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THESIS

**ELECTROMAGNETIC COMPATIBILITY (EMC)
REQUIREMENTS FOR MILITARY AND COMMERCIAL
EQUIPMENT**

by

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September 2009

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**ELECTROMAGNETIC COMPATIBILITY (EMC) REQUIREMENTS
FOR MILITARY AND COMMERCIAL EQUIPMENT**

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ABSTRACT

Until approximately 1970, radio frequency (RF) requirements were driven by military usage, and electromagnetic compatibility (EMC) efforts were conducted by the military and a few select industries. This was largely due to the fact that limited applications and high costs had kept the use of consumer electronics to a minimum.

The past three decades, however, have seen a fundamental shift in this status quo. Starting with the emergence of the microprocessor in the mid-70s, commercial applications began to take the lead of technology development, and the consumer market has grown exponentially.

Widespread use of electronics in both the military and private sectors has impacted the available use of the RF spectrum. As the demands for “connectivity” continue to grow, wireless capabilities are competing for the bandwidth necessary to handle the expanding flow of information society has come to expect. As consumer usage has come to drive electronic development, the military also finds itself in the position of adopting and adapting commercial technology.

This study examines the origins of the military and commercial requirements that regulate EMC, evaluates the adequacy of these requirements with respect to current spectrum demands, and investigates the potential for harmonizing military and commercial EMC assessments.

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EXECUTIVE SUMMARY

Radio Frequency (RF) energy is of particular interest because 1) it will propagate over long distances in Earth's atmosphere and 2) it can be made to carry information by varying the amplitude, frequency and phase of the RF wave. Because the "ideal" transmit window naturally exists between approximately 3 MHz–20 GHz, there is crowding of intentional transmissions competing for space, as well as inadvertent propagation of unintentional emissions (noise) by both natural and man-made sources. The dense population of this particularly desirable range of the electromagnetic spectrum logically leads to interference issues between users.

Electromagnetic Interference (EMI) is a disturbance that interrupts or degrades the performance of a system due to electromagnetic energy generated by an outside source. This energy is transferred to the "victim" system by either electromagnetic radiation or electromagnetic conduction. Radiated EMI occurs when source and victim are separated by a relatively large distance (i.e., greater than one wavelength). Radiated EMI can occur at the signal level, where one signal "jams" another, or it can occur at the hardware level where the RF energy actually induces an unintended current in the system that adversely impacts its operation. Conflicting transmissions are considered a spectrum management issue, while the system anomalies resulting from induced current are referred to as electromagnetic environmental effects (E3). On the simplest level, electromagnetic compatibility (EMC) can be defined as the absence of these effects. Unfortunately, it is not always easy to tell when these effects are truly absent as opposed to undetected.

Until approximately 1970, RF requirements were driven by military usage, and EMC efforts were conducted by the military and a few select industries. A review of the available RF technologies prior to 1970 illustrates the fact that the majority of electronics during this time were developed by and for the military (with the noticeable exceptions of AM/FM radio and television), largely due to the limited applications and high costs of this equipment.

The past three decades, however, have seen a fundamental shift in this status quo. Starting with the emergence of the microprocessor in the mid-70s, commercial applications began to take the lead of technology development and the consumer market has grown exponentially. A review of this changing technology demonstrates just how far reaching these developments have been. As commercially manufactured electronics became increasingly widespread, EMI problems moved from the battlefield to the suburbs. Escalating consumer demand for the latest and greatest gadget also led the private sector to ultimately outpace Department of Defense (DoD) in the development of cutting edge technologies.

Although the U.S. military has maintained a considerable edge over other countries with respect to technological advancement, more and more, this technology is based on commercial developments as opposed to being developed in DoD labs. DoD has recognized the fact that commercial-integration provides opportunities for faster and lower costs in the development of military equipment. Commercial off-the shelf (COTS) use also provides access to what has become a much larger industrial base. With these goals in mind, the Secretary of Defense issued a directive in June 1994 requiring the military to use performance-based requirements in procurements and to apply commercial specifications and standards whenever possible. Recent U.S. Department of Defense Procurement Reform policies expand on this guidance by encouraging the use of COTS equipment as well. Unfortunately, COTS equipment is not necessarily intended to operate in the harsh EMEs that are characterized by military standards, such as MIL-STD-461 and MIL-STD-464. Furthermore, a survey of existing commercial technologies as of 2009 suggests that commercial standards may not provide adequate regulation with respect to commercial needs, let alone the needs of the military.

Commercial needs, however, appear to be converging, in some respects, with the needs of military. Although new technologies, such as cognitive radios and dynamic spectrum access (DSA), might ultimately ease many of the issues related to spectrum management, these approaches do not address issues related to E^3 . In order to maximize battery power and frequency usage, the operational voltages of commercial devices is getting lower and lower, resulting in a circuit that is more sensitive to the induced current

that results from E³. At the same time, we no longer live in the benign EM environment of the 1950s, 1980s, or even 2001. The ambient EME is an additive effect that increases along with the number of devices that create it. Given the exponential increase in emitting devices, combined with the fact that these same devices are more likely to be susceptible, we are reaching a point where E3 effects are going to be a greater problem at the consumer level. Commercial manufacturers will also have to take new measures to ensure proper functionality of their products.

This thesis will provide an overview of current and developing spectrum dependent commercial technologies, examine how these technologies align/overlap with existing military communication and radar systems, and offer a profile of commercial spectrum usage with respect to frequencies from 2 MHz to 40 GHz. This profile will be used to evaluate the sufficiency of EMI requirements currently cited in existing commercial standards with respect to the demands of both modern commercial and military usage.

Chapter I provides an introduction and overview for the study.

Chapter II defines and elaborates on the physics related to EMI including EM wave propagation and free-space path loss.

Chapter III provides a history of the military and commercial spectrum-dependent equipment developed between 1900 and 1969.

Chapter IV examines the effect of the microprocessor on military and commercial spectrum-dependent equipment that was developed from 1970 through the present.

Chapter V reviews the requirements of the primary U.S. military standards for EMC: MIL-STD-461F and MIL-STD-464A.

Chapter VI provides an overview of the U.S. and European commercial EMC standards including: the IEC 61000 series, ANSI C63.12, and CFR 47.

Chapter VII compares and contrasts MIL-STD-461F with the U.S. and European commercial standards. The commercial standards are then evaluated with respect to the spectrum requirements of the equipment from Chapters III & IV.

Chapter VIII summarizes the conclusions of the study to include recommendations for near-term and future actions.

LIST OF ACRONYMS AND ABBREVIATIONS

ABCS	Army Battle Command System
AM	Amplitude Modulation
ANSI	American National Standards Institute
B&W	Black and White
CB	Citizens' Band
CENELEC	Committee for Electrotechnical Standardization
CFR	Code of Federal Regulations
CISPR	International Special Committee on Radio Interference
COTS	Commercial Off-The Shelf
CRT	Cathode Ray Tube
DAB	Digital Audio Broadcasting
DARS	Digital Audio Radio Satellite
DoD	Department of Defense
DSA	Dynamic Spectrum Access
EHF	Extremely High Frequency
EMC	Electromagnetic Compatibility
EME	Electromagnetic Environment
EMI	Electromagnetic Interference
EMR	Electromagnetic Radiation
EUT	Equipment Under Test
FCC	Federal Communications Commission
FM	Frequency Modulation
FSPL	Free-Space Path Loss
GHz	Gigahertz
GIG	Global Information Grid
GOTS	Government Off-The Shelf
GPS	Global Positioning System
HF	High Frequency

Hz	Hertz
IC	Integrated Circuit
IEC	International Electrotechnical Commission
IFF	Identification, Friend or Foe
IRAC	Interdepartmental Radio Advisory Committee
ISM	Industrial, Scientific, and Medical
JFP	Joint Frequency Panel
JTIDS	Joint Tactical Information Distribution System
JTRS	Joint Tactical Radio System
LF	Low Frequency
MBWA	Mobile Broadband Wireless Access
MCEB	Military Communications-Electronics Board
MF	Medium Frequency
MHz	Megahertz
MILSTAR	Military Strategic Tactical Relay
NAVSTAR	Navigation Satellite Timing and Ranging
NTIA	National Telecommunications and Information Administration
NTSC	National Television System Committee
OATS	Open-Air Test Site
OSM	Office of Spectrum Management
PC	Personal Computer
PCS	Personal Communication Services
RADAR	Radio Detection and Ranging
RF	Radio Frequency
RFID	Radio Frequency Identification
SHF	Super High Frequency
SINGARS	Single Channel Ground and Airborne Radio System
SSN	Space Surveillance Network
TCF	Technical Construction File
TV	Television

UHF	Ultra High Frequency
USB	Universal Serial Bus
UWB	Ultra-WideBand
VHF	Very High Frequency
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WRAN	Wireless Regional Area Network
WUSB	Wireless USB

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I. INTRODUCTION

A. BACKGROUND

Electromagnetic Interference (EMI) is the operational disruption of an electronic device caused by an electromagnetic field (EM field) in the radio frequency (RF) spectrum generated by another electronic device [1]. Electromagnetic compatibility (EMC) is an intentionally engineered state where the impacts of these interference effects are eliminated. Historically, EMC has been an important concern for the military [2]. Beginning with the radios and radars deployed during World War II, the Department of Defense (DoD) has struggled with the demanding electromagnetic environment (EME) resulting from dozens of high-powered systems operating in close proximity. This challenge has been made all the more difficult with the growing dominance of commercial off-the shelf (COTS) equipment.

Not too long ago, the military had free reign of almost the entire electromagnetic spectrum. RF requirements were driven by military usage and EMC efforts were conducted by the military and a few select industries. The expense and limited applications of high-end electronics served to keep spectrum-dependent equipment out of the hands of the general public with the notable exceptions of AM/FM radio and broadcast television [3].

The past three decades, however, have seen a fundamental shift in this status quo. Starting with the emergence of the microprocessor in the mid-70s, commercial applications began to take the lead of technology development [4]. The consumer market that began with CB radios, microwave ovens, and garage door openers has grown exponentially and now includes cellular phones, personal computers, portable GPS systems, and RF ID tags.

As consumer usage has come to drive the electronics industry, the Military finds itself in the position of adopting and adapting commercial technology. One of the key difficulties with integrating COTS and/or government off-the-shelf (GOTS) products into complex military systems is establishing EMC in the operational environment.

Unfortunately, commercial products are not designed to operate in the high-power EMEs encountered in the military theater of operations. Furthermore, these commercial systems are not typically tested to the military EMC standards that would provide some indication of performance and potential vulnerabilities when exposed to these environments. Meanwhile, there is no comprehensive set of commercial requirements that covers the entire frequency range utilized in the modern military combat environment. This lack of empirical data means that system integrators cannot predict whether a given piece of COTS equipment will function properly or even survive in a military EME [5].

Of further concern is the possibility that existing commercial standards are outdated with respect to the demands of the commercial EME. Ten years ago, the operational frequency for the vast majority of commercial electronics was below 2 GHz. As such, the requirements of commercial test standards cut off at this point. Today, many common commercial technologies, such as 802.11 wireless systems, operate above 2 GHz; some technologies, such as WiMAX 802.16 systems, operate at frequencies in excess of 5 GHz. The commercial test requirements, however, have not been updated to reflect this expansion. For this reason, the existing commercial EMC standards may not truly adequate for the needs of the current commercial EME—let alone the needs of the military combat environment.

B. PURPOSE

This study provides an overview of current and developing spectrum dependent commercial technologies, examines how these technologies align/overlap with existing military communication and radar systems, and offers a “composite profile” of commercial spectrum usage with respect to frequencies from 2 MHz to 40 GHz. This composite profile forms the basis for an evaluation of the sufficiency of EMI requirements currently cited in existing commercial standards with respect to the demands of both modern commercial and military usage. Finally, the thesis examines the shortfalls and makes recommendations with respect to establishing comprehensive commercial requirements for radiated susceptibility and radiated emissions based on the

actual demands of current commercial technologies. Finally, the thesis will also provide recommendations for vetting COTS equipment into a harsh military EME.

C. RESEARCH QUESTIONS

This thesis will address the following research questions:

- Are the radiated susceptibility and radiated emissions requirements contained in existing commercial standards outdated with respect to the demands of the commercial electromagnetic environment?
- Do commercial electromagnetic compatibility standards provide an adequate basis for predicting operational performance in military electromagnetic environments?
- How can the status of either issue be improved?

D. BENEFITS OF STUDY

This thesis will provide the following benefits:

- Provides an overview of the physics and technological developments that create EMI.
- Provides insight into the discrepancies between commercial EMC standards and actual commercial EMEs that COTS equipment can realistically expect to encounter.
- Provides awareness of the hazards of subjecting COTS equipment to a military EME without any empirical data to suggest that the equipment can function in that environment.
- Provides recommendations for utilizing existing commercial EMC standards to best advantage.
- Provides recommendations for an updated, comprehensive commercial EMC standard.

E. SCOPE

The following study focuses on the spectrum usage of actual commercial systems, both existing and under development that populate the frequency range from 2 MHz to 100 GHz. Based on the collective emissions of these systems, a true profile of modern commercial spectrum requirements can be derived and compared to the requirements for radiated emissions and radiated susceptibility contained in existing commercial and military standards.

F. METHODOLOGY

The thesis methodology is as follows:

1. Conduct literature search and personal interviews for history and justification of existing EMI requirements.
2. Conduct literature search and personal interviews for current commercial technologies and their respective spectrum requirements.
3. Develop a comprehensive profile of actual commercial demands on the electromagnetic spectrum from 2 MHz to 40 GHz.
4. Compare this profile to the corresponding requirements in existing commercial standards and note any shortfall and/or gaps.
5. Compare the commercial profile to the requirements in existing military EMI standards and note any shortfalls and/or gaps.
6. Make recommendations for a comprehensive update to existing commercial EMI test requirements based on discoveries above.

G. THESIS OVERVIEW

Chapter I provides an introduction and overview for the effort.

Chapter II defines and elaborates on the physics related to EMI including EM wave propagation and free-space path loss.

Chapter III provides a history of the military and commercial spectrum-dependent equipment developed between 1900 and 1969.

Chapter IV examines the effect of the microprocessor on military and commercial spectrum-dependent equipment that was developed from 1970 through the present.

Chapter V reviews the requirements of the primary U.S. military standards for EMC: MIL-STD-461F and MIL-STD-464A.

Chapter VI provides an overview of the U.S. and European commercial EMC standards including: the IEC 61000 series, ANSI C63.12, and CFR 47.

Chapter VII compares and contrasts MIL-STD-461F with the U.S. and European commercial standards. The commercial standards are then evaluated with respect to the spectrum requirements of the equipment from Chapters III & IV.

Chapter VIII summarizes the conclusions of the study to include recommendations for near-term and future actions.

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II. EMI OVERVIEW

The following chapter explains the physics of electromagnetic radiation, provides an overview of radio frequency transmission, and details the fundamental principles of electromagnetic interference.

A. ELECTROMAGNETIC RADIATION

In order to understand the effects of EMI, it is necessary to first be familiar with the basic phenomenon of electromagnetic radiation (EMR). EMR is a self-propagating wave with both an electric field and a magnetic field. These components oscillate in phase perpendicular to each other and perpendicular to the direction of propagation (Figure 1). The distance of these oscillations in meters is referred to as wavelength (λ) and the number of oscillations per second is defined as frequency. In International System of Units (SI), the standard measure of frequency is hertz (Hz); 1 Hz is equivalent to one oscillation per second [2].

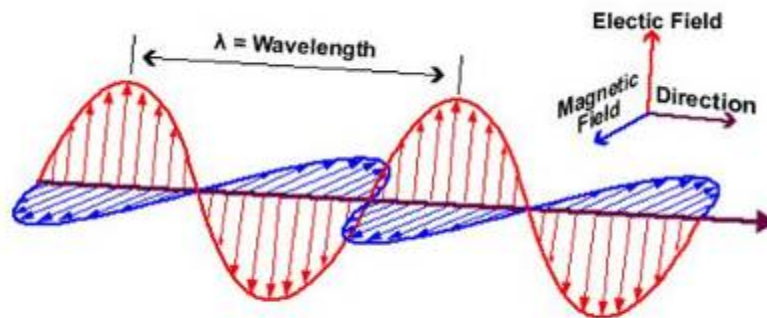


Figure 1. Electromagnetic Wave

EMR with a frequency between 790 and 400 terahertz is detected by the human eye as visible light. Other classifications of EMR include: radio waves, microwaves, terahertz radiation, infrared radiation, ultraviolet radiation, X-rays and gamma rays (Figure 2). The absorption spectra of the Earth's atmosphere allow transmission of only

certain frequency ranges of EMR. One such “window” allows a portion of the ultraviolet frequencies, the entire visible spectrum, and most of the infrared band to propagate. A second window allows the transmission of radio and microwaves. However, the Earth's atmosphere effectively blocks long-range propagation of terahertz radiation, X-rays and gamma rays [6].

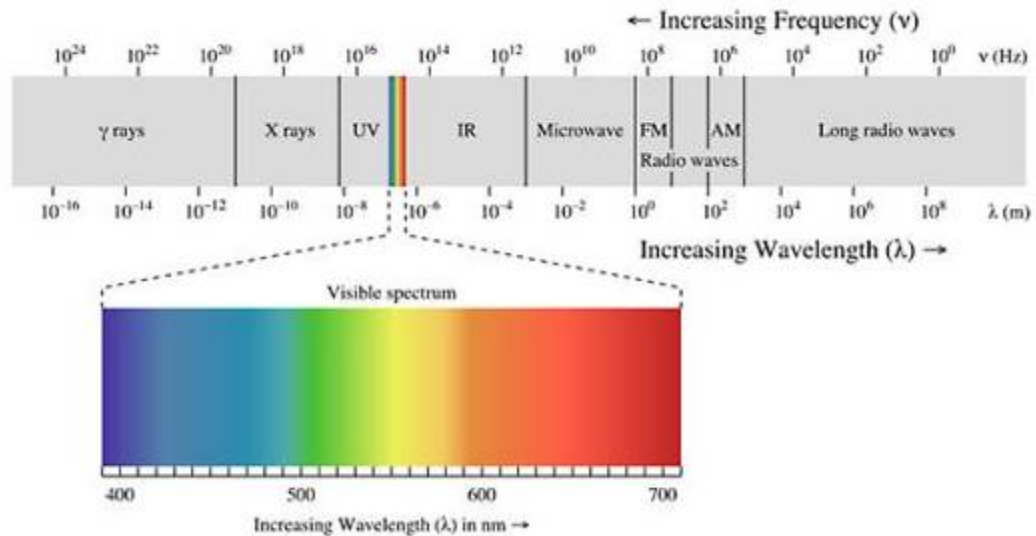


Figure 2. Electromagnetic Spectrum [From ShareAlike 3.0]

In free space, all electromagnetic waves (radio, light, X-rays, etc.) obey the inverse-square law which states that the power density of an electromagnetic wave is proportional to the inverse of the square of the distance from the source.

$$\rho P \propto \frac{1}{r^2}$$

In other words, doubling the distance from a transmitter will reduce the power density of the radiated wave to 1/4 of its previous value [7].

B. RADIO WAVES

RF energy has the operational frequency range of 3 Hz to 300 GHz (including microwave frequencies). This type of energy is of particular interest because: 1) it will propagate over long distances in Earth's atmosphere and 2) it can be made to carry information by varying the amplitude, frequency and phase of the RF wave. Transmission is the process of encoding either analogue or digital information via physical protocols such as modulation, demodulation, coding, compression, equalization, error control, bit synchronization and multiplexing [8].

The RF spectrum itself is divided into discrete frequency bands. A listing of these bands and their associated uses is contained in Table 1. Each of the different RF frequency bands have varying propagation characteristics that make them better suited to some applications than others. LF transmissions follow the curvature of the earth via groundwave propagation and are attenuated rapidly. HF transmissions have greatly increased range due to refraction of these frequencies by the ionosphere (known as skywave propagation); however, the reliability of this particular phenomenon is subject to random atmospheric conditions such as the x-rays generated by solar flares [6].

The most common propagation mode for VHF and higher frequencies is direct line-of-sight propagation between antennas that are not obscured from each other by the curvature of the Earth (i.e., beyond the "radio horizon"). Usually, signals within this distance can be received even if there is not a visual line-of-sight between the antennas (blockage) due to the effects of diffraction and multipath reflection. Examples of line-of-sight transmissions include propagation between a satellite and a ground receiver or reception of television signals from a local TV transmitter [8].

For direct line-of-sight transmissions, the equation for free-space path loss (FSPL) can be used to calculate the loss in signal strength of an electromagnetic wave resulting from a direct path through free space. The FSPL expression merges two effects, the spreading out of electromagnetic energy characterized by the inverse square law and the effectiveness of the receiving antenna.

$$FSPL = \left[\frac{4\pi d}{\lambda} \right]^2$$

Note this path loss equation assumes far-field conditions (i.e., $d \geq \lambda$). At less than a wavelength, other physical factors, such as antenna dimensions, have a dominant impact and require the use of complex near-field equations [7].

Another important characteristic of radio wave propagation involves atmospheric absorption due to molecular resonance with moisture in the air. As previously stated, radio waves are one of the few forms of EMR that readily propagates through the atmosphere. Even so, higher RF bands are increasingly susceptible to absorption effects. As a result, the upper region of the SHF band and the entire EHF band are much less desirable for long-range applications [6].

Because the “ideal” transmit window naturally exists between approximately 3 MHz–20 GHz, there is crowding of intentional transmissions competing for space, as well as inadvertent propagation of unintentional emissions (noise) by both natural and man-made sources. The dense population of this particularly desirable range of the electromagnetic spectrum logically leads to interference issues between users.

C. ELECTROMAGNETIC INTERFERENCE

EMI is a disturbance that interrupts or degrades the performance of a system (the “victim” system) due to electromagnetic energy generated by an outside source. This energy is transferred to the victim system by either electromagnetic radiation or electromagnetic conduction.

Conducted EMI only results from actual physical contact between the source and the victim systems. Example paths for this type of interference include transmission lines, wires, cables, and PCB traces. As a general rule of thumb, this type of interference can be corrected by breaking the contact between the two systems (where possible) or implementing in-line filters to block the interference signal [2].

Radiated EMI involves the EMR/RF principles explained in the preceding sections and occurs when source and victim are separated by a relatively large distance (i.e., greater than one wavelength). Radiated EMI can occur at the signal level, where one signal blocks or “jams” another, or it can occur at the hardware level where the RF energy actually induces an unintended current in the system that adversely impacts its operation. Conflicting transmissions are considered a spectrum management issue, while the system anomalies resulting from induced current are referred to as electromagnetic environmental effects (E3).

Table 1. RF Frequency Bands.

Name	Abbr	Frequency Band		Wavelength	Applications
Low Frequency	LF	30–300 kHz		10–1 km	AM broadcasting, navigational beacons, amateur radio
Medium Frequency	MF	300–3000 kHz		1000–100 m	Navigational beacons, AM broadcasting, amateur radio, maritime and aviation communication
High Frequency	HF	3–30 MHz		100–10 m	Shortwave, amateur radio, citizens' band radio
Very High Frequency	VHF	30–300 MHz		10–1 m	FM broadcasting, amateur radio, broadcast television, aviation
Ultra High Frequency	UHF	300–3000 MHz	Radar Sub-Bands	100–10 cm	Broadcast television, amateur radio, mobile telephones, cordless telephones, wireless networking, keyless entry, microwave ovens
			L Band (1 – 2 GHz)		
			S Band (2 – 4 GHz)		
Super High Frequency	SHF	3–30 GHz	C Band (4 – 8 GHz)	10–1 cm	Wireless networking, satellite links, amateur radio, microwave links, satellite television
			X Band (8 – 12 GHz)		
			Ku Band (12 – 18 GHz)		
			K Band (18 – 27 GHz)		
			Ka Band (27 – 40 GHz)		
Extremely High Frequency	EHF	30–300 GHz	V Band (40 – 75 GHz)	10–1 mm	Microwave data links, radio astronomy, amateur radio, remote sensing, advanced weapons systems
			W Band (75 – 110 GHz)		
			mm Band (110 – 300 GHz)		

Radiated EMI may be broadly categorized into two types; narrowband and broadband. Narrowband interference is caused by tightly focused transmissions (higher power over a smaller frequency range) generated by intentional emitters such as radio and TV stations, wireless networks, cell phones, etc. Broadband interference results from incidental sources that transmit a diffuse transmission (the power is spread over a very wide frequency range) such as transmission lines, electric motors, switched-mode power supplies, computers and other digital equipment. “Noise” is a generic type of broadband interference. Other more exotic sources of broadband interference include solar activity and Electromagnetic Pulse (EMP) energy.

On the simplest level, EMC can be defined as the absence of these effects. Unfortunately, it is not always easy to tell when these effects are truly absent as opposed to undetected.

D. EMC TESTING

In the broadest sense, electrical devices are expected to “operate compatibly” in their intended electromagnetic environment (EME). Although a device might operate satisfactorily for weeks, months, even years in a given environment, past performance isn’t sufficient to predict the compatibility of the device in a different environment. Testing is necessary to adequately characterize the EMC of a device and confirm that it will operate properly in a broad range of EMEs.

EMC radiated testing can be divided into two main categories: emissions testing and susceptibility testing. Emission testing typically involves actual radiated field strength measurements at some prescribed distance from the equipment under test (EUT); this provides an indication of how the EUT might affect other equipment. A spectrum analyzer is used to measure these emissions across a wide band of frequencies. Radiated susceptibility testing indicates the likelihood of how the EUT might be affected by other equipment and typically involves a high-powered source of RF energy that is directed at the EUT. Unlike emissions testing, there is no “measurement” made of the EUT during a radiated susceptibility test. Instead, repeatable operational procedures are established for the EUT that encompass expected performance. These actions are performed while the

device is exposed to an RF field of a given frequency and power level. If the EUT operates satisfactorily, then it passes at that frequency and power level. If the EUT does not function properly, then the power level is reduced until the threshold for satisfactory operation is reached. In actual practice, this process is often reversed; that is, testing begins at a power level much lower than the requirement and is increased until either the requirement is reached or system upset occurs. Working in this iterative “bottom-up” fashion takes much longer, but greatly reduces any possibility of damaging the EUT.

Both RF emissions and susceptibility testing must be conducted in a strictly controlled environment such as an anechoic chamber, reverberation chamber, or open-air test site (OATS). This level of control is necessary to ensure the safety of test personnel from inadvertent exposure to the RF energy and also, to ensure that test results are not contaminated by incidental RF energy in the ambient environment.

A number of different EMC standards, each with their own requirements related to test set-up, power levels, frequencies, and many other details, have been developed over time. Different standards have been adopted by different nations, with some standards designed for harsh military requirements, while others are intended for a benign suburban environment. The study, evaluation, and comparison of these standards is the primary focus of this thesis. First, however, it is useful to know something of the breadth of the various technologies and associated equipment that these standards regulate.

The next chapter will examine the early development of spectrum-dependent equipment.

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III. INITIAL DEVELOPMENT OF RF TECHNOLOGIES (1900–1969)

The following chapter provides a survey of the early development of spectrum-dependent technologies, both military and commercial, and examines the initial factors that led to early regulations efforts.

A. BACKGROUND

Although EMI was first identified at the start of the Twentieth Century, occurrences were few and far between due to the sparseness of electrical equipment. However, the introduction of the vacuum tube oscillator in 1912 enabled narrow-band transmission of voice communication and resulted in an upsurge of commercial radio stations. By the 1930s, interference effects were well documented and recognized as a growing cause for concern; however, it wasn't until World War II ushered in widespread military use of high-powered electronic equipment that EMC started to become a necessary discipline [9].

B. MILITARY ADVANCEMENTS

During World War I, it became apparent that commanders needed a practical means of wireless communication if they were to effectively coordinate military forces that were deployed over increasingly larger geographic distances. Although World War I naval forces made extensive use of vacuum tube radio transmitters, ground mobile radio communication wasn't practical because the radio sets were too heavy and bulky to be taken into the trenches. Instead, ground force communications were accomplished via buried cables that were often damaged by artillery fire. In many instances, homing pigeons became the de facto method for relaying orders to forward-deployed troops [3].

In the years following WWI, considerable effort was devoted to miniaturization of vacuum tubes in order to allow development of smaller electrical devices. The viability of portable short-range radio equipment was further supported by advancements in the use of very high frequencies and frequency modulation [3].

The first backpack “walkie-talkie” units, the SCR 300 (Figure 3), appeared in 1939 and transmitted on frequencies between 27 and 65 MHz. Unfortunately, these sets were heavy and inconvenient to carry. Motorola (Galvin Manufacturing at the time) developed the first handheld AM “handie-talkie” in 1940; it weighed 5 lbs and had a range of one mile. The first portable FM two-way radio was a 40-pound backpack unit that operated at 40–48 MHz with a range of 20 miles. All these devices ran on vacuum tubes, high voltage dry cell batteries, and utilized half-duplex, “push-to-talk” transmissions. These portable radio systems became key elements in the WWII strategic “networking” capability to direct forces via radio relay [10].



Figure 3. SCR 300 Backpack Walkie Talkie

World War II also served as a catalyst for rapid improvements in radar resolution, portability and range. The term RADAR is an acronym for RAdio Detection And Ranging. Independent research and development efforts conducted in the United States, Germany, France, and the Former Soviet Republic contributed to the development of radar capability; however, it was the United Kingdom that first utilized a working prototype for air defense and actually patented the device in 1935 [6].

That initial prototype employed the same fundamental physics used by modern radar systems. The radar transmitter emits high-powered, electromagnetic waves that are in phase when transmitted. When these waves come into contact with an object, some small percentage is reflected back to the radar receiver. Since radio waves travel at a known speed (the speed of light), the radar system can calculate the distance to an object based on the time differential between transmitted and received signals. The phase change of the return signal is also processed by the radar system to determine characteristics such as the altitude, direction, and speed of the detected object. Due to free space-loss considerations, the received signal is much weaker than the original transmitted signal. To compensate for the weak return signal, many radar systems (particularly long-range radars) have extremely powerful transmitters. As a result, EMI became a real concern for the electronic equipment that had to successfully operate in close proximity to the strong RF fields generated by these transmitters.

After the war, military organizations around the world recognized the importance of measuring, analyzing and preventing potential EMC problems. Test procedures and standards were developed for evaluating the ability of hardware to operate in harsh military EMEs. Driven primarily by the needs of the military, EMC emerged as an engineering discipline focused on diagnosing, solving and preventing EMI [4].

C. COMMERCIAL USE

For most of the twentieth century, public consumption of RF technologies was limited to radio and television. Table 2 contains the broadcast frequencies associated with these mediums.

Table 2. Broadcast Frequencies.

Transmission Type	Band	Frequency
Longwave AM Radio	LF	148.5 - 283.5 kHz
Mediumwave AM Radio	MF	530 kHz - 1710 kHz
Shortwave AM Radio	HF	3 MHz - 30 MHz
TV Band I (Channels 2 - 6)	VHF	54 MHz - 88 MHz
FM Radio Band II	VHF	88 MHz - 108 MHz
TV Band III (Channels 7 - 13)	VHF	174 MHz - 216 MHz
TV Bands IV & V (Channels 14 - 69)	UHF	470 MHz - 806 MHz

Amplitude modulation (AM) radio was the first RF signal accessible to the general public. Although, the first experimental AM broadcast was conducted in 1906, licensed commercial AM radio services did not begin until the 1920s. The AM signal is based on variations in radio wave amplitude at a particular frequency (Figure 4). These changes in the signal voltage are then amplified to drive a loudspeaker. AM radio is broadcast on several frequency bands: Long-wave (148.5 kHz–283.5 kHz), Medium-wave (520 kHz–1,610 kHz), and short-wave (1.711 MHz–30.0 MHz). Medium wave is actually the familiar “AM Radio” used for U.S. commercial broadcasting [8].

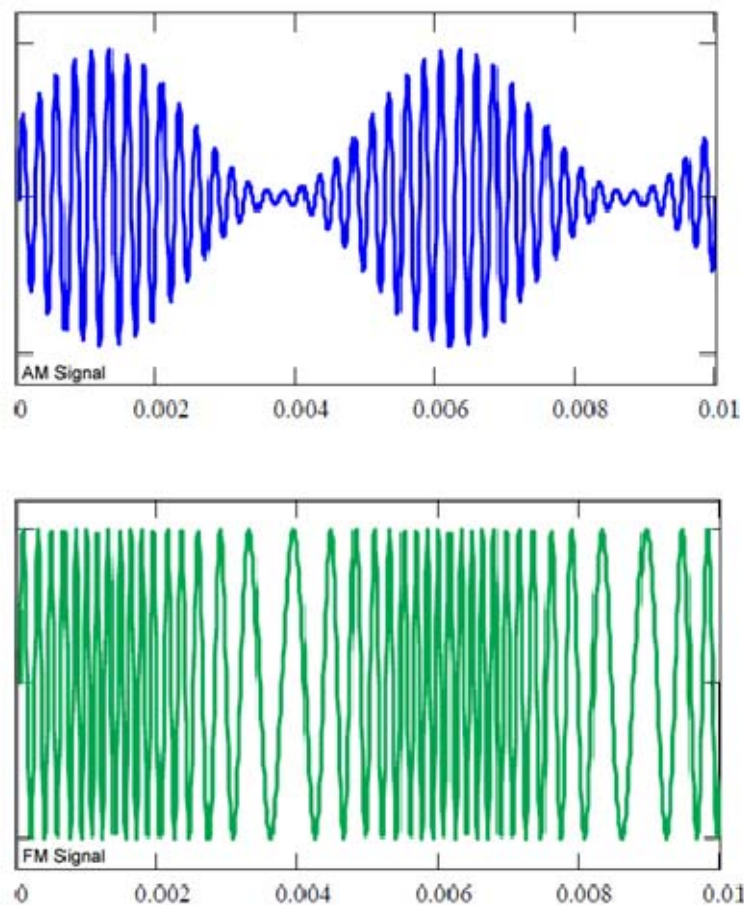


Figure 4. AM (top) and FM (bottom) Modulated Signals [After 5]

Although AM radio was the dominant form of radio broadcast for the first 80 years of the 20th century, the use of frequency modulation (FM) broadcasting was also

developed (Figure 4). FM radio falls within the 87.5–108.0 MHz portion of the VHF spectrum. Despite having been patented in 1933, commercial FM broadcasting was not authorized until January 1, 1941, and it took an additional 30 years before FM listenership exceeded that of AM stations.[8]

Television proved to be the next big market in commercial RF transmission. Although limited low-resolution television broadcasts began in 1928, it wasn't until the U.S. officially adopted National Television System Committee (NTSC) television engineering standards (525 lines of vertical resolution, 30 frames per second) in 1941 that the medium stabilized and began to see practical commercial use. In 1942, there were approximately 5,000 sets in operation, but production of new televisions, radios, and other civilian broadcasting equipment was halted in order to support the military manufacturing demands of WWII. Once production resumed in 1945, television usage grew at a rapid pace. While only 0.5% of U.S. households had a television set in 1946, 55.7% had one in 1954, and 90% by 1962 [8].

Television signals were engineered for display on a cathode ray tube (CRT) and many of the signal parameters utilized by standards, such as NTSC, were selected based on the CRT physics. The image on a CRT is painted by a moving beam of electrons which hits a phosphor coating on the front of the tube. This electron beam is steered by a magnetic field generated by powerful electromagnets close to the source of the electron beam (Figure 5).

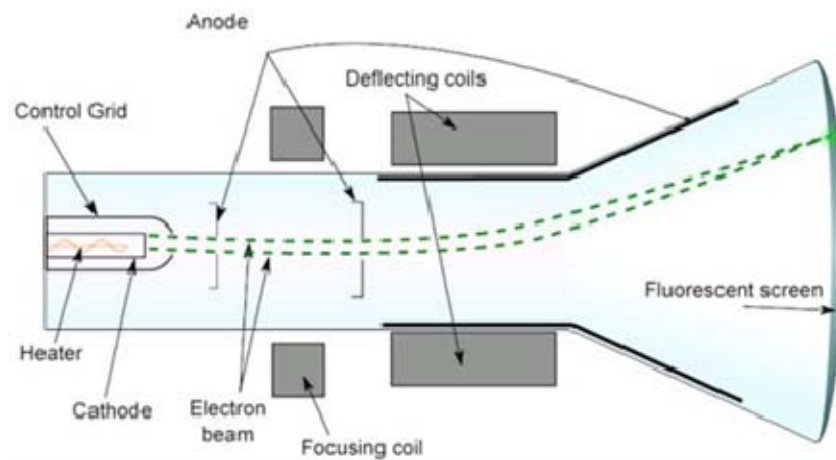


Figure 5. Cathode Ray Tube (CRT) [From ShareAlike 3.0]

Analog television systems are interlaced—that is, even rows of each video frame are transmitted and then followed by the odd rows in their sequence. Each half frame is called a field and the rate at which fields are transmitted is related to the 60 Hz frequency of the electric power grid (thus the 30 frames per second).

Television signals were first broadcast in black and white (B&W). When color television was developed, the color signal was effectively grafted onto the existing B&W system, using gaps in the video spectrum to transmit the color information (Figure 6). All countries use one of three color systems: NTSC, PAL, or SECAM. Standard wideband frequency modulation was used for the monaural audio [8].

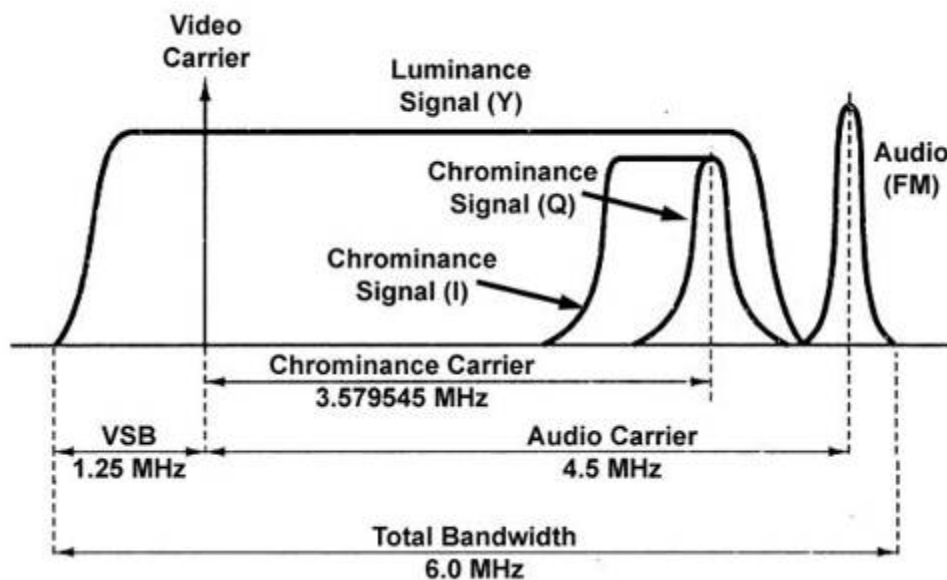


Figure 6. Spectral Content of a Television Signal

D. EARLY EMC REGULATION

As more and more commercial radio stations were established throughout the 1920s, unsavory station operators found that they could guarantee listenership by transmitting a signal powerful enough to effectively block their competitor's broadcast [4]. This type of intentional EMI, combined with the increasing occurrence of inadvertent EMI, underlined the need for governing oversight of the RF spectrum. Early EMC regulations primarily focused on spectrum management to correct these issues.

Spectrum management is a process that allows the most effective use of available radio frequencies by the greatest number of users while simultaneously limiting EMI. Spectrum management involves three related processes: allocation, allotment, and assignment. Allocation establishes a specific frequency band for a specific service, allotment partitions the allocation into discrete channels, and assignment actually licenses a given transmitter to use an allotment.

American spectrum oversight began with the Wireless Telegraphy Board in 1904 and actual wireless legislation began in 1912 with the establishment of the Radio Act to deal with allocation of frequencies. This Act was superseded by the Radio Act of 1927, which divided authority for spectrum allocation between the Federal Radio Commission for commercial users and the Department of Commerce for federal needs. The Interdepartmental Radio Advisory Committee (IRAC), which had previously been established in 1922 to coordinate federal spectrum use, was now tasked by the Department of Commerce to perform this function. Finally, the Communications Act of 1934 was enacted. This Act established the Federal Communications Commission (FCC) as the regulatory agency with jurisdiction over non-federal spectrum use [5].

Across the Atlantic, the International Electrotechnical Commission (IEC) established the International Special Committee on Radio Interference (CISPR) in 1933 to deal with the EMI problem. CISPR subsequently published a series of technical documents that established standard measurement and test techniques and recommended emission and immunity limits. These standards have evolved and endured over the years and still provide the foundation for most of today's commercial EMC regulations and guidance [4].

The military first established EMI emission requirements for equipment in 1945 with JAN-I-225 that mandated measurement of conducted and radiated EMR in the frequency range 0.15–20 MHz. The first susceptibility requirement was introduced in 1950 in MIL-I-6181. As electronics became more sophisticated and diverse, requirements evolved as well. A variety of requirements documents were issued over time with increasing frequency requirements for emission measurements and an increasing emphasis on susceptibility requirements. In 1967 these collective requirements were

consolidated into a series of three military standards: MIL-STD-461, MIL-STD-462, and MIL-STD-463 [11]. The next chapter will examine how the introduction of integrated circuits and microprocessors prompted a landslide of consumer electronics and shifted the development of cutting-edge technologies away from the military and into the private sector.

IV. MICROPROCESSORS AND CONSUMER DEMAND (1970–2009)

This chapter follows the development of spectrum-dependent equipment through the latter part of the Twentieth Century, taking particular note of the impact of computerization.

A. BACKGROUND

Looking across the timeline of consumer electronics, the single most significant factor in the modern course of technology, spectrum use, and EMI is the development of the integrated circuit (IC) in the 1960s, which, in turn, led to the manufacture of the first microprocessor in the 1970s [12]. This breakthrough meant the end to vacuum tube machines and made solid state consumer electronics an integral part of modern society (Figure 7). As commercially manufactured electronics became increasingly widespread, EMI problems moved from the battlefield to the suburbs. Escalating consumer demand for the newest and latest and greatest gadget also led the private sector to ultimately outpace DoD in the development of cutting-edge technologies.

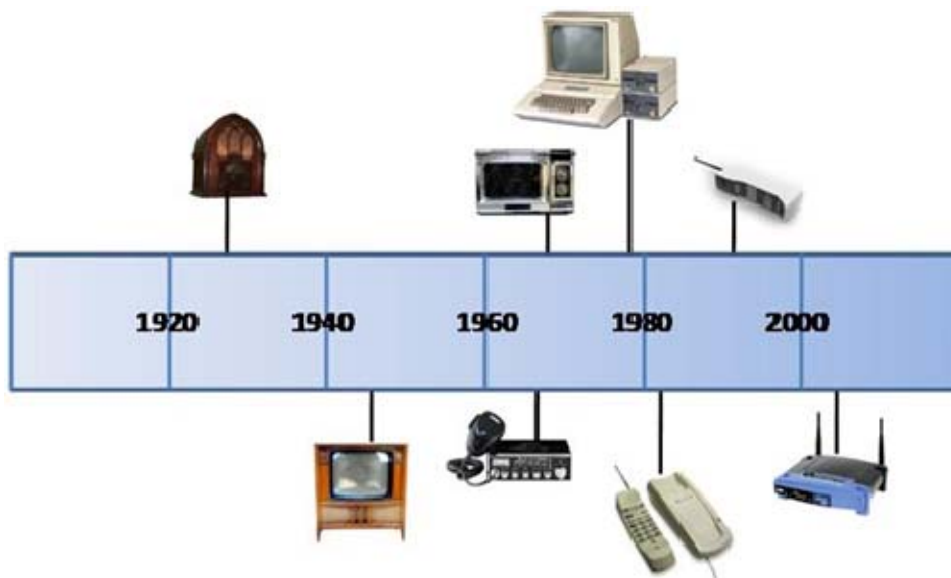


Figure 7. Timeline of Consumer Electronics

B. EMITTERS IN HOMES

While earlier consumer electronics, such as televisions and radios were primarily RF receivers, by 1970 RF transmitters were being incorporated into a growing number of electronics designed for the average consumer. One of the first RF voice transmitters designed and manufactured for the mass market is the Citizens' Band (CB) radio. The CB radio was conceived in 1945 as a means of providing the average citizen a radio band for personal communication. Initially located in the 460 MHz–470 MHz UHF band, the Class D CB service at 27 MHz was opened in 1958 (the 460 MHz–470 MHz band was reassigned for business and public safety uses). CB use hit a peak in the mid- to late-1970s, but has lost much of its appeal in the years since due to the development of cellular technology.

Another early consumer use of RF technology is the motorized garage door opener. Initially, garage door opener remote controls consisted of a simple transmitter that sent an unmodulated signal on a single frequency. As this technology became more common, users found that they could open their neighbor's garage door as well. To rectify this, systems first adopted a selectable digital code (one of 256 presets) and eventually transitioned to a more secure rolling code protocol. Garage door openers use a frequency spectrum range between 300–400 MHz [13].

The first widespread use of home radar equipment wasn't used to detect aircraft, but to cook dinner. Raytheon stumbled upon the concept of using microwaves to cook food while constructing magnetrons for radar sets in 1945. In the 1960s, Litton developed the short, wide configuration of the "Radarange," otherwise known as the microwave oven, which became a common household appliance by the late 1970s. The oven works by passing non-ionizing microwave radiation at a frequency of 2.45 GHz through food. Both 5.8 GHz and 24.125 GHz were considered for microwave cooking, but were ultimately disregarded due to the high cost of power generation at these frequencies. The microwave has become another mainstay of society; it is currently estimated that more than 90% of American households have a microwave oven [14].

C. PERSONAL COMPUTING

Perhaps the most significant direct outgrowth of microprocessor technology is the development and resulting proliferation of personal computers. Apple Computers introduced the world's first personal computer, the Apple II, in 1977 [15]. Throughout the late 1970s and into the 1980s, computers were further developed for household use. In 2001, 125 million personal computers were shipped in comparison to 48 thousand in 1977. Gordon Moore foresaw this growth when he postulated the famous "Moore's Law" in 1965—that every 18 months the capacity of the chip will double while its price drops. As of June 2008, the number of personal computers in use worldwide hit one billion, while another billion is expected to be in use by 2014. Although not readily apparent, a personal computer will emit an RF signal at the clock frequency of the system. These emissions become a greater concern as processor clock speeds climb higher into the gigahertz range. For this reason, personal computers and other devices that contain clocks or oscillators but that do not deliberately generate RF emissions are classified by the FCC as "unintentional radiators" (and are subject to minimal requirements for radiated emissions).

D. WIRELESS TELEPHONY

The first instance of a mass-market "wireless telephone" occurred in the early 1980s with the introduction of the cordless phone. Although still physically connected to the service provider via a "hard-line," the cordless handset maintains a short-range wireless link to the charger/base station. Over the years, the FCC has approved cordless phone operation in several shared frequency bands. The earliest cordless phones operated at 1.7 MHz, but these models were soon replaced by phones that operated at 43–50 MHz. Although the latter model had a large install base by the early 1990s, neither of these phones is still in production. Virtually all telephones currently sold in the U.S. use the 900 MHz, 1.9 GHz, 2.4-GHz, or 5.8 GHz bands, though legacy phones remain in use on the older bands. The recently allocated 1.9 GHz band is used by the popular DECT phone standard and is considered more secure than the other shared frequencies.

The next logical step in wireless phone technology was to eliminate the hard-line altogether and link directly to the provider via a wireless signal. This was the principle behind the development of the cellular telephone. Although the “cell” model for mobile phone base stations was first developed by Bell Labs in the 1960s, it wasn’t until the early 1990s that cell phones were widely used. This change was largely due to the smaller and more convenient form factor made possible by advancements in digital component miniaturization and improvements in battery technology. In the years since, cell phones have become a staple of modern society. The International Telecommunication Union estimated that mobile cellular subscriptions worldwide reached approximately 4.1 billion at the end of 2006 [16]. Because cellular phones utilize full-duplex, two-way transmissions, two frequencies are required for each call. GSM-850 and GSM-1900 are the cell phone frequency standards used in the United States and Canada. GSM-850 uses 824–849 MHz to send uplink information and 869–894 MHz for the downlink. GSM-1900 uses 1850–1910 MHz for the uplink and 1930–1990 MHz for the downlink [17].

A branch of technology closely related to the cell phone is the satellite phone. This type of phone communicates directly with a satellite, which in turn relays calls to a base station or another satellite phone. A single satellite can provide coverage to a much greater area than terrestrial base stations. Satellite radio in the U.S. uses 2.3 GHz for DARS. The Iridium satellite phones utilize L-band spectrum between 1616 and 1626.5 MHz.

E. SATELLITE TELEVISION & RADIO

Although satellite technology has its roots in military applications (the military aspects of satellite technology will be covered in following sections), its functionality was quickly recognized and implemented by the private sector. RCA launched SATCOM 1, the first satellite built specifically for television broadcasts, in 1975. Hughes’s DirecTV, the first national high-powered upper Ku-band DBS system, went

online in 1994, followed by EchoStar's Dish Network in 1996. The Dish Network and DirecTV remain the two primary U.S. providers of subscription satellite television service to this day.

Satellite transmissions start with a transmitting antenna or "dish" at an uplink facility. The uplink dish is pointed toward a specific satellite and the uplinked signals are transmitted within a specific frequency range and received by a satellite transponder tuned to that range. The transponder then sends the downlink signal back at a different frequency in order to avoid interference with the uplink signal. This downlink feed is the signal received by the customer [18].

Satellite TV either operates in the C band for the traditional large dish fixed satellite service or Ku band for direct-broadcast satellite. C-band transmission is susceptible to terrestrial interference while Ku-band transmission is affected by rain.

Satellite radio uses the 2.3 GHz S band in North America and generally shares the 1.4 GHz L band with local Digital Audio Broadcasting (DAB) stations elsewhere. Curvature of the earth limits the reach of the signal, but due to the high orbit of the satellites, two or three are sufficient to provide coverage for an entire continent. Local repeaters enable reception even if line of sight to the satellite is blocked. In the United States and Canada, one holding company, Sirius XM Radio, operates the two satellite radio services, after the acquisition of XM by Sirius in July 2008.

F. WIRELESS STANDARDS

In a century of incredible technological growth, the Internet may well stand as the most influential development of the twentieth century. Although the origins of this entity can be traced back to 1960s networking research projects, funding by the National Science Foundation sparked new interest leading to the commercialized worldwide network that was first popularized in the mid-1990s. As of 2009, an estimated quarter of Earth's population uses the services of the Internet. In a related domino effect, the demand for connectivity to this resource has led to the development of commercial wireless technologies that allow users to access Internet services from virtually any location [19].

IEEE 802.11 is a widely implemented set of standards established in 1997 for the implementation of wireless local area networks (WLAN) computer communication in the 2.4, 3.6 and 5 GHz frequency bands. 802.11b and 802.11g use the 2.4 GHz frequency band, while 802.11a uses the 5 GHz band. 802.11b and g equipment is susceptible to EMI from microwave ovens, cordless telephones and other emitters in this band. Because 802.11a devices operate at a less congested frequency, they are less likely to experience EMI; however, the higher frequency reduces the effective range and signals are absorbed more readily by walls and other solid objects [19].

IEEE 802.16 is a series of Wireless Broadband standards established in 1999 and recently commercialized under the moniker Worldwide Interoperability for Microwave Access (WiMAX) by the industry alliance known as the WiMAX Forum. The IEEE 802.16 specification was designed to operate between 2 to 11 GHz. The commercial implementations are in the 2.3 GHz, 2.5 GHz, 3.5 GHz and 5.8 GHz ranges. Licensed long-range (25 km) WiMAX Internet Access services in the 3.5–4.0 GHz range are already operational in many countries. The FCC recently allocated spectrum in this range for services in the U.S.

IEEE 802.20 and 802.22 are two additional standards still under development. IEEE 802.20 or Mobile Broadband Wireless Access (MBWA) was established in 2002 with the goal of providing multi-vendor interoperable mobile broadband wireless access networks in licensed bands between 1.6 and 2.3 GHz. IEEE 802.22 is a standard for Wireless Regional Area Network (WRAN) that uses white spaces in UHF/VHF TV bands between 54 and 862 MHz to bring broadband access to hard-to-reach, rural areas.

There are also several wireless standards that focus entirely on short range hardware communication. Bluetooth is one such protocol that provides a way to connect and exchange information between devices such as mobile phones, telephones, laptops, personal computers, printers, etc. via a 2.4 GHz short-range RF signal. Although developed in 1994, it has only been in recent years that the Bluetooth technology has seen widespread adoption. Wireless USB (WUSB) is a high-bandwidth wireless extension to USB based on Ultra-WideBand (UWB) wireless technology that is designed for use in USB devices such as game controllers, printers, scanners, digital cameras, MP3 players,

hard disks and flash drives. WUSB operates in the 3.1–10.6 GHz band-range and spreads communication over an ultra-wideband of frequencies [20].

G. MILITARY

Military Spectrum dependence continued to grow during the Korean and, in particular, the Vietnam War. The early 1970s saw the peak of analog military communications. High-fidelity transistorized combat radios became available in the field and enabled infantry, armor, artillery, and air support to communicate directly with each other. All total, the Department of Defense was operating nearly one million transmitters at this time [3].



Figure 8. Single Channel Ground and Airborne Radio System (SINCGARS)

The Single Channel Ground and Airborne Radio System (SINCGARS) was the next generation of military radio, replacing the mobile communication radios used in Vietnam (Figure 8). The SINCGARS radio system operates on any of the 2,320 channels between 30 and 88 MHz and serves as a primary means of tactical command and control for infantry, armor, and artillery units, and, airborne units. More than a quarter-million receivers have been produced [3].

Several notable advancements in military radar technology also occurred during the latter part of the 20th century.

Phased array radar systems offer dramatic improvements in speed and multitasking capability over traditional rotating dish systems. The best-known variant of this type of radar is the AN/SPY-1 that forms the backbone of the Aegis combat system (Figure 9). The system is computer controlled, using four complementary antennas in order to provide full 360-degree coverage. The phased array uses a matrix of evenly spaced aerial elements. By altering the relative phase of the signal fed to each element, the beam that is created by the sum total of the radiated energy can be controlled and steered. Because phased array radars require no physical movement the beam can scan at thousands of degrees per second, fast enough to simultaneously track numerous individual targets while still maintaining a wide-area search at the same time. The lack of moving parts also reduces wear and tear on the system [6].

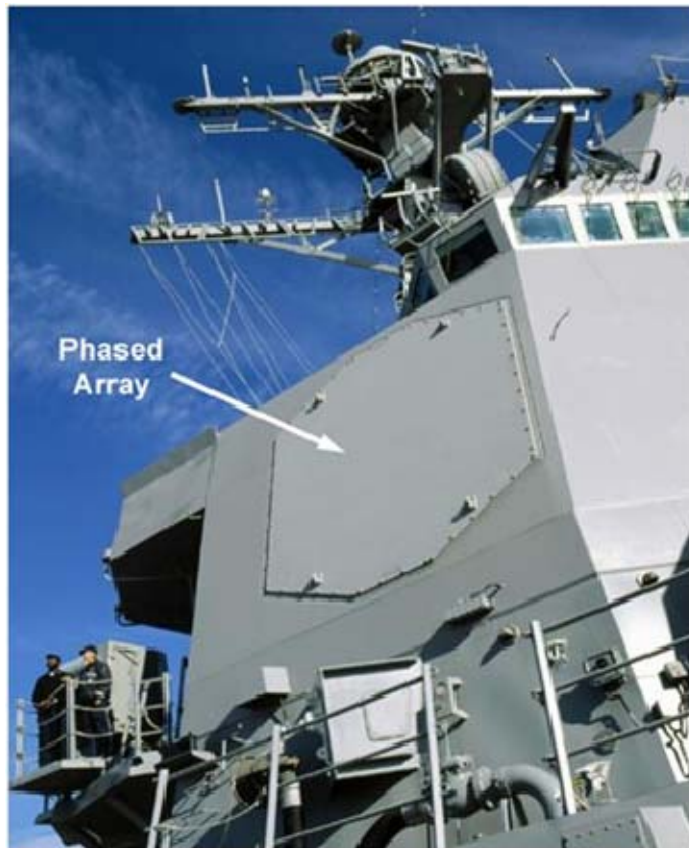


Figure 9. SPY-1 Radar Panel

A tracking system that works in concert with standard radar systems is the Identification, friend or foe (IFF) emitters. This query-and-response system is used to separate allied from enemy aircraft by assigning a unique identifier code to each friendly aircraft's radio transponder. IFF operates in four modes in military aircraft and a fifth mode is currently in the final stages of development. Mode 1 is a nonsecure method used by ships to track aircraft and other ships. Mode 2 is used by aircraft to make carrier controlled approaches to ships during inclement weather. Mode 3 is the standard system and is also used by commercial aircraft to relay their position to ground controllers throughout the world for air traffic control. Mode 4 is the secure, encrypted identification system. Mode 5, also a secure identification system, features updated encryption methods and will ultimately replace Mode 4 [3].

Military satellite systems are another key area of DoD spectrum technology. U.S. military satellite communications have improved and expanded greatly over the past four decades. U.S. satellite transmissions actually have their origins in early DoD communication experiments involving reflecting RF signals off the Moon. Ultimately, these experiments led to the deployment of Explorer 1 on January 31, 1958 (although Sputnik 1, launched by the Soviet Union, preceded Explorer by four months). Tacsat and LES-5 and -6 were experimental satellites that demonstrated UHF (225- to 400-megahertz) links with mobile terminals. The Fleet Satellite Communications (FLTSATCOM) system was DoD's first operational system dedicated to supporting military operations. Most of the FLTSATCOM satellites transmitted in the UHF band although there was a limited deployment of an EHF payload that had a 44-gigahertz uplink and 20-gigahertz downlink. Leasat was a military satellite program that relied on leased commercial satellite services in the X-band and UHF ranges. The FLTSATCOM and Leasat satellites were replaced in 1999 by the UFO satellites. Additional protected satellite systems include the MILSTAR and Air Force Satellite Communications (AFSATCOM) systems. The United States Space Surveillance Network (SSN) has been tracking space objects since 1957. The SSN currently tracks more than 560 operational satellites [18].

The Joint Tactical Information Distribution System (JTIDS) is a secure, high-capacity data link communications system for tactical combat. It uses L-band frequencies (960–1215 MHz) and can handle large amounts of data at high speed. It supplies integrated information distribution, position location, and identification capabilities. The development of the JTIDS began in 1981. Multiservice operational testing was completed in 1996 and implementation began in 1998 [3].

Link-16 is a tactical system providing communication, navigation, and identification. Link-16 was used extensively and proved its effectiveness for the first time during the Gulf War (1990–1991). Although primarily a data network, Link-16 also supports voice communication [3].

The Navigation Satellite Timing and Ranging (NAVSTAR) global positioning system is a U.S. Department of Defense system of 24 satellites that provide navigation information and extremely accurate, three-dimensional position data to both civilian and military users around the world. The satellites emit continuous signals on two different L-band frequencies: 1575.42 MHz and 1227.6 MHz. The GPS program was initiated in 1973 and the first satellites were launched in 1978. The system's initial operational capability was only reached on December 8, 1993, and full operational capability on April 27, 1995. The placement of the satellites ensures that between five and eight satellites are visible from any point on the earth [3].

The GPS system proved invaluable during the Gulf War in 1990. GPS enable accurate navigation in featureless desert combat zones. The Gulf War was also the first “net-centric” conflict. Forces made use of more than 60 communication satellites, AWACS aircraft helped support a variety of joint land, sea, and air operations, and the coalition maintained 59 communication centers and operated on over 7,000 RF frequencies.

Another outgrowth of the Gulf War was the so-called “CNN effect,” i.e., the impact of live broadcasting on military and foreign policy [21]. This was one of the first instances of commercially available technology placing the military at a disadvantage. A reporter could use a briefcase-size satellite phone to broadcast from the middle of a

combat zone. This effect has supposedly a primary motivator for military development of non-lethal weapons, and RF “Pain Ray” technology in an effort to limit wartime images of bloodied casualties.

The Iraq War is the first to be dominated by computerized and digital communications. Joint forces make use of more than 100 communication satellites. Communication has become real time and dependent on commercial IT innovations. The Army Battle Command System (ABCS) enabled commanders to transmit orders, intelligence, logistics information, and other useful data.

A challenge presented by the war in Iraq that DoD technology is still struggling to overcome is the use of improvised explosive devices (IEDs). These devices are constructed so that a receiver is connected to an electrical firing circuit and triggered by a RF transmitter from a distance. Such a device can be triggered by a number of widely available RF mechanisms including car alarms, wireless door bells, garage door openers, pagers, and cell phones. The technology is simple, but the means to proactively defeat it is incredibly complicated. One of the primary approaches initiated by DoD is the development of a system of portable jamming devices that can be used to block radio frequencies, such as cell phone signals. These high-powered jammers disrupting portions of the radio spectrum that insurgents use to trigger IEDs. However, insurgents quickly adapt to countermeasures, and new, more sophisticated IEDs are developed. Also, counter-IED radio jammers can sometimes lock onto other U.S. electronic combat systems because of a lack of coordination of spectrum usage. Unmanned Aerial Vehicles (UAVs) can sometimes lose their radio control links due to ground-based radio interference caused by counter-IED jammers once they are far away from their control base.

Joint Tactical Radio System (JTRS) is the first in a new generation of software-defined radios (SDRs) (Figure 10). The new equipment will integrate voice, data, and video communications links, while providing interoperability with existing radio systems. Spectrum segments used will range from 2 MHz to above 2 GHz. Development began in 1997 [3].

SDRs such as JTRS are viewed as the precursors to a new communication paradigm designed to exploit existing wireless spectrum with a sensing and response protocol that borders on AI. Appropriately enough this technology is sometimes referred to as cognitive radio networks, but more commonly known as Dynamic Spectrum Access (DSA). The vision for this radio technology is that it will handle spectrum management on the fly providing efficient spectrum sharing, real-time spectrum trading, and put an end to the need for command and control spectrum allocation.



Figure 10. Joint Tactical Radio System (JTRS)

All of these developing technologies are planned to ultimately feed into the Global Information Grid (GIG). First proposed in 1999 and still under development, the GIG is envisioned as an integration of all DoD information systems into an over-arching network [3]. This information network will interface with allied information systems and

provide information assurance, interoperability, and information sharing across all DoD assets and be available worldwide from either fixed or mobile connections—quite an advancement from homing pigeons.

This grand vision for the future of warfare hinges on the underlying assumption that there will be available spectrum to accomplish this global connectivity and sufficient bandwidth to move these massive amounts of information. However, access is not guaranteed, and loss of spectrum not only equates to reduced capability in the short-term, it could very well undermine plans for future capability as well.

H. MILITARY USE OF COTS

Although the U.S. military has maintained a considerable edge over other countries with respect to technological advancement, more and more, this technology is being based on commercial developments as opposed to being developed in DoD labs. With the rapid growth in the demand for consumer electronics over the past 25 years, it is no longer the soldier's need for reliable communication on the battlefield that drives the miniaturization of portable communications; rather, it is the need for a cell phone to fit conveniently into a 16-year-old girl's purse that now drives this trend. The competitive nature of the commercial market has created a situation where private industry outpaces military development more often than not. The government role in technology has shifted to more of a director than developer in that procurement decisions serve to speed outside development. This approach is exemplified by the DoD transition to a capability-based acquisition system.

DoD has recognized the fact that commercial-integration provides opportunities for faster and lower costs in the development of military equipment. COTS use also provides access to what has become a much larger industrial base. With these goals in mind, the Secretary of Defense issued a directive in June 1994 requiring the military to use performance-based requirements in procurements and to apply commercial specifications and standards whenever possible. Recent U.S. Department of Defense

Procurement Reform policies expand on this guidance by encouraging the use of COTS equipment as well. DoD has also acknowledged that there is some level of risk involved with this policy.

Military command and control environments have a greater density of electronic equipment sensitive to electromagnetic effects. At the same time, other military environments, particularly Navy shipboard environments, have EMR emitters that operate at very high power/energy levels (such as the AEGIS SPY-1 radar). Because COTS equipment is not designed for either of these scenarios, military standards, such as MIL-STD-461 and MIL-STD-464 *or commercial equivalents* must be enforced. In many cases, the COTS equipment must be upgraded to meet these more rigorous military needs.

The next chapter will examine MIL-STD-461 and MIL-STD-462 in an effort to illustrate and establish the demands of the military EMEs.

V. MILITARY EMC GUIDELINES

This chapter examines the regulatory and environmental requirements related to military EMC, EMI, and spectrum certification.

A. DOD SPECTRUM REGULATION

DoD use of the EM spectrum has become a pivotal aspect of warfighting strategies. Few, if any, of the hundreds of advanced military weapon systems operate without some form of spectrum access. Critical though this access may be, DoD has to cooperate in the use of this resource with other Federal Agencies, local Governments and private Industry. To provide adequate oversight for federal spectrum access, the National Telecommunications and Information Administration (NTIA) was established in 1978 as part of an Executive Branch reorganization. It transferred and combined functions of the White House's Office of Telecommunications Policy (OTP) and the Commerce Department's Office of Telecommunications. NTIA performs its spectrum management function through the Office of Spectrum Management (OSM) governed by the NTIA Manual of Regulations and Procedures for Federal Radio Frequency Management. Two committees advise the OSM: the IRAC and the Spectrum Planning and Policy Advisory Committee (SPAC).

All spectrum dependent equipment/systems owned and operated by the DoD require spectrum certification (Figure 11). Equipment spectrum certification is supported by the Military Communications-Electronics Board (MCEB) FP Equipment Spectrum Guidance Permanent Working Group (ESGPWG) and the NTIA Spectrum Planning Subcommittee (SPS) and Frequency Assignment Subcommittee (FAS) [5].

The MCEB coordinates frequency requests from the service branches and guides the coordination of NTIA spectrum allotments and technical directives. The Joint Frequency Panel (JFP) reviews acquisition proposals for frequency use and must provide approval before funds are authorized for the development of new spectrum-dependent equipment and the Frequency Assignment Subcommittee of IRAC must assign an operational frequency prior to actual operation of developmental equipment.

Most DoD applications for frequency assignments are in the VHF, UHF, and SHF frequency bands, but very little spectrum is designated for the exclusive use of the military. In fact, the massive monetary potential of spectrum auctions to the private sector has brought considerable congressional pressure to surrender large portions of what little spectrum is still controlled by the military. This trend is cause for concern since most of the frequencies used by DoD are selected because they work best with the physics of the systems that use them.

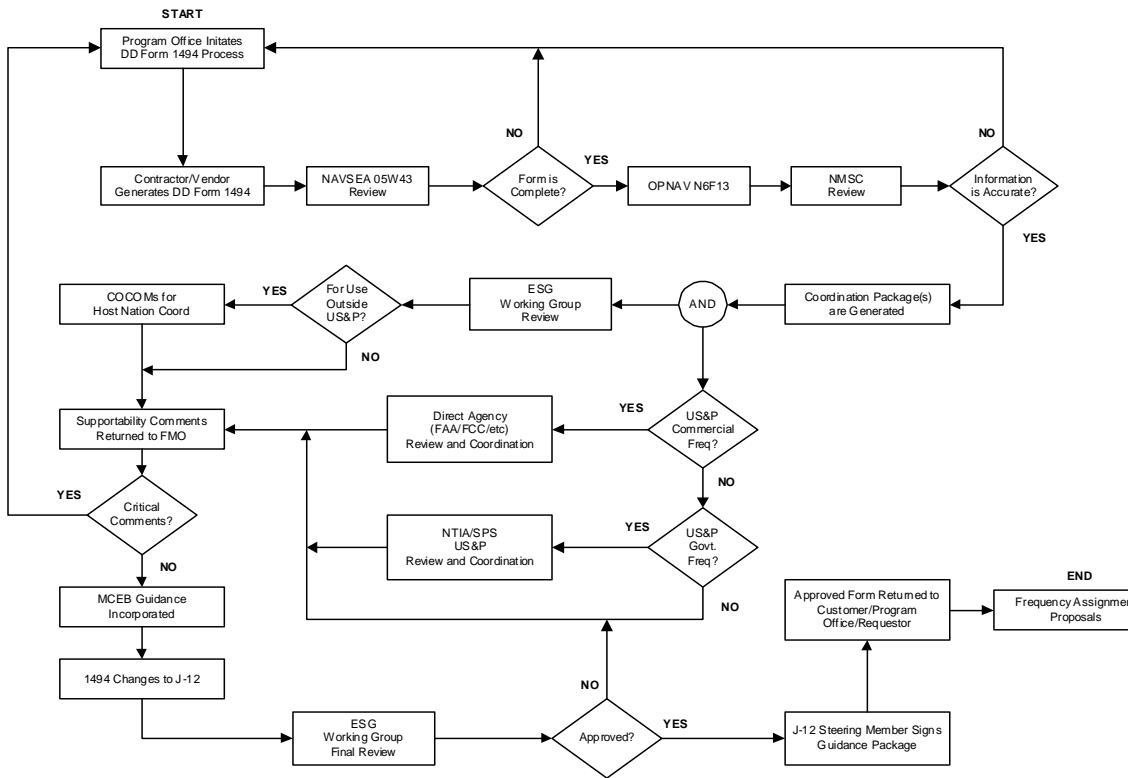


Figure 11. DoD Spectrum Certification Flow Diagram

B. MILITARY EMC REQUIREMENTS

1. Overview

DoD policy requires all electrical and electronic systems, subsystems, and equipment, including ordnance containing Electrically Initiated Devices, to be mutually compatible in their intended EME without causing or suffering unacceptable mission degradation due to Electromagnetic Environmental Effects (E3). Accordingly,

appropriate E3 requirements must be imposed to ensure compatibility with co-located equipment within the applicable external EME and to address hazards of electromagnetic radiation to ordnance (HERO), personnel (HERP), and fuel (HERF). In addition, national, international, and DoD policies and procedures for the management and use of the EM spectrum direct program managers developing spectrum-dependent systems or equipment to consider Spectrum Supportability requirements and E3 control early in the development process and throughout the acquisition life cycle. The two DoD documents used to establish the specific requirements necessary to ensure these levels of compatibility are MIL-STD-461 and MIL-STD-464.

2. MIL-STD-461

In 1966, EMC subject matter experts compiled EMC regulations from roughly 20 existing requirements documents into a single series of specifications that were released in 1967: MIL-STD-461 (EMC requirements), MIL-STD-462 (EMC test set-up and methodology), and MIL-STD-463 (EMC definitions and acronyms). The first revision of MIL-STD-461 (revision A) was issued in 1968. By 1993, MIL-STD-461 and MIL-STD-462 were updated to revision D and MIL-STD-463 was canceled (ANSI C63.14 was used in its place). In 1999, MIL-STD-461 and MIL-STD-462 were combined into a single standard, MIL-STD-461E. The latest revision, MIL-STD-461F was issued in December 2008.

MIL-STD-461F is a system-level test that specifies EMC requirements and limits based on the operational platform for deployment (surfaces ships, aircraft, etc.) and location on that platform (internal or external). The overall requirement is comprised of eighteen sub-tests that cover diverse system characteristics ranging from emissions conducted via power leads to spurious and harmonic radiated emissions. This testing is not inexpensive. The five core tests (RS103, RE102, CS101, CS114 and CS116) will require roughly two days of lab time; the entire standard, seven to ten days. Not all tests are required for every platform. Table V from MIL-STD-461F provides a matrix of the required tests for each of the platform environments—this information is reproduced in Table 3.

Table 3. MIL-STD-461F Platform Requirements [After 22]

Equipment and Subsystems Installed In, On, or Launched From the Following Platforms or Installations	Requirement Applicability																	
	CE101	CE102	CE106	CS101	CS103	CS104	CS105	CS106	CS109	CS114	CS115	CS116	RE101	RE102	RE103	RS101	RS103	RS105
Surface Ships	A	A	L	A	S	S	S	A	L	A	A	A	A	A	L	A	A	L
Submarines	A	A	L	A	S	S	S	A	L	A	A	A	A	A	L	L	A	L
Aircraft, Army	A	A	L	A	S	S	S			A	A	A	A	A	L	A	A	L
Aircraft, Navy	L	A	L	A	S	S	S			A	A	A	L	A	L	L	A	L
Aircraft, Air Force		A	L	A	S	S	S			A	A	A		A	L		A	
Space Systems		A	L	A	S	S	S			A	A	A		A	L		A	
Ground, Army		A	L	A	S	S	S			A	A	A		A	L	L	A	
Ground, Navy		A	L	A	S	S	S			A	A	A		A	L	A	A	L
Ground, Air Force		A	L	A	S	S	S			A	A	A		A	L		A	

The following terms correspond to the entries in Table 3.

A: Applicable

L: Limited

S: Procuring activity must specify in procurement documentation

The following listing explains the tests cited in Table 3.

MIL-STD-461F Subtests:

- CE101 Conducted Emissions, Power Leads, 30 Hz to 10 kHz
- CE102 Conducted Emissions, Power Leads, 10 kHz to 10 MHz

- CE106 Conducted Emissions, Antenna Terminal, 10 kHz to 40 GHz
- CS101 Conducted Susceptibility, Power Leads, 30 Hz to 150 kHz
- CS103 Conducted Susceptibility, Antenna Port, Intermodulation, 15 kHz to 10 GHz
- CS104 Conducted Susceptibility, Antenna Port, Rejection of Undesired Signals, 30 Hz to 20 GHz
- CS105 Conducted Susceptibility, Antenna Port, Cross-Modulation, 30 Hz to 20 GHz
- CS106 Conducted Susceptibility, Transients, Power Leads
- CS109 Conducted Susceptibility, Structure Current, 60 Hz to 100 kHz
- CS114 Conducted Susceptibility, Bulk Cable Injection, 10 kHz to 200 MHz
- CS115 Conducted Susceptibility, Bulk Cable Injection, Impulse Excitation
- CS116 Conducted Susceptibility, Damped Sinusoidal Transients, Cables and Power Leads, 10 kHz to 100 MHz
- RE101 Radiated Emissions, Magnetic Field, 30 Hz to 100 kHz
- RE102 Radiated Emissions, Electric Field, 10 kHz to 18 GHz
- RE103 Radiated Emissions, Antenna Spurious and Harmonic Outputs, 10 kHz to 40 GHz
- RS101 Radiated Susceptibility, Magnetic Field, 30 Hz to 100 kHz
- RS103 Radiated Susceptibility, Electric Field, 2 MHz to 40 GHz
- RS105 Radiated Susceptibility, Transient Electromagnetic Field

With respect to the scope of this paper, the four MIL-STD-461F subtests that are of primary concern are RE101 (Radiated Emissions, Magnetic Field), RE102 (Radiated Emissions, Electric Field), RS101 (Radiated Susceptibility, Magnetic Field), and RS103 (Radiated susceptibility, Electric Field).

RE101: Radiated Emissions, Magnetic Field, 30 Hz to 100 kHz. This requirement is applicable for radiated emissions from equipment and subsystem enclosures, including electrical cable interfaces. The requirement does not apply to radiation from antennas. For Navy aircraft, this requirement is applicable only for aircraft with an ASW capability.

RE102: Radiated Emissions, Electric Field, 10 kHz to 18 GHz. This requirement is applicable for radiated emissions from equipment and subsystem enclosures, all interconnecting cables, and antennas designed to be permanently mounted to EUTs (receivers and transmitters in standby mode). The requirement does not apply at the transmitter fundamental frequencies and the necessary occupied bandwidth of the signal. This requirement is applicable as shown in Table 4.

Table 4. MIL-STD-461F, RE102 Platform Requirements [After 22]

Platform	Frequency
Ground	2 MHz to 18 GHz*
Ships, surface	10 kHz to 18 GHz*
Submarines	10 kHz to 18 GHz*
Aircraft (Army and Navy ASW)	10 kHz to 18 GHz
Aircraft (Air Force and Navy)	2 MHz to 18 GHz*
Space	10 kHz to 18 GHz*

*Testing is required up to 1 GHz or 10 times the highest intentionally generated frequency within the EUT, whichever is greater. Measurements beyond 18 GHz are not required.

RS101: Radiated Susceptibility, Magnetic Field, 30 Hz to 100 kHz. This requirement is applicable to equipment and subsystem enclosures, including electrical cable interfaces. The requirement is not applicable for electromagnetic coupling via antennas. For equipment intended to be installed on Navy aircraft, the requirement is applicable only to aircraft with ASW capability. For Army ground equipment, the requirement is applicable only to vehicles having a minesweeping or mine detection

capability. For submarines, this requirement is applicable only to equipment and subsystems that have an operating frequency of 100 kHz or less and an operating sensitivity of 1 μ V or better (such as 0.5 μ V).

RS103: Radiated susceptibility, Electric Field, 2 MHz to 40 GHz. This requirement is applicable to equipment and subsystem enclosures and all interconnecting cables. The EUT shall not exhibit any malfunction, degradation of performance, or deviation from specified indications, beyond the tolerances indicated in the individual equipment or subsystem specification, when subjected to the radiated electric fields listed in Table 7 and modulated as specified in Table 5. Up to 30 MHz, the requirement shall be met for vertically polarized fields. Above 30 MHz, the requirement shall be met for both horizontally and vertically polarized fields. Circular polarized fields are not acceptable. This requirement is applicable as shown in Table 5 [22].

Table 5. MIL-STD-461F, RS103 Platform Requirements [After 22]

Platform	Frequency
Army ships; Army aircraft, including flight line; Navy (except aircraft); and optional* for all others	2 MHz to 30 MHz
All (except Navy aircraft)	30 MHz to 100 MHz
All	100 MHz to 1 GHz
All	1 GHz to 18 GHz
Optional* for all	18 GHz to 40 GHz

*Required only if specified in the procurement specification There is no requirement at the tuned frequency of antenna-connected receivers, except for surface ships and submarines.

3. MIL-STD-464

Although MIL-STD-461 serves the military needs to ensure component or system level EMC, it is not designed to assess or certify intra-system or inter-system EMC [23]. DoD recognized the need for a standard in order to make these *platform-level* EMC assessments. As a result, a series of requirements were enacted and revised over the years, including MIL-E-6051D, MIL-STD-1818A, and MIL-B-5087B. The current standard, MIL-STD-464, superseded MIL-STD-1385B in 1997, was updated to MIL-STD-464A in 2002 and will be updated to MIL-STD-464B at the end of 2009. Specifically, MIL-STD-464A requirements, verification criteria, and contractor tasks for E³ protection of airborne, ground, and support systems. These effects include EMC and

EMI as well as lightning, static electricity, and electromagnetic pulse effects. The standard is intended for complete systems and platforms, both new and modified and determines their ability to meet operational performance requirements; this includes assessing the test items in the military-specific EME where it will be operated. As shown in Tables 6, 7 and 8, these environments are generally much harsher than either commercial or MIL-STD-461 requirements. Performance to this standard is referred to as electromagnetic vulnerability (EMV).

Table 6. MIL-STD-464A External Shipboard Environments [After 23]

Frequency Range (MHz)	Flight Deck		Weather Deck		Shipboard – Radar Main Beam	
	Electric Field (V/m – rms)		Electric Field (V/m – rms)		Electric Field (V/m – rms)	
	Peak	Average	Peak	Average	Peak	Average
0.01 – 2	45	45	-	-	-	-
2 – 30	100	100	200	200	200	200
30 – 150	61	61	61	61	20	20
150 – 225	61	61	61	61	10	10
225 – 400	61	61	61	61	25	25
400 – 700	151	71	151	71	1940	260
700 – 790	162	95	162	95	15	15
790 – 1000	1125	99	1125	99	2160	410
1000 - 2000	550	112	550	180	2600	460
2000 – 2700	184	158	184	158	6	6
2700 – 3600	2030	184	2030	184	27460	2620
3600 – 4000	290	200	290	200	9710	310
4000 – 5400	290	200	290	200	160	160
5400 – 5900	345	200	345	200	3500	160
5900 – 6000	345	200	345	200	310	310
6000 – 7900	345	200	345	200	390	390
7900 – 8000	345	200	345	200	860	860
8000 – 8400	345	200	345	200	860	860
8400 – 8500	483	200	483	200	390	390
8500 – 11000	510	200	510	200	13380	1760
11000 – 14000	310	200	310	200	2800	390
14000 – 18000	310	200	310	200	2800	310
18000 – 40000	200	200	200	200	7060	140
40000 – 45000	200	200	200	200	570	570

Table 7. Internal Shipboard EMEs [After 23]

Platform	Frequency	Limit
Surface Ships: Metallic	10 kHz – 18 GHz	10 V/m
Surface Ships: Non-metallic	10 kHz – 2 MHz	10 V/m
	2 MHz – 18 GHz	50 V/m
Submarines	10 kHz – 1 GHz	10 V/m

Table 8. External EME for Ground Systems [After 23]

Frequency Range (MHz)	Electric Field (V/m – rms)	
	Peak	Average
0.01 – 2	25	25
2 – 250	50	50
250 – 1000	1500	50
1000 – 10000	2500	50
10000 – 40000	1500	50
40000 - 45000	-	-

The levels cited in MIL-STD-464A are often extremely high; however, they were established on the basis of measured data taken in the respective environments they represent. Building on this understanding of the military regulations and requirements, the next chapter will examine the same aspects of the commercial equipment.

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VI. COMMERCIAL EMC GUIDELINES

This chapter examines the regulatory and environmental requirements related to commercial EMC, EMI, and spectrum certification.

A. COMMERCIAL EMI REGULATION

The growing popularity and diversity of consumer electronics that began in the 1970s compounded the problem of EMI. Previously, the use of vacuum tube technology largely limited EMI to instances of transmission overlap, where one signal would “step on” another. With the advent of modern digital circuitry, faster switching speeds increased emissions while lower circuit voltages increased susceptibility. As a result, equipment became more sensitive to EMR induced current and E3 related upsets. As governments became aware of these growing issues, international organizations were formed development and maintain commercial product standards for EMC [9].

B. EUROPE

The governing bodies in the European Union with respect to EMC include the IEC, CISPR, and the European Committee for Electrotechnical Standardization (CENELEC). The IEC coordinates international standardization and related matters, while CENELEC and CISPR are largely responsible for approving detailed EMC standards to demonstrate compliance with the EMC Directive [5].

Products sold in the European Union must be in compliance with EMC Directive, 89/392/EEC. Article 4 of this document states:

The apparatus...shall be so constructed that (a) the EMC disturbance it generates does not exceed a level allowing radio and telecommunications equipment and other apparatus to operate as intended; (b) the apparatus has an adequate level of intrinsic immunity of EMC disturbance to enable it to operate as intended. [9]

It is the manufacturer’s responsibility to collect and maintain the necessary technical artifacts to support the product “conformity” claim. This supporting evidence is

assembled in a Technical Construction File (TCF). A TCF exists for each product sold in the European Union and results of EMC testing are included in the TCF [9].

IEC has issued four generic standards: IEC 61000-6-1, 2, 3, and 4, which specify emission and immunity requirements for two classes of equipment: “industrial” or “residential, commercial, and light industrial.” Generic standards are also available for products that do not fit in any of the previous categories. The generic standards list the individual test standards (generally, IEC and CISPR documents) that are applicable and the limits that apply [24].

Table 9. IEC Generic Radiated Emissions Requirements (Electric Field).

Standard	Frequency	Environment	Limit	Reference Standard
IEC 61000-6-3	30 – 230 MHz	Residential	30 dB(μ V/m) at 10 m	CISPR 22
	230 – 1,000 MHz		37 dB(μ V/m) at 10 m	
IEC 61000-6-4	30 – 230 MHz	Industrial	30 dB(μ V/m) at 30 m	CISPR 11
	230 – 1,000 MHz		37 dB(μ V/m) at 30 m	

Compliance with provision (a) of the EMC Directive is generally established by meeting an actual set of emissions test requirements. The IEC 61000 test method deemed most useful for evaluating emissions emanating from equipment is IEC 61000-6-4 (industrial emission limits). The standard was prepared by the International Special Committee on Radio Interference (CISPR) and adopted by CENELEC. IEC 61000-6-3 (residential emission limits) and 61000-6-4-4 are generic standards that reference product-family standards like CISPR 11, CISPR-14-1, CISPR 15, and CISPR 22 (Table 9). Compliance with the “intrinsic immunity” requirement of provision (b), however, does not necessarily require test validation. A manufacturer can simply make a case that design and construction of a device makes it robust enough to have intrinsic immunity. Still, immunity testing in to levels representative of real-world environments is the best way to demonstrate compliance. The IEC 61000-4 series of immunity standards consists of 21 generic test methods developed to address upsets and malfunctions in electrical and electronic devices. IEC 61000-4-3 covers test methods for evaluating the immunity of equipment to radiated electric fields in the radio-frequency range (Table 10).

Table 10. IEC Immunity Requirements.

Standard	Parameter	Frequency	Residential Limit	Industrial Limit
IEC 61000-4-3	Electric Field	80 – 1,000 MHz	3 V/m	10 V/m
IEC 61000-4-8	Magnetic Field	50 – 60 Hz	3 A/m	30 A/m
IEC 60945	Electric Field	80 – 2,000 MHz	NA	10 V/m

Products that meet the EMC directive carry the “CE” mark that signifies the manufacturer’s assertion of compliance (Figure 12). The CE marking is an acronym for the French “Conformité Européenne.”



Figure 12. European Union “CE” Compliance Marking

C. UNITED STATES

1. Overview

In the United States, the FCC regulates non-federal government telecommunications, grants authority to use radio frequencies or channels by issuing licenses to private sector entities and local and state governments, and is directly responsible to Congress. The Rules and Regulations that the FCC follows are codified in Title 47 of the Code of Federal Regulations (CFR 47). The FCC imposed legal limits on electromagnetic emissions produced by commercial digital equipment in response to the increased number of systems that were interfering with wired and radio communications. Test methods and limits tied to these requirements were based on CISPR publications.

FCC requirements pertaining to unlicensed intentional, unintentional, and incidental radiation devices are contained in CFR 47, Part 15. There are two sets of limits, one for residential areas and a second for industrial areas. Two other parts of CFR 47 also address license-free RF generators: Part 18 for so-called Industrial, Scientific, and Medical (ISM) devices, and Part 95 for Personal Radio Services.

2. CFR 47, Part 15

In 1975, the FCC established CFR 47, Part 15, to regulate design parameters of unlicensed RF emitters to ensure they do not interfere with radio and TV broadcasts, aircraft navigation and other sensitive radio services. Unlicensed emitters fall into two categories: 1) equipment that does not deliberately generate RF energy and 2) low-power radio transmitters that do not require individual licensing. Part 15 is applicable to a wide variety of consumer devices including TV sets and radios, personal computers, remote controls, commercial networking systems, cable TV boxes, and electronic toys [25]. Personal communication services (PCS) is the name for the 1900 MHz radio band used for digital mobile phone services. PCS devices are covered under Part 15 as well. Three types of PCS services have been established in the FCC rules: narrow-band, licensed operation at 930–941 MHz, broadband, licensed operation at 1850–1910 and 1930–1975 MHz, and broadband or narrow-band unlicensed operation at 1910–1930 and 2390–2400 MHz.

Products intended for use in the U.S. Industrial, Scientific and Medical fields are classified as Class “A” devices and may not be used in residential environments. Devices intended for residential environments are classified as Class “B” devices (Table 11). The requirements for Class B devices are more stringent, the rationale being that home users are likely to be annoyed by interference to TV and radio reception. Class B devices can require either Verification, Certification, or Self Declaration, depending on the type of product. Class A is a looser standard for equipment intended only for business, industrial and commercial settings. Products that fall under the category of Class A are not required to officially submit EMC test data; however, these tests still have to be performed and the data must be kept on hand by the manufacturer. Note in Table 6 that emissions measurements for Class “A” devices are made at a distance of 10 meters, while the Class “B” measurements are made at 3 meters (making the Class “B” requirement more restrictive). Also note that there is no upper frequency limit given above 960 MHz. This upper frequency limit is based on the operational frequency of the device itself. For

example, if the intentional radiator operates below 10 GHz, the required upper measurement limit is either the tenth harmonic of the highest fundamental frequency or to 40 GHz, whichever is lower [26].

Table 11. CFR Part 15 Emission Limits.

Frequency	Class A Device at 10 m	Class B Device at 3 m
30 – 88 MHz	90 $\mu\text{V/m}$	100 $\mu\text{V/m}$
88 – 216 MHz	150 $\mu\text{V/m}$	150 $\mu\text{V/m}$
216 – 960 MHz	210 $\mu\text{V/m}$	200 $\mu\text{V/m}$
Above 960 MHz	300 $\mu\text{V/m}$	500 $\mu\text{V/m}$

The issue of susceptibility of equipment is addressed in Section 15.17, where parties responsible for equipment compliance are advised to *consider* existing sources of high RF energy and to design their equipment in such a way as to increase its immunity to that energy. The responsible party or manufacturer is not required to ensure a specific level of electromagnetic immunity for the equipment. In 1982, Public Law 97-259 was enacted, which gave the FCC the authority to regulate the susceptibility of consumer electronic equipment; however, the FCC allowed manufacturers to develop and implement their own voluntary EMC compliance programs [27].

3. CFR 47, Part 18

CFR 47, Part 18, is applicable to industrial, scientific, and medical (ISM) equipment that intentionally uses RF energy in its basic operation. The ISM band also is widely used for Radio-frequency identification (RFID) applications, with the most commonly used band being the 13.56 MHz band. Requirements for Part 18 are limited to radiated emission controls which are dependent on the characteristics of the RF source. The ISM radio bands were originally reserved for purposes other than communications. In recent years, these bands are being shared with unlicensed communications applications such as wireless LANs and cordless phones in the 915 MHz, 2450 MHz, and 5800 MHz bands. These communications applications are secondary, must not interfere with ISM equipment, and must also accept any interference generated by ISM equipment [28].

4. CFR 47, Part 95

CFR 47, Part 95, is applicable to Personal Radio Services (PRS) that include 218-219 MHz subscription services, Citizens Band CB radio service for personal and business activities, Family Radio Service (FRS), General Mobile Radio Service (GMRS), Low Power Radio Service (LPRS), Medical Implant Communications Service (MICS), Radio Control Radio Service R/C, and Wireless Medical Telemetry Service (WMTS) [29].

5. ANSI C63.12

Although not required by the FCC, American National Standard Institute (ANSI) maintains ANSI C63.12, which contains recommendations and guidance for evaluating both emissions (residential, industrial) and immunity (residential, industrial, severe environments) (Tables 12 & 13) [30].

Table 12. ANSI C63.12 Emission Limits.

Environment	Frequency	Limits	Test Method
Residential	30 – 230 MHz	30 dB(μ V/m) at 10 m	ANSI C63.4
	230 – 1,000 MHz	37 dB(μ V/m) at 10 m	
Commercial/Industrial	30 – 230 MHz	40 dB(μ V/m) at 10 m	
	230 – 1,000 MHz	47 dB(μ V/m) at 10 m	

Table 13. ANSI C63.12 Immunity Limits.

Parameter	Frequency	Residential Limit	Industrial Limit	Severe Limit	Test Method
Magnetic Field	57 – 63 Hz	3 A/m	30 A/m	-	IEC 61000-4-8
Electric Field	26* – 2,5000 MHz	3 V/m	10 V/m	200 V/m*	IEC 61000-4-3

* Lower limit can start at either 26MHz or 80 Mz

ANSI C63.12 is atypical of the commercial standards due its inclusion of a severe limit, making this makes particular standard more flexible and potentially more useful with respect to assessing performance in a military environment. The next chapter further examines this type of correlation between MIL-STD-461F and the various commercial requirements with respect to radiated emissions and radiated immunity characteristics.

VII. ALIGNMENT OF EMC REQUIREMENTS

This chapter compares and contrasts MIL-STD-461F with the U.S. and European commercial standards. These commercial standards are then evaluated with respect to the spectrum requirements of the commercial equipment surveyed in earlier chapters.

A. COMPARISON OF MILITARY AND COMMERCIAL STANDARDS

1. Overview

Military and commercial EMC requirements ultimately have the same two goals: 1) to not interfere with other equipment and 2) to work properly in the expected environment. The fact that the end goals are the same might suggest that these two sets of standards would already be in pretty close harmony. As the following comparisons will demonstrate, there is some potential for substituting commercial radiated emission test results for MIL-STD-461F RE101 and RE102. The issues related to utilizing commercial results for RS103, however, are much more difficult to overcome. Perhaps the greatest obstacle that the commercial radiated susceptibility test data might not even exist. As shown in the preceding chapter, neither U.S. nor European commercial EMC standards actually require immunity testing. However, some of the commercial standards that provide *recommendations* for immunity requirements can still be evaluated with respect to RS101 and RS103.

Two separate efforts to compare the alignment of military and commercial EMC standards have already been conducted. The first study was completed by DoD/Industry Electromagnetic Environmental Effects Standards Committee, chaired by DISA/Joint Spectrum Center and American Standards Committee C63 on EMC, in 2001. The second study was performed by Oak Ridge National Laboratory in 2003. The following overview focuses primarily on comparisons of frequencies and limits between MIL-STD-461F and commercial IEC, CSPR, and ANSI standards. Another consideration that is not examined in the context of this paper is the impact of differing methodologies [31], [32].

The previous studies do address this aspect and provide additional in-depth detail to the topics addressed in the following sections. Both studies are recommended for further reading on this subject.

2. RE101: Radiated Emissions–Magnetic Field

The magnetic field emission limit is due to the potential close proximity of electronic systems installed on military platforms and/or EMI with low frequency sensors and receivers. There is no IEC 61000 test comparable to the RE101 test, due to the fact that commercial equipment is not typically installed in close proximity. Although there is a related test in CISPR 15, the data does not provide the point of maximum emissions or emission levels in close proximity to the EUT. IEEE 1140 contains a procedure only (Table 14).

Table 14. Radiated Emissions–Magnetic Field Comparison.

Test Parameter	RE101	CISPR 15	IEEE 1140
Frequency Range	30 Hz - 100 kHz	9 kHz - 30 MHz	5 Hz – 400 kHz
Limits	Differences in submarine and army limits	Results not translatable to RE101	No limits in standard.

3. RE102: Radiated Emissions–Electric Field

The electric field emission limit is intended to protect sensitive equipment from coupled EMI. RE102 requires an upper limit of 1 GHz or 10 times the highest intentionally generated frequency within the EUT, whichever is greater. CISPR 22 does not extend above 1GHz. IEC 61000-6-4 is the more stringent Industrial requirement for radiated emissions and follows the measurement practices described in CISPR 22. The Class B limits of FCC Part 15 provide radiated coverage from 30 MHz to 1 GHz and align with the limits of RE102 in that frequency range, but there is no requirement for frequencies greater than 1 GHz (Table 15).

Table 15. Radiated Emissions–Electric Field Comparison.

Test Parameter	RE 102	CISPR 11	CISPR 22	ANSI C63.4
Frequency Range	10 kHz – 18 GHz	150 kHz - 1 GHz & 11.7 - 12.7 GHz	30 MHz - 1 GHz	30 MHz - 1 GHz
Limits	severe at low frequencies external to vehicles	except for group 2, class A, no limits below 1 MHz	no limits below 30 MHz	CISPR (FCC) limits apply

4. RS101: Radiated Susceptibility–Magnetic Field

The magnetic field susceptibility limit is intended to ensure performance of equipment is not degraded by low-frequency magnetic fields. Since the strength of magnetic fields fall drastically over the space of a few inches, this aspect is only a key factor where the magnetic source is in extremely close or extremely powerful, such as the Electromagnetic Aircraft Launch System (EMALS). The RS101 commercial counterparts are IEC 61000-4-8 (normal magnetic fields), IEC 61000-4-9 (magnetic pulses), and IEC 61000-4-10 (damped oscillatory magnetic disturbances). Although the frequency range of the IEC 61000-4 series is not as broad, the technical parameters of the three documents in combination, are complementary to RS101 (Table 16).

Table 16. Radiated Susceptibility–Magnetic Field Comparison.

Test Parameter	RS101	IEC 61000-4-8, 9, 10
Frequency Range	30 Hz - 100 kHz	50 or 60 Hz
Limits	Navy & army limits differ	100 A/M

5. RS103: Radiated Susceptibility–Electric Field

The electric field susceptibility limit is intended to ensure that equipment will operate without degradation in the presence of electromagnetic fields generated by emitters in the represented environments. The commercial counterpart is IEC 61000-4-3,

which relates to the requirements for immunity of electrical and electronic equipment to radiated electromagnetic energy. RS103 covers the frequency from 2 MHz to 40 GHz. While IEC 61000-4-3 may cover from 26 MHz to a maximum of 1000 MHz, it is normally applied only above 80 MHz. In addition to this discrepancy in frequencies, the limits are compatible in only a select few military environments. IEC 61000-4-3 provides both a Residential (3 V/m) and an Industrial limit (10 V/m). RS103 applies to a number of platforms and environment. The most benign of these environments would be aligned with the IEC 61000-4-3 Industrial limit; however, the IEC standard would not be suitable for the more stringent military environments that have a RS103 requirement of 200 V/m (Table 17).

Table 17. Radiated Susceptibility–Electric Field Comparison.

Test Parameter	RS103	IEC 61000-4-3	ANSI C63.12 (Severe Environment)
Frequency Range	2 MHz - 40 GHz	80 MHz - 1 GHz	26 MHz – 2.5 GHz
Limits	5 – 200 V/m	1 – 10 V/m	200 V/m

6. Summary

While IEC and MIL-STD-461 are not totally compatible, NAVSEA has been invoking IEC standards since about 1995 on non-combat systems items. A very minimal amount of EMI problems have occurred with COTS below deck. However, there are many EMI susceptibility problems reported with COTS above deck. This observation is consistent with the fact that commercial standards cite a 10 V/m worst-case environment. As indicated by the requirements contained in MIL-STD-464A, the shipboard above deck EME is much higher than this. In fact, even satisfying MIL-STD-461F requirements is not sufficient to ensure proper functionality in the worst-case military environments; that is why MIL-STD-464 was established in the first place. Although it might be possible in some cases to utilize IEC testing in lieu of RE 101, RS 101, and perhaps even RE 102, there is no way to accept commercial results in place of RS 103 for the vast majority of situations. It might be possible to utilize this equipment in an enclosed metal space as the

below deck success rate suggests, but even then, hand-held radios and other emitters are likely to cause intermittent EMI when used in close proximity to COTS equipment.

B. COMPARISON OF COMMERCIAL STANDARDS AND USAGE

The issue of commercial standards, such as IEC 61000-4-3 or ANSI C63.12, falling short with respect to military requirements raises the further question of how well these commercial standards meet the present needs of commercial users.

Table 18. Radiated Susceptibility–Electric Field Comparison.

Technology	Timeframe	Frequency
AM Radio	1930	27 – 65 MHz
TV Band I (Channels 2 – 6)	1950	40 – 48 MHz
FM Radio Band II	1950	88 – 108 MHz
TV Band III (Channels 7 – 13)	1950	174 – 216 MHz
TV Bands IV&V (Channels 14 – 69)	1950	470 – 806 MHz
CB Radio	1970	27 MHz
Garage Door Opener Remote	1970	300 – 400 MHz
Microwave Oven	1970	2,450 MHz
Personal Computer	1970	1 MHz
Cordless Telephone	1980	1.7 MHz, 43 MHz
Personal Computer	1980	10 MHz
Cordless Telephone	1990	900 MHz
Cell Phone	1990	824 – 894 MHz & 1850 – 1990 MHz
DARS	1990	2,300 MHz
Iridium	1990	1616 MHz
Satellite Television	1990	4,000 – 8,000 MHz
Satellite Radio	1990	2,300 MHz
Personal Computer	1990	400 MHz
Cordless Telephone	2000	1,900 MHz, 2,400 MHz, 5,800 MHz
Satellite Television	2000	12,000 – 18,000 MHz
Personal Computer	2000	3,000 MHz
802.11	2000	2,400 MHz, 5,000 MHz
802.16	2000	2,3000 MHz, 2,5000 MHz, 3,500 MHz, 5,800 MHz
802.20	2000	1,600 – 2,300 MHz
802.22	2000	54 – 862 MHz
Bluetooth	2000	2,400 MHz
WUSB	2000	3,100 – 10,000 MHz

Given the earlier observations concerning the extremely short fall-off distance that is characteristic of magnetic fields, it is safe to assume that the commercial requirements pertaining to this characteristic are indeed sufficient. The emission and immunity characteristics associated with electric fields, however, are another matter.

Upon review, the IEC and ANSI standards for radiated electric field emissions and immunity only require testing up to 1 GHz. These standards do acknowledge a need to extend that range to 2 GHz, and ANSI C63.12 actually does extend its test requirement up to 2.5 GHz. However, a review of even the short list of commercial technologies covered in this paper (Table 18) will demonstrate that even at their time of publication, these standards were not sufficient. Furthermore, when these data are plotted by frequency use over the decades of their development, it becomes obvious that commercial technology is on a rising exponential with regards to higher frequency levels (Figure 13).

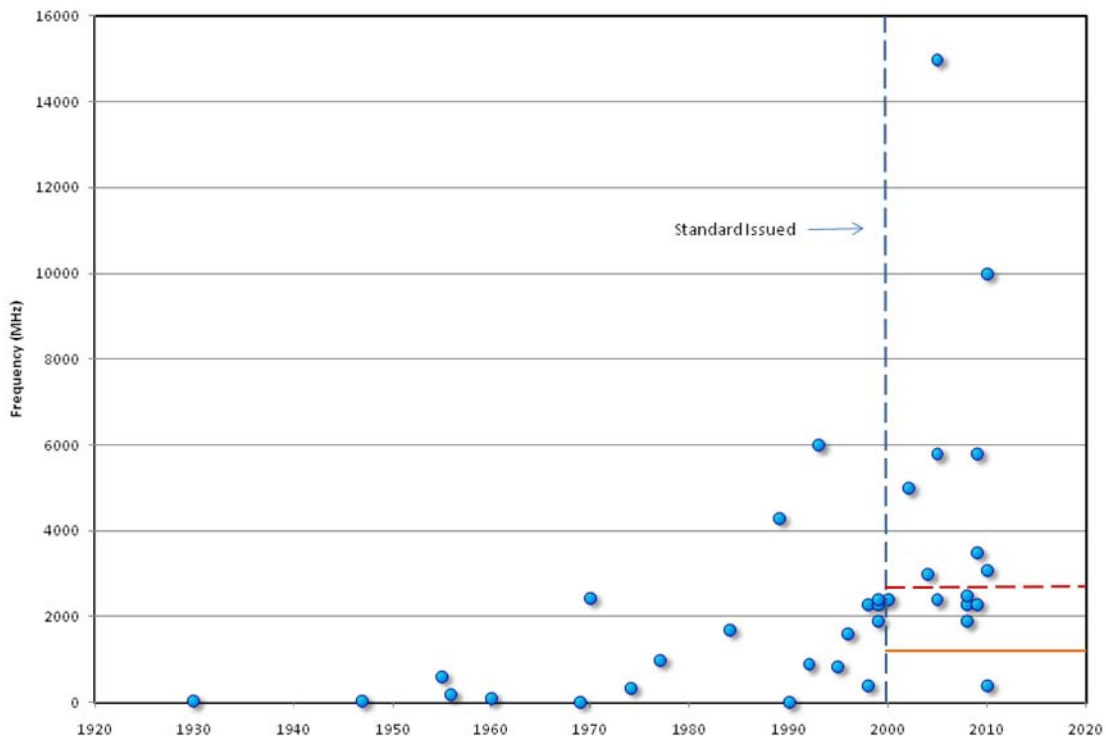


Figure 13. Plot of Commercial Frequency Use Over Time

As indicated by both WiMAX and WUSB technologies, commercial use of the spectrum is steadily moving up into the 5–10 GHz range. Requirements in the existing IEC and ANSI standards must be updated to reflect this growth. There is also the issue of a lack of structured commercial validation for immunity. Immunity is expected, but up

until now, has been assumed to be present as a result of design considerations; actual *test* validation has not been a requirement. Given the competitive demand for spectrum, this approach is reaching a breakdown point.

C. COMPETING FOR RESOURCES

The ever-increasing use of mobile communications, broadcast media, and wireless access has put huge pressure on the available spectrum. Regulatory authorities are placing band allocations closer and closer together (Figure 14). These tighter allocations increase the possibility of interference due to low power harmonic side band transmissions. The fact that electronics are being designed to operate on lower and lower voltages as a means of conserving battery power and reducing heat is also significant. Circuits are now designed to operate on much lower currents and are, therefore, much more susceptible to upset by the induced currents resulting from E3. The likelihood of these effects being present is actually increased by the number of emitters that are present.

UNITED STATES FREQUENCY ALLOCATIONS

THE RADIO SPECTRUM

Radio Services Color Legend:

Blue	Government	Yellow	Mobile
Green	Land Mobile	Orange	Fixed
Red	Maritime	Purple	Space
Pink	Amateur	Light Blue	Other

Activity Code Legend:

Red	Primary	Black	Secondary
Green	Shared		

Allocation Class Designation:

US: United States
 F: Fixed
 M: Mobile
 A: Amateur
 S: Space
 G: Government
 L: Land Mobile
 M: Maritime
 O: Other

US Department of Commerce
 National Telecommunications and Information Administration

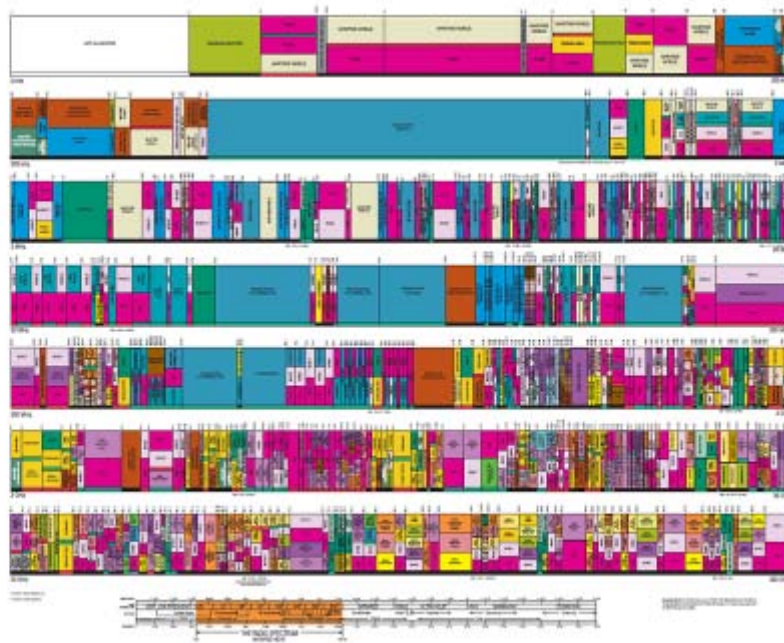


Figure 14. U.S. RF Frequency Allocations.

VIII. CONCLUSIONS

A. SUMMARY

After charting the development of RF devices over the past 100 years, it becomes obvious that both DoD and commercial industry are on the rising edge of an exponential curve for spectrum use. Unfortunately, spectrum is a limited resource. As designers and manufactures develop new methods for squeezing every last bit of use out of the available spectrum, new technologies are actually going to increase the likelihood of EMI unless new approaches to EMC are adopted.

Because this technology is on the rise, it is critical that all EMC standards are updated in a timely manner. According to Moore's law, there is an 18-month turnover for new technology, and we are definitely seeing five-year obsolescence. EMC standards will need to be updated every five years if they are to keep pace with the technologies they are supposed to regulate. When these standards are updated, it is crucial that their requirements take into account the foreseeable needs of the future. This is the only way that they can remain relevant for the span of their use.

With respect to the military's technological needs, there is no way that the military can avoid using COTS equipment—or at least commercial technologies. With an estimated eight-year timeframe for the development and deployment of new equipment, DoD must be able to leverage products that are already available to consumers. Unfortunately, one of the realities of this situation is that this equipment must be tested for EMC. As shown in this report, current emission standards cover only up to 2.5 GHz at best, and there are NO requirements for commercial susceptibility testing. In commercial manufacturing, where pennies saved add up to millions of dollars, the very corners that are cut also reduce the overall robustness of the product with respect to EMI. To introduce these devices into a military EME that is often magnitudes harsher than the environment these devices were minimally designed for, and expect them to perform a mission-critical task, is just an invitation for disaster.

Commercial needs, however, are actually converging with military needs. Although new technologies, such as cognitive radios and DSA, might ultimately ease many of the issues related to spectrum management, these approaches do not address issues related to E^3 . In order to maximize battery power and frequency usage, the operational voltages of commercial devices is getting lower and lower, making them more susceptible to E^3 induced current. At the same time, we no longer live in the benign EM environment of the 1950s, 1980s, or even 2001 (when most of the current EMC standards were published). The ambient EME is an additive effect that increases along with the number of devices that create it. Given the exponential increase in emitting devices, combined with the fact that these same devices are more likely to be susceptible, we are reaching a point at which E^3 effects are going to be a greater problem at the consumer level. Commercial manufacturers will also have to take new measures to ensure proper functionality of their products. These measures need to include better design with respect to preventing EMI and increased frequency requirements for emission testing along with mandatory susceptibility testing.

B. KEY POINTS AND RECOMMENDATIONS

1. Military and commercial EMC standards need to be updated every five years to keep pace with technology
2. DoD must test or require system integrators to test major systems that use COTS to ensure EMC in the expected EME.
 - a. Perform radiated susceptibility testing on COTS equipment, particularly if it is being used in a critical function
 - b. Perform additional radiated emissions testing between 1–18 GHz on COTS items placed in critical areas
3. Military Program Offices need to incorporate item 2 into their budgets and schedules
4. Standardize the selection and decision making process for military use of COTS equipment

- a. Military should create “use cases” that will allow for blanket use of business class equipment
5. Commercial standards need to further categorize equipment and incorporate immunity requirements based on these classifications
 - a. Immunity should be required for business and/or critical systems
 - b. Immunity should be required for devices that are more likely to be operated in a higher EME
 - c. Immunity should not be required for nonessential devices such as toys
6. Commercial standards need to extend frequency ranges for testing of radiated emissions, electric field
 - a. Threshold: 150 KHz – 6 GHz
 - b. Objective: 10 kHz – 10 GHz
7. Commercial standards need to extend frequency ranges for test of radiated susceptibility, electric field
 - a. Threshold: 2 MHz–6 GHz
 - b. Objective: 2 MHz–10 GHz

C. AREAS FOR FUTURE EFFORT

My intention was to provide recommended commercial limits for radiated susceptibility; however, it is necessary to first perform an updated assessment of the present ambient EME. Figure 15 is a graphical representation of this data taken from ANSI C63.12. This plot illustrates the various EMEs levels expected in a variety of environments circa 1999. A similar study should be conducted to determine equivalent levels in 2010.

Based on the results of this study, a determination for a recommended commercial immunity level should be derived. These requirements for immunity should then be

codified by IEEE and/or IEC. These levels should be developed so that they are in harmony with at least the most benign military levels, such as the 10 V/m limit for interior spaces and the 50 V/m limit for ground forces.

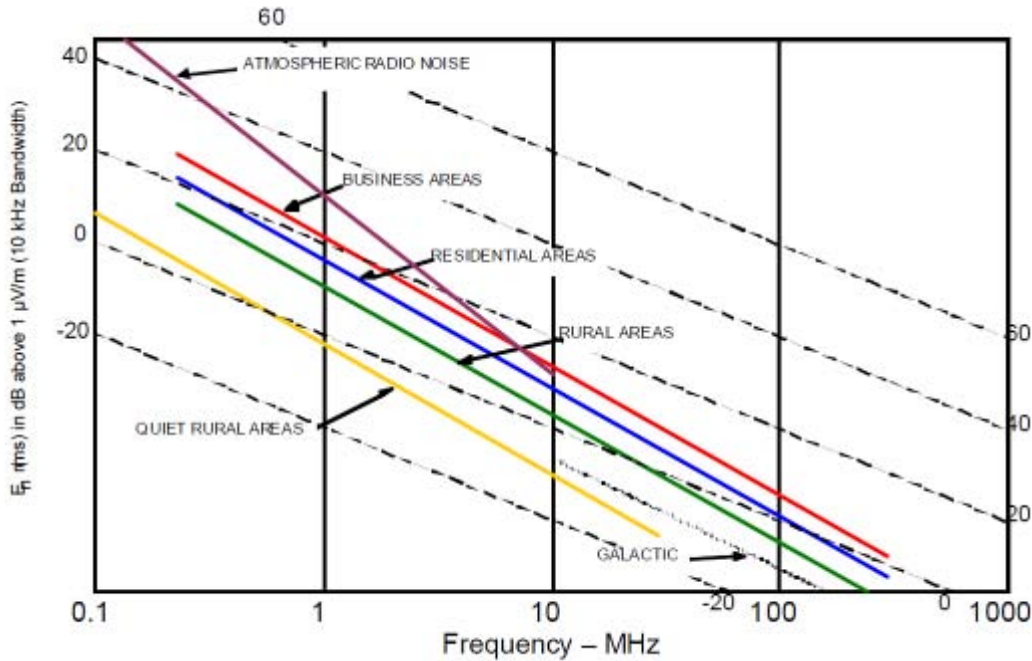


Figure 15. 1999 Ambient EME Levels [From 29]

D. FINAL THOUGHTS

The motivation behind the development of military and commercial requirements is similar; however, the high concentration of electronic equipment typical of military installations will always result in a more severe environment than the residential equivalent. In spite of this fact, commercial equipment can and should be designed and tested to ensure proper operation in the increasingly severe commercial environment. By adopting this more rigorous approach to certification, manufacturers will not only guarantee that their products will continue to function in the changing residential environments, but also provide the data needed to evaluate the potential for use in some of the less severe military environments and/or indicate the extent of modifications that would be necessary in order to function in the more rigorous military EMEs.

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