Communications and radar tracking of objects in hypersonic sub-orbital flight

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Research context and motivation

- The hypersonic regime is a flight condition characterized by high temperatures that strongly affect the properties of the flow field. In these conditions, a significant amount of the kinetic energy is transferred to the gas, whose internal energy increases, generating a region of high temperature around the body. The energy transfer occurs through a strong bow shock wave, which envelops the flying object.
- This phenomenon triggers chemical reactions, and air ionization may occur (provided the temperature is high enough) in the shock layer, generating a certain quantity of charged particles, i.e. a plasma.
- The presence of a non-negligible number of ions and electrons around a body in its hypersonic may significantly impact radio communications (Radio Black out), as well as the radar return (RCS)
- This event involves all objects entering the atmosphere from Earth's orbit or outer space, such as re-entry vehicles, space debris, asteroids, meteorites, and some empowered aircraft currently in the design or testing phase.
- Controlling the blackout plasma effect on communications is critical to ensure the success of space missions and knowing the radar signature is important to track the vehicle or track de-orbiting space debris (or even meteorites and asteroids) impacting the Earth's surface.

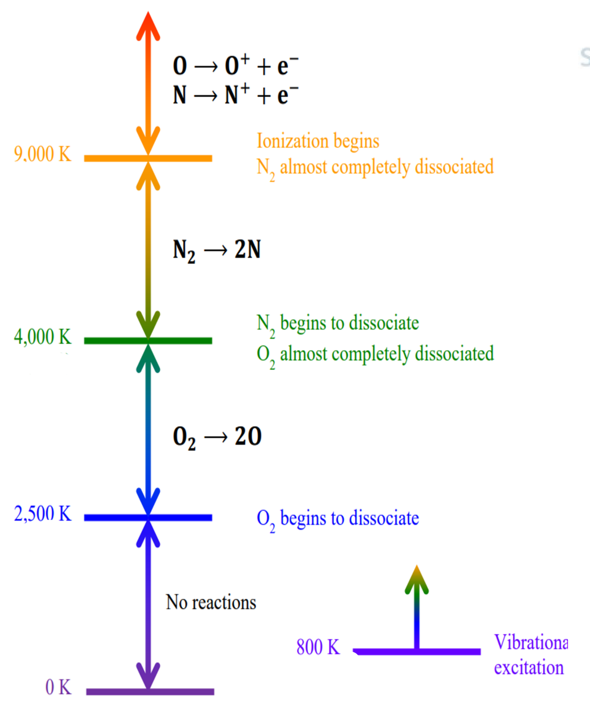

Fig.1- Ranges of vibrational excitation, dissociation, and ionization for air at 1 atm pressure [1].

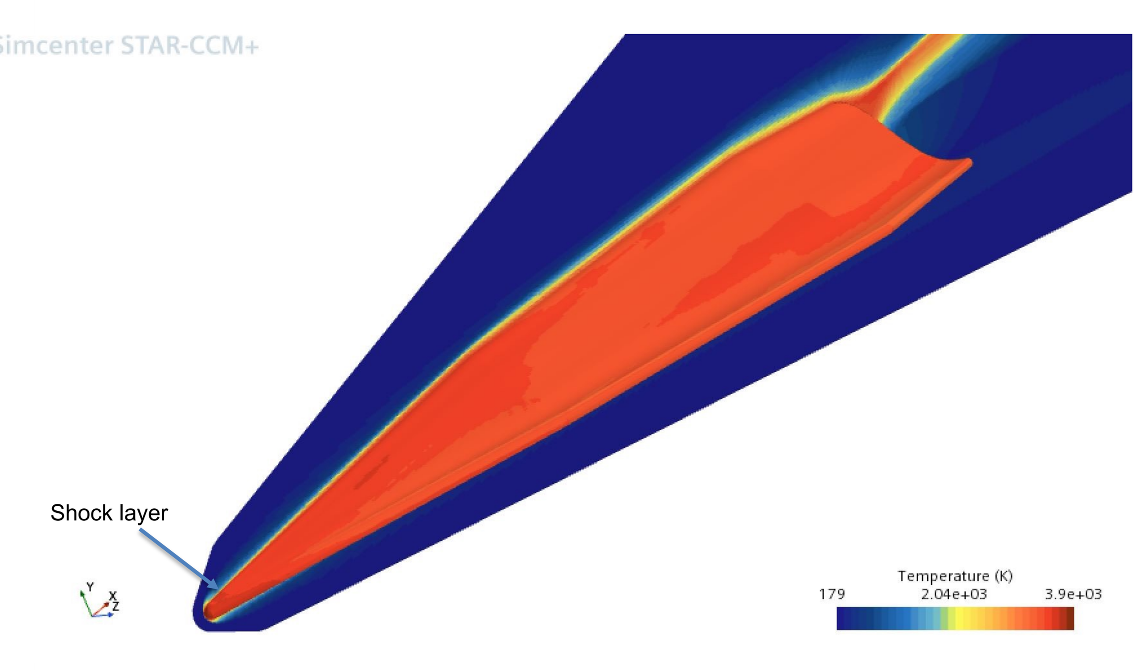

Fig.2 -Temperature field around a hypersonic Waverider at the Mach number of 10 and at the altitude of 30 Kms.

Addressed research questions/problems

- The study aims to identify flight and body shape conditions that generate plasma field around objects flying at hypervelocity in atmosphere, and to evaluate its impact on electromagnetic wave propagation. Radio communication between the vehicle and ground or satellite relay links, or similarly radar cross section, may be affected by plasma; when the link direction crosses plasma layer with plasma frequency near or above the link frequency, a significant path loss emerges ("Blackout" or "Brownout" depending on the level of attenuation). Since the relevant effect on radiation and scattering of electromagnetic waves, an analysis of electromagnetic response on plasma is required.
- Phenomena such as vibrational excitation, dissociation and ionization affect the chemical composition of air and its properties, adding complexity to the physical problem and making the hypersonic flight a though case to model.
- Improvement of existing in-house codes for the EM response is also necessary to comply with the envisaged regimes

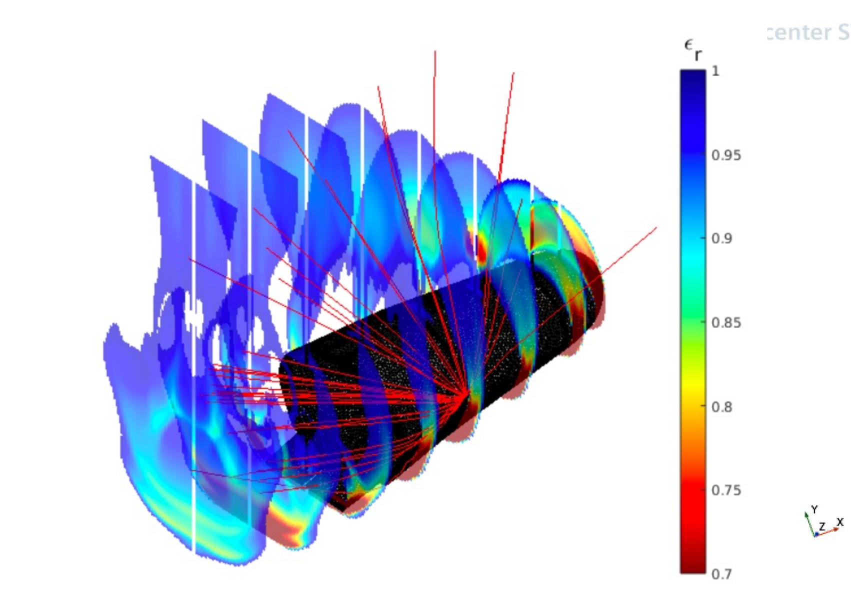

Fig.3 –TM Radiolink for IXV reentry vehicle at Mach 15: selected ray trajectories, with plasma density overlay. Rays depart from the location of the TM antenna; the plasma density is represented as relative permittivity ϵ_r at the frequency of 2.26 GHz [2].

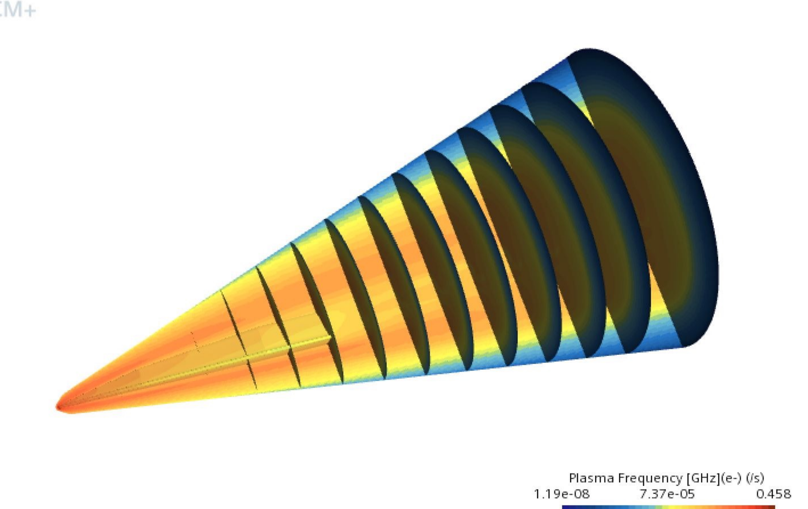

Fig.4 –Plasma Frequency field around a hypersonic Waverider at theMach number of 10 and at the altitude of 30 Kms

Submitted and published works

Novel contributions

- Although numerical (or even experimental) results of hypersonic flow and plasma field during reentry can be found in literature, they are very rare as regards sub-orbital altitudes.
- Several simulations have been performed on different body shapes (cone-sphere, slender bodies, Sphere in a nozzle) to investigate the formation and distribution of plasma field in sub-orbital flight.
- "Waverider" configuration has been analyzed to examine even more complex flow field (whose description is almost absent in literature).

Adopted methodologies

- The physical model has been implemented in the commercial CFD software Siemens STAR-CCM+.
- Air is assumed to be a viscous, highly compressible, chemically reactive gas mixture and composed of 7 species, namely O_2, N_2, O, N, NO, NO^+, e^-.
- Chemical reaction rates are taken from [4] and the transport model is based on the Champman-Enskog method described in [5].
- Vibrational and electronic non-equilibrium conditions have not been considered; a one-temperature model has been adopted.
- Several simulations have been performed on different body shapes
- A validation of the numerical model has been carried out using experimental data related to RAM C-II NASA project.

Future work

- Ambipolar diffusion for charged particles is not well described by Siemens STAR-CCM+; a different CFD commercial software (CFD++ for instance), should be used to take into account quasi-neutrality.

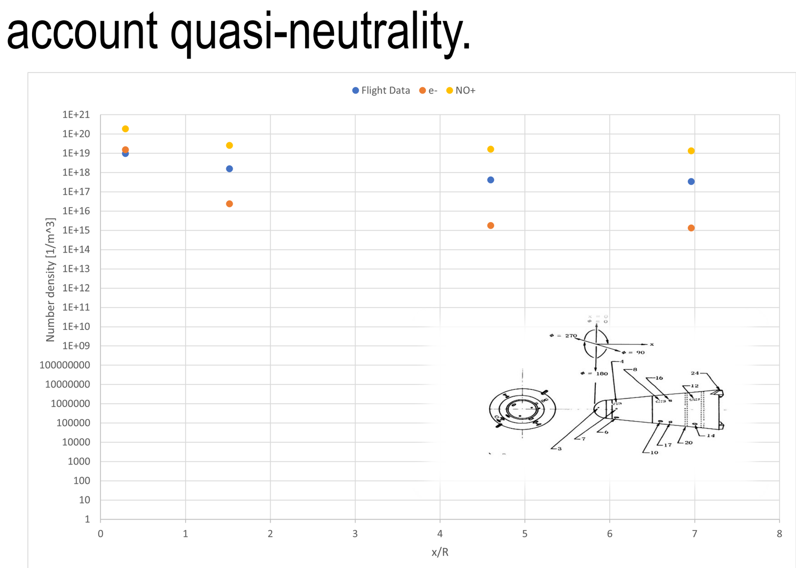

Fig.5 – Comparison between maximum electron number density for different measurement stations along RAM C-II obtained by [5] and the number densities obtained by the numerical model.

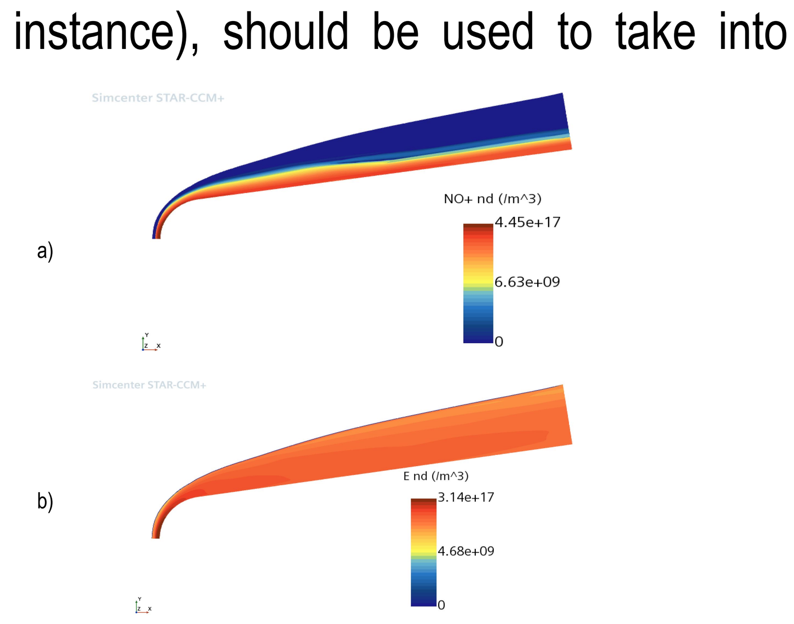

Fig.6 – a)NO^+ number denisty field around RAM C-II vehicle at the Mach number of 10 and at the altitude of 30 Kms, b) e^- number denisty field around RAM C-II vehicle at the Mach number of 23.9 and at the altitude of 61 Kms.

- Vibrational and electronic non-equilibrium conditions may be introduced in the numerical model.
- Analysis of Electromagnetic response on plasma of the computed plasma flowfield. FDTD and Ray tracing (RT) approach will be used (extending the current RT code).
- Setting up an experimental test on High Enthalpy Wind tunnel to produce realistic hypersonic flow conditions and perform a validation of the model for simple body shape.

References

1. Anderson, John David. Hypersonic and high temperature gas dynamics. Aiaa, 2000.
2. Scarabosio, Andrea, et al. "Radiation and Scattering of EM Waves in Large Plasmas Around Objects in Hypersonic Flight." IEEE Transactions on Antennas and Propagation 70.6 (2022): 4738-4751.
3. C. Park, R. Jaffe, and H. Partridge, "Chemical-Kinetic Parameters of Hyperbolic Earth Entry," Journal of Thermophysics and Heat Transfer, vol. 15, no. 1, pp. 76–90, 2001.
4. Gupta, R. N., Yos, J. M., Thompson, R. A., & Lee, K. P. (1990). A review of reaction rates and thermodynamic and transport properties for an 11-species air model for chemical and thermal nonequilibrium calculations to 30000 K.
5. Jones, W. Linwood, and Aubrey E. Cross. Electrostatic-probe measurements of plasma parameters for two reentry flight experiments at 25000 feet per second. Vol. 6617. National Aeronautics and Space Administration, 1972.

List of attended classes

- 01UMKIW – Innovative approaches to the simulation of turbulent flows in aerospace propulsion systems (01/07/2022, 3 credits)
- 01RGBRV – Optimization methods for engineering problems (07/06/2022, 6 credits)
- 01RPVKG – Plasma physics (08/04/2022, 6 credits)
- 02SFURV – Advanced scientific programming in matlab (21/04/2022, 6 credits)
- 01UIJIW – Technological challenges of hypersonic flight (08/07/2022, 4 credits)
- 01DTLIW – Data Driven Methods for engineering (22/09/2022, 2 credits)