UDC 629.78, 533.9.07

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PROBE STUDIES OF LOCALIZED PLASMA, AS A METHOD OF INCREASING THE INTERFERENCE OF SATELLITE RADIONAVIGATIONAL SYSTEMS ON THE AREA OF SC'S ORBIT INJECTION

In article the method of increasing the noise immunity in satellite radio navigation systems during the spacecraft orbit injection, using the new internal characteristics of localized plasma, which are revealed by probe researches is suggested. Research of potential axial, radial and azimuthally plasma's in homogeneities are investigated. The results of the studies disprove the assumption about plasma's azimuthally in homogeneity existence, which should have occurred under the influence of discrete streams of fast electrons. The homogeneity and equipotentiality of localized artificial plasma are finally established and they make possible its utilizing in the SC's antenna compartment for the reliable communication channels through the ionized external medium formation.

Keywords: *spacecraft, plasma, noise immunity, satellite radio navigational system, probe measurements, plasma density, inhomogeneities.*

Introduction

One of the alternative approaches of satellite communications' noise-immunity with the spacecraft (SC) ensuring in the area of its orbit injection, is the usage of a methodology for plasma's density reducing that occurs around SC's corps during its passage into the ionospheric flight area [1]. Plasma can manifest itself as a conductor, or as an insulator according to the electromagnetic waves [2]. The presence of a magnetic field in plasma, largely determines its properties and behavior.

In an article [3] the reduction of plasma's density in the vicinity of antenna SC's compartment with the help of generation of low-temperature homogeneous artificial plasma's with negative radiation is proposed. Mentioned plasma, during its interaction with external plasma on an elementary level lessens the density of the last one that contributes the passage of the radio waves.

The purpose of the article: the definition of important internal characteristics of low-temperature plasma that will contribute to the creation of optimal conditions for the passage of communication radio signals with SC.

To achieve that goal a method of probe researches is proposed.

The main part

Locality and high precisions of measured characteristics are the main advantages of probe method. The other advantage is a relative simplicity of apparatus that is being used [4] and that allows scientists to get the required result quickly and without high costs. However, the undeniable advantages of the method that are burdened by the complexity of theoretical description, and that is conditioned by the presence of a number of factors, such as possible axial, radial and azimuthal heterogeneities.

By measured volt-ampere characteristic of the probe, according to the optimal conditions, it is possible to determine the temperature of electrons T_e, their concentration N_e, the potential of the undisturbed plasma V_{pl} in the vicinity of the probe, and the function of electrons' distribution at velocities or energies $f(E)$.

Special probe circuits [5] provide us with some information about the oscillations, flows, and drift diffusion processes in plasma. The range of pressure variations in which the probe method can be used during plasma studies, covers more than seven orders, starting with $p \geq 0,00133$ Pa.

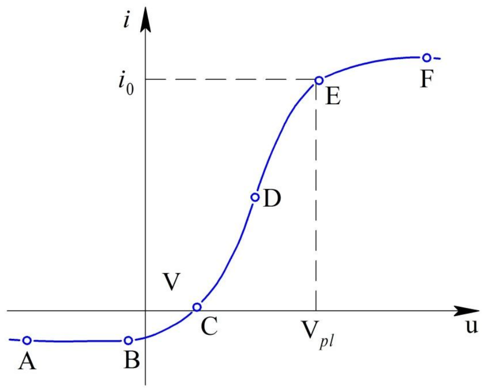

Fig. 1. General view of probe characteristics: AC - ion probe current; CF - an electron probe current

A range of concentration that is measured makes up eight orders $(10^6 - 10^{14}\ cm^{-3})$. During some recent years, the theory and experimental technique have been greatly improved, thus, the probe method is one of the most effective means of plasma diagnosis [6].

During the utilizing of probes with a negative potential V_s according to plasma, the entire current that is entering, is the current of positive ions i_i, Fig. 1. In this case, according to Fig. 1, the current of the probe will correspond to the ion current of saturation i_{i0}:

$$i = i_{eo} = \frac{1}{4} n_i \cdot e \cdot \overline{v}_l \cdot S . \qquad (1)$$

With the reduction of negative potential on the ion current, the electron current that is created by fast electrons that passed through the electric field of probe's retardation is superimposed. In the process of further reduction of negative potential, the electron current i_e begins to increase on the probe, which is connected with a decrease in the electric field of the probe slowing down and a reduction of thickness of some positive charge space near the probe surface. At the CD section, the electron current considerably exceeds the ionic one, and its value corresponds to the expression:

$$i_e = \frac{1}{4} N_e \cdot e \cdot \overline{v}_l \cdot S \cdot \exp(\frac{eV_s}{kT_e}), \qquad (2)$$

or

$$i_e = i_{eo} \cdot \exp(\frac{eV_s}{kT_e}). \qquad (3)$$

Since the average ion velocity $\overline{v}_i$ is less than the average electron velocity $\overline{v}_i$, and when $U = V_{pl}$, the contribution of ions to the probe's full current becomes smaller and smaller, in the current of the probe characteristic E, the probe current is equal to the electron one

$$i = i_{eo} = \frac{1}{4} n_e \cdot e \cdot \overline{v}_e \cdot S, \qquad (4)$$

where $\overline{v}_e = \sqrt{8kT_e/(\pi m)}$, and a point $E - i_{eo}$ is an electron current.

The source of systematic errors, during the plasma's studies by the method of probes, is the discrepancy between the method's preconditions and the real conditions of its usage. As it is shown in [6, 7], in this case the following errors may occur:

1. The influence of the probe's size. It is necessary that the size of the probe and the layers that surround it will be smaller in comparison with the size of the surrounding plasma. In this case, the collision between charges in the vicinity of probe layers should be absent. A condition during which there is no collision, when $T_e \geq T_i$ for a cylindrical probe, looks like this:

$$R_c << (T_i/T_e)^{1/2}, \qquad (5)$$

where R_c – radius of the probe layer.

Collisions between electrons are absent, whether probe's radius

$$r_s << \overline{\lambda}_e. \qquad (6)$$

2. Pollution of the probe's surface changes the work of metal's output and leads to a sharp increase of probe's ohmic resistance. Because of this, its characteristic is distorted.

3. The influence of probe's isolation. The probe's isolator surface charging negatively to the size of the floating potential, and is surrounded by a layer of positive spatial charge, this layer reduces the action of probe's collecting surface.

For correct probe studies, it is necessary to use probes of small sizes, at low gas pressures with unpolluted probes and with a thin insulation. In probe studies of localized plasma, a probe with the length $5,0 \cdot 10^{-3}$ m, and diameter $0,07 \cdot 10^{-3}$ m from molybdenum, is used.

The electron distribution function is one of the most important quantities that characterizes plasma. Kinetic Boltzmann equation for the function of electron velocity distribution looks like the following:

$$\frac{\partial}{\partial t} f(\overline{r}, \overline{v}, t) + \overline{v} \mathrm{grad}_r f(\overline{r}, \overline{v}, t) + \\ + \frac{e}{m}\left(\overline{E} \frac{I}{C} [\overline{v} \cdot H] \mathrm{grad}_v \cdot f(\overline{r}, \overline{v}, t) + \sum S \right) = 0, \qquad (7)$$

where $f(\overline{r}, \overline{v}, t)$ – a distribution function, moreover, quantity $f(\overline{r}, \overline{v}, t) d\overline{v} d\overline{\tau}$ determines an average number of electrons in the value $d\overline{v} d\overline{\tau}$, here $\overline{v}$ – electron's velocity, and $\overline{r}$ – appropriate radius vector, $\overline{H}$ – a tension of magnetic field.

The density of electrons N_e, the average electrons' energy $\overline{E}_e$ and the electron current j at a point $\overline{r}$ at a time t determines by the distribution function, like this:

$$N_e = \int f(\overline{r}, \overline{v}, t) d\overline{v}, \qquad (8)$$

$$\overline{E}_e = \frac{I}{N_e} \int \frac{mv^2}{2} f(\overline{r}, \overline{v}, t) d\overline{v}, \qquad (9)$$

$$j = \int e\overline{v} f(\overline{r}, \overline{v}, t) d\overline{v}. \qquad (10)$$

$\sum S$ – collision integral, which describes the changes in the function during electrons' collisions between themselves S_e, elastic collisions with molecules S_m^n, inelastic collisions with molecules $S_m^{нn}$ and collisions with ions S_i. In a general case

$$\sum S = S_m^n + S_m^{нn} + S_i + S_e. \qquad (11)$$

Integro-differential equation (7) is nonlinear, but its solution in a general form represents a very complicated task. Obtaining the distribution of electrons on the basis of this equation's solution requires clarification of much elementary processes in which the electron takes part. A part of these processes is not known at all, and the other part is known only approximately.

Regarding to this, an important role is played by the experimental determination of the distribution of electrons by energies $f(E)$. On the basis of the obtained $f(E)$, one can determine some important internal plasma's characteristics: such as average energy $\overline{E}_e$ and electron concentration N_e. The functions of the electrons' distribution $f(E)$ allow us to consider about the processes of excitation, ionization, the creation of inverse populations of laser levels, and others.

Modern methods of measuring the electrons' energy distribution are based on the probe method. Their basis is an obtaining of second derivative of electron current on the probe and measuring the plasma's potential. The second derivative of electron current with the help of the Drewwiesten correlation [8] is connected with the electrons' distribution by energies, as following.

The electrons in the prism layer, in the braking electric field, reach the probe's surface without collisions. The expression for the electric current that entering on the probe, in this case, looks like the following:

$$i_e = \frac{1}{4} eN_e S \int_{\nu_1}^{\infty} \nu F(\nu) \left(1 - \frac{2eV_s}{m\nu^2}\right) d\nu, \qquad (12)$$

where ν – module of electrons' velocity; V_s – probe's potential relatively to the potential of undisturbed plasma V_{pl}, in a given point; ν_1 – minimal velocity, in which an electron can reach a probe, connected with the probe's potential in a correlation

$$\nu_1 = \left(\frac{2eV_s}{m}\right)^{1/2}.$$

After twice differentiating (12), one can obtain the formula of Drewestein [8]

$$F(\nu) = \frac{4m}{e^2 S} \cdot V_s \frac{d^2 i_e}{dV_s^2}. \qquad (13)$$

The transition to the function of electrons' distribution by energies, one can obtain:

$$f(E) = \frac{2\sqrt{2}}{eS} \cdot \sqrt{\frac{m}{e}} \cdot \sqrt{V_3} \cdot \frac{d^2 i_e}{dV_s^2}. \qquad (14)$$

During all these the electrons' concentration is

$$N_e = \int_0^{\infty} f(E) dE.$$

Here $f(E)dE$ – is a number of electrons in an interval of energies from E to $E + dE$. From (14) it is visible, that for obtaining the electrons' distribution function it is necessary to measure the second derivative of electric current at the voltage and probe potential V_s, relatively to the potential of the plasma space V_{pl}. The second derivative of the electron current is taken on the basis that in the region to $V_s \le 0$ it is considerably bigger than the second derivative of the ion current $i_e'' >> i_i''$. According to [9], this assumption is true $f(E)$ as long as it is measured not in a wide range of energy, which is equal $E \le (3 \div 4) \cdot \overline{E}_e$,

$$\overline{E} = \frac{\int_0^{\infty} Ef(E) dE}{\int_0^{\infty} f(E) dE}. \qquad (15)$$

Various experimental methods of $f(E)$ measuring and they differ mainly in the ways of obtaining a second derivative of full probe current voltage.

Recently, the determination of second derivative of probe current by voltage is carried out by the method of applying small value to the probe range of alternating signal [9].

In the probe's vicinity, regardless to the source of constant potentials, a source that gives small variable signal ν is introduced. In this case, probe's potential $V + \nu$, and the current is:

$$i = i(V + \nu). \qquad (16)$$

Probe current can be represented by Taylor's number [10]:

$$i = i(V) + \nu i'(V) + \left(\frac{\nu^2}{2!}\right) i''(V) + \left(\frac{\nu^3}{3!}\right) i'''(V), \qquad (17)$$

where $i = \frac{di}{dV}$; $i'' = \frac{d^2 i}{dV^2}$ and so on.

Depending on the shape of a small variable signal, several variants of the method are distinguished:

1. A method of second harmonica [11]

$$\nu(t) = \nu_0 \sin wt. \qquad (18)$$

2. A method of modulation by sinusoid [12]

$$\nu(t) = \nu_0 (1 + \cos \Omega t) \sin wt. \qquad (19)$$

3. A method of modulation by rectangular signal [13]

$$\nu(t) = \nu_0 \left[1 + \frac{\pi}{4} \cos wt - \frac{\cos^2 wt}{3} + \ldots\right]. \qquad (20)$$

4. A method of intermodulation [11]

$$\nu(t) = \nu_{01} \cdot \sin w_1 t + \nu_{02} \sin w_2 t. \qquad (21)$$

In localized plasma, the second harmonic method was used to measure the second derivative of the probe current by voltage. Substituting in (17) equation (18) and converting the members of correlation with $\sin wt$, one can obtain

$$i_{2w} = \frac{\nu_0^2}{4} i''(V) \cos 2wt \qquad (22)$$

From everything that was mentioned above, it is clear that in order to determine the second derivative of the probe current by voltage, it is necessary to measure the amplitude of the second harmonic of the variable signal

$$i''(V) = \frac{4i_{2w}}{\nu_0^2 \cos 2wt}. \qquad (23)$$

The results of probe measuring $i(V)$ and $i''(V)$ showed the important result during probe's displacement in plasma with a localized discharge along the axis and the radius of discharged device.

For carrying out the axial probe measurements $i(V)$ and $i''(V)$ in one of the device's ends with a diameter of $D = 8,2 \cdot 10^{-2}$ m, the number of electrons in $N = 24$ a probe with a mechanism for movement mounted.

After measuring $i(V)$ and $i''(V)$ after every $15 \cdot 10^{-3}$ m of probe's displacement along the axis, a high identity was obtained $i(V)$ and $i''(V)$.

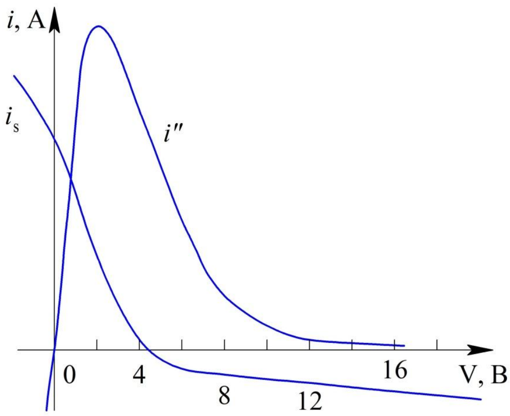

Fig. 2. An instance of determining the probe characteristics $i(V)$ and the second derivative of the probe current by voltage $i''(V)$

Function $i(V)$ was applied in a way, that one curve $i(V)$ precisely superimposed to the other one. Similarly a curve $i''(V)$ superimposed to the previous one, like it was showed at a fig. 2. Differences between these curves exceed 5%. Only in the vicinity of the bit gap ends, the curves $i(V)$ and $i''(V)$ differ from the previous, in decrease of the amplitude to complete disappearance when the probe exited from the bit gap. Processed with the help of EOM $i(V)$ and $i''(V)$, give the identical function $f_e(E)$ and according to all these, the identical parameters of plasma with the general radiation that by mentioned conditions has the following constant meanings:

$$V_{pl} = 2,1 \text{ V}; \ \bar{E}_e = 0,36 \text{ eV};$$

$$N_e = 3,1 \cdot 10^{11} \text{ cm}^{-3}.$$

Axial probe measurements $i(V)$ та $i''(V)$ in molecular and inert gases showed the similar regularity of plasma's parameters in accordance with the probe's movement along the device axis. The obtained experimental dependence remains unchanged by other values of the discharge current in the localized discharge too.

As a result of the fact that $V_{pl} = \text{const}$, a tension of the electric field in localized plasma in the axial direction is zero, hence, the electric field is absent and the plasma is equivalent in this direction.

Since

$$\bar{E}_e = \text{const}$$

and

$$N_e = \text{const},$$

thus, plasma in the longitudinal direction is homogeneous.

In the same device, under the same conditions as well as for the axial ones, radial studies were conducted $i(V)$ and $i''(V)$.

To do this, the device probe was soldered perpendicularly to the axis of discharged gap to the localized device in the lateral surface of the vacuum chamber. Measuring part of the probe was turned to 90^0 and was parallel to the device's longitudinal axis. The probe's dimensions were the same one as with axial probe measurements.

The probe holder precisely passed between the neighbour rod electrodes and with the help of a magnetic field, it was possible to move the probe within $0 \le r \le 50 \cdot 10^{-3}$ m so that the probe had already entered the probe tube and went beyond the limits of the discharge chamber (radius of which was $41 \cdot 10^{-3}$ m)

Placing the probe along the radius

$$r = 0,5;10;15i19 \cdot 10^{-3} \text{ m},$$

measurements of $i(V)$ and $i''(V)$ were superimposed on one another, as it is showed on fig. 2.

After the processing of curves $i(V)$ and $i''(V)$ on ECM, plane parameters had similar values as for axial measurements:

$$V_{pl} = 2,1 \text{ V}; \ \bar{E}_e = 0,36 \text{ eV};$$

$$N_e = 3,25 \cdot 10^{11} \text{ cm}^{-3}.$$

Due to the fact that the plasma of a localized discharge is formed by the large number of identical negative radiations addition under the influence of complicated conditions, its outer surface is surrounded by a non-uniform electric field under the radius formed by a system of rod anodes and alternating cathodes. As a result, some of the individual parts of the plasma adjoin the space, which contains a strong electric field. Other gaps in this plasma are bordered by space with a weak electric field. According to the theoretical studies presented in [14-16], a stream of fast electrons is formed in the dark cortex space, which creates new ions in the process of ionization, and in the excitation processes - resonance radiation during the entrance to the plasma. It should be noted that this is not happening on the border with the faraday space.

Therefore, it is logical to assume that at some intervals of plasma of general radiation that are situated in front of the rod cathodes such plasma parameters as V_{pl}, $\overline{E}_e$, and N_e, can differ from similar parameters in the plasma regions that are located in front of the rod anodes. Then, while moving in a circle with a radius smaller than the radius of plasma, there may be azimuthal hetero-geneity. In order to detect such heterogeneity, a study of plasma of a localized discharge by azimuthal probe was conducted.

The most significant manifestation of azimuthal heterogeneity will be in the case when the largest central angle φ is located between the core electrodes of a localized device.

Then the second S of a radius r, during which the azimuthal probe will move, is equal to $S = r\phi$. Since $\phi = 2\pi / N$, so when $r = R$, we have $S = R \cdot 2\pi / N$. Hence, azimuthal heterogeneity is easier to find in such a localized device in which the bit gap has large radius S and a smaller number of core electrodes N.

However, during extremely small N and large R, a restriction that leads to the fact that a localized plasma may not be created due to the disappearance of complicated discharge conditions, especially for large gas pressures is imposed. This follows from expression (4.9) when $p = d_0 p_0 / S$, and should be $pS < p_o d_0$.

Thus, the most optimal geometry of a discharge gap corresponds to a device with a diameter of $D = 4,6 \cdot 10^{-2}$ m and $N = 16$ as one variant and $N = 10$ in another one. In a case when $N = 16$, a central angle $\phi = 22,5°$, when $N = 10$ - this angle is $\phi = 36°$.

Since all the anodes and cathodes are identical, the determination of azimuthal heterogeneity during probe measurements is sufficient in one sector between adjacent electrodes (anode and cathode). With this purpose, the measurement of the probe characteristics $i(V)$ and the second derivative $i''(V)$ was carried out in three positions of the azimuthal probe:

1 – oppositely to the anode (A),

2 - inside the anode and the cathode (A-K),

3 – oppositely to the cathode (K). The position of the probe in the first variant was changed through $11,25°$, and in the second through $18°$.

Azimuthal measurements were carried out in the following sequence. Initially, under the constant discharge regime, determined pressure, the nature of the gas and power supply, the dependence $i(V)$ and $i''(V)$ at different positions of the probe were removed. Then the measurements of $i(V)$ and $i''(V)$ were performed at different discharge modes, radiuses of azimuthal probe, pressure and in different gases.

Azimuthal measurements were carried out in a localized device with a diameter of $D = 4,6 \cdot 10^{-2}$ m, a length of 0,128 m and the number of electrodes $N = 16$, and showed the following results of current $I = 2 \cdot 10^{-2}$ A, dependence curves $i(V)$ and $i''(V)$ were recorded according to the above-mentioned methods of experimental probe measurements in three positions of azimuthal probe A, A-K and K through $11,25°$. All three curves $i(V)$ were superimposed on each other with a slight disagreement within the measurement error. Curves $i''(V)$ were coincided with each other. As a consequence, azimuthal heterogeneity was not observed in this device.

The possible cause is in a small central angle's value between the electrodes that formed $22,5°$.

During the further search of the azimuthal heterogeneity, the curves $i(V)$ and $i''(V)$ were determined depending on the discharge mode (within $1 \cdot 10^{-2}$ A - $8 \cdot 10^{-2}$ A), the pressure and the nature of gas in the interval 10-82 Pa of neon, argon and nitrogen. Here the dependence of $i(V)$ was determined for the three positions of the probe A, A-K and K of one curve. Measurements with a variable radius of the azimuthal probe yielded similar results.

The curves $i''(V)$ processed on the computer showed the same characteristic properties of the plasma of a localized discharge, which were established with axial and radial probe measurements.

As a result of probe measurements, the absence of azimuthal heterogeneity is established.

It should be noted that this experimental fact confirms the complete homogeneity of the plasma of a localized discharge. The assumption of plasma's azimuthal inhomogeneity, which was supposed to arise under the action of discrete streams of fast electrons from the side of the rod cathodes, was not confirmed.

Conclusions

1. According to the probe researches that were carried out in the plasma of localized discharge in various directions, the fact that localized plasma is homogeneous and equopotential was set.

2. In alocalized plasma, a function of electrons' distribution by energies $f_e(E)$ in the regions of small energies is insignificantly differ from Maxwell distribution $f_m(E)$, but by $E_e > 6-8$ eV has an excess of fast electrons. Such excess of electrons is significantly bigger that in $f_{nv}(E)$ of ordinary plasma with negative radiation

Since localized plasma is a protracted plasma radiation column with high intensity, its utilizing in in the vicinity of SC's antenna compartment is expedient and desirable to create some reliable communication channels through a high-temperature ionized external environment.

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Надійшла до редколегії 23.10.2017

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ЗОНДОВІ ДОСЛІДЖЕННЯ ЛОКАЛІЗОВАНОЇ ПЛАЗМИ, ЯК МЕТОД ПІДВИЩЕННЯ ЗАВАДОСТІЙКОСТІ СУПУТНИКОВИХ РАДІОНАВІГАЦІЙНИХ СИСТЕМ НА ДІЛЯНЦІ ВИВЕДЕННЯ КОСМІЧНОГО АПАРАТУ НА ОРБІТУ

О.В. Шефер

У статті запропоновано метод підвищення завадостійкості супутникових радіонавігаційних систем під час виведення КА на орбіту, шляхом використання нових внутрішніх характеристик локалізованої плазми, котрі виявлені шляхом зондових досліджень. Проведено дослідження потенційних осьових, радіальних та азимутальних неоднорідностей плазми. Результати досліджень спростовують припущення про наявність азимутальної неоднорідності плазми, котра повинна була виникати під дією дискретних потоків швидких електронів. Остаточно встановлено однорідність та еквіпотенціальність локалізованої штучної плазми, що дає змогу використовувати її в околі антенного відсіку КА для утворення надійних каналів зв'язку через іонізоване зовнішнє середовище.

Ключові слова: *космічний апарат, плазма, завадостійкість, супутникова радіонавігаційна система, зондові вимірювання, щільність плазми, неоднорідності.*

ЗОНДОВЫЕ ИССЛЕДОВАНИЯ ЛОКАЛИЗИРОВАННОЙ ПЛАЗМЫ, КАК МЕТОД ПОВЫШЕНИЯ ПОМЕХОУСТОЙЧИВОСТИ СПУТНИКОВЫХ РАДИОНАВИГАЦИОННЫХ СИСТЕМ НА УЧАСТКЕ ВЫВЕДЕНИЯ КОСМИЧЕСКОГО АППАРАТА НА ОРБИТУ

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В статье предложен метод повышения помехоустойчивости спутниковых радионавигационных систем во время выведения КА на орбиту, путем использования новых внутренних характеристик локализированной плазмы, которые выявлены путем зондовых исследований. Проведено исследование потенциальных осевых, радиальных и азимутальных неоднородностей плазмы. Результаты исследований опровергают предположение о наличии азимутальной неоднородности плазмы, которая должна была возникать под действием дискретных потоков быстрых электронов. Окончательно установлено однородность и эквипотенциальность локализированной искусственной плазмы, что позволяет использовать ее в зоне антенного отсека КА для образования надежных каналов связи через ионизированную внешнюю среду.

Ключевые слова: *космический аппарат, плазма, помехоустойчивость, спутниковая радионавигационная система, зондовые измерения, плотность плазмы, неоднородности.*