multipath effects. Some studies have shown that an HP signal could suffer less distortion than a VP signal in hilly areas [25]. However, the VP signal is generally stronger and more stable. As a consequence of these remarks, a new FM conformal antenna should be designed to be primarily vertically polarized. Using an antenna with a CP or 45° slant polarization could produce polarization mismatch nulls if the sense of the polarization is opposite to that of the broadcast signal. A linearly polarized VP antenna appears to be most effective. Figure 2.3 gives a graphical representation of the FM polarization problem in the mobile environment. It shows the possible losses that could occur due to polarization mismatch in automobile FM antenna systems. From the figure we see that the vertically polarized automobile antenna is the only one that does not suffer from polarization mismatch nulls when the transmitted signal is either CP or slanted.
Figure 2.3: A graphical representation of the FM polarization problem in the mobile environment. The antenna on the vehicle is assumed to have no cross polarization although on an actual vehicle this is usually not true.
Signal Propagation Environment

In addition to the above antenna design parameters, signal propagation considerations must be made when designing an FM antenna system. One of the main problems with the FM radio signal is multipath interference. The radio wave received at the automobile antenna generally consists of the direct signal and signals that have been reflected, diffracted, or scattered along the way. Several statistical models have been developed to analyze multipath propagation [26, 27]. Such models predict that the received signal consists of three or four principal stationary waves and several weaker non-stationary waves. All these signals add constructively and destructively with the main signal depending on their phase component. This can cause the signal to fade rapidly, as a function of distance, even though the main signal is very strong. Automobile antenna systems that use diversity (multiple antennas) are being implemented in order to reduce the effect of multipath fading. One form of diversity reception is to switch between multiple antennas placed in different positions on the vehicle; typically, the signal at one of the antennas will be stronger than that of the other antennas [31]. Another type of diversity uses the signals from all the antennas at all times to form an adaptive array antenna system [32]. Another type of diversity system uses multiple antennas with different polarizations. All such diversity systems require the use of more than one antenna and special circuitry in the receiver.

2.2 Numerical Modeling Techniques

In this section we discuss the development of electromagnetic computer models that can be used to develop and analyze automobile antennas and more specifically
on-glass vehicle antennas. Three different models (using three different computer codes) were developed to allow the analysis to extend over a wide range of frequencies. The results from the models were compared to experimental measurement results for verification of the models. Once confidence is established in the accuracy of the model, new concept antennas can be developed using the model. In section 1.3.1 we discussed the different computer codes used in our study. In section 2.2.1 we discuss the modeling of the vehicle at low frequencies (the AM radio frequency band). The results of modeling the vehicle in the resonant region (FM radio frequency bands) are given in section 2.2.2. The discussion of modeling the automobile antennas at higher frequencies is given in Chapter 3.

2.2.1 Low Frequency-Band Analysis

In this section we will present the results of modeling the vehicle at low frequencies. We will specifically discuss analysis in the AM radio band (540-1630 KHz), although the analysis applies to any application where the vehicle is electrically small.

A typical vehicle in the AM band is on the order of $\lambda/100$. The AM antenna must be a separate metallic structure counterpoised with the remainder of the vehicle body. The azimuth gain pattern of the antenna is mostly omnidirectional independent of the geometry of the antenna element. The efficiency of the AM antenna depends on the effective height of the antenna element, its location on the vehicle, and how well the antenna and cable are matched to the radio receiver (see section 2.1.1).
The Wire-Grid Model

The wire-grid MoM technique was used to model the vehicle in the AM band. The shape of the gain pattern of the AM antenna is not of much interest since it is mostly omnidirectional in the azimuthal plane (plane of the automobile). The efficiency of the antenna is a more important parameter. The wire-grid model is not expected to give accurate antenna impedance results. The reason may be that for impedance measurements it is important to model the feed point region accurately and that is not done in the wire grid model. The wire-grid model, however, can be used to study the effect of the location and size of the antenna element on the overall efficiency of the AM antenna system. Such a study can be performed by calculating the far-field pattern of the automobile antennas, and normalizing the results to those of an isotropic radiator or some other reference antenna. Losses due to impedance mismatch and cable attenuation were not considered in this study.

Model Limitations

A wire-grid model of a vehicle (using image theory to account for the ground) was generated using ESP4. The average grid size used was about 30cm or $\lambda/1000$ at 1 MHz. Some wire segments were only about 5cm long. First, we wanted to study the accuracy of the ESP4 wire-grid model. One way of doing that is to check for symmetry of the MoM calculated current modes. We let a vertically polarized plane wave be incident from the back side of the vehicle (which is left-right symmetric) and at grazing incidence ($\theta = 90^\circ$ with respect to the vertical axis). With the problem geometry being totally left-right symmetric we expect the current magnitude on symmetric wire segments to be equal. That was not the case. The current on the
vehicle was asymmetric even as we increased the frequency from 1 MHz to 50 MHz. These results seem to indicate that the ESP4 wire-grid model will not give accurate results if the wires are electrically small.

As discussed in section 1.3.1, the authors of the MoM program MBCPF164 claim to correct the problem with the wire-grid code in ESP4. We tested the same vehicle geometry used with ESP4 using the MBCPF164. For a totally left-right symmetric geometry we did get symmetry in the vehicle body current modes at frequencies of 50 MHz down to 5 MHz. However, at 5 MHz some asymmetry started to appear. Using the same model at 1 MHz gave a very asymmetric result. This seems to indicate that even for MBCPF164 the vehicle wire segments are too small electrically at 1 MHz (the AM band). Further studies need to be made in order to find a solution to this problem. However, for the purpose of this study, the results at 5 MHz may be sufficient to characterize the behavior of the AM antenna on the vehicle. The antenna characteristics are not expected to change significantly between 5 MHz and 1 MHz since the size of the antenna in both cases is electrically small. Figure 2.4 shows a sample plot of the 3-dimensional vehicle grid model used. The magnitude of the current on each wire segment is indicated by the gray-scaled color of each segment. The display program used to generate the above figure (on an SGI workstation) was provided by Dr. A.K. Dominek of the ElectroScience Laboratory. Note that the current distribution on the vehicle body will, in general, be different under antenna transmitting and receiving conditions (although the transmit and receive gain patterns are the same, as required by the reciprocity theorem) due to the presence of the scattering pattern under receive conditions. Also, the current distribution for a receive antenna (except at the antenna feed point) will, in general, vary with
Figure 2.4: AM wire-grid model current display. Plane wave incident from back of vehicle. Vehicle above infinite ground plane. freq=5MHz.
Monopole Antennas | Calculated Gain Level (dB)\textsuperscript{a} | Measured Gain Level (dB)\textsuperscript{b}
---|---|---
75cm roof-top | 0 | 0
150cm roof-top | +10 | +8
75cm fender-whip | -4 | -3

\textsuperscript{a}Wire-grid MoM results at 5 MHz normalized with respect to the first antenna

\textsuperscript{b}Results at 1 MHz obtained using mobile measurement system. Cable and impedance-mismatch losses have been calibrated out.

Table 2.1: Tabular summary comparing MoM calculated and measured results of AM automobile antennas.

the azimuth angle of the incident wave, even if the antenna has an omnidirectional gain pattern. Therefore, calculating and displaying the current distribution over the vehicle body for a receive antenna may not, in general, give significant information about the effectiveness of the antenna. However, if the current distribution can characterize certain properties of the antenna, then we can use the above grid model to calculate that current.

Model Results

To test the accuracy of the model in predicting the gain level of AM antennas we calculated the far-field azimuth gain pattern of three automobile antennas and compared the results to measurements. The first antenna modeled was a 75cm long monopole located at the top center of the automobile roof (the ground plane). The second antenna was a 150cm roof-top monopole. The third antenna was a 75cm monopole located at the back passenger-side edge of the trunk lid (top of fender). Table 2.1 shows that the calculated results are within 2dB of the measured results. Note that the cable and impedance-mismatch losses of the measured antennas have
been calibrated out of the final results. The calculated results do not account for those losses either.

These modeling results indicate that the wire-grid model can be used effectively to study the efficiency of the AM antenna system. The effect of the location and the size of the AM antenna element can be studied. The wire-grid model can also be used for other applications, such as studying the noise interference and coupling between the AM antenna and other electrical devices or wiring in the automobile [33].

2.2.2 Resonant Region Analysis

In this section we will present the results of modeling the vehicle at frequencies at which the vehicle body is a resonant structure. We will specifically discuss the analysis of FM radio band (88-108 MHz) antennas.

The vehicle body is an important part of the FM antenna since the vehicle is on the order of a wavelength (it is a resonant structure). Unlike the AM antenna, the details of the antenna element structure affect the performance of the overall antenna. The geometry and position of the antenna element characterize the important parameters of the vehicle antenna such as gain pattern, polarization, and impedance. Most commercial US FM stations transmit circularly polarized signals (equal horizontal and vertical polarizations).

Plate Model vs. Wire-Grid Model

The Wire-Grid Model

The ESP4 MoM code was used for the FM modeling. At first, a wire-grid model was tested. The advantage of using a wire-grid model is that all the connections between the body and antenna elements (which are usually wires) are wire-to-wire
connections. These type of connections are simpler to model numerically. The disadvantage of the wire-grid model is that the grid has to be fine enough to approximate a conducting plate. We have also learned from the AM modeling that numerical problems could arise if the wire segments are made too small. Figure 2.5 shows the azimuth patterns of two wire-meshed backlite (back window) heater-grid antennas on partial vehicle models (partial geometries were used initially in order to reduce computations). The plots shows how changing the size of the mesh affects the patterns of the antenna. Comparison to measured data also showed that even the fine-meshed model (0.05\(\lambda\) mesh size or current-mode segment size) did not give accurate results. Our analysis showed that the mesh size had to be smaller than 0.01\(\lambda\) (especially near the feed point) in order to obtain accurate results, making the wire-grid model computationally inefficient. Using a non-rectangular shaped grid may also improve the accuracy of the model, but at the expense of an increase in the amount of computations. Therefore, the use of the wire-grid model was not considered further for FM modeling.

**The Plate Model**

The vehicle was then modeled using perfectly conducting plates. Figure 2.6 shows the geometry of the plate model used. The figure also shows a roof-top monopole antenna modeled as a thin wire and attached to the plate roof. This antenna was used as a reference antenna for all the FM antennas that were modeled using ESP4. The main advantage of the plate model is that accurate results can be obtained with a current-mode segment size of 0.1\(\lambda\) to 0.2\(\lambda\) (an order of magnitude larger than the equivalent size for the wire-grid model). The reduction in the number of modes allows the plate model to be more computationally efficient than the wire-grid model. The
Figure 2.5: Comparing two (fine meshed and course meshed) ESP4 all-wire-grid models of a backlight wire heater-grid antenna in order to test the effectiveness of using a wire-grid model. Azimuth pattern at 2° elevation angle above the horizon for both Vertical and Horizontal Polarizations; freq=98 MHz. LS stands for LineStyle of curve.
Figure 2.6: Geometry of an ESP4 model of a FM roof top monopole. The scale of the model and the number of current modes used are indicated.
total number of modes needed to model the current for the full geometry of Figure 2.6 was 315, whereas, 661 wire modes were required to model only the partial geometry of the fine-meshed model of Figure 2.5. Such a reduction in the number of modes translates into a reduction of the computer memory storage used. Note, however, that the computational time required to calculate a specific number of surface patch modes on a 3-dimensional geometry is generally longer than that required for the same number of wire current modes. Therefore, a plate geometry requires fewer current modes than a wire geometry but may not always produce a reduction in the CPU time needed to perform the calculations.

The antenna elements could be modeled using either wires or thin plates. If the antenna is constructed from thin plates, the width of the plates has to be around 1cm ($\approx \lambda/300$) to avoid numerical errors. In this approach, the antenna element can be connected to a plate on the vehicle body using the usual plate-plate junction. If the antenna needs to have a source at the plate-plate junction then that source can be inserted at the overlap current mode between the two plates. An example of this type of antenna-feed structure is shown on the left side of Figure 2.7. The plate-plate feed connection does not model the current flow at the feed point very accurately, except if the width of both plates is very small in terms of a wavelength (about four times the radius of an equivalent circular thin wire). For on-glass antennas one of the plates is usually wide (as shown in Figure 2.7). Therefore, the above feed model can not accurately predict the input impedance of most on-glass antennas. However, the gain pattern calculations are not very sensitive to the current flow at the feed point, and can be accurately predicted using the above feed model.
Figure 2.7: Geometry of an ESP4 model of a plate and wire backlite heater-grid antenna.
If the antenna element must be constructed from wires, then a wire-plate attachment mode must be used. The wire-to-plate junction must occur at a point on the plate a distance no closer than 0.1λ (about 30cm @ FM) to the edge of the plate. This requirement is needed to insure numerical accuracy of the results. It is not always practical to have the wire-plate junction away from the edge, especially with on-glass antennas (such as the model shown on the right side of Figure 2.7). A wire-plate attachment mode can still be used to connect the wire antenna element to the edge of a plate; however, instead of connecting the wire antenna directly to the plate it is connected to a connection-wire, which in turn extends along the surface of the plate to the plate junction point. This plate junction point is placed 0.1λ away from the edge of the plate. The source for the antenna is placed between the antenna feed line and the connection-wire. This modeling technique provides accurate gain pattern results. The input impedance of the antenna, however, can not be accurately determined using the above edge feed model, since the current flow at the feed is not modeled very accurately.

We do know that ESP4 does generate accurate impedance results for wire antennas that are connected to plates using the normal approach (keeping a distance of 0.1λ from the wire connection to the edge of the plate). For the roof-top monopole model given in Figure 2.6 the input impedance was calculated to be equal to \( Z_{\text{in}} = 25.7 - j8.7 \) Ω at 98 MHz. The measured result for a magnetically mounted roof-top monopole was \( Z_{\text{in}} = 25.1 + j14.8 \) Ω. Note that the small difference in the reactance (imaginary part of \( Z_{\text{in}} \)) may be due to the top-end capacitance that makes the monopole appear longer electrically than it is physically. Such an effect is not modeled in ESP4 which, therefore, predicts a more capacitive impedance.
Both antenna connection techniques discussed above (plate-plate and wire-plate) were used in this study. The choice of which technique to use is dictated mostly by the required geometry of the model. Both techniques provide accurate gain pattern results, but can not provide accurate impedance results for antennas that connect to the vehicle at a plate edge.

**The Plate Model Geometry**

The next step was to determine how much of the vehicle body was needed to accurately model the vehicle antenna. Recall that the computer memory used and the CPU run-time both increase as the size of the model becomes larger in the MoM codes. Figure 2.8 shows the FM azimuth patterns for three models of a backlite plate-heater-grid antenna with a top center feed. The first geometry only models the back-side of the vehicle. The second geometry models the full vehicle except for the passenger compartment which is kept open from the underside (open cavity). The third geometry has the passenger compartment closed from the underneath and from the front and back, including the back package shelf (closed cavity). The patterns seem to indicate that modeling the full vehicle, including the passenger compartment, is necessary in order to get accurate results. This indication is further validated by Figure 2.9. The figure shows a model of the same antenna as in Figure 2.8 but with the antenna feed offset from center towards the driver side. The pattern results shown in the figure indicate that the effect of closing the cavity is more significant for the offset-feed antenna then it is for the center-feed antenna. The reason may be that the center-feed antenna-model has complete left-right symmetry and the contribution to the antenna pattern from the passenger compartment is minimal.
Figure 2.8: ESP4 model of a backlite plate-heater-grid antenna. Top center feed. Studying the effect of the geometry. Azimuth pattern at 2° elevation angle above the horizon for both Vertical and Horizontal Polarizations; freq=98MHz. LS stands for LineStyle of curve.
Figure 2.9: ESP4 model of a backlite plate-heater-grid antenna. Feed offset from top center towards driver side. Studying the effect of the geometry. Azimuth pattern at 2° elevation angle above the horizon for both Vertical and Horizontal Polarizations; freq=98MHz. LS stands for LineStyle of curve.
All these results seem to indicate that to get accurate results from the FM model the whole vehicle geometry has to be modeled, including the inside compartment.

Another issue that needed to be resolved concerning the FM model was the importance of modeling the glass of the vehicle. In ESP4, the plates used can be dielectric sheets instead of perfectly conducting sheets. The dielectric sheets are modeled using the sheet impedance approximation [15]. The sheet impedance for vehicle glass at FM frequencies is approximately equal to \(-j7500\ \Omega/\square\). Therefore, the glass at FM frequencies (\(\approx 0.001\lambda\) thick) behaves almost like free space and has little effect on the performance of the antennas that are placed on it. In all the FM models that we used, all the window openings were kept as free space.

**Comparing the Wire and Plate Heater Grids**

An FM heater-grid antenna (heater-grid lines plus additional vertical lines) performs identically to a plate antenna of equal size. To verify whether our model is consistent with this result, we compared the performance of the plate heater-grid antenna and the wire heater-grid antenna shown in Figure 2.7 above. In those two models, the plate antenna element has the exact same dimensions as the wire grid. The FM pattern results for the two models are given in Figure 2.10. The result is consistent with measurement in that the two antennas behave similarly in the FM band. This result also validates the two feeding techniques (the plate-plate connection and the wire-plate connection) since it shows that they both give the same results for the same antenna.

**Computer CPU Times for Different Models**

As noted earlier, the MoM code takes longer to run as the model size gets larger. Figure 2.11 shows CPU times for some of the models that we used. The times shown
Figure 2.10: ESP4 model of a backlight heater-grid antenna. Comparing the offset feed (top driver side) plate heater-grid and wire heater-grid models. Azimuth pattern at 2° elevation angle above the horizon for both Vertical and Horizontal Polarizations; freq=98MHz. LS stands for LineStyle of curve.
Figure 2.11: Different ESP4 FM antenna models. CPU times on the Cray Y-MP8/864 Ohio supercomputer.
are for the ESP4 code running on the Cray Y-MP8/864 Ohio supercomputer\(^1\). The actual CPU times will be different for different computers, but the percentage change in the times from model to model should remain the same. We see from these results how closing the cavity increases the CPU time by 50%. However, the improvement in the accuracy of the results may justify that increase. Also note how using a wire heater-grid antenna requires about 20% more CPU time than a plate heater-grid antenna. Therefore, if the plate antenna behaves the same as a wire antenna of the same size, it is more economical (less CPU time) to use the plate antenna in the model.

**Ground Bounce Effect**

The ground bounce term is the portion of the signal that arrives at the vehicle antenna after reflecting off the ground. Since vehicles are always on the ground, the ground-bounce signal is almost always present and gets combined with the direct signal at the antenna. In a range type measurement, there is always a ground reflected signal and a direct signal between the instrumentation antenna and the vehicle test antenna. Figure 2.12 shows a range measurement setup. From the figure we see that the ground reflected signal appears to come from an imaginary image source in the ground (according to image theory). The image source radiates a signal that is equal to the product of the real source signal \(E_0\) and the complex reflection coefficient of the ground, at the point of reflection \(|\Gamma|\angle\Gamma\). The total signal at the test antenna is the vectorial sum of the direct and reflected signals.

In the computer model the vehicle is in free space. In order to accurately predict the behavior of the real-world antennas using modeling tools, we must incorporate

\(^1\)A grant of 20 hours of Cray time was given to us by the Ohio Supercomputer Center.
the ground bounce term in the model. We can easily do that if we use image theory and follow the same reasoning given above. To add the ground-bounce signal to the direct signal we simply calculate the gain pattern of the antenna twice: once for the incident field at an angle $\alpha$ with respect to the plane of the automobile (direct signal), and a second time with the field incident at an angle $-\alpha$ and multiplied by the reflection coefficient of the ground $|\Gamma|^2 \angle \Gamma$ (ground-bounce signal). The total gain pattern of the antenna is then calculated from the sum of the two signals.

We can easily incorporate the ground bounce term in our computer modeling programs. The addition of the ground bounce term adds very little to the cost of running
the computer codes, and makes the modeling results more accurate representations of the real-world results.

**Arbitrary Polarization Calculation**

The computer modeling tools that we have developed have the ability to calculate and display the antenna gain pattern for any required signal polarization. The modeling programs can calculate the gain pattern of the vehicle antenna for two orthogonal signal polarizations (theta and phi). From those two polarizations we can mathematically calculate the gain pattern for any given signal polarization. Figure 2.13 shows a sample output of the gain-pattern data generated by the computer modeling program ESP4. The data shown are for a heater-grid antenna at 98MHz. The data have been normalized to a free-standing FM-resonant dipole, and the ground bounce signal has been included in the patterns. The plot shows the gain pattern of the antenna for six different polarizations. Those particular polarizations were chosen because they are important in assessing the performance of FM antennas. Other polarizations can easily be calculated.

**Experimental Verification**

In this section we will compare the results of the ESP4 FM models to actual measurements. The models used are plate models with a closed cavity. The vehicle in the model has the same dimensions as the vehicle used in the measurements (1983 Chevrolet Cavalier). The measurements were made at The Ohio State University ElectroScience laboratory. Note that the experimental measurements were done in an outdoor range (not a well controlled environment) and so the results can not
Figure 2.13: Sample gain pattern output for six different polarizations at one frequency generated by the computer modeling program used for on-glass vehicle antennas. Polarizations shown: VP-vertical; HP-horizontal; RSP-right slant; LSP-left slant; RCP-right circular; LCP-left circular
be expected to compare exactly to the model results. A detailed description of the measurements is given in section 2.3.

**Fender Whip Antenna**

The first antenna used in the comparison of the models to measurements is the fender whip monopole. Figure 2.14 shows the azimuth pattern (at 2° elevation angle above the horizon) at 98 MHz. The pattern is given for both the Theta (approximately vertical - VP to within a \( \cos(2°) \approx 1 \) factor) and Phi (horizontal - HP) polarizations. Both the measured and calculated data have been normalized to the roof top monopole data. The result shows that the model is capturing the main features of the antenna accurately. The small differences in the results could be due to measurement errors, or to interactions between the antenna and parts of the vehicle that were not modeled. The average levels for the two patterns are within 2dB of each other for the vertical polarization and within 0.1dB for the horizontal polarization. Note that the signal average of the measured results already reflects any signal loss due to impedance mismatch; the model results do not take into account any impedance mismatch loss. If the measured antenna is well matched (low mismatch loss), then any differences in signal averages between the model and measurement are due to modeling errors. If, however, the measured antenna has a high mismatch loss, then that loss has to be taken into account when comparing the measured and model results. The roof top monopole reference antenna, which was used for normalization, has a low mismatch loss and thus has little effect on the signal average result. The measured fender whip antenna also had a low mismatch loss.
Figure 2.14: Fender whip antenna. Comparing ESP4 model results and measured results. Azimuth pattern at 2° elevation angle above the horizon for both Vertical and Horizontal Polarizations; freq=98MHz. LS stands for LineStyle of curve.
**Heater-Grid Antenna**

The next set of antennas that were compared to measurements were the backlite heater-grid antennas. Figure 2.15 shows the results for the top-center-feed antenna. The model results compare very well with the measured results. The main features of the antenna seem to be modeled accurately. The signal averages are within 1.5dB and 0.5dB for the vertical and horizontal polarizations respectively. The measured antenna had a low mismatch loss. Much of the disagreement between measurement and theory is in the behavior of the nulls. Note, however, that nulls are caused by cancelations (180° phase difference) of two identical signal components. Very small phase changes cause large changes in the behavior of the nulls.

The above results have shown that the FM model that was used can accurately predict the behavior of the vehicle antennas. These models can now be used to develop new antenna concepts.

### 2.3 Experimental Techniques

In this section we present several experimental techniques that can be used in the design and development process of mobile antennas. The experimental techniques also serve for measurement verification of the antenna performance. First, we present the turntable-based range measurement techniques for impedance and polarimetric gain pattern measurements. Then we discuss a mobile measurement systems that we developed to test antenna performance using real-world signals. (See section 1.3.2 for an overview of the different systems.)
Figure 2.15: Top center feed backlight heater-grid antenna. Comparing ESP4 model results and measured results. Azimuth pattern at 2° elevation angle above the horizon for both Vertical and Horizontal Polarizations; freq=98MHz. LS stands for LineStyle of curve.
2.3.1 Full Scale Range Measurements

Impedance Measurements

Input impedance measurements were made using the test apparatus of Figure 2.16. The system consists of a vector network analyzer (VNA) interfaced to a personal computer. The VNA is used either with an internal or external directional coupler. The output from the VNA consists of a spectrum of signals throughout the specified frequency band. Part of the signal travels to the antenna and the other part travels back to the VNA (into port REF) and is used as a reference signal. Part of the signal that travels to the antenna gets radiated and part of it gets reflected back (into port IN) due to impedance mismatch (with respect to 50 Ω). The reflected
signal is then divided by the reference signal, resulting in the reflection coefficient, or the $S_{11}$ parameter. The VNA can be calibrated so that the $S_{11}$ parameter is referenced to the feed point of the antenna [21].

From the complex valued $S_{11}$ parameter, we can calculate the input impedance of the antenna, the standing wave ratio (SWR), and the mismatch loss (in dB) due to the reflected signal [29]:

$$Z_{in} = Z_0 \left[ \frac{1 + S_{11}}{1 - S_{11}} \right]$$

$$SWR = \frac{1 + |S_{11}|}{1 - |S_{11}|}$$

$$L_{mm} = -10 \log |1 - |S_{11}|^2|$$

where, $Z_{in}$ is the input impedance in $\Omega$, $Z_0$ is the characteristic impedance of the coaxial cable used in $\Omega$, $SWR$ is the Standing Wave Ratio ($1 \leq SWR \leq \infty$), and $L_{mm}$ is the mismatch loss in dB.

The impedance of an antenna is typically plotted on a Smith Chart.

**Gain Pattern Measurements**

The pattern and polarization of an antenna can be measured using the same computer-interfaced network analyzer (VNA) system used for impedance measurements. The VNA is setup to transmit a sequence of RF signals (or a single frequency signal) through one antenna and receive the signals at a second antenna. The received signal (consisting of magnitude and phase) is divided by the transmitted signal to obtain the $S_{21}$ parameter. The two antennas used are the instrumentation antenna (a log-periodic, for example) and the automobile antenna under test. Either antenna could be used for transmitting or receiving. With the automobile rotating on
a turntable, the above measurement ($S_{21}$ parameter vs. frequency) could be repeated at each required azimuthal angle. For one rotation of the automobile, a matrix of complex $S_{21}$ data (with one axis being frequency and the other azimuth angle) can be collected. At high frequencies (above 1GHz) the loss in the cables may become excessive. An amplifier may be used to increase the dynamic range of the system. When using an amplifier, it is preferable to amplify the signal before it is transmitted and not after it has been received. This will insure that the environmental noise received with the signal is not amplified. For example, if the instruments are located inside the building near the instrumentation antenna, then the output of the VNA should (i) go through the long cable out to the automobile, (ii) get amplified and transmitted, (iii) get received by the instrumentation antenna and go through a short cable to the input of the VNA.

We built two full scale automobile antenna test ranges at the ElectroScience Laboratory. One range consisted of a rotator with a semi-permanently mounted vehicle. The other range consisted of a drive-on turntable where any vehicle could be tested. Both rotator and turntable were motor-driven and their angular rotation was measured by some angle encoding technique. Figure 2.17 shows a diagram of our rotator-based automobile test range.

To polarimetrically characterize the antenna under test, we must perform two measurements using a pair of instrumentation antennas that have orthogonal polarizations with respect to each other. We have used crossed dipoles and crossed log-periodic antennas as instrumentation antennas. The two measurements can be obtained on two separate azimuthal rotations of the automobile (keeping everything except the instrumentation antenna exactly the same), or they could be obtained
Figure 2.17: Experimental test range for automobile antenna pattern measurements.
in one rotation. To get the data in one rotation either requires the VNA to have
two input ports, or requires the use of a computer-controlled external RF switch to
switch between the two instrumentation antennas. The electric-field polarization of
the test antenna could then be obtained from the ratio of the magnitudes and the
phase difference of the two polarimetrically orthogonal signals. The antenna polar­
ization could then be given as the axial-ratio and tilt angle of the ellipse representing
the rotation of the electric field vector, or it could be given as a point on the Poincare
sphere [34, 21].

An alternative approach would be to use the two polarimetrically orthogonal
signals at the instrumentation antennas to obtain the test-antenna pattern for any
required polarization. For example, using vertically polarized (VP) and horizontally
polarized (HP) instrumentation antennas, the magnitude and phase of the VP and
HP antenna patterns are obtained. The circularly polarized pattern of the test
antenna could then be obtained by shifting the HP data 90° in phase and then
adding the complex data from the two patterns. Similarly, the test-antenna pattern
could be obtained for any other polarization.

The type of range used in automobile measurements is a spherical range. The
electromagnetic wave transmitted from the antenna travels spherically outwards. In
the so-called far field region, the wave is a propagating wave with losses on the order
of $1/(distance)^2$. If the receive antenna is located in the far field of the transmit
antenna, then the wave at the receive antenna can be considered as a plane wave.
Typically, the far-field distance is calculated from the equation $L = \frac{2D^2}{\lambda}$ where, $\lambda$
is wavelength at the frequency of interest, and $D$ is maximum antenna dimension.
At FM frequencies the whole vehicle is considered as part of the antenna; therefore,
for a 3 meter long vehicle the far-field distance at FM frequencies is only about 6 meters. At cellular and GPS frequencies the far-field distance is even smaller.

There is another factor that must be considered when calculating the distance of the automobile from the instrumentation antenna: the ground bounce. In a turntable-based range a ground-bounce term will always exist. The ground-bounce term is the secondary signal that reaches the receive antenna via reflection from the ground. Figure 2.18 shows a range setup with the direct signal and the ground-bounce signal. The ground can be eliminated in the analysis by replacing the instrumentation...
antenna (transmitting in this case) by its image. The ground-bounce signal is then replaced by its image. If the instrumentation antenna transmits an electric field given by $E_0$, then the image will transmit an electric field given by $E_0 \times |\Gamma| \angle \Gamma$, where $\Gamma$ is the complex reflection coefficient of the ground at the angle of incidence. The angle of incidence $\alpha$ can be calculated from the geometry of the problem to be

$$\alpha = \tan^{-1}\left(\frac{h_t(1 + \frac{h_I}{h_t})}{d}\right).$$

(2.7)

The values of $\Gamma$ for VP and HP signals can easily be calculated (see pages 53-56 in [35]). The resulting configuration consists of two antennas, separated by a distance $2h_I$, radiating signals with different amplitude and phase, in free space. Using array theory [28], we can calculate the total resulting signal assuming the two radiating antennas are point sources. The total electric field is given by

$$E = E_0 \sqrt{(1 + \Gamma)^2 \cos^2\left(\frac{\psi}{2}\right) + (1 - \Gamma)^2 \sin^2\left(\frac{\psi}{2}\right)} \angle \tan^{-1}\left[\left(\frac{1 + \Gamma}{1 + \Gamma}\right)^2 \tan^2\left(\frac{\psi}{2}\right)\right]$$

(2.8)

where,

$$\psi = \frac{2\pi h_I}{\lambda} \sin(\beta) + \angle \Gamma.$$  

(2.9)

The above electric field represents the antenna array factor only. The specific antenna radiation pattern must be multiplied by the above result to get the total radiated field by the antenna. When designing an automobile antenna test range, the height of the instrumentation antenna and its distance from the vehicle must be determined, for a given polarization, based on the required field pattern generated in the presence of the ground-bounce term. Figure 2.19 shows the VP and HP field patterns, calculated using equation 2.8, for a particular range setup. The plot shows the field distribution, at the location of the vehicle antenna, in the presence of a ground-bounce term.
Another factor that may influence the location of the automobile is multipath (other than the ground-bounce term). The vehicle should be placed in a location such that the main signal propagating between the instrumentation and test antennas is the direct-path signal. Multipath signals could be detected either during the measurements (by identifying sources of multipath and testing for their existence), or in the post processing using Fourier or spectral estimation techniques.

Calibration of the range measurements can be accomplished by measuring the pattern of a reference antenna, either a free-standing reference (such as a dipole in free space), or an on-vehicle standard (such as a roof-top monopole). The reference data is always obtained from a co-polarized reference antenna, with respect to the instrumentation antenna. The data obtained for the test antenna, could then be
calibrated with the reference antenna data (VP with VP reference and HP with HP reference). This type of calibration, performed before or after each set of measurements would insure that the effects of cable lengths, amplifiers, and any changes in the setup would not be factored into the final data. This type of calibration allows data collected at different times to be compared with each other, as long as the reference antennas used are the same.

2.3.2 The AM/FM Radio-based Mobile Measurement System

An AM/FM mobile measurement system was built in order to measure the automobile antenna performance on-the-road and using commercial signals [36]. Figure 2.20 shows the type of measurements that could be made using this system. A block diagram of the mobile measurement system is shown in Figure 2.21. A battery separate from the automobile battery was used as the primary power source. The computer system was powered by an inverter driven by the battery. (If a laptop computer is used, then the inverter may not be needed.) The receiver used in these experiments was a standard digitally tuned automobile radio. This was chosen because it is known that the AM (and to a lesser extent the FM) input impedance of a standard automobile radio is not 50 ohms. We wanted the data to reflect exactly what a standard automobile radio would experience in the real world. Special purpose instruments such as spectrum analyzers are carefully designed with 50 ohm input impedance. The use of such instruments would distort the measurement of real-world signal levels especially when typical automotive coaxial cables (which have characteristic impedances other than 50 ohms) are used.
The data from the receiver was extracted from the individual AM and FM automatic gain control (AGC) levels using an A/D converter. This AGC data was calibrated in units of dBm using a calibrated radio signal source. The automatic tuning of the radio was accomplished by a modification of the push button tuning system so that a data line from the computer control system could set the buttons. The radio could be set to measure one station or to switch between 3 FM and 3 AM stations.
The antenna gain data obtained using the system was calibrated by performing measurements using either a magnetically mounted monopole in the center of the roof of the vehicle under test (for AM and FM antennas) or a commercially available vertically oriented folded dipole designed for the FM frequency band (for FM antennas only). Each experiment was done in conjunction with measurements from one of these reference antennas. The gain of the antenna under-test is then given with respect to one of these references.

The mobile antenna gain pattern testing was done by driving the vehicle in a large diameter circle and measuring the signal level from a commercial FM or AM radio station as a function of aspect angle (test #2 in Figure 2.20). The orientation
angle of the vehicle can be measured (and stored with the data) using an encoder attached to the outside of the wheel of the vehicle. The use of the large diameter circle permits the vehicle to pass rapidly through multipath effects as the vehicle moves in the circle. During the signal analysis, the data are spatially filtered (running sector averaged) to remove the effects of the multipath. This multipath filtering is done for both the antenna under test and the reference antenna. Figure 2.22 shows sample antenna azimuth patterns obtained using the mobile measurement system.

The mobile system can also be used to measure the signal level received by the antenna as the vehicle is driven on the road in different propagation environments (urban, rural, etc.) (test #1 in Figure 2.20). Such a measurement also characterizes the susceptibility of the antenna to multipath interference. Figure 2.23 shows sample results, obtained using the mobile measurement system, of an antenna road test.

2.4 Antenna Concepts and Designs

In section 2.1 we discussed the design parameters of AM/FM antennas for automobiles. From that discussion we concluded the following about AM antennas:

- The AM antenna must be designed to be an electrically isolated structure fed against the vehicle body.

- The effective height of the AM antenna must be made large.

- To maximize the power transfer to the radio, the AM antenna cable must be made short and must have a high characteristic impedance.

- The AM antenna impedance will be highly capacitive, in general.
Figure 2.22: Sample antenna azimuth patterns from mobile measurement system. Result shows calibrated - raw (dash) and averaged (solid) - data from four commercial broadcast FM signals.
Figure 2.23: Sample results of antenna road test from mobile measurement system comparing the performance of two antennas. Result shows averaged data from two commercial broadcast FM signals. Figure taken from [36].
• The radiation pattern of the AM antenna will in general be omnidirectional, independent of the specific antenna used.

• The AM antenna must be vertically polarized.

The following conclusions were drawn about the FM automobile antenna:

• The vehicle is an integral part of the FM antenna (the vehicle is resonant at FM frequencies).

• Typically, the FM antennas should be designed to be smaller than a wavelength to obtain omnidirectional patterns in azimuth.

• The FM automobile antenna must have a directional gain pattern in elevation that receives signals at elevation angles lower than 50°.

• The impedance of the FM antenna must be around 50Ω.

• It seems most effective for the FM antenna to be vertically polarized (FM-US broadcast signal is circularly polarized).

• Antenna diversity may be needed to overcome the multipath problem.

In this section we will describe two on-glass AM/FM antennas: a windshield film antenna and a heater-grid backlight antenna. Impedance and gain pattern data, both numerical and experimental, will be presented. The FM polarization characteristics of the antennas will be discussed. Also, in this section we will discuss the FM multipath problem and present different FM diversity antennas that can be used to reduce the multipath effect on radio reception. Experimental results showing the effectiveness of these diversity antennas will be given.
2.4.1 The Windshield Film Antenna

The first AM/FM antenna design that we will present utilizes an infrared rejection metal film that is sputtered on the inner surface of one of the inner layers of the automobile front windshield. The metal film provides heat reduction by rejecting infrared light while passing visible light. The film is conducting at RF frequencies with a resistivity as low as 3 $\Omega/\square$. This type of film is already available on certain commercial vehicles. The AM/FM antenna is constructed by forming a gap at the circumference of the windshield between the film and the metallic automobile frame (window bezel) as shown in Figure 2.24. The gap, which separates the metallic film surface from the metallic vehicle body, forms an annular slot antenna. A coaxial feed is grounded to the body of the vehicle with the center conductor coupled to the film. We have found that the most effective design utilizes a capacitive feed to couple to the film. This feed is obtained using a metal patch on the inside surface of the windshield. The gap width, the feed point location, the capacitance of the feed and the impedance of the coaxial transmission line can all be varied to optimize the antenna. This metal film represents an opportunity to economically construct a conformal vehicle AM/FM antenna by using existing parts of the vehicle. Initial work on the film antenna is presented in [37, 36]. Further work is presented in [38, 39, 40, 41, 42].

Impedance Results

The FM band impedance is inductive if a direct connection to the film is made [41]. A capacitive feed thus can not only provide a simple and inexpensive way to feed the film, but impedance matching can be obtained by adjusting the size of the feed patch. This is demonstrated in Figure 2.25 for an on-vehicle test where the antenna
Figure 2.24: AM/FM annular slot film antenna on front windshield of automobile.

input impedance is shown as a function of the size of the capacitive patch. Note that the inductive component of the antenna is progressively canceled as the size of the patch is adjusted. In this example, the best patch size (normally 1 inch by 3.0 inch or larger) produces an antenna with an impedance mismatch loss of less than 0.75 dB (or SWR less than 2).

In the AM frequency band, on the other hand, the film slot antenna has high impedance and is capacitive. Such an impedance is desired since the standard automotive radio has an AM input that is specifically designed to be matched to such
Figure 2.25: FM impedance of the annular slot film antenna on front windshield of automobile.

high input impedance values. Our measurements of the transmission coefficient indicate that the best AM band feed is a direct connection. The mismatch loss induced by a capacitive feed, however, is less than 3 dB for feeds larger than 1 inch by 4 inches.

The metal film is not perfectly conducting. This means that it is important to determine the efficiency of the antenna (ie. how much of the signal is lost due to resistive loss). An integral equation and method of moment solution was developed for the film antenna [43]. The study concluded that the film can be represented by a sheet impedance, which is easily modeled using existing method of moment
codes [15]. The computations made in the study show that the loss in the film is less than 10\% (0.5 dB) for conductivity better than 25 \Omega/\square. The conductivity of the typical film used for infrared heat reduction is less than 4 \Omega/\square. This demonstrates that ohmic loss should not be a problem. If we neglect the small resistive loss in the film we can model the film using the method of moments simply as a perfectly conducting plate.

**Gain Pattern Results and Polarization Study**

The pattern of the film antenna was characterized theoretically using the method of moments (see section 2.2), and experimentally using full scale range measurements and mobile measurements (see section 2.3). The method of moments (ESP4) theoretical results and the range measurement results are compared to each other, for a particular configuration of the film antenna, in Figure 2.26. The model data are obtained by representing the film by an infinitely conducting plate. The experimental data is for a metallic foil placed on the outside of the vehicle windshield. Previous experiments have shown that the antenna performance of a film embedded in the glass and a metallic foil on the outside of the glass is almost identical. Both experimental and theoretical annular slot antennas used a 1 inch gap between the metallic film and the vehicle body, and used a direct-connect feed at the top center of the film. Both the theoretical and experimental gain patterns are normalized to a reference roof-top monopole antenna. Comparing the measured and model data shows that the ESP4 model is able to accurately predict the shape of the antenna pattern as well as the gain levels (to within 3 dB).
Figure 2.26: Comparison of the experimentally measured FM pattern (at 2° above the horizon; using outdoor range) with that from the moment method model calculation, of a metallic film annular slot windshield antenna (direct feed at top center; 1 inch gap). The azimuth patterns at both vertical and horizontal polarizations are shown. Result shown at 98 MHz.
Figure 2.27: Circularly polarized azimuth FM pattern of the annular slot windshield antenna calculated from the vertically and horizontally polarized moment method results. Pattern shown at 98 MHz and at 2° incidence angle above the horizon.

The gain pattern data in Figure 2.26 shows that the film antenna has almost as much gain in the horizontal polarization as it does in the vertical polarization. It also shows that nulls in the VP pattern occur at points where the HP pattern has a maximum and vice versa. This result seems to imply that the film antenna has a polarization that is neither vertical nor horizontal, but more likely a combination of both. Adding the VP and (90° phase shifted) HP patterns from the model data gives the circularly polarized pattern of the film antenna, as shown in Figure 2.27. Commercial FM radio stations transmit either 45° slanted linearly polarized (SP) or circularly polarized (CP) signals (i.e. they transmit equal energy in the HP and VP components; see section 2.1.2). Therefore, linearly polarized HP or VP antennas would ideally be equally efficient in receiving the FM signal. The VP signal is usually
the stronger and more stable signal; therefore, the design goal for FM automobile antennas is to be vertically polarized. The polarization of FM on-glass antennas, however, usually varies with azimuth angle. At certain angles the antenna may be linearly polarized and at other angles circularly polarized. In general, the antenna polarization will be elliptical. If the broadcast signal is CP, then the linearly polarized on-glass antenna would receive the signal efficiently. However, at azimuth angles where the polarization of the on-glass antenna approaches CP, and if the sense of the polarization is opposite of that being broadcast, then the antenna pattern will have a null. A similar situation arises if the broadcast signal is +45° linearly polarized and the on-glass antenna polarization approaches -45° linearly polarized. Figure 2.28 shows the ESP4 model data (from Figure 2.26) for the windshield antenna for a +45° (RSP) and -45° (LSP) slanted linearly polarized incident signal. The plots show that at some azimuth angles the gain pattern of the antenna will have nulls due to a polarization mismatch between the antenna and the incident signal, as discussed above. Therefore, the on-glass antenna should be designed to be mostly VP in order to eliminate the polarization mismatch nulls. However, due to the strong interaction between the on-glass antennas and the vehicle body, it is difficult to control the polarization of those antennas. In most cases the antenna will have strong VP and HP components and a polarization that varies with azimuth angle, as seen in Figures 2.26, 2.27, and 2.28. The effects of the vehicle body on the polarization of the FM on-glass antennas must be further studied. Ways to control the polarization of those antennas must be determined. Techniques of eliminating or minimizing the polarization mismatch nulls by modifying the polarization of the antenna must also be investigated.
In order to test the performance of the annular slot windshield antenna in the "real-world" environment, and to check for the existence of polarization nulls, we need to test the antenna using "real-world" signals. Therefore, the film antenna patterns were also obtained using a mobile measurement system that receives signals from commercial AM and FM radio stations. An example set of mobile measurement system patterns, for a specific test vehicle, is shown in Figure 2.29. Results for the standard fender whip and a particular configuration of the film-slot antenna are shown. In this example, the windshield film antenna is configured with the capacitive patch at the bottom inside of the windshield, on the passenger side. The coaxial cable originates below the dash board and the ground is attached to the frame of the vehicle at the bottom center of the windshield below the feed point.
Figure 2.29: Mobile measurement-system azimuth patterns of the original fender whip on a test-vehicle and an implementation of an annular slot film antenna. Result shows averaged data from two commercial broadcast FM signals.
This permits a very short coaxial cable, which is an advantage in the AM frequency band (high impedance) where the cable behaves as a capacitive shunt. The results in Figure 2.29 show that the film antenna patterns in the real-world environment are close to the predicted CP pattern shown in Figure 2.27. The results also show that the film antenna performs well compared to the standard fender whip.

2.4.2 The Backlite Heater-Grid Antenna

The second AM/FM antenna that we have studied extensively is the heater-grid antenna. The development of the heater-grid antenna is discussed in [44]. The heater grid consists of several thin conducting lines silk-screened on the inside of the back windshield (backlite) of an automobile, as shown in Figure 2.30. The heater grid
represents a large conducting area on the glass that can be isolated from the vehicle body (good AM antenna). The circumferential gap between the heater grid and the vehicle body is approximately one wavelength long at FM frequencies; therefore, the heater-grid can be considered an annular slot antenna. The gap size, however, may not be uniform around the circumference, making the analysis of the heater-grid antenna not as simple as that of the film antenna.

**Power Isolation of the Heater-Grid**

The conducting lines on the heater-grid carry up to 20 Amps of DC current that are used to heat the glass. For the heater-grid to be used effectively as an AM antenna, the RF currents must be isolated from the DC grounds in the circuit. Several techniques have been developed for RF power isolation. A discussion of the existing techniques and the development of a new concept are discussed in [44]. The new concept consists of a bifilar/trifilar RF transformer, using a ferrite torroid, that isolates the AM signals from ground. We have made further testing on the RF transformer and demonstrated that the transformer can not only be used to isolate the AM signal, but can also be used for impedance matching the antenna to the cable. In our tests, we showed that the received AM signal could be increased by 2–3dB when the turns ratio on the transformer were adjusted to produce optimal impedance matching. Note that FM isolation can be achieved using simple RF chokes or inductors.

**The Heater-Grid as an Antenna**

The distance between the horizontal lines on the heater-grid is electrically small (at AM/FM frequencies), such that the RF current flow in the horizontal direction
is the same as it would be on an equivalent conducting plate. In order to allow the RF current to flow vertically, as it would on a conducting plate, 1–3 additional vertical lines must be added to the heater grid. We have developed and tested heater-grid antennas (with 3 additional vertical lines) both theoretically (ESP4) and experimentally (range and mobile type measurements).

Our measurements have demonstrated that the heater-grid antenna (when properly isolated from DC ground) is more effective at AM frequencies than the standard whip monopole antenna. The reason that the heater-grid antenna is more effective is because it has a larger effective height than the whip antenna (see section 2.1).

At FM frequencies, we used an ESP4 method of moments model to calculate the pattern of a heater-grid antenna (with three additional vertical lines). The heater-grid was modeled as a conducting plate. A similar heater-grid antenna was also built and tested on a full scale vehicle in the range. The results of the model are compared to the measured results, for a particular configuration of the antenna, in Figure 2.31. The results show that the heater-grid produces a radiation pattern very similar to that of the annular slot film antenna, indicating that the heater grid antenna behaves as an annular slot.

Different variations of the heater-grid antenna have been tested in conjunction with the trifilar power isolation system. One of the configurations tested is shown in Figure 2.32. The antenna was impedance matched with the DC power isolation installed, as shown in Figure 2.33. The antenna was characterized using the mobile measurement system. Some of the azimuth pattern results are given in Figure 2.34. The average signal level received by the antenna at FM frequencies appears to be comparable to the standard fender whip; however, the pattern of the heater-grid
Figure 2.31: Comparison of the experimentally measured FM pattern (at 2° above the horizon; using outdoor range) with that from the moment method model calculation of the top offset-from-center feed AM/FM backlite heater-grid antenna. The azimuth patterns at both vertical (theta) and horizontal (phi) polarizations are shown. Results shown at 98 MHz.
antenna is more directional (note the polarization mismatch null in the pattern as predicted in Figure 2.27). Our studies have shown that the directionality of the pattern is mainly due to the (resonant) vehicle body and is not an inherent property of the heater-grid antenna. This observation is also true of the film antenna pattern. Therefore, a single on-glass FM antenna may not be able to provide a vertically polarized omnidirectional pattern, as desired. A diversity system may be needed to obtain an omnidirectional FM pattern.
2.4.3 FM Diversity Systems

An FM radio receiver using an antenna with omnidirectional pattern (low minimum-to-maximum gain ratio) and high average gain levels can still experience a fading signal if the power of the received signal drops to a low level (below the dynamic range of the receiver AGC). Such a drop in the received signal power will occur in a multipath environment. In a general multipath environment a vehicle antenna may receive the direct broadcast signal from the transmitter, as well as delayed signals that had reflected or diffraacted from obstacles before arriving at the vehicle antenna. All the RF signals having the same carrier frequency and arriving at the
Figure 2.34: Mobile measurement gain patterns. Heater-grid Backlite antenna on the Olds88. FM feed at top driver-side busbar, with an additional tuning stub. No power isolation was implemented. Result shows calibrated - raw (dash) and averaged (solid) - data from four commercial broadcast FM signals.
antenna at the same time get added together vectorially (signals can be represented by magnitude and phase components).

Of main interest to the radio-propagation problem is the delayed signals that add to the direct signal constructively (to give a maximum) or destructively (to give a minimum). Figure 2.35 shows how these particular delayed signals arise. A vehicle radio receiver at position #1 receives the direct signal from the transmitter and a delayed signal (or more than one signal) that reflects from any object located at the edge of an ellipsoid (first Fresnel ellipsoid). Any signal that reflects from the edge of the first Fresnel ellipsoid will propagate a half-wavelength ($\lambda/2$) longer than the direct signal. A $\lambda/2$ distance in free space corresponds to a phase shift of 180°. Therefore, assuming that the reflection from the obstacle at the edge of the ellipsoid
causes another 180° phase shift in the signal (as would a ground bounce near grazing incidence), the direct and delayed signals at position #1 will be in phase (360° total phase difference). If the magnitude of the signals arriving at position #1 are equal, then the magnitude of the vectorial sum of the two signals will be equal to twice that of each signal (a maximum). As the vehicle moves from position #1 towards position #2, the path difference between the direct and delayed signals received increases from λ/2. The increase in the path difference also corresponds to an increase in the phase difference between the two signals. The signals will no longer be in phase and will add to a value smaller than the maximum value of position #1. The two signals will add to a minimum value (zero if the signals have equal magnitudes) when the total phase difference between them is an odd multiple of 180°. The first minimum value occurs at position #2 where the one λ delayed-path signal (360° phase shift) reflects from the second Fresnel ellipsoid (adding another 180° phase shift). As the vehicle travels further, it will pass through higher order Fresnel ellipsoids and will receive a signal that periodically varies in amplitude (and power) from a maximum value to a minimum value.

In the above discussion we assumed that only the direct signal and one delayed signal arrive at the vehicle antenna. In the real-world environment it is more likely to have multiple delayed signals received at the antenna. In some situations the direct signal is not present and the delayed signals constitute the total received signal. In such complex environments it is difficult to predict the behavior of these multipath signals. However, multipath signals are always present in FM radio propagation, and the received signal power will always fluctuate between a minimum and a maximum value. Automobile radio receivers are designed with an automatic gain control (AGC)
that compensates (by amplification) for received signal fluctuations, resulting in a constant amplitude audio signal. However, if the received RF signal power level falls below the dynamic range of the radio receiver, then the audio frequency signal will fade out.

In our experimental measurements we have determined that in a normal urban driving environment the RF signal at the automobile antenna can vary by as much as 35dB between minimum and maximum. In more complex environments the fluctuations can be more severe. In such cases the RF signal level is likely to drop below the dynamic range of the radio AGC, resulting in a fading signal. These fading signals will be audible to the vehicle driver, especially if the automobile is traveling at a low speed. If an automobile is traveling at a high speed, the fading of the signal may occur too quickly and may not be audible.

From the above discussion it is clear that a single antenna can suffer from multipath fading, even if the antenna pattern has high gain levels and no nulls (omnidirectional). If the antenna has nulls in its pattern, then it is more likely to suffer from multipath fading than the omnidirectional antenna. However, a radio receiver with just a single antenna cannot eliminate the effects of multipath fading. Traditionally, multiple antennas have been used in a diversity system in order to overcome effects of multipath signals. The multiple antennas must be uncorrelated (spatially separated or orthogonally polarized) such that when multipath fading occurs at one antenna it will not occur at the other antenna. Special diversity radio receivers are required for multiple antenna systems. Most current automobile radio diversity receivers use one of two techniques: the selection method and the scanning method. Below is a list of features for the two techniques.
• **Selection Method**
  
  - radio monitors all antennas (using separate receiver channels).
  
  - radio selects antenna with strongest signal at all times.

• **Scanning Method**
  
  - radio selects primary antenna as default.
  
  - radio blindly switches to secondary antenna when primary signal is distorted (according to some set criteria).
  
  - radio maintains selection until current signal is distorted.

The scanning method is the most popular since it requires only one receiver channel. The electronic switching between antennas can be accomplished very rapidly (a few milli-seconds), so that several switches could be made without any audible distortion.

It is desirable that each of the antennas in a diversity system be omnidirectional (free of nulls). The gain level of the antennas does not have to be equal. Usually, one of the antennas is chosen as a primary antenna and is designed to have a gain level that is higher than that of the other antennas (this will minimize the amount of switching between the antennas). If the antennas used have nulls or directionality in their pattern, then the diversity schemes may not be able to eliminate all the multipath fading nulls that are encountered.

On-vehicle antennas, including the fender-whip, tend to have some directionality in the gain pattern. The combined pattern of the multiple antennas used in a diversity system could be designed to be less directional than that of either of the
individual antennas. Such a combined pattern would approach that of an omnidirectional antenna and would improve the performance of the overall antenna system over that of a single directional antenna, even when the incident signal is not experiencing multipath fading. This is one technique of improving the inherent directionality of the on-glass antennas discussed in the previous sections.

We have developed three different types of on-glass diversity antenna systems. We will describe each system in detail in the following sections.

**Single Antenna Diversity**

The first type of diversity system that we developed is the single heater-grid backlite antenna (or single windshield film antenna) with multiple feed points. This type of system is very cost effective in that only one structure (the heater-grid or the windshield film) is needed. We experimentally and theoretically investigated this type of a system.

Both the heater-grid and the windshield film antennas are a type of an annular slot antenna. The pattern of the antennas varies with feed location. When feeding at a particular location, nodes with current minima may exist around the circumference of the annular slot. If such a node exits, then a second feed may be placed at the location of that node without disturbing the current distribution of the original feed. The two feeds will then be decoupled and the antennas may be independent with different (and perhaps complementary or orthogonally polarized) patterns. Since the FM antennas are receive antennas, the current distribution on the antenna will be different as the direction of the incident RF signal varies. Therefore, it may not be possible to find fixed locations of voltage nodes for all azimuth angles. However, the
voltage node locations (as a function of azimuth angle) may be close to each other, so that the two feeds on the annular slot will be sufficiently decoupled for all azimuth angles.

The heater-grid antenna shown at the top of Figure 2.36 has the first feed at the bottom right and the second feed at the top left corner of the heater-grid. The locations were chosen since they were experimentally determined to be more decoupled than other feed locations. We measured the gain patterns of the diversity antenna using the mobile measurement system. Two different measurements were performed. In the first one, the feed HG1 was connected to the radio receiver while the coaxial cable connected to feed location HG2 was terminated with a 50Ω load. Terminating HG2 while measuring HG1 is necessary since in a diversity system both feed cables would be connected to the radio receiver (which has approximately a 50Ω impedance) at all times. In the second measurement, HG2 was connected to the radio while the HG1 feed cable was terminated. If the two antennas (or feed locations in this case) are completely decoupled from each other, then the gain pattern of HG1 would not be affected by making a connection at HG2. However, in our measurements we determined that the average gain level of HG1 dropped by 2 to 4 dB when a 50Ω terminated cable was connected to HG2. Similarly, the average gain level of HG2 dropped by 5 to 8 dB when a 50Ω terminated cable was connected to HG1. These measurements indicate that the two feed locations are not completely decoupled and that some of the signal on one antenna is lost through coupling to the other antenna, which is not being used by the diversity receiver. The pattern plots of Figure 2.36 show the gain patterns of HG1 with HG2 terminated, and the gain patterns of HG2
Figure 2.36: Mobile measurement gain patterns showing diversity output of the two single heater-grid backlite antennas on the Olds88: HG1 and HG2. Result shows calibrated averaged data for each antenna from four commercial broadcast FM signals. The diversity output consists of the maximum of the two signals at any angle.
with HG1 terminated. Also, the maximum gain level from each pattern, for every frequency and at every angle, is calculated as a combined diversity pattern and is overlayed on each plot. All the data shown are the spatially filtered (averaged) data. The minimum, maximum, and average gain levels are indicated for each of the patterns at the top of each plot. The plot shows that combining the two antennas improves the overall gain level by 1 to 2 dB, and the minimum-to-maximum gain ratio by approximately 1 to 3 dB. However, due to the coupling of the antennas the combined gain pattern levels are still lower than those of either one of the antennas used separately, in a non-diversity scheme.

The main reason to use a diversity system is to reduce the effect of multipath fading. Reduction of multipath fading is achieved by using two decoupled antennas such that when one of them experiences a multipath null the other one does not. We have not tested the capability of the above antenna system for reduction of multipath fading. However, due to the strong coupling between the two feed locations we believe that this system may not be efficient at reducing signal fading due to multipath. Further studies must be made to investigate the existence of voltage nulls on the heater-grid or the windshield film antennas and the possibility of designing a single structure to obtain two decoupled antennas for an efficient diversity system.

**Multiple Backlite Diversity**

The second type of diversity system consists of multiple FM antennas on the automobile backlite. Since the antennas are all located on the backlite, decoupling of the antennas cannot be achieved by spatial separation but must be obtained by using antennas that are orthogonally polarized. The polarization of the automobile
on-glass FM antennas is usually not well defined and it varies with frequency and angle. Therefore, developing two orthogonally polarized antennas for the backlite may not be possible. However, the antennas could be designed to have sufficiently different polarization characteristics so that the coupling between them is low.

We developed several AM/FM heater-grid antennas and FM backlite antennas that were used as FM diversity antennas [45]. The gain patterns of the antennas were measured using the same procedure discussed in the previous section.

Any antenna structure on the backlite will couple to the heater-grid due to the proximity of the two structures (within $1/10$ of a wavelength), unless they are completely orthogonally polarized. However, the two antennas can still be used effectively as a diversity pair if the RF current induced by the secondary antenna element on the heater-grid structure is sufficiently uncorrelated from the RF current induced by the actual heater-grid antenna feed. We developed a secondary FM antenna structure that appears to meet the above requirement, when used in conjunction with the heater-grid antenna. The antenna is shown at the top of Figure 2.37. The secondary FM antenna is referred to as RLP1 (the heater-grid antenna is referred to as HG8). The impedance of the antenna was matched to 50Ω using a simple matching network. The gain pattern plots for the diversity antennas are also shown in Figure 2.37. The measurement showed that the levels for the HG8 antenna dropped by less than 3dB due to coupling to the RLP1 antenna. The coupling loss of the RLP1 gain levels due to the HG8 antenna were also less than 3dB. Therefore, the antennas do not appear to strongly couple to each other. The combined diversity patterns given in Figure 2.37 also show that the resulting antenna system has a high gain level and a minimum-to-maximum gain ratio of less the 11.5dB.
Figure 2.37: Mobile measurement gain patterns showing diversity output of the two heater-grid backlite antennas on the Olds88: HG8 and RLP1. Result shows calibrated averaged data for each antenna from four commercial broadcast FM signals. The diversity output consists of the maximum of the two signals at any angle.
In order for the antennas to be effective as diversity antennas they must be effective at reducing signal fading due to multipath. We measured the performance of the antenna pair in a multipath environment using the mobile measurement system. The measurement procedure is identical to the one used to obtain pattern measurements, except that the automobile is driven in a straight line instead of a circle. The location of the measurement was chosen deliberately to be an area of sufficiently high multipath. The parking lot of the ElectroScience Laboratory was used. The measurement setup is shown at the top of Figure 2.38. The plot at the bottom of the figure shows the received raw signal, at one FM frequency, for each of the antennas as well as the combined diversity signal (maximum of the signals at each location). The result shows that the two antennas experience multipath fading at different locations and can be used effectively to reduce multipath fading. The measurement was repeated at other FM frequencies and similar results were obtained. Therefore, although the two backlite antennas couple into each other, they could still be designed to provide an antenna system with high gain-level and low minimum-to-maximum ratio that can reduce signal fading due to multipath.

**Windshield-Backlite Diversity**

One approach to reduce the coupling between two automobile on-glass antennas is to spatially separate them by at least 0.5 wavelengths (approximately 1.5 meters). An antenna on the backlite and another one on the windshield would be separated by that distance. Therefore, it is possible to use a backlite antenna and a windshield antenna as a diversity pair, even if the two antennas have the same polarization.
Figure 2.38: Mobile measurement multipath performance plots of two diversity antennas: the heater-grid OCP backlite antenna (HG8) and the roof-line-loop backlite antenna (RLP1), on the Olds88. Result shows calibrated raw data for each antenna from one commercial broadcast FM signal. The diversity output consists of the maximum of the two signals at any location.
Our first attempts at developing windshield antennas (other than the film antenna) were not successful. The windshield antennas were developed theoretically to have fairly omnidirectional patterns (see [46]). Our experiments, however, determined that the impedance efficiency of the antennas was low. The antennas are inherently narrowband in frequency because of the limited amount of space they occupy on the glass (to minimize visual obstruction the antennas are placed only in the fade-band area). Therefore, matching the impedance of the antennas across the FM band is not simple.

We developed one windshield antenna design whose impedance was matched efficiently across the FM band. Measurements showed that the antenna is fairly omnidirectional and has a gain level that is 5 to 11 dB lower than the roof-top mag-mount. Although this antenna would not be effective as a single FM antenna, it could be used effectively as part of a diversity antenna pair.

We tested the performance of the backlite/windshield diversity antennas. Due to the spatial separation of the antennas, there is essentially no coupling between them. Figure 2.39 shows the gain pattern of the windshield antenna WS4 and a heater-grid antenna HG3 when they are used in a diversity system. The result shows that the gain pattern of either antenna is not affected by the presence of the other antenna. The result also shows that the windshield antenna pattern has very little contribution to the combined diversity pattern. Therefore, the heater-grid antenna would be the primary antenna and the windshield antenna would be used mainly to overcome multipath fading. Therefore, the heater-grid antenna should be designed, as a single antenna, to meet any required standards for FM reception (gain levels and minimum-to-maximum ratios).
Figure 2.39: Mobile measurement gain patterns showing diversity output of one heater-grid backlite antenna and one windshield fade-band antenna on the Olds88: HG3 and WS4. Result shows calibrated averaged data for each antenna from four commercial broadcast FM signals. The diversity output consists of the maximum of the two signals at any angle.
We measured the performance of the backlite/windshield antenna pair in a multi-path environment. Figure 2.40 shows the measurement result for the HG3 and WS4 diversity pair. The result shows that the diversity system can effectively limit the multipath nulls to 10dB.

In this section we have discussed the use of multiple FM antennas in a diversity system. The diversity antennas were used to reduce the effect of multipath fading of signals and also to reduce the directionality of the on-glass antenna patterns. We discussed three different types of on-glass antenna diversity systems: the single antenna structure with multiple feed points, the multiple backlite antennas, and the backlite/windshield antenna system. The measurements showed that these antennas can be used successfully in an FM diversity system. The backlite/windshield diversity provides the most de-correlation between the antennas and appears to be the most effective. However, printing an antenna on the windshield may add significantly to the cost of the system. Therefore, using multiple backlite antenna diversity reduces the overall cost and can be designed to provide an effective system.

In this chapter we described the development of on-glass AM/FM antennas. We discussed the design parameters of the antennas and also discussed the numerical modeling techniques that were used to model these on-glass antennas. Full-scale range type measurement systems and mobile systems used in testing these antennas were also presented. Finally, we presented several AM/FM antenna design concepts that were developed using these numerical and experimental techniques. We showed how a windshield film antenna and a backlite heater-grid can be designed to be effective AM/FM antennas. We also discussed FM diversity systems and antennas and their use in reducing the effect of multipath signals on the FM radio performance.
Figure 2.40: Mobile measurement multipath performance plots of two diversity antennas: the heater-grid OCP backlight antenna (HG3) and the windshield inverted-T antenna (WS4), on the Olds88. Result shows calibrated raw data for each antenna from one commercial broadcast FM signal. The diversity output consists of the maximum of the two signals at any location.
CHAPTER 3

CELLULAR TELEPHONE ANTENNA SYSTEMS

In this chapter we describe the development of on-glass cellular antennas. In section 3.1 we discuss the design parameters of the cellular antenna. In section 3.2 we describe the numerical modeling techniques that were used. A mobile measurement system that can be used to characterize the on-road performance of the cellular antennas is presented in section 3.3. Finally, in section 3.4 we present on-glass cellular antenna design concepts and discuss their limitations. We also discuss the effect of the antenna-vehicle interactions on the performance of the on-glass antennas.

3.1 Design Parameters

This section presents a brief overview of the design requirements of an acceptable cellular automobile antenna. These design requirements can also be applied to other antenna systems that have the same characteristics as the cellular antenna: a resonant antenna, in the presence of a large metallic structure, receiving (or transmitting) a signal from a terrestrial base station.

- **Frequency.** The commercial cellular band in the United States covers the frequencies from 824.04 to 893.97 MHz, a bandwidth ratio of approximately 8%.
The Federal Communications Commission (FCC) has partitioned the frequency band into several regions for signal transmission with the remaining frequencies for signal reception. The cellular telephone companies occupy nearly the whole allocated bandwidth. Therefore, any new cellular antenna should be capable of operating throughout the entire frequency band. A typical automobile is on the order of 10 wavelengths in size in the cellular frequency band. Therefore, the cellular antenna is mainly influenced by its surrounding geometry and not necessarily by the whole vehicle body. At the cellular frequencies the sheet impedance of the glass is finite. Therefore, the loading effect of the glass for on-glass cellular antennas must be considered.

- **Impedance.** The input impedance of commercial cellular telephones are carefully optimized to 50 $\Omega$. Mobile cellular telephones typically transmit up to 5 Watts, whereas hand-held units are designed with only about 0.6 Watts of output power. With cellular transmitter towers often located several kilometers apart, the transmission efficiency of the telephone antennas becomes an important issue for maintaining cellular service. To ensure the highest level of signal transmission, cellular telephone antennas must be optimized to a 50 $\Omega$ input impedance. The impedance design criterion is especially important since the cellular unit is operating in both a transmitting and receiving mode. Operating a transceiver with an impedance-mismatched antenna (standing wave ratio or SWR>2.0) may cause potential damage to the unit.

- **Pattern.** Cellular antennas should be designed to have an omnidirectional gain pattern in azimuth. The cellular pattern should be concentrated at an
elevation angle near grazing incidence with respect to the horizon. The cellular towers are short and the coverage area is small; therefore, most of the signal is usually concentrated at elevation angles below 15°.

- **Polarization.** Cellular towers transmit vertically polarized signals. Therefore, the optimal automobile cellular antenna is vertically polarized. As a result, commercially installed monopole cellular antennas are typically installed with a vertical orientation. However, the cellular system has been designed with a large dynamic range and can adequately operate with an antenna which deviates from vertical polarization. In fact, many vehicle owner's tend to adjust their cellular antenna to conform to the aerodynamic shape of the automobile, with a small deterioration in antenna performance.

The most popular cellular antenna is the omnidirectional $3\lambda/4$ collinear array monopole (in-phase $\lambda/2$ and $\lambda/4$ elements with a 180° phase-shifting coil) that is typically attached to a glass fixture on the automobile (a pigtail antenna). To overcome the effect of multipath on the cellular telephone signal, multiple antenna diversity is being used. The use of diversity systems is still limited. However, conformal or invisible antennas will be needed if multiple antennas are to be used on an automobile.

The most popular cellular transceivers currently are the hand-held units with their own internal antennas. The use of the hand-held unit inside the vehicle compartment may not be very effective. Devices exist that allow the hand-held unit to be connected to an external vehicle antenna when the user is inside the vehicle. Another advantage of these devices is that they allow the hand-held unit to transmit 3 Watts of power instead of the 0.6 Watts it normally outputs. Therefore, even with
the increased popularity of the hand-held units, it seems that there is still a great need for external vehicle cellular antennas.

### 3.2 Numerical Modeling Techniques

In section 1.3.1 we presented an overview of the numerical techniques used for modeling automobile antennas. We also discussed the computer codes that we used to develop our models. In section 2.2 we described the numerical modeling of automobile antennas in the low frequency bands (AM antennas) and the resonant regions (FM antennas). In this section we will present the results of modeling the vehicle at high frequency bands at which the vehicle body is electrically large. We will show results of analysis of cellular telephone band (824-894 MHz in US) antennas.

The cellular antenna is used for receiving and transmitting. The received signal is a vertically polarized signal coming in at an elevation angle only a few degrees above the horizon. The size of the vehicle in the cellular band is on the order of 10λ. MoM can still be used effectively for this problem, but the CPU time and computer memory required become large. UTD can also be used at these frequencies but modeling the details of the antenna geometries may be difficult.

First, we will describe the ESP4 model in detail. We will show how it was developed and the results it produced. We will compare these results to experimental measurements. In the last section we will describe the NEC-BSC (UTD) model that was developed and tested on the cellular antennas.
3.2.1 Plate Model Study

The plate model of the ESP4 was used to construct the vehicle geometry. The antennas were constructed either from wires or plates and were fed using one of the techniques described in section 2.2.2 (Figure 2.7). The first technique was for the wire antenna that is connected to the plates using the offset wire-plate junction. The second technique used plates for the antenna elements, which were attached to the vehicle body using the plate-plate connection. Both techniques work for the cellular model. All the results given in the next sections are for a model using the first technique, the wire-plate connection. We used this technique since we were more familiar with it at the time when the model was being tested. This technique requires the wire-plate connection to occur a distance larger than 0.1λ (only about 3cm @ cellular) from the edge of the plate. All the pattern results given for the ESP4 model were normalized to a roof top monopole. Figure 3.1 shows the geometry of this reference antenna on the model vehicle. The feed connections used in the model do not provide accurate impedance calculations. Therefore, no impedance results will be presented from this study. Note that the cellular antenna has to have a low SWR since it is a transmit antenna. However, the impedance of the antenna can usually be modified without affecting the radiation pattern of the antenna.

The Effect of the Geometry

To minimize the number of modes (and thus the CPU run-time and computer memory storage) used to calculate the current on the vehicle we must reduce the number of plates. To study the effect of the model geometry, we used a monopole antenna connected to the back edge of the roof as shown in Figure 3.2. This antenna
Figure 3.1: Geometry of an ESP4 model of a cellular roof top monopole. The scale of the model and the number of current modes used are indicated.
Figure 3.2: Geometry of an ESP4 model of a cellular pigtail antenna. The scale of the model and the number of current modes used are indicated.
behaves similarly to a window mounted pigtail antenna. The total number of modes required to model the current for the geometry of Figure 3.2 was 1630. The pattern results for different model geometries are given in Figure 3.3. The full vehicle geometry does not model the inside of the vehicle and has very narrow front, back, and side panels (as shown in Figure 3.2). A more detailed model geometry is not needed since the vehicle in the cellular band is not resonant. The antenna pattern is composed of all the rays (direct, reflected, diffracted) that are emitted from the antenna element. The pattern, at a particular angle, is affected by the plates that obstruct (block, reflect, diffract) the path of the antenna rays. Since the pigtail antenna extends above the roof line, it is not affected by the side plates on the vehicle. From the results of Figure 3.3 it also appears that the plates in the front of the vehicle have little effect on the antenna pattern, especially towards the backside. But even towards the front side of the vehicle the change in the pattern due to the extra plates is minimal. This was not the case in the FM band where the vehicle itself is resonant. We saw that modifying the front end of the vehicle model geometry had a large effect on the pattern of backlite FM antennas, even at angles towards the back of the vehicle.

The Effect of the Glass

The pigtail antenna extends above the roof line. We saw that it is not affected by the plates in the front of the vehicle. We also expect it not to be affected by the glass on the vehicle. However, for a glass-mounted antenna, it may be necessary to model the glass. In the cellular band, the sheet impedance for glass (≈ 0.01λ thick) is approximately equal to \(-j600 \, \Omega/\square\). The value of the impedance is low enough to have a loading effect on the on-glass antennas. To study this effect, we modeled a
Figure 3.3: ESP4 model of a cellular pigtail antenna. Effect of varying the geometry. Azimuth pattern at 0.5° elevation angle above the horizon for both Vertical and Horizontal Polarizations; freq=860MHz. LS stands for LineStyle of curve.
fade band loop antenna that is fed against the roof as shown in Figure 3.4. The
effect of the glass was tested by calculating the pattern of the antenna without a
glass sheet, with a glass sheet that does not extend over the whole backlite, and
with a full size backlite glass sheet. The results are given in Figure 3.5. The plots
show that the effect of the glass on the antenna is significant. The glass causes a
shift in the resonance frequency of the antenna. If the amount of this shift can be
calculated, then the glass plate (which requires an additional 215 current modes)
can be eliminated from the model (saving computer storage and CPU time) and the
antenna can be replaced by its larger free-space counterpart. For an antenna on a
dielectric half space, the wavelength in the presence of the dielectric is usually given
by

\[ \lambda_d = \frac{\lambda_0}{\sqrt{\frac{1}{2} + \epsilon_r}} \]  

where, \( \lambda_0 \) is the free-space wavelength and \( \epsilon_r \) is the permittivity of the dielectric. (For
a glass half-space, with \( \epsilon_r = 6 \), the above equation gives \( \lambda_d = 0.53\lambda_0 \).) Since the glass
plate is of finite thickness (\( \approx 5\) mm) the value of \( \lambda_d \) for an on-glass antenna is expected
to be in the range of \( 1\lambda_0 \) (when the dielectric has no effect) to \( 0.53\lambda_0 \) (for a half
space). In our measurements we observed that the shift in the resonance frequency
of a rectangular loop antenna due to the glass plate (at frequencies close to 1 GHz)
was approximately 16% (ie. \( \lambda_d \approx 0.84\lambda_0 \)). For a patch antenna with a dielectric
substrate of \( \epsilon_r = 10 \) (at frequencies close to 1.5 GHz), the shift in the resonance
frequency was much less than that of the loop antenna (only 1.5%), probably since
the patch antenna electric fields are highly concentrated in the dielectric substrate of
the antenna and not in free space. For both antennas, however, a shift in the value
Figure 3.4: Geometry of an ESP4 model of a backlite cellular loop antenna. The scale of the model and the number of current modes used are indicated.
Figure 3.5: ESP4 model of a backlight cellular loop antenna. Effect of the dielectric glass sheet. Azimuth pattern at 0.5° elevation angle above the horizon for both Vertical and Horizontal Polarizations; freq=860MHz. LS stands for LineStyle of curve.
Figure 3.6: Measured input impedance of a rectangular loop antenna with and without a glass cover ($\epsilon_r=6$, thickness=5mm). The frequency in MHz is indicated at five points along the curves.

of the input impedance accompanied the shift in the resonance frequency. Such an impedance shift may be due to the change in the current distribution at the feed point of the antenna due to the presence of the glass cover. Figure 3.6 shows the shift in the resonance frequency and input impedance of a loop antenna with and without a glass cover.

This technique of eliminating the glass sheet by using a larger free-space antenna must be studied further, and may be the subject of future research. Note that no glass sheets were used on any windows other than the one where the antenna is located. The signal propagating through the glass will not be greatly affected.

Another difference between the loop antenna and the pigtail antenna is that the loop antenna is below the roofline. Therefore, the signal going towards the front of
the vehicle has to pass through the passenger compartment and may be affected by
the front end of the vehicle. Figure 3.7 shows a study on the effect of the vehicle
geometry on the loop antenna. The result shows that the geometry at the front end
of the vehicle has little effect on the pattern in the back, but has a significant effect
on the pattern in the front. If it is required to get accurate pattern data at all angles,
then it may be necessary to model the full vehicle. If only approximate pattern data
is needed, then a partial vehicle geometry may be sufficient.

**Computer CPU Times for Different Models**

The CPU time and the computer memory storage are the two limiting factors in
the cellular antenna model. The memory storage is a limited resource and once it is
exceeded, for a particular computer platform, the MoM code can not be run. The
memory storage increases with the size of the model. Although the CPU time is an
unlimited resource, there are limits beyond which the problem becomes impractical.
Figure 3.8 shows the CPU times of several of the models that were tested. The plot
shows how the CPU time increases significantly with the increase in the size of the
model. The times shown are for the Cray Y-MP8/864 Ohio supercomputer.

3.2.2 Experimental Verification

In this section we will show the comparison of the pigtail and loop antenna model
results with measurement results. The measurements were done at The Ohio State
University ElectroScience laboratory on a 1983 Chevrolet Cavalier test vehicle. The
ESP4 vehicle model has the same dimensions as the test vehicle. Note that the
experimental measurements were done in an outdoor range (not a well controlled
Figure 3.7: ESP4 model of a backlite cellular loop antenna. Effect of varying the geometry. Azimuth pattern at 0.5° elevation angle above the horizon for both Vertical and Horizontal Polarizations; freq=860MHz. LS stands for LineStyle of curve.
Figure 3.8: CPU times on the Cray Y-MP8/864 Ohio supercomputer for different ESP4 cellular antenna models.
environment) and so the results can not be expected to compare very well to the model results. Details of the measurement procedure are given in section 2.3.1.

Pigtail Antenna

An exact model of the ESP4 pigtail antenna was built and tested. Figure 3.9 shows the azimuth pattern (at 0.5° elevation angle above the horizon) at 860 MHz. The pattern is given for both the Theta (approximately vertical - VP to within a \( \cos(0.5°) \approx 1 \) factor) and Phi (horizontal - HP) polarizations. Both the measured and calculated data have been normalized to the roof top monopole data. The results show that the model pattern has the same features as the measured pattern but a higher signal level. This difference in the signal levels could be due to a mismatch loss or cable loss in the measured antenna or to inaccuracy in modeling the vehicle or the reference antenna. Some difference may also be due to a ground bounce term. The effect of the ground bounce term was not taken into account in this calculation. A brief study of the ground bounce (see section 2.2.2) showed that its main effect was to lower the HP signal level. The measured pigtail antenna had a low mismatch loss; therefore, that mismatch loss could not account for the differences in the signal level. The coaxial cables connecting the pigtail antenna and the reference monopole during the measurements had different loss factors, which could account for some of the differences in the signal levels (less than 2dB). (The model results assume no loss due to cable or impedance mismatch.) The measured reference antenna was a commercial roof top magnetic mount monopole with an in-line air-core inductance coil (used to increase the gain of the antenna at low elevation angles). The coil was modeled into the ESP4 reference antenna as a lumped inductance. This model of
Figure 3.9: A cellular pigtail antenna. Comparing ESP4 model results and measured results. Azimuth pattern at 0.5° elevation angle above the horizon for both Vertical and Horizontal Polarizations; freq=860MHz. LS stands for LineStyle of curve.
the reference antenna could be inaccurate and could be causing the large part of the
difference in the signal level. The inaccuracy in the reference antenna model would
not affect the shape of the pattern since the antenna is omnidirectional. Therefore,
to compare the shape of the model and measured patterns we shifted the signal
level of the model results in order to get equal signal level averages between the two
results. Figure 3.10 shows the pattern of the signal-level-shifted data. The result
shows that the model is generating a pattern that closely resembles the measured
one. We have previously shown that the pigtail antenna pattern is mainly influenced
by the plates in the back of the vehicle model. Therefore, we can be confident that
we have modeled the backside of the vehicle accurately. To determine how well we
have modeled the front and inside of the vehicle we must use the loop antenna.

Loop Antenna

We know from previous analysis that the loop antenna pattern towards the front
of the vehicle depends on the geometry of the vehicle in the front. Figure 3.11 shows
the pattern results of the measured loop antenna and the model antenna on a full
vehicle with a glass backlite. The difference in the signal levels between the two
patterns is probably due to the inaccuracy of the reference antenna model. Again
we shifted the signal level of the model result in order to get equal averages between
the model and measured data. Figure 3.12 shows the signal-level-shifted patterns.
The results shows that the model pattern closely resembles the measured pattern
for angles in the back of the vehicle. This result reconfirms what we learned from
the pigtail antenna test. There are small discrepancies between the two patterns
for angles towards the front of the vehicle. These discrepancies could be due to
Figure 3.10: A cellular pigtail antenna. Comparing measured and ESP4 model (signal-level-shifted) results. Azimuth pattern at 0.5° elevation angle above the horizon for both Vertical and Horizontal Polarizations; freq=860MHz. LS stands for LineStyle of curve.
Figure 3.11: A backlite cellular loop antenna. Comparing ESP4 model results and measured results. Azimuth pattern at 0.5° elevation angle above the horizon for both Vertical and Horizontal Polarizations; freq=860MHz. LS stands for LineStyle of curve.
Figure 3.12: A backlite cellular loop antenna. Comparing measured and ESP4 model (signal-level-shifted) results. Azimuth pattern at 0.5° elevation angle above the horizon for both Vertical and Horizontal Polarizations; freq=860MHz. LS stands for LineStyle of curve.
measurement errors or to inaccurate modeling of the vehicle geometry. The geometry we are using does not model the passenger compartment of the vehicle, which may have some effect on the antenna pattern. Further tests need to be made to establish the source of this discrepancy. Overall, however, the model results do compare well with the measurements, indicating that the ESP4 model is reasonably accurate. Including more detail in the model may improve the results, but at an expense of increase in memory storage and CPU time.

3.2.3 UTD: A Second Approach

The cellular antenna can be modeled using MoM or UTD. The UTD solution presents some advantages to the analysis. The UTD patterns are formed from the rays that the antenna produces. The rays interact with the vehicle (blocked, reflected, diffracted) before they arrive at the source. These interactions can be individually turned on or off in the UTD analysis; this helps in determining a good position for the antenna on the vehicle. Another advantage that we exploit is that the NEC-BSC code allows the vehicle to be located over an infinite ground plane. This allows the analysis to easily include the ground bounce term. Finally, since UTD is a high frequency technique, it can analyze large geometries that MoM can not efficiently analyze.

As noted earlier in the chapter, the UTD code needs to know the antenna excitation currents before the analysis can be made. This current can be found by modeling the antenna and its surrounding geometry in MoM. Only the geometry within a few wavelengths of the antenna needs to be modeled. The magnitude and phase of the
MoM current is then entered into the UTD analysis and the antenna on the full geometry can then be analyzed. This makes analysis of antennas on electrically large objects possible. In our case, we already have the antenna excitation currents from the MoM analysis that we had performed earlier. For the UTD analysis, we used the exact vehicle geometry as in the MoM case.

The first test we did was to check the effect that second order reflection and diffraction terms (rays that reflect/diffract twice before arriving at the receiver) have on the antenna pattern. Figure 3.13 shows the patterns for the same pigtail antenna used in the MoM analysis. The plot compares the pattern that includes the second order terms with the pattern that does not include them. The results seem to indicate that the second order terms have little effect on the pattern. Not including the second order terms reduces the CPU run-time by 65%. Even with the second order terms included, the CPU time required to run the UTD analysis was about half that required by MoM.

The second test we did was to check the effect of the ground bounce. Figure 3.14 compares the antenna patterns of the vehicle on an infinite ground plane with those of the vehicle with no ground plane. The result shows that the effect of the ground plane is mainly to decrease the signal level of the HP signal. This result confirms what we had found using the MoM analysis. Note that the inclusion of the ground plane does not greatly increase the CPU time required.

Finally, we compared the results of the UTD analysis of the pigtail antenna to the measured results. Figure 3.15 shows the pattern data for the two results. The model data has been normalized to a roof top monopole. The current for the monopole was obtained from the MoM analysis of the roof top monopole. Any inaccuracies in the
Figure 3.13: NEC-BSC model of a cellular pigtail antenna. Effect of 2\textsuperscript{nd} order reflection/diffraction terms. Azimuth pattern at 0.5° elevation angle above the horizon for both Vertical and Horizontal Polarizations; freq=860MHz. CPU time on a SGI workstation. LS stands for LineStyle of curve.
Figure 3.14: NEC-BSC model of a cellular pigtai antenna. Effect of a ground plane. Using full term analysis. Azimuth pattern at 0.5° elevation angle above the horizon for both Vertical and Horizontal Polarizations; freq=860MHz. CPU time on a SGI workstation. LS stands for LineStyle of curve.
Figure 3.15: A cellular pigtail antenna. NEC-BSC model results and measurement results. Azimuth pattern at 0.5° elevation angle above the horizon for both Vertical and Horizontal Polarizations; freq=860MHz. LS stands for LineStyle of curve.
MoM model of that antenna would be reflected in the UTD analysis. The difference in the signal level between the measurement and UTD model data could be due to the inaccuracy of the reference antenna model (as discussed in section 3.2.2). The shape of the pattern of the model antenna, however, seems to compare well to the measured pattern. This indicates that the UTD model is accurately predicting the behavior of the pigtail antenna.

An attempt was made to model the loop antenna in UTD. The antenna currents were obtained from the MoM results. Modeling the antenna in UTD, however, could only be made by ignoring some of the details of the antenna. The results obtained for the UTD loop model did not compare well to the measurements. In order to improve the model results for the loop antenna the details in the antenna geometry must be incorporated in the analysis. Another way of improving the model results is to synthesize the antenna pattern in the UTD analysis rather than the current. Such an approach would avoid modeling the detailed antenna geometry. We have not used this approach yet to model the on-glass antennas.

For the cellular vehicle antennas, MoM appears to be the better modeling tool. As the frequency is increased further, the MoM problem may become too impractical and UTD may need to be used. At those high frequencies, however, the analysis tools that UTD offers do become more valuable and using UTD becomes an advantage.

3.3 Experimental Techniques

Cellular antennas can be fully characterized in a range type measurement, such as the one described in section 2.3.1. We have used these range type measurements in the development of on-glass automobile cellular antennas, in order to study their
impedance, pattern, and polarization characteristics. However, the performance of a vehicular cellular antenna in the "real-world" must be characterized using a mobile measurement system similar to the AM/FM system (described in section 2.3.2). Unlike the AM/FM signal, which is constantly transmitted by the broadcast towers, the cellular signal is setup only temporarily to establish a communications channel between a mobile user and the base-station tower. The current cellular system in the U.S.A. (Advanced Mobile Phone System - AMPS) uses an analog FDMA scheme which allocates a single frequency for each communications channel. Therefore, the communication channel signals can not be used as receive signals in a mobile measurement system. However, each base-station tower in a cell uses one dedicated control channel to locate and identify mobile users. The cellular towers transmit a continuous constant-amplitude signal on these control channels. These beacon signals can be used as test signals in a mobile measurement system.

In AMPS, there are 21 control channels per cellular provider: 313–333 for the first provider and 334–354 for the second provider. The frequency spacing between the channels is 30 KHz, with channel 313 having a frequency of 879.39 MHz and channel 354 a frequency of 880.62 MHz. The entire cellular system covers the frequency band from approximately 824 MHz to 894 MHz. Therefore, if the beacon signals are used as test signals for the mobile system, then the antenna measurements are limited to essentially a single frequency measurement (around 880 MHz).

We have used two types of mobile systems to characterize the vehicular cellular antennas. These systems are mainly used to assess the performance of the antennas when they are on-the-road (where the signal polarization and angle of arrival may be different than those used in the range). The first system uses a computer-interfaced
Figure 3.16: Sample cellular antenna gain pattern data obtained using a cellular mobile measurement system and the control channel signal. Result shows calibrated data - raw (dash) and averaged (solid).

spectrum analyzer. The system is installed in the vehicle which must be located in the line-of-sight of a cellular tower (this insures that we have a direct signal to the vehicle). The vehicle is driven in a large-diameter circle while the computer records the signal levels of the control channel received by the cellular antenna. The data are spatially filtered to remove the effect of multipath signals. The result of the measurement is an azimuthal gain pattern of the antenna-under-test (usually calibrated to a reference antenna measured using the same setup). Figure 3.16 shows
a sample plot of a cellular antenna gain pattern obtained using the mobile system. The plot shows the raw data as well as the spatially filtered data.

The above mobile system can also be used to assess the antenna performance as the automobile is driven along a set path in different propagation environments (downtown, rural, highway, etc.). As the vehicle is driven through different cells, the mobile system must be able to locate and use the strongest control channel signal available. The system must also continuously switch between the antenna-under-test and the reference antenna in order to ensure that the path recorded for both antennas is identical. We have not developed the system to perform this type of measurement yet.

The second mobile system we have used consisted of an actual commercial cellular receiver (activated by the cellular provider). The cellular receiver chosen had the option of displaying a relative value of the strength of the signal being received by the antenna. If this receiver is interfaced to a computer, then it can be used to perform the same type of measurements that the spectrum analyzer system can perform. The advantage of the cellular receiver over the spectrum analyzer is that the receiver has a lower cost and is more rugged. Also, the cellular receiver is designed to automatically locate and use the strongest control channel signal available. We have used the cellular-receiver mobile system to perform azimuthal gain pattern measurements.

3.4 Antenna Concepts and Designs

In section 3.1 we discussed some of the design parameters of cellular antennas for automobiles. Below is a summary of those parameters.
- Frequency Range: 825–895 MHz.
- Impedance: 50 Ω.
- Gain Pattern: omnidirectional in azimuth; low elevation angle.
- Polarization: Vertical.

3.4.1 Antenna-Vehicle Interactions

At cellular frequencies, a typical automobile is electrically large (approximately 10 wavelengths). If the cellular antenna is fed against the vehicle body, the RF current on the vehicle body would only extend to the local geometry around the antenna feed (an area of one to two wavelengths in all directions). The rest of the vehicle would act mainly as an obstruction to the signal propagation; the propagating signal would reflect and diffract from the various conducting parts of the automobile.

We have studied the interactions between the cellular antenna and the vehicle body experimentally [46]. From those studies, we made the following observations.

- For minimal interference from the vehicle body, the antenna should be placed mainly above the roof line (not possible for on-glass antennas). The radiation pattern for an antenna below the roof line, on the back glass, will exhibit interference patterns in all directions but most significantly towards the front of the vehicle (the signal passing through the passenger compartment).

- A vertically polarized (VP) antenna, above or below the roof line, will have less interference from the vehicle body than an antenna with any horizontally polarized (HP) component. The HP component appears to be more strongly...
reflected and diffracted causing degradation to the VP radiation pattern of the antenna.

- Hand-held antennas used inside the vehicle compartments exhibit strong interference patterns, even when they are vertically polarized.

The most common cellular antenna currently is the collinear 3λ/4 array monopole that is either magnetically mounted and fed against the roof or trunk-lid, or is attached to the glass of the vehicle. We studied the performance of the glass mounted monopole antenna (pigtail antenna). Figure 3.17 shows some of the results obtained using a full-scale measurement range. The results present the VP and HP radiation patterns of the pigtail antenna when it is placed vertically and when it is normal to the glass (approximately 45° angle with respect to the horizon). All the data have been normalized to a reference roof-top monopole antenna. The results show that the vertically placed antenna has an omnidirectional VP pattern (to within 5dB). The slanted antenna, however, has a VP radiation pattern that has a strong directionality (close to 20dB). This directionality is mainly due to the presence of the HP component of the signal which appears to generate an interfering VP component through polarization rotation due to reflections and diffractions (as noted in the observations above). The reason for the strong interference from the HP signal may be due to the fact that most of the plate edges in the passenger compartment are oriented horizontally. On-glass antennas will tend to have a polarization similar to that of the slanted pigtail antenna, mainly because they conform to the surface of the backlite glass, which is slanted. In addition to their polarization impurity, on-glass antennas are located below the roof-line, and are subjected to stronger
Figure 3.17: Vertical and slanted pigtail antennas on Olds88. Azimuth pattern at elevation angle of 2° above the horizon for both vertical and horizontal polarizations; freq=860 MHz.
interference from the vehicle body. Therefore, typical on glass antennas will have radiation patterns similar to that of the slanted pigtail antenna. In our research effort we attempt to design on-glass cellular antennas with an improved radiation pattern over that of the slanted pigtail antenna.

In the rest of this section we will present experimental results from the development of two on-glass cellular antenna concepts. We will discuss the limitations of these antennas and present alternative antenna concepts including antenna arrays and diversity systems.

3.4.2 On-Glass Antennas

We designed and tested two types of on-glass cellular antennas. The antennas were designed to be fed counterpoised against the vehicle roof (or other large metallic plates). Placing the antennas at the top of the backlite, near the roof, appears to minimize the interactions of the antenna with the passenger compartment.

Annular Slot Antennas

The first antenna designed was the annular slot antenna. Figure 3.18 shows the annular slot antenna on the backlite, fed against the roof of a vehicle. The annular slot antenna consists of an inner conducting patch surrounded by an outer conducting region. The coaxial cable inner conductor is connected to the inner patch, while the coaxial shield is connected to the outer region, which is capacitively coupled to the vehicle body. A differential voltage on the coaxial cable produces an RF voltage across the deletion gap of the slot, which in turn causes the radiation. The behavior of the slot antenna can be modeled by the complimentary magnetic loop current in the deletion region. The fictitious magnetic loop antenna produces a radiation
Figure 3.18: Cellular concept annular slot antenna on the backlite of a vehicle.

pattern similar to that of an electric dipole antenna perpendicular to the plane of the antenna. Therefore, the annular slot cellular antenna is not expected to produce a radiation pattern that is mostly VP, except if the orientation of the backlite glass is horizontal. Most modern vehicles have a backlite that is oriented 30° to 50° from the horizon.

Two designs of the annular slot antenna were implemented on the backlite glass and tested on an Oldsmobile 88 (Olds88) test vehicle. The antennas were placed at the top of the backlite glass with part of the outer region of the slot antenna capacitively coupling to the bezel of the roof, thus using the roof as an extended ground plane. All the antennas tested were impedance matched to 50Ω with an SWR < 2.0 across the whole cellular band. Different feed positions and ground plane sizes were tested. Figures 3.19 and 3.20 show the VP and HP radiation patterns, respectively, of four variations of the slot antenna, obtained using our outdoor test
Figure 3.19: Four slot antenna concepts on Olds88. Vertical Polarization. Azimuth pattern at elevation angle of 2° above the horizon; freq=860 MHz.
Figure 3.20: Four slot antenna concepts on Olds88. Horizontal Polarization. Azimuth pattern at elevation angle of 2° above the horizon; freq=860 MHz.
range. The results show that the elongated slot antenna, with a center feed produces the most omnidirectional azimuth VP pattern, and that its signal level compares well to that of the slanted pigtail antenna. The results also show that increasing the size of the ground plane beyond that of the elongated slot at the top Figure 3.19 produces no clear overall advantage. It is expected that the nulls in the VP pattern would decrease, and the signal level would increase as the orientation of the glass becomes more horizontal (on sun-roof glass, for example). The Olds88 backlite is slanted 40° from the horizon.

**Loop Antennas**

The second on-glass cellular antenna studied was the gamma-match loop antenna. An implementation of the cellular loop antenna on the backlite of a vehicle is shown in Figure 3.21. The loop antenna was implemented as a gamma-match feed to the edge of the automobile roof. The inner conductor of the coaxial cable was connected
to one end of the loop, while the shield of the cable was connected, through a
ground strip, to the other end of the loop. The ground strip was capacitively coupled
to the roof of the vehicle. Such an implementation of the loop antenna is believed to
to drive currents on to vehicle roof. Using the vehicle roof as part of the loop allows
the physical size of the loop to be smaller. For esthetic purposes, the size of the on-
glass cellular antennas must be made as small as possible. Since the gamma match
is an electrical loop, we believe that to maximize its vertically polarized component
it must be vertically oriented on the glass structure.

The loop antenna designs were impedance matched to $50\Omega$ with an SWR $<
2.0$ across the whole cellular band, and their radiation pattern was measured on
the Olds88 test vehicle. Sample results for the VP and HP patterns are shown in
Figure 3.22. The test results show that the loop antenna produces azimuth patterns
similar to a slanted pigtail antenna, as expected. Further tests showed that the
loop antenna could produce a more VP pattern than the slanted pigtail if it were
implemented on a glass fixture that was vertically oriented (such as a fixed side
window).

The wide-loop antenna was silk-screened onto the backlite of an Oldsmobile 88
vehicle, and was used in conjunction with an actual cellular telephone (that outputs
the power level of the incident signal). The control-channel signals from the cellular
towers were used as reference signals. The operation of the telephone using the on-
glass antenna was subjectively tested in different parts of the city. The results seem
to indicate that the loop antenna can be used effectively as a mobile cellular antenna.
Figure 3.22: Two loop antenna concepts on Olds88. Azimuth pattern at elevation angle of 2° above the horizon for both vertical and horizontal polarizations; freq=860 MHz.
Further road tests (with a computer-interfaced mobile receiver system) are needed in order to quantify the behavior of the on-glass antennas in the "real world" environment. However, from the results that we have obtained so far, it seems that both the loop antenna (for vertically oriented glass) and the slot antenna (for horizontally oriented glass) can be used effectively as automobile cellular antennas.

**New Antenna Concepts**

The microstrip patch antenna is currently used in applications where a conformal antenna is needed. We investigated the use of the patch antenna as a cellular on-glass antenna. The current cellular system covers an 8% bandwidth in frequency (although only half the bandwidth is used for transmitting, which requires a low SWR value; for receiving, the SWR can be higher than 2). Regular patch antennas can be impedance matched over only a small bandwidth (approximately 2%), because of the presence of the ground plane. However, many new designs can increase the bandwidth to the required 8%, usually at the expense of a more complex design and the use of multiple layers [47]. Another disadvantage of using a patch antenna for cellular applications is that its radiation pattern is unidirectional, with a maximum broadside to the patch. If the patch is placed slanted on the front or back windows, the radiation in the opposite direction will be mainly due to the very small backlobe of the antenna. If the patch is somehow placed in a horizontal position, most of the energy would be radiated at angles more than 40° above the horizon. The cellular signal is mostly concentrated at angles less than 40° from the horizon [48].

Patch antennas could, however, be used in a diversity or array-type system. Placing a patch antenna on the front and back glass of an automobile will allow almost
omnidirectional coverage, if the signals from the two antennas are combined properly. In a diversity system, both antenna signals are received and demodulated. The decision on which baseband signal to use is made by the receiver based on some criteria. For transmitting, different criteria would have to be used (for example, the antenna receiving the strongest beacon signal could be chosen). Diversity systems would work with any type of antenna, not just the unidirectional patch antennas. The only specification is that the two (or more) antennas have a low correlation coefficient. A small coefficient could be a result of the antennas being spatially separated or having a different polarization. Diversity systems require special telephone units. Diversity cellular telephones already exist, but are not very common [49].

If a non-diversity telephone is used, the signals from the two (or more) antennas must be combined into one RF signal that can be received by the telephone. Combining the two signals will probably produce an interference pattern at angles where the signals have equal amplitude and opposite phase. In order to minimize this interference, the antennas used must be directional. For a two antenna system, the antennas must have a broad unidirectional pattern like the patch antenna.

The effectiveness of using multiple antennas with a cellular mobile receiver must be further investigated. The design of the individual antennas must be such that when they are combined they would have a minimum interference pattern. The design goal would be to produce an overall pattern that is much more effective than that of the individual on-glass antennas (slot or loop), in order to justify the additional costs of the system.

Another antenna concept that must be further studied is the concept of multiple use antennas. As the applications for mobile communications increase, the number
of antennas needed will increase. One approach to lowering the number of antennas needed is to use one antenna for multiple applications [9]. We have started a study of one type of on-glass antenna that can be used for cellular and GPS applications. A detailed discussion of this antenna will be given in Chapter 5.
CHAPTER 4

GPS NAVIGATIONAL SYSTEM ANTENNAS

In this chapter we describe the development of on-glass GPS antennas. In section 4.1 we give an overview of the GPS system and discuss the design parameters of GPS antennas. In section 4.2 we describe the numerical modeling techniques that were used to model the GPS antenna in the presence of the vehicle. A mobile system that uses satellite signals to characterize the performance of GPS antennas on vehicles is described in section 4.3. Finally, in section 4.4 we present GPS antenna concepts that were developed and tested.

4.1 Design Parameters

This section presents a brief overview of the GPS navigational system as well as an overview of the design parameters for a GPS antenna. The GPS antenna is a resonant antenna in the presence of a large metallic structure. The signal that the antenna receives is a satellite based signal. Other mobile applications that use satellite signals would require antennas with similar characteristics as those of the GPS antenna.
4.1.1 An Overview of the GPS System

The GPS system consists of 24 satellites (three of which are spare) that orbit the earth once every 11 hours and 58 minutes, at an altitude of 12,183 km. Each four satellites are located in an orbital plane that is at a 55° inclination angle with respect to the plane of the earth's equator.

All the satellites transmit code-modulated signals to the receivers at two frequencies: L1 at 1575.42 MHz (19cm wavelength) and L2 at 1227.6 MHz (24cm wavelength). For civilian use, only the L1 frequency is used. The bandwidth of the spread spectrum signal at the L1 frequency is 1.023 MHz. The RF signal transmitted by the satellites is a right-hand circularly polarized (RCP) signal.

4.1.2 Antenna Design Parameters

The antenna receiving the GPS signal must have a wide look angle from zenith down to just above the horizon (a low gain antenna). At low elevation angles (near the horizon), the satellite signal becomes weak as the satellites start to drop out of sight. Most of the signals coming in at those low angles are corrupted by noise or unwanted multipath signals. The antenna must also have an omnidirectional pattern in azimuth. The antenna should be designed to have a right circular polarization, although a linearly polarized antenna will have only a small signal loss (less than 3dB). The automobile GPS antenna needs to operate only across a small bandwidth (approximately 1%) around the center frequency of 1575.42 MHz. The input impedance of a typical GPS receiver is 50Ω.
Conformal vehicle antennas can be designed as separate antenna structures and then installed on the vehicle. The automobile, which is electrically large (approximately 15 wavelengths long), will mainly act as a metallic object that shadows the antenna reception. At the GPS frequencies the sheet impedance of the glass is finite. Therefore, if the GPS antenna is to be placed on the glass, the loading effect of the glass must be considered.

The most popular GPS antennas are the helical type antennas (for example, the quadrifilair helix antenna [50]) and the microstrip-patch type antennas [6]. Both antennas can be designed to be small in size, to have RCP and a broad gain. The microstrip antenna, however, can be made conformal to a vehicle body and appears to be the most commonly used automobile GPS antenna.

4.2 Numerical Modeling Techniques

A detailed discussion of modeling automobile antennas at high frequencies at which the vehicle body is electrically large was given in section 3.2. In that section the analysis was given specifically for cellular antennas. In this section we describe how those numerical techniques can be used for GPS antennas.

We have numerically analyzed vehicle antennas for GPS (1575 MHz L1 frequency) applications. MoM analysis of these antennas on a full vehicle-body (which is electrically large) is impractical. An MoM analysis of the antenna alone (or with a partial vehicle geometry) can still be performed and may be useful in an initial study. Using MoM to obtain the antenna current and then UTD to analyze the antenna performance on the full vehicle geometry may be the best approach to model these antennas (the same approach used on the cellular antennas in section 3.2.3). We
have successfully used the above methods to study on-glass GPS antennas. Another approach is to synthesize the antenna pattern and use UTD to calculate the effects of the vehicle body on the antenna pattern. We have not used this approach yet.

4.3 Experimental Techniques

GPS antennas must receive signals from satellites that are at elevation angles from 10° to 90° above the horizon. Measuring the on-vehicle antenna patterns accurately using the test range (see section 2.3.1) may not be very convenient. Using the actual satellite signals and a GPS receiver is one method of accurately obtaining elevation cuts of the antenna patterns.

At the ElectroScience Laboratory we built a GPS mobile measurement system that uses a commercially available Rockwell GPS receiver [45]. The receiver can be interfaced to a computer, which can record the position of the available satellites and the signal level (ie. the carrier-to-noise ratio of the spread spectrum signal) received from 4 or 5 satellites at any time. If this measurement is taken over a long period of time (about 5–6 hours), then the satellites would have traced a major portion of the overhead sky, and the antenna pattern would have been obtained over several elevation cuts. During each measurement, several antennas could be tested by using an RF switch to switch between each antenna, at a rate of about one minute. At this rate, all the antennas can be measured while the satellite positions have not changed significantly. Figure 4.1 shows sample results of GPS satellite data obtained using the mobile measurement system. In the figure, the level of the signal received from several satellites is plotted versus the angular position of each satellite.
Figure 4.1: Sample GPS satellite data from mobile measurement system.
This measurement technique does not produce absolute antenna gain patterns. The antenna under-test must be compared to a reference antenna whose gain pattern is known (such as a standard patch antenna on the roof of the vehicle).

4.4 Antenna Concepts and Designs

In section 4.1 we discussed some of the design parameters of GPS antennas for automobiles. Below is a summary of those parameters.

- Bandwidth: narrow; less than 1%.
- Impedance: 50 Ω; SWR < 2.0
- Gain Pattern: omnidirectional in azimuth; broad elevation angle.
- Polarization: Right-hand Circular Polarization (RCP).

An on-glass GPS antenna should have a unidirectional pattern in elevation (such as a patch antenna) since the antenna should not radiate any signal into the passenger compartment. Usually, GPS receivers use only the signals from the satellites that are at elevation angles above 10° (from the horizon). Signals at lower elevation angles are weaker and are usually corrupted by multipath. Those are the type of signals that an on-glass antenna would receive if it had a main lobe in the direction of the passenger compartment. That is the reason why a ground-plane backed antenna (such as the patch antenna) would be effective as an on-glass GPS antenna. However, if the antenna does radiate energy equally into and outside of the passenger compartment, then it will only lose up to 3dB of the signal.

Another requirement for a GPS antenna is to have right-hand circular polarization (RCP). Most conformal antennas, however, can only have RCP over a small
angular sector. Outside that sector, the polarization becomes elliptical. Therefore, a linearly polarized on-glass GPS antenna will only lose up to 3dB of the signal due to polarization mismatch.

In the rest of this section we will describe two microstrip antennas: a single patch and a patch array. The antennas were experimentally tested. We will discuss the experimental results and the overall effectiveness of each antenna.

4.4.1 The Microstrip Patch GPS Antenna

The microstrip antenna consists of a patch on a grounded substrate. The patch is fed against the ground. The advantages of the patch are that it is low profile and has a relatively broad look angle broadside to the plane of the patch. The patch is easy to fabricate and usually is low cost. The patch can easily be made circularly polarized (usually over only a small angular sector) [51]. The main disadvantage of the patch is its narrow bandwidth in frequency. However, the L1 GPS band is also narrow (less then 1%), and that disadvantage is not a limitation for the GPS antenna.

There are several degrees of freedom for the rectangular, circularly polarized patch. The position of the feed point (coaxial or microstrip feed) and the aspect ratio of the patch determine the polarization of the patch. The patch size is determined by the frequency of operation and the dielectric constant of the substrate. The higher the frequency and the higher the dielectric constant, the smaller the patch size. Increasing the dielectric constant also increases the radiation resistance of the antenna but it decreases its efficiency, bandwidth and gain. The antenna efficiency, bandwidth and gain can be increased by increasing the thickness of the dielectric
substrate. The characteristics of the GPS patch antenna are small size, low gain, and small bandwidth. Such antennas typically require a thin substrate of high dielectric-constant material.

We built a rectangular microstrip patch antenna on an RT/duroid 6010LM microwave laminate material. The material was semi-flexible so that it could be made to conform to the curvature of the backlite glass. The duroid chosen had a dielectric constant of $\varepsilon_r = 10$ and was 2.45 mm thick. The patch size was 31 mm by 29 mm and the ground plane had an area of 62 mm$^2$. The patch used a coaxial cable feed (although a microstrip feed could be used). The location of the feed was chosen so that the patch input impedance was matched to 50$\Omega$ (SWR < 2.0) over a 30 MHz bandwidth, around the 1575 MHz center frequency. The feed location was also chosen so that the patch had an RCP pattern at broadside. Spinning linear pattern measurements were made and the results showed that the axial ratio was only 3 dB at broadside. The patch antenna was optimized to operate with the backlite glass ($\varepsilon_r = 6$) as a cover. The effect of the glass was to lower the resonance frequency of the antenna (ie. without the glass, the patch size would have been larger).

The on-glass patch antenna performance was compared to commercially available patch antennas intended for automobile applications (placed outside on the roof or trunk, or inside on the back package-shelf). The antennas were compared using range measurements and a GPS mobile measurement system (see section 4.3). The on-glass patch antenna performance compared well to that of commercial reference GPS patch antennas.
4.4.2 The Microstrip Patch Array

One disadvantage of the patch antenna is that the beam-maximum and RCP angular sector are at broadside to the patch. Most modern automobiles have front and back windshields that are inclined to within 30° or 40° from the horizontal. Having the patch antenna conformal to the glass will cause the beam-maximum to be deviated from zenith by only 30° or 40°. At such angle inclinations, the gain pattern of the patch antenna on the backlight will have coverage over most of the upper hemisphere (see the top of Figure 4.2). However, if the automobile glass is more than 60° from the horizontal, then the single patch antenna may not provide ample coverage of the upper hemisphere, as shown at the bottom of Figure 4.2, and would no longer be effective in receiving signals from all the satellites in view. It would be advantageous, in that case, to have an antenna with a tilted beam, such that the beam-maximum is towards the zenith. Antenna arrays (multiple-antenna systems) can be designed to have tilted beams. The tilt angle can be simply adjusted by varying the phase of each array element. Microstrip patch arrays can be used effectively for the GPS on-glass antenna application. Patch arrays have the same advantages of patch antennas (small size, conform to the backlight, ground plane ensures unidirectional beam). Patch arrays can be designed to have an RCP pattern with a tilted beam. In order to minimize the cost of the system, the array should be designed to have one feed and should not use any external phase shifters which are used in standard arrays. Figure 4.3 shows one design that meets these requirements. The patch array has one feed and uses a microstrip line to achieve phase shifting (spatial separation) between the elements. The antenna consists of four linearly polarized patch elements. The elements are edge-fed from a 50Ω microstrip
Figure 4.2: Pattern coverage of a patch antenna on a slanted backlite and a vertical backlite.

The microstrip line is fed in a traveling-wave mode such that the energy along the line is completely absorbed by the patches (not a resonant structure). The impedance, or transmission coefficient, of each element is adjusted (by varying the width of the patches $W$) such that each patch receives an equal amount of energy from the microstrip line. The patch closest to the feed receives $1/4$ of the initial energy, while the second patch receives $1/3$ of the remaining energy. The third patch
Figure 4.3: One type of microstrip patch array that can provide a tilted beam.
receives 1/2 of the energy incident upon it, and finally, the fourth patch receives all of the remaining signal energy.

The other edge of each patch is set equal to $\lambda_d/2$ (half wavelength inside the dielectric), so that the elements are linearly polarized (LP). The first and second patches are separated by a distance of $\lambda_d/4$ so that they remain 90° out of phase with respect to each other. The two patches are oriented at an angle $\theta$ with respect to each other. If $\theta = 90^\circ$, then the two LP patches form one circularly polarized (CP) element with a maximum CP direction normal to the plane of the array ($\beta = 90^\circ$).

As the angle $\theta$ is varied, the two LP patches will no longer be orthogonal to each other in the plane of the array. However, the two patches will be orthogonal to each other in some other plane, oriented at a tilt angle $\gamma$ with respect to the plane of the array. In that case, the direction of maximum CP would be normal to the tilted plane ($\beta \neq 90^\circ$). This design technique allows the beam of the array to have a maximum CP direction tilted with respect to the normal of the array. The angles $\theta$ and $\gamma$ are related by the following equation (obtained by using trigonometric projection of vectors):

$$\theta = \cos^{-1}\left[\frac{-\frac{1}{2} \sin^2 \gamma}{\sqrt{\frac{1}{2}(\cos^2 \gamma + 1)}}\right]$$  \hspace{1cm} (4.1)

The angle defining the direction of maximum CP, $\beta$, is the complimentary angle to $\gamma$ ($\beta = 90^\circ - \gamma$).

The other two patches are similarly designed to form a CP element. The two CP elements form the two elements of the array. Only two elements are needed since the beam of the antenna must be broad for GPS applications. The distance $d$ between the two CP elements determines the phase difference between them, which in turn
determines the tilt angle of the main beam of the array (α). Therefore, the angle α can be varied by varying the distance d between the CP elements.

In the design of the GPS patch array it is desirable to have the direction of maximum gain and direction of maximum CP equal (α = β). The antenna must also have right circular polarization (RCP). We designed and built one such GPS patch array to have a beam tilted by α = β = 50°. For such a tilt angle, the angle θ can be calculated from equation 4.1 to be θ = 100°, and the distance d can be determined from array theory to be d = 0.05 meters. The patch array was built on a grounded dielectric substrate with dielectric constant of ε_r = 10 (same duroid material used for single patch antenna). The value of λ_d for this dielectric at GPS frequencies is approximately 6cm. The width of the transmission line was calculated to be 2.2mm for a line with a 50Ω characteristic impedance. No existing mathematical model can accurately estimate the required values of W, or accurately predict the performance of such a patch array. Therefore, an experimental design and verification process is needed.

The width of each of the patches, W, was adjusted experimentally to obtain an input impedance for the array close to 50Ω (with the array loaded with the backlite glass). The values of W were 2.05cm, 2.2cm, 2.5cm, and 2.8cm for patches 1 to 4 respectively (patch 1 is closest to the feed). We were able to obtain a good impedance match (SWR<1.8) over a 2% bandwidth around the GPS center frequency (1575.42MHz). Then we measured the spinning linear patterns (see section 5.2.2 of [46] for more details) of the antenna in order to determine its polarization and gain characteristics. The results showed that the array did not have a good RCP signal at the desired tilt angle (close to a 5dB axial ratio). Also, the results showed
that the gain level of the array was 2 to 6 dB weaker than that of commercial GPS reference patch antennas. The measurements made on the array using the GPS mobile measurement system showed similar performance results.

The patch array design discussed above is very simple to fabricate and implement (almost as simple as a single patch antenna). However, the performance of the array must be improved, by properly adjusting the element dimensions, before it can be used effectively as a GPS antenna. Due to the lack of accurate mathematical models for such patch arrays, the design adjustments must be made experimentally. Such an experimental process can be time consuming and may not produce a properly designed antenna. Further investigation of the use of other simple antenna arrays for on-glass GPS applications, especially for vehicles with vertically oriented windshields and backlites must be made.
CHAPTER 5

DUAL-USE CELLULAR/GPS ANTENNA SYSTEMS

As new applications for mobile communications systems are introduced, the number of antennas required on the vehicle will increase. One method of reducing the number of antennas is to use one antenna for multiple applications. We have investigated one type of antenna that could be used for both cellular and GPS applications. In this chapter we will discuss the development of this antenna and we will present numerical modeling results (impedance and gain pattern). We will discuss the difficulties in implementing this antenna and present alternative designs that are easier to implement. Numerical results for those antennas will also be presented. (See Chapters 3 and 4 for a discussion of the design parameters and the numerical and experimental techniques for cellular and GPS antennas, respectively.)

There are several differences between the design parameters of cellular and GPS antennas. The cellular antenna must operate between 825MHz and 895MHz, should be vertically polarized (VP), and must have an elevation pattern with maximum coverage below 20° from the horizon. The GPS antenna must operate around 1575MHz, and must have a broad, right-hand circularly polarized (RCP) pattern, with an elevation coverage from zenith angle down to 10° above the horizon.
We have designed one on-glass antenna that appears to meet the above requirements for dual use. The antenna consists of a linearly polarized dipole as a cellular antenna, and a type of crossed dipole for GPS. Figure 5.1 shows the geometry of such an antenna. The value of $d_c$ is adjusted to obtain resonance at the cellular frequencies. The values of $d_{g1}$, $d_{g2}$, and $W$ are adjusted to obtain resonance and an RCP pattern, at a desired tilt angle, at the GPS frequencies. We used the method of moments numerical modeling technique (ESP4 code) to theoretically characterize this antenna. First, we varied the parameters $d_c$, $d_{g1}$, $d_{g2}$, and $W$ in order to obtain resonance in the cellular and GPS bands, and to obtain an RCP gain pattern for GPS. Figure 5.2 shows the impedance plot of the final antenna design. Figure 5.3 shows the SWR and mismatch loss of the antenna. The plots show that the antenna
Figure 5.2: Input impedance of a dual-use GPS/cellular antenna design.

is well matched to 50Ω in the cellular band (SWR < 2), and behaves as a resonant \( \lambda/2 \) dipole. The impedance of the antenna at the GPS frequency is approximately 200Ω (SWR \( \approx 3.2 \)) and can easily be matched to 50Ω with a 4:1 transformer. The theoretical model did not take into account the effect of the automobile glass on the antenna. If the antenna is placed on the inside surface of the glass, then the above dimensions of the antenna must be adjusted to offset the loading effect of the glass. These adjustments should have little effect on the gain pattern of the antenna. Note that the antenna elements were modeled as thin wires. The thickness of the wires will have a slight effect on the antenna impedance.

The gain pattern of the antenna at the middle of the cellular frequency band is given in Figure 5.4. The plots at the top of the figure show the vertically polarized
Figure 5.3: SWR and mismatch-loss of a dual-use GPS/cellular antenna design.

(VP) and horizontally polarized (HP) azimuth-cut patterns of the antenna, when it is oriented vertically ($d_e$ into the page, $d_{g1}$, $d_{g2}$ in the plane of the page). The patterns at the bottom of the figure are for the antenna in a slanted position (as it would be oriented on the backlite of the Olds88). Note that the patterns are for the antennas only, without any vehicle present. The result shows that the vertically oriented antenna has an omnidirectional VP pattern with a low HP component (good characteristics for a cellular antenna). However, if the antenna is placed on a slanted
Figure 5.4: Cellular theoretical azimuth patterns for a dual-use GPS/cellular antenna design. The VP and HP azimuth patterns are given for the antenna oriented vertically (ie. into the page) (TOP figure) and slanted (BOTTOM figure). Note that the patterns are for the antennas only, without any vehicle present.
backlite (35° from the roof of the automobile), its VP gain level drops by 6dB, and the HP component increases by almost 14dB. It is clear that the cellular component of the antenna is optimum when the antenna is oriented vertically, although, the performance of the slanted antenna may be adequate for cellular applications.

The above antenna's GPS characteristics (determined by \( d_{g1}, d_{g2}, \text{and } W \)) can be adjusted with no effect on the cellular frequency performance. The plots at the top of Figure 5.5 show the right-hand circularly polarized (RCP) and left-hand circularly polarized (LCP) elevation-cut patterns of the antenna when it is oriented vertically \((d_{g1}, d_{g2} \text{ into and out of the page respectively, } d_c \text{ in the plane of the page})\). The patterns at the bottom of the figure are for the antenna in a slanted position (as it would be oriented on the backlite of the Olds88). The results show that the antenna polarization is RCP at an angle close to 60° from the plane of the antenna in one direction, and LCP in the other direction. When the antenna is tilted to conform to the slant of the automobile backlite, the maximum of the RCP pattern points towards the zenith, as desired for GPS applications. The polarization of the tilted antenna changes from RCP (at zenith) to linear (in the plane of the antenna). The polarization is linear in the plane of the antenna since it behaves similar to a V-dipole in that plane. Further calculations show that the polarization has an axial ratio less than 3dB over approximately a 50° to 80° angular sector centered at zenith. Figure 5.6 summarizes the polarization characteristics of the antenna (without the effect of the vehicle). This type of crossed-dipole antenna will have a null at some angle in its pattern (since the radiation from the two elements will have a phase-cancelation at some angle); however, the antenna can be designed so that the pattern null is directed towards the ground and will not affect the GPS signal reception.
Figure 5.5: GPS theoretical elevation patterns for a dual-use GPS/cellular antenna design. The RCP and LCP elevation patterns are given for the antenna oriented vertically (TOP figure) and slanted (BOTTOM figure). Note that the patterns are for the antennas only, without any vehicle present.
Figure 5.6: Polarization characteristics at GPS frequencies of the dual-use GPS/cellular antenna design. The result is for the antenna in free space and does not consider the effect of the vehicle.

Note that this type of antenna will radiate (radiation and receive pattern are identical) half its energy into the upper hemisphere and the other half into the lower hemisphere (into the passenger compartment when placed on an automobile backlite). Therefore, this type of antenna is susceptible to interference from unwanted signals reflecting from the ground and from the passenger compartment.

The slanted antenna patterns in the two principle elevation-cut planes are compared in Figure 5.7. We calculated the pattern for other elevation-cut planes and all the results showed that the antenna RCP angular sector is broad, and that the antenna pattern has no nulls in the upper hemisphere.

The next step in the development process was to test the effect of the vehicle body on the antenna performance. The antenna was placed in a location at the top
Figure 5.7: GPS theoretical elevation patterns for a dual-use GPS/cellular antenna design placed in a slanted position. The RCP and LCP elevation patterns are given for two different elevation cuts. Note that the patterns are for the antennas only, without any vehicle present.
of a backlite having the same inclination as the Olds88 backlite. The antenna was in free space (no glass was included in the model). Only a small part of the vehicle was included in the model. At cellular and GPS frequencies, only the geometry in the immediate surroundings of the antenna has a large effect on the antenna performance. Figure 5.8 compares the performance of the slanted antenna, at cellular frequencies, with and without the partial vehicle present. The result shows how the presence of the vehicle causes interference nulls in the antenna pattern. This type of interference occurs for most on-glass cellular antennas, and does not necessarily make the antenna performance unacceptable. Figure 5.9 compares the performance of the slanted antenna, at GPS frequencies, with and without the partial vehicle present. The result shows how the interference from the vehicle body degrades the antenna pattern. Most of the interference occurs near the horizon. The gain of the antenna in the zenith direction (important for GPS) is not degraded, although the polarization of the antenna in that direction is no longer purely RCP but more of an elliptical polarization. Therefore, the overall performance of the antenna appears to be acceptable for both cellular and GPS applications, even with the vehicle present.

One of the disadvantages of the above antenna is that it must be fed in the center. The antenna on a 2-dimensional plane (the glass fixture) would require a twin-line feed to be printed on the glass with the antenna. The twin line feed may cause interference with the antenna performance. Also, to connect the antenna to a coaxial cable would require a balun transformer which must operate over the cellular and GPS frequency bands. An alternative approach would be to convert the dipole antenna into a monopole or sleeve-dipole type antenna. The antenna could then be fed directly with a coaxial cable and counterpoised against the vehicle.
Figure 5.8: Cellular theoretical azimuth patterns (VP and HP) for a dual-use GPS/cellular antenna design placed in a slanted position on the backlite of a partial vehicle geometry.
Figure 5.9: GPS theoretical elevation patterns (RCP and LCP) for a dual-use GPS/cellular antenna design placed in a slanted position on the backlite of a partial vehicle geometry.
body (the ground plane). Figure 5.10 shows two possible concepts. We used the method of moments numerical model to investigate the possibility of converting the GPS/cellular dipole-type antenna developed above into the antenna concepts of Figure 5.10. Note that for these type of antennas (wires or thin plates connected to the edge of a large plate, such as the vehicle roof), the method of moments model can give accurate gain pattern results but not accurate impedance results. We must use experimental measurements to determine the impedance of these type of antennas.

Figure 5.11 shows the calculation results of one of the sleeve-dipole antenna designs. The antenna elements are modeled as thin wires. The figure shows the VP and HP azimuth-cut patterns of the antenna at cellular frequencies. The result is compared to that of the dipole antenna located at the same position on the same partial geometry (Figure 5.8). The result shows that the sleeve-dipole design has a VP pattern with a lower gain level and more nulls than that of the dipole. Other sleeve-dipole designs had similar patterns.
Figure 5.11: Cellular theoretical elevation patterns (VP and HP) for a thin-wire sleeve-dipole dual-use GPS/cellular antenna design placed in a slanted position on the backlite of a partial vehicle geometry.
Figure 5.12 shows the RCP and LCP elevation-cut patterns of the sleeve-dipole antenna at GPS frequencies. The patterns are compared to those of the dipole antenna located at the same position on the same partial geometry (Figure 5.9). The results indicate that the antenna pattern still has good coverage of the upper hemisphere, but the gain level is as much as 3dB lower than that of the dipole, in the zenith direction.

Next, we investigated several different variations of the monopole-type antenna. Figure 5.13 shows the VP and HP azimuth-cut patterns of the antenna at cellular frequencies. The result is compared to that of the dipole antenna. The antenna elements are still modeled as thin wires. For this particular antenna, which has a long (14.5cm) main element, the cellular VP pattern is similar to that of the dipole antenna. The GPS patterns for this monopole-type antenna, shown in Figure 5.14, are similar to those of the sleeve-dipole in that the RCP pattern has good coverage over the upper hemisphere, and the gain level is lower than that of the dipole.

We implemented the monopole-type antenna on the backlite of the Olds88 test vehicle. The impedance measurements we made indicated that the antenna was mismatched at both the cellular and GPS frequencies. One approach to matching the antenna is to modify its dimensions. However, if the dimensions of the antenna are adjusted to improve its impedance efficiency, its gain pattern will be modified (mostly degraded). Therefore, external matching networks must be used in order to match this monopole-type antenna. We have not investigated the use of such networks at this time.

We modified the above monopole-type antenna, experimentally, until we obtained a good impedance match (mismatch loss below 0.5dB). We then modeled the modified
Figure 5.12: GPS theoretical elevation patterns (RCP and LCP) for a thin-wire sleeve-dipole dual-use GPS/cellular antenna design placed in a slanted position on the backlite of a partial vehicle geometry.
Figure 5.13: Cellular theoretical elevation patterns (VP and HP) for a thin-wire monopole-type dual-use GPS/cellular antenna design placed in a slanted position on the backlite of a partial vehicle geometry.
Figure 5.14: GPS theoretical elevation patterns (RCP and LCP) for a thin-wire monopole-type dual-use GPS/cellular antenna design placed in a slanted position on the backlite of a partial vehicle geometry.
antenna in order to obtain its gain pattern. Figure 5.15 shows the cellular patterns of the modified monopole-type antenna. Clearly, the VP pattern of the antenna is degraded compared to the first monopole-type antenna of Figure 5.13. The main reason for the degraded performance is the shorter length (9.5cm) of the main element in the modified antenna. The GPS patterns of the antenna are give in Figure 5.16. The RCP pattern of the antenna appears to be similar to those of the previous designs. We performed spinning linear range-type experimental measurements (see section 5.2.2 of [46]) on the antenna at GPS frequencies. The results showed that the antenna gain levels were as much as 4dB stronger than those of the GPS reference patch antennas at some elevation angles, and almost 10dB weaker at other angles. These measurements are consistent with the numerical calculations that showed that the monopole-type antenna has multiple lobes (peaks and nulls) in its RCP pattern. The performance of the monopole-type antenna was also compared experimentally, using the GPS mobile measurement system, to the other GPS antennas that we had studied (see [45]).

In this chapter we have discussed a new on-glass antenna design that can be used for cellular and GPS applications. We demonstrated (theoretically) that the initial dipole design can be used successfully for both applications. We then attempted to design alternatives to the dipole antenna that would be easier to implement on the automobile glass. Two particular designs were investigated. We demonstrated that we could obtain patterns similar to the dipole antenna in both frequency bands for one of those designs, the monopole-type antenna. The impedance of the antenna, however, was mismatched in both bands. We implemented a modified monopole-type antenna with an efficient impedance match. The GPS pattern of the modified
Figure 5.15: Cellular theoretical elevation patterns (VP and HP) for a narrow-plate monopole-type dual-use GPS/cellular antenna design placed in a slanted position on the backlite of a partial vehicle geometry.
Figure 5.16: GPS theoretical elevation patterns (RCP and LCP) for a narrow-plate monopole-type dual-use GPS/cellular antenna design placed in a slanted position on the backlite of a partial vehicle geometry.
antenna was still similar to that of the dipole, however, the cellular pattern was degraded. A further investigation of techniques of improving the impedance of the monopole-type antenna, while maintaining the desired gain patterns in both the cellular and GPS bands, must be performed. An investigation into practical and cost effective methods of implementing the initial dipole design on an automobile backlite must also be conducted.
CHAPTER 6

AUTOMOTIVE RADAR ANTENNA SYSTEMS

In this chapter we describe the development of on-glass collision avoidance radar antennas. In section 6.1 we give an overview of collision avoidance radar systems and discuss the design parameters of automotive radar antennas. In section 6.2 we present a feasibility study for placing lane-changing radar antennas on the automobile glass. Theoretical, numerical and experimental techniques were used in the study. The numerical techniques used in the study are the same ones described in section 4.2. The experimental techniques that were used are similar to the ones described in section 2.3.1.

6.1 Design Parameters

This section gives an overview of automotive radar systems and presents antenna design parameters for collision avoidance radar systems.

6.1.1 Automotive Radar Systems

Radar systems are currently being used on automobiles for several different applications. One such system is the collision-avoidance radar which is used to detect objects in front of a moving automobile. The radars are used to detect the presence of
an object, calculate the distance to it, its speed, and the closing rate of the automobile towards that object. The radar system can be connected to the brakes, throttle, and automatic transmission of the automobile to allow the use of the radar information for adaptive cruise control and automatic braking of the automobile. The radar might be part of a larger vehicle-automation system that includes infrared and optical sensors.

Another automotive application for radar is the lane-changing (blind-spot) warning radar. Such a system would detect an object in the blind-spot of the adjacent lane of the automobile and provide the driver with a visible or audible warning.

One radar system that is already commercially available in the U.S.A. is the VORAD system (Vehicle On-board Radar) [52, 53]. This system uses a forward-looking collision-avoidance warning radar (at 24.725 GHz) and a side-looking lane-changing warning radar (at 10.525 GHz). The forward-looking Doppler radar uses an FMCW multiple frequency shifting (FSK) modulation scheme, while the side-looking radar uses a pulsed modulation.

There have been differing views around the world on the best frequency to use in vehicle radar systems. Europe appears to favor the frequency band of 76.5 GHz ± 500 MHz, while Japan favors the frequency band of 59.5 GHz ± 500 MHz. The FCC has recently allocated the frequency bands of 46.8 GHz ± 100 MHz and 76.5 GHz ± 500 MHz for the United States. One of the reasons behind these choices of frequency allocations is the atmospheric effects at each frequency band. The frequency of 59.5 GHz lies in the center of the oxygen absorption band and thus the signal at that frequency will be attenuated in a short distance for a given amount of power. In the Japanese market, with its high population density and crowded roads, such
signal attenuation would help reduce the radar interference problem (at the expense of increased input power requirement). In the European and U.S. markets, the radar interference problem may not be as severe and the frequency allocations have been chosen outside the oxygen absorption band to get maximum signal propagation for the given amount of input power.

6.1.2 Antenna Design Parameters

Current radar systems are designed as monolithic integrated circuits (MIC), with the radar circuitry and antenna all embedded on a single substrate. The antennas used for these MIC's is typically a microstrip patch array etched on a dielectric substrate or a horn antenna [54].

The forward-looking collision-avoidance radar requires a narrow beam antenna with high gain in order to detect objects up to 100 meters ahead. The typical antennas have approximately a 30dB gain, with a 3dB beamwidth of 5° in both azimuth and elevation. The side-looking lane-changing radar requires a wider beam antenna that can detect an object in the adjacent lane. The typical antennas have approximately a gain of 8dB, with a 3dB beamwidth of 70° in azimuth and 35° in elevation.

The forward-looking radar MIC is usually installed behind the front bumper or under the hood (behind the radiator grille) of the automobile. The side-looking radar MIC is usually installed behind the rear side fender of the automobile or behind the far edge of the rear bumper.
Figure 6.1: Beam pattern coverage for side-looking on-glass lane-changing radar antennas.

6.2 Antenna Concepts and Designs

In this section we present a study of the feasibility of placing the radar antennas on the automobile glass. In particular, we are interested in designing a lane-changing radar antenna for the glass. Placing the antenna on the back glass (backlite) of the automobile, or on the side glass (sidelite) would allow the radar to have the required coverage, as seen in Figure 6.1. It is also possible to place a back-looking antenna on the side-view mirror, as seen in Figure 6.2. Such an antenna would require a narrower beamwidth in the azimuth plane than the side-looking antenna.

In the rest of this section we will discuss possible on-glass antenna designs that can be used for the lane-changing radar application. We will describe the effect of the glass on these antennas. We will also present the results of a numerical modeling study of the effect of the vehicle body on the side-looking on-glass radar antenna.
6.2.1 On-Glass Antennas

Side-looking antennas could be placed either on the backlite or on the sidelite glass. Backlite antennas require an end-fire beam whereas sidelite antennas require broadside beams. Both types of antennas must have approximately an 8dB gain, with a 3dB beamwidth of 70° in azimuth and 35° in elevation. The types of sidelite antennas that can be used are uni-directional broadside arrays or aperture-type antennas. Possible backlite antennas are end-fire dipole or microstrip arrays, tapered-slot antennas, and traveling-wave Yagi antennas.

Sidelite Antennas: Arrays

A broadside array must be printed on a grounded dielectric substrate to produce a uni-directional beam. Therefore, a dipole or microstrip array could be used as a sidelite antenna. The array would normally be placed on the inside surface of the glass (see Figure 6.3), and, therefore, the design must account for the loading effect of the glass (which acts as a protective cover). Since the thickness and the
dielectric properties of the glass are mostly fixed, the frequency of operation of the radar must be adjusted so that the sidelite glass behaves as an effective radome cover. There are two general designs for the monolithic radome covers: the thin-wall design and the n-order half-wave design [30]. For the thin-wall design the thickness of the radome cover must be approximately $t \approx 0.02\lambda_d$ (where $\lambda_d$ is the wavelength in the dielectric) for 95% transmission when the radome material has a dielectric constant $\varepsilon_r = 6$. To meet this requirement for a glass thickness of $t = 4.2\,mm$, the frequency of operation of the radar must be approximately 600 MHz. This would not be practical for the automotive radar application (the antennas would be too large). In the n-order half-wave design the thickness of the glass must be equal to a multiple of a half wavelength ($t = n\lambda_d/2 = 4.2\,mm$). With the glass having a thickness of a multiple of a half wavelength, the impedance seen by the array will be that of free space. Therefore, there will be minimal internal reflections of the signal inside the glass cover (zero reflection in the broadside direction). To meet the above thickness requirement, the frequency of operation of the radar must be equal.
to $f_o = (14.58 \times 10^9)n$. Therefore, for $n = 1$ the radar frequency must be equal to 14.58 GHz, which is a practical frequency of operation for automotive radars. Larger integer values of $n$ could be used if a higher frequency is desired.

It may also be possible to use an aperture-type antenna behind the sidelite glass to produce a uni-directional beam. The same design procedure discussed above for the glass thickness would also apply for the aperture antenna case.

**Backlite Antennas: Arrays**

A dipole array can be designed to produce an end-fire beam by adjusting the phase shift between the dipole elements [28]. The phase difference between the elements (normally 90°, or less for increased directivity) and the separation between them (normally $\lambda/4$, or less for increased directivity) determine the directivity of the array; the taper of the current magnitude across the array determines the sidelobe level. We designed an 8-element end-fire dipole array (in free space) that meets the design requirements for side-looking radar antennas. The advantage of a dipole array is that it can be easily implemented by printing the elements on the backlite glass without the need for an additional grounded dielectric substrate. The disadvantage of the dipole array is that it requires the use multiple feeds, probably including a balun or hybrid, on the 2-dimensional glass plane. The presence of these feeding structures is likely to cause interference to the overall dipole gain pattern. To overcome this problem it may be possible to use a single feed and connect the dipoles to each other with a feed line. The phase shift between the elements and the magnitude current taper across the array become functions of the spacing between the elements and their impedance values, respectively.
To incorporate an end-fire array into a monolithic integrated circuit (MIC) element, a grounded dielectric substrate (or multiple substrates) must be used. A microstrip patch array can be designed to produce a tilted (nearly end-fire) beam. One advantage of a microstrip array is that the feeding structure can be printed on the other side of the substrate reducing the interference with the radiating patch elements. Another advantage is that the beam can be tilted away from end-fire, if such a tilt angle is required, without producing an image beam symmetric to the main beam (with respect to the plane of the antenna), as in the case of a dipole array. The disadvantages of the microstrip array is that the dielectric substrates and the process of attaching the MIC to the glass increases the cost of the system.

Both the dipole and microstrip array would be placed on the inside surface of the backlite glass. Therefore, the loading effect of the glass must be considered in the design process. Also, the effect of the glass on the generation of an undesirable surface wave must be studied. A discussion on the effect of the glass on the performance of end-fire arrays is given in section 6.2.2.

**Backlite Antennas: Tapered Slot Antennas**

Traveling surface-wave antennas (slow waves whose phase velocity is smaller than the speed of light i.e. $v_{ph} < c$) can produce end-fire beams. Tapered slot antennas (TSA) are moderate gain (up to 17dB) surface-wave antennas [55, 56]. Figure 6.4 shows three designs of TSA: the Vivaldi, the Linear Tapered Slot Antenna (LTSA) and the Constant Width Slot Antenna (CWSA). The antennas are constructed by a metal layer usually printed on a thin dielectric. The antennas are non-resonant structures (usually about $3\lambda$ to $10\lambda$ long) and, therefore, exhibit impedance and
beamwidth characteristics that are wide-band in frequency. Also, the dimensions of the structure can be varied to obtain the desired radiation characteristics without causing a large shift in the frequency of operation. The antennas can be designed to produce symmetric beams in both the E-plane and the H-plane, over wide frequency bands, by forcing the surface wave to illuminate the aperture end of the antenna (the end with large separation between conductors) in a circular region. The larger the circular region, the higher the gain of the antenna. The total antenna pattern is formed from the combination of the feed radiation (usually broad) and the surface wave radiation at the terminal aperture. The H-plane pattern depends mainly on the phase velocity of the traveling wave and the antenna length. The E-plane pattern has an additional dependence on the slot taper shape. The phase velocity mainly depends on the effective dielectric thickness of the substrate used. The antennas are linearly polarized with low cross-polarization in the principal planes. The most effective techniques of feeding the antennas have been with strip lines, slot lines, and fin lines.
If implemented on the backlite glass, the TSA can be printed directly on the glass which would act as the dielectric support. According to [56], the effective thickness of the dielectric substrate supporting a TSA, given by

$$\frac{t_{\text{eff}}}{\lambda_0} = (\sqrt{\varepsilon_r} - 1) \frac{t_{\text{sub}}}{\lambda_0}$$  \hspace{1cm} (6.1)$$

where $\varepsilon_r$ is the relative permittivity of the dielectric and $t_{\text{sub}}$ is the substrate thickness, must have a value between 0.005 and 0.03 in order for the TSA to behave as a traveling surface-wave antenna. The adverse effects of a thick dielectric substrate will be discussed in section 6.2.2.

**Backlite Antennas: Traveling-Wave Yagi**

Another antenna that can launch a surface wave is the Yagi (or Yagi-Uda) antenna [30]. Two implementations of the antenna are shown in Figure 6.5: a dipole
and a monopole implementation. Both antennas are comprised of a single driven element and a several passive elements. The element to the left of the driven element is the reflector and the elements to the right are directors. The length of the driven element determines the resonant frequency. The reflector and the first director mainly determine the front-to-back ratio of the antenna pattern and the rest of the directors determine the gain and sidelobe levels. The antenna is usually designed with three tapered regions, as shown in Figure 6.5. The feed taper affects the efficiency of the excitation and the shape of the feed pattern. The body taper affects the sidelobe level and the bandwidth, and the terminal taper is used to reduce the reflected surface wave. The total antenna pattern is formed, as in the TSA, from the combination of the feed radiation and the surface wave radiation at the terminal aperture. The dipole Yagi in Figure 6.5 was designed (using an MoM model) to produce the desired antenna pattern (with a 15dB front-to-back ratio) for the side-looking radar.

The dipole Yagi antenna can be implemented on the backlite glass by printing the dipole elements directly on the glass. At higher frequencies (above 10 GHz) the element dimensions become small and feeding the dipole on the glass, with a balun or hybrid feed, may not be very practical. The monopole Yagi antenna allows a more practical coaxial feed of the element. However, the antenna requires the ground plane to be orthogonal to the plane of the elements, which makes it difficult to implement on a 2-dimensional glass panel. The advantage of the Yagi antenna over the TSA is that the Yagi has more degrees of freedom to control the phase velocity of the surface wave (by adjusting the element lengths and spacing).
6.2.2 Effect of Backlite Glass on Antennas

All the backlite antennas discussed in the previous sections must use the backlite glass as a dielectric cover. The typical glass thickness is 4 mm and the permittivity is $\varepsilon_r = 6$. The glass thickness at 10 GHz is close to $0.3\lambda_g$, where $\lambda_g$ is the wavelength in glass. For the end-fire array antennas the total radiation is the product of the individual element pattern and the array factor. When a thick dielectric slab covers the array, an undesirable surface wave will probably be trapped in the dielectric and will not radiate till it reaches a discontinuity (the edge of the glass). The radiation from the array and from the surface wave will interfere causing a distorted antenna pattern. The radiation from a surface-wave antenna is the sum of the radiation from the feed directly and the from a surface wave traveling along the antenna and radiating at the aperture. At frequencies above 3 GHz the glass thickness will be more than $0.1\lambda_g$, causing a large portion of the surface wave along the antenna to be trapped in the glass, as shown in Figure 6.6. The trapped surface wave will reflect or diffract off the metal roof post supporting the glass, and interfere with the transmitted wave. From equation 6.1, the effective thickness ($t_{eff}/\lambda_0$) of the backlite glass at 10 GHz is 0.25, whereas, according to [56], the value of $t_{eff}/\lambda_0$ must be smaller than 0.03 in order for the surface wave, generated by the end-fire antenna on the glass substrate, to be radiated at the aperture of the antenna. Only below 1.5 GHz does the backlite glass have a $t_{eff}/\lambda_0$ smaller than 0.03. Therefore, surface-wave antennas operating above 1.5 GHz will not be effective when placed behind the backlite glass. There may exist techniques of offsetting the effect of the thickness of the glass on the surface wave. Some of those techniques may involve adjusting the phase velocity of the wave along the length of the antenna, attenuating the trapped
surface wave using resistive films on the glass, or using the bulge of the glass to leak the trapped wave as it propagates along the curvature. We have not pursued these ideas any further, although they may be the subject of a future study.

6.2.3 Effect of Vehicle Body On The On-Glass Antennas

In the previous section we presented some of the on-glass antennas that could be used for side-looking radar applications. We also discussed the limitations on the performance of the surface-wave antennas due to the thickness of the glass cover. In this section we will discuss the limitations of the antennas due to the presence of the
vehicle body. For the purpose of this study we will assume that the backlite antenna can produce the same beam pattern when placed on the glass as it would in free space.

We used the UTD numerical modeling technique to study the effect of the vehicle on the antennas. The vehicle body was modeled using flat plates. To generate the required beam pattern we used a thin wire model of an 8-element end-fire array. The antenna was placed at different locations in the plane of the backlite (a free space region since the backlite glass was not modeled). To model the bulging of the backlite glass, the antenna, when located in the central region of the backlite, was shifted out of the plane of the backlite. The effect of the ground plane (earth) was not considered in the model.

The initial tests were conducted at 2 GHz. The different locations of the antenna on the backlite produced different distortion levels due to interactions with the vehicle. Figure 6.7 shows the vertically (VP) and horizontally (HP) polarized azimuth and elevation patterns of the antenna in free space and in the presence of the vehicle, as calculated by the UTD model. The antenna location in the model of Figure 6.7 gave the lowest distortion among the other locations tested. Even for this location, however, the presence of the vehicle body appears to cause severe interference producing backlobes and sidelobes on the same order as that of the main-lobe. The interference was more severe when the bulge of the backlite was not taken into account.

The study showed that the majority of the interference was caused by the plates representing the passenger-side roof post, the package shelf and the back seat. On an actual vehicle these plates would not be perfectly flat and would usually be covered
Figure 6.7: UTD model results for an end-fire backlite antenna in the presence of a vehicle body. The vertically (VP) and horizontally (HP) polarized azimuth patterns (TOP figure) and elevation patterns (BOTTOM figure) of the antenna in free space and in the presence of the vehicle are shown at 2 GHz.
by some dielectric cover. Therefore, in a real vehicle the effect of the plates on the antenna pattern may be less severe. To test the effect of these dielectric covers using the model, we coated the roof-post, package-shelf and back-seat plates with a slightly lossy dielectric material ($\varepsilon_r = 2.55$ and $\tan \delta = 0.01$). The results, shown in Figure 6.8, indicate that the pattern distortion is reduced when the plates are coated. This result implies that on an actual vehicle the interference from the body may be less severe than that predicted in the model.

One possible method of reducing the interference from the roof post is to tilt the beam of the antenna away from the roof post (by using a microstrip patch array with a tilted beam, for example). Figure 6.9 shows the calculated results for the antenna with its main beam tilted, in the azimuth plane, by $30^\circ$ out of the plane of the backlite. The result seems to indicate that the pattern distortion is not reduced for a tilted beam and that there is no clear advantage to tilting the beam at low frequency.

Finally, the effect of frequency on the interference between the antenna and the vehicle was studied. Figure 6.10 shows the results of the calculation at 10.5 GHz. The antenna was adjusted in this case to produce a wider beam in order to compensate for the reduction in the effective beamwidth of the antenna. This reduction is due to the increased blockage from the roof-post plate at higher frequencies. The results at 10.5 GHz, as well as at 24 GHz, show that the pattern distortion appears to be lower at higher frequency. For side-looking radar applications, the beam patterns in Figure 6.10 may provide adequate beam coverage, especially since the distortion in the patterns is expected to be lower in the actual vehicle.
Figure 6.8: UTD model results for an end-fire backlite antenna in the presence of a vehicle body. The vertically (VP) and horizontally (HP) polarized azimuth patterns (TOP figure) and elevation patterns (BOTTOM figure) of the antenna in free space and in the presence of the vehicle are shown at 2 GHz. The roof-post, package-shelf and back-seat plates were coated with a lossy dielectric.
Figure 6.9: UTD model results for an end-fire backlite antenna in the presence of a vehicle body. The vertically (VP) and horizontally (HP) polarized azimuth patterns (TOP figure) and elevation patterns (BOTTOM figure) of the antenna in free space and in the presence of the vehicle are shown at 2 GHz. The beam of the antenna was tilted 30° away from the plane of the backlite.
Figure 6.10: UTD model results for an end-fire backlite antenna in the presence of a vehicle body. The vertically (VP) and horizontally (HP) polarized azimuth patterns (TOP figure) and elevation patterns (BOTTOM figure) of the antenna in free space and in the presence of the vehicle are shown at 10.5 GHz.
Range measurements, using a full-scale vehicle on a rotating pedestal (see section 2.3.1), were conducted to evaluate the antenna gain pattern distortion due to the vehicle body. A 2-18 GHz AEL horn was used as the vehicle radar antenna. The results over the frequency band of 6-12 GHz showed that for an antenna on the backlite glass the gain pattern was significantly distorted by the presence of the vehicle body, as predicted by the modeling results. Also, the measurements showed that when the antenna is placed on the side of the vehicle (behind the sidelite glass or behind the fender, for example) its pattern exhibited very little distortion due to the vehicle, as would be expected.

In this section we have discussed the use of on-glass antennas for side-looking radar applications. We discussed the use of a broadside array on the sidelite of the vehicle, and an end-fire array on the backlite. We also discussed the use of backlite traveling-wave end-fire antennas (TSA and Yagi) which have the advantage of a simpler feed than the array. Our study showed that the backlite end-fire antennas may be ineffective at high frequencies due to the thickness of the backlite glass (which causes a trapped surface wave). Also, the study showed that the interference between the vehicle body and the antenna was more severe at lower frequencies. Therefore, at higher frequency the vehicle effect is less severe but the glass effect is more severe, and vice versa. Further investigation into reducing the effect of the glass at higher frequencies is needed.

The effect of the vehicle on a sidelite antenna is minimal, since the antenna main beam is pointing away from the vehicle. Therefore, a broadside array, or possibly an aperture antenna, placed behind the sidelite window may be the most practical antenna for the side-looking radar. The only requirement for that antenna is that
the glass effect be minimal. The antenna and radar system must be designed so that the sidelite glass acts as an effective radome cover.
In this dissertation we discussed theoretical and experimental design and analysis tools for mobile antennas. We presented numerical-modeling and experimental design and testing techniques which can be used to develop on-glass automobile antennas. Improvements to the accomplished work and extensions of these techniques were proposed. Antennas for various mobile applications, developed using those tools, were also presented. The effectiveness and limitations of these antennas were discussed and new alternative antenna designs were outlined.

7.1 Numerical Modeling

We have used a wire-grid method of moments (MoM) code to study low frequency-band antennas. The effect of the AM antenna-element location and size on the efficiency of the overall antenna system was studied. The normalized gain level of the antennas was used as a measure of the system efficiency. Cable losses and losses due to impedance mismatch were not included in the model. The MoM code used in the study produced numerical errors for electrically small wire segments (frequencies below 5 MHz). These numerical instabilities of the code were studied by calculating and displaying the current distribution on the wire-grid model. More work needs to
be done to improve the accuracy of the model at low frequencies. The results of the current model at 5 MHz compared well to measurements.

We have successfully used a MoM code to calculate the gain pattern of on-glass resonant-region and high frequency-band antennas. The body of the vehicle was modeled using PEC plates, the glass windows were modeled as impedance sheets, and the antennas were modeled either as PEC plates or thin wires. The FM antenna results compared very well to measurements. The cellular antenna gain patterns had some discrepancies with the measured results but still compared fairly well. More investigation into the discrepancies at the cellular frequencies is needed. Also, an improved MoM model is needed in future work in order to accurately calculate the input impedance of the on-glass antennas.

A Uniform Geometrical Theory of Diffraction (UTD) model was used to calculate the gain pattern of high-frequency-band antennas. In some cases we used a hybrid UTD/MoM approach, where MoM was used to calculate the currents on the antenna and the surrounding geometry and UTD was used to calculate the radiation from that current in the presence of the whole vehicle body. We showed that there are certain advantages and disadvantages to using the UTD technique to model on-glass cellular antennas. We concluded that the MoM was more suited for on-glass antennas at cellular frequencies and that UTD was more effective for higher frequency-band antennas. The UTD model was used effectively in studying collision avoidance radar antennas on automobiles.
7.2 Experimental Measurement Techniques

We presented several experimental techniques that were used in the design and development process of mobile on-glass antennas. We discussed scale-model and full-scale turntable-based range measurement techniques. We concluded that scale-model testing may not be very effective for AM/FM vehicle antennas, but may be useful for higher frequency-band applications. We described the full-scale range measurement systems that we had developed. The range system allows the automobile antennas to be polarimetricaly characterized. A detailed discussion of the setup of the system and the type of measurements that can be performed using the system was presented.

We also presented three mobile-measurement systems (AM/FM, cellular and GPS) that use commercial off-the-air signals to characterize the "real-world" behavior of the automobile antennas. A description of the system setup and the type of measurements that can be performed was given.

7.3 On-Glass Automobile Antenna Designs

7.3.1 AM/FM Radio Antennas

We presented two AM/FM on-glass antenna design concepts: the windshield annular-slot film antenna and the backlite (back windshield) heater-grid antenna with DC power-isolation system. Numerical modeling and experimental results were presented for both antennas. The performance of both antennas compared well to the current standard whip antenna.

We also discussed the problem of nulls in the azimuth antenna gain pattern due to either the presence of the vehicle body (vehicle resonant at FM) or due to polarization mismatch (on-glass antennas have a polarization that varies strongly...
with azimuth angle). The effects of the vehicle body on the polarization of the FM on-glass antennas must be further studied. Ways to control the polarization of those antennas must be determined. Techniques of eliminating or minimizing the polarization mismatch nulls by modifying the polarization of the antenna must also be investigated.

One solution for reducing pattern nulls (as well as multipath nulls) is to use diversity antennas. We gave a detailed discussion of the multipath environment in FM radio and the different diversity systems used in automobiles. We also discussed the use of multiple on-glass antennas in a diversity system. The diversity antennas were used to reduce the effect of multipath fading of signals and also to reduce the directionality of the on-glass antenna patterns. We discussed three different types of on-glass antenna diversity systems: the single antenna structure (backlite heater-grid or windshield film) with multiple feed points (this concept needs further study), the multiple backlite antennas, and the backlite/windshield antenna system. The measurements showed that these antennas can be used successfully in an FM diversity system.

7.3.2 Cellular Telephone Antennas

We discussed the effect of the vehicle body on the on-glass cellular antennas. We concluded that the effect of the vehicle was to introduce interference nulls in the antenna pattern and to cause the antenna polarization to deviate from pure vertical (which is desired).
We presented two on-glass antenna concepts that were numerically modeled and experimentally evaluated using range measurements. The performance of the on-glass antennas compared well to a 45°-tilted glass-mounted pigtail monopole antenna (current standard). In order to evaluate the effectiveness of these on-glass antennas we characterized their on-road performance using the mobile measurement system. We also presented the possibility of using multiple on-glass antennas in order to minimize the interference nulls in the pattern. The antennas can be used either in a diversity system or can be fed as an array.

7.3.3 GPS Antennas

We presented the on-glass single patch antenna. We showed that such an antenna can be designed to perform effectively with an actual automobile GPS system.

One of the disadvantages of the single patch antenna is that it is difficult to control the beam direction. We presented a design of a 4-element traveling-wave antenna array (very simple to fabricate and implement) whose beam direction can be more easily controlled (useful for vehicles with vertically oriented windshields and backlites). We theoretically designed the antenna and experimentally measured its performance. We discovered that the antenna array performance must be improved before it can be used effectively as a GPS antenna. Further investigation of the use of other simple antenna arrays for on-glass GPS applications must be made.

7.3.4 Dual-Use Cellular/GPS Antenna

We also presented a dual-use GPS/cellular antenna design. The advantage of such an antenna is that it would minimize the total number of antennas on the vehicle. We numerically modeled the antenna and showed that it could be designed to meet
the specification for both the GPS and cellular systems. We presented different variations of the antenna concept that are easier to implement on the automobile glass. Some of these concepts were experimentally tested using range and mobile measurements.

7.3.5 Collision Avoidance Radar Antennas

We discussed the use of on-glass antennas for automotive radar applications, and more specifically, the side-looking lane-changing radar. We discussed the use of a broadside array on the sidelite of the vehicle, and an end-fire array on the backlite. We also discussed the use of traveling-wave end-fire antennas (TSA and Yagi) on the backlite. We showed that the end-fire antennas may be ineffective at high frequencies due to interference from a trapped surface wave resulting from the thickness of the backlite glass. We also showed that the interference between the vehicle body and the antenna was more severe at lower frequencies and that at higher frequencies the interference was at an acceptable level (unfortunately, it is at those high frequencies that the effect of the glass increases). Further investigation into reducing the effect of the glass at higher frequencies is needed. From all the antennas presented, the broadside array placed on the sidelite window may be the most practical antenna for the side-looking radar. The only requirement for that antenna is that the system must be designed so that the sidelite glass acts as an effective radome cover.
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