# Highly Efficient Large-Domain Moment-Method Analysis and CAD of Radio-Frequency Antennas Mounted on or Situated in Vehicles

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## Abstract

*Highly efficient large-domain moment-method analysis and CAD of radio-frequency antennas mounted on or situated in vehicles are presented. A Golf GL is analyzed, with different wire antennas mounted on or situated in it, at 98 MHz (FM) and 860 MHz (cellular telephone band). For different antennas, parts of the vehicle that are of the most importance for the antenna-vehicle electromagnetic coupling are identified. Influence of the positioning and orientation of the antennas on the antenna reflection coefficient is studied. It is demonstrated that an accurate and efficient numerically rigorous electromagnetic computational method must be considered as an indispensable tool for the analysis and design of vehicular wireless communication systems.*

## 1. Introduction

Modern radio, wireless, and satellite communication and radar systems often involve vehicles. From the electromagnetic point of view, these vehicles are antennas and scatterers consisting of metallic and dielectric parts of very complex and different shapes. Given that today's communication and radar applications cover practically the entire electromagnetic frequency spectrum, vehicles included in the communication and radar systems range electrically from very small to ultra large objects. For instance, an automobile in the AM radio band (535 – 1705 kHz) is on the order of $\lambda/100$ ($\lambda$ being the wavelength of the excitation). An automobile in the FM radio band (88 – 108 MHz) is on the order of $\lambda$, i.e., it is a resonant structure. The size of an automobile in the cellular band (824 – 894 MHz in the United States) and GPS (1227 and 1575 MHz) is on the order of few tens of $\lambda$. Finally, a vehicle in the radar Ku band (12 – 18 GHz) is on the order of thousands of $\lambda$. Primary radiators, however, are usually on the order of $\lambda$. Most often these are various kinds of wire antennas, combined wire/plate antennas, microstrip patch antennas, and antenna arrays. The antennas are either mounted on or situated in the vehicles. In some designs, slot antennas and cavity-backed antennas are built into the vehicle bodies.

This is the most challenging and extremely difficult general radiation/scattering electromagnetic (EM) problem, which can be approximately solved only by means of computational electromagnetics (CEM). When the size of the vehicle is neither very large nor very small compared to $\lambda$, asymptotic (high- and low-frequency) CEM methods cannot be used to approach the problem. In the intermediate size region, often called the resonance region, a rigorous numerical solution of EM field equations is required. There is a lack of adequate CEM techniques and methodologies for dealing with this problem with an engineering effectiveness.

## 2. Highly Efficient CEM Analysis of Vehicles

By the rule, partial differential-equation (PDE) methods, such as finite-difference and finite-element methods, require supercomputers even for the simplest 3D open-region problems. In this paper we therefore adopt an integral-equation (IE) formulation for EM modeling of vehicles using a personal computer (PC). We utilize as unknown quantities in integral equations surface equivalent electric and magnetic currents over metallic and dielectric surfaces. Boundary conditions for the tangential components of the electric and magnetic field vectors are stipulated to be satisfied on the surfaces.

Within practically all the existing IE methods, surfaces are modeled by planar rectangles and triangles (a brief review of methods can be found in [1]). The components of the electric and magnetic surface current density vectors are commonly approximated by 2D pulse functions and rooftop functions. As the consequence of the adopted low-order current approximation, these methods imply that the surface elements must be electrically very small (on the order of $\lambda^2/100$ in area), and result in a very large number of unknowns to obtain results of satisfactory accuracy, with all the associated problems.

As the basic surface element we adopt a bilinear quadrilateral [1-3], shown in Fig.1. This, very flexible, quadrilateral is defined uniquely by its four vertices, that

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can be positioned arbitrarily in space. Its edges and all parametric coordinate lines are straight, but its surface, a bilinear surface, is generally curved. The quadrilateral (surface) can be described analytically by a bilinear equation of two local parametric (generally non-orthogonal) coordinates, $u$ and $v$. We approximate the $u$- and $v$-components of electric and magnetic current density vectors over the surface by 2D polynomials in $u$ and $v$ [1-3]. The polynomial degrees can be high, enabling electrically relatively large surface domains (on the order of a couple of wavelengths in each dimension). Consequently, the resulting number of unknowns for a given problem is greatly reduced (for more than an order of magnitude) when compared with small-domain CEM methods.

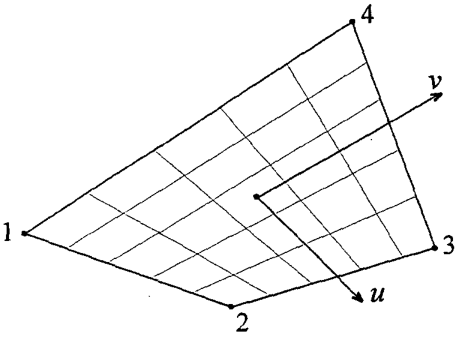

**Fig.1.** Bilinear quadrilateral-surface

With such an efficient CEM tool for large-domain surface EM modeling we are able to analyze electrically large vehicles on even a PC. In this paper we present large-domain CEM models of an automobile (Golf GL) in the antenna mode of operation, at frequencies that are of great practical importance.

## 3. Radiation by Golf GL at 98 and 860 MHz

In this section, we analyze a number of communication antennas mounted on, or positioned inside a Golf GL. Fig. 2 shows the geometrical model of the vehicle and locations of the antennas analyzed.

First, consider the two types of FM radio antennas, a fender-whip λ/4 monopole antenna (Fig.2.A) and backlite heater-grid FM antenna (Fig.2.C). Note that although the backlite antenna is a wire grid, it has been modeled as a conducting surface, as the computation is faster while accurate enough [4]. Fig. 3 shows the far field radiation pattern (at 88° elevation angle) of the analyzed antennas. As expected, the heater-grid antenna has a radiation pattern similar to that of horizontal dipole, with the two nulls shifted due to EM coupling between the antenna and the vehicle. The pattern of the fender-whip antenna has a null in the direction defined by $\phi$=345°, which is the direction of the passenger compartment.

The Golf GL model is 2.4 $\lambda^2$ large in area at 98 MHz and complex in shape. For the analysis of fender-whip antenna, the total number of unknowns for the approximation of currents amounts to 505. The CPU time required for the analysis is only 72 seconds on a PC AMD-K6 266 MHz with 128 MB of RAM memory. For the analysis of backlite antenna, the number of unknowns amounts to 238 (using of symmetry) and the required CPU time is 79 seconds on PC AMD K-6 266 MHz.

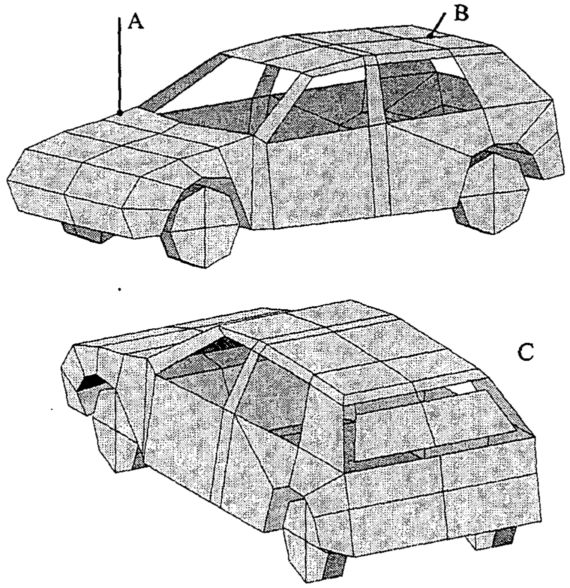

**Fig. 2.** Simulated geometrical model of a Golf GL. The model is constructed from 160 bilinear surface elements. (A) Fender-whip antenna, (B) Pig-tail antenna, (C) Back-lite heater grid antenna

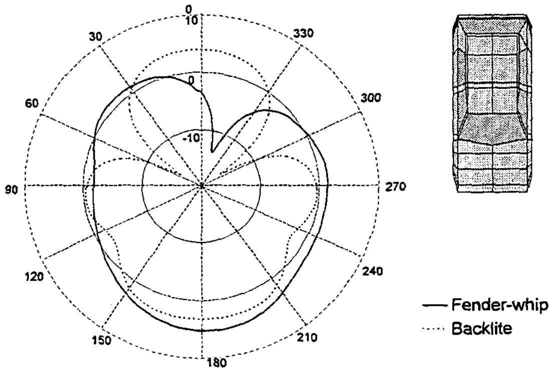

**Fig. 3.** Radiation pattern in the azimuth plane (at 88° elevation angle) of the fender-whip and backlite heater grid antenna.

Next, we analyze two types of cellular-telephone band antennas, pigtail antenna, and a dipole positioned inside the passenger compartment (an approximation of mobile telephone antenna). Fig.4 shows the current distributions on a Golf GL with a pigtail $3\lambda/4$ oblique-monopole antenna mounted on the car roof and a $\lambda/2$ dipole antenna situated inside the car (about the car center), respectively, at 860 MHz. The area of the Golf model is very large at 860 MHz (approximately $185\lambda^2$). The model consists of 315 surface elements. The total number of unknowns in the large-domain MoM analysis with the use of symmetry is 3,081, and the CPU time only 100 minutes on a PC AMD-K6 266 MHz.

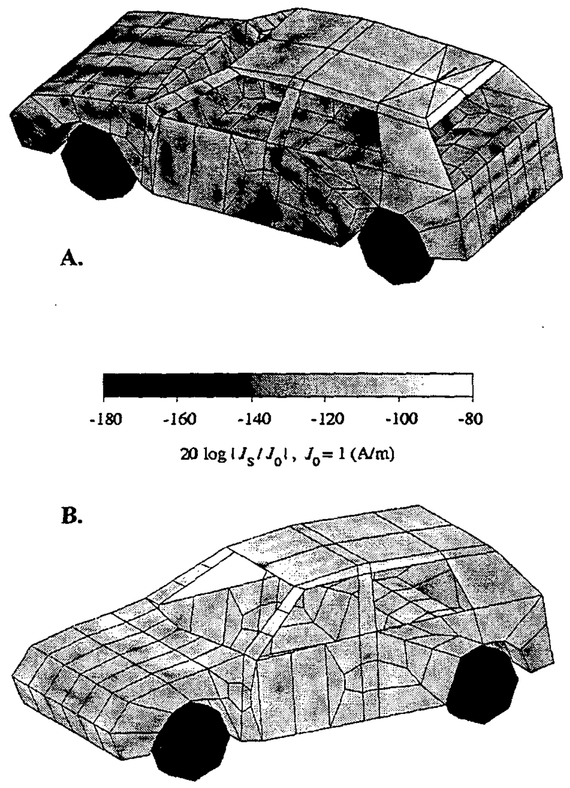

**Fig. 4.** Simulated surface current distribution at 860 MHz for (A) pig tail antenna, (B) dipole antenna situated inside the vehicle.

Shown in Fig.5 are the simulated far-field patterns of the pigtail and inside-dipole antenna. Many deep nulls in the pattern of the dipole antenna situated inside the passenger compartment are due to the heavy coupling between antenna and the vehicle body (higher magnitude of induced currents on the vehicle body - Fig.4). An externally mounted pigtail antenna is thus a preferable terminal antenna for car mobile communications.

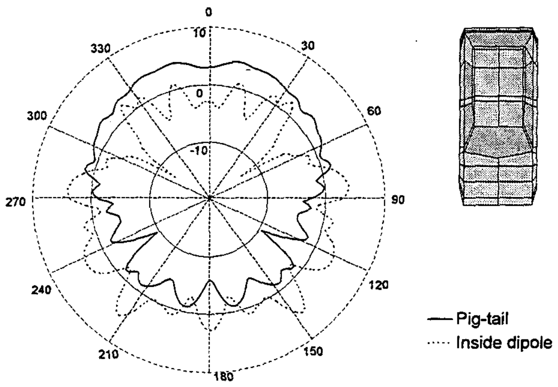

**Fig. 5.** Radiation pattern in the azimuth plane (at 88° elevation angle) of the pig tail antenna and the dipole antenna situated inside the vehicle.

## 4. Modeling of vehicles at wireless communication frequencies

Numerical analysis of EM interactions that are encountered in vehicular mobile communication systems is often very hard and computationally demanding task. In this section, we explore the influence of modeling to the accuracy and computational cost of the simulation.

Consider a pigtail oblique monopole antenna described in previous section. Due to localization of the induced electric currents (Fig.4.A) it is logical to assume that the upper part of the vehicle body (Fig.6) will have the major influence to the characteristics of the antenna. We use three levels of the vehicle approximation: (A) only the roof with support, (B) vehicle roof only, (C) infinite PEC ground plane in place of vehicle roof.

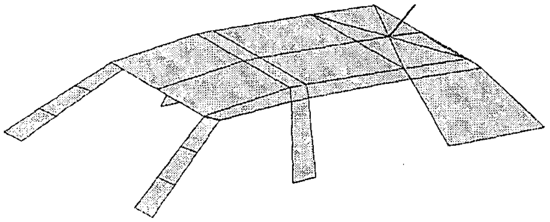

**Fig. 6.** Pig tail antenna - model of vehicle roof with support.

Fig. 7 shows the far field radiation patterns obtained using the above approximations, compared to the original modeling case (whole vehicle). We notice that infinite PEC ground plane does not describe well the far field behavior of the EM field, while the other two approximations follow the "numerically exact" solution, predicting all the major nulls. Table 1 shows the required number of unknowns, computed antenna impedance and the CPU time on PC AMD K-6 266 MHz for all the four modeling cases. We notice that all the models predict the impedance of the antenna extremely consistently. However, the impedance result obtained using ground plane approximation does not depend on the position of the antenna on the roof, and is thus valid only for antennas that are sufficiently distant from the roof edges.

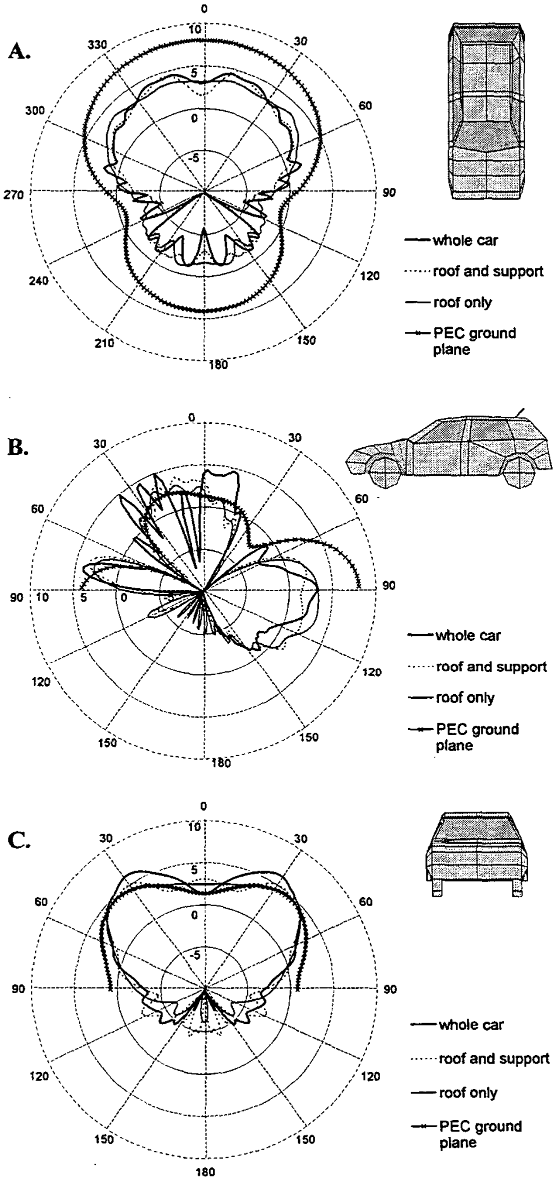

**Fig. 7.** Radiation pattern of the pig tail antenna for different levels of geometry details modeled. (A) far field in the azimuth plane (at 88° elevation angle), (B) far field in the elevation plane (at 0° azimuth angle), (C) far field in the elevation plane (at 90° azimuth angle)

| | Nunknowns | Z [ohm] | CPU time |
|---|---|---|---|
| whole car | 3081 | 42.15 - j48.80 | 100 min |
| roof and support | 425 | 41.99 - j48.57 | 44 s |
| roof only | 329 | 41.17 - j48.22 | 26 s |
| PEC ground plane | 3 | 42.41 - j51.83 | 0.4 s |

**Table 1.** Number of unknowns, CPU time and impedance obtained using four levels of geometry modeling.

## 5. CAD of vehicle mounted antennas

In this section, we explore possibilities for improvements of the fender-whip and pig tail antenna properties. First, we consider the fender-whip antenna (Fig.2.A). Shown in Fig. 8 is the reflection coefficient of the fender-whip antenna for different distances of the antenna from the vehicle's front end. Since the length of Golf GL at 98 MHz is approximately 1.2λ, little improvement can be made with limited change in the antenna position.

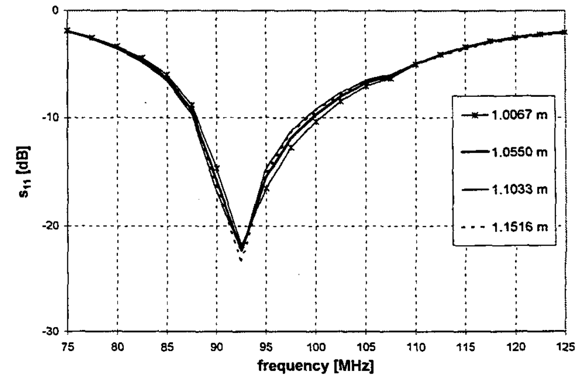

**Fig. 8.** Reflection coefficient of the fender-whip antenna versus frequency, for different distances of the antenna from the vehicle's front end.

Next, consider the pig tail antenna with the subtended angle of 45° (Fig.2.B). Fig. 9 shows the reflection coefficient of the pig tail antenna versus frequency, for different distances of the antenna feeding point from the roof edge. We notice that resonant frequency does not change with position of the feeding point; however, the reflection coefficient can be improved by more than 10 dB if antenna feed point is shifted only 13 cm.

Fig. 10 shows the reflection coefficient of the pig tail antenna versus frequency, for different subtended angles of the antenna when the distance from the roof edge is fixed to 21.3 cm. We notice that the increase in the subtended angle reduces the resonant frequency. Optimal match for (fixed) distance from the roof edge of 21.3 cm is achieved using the antenna angles between 45° and 55° (reflection coefficient has the value of –44 dB).

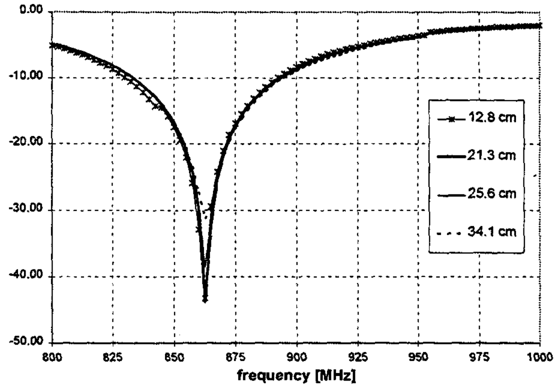

**Fig. 9.** Reflection coefficient of the pig tail antenna versus frequency, for different distances of the antenna from the roof edge.

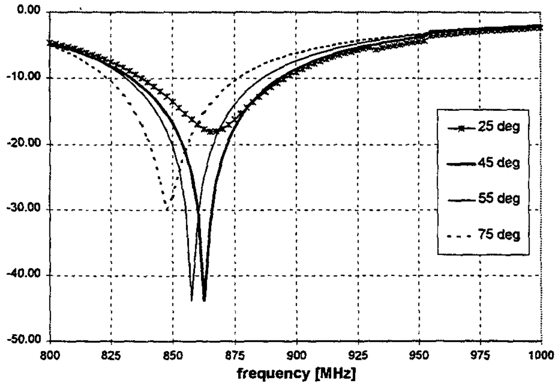

**Fig. 10.** Reflection coefficient of the pig tail antenna versus frequency, for different angles of the antenna; the distance from the roof edge is fixed to 21.3 cm.

## 6. Conclusions

This paper presents a highly efficient large-domain moment-method computational tool and its applications to vehicle mounted antenna characterization and design. A Golf GL is analyzed, and performances of several practical vehicular antennas in FM-radio and wireless-communication bands have been evaluated. The importance of careful modeling has been demonstrated through "real-life" examples. It has been shown that an efficient and highly accurate EM-field computational method, such as the presented large-domain MoM, must be considered as an indispensable tool for the design and characterization of modern vehicular mobile communications systems.

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