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Title

Radio Communication Blackout Mitigation: Ray Tracing Analysis and Signal Characterization including Experimental Validation for Non-magnetized Plasmas

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Abstract

Atmospheric entries are a crucial part of space missions involving the possible loss of goods, data, and life in case of malfunctions. The cutoff of communication, also known as a radio communication blackout, is caused by the plasma surrounding the hypersonic (entry) vehicle in case the critical electron number density exceeds the radio frequency of the antenna. Mitigating radio communication blackouts during hypersonic flights and atmospheric entries is in the interest of the European Union's Horizon 2020 project MEESST (Magnetohydrodynamic Enhanced Entry Systems for Space Transportation), besides heat flux reduction and radiation mitigation using a high-temperature superconducting magnet.

The BlackOut RAy Tracer (BORAT), a ray tracing method to predict the signal propagation in the plasma domain surrounding a hypersonic (entry) vehicle, was further developed. Existing ray tracing techniques can forecast the signal path and intensity, but there is no information on the signal quality.

From analyzing the effects of a magnetic field using ray tracing at brownout conditions, previous results showed the significance of defining the signal quality of rays reaching a receiving antenna. The radiation aperture angle can be increased for sufficiently strong magnetic fields. Still, the pure ray tracing analysis covers neither the plasma's influence nor the magnetic field's effect on the signal characteristics. Increasing the aperture angle gives no further information on signal quality at the receiving antenna and how the signal characteristics changed due to the plasma environment or the applied magnetic field.

Characterizing the electromagnetic signal emerging from a radiation source like an antenna is essential for a better understanding of the nature behind the cutoff of communication. This feature was added to the latest version of BORAT. Two methods are analyzed and compared. One method is the subsequent ray density refinement at the receiving antenna positions. It is used to increase the accuracy without increasing the computational resources. The second is a ray-to-wave transition method. After propagating through the plasma area, the latter converts each ray into a wave, interacting with the other waves and forming a uniform wavefront in the far field.

The method is evaluated using on-ground plasma wind tunnel experiments at the von Karman Institute for Fluid Dynamics (VKI). The experimental setup contains one transmitting and three receiving antennas connected via a Vector Network Analyzer (VNA) measuring the scattering parameter, the magnitude and phase of the ratio of the received and transmitted signal. A new model is implemented to account for the realistic transmitting and receiving radiation pattern, respectively, for better agreement between the numerical fluid simulations in combination with the added ray tracing and signal characterization analysis and the experiment.

The results of the on-ground plasma wind tunnel experiments at VKI show a good agreement with the results from the numerical tools. Possible errors like plasma fluctuations, ablation, signal reflection, and signal losses are considered. The results look promising and will be evaluated for the magnetohydrodynamic fluid simulations using the superconducting magnet to understand what influence the magnetic field has on the signal quality in future work.