A Laboratory Simulation of the Ionospheric Plasma

DANIEL R. PIGACHE*
Office National d'Etudes et de Recherches Aérospatiales, Châtillon, France

Theme

A CORRECT simulation of the ionospheric plasma surrounding a satellite has been obtained in a large vacuum chamber by means of a synthesized plasma stream produced by a low energy and high current density ion source. The plasma density and the beam velocity can be varied independently from 10^3 to 10^6/cm^3 for the density and from 7 to 30 km/sec for the velocity. The electron velocity distribution is Maxwellian and the temperature can be varied between 500 and 2000°K. This plasma wind tunnel is being used for fundamental studies on the wake structure and for testing ionospheric probes.

Contents

The simulation of the spacecraft motion in the ionospheric plasma can be obtained by means of a synthesized plasma stream directed toward a model of the spacecraft. Several plasma wind-tunnels working on this principle have been built in recent years.[1,2] Most of them have been used only for fundamental research such as satellite wake investigations or the diagnosis of streaming plasmas. Scaling laws are frequently used for these fundamental studies and the experimental conditions are then relatively easy to obtain. However the laboratory calibration of plasma diagnostic instruments which will be used on board a spacecraft does not permit any scaling. These instruments (and the plasma volume which is sampled) are generally of a large size, and the associated electronic circuits are adapted to the ionospheric conditions which must be reproduced exactly in the laboratory (in particular the plasma frequency, the electron gyrofrequency and the electron temperature). The correct simulation of the wake effect on these instruments also requires the ion source to be operated at very low acceleration voltage. Correct simulation is not indispensable for the fundamental studies of the wake structure, but if it could be obtained the use of the scaling laws would be no longer required. Moreover the use of a very low energy ion beam reduces to an insignificant amount the perturbation due to the electrons produced by secondary emission on the obstacles.

For these reasons a plasma wind tunnel of large dimensions has been developed with a special effort to obtain, as much as possible, an exact simulation of the ionospheric plasma over large volumes. The two principal difficulties have been the development of an ion source working at low accelerating voltage and high current density, and the obtaining of electron temperatures in the range of 500 to 2000°K, which are lower than what is normally obtained in steady state laboratory plasmas.

The plasma stream is produced in a vacuum chamber of large dimensions (3 m in diameter and 5 m long). The ultimate pressure is of the order of 10^{-5} N/m^2 (1 N/m^2 = 0.75×10^{-2} Torr). The diagnostic instrument under test or the satellite model can be translated along the entire length of the chamber and rotated around a vertical axis. A schematic view of this system is given in Fig. 1.

The basic measurements made on the plasma stream include standard Langmuir probe techniques (for plasma density, electron temperature and plasma potential) time of flight and electrostatic analyser measurements for the ion velocity distribution. For the plasma density there is a good agreement (20% difference at most) between the Langmuir probes and the RF probes measurements. A 2-m-diam stainless steel target, supporting 21 flat Langmuir probes, is used for the time of flight and the density profile measurements. It can also be used as a reference potential. Erroneous probe characteristics are obtained if the probe is not perfectly clean. The electron temperature measured with a dirty probe can be up to 10 times higher than the real temperature. An error of several volts is possible in the floating potential measurements. Satisfactory results are obtained if the probe surface is cleaned by bombardment of 2 kev ions before recording a probe characteristic.

A schematic drawing of the ion source is given in Fig. 2. It is a 10-cm-diam electron bombardment device. Argon is used as the working gas but atmospheric gases can be used if necessary. Most experiments have been performed at 20 ev (10 km/sec for argon ions). The ions are extracted by a single negatively biased grid with very small holes (70 μ). The hole's dimension is smaller than the sheath thickness in the ionization chamber. The ion current density at the extraction grid is very high (4 ma/cm^2 at 20 ev). The ion source and the ion extraction process have been described in Ref. 3.

Owing to the high current density the ion source opening can be reduced by a 3-cm-diam diaphragm. Thus the maximum required plasma density (10^6/cm^3) can be obtained in the test section (about 5 m from the ion source) with a reduced gas flow. The pressure can be maintained at 10^{-4} N/m^2 while the source is operated. At this pressure the density of cold ions produced by charge exchange collisions with the residual neutral atoms is negligible. The density is uniform (with 10% of variation) over

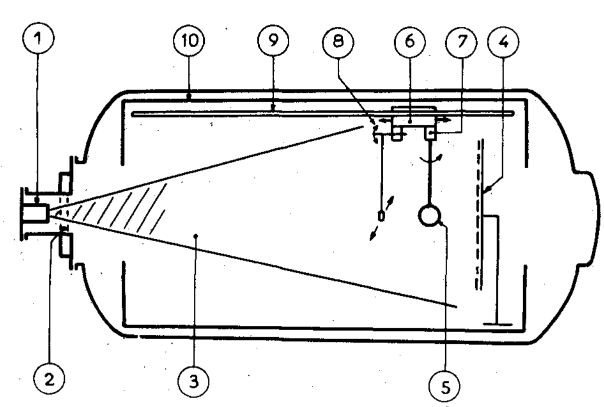

Fig. 1 Schematic of the plasma wind tunnel; 1) ion source, 2) valve, 3) plasma beam, 4) metal target, 5) diagnostic instrument or satellite model, 6) translation motion, 7) rotation around a vertical axis, 8) rotation for transverse exploration of the beam, 9) rail, 10) stainless steel condenser internally coated with a black insulating material.

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Index categories: Plasma Dynamics and MHD; Atmospheric, Space, and Oceanographic Sciences; Research Facilities and Instrumentation.

* Research Engineer.

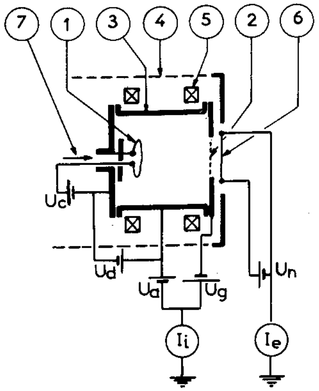

Fig. 2 Schematic of the ion source; 1) cathode filament, 2) grid, 3) anode, 4) negatively biased screen, 5) coils, 6) neutralizer filament, 7) gas injection, I_i) ion current, I_e) electron current, $U_g = -60$ v grid voltage, U_a anode voltage (ion energy eU_a), $U_d = 40$ v discharge voltage.

the entire surface of the 2-m target. The axial variation of the plasma density is given by a $1/r^2$ law (r being the distance from the ion source).

The ion beam is neutralized by the electrons emitted by a 6-cm long directly heated tantalum filament. The filament is immersed in the ion beam at 1 cm from the extraction grid. The voltage drop across the filament is of the order of 6 v. The negative side of the filament is at the vacuum chamber potential. Langmuir probe measurements have shown that the velocity distribution of the electrons is Maxwellian and that the electron temperature and the plasma potential are independent of the probe position in the plasma stream. The accuracy of the potential measurements is of the order of kT_e/e. The lowest electron temperature which has been measured is 500°K. The filament temperature, the voltage drop due to direct heating and the sheath around the filament are such that the average energy of the emitted electrons is at least one order of magnitude higher than the energy of the plasma electrons. This result requires an explanation.

About 95% of the inside wall surface of the vacuum chamber is coated with an insulating material. This surface must be at the floating potential. The metal target can be left floating or biased negatively. In these conditions there is a partial electrostatic confinement of the electrons. The high energy electrons which are able to overcome the potential barrier are lost whereas the electrons of lower energy are reflected. The lost electrons are replaced by an equal number of electrons emitted by the neutralizer. The energy balance is negative and the electron temperature should decrease providing there is a thermalization process for the plasma electrons. This qualitative explanation is supported by the fact that a Maxwellian distribution and a low temperature are obtained only when the collisional thermalization of the electrons is possible.

The average self collision frequency $\bar{\nu}_e$ of the electrons has been calculated. The ion current I_i emitted by the ion source is always nearly equal to the electron current I_e emitted by the neutralizer (as expected for a nearly floating source). As the electron and ion densities are equal everywhere in the plasma beam the average electron confinement time τ_e is equal to the ion time of flight which is directly measured by pulsing the beam. For 20 ev argon ions $\tau_e = \tau_i = 600$ sec. The number of collisions during the electron life $\bar{\nu}_e \tau_e$ is of the order of 200 for the typical experimental conditions ($n = 10^6/\text{cm}^3$ in the test section). It has been verified that a Maxwellian distribution and a very low electron temperature are observed whenever $\bar{\nu}_e \tau_e > 1$. For $\bar{\nu}_e \tau_e \lesssim 1$ the velocity distribution is non-Maxwellian and the average energy of the electrons is higher.

The electron saturation current of the neutralizer is usually much higher than I_e. As the plasma potential is uniform and because of the voltage drop across the filament only a small part of the filament (below or near plasma potential) emits electrons. The plasma potential is repulsive for the electrons coming from the other parts of the filament. If the neutralizer temperature is decreased the length of the emitting segment increases. Consequently the voltage drop across the emitting segment becomes greater. The electrons are thermalized and cooled by the process previously described but the resulting electron temperature in the synthesized plasma beam increases with the average energy of the emitted electrons. The electron temperature can be varied by this method between 500°–2000°K.

This plasma wind tunnel has been used for fundamental research on the wake structures of cylindrical and spherical obstacles or probes. Various flight models of ionospheric probes (*RF* quadrupolar probe, impedance probe, ion directional sensors) have been successfully tested.

References

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