Numerical Modeling of On-Glass Conformal Automobile Antennas

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***Abstract*— This paper presents the development of computer models for the analysis of on-glass conformal automobile antennas. The numerical models used are the method of moments (MoM) and the uniform geometric theory of diffraction (UTD). Models were developed to analyze antennas for low-frequency applications (AM), antennas on a resonant vehicle structure (FM), and high-frequency applications (cellular, global positioning system (GPS), radar). Calculation results were verified using measurements.**

***Index Terms*— Antenna, automobile, geometrical theory of diffraction, modeling, conformal, moment methods, on-glass.**

I. Introduction

THIS paper discusses the development of electromagnetic computer models that can be used to analyze automobile antennas and more specifically on-glass vehicle antennas. Three different models based on the method of moments (MoM) and the uniform geometric theory of diffraction (UTD) were developed (using three different computer codes) 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 II, we discuss the different computer codes used in our study. In Section III, we discuss the modeling of the vehicle at low frequencies [to analyze antennas for low-frequency applications (AM band)]. The results of modeling the vehicle in the resonant region [resonant vehicle structure (FM) radio frequency bands] are given in Section IV. In Section V, we discuss modeling the vehicle antennas at higher frequency bands (cellular telephone, global positioning system (GPS), and vehicular radar bands). The conclusions are given in Section VI.

II. Overview of Numerical Modeling Techniques

The two numerical techniques that we used for our modeling are the MoM and the UTD. The MoM is considered a low-frequency technique while UTD is a high-frequency technique.

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 Newman [1]. ESP4 can calculate the input impedance as well as the gain pattern of the antenna for both azimuth and elevation cuts. ESP4 allows the body to be constructed either as a thin-wire structure, a perfect electric conducting 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.

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 segments become short in terms of wavelength. In [2], this asymmetry is attributed to the computation of nonphysical asymmetric fields for electrically short wires in the original Richmond code [3] (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 [4], 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 vehicle as a wire grid. ESP4 was used to model the vehicle body using plates. We used MoM to model antennas on full-vehicle bodies for frequencies below 1 GHz.

For the high-frequency UTD analysis we used a general-purpose code, the numerical electromagnetic code—basic scattering code (NEC-BSC) Marhefka [5]. 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 not be possible to model an antenna current distribution accurately using UTD, especially if the details of the antenna geometry are important. 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

Manuscript received March 3, 1997; revised January 7, 1998. This work was supported in part by PPG Industries Inc. and the Ohio Supercomputer Center.

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Publisher Item Identifier S 0018-926X(98)05033-9.

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 (TD) methods. The above techniques are not very efficient at modeling an antenna on a vehicle with the radiation occurring in a three-dimensional (3-D) space. It is believed that using the MoM and UTD techniques is the most efficient method for modeling vehicle antennas.

III. Low-Frequency Band Analysis

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

A 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, since both the antenna element and the vehicle body form the radiating antenna structure.

A. 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 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 since the feed-point region is not modeled accurately. The wire-grid model, however, can be used to study the effect of the location and size of the antenna element on the overall antenna efficiency, by calculating the far-field gain of the automobile antennas. Losses due to impedance mismatch and cable attenuation were not considered in this study.

1) 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 30 cm or $\lambda/1000$ at 1 MHz. Some wire segments were only about 5-cm long. To study the accuracy of the ESP4 wire-grid model, we checked for symmetry of the MoM calculated current modes on a symmetric grid. The results showed asymmetry in the calculation of the currents even as we increased the frequency from 1 to 50 MHz (due to numerical errors; see Section II).

As discussed in Section II, the authors of MBCPF164 claim to have corrected the asymmetry problem in ESP4. Calculating the current modes using MBCPF164 (on the same symmetric geometry used with ESP4) produced symmetric results at frequencies of 50 MHz down to 5 MHz (see Fig. 1). However, asymmetry developed below 5 MHz. This seems to indicate that even for the MBCPF164 bridge-current formulation the vehicle wire segments used in the model are too small electrically at 1 MHz (the AM band) and cause similar numerical errors in the MoM calculations. Further studies are needed 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 antennas on the vehicle. The antenna behavior is not expected to change significantly between 5 and 1 MHz since the size of the antenna in both cases is electrically small.

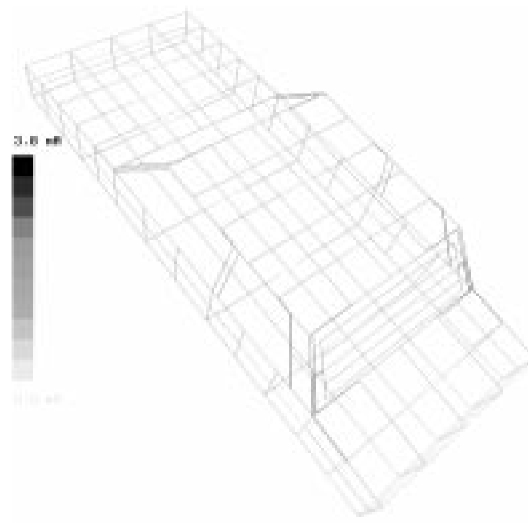

Fig. 1. Magnitude current display on a wire-grid model due to a plane wave incident from back of vehicle (above ground plane). Result shows right–left symmetric current distribution. Frequency = 5 MHz.

B. 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 several automobile antennas (at 5 MHz) and compared the results to measurements (at 1 MHz) [6]. The antennas had different locations and sizes. The comparison showed that the calculated results were within 2 dB 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 (at 5 MHz) can be used effectively to study the efficiency of the AM antenna system.

IV. 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, however, the details of the antenna-element structure affect the performance of the overall antenna. The geometry and position of the antenna-element influence the parameters of the vehicle antenna such as gain patterns and impedances.

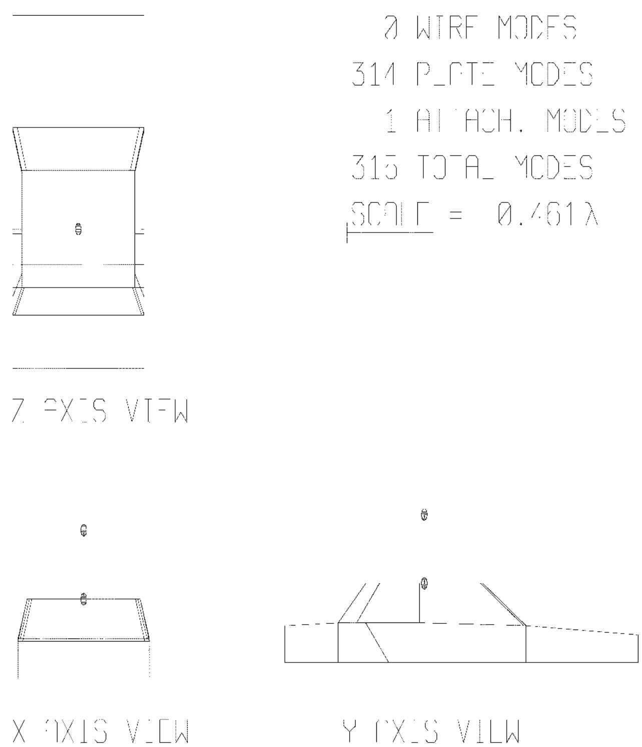

Fig. 2. Geometry of an ESP4 model of a FM rooftop monopole.

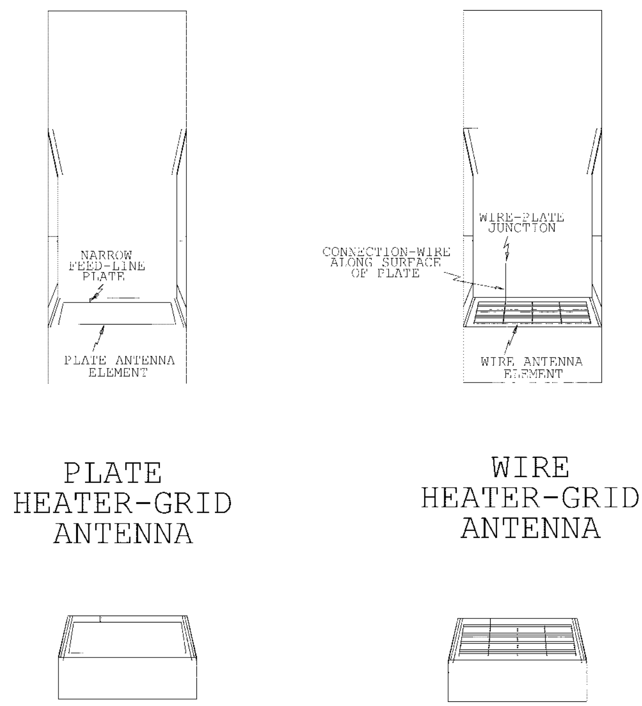

Fig. 3. Geometry of an ESP4 model of a plate and wire backlite heater-grid antenna.

A. Plate Model versus Wire-Grid Model

1) 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 types 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 short. Our analysis showed that the mesh size (or length of the current-mode segment) had to be smaller than 0.01λ (especially near the feed point) in order to obtain accurate results, making the wire-grid model computationally inefficient.

3) The Plate Model: The vehicle was then modeled using perfectly conducting plates. Fig. 2 shows the geometry of a plate model used. The figure also shows a rooftop $\lambda/4$ monopole antenna modeled as a thin wire 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 0.1λ to 0.2λ (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 antenna elements on the vehicle 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 approximately 1 cm ($\approx \lambda/300$) 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 Fig. 3. 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 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 Fig. 3). Therefore, the above feed model cannot 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.

If the antenna element must be constructed from wires, then a wire-plate attachment mode must be used. In ESP4, the wire-to-plate junction must occur at a point on the plate a distance no closer than 0.1λ (about 30 cm @ FM) to the edge of the plate, in order to ensure accurate modeling of the current flow at the junction. 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 Fig. 3). Instead of connecting the wire antenna directly to the plate it is possible to connect it to a connection wire, which, in turn, extends just above 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, but not accurate impedance results. To obtain accurate impedance results the antenna must be placed a distance of 0.1λ from the edge of the plate such as the wire antenna in Fig. 2.

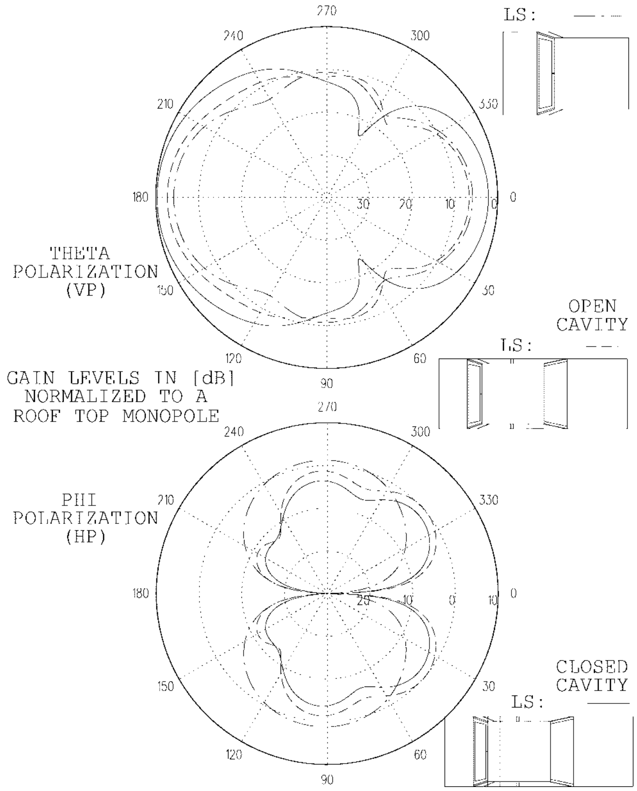

Fig. 4. ESP4 model of a backlite plate-heater-grid antenna, center feed, studying the effect of the geometry. Azimuth pattern at $88°$ elevation angle; frequency $=$ 98 MHz (LS: LineStyle).

3) The Plate-Model Geometry: The next step was to determine how much of the vehicle body was needed to accurately model the vehicle antenna. Fig. 4 shows the FM azimuth patterns for three models of a backlite plate-heater-grid antenna. The first geometry only models the backside 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: completely closed except for window openings). The results indicate that modeling the full vehicle, including the passenger compartment, is necessary in order to get accurate results.

In order to study the effect of glass on the vehicle model, we used the sheet impedance approximation of thin dielectric plates in ESP4 [1]. The sheet impedance for vehicle glass at FM frequencies is approximately equal to $-j7500\ \Omega/\Box$. 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.

4) 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 [6]. To verify whether our model is consistent with this result, we compared the performance of the plate-heater-grid and the wire-heater-grid antennas shown in Fig. 3. In those two models, the plate antenna element has the same dimensions as the wire grid. The calculated FM pattern results were identical for both antennas. This result also validates that both feeding techniques used (the plate–plate connection and the wire-plate connection) produce accurate gain pattern calculations.

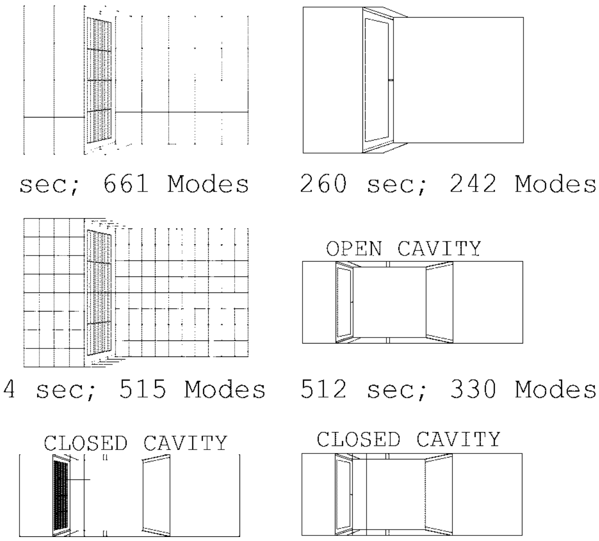

Fig. 5. Different ESP4 FM antenna models. CPU times on the Cray Y-MP8/864 Ohio supercomputer.

5) Computer CPU Times for Different Models: Fig. 5 shows CPU times (on a Cray Y-MP8/864) and total current modes for some of the models that we used. We see from these results how closing the cavity increases the CPU time by 100%. 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 model.

B. Ground-Bounce Effect

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 the ground-bounce term in the model. We can do that if we use image theory. To add the ground-bounce signal to the direct signal we calculate the gain pattern of the antenna twice: once for the incident field at an angle α 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 complex reflection coefficient of the ground Γ (ground-bounce signal). The total gain pattern of the antenna is then calculated from the sum of the two signals.

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

C. Arbitrary Polarization Calculation

The computer modeling tools that we have developed can calculate and display the antenna gain pattern for any required signal polarization. We can calculate the gain pattern of the vehicle antenna for two orthogonal signal polarizations (E_θ and E_ϕ). From those two polarizations we can mathematically calculate the gain pattern for any given signal polarization.

D. 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. 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 be expected to compare exactly to the model results.

1) Fender Whip Antenna The first antenna used in the comparison of the models to measurements is the fender whip monopole. Fig. 6 shows the azimuth pattern (at 88° elevation angle with respect to the vertical axis) at 98 MHz. The pattern is given for both the E_θ (vertical polarizations—VP) and E_ϕ (horizontal polarizations—HP). Both the measured and calculated data have been normalized to the rooftop 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 2 dB of each other for the vertical polarization and within 0.1 dB 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. However, the rooftop 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.

2) Heater-Grid Antenna: The next set of antennas that were compared to measurements were the backlite heater-grid antennas. Fig. 7 shows the results for the top center-feed antenna. The model results compare very well with the measured results. The signal averages are within 1.5 and 0.5 dB 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 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.

V. High-Frequency Band Analysis

In this section, we will present the results of modeling the vehicle at high frequencies at which the vehicle body is electrically large. We will show results of analysis of cellular telephone band (824–894 MHz in the United States) antennas. We will also discuss the modeling of antennas at higher frequencies for such applications as GPS and vehicular radar.

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.

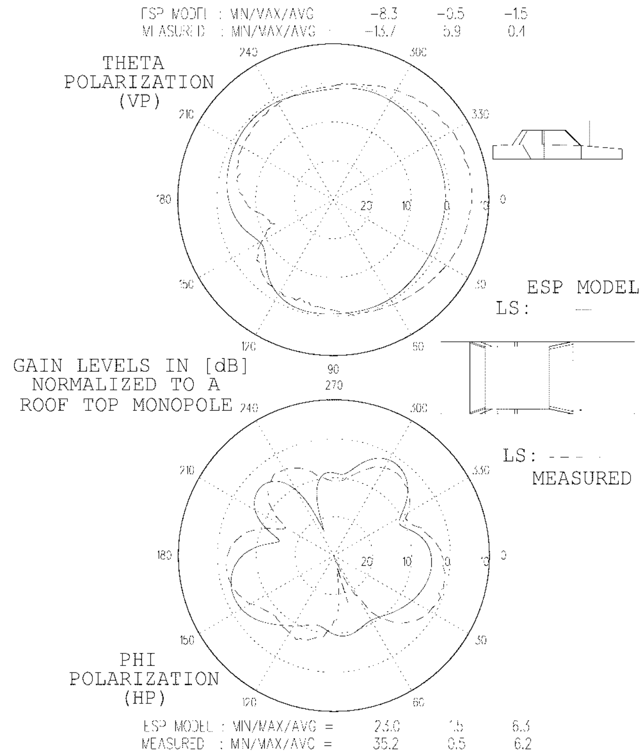

Fig. 6. Fender-whip antenna. Comparing ESP4 model results and measured results. Azimuth pattern at 88° elevation angle; frequency = 98 MHz (LS: LineStyle).

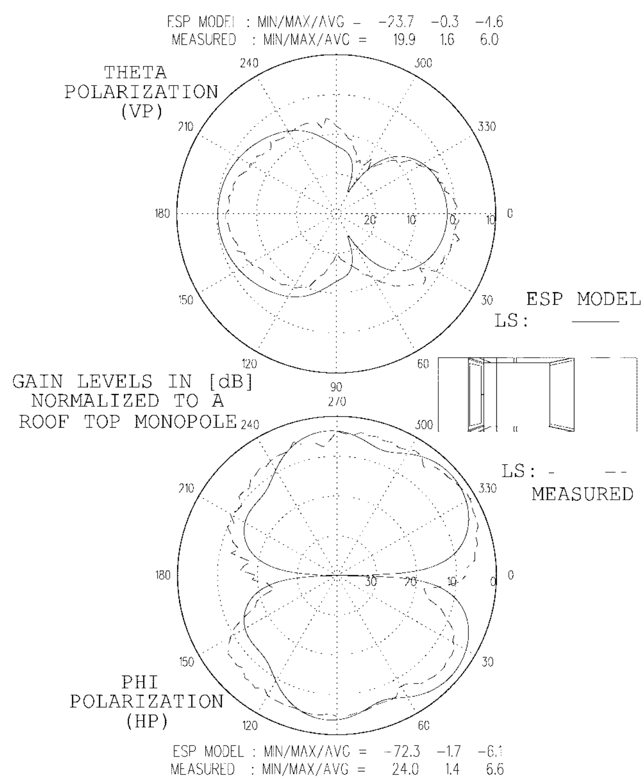

Fig. 7. Center-feed backlite heater-grid antenna. Comparing ESP4 model results and measured results. Azimuth pattern at 88° elevation angle; frequency = 98 MHz (LS: LineStyle).

UTD can also be used at these frequencies but modeling the details of the antenna geometries may be difficult.

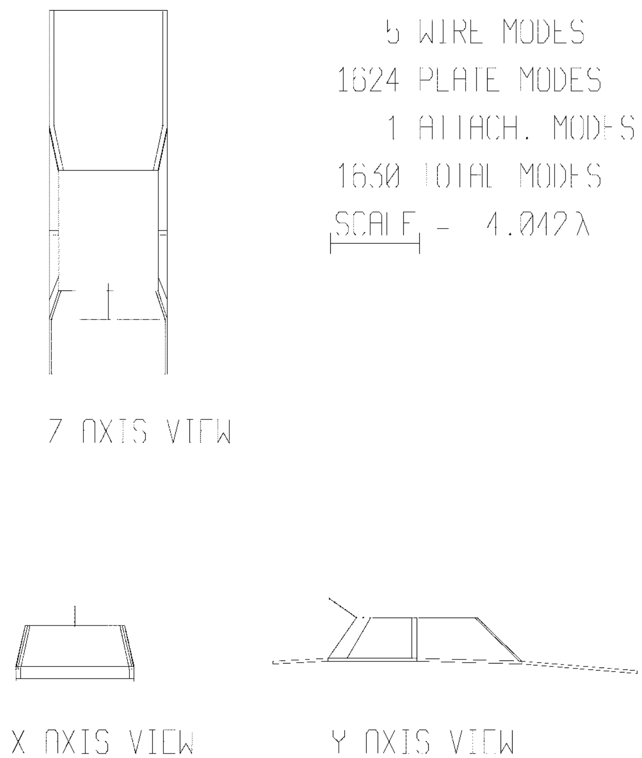

Fig. 8. Geometry of an ESP4 model of a cellular pigtail antenna.

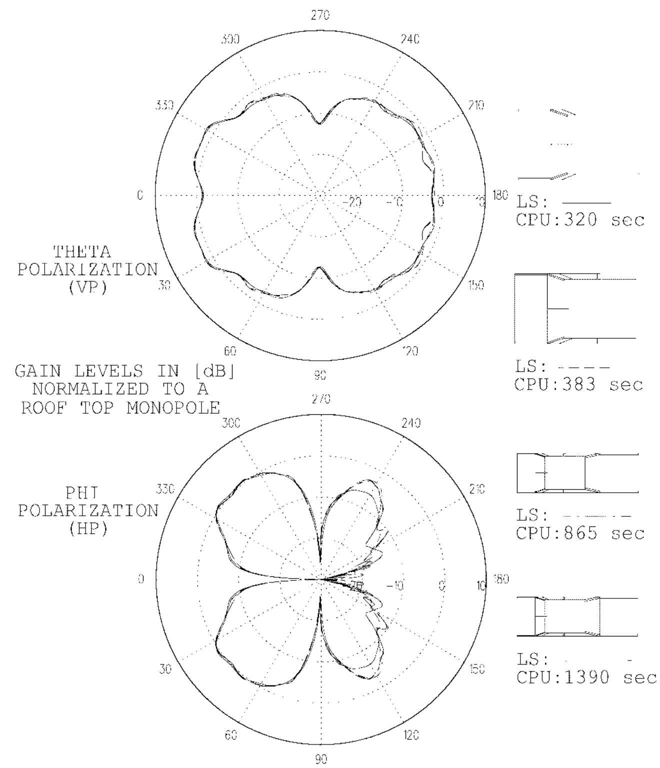

Fig. 9. ESP4 model of a cellular pigtail antenna. Effect of varying the geometry. Azimuth pattern at 89.5° elevation angle; frequency = 860 MHz. CPU run times are indicated (LS: LineStyle).

A. Plate-Model Study

The ESP4 plate model 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 IV (Fig. 3). All the results given in the next sections are for a model using the wire-plate feed-connection technique. All the cellular antenna pattern results were normalized to a rooftop ($3\lambda/4$ colinear array) monopole antenna pattern.

1) The Effect of the Geometry: To minimize the number of modes 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 (pigtail) connected to the back edge of the roof, as shown in Fig. 8. The vehicle geometry shown does not model the inside of the vehicle and has very narrow front, back, and side panels. A more detailed model geometry is not needed since the vehicle in the cellular band is not resonant. To determine whether the full vehicle body must be modeled, we calculated the antenna pattern for four geometries of the vehicle, as shown in Fig. 9. The pattern, at a particular angle, is affected by the plates that obstruct the path of the rays from the antenna. Since the pigtail antenna extends above the roof line, it is not affected by the side plates on the vehicle. From the results of Fig. 9, it also appears that the plates in the front of the vehicle have little effect on the antenna pattern, especially toward the backside. But even toward the frontside of the vehicle the change in the pattern due to the extra plates is minimal.

2) The Effect of the Glass: The pigtail antenna extends above the roof line and we do not expect it not to be affected by the glass on the vehicle. However, for an on-glass antenna, the effect of the glass must be modeled. In the cellular band, the sheet impedance for glass ($\approx 0.01\lambda$ 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 rectangular $3\lambda/4$ loop antenna that is fed against the roof and that is located in the plane of the backlite. The effect of the glass was tested by calculating the pattern of the antenna with and without a glass sheet. The results 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 can be eliminated from the model (saving computer storage and CPU time) and the antenna can be replaced by its larger free-space counterpart. 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, much of the signal going toward the front of the vehicle has to pass through the passenger compartment and may be affected by the front end of the vehicle. Fig. 10 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.

3) Computer CPU Times for Different Models: The CPU run times (on a Cray Y-MP8/864) of the models that were

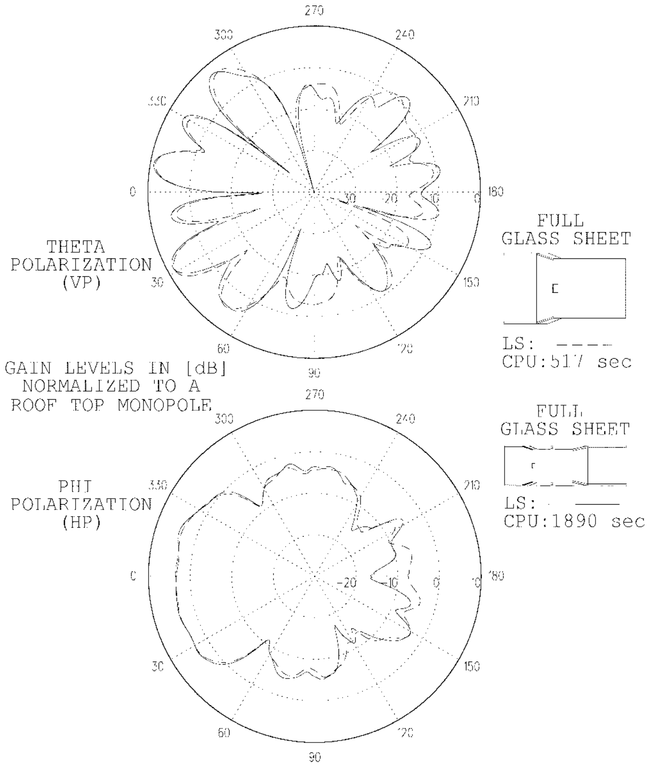

Fig. 10. ESP4 model of a backlite cellular loop antenna. Effect of varying the geometry. Azimuth pattern at 89.5° elevation angle; frequency = 860 MHz. CPU run times are indicated (LS: LineStyle).

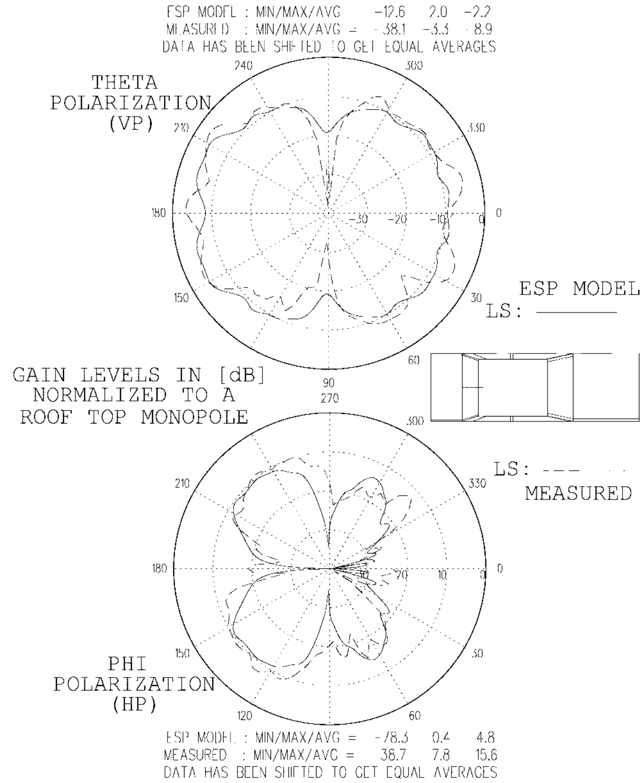

Fig. 11. A cellular pigtail antenna. Comparing measured and ESP4 model (*shifted*) results. Azimuth pattern at 89.5° elevation angle; frequency = 860 MHz (LS: LineStyle).

tested are indicated in Figs. 9 and 10. The results show how the CPU time increases significantly with the increase in the size of the model.

B. Experimental Verification

An exact model of the ESP4 pigtail antenna was built. The azimuth pattern at Θ and Φ polarizations (at 89.5° elevation angle with respect to the vertical axis) at 860 MHz were measured. Fig. 11 compares the calculated and measured patterns, both of which were normalized to the reference rooftop ($3\lambda/4$ colinear array) monopole pattern data. The results show that the model pattern has the same features as the measured pattern but a higher signal level (the plotted data has been shifted to obtain equal averages). The difference in the signal levels is due to inaccuracy in modeling the reference antenna, which was a commercial rooftop monopole with an in-line air-core inductance coil. The coil was modeled into the ESP4 reference antenna as a lumped inductance. A more accurate model of the reference monopole is needed for future calculations.

We know from previous analyses that the loop antenna pattern toward the front of the vehicle depends on the geometry of the vehicle in the front. Fig. 12 shows the pattern results of the measured loop antenna and the model antenna on a full vehicle with a glass backlite. The plotted data has been shifted to obtain equal averages between the model and measured data because of the inaccuracy of the reference antenna model used to normalize the calculated data (same model used for pigtail antenna). The results show that the model pattern closely resembles the measured pattern for angles in the back of the vehicle. There are small discrepancies between the two patterns for angles toward the front of the vehicle. These discrepancies could be due to 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. Overall, however, the model results do compare well with the measurements. Including more detail in the model may improve the results, but at an expense of increase in memory storage and CPU time.

C. UTD: A Second Approach

The UTD solution presents some advantages to the analysis of the cellular antenna (larger geometries possible and ray-tracing is possible).

The CPU time required to run the UTD analysis was about half that required by MoM. The CPU time is reduced further by about 65% if the second-order reflection and diffraction terms are not included in the UTD calculations. These second-order terms have little effect on the cellular antenna pattern.

We compared the UTD calculated patterns of the pigtail antenna to those of the MoM calculations and the measured results. The results showed that the UTD model can accurately predict the behavior of the pigtail antenna [6].

D. Other High-Frequency Applications

We have also analyzed vehicle antennas for GPS (1575 MHz L1 frequency) and radar (10.5 and 24 GHz) applications. In

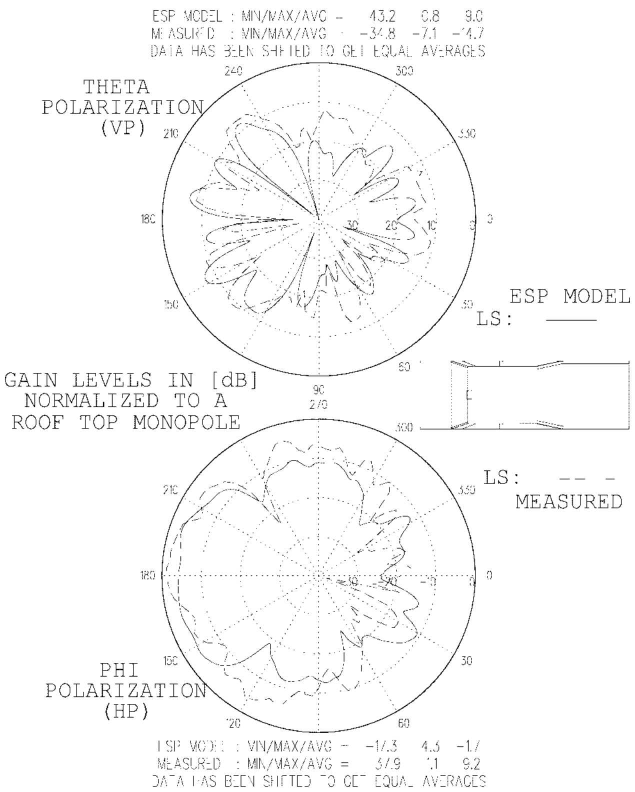

Fig. 12. A backlite cellular loop antenna. Comparing measured and ESP4 model (*shifted*) results. Azimuth pattern at 89.5° elevation angle; frequency = 860 MHz (LS: LineStyle).

both cases the vehicle is electrically large. 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 V-C). We have successfully used the above methods to study on-glass GPS and radar automobile antennas [6].

VI. Conclusions

We have described the development of MoM and UTD computer models that can be used to analyze on-glass automobile antennas. A wire-grid MoM model was used for low-frequency antennas (AM band). The model was used to study the effect of the antenna location and size on the overall antenna efficiency. A plate based MoM model was used at frequencies where the vehicle is resonant (FM band) as well as at higher frequencies (cellular GPS). Antenna-impedance and gain-pattern data were calculated and compared to measurements. At higher frequencies, it may not be possible to model the full vehicle geometry due to computer memory and CPU time limitations and UTD analysis becomes more practical (allows larger bodies and ray-tracing techniques). We have successfully modeled cellular, GPS, and vehicular radar antennas using UTD.

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