

A FMM-FFT Accelerated Hybrid Volume Surface Integral Equation Solver for Electromagnetic Analysis of Re-Entry Space Vehicles

Abdulkadir C. Yücel*⁽¹⁾, Luis J. Gomez⁽¹⁾, Yang Liu⁽¹⁾, Hakan Bağcı⁽²⁾, and Eric Michielssen⁽¹⁾

(1) Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI 48109, USA

(2) Division of Computer, Electrical, and Mathematical Sciences and Engineering, King Abdullah University of Science and Technology, Thuwal 23955-6900, KSA

Space vehicles that re-enter the atmosphere often experience communication blackout. The blackout occurs when the vehicle becomes engulfed in plasma produced by interactions between the vehicle surface and the atmosphere. The plasma often is concentrated in a relatively thin shell around the vehicle, with higher densities near its nose than rear. A less structured, sometimes turbulent plasma wake often trails the vehicle. The plasma shell severely affects the performance of side-mounted antennas as it alters their characteristics (frequency response, gain patterns, axial ratio, and impedance) away from nominal, free-space values, sometimes entirely shielding the antenna from the outside world. The plasma plume/turbulent wake similarly affect the performance of antennas mounted at the back of the vehicle. The electromagnetic characteristics of the thin plasma shell and plume/turbulent wake heavily depend on the type of re-entry trajectory, the vehicle's speed, angles of attack, and chemical composition, as well as environmental conditions. To analyze the antennas' performance during blackout and to design robust communication antennas, efficient and accurate simulation tools for characterizing the antennas' performance along the trajectory are called for.

Previously, a 2D finite-difference time-domain solver was used to characterize the radiation from an antenna mounted on a generic space vehicle (White, *Proc. IEEE Antennas Propagat. Soc. Int. Symp.*, 418-421, 2005). Unfortunately, the solver can only be used to characterize the radiation from simple antennas and platforms. In addition, a ray tracing solver was used to characterize the radiation from antennas on plasma engulfed re-entry vehicles (Vecchi, *Proc. IEEE Antennas Propagat. Soc. Int. Symp.*, 181-184, 2004). Albeit very efficient, the solver does not allow modeling details of complex antennas and plasma environment in a turbulent wake.

In this study, a new hybrid full-wave simulator that addresses the aforementioned challenges in analyzing the radiation from antennas mounted on plasma-engulfed space vehicles is proposed. The hybrid full-wave solver uses a surface integral equation solver to model electric currents on the perfect electric conducting vehicle surface and a volume integral equation solver to model the electromagnetic fields in both the antenna substrates and the plasma surrounding the vehicle. Both solvers are accelerated by a hybrid fast multipole method and fast Fourier transform (FMM-FFT). Input to the solver consists of the inhomogeneous plasma permittivities surrounding the vehicle, which are derived from computational fluid dynamics simulations. Plasma distributions encountered in re-entry scenarios often support numerous high-Q resonances that will slow iterative solvers down to a trickle if not properly dealt with. To address this issue, the proposed solver uses a special block diagonal preconditioner that inverts portions of the impedance matrix that model spatial blocks that exhibit resonant behavior. Computational results that demonstrate the efficiency, accuracy, and modeling versatility of this hybrid full-wave solver applied to the analysis of vehicles loaded with multiple cavity-backed antennas, will be presented.