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The Army has initiated a research and development effort for a new free-field, fast-rise electromagnetic pulse (EMP) simulator, the second-generation Vertical Electromagnetic Pulse Simulator (VEMPS II). Because of the unique performance characteristics of VEMPS II and the technological changes in consumer electronics over the past 10 years, there is a need to evaluate the incidental effects of VEMPS-II-like simulated EMP on modern consumer electronics. Although a similar evaluation of the effects of existing EMP simulators on consumer electronics was performed in 1978, the results obtained may not be directly applicable to the VEMPS II scenario and modern consumer electronics.

One of the proposed site locations for the VEMPS II is the Woodbridge Research Facility (WRF), the location of the Army's lead laboratory for EMP research. The environment at WRF was used as a basis for developing the physical parameters associated with the test efforts described herein. Various types of consumer electronics, identified through a survey of the Woodbridge, VA, community, were exposed to EMP environments similar to the predicted VEMPS II environments, and the results evaluated. The analysis indicates that the impact, if any, of VEMPS II operation on consumer electronics in the public areas outside WRF will be minimal.


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# 1. Introduction

In support of research and development for the proposed second-generation vertical electromagnetic pulse (EMP) simulator (VEMPS II), an extensive testing effort has been conducted to evaluate the effects of predicted VEMPS II operation on typical consumer electronics. A proposed location for VEMPS II is at the Woodbridge Research Facility (WRF), the location of the Army's lead laboratory for EMP research (the Harry Diamond Laboratories' Electromagnetic Effects Survivability Laboratory). The proposed site for VEMPS II places the simulator at a 680-m distance from the closest edge of the industrial park on Dawson Beach Road (directly outside the main gate at WRF). At this location, the predicted electric fields (E-fields) produced by VEMPS II are relatively small and are expected to have no effect on typical consumer electronics likely to be there. Because of the relatively dense population and the growing industry outside the main gate at WRF, the testing efforts have been focused on evaluating consumer electronics that may be in this area.

A total of 91 consumer electronic items (see the appendix), ranging from children's toys to sophisticated medical equipment, were chosen and tested. The lot of 91 items includes a wide variety of manufacturers, costs, and technologies for any particular type of item. This wide range of items, resulting from surveys [1] of the Woodbridge area, increased the probability that any item, or one similar to it, in the public sector was representatively tested.

In order to provide safety margins and assure that the test procedures were sufficient, a worst-case philosophy was used in the testing. Certain parameters that would attenuate the fields produced by VEMPS II (e.g., terrain, trees, and buildings) have been purposely neglected in the field predictions and subsequently in the testing environments. Throughout the testing effort, the consumer electronics were configured in a way that is consistent with their probable use by the public, and that also promotes maximum coupling of electromagnetic energy and therefore the greatest threat. Using overtest conditions provides confidence in the conclusions formulated.

The testing efforts consisted of three independent test sessions. Although the original test plan consisted only of testing at the Defense Nuclear Agency (DNA) FEMPS (Fast EMP Simulator) facility, subsequent testing was necessary to fulfill the overall test objectives. Initially, the consumer electronics were subjected to three different E-field levels at the FEMPS facility. The peak amplitudes and risetimes of these fields were representative of predicted VEMPS II fields for (1) the 680-m off-post fields, (2) a level approximately double the 680-m fields, and (3) a level 2.5 times the 680-m fields. These peak amplitude levels were chosen to provide a considerable overtest environment. The primary concern was to assure that the FEMPS E-fields sufficiently simulated the predicted VEMPS II environment.

The E-fields produced by the FEMPS facility accurately represented the desired "early-time" characteristics (in rise time and peak amplitude) of the predicted VEMPS II E-fields, but the "late-time" portion of the FEMPS E-fields did not accurately simulate the predicted VEMPS II late-time E-field characteristics. The large late-time energies that resulted from reflections of the E-fields within the FEMPS facility could not be eliminated without corruption of the desired early-time characteristics. Hence, the environment for the consumer electronics test consitituted a large overtest. Although items surviving this large overtest environment will survive in a VEMPS II environment, items experiencing upset in the FEMPS test will not necessarily experience upset in the much less threatening environment produced by VEMPS II. The large overtest produced by the FEMPS simulation required the testing efforts to be expanded so that accurate conclusions could be formulated for all items tested.

The second testing session, using a fast-rise switch source at WRF, was conducted on those items that experienced upset during the FEMPS testing. The fast-rise switch source produced E-fields that were a closer overall approximation of the predicted VEMPS II fields than the E-fields produced by FEMPS. Since the FEMPS environment was severe compared to the predicted VEMPS II environment, this second test did not include those items that did not experience upset or damage during FEMPS testing. The FEMPS data, together with the test results obtained at WRF, led to the conclusion that consumer electronics similar to the items tested are not expected to experience significant upset or damage when subjected to the predicted VEMPS II environment at a range of 680 m and greater.

A third test session was conducted to evaluate the integrity of the data collection systems used and to establish the frequency response of the cables in the standard test configuration. The continuous-wave (cw) test demonstrated that the characteristic frequency response of the test configuration cables was within the bandwidth of the data systems used to measure coupled current data. These frequency response data were useful in defining the adequacy of the measurement systems as well as the simulations of predicted VEMPS II E-fields.

# 2. Background

A similar test of consumer electronics [2] was conducted in 1978 with the simulators currently in operation at WRF. The consumer electronics test of 1978 was performed to evaluate the effects on consumer electronics of the AESOP and other similar lower frequency, horizontally polarized simulators at WRF. The actual purpose of the 1978 test was to evaluate the possible effects of TEMPS (the Transportable EMP Simulator) on consumer electronics at a nearby base housing area when TEMPS was at NAVCAMS EASTPAC, Oahu, HI. Nevertheless, the results and procedures used are applicable. A renewed testing effort is necessary because in many aspects the VEMPS II simulator is different from the horizontal simulators; likewise, state-of-the-art electronic equipment is vastly different from the electronics manufactured in 1978.

The major threat to consumer electronics from the horizontally polarized simulators is the possibility of dominant electromagnetic coupling to long horizontal power lines, antenna cables, or telephone lines. Coupled fields could produce large *transient currents* in the power lines, which in turn could enter a building and reach any powered electronic items, thereby causing operational upset or damage. VEMPS II could pose the same threat, except that, rather than coupling to horizontal power lines, the dominant fields could couple to vertical power and phone line runs, as well as to the vertical cable runs of rooftop antennas. Coupling to vertical conductors, rather than horizontal conductors, will be predominant because of the vertically polarized E-fields of VEMPS II. There is also a concern that higher frequencies produced by VEMPS II could couple to shorter cable runs and directly to circuitry within the consumer electronics.

Several measurement techniques and procedures used in the 1978 test have been adopted for this test, where applicable. Sensitivity measurements and the operational diagnostics follow in the same manner. The major differences in the testing efforts are in the simulators used and the types and numbers of consumer electronics items tested.

# 3. Proposed VEMPS II Simulator Environment

The proposed VEMPS II simulator is unique in design, using state-of-the-art technologies. Although performance and design goals have been set, the actual implementation and operation of the simulator are not yet established. As with all leading-edge technologies, development is strongly based on theoretical and analytical predictions that contain some degree of uncertainty. To compensate for these inherent uncertainties, VEMPS II field predictions, as well as the test methods used, were performed in a "worst-case" fashion. All values and procedures used were chosen to produce an environment more threatening than is actually expected, according to the E-field predictions; this worst-case approach provides some safety margin and increases confidence in the conclusions drawn.

VEMPS II, as shown in figure 1, is to be constructed as a vertically oriented biconical simulator, centered 15 m high, that will primarily produce vertically polarized electric fields. The propagation of these vertically polarized E-fields is very different from that of the horizontally polarized E-fields produced by horizontal simulators. The difference between horizontally and vertically polarized fields is the source of the concerns for consumer electronics located outside WRF. The total horizontal E-fields produced from horizontally polarized simulators attenuate rapidly with distance from their source and therefore are somewhat "containable." Vertically polarized fields can however travel greater distances with less attenuation.

VEMPS II E-fields will be purely vertical only at heights of 15 m for any distance (perpendicular to the center of the antenna). At other heights, the angle of the propagating incident wave will be such that the resultant fields will contain vertical and horizontal components, as shown in figure 2. Geometric considerations will easily show that at the 680-m distance, the resulting incident angles of the propagation paths are very small (less than 3°). Therefore horizontal components will be negligible. In fact, several factors cause the horizontal components to be small compared to the vertical components; e.g., at a 680-m distance, the angles are small, resulting in minor horizontal components, and at 680 m, the horizontal surface wave will be approximately zero.

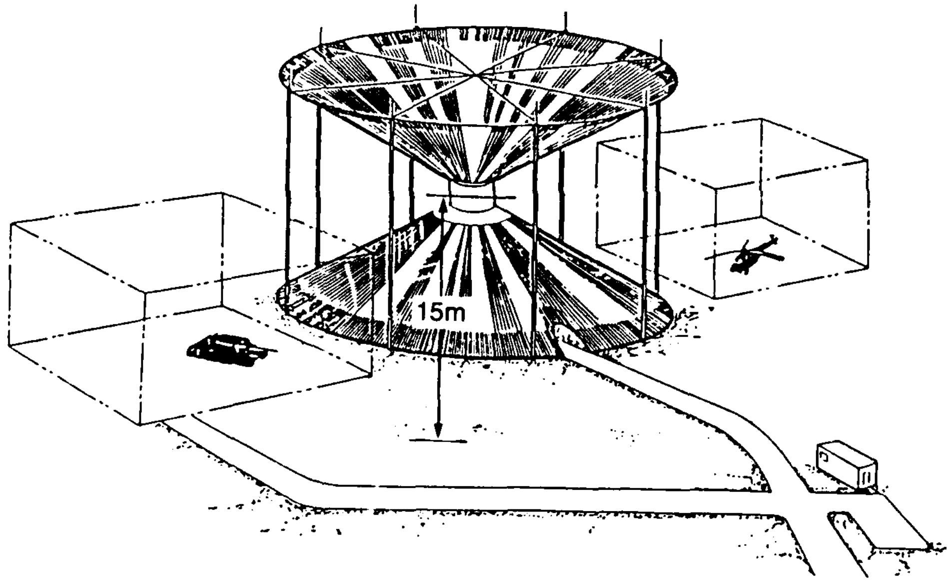



**Figure 1. Artist's conceptual view of VEMPS II facility.**

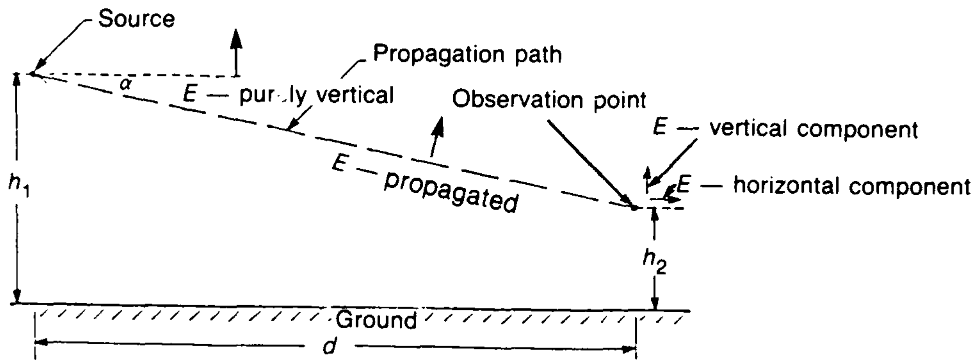



**Figure 2. Incident wave propagation.**

VEMPS II operation will result in the production of ground waves (fields propagated near the earth's surface) that can be expressed as the combination of a space wave and a surface wave. The space wave is the sum of the direct or incident wave and a ground-interacted or reflected wave. The surface wave is that portion of the ground wave that is guided along the earth's surface and is directly affected by the ground characteristics. A detailed description of electromagnetic wave propagation, as it applies here, is given by Jordan and Balmain [3], and is summarized below.

The incident wave component of the space wave travels directly from the source to the observation point in a straight path (most EMP simulators are characterized by their incident field because the incident wave is relatively easy to deal with mathematically and is not dependent upon ground parameters). The reflected wave is the component of the space wave that strikes the ground and is reflected to the observation point (see fig. 3). The

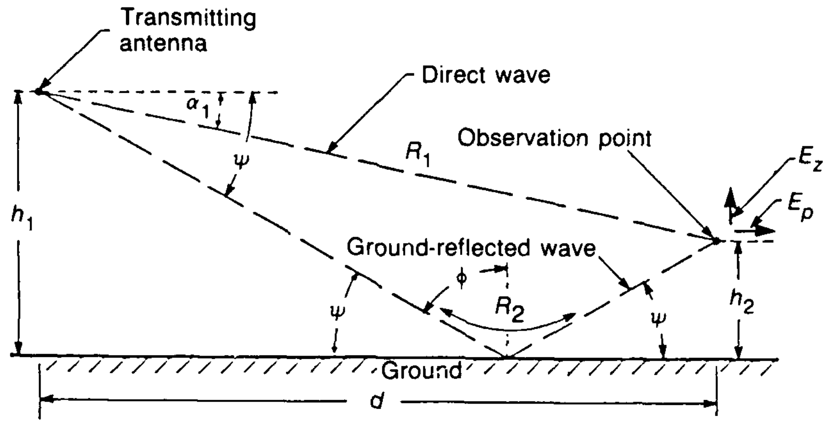



**Figure 3. Space wave propagation.**

angle $\psi$ shown in figure 3 is the reflected wave incident angle. The law of reflection applies here and requires that the reflected wave, incident on the ground, strike the ground and reflect at the same angle. Note the two equal angles in the figure. The reflected wave is attenuated after striking the ground because a portion of its energy is transmitted into the ground. The amount of the ground incident wave that is actually reflected is determined by the reflection coefficients for real earth. For small distances $R$ from an antenna (near field), the mathematical expressions for the E-field are extremely complex, involving inverse $R$, $R^2$, and $R^3$ terms, relating to the radiation, induction, and electrostatic fields, respectively. At greater distances from an antenna, the 680-m distance for example, the radiation field inverse $R$ term is dominant, and the expressions reduce to

$$E_z = -j30\beta\, I\, dl \left[ \cos^2\psi \left( \frac{e^{-j\beta R_1}}{R_1} + R_v \frac{e^{-j\beta R_2}}{R_2} \right) + (1 - R_v)(1 - u^2 + u^4 \cos^2\psi) F \frac{e^{-j\beta R_2}}{R_2} \right] , \tag{1}$$

$$E_p = -j30\beta\, I\, dl \left[ \sin\psi \cos\psi \left( \frac{e^{-j\beta R_1}}{R_1} + R_v \frac{e^{-j\beta R_2}}{R_2} \right) - \cos\psi\,(1 - R_v)\, u \sqrt{1 - u^2 \cos^2\psi}\; F \frac{e^{-j\beta R_2}}{R_2} \left( 1 + \frac{\sin^2\psi}{2} \right) \right] , \tag{2}$$

where

$\beta = 2\Pi/\lambda$ ,

$\lambda$ = wavelength in meters,

$I\, dl$ = differential current element on antenna,

$\psi$ = incident angle of reflection wave at the ground,

$R_1$ and $R_2$ are distances from the dipole and its image, respectively, and

$R_v$ = plane-wave vertical reflection coefficient.

Also in these expressions,

$$u^2 = \frac{1}{\varepsilon_r - jx} \ ,$$

where

$\varepsilon_r$ = relative dielectric constant of the soil,

$$x = \frac{\sigma}{\omega\varepsilon_o} = \frac{18 \times 10^9\ \sigma}{f} = \frac{1.8 \times 10^4\ \sigma}{f_{MHz}} \ ,$$

$\sigma$ = soil conductivity (mho/m),

$\omega = 2\Pi f$, and

$\varepsilon_o$ = dielectric constant of free space.

The attenuation function, $F$, is defined as

$$F = \left\{ 1 - j\sqrt{\Pi\theta}e^{-\theta}\left[\mathrm{erfc}(j\sqrt{\theta})\right]\right\}$$

where

$$\mathrm{erfc}(j\sqrt{\theta}) = \frac{2}{\sqrt{\theta}} \int_{j\sqrt{\theta}}^{\infty} e^{-v^2}\, dv \ ;$$

$$\theta = \frac{-j\beta R u^2\,(1 - u^2\cos^2\psi)}{2}\left[1 + \frac{\sin\psi}{u\sqrt{1 - u^2\cos^2\psi}}\right]^2 .$$

Equation (1) describes the vertical E-field component, and equation (2) describes the radial or horizontal E-field component. The terms in the first set of parentheses, in each equation, are the space-wave contribution, and the terms involving $F$ describe the surface wave. Combining the two equations and separating them into expressions for the two wave contributions, we have

$$E_{total\ space} = E_{\psi(space)} = \sqrt{E^2_{z(space)} + E^2_{p(space)}} = j30\beta I\ di\ \cos\psi \left( \frac{e^{-j\beta R_1}}{R_1} + R_v \frac{e^{-j\beta R_2}}{R_2} \right) ,$$

$$E_{total\ surface} = j30\beta\ I\ dl(1 - R_v)\ F\ \frac{e^{-j\beta R_2}}{R_2} \sqrt{1 - 2u^2 + (\cos^2\psi)u^2 (1 + \sin^2\psi/2)^2}\ .$$

Careful inspection of the above equations will reveal two terms in the space-wave equation that are similar except for an $R_v$ factor in the second term. This variable is the vertical polarization reflection coefficient, and clearly the total space wave is the sum of the incident wave and the ground-interacted wave. The incident wave is attenuated by the inverse $R_1$ term, and likewise the reflected wave is attenuated by the inverse $R_2$ factor.

The reflection coefficients are dependent on frequency, ground incident angle, and the ground parameters, and are determined as follows:

*for horizontal polarization:*

$$R_h = \frac{\sin\psi - \sqrt{(\varepsilon_r - jx) - \cos^2\psi}}{\sin\psi + \sqrt{(\varepsilon_r - jx) - \cos^2\psi}}\ ;$$

*for vertical polarization:*

$$R_v = \frac{(\varepsilon_r - jx)\sin\psi - \sqrt{(\varepsilon_r - jx) - \cos^2\psi}}{(\varepsilon_r - jx)\sin\psi + \sqrt{(\varepsilon_r - jx) - \cos^2\psi}}\ .$$

Figure 4 contains magnitude and phase plots of the vertical and horizontal reflection coefficients for particular ground parameters. It is interesting to note that the horizontal polarization reflection coefficient does not vary to the extent that the vertical polarization reflection coefficient does. Although the plots in the figure are for specific ground parameters, determined by $x$, the values shown are relatively close to the values of 0.02 for conductivity and 25 for permittivity that are used for the soil at WRF [4].

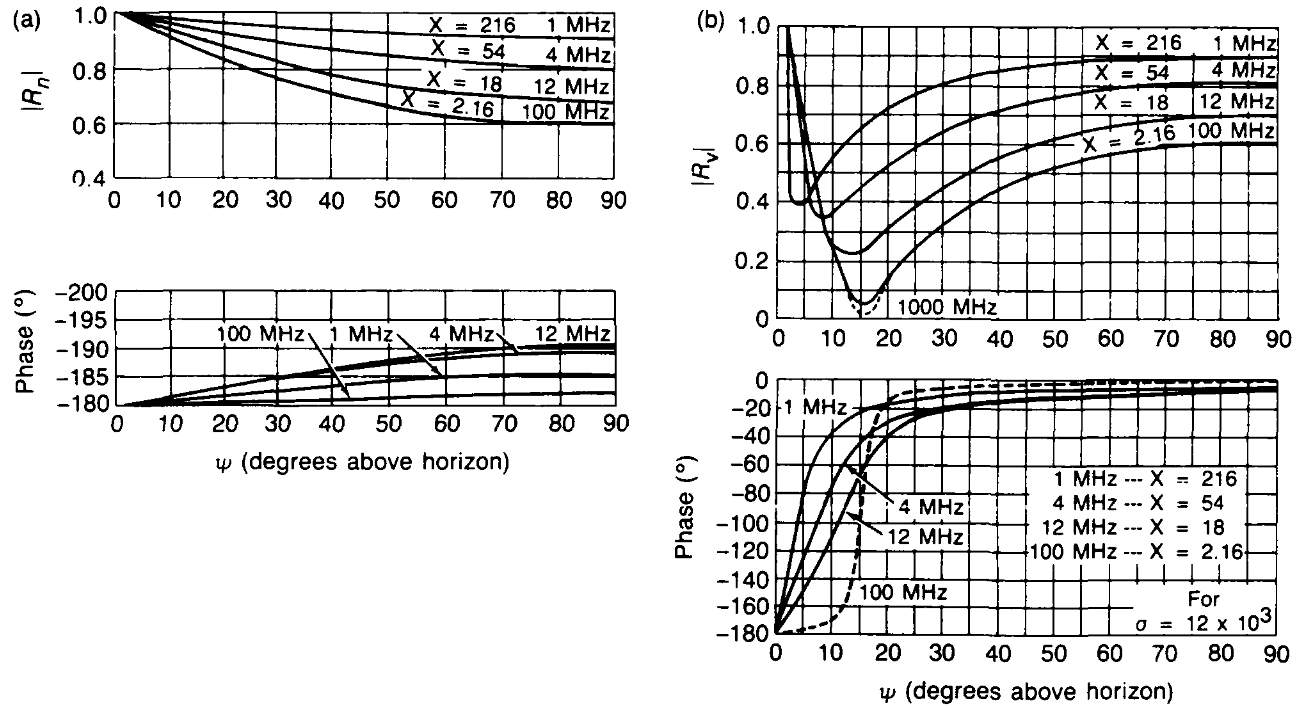



**Figure 4. Reflection coefficients for real earth: (a) horizontal and (b) vertical.**

The phase plot for the vertical polarization reflection coefficient (fig. 4b) reveals that the phase angle can vary from −180° to 0°. This indicates that, depending to a large extent on the incident angle, the reflected wave may be positive or negative with respect to the incident wave. The "knee" on the magnitude plots of the vertical polarization reflection coefficient, where the phase tends to –90° and the magnitude to a minimum, shows the location of the pseudo-Brewster angle (in theory, the ground incident angle at which the impinging wave would be totally transmitted into the ground and hence produce zero reflection). Again, the 680-m distance results in a ground incident angle of less than 3° (dependent on height), and therefore the reflected wave will always be primarily negative.

An important characteristic of the reflected wave is its inherent time delay with respect to the incident wave. Obviously from figure 3, the incident wave travels the shortest path (a straight line), whereas the reflected wave travels the shortest possible "bounce" path (again the law of reflection defines the equal arrival and departure angles and results in the shortest bounce path). $R_2$ will in every case be a greater distance than $R_1$ (except directly at the ground) and, because of the finite velocity of electromagnetic wave propagation, the reflection will arrive at the observation point behind the incident wave. The wave velocity is $3 \times 10^8$ m/s; therefore, the time delay between incident and reflected wave arrival is determined by

$$T_d = \frac{R_2 - R_1 \text{ (m)}}{C} = \frac{R_2 - R_1 \text{ (m)}}{3 \times 10^8 \text{ (m/s)}} \text{ (in seconds).}$$

This time delay will approach zero near the ground and gradually increase with increasing height, for a particular distance. At a 680-m distance, the path lengths $R_1$ and $R_2$ differ by a small amount, and the time lag becomes a critical parameter. We have stated that for small incident angles, the vertical reflection is almost purely negative and will therefore always tend to subtract from the incident wave. Consequently, at heights close to the ground, the reflected wave will arrive before the incident wave reaches peak amplitude, thereby creating a net wave that is lower in amplitude than the incident wave. As height is increased, the delay becomes greater, allowing more of the incident wave to arrive unaffected. At approximately 10 m of height, for the consumer electronics scenario, the time delay will become large enough that the net E-field will reach the incident wave peak amplitude.

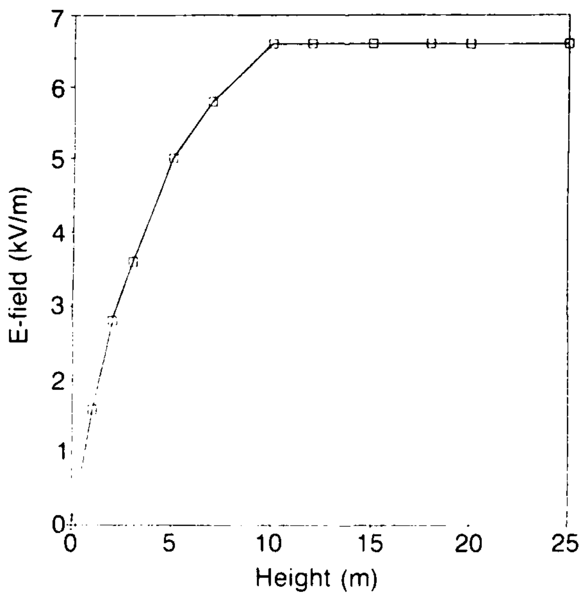
A major effort under this testing program was focused towards prediction of the resulting E-fields from VEMPS II. The FORTRAN computer code GROUND [5] was modified for the VEMPS II scenario and run to provide a height profile of the vertical E-fields at the 680-m range. The modified program GROUND3 calculates the total space wave for a given observation point via time-domain analysis for propagation of the waves and a frequency-domain analysis for determination of the reflection coefficients. At the time of this test effort, because of the complexity, little analysis had been performed involving the surface-wave contribution of pulse sources.

GROUND3 makes several simplifying assumptions in order to efficiently perform calculations. The propagation of all waves is considered planar through free space, originating from a point source at infinity. The earth is assumed flat and the earth parameters constant over frequency. These assumptions are commonly made for pulse sources and are in most instances worst-case assumptions. The VEMPS II E-field height profile, obtained from GROUND3, is given in the appendix for a range of 1 to 18 m. Attention is focused on fields occurring at heights of 7 m and lower because the buildings directly outside the main gate at WRF are one-story buildings.

An estimation of the maximum height of a typical TV/FM antenna atop a one-story building is approximately 7 m. At the 7-m height, the peak field is approximately 6 kV/m. The small time delay at near ground heights (1-m heights) results in peak fields of only 1.60 kV/m. A plot of peak E-field versus height for the 680-m distance is given in figure 5.

During the posttest analysis of the data collected, a computer code was developed that performs field predictions as a result of space-wave and surface-wave contributions. The FORTRAN code GROUNDWAVE [6] was developed to include the surface-wave contribution of pulsed sources. In mechanizing the ··lations for surface-wave effects, asymptotic approximation techniqu. are used. Even with simplified expressions, GROUNDWAVE requires 12 hours of PC time to compute the total groundwave at a particular observation point. Time considerations did not allow a comprehensive analysis based on GROUNDWAVE predictions; however, a comparison of the GROUNDWAVE predictions to the GROUND3 predictions indicates that the surface wave makes a negligible contribution to the total E-field in the 7- to 120-MHz system bandwidth (discussed in sect. 4.3). This late-time surface-wave contribution contains very low amplitudes and frequency content, and therefore does not appreciably affect the overall results.

**Figure 5. VEMPS II peak E-field versus height at 680-m range.**



# 4. Test Approach — Methodology

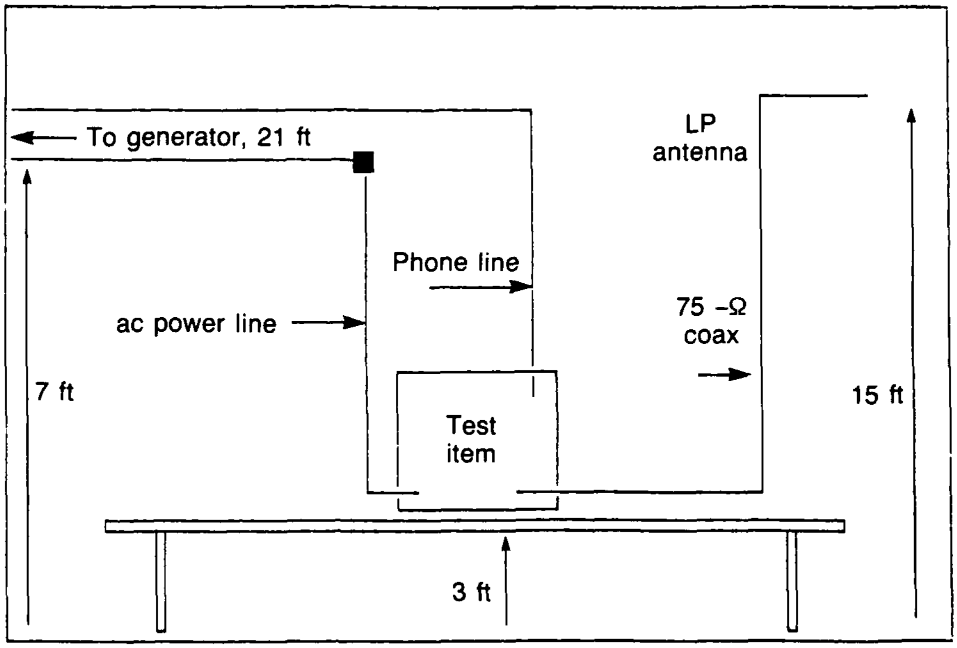
Throughout the test sessions a worst-case testing approach was consistently used. The VEMPS II field predictions were formulated with the assumption that obstructions (such as trees, earth terrain, and buildings) that would tend to decrease the field strengths do not exist. Test configurations, and the items connected in the configurations, were oriented so as to provide maximum coupling of electromagnetic energy.

Worst-case testing is commonly used to assure that analytic assumptions and parametric unknowns do not propagate uncompensated errors that may yield unreliable results. If all parameters are "worst-cased," an overtest condition will usually be produced. This overtest is desirable since it provides confidence in overcoming, or compensating for, the inherent unknowns associated with the test. If an item "passes" a worst-case test, then it may be stated with confidence that the item will endure in the actual expected conditions. However, since the test environment is more severe than the actual expected environment, an item that "fails" a worst-case test will not necessarily fail in its actual environment.

The standard test configuration used for testing most of the items was chosen to represent a typical location of a particular item in its consumer use, as well as providing the greatest coupling of electromagnetic energy. As shown in figure 6, this configuration consisted of a 1-m table, a roof-top TV antenna with connecting cable, a telephone cable, and a power line connected to an ac power source. The 1-m table, constructed from nonconductive materials, was used to place the items in a typical table height location.

The log-periodic (LP) rooftop antenna was suspended 15 ft above ground and connected to applicable consumer electronics items with a 15-ft 75-Ω coaxial antenna cable. Although rooftop TV antennas are often supported by a grounded conductive mast, this is not a universal practice. Therefore, a nonconductive mast was used to support the antennas in the test configurations. Since a path to ground was not furnished, the use of a nonconductive mast was consistent with the worst-case test method.

**Figure 6. Standard test configuration.**




Both the power and phone lines were run 21 ft horizontally, 7 ft above ground, from outside the test volume to above the 1-m table, and then dropped vertically down to the table. Size restrictions in the FEMPS facility (see sect. 3.4), as well as the fact that only one-story buildings are found in the neighborhood around WRF, dictated this one-story mockup test configuration.

Although some items required modified configurations or additional support, most of the consumer electronics items were tested in this standard test configuration. The test configurations common to the test sessions at both FEMPS and WRF are given in the appendix. For a complete description of all test configurations used at FEMPS, see Erler and Dancz [7].

Three types of test data were collected throughout the test sessions: current measurements at all major points of entry (POE's), sensitivity measurements on items containing rf receiver sections, and operational diagnostics. Bulk current probes were used to collect data on currents entering the items via the cable POE's. Operational diagnostics consisted of simply determining if a unit was completely functional before and after each pulse. Although a simple procedure, the diagnostics became quite involved when performed on items possessing many functions that operate in several different modes.

Many of the consumer electronics are rf receivers by design, whose primary functions rely on the ability to detect rf broadcasts. It was necessary to monitor the rf sensitivity of these items via the sensitivity measurements mentioned. The sensitivity of an item is simply a measure of the rf signal strength needed for the unit to be able to discern the signal information. To measure this strength, a signal generator was used to inject a signal into a unit, representing a signal delivered by an antenna. The output power of the signal generator was increased until a power level was achieved that enabled the unit to detect or "lock" onto the signal.

Performing the sensitivity measurements is in itself a simple procedure, but "lock" determination proved to be difficult to define for all items. Several items possess self-contained rf power level meters that will yield an accurate sensitivity level reference. However, most rf receiver items contain only uncalibrated visible or audible indicators. Lock determination, and therefore the sensitivity measurements themselves, depended totally on the operator's visual and aural observation of the item under test. These visible and audible indicators varied for each type of item and in turn for each particular item.

For televisions, and similarly televisions integrated with video cassette recorders (VCR's), a visual lock detection was used to define the sensitivity threshold. A 1-kHz sine wave with 50-percent amplitude modulation was injected into the tuner section of a TV or VCR at carrier frequencies of 61.25 and 627.25 MHz, center frequency vhf channel 3 and uhf channel 40, respectively. In response to the 1-kHz signal, alternating dark and light horizontal bands were produced on the TV screen. The relative power of the carrier frequency needed to produce these bands for an individual unit was defined as the sensitivity threshold for that unit. Each item displayed a set of bands with different characteristics. Several items would display vertically rolling bands that would eventually lock vertically as input power was increased. Other units would eventually produce a totally black display.

Sensitivity measurements for stereo receivers were performed in the same manner as for TV's and VCR's, except for the use of different carrier frequencies, FM modulation, and audible lock indicators. For AM station sensitivity, the 50-percent modulated 1-kHz signal was injected on a 100-kHz carrier. FM sensitivities were performed with the 1-kHz sine wave frequency modulated with a 50-kHz deviation onto a 100-MHz carrier. Depending on the unit tested, lock indicators available included self-contained power meters, tuning lock lights, and the actual audible 1-kHz tone emitted from the attached speakers.

Although the method used for obtaining sensitivity measurements does not provide precise absolute values of sensitivity for comparing different test items, this was not the purpose for the measurements. The intention was to determine whether the ability of a particular item to detect rf signals had degraded after exposure to a test pulse. All that is required to determine sensitivity degradation is a reliable variance from a defined reference. In each measurement, a subjective reference level was determined and used throughout the test. Because of the subjective nature of the observations, an extensive diary was kept by the operator. A complete description of the lock indicator for each item was recorded, along with subsequent sensitivity values. Variances of 20 to 25 percent in the sensitivity values were not considered significant because of the subjectivity of the measurement. Natural degradation could have accounted for slight variances in the sensitivity measurements. Sensitivity variations of 10 to 15 percent from pulse to pulse were common. These variations are largely due to human factors associated with the procedures used, and cannot be taken as indicators of actual degradation unless a clear trend is indicated following several repetitions of the measurement. The degradations noted in the 1978 consumer electronics test, changes in sensitivity on the order of 4 to 1000 times, were far greater than the small variations noted here.

## 4.1 FEMPS Test Approach

Most of the consumer electronics testing effort was conducted at the FEMPS facility and included simulated EMP testing of the 91 consumer electronics items to three different environments. FEMPS was chosen as the pulse source because of its availability at the time of the test and its applicability in representing predicted VEMPS II fields. FEMPS is a fast-rise, vertically polarized, conical monopole EMP simulator owned by DNA. Currently, FEMPS is housed, maintained, and operated by Physics International Corporation of San Leandro, CA, under contract to DNA.

While FEMPS differs from VEMPS II in physical design, the rise time and peak amplitude characteristics of the FEMPS vertical E-fields adequately represent predicted VEMPS II fields. The FEMPS facility was however found to be limited in flexibility. Amplitude levels could be widely adjusted with charge voltage; however, for early-time waveshape repeatability to be maintained, the amount of amplitude variability became limited.

A more significant limitation was the location of FEMPS within a metallic building that contains the radiated fields. This not only limits the physical size of the test configurations but also the test location. While the metallic enclosure of FEMPS is effective at confining the radiated fields, the reflections of the fields within the test volume created undesirable energy in the late-time E-fields. The location chosen was one where the desired early-time characteristics, with waveshape repeatability, could be obtained, yet it was significantly removed from the walls to prevent corruption of the early-time fields by the reflections.

The test location was designated at a range of 16.5 ft radially away from the pulser towards the center of the building. At this location the early-time E-fields were not distorted and the desired peak amplitudes could be obtained with high reliability. The amplitude levels used for the FEMPS test are referred to as low (6.7 kV/m), medium (12.4 kV/m), and high (16.6 kV/m). The low-level amplitude is consistent with the 6.6-kV/m predicted VEMPS II maximum peak amplitude at the 680-m range. The medium level was chosen as an 85-percent overtest of the VEMPS II peak amplitude; the high level was chosen as a 150-percent overtest. Although the test configuration is designed as a mockup of a one-story building, the low-level peak amplitude represents predicted VEMPS II incident field peak amplitude occurring at or above 10-m heights. Testing to maximum VEMPS II amplitude was chosen to provide absolute worst-case peak field levels.

The complete FEMPS effort comprised four individual tests: an antenna coupling study and the low-, medium-, and high-level tests. The antenna coupling study was performed to determine which common antenna cable, 300-Ω twin lead or 75-Ω coaxial, would couple more efficiently, creating a greater threat.

The antenna study revealed that the twin lead cable developed a common-mode current drive, i.e., both leads carried equal current. The coaxial cable however developed a large difference in currents on its conductors. The outer conductor (shield) effectively shielded the inner conductor from coupling energy; hence large currents were induced on the outer conductor with minimal current flow on the inner conductor. Since consumer electronics equipment functioning as an rf receiver is generally designed to respond to a differential signal, the coaxial antenna cable was used throughout the test to provide a worst-case coupled threat.

Before testing, every item was powered and allowed to "burn in" for approximately 12 hours. The burn-in period was part of the pretest operational diagnostics conducted to identify any manufacturer defects. The items were then tested in groups of three at the low-level fields (each item with its own power, antenna, and phone cables). Coupled current data were collected during the preliminary low-level tests only, with a 100-kHz to 125-MHz bandwidth data collection system. Following successful collection of current at the low level (often requiring repeat pulses to obtain usable data), the items were again tested to a low-level pulse without current probes on the POE's. The additional low-level pulse was necessary to determine whether the current probes were absorbing energy and inadvertently attenuating the threat presented to the items. Subsequently, medium- and high-level tests were performed with sensitivity and operational measurements following every pulse (regardless of the number of pulses per level, every pulse was followed by sensitivity and operational verification). The results of the FEMPS tests are discussed in section 5.2.

## 4.2 Fast-Rise Switch Source Test Approach

The fast-rise switch source at WRF is a fast switch that was integrated with a voltage source and an antenna. In this configuration, the switch could create EMP's similar to the predicted VEMPS II environment. The switch can produce vertical E-fields at roughly 1/45 the scale of the VEMPS II fields. Like VEMPS II, the fast-rise switch source is a free-field radiator that does not have the physical restrictions of the structure containing the FEMPS facility. When the consumer electronics effort was initiated, the fast-rise switch source was not available, or the test would have been conducted entirely at WRF. Following the FEMPS test, a successful independent research effort revealed the possibility of a more precise representation of the predicted VEMPS II E-fields. This effort led to the development of the fast-rise switch source as an experimental tool for short-term EMP research and development.

The ability of the fast-rise switch source to produce VEMPS-like fields, in both early- and late-time E-field characteristics, led to its being the means for a follow-on to the FEMPS test effort. The late-time energy present in the FEMPS E-field was determined to be unrealistic, a worst-case threat that will not be produced by VEMPS II. Therefore items that experienced upset at FEMPS (low level) were retested at WRF. Items surviving low-level testing at FEMPS were not retested since they functioned normally even in the enhanced threat environment produced by reflections within FEMPS.

To achieve predicted VEMPS II field levels, the 1:45 scale of the fast-rise switch source dictated a test location at a 15-m range. A complication arises from this short distance requirement. In the discussion of reflection coefficients (see sect. 3), we noted that large incident angles will cause the reflected wave to approach positive values. The 15-m distance will result in large incidence angles for heights greater than 1 m. E-field measurements of the switch output confirmed the existence of positive reflections at heights of 2 m and greater. It becomes evident that an exact simulation of predicted VEMPS II is not a realistic goal for existing facilities. In light of this, an attempt was made to produce an environment for testing that was an equivalent or greater threat than VEMPS II.

The same test configurations and procedures used at FEMPS were used at WRF to maintain consistency and enable comparison of data between the two test sessions. Since the number of test items was smaller, time considerations allowed for these items to be tested individually rather than in groups. The test configurations contained in the appendix represent all configurations used for testing at WRF. The items tested at WRF are given in table 1.

Initially, current data were obtained at a 35-m range from the fast-rise switch source, with a 200-MHz bandwidth measurement system. At the 35-m range, the peak amplitude E-fields were 1600 V/m, at 3-m heights. This peak amplitude is about half the predicted VEMPS II peak amplitude threat at 3 m of height and 680 m of range. Testing was conducted at this low level to provide an initial screen of the items and allow data collection with low likelihood of item upset. Sensitivity measurements and operational diagnostics were performed after each pulse. A second test was conducted at the 15-m location, where peak fields ranged from 3500 V/m at a 1-m height to 4500 V/m at 3-m heights. This location provided a greater threat than the VEMPS II environment at 680 m, which ranges from 1600 V/m peak at a 1-m height to 3700 V/m at a 3-m height.

**Table 1. Items tested at fast-rise switch source**

| Type of item | Models |
|---|---|
| Televisions | Emerson 13 in. |
| | Portland 13 in. |
| VCR's | Sharp VCR (used with Sears 13 in. TV) |
| | Sears VCR (used with RCA 13 in. TV) |
| | Symphonic VCR (used with Sears 13 in. TV) |
| | Goldstar VCR* (used with Sears 13 in. TV) |
| | Akai VCR (used with RCA 13 in. TV) |
| Phones and answering machines | Realistic cordless |
| | GE cellular |
| | Phonemate answering machine |
| Computers and accessories | IBM PC AT |
| | Leading Edge model D |
| Stereo receivers | Kenwood |
| | Sharp compact disk player |
| | Onkyo |
| Satellite dish | Realistic 8.5-ft satellite dish and receiver |
| Medical equipment | Kangaroo feeding pump |
| Radios | Craig car radio |

**Eliminated from testing because of vibration instability.*

## 4.3 Evaluation of Data-Collection Systems and Establishment of Cable Frequency Response in Standard Test Configuration

HDL's recently constructed cw test facility was used to evaluate the data collection systems and to establish the frequency response of the cables in the standard test configuration. Since the data collection systems used to obtain coupled current waveforms were bandwidth limited, they were calibrated only in a specific range of frequencies. Initially, both the measured simulation E-fields and the VEMPS II predicted E-fields appeared to have a spectral content beyond the bandwidth of the data collection systems. So that the integrity of the measurement systems' results could be evaluated, a cw illumination test was conducted to obtain the relative frequency response of the cables in the standard test configuration.

The cw test facility consists of a source generator and a data collection facility developed to interface with the existing Repetitive EMP Simulator (REPS) facility. The interface enables low-power cw illumination of the REPS test area over a frequency range of 100 kHz to 200 MHz via the existing REPS antenna system. The cw system can also step through a frequency range of 100 MHz up to 1 GHz when connected to an external LP (log-periodic) antenna. The frequency range from 100 kHz to 1 GHz covers the EMP spectrum and thereby serves as a means to linearly characterize systems in the frequency domain. The cw facility uses reference-sensor data and system probe-response data to calculate the impulse response function of systems in the frequency domain. For EMP testing, this information is useful because it provides some information about the frequencies, in the EMP spectrum, to which a system will effectively respond.

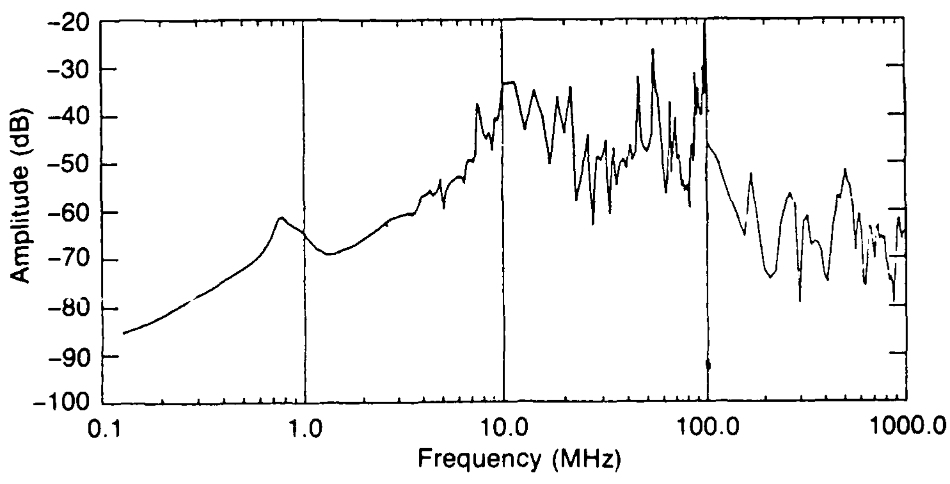
Since the new cw testing facility has not been fully calibrated or characterized, the actual amplitudes of the data may not be absolute, but the data collected represent the relative levels of coupling efficiency for discrete frequencies. The absolute magnitude of the impulse response is not particularly critical for the analysis performed.

In the testing configuration used (consisting of the antenna, power, and phone cables along with the 1-m table), the cables electrically appear as antennas. As with all antennas, there is a band of frequencies for which the gain of the antenna is relatively high compared to its gain at other frequencies. The cw testing allowed us to determine the frequency response of the cables in the test configuration and thereby gain some insight into the coupling characteristics of the system. The cw test data show that the cable response allows a defined range of frequencies to couple with little relative attenuation, while greatly attenuating frequencies outside this band. Through the cw tests, this frequency range or bandwidth of the system was determined.

The results of the cw testing (frequency domain impulse response) are given for the antenna, phone, and power cables in figures 7 to 9. Although each cable has a different response, it is obvious that for all three cables, the predominant frequency range is approximately within 1 decade, from 10 to 100 MHz. The actual 3-dB bandwidth of the cables is difficult to determine from the data obtained, but an estimate of 7 to 120 MHz is within reason. This indicates that frequencies in the 7- to 120-MHz range will be coupled into the system at maximum gain, and frequencies outside this range will not couple as effectively into the system.

The data collection systems used to measure the E-fields produced at FEMPS and at WRF were bandwidth limited to between 100 kHz and 1 GHz. The measured E-field data and the VEMPS II E-field predictions indicate that the E-fields contain frequency components up to 800 MHz.

**Figure 7. Antenna cable impulse response.**



The coupled current data collection system used at FEMPS was bandwidth limited to between 100 kHz and 125 MHz, and the coupled current data system used at WRF was limited to between 100 kHz and 200 MHz. Obviously, there are frequency components of the E-fields that are beyond the accurate measuring range of the coupled current measuring systems. This does not invalidate the coupled current data, however, since we have shown that the standard configuration is bandwidth limited to between 7 and 120 MHz, which is within the bandwidth of the coupled current data systems. The measured E-field data likewise are valid since a separate system with appropriate bandwidth was used.

**Figure 8. Phone line impulse response.**

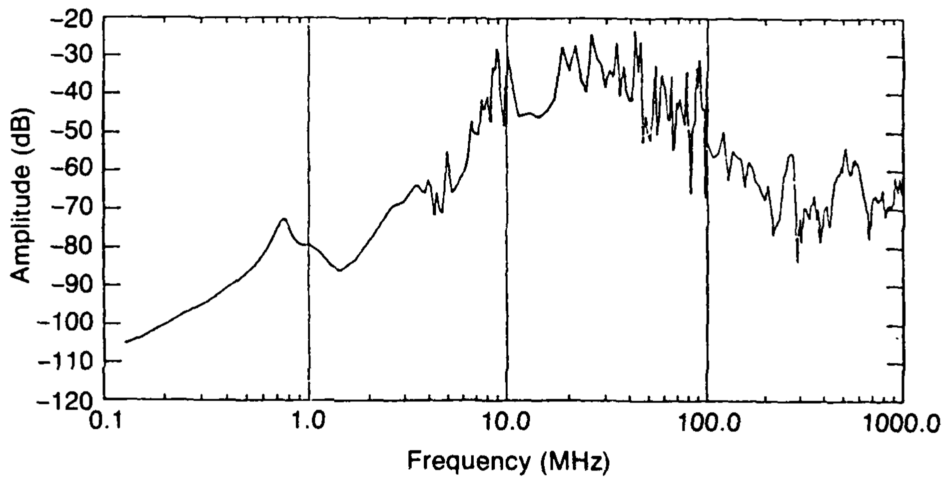
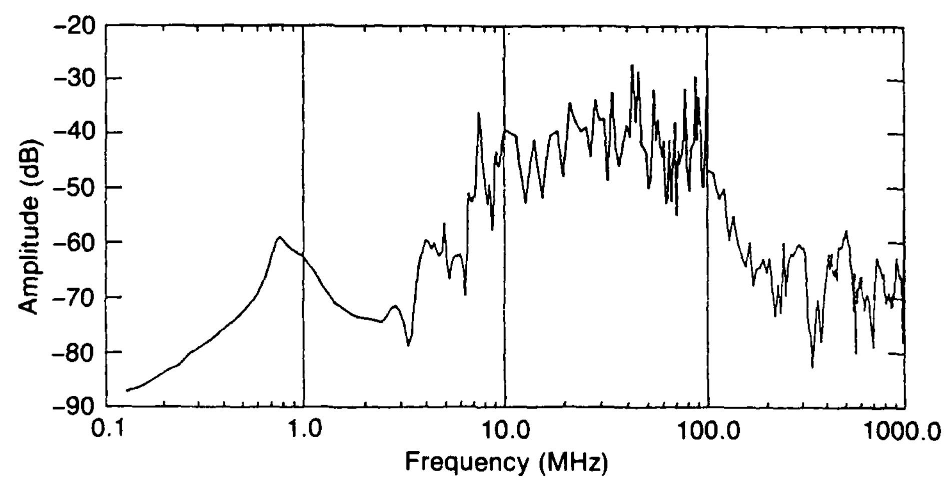



**Figure 9. Power line impulse response.**



# 5. Test Results and Analysis

Because of the way in which consumer electronics are normally configured and used, the data analysis was aimed at the system level rather than at the individual item. Without the influence of the external POE's (antenna, power, and phone cables), the electronics themselves could directly couple only small amounts of radiated energy. However, when these items are integrated into a configuration like that used in the test, coupling of damaging energies is possible. The system-level analysis involves the consumer electronics in the context of the test configuration. It is not the purpose of the analysis to examine each item in detail. Observations and conclusions are made on the types, quality as reflected in cost, or characteristics of the items in general. The test results are more a description of typical consumer electronics than a detailed description of each unit's integrity in the test environment.

Throughout the analysis of the E-field environments, predicted E-fields at a 7-m height and 680-m range were used for VEMPS II, measured E-fields at a 3-m height and a 15-m range were used for the fast-rise switch source, and measured low-level fields at the ground and a 16-m range were used for FEMPS. The E-fields at a 7-m height, used for the VEMPS II analysis, are representative of the maximum fields that a one-story building, with a 10-ft rooftop antenna, would be subjected to. The objective of the simulations was to test the consumer electronics to these maximum field levels, and therefore the simulated E-fields were compared to the predicted VEMPS II fields at a 7-m height.

Based on the discussion of the fast-rise switch source testing, as well as the measured E-fields (sect. 3.5), the large ground incidence angles result in positive reflected fields at the fast-rise switch source test location (a 15-m range). Therefore, the peak E-fields from the fast-rise switch source increase with increasing height. Clearly, the peak E-fields from the fast-rise switch source at a 7-m height are greater than the peak E-fields it produced at a 3-m height. If the E-fields from the fast-rise switch source at a 3-m height can be shown to have been an adequate simulation of the maximum VEMPS II E-fields at a 7-m height, then the simulation at WRF was valid and, in general, an overtest.

The FEMPS facility is completely different from the fast-rise switch source configuration or the proposed VEMPS II facility. Since the ground plane at FEMPS is metallic, the reflected fields will act differently from those from a real earth ground plane. E-field measurements within the FEMPS test volume indicate that the peak E-fields do not vary significantly over height above ground at the test location. The late-time E-fields vary over height, but this is largely due to the reflections of the side walls of the facility. The existing ground plane reference sensor was used to collect E-field data for the analysis of the FEMPS low-level environment.

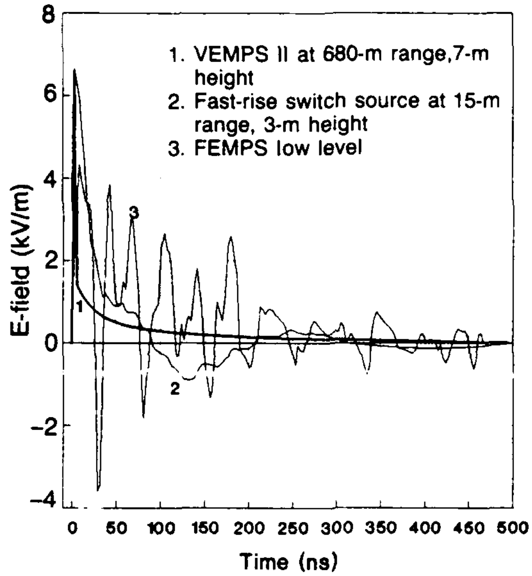
Because of the fast rise times of the VEMPS II E-fields, concerns have arisen over the possibility of direct coupling to internal circuitry. The high-frequency components of the VEMPS II E-field, as a result of the fast rise time, have wavelengths short enough to couple to short cable runs or component leads. Even so, most of the items are enclosed, or partially enclosed, in metallic cases which provide the units with some shielding against most of these frequencies. Additionally, the energy content at the higher frequencies is small compared to the energy at the frequencies that are coupled by the "system." Tests at the FEMPS facility have shown that direct coupling is typically not of concern for consumer electronics as addressed in this effort.

## 5.1 VEMPS II Analysis

The result obtained from the GROUND3 predictions is a height profile of the vertical E-fields for VEMPS II at a 680-m range, given in the appendix. (Note: the profile shown neglects the surface-wave contribution.) Figure 10 is an overplot of the VEMPS II, FEMPS, and fast-rise switch source E-fields used in the analysis. To completely describe the threat that a particular field delivers, a more comprehensive analysis of the field is needed. The simple description of rise time and peak amplitude is not sufficient.

The first calculation discussed here represents the total energy radiated by a plane electromagnetic wave in terms of the propagation vector. From ba-

Figure 10. E-field comparison: time domain overplot.




sic electromagnetic theory, the Poynting (propagation) vector is representative of the instantaneous power density produced by a field and is given as

$$P = E \times H \text{ in watts per meter squared,}$$

where

$E$ = electric field vector and
$H$ = magnetic field vector.

Now energy is defined as the rate of power delivery, or

$$\text{energy} = \text{power} \times \text{time.}$$

For instantaneous values,

$$H = \frac{E}{\eta} \text{ and so } E \times H = \frac{E^2}{\eta} \; ,$$

where $\eta = 377\ \Omega$, the intrinsic impedance of free space.

From these we obtain a new equation for instantaneous power density:

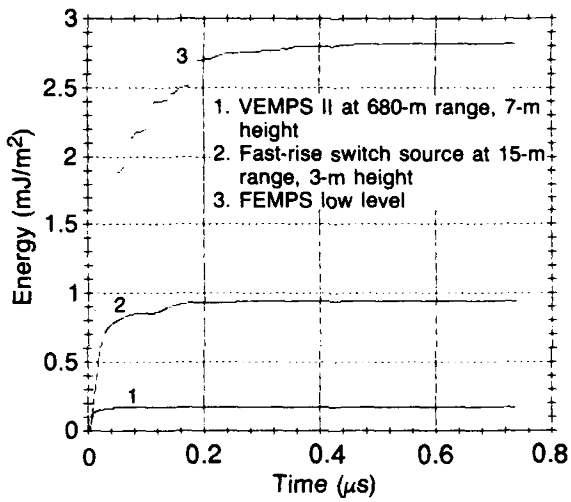
$$P = E \times H = \frac{E^2}{\eta} \; .$$

Integrating this expression over time, we obtain an expression for the radiated energy density for the electromagnetic field:

$$\text{Energy} = \int_0^{t_{max}} P\,dt \quad \text{(in joules per meter squared).}$$

Figure 11 is an overplot of the energy density of the predicted VEMPS II field at a 7-m height and 680-m range, the FEMPS low-level environment, and the fast-rise switch source environment at a 15-m range and 3-m height. The total energy delivered by the VEMPS II field is 0.18 mJ/m$^2$.

**Figure 11. Energy comparison overplot.**




The cw test results have shown our system to be frequency dependent, and therefore total energy calculations do not accurately describe the threat delivered by the field without determination of the frequencies at which the energy is radiated. Energy radiated within the bandwidth of the system (approximately 7 to 120 MHz) will couple efficiently, whereas energy outside the system bandwidth will only couple at attenuated levels. The need for a frequency content description of the field may be satisfied by a Fourier analysis.

The frequency spectrum overplot, resulting from the Fourier transform, is given in figure 12 for the VEMPS II E-field at a 680-m range for heights of 5 and 7 m, as well as for the FEMPS and fast-rise switch source environments. The spectrum shown is for magnitude only, in units of V/m. Figure 13 is the same overplot, but the magnitudes are in decibel units and are normalized to 1 V/m (i.e., 1 V/m = 0 dB). The primary use of the frequency spectra obtained is for a comparison of the fields for VEMPS II, the fast-rise switch source, and FEMPS in the system bandwidth of 7 to

120 MHz. Absolute amplitude values are not sought here; rather, the purpose is only to provide a relative representation of the VEMPS II fields (in the frequency domain) for comparison and validation of test efforts using the FEMPS simulator and the fast-rise switch source. The analysis of the VEMPS II fields helps assure the adequacy of the test simulations.

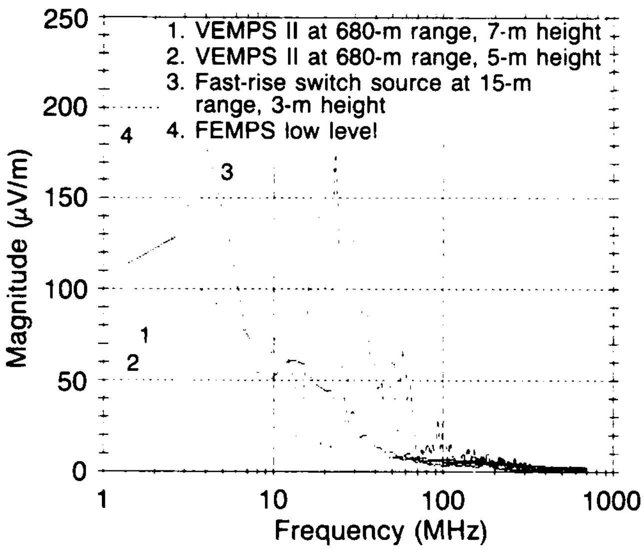



Figure 12. Frequency spectrum overplot (V/m).

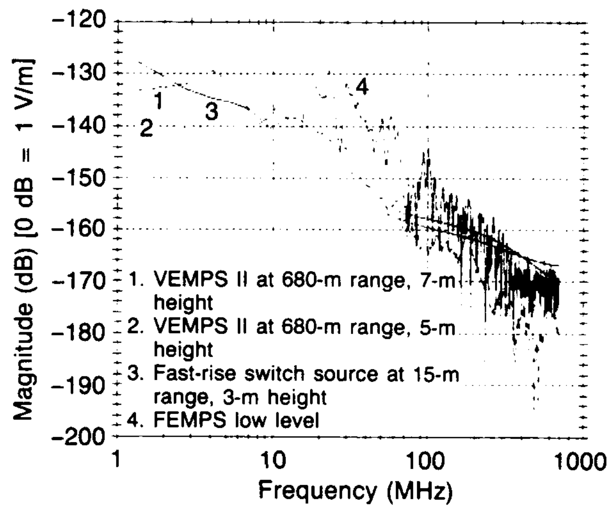



Figure 13. Frequency spectrum overplot (dB).

## 5.2 FEMPS Test

As stated in section 4.1, the antenna coupling tests [7] at FEMPS indicate that the coaxial antenna cables provide the greatest threat; these cables were therefore used throughout the entire test effort. A typical current waveform measured at FEMPS, and its corresponding frequency domain, is shown in figure 14. This particular current was measured on the coaxial antenna cable connected to a typical TV set in the standard configuration. The important observation lies in the frequency spectrum of this waveform. It is obvious that most of the energy of this current is contained within the 7- to 120-MHz frequency band (as indicated by the peaks in the band and by the rolloff on either side of the band). Current measurements on the other POE's show similar responses, as do the currents for the other consumer electronics. The peak amplitudes and total energy coupled differ for each particular item and each POE current measured, as a result of the loading of that item's impedance, but all responses for the standard configuration current measurements show a concentration of energy

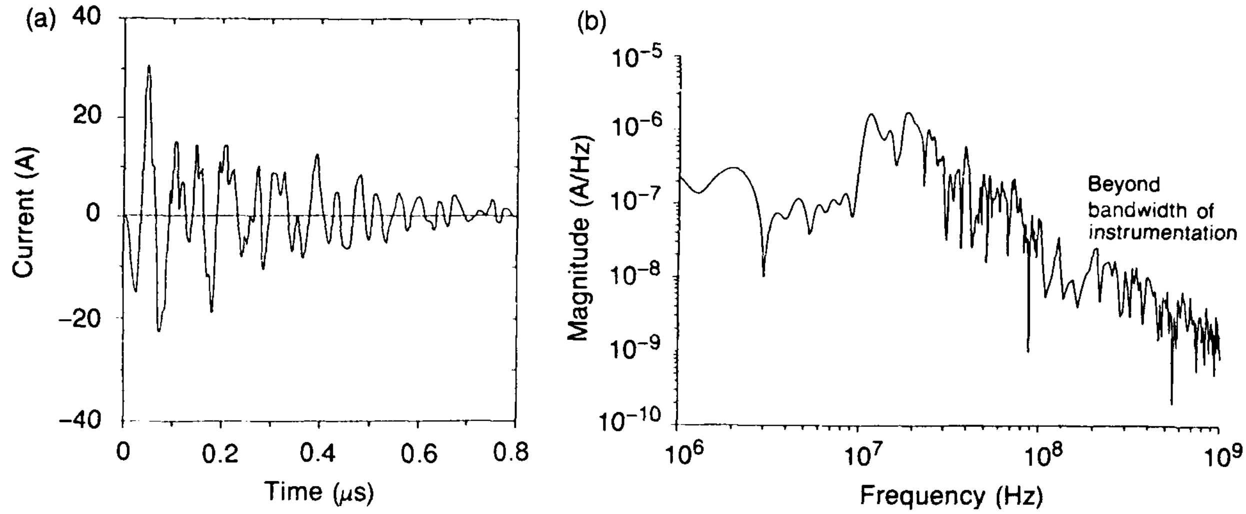



**Figure 14. Typical TV antenna current as measured at FEMPS (low level): (a) time domain, and (b) frequency domain.**

within the 7 to 120 MHz band. The frequency characteristics of the currents measured are consistent with the cw test results and further support the analysis methods used for this effort.

Of the 91 items tested, 18 experienced some form of upset at the low-level (6.7-kV/m) FEMPS environment. Of the 18 items, the Tandy Corp. satellite dish receiver was the only one that experienced apparent permanent failure. The term "apparent" is used because after the FEMPS test was completed, a lockout function on the receiver's remote control was discovered. It is not known whether the satellite receiver was actually damaged or simply in a functional lockout mode; however, all the symptoms exhibited were consistent with the lockout function. Following the apparent failure observation, the unit was sent to be repaired and no further information was obtained. Other responses observed consisted of noncritical upsets, such as TV's changing channels, and several critical upsets, where a unit locked up in a nonfunctional mode.

"Noncritical upsets" are defined as minor changes in the operation of a unit resulting from a test pulse. Those items that experienced noncritical upset were fully operational following the change of state (glitch). "Critical upsets" are defined as temporary operational failures. An item experiencing critical upset is frozen or locked up and completely inoperable, but the failure is only temporary, since the unit can be reset to a fully operational state by turning the unit off and then on again, or by disconnecting and then reconnecting its power cord. "Failure" is defined as an upset resulting in a permanent loss of total functionality.

The percentage of upsets rose from 20 percent at the low level to 27 percent for the medium-level (12.4-kV/m) testing. Although the number of upsets increased from 18 to 25, only one damaged item was noted. The damage was a functional loss of the LED display unit of a Symphonic VCR. At high-level (16.6-kV/m) testing, 33 items were upset, increasing the percentage of upsets to 36 percent of the total number of consumer electronics. More predominant was the increase in damage, to 6 items (over 6 percent of the total).

The failures and upsets throughout the tests were distributed throughout the 91 items. The only apparent pattern or indication that a particular type of item was prone to upset was a high percentage of rf receiver item upsets. That is, those items connected to the antenna cable experienced upset more often than items not connected to the antenna cable. This was apparently due to the large currents induced on the long vertical antenna cable (the antenna cables were the longest vertical couplers). Of the rf receiver items experiencing upset, most were the less expensive models. Table 2 is a summary of the observations and subsequent upset items for the complete FEMPS test effort.

**Table 2. Summary of operational observations at FEMPS**

| Test item type | Test item | Effects at various levels of testing | | |
|---|---|---|---|---|
| | | Low level | Medium level | High level |
| Television | Emerson 13 in. | Critical upset | Critical upset | Failure |
| | Portland 13 in. | Noncritical upset | Critical upset | Critical upset |
| | Zenith 19 in., SD1911W | — | Critical upset | Critical upset |
| | JC Penney 13 in. | — | Noncritical upset | Noncritical upset |
| | Montgomery Ward 25 in. | — | Critical upset | Critical upset |
| | Sony 13 in. | — | Critical upset | — |
| | Sharp 25 in. | — | — | Critical upset |
| VCR | Akai VS515U | Critical upset | Critical upset | Critical upset |
| | Sharp | Critical upset | Critical upset | Critical upset |
| | Sears | Critical upset | Critical upset | Critical upset |
| | Symphonic | Critical upset | Failure | Failure |
| | Goldstar | Noncritical upset | Noncritical upset | Noncritical upset |
| | Mitsubishi HS348UR | — | Critical upset | — |
| | Toshiba M4220 | — | — | Noncritical upset |
| | Magnavox VR9525AT | — | — | Noncritical upset |
| Stereo receiver | Kenwood | Critical upset | Critical upset | Critical upset |
| | Onkyo | Noncritical upset | Noncritical upset | Noncritical upset |
| | JVC | — | Critical upset | Critical upset |
| | Pioneer | — | — | Failure |
| Mobile radio | Johnson 7171 uhf | — | Noncritical upset | Noncritical upset |
| | Johnson SDL6085, 16 channel | — | — | Noncritical upset |
| | GE PSX vhf | — | — | Noncritical upset |
| Computer | Leading Edge model D | Critical upset | Critical upset | Failure |
| | IBM PC AT | Critical upset | Critical upset | — |
| | Hayes 1200-baud modem | — | — | Critical upset |
| CD player | Sharp | Noncritical upset | Critical upset | Critical upset |
| | Sony | — | — | Critical upset |
| Cellular phone | GE | Critical upset | — | Critical upset |
| | NEC | — | — | Critical upset |
| Telephone | Realistic cordless | Critical upset | Critical upset | Critical upset |
| | Panasonic | — | — | Failure |
| Answering machine | Phone mate | Critical upset | Critical upset | Critical upset |
| Garage door opener | Genie | — | Critical upset | Critical upset |
| Medical equipment | Kangaroo feeder pump | Critical upset | Critical upset | Critical upset |
| | Infant monitor | — | Critical upset | Failure |
| Automobile radio | Craig AM/FM cassette | Noncritical upset | Noncritical upset | Noncritical upset |
| Satellite dish | Realistic 8.5 ft. | Failure (not verified) | — | — |

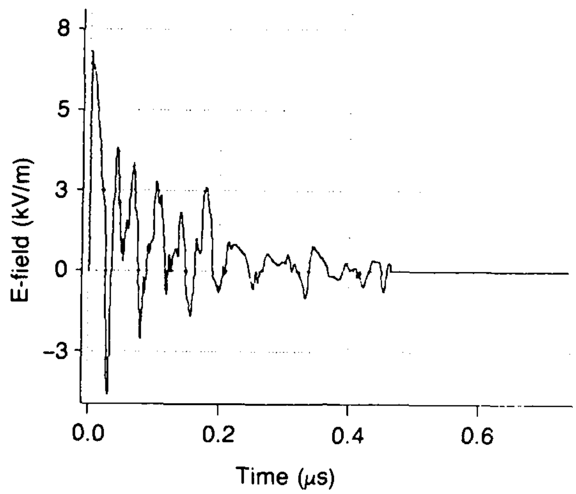
*— indicates no abnormal observation or the unit was not tested at that level because of a previous failure.*

Although various upsets were noted in each FEMPS environment, none of the sensitivity measurements indicated a degradation in sensitivity for any item. Because of the subjective procedures used for the sensitivity measurements, variances of 20 percent were allowed from pulse to pulse. A variance in the sensitivity level for a particular item that could be repeatedly measured would have been classified as degradation. For most measurements, the sensitivity level would vary about the reference level, from shot to shot, indicating the operator's limited ability to precisely discern the lock indication, rather than actual degradation. One concern not addressed directly is the possibility of slow degradation, resulting from repeated exposure to the fields. However, through the end of the FEMPS test, every item had been subjected to at least four pulses, with several items being subjected to more than eight pulses, and no such effect was noted (except those items damaged, which could not be tested for sensitivity).

The FEMPS low-level vertical E-field, shown in figure 15, is plotted against the VEMPS II and fast-rise switch source E-fields in figure 10. The early-time portion of the waveform conforms to the predicted VEMPS II incident field rise time and peak amplitude. It is obvious that beyond 20 ns, the FEMPS field exceeds the VEMPS II late-time field. An energy comparison (fig. 11) indicates the total energy radiated by the FEMPS to be more than 15 times greater than the total energy radiated by the VEMPS II fields (2.8 $mJ/m^2$ radiated by the low-level FEMPS field, compared to 0.18 $mJ/m^2$ radiated by the predicted VEMPS II fields at a 7-m height and 680-m range).

Again, one must consider the frequency spectrum to determine the relative levels of in-band energy. The FEMPS low-level frequency spectrum (fig. 12 and 13) reveals a relative average amplitude three times or 12 dB greater (a 300-percent overtest) than the VEMPS II spectrum (in the 7- to 120-MHz system bandwidth). Over the entire spectrum, the FEMPS environment is 1.25 times or 7 dB greater (a 125-percent overtest). Predominant peaks in the FEMPS spectrum correspond directly with the frequencies of the resonating reflections experienced at FEMPS. The late-time fields resonating within FEMPS account for approximately 45 percent of the total energy of the electromagnetic field and are to a large degree contained within the 7- to 120-MHz bandwidth. It becomes apparent that even the low-level FEMPS environment was a considerable overtest. The medium and high levels were then extremely large overtests.

Figure 15. FEMPS low-level E-field.




The important information gained from FEMPS data concerns those items not experiencing upset. Logically, we conclude that those items not experiencing upset in the FEMPS low-level test, which has been shown to be more severe than the VEMPS II environment, will not experience upset when subjected to the predicted VEMPS II fields. Additionally, items surviving the medium- and high-level testing are assured to function normally in the predicted VEMPS II environment with some safety margin, provided by the worst-case test method. The large overtest conditions produced by FEMPS prompted a more refined test of the items that were upset by FEMPS low-level testing, before any conclusions could be made concerning their sensitivity to VEMPS II.

## 5.3 Fast-Rise Switch Source Test

In order to determine if the item upsets at FEMPS would recur at VEMPS II, or if they were a result of the worst-case test method, an environment that was a more accurate representation of the predicted VEMPS II E-fields was needed. Consequently, the 18 items (including the repaired satellite dish receiver) that were upset in the FEMPS low-level testing were retested at WRF. In order to maintain a relational progression in the test efforts, the test sessions at WRF were performed identically to the FEMPS testing sessions, except that items were tested individually instead of three items per pulse. Current data collected at the 35-m range from the fast-rise switch source demonstrated similar responses to those from FEMPS testing. Peak amplitudes and total energies coupled were different, but the basic responses from common POE's were similar.

Since the currents measured on the same POE for different items responded similarly, only a few examples of the POE currents are given.

Figures 16 to 20 are plots of typical currents measured on the antenna, phone, power, speaker, and computer keyboard cables. The corresponding frequency-domain plots are given in figures 21 to 25. An interesting observation is that the speaker and keyboard cables of shorter length respond with higher frequency content than the longer cables in the standard configuration. Although coupling of higher frequencies by these shorter cables was measured, the data collected for these POE's show that the peak amplitudes are still in the 7- to 120-MHz band.

The simulation of the VEMPS II 680-m environment was conducted at 15 m from the fast-rise switch source pulser. Figure 26 is a plot of the 15-m fast-rise switch source E-field at a 3-m height and is overplotted against the FEMPS and VEMPS II E-fields in figure 10. At this distance, a close representation of the VEMPS II environment was obtained. No upset or sensitivity degradation was recorded during this session; however, one item had to be eliminated from testing. Following the 35-m test, the Goldstar VCR had apparently upset when found powered off after a pulse. This was determined later to have been a vibration-related instability rather than an upset resulting from testing. Under laboratory conditions, the Goldstar VCR will completely power off if jarred or radically vibrated. This item was determined to be unreliable and was therefore eliminated from testing. The remaining 17 items were tested at the 15-m location without upset or failure. Upon completion of the test sessions at WRF, the 17 items had been subjected to a minimum of 10 pulses, with many being subjected to more than 12 pulses.

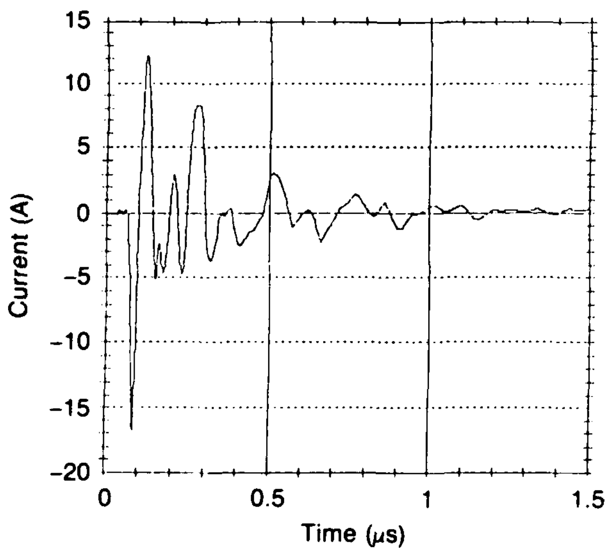



**Figure 16. Time response for typical antenna cable coupled current measured at WRF.**

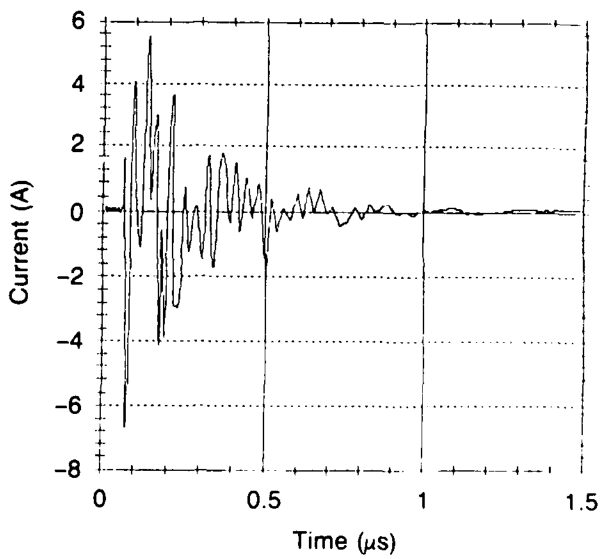



**Figure 17. Time response for typical telephone cable coupled current measured at WRF.**

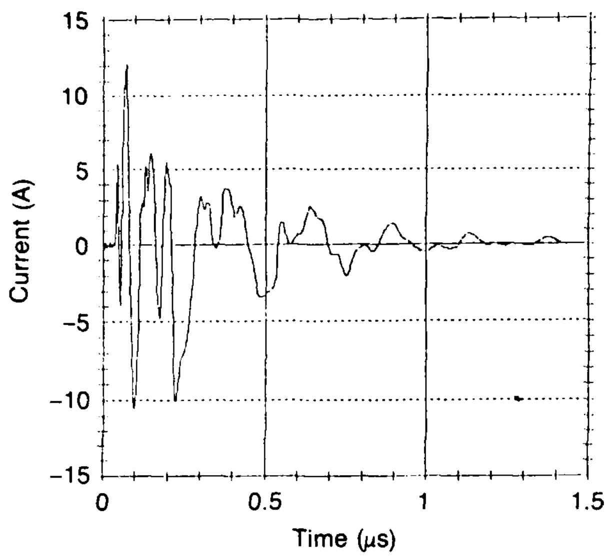



**Figure 18. Time response for typical power cable coupled current measured at WRF.**

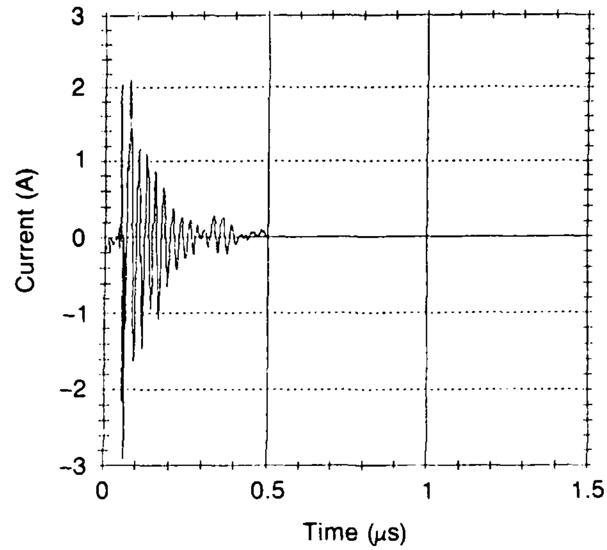
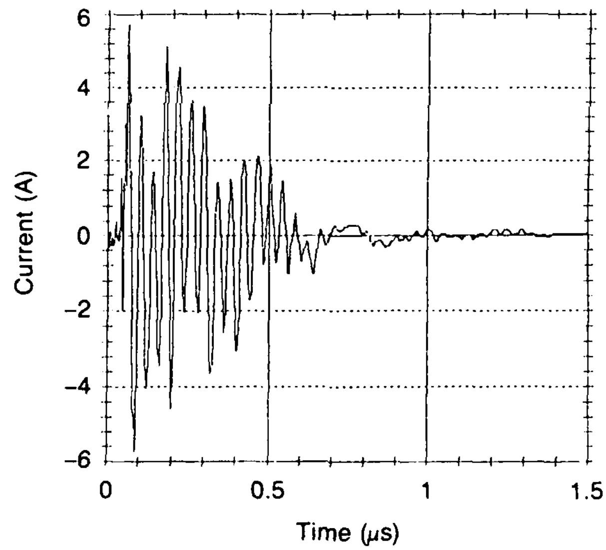



**Figure 19. Time response for typical speaker wire coupled current measured at WRF.**

**Figure 20. Time response for typical computer keyboard coupled current measured at WRF.**




The analysis for the fast-rise switch source environment was performed on the fields at a 15-m range and at a height of 3 m. The total energy radiated at this observation point is 0.95 mJ/m$^2$, as shown in figure 11. This total energy is approximately five times the VEMPS II total energy, but is only one third of the total energy radiated by a FEMPS low-level pulse. The frequency spectrum for the fast-rise switch source environment is overplotted with those of VEMPS II and FEMPS in figures 12 and 13. Comparing the FEMPS, VEMPS II, and fast-rise switch source spectra in the 7- to 120-MHz system bandwidth shows that the fast-rise switch

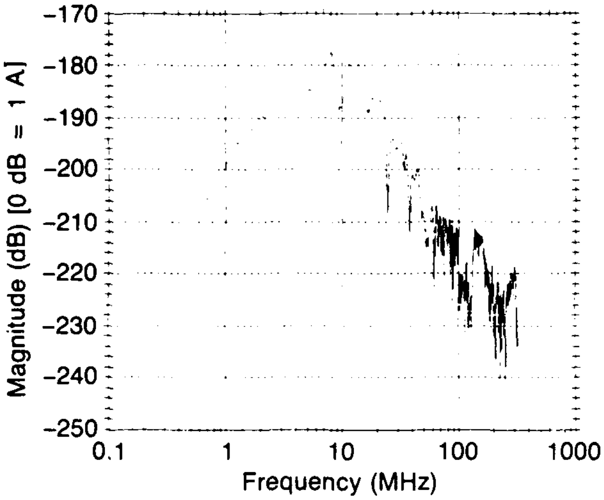



**Figure 21. Frequency spectrum for typical antenna coupled current measured at WRF.**

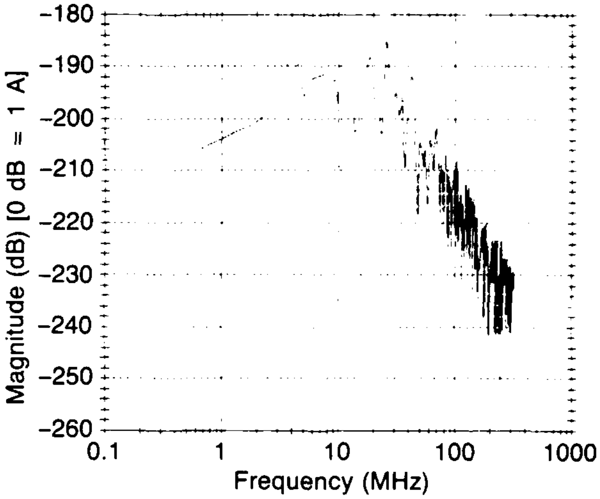



**Figure 22. Frequency spectrum for typical telephone cable coupled current measured at WRF.**

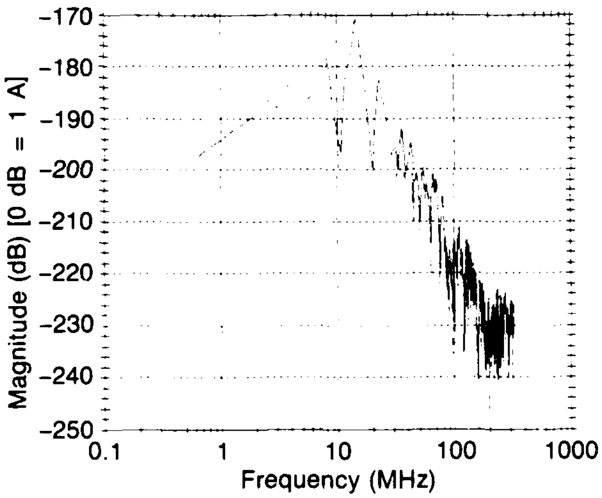



**Figure 23. Frequency spectrum for typical power cable coupled current measured at WRF.**

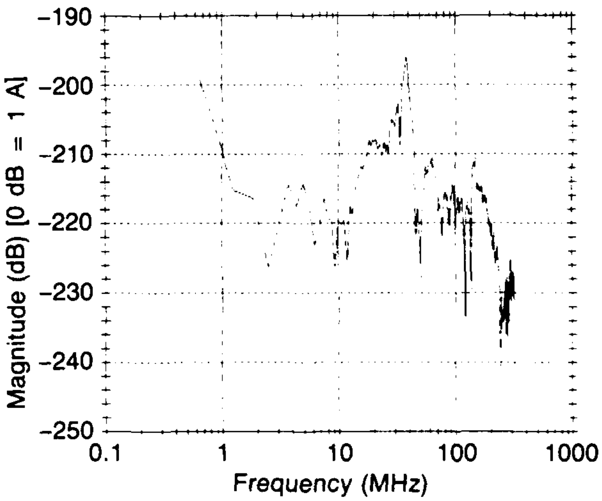



**Figure 24. Frequency spectrum for typical speaker wire coupled current measured at WRF.**

source environment is in closer agreement with the VEMPS II environment than is the FEMPS low-level environment.

The simulation at WRF is still an overtest, with amplitudes that are an average of 4 dB higher (0.58 times greater or a 58-percent overtest) than those of VEMPS II in the 7- to 120-MHz band. This is a considerably better simulation than the 12-dB in-band overtest of the FEMPS low-level environment. The 12-dB higher amplitudes at FEMPS constitute a 300-percent overtest for the in-band frequency content of the E-fields. The

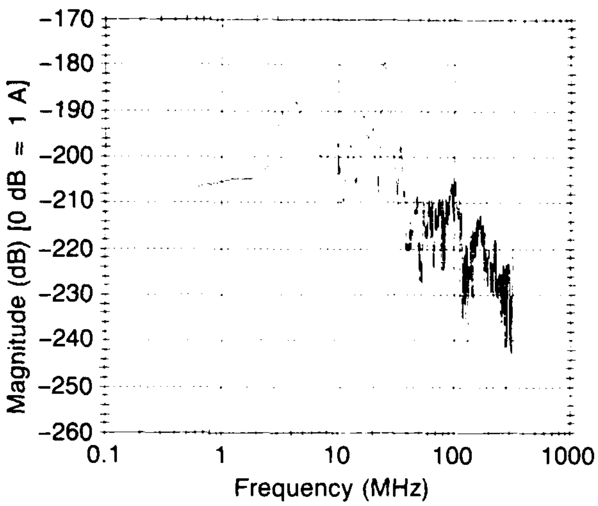



**Figure 25. Frequency spectrum for typical computer keyboard coupled current measured at WRF.**

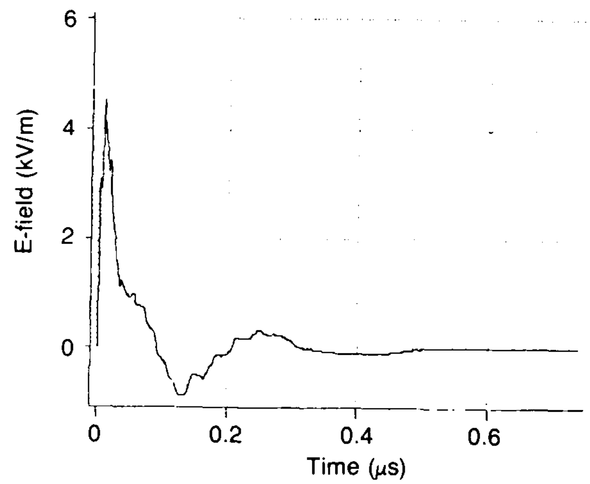



**Figure 26. Fast-rise switch source E-field at 15-m range, 3-m height.**

simulation at WRF, however, is only a 58-percent overtest in the 7- to 120-MHz frequency band. Averaged over the entire spectrum, the VEMPS II and the fast-rise switch source environments are nearly equal. Clearly, the predicted VEMPS II environment was more accurately represented by the fast-rise switch source.

## 5.4 Additional Considerations

Most of the consumer electronics testing efforts were directed towards evaluating consumer electronics at distances of 680 m and greater (from ground level up to one-story heights) from the proposed VEMPS II site. It is necessary to mention that there is a small community of houses, Bayside Park, at a distance of 580 m and more from the proposed VEMPS II site. A relatively dense grove of trees, the Marumsco Creek, a valley, and marshy areas separate Bayside Park from the site. These complicating factors make accurate E-field predictions difficult.

VEMPS II E-field predictions were made for the 580-m range using the same methods as were used for the 680-m E-field predictions. However, the 580-m scenario is complicated by the presence of the valley, the Marumsco Creek, the marshy areas, and the tree grove. At present, the GROUND3 code is not configured for handling these complications directly. E-field predictions for the 580-m range via GROUND3 require several geometric and electromagnetic simplifications to be made. The consequences of these simplifications are not known; therefore, the possibility exists that the actual fields produced by VEMPS II at a 580-m range may be greater than the predicted E-fields.

The most accurate way to evaluate the E-fields that may be produced in the Bayside Park area is through physical testing. The testing could be conducted via low-level VEMPS II operation after its construction. E-fields produced by VEMPS II operating at low output could be measured at various locations in the Bayside Park area, then scaled up to the equivalent E-fields that would be produced by VEMPS II operating at normal output. These data could then be analyzed as in this analysis. E-fields greater than those predicted for the area would only occur at limited and specific locations that might possibly receive higher E-fields reflected from seawater or marshy ground. Even at these locations, only certain consumer electronics oriented in certain ways would be affected. The low-level VEMPS II test would identify these areas, if they exist, and then simple unobtrusive steps could be taken to mitigate the potential disturbance of consumer electronics located there.

# 6. Summary and Conclusions

An extensive effort was undertaken to predict the electric fields resulting from VEMPS II operation that will be produced outside the confines of the Woodbridge Research Facility (at distances of 680 m and greater). Following the analytic predictions, several tests were conducted to evaluate typical consumer electronics in simulated VEMPS II environments. In order to assure a high probability that typical consumer electronics in Woodbridge would be represented in the tests, a survey of the Woodbridge area resulted in selection of a 91-item lot of consumer electronic goods. These items ranged from inexpensive electronic toys to sophisticated medical equipment. The selection of a wide range of qualities, technologies, and manufacturers also enhanced the probability of representing electronics that might be found in the Woodbridge community.

Throughout the test sessions, every item was tested in a configuration that was consistent with the manner in which it would commonly be used. The test items were also oriented in these configurations in such a way as to provide the greatest coupling of electromagnetic energy. This worst-case test philosophy was used throughout the test, in many fashions, to produce test environments that were greater than the predicted VEMPS II environment. By assuring worst-case parameters, an overtest scenario was produced that created a high confidence in the conclusions drawn from the test results. Without the overtest conditions, inherent uncertainties associated with the test would have yielded lower confidence in the conclusions.

Continuous-wave illumination of the test configuration produced results indicating a frequency dependence of the standard configuration. The cables used in the configurations have a predominant frequency band approximately 7 to 120 MHz, whereby electromagnetic energy will couple effectively into the system. The frequency characteristics of the system were useful in comparing the relative energy content of the simulated environments to the predicted VEMPS II environment.

The first test session was conducted at the DNA FEMPS facility. The 91 items were tested in three environments and monitored for operational upset or failure and sensitivity degradation. While sensitivity degradation was not noted, several items experienced some form of operational malfunction. During the FEMPS tests, several studies were conducted to determine if direct coupling to circuitry within consumer electronics could cause upset or damage. None of the studies conducted indicated that direct coupling posed a threat to consumer electronics (within the context of the test efforts).

Posttest analysis of the FEMPS environment revealed that a large overtest environment had been produced. Reflections within the metallic enclosure of the FEMPS facility had approximately doubled the incident energy produced by the pulser. Although worst-case conditions were needed, the environment within the test volume was more threatening than desired. The lowest level FEMPS environment, when compared to the VEMPS II environment, is approximately a 300-percent average overtest for frequencies between 7 and 120 MHz and a 125-percent average overtest over the total frequency domain. The test items not experiencing upset or damage in the lowest level FEMPS environment are not expected to experience adverse effects from VEMPS II operation. Valid conclusions could not be formulated concerning the 18 items that experienced upset at the low-level FEMPS testing, and these therefore were retested at WRF.

A test location was chosen at the WRF's fast-rise switch source that provided a 58-percent overtest in the 7- to 120-MHz system bandwidth and that was the average equivalent of the VEMPS II environment over the total frequency domain. Under this worst-case scenario, no upsets, failures, or sensitivity degradations were noted. The fast-rise switch source simulation provided an environment that reasonably represented the predicted VEMPS II environment without an excessive overtest. The results of test sessions show that typical consumer electronics in the Woodbridge community, at a 680-m range from VEMPS II, will not experience operational upset or failure from the predicted environment resulting from VEMPS II operation. The results of the fast-rise switch-source tests also show that no upsets occur in an environment that is 58 percent greater (7 to 120 MHz) than the predicted VEMPS II environment at a 680-m range. The low-level FEMPS test indicates that no damage of typical consumer electronics will occur in an environment that is approximately three times greater (300 percent greater for frequencies of 7 to 120 MHz) than the predicted VEMPS II environment at a 680-m range.

The E-fields that may be produced at Bayside Park, 580 m and further from the proposed VEMPS II site, were not analyzed in detail because of complications in modeling the terrain along the propagation paths. Initial calculations suggest that there is a possibility of upset to consumer electronics in the Bayside Park area under certain conditions. However, because of the small number of houses, specific types of consumer electronics, and the circumstances necessary, it is not expected that consumer electronics in the Bayside Park area will experience upset. E-field measurements during low-level VEMPS II operation, after its construction, and subsequent analysis would identify any "upset areas" in Bayside Park if they exist.

## Acknowledgement

The author would like to express his appreciation to Thomas J. Bock of Harry Diamond Laboratories for his technical advice and direction throughout the test program.

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## Appendix. Test Items, Electric Field Height Profiles, and Test Configurations

**Appendix**

## Figures

Page



## Table

In the testing of consumer electronics items, performed by personnel of the Woodbridge Research Facility, the 91 test items were chosen to provide a range of manufacturers, types, technologies, and cost (see table A-1). These were tested in configurations which reflect the way in which they might actually be used, as well as promoting the greatest coupling of electromagnetic energy. These test configurations thus uphold a worst-case test philosophy; figures A-1 to A-9 display these configurations.

The analysis of the proposed VEMPS II (Vertical Electromagnetic Pulse Simulator, second generation) produced a profile of the electric field over a range of heights (see fig. A-10 to A-18).

**Table A-1. Complete list of test items (91)**

| Item | Model No. | Serial No. |
|---|---|---|
| **Televisions** | | |
| Sony 27 in. with remote control (R/C) | KV2791R | 7020120 |
| RCA 26 in. with R/C | FPR720WR | 718350071 |
| Casio 2.6 in. portable | TV-400 | 2002700A |
| J.C. Penney 25 in., color | 685-2507M | 626340188 |
| Montgomery Ward 25 in. | GSK15246 | 616866 |
| Sharp 25 in. console with R/C | 25LC156 | 662010 |
| GE Zenith Elect. 19 in. | C-1920W | 691-52390242 |
| Zenith 19 in. | SD1911W | 722-17140916 |
| Sharp 19 in. with R/C | 19MP7 | 342191 |
| Sony 13 in. with R/C, color | KV1929 | 7002803 |
| GE 19 in. with R/C | 8-1930 | FV1T31797 |
| Sony 13 in. with R/C, color | KV1326 | 5037162 |
| Sears R/C 13 in., color | 40551 | V7120706071 |
| Sears 13 in., color | 40351 | V7090729375 |
| J.C. Penney 13 in., color | 685-2104 | KC70101295 |
| Emerson 13 in., color | ECR138/139 | 303-7417720 |
| Panasonic 13 in., color | C 9R | AM53290711 |
| Portland 13 in., color | DCB-415PR | 48554105HR |
| RCA 13 in., color | ELR330W | 516359154 |
| Montgomery Ward 9 in. | 12128 | 3410 |
| Goldstar 5 in., portable | — | KC61000327 |
| Fisher integrated A/V system | PC-203W | V6430800190 |
| **VCR's** | | |
| Magnavox | VR 9525AT | 40558391 |
| Sharp | VC-7842U | 311380 |
| Sears | 53292 | 61033781 |
| J.C. Penney HiFi | 686-5074 | J5SA30651 |

**Table A-1. Complete list of test items (91)** (cont'd)

| Item | Model No. | Serial No. |
|---|---|---|
| VCR's (cont'd) | | |
| Symphonic Direct Access | 5200HQ | H22641154 |
| Mitsubishi HQ Wireless | HS348UR | UR348013948 |
| Mitsubishi Random Access | HS421UR | UR421010731 |
| Toshiba HiFi | M5900 | 16236988A |
| Toshiba R/C | M2220 | 70234130 |
| Toshiba 4-head HQ | M4220 | 66387253 |
| Magnavox | VR 9622AT01 | 52483712 |
| Goldstar | CV-5500 | 6091078 |
| Akai | VS-515U | V670621 |
| **Stereo receivers** | | |
| Kenwood stereo receiver | KR-V95R | 73512323 |
| Onkyo | TX38 | 3609004531 |
| Technics amp/receiver | SA-130 | EE6L19B447 |
| Pioneer | SX1100 | HC3922373 |
| Sony compact disk | CDP-50 | 805423 |
| JVC receiver | RX5VBK | 09107648 |
| Sharp compact disk | DX-111 | 60509529 |
| Fisher integrated A/V system | FM-226 | B34102 8703 |
| **Emergency services** | | |
| Johnson SDL6085-16 channel | SDL6085-16 | — |
| Johnson Challenger 7171 uhf | 7171 uhf | — |
| GE-PSX vhf 2-channel | PSX-2 | — |
| **Satellite dish** | | |
| Realistic 8.5-ft dish | — | — |
| **Camcorders** | | |
| Sony | CCD-V3 | 276829 |
| Montogomery Ward | 10650 | D7W312873 |
| **Radios** | | |
| Sony AM/FM clock radio | ICF-C70W | — |
| Multitech | XP26 | — |
| Sanyo AM/FM Cassette Boom | M9708 | 05320943 |
| Transcend headphone radio | THR-212 | — |
| Sony Walkman radio | SRF-21W | 561608 |
| Realistic table radio | MTA-12 | — |
| Sony car stereo with cassette | XR-17 | 36376 |
| Sony AM/FM cassette recorder | CFM-120 | — |
| Craig | TP508 | 17112777 |

**Table A-1. Complete list of test items (91)** (cont'd)

| Item | Model No. | Serial No. |
|---|---|---|
| **Phones** | | |
| Carrera one-piece | 305 | 9132044 |
| Panasonic | KX-T3135 | — |
| Telemax wall/desk phone | TM3325 | — |
| **Cordless phones** | | |
| Bell Cordless | 32011 | — |
| Realistic Cordless | ET-410 | — |
| **Cellular phones** | | |
| Audiovox | CMT-400 | — |
| NEC | T7041 | — |
| GE | 2000 | |
| **Computers** | | |
| IBM Personal | AT 339 | 5170732885 |
| Leading Edge | DC-2011E | 70530827 |
| Hayes | 07-00038 | A37100153046 |
| **Games** | | |
| Fisher Price Sky Talker | — | — |
| Commodore 64C Computer | — | — |
| Coleco My Talking Computer | — | — |
| Coleco Talking Teacher | — | — |
| **Microwave ovens** | | |
| Sears Kenmore | 87214 | 7E4K25065 |
| Samsung | MW2130U | M70203656 |
| Emerson 1.41 cubic | AT1551EEM | 62912062 |
| **Door openers** | | |
| Sears garage door opener | 53100 | — |
| Genie 1/2-hp door opener | GS-940 | — |
| **CB's/answering machines** | | |
| Realistic 40 channel | TRC-415 | 0143717 |
| Cobra | 19-Plus | 70321754 |
| Phone-Mate | IQ7650 | 469-009187 |
| **Medical equipment** | | |
| Oxygen concentrator (Invacare Prime-Air) | — | — |
| Aquitron infant monitor | 8200 | — |
| Tens (muscle stimulator) | 4500 | — |
| Suction machine (DeVilbiss Vacuaide) | 721 | — |

**Table A-1. Complete list of test items (91) (cont'd)**

| Item | Model No. | Serial No. |
|---|---|---|
| **Medical equipment** (cont'd) | | |
| Kangaroo feeder pump | 330 | — |
| Photography unit | 4224 | — |
| Ventilator | — | — |
| Nova II pacemaker | 281-03 | — |
| Quantum pacemaker | 254-20 | — |
| Cosmos pacemaker | 282-04V | — |

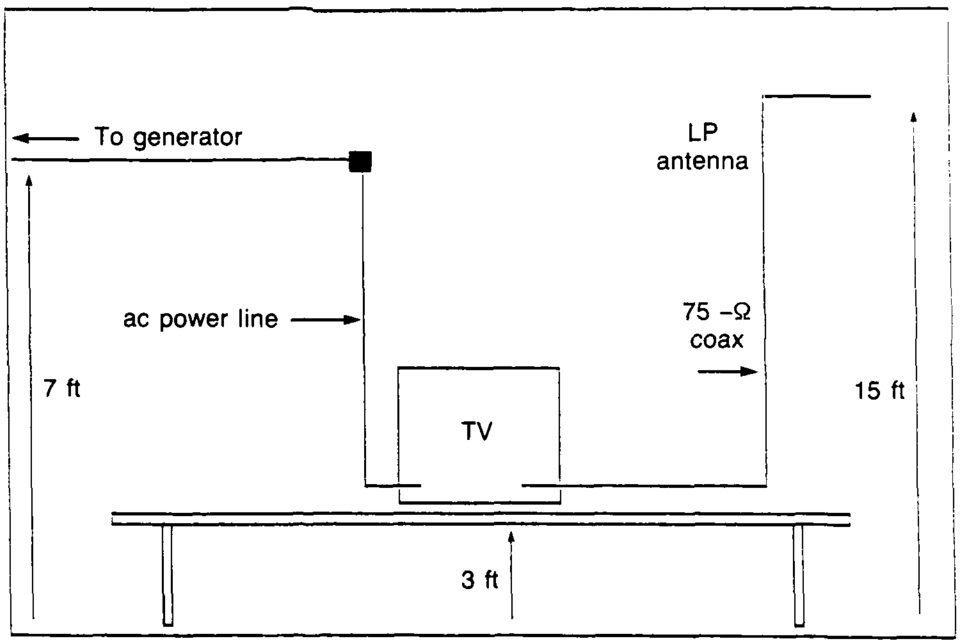



**Figure A-1. Television test configuration.**

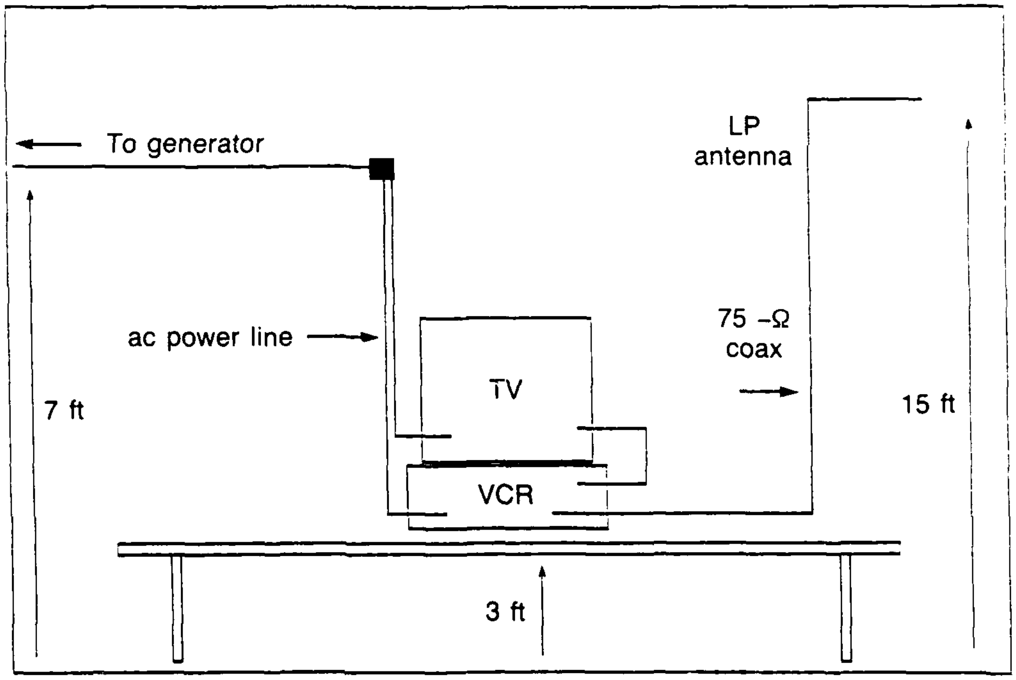



**Figure A-2. VCR test configuration.**

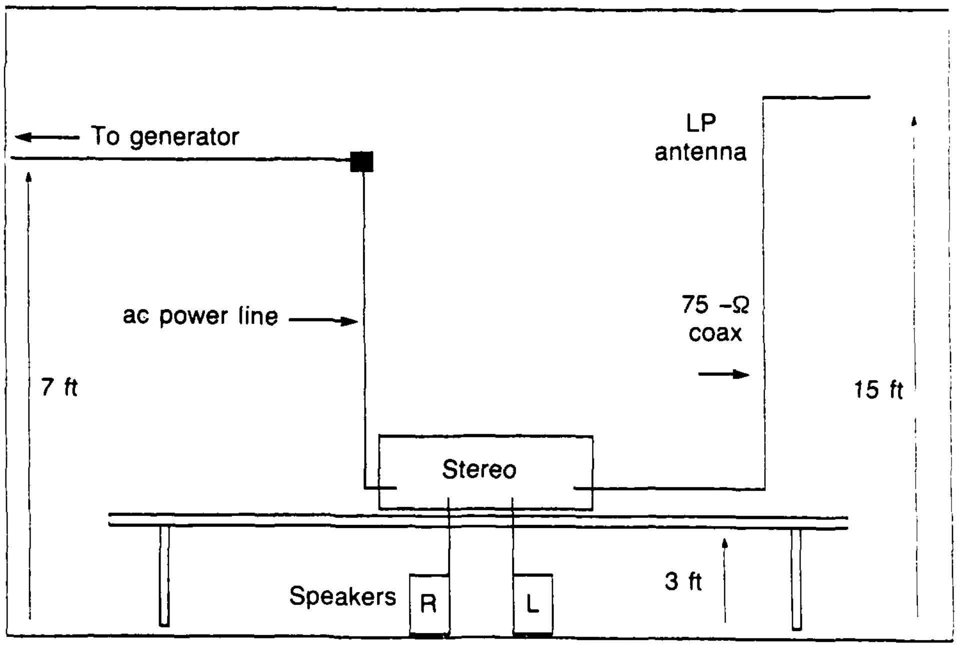



**Figure A-3. Stereo receiver test configuration.**

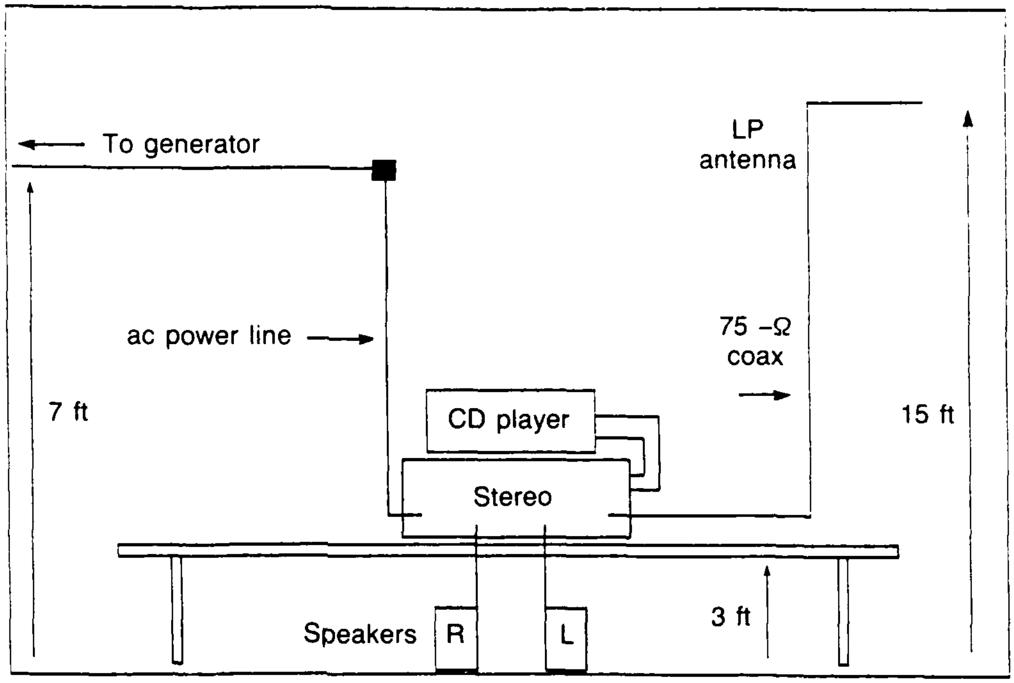



**Figure A-4. CD player test configuration.**

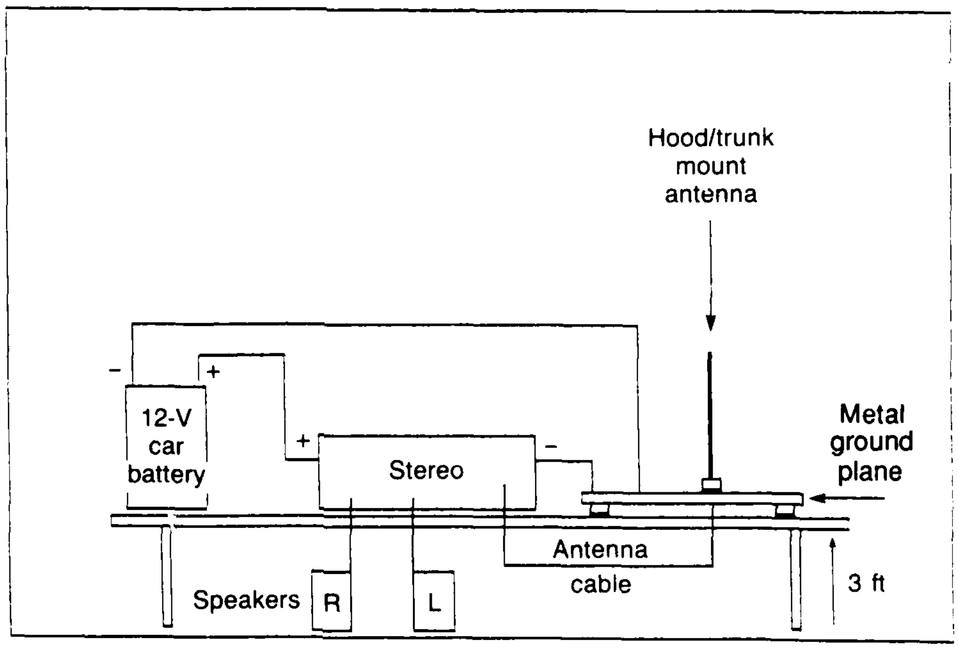



**Figure A-5. Car radio test configuration.**

**Figure A-6. Satellite dish test configuration.**

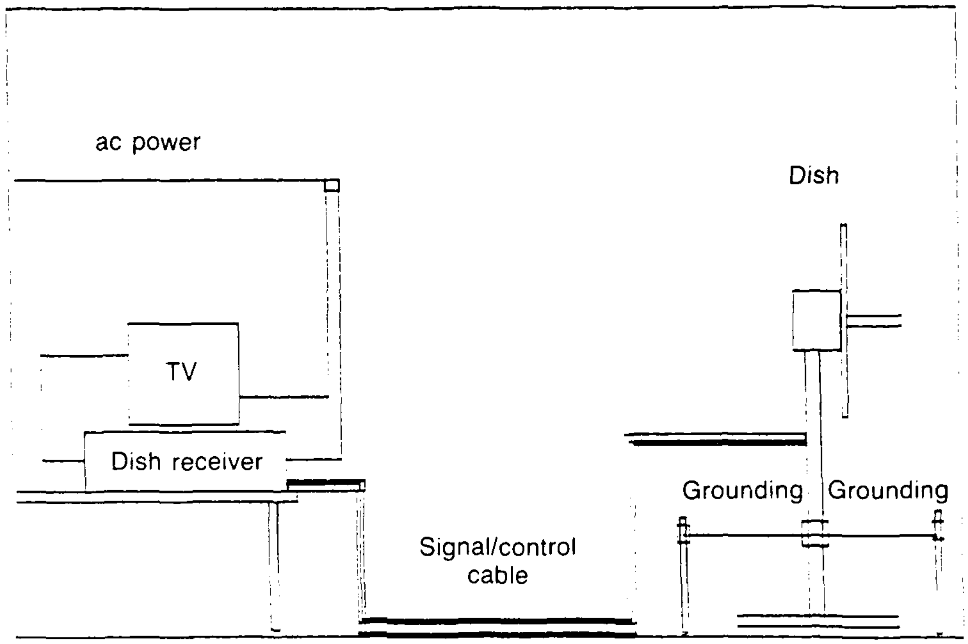



**Figure A-7. Medical pump test configuration.**

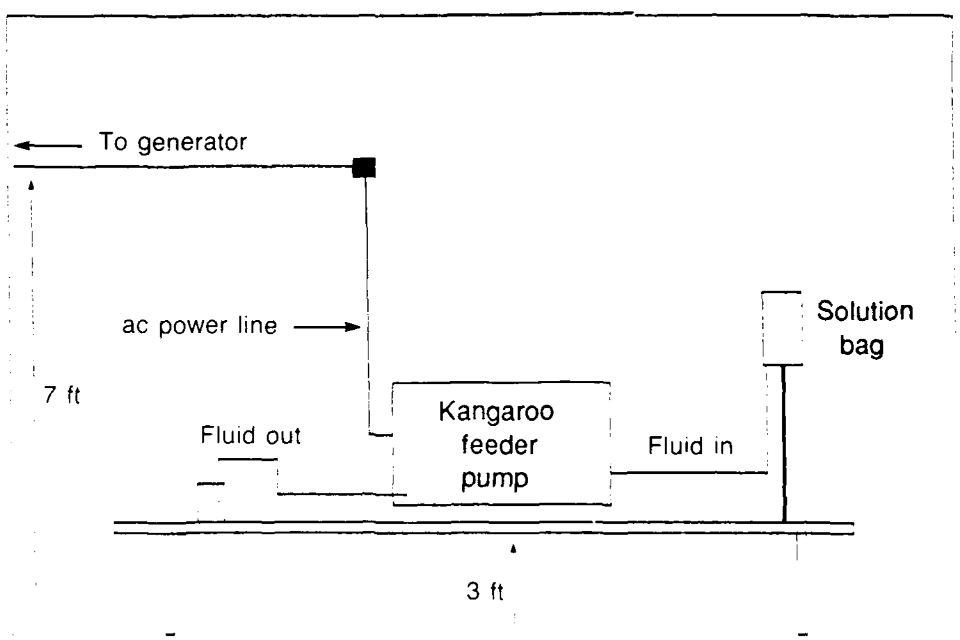


**Figure A-8. Computer test configuration.**

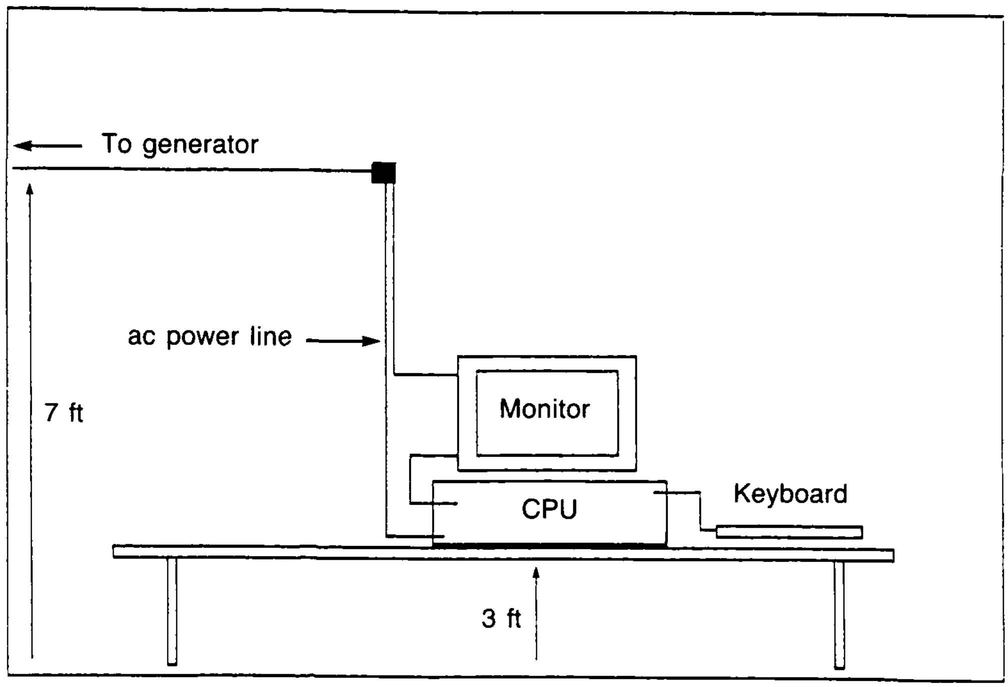



**Figure A-9. Phone/ answering machine test configuration.**

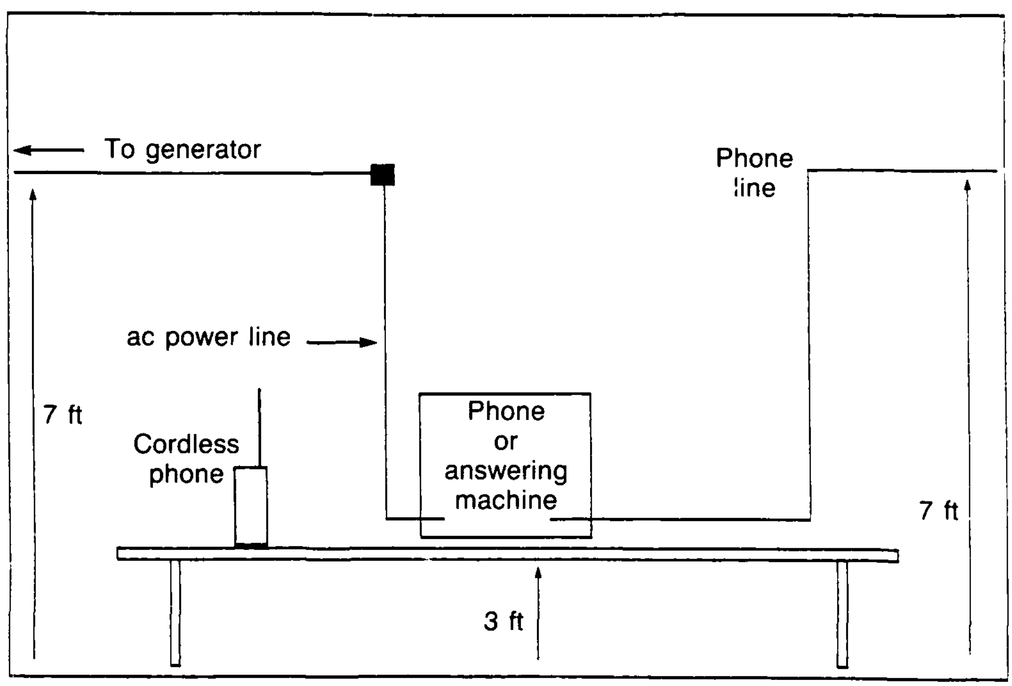


**Figure A-10. Total field, vertical polarization, vertical component height = 1.0 m.**

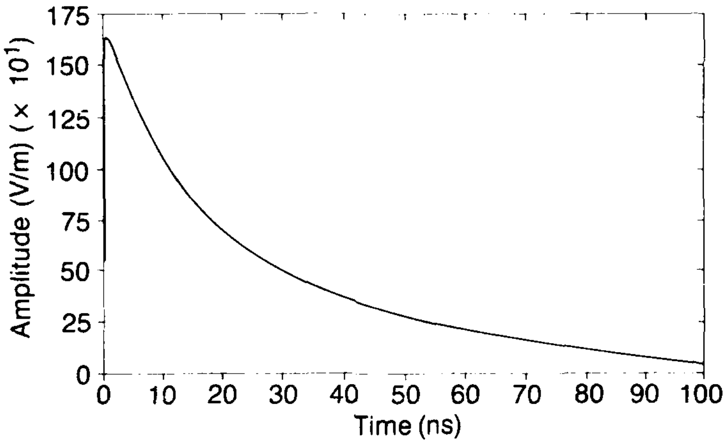



**Figure A-11. Total electric field, vertical polarization, vertical component height = 2.0 m.**

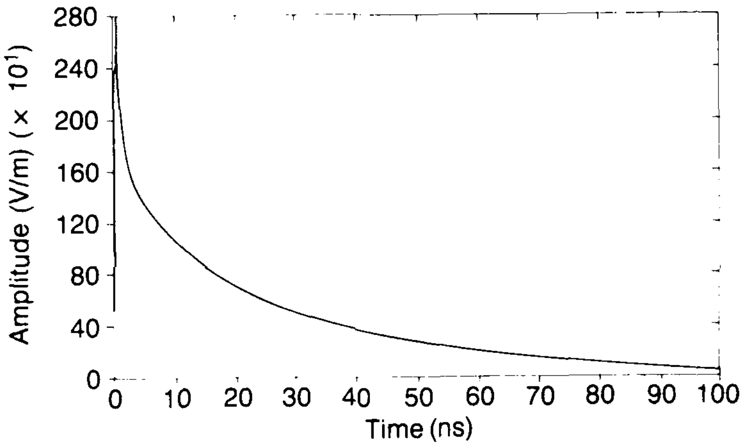



**Figure A-12. Total electric field, vertical polarization, vertical component height = 3.0 m.**

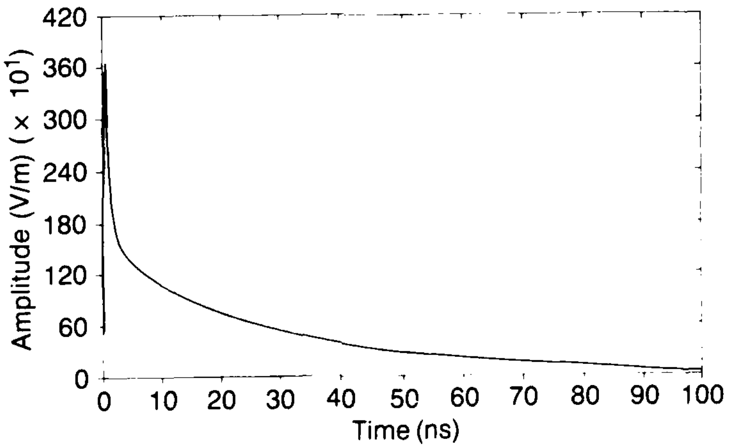


**Figure A-13. Total electric field, vertical polarization, vertical component height = 5.0 m.**

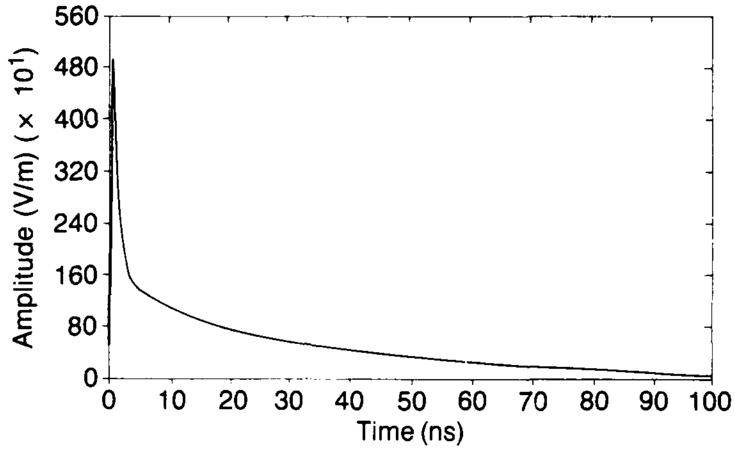



**Figure A-14. Total electric field, vertical polarization, vertical component height = 7.0 m.**

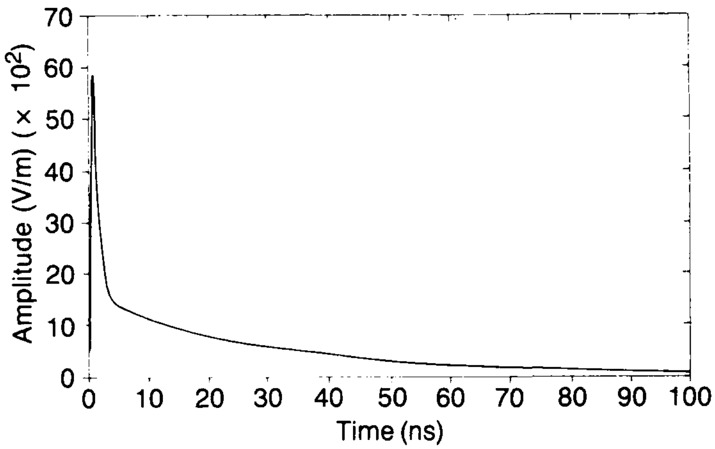
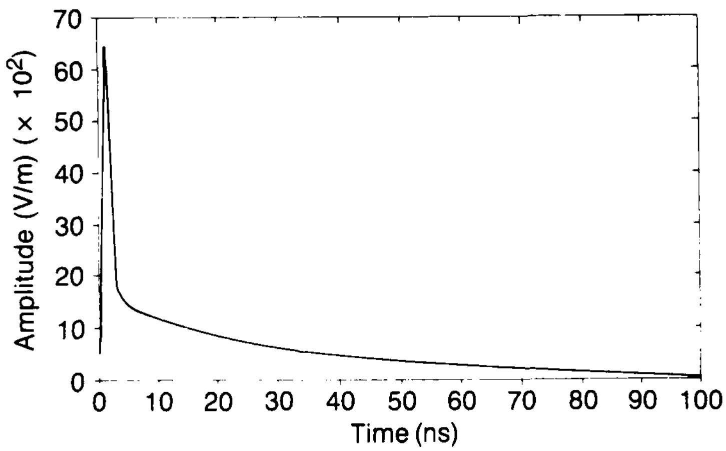



**Figure A-15. Total electric field, vertical polarization, vertical component height = 10.0 m.**



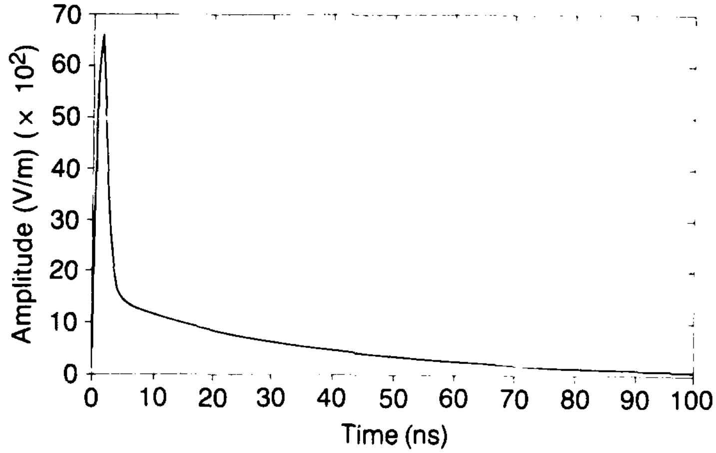



**Figure A-16.** Total electric field, vertical polarization, vertical component height = 12.0 m.

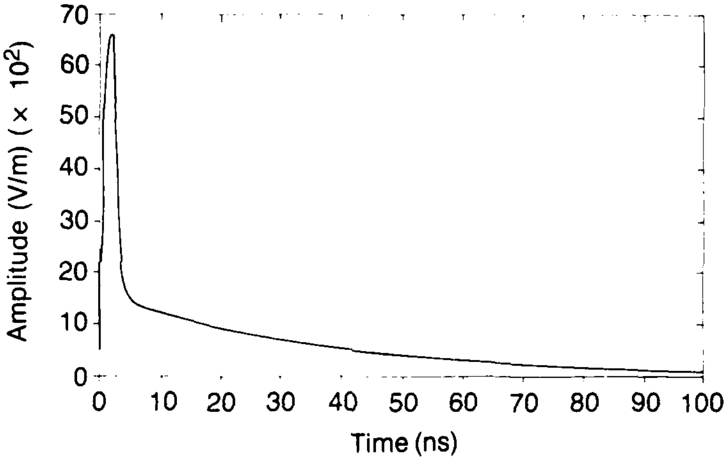



**Figure A-17.** Total electric field, vertical polarization, vertical component height = 15.0 m.

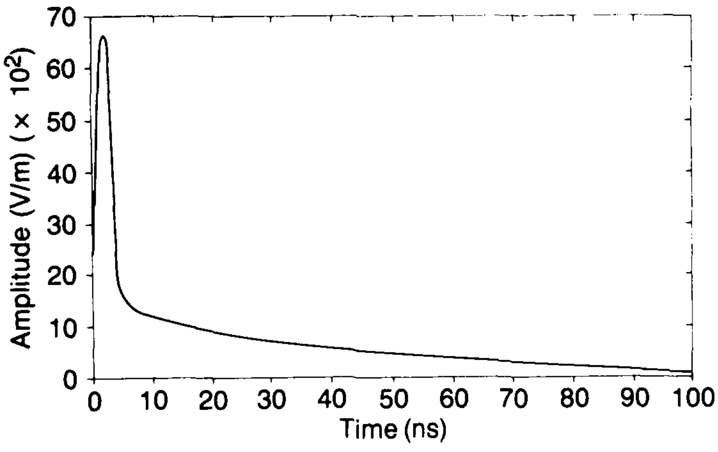



**Figure A-18.** Total electric field, vertical polarization, vertical component height = 18.0 m.

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