# PERTURBATION OF MAGNETIC FIELD BY A NONSTATIONARY GAMMA-RAY SOURCE

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The perturbations of a magnetic field in the neighborhood of a nonstationary source of gamma rays, and also the radio emission associated with these perturbations, are investigated on the basis of the results from numerical integration of the system of Maxwell equations describing the space and time variations of the fields.

1. The physical picture of the phenomena leading to the perturbation of a magnetic field by a nonstationary gamma-ray source and the qualitative behavior characterizing these perturbations together with their dependence on initial parameters evidently can be considered to have been explained at the present time [1, 2]. The question has been less well studied from the quantitative aspect. Thus, approximate equations obtained from the Maxwell equations by neglecting the spatial derivatives in them were solved in estimating the field amplitudes in the current zone and in the radiated signal [1]. Only "local" perturbations of the external field in the current zone are taken into account under this approximation, and the effects of field propagation together with a gamma-ray pulse from the internal regions are not considered. The approach used in [2], where the amplitude and time dependence of the fields produced are estimated, is free of this deficiency but only on the basis of an analysis of the solution for some simulated problem. Without discussing in greater detail the advantages and disadvantages of the approximate methods for the estimation of fields developed in the papers mentioned, we point out that a solution of the problem of perturbation of a magnetic field by a gamma-ray source has not been published up to this time in sufficiently general formulation without some kind of substantial simplification.

A formulation of the problem for numerical integration of the equations describing the perturbations is given below, a computational scheme is presented in brief form, and the resultant quantitative results are presented and discussed.

2. As in [1, 2], we describe the perturbations of a magnetic field under the action of a gamma-ray pulse emitted by a nonstationary isotropic source in air of normal density by the equation system

$$\operatorname{rot} \mathbf{H} = \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi}{c}(\sigma \mathbf{E} + \mathbf{j});$$
$$\operatorname{rot} \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{H}}{\partial t},$$

where $\mathbf{E}$ and $\mathbf{H}$ are the electric and magnetic field; $\sigma$ is the air conductivity developed through the effect of gamma radiation; $\mathbf{j}$ is the component of the current density which arises because of curvature of Compton-electron trajectories in the electromagnetic field; c is the velocity of light. We assume the air density and the unperturbed magnetic field $\mathbf{H}_0$ are uniform within the limits of the volume most important for the excitation of the radiated signal.

It is completely reasonable that it is necessary to consider the nonstationary gamma-ray source to be elevated above the surface of the ground which plays the role of an underlying conducting surface.

In the following, we use the dimensionless coordinate $x = \mu r$ and the dimensionless time $y = \mu ct$; following [1], we consider the electron conductivity of air to be

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$$\sigma = e\omega\mu^3\nu N \frac{e^{-x}}{4\pi x^2} r(y-x), \tag{2.1}$$

where the dimensionless function r(y) is found from the equation

$$\frac{dr}{dy} + \frac{\gamma}{\mu c} r = f(y); \quad r(0)=0. \tag{2.2}$$

In computing the current density, we consider that a Lorentz force $\mathbf{E} + {}^1/c[\mathbf{vH}]$ acts on a Compton electron which is moving radially on the average. Because of the deflection of a Compton electron in the magnetic and electric fields, there arises a transverse current component

$$j_\varphi = \frac{el}{\varepsilon}(E_\varphi + H\vartheta) j_r, \tag{2.3}$$

where

$$j_r = e\mu^4 l N c \frac{e^{-x}}{4\pi x^2} f(y-x) \tag{2.4}$$

is the radial component of the Compton-electron current density. In Eqs. (2.1)-(2.4), $l \simeq 3$ m and $\mu^{-1} \simeq 250$ m are the mean ranges for a Compton electron and for a gamma ray; e, $\omega$, $\gamma$, $\vartheta$ are, respectively, the charge, mobility, secondary-electron attachment probability, and the number of secondary electrons created by a single Compton electron; N is the total number of gamma rays emitted by the source; $\varepsilon$ is the energy of a Compton electron; $f(y)$ is the source intensity as a function of time $\left(\int_0^\infty f(y)\,dy = 1\right)$. The time behavior of the source is approximated by the relation

$$f(y) = \frac{1}{I}\frac{ye^{\Omega y}}{A + e^{(\Omega+\Delta)y}}; \quad I = \int_0^\infty \frac{ye^{\Omega y}}{A + e^{(\Omega+\Delta)y}}\,dy; \ \Omega, \ \Delta, \ A \text{ is const.}$$

In the growth stage, this relation roughly describes the source behavior assumed in [3] ($e^{+\alpha t}$, where $\alpha = 10^8$ $\mathrm{sec}^{-1}$) and in the decay stage, the behavior assumed in [4, 5] ($e^{-\beta t}$, where $\beta = 10^6$ $\mathrm{sec}^{-1}$). Thus the relation chosen provides an opportunity to describe all stages of the process in unified fashion.

We introduce the new functions H, h, and $\mathscr{E}$,

$$H_r(r, \vartheta, t) = H_0 \cdot H(x, y)\cos\vartheta;$$

$$H_\vartheta(r, \vartheta, t) = H_0 \frac{h(x, y)}{x}\sin\vartheta;$$

$$E_\varphi(r, \vartheta, t) = H_0 \frac{\mathscr{E}(x, y)}{x}\sin\vartheta$$

(a spherical coordinate system is used with the z axis in the direction of the initial field) which satisfy the equations

$$\begin{gathered} \frac{\partial h}{\partial x} + H = \frac{\partial \mathscr{E}}{\partial y} + [K + M]\mathscr{E} + Mh; \\ \frac{\partial \mathscr{E}}{\partial x} = \frac{\partial h}{\partial y}; \quad \frac{2\mathscr{E}}{x^2} = -\frac{\partial H}{\partial y}; \\ K(x, y) = k\frac{e^{-x}}{x^2} r(y-x), \quad k \equiv \frac{e\omega\mu^2\nu N}{c}; \\ M(x, y) = m\frac{e^{-x}}{x^2} f(y-x), \quad m \equiv \frac{e^2 l^2 \mu^3 N}{\varepsilon}. \end{gathered} \tag{2.5}$$

At the initial time, H(x, 0) = 1, h(x, 0) = −x, and $\mathscr{E}$(x, 0) = 0. We seek a solution of the system (2.5) in the region $a \le x \le y$ ($a \ll 1$). To ensure the uniqueness of the solution, we require satisfaction of the following boundary conditions: $\mathscr{E}(a, y) = 0$ when $x = a$ and $\mathscr{E} + h = -x$ and $H = 1$ when $x = y$. The conditions for $x \to 0$ correspond to a problem in which the source is surrounded by an ideally conducting sphere of small radius $a$. The conditions for x = y comprise the continuity of the quantities $E_\varphi + H_\vartheta$ and $H_r$ at the front of a perturbation propagated at the speed of light.

3. For a numerical solution* of the system (2.5), we used a rectangular grid in the strip $a \le x \le 60$, $0 \le \tau < \infty$ in the (x, $\tau$) plane where $\tau = y - x$. The equation was solved by the method of chasing with respect

*The basic ideas for the scheme of numerical integration are those of A. A. Milyutin and E. I. Dinaburg.

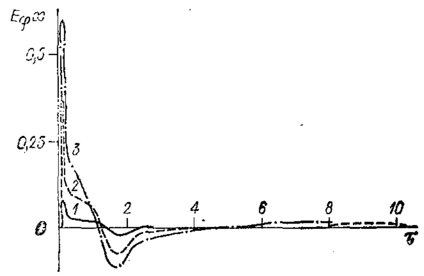

Fig. 1

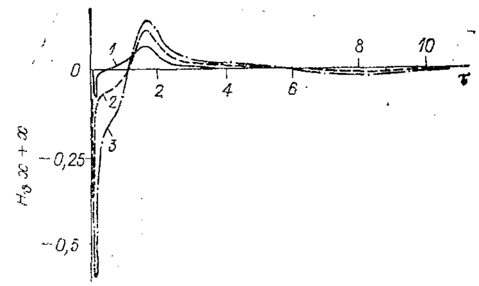

Fig. 2

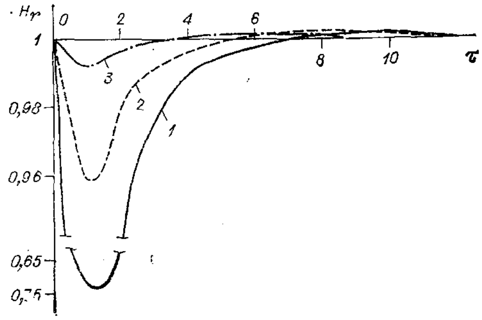

Fig. 3

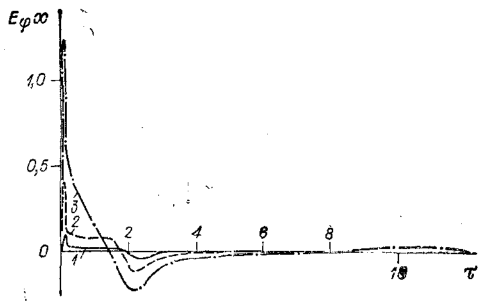

Fig. 4

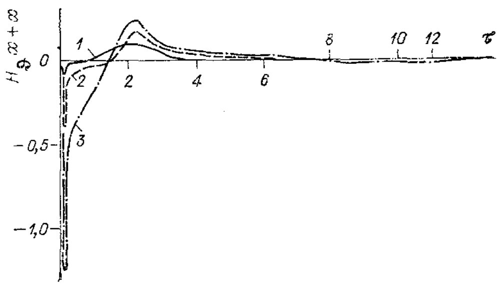

Fig. 5

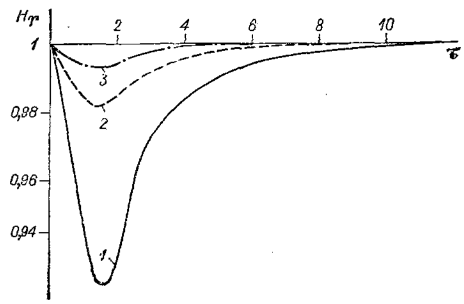

Fig. 6

to the variable x for each value of $\tau$. A stable scheme was used in the solution (this situation was investigated separately) which had second-order approximation with respect to $\Delta x$ and first order with respect to $\Delta\tau$.

We give the results of a numerical solution of the problem. The actual calculations were performed for the following values of the dimensionless constants: $\Omega=250$, $\Delta=8.3$, $A=2.93\cdot10^9$, $a=0.01$ and for values of the constants $k=1.54\cdot10^5$ and $m=80$.

The time dependences of the electromagnetic field components $E_\varphi$, $\Delta H_\vartheta$, $H_r$ are shown in Figs. 1-3, respectively. The various curves correspond to different source distances: 1) $x=0.4$, 2) $x=2$, 3) $x=6$. Further increase in x does not lead to a change in the time dependence of the fields and this is evidence that the wave signal is already formed. The values $1.54\cdot10^7$ and $m=8\cdot10^3$, which correspond to a 100-fold increase in source activity, were used in the calculation of the fields in the addition to the values $k=1.54\cdot10^5$ and $m=80$. The results are shown in Figs. 4-6.

4. We discuss the results. The basic physical features of the behavior of the fields were explained in an analysis of a solution for simulated problems [2]. It is interesting to compare the qualitative results obtained in that paper with the exact relations given in Sec. 3. As is clear from Figs. 1, 2, 4, and 5, the quantity $E_\varphi(\tau)$ agrees with the quantity $-\Delta H_\vartheta(\tau)$ at large distances from the source (actually outside the current zone) over the entire duration of the signal. This property is more characteristic of any electromagnetic signal in the wave zone but it occurs in the present case for fields at the signal front and in the current zone, which is nontrivial. The reason for the expression

$$E_{\varphi}+\Delta H_{\vartheta}=0 \quad (4.1)$$

for the wave fields is the "transverseness" of the electromagnetic waves, i.e., the smallness of the longitudinal components of the fields in comparison with the transverse components. It can be noted that the property of "transverseness" is more characteristic of fields at the pulse front and in the current zone, which follows directly from the results of numerical integration. In fact, at early times ($\tau \lesssim 0.1$-$0.2$), the values of the components $E_{\varphi}$ and $\Delta H_{\vartheta}$ reach values $\approx 0.2H_0$ at $x=0.4$, for example, while $\Delta H_r \approx 0.03H_0$ at the same point. At later times ($\tau \simeq 0.5$-$1.0$), the values of the field components $E_{\varphi}$, $\Delta H_{\vartheta}$, and $H_r$ are comparable in the current zone ($x \lesssim 1$) and then the relation (4.1) does not hold. Using Eq. (4.1) and the smallness of the quantity $\Delta H_r$, one can simplify the system (2.5) considerably and obtain a number of rather general relations for the electric field, for example. One can show that the electric field is a maximum at the time the gamma-ray flux reaches a maximum with its dependence on the coordinate $r=\mu^{-1}x$ having the form

$$E=\frac{H_0\Lambda}{x}\varkappa\int_0^x \exp\left(-\varkappa\int_{-x'}^{x}\frac{e^{-x''}}{(x'')^2}\,dx''\right)\frac{e^{-x'}}{x'}\,dx', \quad (4.2)$$

where $\Lambda \equiv K/M$, and $\varkappa=(k\mu c/2\gamma)f_{max}$ is a dimensionless coefficient the value of which is $\approx 10^4$-$10^6$ in versions containing the computational results given. Therefore the exponential in the integrand differs from zero in the current zone only for x' sufficiently close to x. We make the substitution

$$\varkappa\int_{x'}^{x}\frac{e^{-x''}}{(x')^2}dx''\approx\varkappa(x-x')\frac{e^{-x}}{x},$$

and we then have from Eq. (4.2)

$$E\approx H_0\Lambda. \quad (4.3)$$

This estimate is quite approximate but it allows one to conclude that the amplitude of the electric field in the near zone changes little with changes in distance and source activity.

If one turns to the results of the numerical integration of the system, one can note that the electric field at the pulse front, at $x=0.4$, for example, changes from $\approx 0.19H_0$ to $\approx 0.22H_0$ for an increase in source activity by two orders of magnitude. The electric field changes from $0.19H_0$ to $0.18H_0$ (see Fig. 1) for constant source activity and a variation of x over the range 0.4-2.0. With further increase in x where the electromagnetic pulse leaves the current zone, the change in the field becomes markedly significant. Equation (4.2) for $x \ll 1$, when $xe^{-x}<1$, can be written in the form

$$E\approx\frac{H_0\Lambda}{x}\varkappa\int_0^{\infty}\exp\left[-\varkappa\int_{x'}^{\infty}\frac{e^{x''}}{(x'')^2}\,dx''\right]\frac{e^{-x'}}{x'}\,dx'. \quad (4.4)$$

Equation (4.4) indicates that the field amplitude outside the current zone should decrease in inverse proportion to the distance. Numerical calculations confirm that the quantity $E_{\varphi}x$ remains practically constant with a change in x from 6 to 10 (see Figs. 1, 4).

As far as the absolute value of the field in the current zone is concerned, it is determined by the quantity $\Lambda \equiv M/K^* \approx 5\times 10^{-2}$ as follows from Eq. (4.3), which is in agreement with the results of the numerical calculation.

We turn to the wave field. First of all, we note the agreement of the general nature of the variation of the radiation fields predicted in [2] and obtained from numerical calculations. In fact, the radiated signal has three half-cycles; the peak value of the field in the first half-cycle is greater than that in the second, and in the second it is greater than in the third. The duration of the leading pulse of the field (at 0.5 of the maximum value) roughly corresponds to the characteristic duration of effect $\tau\approx 0.06$ for sources of any intensity (varying by two orders of magnitude in the calculations), which agrees with previous results [2]. The field amplitude is approximately doubled with an increase in source activity by a factor of 100 (see Figs. 1, 4), which corresponds to the logarithmic dependence of amplitude on source activity found previously [2]. The characteristic length of signal half-cycles is a quantity of the order of several units (in dimensionless units of $\tau$) which is directly associated with the characteristic dimension of the source (which

*As in Russian original – Publisher.

is also several units in the present case). We note that the range of the gamma rays was doubled for the numerical integration in one of the versions; the length of the second and third half-cycles of the signal was then doubled. Thus one can assert the satisfactoriness of the physical picture given in [2] for perturbations of the magnetic field. The set of results in that paper [2] can evidently be considered as a complete description of perturbation of the field by a gamma-ray source in air of normal density.

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