Determination of Electromagnetic Emission from Electric Propulsion Thrusters under Ground Conditions

IEPC-2017-167

Presented at the 35th International Electric Propulsion Conference
Georgia Institute of Technology • Atlanta, Georgia • USA
October 8 – 12, 2017

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Abstract: The paper presents analysis and methodological generalization of the available methods used for determining characteristics of self emission from electric propulsion (EP) thrusters in the radio-frequency range that can represent interference for the "Earth-Spacecraft (SC)" channel of space communication systems. Peculiarities in the determination of self electromagnetic emission from the models of stationary plasma thrusters of SPT-100 and SPT-140 types in the radio-frequency range are discussed by the example of the measuring complex designed by RIAME MAI, and appropriate test results are presented. Frequency distribution of the electric field intensity in the radio-frequency range for the vertical and horizontal polarizations of the received signal is considered as the main characteristic. Comparative analysis was carried out for the EP self-emission measurement data obtained using the developed complex and measurement data obtained in the metal vacuum chambers. Influence of the thruster accrued operating time on the variation of its emission characteristics in the radio-frequency range was studied using the thruster model of SPT-140 type (with the power of 4.5-5 kW) for the development of grounds of the predictive analysis for the variation of electromagnetic environment during the SPT lifetime. The work was fulfilled in the interests of the Information Satellite Systems - Reshetnev Company under the support of the Ministry of Education and Science of the Russian Federation.

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High-power EP thrusters can be a basis for the development of promising nuclear EP systems for self-contained and piloted space complexes. Application of high-power cruise EP thrusters on board inter-planet spacecraft requires investigations in the area of activities related to studying complex electrodynamic action of EP thrusters on the onboard equipment of a spacecraft under ground conditions, including the development of methods for determining characteristics of the EP self-emission in the radio-frequency range that can represent interference for the "Earth-SC" channel of space communication systems.

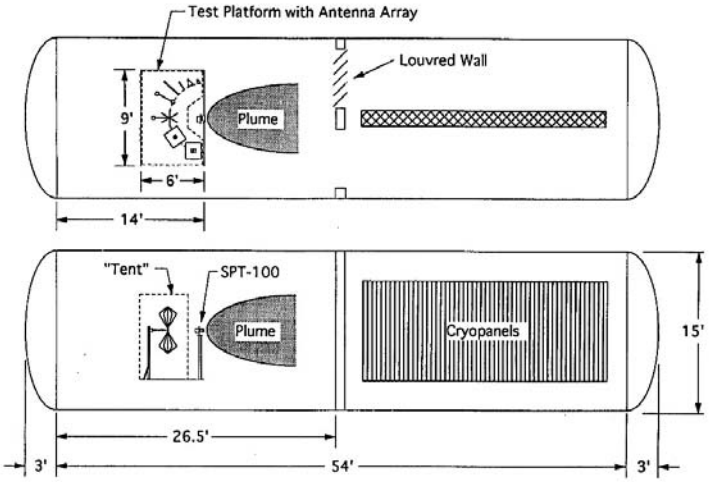

Figure 1. Test facility of the Lewis Research Center, NASA.

Taking into account that standard operation of various EP types is possible in vacuum of not worse than 10^{-5}-10^{-4} torr, for the reliable measurements of electromagnetic emission it is necessary to provide both the absence of reflections, i.e. "anechoicness" (the anechoicness factor should not be worse than -25 dB), and the required level of vacuum. In the course of EP development, this rather complicated task was solved by various technical means in different countries.

In the beginning of 1990-ies the Lewis Research Center was studying this problem actively. The EP self-emission was investigated using the metal vacuum chambers and standard measuring devices[1] according to a simplified procedure (Fig. 1).

It is necessary to note that making measurements in the metal vacuum chamber has essential disadvantages. The vacuum chamber structure itself represents a resonant chamber with the current-conducting walls, in which a large number of oscillation modes can appear during the EP operation. In addition, interference appears between the direct signal from EP and a sum of all primary and secondary reflections from the walls. As a result, substantial uncertainty appears during the assessment of electromagnetic field intensity at every frequency in the pick-up antenna aperture.

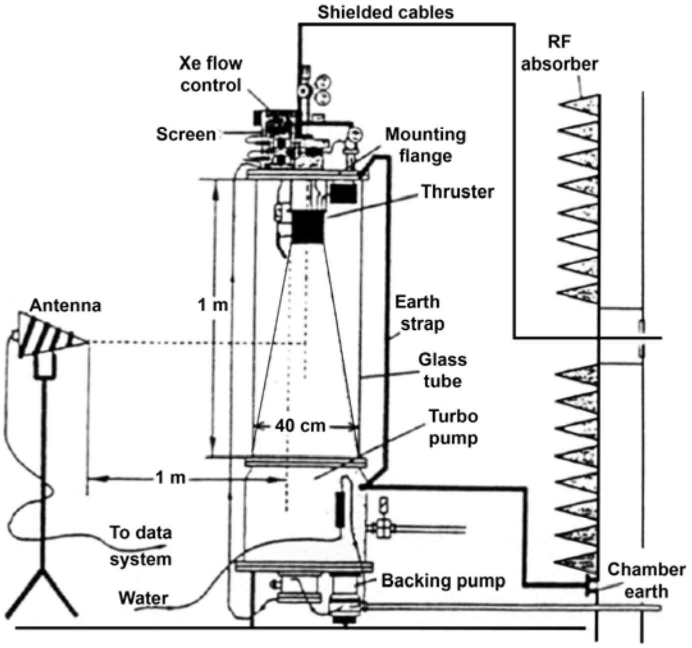

Figure 2. General view of the DASA/MBB test facility.

Attempts to increase reliability of measurements carried out for assessing the EP self-emission were made in different countries. So, for example, in order to study characteristics of electromagnetic emission from the ion thruster T5 mounted on board the spacecraft ARTEMIS, a facility comprising anechoic chamber was used at the Munich division of DASA/MBB (Germany) (Fig. 2)[2]. The thruster was mounted at the end of the glass cylinder of 40 cm in diameter and 1 m in length. The cylinder was mounted vertically on the turbo-molecular pump providing required vacuum. The use of anechoic chamber was the next step forward, but the presence of technologic systems and vacuum pump within the measuring volume did not allow avoiding multiple reflections, which decreased general accuracy of measurements.

The tendency to separate vacuum and measuring zones was further developed by the Aerospace Corporation (USA).[3, 4] Its equipment for testing EP thrusters with regard to

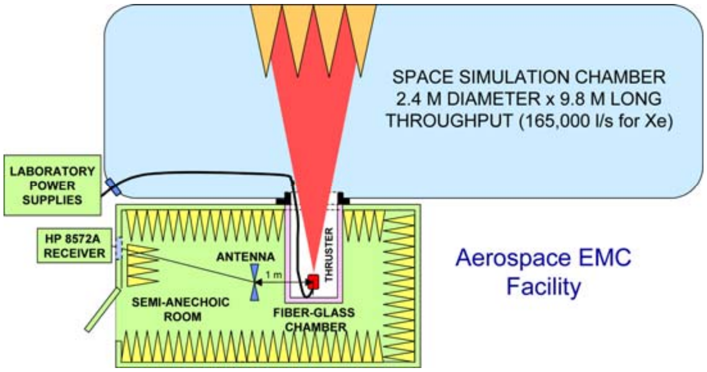

Figure 2. Test facility of Aerospace company designed to measure electromagnetic emission from EP thrusters.

electromagnetic compatibility (EMC) comprised two additional functional elements integrated into the standard test facility with the chamber of large volume (Fig. 3). Such elements are:

- additional dielectric radio-transparent vacuum chamber, in which the thruster is mounted. It is a fiberglass cylinder with the diameter of 0.9 m and length of 1.8 m that is transparent for electromagnetic emission. It is connected to a large metal vacuum chamber with the pumping rate of 165 000 l/s;
- shielded anechoic room that limits working space around the dielectric cylinder by 5m×3m×3m. It secures the external electromagnetic radiation shielding by more than 100 dB within the frequency range from 14 kHz up to 18 GHz and absorption of internal emission due to the application of radio-absorbing coatings from -6 dB (80-250MHz) to -30 dB for the frequencies over 250 MHz. The room is under the atmospheric pressure.

For the enhancement of such facilities, we proposed a new approach. It is based on providing mobility to the anechoic room and a possibility for its quick disconnection and movement relative to the primary vacuum chamber. Configuration of such test facility is presented in Fig. 4.[5]

As is clear from the figure, the mobile anechoic room is mounted on a railtrack and can move relative to the main vacuum chamber equipped with the pumping system.

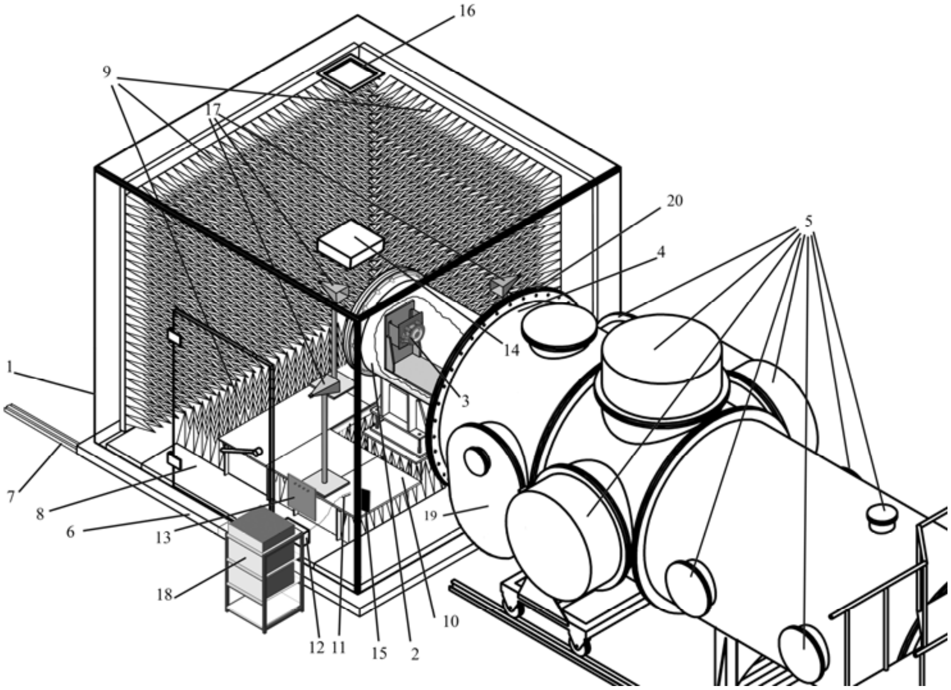

Figure 4. Arrangement of the shielded anechoic room being a part of test facility:
1 – anechoic room; 2 – radio-transparent cylinder; 3 – EP thruster; 4 – primary vacuum chamber; 5 – pumping system; 6 – mobile platform; 7 - railtrack; 8 - door; 9 – radio-absorbing coating; 10 – dielectric floor; 11 - mains-operated extension cord; 12 - feedthrough power-supply filter; 13 – panel with bulkhead connectors; 14 - reversible fan assembly; 15 – fan control panel; 16 - additional ventilation window; 17 – pick-up antennas; 18 – vertical bay with measuring devices; 19 - manhole; 20 – connecting flange.

A radio-transparent vacuum section, in which EP thrusters are mounted for their testing, is located inside the anechoic room. All communication lines providing EP operation are laid from the primary metal vacuum chamber.

Reliable interface for two vacuum volumes is provided by a quick-disconnect vacuum joint described in Ref. 6. A floor of the dielectric sheet material is constructed above the bottom pyramidal absorbers. Pick-up antennas overlapping the specified frequency band can be mounted on this floor. Signals from antennas are transmitted from the shielded room through the bulkhead connectors to the devices for spectral-temporal analysis. The ideology of hardware-software complex construction described in Ref. 3, 4, 7 was used.

To define the achievable metrological accuracy, we compared the EP self-emission measurement results obtained in the metal vacuum chamber and in the anechoic room. For this we have set up and made the experiment using SPT-100 thruster as a test one. Initially, it was mounted in the radio-transparent vacuum section of the anechoic room, and afterwards – in the primary metal vacuum chamber of the test facility. Geometry of such two locations of the thruster is shown in Fig. 5.

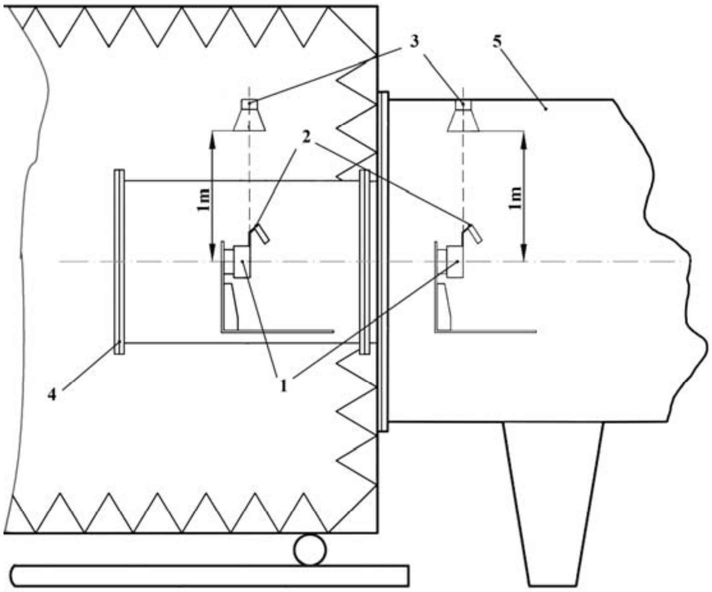

Figure 5. Arrangement of SPT and antenna while making measurements in the radio-transparent cylinder and metal vacuum chamber. *1 - SPT, 2 – cathode-neutralizer, 3 - antenna, 4 – radio-transparent cylinder, 5 – metal vacuum chamber*

During measurements, the power of the signal in the spectrum analyzer filter band was converted into the value of electric field intensity in the aperture of antenna in view of its antenna factor and transmission factor of the measuring link, as this is described in Ref. 7. Measurements were made for two types of polarization. As an example, Fig. 6 shows the dependences for the electric field intensity excess above the background for two variants of the SPT-100 locations (vertical polarization). The frequency band is limited from above by 3 GHz, because above this value the level of radiated emission was comparable to the background.

As is obvious from the plots, because of multiple reflections in the metal chamber and manifestation of its resonant properties, at some frequencies the measured level of radiated emission may be more than 3 times higher than that in the anechoic room. The plots correspond to the results obtained for vertical polarization and account for attenuation in the dielectric cylinder.

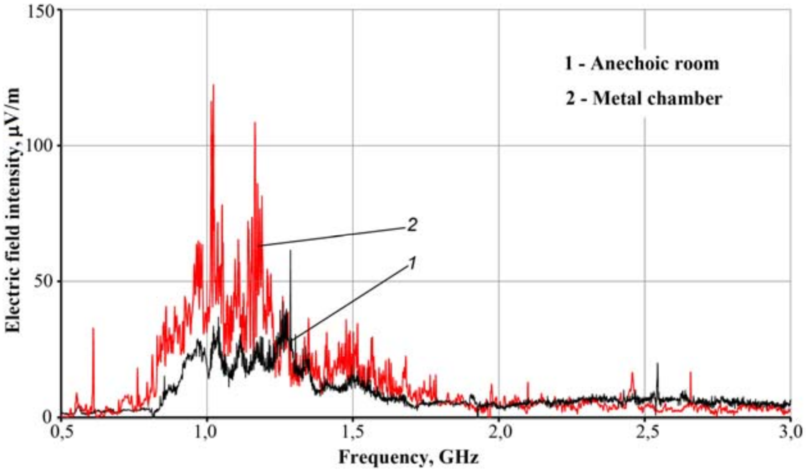

Figure 6. Results of comparison for the SPT-100 emission excess above background in the anechoic (1) and metal (2) chambers.

It should be noted that the spectra follow each other qualitatively being different in the mean values. The latter may be related to the noncoherent combining of direct signal and multiple reflections from the walls of the metal vacuum chamber, because of the procedure of averaging the representations in spectrum analyzer. Thus, transition to the EP emission measurements in the combined facilities comprising anechoic rooms allows considerable increase for measurement accuracy and avoiding errors overvaluing the EP actual emission levels.

Let's discuss the potentialities of measuring EP emission using such measuring complex. It is the most simple to make measurements in the EP rear hemisphere, including the direction to the thruster exit plane (ref. to Fig. 7). Similarly to the variant shown in Fig. 1, the antennas are located along the circle with the radius of 1 m. From the analysis point of view, let's restrict ourselves to three main locations: 1 – antenna axis is perpendicular to the cylinder axis; 2 – antenna is at an angle of 45° to the cylinder axis, and 3 – antenna is located after the thruster, and its axis coincides with the cylinder axis. As an example, Fig. 8 shows background (BG) and SPT-100 emission levels as a function of frequency for the vertical (VP) and horizontal (HP) polarizations with the antenna location according to option 1.

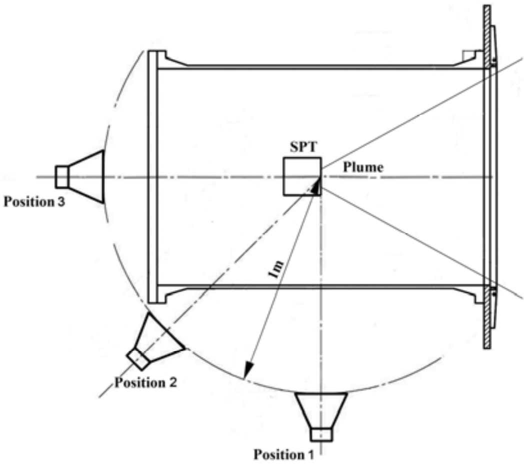

Figure 7. Measurement geometry

As is obvious from the plots, the vertical polarization component is dominating within this frequency range. Fig. 9 shows the results of measurements for the excess of vertically polarized EP emission over background for all three location options of the pick-up antennas in absolute values. It is evident that the SPT-100 emission in the rear hemisphere is not isotropic one, but has directive properties. In the case of the chosen geometry of measurements, the maximum emission was recorded at an angle of 90° to the thruster plume.

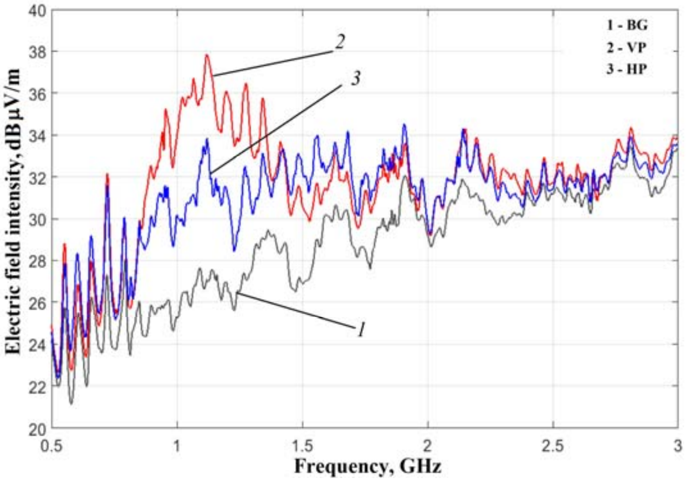

Figure 8 – SPT-100 emission as a function of frequency for the location option 1.

Study for the influence of SPT-100 operation modes on the characteristics of its emission is of definite interest. Similar works are described in Ref. 8, for example. It is shown that the discharge voltage increase caused increase in the thruster noises. During the described test, the SPT-100 operation mode was varied with the fixed propellant consumption rate and discharge voltage of 300 V by changing magnetic field due to the variation of current in the coils of magnetic system. As a result, two modes (from the point of view of magnetic field) were defined, in one of which the thruster emission was minimum, and in another it was maximum. Distinctive form of the EP emission excess over background (vertical polarization) is shown in Fig. 10 for U_d=300 V, I_d=4.2 A, m=4 mg/s and two configurations of magnetic field.

In the mode 1, currents in the magnetic coils of the thruster were the same and equal to 4 A. With such relation of thruster currents the plasma plume divergence was about 90°. In the mode 2, current in the outer coil was higher than in the inner one (4.8 and

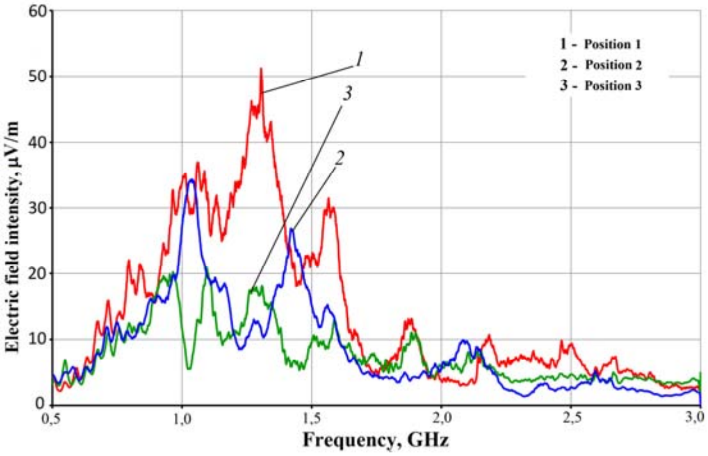

Figure 9. SPT-100 emission excess over background for three options of pick-up antenna location (vertical polarization).

4 A). With such relation of currents in the coils the plume was "pressed out" from the external walls of the discharge channel and, correspondingly, the divergence angle became more narrow, but the wear of internal channel walls increased substantially.

As is obvious from the figures, in the mode 2 the thruster emission is noticeably higher than in the mode 1, and at some frequencies the difference in the emission levels for two modes may be as high as an order of magnitude. Thus, we can suppose that the intensity of radio-frequency emission from the thruster is stipulated by the processes proceeding in the near-wall regions of the discharge channel, quantitative assessments for which require additional experiments. Nevertheless, we can conclude now already that by changing currents in the magnetic system it is possible to select optimum values not only from the point of view of obtaining optimum integral performance of the thruster, but for minimizing its emission also.

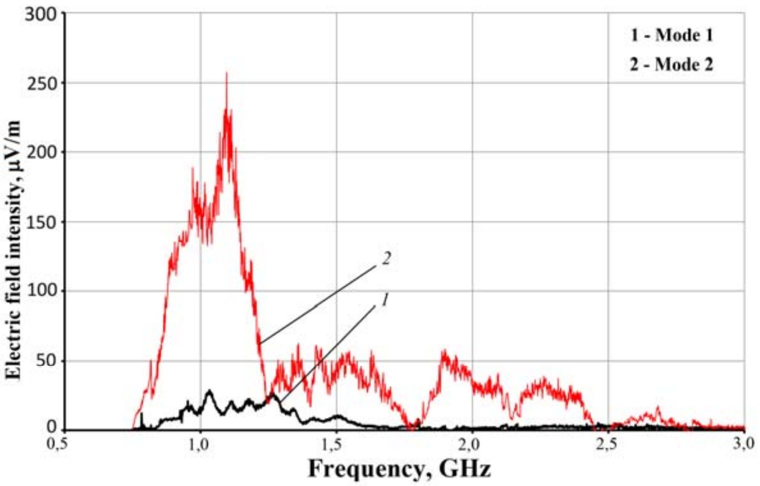

Figure 10. SPT-100 emission excess over background for marginal modes (vertical polarization).

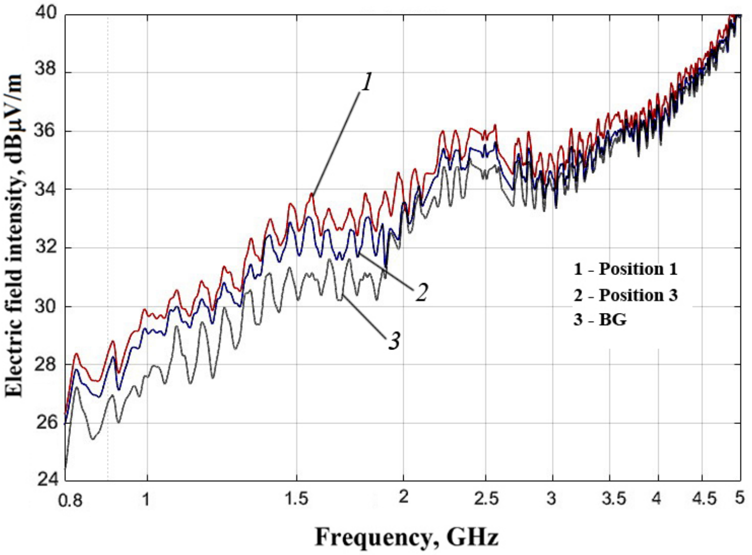

Figure 11. Emission from the thruster model of SPT-140 type as a function of frequency for the location options 1, 3.

Similar measurements were made with the thruster model of SPT-140 type (4.5-5 kW). Emission with vertical polarization as a function of frequency is presented in Fig. 11 for the antenna location options 1 and 3 (ref. to Fig. 7). According to the results of comparison with SPT-100, the latter has higher emission than SPT-140 with maximum excess of 6 dB within this range. This may be explained by both the more perfect design of the SPT-140, and by the fact that during that test the model operated with the standard power processing unit providing automatic mode control, in contrast to the SPT-100 that operated with the test-facility systems. On the basis of assessment for the emission directivity characteristics of the SPT-140 model, we can state that with the chosen measurement geometry the emission maximum was registered at the angle of 90° to the thruster plume, as it was for the SPT-100 also (ref. to Fig. 12).

One of the practically important applications of such measurement complexes is in the possibility to study dynamics of the EP thruster emission variation during its lifetime. With this, a question emerges concerning the possibility to provide acceptable thermal mode for the radio-transparent vacuum section during long-term tests. For this purpose, four thermal sensors were located with the step of 320 mm along the generatrix of such vacuum section. The thruster model of SPT-140 type was used during thermal tests (operation mode: U_d=300 V, I_d=15 A, propellant mass flow rate 13.1 mg/s, vacuum level $2.7 \cdot 10^{-4}$ torr). Time dependence of temperature for four points of the thermal sensor location on the radio-transparent vacuum section surface is presented in Fig. 13. It is obvious from the plots that after 5 hours of continuous operation of the thruster the maximum temperature reached steady-state values and did not exceed 65°C, that being certainly lower than the critical temperature.

Thus, the presented measuring complex allowed verification for the possibility of the long-term continuous operation of electric propulsion thrusters with a possibility of real-time measurement for the emission characteristics. This makes it possible to compare emission characteristics of the same EP model with different accrued operating times by test. Influence of the thruster accrued operating time on the variation of its emission characteristics in the radio-frequency range was studied using the thruster model of SPT-140 type (with the power of 4.5-5 kW) for the development of grounds of the predictive analysis for the variation of electromagnetic environment during the SPT lifetime. As an example, Fig. 14 presents averaged spectra of the emission from the thruster model under test, corresponding to 100 and 4700 hours of accrued operating time. As is clear from the plots, within the frequency range of 6-12 GHz the emission grows with the accrued operating time, with a double excess in the frequency range used for space communication (7-8 GHz). The described studies were fulfilled in the interests of the Information Satellite Systems - Reshetnev Company under the support of the Ministry of Education and Science of the Russian Federation.

The fulfilled studies confirmed necessity in the EP self-emission monitoring at every stage of its lifetime. In general, it is necessary to state that both in Russia and abroad the systematic approaches are defined and the basis for experimental complexes is laid, which allow study for electromagnetic emission from electric propulsion thrusters of various types under ground conditions.

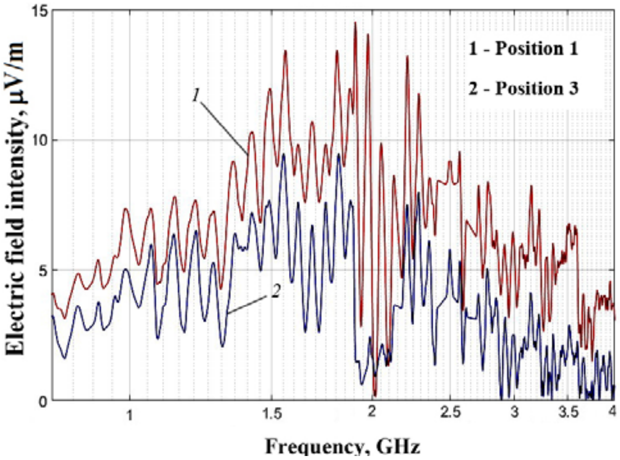

Figure 12. The SPT-140 emission excess over background for two options of pick-up antenna location (vertical polarization).

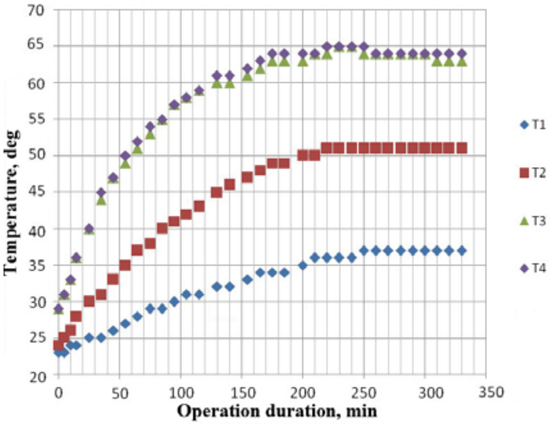

Figure 13. Time dependence of temperature for the walls of radio-transparent vacuum section.

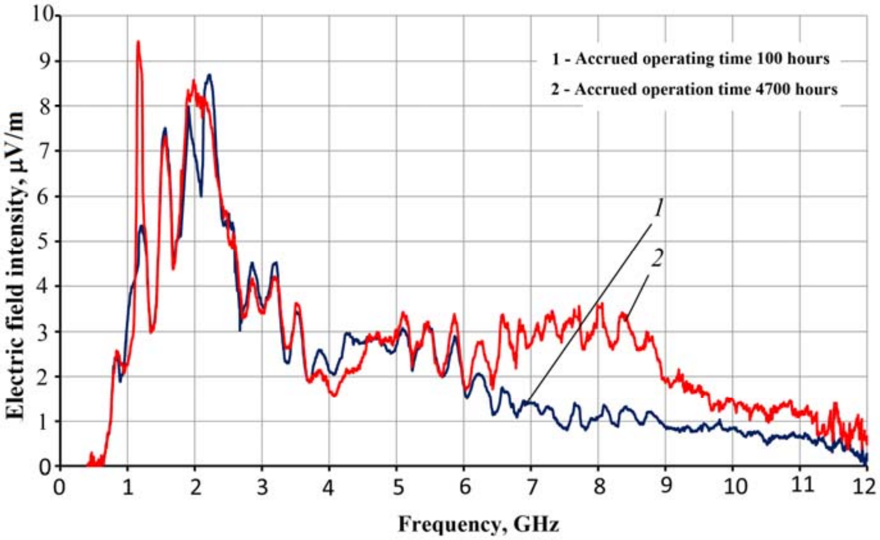

Figure 14. Variation of the SPT-140 emission spectrum during its lifetime.

Conclusions

1. Test facilities designed to study the EP self-emission under ground conditions are reviewed revealing trends in their development.

2. Peculiarities of developing and constructing combined test complexes are considered by the example of the measuring complex of RIAME MAI that allows testing for any type of EP thruster with the power of up to 10 kW, SPT-140 including, with regard to experimental determination of its electromagnetic emission within the broad frequency range.

3. The expected effect of decrease in the number of reflections within the measurement zone due to the use of separation for the vacuum and measurement volumes was verified by test by the example of the measuring complex of RIAME MAI. Thus, the variation of fluctuations of the measured electric field generated by EP thruster decreased more than 2.5-3 times comparing to the similar measurements in the metal chamber.

4. Spatial distribution of emission from the thruster models of SPT-100 and SPT-140 types was studied in the rear hemisphere in the radio-frequency range. It is shown that the emission has directive properties, and its maximum value is reached in the case of the orthogonal location of pick-up antenna relative to the plasma plume.

5. The self magnetic field influence on the emission in the radio-frequency range was studied by the example of the thruster SPT-100. It is shown that during the formation of marginal modes with maximum and minimum emission due to the variation of currents in the SPT-100 magnetic system, the difference in the emission levels in the radio-frequency range can be as high as an order of magnitude.

6. The influence of accrued operating time on the spectral characteristics of emission from the thruster model of SPT-140 type was studied. It is shown that within the frequency range of 6-12 GHz the emission grows with the accrued operating time, and comparing to initial values it more than doubles in the frequency range of 7-8 GHz at the accrued operating time of 4700 hours.

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