Abstract

At hypervelocity, an object generates a detached shockwave, causing intense compression and heating of the air. The resulting high temperatures drive internal energy redistribution through vibrational and electronic modes, along with chemical reactions such as dissociation, exchange, and ionization within the flow field. If ionization occurs, typically near the nose of the vehicle, charged particles form and are convectively transported along the body into the trailing wake. This plasma envelope strongly influences electromagnetic (EM) wave propagation, affecting both radio communications and the radar signature of the aircraft.

This research investigates the effects of plasma formation around slender vehicles during hypersonic suborbital flight, considering conditions different from the reentry of blunt bodies, which typically experience higher altitudes and Mach numbers.

The main objectives of the study are to identify the flight conditions that induce relevant plasma formation and to assess its effect on the vehicle's Radar Cross Section (RCS). To achieve this, a systematic approach is employed combining Computational Fluid Dynamics (CFD) to evaluate plasma properties with Computational Electromagnetics (CEM). This latter employs both the Finite-Difference Time-Domain (FDTD) method and a custom Ray Tracing (RT) approach to analyze electromagnetic wave propagation and scattering. This approach is first applied to a simplified geometry—a slender blunted-nose cone—before being extended to a more realistic scenario involving a hypersonic glide vehicle.

The plasma model incorporates a seven-species, two-temperature framework to capture non-equilibrium thermochemical processes and accurately describe dissociation and ionization phenomena. Despite the lack of more recent and experimental data, validation against RAM C-II flight measurements reveals coherence in electron density patterns and peak values, providing a certain level of reliability in the results. CFD analyses for the slender blunted-nose cone identified the flight conditions leading to significant plasma formation, characterized by elevated electron number

densities and pronounced plasma and collision frequencies. These effects are most prominent in the stagnation region, where high temperatures trigger intense thermochemical activity, and in the wake, where localized ionization further contributes to the production of charged particles. Electromagnetic analyses quantified the impact of these plasma features on bistatic RCS, showing that the plasma envelope substantially amplifies scattering effects at high Mach numbers and moderate altitudes. At these conditions, plasma-induced effects dominate, whereas at lower Mach numbers or higher altitudes, the influence diminishes, causing the RCS to approximate vacuum-like behavior. In the case of the hypersonic glide vehicle, the streamlined design confines the plasma field to a narrow region near the surface, significantly reducing its overall impact. The CEM results emphasize that plasma-induced effects on the RCS are most significant near the nose, where localized diffractive phenomena are amplified by higher plasma densities. Conversely, the limited electron number density in the wake, combined with the slender aerodynamic design, results in minimal scattering contributions from this region.

This dissertation enhances our understanding of plasma formation and its impact on electromagnetic scattering in hypersonic suborbital flight. By identifying key flight conditions for plasma generation and quantifying their effect on the RCS, this study provides valuable insights into how flight conditions and vehicle geometry influence plasma dynamics and radar signatures, offering a foundation for optimizing hypersonic vehicle design and addressing the evaluation of the radar signature in a plasma scenario.