EMC Analysis for Sustainer Electric Propulsions and Deep Space Communication Systems

Andrey Plokhikh[1], Nikolay Vazhenin[1], Aleksey Volkovsky[2], Galina Soganova[1]

[1]Research Institute of Applied Mechanics and Electrodynamics (RIAME), 125080 P/O box 43, Moscow, Russia
riame@sokol.ru

[2]Moscow Aviation Institute (MAI), 125993, 4 Volokolamskoye shosse, Moscow, A-80, GSP-3, Russia

Abstract

General solution for the problem of EMC calculation as applied to the sustainer electric rocket propulsions (EP) and deep-space radio communication systems in its classical statement is considered. EP is described as a source of unintended noise of artificial origin of the white Gaussian noise type with the known spectral characteristics of radiation. An onboard receiver of the deep-space communication radio link is considered as the receptor, noise susceptibility of which is assessed by the variation of the radio link quality parameters – communication range and information rate. Calculation results for the EP emission susceptibility of both information channel and phase synchronization channel of the deep space communication radio link designed for a spacecraft in the orbit of Mars are presented. Recommendations are given for securing EP EMC with onboard systems of a spacecraft.

1. Introduction

Considerable interest was expressed recently to the electric propulsions (EP) of spacecraft (SC). Their fundamental difference from jet engines of other types is in the use of electric energy for the acceleration of mass injected by the thruster and thrust generation [1]. The first stage of successful EP application as orbit correction and attitude control thrusters for geostationary satellites has started as long ago as in the 90-ies of the past century, and projects of their use as sustainer propulsions for deep space missions are being considered actively now, as well as their use for securing operation of transport systems ensuring payload injection into geostationary and other orbits. Practically continuous EP operation during the entire mission is assumed in all these cases, thus it is necessary to assess and secure EP electromagnetic compatibility with the operation of onboard radio systems, with communication systems in particular.

2. EP Background

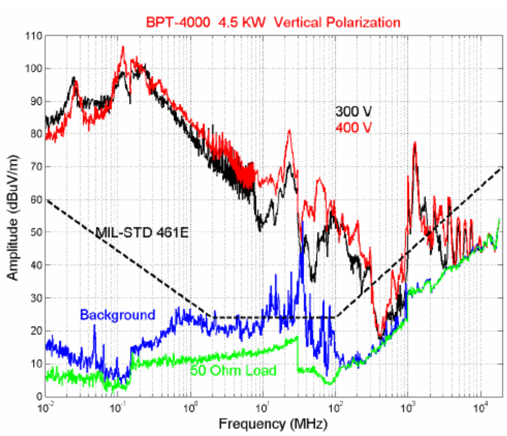

Fig. 1. Example of vertically polarized emission spectra from BPT-4000 operating at 4.5 kW [2].

Three EP concepts, which are perspective for solving sustainer tasks, are being worldwide implemented currently: ion thrusters, stationary plasma thrusters (SPT), and thrusters with anode layer. Taking into account that the greatest test and application experience is accumulated as applied to SPT, let's continue discussion based on the EP of this type and propulsion systems on their basis (EPS). As is well known, SPT operation associated with propellant ionization and its acceleration proceeds with the emission of electromagnetic energy within the frequency range of 10 kHz - 20 GHz [1, 2]. A number of publications [1-5] are devoted to the analysis of EP self-emission characteristics in spectral region. We shall not concentrate on the peculiarities of test facility and shall present spectral characteristics of emission for advanced EP of Aerojet BPT-4000 type for vertical and horizontal polarizations as an example (Fig. 1) [2, 4]. As is obvious from Fig. 1, BPT-4000 self emission is broadband and at some frequencies it exceeds substantially the MIL-STD 461E level. In view of relative band limitedness of deep space communication systems for example, one of the simplest models of EP emission is a model in the form of additive white Gaussian noise in the receiving antenna band, which fits with the analysis of communication system noise immunity. Such model is the most acceptable at the modest communications rates.

3. Correlation Between the Equivalent Noise Parameters at the Receive Path Input and Characteristics of EP noise Emission

Let's study interrelation of EP noise-like emission characteristics obtained by test and equivalent noise temperature at the input of the communication system receiver. Let as a result of test studies for EP emission under ground conditions there be obtained the value for spectral density of electromagnetic field strength $E_{f\,\mathrm{m}dB\,\Delta\mathrm{f}}$ in dBuV/m , measured at a distance R_m from EP within the frequency band Δf = 1 MHz and the power spectral density at the receiver input is:

$$G_f = \frac{P_f}{4\pi R_{Rx}^2} S_{A\,Rx} = \left(\frac{R_m}{R_{Rx}}\right)^2 \frac{\left(E^2_{f\,m\Delta f} - E^2_{f\,0\Delta f}\right)}{2Z\cdot\Delta f}\frac{G_A\eta_A\lambda^2}{4\pi} \qquad (1)$$

where $Z = 120\pi$ is the wave impedance of free space, $E_{f\,0\Delta\mathrm{f}}$ is the background field intensity measured at the operating EP, Δf is the frequency band, within which EP emission characteristics were measured, S_{ARx}, G_A, η_A are the effective area, directivity factor and efficiency of receiving antenna for the given EP viewing angle, respectively, R_{Rx} is the distance between EP and receiving antenna, λ is the carrying oscillation wavelength. Examples of the antenna equivalent noise temperature variation in view of the EP noise emission for different values of background noise are presented in Fig.2. Calculations were made for an omni directional antenna and $G_A = 1, \eta_A = 1, \lambda = 4.2\,cm,$ $R_{Rx} = 1\,m, \Delta\mathrm{f} = 1\,\mathrm{MHz}.$ Fig. 3 shows the equivalent noise temperature increment due to the EP emission as a function of pickup antenna distance to EP. Plots are presented for different EP modifications with the emission within the range of 44 - 60 dBμV/m MHz measured at the distance of 1 m from EP. Calculations were made for the beam pickup antenna that is similar to the one used for Deep Space 1 project. If as the first approximation for the average self-emission value of typical SPT with the power of 5 kW we assume the level of 48 dBμV/m MHz generated at the distance of 1 m, then at the distance variation from 0.5 m up to 4 m the range of possible antenna noise temperature values will be 1000…20°K.

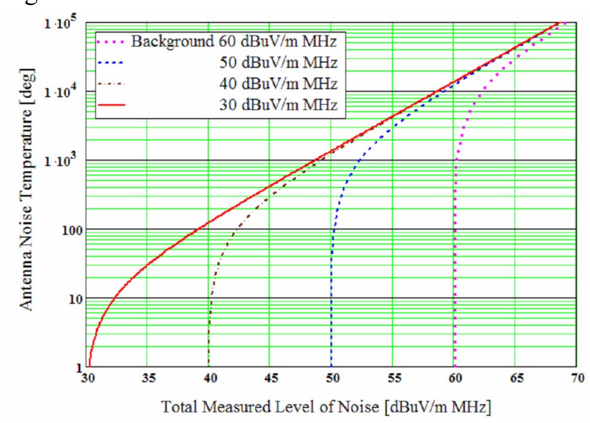

Fig. 2. Noise temperature as a function of measured noise signal at the antenna input

4. Analysis for the EP and EPS influence on the Operation of Command Radio Link of the Deep Space Communication System

The task of analyzing the influence of EP self electromagnetic emission on the operation of communication radio links was considered in a number of publications, in [5] for example Yet these assessments were of approximate nature to a great extent and did not take specificity of operation of the deep space communication radio links into consideration in full. Let's use characteristics of the modern command radio links presented in Table 1 as the basis for our calculations. Maximum range corresponds to the stable operation in the Mars orbit. Let's present basic calculation relationships for assessing energy data of the considered command deep space radio link without taking EP effect into account. Average signal power at the onboard receiver input is defined by the power equation of the following form

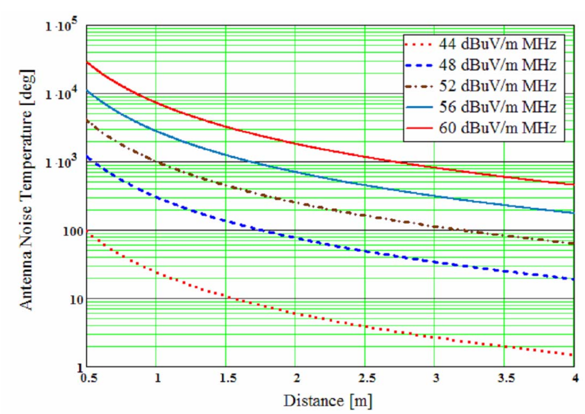

Fig. 3. Noise temperature as a function of EP distance

TABLE 1 CHARACTERISTICS OF COMMAND RADIO LINK

Coding method	Irredundant binary block code
Modulation method	PCM-PSK-PM (with harmonic sub-carrier)
Carrier frequency	7.2 GHz
Transmitter power	20 kW
Transmitting antenna mirror diameter	70 m
Transmitting antenna gain	72.5 dB
Energy loss along the transmitting radio path	- 0.5 dB
Pickup antenna gain	0 dB
Energy loss due to the path imperfection and along the receiving radio path	- 2 dB
Total equivalent noise temperature of the receiver	500 K
Equivalent noise bandwidth for the carrier phase lock	100 Hz
Demodulator energy loss	- 1.5 dB
Maximum communication range required	400 M km
Required probability of binary digit reception error	10^{-5}

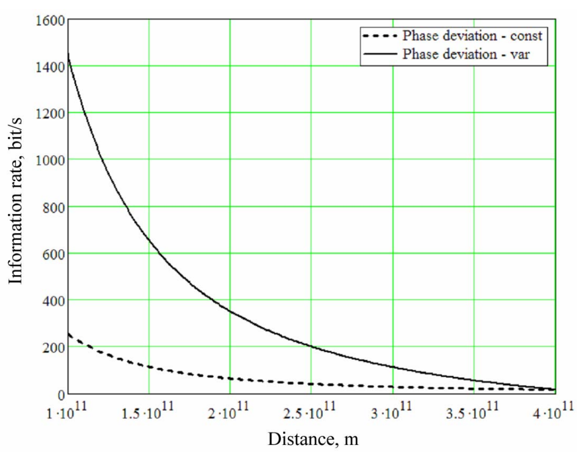

Fig. 4. Information rate as a function

$$P_s = \frac{P_{Tx} G_{Tx} G_{Rx} \lambda^2 L}{(4\pi R)^2} \quad (2)$$

where P_{Tx} = 20 kW = 43.01 dBW is the transmitter power, G_{Tx} = 72.5 dB is the transmitting antenna gain, G_{Rx} = 0 dB is the receiving antenna gain, λ = 0.042 m is the carrying oscillation wavelength, L = - 2.5 dB is the resultant energy loss in the transceiving radio channels and due to the imperfection of propagation path, R is the communication range, maximum value of which in the example under consideration is R_{max} = 400 million km. So, for the maximum range we have the following minimum possible received power: $P_{s\,\min}$ = - 168.6 dBW. The received signal power is divided between the carrier synchronization channel and the command-and-program data extraction channel. For the PCM-PSK-PM with harmonic sub-carrier the harmonic component power at the carrier frequency and equivalent power (in view of the demodulator loss) of the informational component of the spectrum are expressed by the following equations, respectively:

$$P_c = P_s J_0^2(\varphi)\,,\; P_i = P_s 2 J_1^2(\varphi) L_p \quad (3)$$

where $J_0(\varphi)$ and $J_1(\varphi)$ are the Bessel functions of the first kind of zero and first orders, respectively, φ is the carrier phase deviation, L_p = - 1.5 dB is the energy loss in the data extraction channel (demodulator). Let's assume that at the communication range variation there should be satisfied the condition h_i^2 = 10.1 dB securing the required bit error ratio, and the carrier phase deviation φ remains to be equal to 0.5 radian. The communication diagram corresponding to such situation in the coordinate system "communication range – information rate" is presented in Fig. 4 by dotted line. Based on (1)–(3), it may be written as:

$$r(R) = \frac{P_{Tx} G_{Tx} G_{Rx} \lambda^2 L L_p 2 J_1^2(\varphi)}{(4\pi R)^2 h_i^2 k T_n}\,. \quad (4)$$

It is obvious from this figure that at the range of half maximum, for example, nearly fourfold data rate increase is ensured comparing to the maximum range. It is still possible to obtain larger benefit, if we take into account that range reduction improves energy relationships not in the information extraction channel only, but in the synchronization channel also. With this, in order to limit "excess" growth of the signal-to-noise ratio in the «phase-locked-loop (PLL) frequency band above the threshold level, it is necessary to use higher values of phase deviation in the transmitter at the shorter ranges, i.e. to use adaptive φ tuning for improving signal-to-noise ratio in the information channel. As sustainer EP we shall consider both single EP of SPT type, and EPS on its base presented in Table 2. Noise temperatures presented in the table correspond to the EP and EPS location at the distance of 1 m from the SC pickup antenna. It is assumed that at the increase in the number of thrusters in the system, their noise temperatures are summarized additively. Let's study EP and EPS influence on the command link described above at the constant carrier phase deviation φ = 0.5 radian that was chosen based on the communication securing at the range of $4\cdot10^{11}$ m. Corresponding maximum communication ranges defined by the achievement of threshold signal-to-noise ratio in the PLL band at φ = 0.5 radian are presented in Table 2. It is evident that installation of even one thruster causes maximum communication range reduction by a factor of 1.7.

TABLE 2 CALCULATION RESULTS FOR EP AND EPS

EPS Option	Noise temperature of the additional additive noise	Resultant equivalent noise temperature of receiver	Maximum range by synchronization channel at phase deviation of 0.5 radian	Extreme range by synchronization channel at phase deviation of 0 radian
Without EPS	0 K	500 K	$4 \cdot 10^{11}$ m	---
1 EP	1 000 K	1 500 K	$2.3 \cdot 10^{11}$ m	$2.45 \cdot 10^{11}$ m
EPS with 4 EP	4 000 K	4 500 K	$1.3 \cdot 10^{11}$ m	$1.41 \cdot 10^{11}$ m
EPS with 10 EP	10 000 K	10 500 K	$0.87 \cdot 10^{11}$ m	$0.93 \cdot 10^{11}$ m

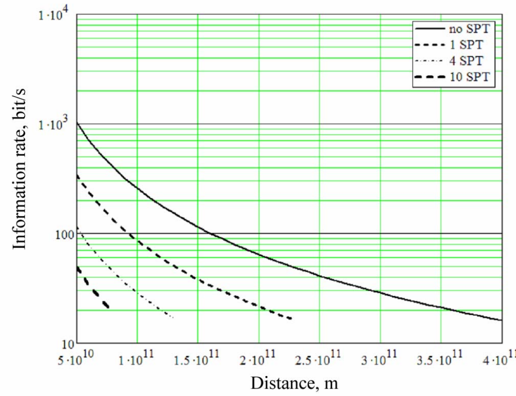

Fig. 5. Information rate as a function of communication range

Besides, signal-to-noise ratio reduction in the information channel leads to the decrease in the attainable command-and-program information rate. Corresponding communication diagrams (4) at φ = 0.5 radian are presented in Fig. 5. Next stage in the command radio link integration with EP should be moving away of the latter from the receiving antenna system. As follows from Fig. 3, separation by 4 m results in the reduction of the equivalent noise temperature by a factor of 16 comparing to the distance of 1 m. Thus, EMC calculation for the sustainer EP and SC radio systems is a complicated problem associated with the determination of electromagnetic environment for the given SC geometry and subsequent calculation of quality parameters for the radio system operation.

5. CONCLUSIONS

It is shown that for securing electromagnetic compatibility between sustainer EP and onboard deep space communication systems it is necessary to realize their common systems designing with due account for EP optimal modes and SC integration minimizing the level of emission reaching antenna systems used for communication and data transfer. At that the designed communication radio systems should use optimal frequency ranges and specialized algorithms for signal procession, which should take into account the spectrum-time structure of EP emission.

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