Finite-Difference Time-Domain Modeling of Ultra-High Frequency Antennas on and Inside the Carbon Fiber Body of a Solar-Powered Electric Vehicle

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Abstract **─** Finite-difference time-domain simulations are performed on a 900 MHz band antenna inside and outside the carbon fiber body of a solar-powered electric vehicle. Data is analyzed to determine the optimal antenna placement for transmission to a receiving antenna located toward the rear of the solar vehicle. Modeling data is compared to experimental results. Computational fluid dynamics are used to determine acceptability of external antenna placement. It is found that the ideal antenna would be inside the vehicle's body and oriented vertically, but that the portion of the body surrounding the antenna must be constructed of a non-conductive material.

Index Terms **─** Antenna CFD, FDTD and vehicle antenna modeling.

I. INTRODUCTION

Since the first World Solar Challenge in 1987, student groups and others from around the world have been designing, building and racing solar-powered electric vehicles. These vehicles, primarily one-person, three-wheeled vehicles are designed to travel during the daylight hours for one to two weeks across 1200 to 2400 miles, while only charging their batteries from their solar array. During this race, the solar vehicle is flanked in front and back by lead and chase vehicles in order to protect the solar vehicle.

Radio communication, both audio and telemetry data, is required between these vehicles to enhance safety and racing strategy. The telemetry receiving antenna is usually located behind the solar vehicle in the chase vehicle.

Over the last two decades, radio and cell

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phone communication in passenger vehicles has been studied by several types of modeling and experimentation [1]. Applications from modeling and experimentation include installing miniature printed magnetic phonic crystal antennas into vehicular platforms and studying the effects of signal bounce and attenuation on vehicles in urban environments [2, 3]. Modeling methods have included Method of Moments (MoM) [4-8], Geometric Theory of Diffraction (GTD) [9], Finite-Integration (FI) [10, 11] and Finite-Difference Time-Domain (FDTD) [12]. All of these methods require significant computer resources to solve and report the field strength or gain patterns and polarization information of antenna signals within or around a vehicle. FDTD is a simple and accurate approach to a differential numerical solution of Maxwell's curl equations [13]. The FDTD method allows simulation of complex geometric shapes, uses no linear algebra, is accurate and robust, treats impulsive or nonlinear behavior naturally, is a systematic approach to modeling and is becoming increasingly powerful as computing resources improve [13].

The FDTD method was first described in 1966 by Yee [14]. This research proposed what is now known as the Yee cell, a method of gridding a physical model in order to solve alternately for the electric and magnetic fields in the modeling space as the simulation steps through time. This method is a numerical solution to Maxwell's curl equations, which describe the behavior of the electric and magnetic fields of EM radiation in one, two, or three dimensions. Until recently, most three dimensional simulation methods including FDTD, were too computationally demanding to simulate large models. However, advances in personal computing technology have enabled highly accurate modeling of complicated structures in three dimensions.

This study uses Remcom's XF 7.3.0 software to simulate the electromagnetic fields around the 2012 Oregon State University solar vehicle, resulting from a 900 MHz band antenna. Antenna placement is explored. The goal of the investigation is to determine the optimal antenna placement for data transfer to the chase vehicle during the solar vehicle competitions. To determine effects of antenna location on vehicle efficiency, all simulations with external antenna locations are also analyzed for aerodynamic effects using computational fluid dynamics.

II. METHODS

FDTD simulations were carried out using Remcom's XF 7.3.0 software. A PEC monopole antenna with a center frequency of 915 MHz was modeled to represent the antenna of the FLC910E Ethernet radio from Data-Linc Group. The solar vehicle body, titanium frame and human driver were modeled in XF, with the vehicle body modeled as a thin carbon fiber shell with a conductivity of $2x10^5$ S/m [15]. The antenna was fed with a 50 ohm voltage source excited at 915 MHz. Outer boundary conditions were all set to Perfectly Matched Layer (PML) conditions with seven absorbing layers. Far field sensors were used to detect realized gain. Realized gain is the gain of the antenna reduced by impedance mismatch losses. This allows for a consistent, qualitative comparison of system performance between potential antenna locations. Solidworks Flow Simulation 2013 was used to perform the Computational Fluid Dynamics (CFD) for 50 mph air flow. A computational domain that is 80 meters long, 20 meters wide and 6 meters tall was setup with a velocity opening in the front of the vehicle, a ground plane with moving air below the vehicle and environment (1 atmosphere at STP) pressure openings on the remaining sides of the car. The vehicle was located 30 meters from the front of the opening, centered width wise and was placed 6 inches above ground for ground clearance.

Experimental results were obtained by recording signals around the frequencies of interest (900-912 MHz) for five seconds of data, using a Terratec T Stick software defined radio. The software defined radio antenna was oriented vertically for all vertical antenna positions and horizontally for all horizontal positions. Measurements were taken at twelve evenly spaced locations around the car, fifteen feet from the center of the vehicle. The vehicle and all antennas were in the center of a field away from any other buildings or significant metal objects. Normalized average power was computed for each data point by:

$$P = 10log\left(\left[\frac{A}{N}\right]^2\right), \tag{1}$$

where P is the normalized average power at a particular XY point and antenna position, A is the amplitude of the FFT under those conditions and N is the normalization factor, or the average amplitude of the FFT of all twelve XY points for the top vertical antenna position.

III. RESULTS

Six different antenna positions were analyzed for their gain patterns (see Fig. 1). The "inside back" position is the location of the antenna during the 2012 American Solar Challenge. "Inside front" is a proposed internal position for improving gain toward the receiver. The "top" and "back" positions are proposed external positions that are likely to improve the gain but could potentially increase aerodynamic drag. Both horizontal and vertical orientations are analyzed at these external locations. Vertically polarized realized gain plots were analyzed for each antenna location in the XY, YZ and XZ planes (Figs. 2, 3 and 4). Special attention was paid to transmission toward the rear of the vehicle, as that is the location of the receiving antenna in the chase vehicle during highway races. To address concerns of increased aerodynamic drag due to antenna placement outside the vehicle, Computational Fluid Dynamics (CFD) was performed on the vehicle with and without external antennas. For EM safety analysis, SAR data is considered for each antenna position.

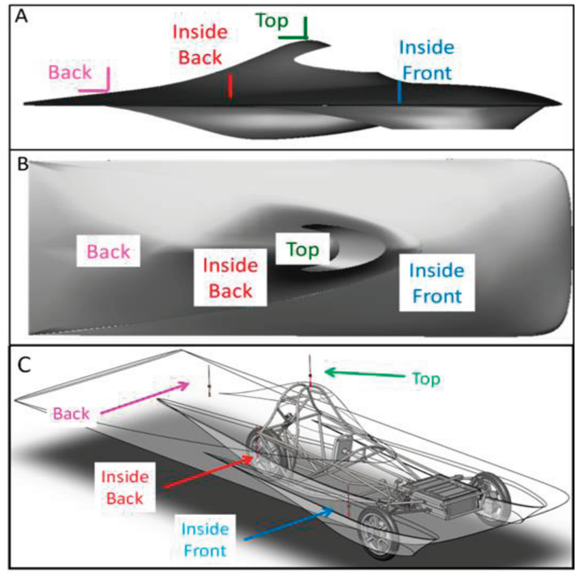


Fig. 1. Locations of antenna in and on the solar vehicle body. Positions "inside back" and "inside front" are inside the body and are both vertical antennas. Positions "top" and "back" are outside and are analyzed for both vertical and horizontal antennas. Colors of the numbers in this figure correlate to the colors of the lines in Figs. 2, 3 and 4.

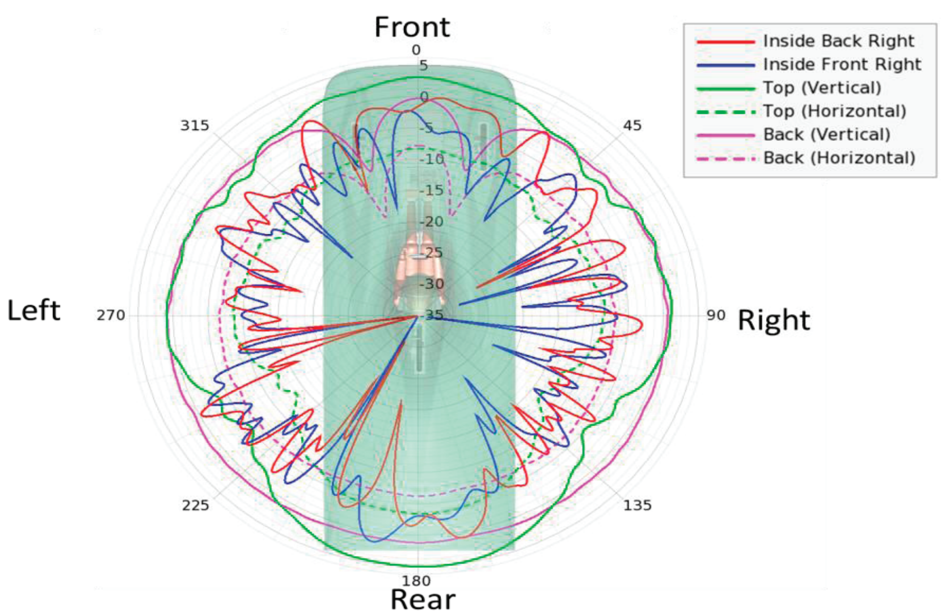


Fig. 2. XY cut of a theta-polarized realized gain plot for six antenna positions.

Realized gain was analyzed for antennas located inside the solar vehicle's body. "Inside back" is the antenna placement during the 2012 American Solar Challenge and "inside front" is a proposed improved antenna location that is closer to the windshield (see Fig. 1); both modeled in a vertical orientation. It was found that for both internal antenna locations, the signal strength toward the rear of the vehicle was significantly attenuated when observing both the XY and YZ realized gain plots, compared to external antenna locations (see red and blue lines in Figs. 2 and 4, respectively). In the XZ gain plot the inside back antenna displays a null at 270 degrees (toward the right of the vehicle; see Fig. 4), which may explain some of the communication difficulty when the car is racing on a track and the receiver is stationary. Transmission in all directions of the XY plane is important during track races. The internal antennas were both found to have relatively high gains toward the top of the vehicle (see Figs. 3 and 4).

In an attempt to increase signal strength toward the rear of the vehicle, vertically-oriented antennas were modeled at the top of the vehicle and the center back of the vehicle (see Fig. 1). These vertical external antennas both showed significantly increased gain toward the right and left of the vehicle, with the top antenna being the strongest transmitter (see the solid green line in Figs. 2 and 3).

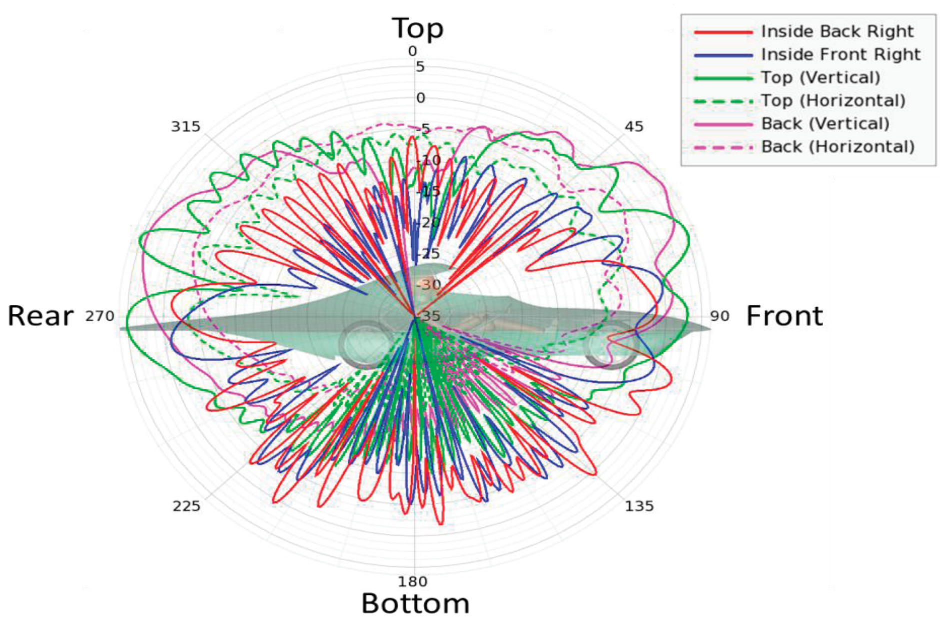


Fig. 3. YZ slice of theta-polarized realized gain plot for the six antenna positions.

With the prediction that they would cause less aerodynamic drag than vertical antennas, horizontal antennas in these two external locations were modeled for their signal gain and aerodynamics. Computational Fluid Dynamics (CFD) modeling was performed on the bare solar vehicle body as well as the body with each of the four externally located antenna positions. It was found that all antenna positions had negligible drag impact on the car at 50 mph, as determined by CFD. Also, as seen in the dotted lines of Fig. 2, the signal gain in the XY direction for a horizontally polarized antenna is not as strong as for the vertically polarized antennas, making horizontal antennas doubly undesirable.

SAR data was analyzed to determine the energy absorbed by a 147 lb human phantom in the driver's seat for each antenna position. All external antenna locations resulted in no energy absorbed. The inside front and inside back positions produced peak absorption of 4 and 2 mW/kg, respectively (both averaging about 2 mW/kg). If the carbon fiber backing on the seat is removed, the energy absorbed from the antenna located in the inside back location increases to a peak 1 g average SAR of 170 mW/kg.

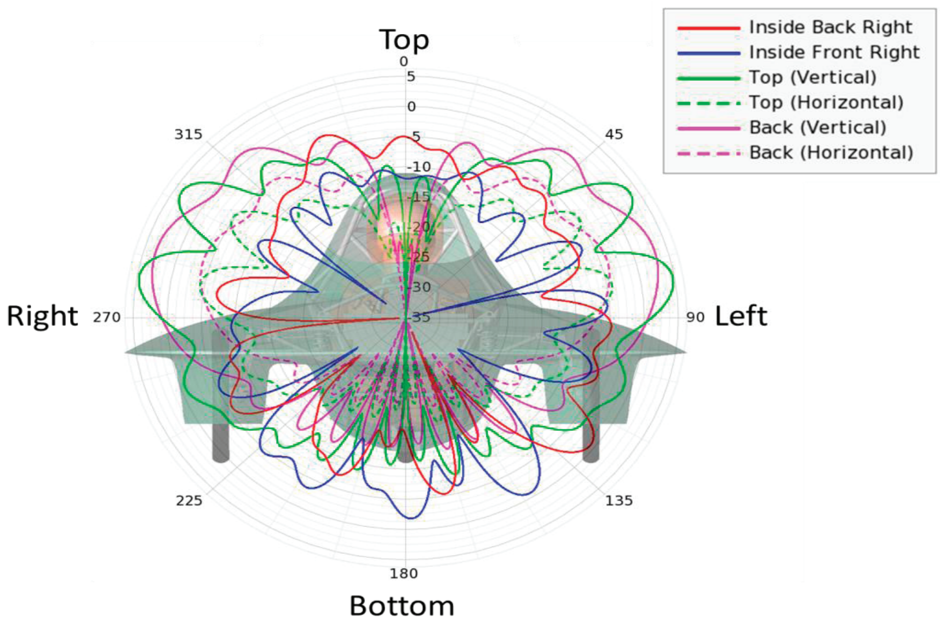


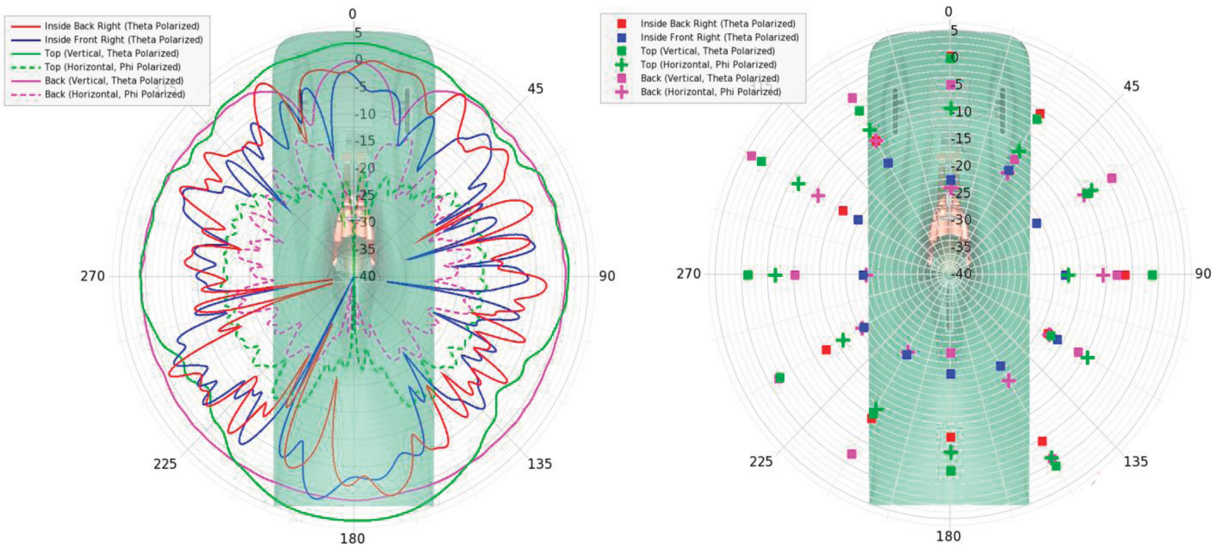
Fig. 4. XZ slice of theta-polarized realized gain plot for the six antenna positions.

Experimental results were obtained using a software-defined radio. To make the modeling results more comparable to the experimental results, modeling results were reported for the polarization that matches the transmitting antenna orientation; theta polarized data are reported for vertical antenna positions and phi results are reported for horizontal antenna positions (see Fig. 5 (a)). Experimental results were obtained with the receiving antenna in the same orientation as the transmitting antenna in or on the car. As seen with the modeling results, external vertical antenna positions were by far the strongest locations, with the overall strongest transmitting position being the top vertical (see Fig. 5 (b)). Although we had expected that the inside antenna positions would be least powerful, we found that the positions with the lowest transmission were the inside front and outside back horizontal. The top horizontal antenna position performed better than expected. The location of the antenna during the 2012 American Solar Challenge, the inside back was found to be a mediocre position, a stronger performer at all measured locations in the XY plane than the inside front, but generally weaker than external vertical antennas.

IV. DISCUSSION

The telemetry antenna modeled in this study is required to transmit data between the solar vehicle and its chase vehicle, which is located toward the solar vehicle's rear during cross country races and anywhere in the XY plane during track races. Six antenna positions were studied to assess their signal strength and aerodynamic drag for purposes of choosing the best antenna position and orientation for racing conditions. The optimal antenna position would be one where the signal strength is high toward mainly the rear, but also the sides and front of the vehicle and the aerodynamic drag is not significantly increased.

It was found that although externally placed, vertical antennas are most effective at transmitting signal toward the rear of the vehicle. The body of the solar vehicle is designed to hold the solar array, contain the driver and electronics and have as little aerodynamic drag as possible. This is done by minimizing both the frontal cross sectional area and low pressure regions on the back side of any structures in the vehicle. The antenna modeled here does not appear to contribute a detectable amount of drag by Solidworks 2013 Flow Simulation. Experimental studies have shown that vehicle antennas typically produce approximately 1 N of drag force, which would be approximately 23 W of power loss [16]. Although this is a significant amount of drag in solar car racing (23 W of drag could decrease average speed by 0.5 or 1 mph), it is not accurately detectable using CFD.



(a) (b)

Fig. 5. (a) XY slice of realized gain from modeling and (b) normalized average power from experimental measurements.

Modeling and experimental results suggest that the proposed internal antenna position, “internal front,” was not any better for transmission in the XY plane than was the original “internal back” position. Experimental results confirmed that in fact, the “internal front” position was a worse location for the transmitting antenna than “internal back.”

Simulations suggest that horizontal positioning of the antenna on the outside of the vehicle was found to improve neither the aerodynamics nor the signal transmission in the XY plane, which is the plane of interest to receivers at ground level. The signal transmission of a horizontal antenna is expected to be reduced in the horizontal direction. The two horizontal antenna positions modeled did show a higher gain toward the +z axis (above the vehicle), but this information is only useful if one were interested in detecting the signal from the space above the vehicle. Experimental results in the XY plane indicate that horizontal orientation of the antenna in the back of the vehicle is highly discouraged, while a horizontal antenna on the top of the vehicle produced higher than expected signal strength.

Discrepancies between modeled and simulated results could come from several factors. In the simulation the car was modeled in free space without ground underneath, while during experiments the car was in a field. The simulation did not include every component currently on the car, there are several electronic and some small mechanical systems that were not practical to simulate.

SAR data indicate that all antenna locations are very much below the FCC safety limit of 1600 mW/kg peak 1 g averaged SAR (80 mW/kg whole body average SAR). The carbon fiber seat back had a significant effect on energy absorbed by the driver. Removal of the seat back increased the peak energy by more than 40x, resulting in an energy absorption that is about 10% of the FCC limit. Thus, the internal configuration of the vehicle could affect the safety of the antenna, especially if multiple antennas are to be considered.

It is concluded that two of the proposed antenna positions will satisfy both of the design constraints of increased XY transmission and low aerodynamic drag, compared to the original placement used in the 2012 American Solar Challenge. Future improvements of the vehicle would include incorporating a vertical antenna inside the body of the vehicle, but in an area that is free of conductive carbon fiber. Other solutions to explore are antennas incorporated into the composite structure of the car's body surrounded by non-conductive materials. The simulation and modeling data are found to be in enough agreement to help the designers engineer better communications in future revisions of the vehicle.

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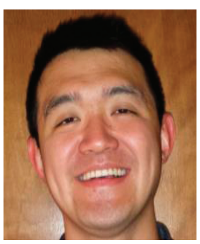

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