Hypothetical electromagnetic bomb

Abstract

Directed energy is not a science fiction. These are real weapons being tested in real scenarios… And those nations that are not prepared to exploit directed energy will stagnate or even worse, lose, by clinging to outmoded traditional forms of warfare. They will fall behind, just as civilizations that clung to the bow and arrow lost to the rifle and just as bullets and bombs will fall to DEW…(Beason, 2005)

In this study, HPM theory and the general design principles introduced in the previous chapter are to define a notional e-bomb. Our e-bomb includes an HPM power source, appropriate waveguide, and an antenna/reflector. The pulse generated by the HPM source follows a rectangular wave shape.

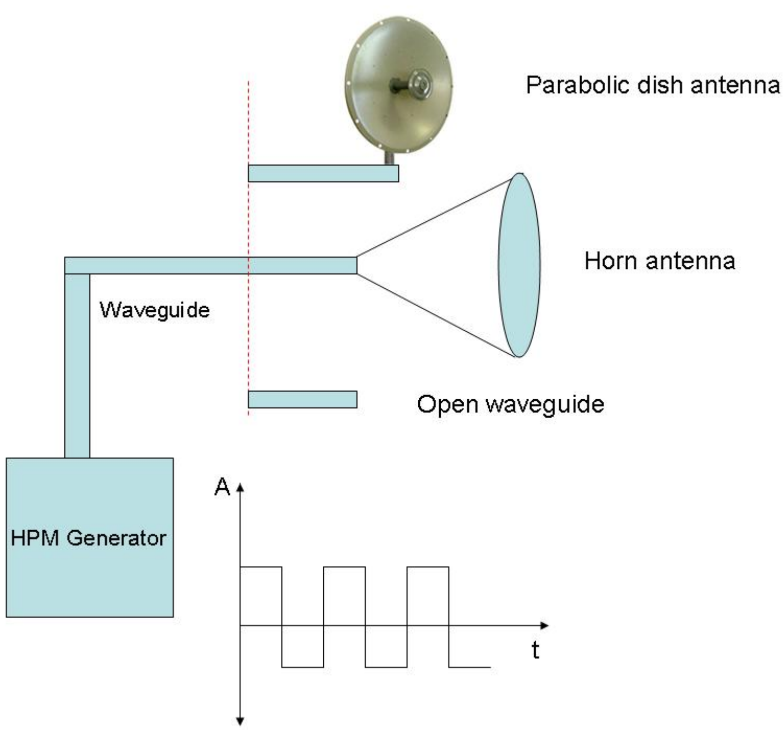

Figure 14. E-Bomb major elements

First, the theory behind HPM technology is defined. Next, the device radiated output is described and used to define the propagation pattern of generated electromagnetic field to ill be estimated as a function of range. Then, the coupling mechanisms between the HPM device output and the target system are defined. After defining the yield for the conception e-bomb from an HPM source, the impact on electronic systems is considered. The basis for consideration is according to the known, published threshold values of electronic systems. The possible effects are analyzed and the potential lethality range for different targets is estimated. A flow diagram of the described process is shown in Figure 15.

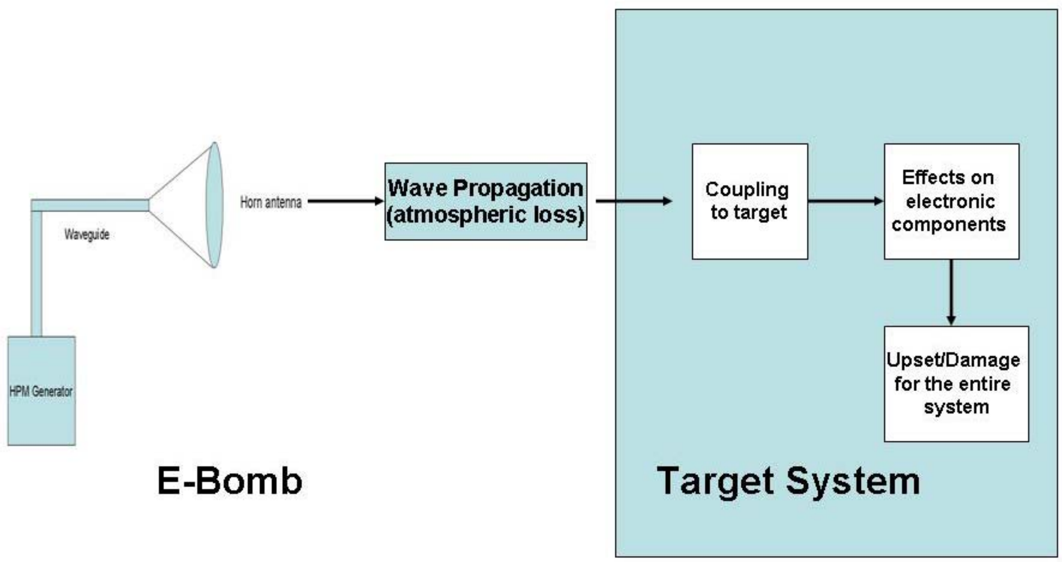

Figure 15. The e-bomb microwave flow from the power source to the damage/upset of target system.

To support the interaction assessment, a MATLAB model is used to simulate e-bomb effects using HPM theory. Published data for relevant systems is then used to validate the model.

Finally, defense against e-bomb are considered, and the advantages/disadvantages of different types of e-bomb design features are evaluated in terms of the military utility.

A. NOTIONAL PHYSICAL PRINCIPLES

1. Specifications

For our model, a frequency range between 0.5 GHz and 3 GHz is used. The reason to choose this range is that the ultrahigh frequency (UHF) region from 300 MHz to 3 GHz is extensively populated with radars, television broadcasting and mobile communications involving aircraft and surface vehicles. For most military operations environments, collateral effects on important use civilian systems is unacceptable, and should be avoided.

According to the described frequency range, an appropriate rectangular waveguide is chosen from Table 1. If there is more than one appropriate waveguide for the specified frequency range, the one with greater dimensions in size is used, since it provides a better field strength in far field. It also provides relatively lower field strength in the waveguide, which avoids the field strength exceeding the atmospheric breakdown limit (leading to ionization instead of propagation).

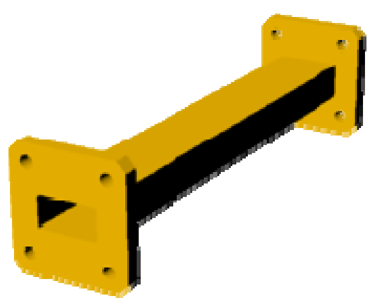

Figure 16. Rectangular waveguide

For the simulation model, the frequency (f) and the duration of the microwave pulse/pulsewidth (τ) will be decided by the user. For the purpose of this study, 100 nanoseconds (ns) is chosen as the default pulsewidth to make relevant but meaningful comparison between the different classes of e-bomb. For frequencies at or above 1 GHz frequency, 100 ns pulsewidth will contain 100 cycles and from an interaction viewpoint, 100 cycles should be adequate to ring up most system resonances, resulting in a steady-state maximum signal (voltage or current) at the failure port (Taylor and Giri, 1994).

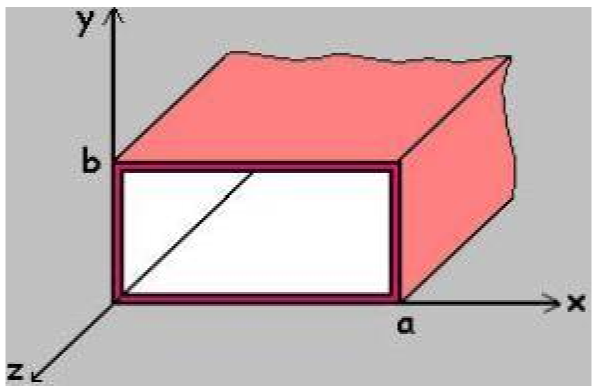

Figure 17. Waveguide dimensions

As seen on Figure 17, let the inner dimensions of the waveguide be :

a: larger dimension of the waveguide

b: smaller dimension of the waveguide.

Since a>b, the TE_{10} mode has the lowest cutoff frequency, it is generally desirable to have only one propagating mode in the waveguide. This minimizes dispersion and allows more efficient operation of the waveguide (Taylor and Giri, 1994).

The model impedance for the rectangular waveguide that operates in TE_{10} mode is

$$Z_{1,0} = Z_0\left[1-\left(\frac{\lambda}{2a}\right)^2\right]^{-1/2} \tag{1}$$

where

Z_0 : wave impedance of free space ($\mu / \varepsilon = 120\pi$)

λ : operating wavelength ($\lambda = \frac{c}{f}$, where the c is the speed of light in free space, 3x10^8 m/s)

a : larger dimension of the waveguide (Taylor and Giri, 1994).

For our e-bomb simulation, the dimensions of the waveguide are entered by the user. Free space wave impedance will be reference impedance in the simulation as shown in equation (1).

Once the model impedance is determined, the peak electric field (E-field) in the waveguide is given by:

$$E_{\max}(waveguide) = \sqrt{\frac{4}{ab} Z_{1,0} P_{avg}} \qquad (2)$$

where

$Z_{1,0}$: model impedance of waveguide

P_{avg} : average power of HPM source

a : larger dimension of the waveguide

b : smaller dimension of the waveguide (Taylor and Giri, 1994) (Giri and Tesche, 2003) (Giri, 2004).

For the simulation, the average power will be entered by the user in terms of the classifications of e-bomb, which will be defined later in this chapter.

Another issue for HPM propagation is the atmospheric breakdown limitations. The upper limit of microwave power that can be transmitted in a waveguide and in the air is determined by the dielectric strength of the medium in which the microwave pulse propagates. As a rule of thumb, 3 MV/m maximum field strength is assumed the maximum field strength that the atmosphere can propagate. The upper limit of the breakdown field strength depends on the pulsewidth. A simplified expression for the critical electric field strength, E_{bd} [V/m], for dielectric breakdown of a microwave pulse in air at atmospheric conditions is given by (Larsson, Johansson, and Nyholm, 2006)

$$E_{bd} = 22.5p\left[1+\frac{42\times10^{-3}}{p\tau}\right]^{3/16} \tag{3}$$

where

p : ambient pressure in pascals

τ : pulsewidth of microwave.

Obviously, if the pulsewidth is increased, the breakdown field strength will decrease. In the e-bomb simulation, 1013.25 hectopascal (hPa) will be used since it is the average atmospheric pressure at sea level on the earth (see Figure 18 which shows the breakdown field strength as a function of air pressure for different pulsewidths).

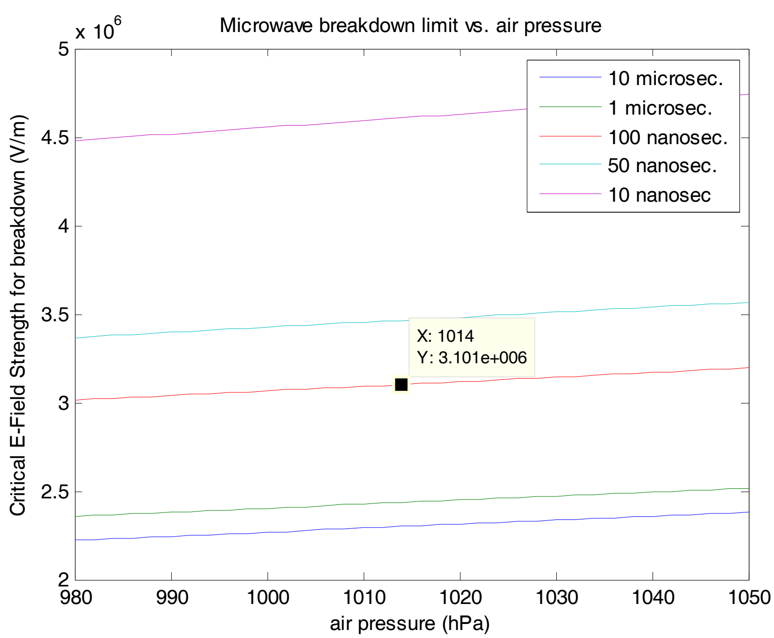

Figure 18. The critical electric field strength for different pulsewidths

For the standard atmospheric conditions (1013.25 hPa), the maximum field strength that can propagate in the atmosphere is around 3.10 MV/m for 100 ns. pulsewidth (the standard pulsewidth for the simulation).

The breakdown limitation formula shown in equation (3) is valid for air only. The waveguide may be filled with different inert gas, for example sulphur hexafluoride (SF_6), which has a critical field strength level of 3-4 times that of air at microwave frequencies (Larsson, Johansson, and Nyholm, 2006). Combinations of SF_6 and Nitrogen (N_2) have also proved valuable when working with pulse power technology at peak output.

If the waveguide is vacuumed and then filled with appropriate gas with a high dielectric strength, a field strength up to 74 MV/m can be sustained in the waveguide (Taylor and Giri, 1994).

As mentioned before, in HPM applications at GW power range, the waveguide and the horn are evacuated. But the dimensions of the horn aperture must have a minimum value at which the power density and the peak electric field at the aperture of the antenna enable the transition from the vacuum to 1 atm. SF_6 gas. This means that the peak electric field at the aperture of the antenna must also be below the breakdown electric field. For the simulation, this value is around 3.10 MV/m. As seen on Figure 19, if the aperture has dimensions a' (width of the aperture, larger dimension) and b' (height, smaller dimension), corresponding to the a and b of the waveguide, the peak electric field at the aperture is estimated by

$$E_{peak}\,(at\, the\, aperture) = E_{bd} = E_{\max}\,(waveguide) \times \sqrt{\frac{ab}{a'b'}} \qquad (4)$$

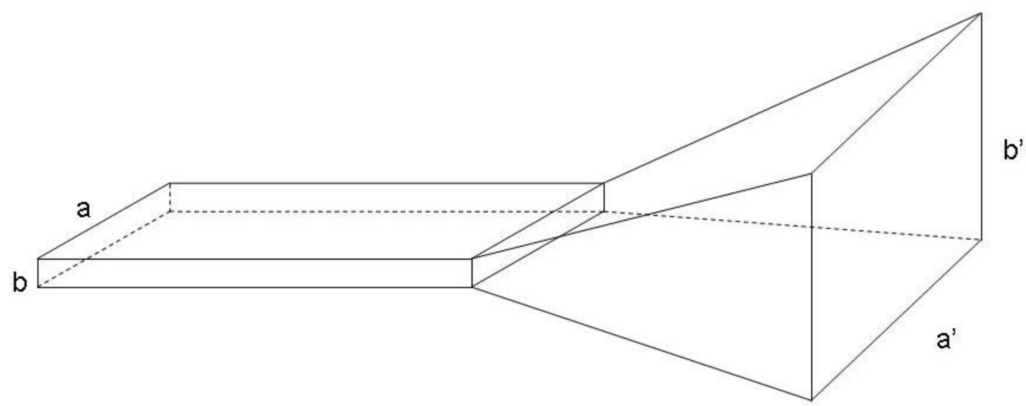

Figure 19. Aperture details of the proposed horn antenna

If it is assumed that $\frac{a}{a'} = \frac{b}{b'}$, the equation (4) becomes

$$E_{peak}\,(at\,the\,aperture) = E_{bd} = E_{\max}\,(waveguide) \times \left(\frac{b}{b'}\right) \qquad (5)$$

Once the minimum value for b' is calculated, other dimension of the horn, a', can be calculated as well (Taylor and Giri, 1994) (Giri, 2004).

For example, at f = 1.2 GHz and $\mathrm{P}_{\mathrm{avg}}$= 2GW, the peak electric field in the waveguide is found to be 14.3 MV/m, which means that $\frac{b}{b'}$ should be about 0.2165 in order to keep the electric field below 3.10 MV/m at the aperture of the horn antenna. As a result, the minimum dimension of b' is (97.79 mm/0.2165) = 45.17 cm. Using the same ratio for a', it is found to be that a' is (195.58 mm/0.22) = 90.33 cm.

The other option can be the use of parabolic dish (see Figure 20) instead of horn antenna. If the focal length of the parabolic dish (F) is known, the peak electric field at the aperture can be estimated without using the dimensions of the antenna by

$$E_{peak}\,(at\,the\,aperture) = E_{\max}\,(waveguide)\frac{a \times b}{F\lambda} \quad (6)$$

(Giri and Tesche, 2003)

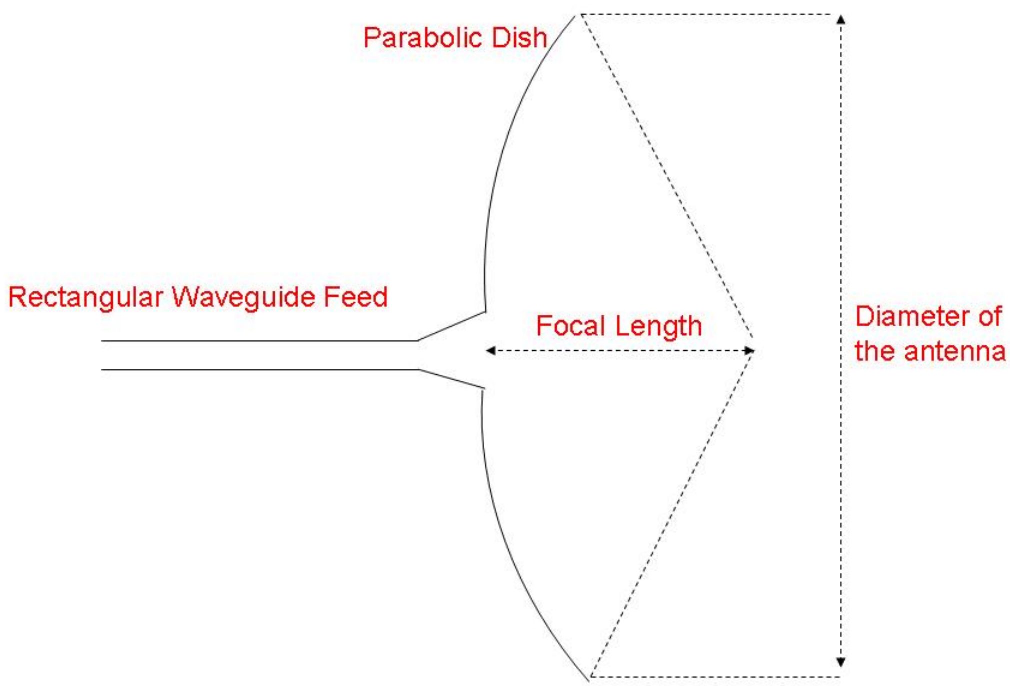

Figure 20. Aperture details of the proposed parabolic dish antenna

Once the electric field at the aperture of the antenna is found, the far field parameters may then be estimated by

$$E_{peak}\,(far\ field) = E_{peak}\,(at\,the\,aperture) \times \left(\frac{area\,of\ the\ reflector}{r\lambda}\right) V/m \quad (7)$$

$$p_{avg}\,(far\ field) = \left[\frac{E^2{}_{peak}\,(at\,the\,aperture)}{2Z_0}\right] Watts/m^2 \quad (8)$$

$$u = p_{avg} \times \tau \quad Joules/m^2 \quad (9)$$

where

r : target distance (in meter) from the e-bomb

$E_{peak}(far\ field)$: E-field strength from the e-bomb at the distance r

$area\ of\ the\ reflector$: $a' \times b'$ for the horn antenna

$\pi \frac{d^2}{4}$ for the parabolic antenna where d is the diameter of the parabolic dish

$p_{avg}(far\ field)$: average power density

u : energy density (Taylor and Giri, 1994) (Giri and Tesche, 2003) (Giri, 2004).

The field strength at one meter from the antenna is called the figure of merit (FOM). According to the far field parameters, the E-field and range product gives the FOM of the e-bomb. FOM provides a convenient comparative performance measure for HPM device outputs that is conveniently and easily scaled to the device peak field output at ranges beyond far-field.

As the microwave signal propagates through the troposphere, it is attenuated through energy absorption by atmospheric gases and by rain. Rain droplets also scatter as well as absorb microwave transmissions; however, the scattering of energy out of a beam is small when compared to the absorption loss.

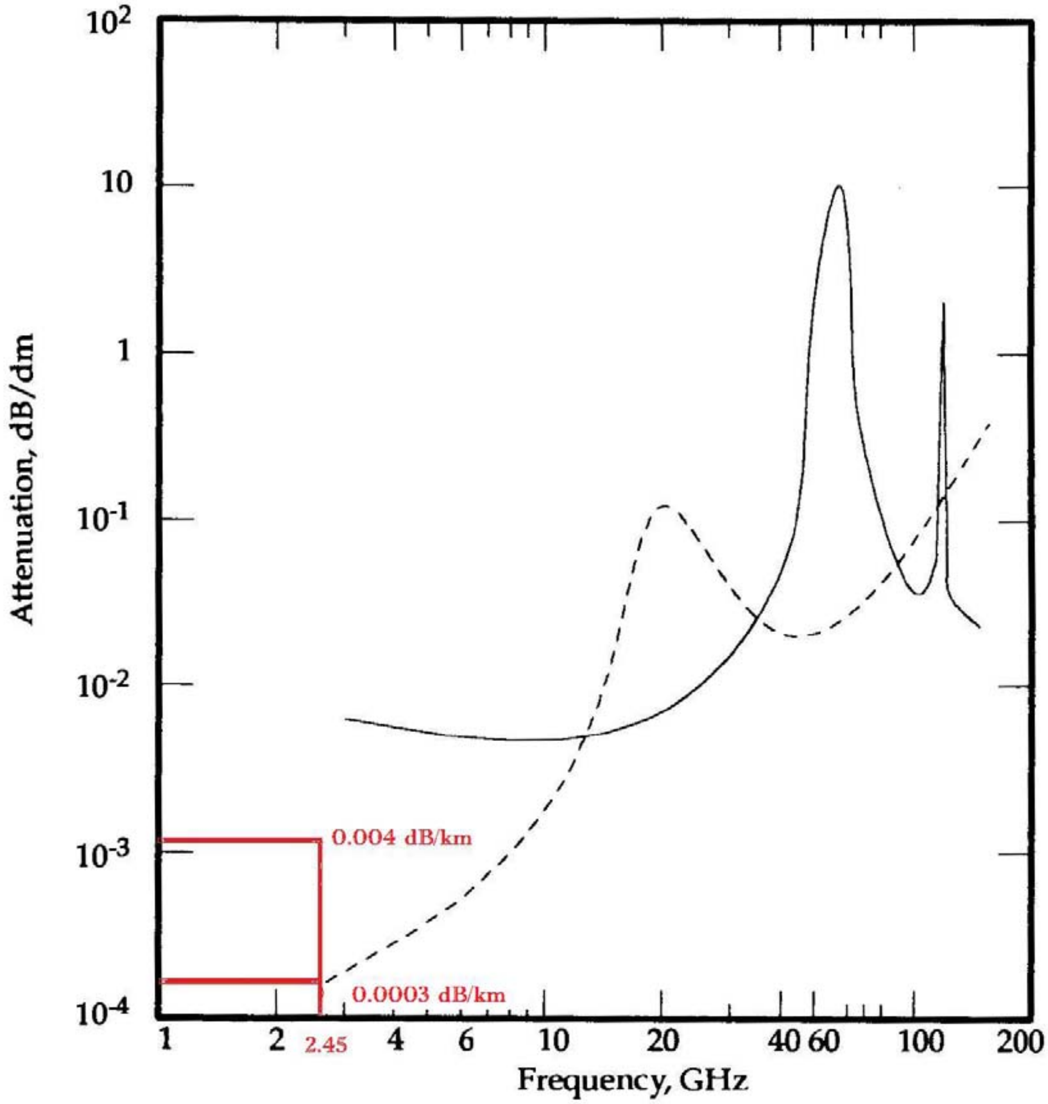

Figure 21. Atmospheric attenuation of microwave propagation at 0^o C and 1 atm due to oxygen and water absorption (Taylor and Giri, 1994).

According to Figure 21, the attenuation due to the atmosphere is not significant below 1GHz. Consider the commonly used frequency at 2.45 GHz, where commercially available devices such as microwave ovens, cell phones etc. are operated. Among these devices, a microwave oven source can be used as a general HPM generator for an e-bomb. Any later HPM sources that will be defined as the source of e-bombs in this study will not be operated more than 2.45 GHz. Since the atmospheric attenuation increases by the frequency, the maximum frequency in this study (2.45 GHz) will be used as the reference frequency for the upper limit of atmospheric attenuation. For the microwave oven operating frequency (2.45 GHz), the atmospheric attenuation is around 0.0003 dB/km. Since for the e-bomb simulation any loss in the HPM source, in the waveguide and at the reflector is neglected, 0.004 dB/km attenuation is chosen as the default atmospheric attenuation in order to fully compensate any ignored losses and provide a conservative output estimate.

Attenuation (loss) due to the rain is estimated by

$$L_R = xR^y \quad dB/km \tag{10}$$

where R is the rain rate in millimeters/hour. The constants x and y are dependent on operating frequency according to

$$x = x_1 f^{x_2} \qquad f \text{ in } GHz \tag{11}$$

where

$$x_1 = 6.39\times10^{-5} \qquad x_2 = 2.03 \qquad f < 2.9\,GHz \tag{12}$$

$$x_1 = 4.21\times10^{-5} \qquad x_2 = 2.42 \qquad 2.9\,GHz \le f \le 54\,GHz \tag{13}$$

and

$$y = y_1 f^{y_2} \qquad f \text{ in } GHz \tag{11}$$

where

$$y_1 = 0.851 \qquad y_2 = 0.158 \qquad f < 8.5\,GHz \tag{12}$$

$$y_1 = 1.41 \qquad y_2 = -0.0779 \qquad 8.5\,GHz \le f \le 25\,GHz \tag{13}$$

$$y_1 = 2.63 \qquad y_2 = -0.272 \qquad 25\,GHz \le f \le 180\,GHz \tag{14}$$

(Taylor and Giri, 1994)

Figure 22 shows the attenuation due to the rain for different rain rates at interested frequencies. The attenuation increases when the operating frequency increases. It also increases when the rain rate increases. For moderate rainfall, R = 5 mm/h, the corresponding path loss is 0.00038 dB/km at 1.2 GHz, 0.0008 dB/km at 1.7 GHz, 0.0012 at 2 GHz, and 0.002 dB/km at 2.45 GHz.

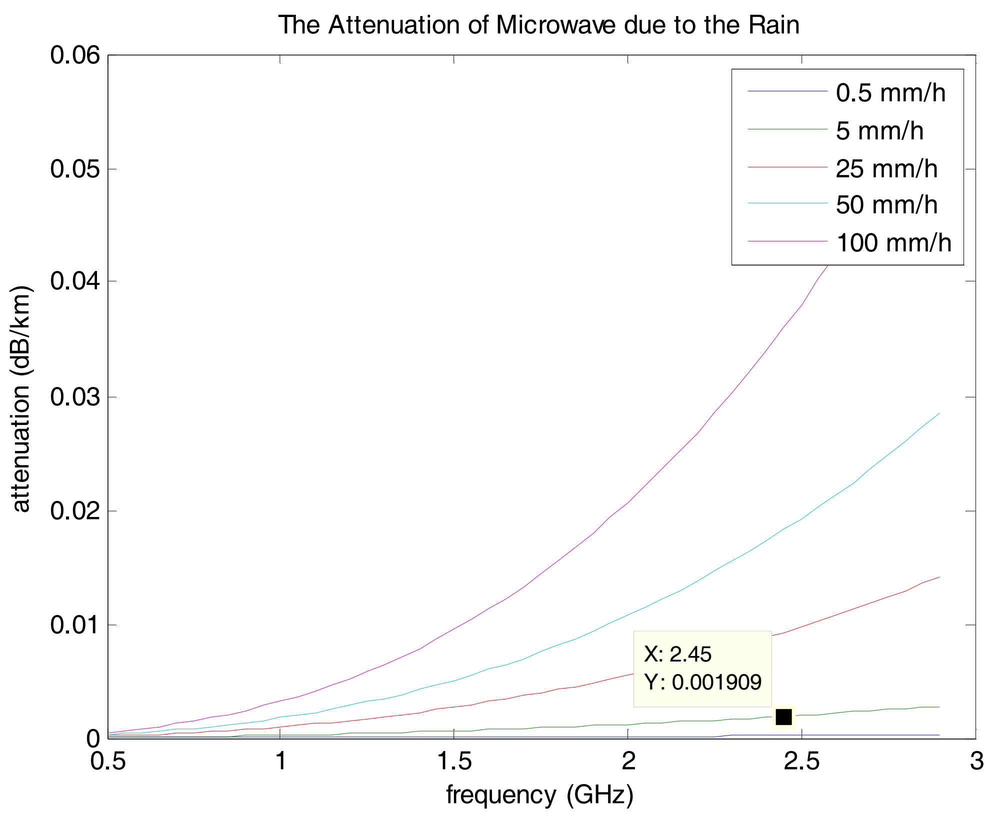

Figure 22. Attenuation of microwave due to the rain at different rain rates.

Up to this point, the basic theory for the hypothetical e-bomb is defined including the propagation features in the atmosphere. This theory as described will be used as the basis for MATLAB simulation calculation.

2. Classifications of the Source Elements

To show a wide range of different applications, source technologies and the range of effects on different targets, three types of e-bomb will be categorized an evaluated:

- Low-Tech (Small) E-Bomb
- Medium-Tech (Moderate) E-Bomb
- High-Tech (Powerful) E-Bomb

a. Low-Tech (Small) E-Bomb

A low-tech e-bomb is characterized by marginal performance, minimal technical capabilities, and is easily assembled and deployed (Giri and Tesche, 2003).

For this thesis, it will be assumed that low-tech (small) e-bombs will be used against relatively small and unshielded systems. Unshielded systems are considered to be fully exposed by e-bomb electromagnetic waves.

Low power levels are generally in the kW levels (Giri, 2004). For the simulation, a microwave oven specifications will be used to define the low-tech e-bomb. There are commercially available magnetron microwaves in the range of 800-2000 watts, which makes for an easily procured HPM generator.

Though militarily not applicable, the purpose of using a microwave oven source is to show that low-tech e-bomb designed from commercially available sources with average power level between 800-2000 watts are possible to produce field strength levels at about kV/m level at km distances with a reasonable antenna.

A commercially available continuous wave (CW) microwave oven has the operating frequency of 2.45 GHz. From Table.1, corresponding rectangular waveguide can be either WR340 or WR430. For this study, both waveguides will be used. According to the outputs of each e-bomb (WR340 and

WR430), the better output of the two will be chosen for the analysis of low-tech e-bomb. It will also set a rule to choose the appropriate waveguide in situations presenting more than one option.

For radiating the low-tech e-bomb output, a parabolic (dish) antenna with 1.54 m^2 aperture area (d=1.4m) with 0.371m focal length (F) will be used where d is the diameter of the dish antenna. Focal length and aperture area are chosen arbitrarily, but it is clear that such an antenna is available commercially. As mentioned before, the pulsewidth is chosen to be 100ns. Specifications for the "Low-Tech (Small) E-Bomb" are shown in Table. 2.

Operating frequency (f)	2.45 GHz
Average power (P_{avg})	800-2000 watts
WR340 waveguide dimensions ($a \times b$)	0.086x0.043 m
WR430 waveguide dimensions ($a \times b$)	0.10922x0.05461 m
Aperture area of the reflector (A)	1.54 m^2 (d=1.4 m)
Focal length of the reflector (F)	0.371 m
Pulsewidth (τ)	100 ns

Table 2. Specifications of Low-Tech (Small) E-Bomb

b. Medium-Tech (Moderate) E-Bomb

The medium-tech e-bomb, as defined in this thesis, requires the skills of a qualified electrical engineer and relatively more sophisticated components such as commercial radar systems that can be modified to become a weapon system like e-bomb (Giri and Tesche, 2003).

For the simulation, it will be assumed that medium-tech (moderate) e-bombs will be used against moderately shielded systems. A 30 dB shielding effectiveness is assumed for moderately shielded systems. Civil aviation aircraft provide a good example for moderately shielded systems that might have roughly 30 dB shielding.

It is known that sufficiently intense electromagnetic signals in the frequency range of 200 MHZ to 5 GHz can cause electronic damage in many systems. For the simulation of medium-tech e-bomb, 1.2 GHz and 1.7 GHz are chosen as the operating frequencies due to their common applicability to standard radar and communications technologies that are similar in form. Moderate power levels can be in the range of 1 to 20 MW (Giri, 2004). For the average power, a range between 1-20 MW will be analyzed to decide the most effective power source and operating frequency. There are also commercially available radar systems that operate around 1.2 GHZ and 1.7 GHz frequency level and radiate an average power up to 20 MW.

For the medium-tech e-bomb, corresponding rectangular waveguides are chosen to be WR770 for 1.2 GHz frequency and WR650 for 1.7 GHz frequency from Table.1. After comparing the outputs of each frequency option of the moderate e-bomb, a conservative estimate will be identified that covers the largest output from the two as the medium-tech (moderate) e-bomb for the analysis the potentially lethal effect on different systems.

Based on the initial work by Giri (Taylor and Giri, 1994), a parabolic (dish) antenna with 4.9 m^2 aperture area (d=2.5m) with 0.5m focal length (F) will be used for reflector of the medium-tech e-bomb. Focal length and aperture area are chosen arbitrarily. The pulsewidth is to be 100ns (as was done for low-tech e-bomb). Specifications for the “Medium-Tech (Moderate) E-Bomb” are shown in Table.3.

Operating frequency (f)	1.2 GHz and 1.7 GHz
Average power (P_{avg})	1-20 MW
WR650 waveguide dimensions ($a \times b$)	0.1651x0.08255 m
WR770 waveguide dimensions ($a \times b$)	0.19558x0.09779 m
Aperture area of the reflector (A)	4.9 m^2 (d=2.2 m)
Focal length of the reflector (F)	0.5 m
Pulsewidth (τ)	100 ns

Table 3. Specifications of Medium-Tech (Moderate) E-Bomb

c. High-Tech (Powerful) E-Bomb

More sophisticated high-tech and high-power electromagnetic systems would certainly require specialized and sophisticated technologies and perhaps even specifically tuned output to cause severe damage to a specific target (Giri, 2004).

For the e-bomb simulation, it will be assumed that high-tech (powerful) e-bombs will be used against fully shielded systems. A 40-50 dB shielding effectiveness is assumed for fully shielded systems. Military systems are a good example of fully shielded systems and are procured with shielding requirements in order to perform designed missions.

Following the initial work by Giri (Taylor and Giri, 1994), The operating frequency of high-tech (powerful) e-bomb is chosen to be 2 GHz. High power levels can be in the range of 100's of MW to GW's (Giri and Tesche, 2003). For the average power, a 20 GW source will be used to assess the effects of powerful e-bomb on target systems. A 20 GW vircator source has been reported by Benford in 1987 (Benford, 2004). Obviously, the technology has been improved for the past 20 years and more power is achievable with a reasonable, compact size. Once the lethality generated by a 20 GW source is assessed, one can easily think about the effects of possible lethality level generated by the current technology.

For the high-tech e-bomb, corresponding rectangular waveguide is chosen to be WR510 from Table.1.

A horn antenna with 12.5 m^2 aperture area (5x2.5m) will be used for the high-tech e-bomb. The horn dimensions are chosen arbitrarily. The pulsewidth is to be 100ns. Specifications for the "High-Tech (Powerful) E-Bomb" are shown in Table. 4.

Operating frequency (f)	2 GHz
Average power (P_{avg})	20 GW
WR510 waveguide dimensions ($a \times b$)	0.12954x0.06477 m
Aperture area of the horn (A)	12.5 m^2 (5x2.5 m)
Pulsewidth (τ)	100 ns

Table 4. Specifications of High-Tech (Powerful) E-Bomb

B. COUPLING ESTIMATES

All electronic equipment is susceptible to malfunctions and permanent damage under electromagnetic illumination of sufficient intensity. The intensity level for system vulnerability is dependent upon the coupling from the external fields to the electrical circuits and their corresponding sensitivity characteristics.

A temporary malfunction (or upset) can occur when an illuminating electromagnetic field induces current and voltages in the operating system electronic circuits at levels that are comparable to the normal operating signals. Permanent damage can occur when these induced stresses are at levels that produce joule heating to the extent that thermal damage occurs. (usually between 600 and 800 degrees Kelvin) (Benford, Swegle, and Schamiloglu, 2007).

No matter what kind of e-bomb is used or which power/frequency/mode is applied, two principal coupling modes are recognized in open literature in assessing how much power is coupled into target systems:

- Front Door Coupling
- Back Door Coupling

Both coupling mechanisms are explained here, although, only the back door coupling will be used in the simulation in order to assess the lethality of three classes of hypothetical e-bombs. Considering that front door coupling inherently has more energy delivered into target systems than the energy delivered through back door coupling, it can be assumed that, in reality, more susceptibility can be achieved than the susceptibility shown in this study.

All the coupling estimates will assume that the target system is in the main lobe of the e-bomb antenna. Clearly, if the target is in the sidelobes or at random angles, the coupling efficiency will decrease, and less power will be delivered to the target.

1. Front Door Coupling

Front Door Coupling is typically observed when the power radiated from the e-bomb is directly coupled into the electronic systems, which involves an antenna such as radars, EW or communications equipments. The antenna subsystem is designed to couple power in and out of the equipment, and thus provides an efficient path for the power flow from the electromagnetic weapon to enter the equipment and cause damage (Kopp, 1996).

For front door coupling to gain entry through an antenna, it can be appropriate to operate the e-bomb at the in-band frequency of target system if it is known (Benford, Swegle, and Schamiloglu, 2007). For this reason, most front door coupling is efficient for only a narrow band of frequency, and is inefficient outside the band.

2. Back Door Coupling

Back Door Coupling occurs when the electromagnetic field from the e-bomb produces large transient currents (termed spikes, when produced by a transient source) or electrical standing waves (when produced by a HPM weapon) thru cracks, small apertures and on fixed electrical wiring and cables interconnecting equipment, or providing connections to power mains or the telephone network. Equipment connected to exposed cables or wiring will experience either high voltage transient spikes or standing waves, which can damage power supplies and communications interfaces if not shielded or inherently robust. Moreover, should the transient penetrate into the equipment, other devices inside can be damaged through mutual coupling. Any cable can comprise multiple linear segments, which are typically at close to right angles; therefore, whatever the relative orientation of the e-bomb, one or more segments can provide very good coupling efficiency. Network cables use fast, low-loss dielectrics and are thus very efficient at propagating such transients with minimal loss (Kopp, 1996). Back door coupling can generally be described as wideband, but may have narrow-band characteristics because of resonance effects (coupling to cables for example).

Theory for the back door coupling is more complex than that for the front door coupling. Since the cross section of coupling is difficult to determine for the target system, the susceptibility results can be different from the expected (Benford, Swegle, and Schamiloglu, 2007).

For the validation of the hypothetical e-bomb model and the assessment of each e-bomb's lethality, a basic theory relating field strength to coupled current will be used in the simulation.

The point form of Ohm's Law indicates that the conduction current density generated on a wire or a coaxial cable depends on the conductivity of that material and the electric field strength that the wire/coaxial cable is subjected to. Current density in Ampere/square meter is given by

$$J = \sigma E \quad \text{A/m}^2 \tag{15}$$

where

σ	:	Conductivity of material (target system design)
E	:	E-field strength that the wire/coaxial cable is subjected to (Ulaby, 2006).

The conductivity of the materials used in the simulation is shown in Table.5.

Material	**Conductivity, σ Siemens/meter (S/m)**
Silver	6.2×10^7
Copper	5.8×10^7
Gold	4.1×10^7
Aluminum	3.5×10^7
Iron	10^7

Table 5. Conductivity of materials used in the simulation (Ulaby, 2006)

Once the current density is determined, for an arbitrary surface S, the total current flowing through that surface is given by

$$I = \int_S J.ds \qquad Ampere\ (A) \tag{16}$$

For circular wire, equation (16) becomes

$$I = J\left(\frac{\pi d_w^{\ 2}}{4}\right) \tag{17}$$

where

J	:	Current density
d_w	:	Diameter of the wire (Ulaby, 2006).

For coaxial cables, equation (16), the surface integration, becomes

$$I = J(2\pi r_c l) \tag{18}$$

where

J	:	Current density
r_c	:	Radial distance of coaxial cable from the axis of the center conductor
l	:	Length of coaxial cable (Ulaby, 2006).

Once the total current flowing through the wire/cable is determined, the coupled power can be expressed by

$$P_c = I^2 R_m \tag{19}$$

where

P_c	:	coupled power
R_m	:	matched load of the target system.

Using the field-current relationships, the coupled power into the target system is compared with known electromagnetic susceptibility limits of electronic circuits and components in order to determine the potential susceptibility of each e-bomb against different targets.

C. EFFECTS ON TARGETS

E-bomb interactions with system electronics can be categorized in four levels of destructive effect (upset, lock-up, latch-up, and burnout) and are dependent upon:

- Distance to the target
- Vulnerability of the target
- Operating frequency
- Coupled power level and power density on the target
- Bandwidth
- Burst rate and pulse duration
- Dwell time on the target
- Coupling mode or entry points

These four potential effects of e-bombs on targets can be categorized into a hierarchy of lethality (described in the following paragraphs), each of which require increasing microwave emission on the target.

1. Soft-Kill

A soft kill is produced when the effects of the weapon cause the operation of the target equipment or system to be temporarily disrupted. A good example is a computer system, which is caused to reset or transition into an unrecoverable or hung state. The result is a temporary loss of function, which can seriously compromise the operation of any system that is critically dependent upon the computer system in question (Kopp, 1996).

Soft kill can occur in two forms:

a. Upset

Upset is a temporary alteration of the electrical state of one or more nodes, in which the nodes no longer function normally. Upset means particular interaction as observed between a weapon and the operating state of the target system at the time, as the state changes, upsets could subside. Given operating state, the upset continues until the impressed radiation is terminated. Once the signal is removed, the affected system can be easily restored to its previous condition. Interference caused by jamming equipment or lightning are examples of this type of deny effect (Deveci, 2007).

b. Lock-up

Lock-up is similar to upset in that the electrical states of affected nodes are temporarily altered, but the functionality of these nodes remains altered after the radiation is removed. Lock-up produces a temporary alteration similar to upset, but electrical reset or shut off and restart is necessary to regain functionality after the radiation is removed. Degrading is an example that requires the intervention by an external operator or special safeguard procedures to reload the target system (Deveci, 2007).

2. Hard-Kill

A hard kill is produced when the effects of the weapon cause permanent electrical damage to the target equipment or system, necessitating either the repair or the replacement of the equipment or system in question. An example is a computer system that experiences damage to its power supply, peripheral interfaces and memory. The equipment may or may not be repairable, subject to the severity of the damage, and this can, in turn, render inoperable — for extended periods of time — any system that is critically dependent upon this computer system (Kopp, 1996).

Hard kill can be seen in two forms:

a. Latch-up

Latch-up is an extreme form of lockup in which parasitic elements are excited and conduct current in relatively large amounts until either the node is permanently self-destroyed or the electrical power is switched off to the node. This effect can run down batteries supplying power to the affected nodes or can pull down power supply voltages. No responding semiconductor devices to an input or transistors failing on a circuit board due to overloads from radiation are two latch-up examples (Deveci, 2007).

b. Damage/Burnout

Damage/burnout is electrical destruction of a node by some mechanism like latch-up, metallization burnout, or junction burnout. Because electrical overstress can cause charge buildups in passivation layers and dielectric layers that decay with the time, damage is often distinguished as to its degree of performance. One will often find the term “permanent damage” or “electrical burnout” used to describe the more catastrophic kinds of damage. Damage/burnout occurs when the high-power microwave energy causes melting in capacitors, resistors or conductors. Burnout mostly occurs in the junction region where multiple wires or the base collector or emitter of a transistor come together, and often involves electrical arcing. Consequently, the heating is localized to the junction region. A lightning strike’s effect on electronic devices is a burnout example (Deveci, 2007).

D. MODEL

It is far too complicated to ideally and faithfully represent the effects of proposed e-bombs through back-of-envelop calculation methods since it involves a wide range of interacting and interdependent parameters and equations. However, reliable and dependable predictions for coupling to a wide variety of electric circuitry environments and components are still needed and valuable when used to assess the potential effects of e-bombs. For this reason, a MATLAB simulation is used to simulate each type of described e-bomb. The flow diagram of this simulation is shown on Figure 23. The output designated by the numbers is the output plots of the simulation and defined in the next paragraph.

The MATLAB code for the simulation is shown in Appendix-B. The model’s output is:

- The maximum E-field that can propagate in the air without breakdown
- Minimum dimensions of the horn antenna in order to avoid the breakdown in the air
- "E-field strength vs. the distance" plot of e-bomb (without loss) (1)
- "E-field strength vs. the distance" plot of e-bomb with atmospheric loss (2)

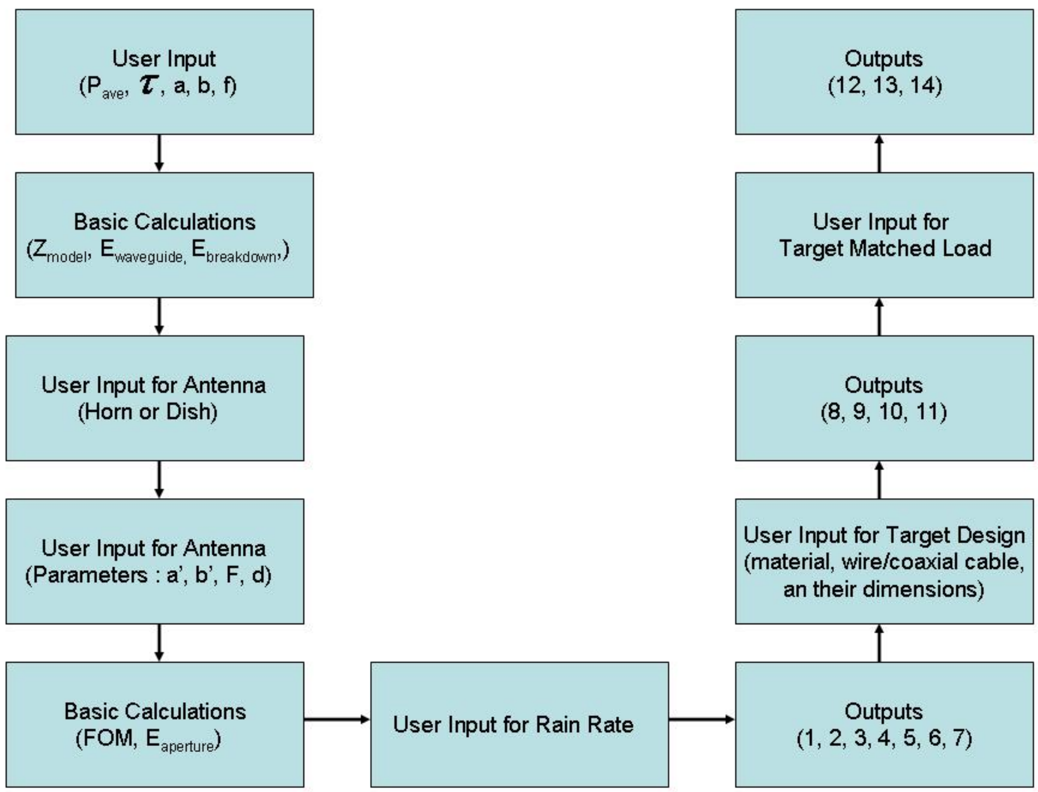

Figure 23. Flow Diagram of MATLAB Simulation

- "E-field strength vs. the distance" plot of e-bomb with atmospheric loss + loss due to rain (3)
- "Average power density vs. the distance" plot of e-bomb with atmospheric loss (4)

- “Average power density vs. the distance” plot of e-bomb with atmospheric loss + loss due to rain (5)
- “Energy density vs. the distance” plot of e-bomb with atmospheric loss (6)
- “Energy density vs. the distance” plot of e-bomb with atmospheric loss + loss due to rain (7)
- “Flowing current vs. the distance” plot of e-bomb with atmospheric loss (for chosen material) (8)
- “Flowing current vs. the distance” plot of e-bomb with atmospheric loss + loss due to rain (for chosen material) (9)
- “Flowing current vs. the distance for shielded systems” plot of e-bomb with atmospheric loss (for chosen material) (10)
- “Flowing current vs. the distance for shielded systems” plot of e-bomb with atmospheric loss + loss due to rain (for chosen material) (11)
- “Delivered power vs. the distance for unshielded” plot of e-bomb for atmospheric loss and rain loss (for chosen material and chosen matched load) (12)
- “Delivered power vs. the distance for shielded systems” plot of e-bomb with atmospheric loss (for chosen material and chosen matched load) (13)
- “Delivered power vs. the distance for shielded systems” plot of e-bomb with atmospheric loss + loss due to rain (for chosen material and chosen matched load) (14)

According to the results obtained from the simulation, a susceptibility assessment is performed and critically analyzed. Finally, an assessment of military utility is conducted.

E. VALIDATION OF THE MODEL

Consider a scenario that includes a medium-tech (moderate) e-bomb used against a commercial airplane. The e-bomb in this scenario will be radiating microwave energy 500 feet away from the airplane. The inherent question is, "Can medium-tech e-bombs generate a field strength or deliver a force into the airplane electronic systems, such as radars, communication devices, electronic modules etc., that cause damage to important electronic devices?"

The answer to this question leads to the need to validate the proposed simulation in this thesis. A validated model adds credibility to the results obtained in terms of expected "real world" coupling effects. Such a validation scenario is shown in Figure 24.

For this scenario, a medium-tech (moderate) e-bomb is used in the system interaction estimations. As mentioned before, the interested target for moderate e-bomb is civil aviation. It is assumed that the electrical systems on the airplane involve coupling to a representative cable that is 100 ohms impedance matched to a load circuit. The specifications for the moderate e-bomb is shown in Table 6. All specifications are chosen to be arbitrary, but, at the same time, providing specifications that meet the criteria defined in moderate e-bomb classifications.

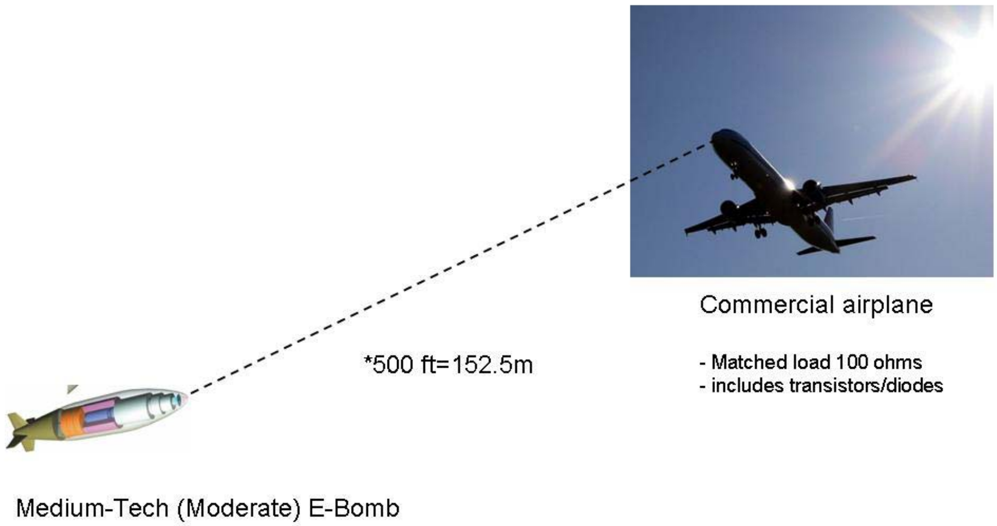

Figure 24. Scenario for validation of e-bomb simulation

Operating frequency (f)	1.2 GHz
Average power (P_{avg})	700 kW
WR770 waveguide dimensions ($a \times b$)	0.19558x0.09779 m
Aperture area of the reflector (A)	3.14 m^2 (d=2 m)
Focal length of the reflector (F)	0.5 m
Pulsewidth (τ)	100 ns

Table 6. Moderate E-Bomb specifications for validating scenario

As a first step and upon completing a simulation run, the results of the simulation are compared to the (High Intensity Radiated Field) HIRF Environment Standards for commercial aircrafts.

The HIRF environment standards guide is a document that provides technical guidance to demonstrate compliance with best-practice aircraft high intensity radiated field certification regulations. The HIRF regulations are applicable to any civilian aircraft. The more specific area of applicability to each aircraft is the continued availability of functions related to safe takeoff, flight, and landing during and after exposure to HIRF. It must be demonstrated and certified that aircraft systems that perform functions related to safe takeoff, flight, and landing must not be lost when the aircraft is exposed to the Severe or Certification HIRF Environment (HIRF Standards, 2003).

The environments were defined from considering all deployed emitters operating at peak output located in the continental United States, Hawaii, Alaska and Puerto Rico, plus the five participating European countries: United Kingdom, Germany, Sweden, France, and the Netherlands (HIRF Standards, 2003).

The external environment is found to exist due to the radiation of Radio Frequency (RF) electromagnetic energy into free space. This energy is radiated from radio, television, radar emitters, and from other sources. Figure 25 depicts many of these common electromagnetic sources that couple to and cause interference with electrical wiring of aircraft. Two of these sources of great concern to the aircraft designers and manufacturers are the high-energy external RF emissions from radars and radio transmitters and the effects of direct and indirect lightning. Contributing to the electromagnetic environment are more than 500,000 emitters in the U.S. and Western Europe. The HIRF environments are a composite of transmitters that are airborne, land-based, offshore platforms, and ship-based. These transmitters are becoming more sophisticated, more efficient, more powerful, and more numerous. The emitters cover the entire Radio Frequency (RF) spectrum and their radiated fields vary greatly in energy levels and signal characteristics.

The Severe HIRF Environment is based on the “worst case” estimate of electromagnetic field strengths that a civil aircraft might encounter.

The International Civil Aviation Organization (ICAO) flight standards allow flight to within 500 feet of the ground under visual flight rules (VFR) for fixed wing aircraft. Although this is uncommon for many aircrafts, it is permissible. At such an altitude, aircraft have the potential to come extremely close to terrestrial-based emitters that produce RF field levels at the aircraft in excess of 7,000 volts/meter. This resulted in the committee establishing two Severe HIRF environments, one for fixed wing aircraft and one for rotorcraft. The material in HIRF standards deals only with flights above 500 feet except during landing and takeoff at civil airports (HIRF Standards, 2003).

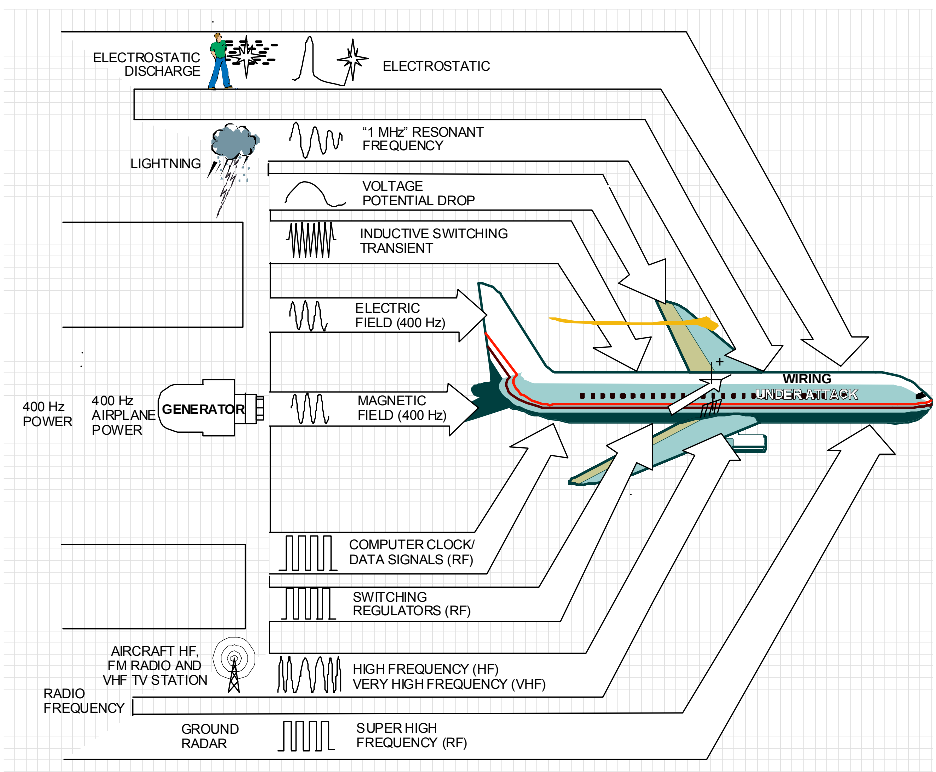

Figure 25. HIRF Environment for an aircraft

The Fixed Wing Severe HIRF Environment is defined as "the worst case estimate of the electromagnetic field strength levels in which the airspace in which fixed wing flight operations are permitted" (HIRF Standards, 2003).

For the simulation in this study, Fixed Wing Severe HIRF Environment is used to compare the output of the study. These composite levels are shown as a function of frequency in Table 7.

FREQUENCY	FIELD STRENGTH (V/m)	
	PEAK	AVERAGE
10 kHz – 100 kHz	50	50
100 kHz – 500 kHz	60	60
500 kHz – 2 MHz	70	70
2 MHz – 30 MHz	200	200
30 MHz – 70 MHz	30	30
70 MHz – 100 MHz	30	30
100 MHz – 200 MHz	90	30
200 MHz – 400 MHz	70	70
400 MHz – 700 MHz	730	80
700 MHz – 1 GHz	1400	240
1 GHz – 2 GHz	3300	160
2 GHz – 4 GHz	4500	490
4 GHz – 6 GHz	7200	300
6 GHz – 8 GHz	1100	170
8 GHz – 12 GHz	2600	330
12 GHz – 18 GHz	2000	330
18 GHz – 40 GHz	1000	420

Table 7. Fixed Wing Severe HIRF Environment (HIRF Standards, 2003)

The second step to validate the model is to show whether the generated E-field is sufficient to couple enough power into the target system. For this reason, estimated coupled power into the target is compared to published damage threshold levels for devices such as representative transistors, SCRs, diodes, and integrated circuits. A valuable damage threshold level report was published by Defense Nuclear Agency (DNA) in 1977. DNA defined the damage threshold levels in kilowatts of the power. A damage threshold power range derived from experimental evidence and representative devices is demonstrated by the horizontal bars in Figure 26. According to the data shown in the figure, a damage threshold power may be as low as 1 watt for microwave diodes or as high as 40 kW for high power transistors.

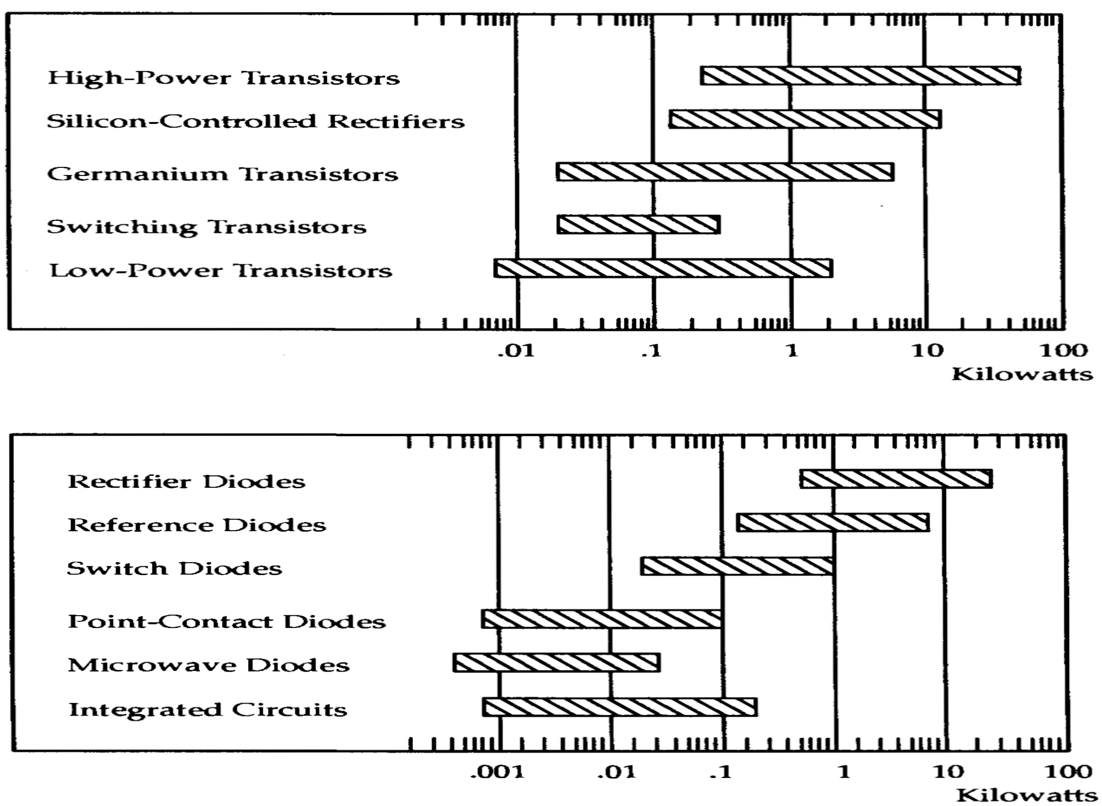

Figure 26. Damage threshold power range of representative transistors, SCRs, diodes, and integrated circuits (Mendel, 1997)

The airplane in the chosen scenario is assumed to have a 30 dB shielding (moderate). The 30 dB shielding also corresponds to the level of shielding that is necessary for the avionics in civil aircraft and helicopters in order to withstand the radar frequency HIRF environment (Bäckström, and Lövstrand, 2004).

For the medium source representation of an e-bomb specified in Table 6, a field strength at 267.9 kV/m is created in the waveguide. Since it is less than the breakdown field strength, 3.1 MV/m, no vacuum is required for the waveguide. The generated E-field at the aperture of the antenna from this waveguide field is then about 41 kV/m, which is also less than the breakdown level. The corresponding FOM is 514 kV/m. (recall that FOM is the far-field output of the device as it would be measured one-meter from the source antenna and in the direction of maximum field output).

Using the FOM, estimates at far-field electromagnetic environments produced by the source can be easily generated as a function of range (Field strength = FOM/range). The E-field strength of moderate e-bomb with atmospheric losses vs. the range is shown in Figure 27. According to this figure, the hypothetical moderate e-bomb produces an E-field strength of 3.36 kV/m at 153 meters (500 feet is converted to 152.5 meters and approximated to 153 meters). Notice that this environment almost identically matches the HIRF threshold at 1 GHz for reliable equipment operations. The 3 kV/m result is therefore tagged as important and significant.

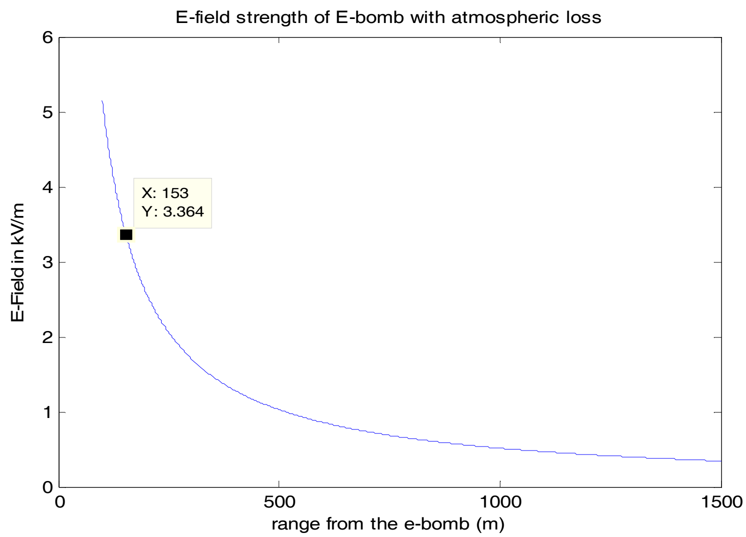

Figure 27. E-field strength of moderate e-bomb

If it is assumed that the civil airplane considered in the validation model has electrical equipment configuration that involve a 2 mm-diameter-copper wire (common), the coupled electric field delivers 613 A current into a matched, fully exposed, unshielded electronic system (see Figure 28).

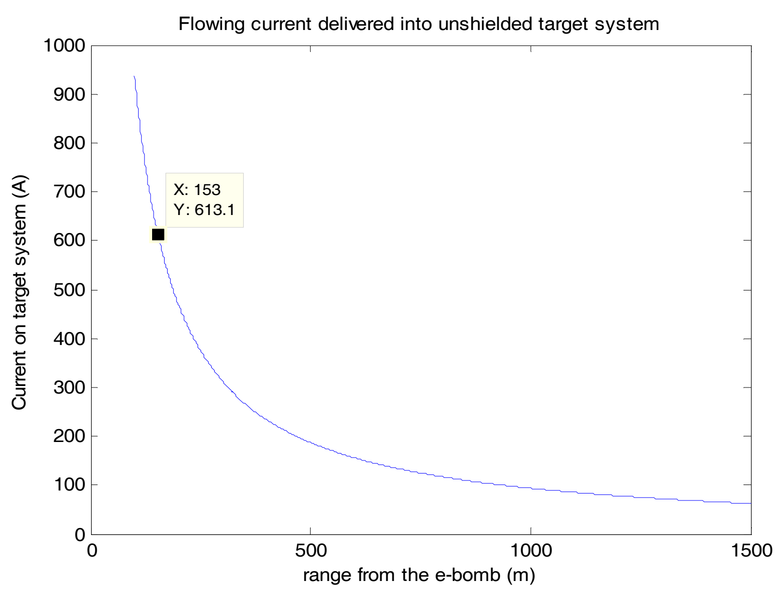

Figure 28. Current vs. the range plot of moderate e-bomb for unshielded systems

When the 30 dB shielding is applied to the simulation, corresponding current coupled into the system decreases to 19 A (see Figure 29).

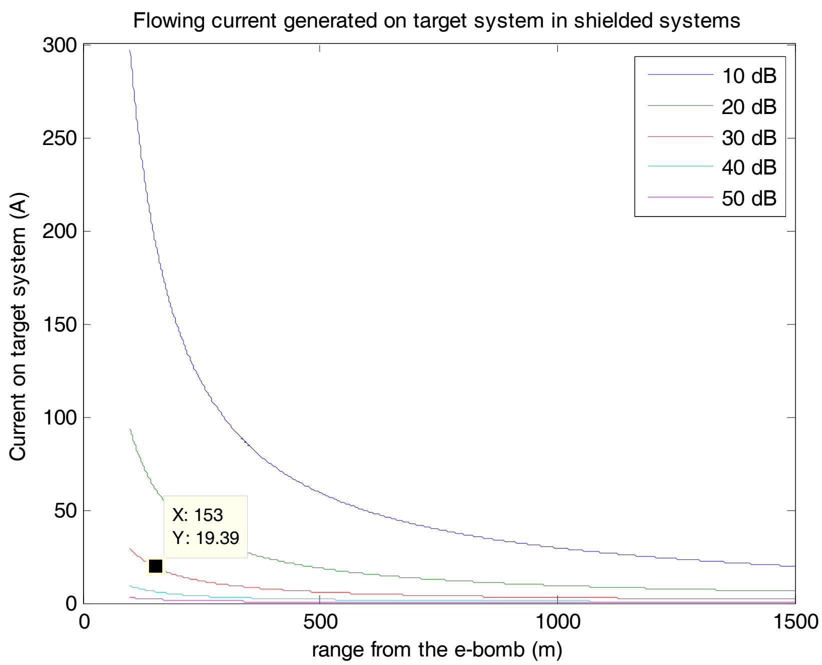

Figure 29. Current vs. the range plot of moderate e-bomb for shielded systems

Corresponding power coupled into the 30 dB-shielded target system is 37.6 kW for a 100 ohms-matched load circuit (see Figure 30)

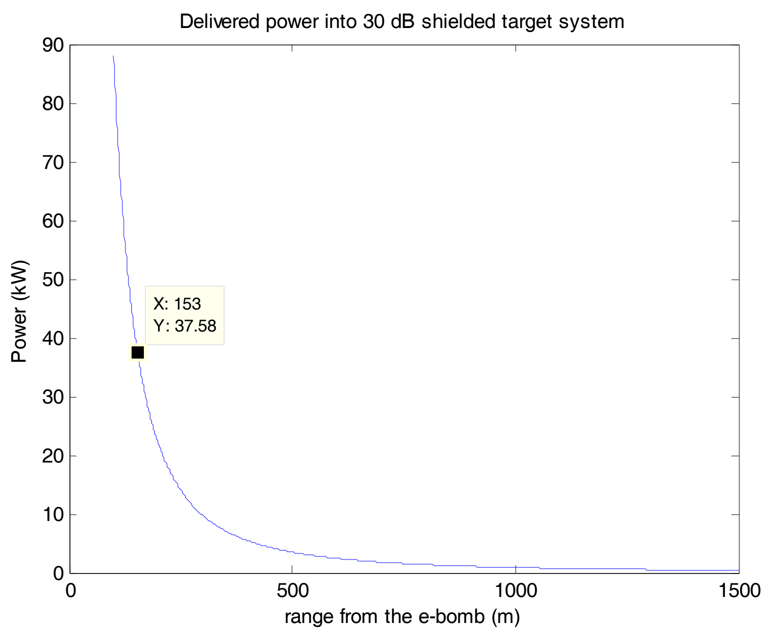

Figure 30. Delivered power into 30 dB shielded systems vs. the distance

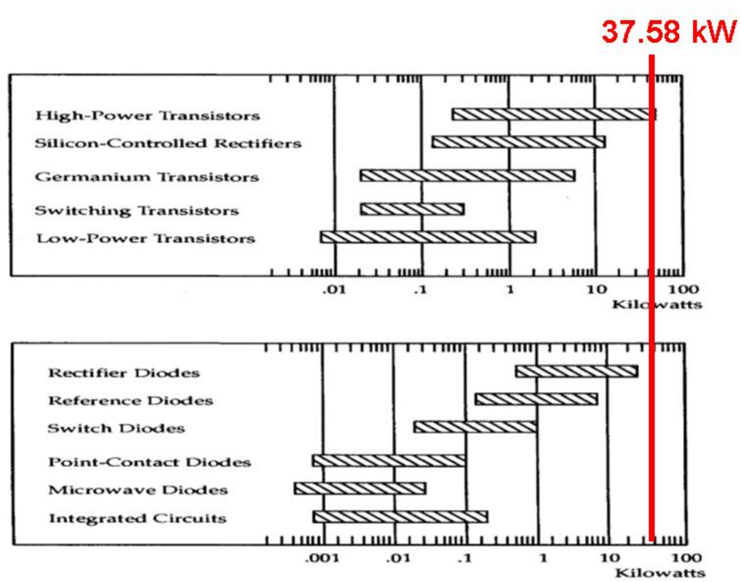

Figure 31. Delivered power into the 30 dB-shielded system

The power produced by the moderate e-bomb in 30 dB-shielded system falls on the upper side of the range for damage threshold levels of representative devices (see Figure 31). That means, the medium technology e-bomb in the scenario produces outputs on electronic equipments of a commercial airplane, which is 500 feet away from the e-bomb, that most likely exceed all known electromagnetic device damage susceptibility limits. The results show that the field strength produced by hypothetical moderate e-bomb is also consistent with the field data given by HIRF standards. (3.364 kV/m vs. 3.3 kV/m).

As a result, the scenario explained in this section validates the model developed to represent the hypothetical e-bomb. Model results are consistent with the HIRF environment thresholds and have exceeded all device damage limits. It is therefore a realistic expected exposure level and, because of the delivered power expected, it produces an important result. The validated model is used to assess the potential lethality effect of each type of e-bomb. HIRF standards in field strength have been tied to damage thresholds, so they are used as the reference to assess the potential lethality of e-bomb on commercial airplanes. Potential lethality is described because actual coupling levels in real (not modeled) systems will depend on many additional factors. This fact does not guarantee lethality, but does provide a condition of potential lethality based on our understanding of the system, the model used, and the database of damage criteria available.

F. POTENTIAL LETHALITY OF HYPOTHETICAL E-BOMB

The potential lethality of each type of e-bomb of interest depends on the target attacked. Targets are classified as:

- Unshielded Systems
- Moderately Shielded Systems
- Fully Shielded Systems

Unshielded systems are fully exposed by electric fields produced by radiating sources and will be considered in the interest of the low-tech (small) e-bomb. Moderately shielded systems are the systems that have 30 dB shielding. Civil aviation is in the interest of the medium-tech (moderate) e-bomb. In addition, civil aviation can be considered as moderately shielded systems according to the data, which is consistent with HIRF standards. Fully shielded systems are the systems that have 40-50 dB shielding effectiveness (SE). Military systems can be considered in this group and is in the interest of the high-tech (powerful) e-bomb.

The potential lethality ranges is estimated by using the known/published susceptibility levels from DNA reports as described earlier.

1. Low-Tech (Small) E-Bomb

The specifications for a low-tech e-bomb, as used in the simulation, are defined in Table 1. The low-tech simulation is run for each power level of the e-bomb. In the first step, it is assumed that the e-bomb is designed by using WR340 (a=0.086 m, b=0.043 m) waveguide. The output of the e-bomb is shown in Table 8.

P_{avg} (Watts)	E_{max} (waveguide) (kV/m)	E_{peak} (at the aperture) (kV/m)	FOM (kV)
800	21.55	1.75	22.06
900	22.86	1.86	23.04
1000	24.10	1.96	24.67
1100	25.27	2.06	25.87
1200	26.40	2.15	27.02
1300	27.47	2.24	28.12
1400	28.51	2.32	29.18
1500	29.51	2.40	30.21
1600	30.48	2.48	31.20
1700	31.41	2.56	32.16
1800	32.32	2.63	33.09
1900	33.21	2.70	34.00
2000	34.07	2.77	34.88

Table 8. Simulation output for field strengths of low-tech e-bomb with WR340 waveguide

If the e-bomb is designed by using WR430 (a=0.10922 m, b=0.05461 m) waveguide, the strength of the E-field produced by the low-tech e-bomb slightly increases. It also decreases the field strength in the waveguide. This must be noted in order to use as a rule of thumb for high-level powers. Output of the simulation is shown in Table 9.

P_{avg} (Watts)	E_{max} (waveguide) (kV/m)	E_{peak} (at the horn) (kV/m)	FOM (kV)
800	15.6	2.05	25.8
900	16.5	2.17	27.3
1000	17.4	2.29	28.8
1100	18.3	2.40	30.2
1200	19.1	2.51	31.6
1300	19.9	2.61	32.9
1400	20.6	2.71	34.1
1500	21.4	2.81	35.3
1600	22.1	2.90	36.5
1700	22.7	2.99	37.6
1800	23.4	3.07	38.7
1900	24.1	3.16	39.77
2000	24.7	3.24	40.8

Table 9. Simulation output for field strengths of low-tech e-bomb with WR430 waveguide

Given that the e-bomb includes WR430 waveguide and has two power levels, 1500 watts and 2000 watts, the produced field strength at a range 1 km from the e-bomb is 35.3 V/m for 1500 watts and 40.8 V/m for 2000 watts (see Table 9). These estimates do not include the atmospheric losses.

P_{avg} (watts)	E r = 1m	E r = 500 m	E r = 1 km
1500	35.3 kV/m	70.6 V/m	35.3 V/m
2000	40.8 kV/m	81.6 V/m	40.8 V/m

Table 10. Evaluation Field strengths of low-tech e-bomb at different ranges

Among the different power levels, a 2000-watts source is chosen with WR430 waveguide in order to estimate the potential lethality range for different types of targets.

Some of the simulation outputs for different parameters of the e-bomb are shown on Figure 32 (All simulation output for the low-tech e-bomb is shown in Appendix-C). The results show that for the ranges less than 1500 meters, the atmospheric loss due to the moderate rain is insignificant. Assuming a lossless propagation environment, the E-field strength at 1 km from the e-bomb is 40.8 V/m where E-field strength with atmospheric loss is 40.78 V/m and E-field strength with atmospheric loss and rain loss is 40.77 V/m at the same range.

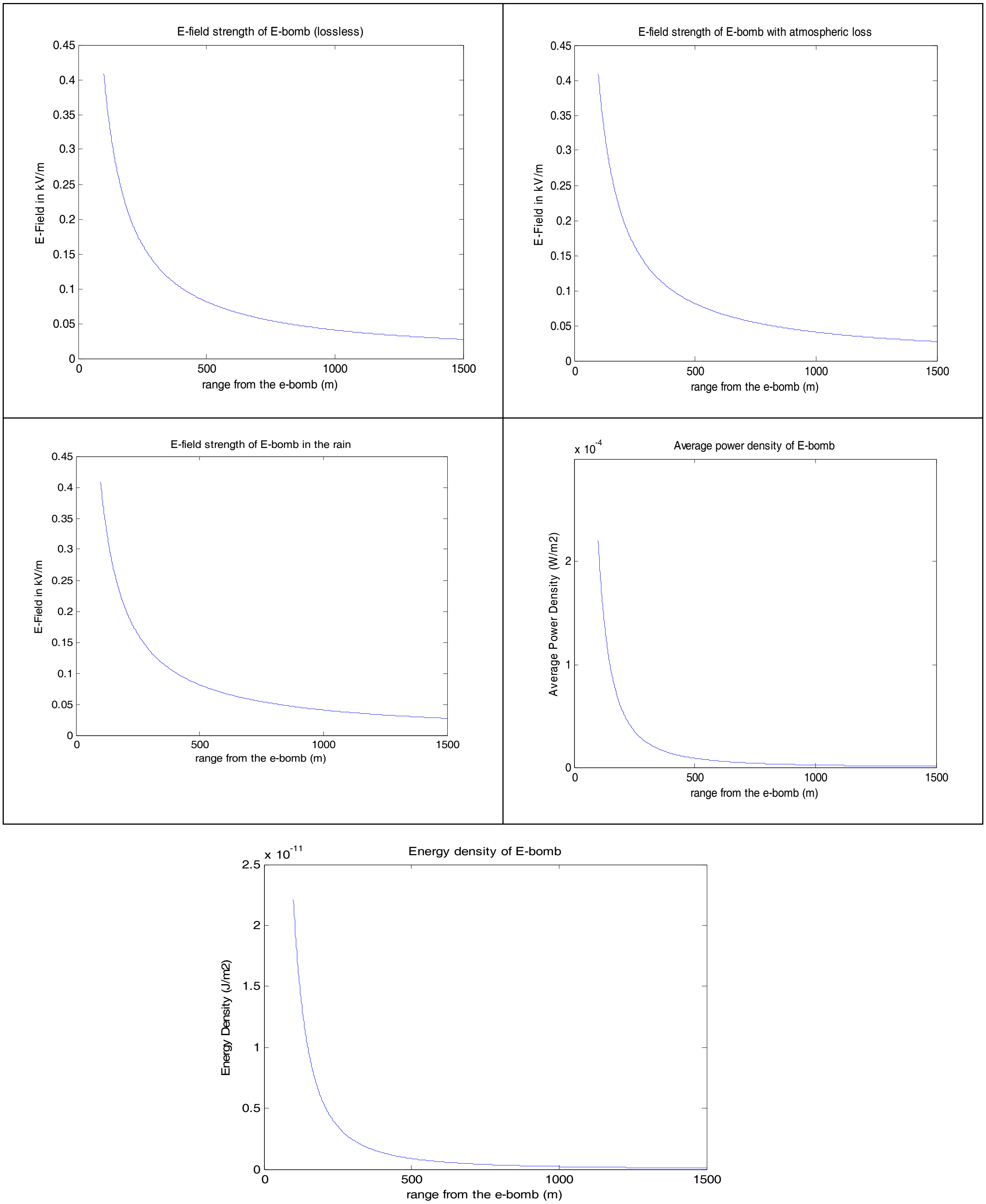

Figure 32. Simulation output for low-tech e-bomb

Upset levels as low as 15 V/m have been reported for the electronic control module in a public bus engine (Bäckström and Lövstrand, 2004). According to the referenced report, 15 V/m field strength caused an engine to stop. If considered as a threshold value for public bus engines, according to the simulation, the low-tech e-bomb model produces field strength that exceed the electromagnetic susceptibility limits of the cited public bus for ranges up to 2.7 km (see Figure 33). That means, the proposed low-tech e-bomb has a potential upset effect out to a range of 2716 meters as compared to the public bus data.

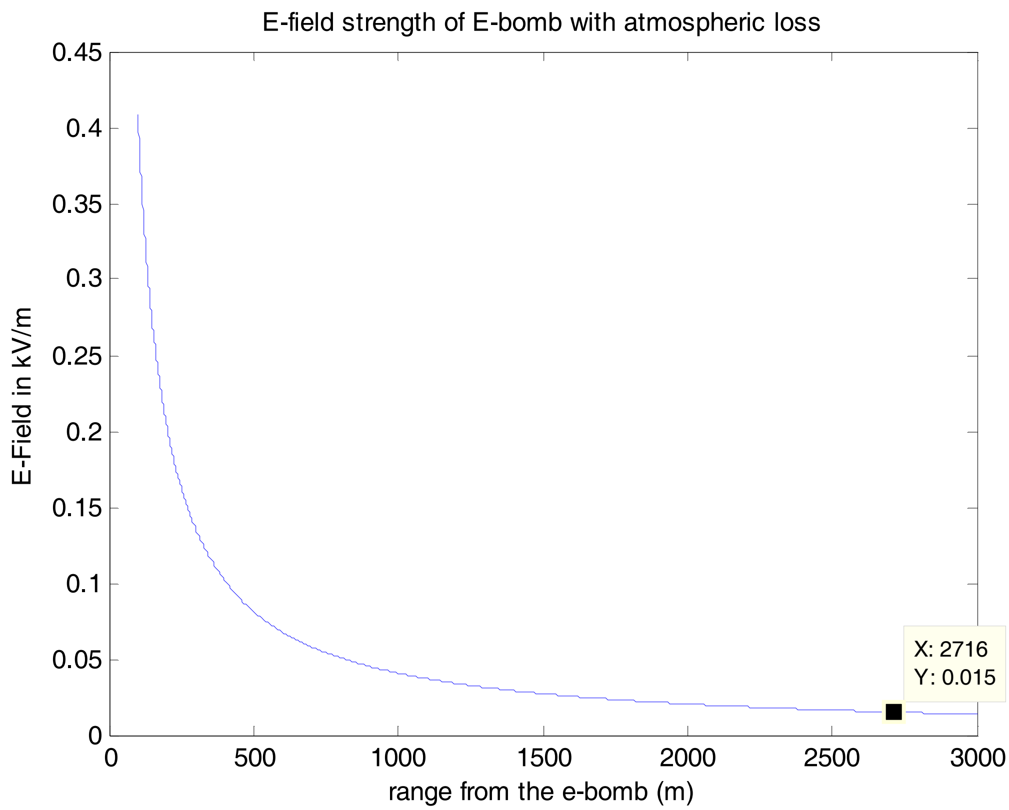

Figure 33. Low-tech E-bomb lethality range for public bus threshold level

Another upset threshold level al low as 30 V/m was reported for personal computers (PC) when 30 V/m field strength caused disruption and as a result computer had to be rebooted in order to gain operation (Bäckström and Lövstrand, 2004). If this level is considered as the upset threshold value for similar electronic to PCs, according to the simulation, the low-tech e-bomb produces field strength that exceeds the electromagnetic susceptibility limits of PC up to 1.36 km away from the antenna (see Figure 34). That means, the proposed low-tech e-bomb has a potential upset effect range of 1359 meters against personal computers, or similar electronics. One can think that the new PCs are even more susceptible to microwave radiation than older ones. In this case, it is clear that the lethality range of e-bomb is even greater than 1.36 km against PCs.

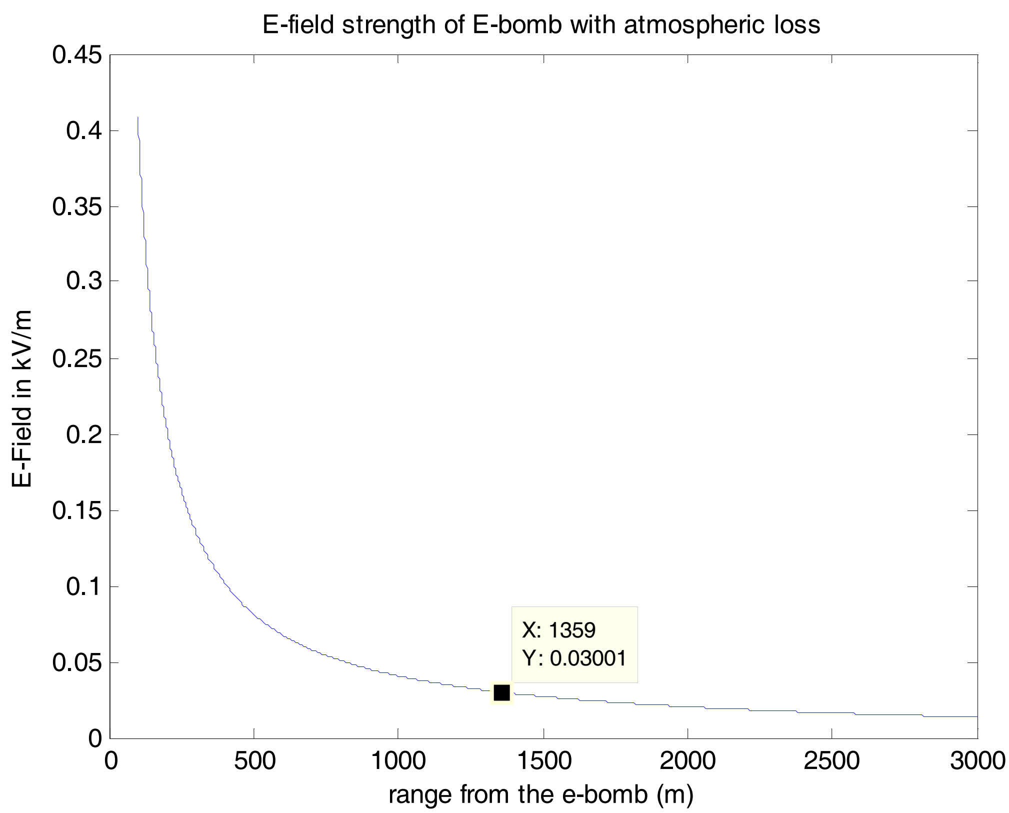

Figure 34. Low-tech E-bomb lethality range for personal computer

In the same article, permanent damage level for exposure to fields as low as 100 V/m is reported for PC flat screens (Bäckström, and Lövstrand, 2004). In this case, the low-tech e-bomb model produces field strengths that exceeds the electromagnetic susceptibility limits of PC flat screens threshold up to 400 meters (see Figure 35). That means, the proposed low-tech e-bomb has a potential lethality range of 407 meters against personal computer flat screens.

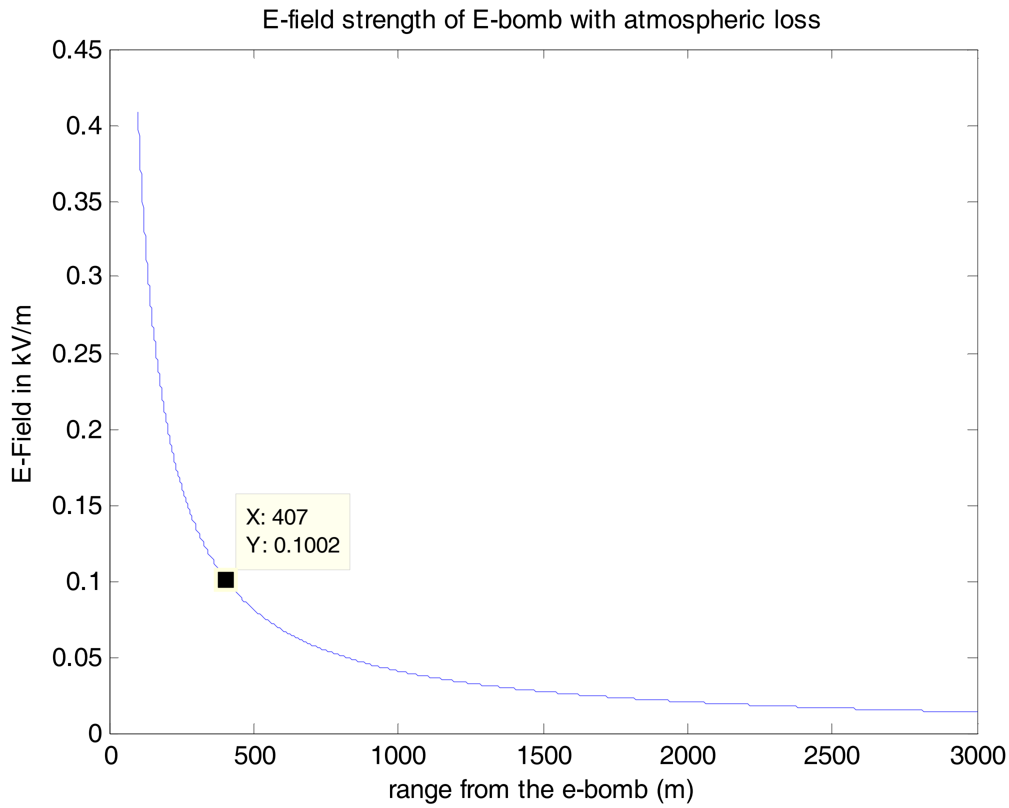

Figure 35. Low-tech E-bomb lethality range for personal computer flat screen

Finally, for the KIM-1 microprocessor, upset level as low as 2 V/m were reported (Taylor and Giri, 1994). For any electronic devices that involve KIM-1 microprocessor, the low-tech e-bomb model produces field strength that exceeds the electromagnetic susceptibility limits of KIM-1 microprocessor for all ranges up to 20 km (see Figure 36). That is, the proposed low-tech e-bomb has an upset threshold range of 20 km against the fully exposed electronic devices that involves KIM-1 microprocessors.

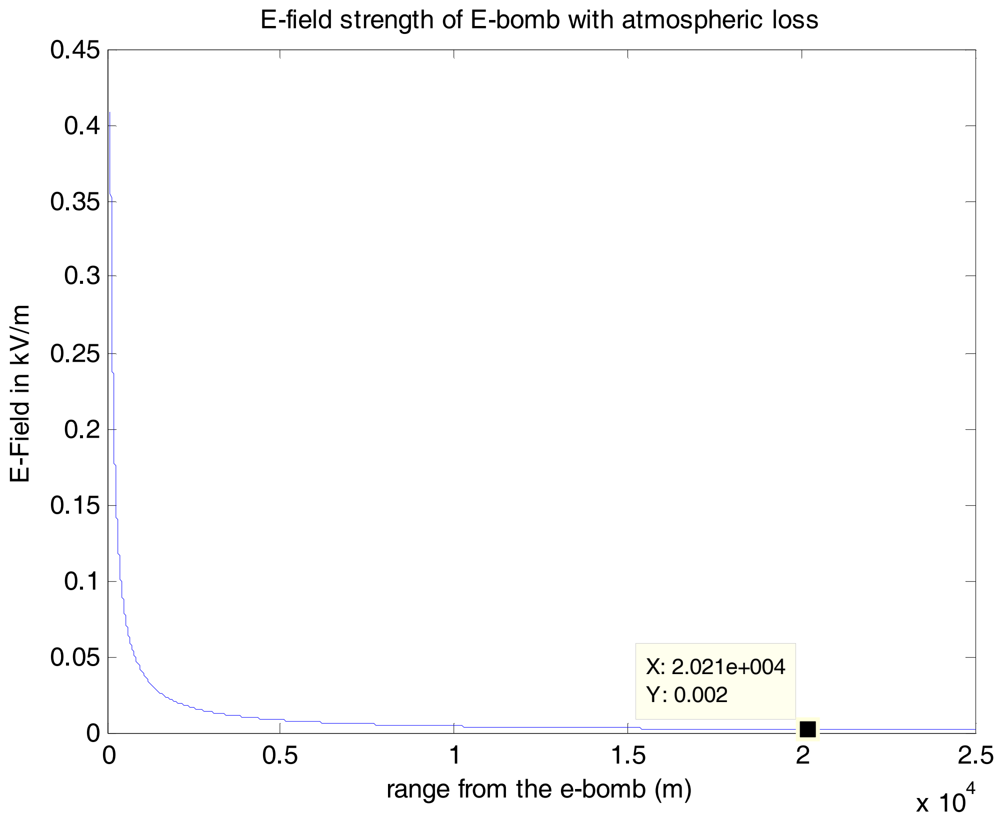

Figure 36. Low-tech E-bomb lethality range for KIM-1 microprocessor

2. Medium-Tech (Moderate) E-Bomb

The specifications for medium-tech (moderate) e-bomb are defined in Table 1. The medium tech simulation is run for two operating mode of e-bomb. The first mode has the operating frequency of 1.2 GHz and corresponding waveguide is WR770 (a=0.19558 m, b=0.09779 m). Table 11 shows the different output of the e-bomb in terms of different power levels between 1-20 MW.

P_{avg} (MW)	E_{max} (waveguide) (MV/m)	E_{peak} (at the aperture) (kV/m)	FOM (MV)
1	0.32	48.9	0.96
2	0.45	69.3	1.35
3	0.55	84.8	1.66
4	0.64	97.9	1.92
5	0.71	109.5	2.14
6	0.78	120.0	2.35
7	0.84	129.6	2.54
8	0.90	138.5	2.71
9	0.96	146.9	2.88
10	1.01	154.9	3.03
11	1.06	162.4	3.18
12	1.11	169.7	3.32
13	1.15	176.6	3.46
14	1.19	183.3	3.59
15	1.24	189.7	3.72
16	1.28	195.9	3.84
17	1.32	202.0	3.95
18	1.36	207.8	4.07
19	1.39	213.5	4.18
20	1.43	219.1	4.29

Table 11. Simulation output for field strengths of medium-tech e-bomb with WR770 waveguide

Proposed e-bomb produces 3.72 kV/m field strength at 1 km for 15 MW power level and 4.29 kV/m for 20 MW at the same point (see Table 12). Calculations do not include atmospheric losses.

P_{avg} (MW)	E r = 1m	E r = 1 km	E r = 5 km	E r = 10 km	E r = 100 km
15	3.72 MV/m	3.72 kV/m	744 V/m	372 V/m	37.2 V/m
20	4.29 MV/m	4.29 kV/m	858 V/m	429 V/m	42.9 V/m

Table 12. Field strengths of low-tech e-bomb at different ranges

The second mode has the operating frequency of 1.7 GHz and corresponding waveguide is WR650 (a=0.1651 m, b=0.08255 m). With the increased frequency and relatively smaller waveguide the strength of E-field produced by the medium-tech e-bomb increases about 60% (see Table 13).

P_{avg} (MW)	E_{max} (waveguide) (MV/m)	E_{peak} (at the aperture) (kV/m)	FOM (MV)
15	1.40	216.4	6.01
20	1.61	249.9	6.94

Table 13. Simulation output for field strengths of low-tech e-bomb with WR430 waveguide

Given that the e-bomb operating frequency is 1.7 GHz and is configured for two power levels, 15 MW and 20 MW, the produced field strength at 1 km from the e-bomb is 6.01 kV/m for 15 MW and 6.94 kV/m for 20 MW (see Table 14). Atmospheric losses are not included.

P_{avg} (MW)	E r = 1m	E r = 1 km	E r = 5 km	E r = 10 km	E r = 100 km
15	6.01 MV/m	6.01 kV/m	1.202 kV/m	601 V/m	60.1 V/m
20	6.94 MV/m	6.94 kV/m	1.388 kV/m	694 V/m	69.4 V/m

Table 14. Field strengths of low-tech e-bomb at different ranges

Among the different power levels, 20 MW source is chosen with WR650 waveguide in order to estimate the potential lethality range of the moderate e-bomb simulation for different types of targets.

Some of the simulation output for different parameters of the e-bomb is shown on Figure 37 (All simulation output for the medium-tech e-bomb is shown in Appendix-C). The results show that at 4 km, the atmospheric loss due to the moderate rain decreases the field strength by 1 V/m. Lossless E-field strength at 4 km from the e-bomb is 1.735 kV/m where E-field strength with atmospheric loss is 1.732 kV/m and E-field strength with atmospheric loss and rain loss is 1.731 kV/m at the same range.

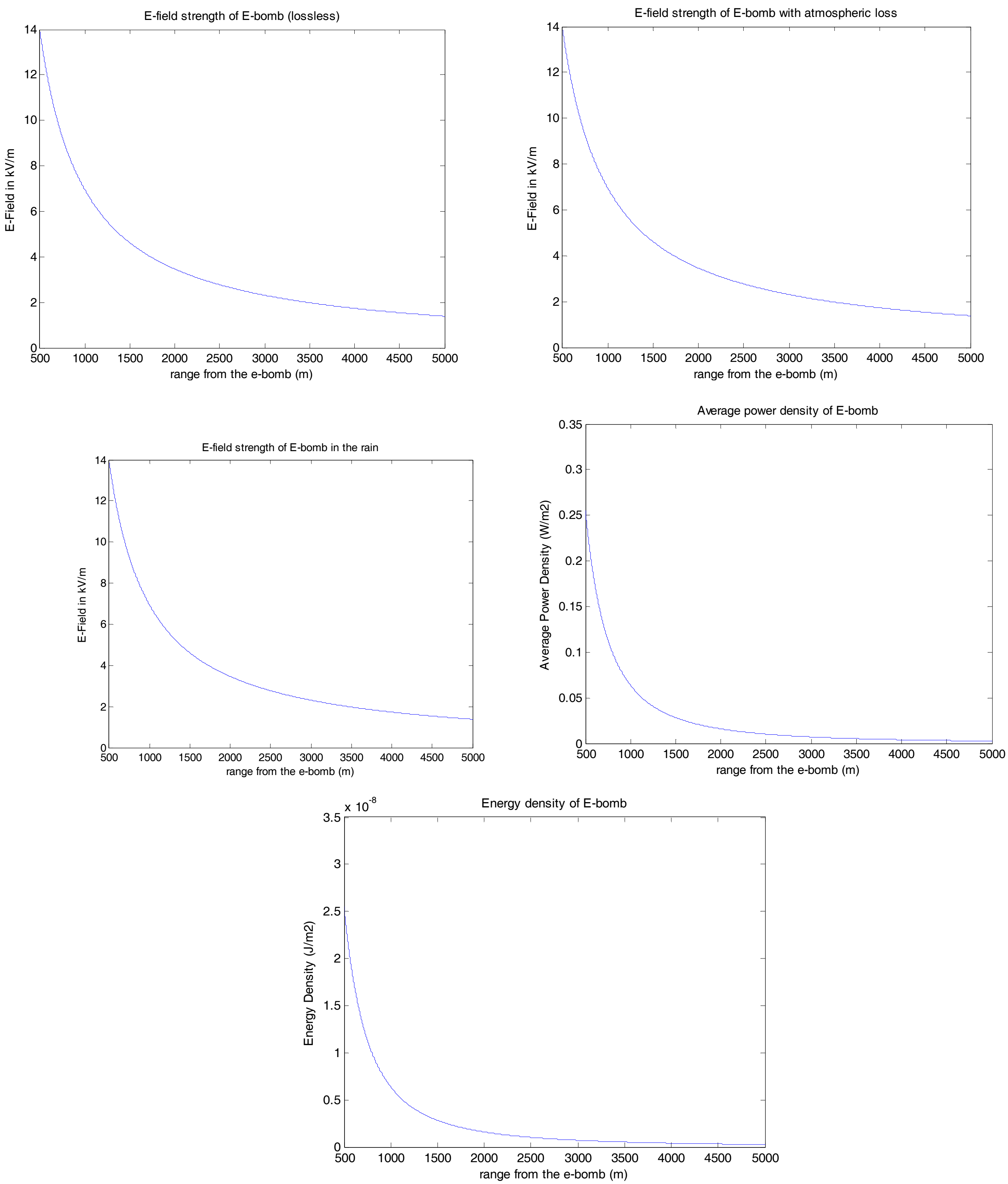

Figure 37. Simulation output for medium-tech e-bomb

In evaluating the outputs from the medium-tech e-bomb model, it will be appropriate to compare the radiated field strengths to the “design-to” standards for commercial aircraft (i.e., HIRF standards). As mentioned before, 30 dB shielding models commercial aircraft shielding effectiveness.

The HIRF standards shows that at the frequency range between 1-2 GHz, the maximum electric field strength environment in which the commercial airplanes fly is 3.3 kV/m (HIRF Standards, 2003). According to the simulation results, it can be concluded that the medium-tech e-bomb produces field strength that exceeds the HIRF standard limits of commercial airplanes up to a range from source of 2.1 km (see Figure 38). That is, the proposed medium-tech e-bomb has a potential lethality range of 2100 meters against commercial airplanes.

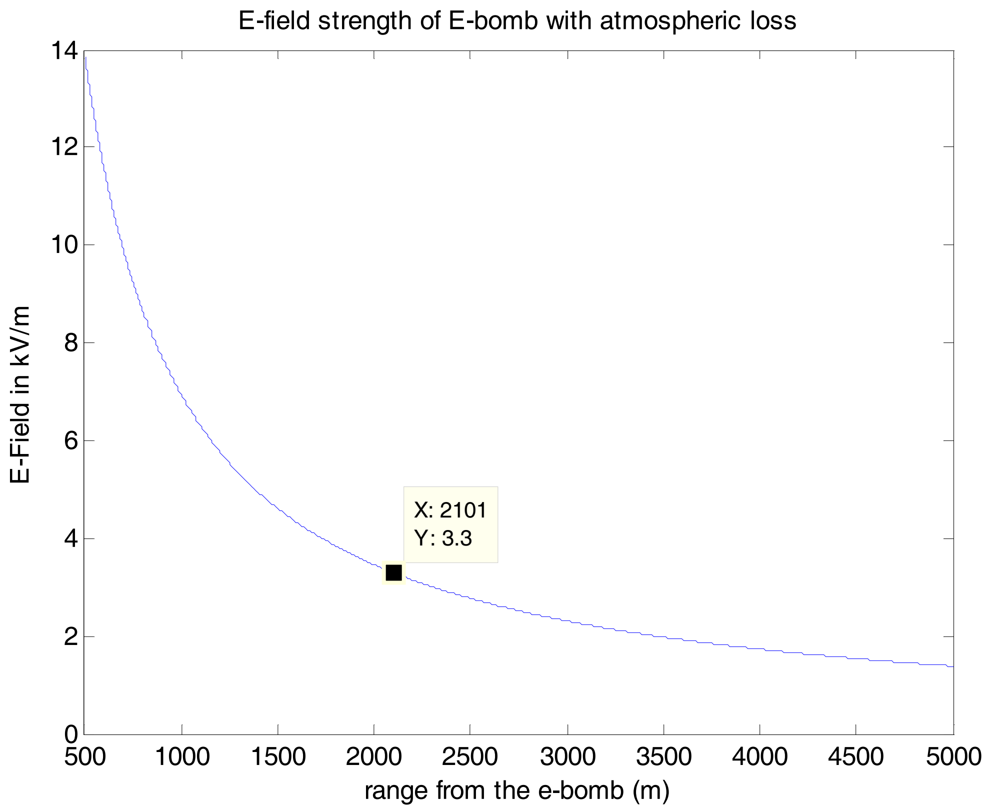

Figure 38. Medium-tech E-bomb lethality range for commercial airplanes

In the DNA report (*DNA EMP Awareness Course Notes,* Mindel, I. N. DNA Report No DNA2772T), it can be concluded that all known representative transistors, silicon-controlled rectifiers, diodes, and integrated circuits are susceptible to be damaged by 30 kW power level (Mendel, 1997). If this level is considered as a threshold value for any electronic system that includes one or more of those devices; according to the simulation, the medium-tech e-bomb delivers power into moderately shielded (30 dB) systems enough to exceed the electromagnetic susceptibility limits of those systems up to 2.3 km (see Figure 39). That is, the proposed medium-tech e-bomb has a potential lethality range of 2306 meters against moderately shielded systems.

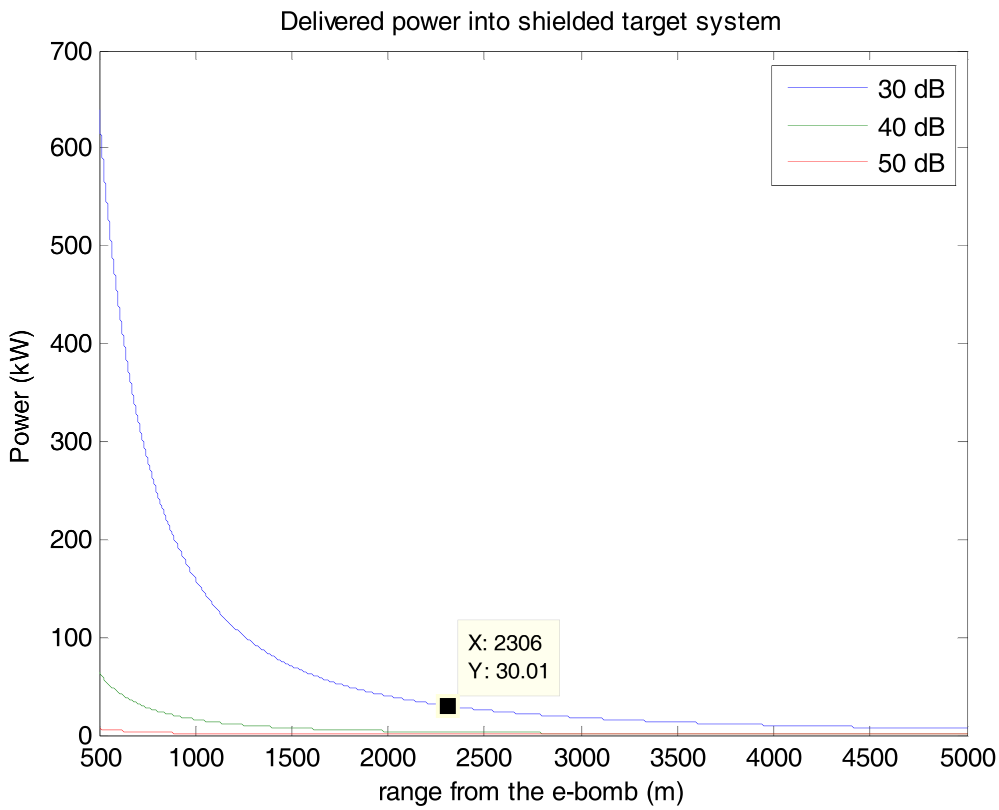

Figure 39. Medium-tech e-bomb potential lethality range for moderately shielded electronic systems

If the system is a 40 dB-shielded (fully shielded) military system, in this case, simulation results show that the medium-tech e-bomb produces power that exceeds the electromagnetic susceptibility limits of representative devices up to 730 meters (see Figure 40). That is, the proposed medium-tech e-bomb has a potential lethality range of 730 meters against 40 dB-shielded military systems.

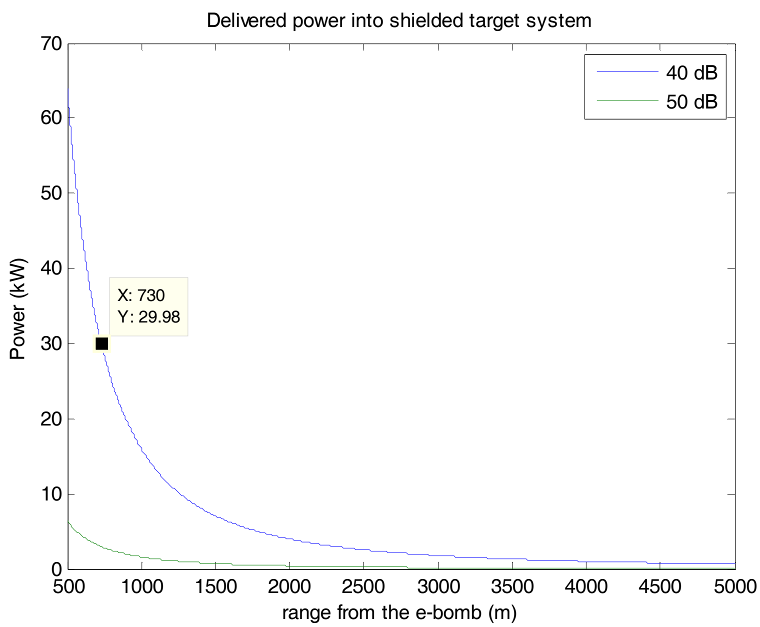

Figure 40. Medium-tech e-bomb potential lethality range for military systems (40 dB SE)

If the military system is shielded by 50 dB, the potential lethality range for permanent damage of the system then reduces to 231 m (see Figure 41).

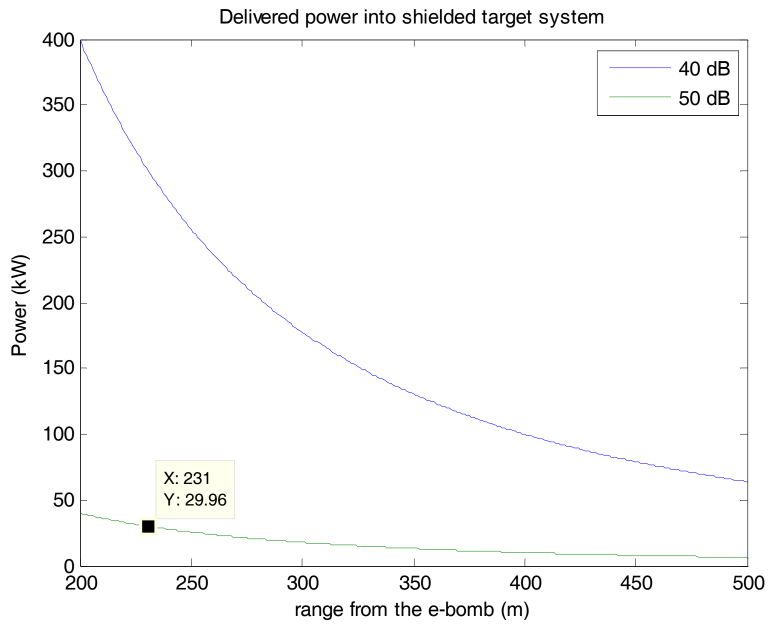

Figure 41. Medium-tech e-bomb potential lethality range for military systems (50 dB SE)

Recently, test results of HPM effects on Swedish Fighter Aircraft were published in open literature (Bäckström and Lövstrand, 2004). The test was conducted at microwave test facility (MTF) designed by the U.S. company TITAN Beta. Currently, the test facility is operated by Aerotech Telub for the systems owned by Swedish Defense Material Administration.

Figure 42. The Swedish MTF testing the HPM effects on Swedish Fighter Aircraft (Bäckström and Lövstrand, 2004)

The described test investigated susceptibility of the military systems to HPM. The results showed that upset began to occur around a few hundred volts per meter. On the other hand, the threshold level for permanent damage was reported at the field strength of 15-25 kV/m.

If the upset level for military systems is assumed 750 V/m according to the empirical data reported by Bäckström, and Lövstrand, it can be concluded that the potential upset range of proposed medium-tech e-bomb model against the military aircrafts is about 9.2 km (see Figure 43).

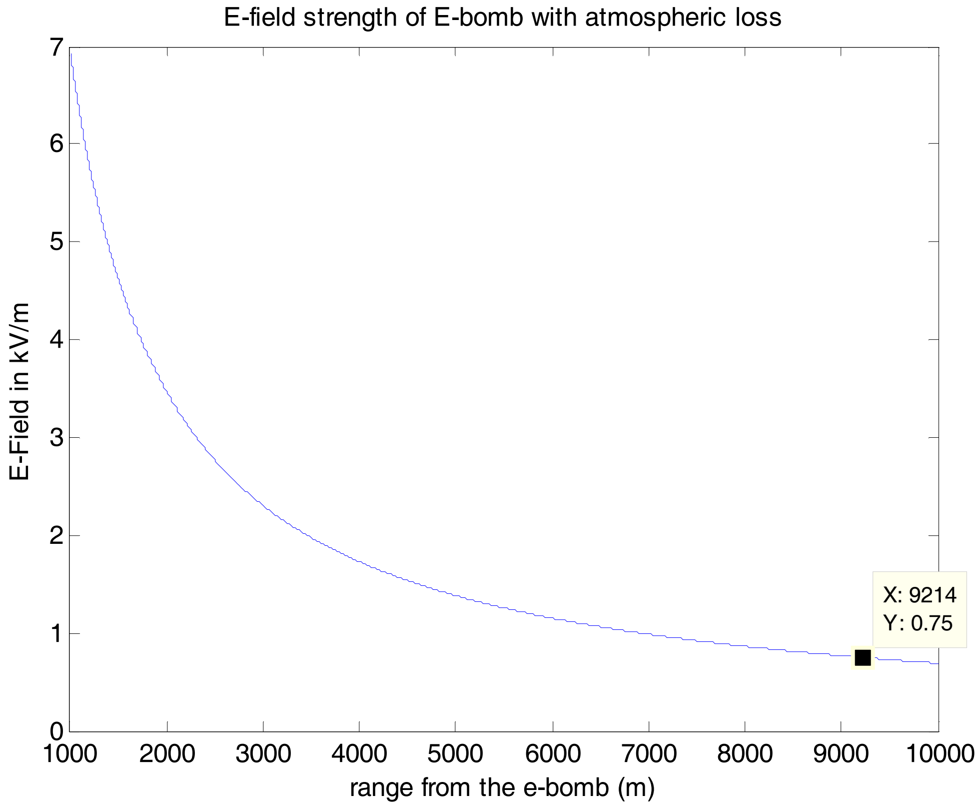

Figure 43. Medium-tech e-bomb potential upset range for Swedish Fighter Aircraft

From the empirical data in the Swedish fighter testing, 15 kV/m field strength was assumed as the threshold value of military aircrafts for permanent damage. Under this assumption, the output of the simulation shows that the medium-tech e-bomb model produces field strength that exceeds the electromagnetic susceptibility limits of Swedish Fighter Aircraft for ranges up to 463 m (see Figure 44).

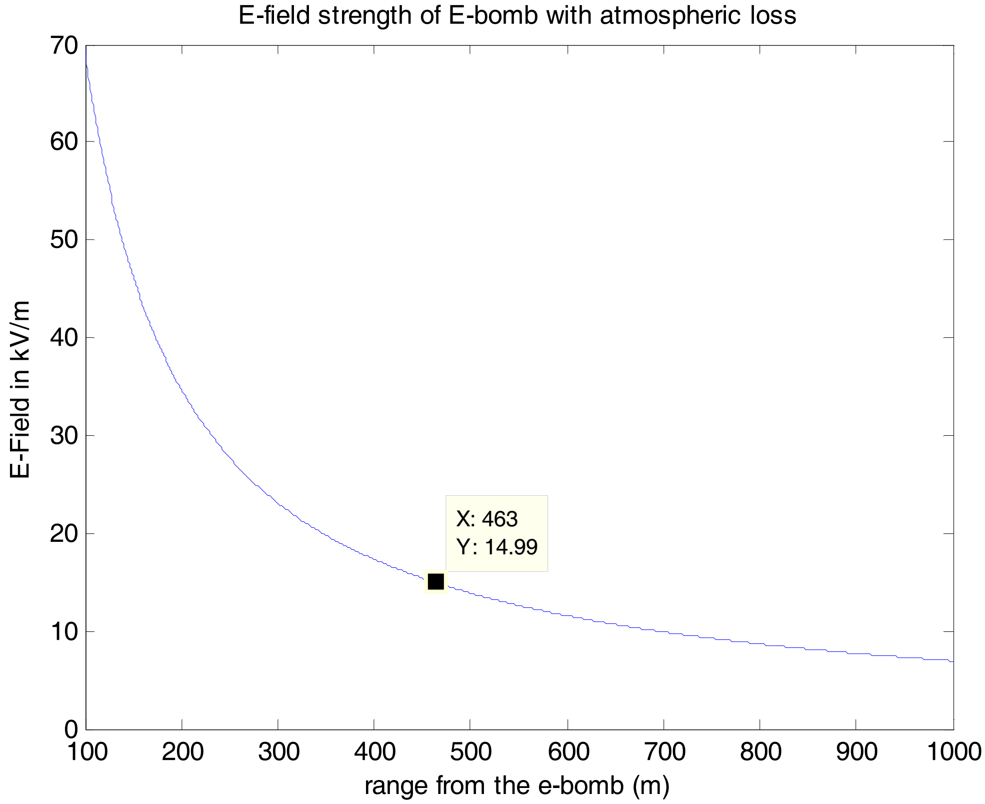

Figure 44. Medium-tech e-bomb potential lethality range for Swedish Fighter Aircraft

The comparison of simulation results of military systems for the stated assumptions and the empirical data are shown in Table 15. The output data shows that 40-50 dB shielding effectiveness assumption for military systems is valid since the output of assumed data is consistent with the empirical data.

Potential Lethality range for Permanent damage against 40 dB shielded military systems	**Potential Lethality range for Permanent damage against Swedish Fighter Aircraft**	**Potential Lethality range for Permanent damage against 50 dB shielded military systems**
730 m.	463 m.	231 m.

Table 15. Potential Lethality range comparison of military systems for moderate e-bomb

It has also been reported that the unshielded computers suffer bit errors when exposed to microwave fluence as low as 10^{-8} μJ/cm^2 (= 10^{-10} J/m^2) through the back-door coupling (Florig, 1988). This threshold value can be compared to the energy density of the e-bomb model in the simulation. The simulation output shows that the medium-tech e-bomb produces energy density that exceeds the electromagnetic susceptibility limits of unshielded computers up to 8 km (see Figure 45). That is, the proposed medium-tech e-bomb has the potential upset range of 7963 m against the unshielded computer in terms of causing bit errors.

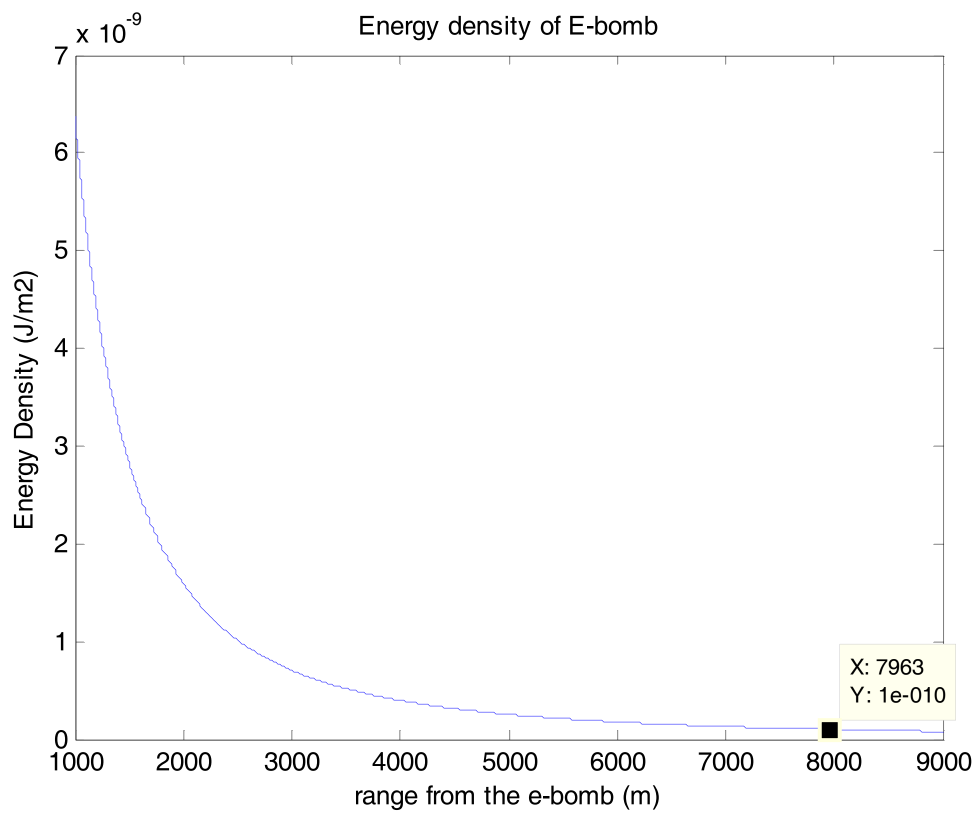

Figure 45. Medium-tech e-bomb potential upset range for unshielded computers

3. High-Tech (Powerful) E-Bomb

The specifications for high-tech (powerful) e-bomb are defined in Table 1. The proposed e-bomb now has 2 GHz operating frequency and corresponding waveguide is WR510. Table 16 shows the simulation output for the high-tech e-bomb.

P_{avg} (MW)	E_{max} (waveguide) (MV/m)	E_{peak} (at the aperture) (kV/m)	FOM (MV)
20	66.4	1.72	143.35

Table 16. Simulation output for field strengths of high-tech e-bomb

The results show that the produced field strength is 143.35 kV/m at 1 km from the e-bomb and 14.4 kV/m at 10 km (see Table 17). These estimates do not include atmospheric losses.

P_{avg} (MW)	E r = 1m	E r = 1 km	E r = 5 km	E r = 10 km	E r = 100 km
20	143.35 MV/m	143.35 kV/m	28.67 kV/m	14.335 kV/m	1.44 kV/m

Table 17. Field strengths of high-tech e-bomb at different ranges

Some of the simulation output for different parameters of the e-bomb is shown in Figure 46 (All simulation output for the high-tech e-bomb is shown in Appendix-C). The results show that at 9 km, the atmospheric loss due to the moderate rain decreases the field strength by 20 V/m. Lossless E-field strength at 9 km from the e-bomb is then 15.93 kV/m where E-field strength with atmospheric loss is 15.86 kV/m and E-field strength with atmospheric loss and rain loss is 15.84 kV/m at the same range.

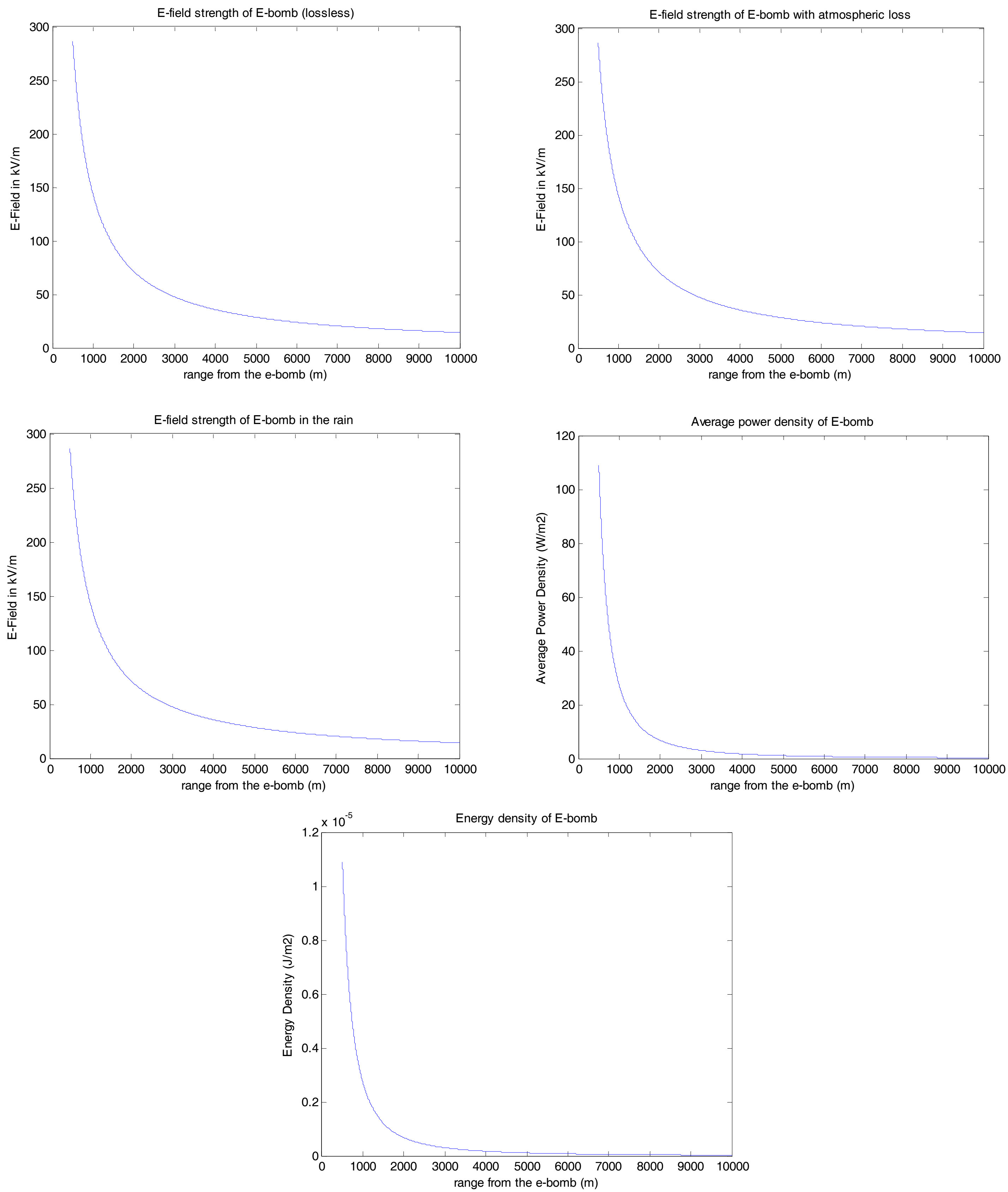

Figure 46. Simulation output for high-tech e-bomb

According to the HIRF standards, simulation results show that the high-tech e-bomb produces field strength that exceeds the standard environment limits of commercial airplanes up to 42.6 km (see Figure 47). That is, the proposed high-tech e-bomb has a potential lethality range of 42,590 meters against commercial airplanes.

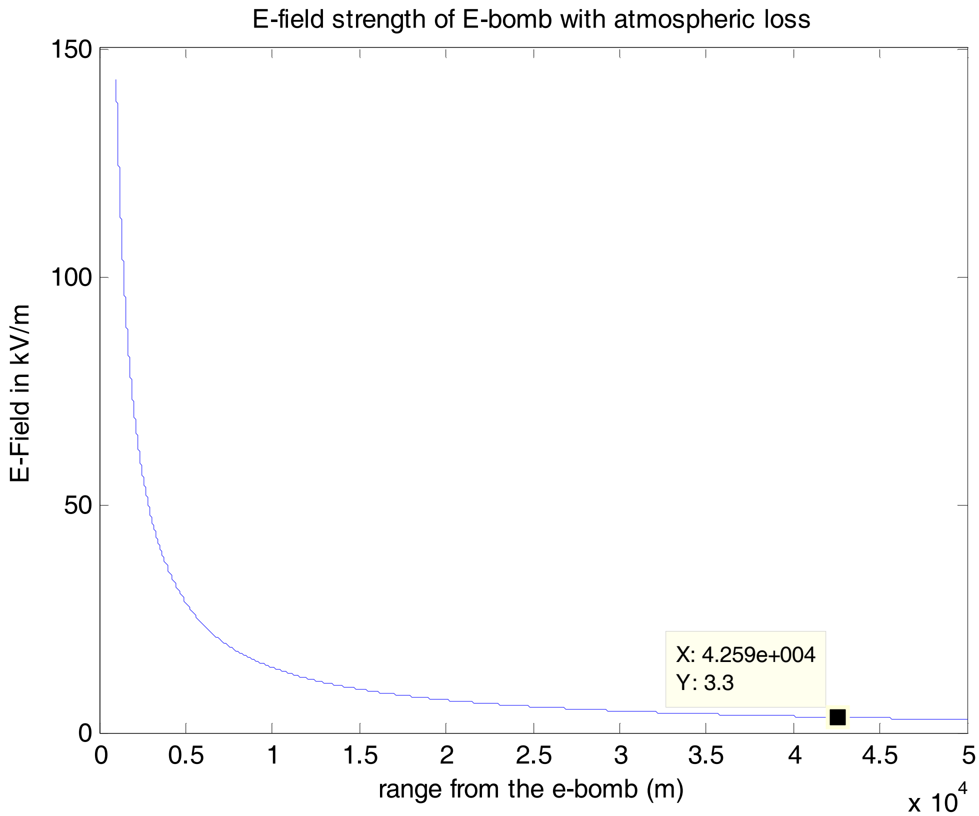

Figure 47. High-tech e-bomb potential lethality range for commercial airplanes

Simulation outputs shows that moderately shielded electronic systems are susceptible to the high-tech e-bomb up to 46.7 km (see Figure 48). That is, the proposed high-tech e-bomb has a potential lethality range of 46.67 km against moderately shielded systems.

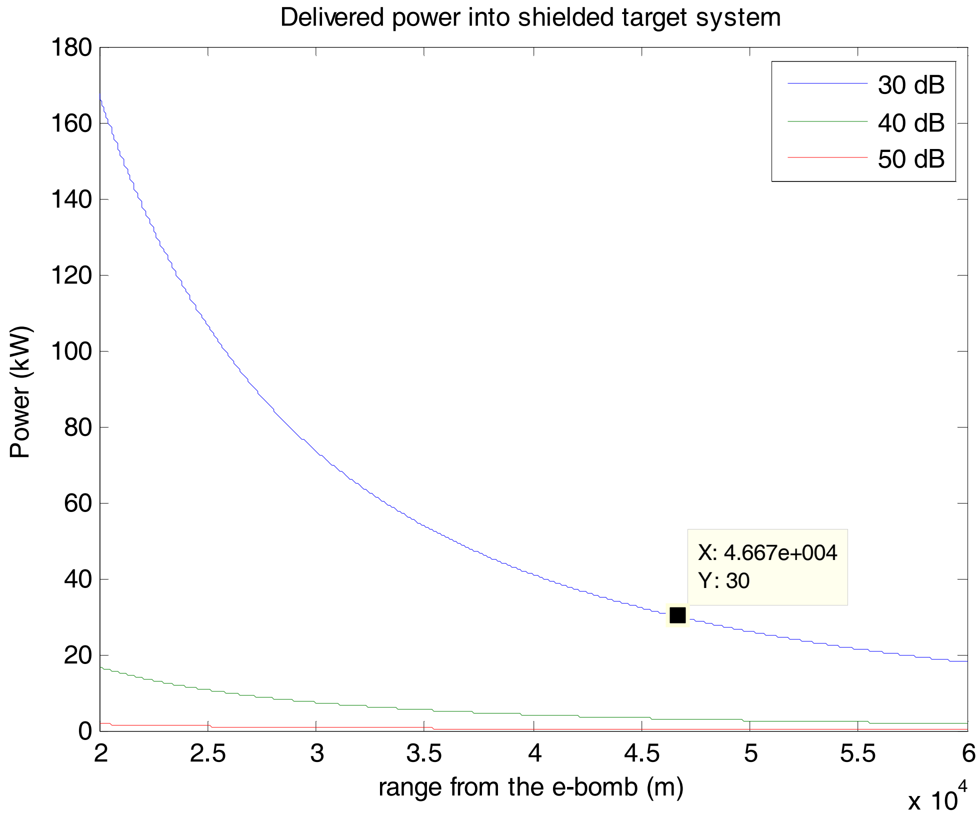

Figure 48. High-tech e-bomb potential lethality range for moderately shielded electronic systems (30 dB SE)

If the electronic equipment is a 40 dB-shielded (fully shielded) military system, in this case, simulation results show that the high-tech e-bomb produces power that exceeds the electromagnetic susceptibility limits of representative devices up to 15 km (see Figure 49). That is, the proposed high-tech e-bomb has a potential lethality range of 14.98 meters against 40 dB-shielded military systems.

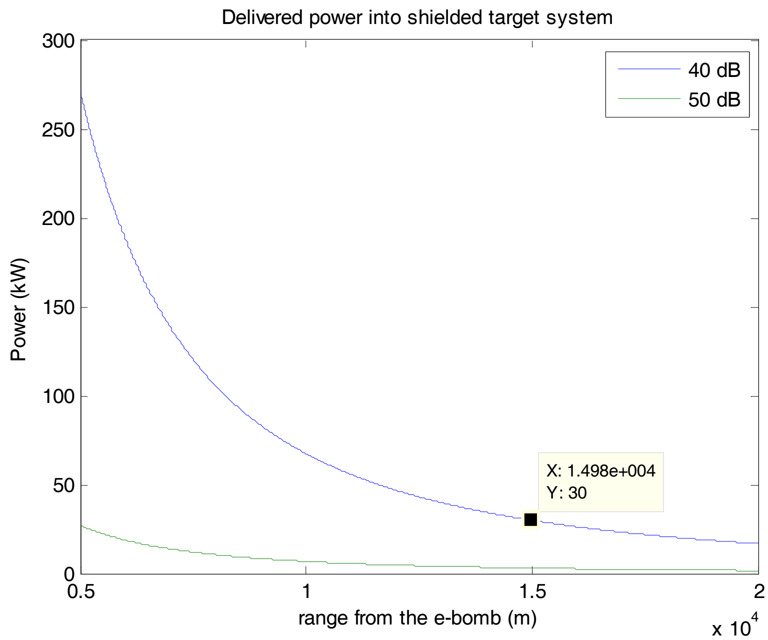

Figure 49. High-tech e-bomb potential lethality range for military systems (40 dB SE)

If the military system has 50 dB in shielding, the potential lethality range for permanent damage of the system then drops to 6.72 km (see Figure 50).

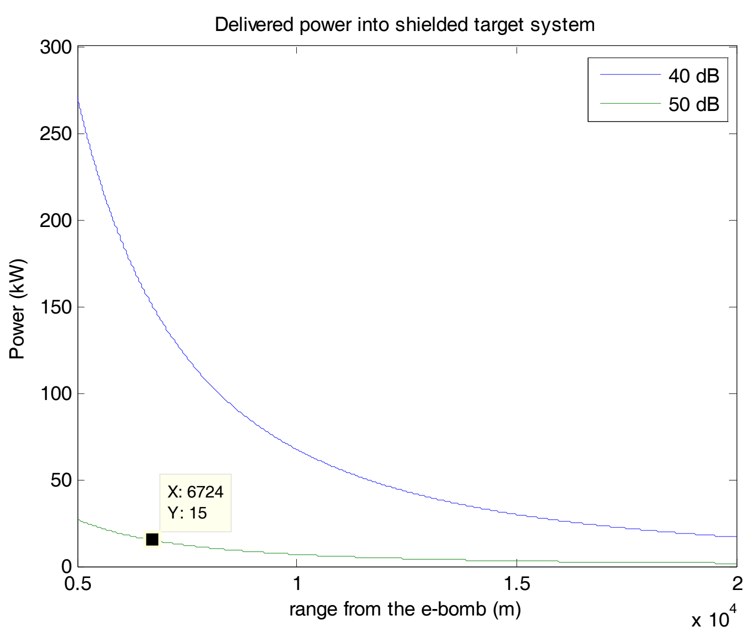

Figure 50. High-tech e-bomb potential lethality range for military systems (50 dB SE)

The high-tech e-bomb produces more than 15 kV/m field strength, which was the permanent damage threshold level for Swedish Fighter Aircraft, up to 9.5 km (see Figure 51), which means that the potential lethality range for e-bomb is 9,500 m.

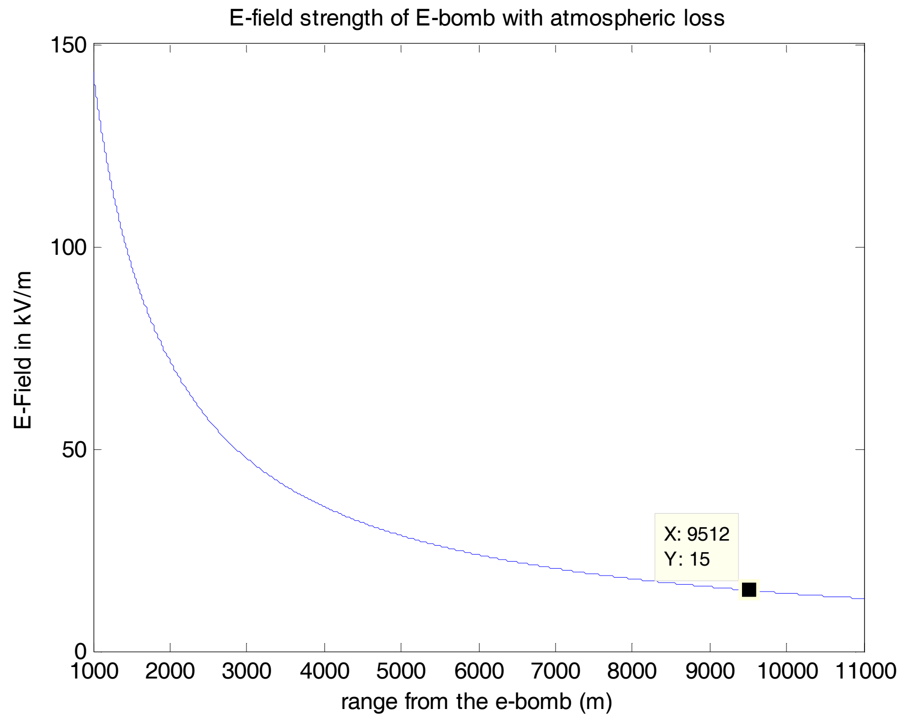

Figure 51. High-tech e-bomb potential lethality range for Swedish Fighter Aircraft

The comparisons of simulation results of military systems for the assumption data and the empirical data are shown in Table 18. The data again verifies the 40-50 dB shielding effectiveness is appropriate for military systems.

Potential Lethality range for Permanent damage against 40 dB shielded military systems	**Potential Lethality range for Permanent damage against Swedish Fighter Aircraft**	**Potential Lethality range for Permanent damage against 50 dB shielded military systems**
14980 m.	9512 m.	6724 m.

Table 18. Lethality range comparison of military systems for powerful e-bomb

Finally, according to the reported data, the simulation shows that the proposed high-tech e-bomb has a potential upset range of 153.8 km against the unshielded computer in terms of causing bit errors (see Figure 52).

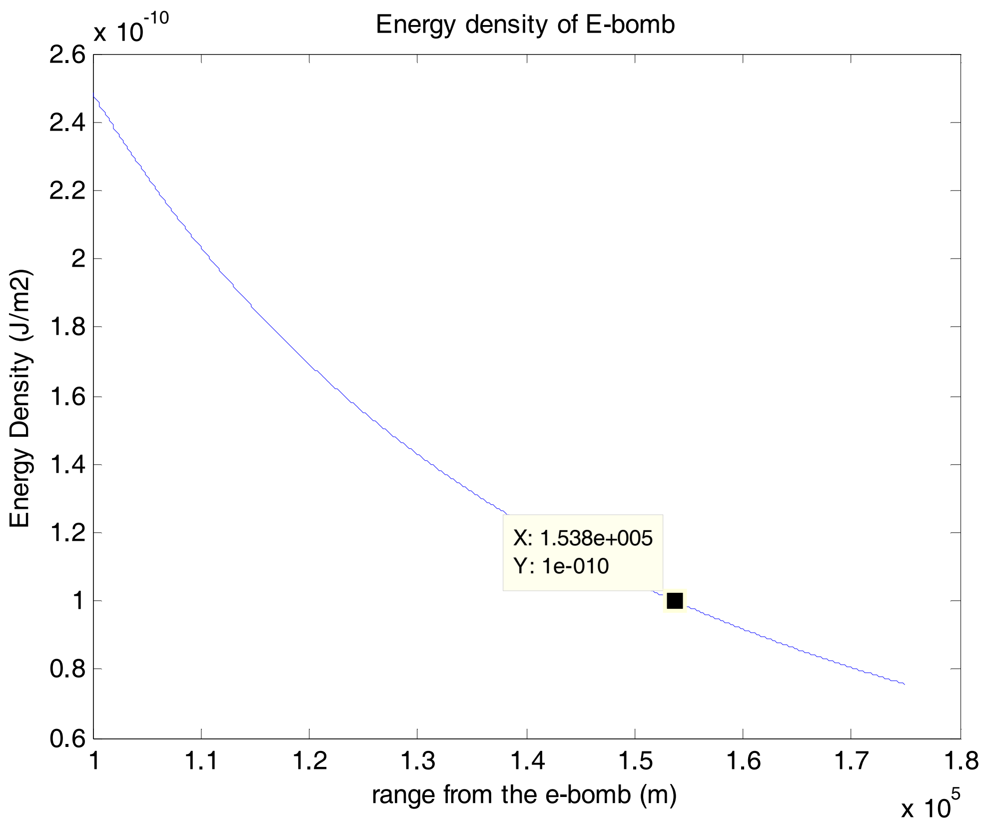

Figure 52. High-tech e-bomb potential upset range for unshielded computers

G. DEFENSE AGAINST E-BOMB

The possible effect of an e-bomb could be upset or permanently damage on electronic devices within the lethality range. Even though the electronic device is turned off, there is still a high possibility that the device could be detrimentally affected.

The fact that the best protection against any weapon is destroying the platform on which the weapon is delivered, is also valid for e-bombs. But sometimes this solution can not be easily implemented or even possible.

In this case, the best protection against e-bombs seems to be hardening the electronic equipment against microwave radiation.

From the defense perspective, in the event of a war, e-bombs could be the first kind of weapons to be used against communication systems and air defense systems. In such a case, it is vital to prepare by hardening in advance all the defensive countermeasures before the attack.

The most effective method for shielding is to wholly contain the equipment in an electrically conductive enclosure, termed a Faraday cage, which prevents the electromagnetic field from gaining access to the protected equipment (Kopp, 1993). But even in this case, since most such equipment must be fed with power from the outside world, the penetrations, the cracks, the scams, etc, create a vulnerability at the entry points against an electromagnetic environment such as from e-bombs.

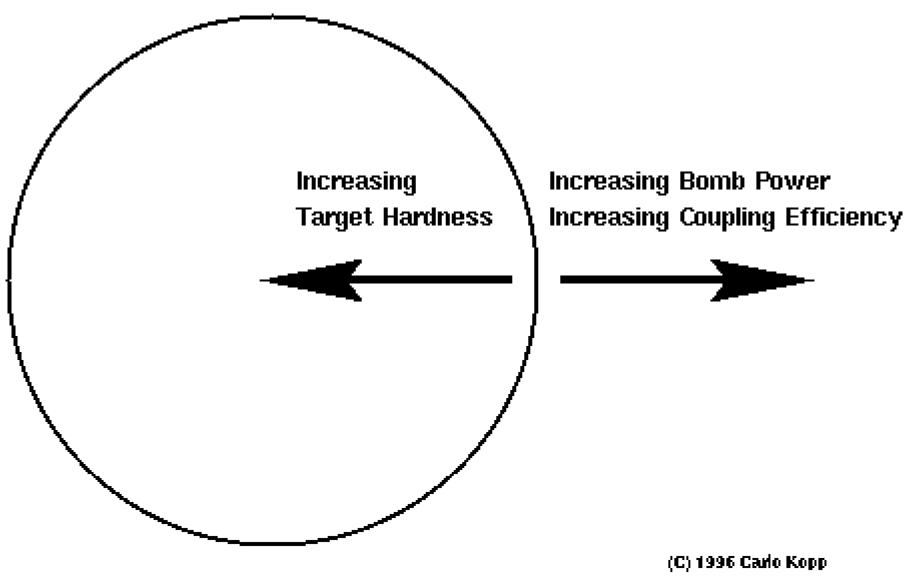

FIG.5.1 E-BOMB LETHAL RADIUS

Figure 53. Shielding Effect against e-bomb (Kopp, 1996)

Figure 53 shows the effect of shielding the electronic devices. If the shielding effectiveness is increased to a level at which the e-bomb lethality range does not make sense anymore, use of e-bomb would cease to be a good option for the opponent. The counter attack for the shielding is increasing the power of the e-bomb source. At some point, however, the breakdown in the atmosphere will be a limiting factor for the design of such a high power source-e-bomb.

The technology for protection from high-power microwave energy through topological shielding with terminal protection devices and filter isolation is available. It can be used to provide adequate hardening for any level of exposure. However, as the incident fluence is increased, the degree of required protection becomes more difficult to achieve (Taylor and Giri, 1994).

As shown in the previous sections, even though a 50 dB shielding effectiveness is achieved, there could still be a threat for the electronic devices from e-bomb. More shielding effectiveness (i.e., 60, 70 dB) will obviously provide a better protection. On the other hand, it may not be possible to retrofit harden old systems up to this level. They may require a complete replacement. In simple terms, hardening by design in the system acquisition phase would be easier and cheaper and more effective than attempting to harden the existing device (Kopp, 1993). Even in this case, sometimes the entire topological shielding concept could not be a cost-effective approach. Hardening most military systems and mass-produces commercial equipment including PCs and communications equipment against HPM would add somewhere between from 3% to 10% to the total cost, if hardening is engineered into the original design. To retro-fit existing military electrical equipment with hardening would add about 10% to the total cost (Wood, 1999).

Other than shielding, passive electronic counter measures such as using low probability of intercept (LPI) techniques could be a good way to protect the systems. New LPI radar technology is a good example for these measures. If it can be achieved to hide the radar emissions from the enemy, there would not be any observable target for enemy to launch an e-bomb to attack.

Another technique could be to choose an appropriate topology for communications networks. In network centric warfare, the ratio of the capability of the communication network for all nodes to that of the reference network is called network richness (Pace, 2007). The network richness for a network is given by

$$I_R = \frac{1}{C_M{}^R} \sum_{\mu=1}^{N_T} K_\mu \sum_{v=1}^{N_\mu} L^{\mu v} \left(\sum_{\gamma=1}^{N_{\mu v}} \frac{F_\gamma{}^{\mu v}}{d_\gamma} \right) \tag{20}$$

where

$C_M{}^R$	:	Reference network connectivity measure
N_T	:	# of node
K_μ	:	node μ capability value (0< K < 1)
N_μ	:	# of nodes connected to the node μ
$L^{\mu v}$	:	information flow parameter of route γ connecting node μ, v ((0< L < 1)
$N_{\mu v}$	:	# of routes connecting pair of nodes μ, v
$F_\gamma{}^{\mu v}$	:	connection capacity of route γ connecting node μ, v (F is either 0 or 1)
d_γ	:	# of links of route γ connecting node μ, v.

According to equation (20), maximum value of network richness can be 1 where all nodes are connected to each other and all links and nodes have maximum capability. A better interactive network topology could be chosen as protection against e-bomb attack in order to maintain the operability of the network even though some portion of the network may be permanently damaged after the e-bomb attack. The concept here is that the network would self-heal by re-routing mission critical information to more robust paths.

H. MILITARY UTILITY

Within this study, three types of hypothetical e-bomb have been proposed. Such an immature weapon concept will definitely have disadvantages in design and application phases. However, the foreseen advantages, as seen in the simulation results, make it attractive to put more effort in exploring the military utility of such a weapon.

1. Advantages

If the e-bomb can be produced, it will definitely be a key element of Electronic Warfare (EW). Electronic Attack, one of 3 divisions of EW, involves the use of electromagnetic or directed energy to attack personnel, facilities or equipment with the intent of degrading (Scleher, 1999). It is shown in the previous sections that such a weapon can most likely produce power outputs that exceed the known susceptibility levels of most of electronic devices, even if they are shielded. If it can be used as intended in the battlefield, e-bombs can potentially permanently damage opponent's electronic equipment. Or opponent's systems can be upset as a result of e-bomb attack, which gives a reasonable time for other assets to attack the enemy forces.

If the enemy is mostly dependent on a network to maintain command, control, communication, computer, intelligence, surveillance and reconnaissance (C4ISR), an e-bomb attack can probably degrade network functionality. Since the new generation battlefield concentrates on network centric warfare, one could say with confidence that an e-bomb will be an important threat to C4ISR for the future battlefield.

Another advantage of using e-bomb is the multiple effects on enemy systems. The first phase of the air war includes suppression of enemy air defense (SEAD) systems. Anti-radiation missiles (ARM) are universally accepted weapons in order to accomplish SEAD missions. By comparison, one e-bomb can degrade multiple systems of diverse types whereas the ARM is used against only one system. When considering the cost/benefit issue of such missiles, the e-bomb can be an attractive weapon in comparison of ARM.

Outside the battlefield, there are several industries and institutions that support the armed forces such as companies producing defense products, TV stations broadcasting anti-propagation programs etc. If these support organizations are considered as viable military targets, and if it is considered that such buildings are moderately shielded, the e-bomb lethality against these targets will be much higher than that achieved against military targets.

Another major advantage for the e-bomb is that it can be delivered from any platform with a navigation-attack system capable of delivering GPS guided munitions. As we can expect GPS guided munitions to be the standard weapons for almost every platform for the foreseeable future, every platform can deliver e-bombs. It also gives an advantage to multi-role platforms.

2. Disadvantages

The potential lethality range of e-bomb mostly depends on the coupling efficiency of electric field strength into the target system. Since the coupling is a complex issue and has many parameters, a desirable lethality range can be reliable with accurate intelligence of opponent’s system design and protection features. Such information is very difficult to obtain. That is why e-bomb damage assessment is an area that still needs improvement.

You will never know precisely how effective the e-bomb devastated the system. Even though the damage assessment does not seem possible to decide whether a soft kill or a hard kill is achieved; some methods can help to evaluate the result of e-bomb attack. Consider that the e-bomb is used against an enemy radar. If the e-bomb damaged the target radar, the enemy radar will stop transmitting for a long period unless an emission silence has been ordered at that time. That is the result of passive electronic support systems operated to assess the electronic activity of the enemy’s emitters could give an idea whether the e-bomb devastated the system or not. One can say, the e-bomb attack is successful, if the end result was that there is no electronic activity after the attack where there was before the attack.

> In the context of targeting military equipment, it must be noted that thermionic technology (i.e., vacuum tube equipment) is substantially more resilient to the electromagnetic weapons effects than solid state (i.e., transistor) technology. Therefore a weapon optimized to destroy solid state computers and receivers may cause little or no damage to a thermionic technology device. Therefore a hard electrical kill may not be achieved against such targets unless a suitable weapon is used. (Kopp, 1993).

Another limitation of designing the e-bomb is the atmospheric limitation. In order to overwhelm this limitation, the waveguide and the reflector can be vacuumed and filled with appropriate gas to increase the breakdown limitation. In application, high breakdown limits such as 100 MV/m do not seem realistic. This is a big barrier to the technological improvement of such weapons.

The antenna is also a limiting factor for e-bombs. More effective range depends on the aperture size of the reflector. Since a big antenna is not appropriate in terms of delivering e-bombs to long distances, improvements in this area need to be achieved in the future. Arraying antennas might be worth investigating.

The accuracy of delivery can be another disadvantage for e-bombs. Our notional high-tech e-bomb has a potential upset range up to 15 km against military systems. If the e-bomb cannot be delivered to the intended point in the battlefield, it will obviously decrease effects considerably.

A notional low-tech (small) e-bomb has been introduced to show that it is easily designed with commercially available devices and does not require high level engineering experience. Moreover, that low-tech e-bomb is shown to produce power output more than the susceptibility level of unshielded systems up to 3 km. Many electronic systems don’t have any shielding. Terrorists can produce such weapons easily for use against civilian systems. It can lead to temporary panic in daily life.

The possibility that enemies or terrorists will have such weapons indicates the advisability of shielding our own assets. This necessity will increase production and maintenance cost of such systems.

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IV. COMPARISON OF WEAPONS BY USING MULTIPLE OBJECTIVE DECISION MAKING

> No matter how rich and prosperous, a nation without independence, cannot be subject to any behavior before the humanity, at a higher level than serving.
>
> — Mustafa Kemal Atatürk

After all the information proposed in the previous chapters, is it worthwhile to invest in research and development of an e-bomb? Even if such a weapon can be produced, is it really as lethal as other electromagnetic weapons? What would make proposed e-bombs attractive in comparison with other weapons? All these questions can be addressed using the method of Multi-Objective Decision Making.

Utilizing the information presented in the previous chapters, formulation for the comparison among the three types of weapons (the HEMP, the HPM, and the e-bomb) is detailed in this chapter. In order to do this, multi-objective decision analysis are used to assess the three types of weapons.

This chapter proceeds as follows: some basic principles are defined to introduce Multi-Objective Decision Making; a model is proposed in order to compare electromagnetic weapons; and the output is analyzed.

A. MULTIPLE OBJECTIVE DECISION

Decision making is defined in the open literature as:

> Decision making is the process of selecting a possible course of action from all the available alternatives. In almost all such problems multiplicity of criteria for assessing alternatives is pervasive. That is, for many such problems, the decision-maker wants to attain more than one objective or goal while satisfying the constraints dictated by environment, processes, and resources. Another characteristic of these problems is that the objectives are frequently appear to be non-commensurable (Hwang and Masud, 1979).

Since the early 1960s, a large and diverse literature has been published in order to solve the multiple-objective decision problems that occurs because of the complexity of diverse situations and the multiplicity of factors that are involved. Theoretical and methodological developments have been based on a number of different opinions, reflecting the breadth of disciplines involved (Chankong and Haimes, 1983).

Multi-objective decision making involves an entire process of problem solving. A lucid description of the corresponding decision situation that defines the problem structure and the decision environment of the decision problem is a fundamental to a multi-objective decision problem. Such description can be accomplished by identifying the boundaries and the basic components of the problem. If the multi-objective decision process and the decision situation is considered as a black box, structurally, there will be some input information, and a process that is defined by the decision maker. As a result, a decision will be produced as output (Chankong and Haimes, 1983).

One way to make a multi-objective decision is to estimate the overall measure of effectiveness of each alternative. The approach of measure of effectiveness of any system depends on five key components: The decision-maker, a set of alternatives (course of actions), the environment in which the alternatives are shaped, a set of objectives and a set of decision rule. The flow diagram of this process is shown in Figure 54. According to the output of this process, some alternatives come better than others depending on the preferences of the decision maker.

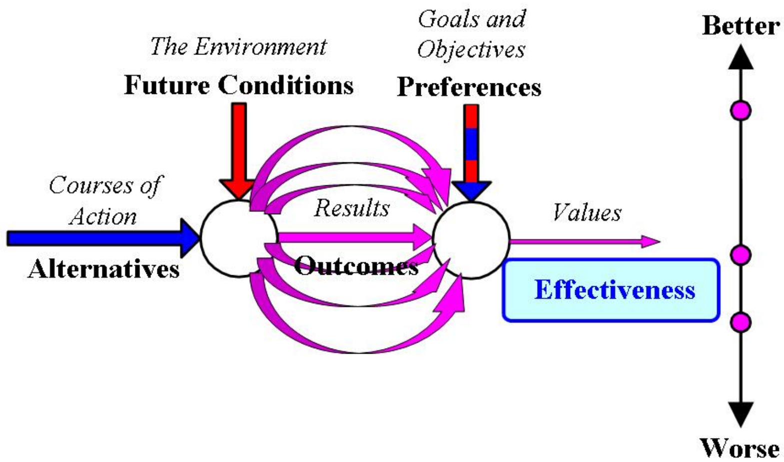

Figure 54. Measure of Effectiveness Model (Airola, 2007)

After defining the alternatives and the battle scenario (environment), the key step in evaluating each alternative is to define the objectives that are to be measured. The most common method to define the objectives and related sub-objectives is additive value model. Overall measure of effectiveness can be expressed in "additive value model." This model defines the objectives in a hierarchical structure in which the relevant objectives are grouped as a set of objectives. Objectives at the lower level in the hierarchical structure are more specific and more operational than those at the higher level. That is, the objectives at the lowest level of the hierarchy are the most specific and the most operational objectives overall (Chankong and Haimes, 1983).

For multiple objective decision making, structuring the objective hierarchy is the most important step. Objective hierarchy permits you to go from multiple objectives to a single measure of effectiveness (Airola, 2007).

An objective defined in the structure gets operational if the level of achieving such an objective can be assessed in a practical way. To make the objective operational, each objective is defined in terms of a group of attributes in the lowest level. An attribute is a measurable quantity whose measured value reflects the degree of achievement for a particular objective. An attribute can be measured in quantity even though the achievement is defined in qualitative terms (Chankong and Haimes, 1983). The relation between an objective and an attribute is defined in open literature:

> In many instances, the value of an attribute will give an obvious and direct indication of the degree of achieving an associated objective. These are called the proxy attributes. For example, the attribute "net profit" measured in terms of dollars is a direct measurement of the degree of achieving the objective "maximizing profit." For some problems, it may be possible to formulate accurately the multi-objective decision problem in such a way that objectives and attributes are related only by direct relationships. This type of direct relationship between objectives and attributes is, indeed, what we would like to have. The idea of articulating objectives into hierarchical levels is, in fact, a way of achieving this goal. For each objective in the lowest level there should ideally exist an attribute or a set of attributes whose value is a direct measurement of the level of achieving that objective (Chankong and Haimes, 1983).

Proxy attributes are operationally measurable and assessable. They are also controllable. That is, whatever the decision-maker does, it affects the attributes. Another property of attributes is to be mutually exclusive, in order to avoid double counting.

Once the hierarchical structure is designed, the next step is to define the model mathematically. In this case I will use an additive value model where the value of the model depends on the added value of each objective/attribute and the assigned weight of the objective/attribute. The additive value model is expressed mathematically as

$$v(A) = w_1 v_1(A_1) + w_2 v_2(A_2) + \ldots.. \qquad (21)$$

where $v(A)$ is alternative's value, i is the number of the value measured, A_i is the alternative's score on the ith value measure, $v_i(A)$ is single dimensional value of score of A_i, and w_i is the weight of ith value measure. ($\sum_{i=1}^{n} w_i = 1$)(Parnell, Driscoll, and Henderson, 2008).

Value functions measure returns to scale on the value measures. There are four basic shapes: linear, concave, convex, and an S-curve. In the linear value function, each increment of the measure is equally valuable and adds same value to overall measure. In the concave value function, each increment of the measurement is worth less than the preceding increment and adds less value to overall measure. In the convex value function, each increment of the measure is worth more than the preceding increment and adds more value to overall measure. And finally, the S-curve has the characteristic of both convex and concave since it involves both value functions (Parnell, Driscoll, and Henderson, 2008). For the model proposed in this study, a simple linear value function will be used for each of the attributes.

After defining the ranges for each objective/attribute, and measuring the value, the next step is to find the additive value of individual objective/attribute to the overall effectiveness. Every individual measure of effectiveness has value associated with it. This allows decision makers to convert disparate measures (km, tons, lbs, %availability etc) into a common unit, effectiveness. It also sets bounds on needed performances. Figure 58 shows an example of how to compute the value function using the linearity. As mentioned before, it is assumed that all value functions are linear. The value function is given by

$$v_i(A) = \frac{measured\ value - not\ enough}{good\ enough - not\ enough} \tag{22}$$

where measured value is the measurement of specific objective/attribute, not enough is the down limit of the range of individual objective/attribute, and good enough is the upper limit of the range of individual objective/attribute. “not enough” and “good enough” values are defined by decision-makers. By doing this calculation, a linear scale is established between minimum value (0) and maximum value (1).

After calculating each individual attribute’s value function, the last step in calculating the overall measure of effectiveness is to apply equation (21). For any level of objectives/attributes in the hierarchical structure, the total measure of effectiveness is expressed by the sum of products of each attribute's additive value and the assigned weight of that attribute.

Weights play a key role in the measure of effectiveness model. The weights can be considered as the mirror of the decision-maker since the decision-maker's preferences will form the priorities in the attributes or objectives. Weights assigned to each individual objective/attribute and the defined range to set the best and the worst value for individual objective/attributes directly affect the result of measure of effectiveness. That is why the decision-makers must be careful and sensitive while forming the measure of effectiveness structure, deciding on the assigned weights and defining the ranges. There are many subjective ways to determine the weights, but there are some other ways that the weights are assigned more precisely, in which the preferences of the group are represented in a better way. One common way to assess weights from a group of experts is defined in the open literature as:

- *Vote. (Have each individual spread 100 points over the value measures based on the measures' range.)*
- *Discuss significant differences. Have the "outliers" discuss their rationales.*
- *Revote until the group agrees on the ordinal ranking of the value measures.*
- *Vote again requiring each person's weights to follow the group's ordinal ranking of the value measures.*
- *Average the weights (cardinal ranking of weights) and normalize so they sum to one.*
- *Discuss significant differences. Have the "outliers" discuss their rationales.*
- *Repeat last two steps until the group agrees* (Parnell, Driscoll, and Henderson, 2008).

According to this approach, if there are disagreements about the weights that can not be resolved, they must be recorded for later evaluation of alternatives in order to do a sensitivity analysis to determine if they are significant. Mostly, the preferred alternatives are not sensitive to the weight range evaluated (Parnell, Driscoll, and Henderson, 2008).

For this study, a common-sense approach will be used to assign the weight for each attributes and the objectives.

B. MEASURE OF EFFECTIVENESS MODEL FOR ELECTROMAGNETIC WEAPONS

Measure of effectiveness model for electromagnetic weapons is slightly different from any model for lethal weapons. The most important features of electromagnetic weapons are that they are not lethal, not explosive, but capable of degrading the opponent's electronic systems. Since there is no published/proven electromagnetic weapon on the shelf, the proposed model will assess mostly the qualitative aspect of electromagnetic weapons. Since the purpose of this study is to show whether the e-bomb is worthy of R&D facilities, the proposed model is intended to be useful to make a recommendation for this question.

The effectiveness of electromagnetic weapons are evaluated under five objectives: Design, Compatibility, Lethality, Operational Suitability and Human Factors. Each of them are identified, including the sub-objectives/attributes. Then, they are weighted according to the importance given by the author of the study. Next, the acceptable range for each individual attribute will be defined, and finally, assigned value if each attribute is computed to show the overall effectiveness on electromagnetic weapons. Figure 55 shows the proposed measure of effectiveness model structure.

Various colors show the separation between the levels in the hierarchy. According to the color designation, pink represents second level, yellow represents third level and blue represents fourth level of objectives/attributes.

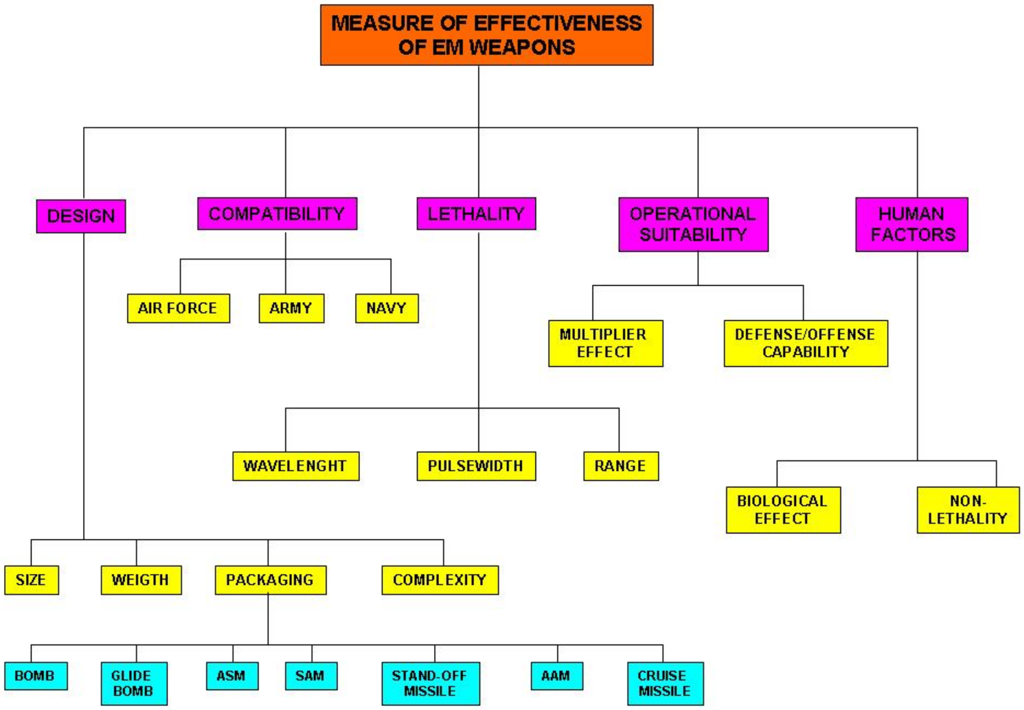

Figure 55. Measure of Effectiveness Model for Electromagnetic Weapons

The weights assigned to each individual second level objective are:

- DESIGN : 0.10
- COMPATIBILITY : 0.15
- LETHALITY : 0.50
- OPERATIONAL SUITABILITY : 0.20
- HUMAN FACTORS : 0.05

The most important measurement for comparing the weapons is of course the lethality. Even though electromagnetic weapons are non-lethal weapons against human, there is still a lethality issue against electronic systems. For this objective, it is intended to give more effectiveness to the weapon with more effect on electronic systems. More lethality means a better electromagnetic weapon. The attributes that drive lethality are the lethal range of the weapon, wavelength and pulsewidth of the signal. Lethality range is a measurable factor. The expected potential lethality will be used as the lethality range of the notional e-bomb.

For the comparison, the lethality range will be determined against a specified target. For this study, Swedish fighter aircraft will be that target. The second attribute, wavelength, determines the coupling efficiency of the electromagnetic weapon. Shorter wavelengths generally offer better coupling performance, better power transfer performance, and better antenna performance for a given antenna size (Kopp, 1996). The last attribute, pulsewidth, is an important determinant of damage threshold power. The damage threshold power required for thermal second breakdown is given by

$$P_D = A_J \frac{K}{\sqrt{\tau}} \tag{24}$$

where A_J is the junction area of representative electronic device, K is the proportionality constant and τ is the pulsewidth of the signal (Taylor and Giri, 1994). According to equation (24), the higher pulsewidth results in lower damage threshold power. That is, less power is enough to create a damage effect on target. For the measure of effectiveness model, the greater pulsewidth is better in order to provide damage on intended target. The “weights,” “good enough” and “not enough” values are provided in Table 19 for lethality range, pulsewidth and wavelength.

Attributes	**Weights**	**Good Enough**	**Not Enough**
Lethality Range	0.70	200 km	1 km
Wavelength	0.15	0.05 m	2.0 m
Pulsewidth	0.15	1000 ns	10 ns

Table 19. MOE values for lethality attributes

The second most important objective is operational suitability. By Operational suitability measures the role of the weapon in the battlefield. Some weapons are used to defend the units/systems where others are used to attack/destroy enemy units/forces. Similarly, some weapons are effective only on one target where others are mass-destructive. For the comparison of electromagnetic weapons in terms of the operational suitability, two attributes are proposed to drive the effectiveness: Multiplier effect and Defense/Offense Capability. Multiplier effect is the ability of electromagnetic weapon to achieve kills against multiple targets of diverse types within its lethal footprint. This is defined as qualitative measurement in the model. Assessment is made whether the weapon is capable of achieving this particular mission or not. The second attribute, Defense/Offense Capability, is the definition of electromagnetic weapon in terms of tactical usage. For the comparison, an offensive weapon is assumed better than a defensive weapon. The “weights,” “good enough” and “not enough” values are provided in Table 20 for operational suitability attributes.

Attributes	**Weights**	**Good Enough**	**Not Enough**
Multiplier Effect	0.70	YES=1	NO=0.5
Defense/Offense Capability	0.30	Offensive=1	Defensive=0

Table 20. MOE values for operational suitability attributes

The third objective is the compatibility, the integration of the electromagnetic weapon with different platforms (degree of usability with navy, army or air forces). This attribute is measured qualitatively. One weapon can be compatible with surface ships, but not aircrafts. If it is compatible with any platform, it adds value to the compatibility measure. Compatibility with air forces is considered to be the most important since most electromagnetic weapons are meant to be used as SEAD (suppression of enemy air defense) operation. It is assumed that in the future, mostly air forces will use the electromagnetic weapons. The “weights,” “good enough” and “not enough” values are provided in Table 21 for compatibility attributes.

Attributes	**Weights**	**Good Enough**	**Not Enough**
Air Forces	0.50	YES=1	NO=0
Navy	0.25	YES=1	NO=0
Army	0.25	YES=1	NO=0

Table 21. MOE values for compatibility attributes

The design (physical and technical characteristics) of an electromagnetic weapon either for bomb or missile application, is an important issue. The size, weight, complexity and packaging are main factors that drive the design of electromagnetic weapon. The size of the weapon can limit the power source, in turn constraining the lethality and means of delivery. If the size is small, the required power to damage the target can not be packed into the weapon. Similarly, if the size is large, in this case it will limit the flexible use of weapon. That is, the weapon can be used to defend any unit, but can not be delivered as a missile. For the proposed model, qualitative measures will be used to define the size of the weapons. Small and large size is not good, where moderate size is more desirable for electromagnetic weapons. Weight can also be a limiting factor for the means of delivery. If it is a heavy weapon, it can not be delivered as missile or glide bombs. In this case, a lighter weapon is more desirable. Weight is also a qualitative measurement. Another attribute, packaging, is the ability of electromagnetic weapon to be packed in different warheads such as bombs, glide bombs, missiles etc. This flexibility can provide tactical advantage for the electromagnetic weapon. If any weapon can be carried within a cruise missile, or stand-off missile, the operational effectiveness of the weapon will clearly increase. The packaging attributes are measured whether the weapon has that individual flexibility or not. The last attribute under the design is the complexity. Since the technology is not mature in this area, a qualitative value is assigned to each electromagnetic weapon according to the technological complexity for design. The “weights,” “good enough” and “not enough” values are provided in Table 22 for design attributes.

Attributes	**Weights**	**Good Enough**	**Not Enough**
Size	0.25	Moderate=1	Small,Large=0
Weight	0.25	Light=1	Heavy=0
Packaging	0.25		
Bomb	0.14	YES=1	NO=0
Glide Bomb	0.14	YES=1	NO=0
ASM	0.14	YES=1	NO=0
SAM	0.14	YES=1	NO=0
Stand-off Missile	0.16	YES=1	NO=0
AAM	0.14	YES=1	NO=0
Cruise Missile	0.14	YES=1	NO=0
Complexity	0.25	LOW	HIGH

Table 22. MOE values for design attributes

The last objective is human factors. There are two attributes defined as drivers for human factors: non-lethality and environmental effect. Even though all electromagnetic weapons are meant to be non-lethal weapons, non-lethality is considered to be an important attribute, which is shown in the proposed model. If the weapon is not lethal, it is assumed that it is better for humanity. The other attribute is the environmental effect of the electromagnetic weapon. It is generally accepted that biological effects from radiation occur as a result of power absorption. For animals and humans, this process is complicated by non-uniform power absorption and the internal thermal regulation process. Clayborne and Giri define biological effects due to the radiation (Taylor and Giri, 1994). According to the data, exposure levels less than 100 W/m^2 does not have any biological effect. For human factors, the less biologically effective weapon is the better electromagnetic weapon. The exposure level will be converted to the range in meters. Corresponding range represents the maximum range that an electromagnetic weapon can have biologic effects on humans. Figure 56 shows the maximum biological range of high-tech e-bomb. Beyond 522 meters, one can say the e-bomb is not dangerous to humans.

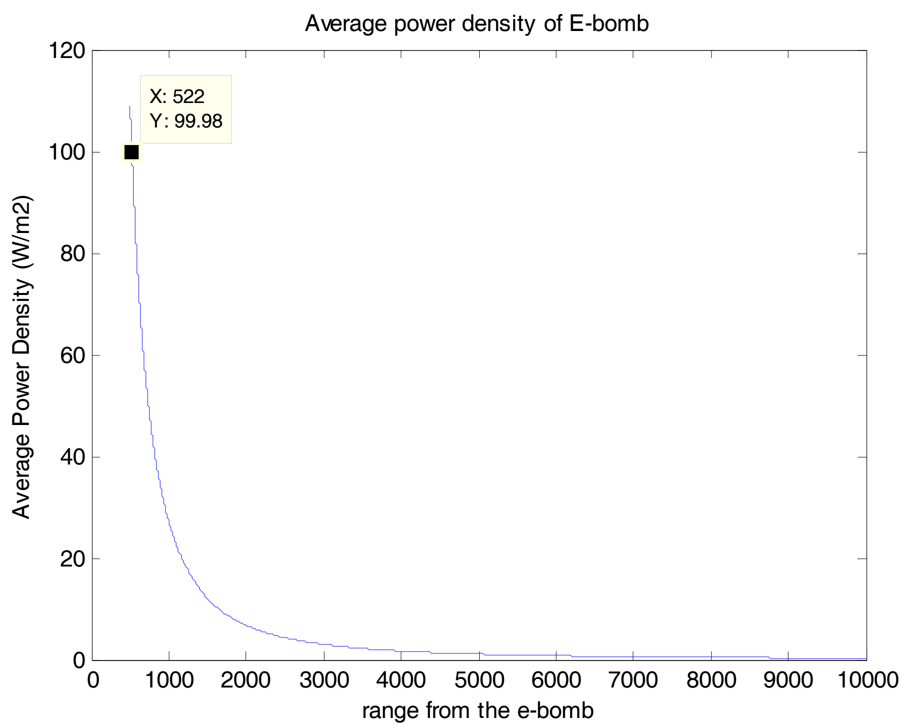

Figure 56. Maximum biological effect range of e-bomb

The “weights,” “good enough” and “not enough” values are provided in Table 23 for human factors attributes.

Attributes	Weights	Good Enough	Not Enough
Non-lethality	0.50	YES=1	NO=0
Biological Effect	0.50	500 m	10,000 m

Table 23. MOE values for human factors attributes

At the very least, the method of analysis for measure of effectiveness proposed in this study offers a way to choose the numerical quantities related to the electromagnetic weapons that are consistent with each other, with an assumed objective, and with the decision-maker's expectation of the future. The methods provides its answers by process that are accessible to critical examination, capable of duplication by others, and more or less, readily modified as new information becomes available.

Figure 57 shows the MOE of EM weapons with weights.

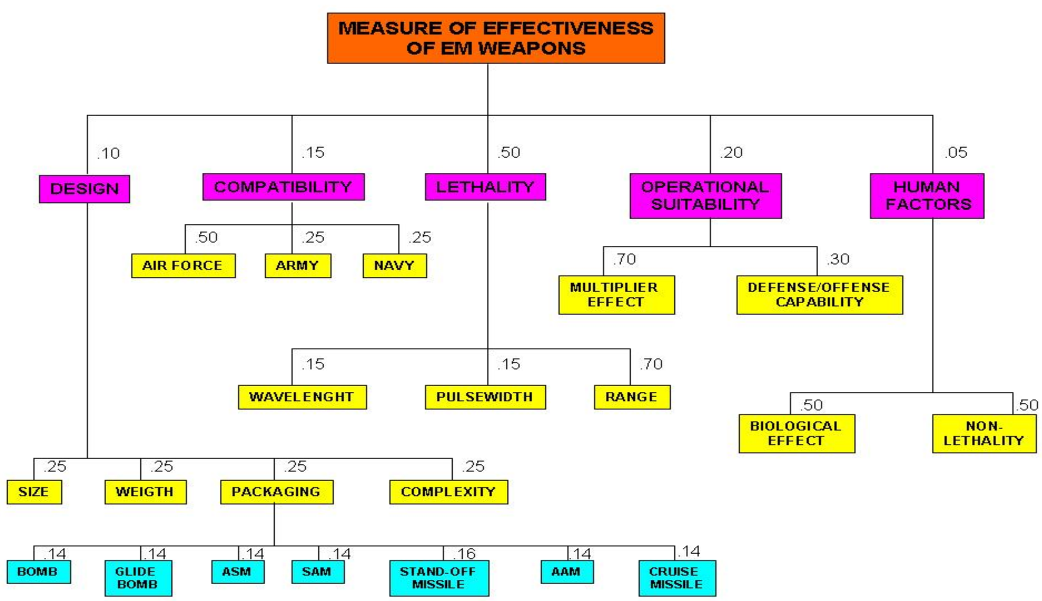

Figure 57. Measure of Effectiveness Model for Electromagnetic Weapons with weights

C. ANALYSIS OF THE MODEL OUTPUT

The specification of each electromagnetic weapon in terms of the measure of effectiveness attributes is defined in Table 24. For the hypothetical e-bomb, high-tech (powerful) e-bomb will be used as reference.

Specifications	**HEMP**	**HPM Weapon**	**E-Bomb**
Design			
Size	Moderate	Large	Moderate
Weight	Light	Heavy	Light
Packaging			
Bomb	NO	NO	YES
Glide Bomb	YES	NO	YES
ASM	NO	NO	YES
SAM	YES	NO	YES
Stand-off Missile	NO	NO	YES
AAM	YES	NO	YES
Cruise Missile	YES	NO	YES
Complexity	HIGH	MODERATE	MODERATE
Compatibility			
Air Forces	YES	YES	YES
Army	YES	YES	YES
Navy	NO	YES	YES
Lethality			
Range	450 km*	~10 km	160 km**
Pulsewidth	500 ns	1000 ns	100 ns
Wavelength	1.5 m	0.1 m	0.15 m
Operational Suitability			
Multiplier Effect	YES	YES	YES
Defense/Offense Capability	Offense	Defense	Offense
Human Factors			
Non-lethality	YES	YES	YES
Biological Effect***	27,272 m	538 m	522 m

Table 24. MOE Specification of Electromagnetic Weapons

* As mentioned before, the electric field measured in Honolulu (800 miles away from the Starfish test facility) was 5.4 kV/m. Such an electric field will have field strength of 15 kV/m (the threshold level for Swedish Fighter) at 450 km.

** Even though the lethality range of proposed e-bomb against Swedish Fighter Aircraft is about 10 km, since the e-bomb can be delivered as cruise

missile, or any other missile, the average reasonable range of the missile (150 km) is added the lethality range of e-bomb.
*** Biological effect ranges are calculated by estimating the range at which the power density becomes 100 W/m^2.

For the specifications of the HEMP, the open literature data has been used. For HPM weapon specifications, the proposed weapon (f=3 GHz, antenna aperture = 100 m^2, pulsewidth=1000 ns) by Clayborne and Giri has been used.

Using the data given in Table 24, each electromagnetic weapon is assessed in terms of the effectiveness model proposed by this study.

Figure 58 shows the measure of effectiveness organization with weights and attribute values.

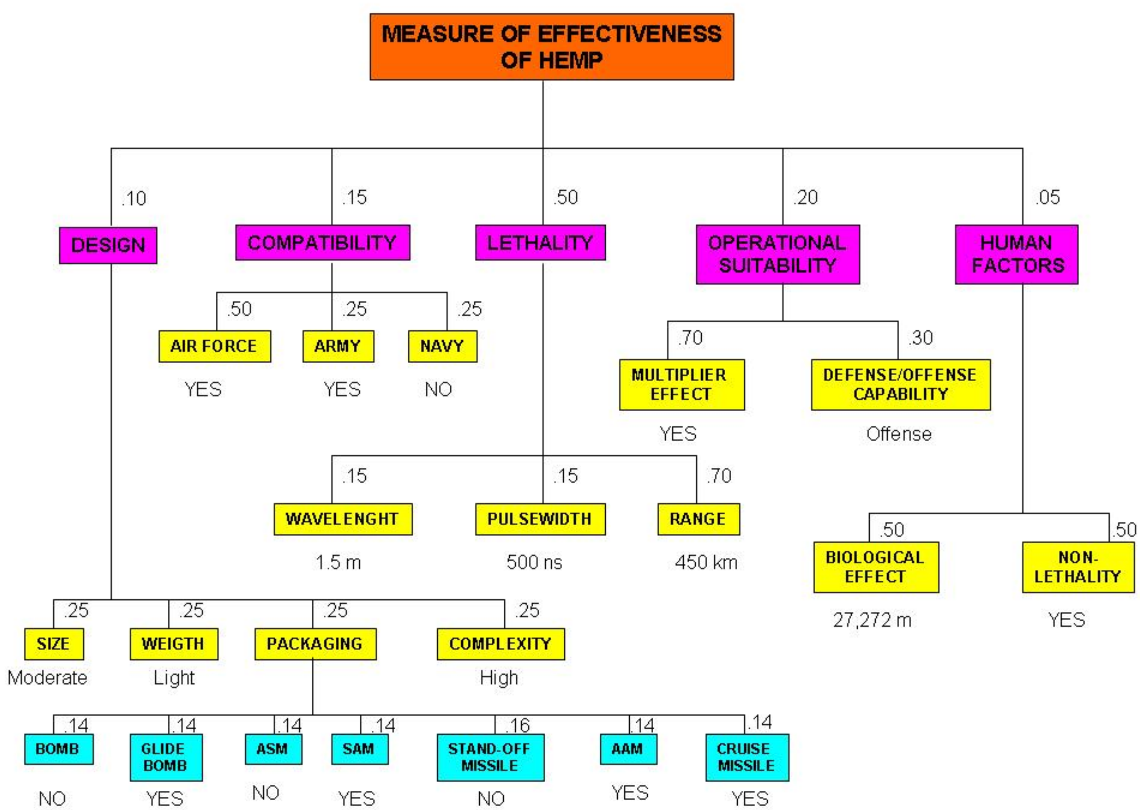

Figure 58. MOE of HEMP

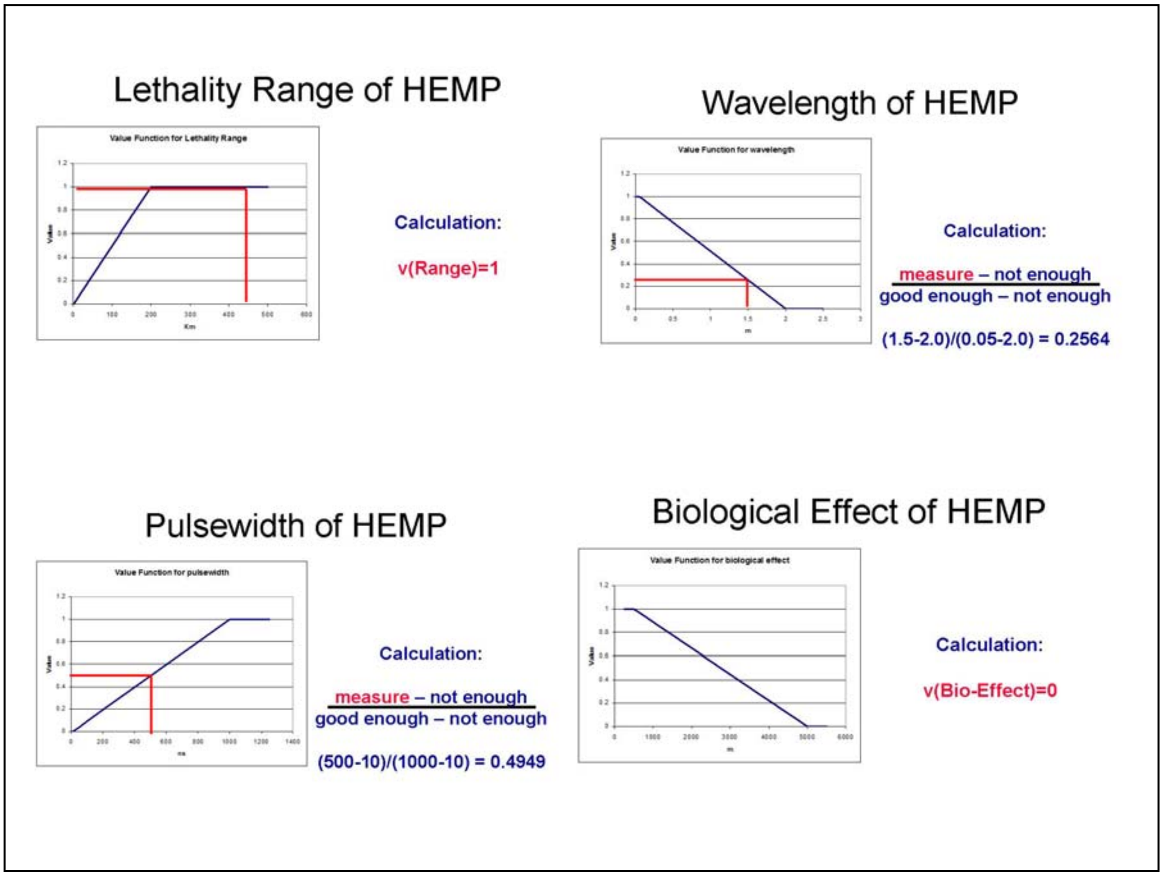

Figure 59. Single attribute calculations for HEMP

After finding the single individual attributes (Figure 59), the additive value method gives the overall effectiveness of HEMP under the assumed model, as to be 0.8078.

The same methodology is applied to measure the effectiveness of HPM weapon. Figure 60 shows the MOE structure for HPM weapon including assigned weights and the measurements/assumptions of each attributes.

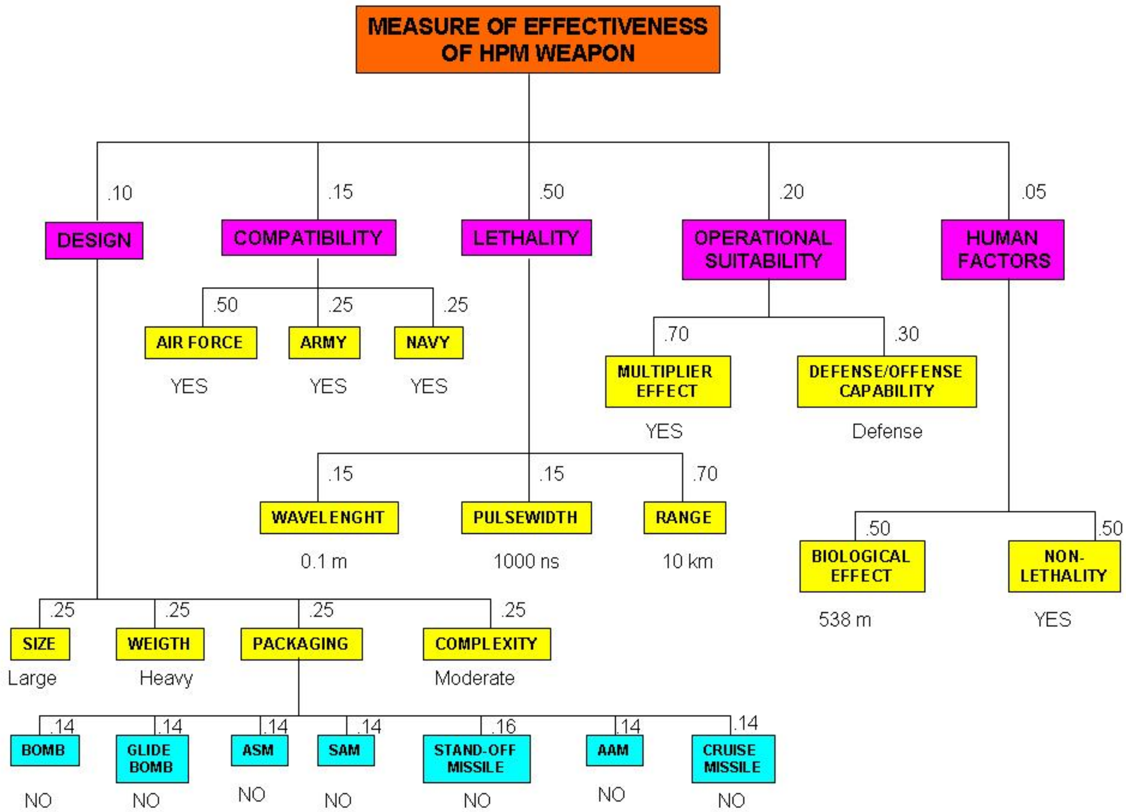

Figure 60. MOE of HPM Weapon

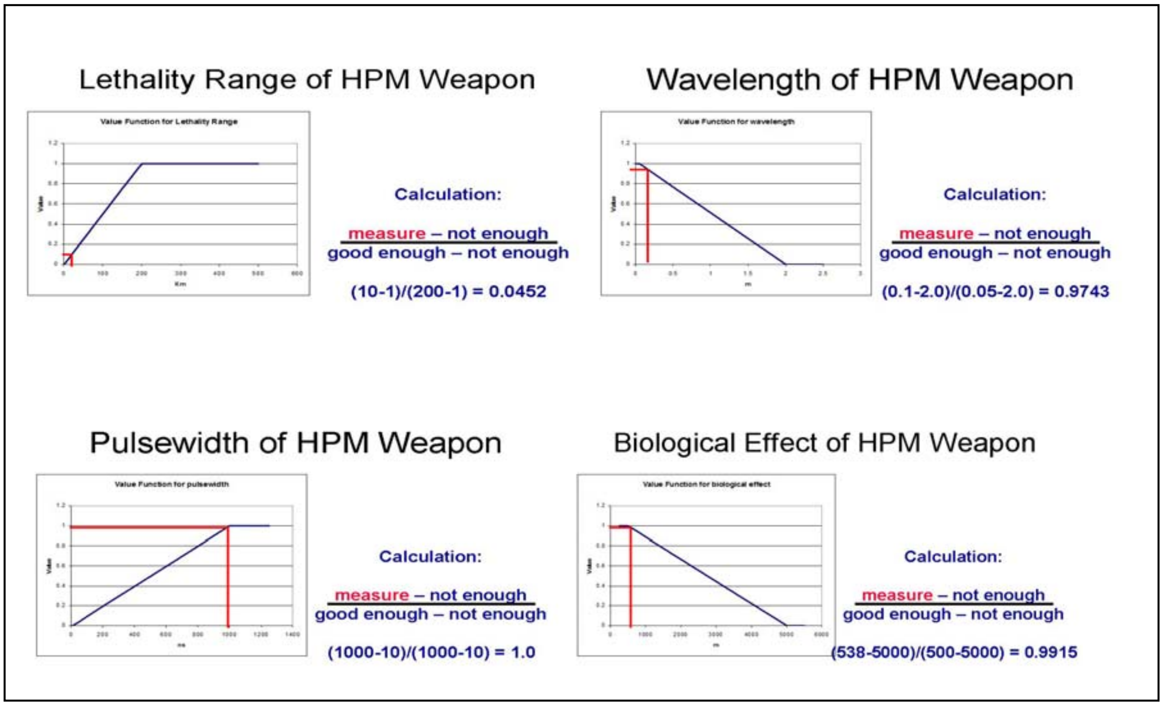

Figure 61. Single attribute calculations for HPM weapon

When same single attribute calculation is done (see Figure 61) and the additive value method is applied, the overall effectiveness of HPM weapon is found to be 0.5162. And finally, the same method is followed for the measurement of effectiveness for e-bomb. Measured/assumed values for an e-bomb are shown in Figure 62.

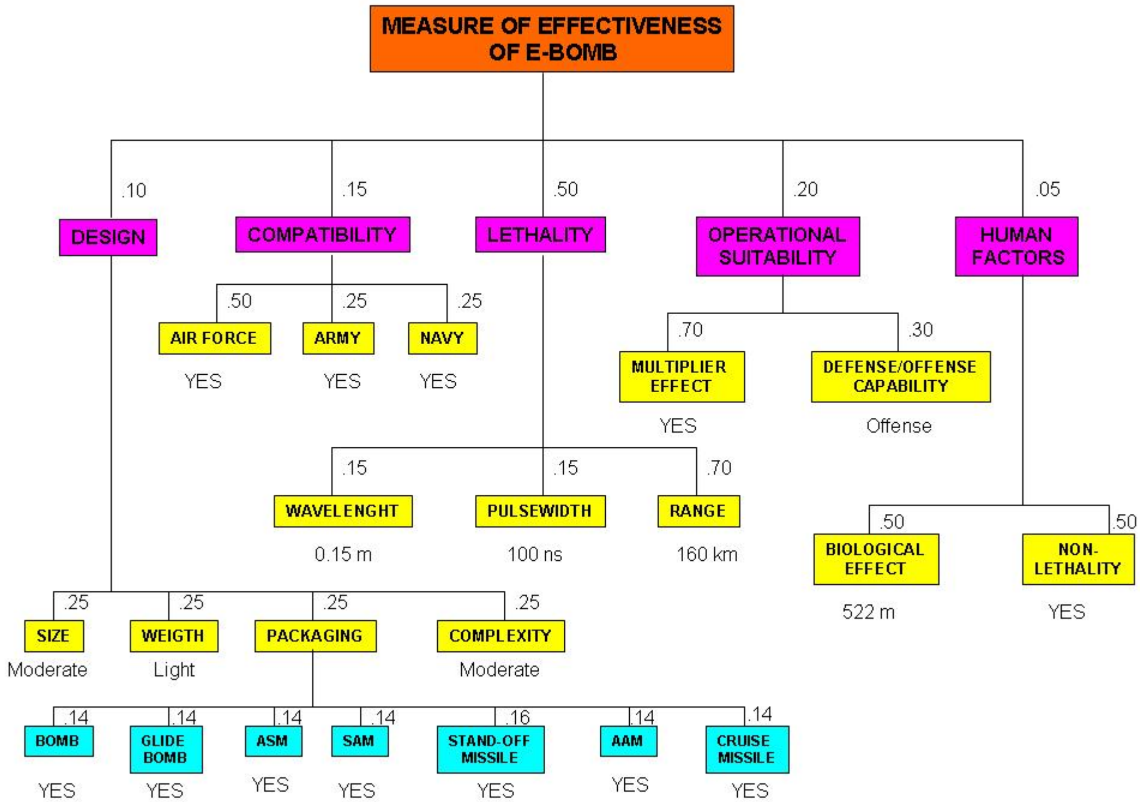

Figure 62. MOE of E-Bomb

The single attribute calculation (see Figure 63) and the additive value method show that under the assumed model, the overall effectiveness of e-bomb is 0.8449.

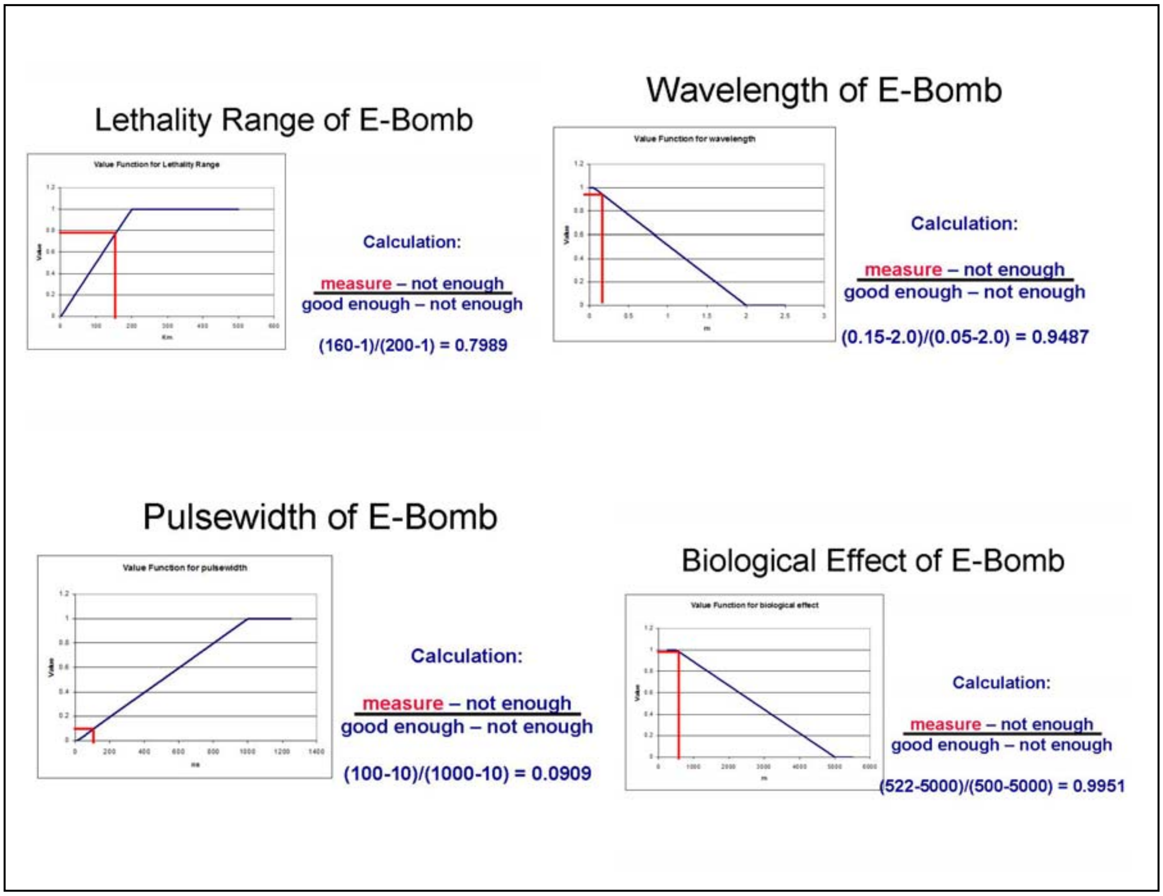

Figure 63. Single attribute calculations for E-Bomb

Since, technologically similar methods are applied to produce such weapons, and there is no reported electromagnetic weapon that has a credible cost estimate, the costs for all electromagnetic weapons proposed in this study are assumed to have same magnitude of cost. This turns the problem into a "maximizing the effectiveness" problem. When three effectiveness models are compared, one can realize that the proposed e-bomb has the best effectiveness among all other options. Surely, the analysis has so many deficiencies. However, if it is considered that there is no real weapon in this area, the purpose of this study can be understood better. This study tries to show that in the future, such weapons will have an important role in the battlefield. Among these weapons, the e-bomb deserves to get the most attention for exploring.

Another interpretation could be that the e-bomb is a mass-destructive non-nuclear electromagnetic weapon. When considering that the HEMP is know as the electromagnetic effect of the nuclear bomb, the cost-effectiveness analysis shows that the e-bomb has also same effect with HEMP.

The HPM weapons are large in size and weight and have a short range. These features make it a fixed weapon. That is why the effectiveness of the HPM weapon is relatively less than the other two electromagnetic weapons. In fact, with its huge design, it is not useful in the battlefield for offensive purposes. It can, however, be used as a defensive weapon against missiles.

On the other hand, HPM weapons are important because they provide the theory for proposed hypothetical e-bombs. With different applications, such as missile, cruise missile etc. the e-bomb can be used as effectively as HEMP.

The proposed model to measure the effectiveness of electromagnetic weapons is believed to be organized to give the best effectiveness analysis. However, it is open to interpretation. Nevertheless, since the qualitative data in this study is limited, and the qualitative data provided is calculated based on the published theoretical data rather than physical measurement, the output of the model may be accordingly inaccurate. If the real data for the proposed model can be measured in the future, the output of the model will be at least somewhat different from the output of this study.

If satisfactory solutions can be found for future problems in e-bomb design, e-bombs promise to be an important and robust weapon in both strategic and tactical operations, offering significantly reduced collateral damage and lower human casualties than established weapons.

References

Albuzio, A., Concheri, G., Nardi, S., Dell'Agnola, G., 1994. Effect of humic fractions of different molecular size on the development of oat seedlings grown in varied nutritional conditions. In: Senesi, N., Miano, T.M. (Eds.), Humic Substances in the Global Environment and Implications on Human Health. Elsevier B.V., pp. 199–204.

Arancon, N.Q., Lee, S., Edwards, C.A., Atiyeh, R.M., in press. Effects of humic acids and aqueous extracts derived from cattle, food and paper-waste vermicomposts on growth of greenhouse plants. Pedobiologia.

Atiyeh, R.M., Arancon, N., Edwards, C.A., Metzger, J.D., 2000a. Influence of earthworm-processed pig manure on the growth and yield of green house tomatoes. Bioresource Technology 75, 175–180.

Atiyeh, R.M., Subler, S., Edwards, C.A., Bachman, G., Metzger, J.D., Shuster, W., 2000b. Effects of vermicomposts and composts on plant growth in horticulture container media and soil. Pedobiologia 44, 579–590.

Atiyeh, R.M., Edwards, C.A., Subler, S., Metzger, J.D., 2000c. Earthworm processed organic wastes as components of horticultural potting media for growing marigolds and vegetable seedlings. Compost Science and Utilization 8 (3), 215–223.

Atiyeh, R.M., Dominguez, J., Subler, S., Edwards, C.A., 2000d. Changes in biochemical properties of cow manure processed by earthworms (*Eisenia andreii*) and their effects on plant-growth. Pedobiologia 44, 709–724.

Atiyeh, R.M., Lee, S., Edwards, C.A., Arancon, N.Q., Metzger, J.D., 2002. The influence of humic acids derived from earthworms-processed organic wastes on plant growth. Bioresource Technology 84, 7–14.

Atiyeh, R.M., Subler, S., Edwards, C.A., Metzger, J., 1999. Growth of tomato plants in horticultural potting media amended with vermicompost. Pedobiologia 43, 1–5.

Barakan, F.N., Salem, S.H., Heggo, A.M., Bin-Shiha, M.A., 1995. Activities of rhizosphere microorganisms as affected by application of organic amendments in a calcareous loamy soil 2. Nitrogen transformation. Arid Soil Research and Rehabilitation 9 (4), 467–480.

Bosland, P.W., Vostava, E.J., 2000. Peppers: Vegetable and Spice Capsicums. CABI Publishing, New York, USA.

Bwamiki, D.P., Zake, J.Y.K., Bekunda, M.A, Woomer, P.L., Bergstrom, L., Kirchman, H., 1998. Use of coffee husks as an organic amendment to improve soil fertility in Ugandan banana production. Carbon and nitrogen dynamics in natural and agricultural tropical ecosystem 1998, 113–127.

Cacco, G., Dell'Agnola, G., 1984. Plant growth regulator activity of soluble humic complexes. Canadian Journal of Soil Sciences 64, 225–228.

Canellas, L.P., Olivares, F.L., Okorokova, A.L., Facanha, A.R., 2000. Humic acids isolated from earthworm compost enhance root elongation, lateral root emergence, and plasma H^+-ATPase activity in maize roots. Plant Physiology 130, 1951–1957.

Edwards, C.A., 1998. The use of earthworms in the breakdown and management of organic wastes. In: Edwards, C.A. (Ed.), Earthworm Ecology. CRC Press, Boca Raton, FL, pp. 327–354. E. (Eds.), Earthworms in Waste and Environmental Management. SPB Academic Press, The Hague, Netherlands, pp. 21–32.

Follet, R., Donahue, R., Murphy, L., 1981. Soil and Soil Amendments. Prentice-Hall, Inc., New Jersey.

Grappelli, A., Galli, E., Tomati, U., 1987. Earthworm casting effect on *Agaricus bisporus* fructification. Agrochimica 21, 457–462.

Johnston, A.M., Janzen, H.H., Smith, E.G., 1995. Long-term spring wheat response to summerfallow frequency and organic amendment in southern Alberta. Canadian Journal of Plant Science 75 (2), 347–354.

Lee, Y.S., Bartlett, R.J., 1976. Stimulation of plant growth by humic substances. Journal of the American Society of Soil Science 40, 876–879.

Maynard, A.A., 1993. Evaluating the suitability of MSW compost as a soil amendment in field-grown tomatoes. Compost Science and Utilization 1, 34–36.

Muscolo, A., Felici, M., Concheri, G., Nardi, S., 1993. Effect of earthworm humic substances on esterase and peroxidase activity during growth of leaf explants of *Nicotiana plumbaginifolia*. Biology and Fertility of Soils 15, 127–131.

Muscolo, A., Bovalo, F., Gionfriddo, F., Nardi, S., 1999. Earthworm humic matter produces auxin-like effects on *Daucus carota* cell growth and nitrate metabolism. Soil Biology and Biochemistry 31, 1303–1311.

Mylonas, V.A., Mccants, C.B., 1980. Effects of humic and fulvic acids on growth of tobacco. I. Root initiation and elongation. Plant and Soil 54, 485–490.

Nardi, S., Arnoldi, G., Dell'Agnola, G., 1988. Release of hormone-like activities from *Alloborophora rosea* and *Alloborophora caliginosa* feces. Journal of Soil Science 68, 563–657.

Pascual, J.A., Garcia, C., Hernandez, T., Ayuso, M., 1997. Changes in the microbial activity of an arid soil amended with urban organic wastes. Biology and Fertility of Soils 24 (4), 429–434.

SAS Institute, 2001. SAS Procedures Guide, Version 8. SAS Institute, Cary.

Sims, G.K., Ellsworth, T.R., Mulvaney, R.L., 1995. Microscale determination of inorganic nitrogen in water and soil extracts. Communications in Soil Science and Plant Analysis 26, 303–316.

Subler, S., Edwards, C.A., Metzger, J., 1998. Comparing vermicomposts and composts. BioCycle 39, 63–66.

Tomati, U., Galli, E., 1995. Earthworms, soil fertility and plant productivity. Acta Zoologica Fennica 196, 11–14.

Valdrighi, M.M., Pera, A., Agnolucci, M., Frassinetti, S., Lunardi, D., Vallini, G., 1996. Effects of compost-derived humic acids on vegetable biomass production and microbial growth within a plant (*Cichorium intybus*)-soil system: a comparative study. Agriculture, Ecosystems and Environment 58, 133–144.

Wilson, D.P., Carlile, W.R., 1989. Plant growth in potting media containing worm-worked duck waste. Acta Horticulturae 238, 205–220.

Zink, T.A., Allen, M.F., 1998. The effects of organic amendments on the restoration of a disturbed coastal sage scrub habitat. Restoration-Ecology 6 (1), 52–58.