Beyond LOS Detection of Hypersonic Vehicles

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***Abstract*—RCS modeling of a typical hypersonic vehicle and its plasma sheath was investigated. The plasma parameters were analyzed to determine which were most dominant for accurate RCS prediction. HF was determined to provide BLOS detection and good conductivity of the plasma, for optimum RCS.**

***Index Terms* – HF, hypersonic, over-the-horizon radar, plasma, RCS.**

I. INTRODUCTION

RF propagation to and from hypersonic vehicles has been studied since the early years of the US and Soviet space programs. Primarily, this interest concentrated on techniques to mitigate the communication "blackout" that occurred during spacecraft reentering the atmosphere, due to the extreme temperature. Molecular oxygen and nitrogen would dissociate into atomic oxygen (2000K), atomic nitrogen (4000K), as well as ions and free electrons [1]. This generation of positive ions and negative free electrons would have formed a plasma, shielding the spacecraft from RF communication [2].

The electrical properties of the plasma generated by hypersonic travel depend on parameters such as the charge densities, masses, velocities, and collision frequency of the ions and free electrons. These parameters depend on speed, altitude, and temperature. Furthermore, these parameters fluctuate rapidly during flight [3]. The statistical-mechanic and thermodynamic characterizations of these parameters is an area of ongoing research that is beyond the scope for our purposes. Rather, our goal is to contrive a modeling technique, in order to characterize the radar cross section (RCS) that would provide a reliable and practical detection method for hypersonic vehicles.

II. PLASMA MODEL

Plasma densities ranging from 10^{15} to 10^{19} m^{-3} are typical for hypersonic vehicles [4]. Since the mass of the free electrons is orders of magnitude less than that of the ions, we will assume that the plasma conductivity is dominated by the electrons, thus ignoring the contribution from the ions. The plasma frequency can be calculated by:

$$\omega_p = q_e\sqrt{\frac{N_e}{\varepsilon_0 m_e}}\,, \tag{1}$$

where q_e is electron charge (C), m_e is electron mass (Kg), and N_e is the electron density (m^{-3}). Using the aforementioned range of plasma densities, the plasma frequency ranges from 284 MHz to 28 GHz. From the Drude model, the real component of permittivity, $Re\{\varepsilon = \varepsilon' - j\varepsilon''\}$ is:

$$\varepsilon' = \varepsilon_0\left(1 - \frac{\omega_p^2}{\omega^2+\gamma^2}\right), \tag{2}$$

where γ is the electron collision frequency [5]. At frequencies above the plasma frequency, ε' will be positive, asymptotically approaching unity. The radio waves will transmit through the plasma as a lossy dielectric,

$$e^{-\omega\varepsilon'' x}e^{-j\omega\sqrt{\mu_0\varepsilon'}\cdot x}. \tag{3}$$

Below the plasma frequency (assuming $\omega_p^2 \gg \gamma^2$ in the upper atmosphere), ε' will be negative, and the radio waves will reflect as from a conductor. Based on an empirically derived formula for plasma frequency vs temperature, the collision frequency at 3000K is approximately $\gamma = 5$ MHz [6]. To detect the features of the vehicle itself, one would need to choose a radar frequency above the plasma frequency. Unless the radar is agile enough to adapt to varying plasma densities, collision frequencies, etc., an operational frequency well above 28 GHz would be necessary, since the plasma would tend to be absorptive near the plasma frequency.

A major disadvantage of the Ka radar band is that it suffers from relatively high absorption, due to water droplets. Furthermore, for a terrestrial-based radar to detect a hypersonic vehicle traveling horizontally, a Ka-band radar would provide very little detection range. A vehicle flying at Mach 8 at an altitude of 70 km, would have a maximum line-of-sight (LOS) range of 1000 km. At Mach 8, it would close this distance in 7 minutes. It would be more advantageous to use a frequency below the plasma frequency and detect the plasma sheath, instead of the actual vehicle that would be shielded within the sheath. This also eliminates the need to precisely predict the various plasma parameters, as the sheath would appear to be relatively conductive, over a broad range of varying parameters. Fig. 1 demonstrates beyond-LOS (BLOS), by refracting from the ionosphere, using 30 MHz [7].

A first-order approximation for plasma sheath is to assume a conical shape, with a blunt vertex at the leading tip of the vehicle. The half angle of this conical sheath can be visualized in Fig. 2 and calculated by:

$$\alpha = \sin^{-1}(1/M)\,, \tag{4}$$

where $M = u/s$ is the Mach number, u is the vehicle speed, and s is the speed of sound, i.e., the speed of the outwardly propagating shockwave. At Mach 8, which is sufficient for plasma generation, the half angle is $\alpha = 7.2°$.

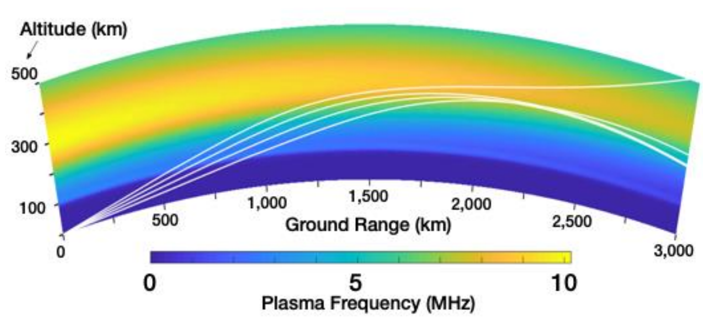

Fig. 1. BLOS refraction from the ionosphere, at 30MHz.

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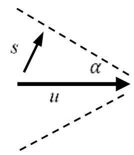

Fig. 2. Plasma sheath angle, $\sin\alpha = s/u$.

The DC conductivity can be calculated from:

$$\sigma_o = \frac{N_e q^2}{m_e v}, \quad (5)$$

and the AC conductivity from:

$$\sigma(f) = \frac{\sigma_o}{1+(2\pi f/v)^2}. \quad (6)$$

Fig. 3 shows a simulated plasma sheath, constructed around a 2m-diameter and 2m-long reentry-shaped vehicle, simulated as a PEC in HFSS. The radiation propagation space ("air box") was a cube, 32 m on side, with the vehicle in the center. Curvilinear meshing was applied in the initial setting, and was done automatically. The nose of the plasma used a conductivity of $38\ \Omega^{-1}\text{m}^{-1}$, corresponding to $N_e = 10^{19}\ \text{m}^{-3}$, at a thickness of 20% of the nose radius [5]. The rest of the cone/cylinder section used $0.38\ \Omega^{-1}\text{m}^{-1} \Rightarrow N_e = 10^{17}\ \text{m}^{-3}$. These parameters yielded penetration depths of 1.4 cm and 14 cm, respectively, at 30MHz. While the penetration depth is affected by the plasma density, it is not significantly affected by the temperature-dependent collision frequency.

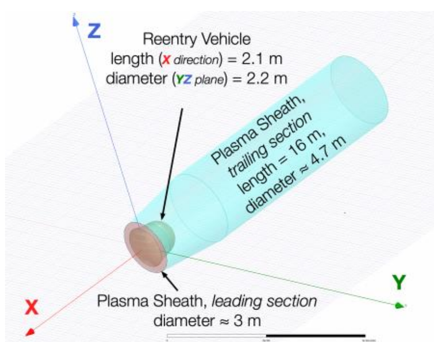

Fig. 3. HFSS model of reentry vehicle shrouded by plasma sheath.

III. RCS Results

The RCS of the vehicle alone (red, smaller) and the plasma sheath alone (green, larger) are superimposed in Fig. 4, at 30MHz. Equal θ and ϕ polarization was used, to mimic circular polarization. The broadside RCS (90°) from the plasma sheath is almost 16 dB higher than the RCS of the PEC vehicle alone. The RCS of the PEC vehicle engulfed in the plasma is shown in Fig. 5, depicting the vehicle completely shielded by the plasma. These results confirm the efficacy of an over-the-horizon radar (OTHR) for BLOS detection of hypersonic vehicles.

IV. Conclusion

A plasma sheath was constructed around a capsule-shaped reentry vehicle, in HFSS, to simulate the plasma generated at Mach 8. This sheath was made of two representative plasma densities, with the higher density at the leading edge of the vehicle, where the temperature would be the most extreme. The RCS of the vehicle and plasma sheath were simulated at upper HF, to show the capabilities of BLOS detection, using the ionosphere, from an OTHR. The HFSS simulations showed that the RCS is dominated by the plasma sheath, rather than the vehicle shape and material. These results demonstrate that the RCS is enhanced at HF, as it is well below the plasma frequency of the plasma sheath.

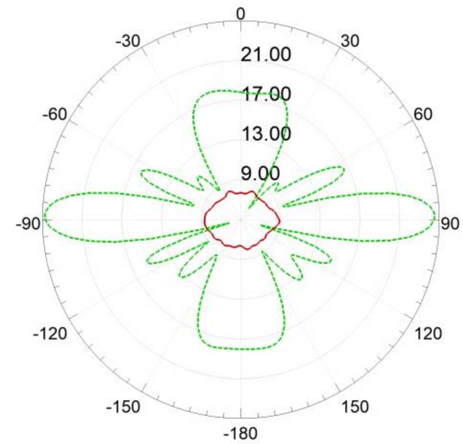

Fig. 4. HFSS RCS simulations of the PEC reentry vehicle, without plasma sheath (red), and RCS of the plasma sheath (green), without the vehicle, values expressed in dBsm.

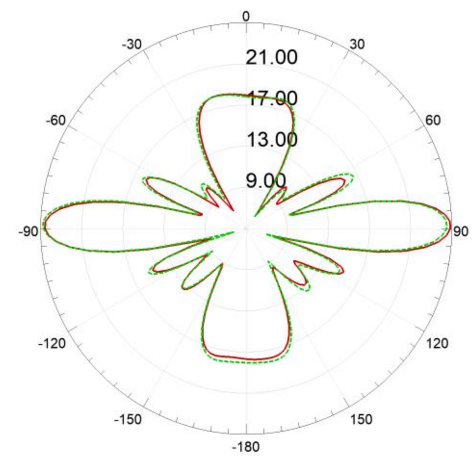

Fig. 5. HFSS RCS simulations of the PEC reentry vehicle engulfed in the plasma sheath (red) compared to the plasma sheath alone (green).

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