International Journal of Engineering & Technology, 7 (4.8) (2018) 17-21

International Journal of Engineering & Technology

Website:www.sciencepubco.com/index.php/IJET

Research paper

Further development of satellite telecommunications radio signals noise immunity increasing method

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Abstract

The problem of radio communication loss during spacecraft passage at hyperspeed through dense layers of atmosphere at heights of 60-120 km as result of plasma ionization shock wave formation is analyzed. As a result, this part of spacecraft trajectory is the most problematic from navigation and control point of view. A part of this unsolved problem is identified and an innovative method for solving it is proposed – a method of resonant radio signal regeneration developed, which based on interaction of outer ionized layer elementary particles with artificially generated high intensity negative radiation. Technical means for artificial low-temperature plasma energy-efficient formation have been developed. A design for equipotential low-temperature plasma of high intensity, which based on near-cathode region glow discharge and depends on electrodes geometric parameters and gaseous medium physical parameters proposed. This method, in comparison with existing spacecraft radio communication methods, does not introduce changes into spacecraft external design and does not affect flight aerodynamics. High-temperature plasma shell with artificial intense negative radiation interaction simulation confirms the formation of resonant regenerative transport layer that facilitates radio signal passage through plasma ionization shock wave around spacecraft.

Keywords: *ionospheric plasma, negative radiation, noise immunity, radio signal, satellite telecommunications, spacecraft*.

1. Introduction

One of the important modern Ukraine priorities as a space state is development of national satellite telecommunications segment. (Sustainable Development Strategy "Ukraine – 2020", 2015).
Using terrestrial and satellite radio systems, the task of information exchange between moving objects is solved. This problem is especially acute during launch spacecraft into orbit, as there are boundary conditions such as flight path, external gas environment aerodynamic resistance, solar and geomagnetic activity and other factors that significantly affect the quality of communication with the spacecraft.
For radionavigation systems that have transmitting device and radio reception device, intermediate medium is environment in which radio waves propagate. During radio waves propagation in natural ways, environment of electromagnetic oscillations propagation is that element of radio system, which is practically not manageable (Ippolito, 1981).
When spacecraft entering atmosphere at hypersonic speeds, due to external gas environment aerodynamic resistance, it's shell is heated. These spacecraft include: manned space objects, descent spacecrafts, space probes, intercontinental missile warheads, sample capsules, as well as objects that can or should be burned, for example, satellites that have worked their resources, and so on.
As a result of heating, there is a huge amount of heat, which leads to plasma formation around the spacecraft. Plasma completely absorbs radar radiation. As a result, a frequency-selective fading environment is formed, which is not penetrating to signals of satellite telecommunication systems.
This environment limits radio signals passage during a few minutes. This period is the most dangerous in terms of reliability and safety of the spacecraft's flight (Fig. 1, segment 4-5).
Analysis of all existing plasma "breaking" methods has shown that at this time there are no such methods that would yield a quality result when used in onboard systems. This is due either to increased mass-grossing values, or to significant energy costs, or to spacecraft aerodynamics deterioration (Kucher, 2015; Litvina,2007; Konyahin, 2001; Wolverton, 2009; Shevyakov, 2014; Izhovkina et al., 2014).
For example, there are several innovative approaches to solving this problem, in particular on-board antennas with thermal protection, whose original designs have reduced radiotransparency sensitivity to high-temperature aerodynamic heating effect or using "long" heat-resistant antennas, carried out plasma shell film.
It is also proposed to noise immunity increase of satellite telecommunications radio signals by supplying refrigerant through the porous heat protection on its surface, reducing temperature of antenna compartment radiating surface to desired temperature.
It is proposed to construct thermal protection from combination of materials with different temperature coefficients, which leads to temperature field redistribution over thermal protection surface and provides increased radiotransparency of spacecraft antenna compartment. However, the problem of radio waves passing without loss and distortion through such plasma remains unresolved.

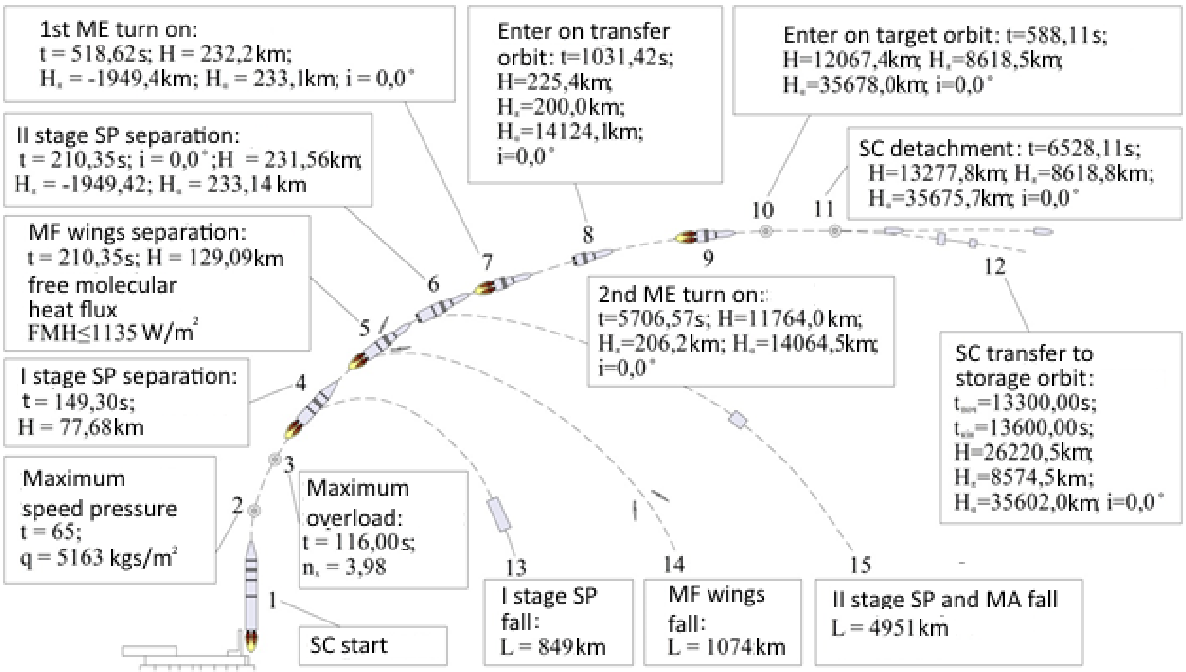

Fig. 1: Stages of spacecraft launch into orbit scheme: SP – structure part, which is separated; MF – main flyer; MA – middle adapter; ME – march engine; H – flight height; Hπ – perigee height; Hα – apogee height; i – tilt; t – flight time; tst – spacecraft transferring to storage orbit start time; tend – spacecraft transferring to storage orbit end time; L – approximate fall distance from the launch point.

The solution project of this problem, developed by Chinese scientists, is based on signal amplification, which can be created by resonance or coordinated electromagnetic oscillations between plasma shell and special layer, surrounding spacecraft. The developers propose adding a "matching layer" to create necessary resonant conditions during launch of spacecraft into orbit. It is assumed that the matching layer will ensure a steady energy circulation between plasma and specified layer. As a result, radio signal coming from the Earth can be distributed through the matching layer and the plasma shell without interruption.

However, for effective work of this approach, the thickness of alignment layer and plasma shell should be less than the length of electromagnetic waves used for communication with spacecraft. Therefore, proposed method will not work with the existing ultra-high-frequency and extremely high-frequency range of spacecraft onboard systems.

Works (Litvina, 2007; Konyahin, 2001; Wolverton, 2009) suggest a method for information transmission through plasma, which is based on simultaneous influence on plasma by electrons flow, acoustic wave and information signal.

2. Main Body

Electron flux injection into plasma is accompanied by excitement of its longitudinal plasma oscillations of different charge densities. In this process, oscillations occur at their own plasma frequency and do not require additional modulation of electronic flow. Such modulation, according to Litvina (2007), is carried out automatically, and it precisely leads to beam focusing and excitation of rather strong waves. In the presence of sound waves in plasma, the interaction of plasma and acoustic waves occurs. As a result, waves with a frequency lower than resonance are formed. The process of outgoing waves interaction and new waves formation is explosive in nature (unstable modulation) and leads to cavities appearance in plasma with reduced density. Such cavities are formed along the electrons beam and their number depends on acoustic oscillations half-waves number.

Consequently, the simultaneous influence on the plasma by electron flow, acoustic waves and radio signal forms windows with lower electron density, which allows the electromagnetic wave to carry information through shock wave plasma.

Free channels existence in dense plasma is about 15 - 20 μs. For a height of H = 10 km, the specified time is not less than 100 μs, which allows to extend communication range. The elevation H up to 10 km significantly reduces use of proposed method to increase radio communication signals noise immunity with spacecraft at the time of its launch into orbit. Exactly at altitudes of 60-120 km there is a loss of flight control center communication with spacecraft.

In (Shefer, 2017a), a progressive energy-efficient method of influence on plasma radio-impact shell was proposed, with a goal to density local weakening. This method is based on noise-proof communication channel formation by the influence on plasma shell from spacecraft side. This is possible with interaction of high-temperature plasma elementary particles with an artificially created low-temperature plasma source (Shefer, 2017b; Shefer, 2017c).

It is proposed to generate, in antenna compartment vicinity, a negative radiation low-temperature plasma that locally "enlightens" the ionized external flux of the plasma, thereby forming a jamming channel. The process takes place without interference in spacecraft outer structure and depends on plasma electrodes geometry and type, pressure and type of gas filler.

For effective formation of "window" with reduced density in external ionized medium, it is necessary to develop a method for quasineutral, equipotential, artificial negative radiation plasma creation.

Investigation of negative radiation plasma, which was formed in a discharge with a plane-parallel gap, established a series of inhomogeneities (Smirnov, 2015) both in the longitudinal and radial directions. According to studies (Smirnov, 2015), it was found that in the cathode part of negative radiation, positive ions concentration n_i is greater than electron concentration n_e ($n_i > n_e$), and in anode part, on the contrary, $n_e > n_i$. Significant contribution to space potential distribution heterogeneity V_{pl} of electric field intensity E, the energy of electrons E_e and ions E_i, n_e and n_i concentration, and other parameters of this plasma makes ambipolar diffusion process of electrons and ions to discharge chamber bounding walls. For example, in (Mustafaev, 2000) it was shown that electrons symmetric distribution is violated due to ambipolar diffusion. This diffusion and accompanying recombination of charge carriers on discharge chamber walls make disturbance to elementary processes, leads to plasma heterogeneities occurrence and disperses discharge energy.

Despite the fact that the intensity of negative light plasma radiation, in comparison with positive column plasma, is much higher and energy input per volume unit of this plasma is lower, the practical use of this plasma is much less than positive column plasma, due to the fact that its sizes are very small. In order to eliminate these disadvantages and to use the positive properties of negative radiation plasma, causes of ambipolar diffusion occurrence and ensuring conditions for its uniformity throughout negative radiation volume were investigated.

In this scientific work are being investigated possibility of plasma obtaining in short glimmering discharge with radiation high intensity, sufficiently large dimensions, without electrons and ions ambipolar diffusion, sufficiently homogeneous both in longitudinal and radial direction.

The plasma emission analysis shows that v - processes occurs only in cathode and anode end surfaces of negative radiation plasma. From plasma cylindrical surface there is charge carrier ambipolar diffusion, which reduces plasma efficiency If v - processes are also created from lateral surface, losses of charge carriers are sharply reduced and plasma efficiency will increase substantially.

From negative radiation charge carriers can not pass through electrodes to bounding wall due to fact that passing through strong electric field between electrodes, they fall either on cathode or on anode. As a result, negative radiation plasma is distant from the bounding wall and does not interact with it. If place rod anodes and alternating cathodes along the concave or convex surface of discharge chamber, we obtain, in discharge ignition case, overall negative radiation from many elementary discharges.

The large number of rod anodes and alternating cathodes placement in a circle along discharge tube inner surface creates a discharge gap in form of cylindrical cavity (Fig. 2).

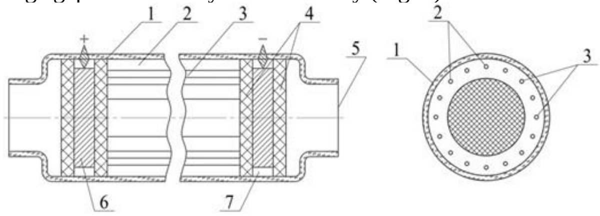

Fig. 2: A gas discharge device for generating a large sizes overall negative-radiation plasma: 1 – vacuum chamber; 2 – anodes; 3 – cathodes; 4 – elec-trodeholders insulators; 5 – quartz glass window; 6 – anode holders; 7 – cathode holders; 8 – overall negative radiation plasma.

In this case, gas discharging device is a system of rod anodes and cathodes of 0.19 m length, arranged in circle with $6.2 \cdot 10^{-2}$ m diameter in transparent gas-discharge tube of 0.28 m length and $7.2 \cdot 10^{-2}$ m diameter. Each pair of adjacent electrodes (anode and cathode) is a separate discharge gap along entire device. After thorough vacuum treatment, gas-discharge device was filled with one of inert or molecular gases. The pressure of filled gas, the distance between adjacent electrodes and between electrodes and bounding walls were chosen to meet complicated discharge conditions.

As a result, if anode voltage is switched on within the range of 380 - 500 V, a weakly anomalous discharge gap is established in gas-discharge device, gap regions of which are located only in the inner zone of discharge gap. Under steady-state conditions, only one region of radiation was detected in each glimmering discharge negative radiation. In cross-section, the shape of each negative radiation is half-ellipse, extending to the center. Since all negative radiation was identical and any one of them was between the same neighbor, it imperceptibly merged into one common radiation that has shape of cylindrical pillar whose diameter is more than half the diameter of the gap. In spite of the fact that separately negative radiation of each discharge did not reach the axis of device during all discharges ignition, overall radiation filled entire central region along entire device. In the process of plasma discharge overall radiation is well observed directly through the lateral surface of discharge device free end. The boundaries of overall radiation plasma are clearly visible (Fig. 3 and Fig. 4).

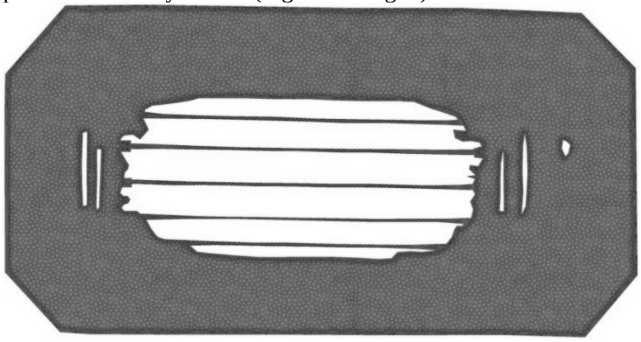

Fig. 3: Overall radiation plasma discharge. View through cylindrical glass transparent vacuum chamber lateral side

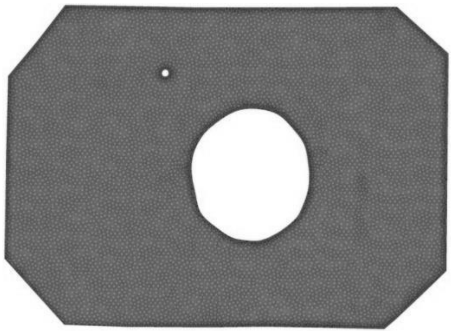

Fig. 4: Localized discharge. View from vacuum chamber end

The geometry of discharge gap consists of rod anodes and cathodes length, which are arranged evenly over cylinder generatrix along inner cylindrical surface of discharge chamber. In this arrangement, anode and cathode alternate so that any pair of adjacent rod electrodes is anode and cathode and forms separate elementary discharge gap. In this case, each anode (and cathode) is between two cathodes (anodes). Such geometry of electrodes location binds individual discharge gaps to one general discharge gap. The diameter of rod electrodes is selected so that it does not significantly reduce transparency of discharge gap. The most optimal diameter of electrodes is within the range of 0.8 - 3 mm. The length of electrodes l was selected so that diameter of discharge gap D was significantly less than l ($D \ll l$). This is necessary to reduce the effect of face heterogeneities in discharge process. In general, the gap space is a transparent cylinder with clear boundaries, Fig. 2, as a consequence, the discharge in the future is called localized.

Anode holders and cathode holders have been introduced to place electrodes in a circle in discharge device construction. Each of these elements consists of a metal ring with apertures for rod anodes (or cathodes) and two cylindrical clips from the insulator that completely isolate electrodes ends with ring from discharge process (Fig. 5).

In anode holder all the anodes are connected by metal ring and have one output through dielectric in a glass chamber. A similar output is from cathode holder.

Since localized discharge plasma is formed in space created by system of electrodes, its surface for interaction with fast electrons is considerably larger than the analogous surface of ordinary discharges negative radiation glimmering plasma. Under conditions of sufficiently large plasma length, when the length of the localized discharge L is much larger than its diameter $L \gg D$, plasma surface that interacts with fast electrons is the basis. As a result, plasma generation is the only process of direct interaction with surrounding bodies, since charge carriers ambipolar diffusion on vacuum chamber inner walls is unlikely. It is characteristic that at this level plasma generation is not bilateral, as in the classical negative radiation plasma, but rather one-sided, since rod anode and cathode are located at very short distances from each other.

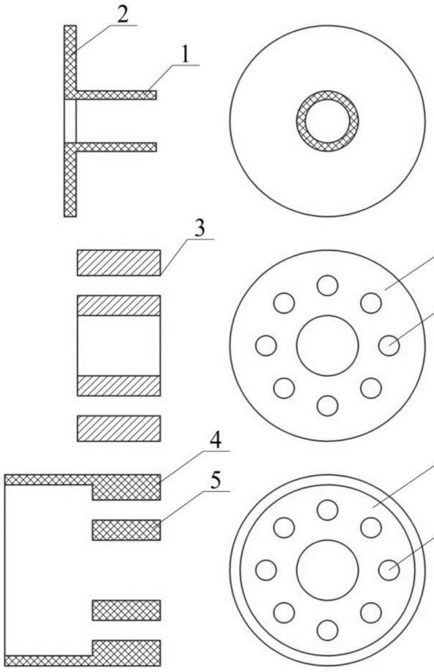

Fig. 5: Discharge device design: 1 – electrode holder isolation; 2 – face isolation; 3 – rod electrodes guide; 4 – metal electrode holder; 5 – electrode insulator

As a result, use of *v* - processes from entire plasma area will lead to a more intense electric charge transfer between anodes and cathodes, which should affect entire discharge electrical conductivity increase.

In a gas-discharge localized device, radiation plasma is formed not between electrodes, but in electrode system center of cylindrical pillar. This is due to the fact that a distance l is established between adjacent rod electrodes, under condition of selected gas pressure p, that normal discharge does not fit, that is, the condition

$$lp > l_0 p_0 \quad (1)$$

where p_0 – gas pressure at 133,(3) Pa; l_0 – distance between electrodes, which is necessary for the placement of normal short glimmering discharge at pressure p_0.

Under this condition, discharge zones will be displaced in direction where they have free space. Since each pair of rod electrodes creates a short discharge, the negative radiation is shifted most of all. Since the central region of the discharge gap is free of electrodes, in it displaces cathode region discharge zones.

From previous experimental studies of coplanar discharge it was found that under complicated conditions, anode and cathode can be bring closer to a very small distance between them and to combine them in one plane. Based on this in localized device rod anodes and cathodes are located on single cylindrical surface at a distance of $0.25l_0$, i.e.

$$lp = 0.25 l_0 p_0 \quad (2)$$

The close location of rod anodes and cathodes during complicated conditions creation is reflected in character of localized gap overall electric field. With electrolytic bath aid, a study of gap form was performed, which showed that in the central region of this gap, the equipotential space without an electrostatic field is localized (Fig. 6). This circumstance has a significant effect on localized discharge plasma.

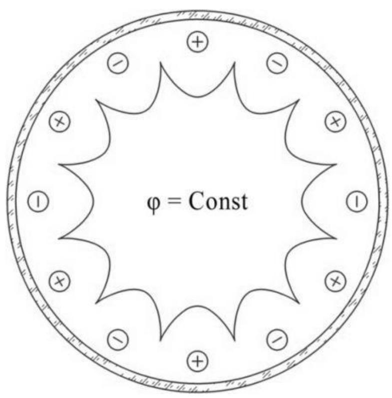

Fig. 6: Localized discharge gap electrostatic field geometry: "+" – rod anodes; "-" – rod cathodes

During discharge ignition in localized device between each pair of rod electrodes a short glimmering discharge is established along entire rod length, in which, due to one-sided complicated conditions, all negative radiation is displaced to electrode system central region. Since all the negative radiation is identical, they collide with each other and merge, forming one common negative radiation that is in bright pillar form and is positioned exactly along entire discharge gap axis.

As a result of ionospheric medium elementary particles and artificially generated energy-efficient negative-emission plasma interaction, there is positive ions and negative particles neutralizing process, or ion-ion recombination, with stabilizing neutral particle participation.

The process of radio signal passing is associated with resonant regeneration, which takes place during resonant electromagnetic field formation between the outer plasma shell and internal artificial negative radiation.

The results of this neutralization process modelling, according to Kryukovskiy (2012), and "window" formation with reduced density in external ionized medium, are shown in Fig. 7.

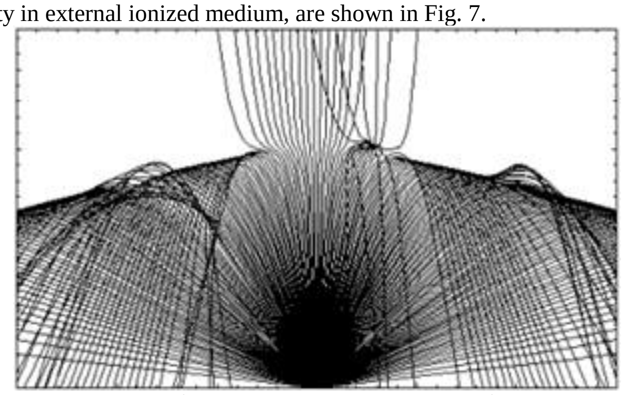

Fig. 7: Formation of "window" with reduced density for passing radio signals

Studies have shown that transporting thickness of the resonant regeneration field is more than 10 cm, which unequivocally indicates radio signal unimpeded passage through the outer plasma high-temperature shell, regardless of the spacecraft height and speed.

3. Conclusion

Output of radio signal through plasma shell is possible on basis of electromagnetic radiation regeneration properties use. When a radio signal hits the plasma, there is a current that conventionally divided into thermal and resonant particles currents. These currents come at distance much larger than decay radius in the plasma. When the resonant currents reach plasma limits in free space, regeneration of electromagnetic field occurs. Consequently, for radio signal output through the plasma, it is necessary that resonant currents damping characteristic length in a dense outer plasma is the greater thickness of plasma sampler. The presence of external field, which is formed by negative radiation plasma, raises radio signal transport length, which confirms results of simulation.

Developed device, based on described physical processes, al-lows to obtain a number of technical advantages, namely: to use standard onboard radar systems and to provide communication without additional significant energy inputs.

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