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SATELLITE-BASED DETECTION OF THE ELECTROMAGNETIC SIGNAL FROM LOW AND INTERMEDIATE ALTITUDE NUCLEAR EXPLOSIONS

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PREFACE AND SUMMARY

For a variety of reasons nuclear explosions at low and intermediate altitudes (a few to 20 or so kilometers) are particularly difficult to detect. One possibility to improve detection in this altitude range is by satellite-based detection of the electromagnetic signal produced by the explosion. In the present paper, this possibility is examined and shown theoretically to offer sufficient promise that the inclusion of this detection technique in the Project VELA satellite would appear worthwhile.

I. INTRODUCTION

A standard technique for detecting nuclear explosions at low and intermediate altitudes is by ground observation of the electromagnetic signal radiated from the explosion.[1] A difficulty with this technique is that at the great distances of interest for detection, explosion signals are similar to the signals produced by spherics. The reason is that the high frequencies characteristic of explosion signals are attenuated by propagation to great distances over the earth's surface, leaving only low frequencies characteristic of spherics. If the explosion signals could be observed line-of-sight and attenuation avoided, the high frequencies could serve to distinguish explosions from spherics. For this purpose satellites capable of observing the entire surface of the earth could be instrumented to detect the high frequencies.

Satellite detection has the property that, because of the great altitude of satellites, explosion and spheric signals must traverse the ionosphere to be detected. This is advantageous since electron densities in the F-layer are high, corresponding to plasma frequencies from 10^6 to 10^7 cps, and therefore spheric signals are screened out. However, because of the high plasma frequencies

[1] R. Latter, R. F. Herbst, and K. M. Watson, Ann. Rev. of Nuc. Sci., 11, (1961).

there is the disadvantage that only the highest frequencies in the explosion signal can penetrate the ionosphere and these frequencies are dispersed by the ionospheric plasma leading to rather low intensity signals. Despite this degradation, the signals appear quite detectable. In the present paper we estimate the magnitude of the explosion signal—including effects of ionospheric dispersion—which would be observed by an instrumented satellite.

II. THE HIGH FREQUENCY ELECTROMAGNETIC SIGNAL

The most intense high-frequency electromagnetic signal from a nuclear explosion is that due to the interaction of the prompt-gamma-ray produced Compton currents with the earth's magnetic field.[2, 3] The gamma rays produce Compton-recoil electrons whose motion is initially radially outward from the burst point. The earth's magnetic field turns these electrons so that there is a transverse current in addition to a radial current. The Compton electrons lose energy and slow down by ionizing air, which leads to a highly conducting region surrounding the burst point. Within this region, it is easily shown[4] that the magnitude of the electric field intensity E_s is given by j/σ, the transverse current density j divided by the conductivity of the region σ. In particular, for a sea-level explosion, this electric field intensity is[5]

$$E_s = B_o \frac{\nu_c(\alpha + \beta)}{2\gamma q} \left(\frac{R}{c}\right)^2 \quad (1)$$

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[2] W. J. Karzas and R. Latter, J. Geophys. Res., 67, 4635, (1962).

[3] W. J. Karzas and R. Latter, Phys. Rev., 137B, 1369, (1965).

[4] See Eq. (15) of Reference 2.

[5] See Eqs. (15), (18) and (35) of Reference 2. In Eqs. (33) to (36) of Reference 2, there is a typographical error—$|b(\tau)|$ should be deleted.

where B_o is the earth's magnetic field, ν_c the collision frequency for slow electrons in air, α the exponential rise rate for the prompt gamma-ray pulse, R the Compton electron range, γ the electron relativistic mass factor, β the electron attachment rate to oxygen, and $q \approx 3 \times 10^4$ the number of secondary electrons produced by each Compton electron.

As the explosion altitude is increased above sea level, the Compton electron range increases, so that the electrons are turned by the magnetic field through a larger angle before they are stopped. The transverse current per electron thus increases, as does the electric field, until the electron range becomes comparable to the Larmor radius. After this point is reached, the peak electric field intensity in the conducting region no longer increases with altitude. This limiting electric field is given by[6]

$$E_s \approx \frac{m\omega \nu_c R}{eq(1-v/c)} , \qquad (2)$$

where

$$\omega = eB_o/\gamma mc . \qquad (3)$$

An analysis of the altitude dependence of the electric field in the conducting region can be made, assuming an exponentially

[6] See Eq. (72) of Reference 3.

rising gamma-ray flux. The result is[7]

$$E_s = \frac{m\omega\nu_c R}{eq(1-v/c)} \; \frac{1-[1+\alpha(1-v/c)R/c]\, e^{-\alpha(1-v/c)R/c}}{1-e^{-\alpha(1-v/c)R/c}} \, . \quad (4)$$

This expression agrees with Eqs. (1) and (2) for the two limiting cases $\alpha(1-v/c)R/c \ll 1$ and $\alpha(1-v/c)R/c \gg 1$, provided $\beta \ll \alpha$. (The electron attachment rate, β, is proportional to the square of the air density, so that attachment can be neglected at early times and intermediate altitudes.)

The electric field outside the conducting region at a distance, r, from the burst point is given approximately by[8]

$$E \approx E_s r_s / r \quad (5)$$

where r_s is the radius of the conducting region. For explosion altitudes up to about 20 km, for which the gamma-ray mean-free-path is less than the atmospheric scale height, r_s is typically of the order of a few gamma-ray mean-free-paths.

From Eqs. (3) to (5) it can be shown that the peak electric field intensity in volts per meter at a distance r kilometers from the burst point (ignoring ionospheric propagation) ranges from about $10^3/r$ for a sea level explosion[2] to about $10^6/r$ for the limiting high-altitude case.[7]

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[7] W. J. Karzas and R. Latter, RAND Memorandum RM-4194-PR, (SRD).

[8] See p. 4638 of Reference 2 and Eq. (63) of Reference 7.

The time variation of the electromagnetic signal at sea level is the same as that of the prompt gamma-ray emission from the explosion. At higher altitudes the signal has the rapid rise time characteristic of the gamma-ray emission but a decay time determined by the Compton electron Larmor frequency ($\sim 10^6 \sec^{-1}$). These properties of the signal are satisfied by the analytic form, which also approximates well the complete signal form,[7]

$$E(r,t) \approx E_s \frac{r_s}{r} \, 1/2 \, (1 + \tanh \alpha\tau) \, e^{-\delta\tau}, \qquad (6)$$

where E_s, r_s, and δ vary with the burst altitude, α is the gamma-ray rise time constant, and $\tau = t - r/c$ is the retarded time. We shall find this approximate analytic form useful for analyzing the effect of ionospheric propagation on the signal.

III. EFFECT OF IONOSPHERIC PROPAGATION

To estimate the effect of the ionosphere on the explosion signal, we assume that the thickness of the ionosphere is small compared to the distance of the burst point to the satellite. This allows us to treat the distance from the burst point as a constant as the signal traverses the ionosphere. Thus, the signal after propagating through the ionosphere is given by[9]

$$E_o(r,t) = \int d\omega e^{i\omega\tau} e^{-i\int \frac{dx}{c}\left[\sqrt{\omega^2-\omega_p^2(x)}-\omega\right]} \hat{E}(\omega, r), \qquad (7)$$

where

$$\omega_p^2(x) = \frac{4\pi e^2}{m} n_e(x) \quad , \qquad (8)$$

$$\hat{E}(\omega, r) = \frac{1}{2\pi}\int_{-\infty}^{\infty} d\tau\, e^{-i\omega\tau} E(r,t) \; . \qquad (9)$$

$E(r,t)$ is given by Eq. (6) and $n_e(x)$ is the ionospheric electron density at position x along the path from the burst point to the observation point. This integral can be evaluated by the method of steepest descent if we make the approximation that the ionosphere consists of a layer of thickness (along the path) L with <u>constant</u> electron density. Thus we assume that

$$\left(\sqrt{\omega^2-\omega_p^2}-\omega\right)\frac{L}{c} = \int \frac{dx}{c}\left(\sqrt{\omega^2-\omega_p^2(x)}-\omega\right). \qquad (10)$$

[9] W. J. Karzas and R. Latter, Phys. Rev., 126, 1919 (1962).

With the approximation of a constant density layer, we find using the method of steepest descent,[9]

$$E_o(r,t) = \left(\frac{2\pi c}{\omega_p^2 L}\right)^{1/2} (z^2 - \omega_p^2)^{3/4} \, 2\mathrm{Re}\left\{\hat{E}(z,r)\, e^{i\frac{\pi}{4}}\, e^{i\frac{\omega_p^2 L}{c}(z^2-\omega_p^2)^{-1/2}}\right\} , \tag{11}$$

where

$$z = \omega_p \frac{1 + c\tau/L}{\left[\frac{2c\tau}{L}\left(1 + \frac{c\tau}{2L}\right)\right]^{1/2}} . \tag{12}$$

The Fourier transform of Eq. (6) is

$$\hat{E}(\omega, r) = E_s \frac{r_s}{r} \frac{1}{4i\alpha} \operatorname{csch}\left[\frac{\pi}{2\alpha}(\omega - i\delta)\right] , \tag{13}$$

which gives

$$E_o(r,t) = \frac{E_s r_s}{r} \left(\frac{\pi c}{2\omega_p^2 L}\right)^{1/2} \frac{1}{\alpha} \frac{(z^2 - \omega_p^2)^{3/4}}{\left[\sinh^2 \frac{\pi z}{2\alpha} + \sin^2 \frac{\pi\delta}{2\alpha}\right]^{1/2}}$$

$$\cos\left[\frac{\omega_p^2 L}{c}(z^2 - \omega_p^2)^{-1/2} + \tan^{-1}\left(\tan\frac{\pi\delta}{2\alpha}\coth\frac{\pi z}{2\alpha}\right) - \frac{\pi}{4}\right] . \tag{14}$$

If the signal decay rate, δ, is small compared to the rise rate, α—as is usually the case—this simplifies to

$$E_o(r,t) = \frac{E_s r_s}{r} \left(\frac{\pi c}{2\omega_p^2 L\alpha^2}\right)^{1/2} (z^2 - \omega_p^2)^{3/4} \operatorname{csch}\frac{\pi z}{2\alpha} \cos\left[\frac{\omega_p^2 L}{c}(z^2 - \omega_p^2)^{-1/2} - \frac{\pi}{4}\right] , \tag{15}$$

which represents the usual dispersed wave—rapid oscillations with a slowly varying envelope. The peak of the envelope occurs at a time such that

$$\frac{3}{2}\tanh y = y - a^2/y \,, \tag{16}$$

where

$$y = \pi z/2\alpha \tag{17}$$

and

$$a^2 = (\pi\omega_p/2\alpha)^2 \,. \tag{18}$$

The peak value of the dispersed electric field is then

$$E_{peak} = E_s \frac{r_s}{r} \frac{2}{\pi} \left(\frac{3}{2}\right)^{3/4} \left(\frac{\alpha c}{\omega_p^2 L}\right)^{1/2} y^{3/4} \operatorname{sech} y \,(\tanh y)^{-1/4} \,. \tag{19}$$

If a is small compared to one, that is, if[10] $\omega_p << \alpha$, y is independent of a and has the value 1.3. In this case

$$E_{peak} = 0.55\, E_s \frac{r_s}{r} \left(\frac{\alpha c}{\omega_p^2 L}\right)^{1/2} \,. \tag{20}$$

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[10] From F.S. Johnson, Satellite Environment Handbook, Stanford University Press, (1961), we obtain the following properties of the ionosphere:

	$\frac{1}{c}\int \omega_p^2(x)dx \approx \frac{\omega_p^2}{c} L$	$\omega_{p\,max}$
Daytime, minimum of sunspot cycle	1.8×10^{12} sec^{-1}	3×10^7 sec^{-1}
Daytime, maximum " "	6.5×10^{12}	7×10^7
Nighttime, minimum " "	3.2×10^{11}	2×10^7
Nighttime, maximum " "	1.4×10^{12}	3×10^7

An estimate of the duration of the signal can be made by taking as the signal length the time delay to the peak. This gives

$$\Delta\tau \approx \frac{\omega_p^2 L}{\alpha^2 c} \quad . \tag{21}$$

For

$$\alpha = 3 \times 10^8 \text{ sec}^{-1} \text{ and } \frac{\omega_p^2 L}{c} \approx 10^{12} \text{ sec}^{-1} ,$$

we find a signal duration of $\Delta\tau \approx 10^{-5}$ sec, and peak electric fields in volts per meter ranging from $10/r$ to $10^4/r$, where r is in kilometers. Thus for a twenty-four-hour-orbit satellite at about 50,000 km altitude, we could expect a signal with a duration of a few tens of microseconds and a peak intensity of from 1/5 millivolts/meter to 1/5 volts/meter, depending on the explosion altitude. The frequencies in the signal are of the order of several tens of megacycles.

IV. DISCUSSION

The detectability of this signal depends upon the intensity of interfering background noise. If it is assumed that the only background noise is due to cosmic noise—which appears likely at satellite altitudes—then the intensity of the interfering noise electric field[2, 3] is a little more than 10^{-5} v/m. Comparing this with the signal strength of 2×10^{-4} to 0.2 v/m indicates that detection should be relatively straightforward.