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INVESTIGATION OF AN ELECTROMAGNETIC PULSE GENERATED BY A SYSTEM ON A STANDARD SPACECRAFT

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Results on generation of an electromagnetic pulse on a spacecraft under the action of X-ray and gamma radiation are described. The computational technology used is based on a hierarchical system of mathematical models constructed on a system of the Maxwell–Vlasov equations and spacecraft models that rather accurately describe all physical processes typical of origination of secondary electromagnetic fields and the object geometry. It is shown that polarization components of the electric field, which are directed normal to irradiated surfaces, depend weakly on geometric factors and are mainly determined by the photon radiation flux density. Formation of the magnetic field is determined by the dynamics of variation of the first derivative of the dipole moment of the electron layer formed owing to emission of particles under the action of ionization radiation and depends on the object shape, characteristic size of the irradiated surface, and spacecraft attitude.

Key words: *electromagnetic pulse, spacecraft, mathematical models, ionization radiation.*

Introduction. Irradiation of any object by intense fluxes of penetrating radiation leads to emission of electrons from the outer and inner surfaces of the object and to emergence of a system-generated electromagnetic pulse (SGEMP), which can deteriorate radioelectronic equipment [1–5]. Spacecraft with large amounts of microprocessor equipment in control and communication systems can be especially sensitive to the action of electromagnetic fields. Because of the specific features of their operation, these systems cannot be reliably protected and rapidly replaced upon their damage.

Experimental investigations of the SGEMP in spacecraft are extremely complicated and require large (next to impossible) material and time expenses. In this case, a large portion of research is performed with the use of computational experiments based on mathematical models of generation of electromagnetic fields with allowance for formation of powerful electron fluxes under the action of photon radiation. Origination of an electromagnetic field due to the motion of charged particles is known to be described by the Maxwell equations. Their solution can be obtained by the simplest way if the currents are independent of electromagnetic fields. Nevertheless, the electron-flux dynamics determines the evolution of electromagnetic fields on one hand and depends on the latter on the other hand, because the generated fields substantially change the motion of charged particles. In this case, the evolution of electromagnetic fields and the motion of charged particles should be considered in a self-consistent manner on the basis of the Maxwell–Boltzmann equations.

A hierarchical system of mathematical models developed for studying secondary electromagnetic effects (SEME) is described in [6]. This system consists of self-consistent one- and two-dimensional models on the basis of the Vlasov–Maxwell equations and a three-dimensional electrodynamic model based on the Maxwell equations. Yet, the mathematical model is determined not only by the system of equations with initial and boundary conditions, which describe physical processes, but also by models of the object examined. Most engineering systems have a complicated structure, and this makes a detailed mathematical description of these system rather difficult. At the

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moment, there are no ready-made models of objects used in SEME studies. Therefore, one of the problems considered in the present work was the development of idealized models of the object, which could be used within the framework of the mathematical system developed.

With allowance for the SGEMP nature, it is clear that the self-consistent three-dimensional model based on the Vlasov–Maxwell equations is the most complete one. As there is no such a model in the system of models [6], SEME calculations with allowance for the real shape of the irradiated object can involve a three-dimensional electrodynamic model, where the space–time distribution of the current density is prescribed on the basis of results of self-consistent calculations of fields and currents in one- or two-dimensional models for the corresponding sections of a three-dimensional object. This method of determining the currents implies that the process of formation and evolution of electron fluxes depends weakly on three-dimensional geometry. The reason for using this approach is a strong localization of the electron current near the irradiated surface, which is observed in self-consistent one- and two-dimensional SGEMP calculations, especially for high photon-flux intensities [2, 4, 5, 7].

The transition from a complete mathematical model to a system of simplified models with minimum losses of SEME information is to be compensated by complication of the modeling process. Instead of one numerical experiment, one has to perform a set of computations with models of lower dimensions and with models of the same dimensions but less complicated from the viewpoint of allowance for physical processes. All computational experiments should be performed in a certain sequence for the results obtained to be used in the model of the next level. Actually, this means the development of a computational technology for SGEMP simulation, which would allow for both physical processes typical of this phenomenon and the three-dimensional shape of irradiated objects. Implementation of this technology requires:

— a hierarchical system of mathematical models with different spatial dimensions and degrees of simplification of physical processes;

— certain assumptions related to physical features of SGEMP formation in examined objects, which will be employed for decomposing the three-dimensional object into elements (e.g., an assumption of minor mutual influence of elements);

— system of models of object elements of different dimensions and a particular sequence of numerical experiments with each model;

— numerical experiments on SGEMP research on object elements with the use of self-consistent models in one- and two-dimensional formulations and on a three-dimensional object with allowance for interaction of its elements.

Three-dimensional SGEMP research is the final stage of the study; the main challenge of this stage is not to find the basic features of the phenomenon because they have been already clarified with the use of one- and two-dimensional models but to determine the influence of three-dimensional effects on these features.

The objectives of the present activities were:

— development of idealized spacecraft models suitable for SGEMP research within the framework of the system of mathematical models [6];

— development of a computational technology for SGEMP simulations with allowance for the three-dimensional geometry of the spacecraft;

— implementation of the computational technology for predicting the SGEMP of a standard spacecraft.

Simulation of a System-Generated Electromagnetic Pulse on a Spacecraft. Let us study the SGEMP on a spacecraft subjected to X-ray radiation (XR). We assume that the photon spectrum has the Planck form [2] and the time evolution of the XR intensity $F(t)$ is defined by the expression [7]

$$F(t) = (U_0/T_h)\sin^2(\pi t/2T_h), \qquad 0 < t < 2T_h,$$

where t is the time, U_0 is the XR fluence, and T_h is the pulse duration at the half-height.

X-ray radiation initiates electron emission from the spacecraft surface, which is responsible for surface sources in the Vlasov equation. The parameters of this emission can be calculated by the Monte Carlo technique [8] or by the numerical-analytical model [9].

In most cases, we can assume that the spacecraft includes a composite cylindrical casing with an instrumentation module and antenna and solar arrays (SA) connected to the casing by aluminum force elements (Fig. 1). Naturally, we can consider the solar arrays and the casing as individual elements of the spacecraft. If these elements were electrically independent, we could confine ourselves to separate consideration of the SGEMP on individual

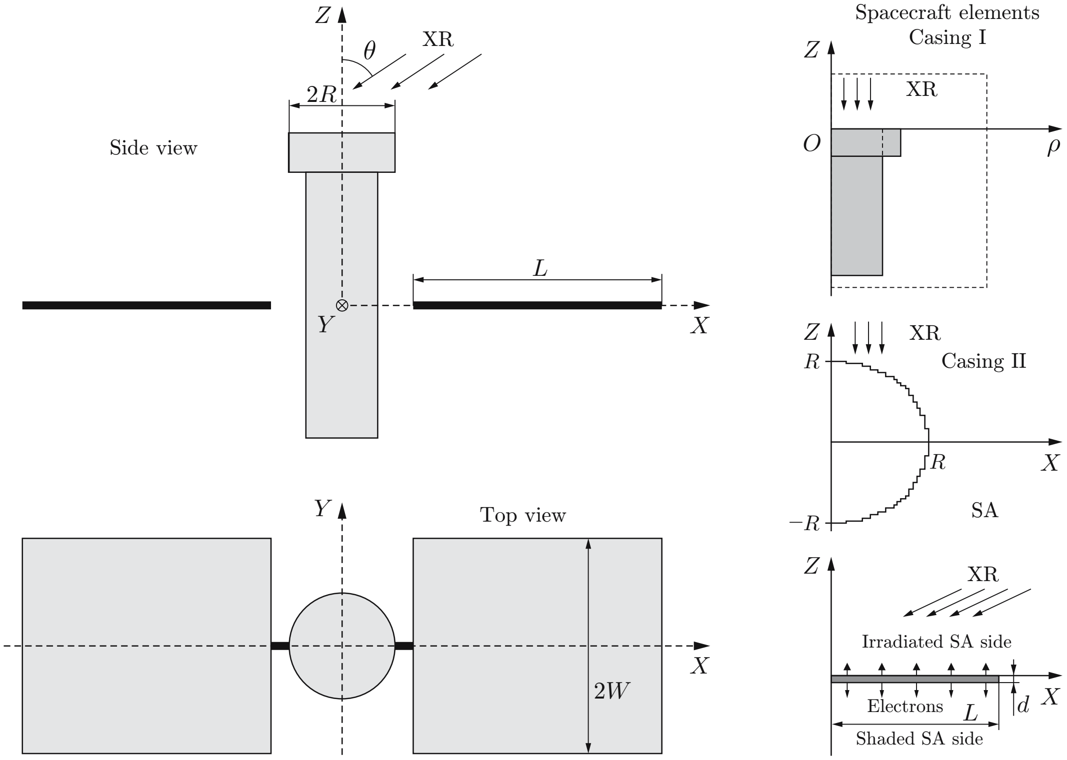

Fig. 1. Three-dimensional model of the spacecraft and its elements.

elements, and this approach would be correct. Nevertheless, this is not the case in reality, and we need a three-dimensional model taking into account the mutual influence of the solar array and the casing.

In accordance with the general approach to simulation of complicated systems, computational experiments are performed stage by stage with consecutive transitions from simple models to more complicated ones [10]. The first stage involves the use of one-dimensional models, which allow a detailed study of the influence of initial data on the SEME. Based on the results obtained, one can determine the qualitative dependence of characteristics of the electromagnetic field on the XR fluence, characteristic time of radiation, and parameters of electron emission, which ensures understanding of relations between individual components of the mathematical model and the properties of the physical process.

At the second stage, numerical experiments are performed with two-dimensional models, which partly take into account the influence of the finite size of the object on generation of electromagnetic fields. Scales with essential edge effects are determined, and assumptions on current localization and a small effect of geometry on current generation are checked. The space–time distribution of the electron-flux density is calculated to be subsequently used in the three-dimensional model. The latter implies that numerical experiments in a two-dimensional formulation will be performed with models corresponding to characteristic two-dimensional sections of the spacecraft.

In the general case, the XR is incident at a certain angle onto the solar arrays and onto the end-face and side surfaces of the spacecraft (see Fig. 1); hence, the following two-dimensional models of spacecraft elements are necessary:

— finite-length casing in a cylindrical coordinate system; electron emission proceeds from the upper end face (casing I);

— infinite-length casing in the Cartesian coordinate system; electron emission proceeds from the side surface with allowance for the angle of incidence of photons (casing II);

— solar arrays in the Cartesian coordinate system; electron emission proceeds from the irradiated (sunny) and shaded sides; the angle of XR incidence is taken into account.

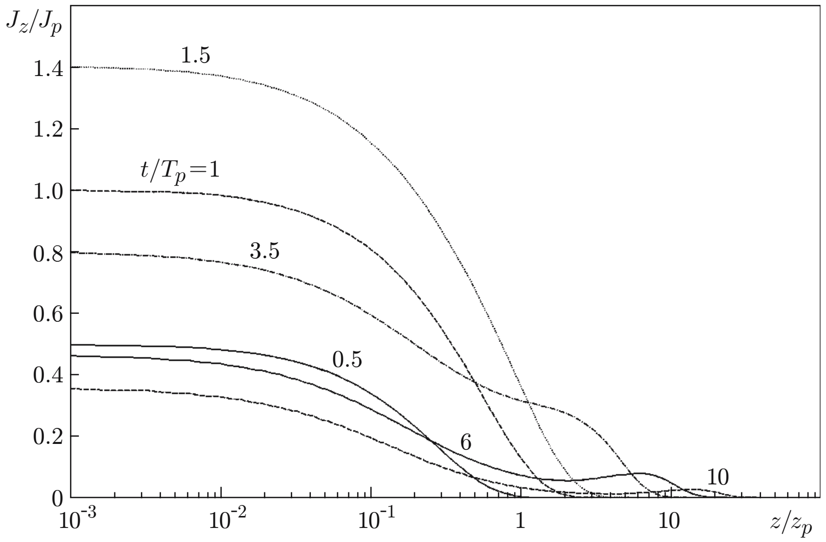

Fig. 2. Current density versus the distance to the emission surface at different times.

The final stage of simulation involves the use of a three-dimensional model for taking into account the mutual influence of individual elements of the spacecraft and the attitude of the latter with respect to the radiation direction; currents obtained in self-consistent calculations with the above-mentioned two-dimensional models of the object are used in this model.

One-Dimensional Computations. If the intensity of the XR flux onto the metallic surface is rather high, the surface electron layer is formed at distances much smaller than the characteristic spacecraft size [2, 5, 11, 12], which allows computations of parameters of the electromagnetic field in a one-dimensional approximation. A specific feature of the one-dimensional model [6] is that it takes into account the angle of XR incidence owing to a proper choice of the reference system moving together with the XR front and all components of the electromagnetic field (wave and polarization components) are calculated, whereas only the polarization component is determined in conventional one-dimensional models [3–5, 12].

The problem has two time scales: one of them (T_h) is related to the characteristic duration of the XR pulse, and the other is related to the plasma frequency of emitted electrons $T_p = (m_e/(4\pi e^2 N))^{1/2}$ (e and m_e are the electron charge and mass, respectively), which depends on radiation intensity, yield of emission electrons Y, and velocity of emitted electrons $\langle v_e \rangle$:

$$N \approx YU_0/(\langle v_e \rangle T_h).$$

If the radiation intensity is not very high and the mean velocity of emission electrons is rather high, so that $T_p \gg T_h$, the duration of the emission pulse is smaller than the time needed for a dipole layer to form. In this case, particles form an expanding cloud around the irradiated object, which does not manifest collective properties of plasma.

In the case of high radiation intensities, where $T_p \ll T_h$, the electron current is limited by the spatial charge of the previously emitted particles, which leads to formation of a dipole layer. As the number of emitted and returning electrons is approximately identical, the concentration of electrons near the surface is in quasi-static equilibrium with the XR flux and is determined by the expression

$$N(t) \approx 2YF(t)/\langle v_e \rangle.$$

Taking into account the characteristic size of the dipole layer $z_p \approx \langle v_e \rangle T_p$, we can estimate the electric field $E(z=0,t)$ near the emission surface [4]:

$$E(0,t) \approx 4\pi e N(t) z_p \sim \sqrt{4\pi m_e \langle v_e \rangle Y F(t)}\,. \tag{1}$$

Figure 2 shows the results of one-dimensional calculations of the spatial distribution of the electron current at different times in the vicinity of an aluminum surface irradiated at an angle $\theta = 0$ by a XR flux increasing linearly

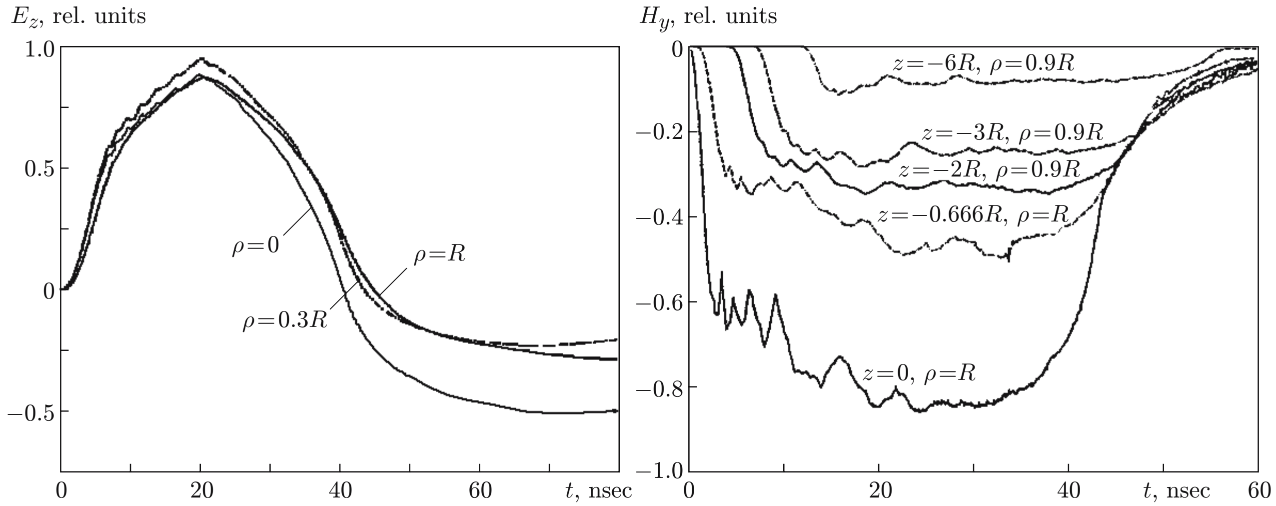

Fig. 3. Electric and magnetic fields versus time at different points above the end face of the spacecraft.

with time. It is seen from numerical calculations that the electron dipole layer is formed in an immediate vicinity of the emission surface. The size of this layer ranges from fractions of a millimeter to tens of centimeters, depending on the surface material, quantum energy, and XR flux. If the X-ray radiation is incident onto the surface at an angle θ, a field of an electromagnetic wave propagating in the direction specular to the XR flux direction is formed in addition to the spatial charge field. The evolution of this wave is determined by the first derivative of the dipole moment $\dot{P}(t) = \int\limits_0^\infty dz\, j_z(t,z)$ [12]:

$$H_y(t,z) = \frac{4\pi}{c}\,\tan\theta\,\dot{P}\Big(t - \frac{x}{c}\sin\theta - \frac{z}{c}\cos\theta\Big), \qquad E_x^w(t,z) \cong \cos\theta\, H_y(t,z). \tag{2}$$

The results obtained allow us to draw the following conclusions:

— the XR-induced electromagnetic fields can be divided into “quasi-steady” fields determined by polarization separation of charges (polarization part of E_z) and “wave” fields related to formation of a directed electromagnetic wave (magnetic field, tangential component of the electric field E_x, and the wave part of E_z);

— the “quasi-steady” fields are determined by the instantaneous value of the XR flux density and by the material of the irradiated surface (1), depend weakly on the angle of incidence of photons, and rapidly decrease with distance from the emission plane at distances $z_p \approx \sqrt{m_e\langle v_e\rangle^3/(8\pi e^2 YF(t))}$;

— the “wave” components of the electromagnetic field depend on the rate of formation of the dipole layer $\dot{P} \sim m_e\langle v_e\rangle^2/(36eT_p)$ and on the angle of XR incidence onto the irradiated surface (2); they propagate in a specular direction to the angle of XR incidence onto the irradiated surface. As functions of time, they have the form of a monopolar pulse [13].

Based on the data of one-dimensional calculations, we can conclude that the most dangerous objects from the viewpoint of formation of the maximum amplitudes of the electromagnetic field and generation of the most high-frequency signal are elements made of materials with a high yield of electrons (high value of Z) and subjected to radiation at high angles of XR incidence.

Two-Dimensional Calculations. The one-dimensional model fails to take into account the effects related to the finite size of the spacecraft ($\sim R$), which lead to appearance of a third time parameter $T_l \cong R/c$ (c is the velocity of light) in addition to T_h and T_p in the problem. Appearance of this parameter is a consequence of not only quantitative but also qualitative changes in SGEMP properties, in particular, the possibility of excitation of intrinsic oscillations with a frequency of the order T_l^{-1}.

If the photon flux is directed along the centerline of the cylindrical casing, i.e., perpendicular to its end face (casing I), we can use the axial symmetry of the problem and perform calculations in a cylindrical coordinate system with allowance for both the casing radius and its length. The calculated results for the electric and magnetic

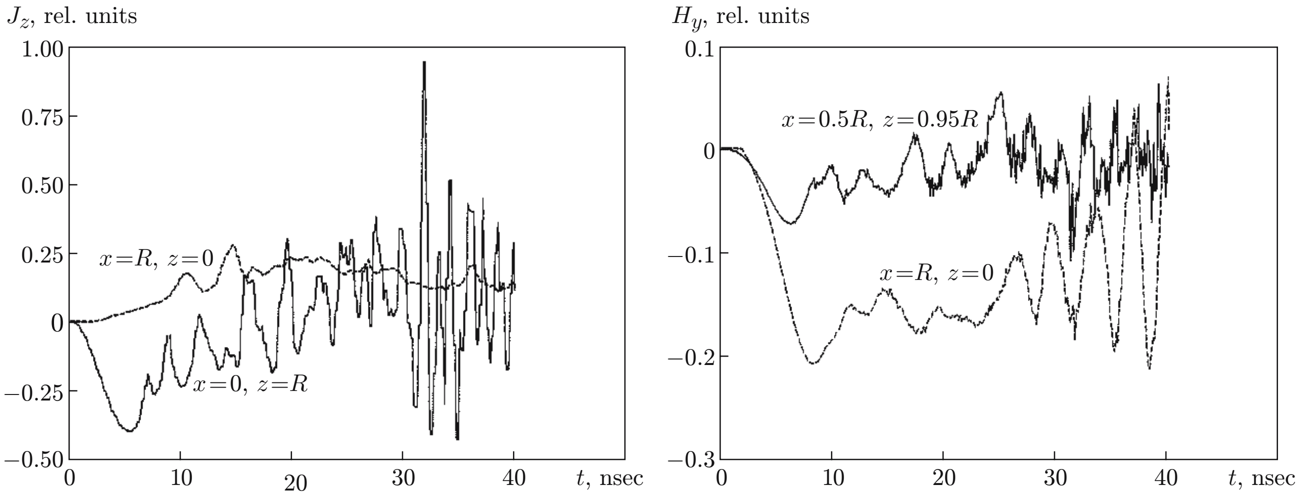

Fig. 4. Electron current density J_z and magnetic field versus time at different points near the side surface of the spacecraft.

fields are plotted in Fig. 3. If the photon flux is directed perpendicular to the centerline of the cylindrical casing, the electromagnetic field can be determined by a two-dimensional model, in which the casing is assumed to be an infinite cylinder (casing II). This geometry of the problem allows us to take into account the changes in parameters of electron emission due to changes in the angle of incidence of photons onto the spacecraft surface and the influence of the cylindrical shape on formation of the electron current. The dynamics of the electron current along the radiation direction and magnetic field is shown in Fig. 4.

Simulation of electromagnetic fields in a self-consistent two-dimensional formulation shows that the basic features of formation of the electromagnetic field and the current of emitted electrons largely coincide with those obtained in one-dimensional calculations. The finite size of the spacecraft casing and irradiated surface are manifested in the following features:

— under the action of the field of the spatial charge of emitted particles, the electron cloud is spread in the direction parallel to the radiation plane; corresponding longitudinal components of the electron current appear; these components are commensurable with the emission current;

— formation of the magnetic field occurs for all angles of XR incidence onto the spacecraft surface and is determined by the gradient of the emission current at the boundary of the irradiated and shaded surfaces in accordance with the equation

$$\Delta \boldsymbol{H} - \frac{1}{c^2}\,\frac{\partial^2 \boldsymbol{H}}{\partial t^2} = -\frac{4\pi}{c}\,\nabla \times \boldsymbol{j}; \tag{3}$$

— after irradiation, an uncompensated electric discharge remains on the spacecraft casing, because the generated fields cannot return to the irradiated object some part of high-energy electrons whose kinetic energy exceeds a certain limiting value $w_0 = e\varphi_0$ determined by the surface potential formed in the course of emission φ_0;

— in the case of spacecraft irradiation, intrinsic high-frequency oscillations of the surface current can be excited.

The "residual" field can be estimated on the basis of the "quasi-static" behavior of the electric field and the exponential form of the distribution of electrons in terms of energy [$\sim \exp\left(-w/\langle w\rangle\right)$, where $\langle w\rangle$ is the mean energy of emitted electrons]. We assume that electrons that "run away" have the energy w greater than w_0. Taking into account the law of conservation of the charge and the relation between the charge on the casing and its potential $Q_e = C_l\varphi_0$ via the capacity $C_l \approx R$, we obtain the equation for w_0 [14]:

$$w_0 = \frac{eYU_0S_l}{C_l}\,\exp\Big(-\frac{w_0}{\langle w\rangle}\Big) \tag{4}$$

(S_l is the irradiated area). Solution (4) allows us to estimate the order of magnitude of the electric field strength remaining after the action of XR and the value of the current on the spacecraft surface:

$$E_n = 4\pi\sigma \approx 4\pi Q_e/S_l, \qquad I_e = Q_e/T_h.$$

The dependence of the magnetic field on the XR parameters can be estimated from Eq. (3), the spacecraft casing being assumed to be an ideal conductor. If we assume that the emission current is uniform along the irradiated surface and is localized at a distance of the order of z_p, we can use the Green function for the wave equation in the free space to obtain

$$H_\varphi \sim \frac{2\sqrt{2}}{c}\int\limits_0^\pi d\varphi\,\frac{\cos\varphi\,\dot{P}(t-\sqrt{2}\,T_l\sqrt{1-\cos\varphi}\,)}{\sqrt{1-\cos\varphi+\alpha^2}} \sim \frac{\langle\dot{P}\rangle_{[t,t-2T_l]}}{c}, \qquad \alpha \simeq \frac{z_p}{R}.$$

Because of the "quasi-static" changes in parameters of the dipole layer, $\dot{P}$ follows the time evolution of the XR flux density $[\dot{P} \approx \sqrt{YF(t)}]$.

One of the main elements of the spacecraft is the solar arrays, which are especially SGEMP-sensitive because of their functional features and a large area (up to tens of square meters). In the two-dimensional model, the solar array is considered as a parallelepiped infinite in one direction (OY) and having finite dimensions in two other directions: L along OX and d along OZ ($d \ll L$). It is assumed that the cross section of the solar array coincides with the cross section of a photocell, which is a layered dielectric structure with metallic contacts in the middle covered by silica glass (SiO_2) on the working side and by paint on the other side. The calculated electron current arising owing to normal XR incidence onto the SA plane is plotted in Fig. 5.

The calculated results show that:

— the edge effects manifested in the difference between the electron currents calculated by the one- and two-dimensional models, formation of a magnetic field, scatter of electrons along the emission surface, and appearance of a longitudinal components of the electric field are significant at distances $x \approx z_p$;

— because of the difference in the emission currents on the irradiated and shaded sides of the solar array, strong nonuniformity in the spatial distribution of the electric field is observed.

Three-Dimensional Simulation. The final stage of SGEMP simulation is a computational experiment with a three-dimensional spacecraft model (see Fig. 1). The main requirement to the three-dimensional physico-mathematical model is the allowance for factors that cannot be described by models of lower dimensions: interaction of individual spacecraft elements and spacecraft attitude in the XR flux.

Based on the results of SGEMP simulation on spacecraft elements by self-consistent two-dimensional models, we can state that the main influence on electron current formation is exerted by the process of restriction of the current by the spatial charge, which has a one-dimensional character. The edge effects are manifested at distances commensurable with the thickness of the electron dipole layer ($\sim z_p$). These effects cannot affect the evolution and spatial distribution of electron currents outside of this zone, in the case of a high XR intensity, where $z_p \ll R$, and the formation of electron currents can be assumed to be weakly dependent on the three-dimensional geometry. In this case, the currents calculated by self-consistent one- and two-dimensional models can be used in the three-dimensional electrodynamic model.

The formation of an electromagnetic field on a three-dimensional spacecraft model was studied for the case where XR irradiation occurs at an angle of 45° to the OZ axis and along the OX axis. The calculation results show that the polarization components of the electric field, directed normal to irradiated surfaces, depend weakly on geometric factors. Their time shape and amplitude are determined by the photon radiation flux density. Allowance of interaction of individual spacecraft elements does not lead to catastrophic changes in the amplitude values of electromagnetic field parameters obtained by models of lower dimensions, which offer a correct idea on the magnitude of generated fields. The currents in connecting rods have approximately the same amplitudes and shapes as the currents in the spacecraft casing. In contrast to the case of irradiation along the axis of the spacecraft casing, where magnetic fields are generated by the edge effects, oblique XR incidence onto the casing and solar arrays leads to additional generation of an electromagnetic wave, which leads to changes in the pulse shape and to an increase in the amplitude of the fields (Fig. 6). Oblique irradiation of the spacecraft excites all modes of intrinsic oscillations of the electromagnetic field, determined by the longitudinal and transverse size of the casing and by the length of the solar array.

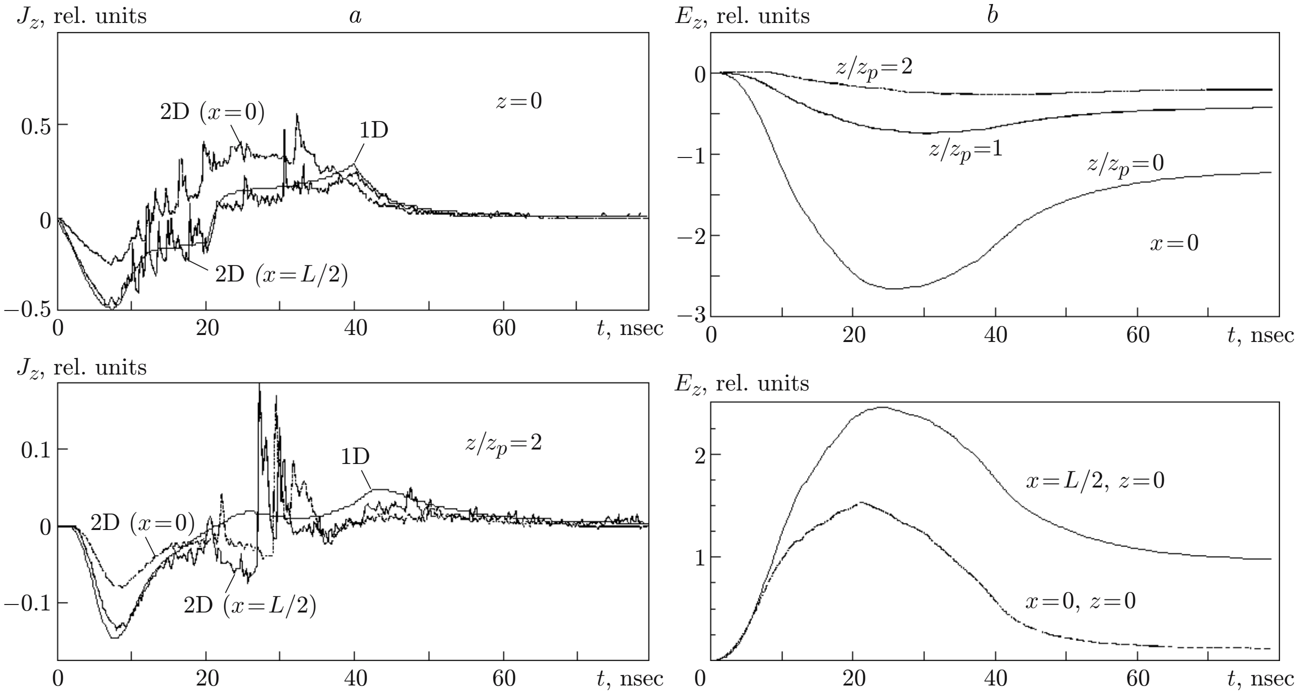

Fig. 5. Electron current density J_z (a) and electric field E_z (b) versus time at different points above the solar array surface (1D and 2D denote to the one-dimensional and two-dimensional approximations.)

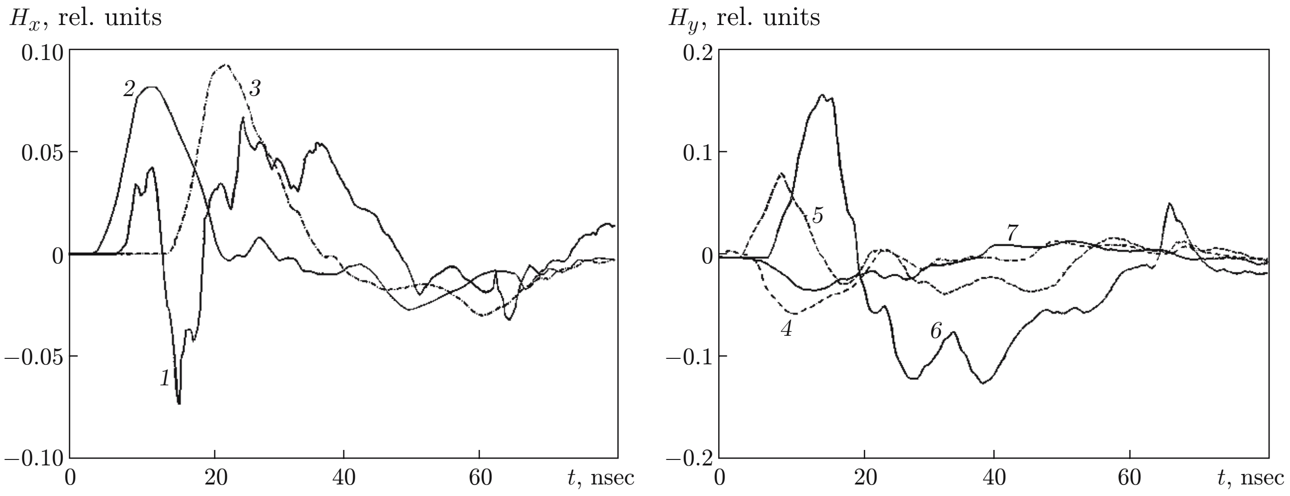

Fig. 6. Components of the magnetic field versus time at the surface of a three-dimensional spacecraft model irradiated by the XR flux at an angle $\theta = \pi/4$, $\varphi = 0$ calculated in the $\dot{P}$-approximation: 1) spacecraft casing: $x = 0$, $y = -R$, and $z = 2R$; 2) right SA panel (irradiated surface): $x = L/2 + R$ and $y = -W$; 3) left SA panel (irradiated surface: $x = -L/2 - R$ and $y = -W$; 4) edge of the right SA panel (irradiated surface): $x = L + R$ and $y = -W$; 5) middle of the right SA panel (irradiated surface): $x = L/2 + R$ and $y = 0$; 6) connecting rod; 7) middle of the right SA panel (shaded surface): $x = L/2 + R$ and $y = 0$.

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