Theoretical Notes
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FAST ELECTROMAGNETIC SIGNALS PRODUCED BY NUCLEAR EXPLOSIONS IN THE TROPOSPHERE

by

J. Karl Theobald

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ABSTRACT

Observations during the Pacific tests in the summer of 1962 by the author and others confirm the presence of high-frequency components of the electromagnetic signal which vary in polarity according to the eastern or western location of the recording station from the detonation point. The interaction of relativistic Compton electrons produced by the gamma rays from the detonation with the geomagnetic field is discussed and shown to be capable of producing the signals observed.

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INTRODUCTION

Observations during the 1962 Pacific tests confirm the existence of a component of the "radio flash" which depends on the magnetic bearing of the nuclear detonation from the observation point. An example of the observed pulse shape is given in Fig. 1. The rise time of this pulse is about that of the recording equipment (10^{-8} sec). From the east the signal is positive at the base of the antenna, from the north it is small, and from the west, negative. It is superposed on a slower signal which will not be discussed in this report.

The observed polarity is consistent with the idea that this signal is produced by secondary electrons of high energy as they are deflected by the geomagnetic field. Such electrons are produced by the gamma radiation from the explosion, which has an average energy of about 2 MeV. Since the synchrotron radiation from relativistic electrons is directed forward, the source appears small, which eliminates the difficulty of trying to explain a fast pulse from an extended source. As the gamma rays, electrons, and synchrotron radiation all travel at essentially the speed of light, it is unnecessary to specify the radius of origin of each component of the signal if a correction is made for absorption at distances near the zero point.

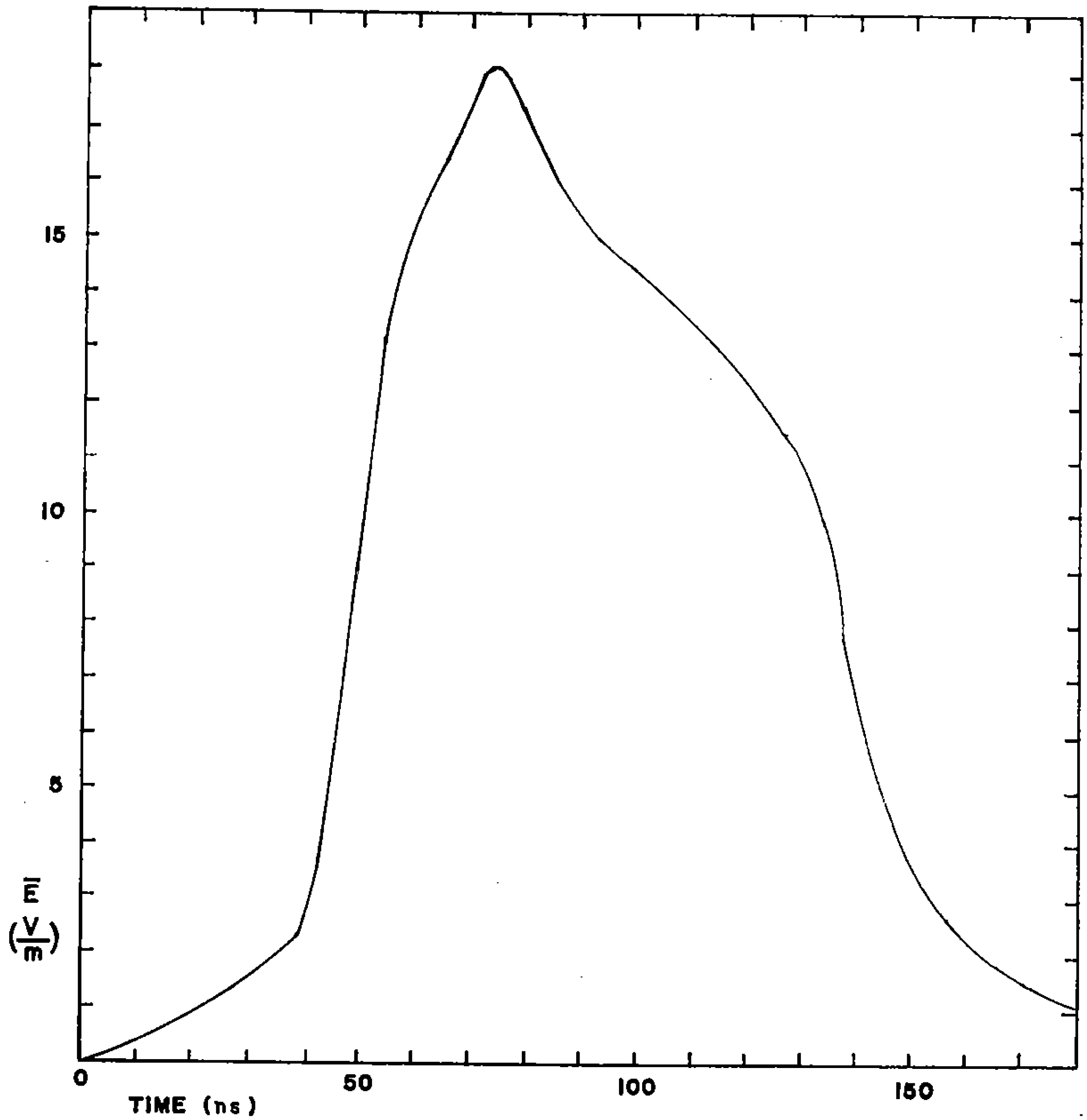

Figure 1. Fast electromagnetic pulse form.

The geomagnetic field will be assumed to be unchanged by the explosion. This assumption will be justified as far as the effect of the deflection of Compton electrons is concerned, but currents may well exist which will produce an additional field.

THE SOURCE REPRESENTATION

The low-yield explosion may be represented for our purposes by 10^{20} photons. Buildup need not be considered since this report is concerned with very early times, so these photons can be expected to be distributed exponentially in time and isotropically radiated from a point source, with absorption by the atmosphere appropriate to an average energy of 2 MeV.

$$\gamma = \frac{\gamma_0 \exp(\alpha t - \mu r)}{4\pi r^2}$$

(t represents local time.)

This expression will be used in the evaluation of conductivity effects. In the signal calculation it will be necessary to take into account the spectrum of the photons from fission as given by Motz.[1] It then becomes expedient to represent the photons as a delta function in time, having the energy distribution in Fig. 2.

(1) J. W. Motz, Phys. Rev. 86, 753 (1952).

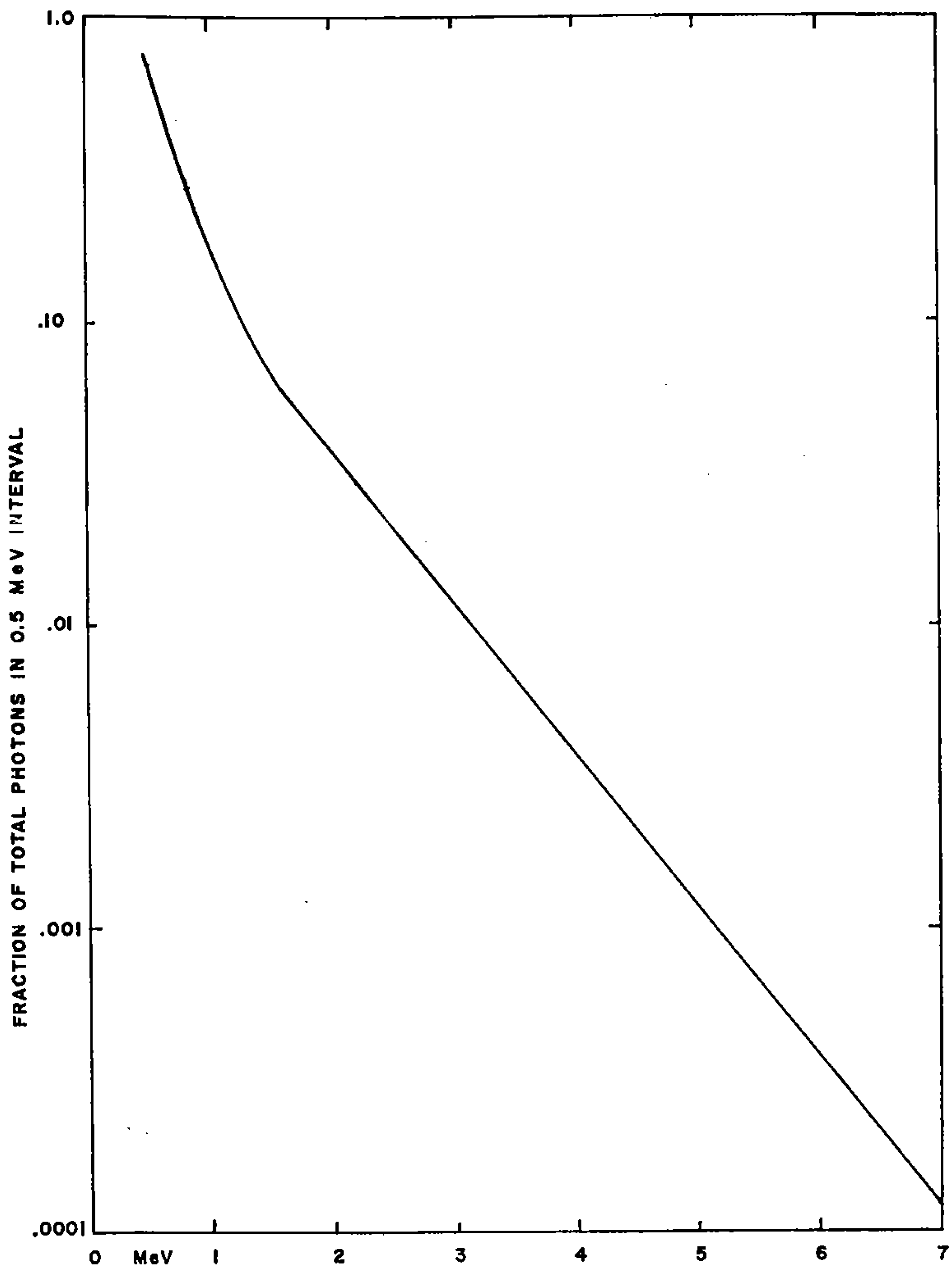

Figure 2. The Motz spectrum.

Atmospheric conductivity is due to tertiary electrons produced by the Compton recoil electrons, which lose some 33 eV per ion pair. This leaves about 10 eV as the average energy of the tertiary electron, which loses energy at an initial rate of 10^{12} inelastic collisions per second and comes to equilibrium with the ambient electric field in a negligibly short time. The latter field is of the order of 10^4 V/m, the equilibrium energy is about 0.2 eV, and the collision frequency will be 3×10^{11} $\sec^{-1}$. The mean attachment time to oxygen molecules will be 10^{-8} sec.[2] Photo-detachment and recombination of the negative ions will be negligible in regions of conductivity low enough for the propagation of electromagnetic radiation.

The conductivity is given by the expression:

$$\sigma = \frac{K e^2 \gamma_o \exp(\alpha t - \mu r)\, \tau_e}{m \nu_c\, 4\pi r^2} \qquad (1)$$

In MKS units

$K = 200$ electrons/photon meter

$\frac{e^2}{m} = 2.8 \times 10^{-8}$ coulomb^2/Kg

$\nu_c = 3 \times 10^{11}$ collisions/sec

$\gamma_o = 10^4$ photons/sec

$\alpha = 10^8$ $\sec^{-1}$

(2) Chanin, Phelps, and Biondi, Westinghouse Research Report WRL-SP-403FD317-P1, 1959.

$\mu = 0.003\ m^{-1}$

$\tau_e = 10^{-8}$ sec electron lifetime

αt_{max} is taken as 55

It is first necessary to calculate the effect of the radial current on the geomagnetic field. This can be done by considering the currents induced in a conducting medium as a magnetic field travels through. It is unnecessary to write an expression for the field. The inducing current density is:

$$j_s = \mu e \delta \frac{\gamma_o \exp(\alpha t - \mu r)}{4\pi r^2} \tag{2}$$

$$\delta = \frac{R^2}{2\rho} \text{ for } R \ll \rho$$

where

δ is the total deflection of the electron.

R = electron range (4 meters).

ρ = radius of curvature (240 meters).

The induced current density due to a field B moving with velocity c through a medium of conductivity σ is σBc. Evidently, if $\sigma Bc = j_s$, the field is very quickly cancelled. This will give a maximum B.

$$\frac{\mu e R^2 \, \gamma_o \exp \, (\alpha t - \mu r)}{2\rho \;\, 4\pi r^2} = \frac{K e^2 \, \gamma_o \exp \, (\alpha t - \mu r) \; \tau_e Bc}{m\nu_c \;\, 4\pi r^2} \tag{3}$$

$$B_{max} = \frac{\mu R^2 m \nu_c}{2\rho K c e \tau_e}$$

Inserting numbers, $B_{max} = 3 \times 10^{-7}$ webers/m^2 = 0.003 gauss. So we see that the geomagnetic field is unchanged.

It must be clearly understood that the foregoing is concerned only with the induction field of the ring current produced by the deflection of the Compton electrons. This field is not expected to show any relativistic effects. The ambient magnetic field may be changed by the effects of currents flowing in the ionized region due to other causes. Our time scale is such that these effects can be neglected because of the comparatively long time necessary to set up such currents and to propagate the resulting fields. Nor are we justified in making statements on this basis about the magnetic component of the synchrotron radiation, which is a relativistic effect not simply connected with the ring current. If the rise of the photon flux is fast compared to the electron attachment time, the e-folding time of the photon flux must be substituted for the electron attachment time.

The next question has to do with the source region of the signal, which one expects to be strongly absorbed near the origin. The propagation constant is given by:

$$\beta = \omega \left[\frac{\mu\epsilon}{2}\left(\sqrt{1 + \frac{\sigma^2}{\epsilon^2\omega^2}} - 1\right)\right]^{1/2} \text{ meter}^{-1}$$

For the case $\sigma^2 \ll \epsilon^2\omega^2$, this reduces to:

$$B \doteq 60\pi\sigma$$

since μ and ϵ have their free space values at frequencies of interest here.

Using Eq. (1) for σ and inserting the same numbers, we obtain the following:

$r(m)$	$\beta_{max}(m^{-1})$
300	0.11*
600	0.10×10^{-1}
900	0.18×10^{-2}
1200	0.35×10^{-3}
1500	0.83×10^{-4}

The table indicates strong absorption inside two free paths for the average gamma photon, so the signal will be assumed to be produced at a spherical surface of 1 Km radius by the photons reaching that distance.

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* $\sigma \sim \epsilon\omega$ at 300 meters for $\omega = 10^8$ sec^{-1}, so this value is a little high.

The time behavior of the signal from a delta function of photons is determined by the distance from a source point on the surface of the sphere to the detector.

From simple trigonometry, (Fig. 3), neglecting δ^2 compared to δR and $\delta\rho$

$$\delta = \frac{\rho R(1 - \cos\psi)}{R - \rho}$$

where

ψ = angle between the source point radius vector and the line of sight.

ρ = radius of source sphere.

R = distance from origin to detector.

We divide the source sphere into annuli, using an increment of 0.01 radian. R will be taken as 20 Km. We estimate the number of electrons of high energy (comparable to the energy of the responsible photon) by comparing the radiation pattern for synchrotron radiation with the Compton recoil distribution. The resulting factor is about ten percent and is not particularly energy dependent. The Motz spectrum is divided into intervals of 500 KeV, 10% of the photons produce radial electrons having the photon energy, and each electron radiates for 2×10^{-9} sec, after which it is lost in the more numerous electrons of the lower energy group. (For electrons of 0.5 and 1 Mev, 1×10^{-9} sec was used as the pulse width in the calculation.) These widths are less than the width of the outer

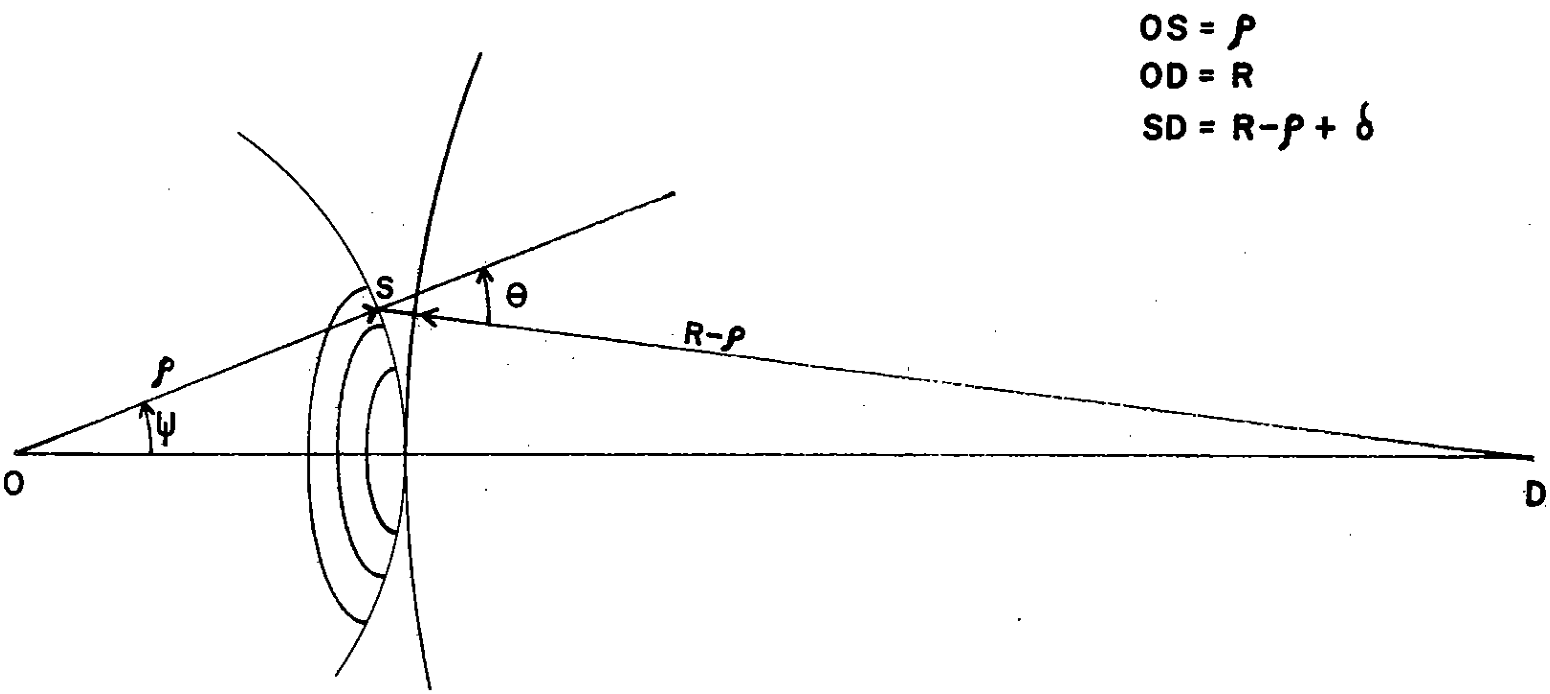

Figure 3. Path difference of signals from a spherical source.

annuli and this is taken into account in summing the contributions by simply multiplying the sum by the ratio of pulse width to zone width. This completes the formulation of the signal source.

SYNCHROTRON RADIATION

It is perhaps appropriate to review the significant features of the radiation mechanism under discussion. The details are to be found in textbooks. The radiation pattern for energy is given by:

$$\frac{dW}{dt'} = \frac{e^2\dot{v}^2(\beta - \cos\Theta)^2}{16\pi^2\epsilon_o c^3(1 - \beta\cos\Theta)^5} \tag{4}$$

It has zeros at $\beta = \cos^{-1}\Theta$.

The field at $\Theta = 0$ is given by:

$$E = \frac{e\dot{v}}{4\pi\epsilon_o(1 - \beta)^2 rc^2}$$

$$\dot{v} = \frac{Be\beta c}{m} = \frac{Be\beta c\sqrt{1 - \beta^2}}{m_o}$$

$$E = \frac{Be^2\beta\sqrt{1 - \beta^2}}{4\pi\epsilon_o m_o rc(1 - \beta)^2} \tag{5}$$

Equations (4) and (5) allow us to calculate the field strength for each annulus for each energy interval. The polarization is antiparallel to $\dot{v}$. We will consider only horizontal components of the geomagnetic field, which is 1/3 gauss, and calculate the signal on the east-west axis. The increment of solid angle in our annular source structure follows the series of odd numbers:

$$d\omega_n = (2n + 1)\ d\omega_o \tag{6}$$

$$E_n = (2n + 1)\ \frac{d\omega_o}{4\pi}\ \gamma(\epsilon)\ 0.1\ \frac{\exp\ [-\mu(\epsilon)\rho]}{\rho^2}\ \frac{t_r}{t_n}\ E(\Theta_n)$$

The successive terms of Eq. (6) are: $(2n + 1)\ d\omega_o/4\pi$, the solid angle term; $\gamma(\epsilon)$, the number of photons in the energy group ϵ; 0.1, the correction factor for the angular distribution of Compton electrons; gamma ray absorption and inverse r^2 at the source radius; the ratio between pulse and zone widths (meaningless if allowed to exceed unity); and the electric field produced at 20 Km by one electron of energy ϵ at the angle Θ_n which is appropriate to the solid angle of the annulus in question.

In Fig. 4 we see the results of a numerical calculation carried out in the manner outlined here. The necessary approximations have been severe, if not drastic, so the agreement with the observed curve in Fig. 1 must be regarded as quite good. It may be argued that since the photon distribution in time is not a delta function and since there are buildup effects, the relation between Figs. 1 and 4 is to be expected. The observed signal, however, was chosen for ease of reading from a score of signals of similar form and magnitude which show no correlation with

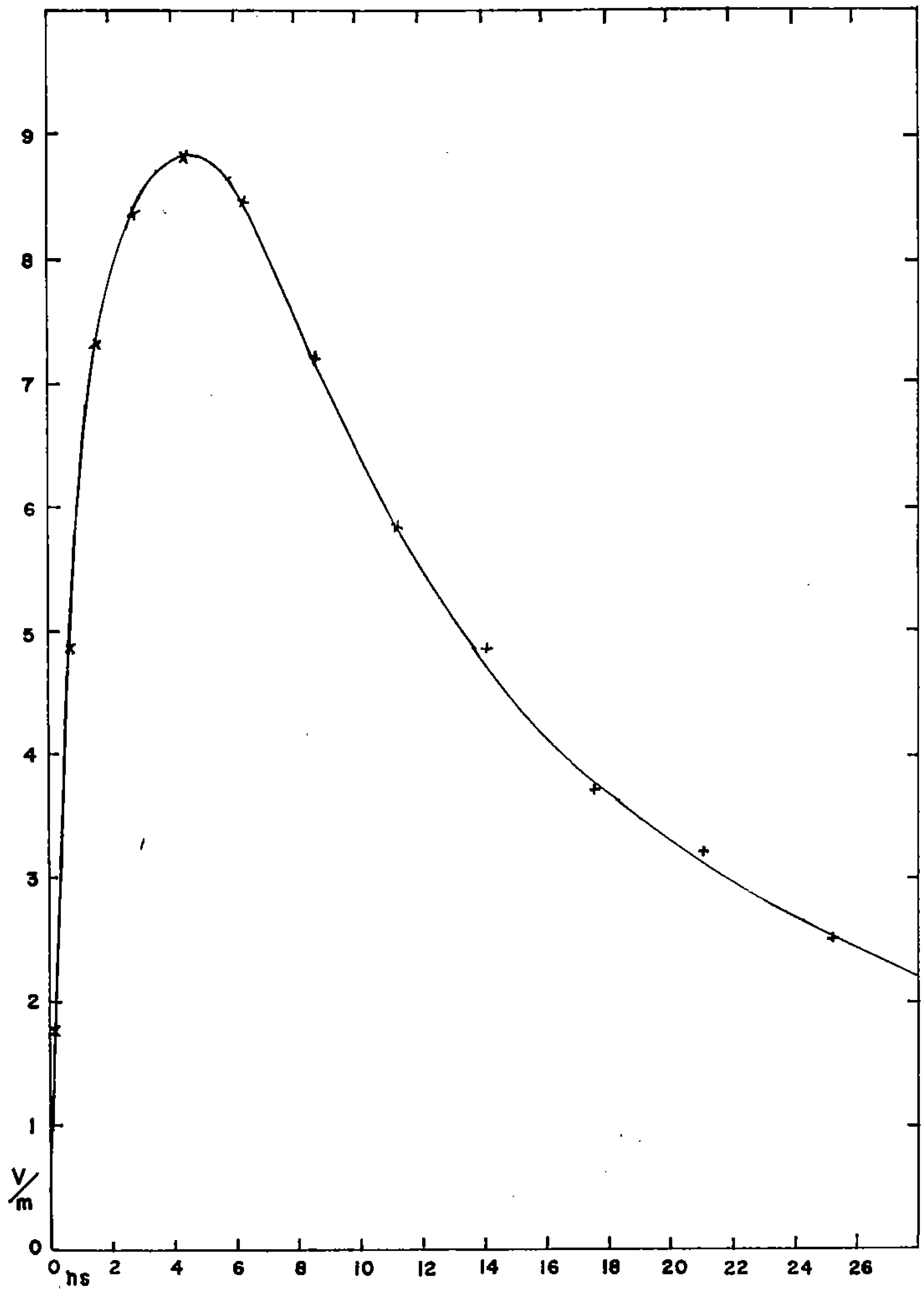

Figure 4. Calculated pulse form.

any of the parameters used in calculations of this sort, showing, for example, little if any difference in amplitude when observed from the southeast instead of east.

We may conclude that the magnetic field of the earth is adequate to produce signals having the form and magnitude of those showing the east-west variation.