TN 302

Theoretical Notes
Note 302

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Modifications to the EMP from a nuclear burst due to a previous burst nearby are considered. Possible synergisms are looked for, and three significant ones are described. These involve smog produced by the first burst, lingering electric fields from the first burst, and its highly conducting fireball. These synergisms can lead to a moderate increase in the maximum amplitude of the EMP, and also modify exposure geometry.

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CONTENTS

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1. INTRODUCTION

In this report we shall discuss briefly several effects that occur in the EMP from multiple low-altitude nuclear bursts. Our goal is to include all important effects, and to categorize them either as being approximately additive from the single burst effects or as being synergistic. As used here, synergistic means that the multiple burst effect is much larger than the sum of the single burst effects.

We shall assume in this report that the minimum time spacing between bursts is

$$\Delta T = 1 \text{ millisecond} . \quad (1)$$

Since

$$c\Delta T = 300 \text{ km} , \quad (2)$$

the high-frequency or early-time parts of the EMP from two bursts will interact with each other only if the burst points are separated by distances of the order of 300 km or more. The fields from a burst at this distance are very small compared with those from a nearby burst and can hardly have any significant effect.

Thus we need only to consider the interaction of the late-time environments from a first burst with the early-time or the late-time effects from a second burst.

For bombs located a few kilometers or even a few tens of kilometers apart, it should not be difficult to get them to explode with ΔT of the order of that given by Equation 1; the radiation from a first burst could be used to trigger later ones. It would be necessary, of course, to arrange that all RV's be in the desired altitude range at the same time.

One could discuss, by the same techniques used below, the interactive effects for shorter ΔT.

2. GENERAL DISCUSSION OF INTERACTION

In this section we discuss, in general terms, the interaction of the environment from a first burst with the effects from a second burst.

Maxwell's equations, which determine the EMP, are:

$$\frac{1}{c}\frac{\partial\vec{B}}{\partial t} = -\nabla\times\vec{E}\ , \tag{3}$$

$$\frac{1}{c}\frac{\partial\vec{E}}{\partial t} = \nabla\times\vec{B} - 4\pi\vec{J} - 4\pi\sigma\vec{E}\ . \tag{4}$$

Here $\vec{E}$ and $\vec{B}$ are the electric and magnetic fields, $\vec{J}$ is the Compton current density and σ is the air conductivity. In order to look for synergisms, we must look for the nonlinearities in these equations.

The most obvious nonlinearity is provided by the σE term. If we try to write the electric field as the sum $\vec{E} = \vec{E}_1 + \vec{E}_2$ of the fields from the individual bursts, and similarly $\sigma = \sigma_1 + \sigma_2$, we find that

$$\sigma\vec{E} = \sigma_1\vec{E}_1 + \sigma_2\vec{E}_2 + (\sigma_1\vec{E}_2+\sigma_2\vec{E}_1)\ . \tag{5}$$

Obviously, the cross terms prevent the sum of the solutions from the individual bursts from being a solution for the double burst.

In order to make headway, let us assume that we have found the complete solution for the first burst alone, which satisfies

$$\frac{1}{c}\frac{\partial\vec{B}_1}{\partial t} = -\nabla\times\vec{E}_1\ , \tag{6}$$

$$\frac{1}{c}\frac{\partial\vec{E}_1}{\partial t} = \nabla\times\vec{B}_1 - 4\pi\vec{J}_1 - 4\pi\sigma_1\vec{E}_1\ . \tag{7}$$

Now, during the time span of the second burst, let us write

$$\vec{J} = \vec{J}_1 + \vec{J}_2 + \delta\vec{J} \ , \tag{8}$$

$$\sigma = \sigma_1 + \sigma_2 + \delta\sigma \ . \tag{9}$$

Here $\vec{J}_2$ and σ_2 are the Compton current and conductivity that would be present if the first burst had not occurred and $\delta\vec{J}$ and $\delta\sigma$ are the changes in those quantities due to the interaction. Let us also write

$$\vec{E} = \vec{E}_1 + \vec{E}^* \ , \tag{10}$$

$$\vec{B} = \vec{B}_1 + \vec{B}^* \ , \tag{11}$$

where the starred fields are to be determined by substituting these expressions for $\vec{E}$ and $\vec{B}$ in Maxwell's Equations 3 and 4. On then subtracting Equations 6 and 7 from 3 and 4, we obtain

$$\frac{1}{c}\frac{\partial\vec{B}^*}{\partial t} = -\nabla \times \vec{E}^* \ , \tag{12}$$

$$\frac{1}{c}\frac{\partial\vec{E}^*}{\partial t} = \nabla \times \vec{B}^* - 4\pi(\vec{J}_2+\delta\vec{J}) - 4\pi\sigma\vec{E}^* - 4\pi(\sigma_2+\delta\sigma)\vec{E}_1 \ . \tag{13}$$

These equations differ from those for a single burst in three ways:

1. the Compton current is altered; the term $\delta\vec{J}$ is the sum of the change in $\vec{J}$ due to burst #2 and the change in J_2 due to burst #1, i.e.,

$$\delta J = \delta J_1 + \delta J_2 \ ; \tag{14}$$

2. the conductivity σ is the total conductivity due to both bursts, in the time frame of the second burst;
3. there is an additional source term $4\pi(\sigma_2+\delta\sigma)\vec{E}_1$; this is the conduction current driven by $\vec{E}_1$ in the changed conductivity $\sigma_2 + \delta\sigma$.

3. THE LATE-EARLY INTERACTION

In this section we discuss the interaction of the late-time environment from a first burst with the early-time effects from a second burst.

3.1 SMALL ΔT

We first consider burst time intervals between

$$1 \le \Delta T \le 100 \text{ milliseconds} . \tag{15}$$

During this time interval the fireball from the first burst is still fairly small and the principal interaction is due to fields and chemical species (smog) left over from the first burst.

The conductivity σ_1 and Compton current $\vec{J}_1$ from the first burst are generally small, in this time frame, compared with the early-time quantities σ_2 and $\vec{J}_2$ from the second burst. We need to consider, however, the effect of the quantities $\delta\sigma$, $\delta\vec{J}$, and $\vec{E}_1$ in Equation 13.

Let us define

$$\sigma^* = \sigma_2 + \delta\sigma \approx \sigma , \tag{16}$$

since σ_1 is small. The quantity σ^* is determined primarily by the ionization rate and the electron attachment rate at early times for the second burst. While the ionization rate is unaffected by burst #1 (neglecting the fireball), the attachment rate can be substantially increased by the smog left over from burst #1. It was estimated in Reference 1 that, for a large yield burst, the presence of HNO_3 formed in the smog reactions will increase the attachment rate by a factor of 3 or 4 in the millisecond time frame. This will cause the electron density produced by the second burst to be reduced by about the same factor, and cause σ^* to be less than σ_2. The result is that electric fields produced by the second burst will be larger than normal, which decreases the electron mobility and further decreases σ^*. Some mitigation of

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[1] Scheibe, M., and C. L. Longmire, "The Effect of Ionization Induced Smog on EMP Environments," MRC-N-362 (initially labeled AMRC-N-97), September 1978.

these changes comes from the fact that the largest electric fields usually occur in the rapidly rising part of the gamma pulse where the rise rate also limits the electron density. Still, electric fields can be expected to increase by a factor of 4 to 10 due to the estimated amount of HNO_3 for the case mentioned. Thus it is expected that the $\delta\sigma$ effect is a significant synergism for large yield bursts.

Again ignoring the fireball in this time frame, we expect the principal cause of $\delta\vec{J}$ will be the magnetic field left over from burst #1. If the field B_1 is larger than about 10 gauss, it will affect significantly the motion of the Compton electrons generated by burst #2, thus giving rise to a $\delta\vec{J}_2$. Such large magnetic fields occur only near the first burst point for $\delta T \geq 1$ millisec. The effect of the magnetic field is to reduce the magnitude of the Compton current and change its direction. The same effect, but larger, occurs from the magnetic field B* produced by the second burst. Therefore, we do not expect this effect to be a highly important synergism. It would be wise, however, to pursue this effect to the point of bounding field amplitudes and exposure geometry.

The left-over electric field $\vec{E}_1$ probably does produce a significant synergism, especially if $\vec{E}_1$ is raised to the level of 10^5 V/m by smog effects. The field $\vec{E}_1$ is approximately in the θ-direction (Reference 1), and therefore $\sigma^*\vec{E}_1$ represents a transverse source current. $\vec{E}_1$ is nearly constant on the early-time-scale of the second burst, but σ^* builds up with the rise rate of the gamma output of the second burst, so that the current σ^*E_1 rises rapidly, and moves outward with the speed of light. The calculational problem here is similar to that of the high-altitude EMP, and is posed approximately by the ray equation,

$$\frac{1}{r}\frac{\partial}{\partial r} rE_t(r,\tau) + 2\pi\sigma^*(r,\tau)E_t = -2\pi\sigma^*E_1(r,\tau) \quad , \qquad (17)$$

where τ is the retarded time, E_t is the transverse part of $\vec{E}^*$, and E_1 is the transverse part of $\vec{E}_1$. The solution of this equation saturates at

$$E_t = - E_1 \ , \tag{18}$$

provided σ^* exceeds

$$\sigma^* > \frac{1}{2\pi\lambda_\gamma} \approx 10^{-5} \text{ cm}^{-1} \approx 3 \times 10^{-5} \text{ mho/m} \ . \tag{19}$$

This value of σ^* is reached out to distances of about 2.5 km for a nominal 1 megaton burst, so that synergistic interaction will occur for bursts within about 4 km of each other. At ranges R larger than 2.5 km from the second burst the field falls off as

$$E_t \approx - \frac{2.5 \text{ km}}{R} E_1 \ , \tag{20}$$

propagating as a free spherical wave. Thus this synergism converts an essentially static electric field E_1 into a sharply-rising propagating pulse. The same effect would be produced by the large vertical electric field under a thunderstorm. This effect also deserves further evaluation.*

It should be noted that early-time fields of the order of 10^5 V/m would be generated by the second burst by itself. However, these fields are radiated only in directions near the horizontal. The synergistic fields described by Equation 17 et seq. are radiated into larger solid angles. When added to the normal early-time fields for the second burst at angles near horizontal, they yield a pulse which shows both polarities.

3.2 LARGER ΔT

For burst time intervals greater than 0.1 second, the fireball from the first burst becomes a dominant phenomenon. In Reference 2 the fireball properties of importance to EMP have been discussed. Figures 1 through 4 of that reference show radius-time contours of air temperature, air density, electron density, and air conductivity in the fireball for a

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[2] Hobbs, W. E, and C. L. Longmire, "Fireball Effects in Late-Time EMP From Surface Bursts," MRC-R-249, Mission Research Corporation, February 1978.

* Some calculations using LEMP are underway.

1 megaton surface burst. The electron densities and conductivities in these figures do not include those induced by neutron and gamma radiation, so that these have to be added outside the fireball. Inside the fireball, thermal ionization is dominant.

At temperatures greater than about 1000°K (≈ 0.1 eV), attached electrons and most molecular clusters evaporate. At this temperature, radiation induced (electronic) conductivity is controlled by balance between the ionization rate and the dissociative recombination rate. At slightly higher temperature (≈ 0.3 eV), thermal ionization is dominant, and the conductivity is of the order of 1 mho/m, which is high on EMP scales. According to Figure 4 of Reference 1, the maximum radius of the 1 mho/m contour is about 1.1 km, and this radius applies from about 0.5 second to about 5 seconds. Any smog effects of the type discussed in Section 3.1 would have to occur outside this region. At present we do not know the maximum radius of significant smog effects, but it appears unlikely to be much greater than 1 km for a 1 megaton burst. This would mean that the smog synergism would be wiped out by the fireball by times $\Delta T \approx 1$ second. By times of 10 seconds the fireball rises off the ground, sucking up the nearby cooler air behind it.

The magnetic fields left over from burst #1 are too small after 0.1 second to affect significantly the early-time EMP from the second burst. In addition the magnetohydrodynamic interaction of the fireball with the geomagnetic field produces changes in that field which are too small to produce important synergism with the early-time EMP from the second burst. In the MHD effect, the geomagnetic field is pushed out of the fireball and increased just outside the fireball by a factor of about 2.

The left over electric field (outside the fireball) may cause a significant synergism in this time frame, but it should be diminishing with time. The reason is that the conductivity should now be ionic, and ionic conductivity falls as the square root of the source (gamma flux), whereas the Compton current falls as the source itself. The electric field therefore should fall as

$$E \sim \frac{J}{\sigma} \sim \sqrt{\text{source}} \ . \tag{21}$$

The fireball itself provides a synergism with the early-time effects of the second burst. It presents a region of high conductivity, higher than most soils, with a sharp outer boundary. (Just how sharp is not known very well, but could be ascertained.) Thus the nominally radial electric field from the second burst will interact with its surface, producing transverse (and therefore propagating) electric and magnetic fields, much as normally occurs at the ground-air interface. One difference, of course, is that the fireball surface is spherical, and there is only one tangent point along a ray from the second burst point, and another difference is that gammas can transit the fireball without severe attenuation. We can expect a transverse EM pulse to be launched in the region near the tangency circle, of similar amplitude and shape to that normally launched along the ground-air interface. This pulse will be subject to diffraction and attenuation as it propagates away. The amplitude of the pulse is probably not greater than the normal ground pulse, but the pulse is radiated in some new directions. The pulse amplitude will be governed to some extent by the temperature and density profiles just outside the fireball surface. We recommend some detailed studies of this effect.

4. THE LATE-TIME INTERACTION

In this section we discuss the interaction of the late-time environment from a first burst with the late-time effects from a second burst.

4.1 SMALL ΔT

We again first restrict our attention to burst time intervals ΔT between 1 and 100 milliseconds, during which the fireball from the first burst is not a dominant effect. The time δt after the second burst that we are considering now are in the range from about 1 microsecond to 100 milliseconds. The EMP from the second burst will be in either the diffusion phase or the quasistatic phase.

For the smaller δt's, $\delta t \ll \Delta T$, there will be regions of space around the second burst where $J_2 \gg J_1$ and $\sigma_2 \gg \sigma_1$, the left-over electric field E_1 will have been long since shorted out, and $B_2 \gg B_1$. In this region the fields around the second burst will be essentially normal, except that smog produced by the first burst may affect the air conductivity. An increased attachment rate due to HNO_3 would lower the conductivity, increase electric fields, and increase magnetic relaxation (diffusion) rates. As a result of the latter, the magnetic fields would also increase. As an estimate, the magnetic field and the horizontal electric field at the ground would increase as the square root of the effective attachment rate.

For $\delta t \gtrsim \Delta T$, there will be a region between the two bursts where $J_2 \approx J_1$ and $\sigma_2 \approx \sigma_1$. If the smog effect were not important, we would have in this region,

$$\sigma \approx \sigma_1 + \sigma_2 , \tag{22}$$

$$\vec{J} \approx \vec{J}_1 + \vec{J}_2 . \tag{23}$$

The fields would then be less in magnitude than the vector sum of the fields for the individual bursts, because of Equation 22. (The sum of two $\vec{J}$'s produces the sum of the fields if the conductivity is the same in all cases.) In this time frame, the smog effects from the two bursts are probably approximately additive, so that they can be included in σ_1 and σ_2; thus the statement about the fields probably applies even with smog.

4.2 LARGER ΔT

We now consider the effect of the fireball from the first burst on the late-time EMP from the second burst. The principal effect here is that the fireball presents a large, highly conducting volume to the second burst. Electric fields inside this volume will be much less than normal. However, the fireball can collect a large amount of Compton current and run it into the ground underneath it, from whence the current flows back to the second burst point. Further, if the fireball has lifted off the ground, the electric field between the fireball and ground can be significantly larger than normal, as sketched in Figure 1. The importance of this effect is perhaps mitigated by the point that we may no longer be much concerned about equipment in that location.

The MHD effects of two nearby fireballs are roughly additive (except that the geomagnetic field excluded from one cannot pass through the other). Thus the electric fields induced in the ground, and acting on cables therein, can be obtained roughly by adding up those from a pair of magnetic dipoles.

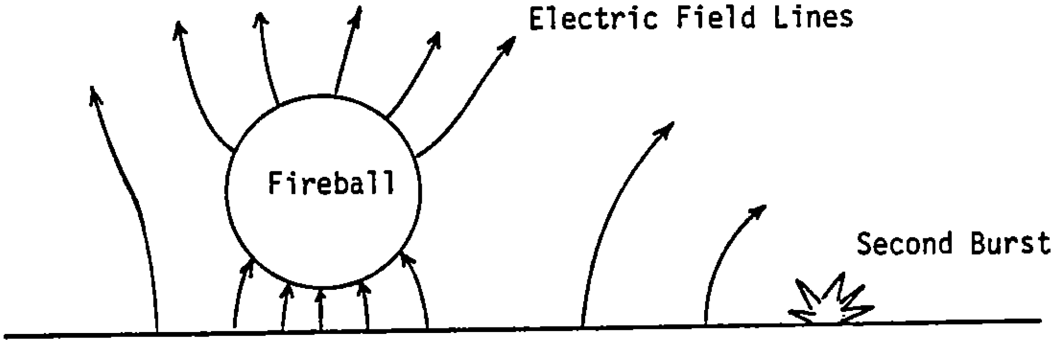

Figure 1. Concentration of electric field lines by fireball slightly above the ground.

5. SUMMARY AND COMMENTS ON MANY BURSTS

The significant synergisms described above are:

a. Effect of smog in increasing attachment rate for second burst, increasing electric field;

b. Left-over static electric field converted into high-frequency pulse by second burst;

c. Highly conducting fireball generates additional high-frequency fields from second burst, and increases late-time electric field between fireball and ground.

A careful study may lead to the conclusion that system EMP specifications would have to be increased on account of some of these effects.

It is the author's expectation that these synergisms will be significant only for bursts within 3 or 4 km from each other; for larger distances, the EMP affects should be no worse than additive. If there are a large number of bursts in a region with dimensions of this size, that region should probably be given up anyway. Pending closer looks at the synergisms, this author expects that the synergisms of importance can be analyzed in terms of pairs of bursts.