EXHAUST PLASMA PLUME IMPACTS ON ONBOARD ANTENNA FIELD DISTRIBUTION

B.S.Borisov, V.I.Garkusha, A.G.Korsun, L.Yu.Sokolov, V.A.Strashinski
Central Research Institute of Machine Building Kaliningrad, Moscow region, Russia

Abstract

In space experiments with arcjet EPICURE on Cosmos satellites in 1987 (see AIAA paper 91-2349) a very visible impact to transmission of radio frequency signals through plasma plume had been observed. The registered RF field patterns on the Earth surface occurred to be asymmetric relative to an orbital plane and different for ascending and descending revolutions in a good agreement with the analytical model of exhaust plasma plume expanding in the Earth magnetic field. Scattering of radio waves in the length range of decimeters and meters resulted in shadow region formation.

In vicinity of the radio shadow boundary an intensity oscillation and an exponential decay have been observed in the "light" and "dark" regions of the field patterns respectively. While concerning diffraction effects the experimental field patterns may be described using Airy function with argument expressed via the parameters of the exhaust plasma plume. The latters being computed using Airy approximation of antenna field patterns, occurred to be in a good agreement with that measured in vacuum chamber. A new space plasma experiment is proposed for more correct determination of the radio shadow boundaries using more dense ground receiving network.

Nomenclature

- \( \bar{V} \): orbital satellite velocity
- \( \gamma \): adiabatic index
- \( \varepsilon \): dielectric permeability
- \( \theta \): angle between vectors \( \bar{V} \) and \( \bar{U} \)
- \( \lambda \): wave length
- \( \sigma \): plasma conductivity
- \( \omega \tau e \): Hall parameter

Introduction

The potential interaction between RF signal and charged species of the electric thruster plume may present a serious communications impact. The radio waves scattering in plasma plume as an important aspect of the electromagnetic compatibility is being not properly evaluated since thruster power levels and mass flow rates are currently low and plasma velocities are high enough so that available electron densities are often much lower than critical ones for carrier frequencies used.

On the other hand it is known that in the case of inclined incidence of radiation on inhomogeneous plasma layer the scattering takes place at lower electron density than that for the case of normal rays incidence. This effect sometimes allows to set long-range communications in VHF-range using an ionosphere waveguide. The basic physical processes of interaction between RF-signals and thrusters plasma plumes are essentially the same.

Consequently even rarefied beams of ion thrusters may effectively scatter radio waves under certain conditions. The scattering effects naturally depends on thruster type, input power level, mass flow rate and specific impulse. Arcjet and MPD thrusters may produce much more vast scattering zones with their dense plasma plumes.

The refraction/scattering effects are sufficiently different from other aspects of the electromagnetic compatibility problem such as permanent and varying magnetic fields, radio frequency and conducted electrical emission. The latters strictly...
depend on the "individuality" of the given electric propulsion system - discharge and power supplies instabilities, shielding and cables layouts etc. In contrary the refraction/scattering effects in the exhaust plasma plumes are an inherent features of almost all electric propulsion systems operation in space.

There is no reason to overestimate the potential hazard of these refraction/scattering effects since most transmission impacts may be avoided if the RF propagation path encounters only the less dense regions of the thruster plume. This can be accomplished in practice by placement of the thrusters and communications antennas on the spacecraft such that there is a wide angular separation between the RF lines of sight and the thrust axes.

At any rate plasma refraction/scattering effects should be thoroughly studied before electric thrusters become standard onboard equipment. The investigation will help designers of future electrically propelled spacecrafts to minimize the hazard of communication disruption by thruster plasmas [1].

Observation and evaluation of RF refraction/scattering effects in plasma have been the main objective of space experiments with arcjet EPICURE on Cosmos satellites in 1987. Hardware description and preliminary experimental results have been yet published [2]. The given report presents new materials on the space experiment as a result of more detail experimental data processing and updated revision.

**Plasma source**

In order to conduct space experiments on interaction between RF-signal and the thruster plume the experimental onboard arcjet hardware EPICURE has been developed. The device included two identical plasma sources of 6.5 kg each and power processing unit (PPU) weighting 6 kg. The hardware basic characteristics are:

- input power <2 kW (28V x 70A);
- propellant caesium;
- total propellant load 0.3 kg;
- mass flow rate 30×10^{-6} kg/s;
- operation mode pulse regime (16s for plasma generation and 8s for pause);
- switching multiplex.

Easily ionisable caesium was selected as a propellant with plasma source design based on the well-known MPD concept providing more wide possibilities in adjustment of discharge parameters than an ordinary arc. The resultant version of the plasma source has been directly supplied from the spacecraft 28V d. c. power bus without voltage converting.

The power processing and control unit provided switching on/off the heater and anode circuits, measuring circuits parameters and forwarding appropriate signals to the spacecraft telemetry system.

The assigned level of anode current had been maintained within 6% accuracy with feedback loop that controlled heater circuit switching on/off. In nominal operation mode the anode current was 50 A at the anode voltage of 24 V. (The voltage drop across the Bitter solenoid was of about 4 V).

The plasma plume basic characteristics - electron density \(n_e\), temperature \(T\), and Mach number \(M\) - were measured by Langmuir cylindrical double-probes located along the vacuum chamber axis at the distances \(R\) of 0.3; 0.7; 1.2m from the plasma accelerator nozzle exit orifice. The plasma source was mounted on a rotating gear to scan the plasma plume. The measured profiles of \(M\) and \(n\) had been compared with theoretical ones. For nominal operating mode with ion flow rate \(N = 1.5\times10^{20} s^{-1}\) the parameter absolute values were:

\[n_e = 0.7 \cdot 10^{16} m^{-3}; \quad T = 0.5-0.8 \text{ eV}; \quad M = 2.5-3\] at \(R = 0.7 m\).

The EPICURE hardware had undergone all kinds of preflight tests to meet requirements generally applied to payloads. As a result the assigned hardware reliability index equalled to 0.95 was verified with a confidence probability of 0.8.

**Space experiment layout**

Experiments with EPICURE arcjet were conducted on two Cosmos satellites have been launched in an orbit with an altitude of about 800 km and inclination of 65 degrees.

The location of arcjet unit in a satellite rear section is shown in Figure 1. The nozzle opening of the arcjet was oriented to make the angle 150 deg. between the plasma injection and the velocity vector of the three-axes-stabilized cylindrical spacecraft.

The telemetry loop and S-band responder antennas were located at the distances of about 3.5 m and 1.6 m from the arcjet nozzle respectively.

The well known method of radio probing was used for plasma monitoring. The telemetric and responder signals emitted by onboard antennas played a role of probing signals. Passed through plasma these signals were simultaneously received by a number of on-ground measuring sites with registration of the automatic gain control (AGC) level (i.e. signal
amplitude). Up to ten measuring sites spread in the European part of the former USSR have been involved in the experiment. The measurements were made both in ascending and descending orbital revolutions.

The important methodological advantage of those space experiments revealed in the fact that the satellite trajectories were periodically closed making possible to conduct measurements in "similar" orbital revolutions, i.e. in similar geometric conditions, and to collect data statistics.

The prognosis and processing of the experimental results were based on the mathematical models of plasma expansion in space and radiation scattering calculations.

**Plasma Expansion in Space**

Plasma expansion in space is influenced by two main factors - space vacuum and the Earth magnetic field. The magnetic field B affects the electron distribution in those plume regions where the magnetic pressure exceeds plasma pressure \( nT < B^2/2 \) far from the source. For the description of the dense plasma flow core the model of free molecular outflow from a point source [3] or simple Roberts approximation [4] are often used. The latter, however, does not quite accurately describe the peripheral region of the plasma plume where radio wave scattering takes place in fact.

The more correct description of the plasma stream exhausted into space was provided with self similar solution of ordinary gas dynamic equations system for flow region sufficiently distant from the source, where Mach number is great (\( M > 1 \)) with the assumption that temperature equalization due to thermal conductivity across and along the flow occurs in the vicinity of the source. In polar coordinates \( r, \theta, \phi \) the solution for plasma density distribution appears as [5]:

\[
N = \dot{N}k \frac{(\gamma - 1)}{\pi Uc_r^2 \cos^2 \theta (1 + k \cdot \tan^2 \theta)} \quad (1)
\]

The obtained solution corresponds to jet adiabatic expansion with velocity achieving maximum and practically constant value far away from the source:

\[
U_r^2 = \frac{U_m^2 = U_{c0}^2 (1 + \frac{2}{\gamma - 1} \cdot \frac{1}{M_0^2})}{(2)}
\]

and with temperature distribution:

\[
T = T_{c0} \left( \frac{\alpha_0}{a} \right)^2 (\gamma - 1) \quad (3)
\]

where \( \dot{N} \) is particles flow rate, \( U \) is plasma velocity, \( M \) is Mach number, \( T \) is average plasma temperature, \( \gamma \) is adiabatic index equal to \( 5/3 \) and \( a \) is the characteristic dimension of jet cross-section. The subscript "c" refers to the flow parameters at the axis, index "m" - to maximum values for \( r \to \infty \) and index "0" - to values at initial point of \( r = 0 \).

The input parameters of the electron density distribution (1) namely \( N \), \( U \) and the jet divergency factor \( k \) have been determined by a conjunction of experimental and theoretical profiles of \( n \), \( T \) and \( M \) and using the relationship:

\[
\left( \frac{n_c T_c}{n T} \right)^{\frac{1}{\gamma}} \cdot \left( 1 + \frac{T_g^2 \theta}{T} \right) = 1 + k \cdot \tan^2 \theta
\]

This relationship is shown in Fig. 2 where experimental points are also plotted. The actual value of \( k \) equal to 3.4 is determined at sufficient distance (\( R = 1.2 \text{ m} \)) from the nozzle exit where kinetic processes are believed to be over. Note that Roberts approximation does not follow the experimental data at the jet periphery.

Concerning the space experiment this axesymmetric plasma density distribution was used for S-band scattering calculations.

Far away from the plasma source the Earth magnetic field hinders plasma expansion across B. Inertial plasma motion turns into diffusion expansion across B. This diffusion zone is also described with self-similar solution using the approximation of fully ionized and magnetized plasma and condition to be satisfied:

\[
(\omega_e T_e) \frac{a}{h} << 1
\]

where \( (\omega_e T_e) \) is Hall parameter, \( a \) and \( h \) are characteristic dimensions of the flow across and along the magnetic field \( B \) respectively.

The density distribution is described in Cartesian coordinates \( x, y, z \) \((B = B_x)\) in the following way [6]:

\[
n = \frac{3N}{4 \sqrt{2 \pi} a h} U_{c0}^2 \left( 1 - \frac{z^2}{a^2} \right) \exp \left[ -\frac{1}{2} \left( \frac{z}{h} - \cot \beta \right)^2 \right] \quad (4)
\]

\[
U_m^2 = \frac{2}{9} U_{c0}^2 + U_B h;
\]

\[
h = U_m; \quad h' = \frac{d h}{d x}
\]
scattering characteristics the ray approximation may be used in the frames of geometric optics.

The base of scattering calculations is the ordinary method of the eikonal equation numerical solution with dielectric permeability being expressed via electron density distributions according to the mathematical models of plasma expansion in space mentioned above. The subsequent set of characteristic equations has been linearized for thin elementary ray tubes to save the computer run time. The resultant PC software allows to compute and plot ray path patterns, intensity distributions and caustic surfaces for scattered radiation.

Fig. 4 shows the computed ray path patterns for telemetric signals in the planes of symmetry of plasma petals in ascending (a) and descending (b) orbital revolutions respectively. Note that in ascending orbital revolutions angular dimension of the shadow region lower wing are of about 50 deg. and of about 70 deg. in descending ones relative to vector U.

Fig. 5 shows the computed ray path patterns for S-band signals (a) and the intensity distribution in vicinity of the shadow boundary (b). Note that petal-shaped or spoke-shaped models of plasma formations were used for telemetric signals scattering calculations, prognosis and analysis of the experiments results.

According to expression (4) the plasma density distribution is parabolic across and exponential along the magnetic field B.

If the magnetic field is directed along the jet axis \((\mathbf{U} \times \mathbf{B} = 0)\) equiconcentrals in the plasma formation have a shape of highly stretched spokes. If the jet is not directed along the magnetic field \((\phi \neq 0)\), the equiconcentrals acquire a petal shape with vectors \(U\) and \(B\) laying in the petal plane of symmetry.

Petal-shaped or spoke-shaped models of plasma formations were used for telemetric signals scattering calculations, prognosis and analysis of the experiments results.

Fig. 3 shows the prognosed views of plasma formations adjacent to the spacecraft in ascending and descending orbital revolutions respectively for the Northern hemisphere. For ascending revolutions the angle \(\gamma\) between vectors of plasma velocity \(U\) and magnetic field \(B\) had been changing from of about 83 deg. up to 98 deg., therefore the plasma formation acquired the shape of rather flattened and thin petal. For descending revolutions the angle \(\gamma\) was much lesser - within the range of about 22 - 37 deg. so that the plasma petal occurred to be more stretched along the magnetic field and more thick.

Since in both cases the inner cores of the plasma flows were overdense and intransparent for probing signals the radio wave scattering was expected to be resulted in formation of shadow regions with boundaries intercepting the Earth surface. According to prognosed shapes of plasma petals the shadow regions for descending revolutions were expected to be more vast than for ascending ones.

**Wave Scattering Calculations**

In reality sizes of plasma formations are large enough comparing to wave lengths of carrier frequencies. Gyromagnetic effects and RF absorption are usually insufficient. Therefore for calculations of scattering characteristics the ray approximation may be used in the frames of geometric optics.
reached one of the ground receivers the amplitude of the receiving signal fell down the upper sensitivity range limit of the receiver (more than 35 dB), in other words the signals were "cut off" and the satellite communications were lost. This effect is clearly seen in Fig. 6b.

Fig. 6a shows the AGC level decreasing just before and at the moment of signal "cut off". Using the data on the moments of the signals "cut off" and on instant mutual positions of the satellite and receiving sites the shadow boundary contours on the Earth surface were plotted in Figure 7 in ascending and descending revolutions both for telemetric and DME-transponder signals respectively as denoted.

The origin of coordinates is placed in a subsatellite point, distances from ground receivers to a satellite route are put on the axis "X" and the axis "Y" features the distance $Y = V \cdot \Delta t$, where $V$ is the spacecraft velocity and $\Delta t$ is the time interval from the parameter passage moment (the parameter is the shortest distance between the given ground receiver and a subsatellite point) to the moment of the signal disruption. Figure 7 shows that the shadow boundary contour is asymmetric for VHF-band relative to the satellite route and shifted to the left in regard to the satellite motion.

Such behavior of the shadow boundary is in qualitative agreement with the theoretical prognosis on plasma dynamics and refraction/scattering effects (see Figures 3, 4 and 5). As it has been prognosis the angular dimensions of shadow zone in the descending revolutions occurred actually to be much greater than in the ascending ones in compliance with the Earth magnetic field lines local inclination. The maximum angular dimension of the shadow zone lower "wing" in the ascending revolutions was greater than 60 degrees relative to a plasma jet axis so that the shadow boundary passes slightly ahead of the satellite along its route.

As expected, the shadow region angular dimensions for S-band occurred to be much smaller achieving only 6 degrees relative to a plasma jet axis. Therefore a strong attenuation (more than 20 dB) was recorded by two receivers only in the vicinity of a satellite route as shown in Figure 7.

Fig. 7 actually shows the boundary of "darkness". A more detailed analysis of an AGC level time behavior has revealed an interference pattern of the signal intensity in the "light" region adjacent to the "darkness" boundary as it is shown in Fig. 8. Again the experimental pattern qualitatively agrees with prognosis on angular dimensions of the predicted shadow regions.

During the experiment an interesting observation had been made when the satellite occurred to be almost at the local radio horizon i.e. out of the signal range. For certain geometries an unexpected communications restoration had been occasionally observed as a result of signal reflection in plasma.

**Discussion**

The main result of the space experiment "Shadow" reveals in the fact that the obtained data qualitatively and to some extent quantitatively proved the theoretical prediction concerning an asymmetric nature of exhaust plasma plume expansion in the magnetic field.

The resulting three dimensional petal like configuration should have a plane of symmetry in which a plasma jet velocity vector $U$ and a local geomagnetic field vector $B$ are lying. In a altitude movement of an orbiting satellite the angle between vectors $U$ and $B$ alters due to local pitch angle changing. According to this changing the shape of plasma petal has to undergo a continuous deformation together with the radio shadow boundary on the Earth surface. Figure 7 is not an instant profile of this boundary but illustrates only its typical view for medium latitudes of the Northern hemisphere. A method of plotting the shadow boundary contour shown in Figure 7 provides levelling of its alternation due to approximately 15 degree changing of pitch angle when the satellite moves approximately 5000 km along the orbit path.

Fig. 7 shows intersection lines of the plasma petal symmetry plane (the plane formed by vectors $U$ and $B$) with the Earth surface for ascending and descending revolutions. As it has been expected this lines almost coincide with the symmetry axes of the radio shadow boundary contours.

According to general theory of geometric optics for inhomogeneous medias [7] the asymptotes do exist for caustic surface cross sections under conditions of the experiment particularly for the orbital plane. In this case the field pattern in vicinity of shadow region boundaries may be approximated using Airy function with argument

$$\zeta = \frac{X_N}{(2k^2)^{\frac{1}{3}}},$$

where $k$ is the wave number, $X_N$ is the normal distance between the point of observation and the caustics asymptote and $R$ is the radius of caustics curvature at $X_N = 0$ in the plane of cross section. For high values of $|X_N|$ the normal intensity distribution is oscillatory in the "light" region as a result of interference.
\[
I = \frac{2A}{\sqrt{X_N}} \sin^2 \left[ \frac{3}{2} \left( -\frac{X_N}{3} \right) \sqrt{\frac{2 k^2}{\rho}} + \frac{\pi}{4} \right].
\]

In the "dark" region \((X_N > 0)\) the intensity decreases exponentially.

\[
I = \frac{A}{2 \sqrt{X_N}} \exp \left( -\frac{4 X_N^2}{3} \sqrt{\frac{2 k^2}{\rho}} \right).
\]

The curvature radius \(\rho\) depends on radiation scattering patterns that may be computed using the plasma expansion mathematical models and refraction/scattering calculation methods mentioned above for inhomogeneous media between the transponder and receiver.

These interference effects as well as occasionally observed signal restorations seem to be neither harmful nor useful from practical view point and are used here as an added proof of validity of the software has been developed for refraction/scattering effects evaluation.

However the analysis of the radio shadow boundaries contours is more visual and informative way to check up the theory. Therefore it is desirable to measure these contours more accurately than in the experiments described above. To get to this end the more dense ground receiving network must be used. On the other hand deployment of properly dense special receiving network is extremely expensive and consequently unrealistic.

International Space Experiment

Possible solution is to use available worldwide spread network of amateur VHF receivers. This idea has been put in the base of the proposal to perform a new plasma space experiment using Russian orbital station MIR almost in the same geometry as in 1987 [2].

An arcjet plasma source should be delivered to orbital station MIR by PROGRESS cargo vehicle and connected to the onboard power bus, command and telemetric systems. An amateur ICOM Inc. VHF apparatus already installed on board orbital station MIR should be used as a radio beacon for transmission of sounding signals in the form the Universal Time marks.

The task of every individual participant is to register a moment of signal cut-off using the Universal Time marks and to address this information along with data on its geographical position to the Information Storing Center.

The required accuracy of cut-off moment definition should be 0.5-1 s whereas the required accuracy of geodetic conjunction for the receiving point is of about 5 km. The layout of the space experiment is shown in Fig. 9.

In order to cover all regions of interest from the geophysical viewpoint the onboard plasma source ought to be fired while flying over Europe (including the former USSR), Japan, North and South America, Australia and some equatorial regions where the amateur receiving network is appreciably dense. Predicted width of the shadow zone on the Earth surface is of about 400-500 km for ascending revolutions (Northern hemisphere) and of about 2000 km for descending ones.

Mass, voluntary and gratuitous participation of VHF-amateurs is the general condition for realization of this project. Only under these circumstances rather large expenditures would be proved for MIR station updating, launch the scientific payload into orbit and service. Therefore success of the experiment would depend on the number of participants. The greater this number the more precise scientific result would be issued. The support of the proposed project by the electric propulsion community is believed to enlarge the number of voluntary participants. On the other hand the realization of this project will serve to popularization of electric propulsion technology.

Conclusion

1. In space experiments with arcjet EPICURE on Cosmos satellites in 1987 a very visible impact to transmission of radio frequency signals through plasma plume had been observed. The registered RF field patterns on the Earth surface revealed the significant role of exhaust plasma plume subdense region in RF refraction/scattering effects. The latter result in formation of radio shadow zone much more vast than one may expects taking into account only overdense plasma flow core.

This suggests that even rather rarefied exhaust plasma plumes and beams may effectively scatter RF signals under certain conditions disrupting communications with electrically propelled spacecraft. Therefore the refraction/scattering effects in exhaust plasma plumes being an inherent feature of almost all electric propulsion systems operation in space are an important aspect of the electromagnetic compatibility problem.

There is no reason to overestimate the potential hazard of these refraction/scattering effects since most transmission impacts may be avoided if the RF propagation path encounters only the less dense regions of the thruster plume.
Nevertheless plasma refraction/scattering effects should be thoroughly studied before electric thrusters become standard onboard equipment. The investigation will help designers of future electrically propelled spacecrafts to minimize the hazard of communication impact by thrusters plasma plumes.

2. In general the results of performed space experiment occurred to be in a good agreement with their prognosis based on developed mathematical models of plasma expansion in space and subsequent calculations of refraction/scattering effects.

There is a reason to suggest that the mathematical models mentioned above are valid for uniform description of electron density distributions in exhaust plasma plumes for different types of electric thrusters.

Therefore these models together with available PC codes for calculations of radiation scattering in plasmas could be used as a draft version of universal methodology for refraction/scattering effects evaluation and prognosis of communication conditions at the stage of mission analysis. In perspective this universal methodology being properly updated could be included in the methodological basis of national or international standards for electric propulsion systems preflight qualification on electromagnetic compatibility.

3. The important results of performed space experiments had been obtained using only available on-board and ground standard systems as diagnostic tools saving a lot of time, efforts and money. The same method of exhaust plasma plumes monitoring should be used in future electric thrusters flight tests providing new knowledge on the discussed aspect of the electromagnetic compatibility problem.

References.


Fig. 3. Compared shape of plasma formations in space experiments with arcjet EPICURE for ascending (a) and descending (b) revolutions.
Fig. 4. Ray path pattern for petal model of plasma expansion on ascending (a) and descending (b) revolution.

Fig. 5. a). Ray path pattern for axesymmetric model of plasma expansion, b). Interferential pattern in the vicily of the radio shadow boundary.
Fig. 6. Signal cut-off a) AGC level behavior, b) plasma source telemetric readings.
Fig. 7. Radio shadow boundaries contours on the Earth surface.

Fig. 8. RF field pattern at radio shadow boundary of S-band and telemetric signals (VHF-band). 1 - data of mission control center; 2, 3 - data of receivers located to the south and 4, 5 - to the north of satellite trace.

Fig. 9. Space experiment geometry. 1 - onboard beacon; 2 - plasma; 3 - VHF-receivers.