INTERNATIONAL STANDARD

IEC 61000-2-13

First edition
2005-03

BASIC EMC PUBLICATION

Electromagnetic compatibility (EMC) –

Part 2-13:
Environment –
High-power electromagnetic (HPEM) environments –
Radiated and conducted

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

ELECTROMAGNETIC COMPATIBILITY (EMC) –

Part 2-13: Environment – High-power electromagnetic (HPEM) environments – Radiated and conducted

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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International Standard IEC 61000-2-13 has been prepared by subcommittee 77C: High power transient phenomena, of IEC technical committee 77: Electromagnetic compatibility.

It has the status of a basic EMC publication in accordance with IEC Guide 107.

The text of this standard is based on the following documents:

FDIS	Report on voting
77C/153/FDIS	77C/155/RVD

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until the maintenance result date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed;
- withdrawn;
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

INTRODUCTION

IEC 61000 is published in separate parts according to the following structure:

Part 1: General

General considerations (introduction, fundamental principles)

Definitions, terminology

Part 2: Environment

Description of the environment

Classification of the environment

Compatibility levels

Part 3: Limits

Emission limits

Immunity limits (in so far as they do not fall under the responsibility of the product committees)

Part 4: Testing and measurement techniques

Measurement techniques

Testing techniques

Part 5: Installation and mitigation guidelines

Installation guidelines

Mitigation methods and devices

Part 6: Generic standards

Part 9: Miscellaneous

Each part is further subdivided into several parts, published either as International Standards or as technical specifications or technical reports, some of which have already been published as sections. Others will be published with the part number followed by a dash and a second number identifying the subdivision (example: 61000-6-1).

ELECTROMAGNETIC COMPATIBILITY (EMC) –

Part 2-13: Environment – High-power electromagnetic (HPEM) environments – Radiated and conducted

1 Scope

This part of IEC 61000 defines a set of typical radiated and conducted HPEM environment waveforms that may be encountered in civil facilities. Such threat environments can produce damaging effects on electrical and electronic equipment in the civilian sector, as described in IEC 61000-1-5. It is necessary to define the radiated and conducted environments, in order to develop protection methods.

For the purposes of this standard, high-power conditions are achieved when the peak electric field exceeds 100 V/m, corresponding to a plane-wave free-space power density of 26,5 W/m^2. This criterion is intended to define the application of this standard to EM radiated and conducted environments that are substantially higher than those considered for "normal" EMC applications, which are covered by the standards produced by IEC SC 77B.

The HPEM environment can be:

- radiated or conducted;
- a single pulse envelope with many cycles of a single frequency (an intense narrowband signal that may have some frequency agility and the pulse envelope may be modulated);
- a burst containing many pulses, with each pulse envelope containing many cycles of a single frequency;
- an ultrawideband transient pulse (spectral content from tens of MHz to several GHz);
- a burst of many ultrawideband transient pulses.

The HPEM signal could be from sources such as radar or other transmitters in the vicinity of an installation or from an intentional generator system targeting a civilian facility. Radiated signals can also induce conducted voltages and currents through the coupling process. In addition, conducted HPEM environments may also be directly injected into the wiring of an installation.

There is a critical distinction between the HEMP (high-altitude electromagnetic pulse) environment and the HPEM environment, in terms of the range or the distance of the affected electrical or electronic components from the source. In the context of HEMP, the range is immaterial, as the HEMP environment propagates downward from space to the earth's surface and is therefore relatively uniform over distances of 1 000 km. On the other hand, in the HPEM context the environment and its effects decrease strongly with range. In addition, the HEMP waveshape is a series of time domain pulses while the HPEM environment may have a wide variety of waveshapes.

Consequently, the standardization process for HPEM environments is more difficult. The recommended approach is to investigate the various types of HPEM environments that have been produced to date and are likely to be feasible in the near future, and then to develop suitable HPEM standard waveforms from such a study. Such HPEM environment standard waveforms can be amended in due course, depending on emerging technologies that make it possible to produce them.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050-161, *International Electrotechnical Vocabulary (IEV) – Chapter 161: Electromagnetic compatibility*

IEC 61000-1-5, *Electromagnetic compatibility (EMC) – Part 1-5: General – High power electromagnetic (HPEM) effects on civil systems*

IEC 61000-2-9, *Electromagnetic compatibility (EMC) – Part 2: Environment – Section 9: Description of HEMP environment – Radiated disturbance*

IEC 61000-2-10, *Electromagnetic compatibility (EMC) – Part 2-10: Environment – Description of HEMP environment – Conducted disturbance*

IEC 61000-2-11, *Electromagnetic compatibility (EMC) – Part 2-11: Environment – Classification of HEMP environments*

IEC 61000-4-3, *Electromagnetic compatibility (EMC) – Part 4-3: Testing and measurement techniques – Radiated, radio-frequency, electromagnetic field immunity test*

IEC 61000-4-4, *Electromagnetic compatibility (EMC) – Part 4-4: Testing and measurement techniques – Section 4: Electrical fast transient/burst immunity test.*

IEC 61000-4-5, *Electromagnetic compatibility (EMC) – Part 4: Testing and measurement techniques – Section 5: Surge immunity test*

IEC 61000-4-6, *Electromagnetic compatibility (EMC) – Part 4-6: Testing and measurement techniques – Immunity to conducted disturbances, induced by radio-frequency fields*

IEC 61000-4-12, *Electromagnetic compatibility (EMC) – Part 4: Testing and measurement techniques – Section 12: Oscillatory waves immunity test*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-161 as well as the following apply.

3.1
attenuation
reduction in magnitude (as a result of absorption and scattering) of an electric or magnetic field or a current or voltage; usually expressed in decibels

3.2
bandratio
br
ratio of the high and low frequencies between which there is 90 % of the energy; if the spectrum has a large dc content, the lower limit is nominally defined as 1 Hz

3.3
bandratio decades
brd
bandratio expressed in decades as: $brd = \log_{10}(br)$

3.4
burst
typically a time frame in which a series of pulses occurs with a given repetition rate. When multiple bursts occur, the time between bursts is usually defined

3.5
conducted HPEM environment
high power electromagnetic currents and voltages that are either coupled or directly injected to cables and wires with voltage levels that typically exceed 1 kV

3.6
continuous wave
CW
time waveform that has a fixed frequency and is continuous

3.7
electromagnetic compatibility
EMC
ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment

3.8
electromagnetic disturbance
any electromagnetic phenomenon which may degrade the performance of a device, equipment or system

3.9
electromagnetic interference
EMI
degradation of the performance of a device, transmission channel or system caused by an electromagnetic disturbance

NOTE Disturbance and interference are respectively cause and effect.

3.10
(electromagnetic) shield
electrically continuous housing for a facility, area, or component used to attenuate incident electric and magnetic fields by both absorption and reflection

3.11
(electromagnetic) susceptibility
inability of a device, equipment or system to perform without degradation in the presence of an electromagnetic disturbance

NOTE Susceptibility is a lack of immunity.

3.12
high-altitude electromagnetic pulse
HEMP
electromagnetic pulse produced by a nuclear explosion outside the earth's atmosphere

NOTE Typically above an altitude of 30 km.

3.13
high-power microwaves
HPM
narrowband signals, nominally with peak power in a pulse, in excess of 100 MW at the source

NOTE This is a historical definition that depended on the strength of the source. The interest in this document is mainly on the EM field incident on an electronic system.

3.14
hyperband signal
signal or waveform with a pbw value between 163,64 % and 200 % or a bandratio >10

3.15
hypoband signal
narrowband signal
signal or waveform with a pbw of <1 % or a bandratio <1,01

3.16
intentional electromagnetic interference
IEMI
intentional malicious generation of electromagnetic energy introducing noise or signals into electric and electronic systems, thus disrupting, confusing or damaging these systems for terrorist or criminal purposes

3.17
L band
radar frequency band between 1 and 2 GHz

3.18
mesoband signal
signal or waveform with a pbw value between 1 % and 100 % or a bandratio between 1,01 and 3

3.19
percentage bandwidth
pbw
bandwidth of a waveform expressed as a percentage of the centre frequency of that waveform

NOTE The pbw has a maximum value of 200 % when the centre frequency is the mean of the high and low frequencies. The pbw does not apply to signals with a large dc content (e.g., HEMP) for which the bandratio decades is used.

3.20
point-of-entry
PoE
port-of-entry
PoE
physical location (point) on an electromagnetic barrier, where EM energy may enter or exit a topological volume, unless an adequate PoE protective device is provided

NOTE 1 A PoE is not limited to a geometrical point.

NOTE 2 PoEs are classified as aperture PoEs or conductive PoEs according to the type of penetration. They are also classified as architectural, mechanical, structural or electrical PoEs according to the functions they serve.

3.21
pulse
a transient waveform that usually rises to a peak value and then decays, or a similar waveform that is an envelope of an oscillating waveform

3.22
radiated HPEM environment
high power electromagnetic fields with peak electric field levels that typically exceed 100 V/m

3.23
sub-hyperband signal
a signal or a waveform with a pbw value between 100 % and 163,64 % or a bandratio between 3 and 10

3.24
transient
pertaining to or designating a phenomenon or a quantity which varies between two consecutive steady states during a time interval which is short compared with the time-scale of interest

NOTE A transient can be a unidirectional impulse of either polarity or a damped oscillatory wave with the first peak occurring in either polarity.

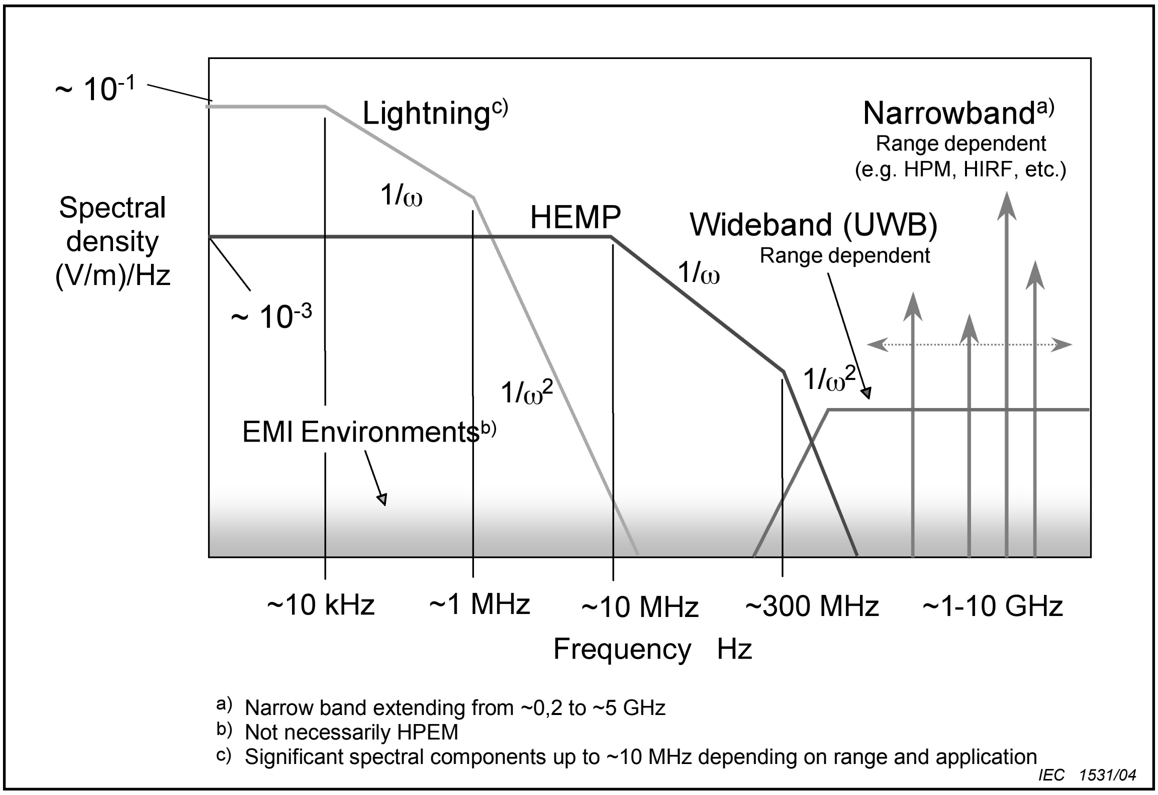
3.25
ultrawideband
UWB
a signal that has a percent bandwidth greater than 25 %

4 General

Figure 1 is provided to help understand the relationship of HPEM environments to other electromagnetic environments. Note that the fast portion of the HEMP electric field Fourier transform from IEC 61000-2-9 is generally most important at frequencies below 300 MHz. The two major types of radiated HPEM environments (narrowband and wideband) are typically found at higher frequencies, as shown.

It is noted in Figure 1 that the wideband spectral density will decrease at very high frequencies (typically above 3 to 5 GHz), however the figure is not intended to portray a specific UWB pulse. Lightning environments are also variable, but they often contain some content up to 10 MHz [19][1)]. It is important to understand that the differences shown in the environments can produce different types of effects in electronic systems.

1) Figures in brackets refer to the bibliography.



NOTE The magnitude of the electric field spectrum is plotted on the y-axis.

Figure 1 – Several types of HPEM environments compared with the IEC HEMP waveform

The IEC recognises certain major trends in civilian electronic systems as follows:

a) increasing use of automated electronic systems in every aspect of civilized societies – communication, navigation, medical equipment, etc.,

b) increasing susceptibility of electronic systems due to higher package densities, use of monolithic integrated circuits (MIC) (system on a chip), multi-chip modules (MCM) (mixing analogue, digital, microwave, etc.), and

c) increasing use of EM spectrum which includes radio, TV, microwave ovens, aircraft electronics, automobile electronics, cell phones, direct broadcast satellites, etc. It is easy to envision a component failure leading to a subsystem and consequently a system-level failure, due to an intense HPEM signal. Several such effects are documented in IEC 61000-1-5.

Two examples of accidental electrical system failures due to RF fields include:

a) the firing of an aircraft missile due to a radar exposure of an improperly mounted shielded connector on a missile cable on the U.S. aircraft carrier *Forrestal* in 1967, and

b) U.S. FDA documented medical equipment problems (1979-1993) in devices such as blood cell counters, cardiac monitors, neo-natal monitors, etc. due to exposures to electromagnetic fields. These and many other documented examples of accidental electronic system failures argue for the creation of an HPEM standard that can be useful to manufacturers of electronic components, subsystems and systems in many industries.

Annex A presents four types of intentional electromagnetic environment, coupling and interference combinations that can create system malfunctions. In Annex B, some examples of HPEM generators are presented, categorized on the basis of the technical sophistication level involved in assembling and deploying them. Annex C documents typical HPEM waveforms (radiated and conducted) in time and frequency domains. Annex D defines a way of determining the bandratios of waveforms representing the HPEM environments.

A logical extension of recently developed HEMP standards (IEC 61000-2-9, IEC 61000-2-10, and IEC 61000-2-11) is to define and classify the man-made HPEM threat environment, in the context of civilian electrical and electronic systems. In a manner similar to the HEMP standards, the HPEM environment consists of two major parts: a radiated environment and a conducted environment; in the interest of efficiency, both aspects are considered in this standard.

5 Description of radiated environments

The present interest is the potential high-power electromagnetic threat to civilian electronic systems and facilities. It is now well established that sufficiently intense electromagnetic signals in the frequency range of 200 MHz to 5 GHz are known to cause electronic damage in many systems. The operating wavelengths range from 1,5 m to 6 cm. HPEM generators are effective in this frequency range for the following reasons.

– There are deliberate antennas operating in this frequency range, which provide a path into the system (intentional coupling paths).
– Typical apertures, slots, holes and hatch openings have their resonance in this frequency range (inadvertent coupling paths).
– Typical rivet spacings at the junction of two metallic surfaces at the skin level are about a quarter to a full wavelength in this frequency range (1 GHz to 2 GHz).
– Physical dimensions of circuit boxes are themselves resonant in this frequency range (1 GHz to 2 GHz).
– The interior coupling paths (e.g., transmission lines, cables at a height above the ground plane) are roughly a quarter to a full wavelength in this frequency range (1 GHz to 2 GHz).

One can classify the potential HPEM threats into three categories, based on frequency coverage, as narrow bandwidth, moderate bandwidth and ultrawideband. Various definitions of bandwidths have been suggested in the literature, and an accepted definition [1] is:

$$\text{fractional bandwidth} = \frac{2\,(f_h - f_\ell)}{(f_h + f_\ell)} \qquad (1)$$

$$\text{percent bandwidth} = \frac{2\,(f_h - f_\ell)}{(f_h + f_\ell)} \times 100 \qquad (2)$$

Basically, this definition is the ratio of bandwidth (difference between the high and low frequencies in the signal, traditionally the 3 dB points) to the centre frequency f_c , which is the average of the high and low frequencies, f_h and f_ℓ. It is easily seen that the maximum possible value for the percentage bandwidth is 200. A DARPA panel [1] has defined a definition of ultrawideband signal as a signal that has a pbw (percentage bandwidth) >25 % using the following classification:

– Narrowband signal	percent bandwidth <1 %	(ex: AM radio signal)
– Moderate bandwidth signal	percent bandwidth ~ 1 % to 25 %	(ex: TV signal)
– Ultrawideband signal	percent bandwidth >25 %	(ex: see Annex D)

However, we observe that the above pbw (percent bandwidth) definition comes from a "communication signal" view point and is inadequate, in the context of ultrawideband signals, when practical waveforms have already achieved percent bandwidths of >190 % out of a possible maximum of 200 %. Therefore one shall use the following definitions [2]:

$$\text{bandratio} = br = \frac{f_h}{f_\ell} \qquad \text{bandratio decades} = brd = \log_{10}(br) \qquad (3)$$

$$pbw = 200\frac{(br-1)}{(br+1)} \qquad br = \frac{[1+\frac{pbw}{200}]}{[1-\frac{pbw}{200}]} \qquad (4)$$

Using the inherent features of above definitions, and in a manner consistent with the emerging technologies, the following definitions for bandwidth classification are defined below in Table 1.

Table 1 – Definitions for bandwidth classification

Band type	Percent bandwidth (*pbw*)	Bandratio (*br*)
Hypoband or narrowband	≤1 %	≤ 1,01
Mesoband	1 % < *pbw* ≤ 100 %	1,01 < *br* ≤ 3
Sub-hyperband	100 % < *pbw* ≤ 163,64 %	3 < *br* ≤ 10
Hyperband	163,64 % < *pbw* ≤ 200 %	*br* > 10

One can provide examples of HPEM generators that employ current and emerging technologies, for each category of the four-band classification.

The above classification is necessary to describe potential HPEM threat environments. Another way of categorising the environments is based on the level of sophistication of the underlying technologies involved in producing the environment as low, medium and high-tech systems, as outlined in Annex B.

5.1 General attributes of HPEM

In the context of civilian electronics systems and facilities, various elements of electromagnetic threat environments shall include:

a) source characterisation;

b) feed and antenna system;

c) propagation distances and losses;

d) coupling to the facility exterior;

e) transfer function to the system interior.

The source shall be characterised by its output power, frequency, frequency agility, duration and repetition rates for pulsed sources and burst lengths. Feed and antenna systems in the frequency range of 200 MHz to 5 GHz consist of electromagnetic horns and reflectors.

– Frequency range 200 MHz to 5 GHz
– Wavelength range 150 cm to 6 cm
– CW source power (rms) 1 kW (microwave oven) to 10 MW (radar tubes)
– CW source power (peak) *P* = 2 kW to 20 MW (2 times rms power for sinusoids)

– Antenna aperture area A = up to 10 m^2 (a practical sized antenna that can be truck mounted and be driven under overpasses and on bridges)

– Peak E-field on radiating aperture, where Z is the impedance in ohms

$$E_a = \sqrt{PZ/A}$$

– Peak radiated E-field $E_f = E_a A/(r\lambda)$

– Assuming an antenna aperture area of 10 m^2 and an impedance of 377 ohms

$2\ \text{kW} < P < 20\ \text{MW}$

$274\ \text{V/m} < E_a < 27{,}4\ \text{kV/m}$ (no antenna losses)

$4{,}57\ \text{kV} < r\,E_f$ (at f = 0,5 GHz) $< 457\ \text{kV}$

$9{,}13\ \text{kV} < r\,E_f$ (at f = 1 GHz) $< 913\ \text{kV}$

$18{,}27\ \text{kV} < r\,E_f$ (at f = 2 GHz) $< 1{,}83\ \text{MV}$

$27{,}40\ \text{kV} < r\,E_f$ (at f = 3 GHz) $< 2{,}74\ \text{MV}$

CW sources that can produce average power levels in the range of 1 kW (continuous) to 10 MW (pulsed) are readily available today, and the estimates above appear to be environments that can be easily produced. We can now estimate the electric field levels as a function of frequency and range with the above commercial sources. This leads to the results in Table 2.

Table 2 – Range of radiated electric field at various frequencies and power levels

Frequency	Range	Variation of E-field with an antenna aperture of 10 m^2 and output powers of 2 kW to 20 MW		
500 MHz	300 m	15,23 V/m	to	1,52 kV/m
	1 km	4,57 V/m	to	457 V/m
1 GHz	300 m	30,43 V/m	to	3,04 kV/m
	1 km	9,13 V/m	to	913 V/m
2 GHz	300 m	60,90 V/m	to	6,09 kV/m
	1 km	18,27 V/m	to	1,83 kV/m
3 GHz	300 m	91,33 V/m	to	9,13 kV/m
	1 km	27,40 V/m	to	2,74 kV/m

The CW results indicate that with the commercially available sources that have rms outputs ranging from 1 kW to 10 MW, it is indeed possible to produce greater than 100 V/m signals at kilometre distances, with modest sized antennas. The frequency range of sources in the L-band is likely to cause more electronic damage than higher bands (10 GHz radar for example) [21].

In the context of hyperband HPEM systems, TEM horns and reflectors fed by TEM transmission lines are established as efficient radiators. For example, half-cycle and single cycle sine wave generators at 1 GHz, with amplitudes of 100 kV (peak-to-peak) are realistic and practical sources. One could consider a single TEM horn antenna for radiating such a pulse.

In summary, the parameter space for a hyperband system from commercial components is:

– source waveform half-cycle or full-cycle sine wave

– amplitude, V_p 100 kV peak-to-peak for full cycle
  50 kV for the half cycle

– “frequency” 1 GHz (nominal)

– antenna type a TEM horn

– antenna volume 30 cm × 30 cm × 30 cm (1 wavelength in each dimension)
– peak field at 1 km distance, E_f ~ 50 V/m (time domain peak)
– bandwidth ~ 100 MHz to a few GHz

A calculation of the TEM horn radiation indicates (rE_f / V_p) of about 0,5. This antenna is not necessarily an optimal design, however one could still produce an impulse-like signal with amplitude of about 50 V/m at 1 km with a hyperband capability.

As in the case of narrowband sources, it is possible to make an array of sources and antennas. The time domain field at early times will be additive. For example, a 3 m × 3 m array could contain about 150 elements, and the peak signal can reach up to 7,5 kV/m at a distance of 1 km.

5.2 HPM waveform characteristics: phaser (hypoband or narrowband)

The term "phaser" stands for pulsed high-amplitude sinusoidal electromagnetic radiation. A progression of potential phaser designs are referred to as Mark N phasers and are defined by source powers of 10^N GW [3]. Thus a Mark 0 phaser has a power out from the source of 1 GW. The power out of the source is typically referenced to the lowest order waveguide mode which can be coupled into a pyramidal horn antenna as described in detail in [3]. A good example is a relativistic magnetron source that is commercially available [4] with the following capabilities.

– Frequency = 1,1 GHz
– Peak power = 1,8 GW (average power = 0,9 GW)
– Pulse width = 60 ns (contains 66 cycles)

This commercial source can easily be modified to produce an average power of 1 GW, with a slightly increased pulse duration of 100 ns to contain greater than 100 cycles of L-band sinusoidal signal. This makes the quality factor $Q = \pi M = 314$, $pbw = (100/Q) = 0{,}32$, and $br = 1{,}0032$. With an antenna of about 10 m^2 aperture area, it is estimated that such a source can easily produce fields of 2,3 kV/m at 3 km and 700 V/m at 10 km. These generator systems can also be truck-mounted and can come in close proximity to civilian electronics systems and facilities, producing much higher field levels.

Several narrowband generator systems in the frequency range of 0,4 GHz to 15 GHz exist. Examples are:

– the Swedish Microwave Test facility, Linkoping, Sweden;
– the Orion system in U.K., which uses relativistic magnetrons and horn-fed reflector antennas;
– Super Reltron based system in CEG, Gramat, France, called the Hyperion;
– Super Reltron based system at WIS, Munster, Germany.

It is noted that these systems are used in studying the vulnerabilities of electronic systems. However, systems such as these may also be acquired by organizations/groups intent upon harming civilized societies. Therein lies the potential threat in the present context of civilian electronics systems and facilities.

5.3 Dispatcher (mesoband)

The term "dispatcher" stands for damped intensive sinusoidal pulsed antenna, thereby creating highly energetic radiation. While the phaser is a narrowband device in which about 100 cycles of a single frequency radiation are produced in each pulse, Baum [5, 6] has described certain sources that integrate an oscillator into the antenna system. Examples are:

a) a low–impedance quarter wave transmission line oscillator feeding a high-impedance antenna, and

b) a low-impedance quarter wave transmission line feeding a TEM fed reflector.

The transmission line oscillator consists of a quarter wave section of a transmission line (perhaps in oil or high-pressure gas medium for voltage stand off) that is charged by a high voltage source and a self-breaking switch across the transmission line. When the switch closes, a pulsed signal is fed into the antenna connected to this transmission line that radiates an HPEM signal.

As an example, 500 MHz corresponds to a quarter wavelength in transformer oil of 10 cm, which is very compact. The charge voltages can be in the range of 100s of kV. The half wave section doubles the length for a given frequency and thus increases the stored energy. This is included here as an emerging system that may be used in creating HPEM environments on electronic systems such as civilian electronics systems and facilities.

5.4 Disrupter (sub-hyperband and hyperband)

A "disrupter", which is not an acronym, is basically a sub-hyperband or hyperband source/ antenna system such as the impulse radiating antenna (IRA), and it produces an HPEM signal that has a bandratio greater than or equal to 10 [7–9]. If such a system operates from 200 MHz to 2 GHz, it has a bandratio of 10. Examples of IRAs are provided in Annex B.

The disadvantage of such a system is that the energy is spread over an extremely wide band of frequencies. Although there can be very intense values of peak power, the power in the narrow band of frequencies is low. This is the reason to call them disrupters in distinction to phasers, which have high power levels at narrow bands of frequencies. As an example of a disrupter, consider a 500 kV transient source, with a 5 ns duration into a 200 ohm antenna, and a repetition rate of 1 kHz. Such a system would have a peak power of 1,25 GW, but an average power of 6,75 kW. Such a system, which is quite practical, can result in severe disruption of electronic systems.

In this clause, we have given examples of potential electromagnetic generator systems that can, in principle place harmful levels of HPEM fields on civilian electronic systems and facilities. No effort is made to evaluate the likelihood of such threats. It is felt that it would be useful to assess the vulnerabilities of commercial facilities to such emerging threats and to harden against them in the cases where it makes economic sense. The HPEM threats can come in many forms, such as narrowband, moderate band and ultrawideband. They all have different levels of disruption or damage potential. The HPEM threats can also vary in their level of sophistication in terms of their design and fabrication. This makes the development of environment standards more difficult; however, the test procedures are expected to be straightforward, once reasonable standards are developed.

5.5 Impact of technology on radiated environments

An important distinction between HEMP and HPEM is that the HEMP environments are range independent, while the radiated HPEM environments are a strong function of the range, or the relative distance between the source and the intended or unintended victim system. At a given range, the HPEM signal strength depends on the developing and emerging source technologies and the sophistication of the antenna design.

5.5.1 Hypoband and mesoband HPEM environments

Mark 0 phasers (1 GW of narrowband average power) are state-of-the art generator systems, but in the future, more powerful phasers will become commercially feasible. A (rE_p) product of 15 MV is easily feasible with a Mark 0 phaser. This translates to 5 kV/m at a range of 3 km. Developments in high-power microwave source technology, such as better cathode materials etc., will easily enhance these numbers in the future.

This environment standard combines the hypoband (or narrowband) and the mesoband HPEM signals. The waveform to be applied is a damped sinusoid given by

$$E(t) = E_o \; e^{-\alpha t} \sin(\omega_o t) \; u(t) \qquad (5)$$

The normalised waveform ($E(t) / E_o$) has been plotted in Figure 2 for the parametric values of f_o = 1 GHz, $\omega_o = 2\pi f_o$ and the damping constant of $\alpha = 10^8$ radians/s.

Note that the three parameters that uniquely define the proposed waveform for the environment are the "peak" signal E_o (the value of the envelope at t = 0 in Figure 2), the damping constant α (radians/s) and the fundamental frequency f_o (Hz). The Fourier transform and the corresponding spectral magnitude of the above signal are analytically known, and the spectral magnitude is plotted in Figure 3.

It is also observed that the time-domain peak, the spectral content, the dc component, the bandwidth, and the quality factor Q of this standard waveform are all known in closed form, as listed below:

$$E_p = E_o \exp\left(\frac{-\alpha}{4 f_o}\right) ; \; \omega = 2\pi f \text{ (time domain peak value)} \qquad (6)$$

$$\tilde{E}(f) = \frac{\omega_o E_o}{(\alpha^2 + \omega_o^2 - \omega^2) + 2j\alpha\omega} ; \qquad |\tilde{E}(f)| = \frac{\omega_o E_o}{\sqrt{(\alpha^2 + \omega_o^2 - \omega^2)^2 + 4\alpha^2\omega^2}} \qquad (7)$$

$$|\tilde{E}(0)| = \frac{\omega_o E_o}{\alpha^2 + \omega_o^2} ; \qquad \text{spectral peak} = \frac{E_o}{2\alpha} \qquad (8)$$

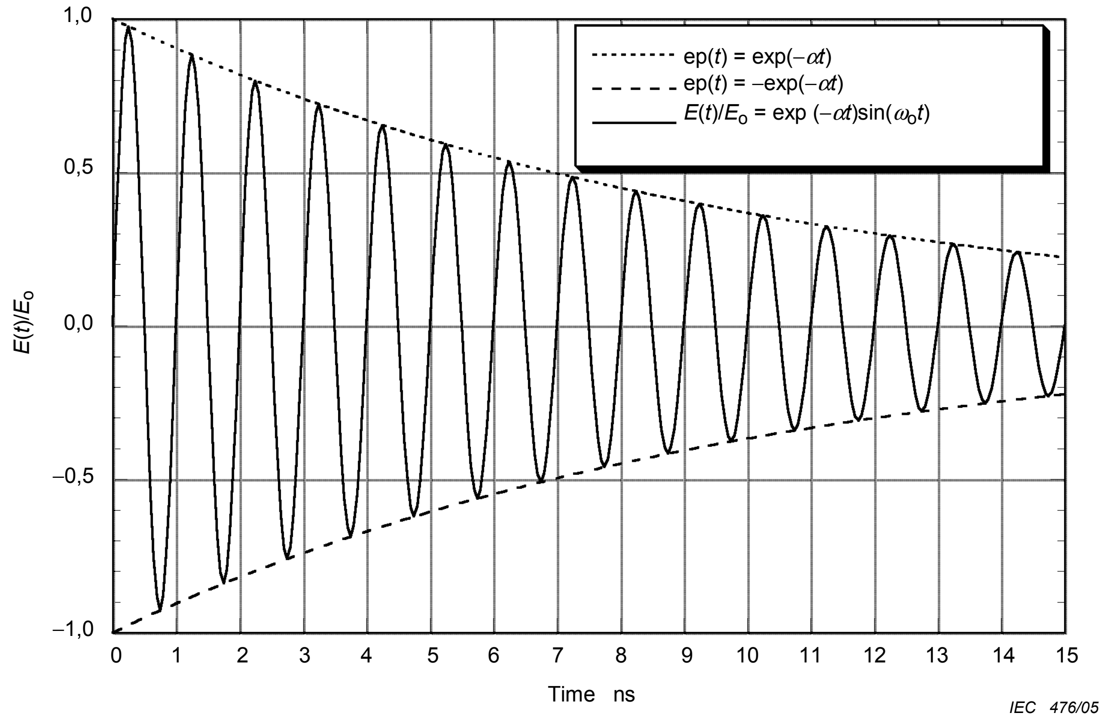


Figure 2 – A damped sinusoidal waveform for hypoband and mesoband HPEM environments

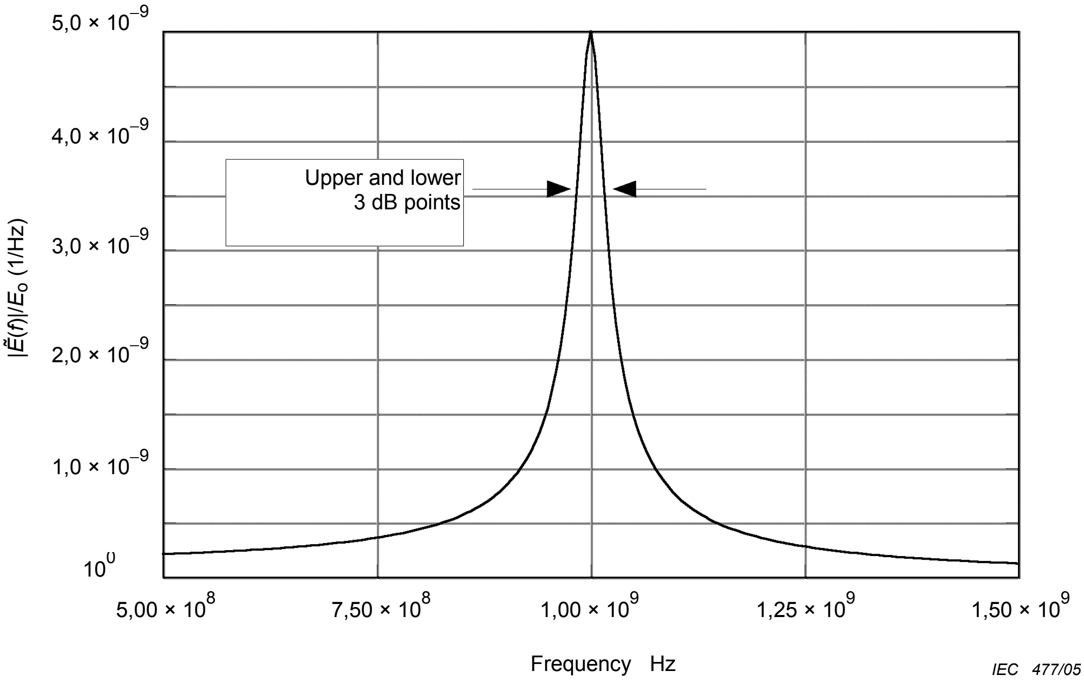


Figure 3 – The spectral magnitude of the time waveform in Figure 2

Quality factor $$Q = \frac{\omega_o}{\Delta\omega} = \frac{f_o}{\Delta f} = \frac{f_o}{f_h - f_\ell} = \left(\frac{\omega_o}{2\alpha}\right) = \frac{\pi f_o}{\alpha} = \pi M \quad (9)$$

percent bandwidth $$pbw = 100\left(\frac{\Delta f}{f_o}\right) = \frac{100}{Q} = \frac{100}{\pi M} = \frac{100\alpha}{\pi f_o} = \frac{200\alpha}{\omega_o} \quad (10)$$

bandratio $$br = \frac{f_h}{f_\ell} = \frac{\omega_h}{\omega_\ell} = \frac{\omega_o + \alpha}{\omega_o - \alpha} \quad (11)$$

where $f_\ell = f_o - \left(\frac{\alpha}{2\pi}\right)$ and $f_h = f_o + \left(\frac{\alpha}{2\pi}\right)$.

For an illustrative example, given E_o = 102,532 (V/m), f_o = 1 GHz, and $\alpha = 10^8$ radians/s, we have a time domain peak = 100 V/m, a spectral peak = $5,127 \times 10^{-7}$ (V/m)/Hz, a period of the damped sinusoid of 1 ns, f_h = 1,016 GHz, f_ℓ = 0,984 GHz, M = 10, Q = 31,415, pbw = 3,183 %, and br = 1,033 (mesoband, since br > 1,01). It is also observed that we have M = 10 cycles of damped sinusoid, before the amplitude drops to (1/e) times the peak. Since pbw = [100/(πM)], it is noted that we need $M \geq 31,83$ for pbw to be <1 % and to qualify as a hypoband or narrowband signal. In a typical CW environment, the value of M is at least 50, and thus it is a narrowband signal. Table 3 provides seven examples that shall be applied as HPEM threat environments.

Table 3 – Typical HPEM standard environments in the hypoband (or narrowband) and mesoband regimes

No.	Fundamental frequency f_O	E_o resulting in peak of 100 V/m	Damping constant α (rad/s)	No. of cycles t_o (1/e) N	Band-ratio *br*	Percent bandwidth *pbw*	Remarks
1	200 MHz	101,26	10^7	20	1,0161	1,59	Mesoband
2	500 MHz	100,84	$1,67 \times 10^7$	30	1,0167	1,06	Mesoband
3	1 GHz	100,25	10^7	100	1,0032	0,32	Hypoband or narrowband
4	2 GHz	100,25	2×10^7	100	1,0032	0,32	Hypoband or narrowband
5	3 GHz	100,25	3×10^7	100	1,0032	0,32	Hypoband or narrowband
6	4 GHz	100,25	4×10^7	100	1,0032	0,32	Hypoband or narrowband
7	5 GHz	100,25	5×10^7	100	1,0032	0,32	Hypoband or narrowband

5.5.2 Sub-hyperband and hyperband HPEM environments

HPEM generator technologies, which can radiate a flat electromagnetic spectrum from 10s of MHz to several GHz, are presently capable of producing a time-domain (*rE*) product of several MV. With advancements in high-power and fast switching technologies, the (*rE*) product is likely to get higher.

One of the requirements of the HPEM standard for the ultrawideband environment is that it should be practical in the sense that one should be able to produce this environment with reasonable ease for testing purposes. From this point of view, we shall assume a nominal 1 m IRA (Impulse radiating antenna with a TEM feed impedance of 200 Ω) fed by a 2,5 kV variable voltage (2,5 kV is the maximum value), 100 ps rise time and 0,4 ns pulsewidth pulser. Such a pulser is readily available commercially. The radiated ultrawideband fields from such a nominal HPEM generator are shown in Figures 4 and 5 in the time and frequency domains.

This HPEM generator system described above is practical and useful as a means to produce an HPEM environment for vulnerability studies. The time domain peak is range dependent, as can be observed in Figure 4. However approximately 90 % of the energy content of these waveforms is spread over a range of frequencies from ~ 100 MHz to ~ 3 GHz producing a bandratio of 30.

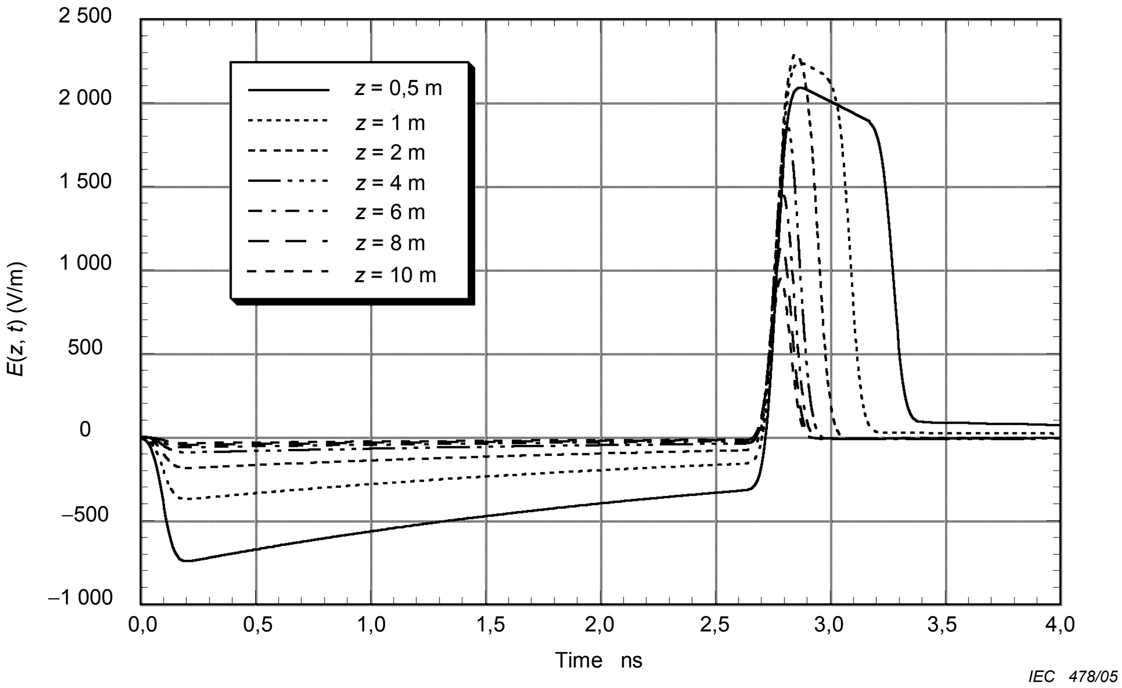


Figure 4 – Hyperband HPEM environment waveforms for variations in range in metres

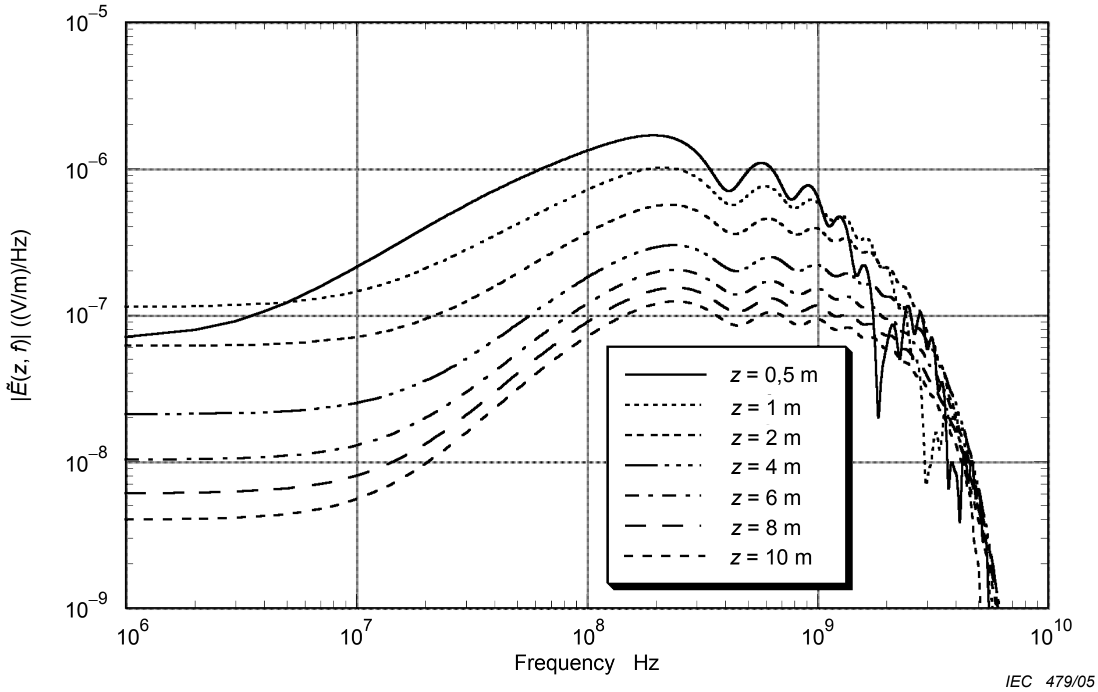


Figure 5 – Hyperband spectral magnitude of HPEM environments from Figure 4

5.6 Conducted waveforms produced from radiated fields

As described above, there are many types of radiated field threat environments that may illuminate equipment and systems directly. Of course nearly all equipment and systems are connected to data lines and to the power supply, so there are cables entering the equipment. As has been recognised in dealing with EMC of electronic equipment, it is important to consider both the radiated fields that are incident on a system and the conducted environment that is coupled to the equipment cables locally. This is the purpose of the companion IEC 61000-4-3 (radiated tests) and IEC 61000-4-6 (conducted tests for the coupled radiated fields) for EMC applications.

For this standard we make several assumptions that are appropriate given the nature of the threat and the location of equipment relative to the electromagnetic generators that may be used. In particular the generators are expected to be outside of an installation or are located in an adjacent room in a large building. For the external generator case, it is clear that high-frequency radiated fields will induce currents and voltages on external power lines and communication lines. However, given that the frequencies of interest are greater than 0,1 GHz, it is unlikely that these induced voltages will be able to propagate well over the large distances necessary to reach individual equipment inside of the building. As is described later in Clause 6, frequencies below 1 MHz propagate well on power lines, however, these disturbances are more easily created through direct injection into cables.

For the case of a generator in a nearby room with a dielectric wall, or for the case of the radiated fields entering a building through windows, the cables attached directly to equipment or systems are of the greatest interest. In this case the cables are fairly short, and will limit the amount of voltage induced.

Studies have been performed for both CW and pulsed EM fields for the coupling to metallic cables. These studies have considered coupling to finite length lines at all possible angles of incidence. For the case of a 1 m straight cable, the maximum induced voltage is computed. From the calculations, the voltage induced per incident electric field into an assumed load of 100 Ω is plotted in Figure 6. Note that these results should not be applied outside of the frequency range shown.

Ordinarily one would expect the induced voltage per incident electric field (an effective coupling length) to be bounded by the physical length at low frequencies and the wavelength at high frequencies [20]. It is possible, however, to exceed these “limits” due to the consideration of coupling geometries that include grazing incidence angles.

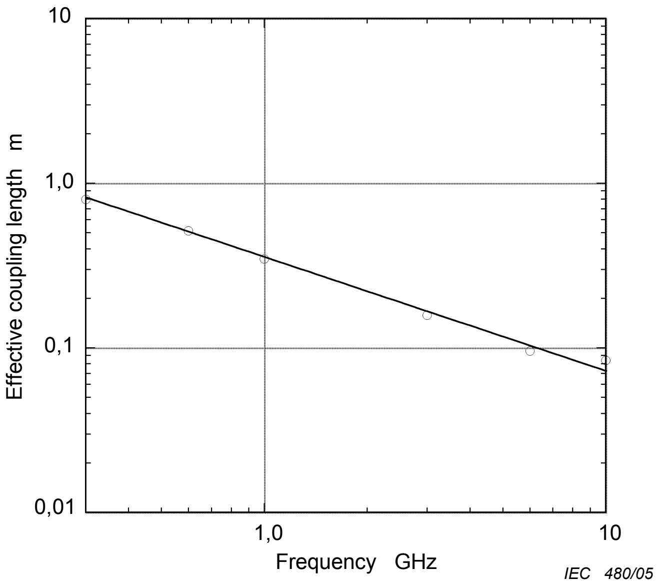


Figure 6 – Effective coupling length for a 1 m metallic cable

As indicated in Figure 6, an analytic approximation to the calculations is found to be:

$$\text{Effective coupling length (m)} \sim 0{,}36\, f^{-0{,}69} \text{ for } f \text{ in GHz} \qquad (12)$$

For CW frequencies between 300 MHz and 10 GHz, this equation shall be applied to determine the maximum induced current/voltage on a cable entering a system or equipment. The applicable time waveform shall be the same as the incident electric field waveform for the radiated field. For monopolar pulsed time waveforms, one can still use equation (12) by computing an approximate frequency from the pulsewidth: f_a = 1/(3**pw*), where *pw* is in units of nanoseconds and f_a is in units of GHz.

6 Description of conducted HPEM environments

As described in 5.6 conducted HPEM environments are a potential threat to electronic equipment connected to power and communications lines. In most modern buildings there is a personal computer on nearly every desk, and these computers are typically connected to the power supply and to a telephone cable or local area network (LAN). In this clause the threat environments for directly injected transients are presented.

In the case of data communications, at the present time, most communications circuits that enter a building will pass through a router or switch before sending the data to individual equipment. This means that this interface electronic equipment is potentially vulnerable to HPEM conducted pulsed voltages and currents that may be transmitted into the building from the outside. For older installations, telephone lines enter a facility and are wired directly to individual telephones or computers inside. In this situation, internal electronic equipment could be damaged by externally injected HPEM pulsed voltages.

In the case of the power circuitry, the problem is more direct. All internal electrical equipment is connected to the power supply, although there may be transformers and circuit breaker panels between the outside and the inside. Experiments have demonstrated that for frequencies below 1 MHz, disturbances will propagate easily throughout a building and pose a hazard to all of the connected equipment inside. In addition there is evidence that power frequency voltages injected into the facility grounding system can also cause significant problems for the operation of internal electrical equipment.

Another category of concern includes alarm systems, which may be triggered or damaged by HPEM environments. Alarm systems have been impacted by the EM fields produced by nearby lightning strikes, and the HPEM environment can be more severe, especially in terms of the higher frequency content that couples more efficiently to the alarm wiring.

6.1 Frequency range of interest

For the power system cabling inside of a building, experimental studies indicate that losses in the power cables and the impedance mismatches caused by switch panels and sharp turns in the wiring, results in significant attenuation per cable length for frequencies above 1 MHz. For cases where the disturbance would be injected outside of the building, a 10 MHz signal would be attenuated by approximately 40 dB at the equipment power supply cable. For interference in the grounding system of building, frequencies at or above the power frequency can be effective in creating interference. For power cables the range of frequencies to be considered shall therefore be between 50 Hz and 1 MHz.

For the communications system higher frequencies will propagate well, especially on the newer cables that can support gigabit/s data rates. For high quality cables that are accessible outside of a building, frequencies up to 1 GHz will propagate without significant attenuation. Injected disturbance levels do not have to be very high to produce an unacceptable signal to noise level. Susceptibility tests of computer connections of Ethernet cables have found a significant damage vulnerability to single pulses with pulse widths greater than 100 µs. Therefore the threat frequencies of interest for external data cables shall range from 1 kHz to 1 GHz.

6.2 CW waveform characteristics

Experiments have been performed to examine the ability of the wiring of building power circuits to propagate frequencies higher than those typically used for power (50 – 60 Hz). These experiments were intended to evaluate the propagation of CW voltages throughout the electrical circuits of a real building including the effects of wire geometry and switchboards within the building. Figure 7 illustrates the building geometry used in measurements performed by Parfenov, *et al.* [14].

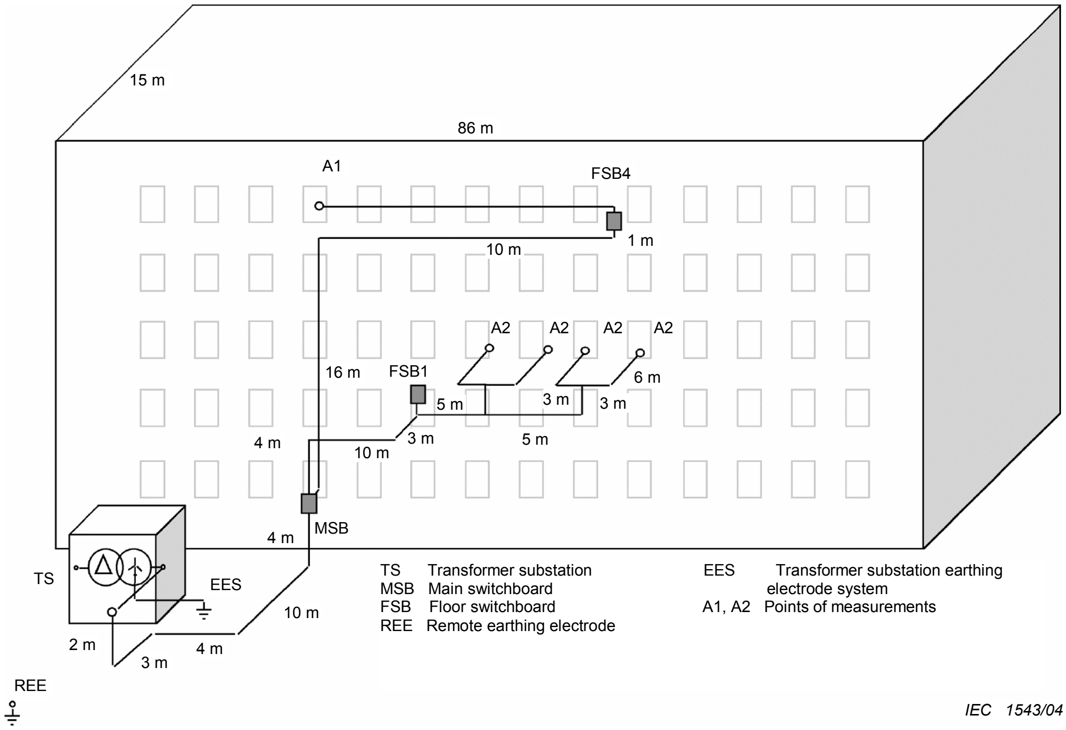


Figure 7 – Building used for HPEM conducted propagation experiments

The building tested was supplied by a pad-mounted delta-wye 1 MW, 10 kV/380 V transformer as shown in Figure 7. The building had five floors, and measurements were performed on the 1st and 4th floors. Note that the main building switchboard and the floor switchboards were part of the experiment.

In terms of the testing, pulses were injected on the secondary side of the transformer, and the testing was performed in an unenergised mode and at low levels in order to avoid damage to the wiring. Injections were performed with both CW and pulsed waveforms in the following ways:

a) phase 1 and neutral;

b) phase 2 and neutral;

c) phase 1 and the remote earthing electrode;

d) phase 2 and the remote earthing electrode;

e) neutral and the remote earthing electrode.

In all cases the measurements were made in the building between phase 1 and the neutral at the wall plugs. The CW frequencies tested ranged from 500 Hz to 10 MHz.

The results of the propagation experiment indicated that Experiment a) provided the lowest attenuation with minimal loss (less than 5 dB) between 500 Hz and 1 MHz. Above 1 MHz signals are attenuated rapidly reaching a reduction of 40 dB at 10 MHz.

For the other four injection methods, the results indicated that the attenuation was at least 40 dB across the entire band tested, although there were several resonant frequencies where the attenuation was marginally less. It is clear that injections between a phase and neutral of the power system are the most effective means of propagating conducted energy into the power cords of electronics inside of a building.

For communications cables, it is expected that higher frequencies can be propagated efficiently as modern cables have been designed to propagate high rates of data. A typical category 5 cable is certainly capable of transmitting frequencies up to 100 MHz without significant attenuation. In addition, new data rates of 1 gigabit/sec and higher are becoming more common. However, it should be noted that communications cabling outside of a building does not usually connect directly to end-user equipment inside, but rather is connected to routers and switches. It is therefore this equipment that would be exposed to injected signals from outside of the building.

While higher frequency HPEM environments are generally of greatest concern, there is one major exception that deals with the earthing system. It has been found in several experiments that CW signals at or near the power frequency injected into the earthing systems of buildings can create disruptions of the operation of the equipment inside. Voltage levels as low as 400 mV and currents as low as 10 amperes have disrupted the operation of telephone switching facilities, cellular phone stations and office buildings [15].

6.3 Pulse waveform characteristics

The experiment described in Figure 7 also considered the propagation of pulse waveforms through the electrical power network within the building [14]. The pulse characteristics employed were varied but generally included a rise time of 30 ns with pulse widths that varied between 30 ns and 10 µs. The pulses had a peak value at the injection point of 1,5 kV and were repetitively pulsed at 5 Hz. From an assessment of the insulation and from the results themselves, it was clear that the injected 1,5 kV pulses would not cause insulation damage in the wiring of the building.

It was no surprise that the least attenuation of pulsed signals from the outside of the building to the wall plugs inside occurred when the phase line measured inside was the same as the phase line injected outside. It was also found that the attenuation was lowest with the widest pulse (10 µs), with no discernible attenuation noted. By Fourier analysing the pulse results, it was determined that the attenuation indicated was the same as from the CW experiments. Pulses with widths greater than 300 ns were found to propagate from the external phase to neutral to the indoor wall plugs with little (less than a few dB) attenuation.

In terms of the voltage withstand capability of building electrical wiring, it is expected that the wiring should be able to withstand peak pulsed voltages of between 6 kV and 10 kV, depending on the pulse width and the condition of the wiring. The voltage withstand level for communications cables is expected to be lower due to the lower operating voltage of those cables. It should be noted that electronic equipment have been shown to be vulnerable to pulsed levels as low as 500 V (Ethernet computer cards) [16] and 1 kV (computer power supplies) for pulse widths of 1 ms [14]. Vulnerability levels of equipment tend to increase with narrower pulse environments. It is clear that both power and telecom wiring is capable of supporting levels of conducted pulse environments that are high enough to damage equipment inside of a building.

Another aspect of pulse injection is that damage is not the most likely occurrence. In fact malfunctions of digital equipment are more likely at lower levels of environment. For this reason, repetitive pulses are a serious threat to an electronic system, as malfunctions can be induced over and over, preventing equipment from operating normally. Experiments have found that pulse repetition rates from hundreds of pulses per second up to 1 million pulses per second have been shown to induce malfunctions in electronic equipment [16]. It is understood that this is due to the enhanced possibility of having a disturbance pulse arrive during a vulnerable operational state, or that a resonance is set up at particular frequencies that are being used by the digital system.

6.4 Impact of technology on conducted environments

Unlike the situation for the radiated HPEM environments, there is no major advancement of the state of the art required to produce the levels of conducted environments discussed in the previous clauses. This is because all of the threat waveforms can be easily produced using available generators that are typically used in EMC investigations. Since there does not appear to be any advantage in moving to pulses with frequency content above 100 MHz, due to high-frequency propagation losses in existing telecom wiring networks, the main issues for the future involve the reduction of generator size and improvements in injection.

6.4.1 CW environments

As described in 6.2, the main importance of CW environments as an intentional interference threat comes from the injection of low frequency currents into the earthing system of a facility. For this purpose, existing briefcase test generators are sufficient to create operational problems, if the facility is not properly grounded. As an example, Figure 8 (left side) illustrates a briefcase generator which operates up to 12 V and 10 A for frequencies of 50, 200 and 400 Hz.

In order to establish low-frequency CW threats for the earthing system of a facility, frequencies between 1 Hz and 1 000 Hz will be considered. Voltage and current levels up to 100 V and 100 A will also be considered.

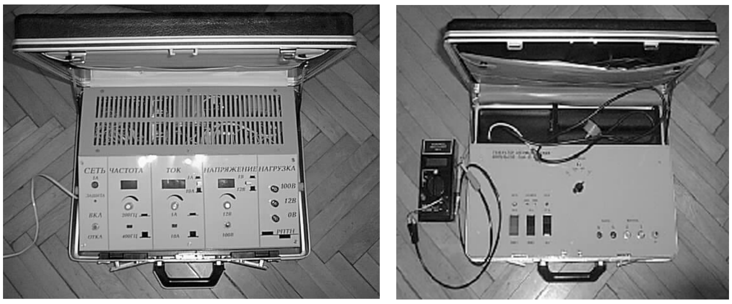


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Figure 8 – Examples of briefcase generators for producing conducted environments: CW generator (left) and impulse generator (right) [15]

6.4.2 Pulse environments

In terms of pulse generators, many of the laboratory generators used to test compliance to EMC and to insulation safety standards generate sufficiently high peak pulse levels to provide a conducted threat to electronic equipment. In particular the "ITU" pulse defined in IEC 61000-4-5 provides a significant threat to computer equipment connected to Ethernet cables at levels above those typically specified for normal EMC purposes. There are similar, but smaller pulsers designed for fieldwork as shown in Figure 8 (right side).

Based on the information available to date, it appears that existing IEC EMC test generators produce waveforms that when injected on external power or communications lines to a facility can create interference inside of the facility. For this reason pulse waveforms as defined in IEC 61000-4-4, IEC 61000-4-5 and IEC 61000-4-12 shall be considered as appropriate pulse threats. Peak voltage levels up to 10 kV shall be considered.

Annex A
(informative)

Four types of intentional electromagnetic environment interactions

An intentional electromagnetic environment is a man-made threat specifically designed to cause interference or damage to electrical and electronic components or systems. Such environments can be categorized into four types [10], as follows. For the purpose of illustrating the consequences of such environments, one may choose a civil aviation example of an aircraft landing at a civilian airport.

A.1 Noise

Sensitive receivers in civilian electronic systems are designed to operate at electric field levels as low as 1 μV/m, within a narrowly tuned receiver bandwidth. It is very easy to overpower the signal to be received by a decade or more of field strength. The user of the electronic device/equipment experiences noise in the receiver that lasts as long as the disturbing environment.

Consequences are not critical. In the worst-case scenario, the pilot aborts landing and makes another try or goes to an alternate airport.

A.2 False information

Once again with a decade or more field strength above the signal level, the intentional electromagnetic signal may be designed to feed false information to the receiver.

Consequences can be critical, since the aircraft may be forced to land somewhere other than the runway.

A.3 Transient upset

It is noted that one requires several volts of signals to affect the logic state of an electronic component. At a frequency of ~1 GHz, an effective coupling height of 0,1 m is typical for unhardened/open systems. This implies that tens to hundreds of V/m of tuned narrowband fields are required to cause an effect. The pulse width is assumed to be such that the quality factor Q of the threat environment is greater than the victim system Q [11-13, 17]. At the nominal frequency of 1 GHz, approximately 100 cycles or a 100 ns pulse duration should be sufficient.

Consequences depend upon system design for recovery and repetition rate of the threat environment, and could in some cases be catastrophic.

A.4 Permanent damage

For permanent damage to occur, semiconductor junctions in the electronic equipment must be exposed to overvoltages that result in breakdown. This phenomenon means that the bias on the junction is also a factor. At a nominal frequency of 1 GHz, this requires incident electric field strengths of several kV/m [17, 21].

For communications receivers it is also possible to produce damage so no further signals can be received. This could occur for incident field levels of a few hundred volts per meter.

Consequences in either case are related to the role of the damaged electronics or receivers to the flight safety of the aircraft.

Annex B
(informative)

Examples of low, medium and high-tech generators of HPEM

One possible way of classifying the emerging HPEM systems is based on the technical sophistication level in assembling and deploying such systems.

B.1 Low-tech generator systems

These types of generator systems

- require minimal technical capabilities,
- possess marginal component performance, and
- are easily assembled and deployed while hiding behind dielectric truck walls or in similar vehicles.

A readily available CW microwave source in the S-band (2,45 GHz) is the magnetron in a microwave oven. Typical and readily available microwave ovens are rated at 800 W to 1 500 W of rms continuous microwave power. With 1 100 W of rms continuous microwave power at 2,45 GHz from a microwave oven, the peak electric field in the output waveguide is about 25 kV/m. Starting from such an E-field in the waveguide aperture, (rE_{peak}) factors obtainable are listed in Table B.1.

Table B.1 – Radiated fields from a microwave oven magnetron fitted with different antennas

Antenna type	Power rms	Peak E-field in WR 340	rE_{peak}	E_{peak} r = 300 m	E_{peak} r = 1 km
Open-ended WR 340	1 100 W	25 kV/m	540 V	1,8 V/m	0,54 V/m
Pyramidal horn	1 100 W	25 kV/m	2 200 V	7,3 V/m	2,2 V/m
Reflector antenna (1,8 m diameter)	1 100 W	25 kV/m	4 680 V	15,6 V/m	4,7 V/m

B.2 Medium-tech generator systems

These types of generator systems

- require the skills of a qualified electrical engineer,
- have relatively more sophisticated components, and
- can be a modified commercially-available radar system.

Commercially available radars can be modified to become an HPEM generator system (narrowband or ultrawideband); examples of complete systems offered for sale by Radio Research Instruments Co., Inc. of Waterbury, CT [2] are: AN/FPS-36, AN/FPS-71, AN/FPS-75 and AN/FPS-77.

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2) The four systems listed here are examples of products available commercially. This information is given for the convenience of users of this International Standard and does not constitute an endorsement by IEC of these products.

The AN/FPS-71 search radar is chosen for illustrative purposes in the formulas below.

The aperture area	A	=	93,5 m^2
Peak power output from the magnetron	P	=	5 MW
Average power from the magnetron	P_{avg}	=	2,5 MW
Frequency of operation	f	=	1,285 GHz
L-band waveguide dimensions	a	=	longer dimension = 16,51 cm
	b	=	shorter dimension = 8,26 cm
Dominant modal impedance	Z_{10}	=	534 Ω
Focal length of the reflector	F	=	2,5 m (assumed)

E-field on the aperture: E_a = 630 kV/m ($ab/F\lambda$) ~ 15 kV/m

Far field rE product: $rE_f = E_a$ (A/λ) ~ 6 MV

The (rE_f) estimated above indicates that this commercially available system, which is powered by a 5 MW magnetron source, is capable of producing peak fields listed in Table B.2.

Table B.2 – Radiated peak electric fields from a commercial HPEM generator

Range *r*	**Peak E-field** **Antenna size 93,5 m^2**	**Peak E-field** **Antenna size 9,35 m^2**
300 m	20 kV/m	6,3 kV/m
1 km	6 kV/m	1,9 kV/m
10 km	600 V/m	190 V/m

This commercial system has a large antenna aperture 93,5 m^2, which can easily be scaled down by a factor of 10, in which case the peak electric fields as shown in Table B.2 will decrease by a factor of $\sqrt{10}$. These levels are still significant with regard to system effects.

B.3 High-tech generator systems

These types of generator systems

- require specialised and sophisticated technologies, and
- may be specifically tuned to cause severe damage to specific targets.

Examples of high-tech HPEM generators are impulse radiating antennas (IRAs) [8]. A schematic diagram of the reflector type of IRA is shown in Figure B.1, and some example systems are listed in Table B.3.

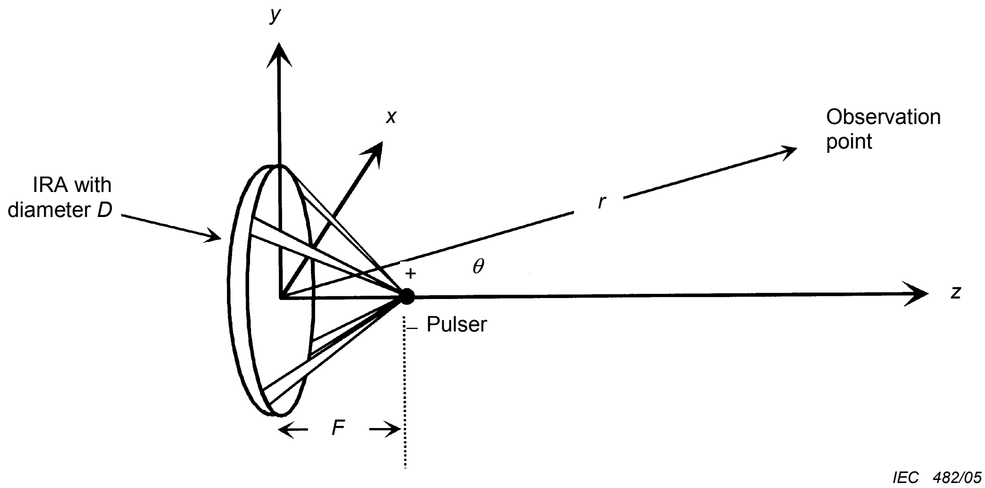


Figure B.1 – Line schematic of a reflector type of an impulse radiating antenna (IRA)

Table B.3 – Examples of reflector types of impulse radiating antennas

No.	Name	Pulser	Antenna	Near field	Far field	r E	Band-ratio, *br*	Band
1	Prototype IRA USA	± 60 kV 100ps/20ns 200 Hz burst	3,66 m dia (F/D)=0,33	23 kV/m at r = 2 m	4,2 kV/m at r = 304 m	1 280 kV	100	Hyper
2	Upgraded prototype IRA USA	± ~ 75 kV 85 ps/20 ns ~ 400 Hz	1,83 m dia (F/D)=0,33	41,6 kV/m at r = 16,6 m	27,6 kV/m at r = 25 m	690 kV	50	Hyper
3	Swiss IRA	2,8 kV 100 ps/4 ns 800 Hz	1,8 m dia (F/D)=0,28	1,4 kV/m at r = 5 m	220 V/m at r = 41 m	10 kV	50	Hyper
4	Netherlands IRA	9 kV 100 ps/4 ns 800 Hz	0,9 m dia (F/D)=0,37	7 kV/m at r = 1 m	Not available	34 kV	25	Hyper
5	German IRA	9 kV 100 ps/4 ns 800 Hz	0,9 m dia (F/D)=0,37	7 kV/m at r =1 m	Not available	34 kV	25	Hyper

As per the definition in Equation (5), all of the high-tech systems are hyperband HPEM generators, since their bandratios are >10. However, it is observed that they can also be turned into sub-hyperband generators by reducing the antenna diameter (increases the lower cutoff frequency) or by degrading the rise time of the voltage pulse into the antenna (lowers the upper cutoff frequency).

Annex C
(informative)

Examples of typical HPEM waveforms (conducted and radiated)

In this annex, we document some typical HPEM environment waveforms in time and frequency domains. The temporal and spectral quantities in this annex are related by the following Fourier transform pairs.

$$g(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\tilde{G}(\omega)e^{j\omega t}\,d\omega \qquad \tilde{G}(\omega) = \int_{-\infty}^{\infty} g(t)\ e^{-j\omega t}dt \qquad \text{(C-1)}$$

It follows that the time waveform values at t = 0 and the dc Fourier components are given by,

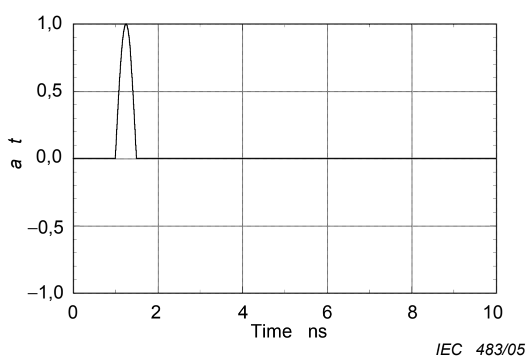
$$g(0) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\tilde{G}(\omega)\,d\omega \qquad \tilde{G}(0) = \int_{-\infty}^{\infty} g(t)\ dt \qquad \text{(C-2)}$$

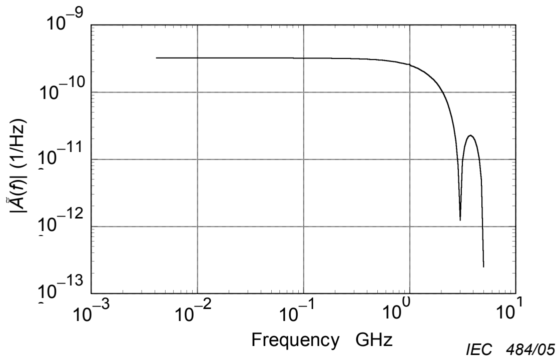
It is observed that $g(t)$ can be a voltage or current waveform in the case of conducted HPEM environment, or it can be an electric or magnetic field in the case of a radiated HPEM environment. It is also noted that some of the waveforms listed in this appendix cannot be considered radiated environments if they have a non-zero area under the time domain curve, which would result in a non-zero dc component in the frequency domain.

In general we will consider examples of dimensionless quantity a(t) as defined by,

$$g(t) = g_o\, a(t) \qquad \text{(C-3)}$$

and $\tilde{A}(\omega)$ will represent the Fourier transform of $a(t)$. In terms of units and dimensions, as an example, if $g(t)$ represents a conducted voltage waveform, $g(t)$ and g_o will have the units of voltage, $\tilde{G}(\omega)$ will have the units of V/Hz and $\tilde{A}(\omega)$ will have the units of (1/Hz). For convenience most spectral magnitude plots that follow are presented in terms of frequency in hertz, so the spectral magnitude is written as *A(f)*.





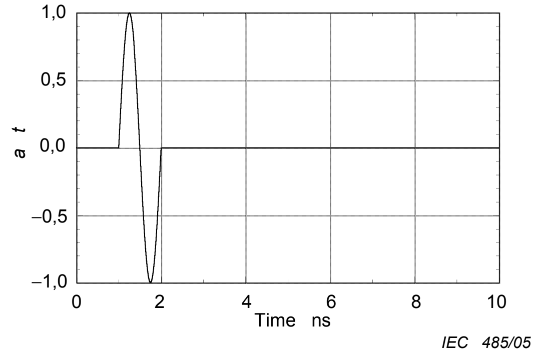
$a(t) = \sin(\omega_o(t-T))\ u(t-T)$ for $0 \le t \le (3T/2)$

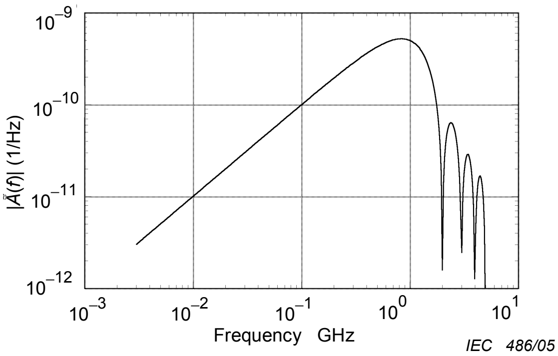
$$\left|\tilde{A}(f)\right| = \left|\frac{2\omega_o \cos(\omega T/4)}{(\omega_o^2 - \omega^2)}\right|$$

$$\omega_o = 2\pi f_o\ ;\ \ f_o = 1\ \text{GHz}\ ;\ \ T = 1\ \text{ns}$$

Figure C.1a – Transient waveform **Figure C.1b – Spectral magnitude**

Figure C.1 – Half-sinusoid at f_o = 1 GHz





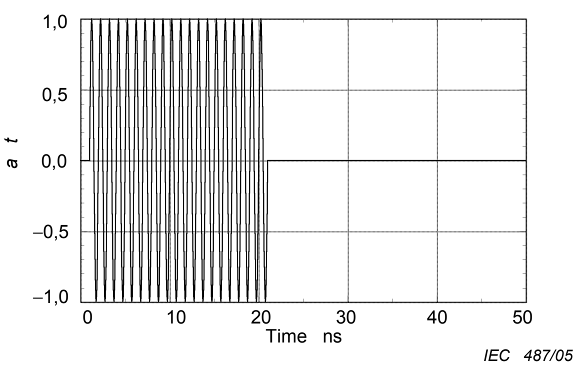
$a(t) = \sin(\omega_o(t\text{-}T))\ u(t\text{-}T)$ for $0 \leq t \leq (2T)$

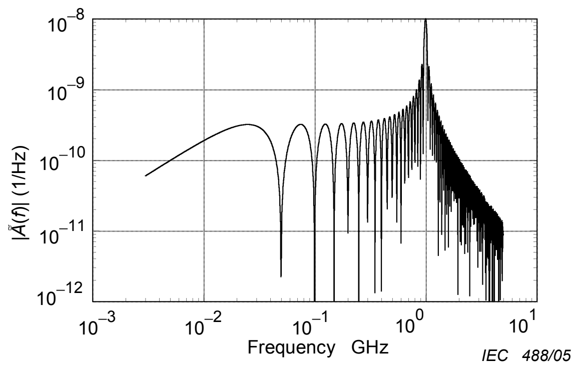
$$\left|\tilde{A}(f)\right| = \left|\frac{2\omega_o \sin(\omega T/2)}{(\omega_o^2 - \omega^2)}\right|$$

$$\omega_o = 2\pi f_o;\ \ f_o = 1\,\text{GHz};\ T = 1\,\text{ns}$$

Figure C.2a – Transient waveform **Figure C.2b – Spectral magnitude**

Figure C.2 – Full sinusoid at *f* = 1 GHz





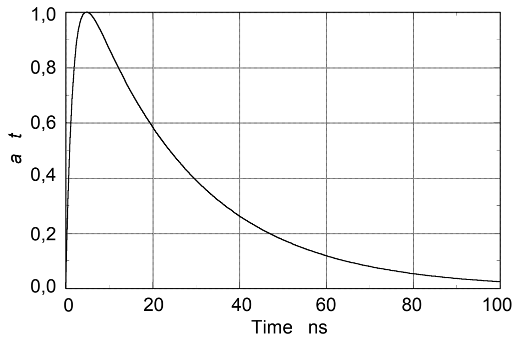
$a(t) = \sin(\omega_o(t\text{-}T))\ \mathrm{u}(t\text{-}T)$ for $0 < t < T(N{+}1)$

$$\left|\tilde{A}(f)\right| = \left|\frac{2\omega_o \sin(N\omega T/2)}{(\omega_o^2 - \omega^2)}\right|$$

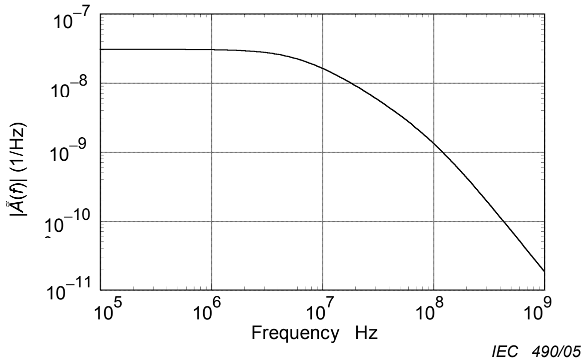
$$\omega_o = 2\pi f_o;\ \ f_o = 1\ \text{GHz};\ T = 1\,\text{ns}$$

Figure C.3a – Transient waveform **Figure C.3b – Spectral magnitude**

Figure C.3 – 20 cycles of sinusoid at *f* = 1 GHz (*N* = 20)



IEC 489/05



IEC 490/05

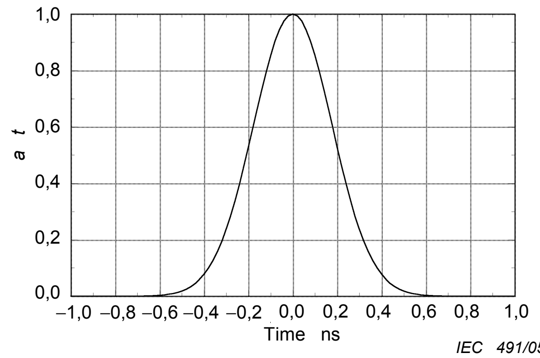
$$a(t) = 1{,}31\left(e^{-\alpha t} - e^{-\beta t}\right)u(t)$$

$$|\tilde{A}(f)| = \left|\frac{1{,}31(\beta-\alpha)}{(\alpha+j\omega)(\beta+j\omega)}\right|$$

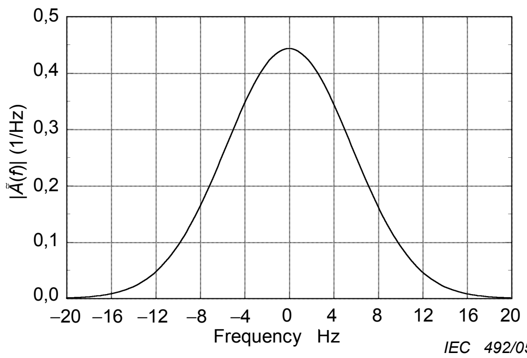
$\alpha = 4{,}0 \times 10^7$ radians/s ; $\beta = 6{,}0 \times 10^8$ radians/s

Figure C.4a – Transient waveform **Figure C.4b – Spectral magnitude**

Figure C.4 – Difference of exponential waveform



IEC 491/05



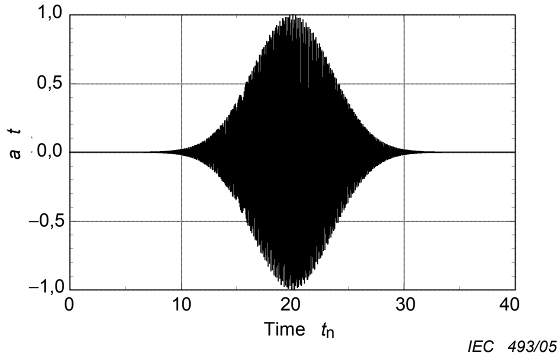
IEC 492/05

$$a(t) = e^{-\left(\frac{2(t-t_s)}{\alpha}\right)^2}$$ with $t_s = 0$; $\alpha = 0{,}5$ ns

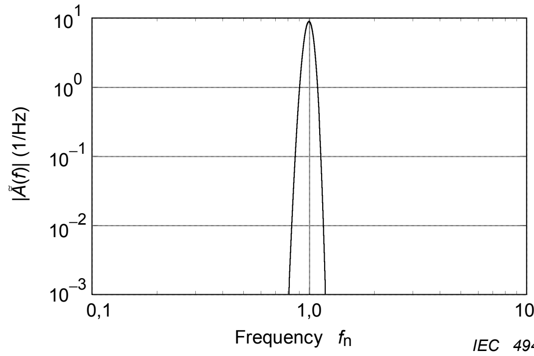
$$\left|\tilde{A}(f)\right| = \sqrt{\frac{\pi\alpha^2}{4}}\ \exp\left(\frac{-f^2\alpha^2}{16}\right)$$

Figure C.5a – Transient waveform **Figure C.5b – Spectral magnitude**

Figure C.5 – Gaussian waveform



IEC 493/05



IEC 494/05

$$a(t) = \cos(2\pi f_o\,(t - t_s))\, e^{-\left(\frac{2(t-t_s)}{\alpha}\right)^2}$$

$$\left|\tilde{A}(f)\right| = \sqrt{\frac{\pi\alpha^2}{4}}\ \exp\left(\frac{-\alpha^2(\omega-\omega_o)^2}{16}\right)$$

with $t_n = (t/t_o) = tf_o$; $(t_s/t_o) = 20$; $\alpha = 10$ $f_n = (f/f_o)$

Figure C.6a – Transient waveform

Figure C.6b – Spectral magnitude

Figure C.6 – Sinusoidal waveform with a Gaussian-amplitude modulation

Annex D
(informative)

Determination of the bandwidth of typical HPEM waveforms

It is recalled that using the bandratio *br* and the percent bandwidth *pbw*, we have defined the four bandwidth classification as follows:

$$\text{bandratio} = br = \frac{f_h}{f_\ell} \qquad \text{bandratio decades} = brd = \log_{10}(br) \qquad (D.1)$$

$$pbw = 200\frac{(br-1)}{(br+1)} \qquad br = \frac{[1+\frac{pbw}{200}]}{[1-\frac{pbw}{200}]} \qquad (D.2)$$

hypoband = narrowband	→	$pbw \leq 1$ %	or	$br \leq 1,01$
mesoband	→	1 % < $pbw \leq 100$ %	or	$1,01 < br \leq 3$
sub-hyperband	→	100 % < $pbw \leq 163,64$ %	or	$3 < br \leq 10$
hyperband	→	163,64 % < pbw < 200 %	or	$br > 10$

In this annex, we define a way of determining the bandratio *br* for typical HPEM waveforms [18] and contrast it with the more common definition of 3 dB points, which are the frequencies where the spectral amplitude drops by 3 dB.

The criterion for the finding of f_ℓ and f_h should be based on the energy content in a certain spectral interval, as follows.

Find $\Delta f(f_h, f_\ell) = f_h - f_\ell$ such that $\Delta f(f_h, f_\ell) = f_h - f_\ell$ becomes minimal and

$$\frac{\int_{f_\ell}^{f_h} \left| \tilde{V}(j\omega) \right|^2 d\omega}{\int_0^\infty \left| \tilde{V}(j\omega) \right|^2 d\omega} = 0.9 \qquad (D.3)$$

This definition ensures that 90 % of the overall energy is contained in the interval [f_ℓ, f_h].

In the following clauses, some examples are considered.

D.1 Signals with a significant *dc* part in the spectrum

For the example shown in Figure D.1, a spectral magnitude with a large dc part, one can use the following procedure. Use 1 Hz as the lower frequency limit f_ℓ and find the upper frequency limit f_h that contains 90 % of the energy. Then calculate the bandratio decades *brd* from 1 Hz to f_h Hz and calculate the bandratio *br* via $br = 10^{brd}$.

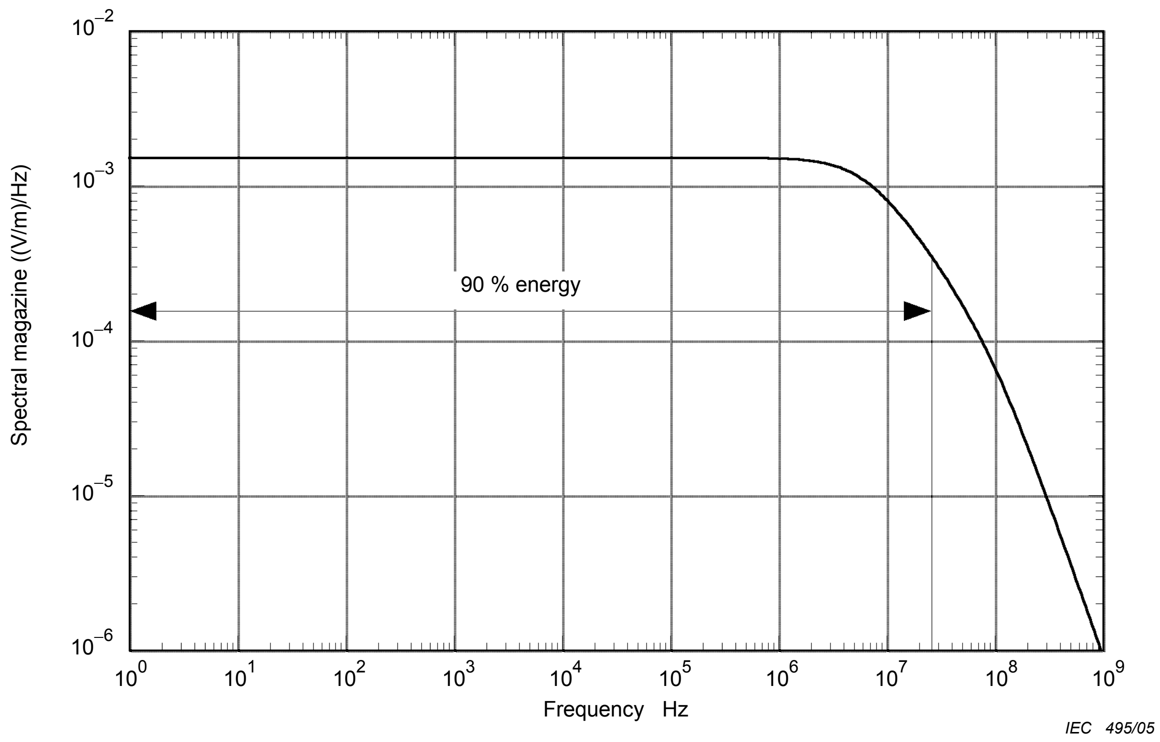


Figure D.1 – A waveform spectrum with a large *dc* content (e.g. the early-time HEMP from IEC 61000–2-9)

D.2 Signals with a multipeaked spectrum

The majority of the energy in Figure D.2 is not contained in the 3 dB frequency interval [f_1, f_3]. The bandwidth of "multipeaked" signals is much better determined using the 90 % energy definition, which is found from integrating the frequency waveform to find the values f_{low} and f_{high}.

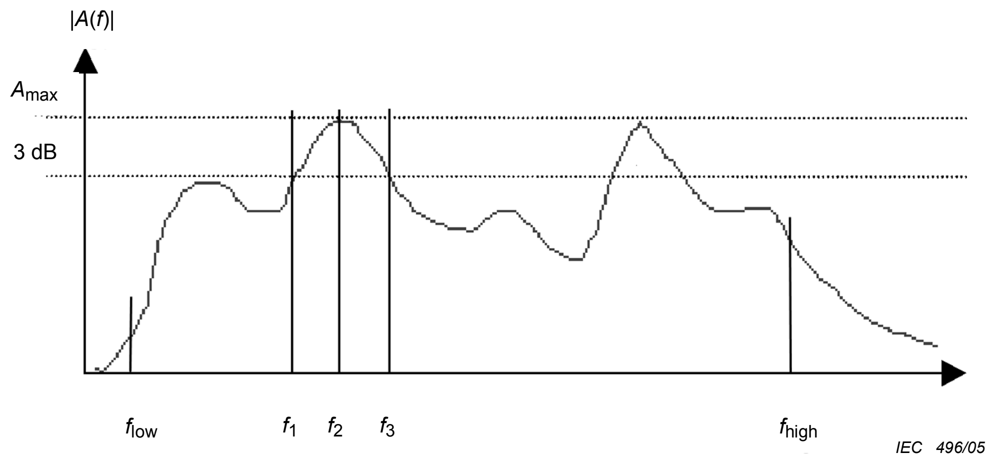


Figure D.2 – A waveform with a multipeaked spectral magnitude in units of 1/Hz

D.3 Damped sinusoidal signals with a low Q

Low Q damped sinusoids are considered as a possible threat signal due to the broad bandwidth with a well-defined centre frequency. In this case the usual 3 dB definition for bandwidth leads to an interval [f_ℓ, f_h] which contains just 56 % of the overall signal energy. The overall energy content can be calculated using the theorem of Parseval for a spectrum $\tilde{A}(j\omega)$ and a time domain signal $V(t)$):

$$\int_{-\infty}^{\infty} \left|V(t)\right|^2 dt = \frac{1}{2\pi} \int_0^{\infty} \left|\tilde{V}(j\omega)\right|^2 d\omega \qquad \text{(D.4)}$$

Using this theorem, the energy, U, in a certain frequency interval [f_a, f_b] can be calculated via:

$$U[f_a - f_b] = \frac{1}{2\pi Z} \int_{f_a}^{f_b} \left|\tilde{V}(j\omega)\right|^2 d\omega, \qquad \text{(D.5)}$$

where Z is the impedance relating V and I for this example. For the damped sine signal spectrum, one can determine the following energy contents:

- energy in [0, ∞]: 100 %
- energy in [f_ℓ, f_h]: 56 %
- energy in [0, f_ℓ]: 26,5 %
- energy in [f_h, ∞]: 17,5 %

These values indicate that while only 56 % of the energy is contained within the 3 dB frequencies, 82,5 % of the energy is contained between 0 Hz and the upper 3 dB point. This means that for analytic damped sinusoids, there is not much difference between the different methods for calculating the bandwidth. In Figure D.3 below, the upper 3 dB frequency is 1,26 GHz and the 90 % energy upper frequency is 1,38 GHz, indicating a very small difference.

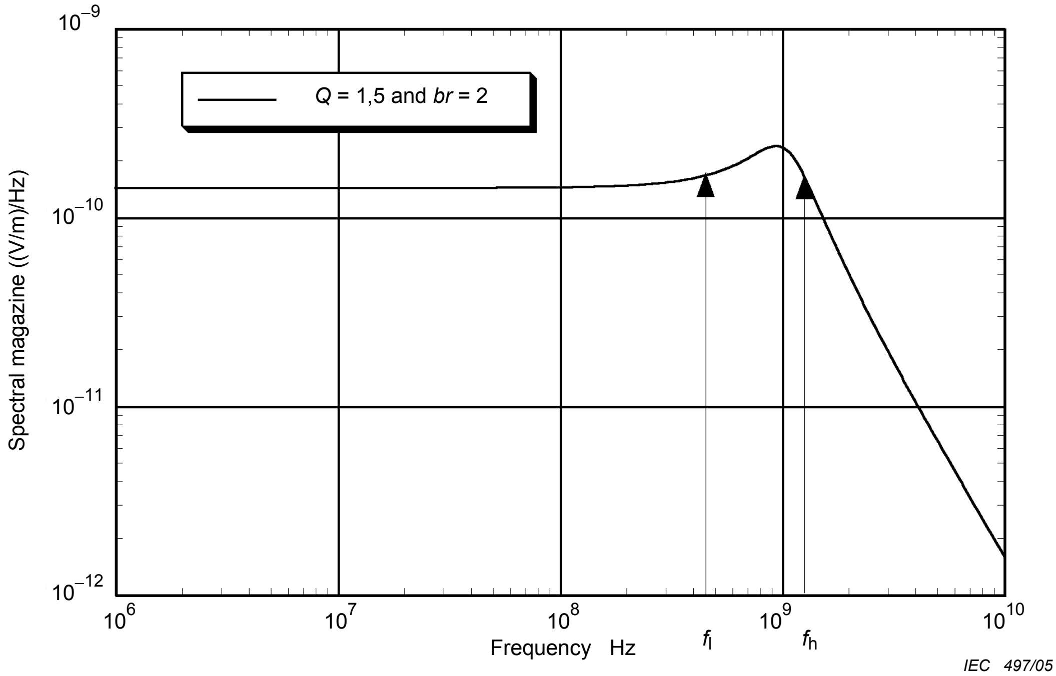


Figure D.3 – Spectral magnitude of a damped sinusoidal waveform with a low Q and a bandratio value computed using the 3 dB frequency points

D.4 Damped sinusoidal signals with a high Q

Figure D.4 shows that the energy definition is also consistent with the 3 dB method to compute the bandwidth for a very narrow peak in the frequency domain. It is clear that while 56 % of the energy is contained between the 3 dB points for this analytic damped sinusoid, only a slightly larger bandwidth would be computed to encompass 90 % of the energy due to the rapid decrease in the spectral magnitude on each side of the centre frequency.

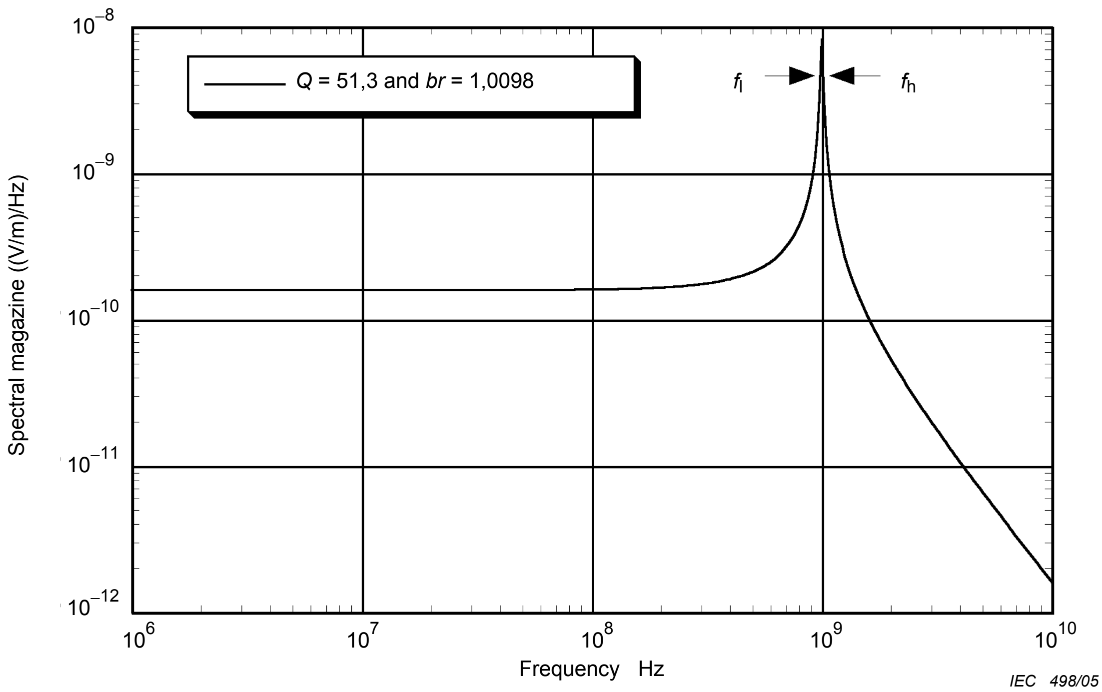


Figure D.4 – Spectral magnitude of a damped sinusoidal waveform with a high Q and a bandratio value computed using the 3 dB frequency points

Bibliography

[1] OSD/DARPA, *Ultra-Wideband Radar Review Panel, Assessment of Ultra-Wideband (UWB) Technology*, Defense Advanced Research Project Agency (DARPA), Arlington, VA, 1990.

[2] Baum, C. E., *Modification of TEM-Fed Reflector for Increased Efficiency*, Sensor and Simulation Note 458, July, 2001, p8.

[3] Taylor, C. D. and GIRI, D. V., *High-Power Microwave Systems and Effects*, Taylor and Francis, 1994.

[4] Benford, J., Microwave Sciences, Inc., Lafayette, CA, Private Communication.

[5] Baum C. E., *Switched Oscillators*, Circuit and Electromagnetic System Design Note 45, 10 September 2000.

[6] Baum, C.E., *Antennas for Switched Oscillators*, Sensor and Simulation Note 455, 28 March 2001.

[7] Baum, C. E., *Radiation of Impulse-Like Transient Fields*, Sensor and Simulation Note 321, 25 November 1989.

[8] Giri, D. V., Lackner, H., Smith, I.D., Morton, D. W., Baum, C. E., Marek, J. R., Prather, W. D. and Scholfield, D. W., *Design, Fabrication and Testing of a Paraboloidal Reflector Antenna and Pulser System for Impulse-Like Waveforms*, IEEE Trans. Plasma Sciences, Volume 25, p. 318-326.

[9] Mikheev, O. V. *et al.*, *New Method for Calculating Pulse Radiation from an Antenna with a Reflector*, IEEE Transactions on Electromagnetic Compatibility, February 1997, Volume 39, Number 1, p 48-54.

[10] Baum, C. E., Air Force Research Laboratory, Kirtland AFB, NM, Personal Communication, March 2001.

[11] Baum, C. E., *Maximization of Electromagnetic Response at a Distance*, IEEE Trans. on Electromagnetic Compatibility, August 1992, pp 148-153. Also published as Sensor and Simulation Note 312, October 1988.

[12] Bohl, J., *High Power Microwave Hazard Facing Smart Ammunitions,* System Design and Assessment Note 35, 14 December 1995.

[13] Lovetri, J. and Wilburs, A., *Microwave Disturbance of a Personal Computer: Experimental and FDTD Simulations*, Proceedings of International Symposium on Electromagnetic Compatibility, Zurich, 1999.

[14] Fortov, V., Loborev, V., Parfenov, Yu., Sizranov, V., Yankovskii, B., and Radasky, W., *Estimation of Pulse Electromagnetic Disturbances Penetrating into Computers Through Building Power and Earthing Circuits*, Metatech Corporation, Meta-R-176, December 2000.

[15] Fortov, V., Parfenov, Yu., Zdoukhov, L., Borisov, R., Petrov, S., Siniy, L. and Radasky, W., *Experimental Data on Upsets or Failures of Electronic Systems to Electric Impulses Penetrating into Building Power and Earthing Nets*, Metatech Corporation, Meta-R-187, December 2001.

[16] Radasky, W., Messier, M., Wik, M., *Intentional Electromagnetic Interference (EMI) – Test Data and Implications,* 14th International Zurich Symposium and Technical Exhibition on EMC, February 2001.

[17] Bäckström, M., *HPM Testing of a Car: A representative Example of the Susceptibility of Civil Systems*, Workshop W4, 13th International Zurich Symposium and Technical Exhibition on EMC, February 1999, pp 189-190.

[18] Nitsch, D., Visiting Scientist at NRL, Washington DC, Personal Communication, March 2002.

[19] Uman, M., *The Lightning Discharge***,** Academic Press, 1987, p. 118.

[20] Silfverskiöld, J., Bäckström, M., Lorén J., *Microwave Field-to-Wire Coupling Measurements in Anechoic and Reverberation Chambers*, IEEE Transactions on Electromagnetic Compatibility, Feb 2002, Vol. 44, No. 1.

[21] Bäckström, M., Nordstrom, B., Lövstrand, K. G., *Is HPM a Threat Against the Civil Society?,* URSI XXVIIth General Assembly, Maastricht, the Netherlands, August 17-24, 2002.

[22] IEC 61000-5-3:1997, *Electromagnetic compatibility (EMC) – Part 5-3: Installation and mitigation guidelines – HEMP protection concepts.*

[23] IEC 61000-5-6:2002, *Electromagnetic compatibility (EMC) – Part 5-6: Installation and mitigation guidelines – Mitigation of external EM influences.*

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