The electro-magnetic pulse produced by a nuclear bomb explosion high above the atmosphere.

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Introduction.

This article discusses the electromagnetic pulse produced by a high, exoatmospheric nuclear explosion, commonly abbreviated HEMP. The gamma rays produced in the nuclear explosion above the atmosphere produce electrons in the atmosphere by Compton scattering. The electron current, is initially downward. This downward current does not produce a downward propagating electro-magnetic field, but its deflection in the earth magnetic field produces a transverse component of the current, which does result in an electromagnetic wave propagating downward. This was realized in the early 60's, in connection with nuclear bomb tests well above the atmosphere, in particular the "Starfish" explosion in 1962, 1.4 Megatons, 400 km above Johnston Island in the Pacific Ocean. The atmospheric test ban of 1963 has prevented further explosions of this sort. The U.S. Department of Defence, in unclassified reports[1)], notes that in connection with the Starfish test 30 street light circuits went out on the Hawaiian island Oahu, on which Honolulu is located, 1200 km from ground zero. The electric fields of the pulse is canonically stated[1)] to be ~50,000 volts/meter. It is often asserted[2)] that such an explosion, although it would not harm the population, would disable the electric power and communications networks of a whole continent, and so make appropriate military response impossible. Given the military and political implications of this pulse, as well as the fact that no nuclear weapons expertise is required to calculate it, I thought it worth while to try to check these assertions. In the following, cgs units are used.

HEMP produced by a high altitude nuclear explosion.

Field equations.

In adequate approximation, the problem of the electromagnetic wave produced below it by an explosion at several hundred km altitude, the surface of the earth can be taken as flat. The solution to this problem has been given by Karzan and Latter[3)] and by Longmire[4)]. Here we follow the same physics. The relevant Maxwell's equations are

$$1/c\partial B_y/\partial t = -\partial E_x/\partial z; \qquad 1/c\partial B_x/\partial t = \partial E_y/\partial z.;$$

$$1/c\partial E_x/\partial t + \frac{4\pi\sigma}{c}E_x + \frac{4\pi}{c}j_x = -\partial B_y/\partial z\ , \quad 1/c\partial E_y/\partial t + \frac{4\pi\sigma}{c}E_y + \frac{4\pi}{c}j_y = +\partial B_x/\partial z\ ,$$ units are cgs.

t and z are time and distance from the explosion. σ is the conductivity due to the ionization produced by the Compton electrons.

It is useful to introduce the retarded time [3,4)] τ , $\tau = t - z/c$. $\frac{\partial}{\partial t} \to \frac{\partial}{\partial \tau}, \quad \frac{\partial}{\partial z} \to \frac{\partial}{\partial z} - \frac{\partial}{c\partial\tau}$;

The field equations become:

a} $\frac{\partial B_y}{c\partial\tau} = -\frac{\partial E_x}{\partial z} + \frac{\partial E_x}{c\partial\tau}$; b) $\frac{\partial E_x}{c\partial\tau} + \frac{4\pi}{c}(\sigma E_x + j_x) = -\frac{\partial B_y}{\partial z} + \frac{\partial B_y}{c\partial\tau}$, and

a') $\frac{\partial B_x}{c\partial\tau} = \frac{\partial E_y}{\partial z} - \frac{\partial E_y}{c\partial\tau}$; b') $\frac{\partial E_y}{c\partial\tau} + \frac{4\pi}{c}(\sigma E_y + j_y) = \frac{\partial B_x}{\partial z} - \frac{\partial B_x}{c\partial\tau}$;

Adding a) and b), and subtracting a') from b'), also noting that for the plane wave moving along z, $B_y = E_x$, and $B_x = -E_y$, there is finally the very simple result:

(1) $\partial E_i/\partial z + \frac{2\pi\sigma}{c}E_i + \frac{2\pi}{c}j_i = 0$; where i = x or y. The electric field E, the current j and the conductivity o are functions of z and the pulse time τ .

Gamma flux.

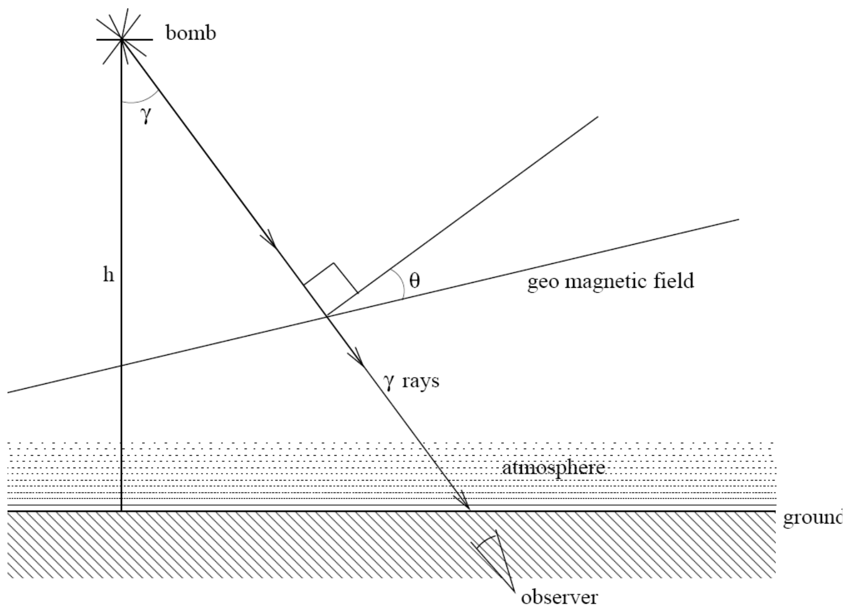

Fig. 1. Geometry

The assumed geometry is shown in Fig. 1. The earth surface is taken as a plane, the curvature is ignored. The angle of observation with respect to the vertical is γ The coordinate system is taken with the z direction from the ground to the burst, along the direction defined by the angle γ, and the x direction in the plane defined by z and the magnetic field. The angle of the magnetic field with respect to x is θ. The height of the explosion is h. In the following, for numerical examples, h is taken to be 500 km and θ to be 45^0.

The average gamma energy is ~ 1.5 MeV. The number of prompt gamma rays produced by a nuclear explosion is between .3% and 1% of the energy released in the explosion [4),5)]. Here the upper value is taken, which corresponds to 1×10^{26} gamma rays per Mton yield, with average gamma ray energy 1.5 MeV, and with burst duration about 20 nano-seconds. The gamma rays Compton scatter in the atmosphere, transferring their energy to electrons, with a cross-section[6)], $\sigma_\gamma = 0.17\times10^{-24} cm$. The gamma flux as function of altitude, $f_\gamma(z)$, is:

$$f_\gamma(z) = f_{\gamma,0}\exp-\int_z^{h/\cos\gamma}\rho(z)\sigma_\gamma\frac{A}{2}dz\,,$$

where z is taken from the ground towards the explosion, $f_{\gamma,0}$ is the incident gamma flux, which, for a 1Mton explosion is then:

$$f_{\gamma,0} = \frac{10^{26}}{4\pi h^2}\cos\gamma^2 = 3.2\times10^9\cos\gamma^2\,,\ \text{for h = 500 km,}$$

$\rho(z)$ is the atmospheric density, $\rho(z) = .0013e^{-z\cos\gamma/6.8km}g/cm^3$, and A is the Avogadro number. The gamma flux as function of atmospheric height is then:

$$f_\gamma(z) = 8\times10^{24}/h^2\times\cos^2\gamma\exp(-45/\cos\gamma\times\exp-z\cos\gamma/6.8km)\,.$$

In the following, for convenience, $z\cos\gamma/6.8km$ will be replaced by the dimensionless z. Then, for h = 500km,

(2) $$f_\gamma = 3.2\times10^9\cos^2\gamma\exp(-45/\cos\gamma\times\exp-z)$$

<u>Transverse Compton electron current</u>.

As already noted, the down moving Compton current does not produce a down moving electro-magnetic wave. However, the current spirals around the earth magnetic field, thus producing transverse components. For a typical magnetic field of the order of .5 gauss, at 45^o to the horizontal plane, and an average electron momentum of 1.1 MeV/c, the Larmor radius is 5000 cm. At the relevant atmospheric density of ~ $2\times10^{-5} g/cm^3$, typical electron range is of the order of 20,000 cm, ~ 4 times the Larmor radius. The component of the current along the field is undeflected, the component perpendicular to the field spirals with the Larmor radius. In the following the Compton electron total energy (including rest energy) spectrum is approximated by a uniform (top hat) distribution from .5 MeV to 2 MeV, with amplitude so that the electron kinetic energy flux equals the gamma energy flux. The consequent transverse currents are:

(3)
$$j_x(\tau) = ecf_\gamma(z)/\lambda * \cos\xi \sin\theta \cos\theta * \frac{2}{1.5} * \int_{E_{\min}}^{2MeV} dE\beta \frac{(1-\cos\omega t)}{d\tau/dt}$$
$$j_y(\tau\} = ecf_\gamma(z)/\lambda * \cos\xi \cos\theta * \frac{2}{1.5} * \int_{E_{\min}}^{2MeV} dE\beta \frac{\sin\omega t}{d\tau/dt}$$

τ is the retarded time. $\tau(t) = (1-\beta(\sin^2\theta + \cos^2\theta(\sin\varpi t)/\varpi t))t$.

t is the time after the scattering of the gamma ray on the electron.

λ is the mean free path of the gamma rays,

(4) $$\lambda = \frac{1}{\sigma_\gamma \frac{A}{2}\rho(z)},$$

β is the electron velocity divided by the light velocity c,

ξ is the average production angle of the Compton electrons, $\xi \cong 30^0$,

ω is the Larmour frequency, $\varpi = \frac{\beta c B(gauss)}{10^4/3* pc(MeV)}$,

E_{min} is the minimum energy for which the Compton electron is still in motion at pulse (retarded) time τ. The lifetime, Δt, of the electron is

$$\Delta t = \frac{electronrange}{\beta c} = \frac{(E-.5MeV)*.5gcm^{-2}MeV^{-1}}{\beta c\rho(z)},$$

E is the total energy of the electron, including its rest energy, and consequently,

$E_{\min} = (7.2*10^7 t(\tau)(\sec)*e^{-z} + .5)$ MeV

<u>Conductivity.</u>

The conductivity is due to the ionization electrons produced by the Compton electrons, ~ 30,000 ionization electrons per MeV Compton energy, with average kinetic energy of the ionization electrons $E_{ion,0} = 15eV$. The consequent conductivity is

$\sigma = \frac{n_e e\Delta v_{x,y}}{E_x}$, where n_e is the density of ionization electrons and $\Delta v_{x,y}$ is their average velocity in the x,y direction, produced by the Field $E_{x,y}$, between collisions.

$$n_e(z) = \frac{f_\gamma(z)}{\lambda} * 1.5MeV * 30{,}000 ionizationelectrons/MeV = 45{,}000\frac{f_\gamma(z)}{\lambda};$$

$$\Delta v_{x,y} = \frac{1}{2}*\frac{e}{m}E_{x,y}*\Delta t_{coll.} \;;\quad \Delta t_{coll.} = \frac{1}{v_{ion.}*\sigma_{coll.}*A/15*\rho(z)} \;;$$

the factor ½ accounts for averaging over the time between collisions,

$v_{ion.} =$ velocity of the ionization electrons; initially this is: $v_{ion,0} = \sqrt{\frac{2*15eV}{mc^2}}*c = .0077c$,

and $\sigma_{coll.} = 6*10^{-16} cm^2$ is the cross-section for the scattering of 15 eV electrons on nitrogen or oxygen atoms[7)]. The conductivity is then:

(5) $\sigma = f_\gamma(z)/\lambda * 45{,}000 * \frac{e^2}{2m} * \Delta t_{coll}$; with Δt_{coll} the time between collisions.

The conductivity is inversely proportional to the electron velocity $v_{ion.}$. This decreases with time, since in the collisions with the gas molecules, the electron looses, per collision, on the average, a fraction of its energy equal to the electron mass divided by the molecule mass, approximately 1.8*10^{-5}. This is a non-negligible effect.

$$\frac{1}{E_{ion.}}\frac{dE_{ion.}}{dt} = -1.8*10^{-5} * v_{ion.}\sigma_{coll.} * \frac{A}{15} * \rho(z),$$

$$\frac{\sqrt{E_{ion.,0}}}{E_{ion.}^{3/2}}\frac{dE_{ion.}}{dt} = -1.3*10^{8}\sec^{-1} e^{-z} \equiv 1/\Delta$$

where $E_{ion.} and\ E_{ion.,0}$ are the energy of the ionization electron as function of time, and its initial energy, that is 15 eV.

Solution: $E_{ion.} = E_{ion.,0}/(1+t/\Delta)^2$, where $\Delta = 1.5*10^{-8}\sec * e^{z}$,

$$v_{ion.} = v_{ion,0}\sqrt{\frac{E_{ion.}}{E_{ion.,0}}} = \frac{v_{ion,0}}{1+t/\Delta};$$

The average velocity is then: $< v_{ion.} >= \frac{1}{\Delta t}\int_0^{\Delta t} dt v_{ion} dt$, where

$\Delta t \cong \frac{.75 MeV * .5 g * cm^{-2} MeV^{-1}}{.92 * c * .0013 g * cm^{-3} e^{-z}} = 1.05*10^{-8} e^{z}$ is the average time of contribution of electrons to the current. The near equality of Δ and Δt seems an accident of nature. Then $v_{ion} \cong .76 v_{ion,0}$

A correction of the opposite sign is due to the electric field, which, between collisions, increases the average energy of the ionization electrons during the pulse. The average energy gain, per collision, is $\Delta E_{ion} = \frac{(\Delta p_x)^2}{2} = (eE_x \Delta t_{coll})^2/2m$, and $dE_{ion}/dt = \Delta E_{ion}/\Delta t_{coll}$,

$$\Delta t_{coll} = \frac{1.8*10^{-16} gcm^{-3}\sec^{-1}}{\rho(z)};$$

$$v_{ion}(t) = v_{ion.0}\sqrt{1+t/t_0}\ ,\quad \frac{1}{\Delta t} \equiv \frac{e^2 E_x{}^2 \Delta t_{coll}}{m^2 v_{ion,0}}$$

$$< v_{ion} >= v_{ion,0}\frac{2/3\langle(1+\Delta t/t_0)^{3/2} - 1\rangle}{\Delta t/t_0} \cong v_{ion,0}(1+1/4*\Delta t/t_0).$$

Depending on the angle γ of the propagation being considered, as well as on the direction of the magnetic field, this correction increases the velocity of the ionization electrons by from 2% to as much as 20%. In the following, an average increase of $< v_{ion} >$ of 10%, from .0077*.76 *c=.0058*c to .0064*c has been used.

Finally, the conductivity used in these calculations is:

(6) $$\sigma = \frac{f_\gamma(z)}{\lambda} * \frac{e^2}{2m} * \frac{45{,}000}{.0064 * c * \sigma_{coll} * A/15 * \rho(z)}$$

<u>Back reaction of the electric field on the current which produces it</u>.

The transverse momenta of the compton electrons constituting the transverse current are reduced by the electric and magnetic fields which they produce. $\frac{dp_{x,y}}{dt} = eE_{x,y}(1 - \frac{v_z}{c})$. Using the rough approximation for the electron velocity, $\Delta v_{x,y} = -c\frac{\Delta p_{x,y}}{\sqrt{p_e{}^2 + (mc)^2}} * (1 - v_z / c)$, where $c\sqrt{p_e{}^2 + (mc)^2}$ is the average total energy of the Compton electrons composing the current, ~ 1.2 MeV. The average reduction in the x,y component of the electron velocity is: $\frac{< \Delta v_{x,y} >}{c} = -\frac{c}{2} * \frac{eE_{x,y}(1 - v_z / c)\Delta' t}{1.2MeV}$. where $\Delta' t = \frac{E_\gamma (MeV) * .5gcm^{-2}MeV^{-1}}{\beta c \rho(z)}$ = $\frac{.41g / cm^2}{c\rho(z)}$, and $v_z / c = \cos\xi * \beta(\cos^2\theta\cos\varpi t + \sin^2\theta)$.

The effective current is: $j_{x,y,eff} = j_{x,y} + j_{x,y,backreaction}$; with

(7) $$j_{x,y,backreaction} = -f_\gamma(z)/\lambda * \frac{e^2}{2} * \frac{E_{x,y}c^2\Delta' t}{1.2MeV} * \frac{2}{1.5}\int_{E_{\min}}^{2} dE(1 - \beta\cos\xi(\cos^2\theta\cos\varpi t + \sin^2\theta)) / \frac{d\tau}{dt}.$$

<u>EMP field strength and pulse duration</u>.

The field equations become:

$$\frac{dE_{x,y}}{dz} = (\frac{6.8km}{\cos\gamma} * \frac{2\pi\sigma}{c}) * (-E_{x,y} + \frac{2\pi}{c}(j_{x,y} + j_{x,y,backreaction})).$$

With the above expressions, (6) for σ, for $j_{x,y}$, (7) for $j_{x,y,backreaction}$, (2) for $f_\gamma(z)$, (4) for λ, the field equations become:

$$\frac{dE_x}{dz} = \cos\gamma\begin{pmatrix} -E_x(a + b * \frac{2}{1.5} * \int_{E_{\min}}^{2MeV} dE(1 - \beta\cos\xi(\cos^2\theta\cos\varpi t + \sin^2\theta)) / \frac{d\tau}{dt}) + \\ c * \cos\xi\sin\theta\cos\theta * e^z * 2/1.5\int_{E_{\min}}^{2MeV} dE\beta\frac{(1 - \cos(\omega t))}{d\tau / dt} \end{pmatrix} * \exp((-45/\cos\gamma)\exp(-z))$$ and

$$\frac{dE_y}{dz} = \cos\gamma\begin{pmatrix} -E_y(a + b * \frac{2}{1.5}\int_{E_{\min}}^{2MeV} dE(1 - \beta\cos\xi(\cos^2\theta\cos\varpi t + \sin^2\theta)) / \frac{d\tau}{dt} + \\ c * \cos\xi\cos\theta * e^z * 2/15\int_{E_{\min}}^{2MeV} dE\beta\frac{\sin(\omega t)}{d\tau / dt} \end{pmatrix} * \exp((-45/\cos\gamma)\exp(-z)).$$

with a=29.4 per unit z, b=16.4 per unit z and c=435 $\sqrt{ergcm}$ /cm^2 per unit z, assuming a magnetic field strength of .5 gauss, a height of 500 km, and a bomb strength of 1 Megaton

Figure 2 shows the pulse shapes for E_y and B_x and figure 3 those for E_x and B_y, for different angles with respect to the vertical and consequent differences in distance from ground zero, taking the magnetic field angle θ as 45^0 and the gamma ray pulse duration to be 20 nanoseconds. For a pulse duration of 10 nsec the pulse heights are larger by 10% and the pulse length shorter by 20%, leaving the energy flux unchanged.

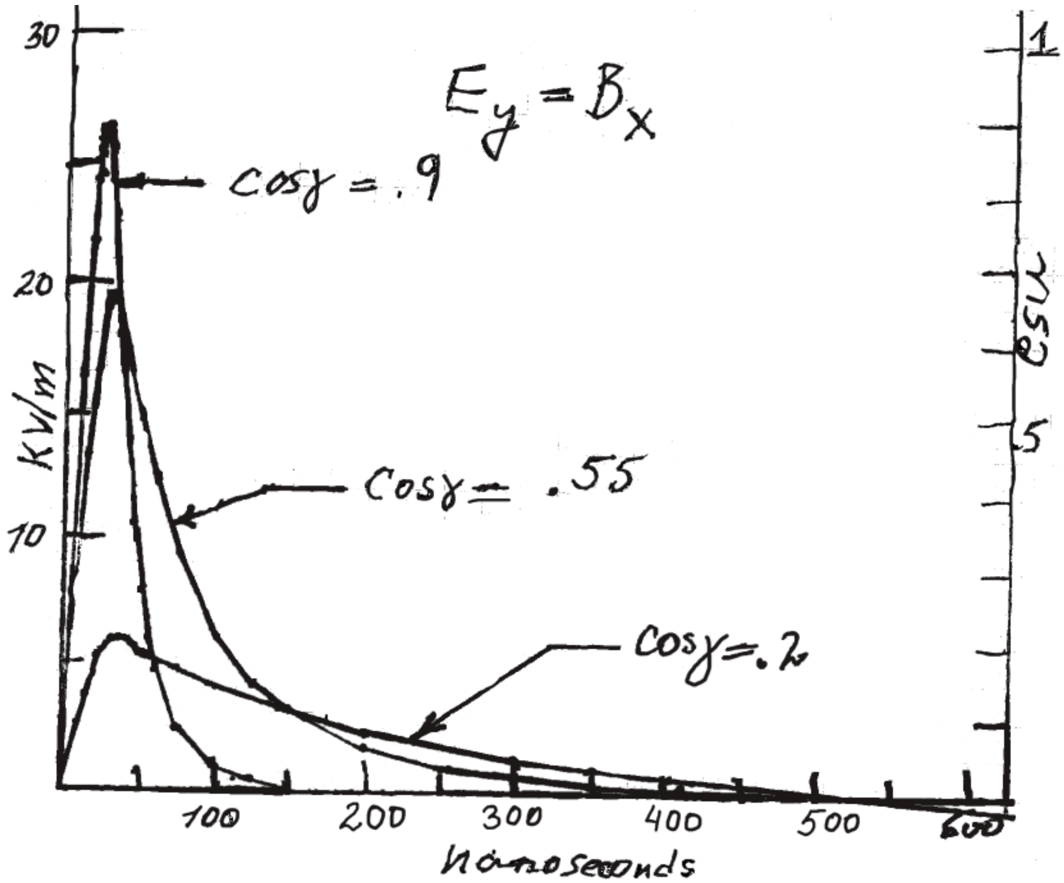

Figure 2. E_y and B_x as function of time for several observer directions γ, for a 1Mton bomb at 500 km height and a magnetic field of .5 gauss at 45^0 to direction of propagation.

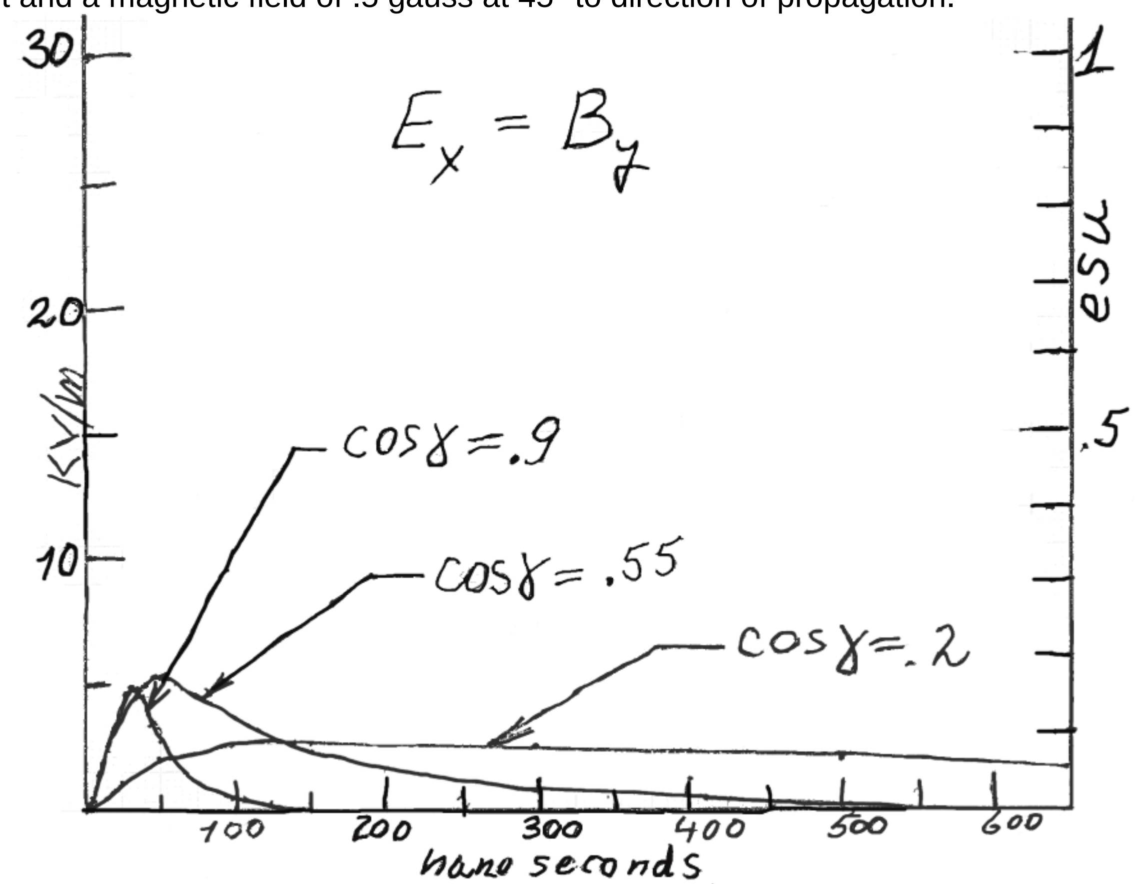

Figure 3. E_x and B_y as function of time for various observer directions γ, for a 1Mton bomb at 500 km height and a magnetic field of .5 gauss at 45^0 to direction of propagation.

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Figure 4 shows the variation of pulse heights and pulse width for directly overhead explosions (cos γ =1) at 500 km altitude, as function of the bomb strength, over a range of two orders of magnitude, .1Mton to 10 Mton. It illustrates the saturation effect: for explosions above a certain strength, the pulse heights vary by less than a factor of two. The Pulse height is limited by the reactive effect of the ionization produced by the current. This limits the HEMP pulse heights which can be achieved to those calculated here. In particular, specialized HEMP weapons of substantially higher HEMP yields, as are sometimes imagined, are not possible.

The summary table below gives the total energy flux, the pulse heights and the pulse width in the EMP produced by a 1 Mton explosion at 500 km, as function of the observer angle. The magnetic field of .5 gauss is taken to be at 45^0 to the direction of propagation.

Summary Table

cosine of observer direction	.9	.55	.2
energy flux, ergs/cm^2	47	53	20
pulse height, Kvolts/m	27	20	6.2
pulse halfwidth, μsec,	.032	.065	.260

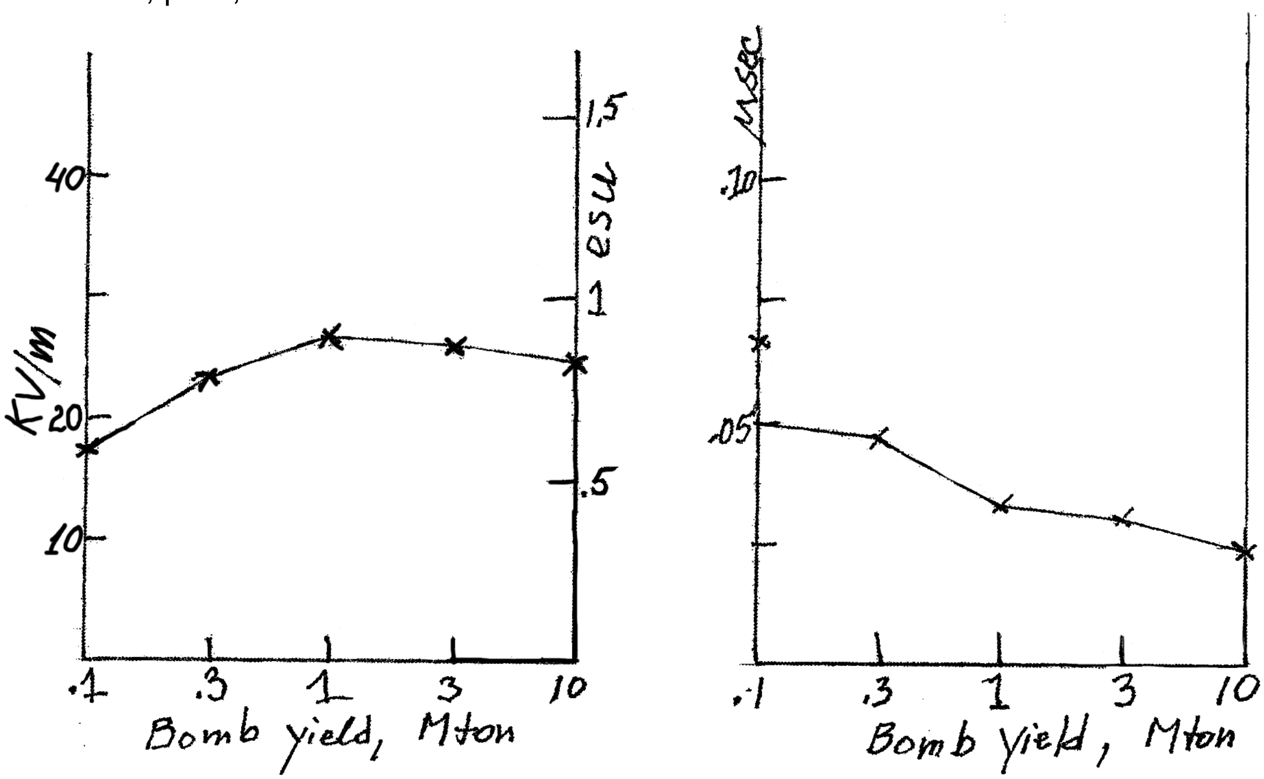

Figure 4. The variation of pulse heights (left) and pulse width (right) with bomb strength (above ground zero, height 500 km, theta =450, geomagnetic field .5 gauss).

Damaging effects of HEMP on electronic instruments, telecommunication and electric power networks

<u>Observation of the Starfish test on Hawaii.</u>

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Although such a high altitude nuclear explosion would not directly endanger human life, it is common, in military and governmental circles to credit the HEMP with devastating effects on the communications and electric power networks of a whole continent, which could disable the society and the ability to respond to such an attack, unless these devices are especially shielded or protected. The effects to be expected from such electromagnetic pulses are however far from obvious, and difficult to calculate or to evaluate experimentally.

July 8 1962, 11 PM the “Starfish” test, a 1.4 Megaton nuclear explosion at an altitude 400 km above Johnston island, could be “observed” from the Hawaiian islands, 1200 km to the west. This event had been announced previously and according to the newspapers, the population joyfully anticipated it. According to the Honolulu Star-Bulletin of the next two days [8)], the sky lit up bright blue, as in daylight, for some seconds, streetlights on Ferdinand St. In Manoa and Kawainui St. In Kailua went out the instant the bomb went off, and “police were sent off to a South St. warehouse, when a burglar alarm started ringing at the time of the blast”.. Fuses blew out in Kasmuki, Kahala, Kaluji, Maili, Wajanae, Makaha, Wahsaura, Kailua and Sandy Beach, and the Federal Aviation Agency reported occasional radio communication blackouts over a period of two hours.

These reports, of Honolulu street lights going out, burglar alarms sounding, and circuit breakers popping are frequently cited as evidence for the danger posed by the HEMP, but such things happen also without nuclear bomb explosions, and the connection cited with the nuclear explosion of these incidences are far from clear. The outstanding fact seems to be that life went on normally in Hawaii, during and after the Starfish test, the Honolulu Star-Bulletin appeared normally the next day. In response to such an article citing these alleged Starfish effects [9)], there are answers by Alan S. Lloyd, Manager, Consumer Services, Hawaiian Electric Company [10)] stating categorically that ”there was absolutely no adverse effect on our utility power and communications system on the island of Oahu where the city of Honolulu is located”, and by E.C. Schoen, Chief Engineer, Hawaiian Telephone Company, that, in connection with these nuclear bomb tests “No one, that I have talked to, can recall any increase in troubles associated with telephone sets or any other type of difficulty”

Damage to microelectronics.

One of the often cited dangers of electro-magnetic pulses is damage to microelectronics, a very important element of our modern society. Given the modest sizes of electronic instruments, such as computers radios, telephones, the effects of pulses such as those calculated above are relatively easy to test in the laboratory, and some colleagues here at CERN, the European centre for particle physics, in their spare time, are trying to study the effects of electric and magnetic pulses with waveforms as expected in the HEMP, on several highly sophisticated microelectronic circuits as well as some cell phones. Until now they have not succeeded in damaging a circuit, with voltages up to 130 kV/m, although at the higher voltages the processes in progress could be disturbed [12)]. This work is continuing.

Damage to telecommunication and electric power networks.

As noted above, the Hawaiian systems were not disrupted by the Starfish (or other) high altitude nuclear test. I am not capable to estimate the damaging effects to be expected. It should be noted that although it is sometimes asserted that the voltages could propagate and build up on the network lines for hundreds of kilometres, and therefore become extremely large, it is my understanding that this is false, that the electric field cannot build up over greater distances than the order of the coherence length, that is, the pulse length, 50 nanosec*c = 15m.

Strong electromagnetic pulses are produced by lightning currents. The voltages are typically greater than the EMP voltages calculated above, for distances within a few hundred meters of the current, and since they are ~ 100 microseconds long, compared to the 50 nanoseconds of the HEMP, their energy flux is correspondingly greater. Lightning strokes within several hundred meter distances occur typically once per several years, yet I have not succeeded in finding clear evidence of damage caused by lightning electromagnetic fields, as distinguished from the effects produced by the lightning currents, to telecommunication networks, power distribution networks, or microelectronics,

Conclusion on damages.

It is not clear that spending billions, as some propose[13)] to congress, on hardening of telecommunication, electric power networks, and public microelectronics to “protect” against a possible HEMP, is in the public interest

Acknowledgements.

These meandering s of an old man were motivated by an article3 in the Bulletin of the Atomic Scientists by a young man named Nick Schwellenbach [13)]. It is a pleasure to acknowledge the help of friends and colleagues, Freeman Dyson, Dave Jackson, R.L. Garwin, Guido Altarelli, Michael Jones, Don Cundy, C.L. Longmire, Carl Baum and others, without which this work would not have been completed.

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