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THE MITIGATION OF RADIO NOISE AND INTERFERENCE FROM ON-SITE SOURCES at RADIO RECEIVING SITES

November 2009

by

Wilbur R. Vincent
George F. Munsch
Richard W. Adler
Andrew A. Parker

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Naval Postgraduate School
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ABSTRACT *(maximum 200 words)*

Radio noise and interference from sources within the confines of radio-receiving sites is described and effective mitigation techniques are presented along with ineffective techniques. Of special concern is that many signals and most cases of noise and interference were non-stationary and could not be described with conventional stationary statistical techniques. Instrumentation used to cope with the intermittent and the time-varying properties of signals, noise, and interference is described.

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PREFACE

This document has been prepared for the designers, operators, and maintenance personnel of radio-receiving sites. Much of the information in this document also applies to data-processing facilities. The content is based on knowledge gained from extensive investigations of signal-reception issues conducted at more than 40 radio-receiving facilities as well as electromagnetic interference problems at a number of data-processing facilities. Much of the field work was conducted under the Signal-to-Noise Enhancement Program (SNEP) of the U.S. Naval Security Group (now disestablished). The SNEP program was about three decades in duration, a sufficient time to investigate signal-reception and signal-processing issues in depth.

This document was prepared because of the widespread lack of valid technical information about site performance at all levels of receiving-site operation. For example, the information about ógrounds and groundingô available to site personnel was especially confusing and often downright incorrect.

Complex analytical procedures have been avoided to make the text as readable as possible, but it is assumed the serious reader will have a good knowledge of the physical laws related to basic electricity. This includes an understanding of the flow of electricity in complex circuits, some understanding of the impact of reactive impedance on the flow of electricity, a basic knowledge of the properties of electric and magnetic fields surrounding conductors carrying electric current at both low and high frequencies, and the inductive and capacitive coupling of current and voltage from one conductor to another.

The basic principles of noise and interference mitigation techniques are also included. The integrated use of electromagnetic barriers, filters and grounds to confine electromagnetic noise to its source device is described. This is an effective technique to mitigate identified sources. Practical mitigation examples are described as well as ineffective solutions.

This is the first issue of this handbook. Time and funds for its preparation have been minimal thus some aspects have not been included. Additional editions will be required to keep it up to date and add additional pertinent material.

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1. INTRODUCTION

This handbook provides information about sources of radio noise and interference at radio-receiving sites where sources are located within the boundaries of a site. This includes sources that are within the main building, auxiliary buildings and other facilities associated with a radio-receiving site. Mitigation principles and techniques are included. A companion handbook[1] provides information about off-site sources of radio noise and interference and mitigation techniques for them.

The objectives of this handbook are simple. It is the provision of the information needed to design, construct, and operate a modern radio-receiving site that is free of harmful sources of on-site radio noise and interference, thus permitting a radio-receiving site to detect and process low-level radio signals.

In recent years on-site sources have become more pervasive due to the widespread use of power-conversion devices based on switching techniques. These devices convert electrical power from one form to another (e.g. direct current to alternating current, alternating current into direct current, a supply voltage to other desired voltages, the production of variable-frequency electric power, etc.) The widespread introduction of digital data-processing devices into radio-receiving sites has also resulted in many cases of increased noise levels at the input terminals of radio receivers. It is recognized that power-conversion and data-processing devices have added significant capabilities to radio-receiving sites, thus it is not the intent of this handbook to eliminate their use. It is the intent to provide the information needed to successfully employ such devices in and around a radio-receiving facility without degrading the ability of a site to receive low-level signals.

Extensive illustrations and examples of data are provided, along with photographs, to support the information and procedures contained in the handbook. Time-history views provide a means to examine the details of impulsive and time-changing noise, interference and signals. Broadband current probes are used to measure the properties of EMI current flowing on a variety of conductors in a site where the EMI (Electromagnetic Interference) current can consist of one or more discrete-frequency components, broadband noise and interference or commonly mixtures of both. The instrumentation used to provide examples of data for this document is described in Appendix A.

One additional complication is encountered while investigating signal-reception issues at radio receiving sites. Many signals are intermittent and occur at unknown times, at unknown frequencies, with unknown spectral and temporal properties and for unknown durations. Noise and interference is usually from multiple sources where each source produces noise and interference that is erratic in occurrence, erratic in temporal and spectral content and of erratic duration. In many cases the signals, noise and

[1] Wilbur R. Vincent, George F. Munsch, Richard W. Adler and Andrew A. Parker, ***The Mitigation of Radio Noise from External Sources at Radio Receiving Sites***, 6th edition. Report No. NPS-EC-07-002, Signal Enhancement Laboratory, Department of Electrical and Computer Engineering, Naval Postgraduate School, Monterey CA

interference fit non-stationary statistical rules rather than the conventional stationary statistical rules. Thus, simplistic measures of signals, noise and interference such as average, root-mean-square, peak, quasi-peak, amplitude probability distributions, etc. are not sufficient to even crudely describe many actual cases. To avoid the complexities of non-stationary statistical descriptions of signals, noise and interference in this document, graphical time-history views of signals, noise, and interference are provided. These views are calibrated in frequency, amplitude, and time duration as well as containing such information as date, time of day and location. Many of the views illustrate the difficulty of describing the properties of signals, noise and interference in simple terms.

The reader will find that some of the information in this handbook is considerably different from that in other sources, and in some cases it conflicts with the information from other sources. In such cases it is hoped the reader will rely on basic electrical theory to evaluate such differences and conflicts.

2. THE ON-SITE RADIO-NOISE PROBLEM

On-site sources of radio noise that adversely affect the reception of desired radio signals are a major problem, preventing the reception of low-level signals at many HF through UHF receiving sites. Figure 1 illustrates the general nature of the problem where the building housing the receiving equipment is shown as a rectangle outlined in black and with light yellow fill. A typical signal path from an antenna to a radio receiver is shown in blue. Noise sources are shown in red ovals, and typical entry paths from sources into the RF path are shown as red dotted lines.

Many sites have outlying facilities which also contain sources of noise. These are shown by the red oval titled ñNearby Sources,ò and noise from such sources can be received by the siteõs antenna and be passed along to the input terminals of a receiver. Other sources can be inside the receiver building where it can leak into the RF paths by a variety of mechanisms. Still other sources of radio noise can be generated by filters, switches, amplifiers, and other components within the RF distribution system which are saturated thus generating intermodulation products and intermodulation noise.

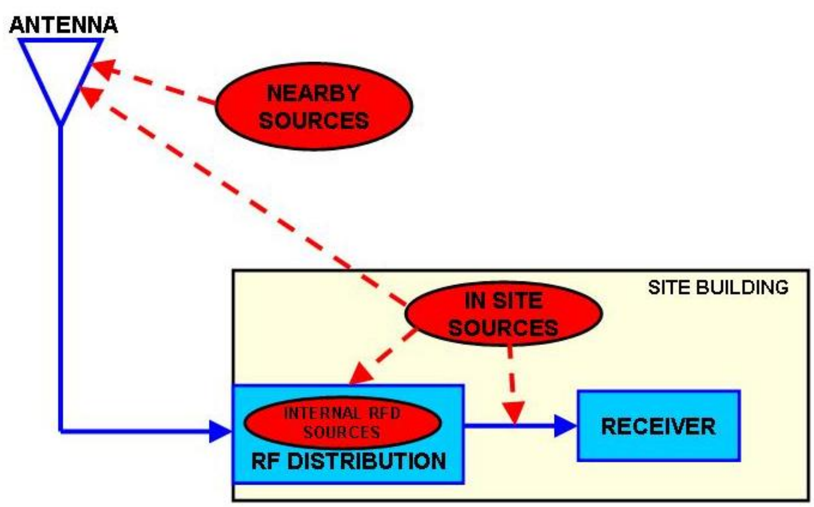

Figure 1 Block Diagram of On-Site Sources

Each item in the block diagram of Figure 1 will be dealt with in subsequent parts of this document. Emphasis is given to identifying sources, understanding the paths radio noise takes from its source to the input terminals of a receiver, and the application of effective mitigation actions. Numerous examples will be provided to support the implications presented in the block diagram.

Of special interest is that all of the sources and the associated paths radio noise takes to appear at the input terminals of a radio receiver are completely within the control of site planners, site managers, and site operators. Eliminate the sources and/or the paths of entry of the noise into the RFD, and radio noise and interference problems will disappear.

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3. RECEIVED SIGNALS

3.1 Signal Dynamic Range

Some information about the nature of ambient signals delivered by an antenna to the RF-distribution system of a site and its receivers is necessary to fully understand the adverse impact of radio noise and interference on the reception of signals. Thus a brief description of some aspects of received signals is provided for background information.

Figure 2 shows the amplitude of signals received at an HF site from a vertical monopole antenna over the frequency range of 7.7 to 17.7 MHz. The signals in this example were received at 1600 hours local time, a time-of-day of minimum signal amplitudes. Signals above and below the frequency range were very low in amplitude due to radio-propagation limitations and were excluded from the data. The clusters of high-level signals originate from transmitters in the International Broadcast Service. The common wavelength identifiers of each international broadcast band are shown above each cluster. Signals in between the clusters of high-level signals are from other radio services and are normally the signals of highest interest to a receiving site.

At nighttime when ionospheric absorption is low, HF signals will be 30- to 50-dB higher in amplitude than shown in Figure 2.

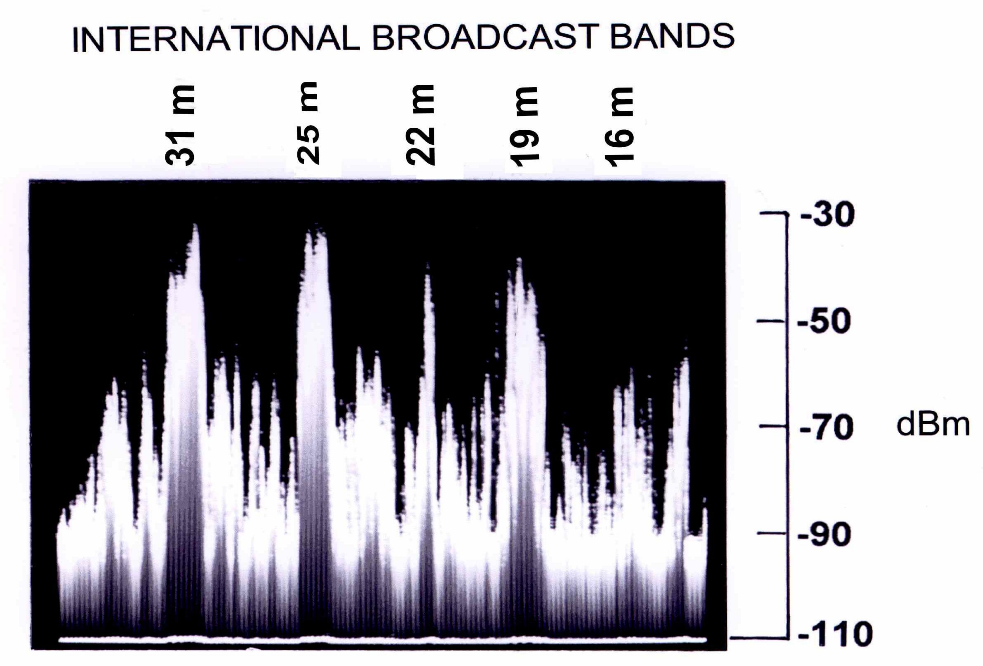

Figure 2 Example of Daytime Signal Levels in the HF Band

Similar signals levels can be found at other HF receiving-sites since the distribution of transmitting sources is widely spread around the earth. Only minor site-to-site variations have been noted during measurements at more than 40 radio-receiving sites.[2]

The total ambient signal power at the output terminals of an HF antenna was measured at 2-hour intervals over four days at a European site, and Figure 3 shows the result where a band-pass filter was used to exclude out-of-band signals. This example shows the broadband signal power within the 2- to 30-MHz frequency range that was delivered to the siteỗs RF-distribution system and on to the input terminals of the siteỗs radio receivers. All broadband devices in the siteỗs RF-distribution system and the receivers must have sufficient dynamic range to handle the total signal power while still receiving low-level signals.

Most HF and VHF/UHF receivers are capable of detecting a signal as low as -130 dBm in a 3-kHz bandwidth. This indicates that a broadband dynamic range of about 100 dB is required for all components in the RF distribution path during the daytime and up to about 140 dB at the nighttime hours. Any linear component in the RF-distribution system and in the broadband portion of a receiver that does not have this dynamic range will saturate and cause excessive intermodulation products and intermodulation noise which will appear at the input terminals of the receiver. Since the needed dynamic range is extremely difficult to achieve in standard broadband amplifiers and in receivers, automatic gain control is often used to limit the operating range of amplifiers and receivers at the expense of losing low-level signals.

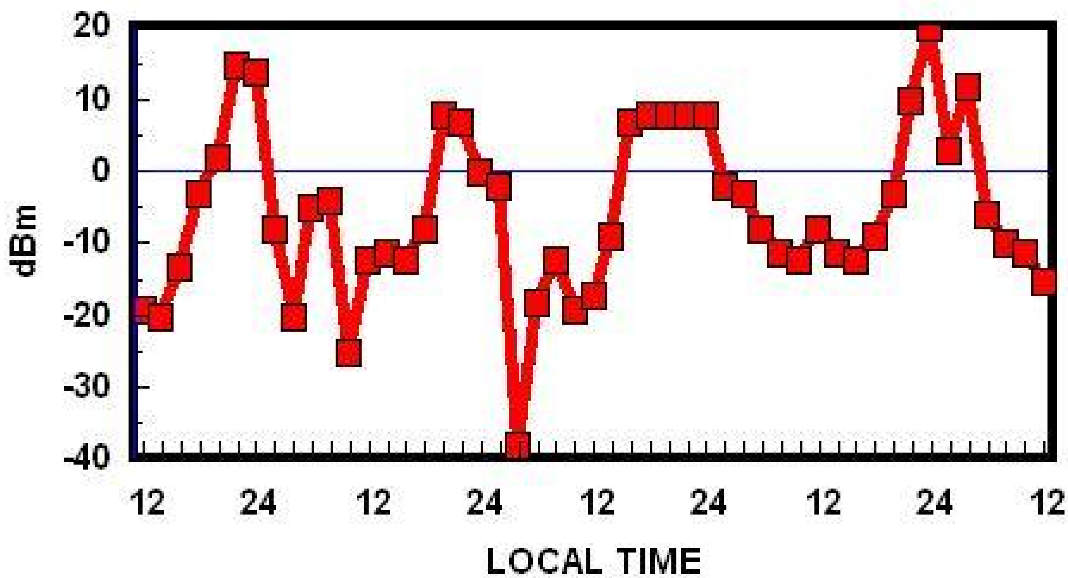

Figure 3 Diurnal Variations in Total HF Received Signal Power

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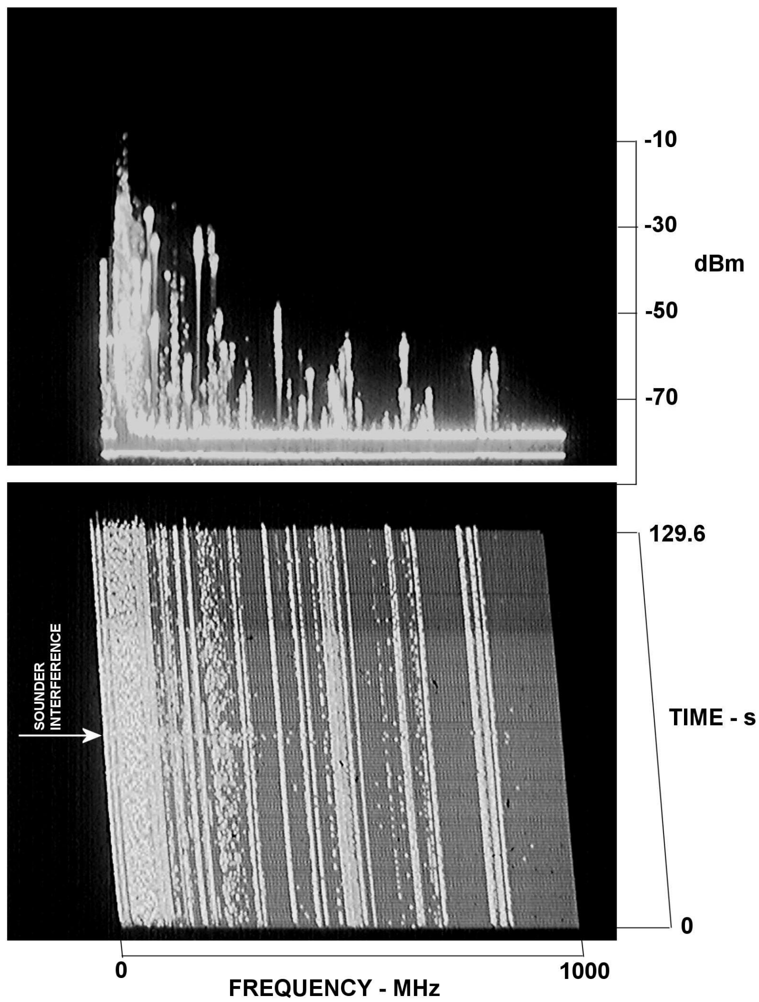
[2] Wilbur R. Vincent, Richard W. Adler and George F. Munsch, ***An Examination of Man-Made Radio Noise at 37 HF Receiving Sites,*** Report No. NPS-EC-05-003, Signal Enhancement Laboratory, Department of Electrical and Computer Engineering, Naval Postgraduate School, Monterey, CA

Figure 4 shows a typical example of signal levels in the VHF band. In this case the primary strong sources are FM and Television stations located on nearby hill or mountain tops that are within line of sight. Occasionally one will encounter strong signals from other nearby sources such as mobile or fixed communications sites.



K-VHF, 28A/29A, 080923, 1421, 500, 1000, 30, 1000, A1-V, NF, 0, 0, -10
SOUNDER AT 15 WATTS

Figure 4 Example of Strong Signals in the VHF Band

Experience has shown that the RF Distribution System at many sites contains components that lack sufficient dynamic range for effective signal reception. This is especially the case for nighttime signal reception at HF sites and at VHF/UHF sites that have nearby transmitting facilities. Site designers, managers, maintenance personnel and operators must take into consideration the presence of high-level signals from nearby sources and their potential impact on the reception of desired low-level signals. All components in the signal path from an antenna to a receiver must have sufficient dynamic range to cope with the total signal power delivered by the antenna.

4. FACILITY GROUNDS

4.1 General Comments

Grounds are often misunderstood, misused, mistaken, and confused by site designers and site operators. Added to the confusion are the numerous names that are used for grounds. A partial list of these names includes:

Single-point ground
Multiple-point ground
Signal ground
Red ground
Black ground
Green-wire ground
Shield ground
Radio-frequency ground
Computer ground
Equipotential ground
Room ground
Facility ground
Power ground
Electrical ground
Earth ground
Lightning ground
Antenna ground

With the proliferation of names, many of them without a precise technical definition, it is no wonder that grounds are a confusing topic to the designers, managers, and operators of a receiving site.

An additional vital, but often ignored, aspect of all ground conductors in a site is that they can, and do, conduct unwanted levels of EMI current and voltage from their source(s) to other locations in a site. This is further complicated by the electrical connection of a siteÕs ground conductors to many other conductors such as equipment cases, equipment racks, electrical fixtures, communications cable shields, coaxial cable shields, conduits, and even the building structure. All such conductors are a part of the total electrical and RF ground system of a site, and no part of this total ground system can be ignored when investigating electromagnetic interference problems.

The following discussion will attempt to eliminate some of the confusion about site grounds.

4.2 The NEC® Ground

The National Fire Protection Association (NFPA) publishes the National Electric Code® (NEC®). The NEC specifies details of a comprehensive ground system for all buildings with electric power. The NEC ensures that facility and personnel safety is maximized, and all sites operated by US entities should be in full compliance with the NEC. The NEC describes an earth ground located at the entrance of electric power into a facility, and it specifies the use of green-wire-ground conductors for the supply of electric power to all devices within a facility that use electric power.

The sole purpose of the NEC green-wire ground is for the safety of equipment and personnel. No additional ground system or set of ground conductors is needed to satisfy the equipment and personnel safety requirement of the NEC at a receiving site or at any other facility.

Each site should have a copy of the most recent edition of the NEC[3] and have someone fully trained in the use of, and full compliance with, the NEC. Of interest is that several individuals and organizations offer excellent training for the NEC[4].

4.3 An Additional Aspect of the NEC Green-Wire Ground

The NEC green-wire ground conductors, as well as their associated electric-power conductors and metal conduits, often carry harmful levels of current and voltage throughout a site at frequencies higher than the electric power-related frequencies considered by the NEC. The NEC green-wire conductors as well as additional conductors such as cable shields, conduits, cabinet surfaces, equipment racks, and even the building structure also carry unwanted levels of EMI current from sources to victims. The high-frequency aspects of the flow of electric current and voltage in grounds is not covered by the NEC, and an understanding of the adverse impact of such current and voltage on the reception of radio signals is essential as well as the mitigation actions needed to reduce such current and voltage to harmless levels.

Knowledge of the basic rules for the flow of electricity is essential in understanding the full role of ground systems. Two factors must be considered. The first is that low-frequency EMI current flows in complete circular paths from its source back to its source. This circular path may be simple, or it may be complex due to connections to other conductors. The exception to this simple circular rule is that current and voltage can be coupled by magnetic fields that surround all current-carrying conductors (inductive coupling) and by electric fields from voltage on conductors (capacitive coupling) onto all other nearby conductors. This provides even more paths for high-frequency current and voltage to reach the input terminals of a receiver. This is highly important because of the very close proximity of conductors carrying EMI current and voltage to many other conductors and conducting objects in a receiving site.

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[3] Copies of the National Electric Code (NEC 2008) can be obtained from NFPA Headquarters, 1 Battery Park, Quincy MA, 02169-7471, any of its regional offices, or from many commercial organizations. Further information is available at www.nfpa.org

[4] One excellent source of training in the NEC is www.mikeholt.com

In addition, the flow of high-frequency EMI current on the electrically-long conductors commonly found in a receiving site will result in current and voltage peaks and nulls with distance along a conductor These peaks and nulls are identical to the standing waves found on unmatched transmission lines and on antennas. Thus, the magnitude of high-frequency current and voltage along a ground or along a conductor of any kind will change significantly with distance and with frequency.

In this handbook, the measurement and documentation of EMI current from the magnetic fields that surround a conductor is emphasized rather than EMI voltage from the electric fields between the conductors. This is because a definitive value of EMI current can be obtained at any selected measurement point along a conductor with an appropriate current probe placed around a conductor. However, the measurement of EMI voltage requires a zero-voltage reference point which is virtually impossible to obtain in a receiving site except at the exact source of an EMI current or voltage. Since multiple EMI sources are common in a facility, a zero-voltage reference is almost impossible to obtain at the high frequencies of concern because of standing waves. A ground bus or system, no matter how large or extensive, cannot provide a zero-voltage ground reference at the high frequencies encountered at receiving sites.

One additional complication needs consideration. Most EMI voltage and current flowing on conductors in a receiving site is highly impulsive, thus contains frequency components over a very wide part of the radio spectrum. Because of this, wide-band measurement techniques are essential to measure, document and understand EMI flowing on ground conductors, or any other conductor, as well as discrete-frequency measurements. Also of interest is that a description of the spectral and temporal properties of EMI current and/or voltage is often highly useful in identifying sources.

To further complicate the understanding of a ground is that high-frequency EMI current and voltage flowing on grounds and other conductors often changes in value with time. This includes the occurrence of transients as well as sudden and large changes in current and/or voltage as sources are turned on and off. Thus, knowledge of the time history of changes of current and voltage is essential in diagnosing intermittent problems associated with erratic EMI current flowing in grounds.

Figure 5 shows an example of standing waves along ground conductors for two equipment racks and along the conduit providing power to the racks. EMI current was injected into a ground bus at the power panel supplying power to equipment in the racks. Current was injected at a series of fixed frequencies and at a level of 750 μA rms. The injection level was set to the ambient broadband EMI current level flowing on the ground bus at a frequency of 2 MHz at this receiving site. The blue curve shows the measured current flowing in a ground bus at an equipment rack located about 10 feet from the injection point and as the injection frequency was varied. Peaks and nulls were found with frequency similar to the peaks and nulls found on a transmission line or an electrically long antenna. At the high-frequency end of the data, current peaks on the ground bus significantly exceeded the injection level.

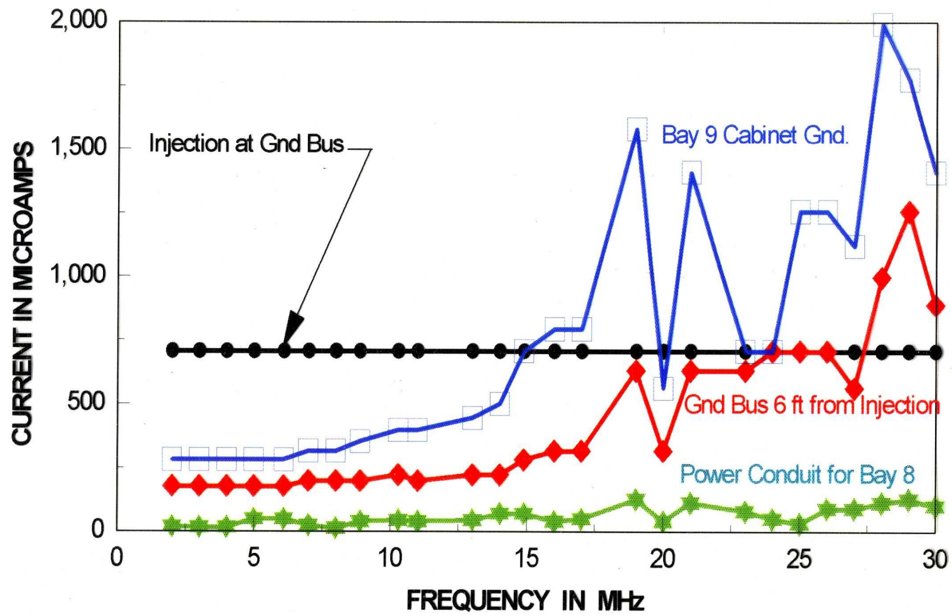

Figure 5 Standing waves along Ground Conductors

EMI current was also measured on a second ground bus leading to another nearby equipment rack as shown by the red line on the graph. Similar standing waves existed on this ground bus although at a lower level. EMI current was also measured on a power conduit as shown by the green line. It was somewhat more orderly and exhibited only minor variations with frequency. In this case the conduit was located on a cement floor and was separated from the ground busses and the ground busses were isolated a few inches above the floor. The conduit also fed electric power to another set of equipment racks, thus it did not provide a good closed path from the source of the EMI current back to its source.

The data in Figure 5 show that grounds are not simple devices where the flow of current and its associated voltages are described by the limited concepts of direct current and voltage or at the low frequencies of the electric power system. The reactive impedance aspects of electrically-long grounds and conductors carrying EMI current must be considered in modern sites. The data show that zero-voltage points simply do not exist at any point along the ground system except at the exact point of injection of EMI current into a ground conductor. Additional information about the broadband nature of EMI current will be presented later in this document.

Other electrically-long conductors can carry high-frequency EMI current such as cable shields and common-mode current flowing in unshielded cables, and they also will have standing waves for discrete-frequency cases. Standing waves were explored further using a multi-conductor cable 250 feet in length (Cable 1) placed on the ground in an open area. A second cable (Cable 2) was placed adjacent to and parallel with the first one. A constant level of current was injected into the shield of Cable 1 at a frequency of 2 MHz, and the shield current was measured at 10-foot intervals along the cable. The dark line on the plot of Figure 6 shows the current magnitude along the length of Cable 1. The distinctive standing waves on the cable shield are identical to those along a long-wire antenna.

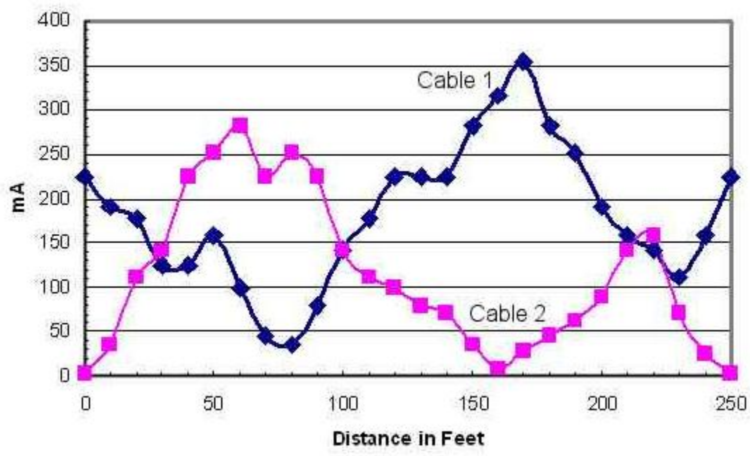

Figure 6 Variation of EMI Current Level on Cable Shields with Distance

Next, one must consider the very tight coupling of EMI current and voltage from one conductor to another nearby conductor. The mutual impedance from one conductor to another nearby conductor (especially conductors in the same cable bundle) is very low, thus high-frequency current and voltage is efficiently transferred from one cable to another by inductive and capacitive field coupling. This is shown by the lighter line in Figure 6. Note that the current in Cable 2 also varies with distance, but it is opposite in phase. The current is near zero at each end of the second cable and peaks at approximately the nulls of the current in Cable 1. The data is not entirely smooth since the ground material under the cables was not uniform along the cable length and the cables were not perfectly straight nor evenly spaced apart over their length.

The example shows that the tight coupling of EMI current and voltage from one conductor to another nearby conductor greatly enhances and complicates the spread of EMI current and voltage throughout a site. A single conductor with excessive levels of EMI current or voltage can efficiently infect other conductors and provide paths for EMI current and/or voltage to enter leakage points in signal paths.

The two examples show the distinctive standing waves formed by a discrete-frequency source of EMI current. In actual cases, the EMI current often contains broad-band spectral components rather than a single spectral component as was used to obtain the standing-wave plots. Thus, overlapping standing waves will exist and the peaks and nulls of the standing wave current will be smoothed into a more continuous shape.

4.4 Other Ground Systems

Receiving sites sometimes contain other ground conductors and ground systems in addition to the NEC Green-wire ground. In addition, many other conductors such as cable shields, conduits, equipment-rack and cabinets, and the metallic parts of the building structure are all electrically connected to the NEC green-wire ground. It is common practice to bond together large used and unused metallic objects such as equipment racks and cabinets from a general electrical safety standpoint. All of these conductors are a part of a siteҫs ground system.

The shields of antenna and communications cable should always be grounded to earth at their entrance point into a building with a suitable termination plate and a short conductor bonded to an earth ground rod as specified by the NEC.

Equipotential ground systems are sometimes added to a receiving site, or a portion of a site, where the stated reason is usually to provide a near-zero-voltage reference for electronic systems and components. Unfortunately they only provide a near-zero voltage reference and an equipotential surface when their dimensions are electrically less than about 1/20th of the wavelength of the highest-frequency EMI current that flows in such a ground system. Since the wavelength of EMI current flowing in the grounds of modern sites is physically much shorter than the dimensions of any practical equipotential ground systems, standing waves of current and voltage will exist across its surface similar to that shown in Figure 4 for a linear ground conductor and similar to that found on a flat-plate antenna operating at frequencies where the signalҫs wavelength is shorter than the antenna dimensions. Thus <u>equipotential ground systems cannot provide an equipotential surface or reference in a modern site, and they are not effective in controlling EMI problems.</u> In many cases an equipotential ground will exacerbate EMI problems in a site rather than correct or minimize such problems because they effectively inductively and capacitively couple EMI current (magnetic fields) and voltage (electric fields) to many nearby conductors.

In past years the equipotential ground was effective when one needed to provide an equipotential surface only at the fundamental and the low-order harmonics of the electric power frequency. This changed with the introduction of modern digital devices and power-control systems into receiving sites along with the accompanying high-frequency and broadband spectral components of EMI current and voltage.

The use of a so-called equipotential ground system in a receiving site is no longer practical, and their use can be detrimental to site performance.

Some sites contain additional ground systems. In all cases a valid technical reason should be clearly stated for additional ground conductors and systems other than the NEC green-wire system.

4.5 Earth Ground

Some documents state, or imply, that grounding a device or system that contains a source of high-frequency EMI current and/or voltage to earth (or equipment that is susceptible to EMI) will correct EMI problems. Furthermore some documents state that the earth actually absorbs EMI. These statements are highly misleading and are often downright incorrect. They are not supported by the accepted principles of basic electricity.

A review of Ohm's law[5] and Kirchoff's[6] first law of current flow and his second law of voltage is useful in understanding the flow of low-frequency EMI current in a complex multi-path ground circuit. The concepts developed by these two individuals have withstood several centuries of tests and experiments, and they describe the flow of low-frequency EMI current and its associated voltages in electrical circuits including ground conductors. Only minor modifications to their laws (with the introduction of circuit impedance in addition to resistance) are needed to describe the flow of EMI current in ground systems at higher frequencies as well as the presence of standing waves of current and voltage (hence magnetic and electric fields) on ground conductors.

The electrical path into an earth ground rod is always considerably higher in resistance and in reactive impedance than other paths within the complex configuration of ground conductors and other metallic conductors of a site. Since EMI current will always flow in the path of lowest impedance, it will flow primarily in the other metallic paths, and only insignificant levels of EMI current will flow into the higher impedance path of a ground rod and into the earth. Numerous attempts to measure EMI current flowing into the ground rods at a number of receiving and data-processing sites have shown such current to be insignificant and orders of magnitude lower than the EMI current flowing in other conductors of these sites.

While an earth ground is absolutely necessary to comply with the personnel and site-safety requirements of the NEC, it does not provide a useful means to control or eliminate high-frequency EMI in a receiving site. Furthermore, there is no valid physical or electrical mechanism associated with an earth ground that will permit the absorption of alternating EMI current or voltage into the earth; however the earth and an earth ground do play a significant role in the control of static discharges from lightning and for the safety requirements of the NEC.

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[5] Georg Simon Ohm formulated his law of current flow in a resistor and the voltage drop across a resistor while a high-school teacher and published his findings in 1827.

[6] Gustave Robert Kirchhoff formulated his two electrical circuit laws in 1845 while a university student in Germany. These two laws remain the fundamental means of determining the performance of circuits at direct current and at low alternating current frequencies in circuits were impedance is low.

4.4 Antenna Related Grounds

It is beyond the scope of this document to provide detailed information about ground systems for antennas, and there are numerous references available to antenna designers on the topic. However, most forms of monopole receiving antennas require a ground counterpoise or mesh to provide a path for the flow of image current. This is commonly provided by the counterpoise wires or a ground mesh located under and around a monopole antenna. Such wires provide a lower-impedance path for the flow of image current than an earth-ground path. Counterpoise wires should never be used for any other purpose such as a general electrical or lightning protection ground system.

Since ground counterpoise conductors are an integrated part of the antenna system, and all other nearby conductors must be free of EMI current to avoid coupling harmful levels of such current into the counterpoise conductors. This includes power and communication cables that are buried below the counterpoise conductors or supported above them.

4.5 Other Factors

Always use standard compression fittings and/or stainless-steel bolts to connect sections of a ground system together. Firmly tighten all joints.

Never use welded or CADWELD® joints in a ground system or at any other location in a receiving site. Numerous cases of poor welding have been noted in receiving sites which can be blown apart with a sudden surge of fault current. In addition, contamination in welded joints can result in inclusions with non linear electrical properties. These can produce intermodulation components and intermodulation noise when EMI current flows through them.

5. TYPICAL SOURCES OF NOISE AND INTERFERENCE

5.1 General Comments

A variety of sources have been identified that inject harmful levels of radio noise and interference into the RF paths leading to radio receivers, and a number of typical examples are described in this section along with examples of the problems generated.

5.2 Saturated Components in the RF Paths

The saturation or overload of components in RF paths between an antenna and a receiver from the normal ambient signal environment and from high levels of man-made interference is a common source of unwanted and harmful radio interference. Examples of such components are broadband amplifiers, multicouplers, signal dividers, RF filters, and dirty and/or corroded coaxial connectors. Welds on galvanized steel used on antenna towers, antenna components, ground conductors, antenna supports, and objects near an antenna also have nonlinear characteristics that will saturate at very low levels of RF current. These kinds of sources produce unwanted radio interference from intermodulation (IM) components and broadband IM noise.

Figure 7 shows a brief burst of intermodulation noise caused by a strong signal burst that overloaded the amplifier of a multicoupler. Such bursts of IM noise can be similar to some short-duration signals, and when present they put an unwanted burden on a receiving system which must differentiate them from desired signals.

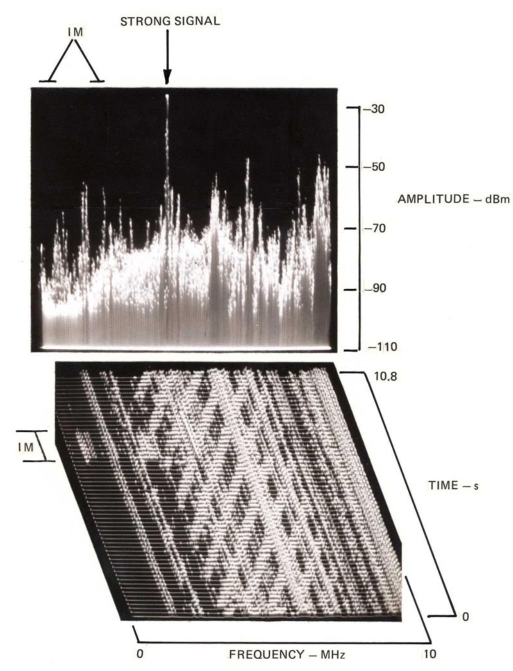

Figure 7 In-Band IM Noise

Figure 8 shows another example of interference caused by saturated components in an RF path to a receiver. Multiple high-level signals from international broadcast stations in the HF band exceeded the dynamic range of a component in the RF path and caused the closely-spaced IM products. In this case the broadcast signals were all below the frequency range shown. Ionospheric propagation limitations prevented normal signals from being received within the frequency range of the example at the time of day of the example, thus all of the spectral components in the view are IM products. The reduction in amplitude of the IM products in the lower one-third of the time-history view is because of fading of the ambient signals that overloaded the RF components. The maximum amplitude of the IM products is shown in the upper amplitude-vs.-frequency view. Additional IM products also existed at lower and higher frequencies, including the lower frequencies where the broadcast signals were received.

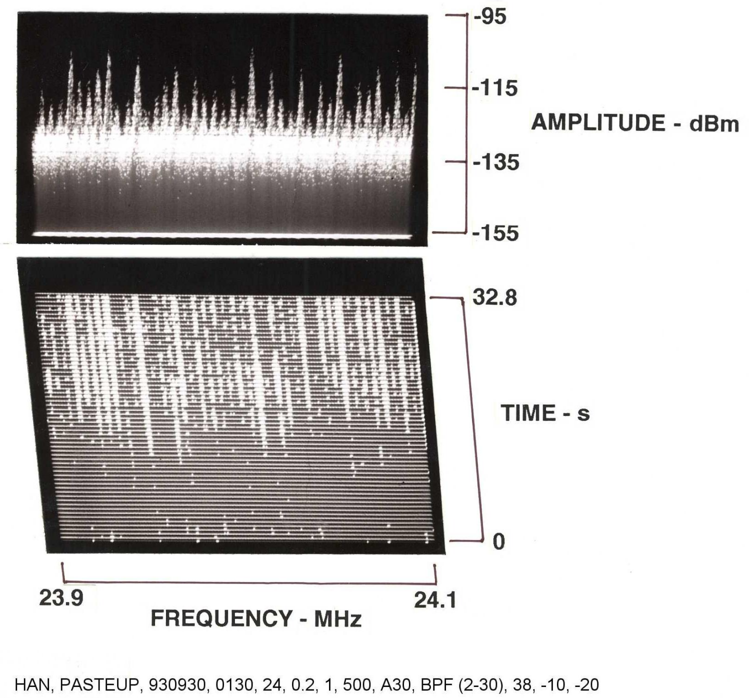

Figure 8 Above-Band IM Products

The term IM product refers to the textbook description of intermodulation where two or more discrete-frequency signals applied to a nonlinear component produce harmonics of each signal and other products in accordance with the following:

$f_{IM} = mf_1 \pm nf_2 \pm of_3$é é é

where f_{IM} is the frequency of each intermodulation product generated.
f_1, f_2, f_3é é are discrete-frequency signals applied to a nonlinear joint.
m, n, oé é are integers from 1 to a higher number.

The term ñIM noiseò is also used throughout this document. Since f_1, f_2, f_3é are often not pure discrete frequencies but are normal signals that have spectral width, the IM products will also have spectral widths but with widths multiplied by m, n, and oé é When the spectral widths of the ambient signals are wide as in many practical instances, the IM products will appear as broadband noise. Thus, both terms IM products and IM noise describe two important aspects of intermodulation.

The previous Figure 7 shows one example where a strong signal about one-second in duration produced IM products and noise also about one-second in duration. Even shorter duration IM products and noise can occur, and Figure 9 shows an example. In this case a frequency-hopping transmitter emitting pulses in the low portion of the VHF band was operated adjacent to a receiving facility. Its strong VHF signals overloaded components in the RF path and produced high-level impulses of IM noise from 60 MHz up to 1000 MHz. Figure 9 shows an example of the resulting IM pulses in a 10-MHz wide portion of the radio spectrum centered at 309 MHz.

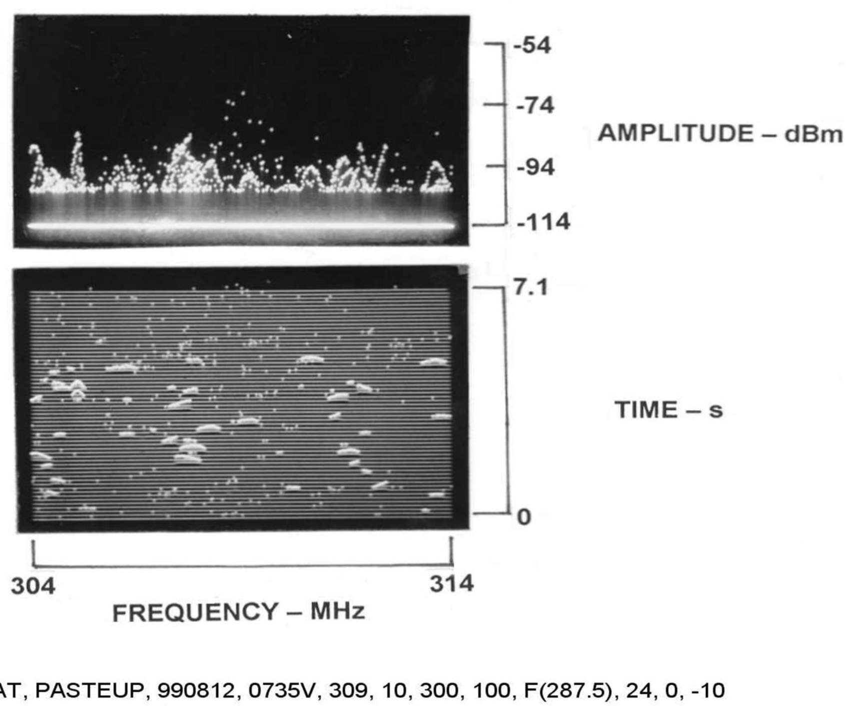

Figure 9 Intermodulation Pulses in the UHF band from a VHF Source

Two factors contributed to the excessive IM products and noise shown in Figure 9. First, the VHF frequency-hopping transmitter was operated too close to the receiving antenna thus resulting in extremely high electromagnetic-field levels at the receiving antenna. Second, a very low-dynamic-range multicoupler was incorporated in the RF path between the receiving antenna and the receiver, and it could not handle the normal signal environment.

5.3 Cable Leakage

Leakage of noise and other spectral components into RF cables running from antennas to receivers has been noted at all receiving sites that use single-shielded coaxial cables. Receiving sites using high-quality double-shielded coaxial cable and properly-assembled coaxial connectors seldom encounter cable-leakage problems.

Figure 10 shows an example of severe leakage encountered at a receiving site. In this case a 5-MHz frequency-reference signal was distributed throughout the site over single-shielded RG-58 coaxial cable[7]. Radio signals were carried from the entry into the building and to receivers on single-shielded cables. Leakage of the reference signal and a second lower-level signal into a single-shielded cable feeding the receiver was exceptionally high. Of interest was that no detectable leakage was found in a parallel double-shielded coaxial cable feeding another receiver. This example clearly indicates that the use of single-shielded coaxial cable in a receiving site must be prohibited.

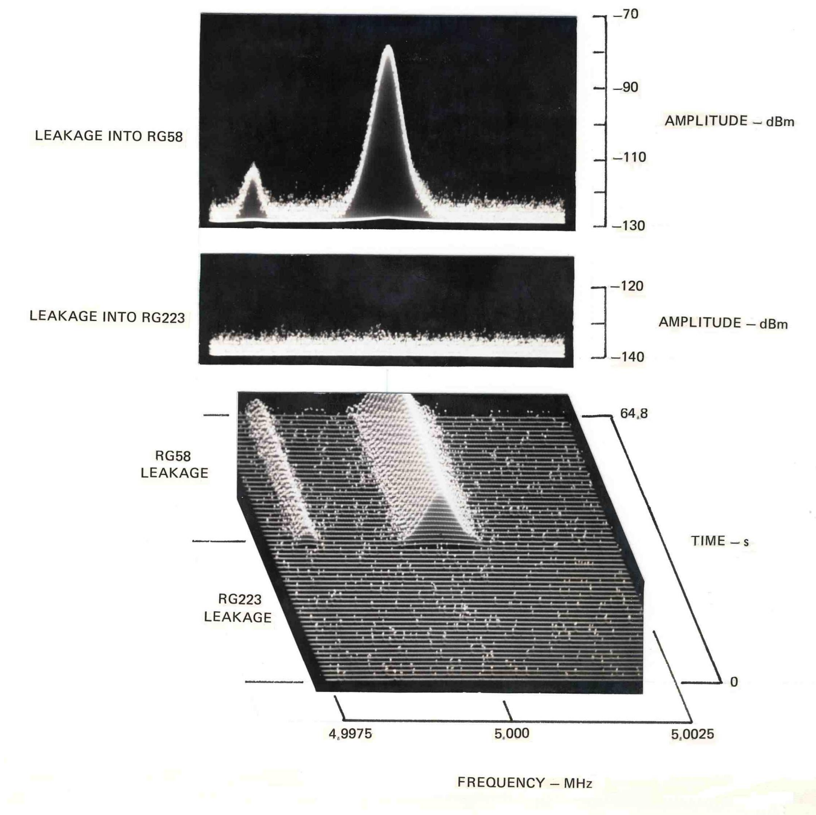

Figure 10 Example of Leakage into Coaxial Cables

To better understand the leakage of signals from one cable to another, two single-shielded cables (type RG-58) fifty feet long were run in a straight line along the earth. Two fifty-foot double-shielded cables (type RG-223) were added to the configuration.

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[7] See Section 8 for a discussion of coaxial cable designations, old and new.

Test signals were first injected into one of the single-shielded cables and then into one of the double-shielded cables. The far end of each driven cable was terminated in a fifty-Ohm coaxial terminator. The far ends of the un-driven cables were also terminated with 50-Ohm terminators, and the signal levels that leaked into the un-driven cables were measured with a spectrum analyzer at frequency intervals from 5 to 25 MHz.

Figure 11 shows the result of this measurement where the leakage loss is expressed in dB. The single-shielded to single-shielded coaxial cable provided only about 70 dB of isolation near the center of the frequency range while the double-shielded to double-shielded loss was greater than 140 dB (not measurable with the test setup available). The single-shielded cable to single-shielded isolation is clearly insufficient to provide acceptable signal isolation from one antenna cable to another since at least 130 dB of cable-to-cable isolation is needed to the avoid cross talk of received RF signals. The isolation provided by single-shielded to double-shielded cable also did not meet the needed isolation levels. Because of these findings only double-shielded coaxial cable should be used throughout a receiving site.

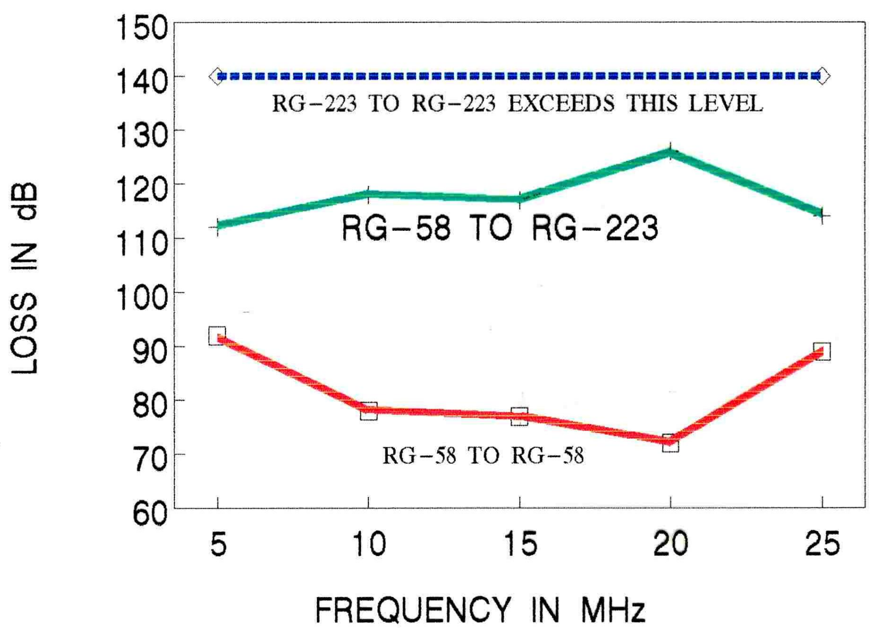
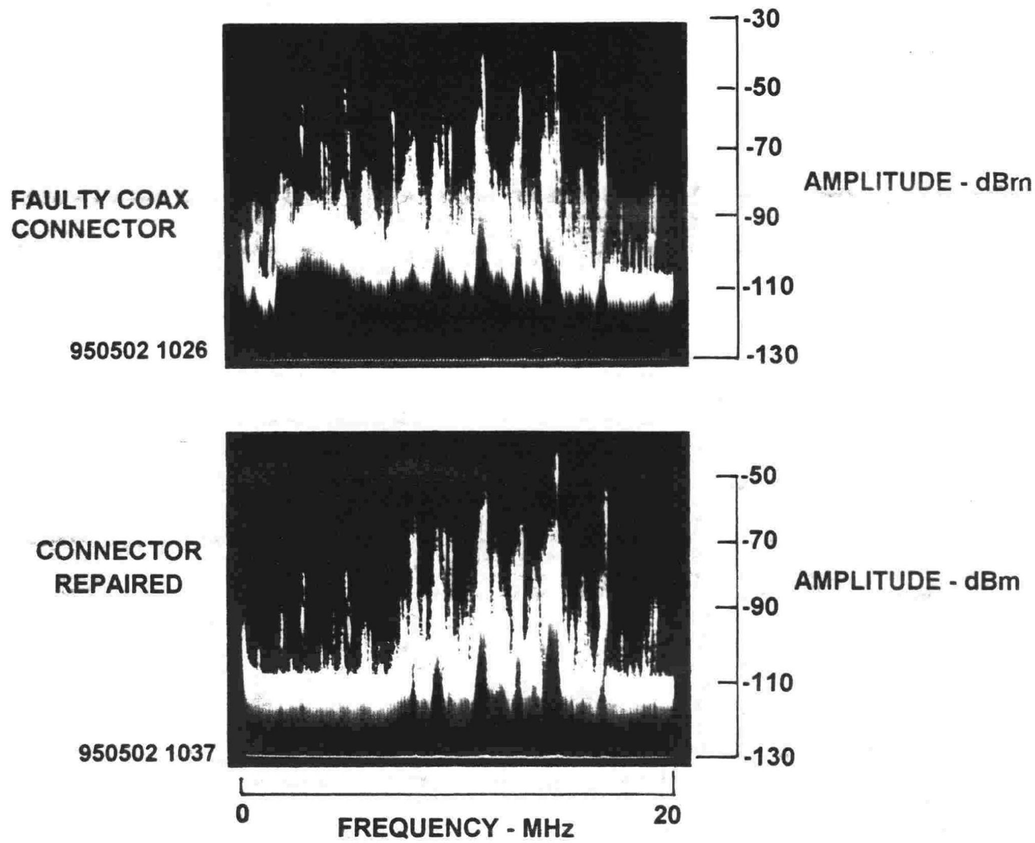


Figure 11 Cable-to-Cable Coupling Loss

The upper view of Figure 12 shows signals and noise at the input terminals of a receiver when an improperly assembled coaxial connector was installed on a coaxial cable in the RF-Distribution path for that receiver. The shield of the cable was open at one end enabling EMI current and voltage on the cable shield to enter the signal path. The noise floor over the low-frequency portion of the frequency range is excessively high. The lower view shows the reduction in the noise floor when the shield was properly connected.



SAB, 950502, 1026/1037, 10, 20, 3, 2000, HF OMNI, NF, 0, 0, -50

Figure 12 Impact of Improperly Assembled Coaxial Connector on Noise Level

5.4 Antenna Issues

A number of sources of radio-interference and radio-noise related to antenna construction or antenna field issues have been identified. Examples are provided to illustrate some typical problems.

Experience has shown that welding on galvanized metal after galvanizing produces nonlinear joints. Welding prior to galvanizing does not normally produce nonlinear junctions.

A single alternating-frequency current conducted through a welded joint on galvanized metal will result in the production of harmonics. Current from multiple signals flowing through a non-linear joint will result in the production of intermodulation products and intermodulation noise as well as harmonics. Such sources can inject massive numbers of spectral components of current and voltage into the tower structure where the tower structure is physically close to its receiving antennas. This current and voltage can be coupled into the nearby receiving antennas, resulting in unwanted noise and interference being fed to all receivers connected to the antennas.

Figure 13 shows an example of a weld on a galvanized portion of an antenna tower at a receiving site. This tower was located on a hilltop receiving site in direct line of sight to television, FM, and AM broadcast transmitters as well as being close to other commercial and military communication sites. Such sources injected significant levels of current and voltage into the tower and its associated cable shields. If nonlinear joints are present on such structures, intermodulation products and broadband intermodulation noise sources will exist.

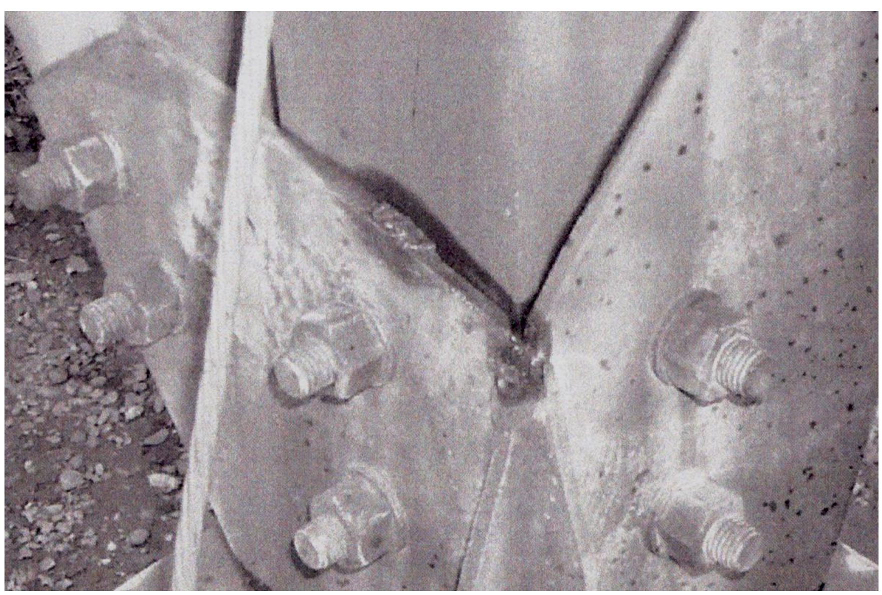


Figure 13 Weld on Galvanized Metal of a Receiving Antenna Tower

Figure 14 shows a ground conductor welded to a galvanized metal component of a tower at a receiving site. This tower was adjacent to the tower shown in the previous figure. The weld was clearly of poor quality, and it was necessary to use a tie wire to maintain its mechanical properties. In addition to its ability to produce intermodulation products and broadband intermodulation noise, the poorly welded joint would be blown free of the tower from surge current induced by a lightning strike.

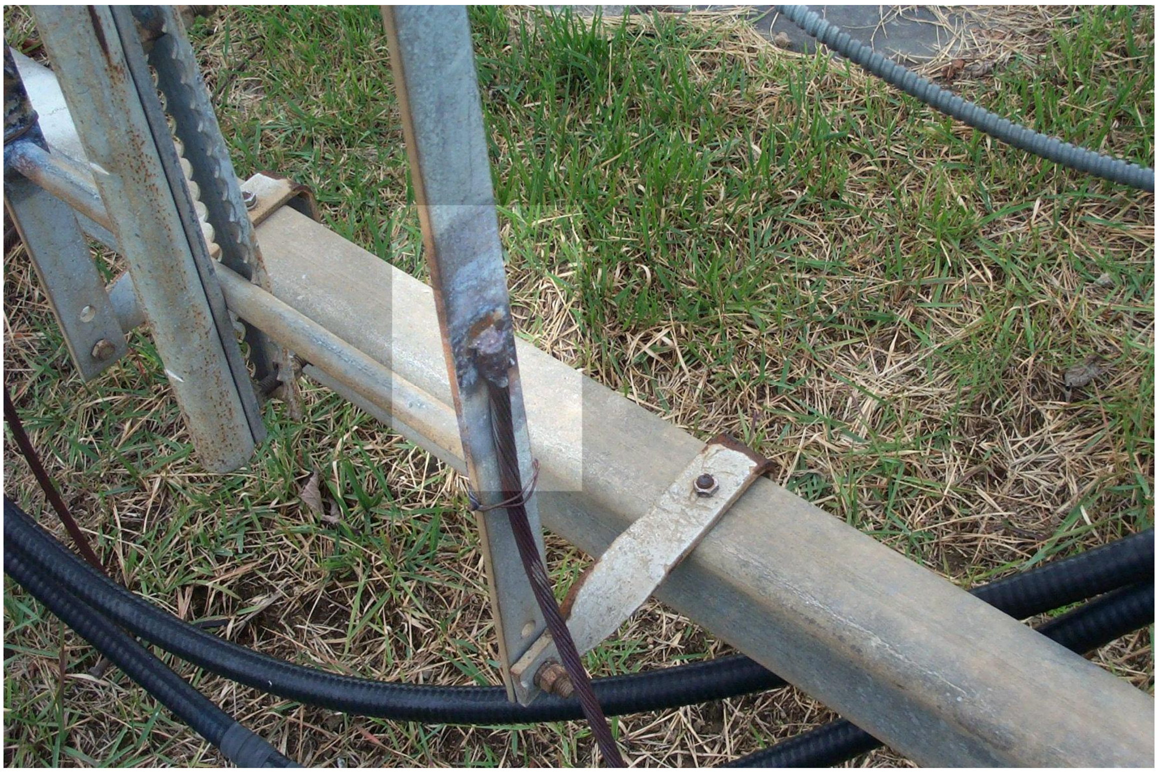


Figure 14 Ground Wire Welded to Galvanized Metal on Antenna Tower

The solution to the ground cable connection is to use a standard electrical compression fitting on the ground conductor and bolt the fitting to the tower. All other tower fittings should be bolted.

<u>Welding on the galvanized metal components of a receiving or transmitting antenna tower should be prohibited.</u>

Impurities in a CADWELD® can also produce nonlinear joints which can be a source of harmonics, intermodulation products and broadband intermodulation noise. Figure 15 shows an example of a CADWELD® that connects an antenna counterpoise wire to a ground stake. A large number of such welds existed in the ground plane for the antenna.

The use of mechanical electrical fittings fabricated of bronze will eliminate the possibility of these connections being sources of low-level intermodulation products and noise in the antenna counterpoise system. This will also eliminate the high levels of intermodulation when nearby radio transmitters are operated. CADWELD® joints should not be used on or near antenna fields or at any other location within or near a receiving site.

Figure 15 CADWELD® on Antenna Counterpoise Wire

The rusty joint effect is well known to old-time radio engineers, especially when the rusty joint is in the antenna system. Figure 16 shows an example of such a joint that was part of an antenna guy. Also of concern is the use of chain in the guy because its joints can move from wind resulting in intermittent contacts. A thin layer of insulating oxide is formed on galvanized metal, and wear from movement can intermittently make and break through the layer. Non-conducting line should be used for all antenna guy material or metallic guys with properly installed and spaced compression insulators.

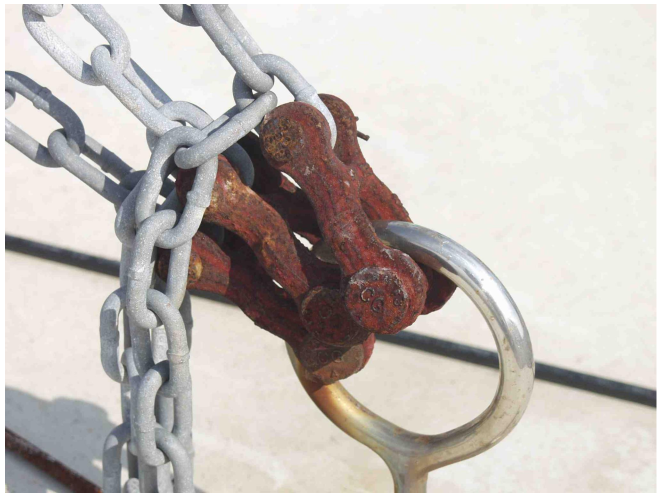


Figure 16 Example of a Rusty Joint

Figure 17 shows an example of multiple incidental contacts between conductors where the conductors are physically and electrically close to receiving antennas. Low-level standing waves of current and voltage exist on such conductors from ambient radio signals. The intermittent contacts formed by minor movement of the conductors result in impulses due to small potential differences between the conductors. These low level impulses radiate and result in low-level and erratic impulsive noise at the input of the site's receivers.

Figure 17 Example of Incidental Contacts

5.5 Shielded Room Issues

Shielded rooms are often used to isolate sources of EMI from nearby antennas and signal-distribution components. A properly designed and installed shielded room can be an effective means of controlling EMI problems when extreme measures are needed, but with time and modifications many become ineffective shields.

A few common examples of problems with shielded rooms are shown in this section. The technical details associated with the use of small and large shielded spaces are presented in more detail in Section 7. Figure 18 shows where a water pipe penetrated a wall of a shielded room. This pipe can conduct EMI current and voltage from outside sources into the room, and it can conduct EMI current and voltage from sources in the room to locations outside the room. The outside surface of the water pipe should be electrically connected to both sides of the shielded-room wall. This provides a low-impedance path for EMI current to flow back to its source rather than into or out of the shielded room.

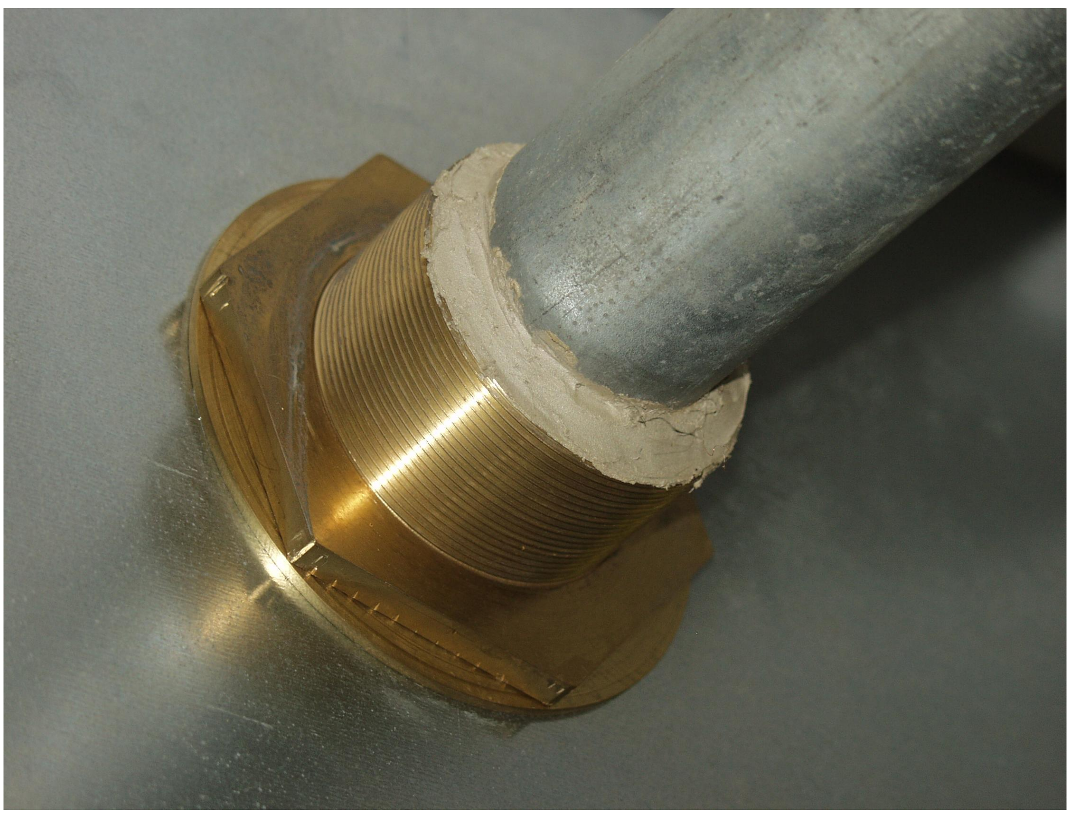


Figure 18 Water Pipe Penetrating a Shielded Room

Figure 19 shows another penetration of a shielded room. In this case a coaxial cable associated with the siteôs security system penetrated the shielded room. Its shield carried EMI current and voltage into and out of the shielded room. This kind of conducting penetration must be avoided since a single such penetration as shown can completely destroy the effectiveness of a shielded room. In this case a standard coaxial bulkhead connector at the penetration point would have provided a satisfactory means of terminating the cable shield on both sides of the wall of the shielded room.

Figure 19 Coaxial Cable Penetration of a Shielded Room

Of interest is that other similar penetration tubes have been found that carry non-conducting fiber-optic cables into and out of shielded rooms. Such penetrations are acceptable since non-conducting cable can not conduct EMI current or voltage into or out of the room, however some fiber-optic cables are constructed with metallic armor, and these should be treated the same as the shield on coaxial cable.

The use of shielded rooms is recommended only for special needs and for the isolation of major sources of EMI. Most sources of EMI can be sufficiently contained by enclosing the actual source inside an inexpensive commercial metal enclosure along with the control of each penetrating conductor as described later in Section 7.

5.6 Power-Conversion Devices

In recent years a wide variety of power-conversion equipment has become available for general use. Most such equipment employs electronic switching techniques to convert electric power from one form to another form. Examples are Uninterruptible Power Supplies (UPS), switching power supplies, and variable-frequency power sources.

Many power-conversion devices, but not all, are sources of harmful levels of EMI current and voltage that is injected onto the NEC green-wire ground, power conductors, other grounds, cable shields, and other conductors of a site. Since the EMI current and voltage generated by these equipments is often impulsive, spectral components of their current and voltage often extend from low-order harmonics of their power source up into the UHF frequencies. Some such devices are designed to limit the flow of EMI current and voltage on external conductors to low levels while many other similar equipment is not so designed.

The Federal Communications Commission (FCC) recognized that many electronic devices and power-conversion equipments generate harmful levels of EMI current and voltage. The FCC's Class A and Class B ratings for acceptable levels of EMI voltage were developed and published several years ago.[8] The FCC Class A rating describes acceptable levels of EMI voltage for devices employed in commercial facilities where relatively high-levels of EMI current and voltage can be tolerated. The FCC Class B rating describes lower levels of EMI voltage for devices that are sold for residential use. Other specifications (such as the MIL standards) exist that describe acceptable levels of EMI voltage and current for various military systems, but they do not always apply to radio-receiving sites.

Unfortunately, no document is presently available that covers the specific radio noise and interference requirements for radio-receiving sites, although the FCC Class B specification is sometimes, but not always, used for the purchase of equipment for such sites with varying degrees of effectiveness. Of concern is that many new electronic devices and systems containing power-conversion devices are designed to Class A standards and are intended only for industrial purposes, but they are frequently installed at receiving sites. Modern air-handling systems, variable-speed electric-motor controllers and large Uninterruptible Power Systems are prime examples.

Figure 20 shows an example of a label added to electronic devices made in the United States that are intended only for use in non-residential locations. Any device containing this or a similar label is almost certain to produce harmful levels of radio interference at a receiving site. Devices with such a label should not be procured for use in and around a receiving site. In addition, any device containing electronic equipment that does not have such a label should not be procured for use at a radio-receiving site unless it has been tested to ensure that it meets the FCC Class B requirements or the EMI current levels provided in Table 1 later in this section.

[8] See Section 8 for more detail.

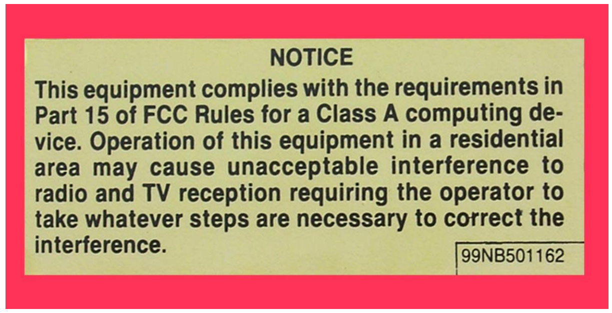


Figure 20 Radio-Interference Label from a Class A Device

Computers, home electronics, and other electronic devices usually have a label indicating that they meet the FCC Class B requirements, or this is stated in their instruction manual. Such devices can be used in a radio-receiving site with little concern that they will generate harmful levels of radio interference although Class B devices should not be used in close proximity to a siteôs receiving antennas. Be aware that adding external peripheral devices to any item with internal noise sources may cause them to no longer meet the Class B requirements, and thus be an interference source.

The U.S. Navy Signal-to-Noise Program (SNEP) Teams have examined radio-noise and radio-interference problems from both internal and external sources of interference and noise at more than 40 sites at various locations around the globe. Their work consisted of identifying the sources of harmful levels of noise and interference, determining the maximum tolerable levels of EMI current from sources, evaluating the loss of signals from noise and interference, and developing mitigation actions for sources. Extensive measurements have resulted in estimates of the maximum tolerable levels of EMI current at these sites for the reception of low-level signals.

Table 1 provides maximum permissible levels for a small receiving site and a large receiving site. Two frequency ranges were examined. Linear scaling can be used to determine the approximate maximum current for frequencies between the two ranges.

LARGE SITE

Frequency Range	Maximum Current
0 to 10 kHz	2 mA
100 kHz to 100 MHz	10ε A

SMALL SITE

Frequency Range	Maximum Current
0 to 10 kHz	2 mA
100 kHz to 100 MHz	2 ε A

Table 1 Maximum Permissible Limits for Conducted EMI Current

The values of maximum permissible EMI current at frequencies between 100-kHz and 100 MHz are quite low. These low levels were determined from extensive measurements at many receiving sites, and the reasons for the low levels are twofold. The first is that the limits apply to sites that are designed to detect and process low-level radio signals without harmful radio-interference or added noise above ambient noise levels. The second is that multiple leakage paths can exist for EMI current and voltage to enter the signal paths at all sites, but the permissible leakage level is often determined by only one or two elusive and difficult to identify points of the lowest transfer impedance for EMI current or voltage to enter a signal path. The test equipment needed to identify low-impedance transfer points is seldom available at a receiver site.

Exceptions have been noted to Table 1. Some sites that have nonlinear joints in the antenna system, its counterpoise, or within its signal paths can be susceptible to low levels of EMI current. Sites with power, control, and communications cables underneath its antennas (including buried cables) can be susceptible to low-levels of EMI current flowing on the shields of such cables. Other sites designed with high levels of isolation in signal paths can tolerate somewhat higher levels of EMI current. This indicates that an examination of the properties of low-level radio interference and noise at the input terminals of a receiver is critical, and a determination of its sources is a requisite item in determining the ability of a site to perform as intended.

The maximum EMI current levels in Table 1 are based on the detection of typical signals with a 0-dB signal-to-noise ratio at a receiver bandwidth of 3 kHz. If a site must detect signals at negative signal-to-noise ratios or narrow-band signals with receiver bandwidths less than 3 kHz, the maximum permissible EMI current levels will be even lower than those shown in Table 1.

A few examples of excessive EMI current flowing on cables in a receiving site will demonstrate the problem. Figure 21 shows EMI current flowing on one of the 3-phase output power conductors of a Power Distribution Unit (PDU) over the frequency range of 100 kHz up to 10 MHz. This particular PDU was located within a shielded room that housed the RF-distribution equipment for an HF receiving site. The PDU contained a switching power supply for its electronics along with other digital control devices, and it provided electric power to all equipment located within the shielded room.

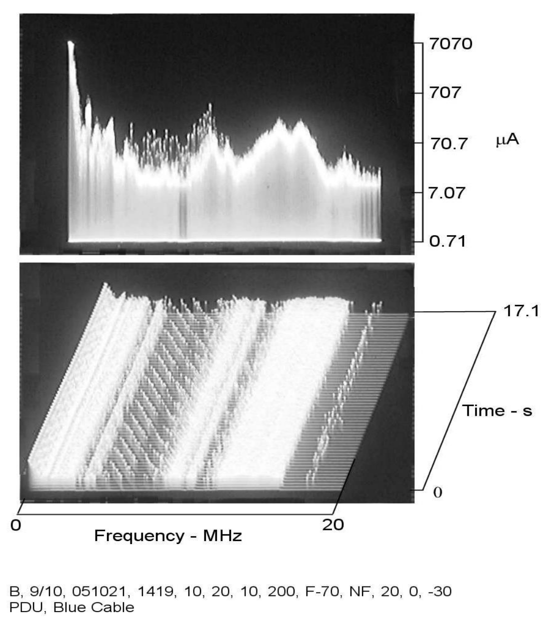
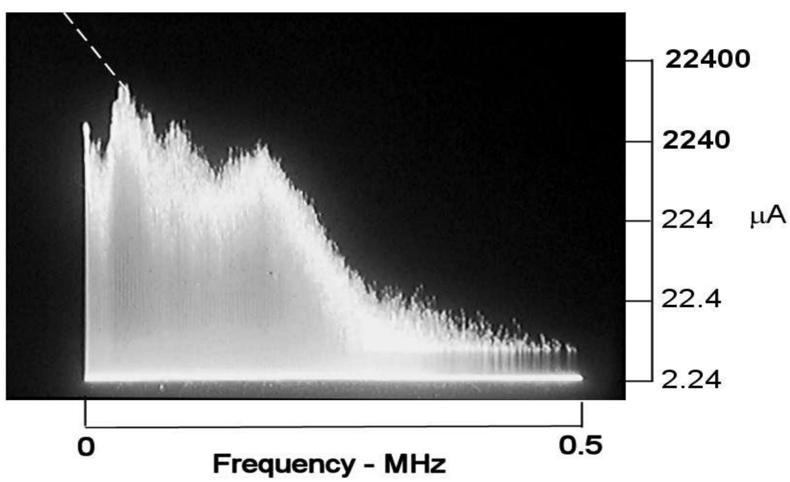


Figure 21 EMI Current Flowing on PDU Power Conductor

Severe peaks and nulls in noise amplitude were found across the entire frequency range of the data at levels significantly above the minimum tolerable level provided in Table 1. The slanting lines in the time-history view over the frequency range of about 3.5 to 8 MHz are from repetitive impulsive noise with a period of 8.3 ms (a pulse occurrence rate of 120 per second). The amplitude of these impulses is shown in the upper amplitude-vs.-frequency view. The noise in the remaining part of the HF band was a combination of impulsive noise at lower levels and closely-spaced spectral components related to harmonics of the power-line frequency and of the switching rate of the power-converter device.

The PDU was examined to determine if it was procured in accordance with the FCC Class B noise voltage rating. No label was found on the unit, a violation of the FCC rules. While the voltage level of noise was not measured in accordance with the FCC test procedures, the high noise current level clearly indicate this unit was either manufactured to the FCC Class A industrial noise requirement or the noise requirement was simply ignored.

Figure 22 shows noise on one of the 3-phase conductors feeding power into the shielded room. In this case the power is provided to a 30-kVA UPS located in an adjacent shielded room, and it passed through a large low-pass filter located on the UPS side of the wall of the shield separating the two rooms. The drop in noise amplitude above about 200 kHz is caused by the filter. Note that the noise level at 500 kHz is very low, and the device met the requirements of Table 1 for a large site at all frequencies above about 1 MHz. The filter installation was effective at the higher frequencies, but excessive levels of noise and harmonic components of the power-line frequency and the switching rate of the UPS exceeded the low-frequency level stated in Table 1.



B, 7, 051023, 1145, 0.25, 0.5, 3, 100, F-70, NF, 20, 0, -20
Blue Cable, UPS J Box in B

Figure 22 UPS Noise after a Filter

The data in Figure 22 shows the difficulty of placing a relatively large UPS adjacent to a room containing radio-frequency distribution equipment. The filters on the power conductors and the use of a ground stud connected to both sides of the wall of the shielded room separating the UPS from the signal paths equipment were effective at the high frequencies of primary interest to the site, but practical filter-design considerations made it impossible to meet the low-frequency requirements.

At this site, electric power for the UPS and other portions of the RF-distribution room was supplied by underground cables that ran under the antenna field at a depth of about 4 feet. Of concern was that EMI current on these cables might be inductively coupled into the counterpoise wires of the monopole antennas at the facility. The concern for this was highlighted by the reception of excessive levels of impulsive noise by the antennas. To check this, a test dipole was placed on the ground in parallel with the counterpoise wires.

Figure 23 shows the amplitude of spectral components of noise collected by the test dipole antenna over the frequency range of 4.5 to 5.5 MHz at three locations. The top location was near the center of the antenna field, the middle location was near the edge of the antenna field, and the bottom location was near a nearby large facility. The data clearly show that excessive spectral components of noise were injected into the test antenna and also into the siteǿs antenna counterpoise wires from EMI current flowing on the underground cables.

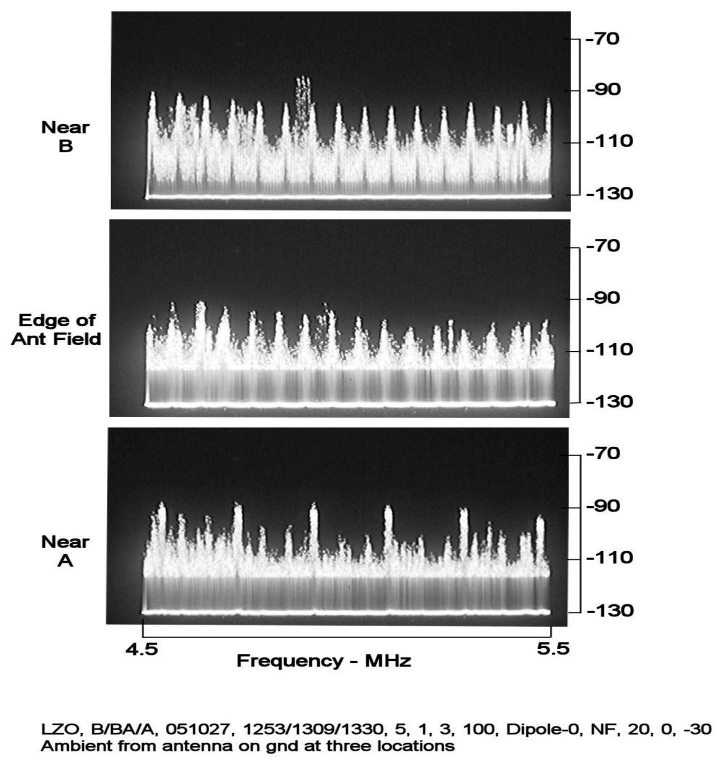


Figure 23 Noise from Underground Power Cables

Multiple sources of noise current carried by the underground power cables were identified including the UPS at the location along with other power-conversion devices in another nearby building associated with air-handling systems, power-conversion devices associated with water-control pumps, another a even larger UPS in an adjacent building, and several additional power-conversion devices operating at lower power levels.

The underground power cables located directly under the antenna field were installed in accordance with the requirements of the NEC, but those requirements were insufficient to ensure the noise-free operation of a radio-receiving site.

An examination of the power-conversion devices contributing to the harmful levels of radio noise in Figures 21, 22 and 23 did not reveal the expected Class B or Class A labels required by the FCC for such devices marketed for general sale. Additional examination and measurements indicated that all were intended for industrial use rather than meeting the FCC Class B requirement for residential use. The use of such devices in and near a radio receiving site can significantly degrade the ability of a site to receive low-level radio signals of special interest, and they should not be installed in such facilities.

5.7 Building Issues

Examples of problems found in existing buildings are provided to illustrate the general nature of items that must be avoided to achieve a low-noise radio-receiving capability.

Never install electronic equipment or devices in a receiving site which inject harmful levels of EMI current or voltage into conductors attached to the equipment or device. One way to achieve this is to ensure that all electronic equipment or devices, or any larger system that includes electronic equipment or devices, meets the FCC Class B radio noise and interference requirements or meets the EMI current limits provided in Table 1 on Page 30. Avoid the use of any electronic equipment or device or other system that contains a label similar to that shown in Figure 24[9]. Some items of equipment do not have such a label, but still contain electronic devices. In such cases, the person responsible for the procurement and installation of such equipment must make certain that it complies with the FCC Class B radio-noise and interference requirements and/or the EMI current limits provided in Table 1. There should be no exception to this process. Compliance will ensure that the buildings and facilities of a radio-receiving site will function as planned and as needed to achieve its mission.

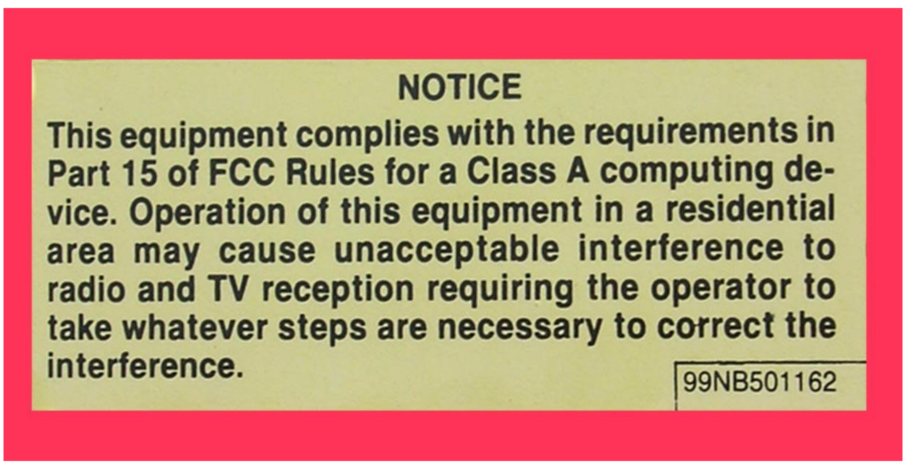


Figure 24 Example of FCC Class A Label

If such a device is essential for the operation of a radio-receiving site, it must be modified in accordance with the principles provided in Section 7 of this document and tested prior to its use. Examples of such potential equipment and devices are Uninterruptible Power Supplies, switching power supplies, recent air-conditioning equipment with electronic controllers, the controllers for variable-speed electric motors, and other similar devices.

[9] This label is used elsewhere in this document. It is reused several times because of the critical need to avoid the installation and use of such equipment or devices in a radio-receiving site unless it has been modified in some way to fully comply with the FCC Class B requirements or the EMI current limits provided in Table 1.

In addition to the above items, other building issues that impact the operation of a radio receiving site can exist. Figure 25 shows a support bracket fabricated out of galvanized steel and bolted to the side of a shielded room. This bracket was welded after galvanizing. While it provided excellent mechanical support, EMI current was flowing on the surface of the shielded room and such current passed through the nonlinear joints of the welds. The resulting harmonics, IM products and IM noise generated by the nonlinear joints added significantly to the RF environment inside the room which contained RF cables, RF preamplifiers and other low-level radio systems.

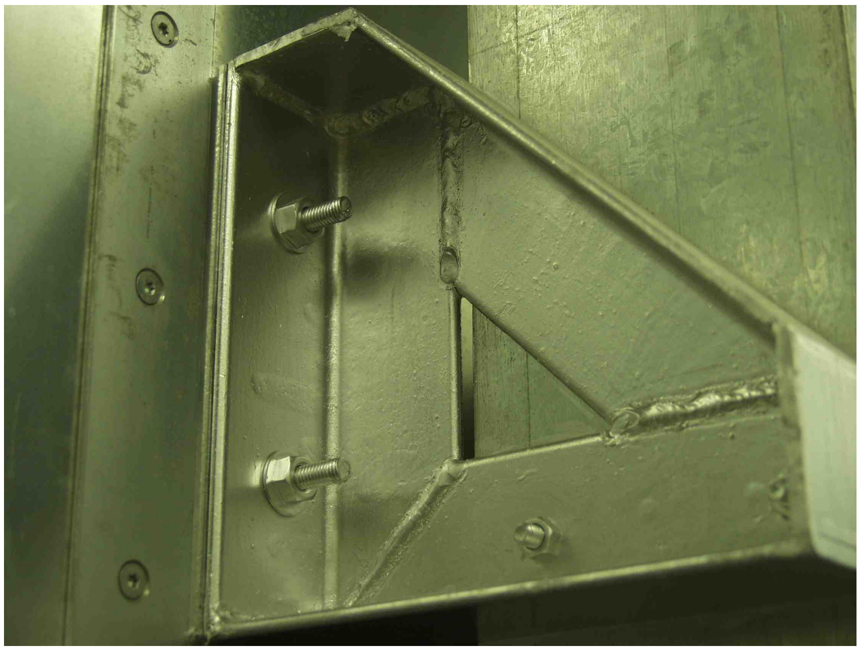


Figure 25 Weld on Galvanized Steel inside a Radio-Receiving Building

Cable shields, conduits, pipes, and other conductors in a building often carry significant levels of current at harmonics of the electric power frequency and other high-frequency spectral components. Incidental contacts between such conductors and other nearby conductors produce transients of current and voltage that contain high-frequency spectral components, and such transients can cause two problems. The first is undesired intermittent noise in the output of a receiver. Second, such transients have been noted to disrupt the operation of computers and data-processing devices.

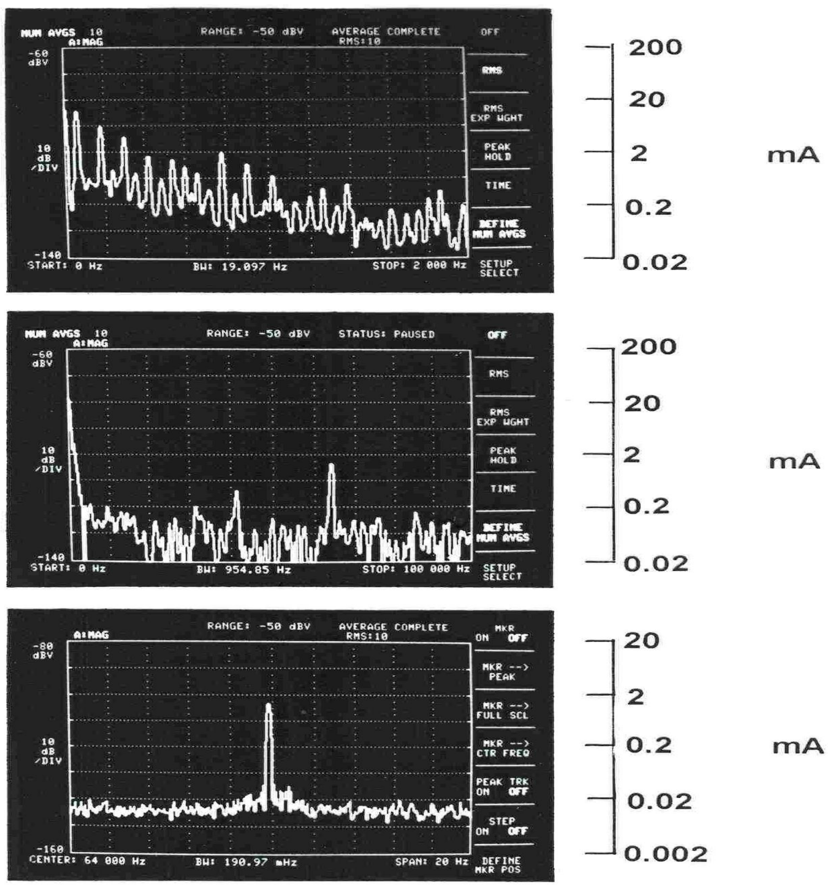
Figure 26 shows a photograph of unwanted intermittent contacts. MC cables providing power to electronic devices were in loose contact with each other. Also two of the cables were in intermittent contact with a metal floor stanchion. Unfortunately, the MC cable shields carried significant levels of current at harmonics of the electric power, and a person walking on the floor above can cause sufficient movement to produce harmful levels of transients.

Figure 26 Incidental Contact, Example 1

Still another example of incidental contacts between conductors is shown in Figure 27. In this case an extra length of MC cable was coiled and left under the floor in loose contact with other conductors. It also resulted in unwanted transients when anyone walked on the floor above the cable. Of interest is that the photograph shows that other metal objects were properly bonded together to avoid the production of transients.

Figure 27 Incidental Contact, Example 2

Significant levels of low-frequency current at the fundamental and harmonics of the electric-power frequency and at higher frequencies are found on ground buses, conduits, and other conductors of a building. Figure 28 shows three views of spectral components of current flowing on a green-wire ground from a cabinet containing digital devices. The top view shows current at the fundamental frequency and at harmonics over the frequency range of 0 to 2000 Hz. The middle view shows a coarse view of components over the frequency range of 0 to 100 kHz. The bottom view shows an expanded view of a strong component found at 64 kHz. Other cases have shown that 50- or 60-Hz levels as high as 8 A have been found flowing on conduits along with harmonic levels up to 1 A.

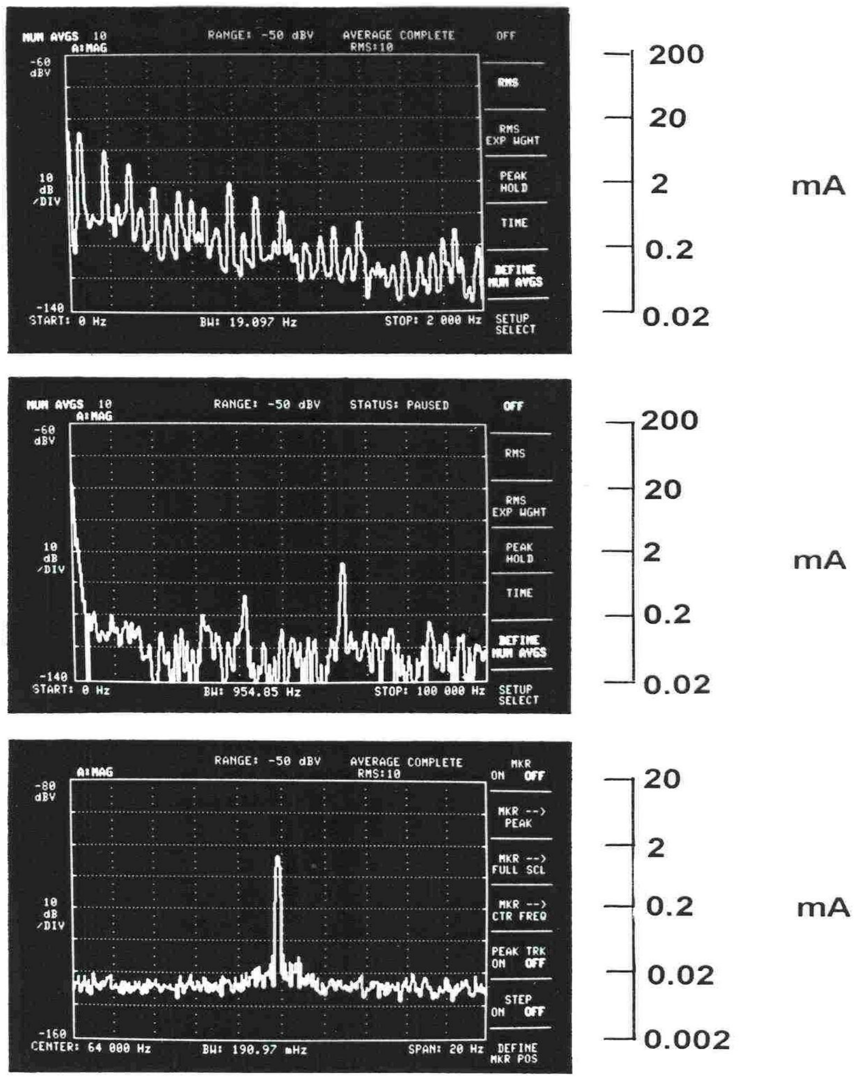


KUN, RM 332, 990212, R408, 1358, CAB GND, CT5 (20/1), P6021 (10mA/mV), 0

Figure 28 Example of Current Flowing on a Cabinet Ground

The source of the unwanted current levels is usually poorly-designed power supplies and electronic equipment. Unwanted current levels can be avoided by purchasing and installing only well-designed electronic equipment and devices that comply with the FCC Class B noise requirements or the current levels provided in Table 1.

Figure 29 shows another example of unwanted current flowing on a cabinet ground conductor. In this case multiple and sensitive digital signals appeared on a major ground conductor of a data-processing facility. Further investigation identified the same digital signals on several cable shields and on several other ground conductors. The source was a signal cable whose shield was open at one end. This was done to reduce low-frequency current also flowing on the cable shield to harmless levels, but it allowed the high-frequency digital signals to appear on the shield of the signal cable as well as on other nearby conductors.



KUN, RM 332, 990212, R408, 1358, CAB GND, CT5 (20/1), P6021 (10mA/mV), 0

Figure 29 Example of Current Flowing on a Ground Conductor

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6. STATISTICAL PROPERTIES OF NOISE AND INTERFERENCE

Radio noise and interference at the input terminals of radio receivers can originate from a variety of off-site and on-site sources. Prior to 1998 external sources dominated the noise and interference levels at the input terminals at most HF and VHF receiving sites. Occasional on-site sources would sometimes be found, but they were often lower in amplitude than noise from off-site sources. After about 1998 site-improvement programs started to introduce power-conversion devices into radio-receiving sites. The power-conversion devices convert alternating electric power into other forms of electricity using digital switching techniques. In addition, new and extensive digital signal-processing devices were added to receiving sites at about the same time.

These devices include switching power supplies, variable-speed controls for motors, uninterruptible power sources, and a great variety of digital control and processing equipment. While many such devices were designed such as to limit their emission of noise and interference, others were not. Those that did not generally increased the noise and interference levels at the input terminals of radio receivers, and this limited the ability of a receiver to detect and process data from low-level signals, thus degrading site performance.

Also at about 1998 external power-line sources started to decrease in numbers as electric utilities and base-maintenance facilities started to change insulators on <u>distribution lines</u> within line of sight of receiving antennas from ceramic and glass bells to polymer types as well as updating other aspects of their overhead power lines. Of interest is that higher voltage <u>transmission lines</u> seldom were identified as sources of radio noise since their design, construction techniques and hardware usually met low radio-noise-emission standards.

Unfortunately, the spectral and temporal properties of noise and interference from both off-site and on-site sources often change significantly with time. Rarely does a single and stable source dominate noise levels at the input terminals of a receiver. Multiple simultaneous sources often exist. Significant changes in the spectral and temporal properties of each individual source can, and do, occur erratically within seconds, minutes and to a lesser extent hours. This along with the ever-changing impulsive nature of noise and interference make it extremely difficult to describe its properties. Significant changes in the temporal and spectral properties of noise and interference often occur at time intervals comparable to message lengths.

Figure 30 shows an example of erratic noise and interference found over the 1- to 20-MHz portion of the HF band at a receiving site where the data was obtained with a conventional scanning spectrum analyzer. Four sequential scans are shown where the spacing between the first two scans is about 20 seconds, and the spacing between the other examples is only a few seconds. A careful examination of the four examples shows significant differences in detail from one to the next one. The spectral and temporal properties of the noise and interference changed significantly from example to example, and the changes cannot be understood from such sequential examples. These examples illustrate the difficulty in describing erratic noise and interference with standard instruments.

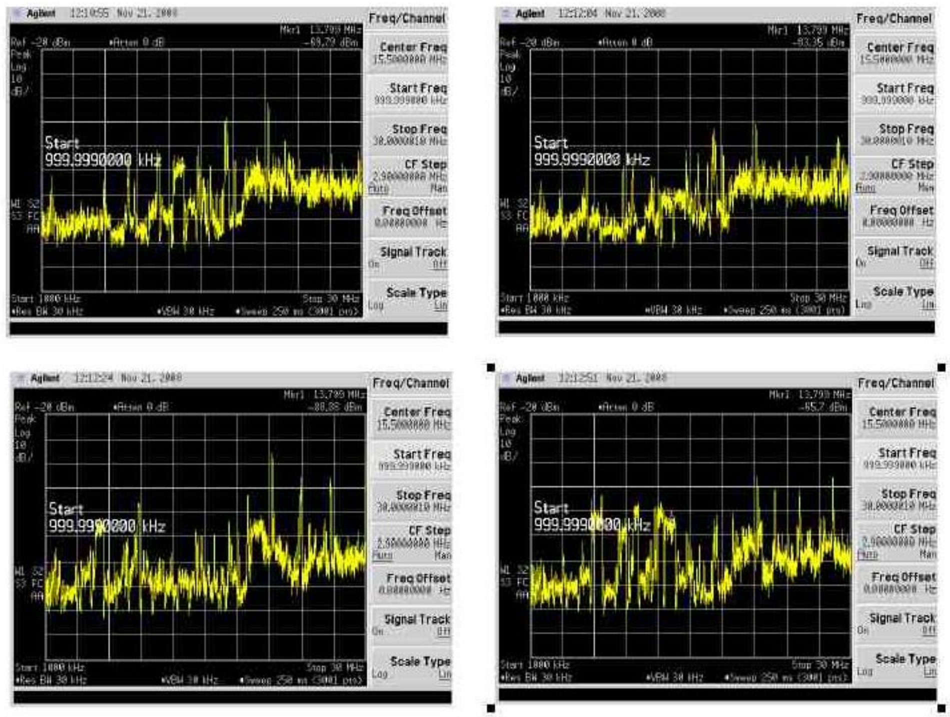


Figure 30 Example of Erratic Noise and Interference

Two additional factors must be considered. The properties of noise and interference are further complicated by the broadband nature of impulsive noise. The amplitude and the spectral and temporal properties of impulsive noise and interference are a function of measurement bandwidth. Conventional electromagnetic compatibility receivers, conventional radio receivers and spectrum analyzers all have measurement bandwidths less than the bandwidth of most cases of impulsive noise. For example, the measurement bandwidth of the noise and interference shown in Figure 30 is a 30-kHz Gaussian-shaped bandwidth. Its amplitude would be less with a measurement bandwidth of 3 kHz, and its temporal structure would be different. Thus, the amplitude, and the temporal properties of all examples of impulsive noise and interference provided in this handbook are dependent on measurement bandwidth. A general scaling rule for amplitude changes with bandwidth is provided in Appendix A.

In addition to the measurement bandwidth issue, the amplitude of noise and interference appearing at the input terminals of a receiver changes significantly across a even a relatively small frequency band. The frequency-flat noise produced by laboratory test sources is seldom encountered at the input terminals of a radio receiver. Significant peaks and nulls in amplitude with frequency are shown in many of the examples provided which illustrates this condition.

Laboratory and acceptance testing of radio receiving equipment and data processing devices is commonly done using time-stable signals and time-stable noise. Both can be measured and quantified with stationary statistical values such as average, root-mean-square, amplitude probability distributions, etc. However, in actual practical cases the noise and interference at the input terminals of a receiver, as well as signals, are often highly erratic, and can only be described as a non-stationary statistical process.

Brief statements for the meaning of stationary and non-stationary data or processes are provided to aid in understanding and defining the properties of noise and interference encountered at the input terminals of a radio receiver.

- Noise and interference data and signals are stationary if their statistical properties (such as average, root-mean-square, amplitude probability, and other measures) are all stable and constant during a time interval of interest.
- Noise and interference data and signals are non-stationary if any of their statistical properties (such as average, root-mean-square, amplitude probability, and other measures) change during a time interval of interest.

Thus, little experience is gained during standard laboratory and acceptance testing of equipment related to its performance under the erratic and changing conditions such as encountered at radio-receiving facilities. Also, there is a major paucity of instrumentation and procedures to cope with the erratic noise, interference and signals encountered at radio-receiving facilities. The lack of attention to this problem also results in a lack of personnel who are trained to understand and cope with practical field conditions.

Unfortunately, the complexity of applying non-stationary statistical processes has discouraged personnel associated with receiving sites from its use. In past years, progress in understanding non-stationary statistical processes has been slow and largely limited to a few mathematicians and specialized statistical individuals. Recently, this has changed because a large variety of cases have been found to fit the definition of a non-stationary process, and considerable attention is now being devoted to such cases. For example, a recent series of conferences at Cambridge University[10] in England dealt with practical communications problems related to the erratic noise and interference encountered at radio-receiving facilities as well as other similar and related problems. A few text books directed at solutions to such practical problems are starting to appear[11] although much additional material related to practical applications is needed.

New applied research programs and additional conferences, such as the University of Cambridge conference, are urgently needed where mathematicians, statisticians and engineers can explore practical problems such as the impact of erratic and non-stationary interference and noise on the reception and processing of erratic and non-stationary radio signals.

[10] http://www.newton.ac.uk/reports/9899/nsp.html

[11] *Nonlinear and Nonstationary Signal Processing*, Edited by W. J. Fitzgerald, University of Cambridge (ISBN-13:9780521800440 | ISBN-10: 0521800447)

Real-time, time-history presentations of signals, noise and interference are used throughout this handbook (and in its complementary handbook for off-site noise sources) to graphically portray the time-changing spectral and temporal properties of noise, interference and signals. This provides an alternate approach to investigate practical field problems and to provide the information needed to identify sources. While this approach offers a convenient graphical way to portray actual conditions, it does not provide a means to supply simple values for noise and interference or the numerical values needed to evaluate the loss of received signals due to noise and interference.

A few additional graphical examples of noise and interference at the input terminals of radio receivers are provided to illustrate the difficulty of defining their properties in simple terms. Figure 31 shows two examples of intermittent interference from the controllers for variable-speed electric-motor drives. The left view shows interference across the 415- to 435-MHz portion of the spectrum of interest at the input terminals of a VHF receiver. The right shows an example of interference at the input terminals of an HF receiver where the spectrum analyzer frequency span was set at zero to better portray the temporal structure of the interference at a specific frequency. In both cases the interference erratically changed with time. Also, significant differences in the temporal structure of the two cases are shown.

In both examples, the interference extended well above and below the frequency ranges shown.

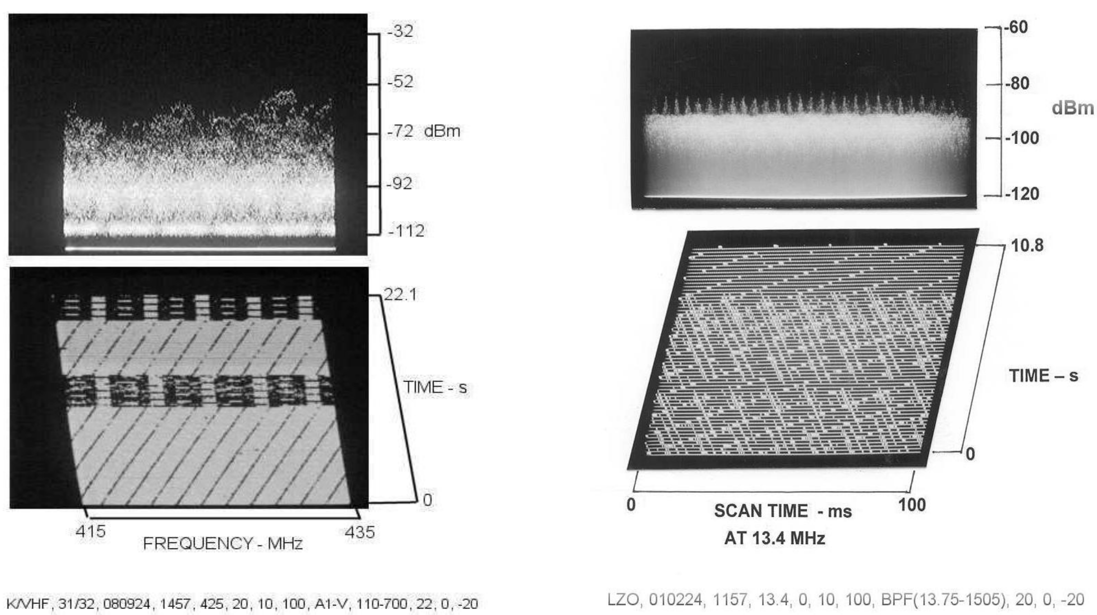


Figure 31 Severe Radio Interference from Variable-Speed Electric-Motor Drives

Figure 32 shows two examples of intermittent interference to receivers. The left view shows interference from three frequency-hopping sources located off-site but less than a km from the receiving site. A number of ambient signals are shown as well as the frequency-hopping emissions. In this case, interference to signal reception only occurred when a hopping signal burst was within or near the bandwidth of a VHF receiver, thus the occurrence of interference was erratic and unpredictable.

The right view shows variable-frequency emissions causing intermittent interference to an HF receiver. In this case, multiple emissions from the radio-frequency heaters of multiple plastic molding machines caused the intermittent interference. Such emissions are permitted for the Industrial, Scientific and Medical (ISM) radio service within the band of 27.120 MHz ± 160 kHz. The emissions originated from a factory located more than 10 km from the receiving site, and the emissions are clearly outside their allocated frequency band.

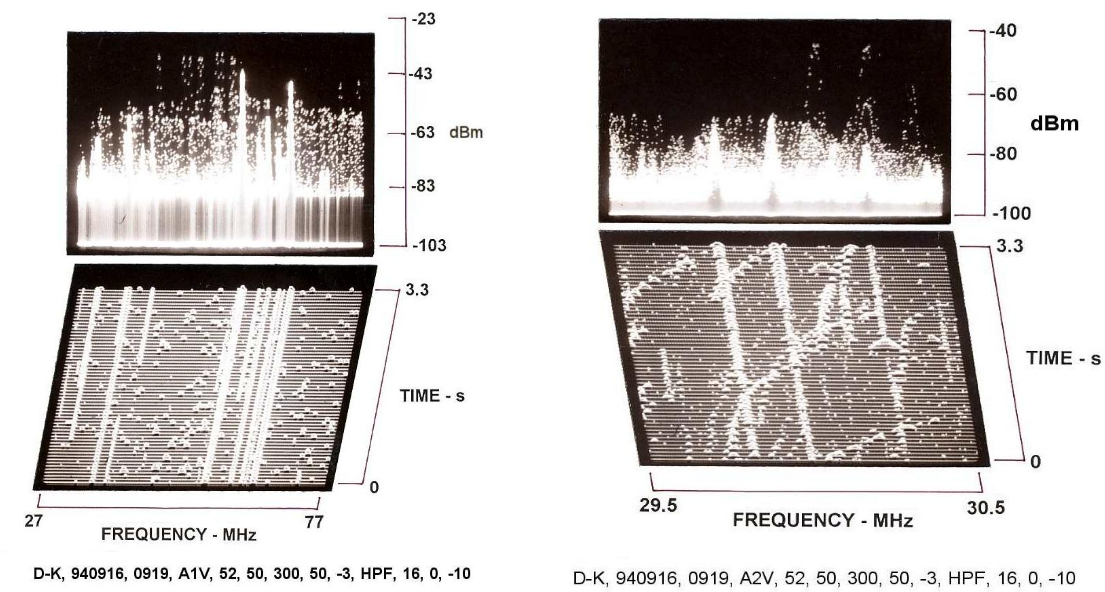
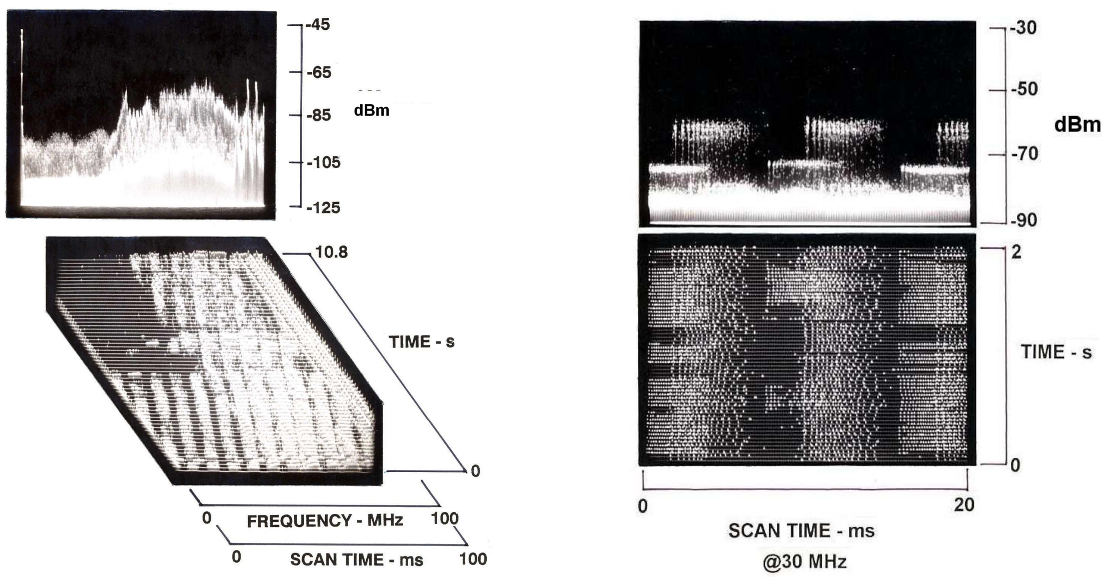


Figure 32 Intermittent Interference from Frequency-Hopping and ISM Emissions

Radio interference from sources on electric utility distribution lines is frequently encountered at HF and VHF receiving sites. Figure 34 shows two examples of such interference. The left view shows interference from two sources where one operated continuously over the 10.8 s observation time and the other only over the lower half of the time-history view.

The right figure shows the complex temporal structure of two simultaneous sources. In this case the frequency scan of the spectrum analyzer was set at zero-frequency scan and the scan time was changed to enhance the detail of temporal structure. The amplitude differences of the three sources are shown in the upper view. The two views show the details of the interference at the input terminals of a receiver set at a frequency of 30 MHz.



SI, 860713, 1500, 13.4 kV, 1 m, 50, 100, 300, 100, 24, 0, -20

J, 951026, 1354, 30, 0, 300, 30LS, BP, 0, 0, -10

Figure 33 The Complex Structure of Intermittent Power Line Interference

Figure 34 shows two views of signals and interference in the unlicensed 2.4-GHz wireless band. The left view shows the dense population of signals in the band along with an emission from a microwave oven. The upper view shows the densely packed and overlapping signals from multiple 802.11b devices as well as other sources. Interference from a microwave oven is shown about ¾ of the way down the time axis of the time-history view.

The right pair of views shows signals and interference prior to the addition of a wireless router in a home office. The slanting lines are caused by the synchronizing pulses emitted by two fairly strong emissions from existing nearby 802.11b Access Points along with a third low-amplitude 802.11b signal. Strong intermittent interference is shown in the time-history view while the amplitude of each emission is shown in the upper amplitude vs. frequency view. Two narrow-band signals are also shown in the time-history view along with intermittent interference from an unknown source.

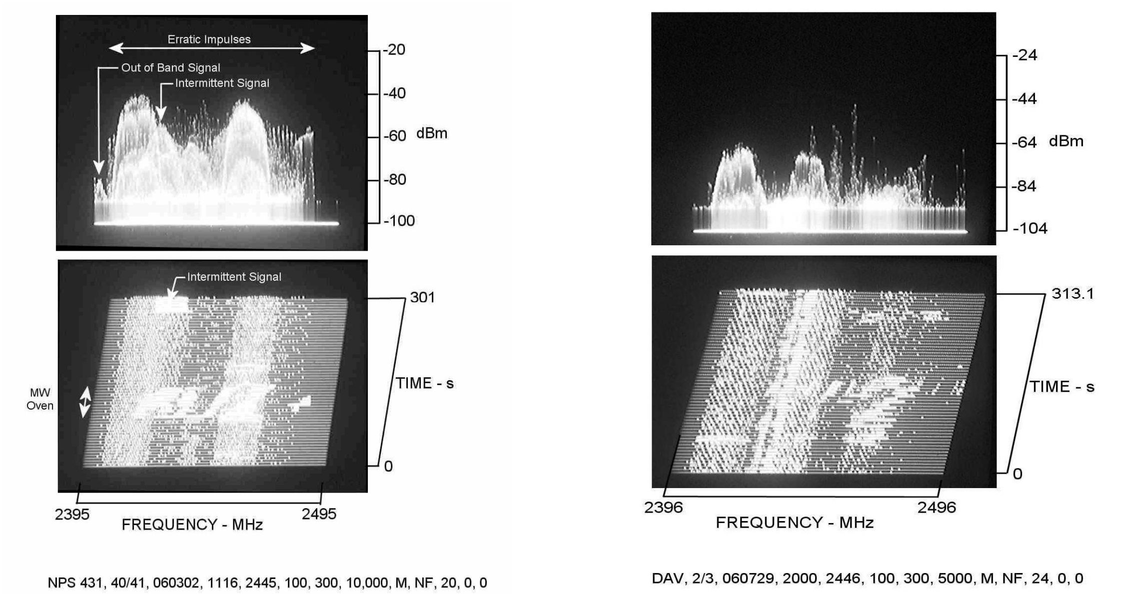


Figure 34 Signals and Interference in the 2.4-GHz Wireless Band

While emphasis has been given to the erratic structure of noise and interference, the temporal and spectral structure of signals can also be erratic and be statistically non-stationary. Burst signals that occur at random and unknown times are an example.

Figure 35 shows two examples of signals severely distorted by propagation effects. The left view shows an HF signal severely distorted by selective fading where the fading was caused by its arrival from a distant source over multiple ionospheric propagation paths. Four discrete-frequency synchronizing signals can be seen at the upper edge of the time-history view followed by the main band-limited short-duration PSK signal. The strong signal near the left edge of the frequency scale is not related to the signal of interest. The severity of the distortion changed from very little to severe with time.

The example in the right view shows the distortion of a UHF signal caused by the movement of objects in the path between its source and the receiving antenna. In this case the source was a spread-spectrum signal with a spectral width of slightly less than 2 MHz. The spectral sidebands of the signal were suppressed. A narrowband signal exists near the upper frequency limit of the example at slightly higher amplitude than the primary signal of interest.

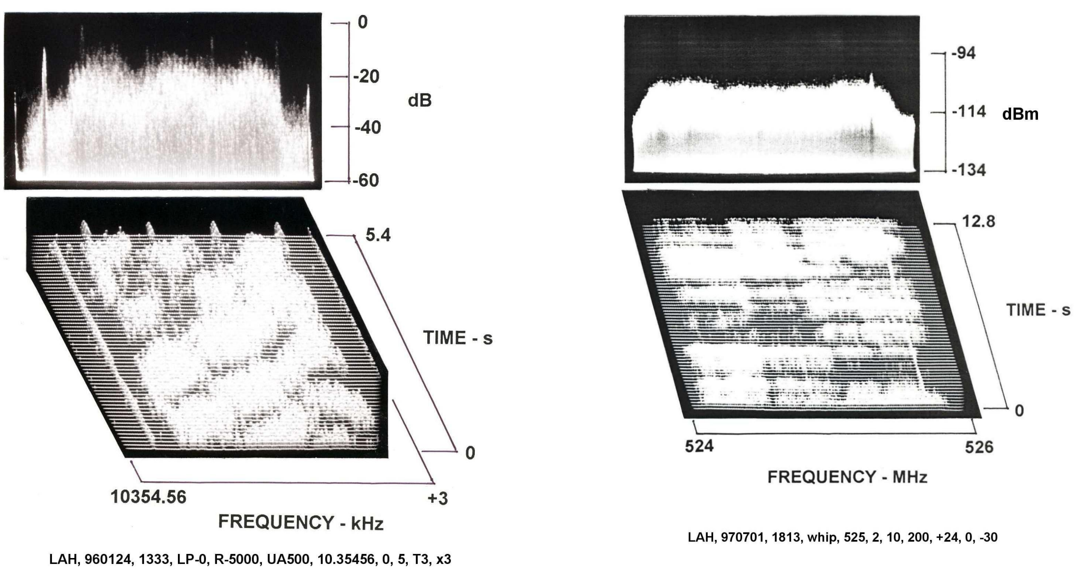


Figure 35 Erratic Signals

7. MITIGATION TECHNIQUES

7.1 Mitigation Principles

The only effective mitigation technique is to identify each actual source of noise and interference and reduce the emission levels of each source sufficiently to prevent harmful effects.

A large variety of power-conversion devices and other sources are used in modern radio-receiving sites. Examples are switching power supplies, variable-speed drives for the electric motors in air-handling and air-conditioning systems, temperature control devices, Uninterruptible Power Supplies, water-flow control equipment, and many other devices and systems. These devices and systems are highly useful, and they usually add significant capabilities to the operation of a receiving site. Some of these devices are sufficiently noise quiet that their use is acceptable and desirable. Others have been found to be major sources of radio noise, and their use in a radio-receiving site is not acceptable. The rule is: never install a power-conversion device or any other noise or interference source in a receiving site that is, or will become, a source of harmful levels of radio noise.

In general, devices and equipment purchased which meets the FCC Class B radio-noise requirements will function in a satisfactory manner in a radio-receiving site. Nevertheless, some such devices installed in a critical location may still cause low-levels of radio noise and interference. A more appropriate set of guidelines is provided in Table 1. Once a device that generates harmful levels of radio noise and interference is installed in a receiving site, the only option is to remove the offending device or implement effective mitigation procedures. The basic principles of mitigation of power-conversion devices and other sources are described in this section followed by other sections containing specific examples of unsuccessful and successful installations.

The techniques described in this section are not new. They were developed and successfully applied to radio noise and interference problems in the very early days of radio. Nanevicz and his colleagues reviewed these techniques in the 1980s and used the term ñTopological Controlò to describe the EMI control techniques[12]. Later, the students and staff of the Signal Enhancement Laboratory of the Naval Postgraduate School expanded on these concepts under the name ñBarrier, Filter and Ground (BFG)ò techniques to mitigate sources of radio noise and interference where the name represents the three primary factors necessary for a successful mitigation process (electromagnetic shields or barriers, filters, and grounds).

[12] J.E. Nanevicz, *Topological Anomalies in Test Methods*, Paper Presented at the EMP Workshop on Compatible Interference Control Techniques at the 1980 IEEE Electromagnetic Compatibility Symposium in Baltimore MD.

Figure 36 shows the basic aspects of the BFG process where a source is completely enclosed within an electromagnetic barrier. The barrier can be metal such as steel or aluminum. Special materials such as MμMetal are seldom required to achieve a sufficient level of control. The shield can have electrically small holes such found in copper screen or punched aluminum material, and standard commercial metal boxes or cases often provide sufficient shielding. Expensive shielded rooms are only required for special cases or physically large systems.

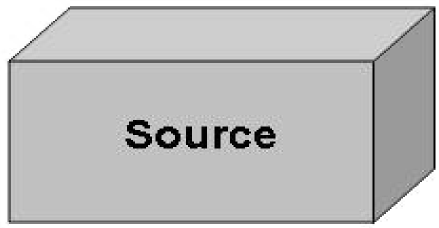


Figure 36 Source Enclosed within an Electromagnetic Barrier

Figure 36 describes a somewhat impractical case since external sources of electric power usually must be provided to the source, a ground must be provided for compliance with the NEC, the source probably will be connected to other devices, and conductors are often required to control the operation of a source. These items require that conductors penetrate the electromagnetic shield.

Figure 37 shows how power can be applied to a source. A bulkhead type of filter can be installed directly onto the metallic surface of an enclosure and alternating- or direct-current power can be provided to internal devices through the filter. The filter allows low-frequency electric power to be provided to the source at very low loss while higher-frequency noise is attenuated and cannot be conducted onto the outside power conductors at harmful levels. In addition, the filter prevents external interference and noise from penetrating into the shielded enclosure. Small and inexpensive filters can be used on low-power sources, but large filters will be required for high-power sources. The primary rule is that <u>no conductor can be allowed to penetrate the electromagnetic shield without a filter or other means</u> to prevent the flow of harmful levels of EMI current or voltage to leave or enter the enclosure.

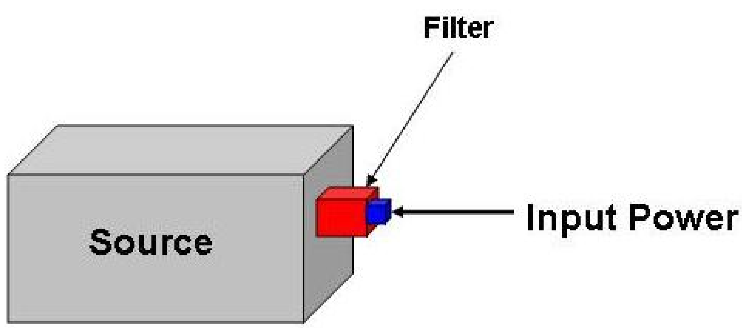


Figure 37 Provision of Power to a Source

Most sources also must operate or be connected to an external device. For example, many power-conversion devices operate variable-speed induction electric motors by varying the frequency of the power provided to the motor. A second filter can be installed on the surface of the electromagnetic barrier to prevent the conduction of noise current and noise voltage onto conductors leading to external locations or the conduction of noise current and voltage from external sources from entering the enclosure as shown in Figure 38.

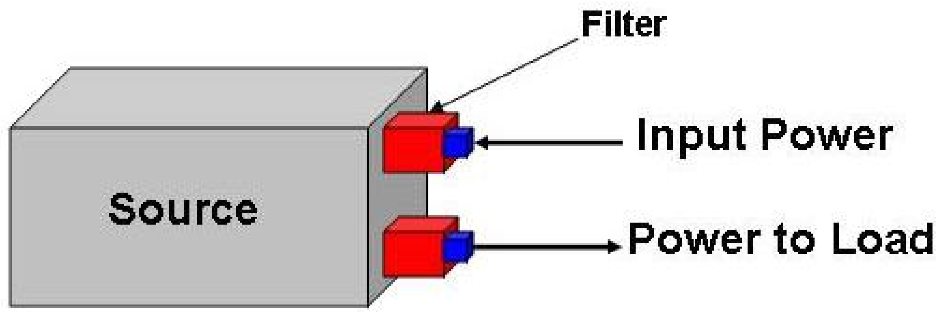


Figure 38 Provision of Power to a Load

Alternatively, the electromagnetic barrier can be extended to include the conductors from the barrier to a load. For example, most electric motors are sufficiently enclosed in metal to provide a suitable electromagnetic barrier. Figure 39 shows such a configuration where metal conduit is used between the source and a motor or other load to shield the conductors. The conduit or shield around the conductors must be electrically bonded to both the source barrier and to the barrier enclosing the motor or other load. Open shields cannot be used.

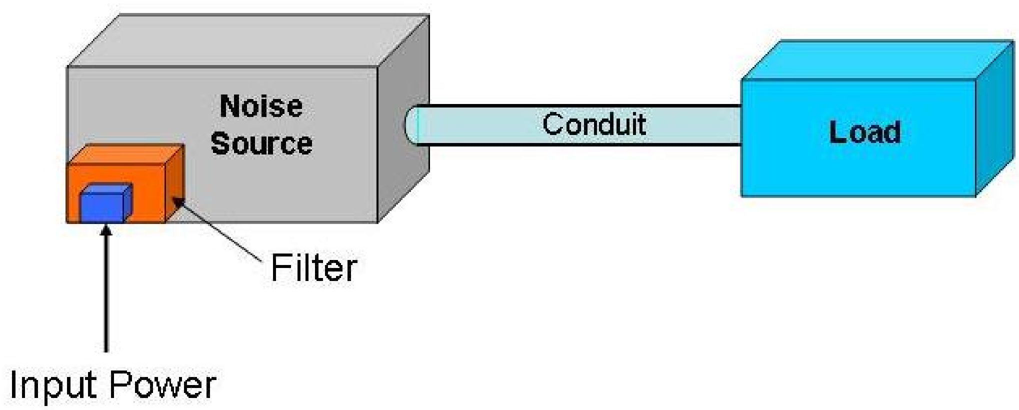


Figure 39 Source-to-Load Connection

Most electrical and electronic installations require a safety or green-wire ground. Unfortunately, ground conductors often carry significant amounts of high-frequency noise current and voltage (often at higher levels than on the power conductors). Figure 40 shows an effective means to prevent the conduction of high-frequency noise current and voltage from an internal source to an outside conductor over a ground wire or from an external source into the barrier. Ground conductors inside the barrier are bonded to the inside surface of the barrier. Ground conductors outside the barrier are bonded to the outside surface of the barrier. This provides a path for noise current flowing on the internal ground conductor to return to its source inside the barrier. The barrier also prevents the conduction of high-frequency noise current and voltage from external sources into the barrier. Since the barrier will conduct low-frequency power-related current with little loss, all safety aspects of the NEC green-wire ground are maintained.

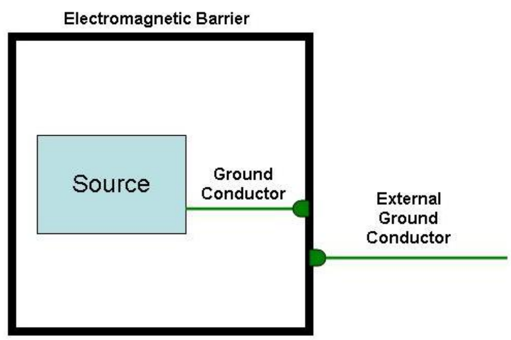


Figure 40 Barrier Treatment of a Ground Conductor

As shown in Figure 40, it is advisable to use separate closely-spaced ground connections for the internal and external grounds since unwanted ground current may pass through a single stud.

Figure 41 shows a ground configuration that meets the requirements of the NEC, but it violates BFG principles. In this case the green-wire ground is carried into the interior of the electromagnetic barrier through a hole, and noise and interference current will flow into and out of the barrier. This configuration should never be used for electronic devices in a radio-receiving site.

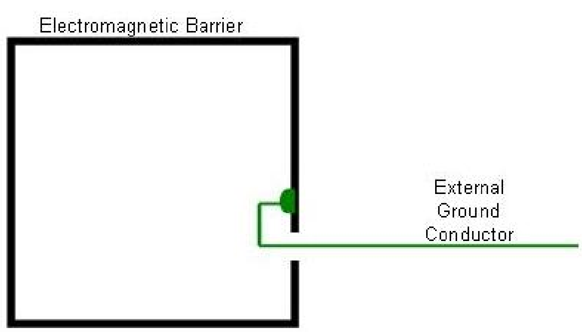


Figure 41 Improper and Ineffective Treatment of a Ground Conductor

Unfortunately, the method of grounding shown in Figure 41 is frequently used in electronic equipment, and Figure 42 shows two views of a popular type of chassis power connector that fits this case. The ground conductor of the plastic connector protrudes inside a chassis barrier, and it connects to the inside surface of the barrier. The connector meets all requirements of the NEC green-wire ground, but it does not provide a means to control high-frequency noise current or voltage flowing on any conductor. This type of power connector can be used on devices or equipment that does not contain a source of EMI or on equipment that is not susceptible to EMI (such as an incandescent light bulb), but its use in electronic equipment should be strictly avoided.

Figure 42 Chassis Power Connector that does not comply with BFG Needs

Figure 43 shows another popular type of chassis power connector that is available from a number of manufacturers. In this case the connector provides a filter for each power conductor and the ground configuration of the connector meets all BFG requirements. The external ground wire is connected to the external surface of an equipment case or chassis while the internal ground is connected to the internal surface of the equipment case or chassis. While the figure shows a low-power connector, this style is available in a variety of power ratings and filter configurations. It is recommended for use in all electrical and electronic equipment that contains a source of EMI or is susceptible to EMI.

Figure 43 Chassis Power Connector that meets BFG Needs

Many devices require additional conductors that penetrate an electromagnetic barrier. For example coaxial bulkhead fittings provide a means to interconnect coaxial cables between multiple barriers. However, one must use connector types that comply with the Barrier-Filter-Ground principles. Figure 44 shows three insulated bulkhead coaxial connectors that do not allow the coaxial cable shield to be terminated on each side of a barrier. The use of these types of insulated connectors must be avoided since they destroy the integrity of an electromagnetic barrier. EMI current from a source inside the barrier will be carried outside the barrier on the cable shield. Also, EMI current from outside sources will be carried to victim devices inside a barrier.

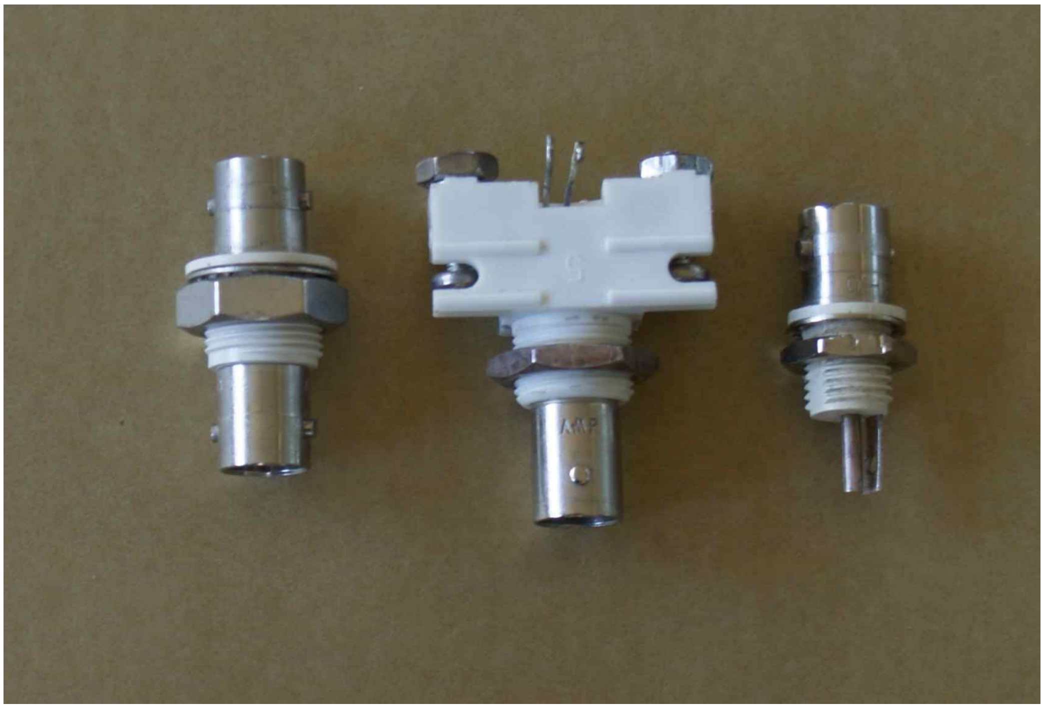


Figure 44 Examples of Insulated Bulkhead Connectors

It is important that the processes illustrated in Figures 36 through 44 be strictly followed to eliminate noise problems from power-conversion and other digital devices. Any uncontrolled conductor that is allowed to penetrate a barrier, regardless of its importance, will carry high-frequency noise current outside the barrier where it can be coupled into other nearby cables or conducting material by direct conduction or by inductive and/or capacitive coupling. There is no shortcut to the mitigation process.

7.2 Effective Examples

It is impractical in this handbook to provide a specific mitigation example, design or instructions for each of the many sources of radio noise and interference associated with power-conversion and other devices. Successful mitigation actions depend on the physical configuration of the actual source of noise. It must be physically possible to implement the barrier, filter, and ground techniques described in Section 7.1. For example, physically small sources can often be effectively mitigated with minimal alteration to a source and often at low cost. Poorly designed low-power sources of EMI and physically large devices sometimes require considerable modification and at high cost. The general approach is identical to all types of sources, and this section describes actual procedures used to mitigate radio-noise problems.

After a power-conversion source is located and identified, it must be inspected to determine the best approach to limit the transfer of radio noise from the source onto other conductors such as power wires, conduits, ground conductors, cabinet walls and other conductors associated with the operation of the source. The actual source of impulsive current and voltage must be placed inside an electromagnetically shielded enclosure. This can be a small enclosure for a physically small source or it can be a large shielded room for a physically large device.

Figure 45 shows an example of a successful installation of filters on the metal box containing the power-conversion devices for two variable-speed electric-motor drives. In this case two filters were required since the system required both 120-V single-phase and 240-V three-phase electric power. The two filters were bolted directly onto the side of the metal box, and care was taken to ensure that the filter case was in direct electrical contact with the housing. An additional small box was added to each filter to provide physical support for the input power conductors. These two filters prevented noise current and voltage from escaping the metal box over the power conductors and green-wire ground conductor.

Figure 45 Filter Installation to Suppress Motor-Controller Noise

Conductors from the controller to two electric motors exited the case on its lower side. These conductors were inside conduits that ran from the controller's case to each motor, and the conduits were bonded to the controller's case and to the motor's housing. Additional conductors associated with an external control box were provided to adjust the speed of each motor, and they also exited the bottom of the controller's case. These conductors were in a flexible shielded cable, and the shield was terminated at the controller's case and at the control-box case. No unshielded conductor was allowed to penetrate the controller's case. All radio noise problems associated with the controller were successfully mitigated.

Figure 46 shows two views of a 1.4 KVA UPS that was modified for use in a small receiving site. This particular UPS injected sufficient impulsive noise current onto its power conductors and onto the input and output green-wire grounds that its use in a receiving site prior to modification was unacceptable.

A filter for input 120-V power was added inside the case of the UPS as shown in the left view. There was not sufficient room inside the UPS for the output filter so it was added to the outside of the UPS case and was enclosed in a metal box to protect the short wires from the filter to the electrical sockets. The filter styles and their installation complied with the BFG principles, and the modification to the standard UPS successfully corrected a radio-noise problem.

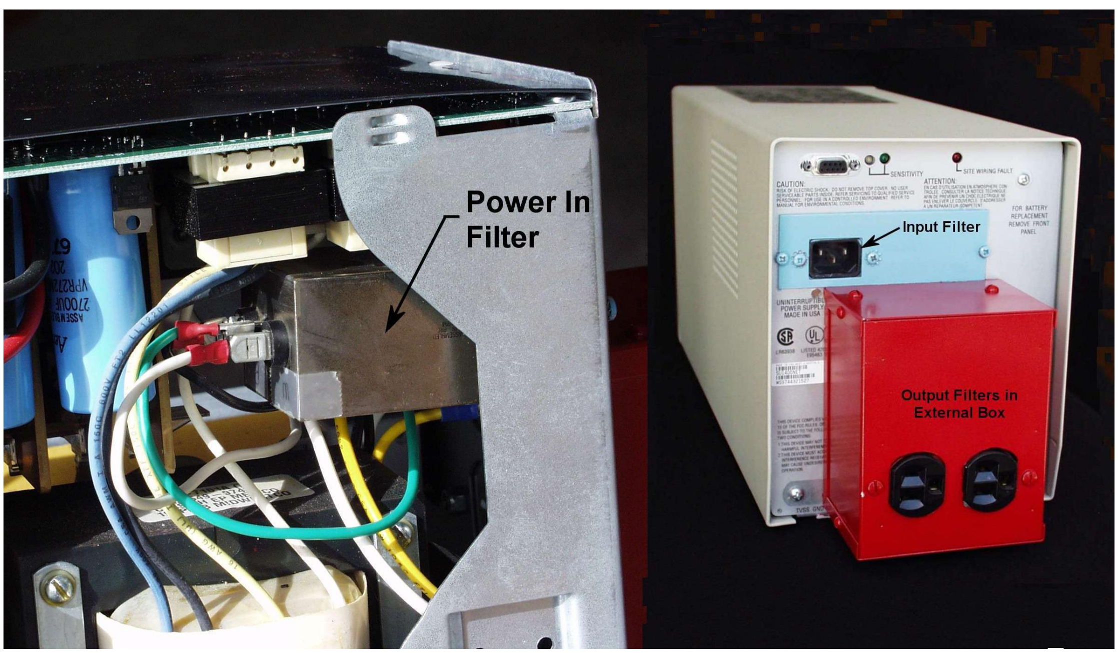


Figure 46 UPS Modified to Comply with BFG Principles

Figure 47 shows the rear panel of the Model 7200B Time-History Display described in Appendix A. This instrument contains high-level digital devices and switching power supplies that generate significant levels of impulsive noise, but its case was designed in accordance with the BFG principles described in this section. The power connector shown in the photograph is a small unit containing an integrated filter of the type described in Figure 43. The unit can be operated in close proximity to the antennas of a receiving site without producing detectable noise or interference.

Figure 47 Power Connector that Complies with BFG Principles

Figure 48 shows coaxial bulkhead fittings on the rear of the Model 7200B Time-History Display. Five bulkhead fittings were required to pass signals in and out of the unit. Non-insulated bulkhead connectors were used to terminate the shields of coaxial cables on both the inside and the outside of the instrumentǒs case in accordance with BFG principles.

Figure 48 Coax Feed Bulkhead Connectors that Comply with BFG Principles

7.3 Ineffective Examples

An example of an ineffective filter installation is provided to illustrate some common deficiencies that occur in improperly engineered attempts to solve electromagnetic-noise problems. Figure 49 shows a filter installed to prevent EMI current and voltage from a source from being received by nearby antennas. In this case the source was the electronic controller for a variable-speed fan motor of an air-conditioning unit. The physically-small electronic controller was located inside the large metal housing of the air-conditioner unit. Power to the air-conditioning unit and the variable-speed controller unit was provided through a metal conduit running to a filter located about 15 feet from the air-conditioner unit. Conduit then ran from the filter enclosure to the power panel.

The controller-to-filter conduit was properly terminated on the bottom left side of the filter box. The conduit to the power panel was terminated at the bottom right side of the filter enclosure. The filter was nicely installed in the standard metal housing that provided an excellent and acceptable shield around the filter; however other aspects of the installation completely negated the effectiveness of the filter.

Figure 49 Improper Filter Configuration

Several improper aspects of the filter installation resulted in the total lack of suppression of a severe electromagnetic impulsive noise problem. These aspects were:

- The conductors from the controller to the filter carried high levels of impulsive current along with the normal variable-frequently power to operate a fan motor. Some of this impulsive current was inductively and capacitively coupled to the interior surface of the shield case and was, in turn, inductively and capacitively coupled to the output conductors. There was no electromagnetic isolation or barrier between the input and the output of the filter.

- The green-wire ground conductor also carried high levels of impulsive current and voltage, and the input and output green wires were connected directly together as shown by the green conductor running across the bottom of the case. This provided a direct conducting path for noise current and voltage to bypass the filter. Because the green-wire ground is close to the power conductors, its EMI was inductively and capacitively coupled back onto the power conductors and onto other conductors associated with it in the power panel.
- The physically-small source device was located inside a very large metal enclosure located about 15 feet from the filter. While the conduit from the filter was bonded to the external surface of the large enclosure, electrically long conductors from the source inside the enclosure injected excessive impulsive and broadband noise current into its associated conductors and onto all nearby conductors. The open bottom to this large enclosure and other untreated conductors penetrating the enclosure allowed impulsive noise to appear on the outside of the case and on all associated conduits as well as all power wires and all green-wire ground conductors associated with the large enclosure. This induced noise current and voltage onto the outside surface of the conduit as well as well as on the power conductors and the green-wire ground conductors running inside the conduit to the filter. These conducting objects constituted a complex, but effective, radiator of the noise. Nearby receiving antennas intercepted the noise fields resulting in high levels of radio interference to all radio receivers at the site.

There is no simple corrective action that can be taken to alter or correct the deficiencies of the filter installation shown in Figure 49. The only viable corrective action was at the source itself. In this case the source device was very small and its enclosure could have been a small and inexpensive metal box along with appropriate filters for all conductors penetrating the small enclosure in accordance with the principles shown in Section 7. These inexpensive and effective mitigation actions required:

1. The small source device itself must be enclosed in a small metal box.
2. All conductors entering and exiting this metal box must pass through filters with the exception of the green-wire ground which must be terminated on the outside and inside surface of the enclosure.
3. The green-wire ground must be connected as shown in Figure 40.
4. Finally, remove and scrap the existing filter and its enclosure and reconnect all power conductors and their conduits in a normal configuration.

Figure 50 shows another example of a harmful source of impulsive noise. The photograph shows the side panel of a heavy-duty switching power supply. A hole was punched in the panel to provide a means for the DC leads of the power supply to exit its case. In this case, high-frequency components of impulsive noise were present on the direct-current supply conductors, and it created harmful levels of interference to other nearby digital devices and to the reception of radio signals. The corrective action was: add a filter to the DC leads and to the AC input power of the switching power supply.

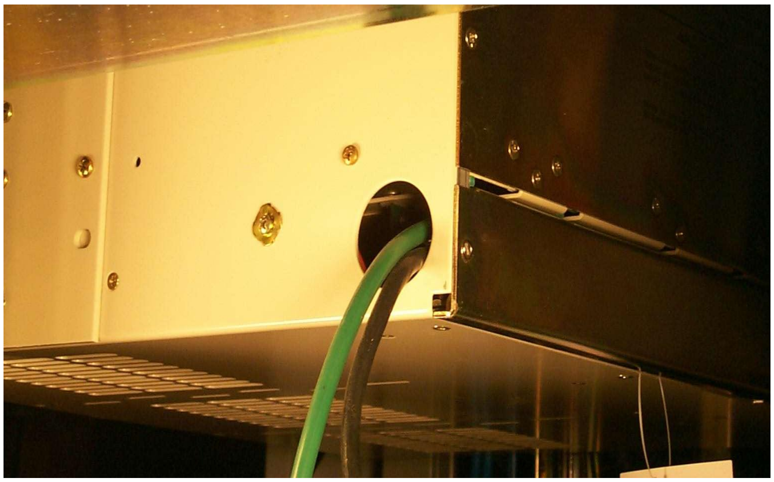


Figure 50 Unfiltered Conductors Exiting a Switching Power Supply

Figure 51 shows a computer power supply with a type of power connector normally considered unacceptable (see Figure 42). However, the internal circuits of the switching power supply in this computer were designed to meet the low-noise emissions requirements of the Federal Communication Commission Class B noise specification, and a label on the computer indicated it had been tested to the Class B specification. In this specific case, the use of the unfiltered connector is acceptable.

Figure 51 Computer Power Supply not in Accordance with BFG Principles

7.4 Saturated Components in the RF Path

Examples of the intermodulation products and intermodulation noise created by saturated components in the RF paths of receiving sites are provided in Section 5.2. The following procedures will aid in obtaining and maintaining a noise-free RF distribution system which is free of components which introduce noise and intermodulation.

- Limit the bandwidth of RF paths with band-pass filters located prior to the use of any item whose dynamic range cannot handle the full level of signal, noise and interference power collected by an antenna. Ensure that all band-pass filters can handle the maximum level of signal, noise and interference power received by an antenna including all out-of-band emissions. Filters rated for 1-Watt of total power will usually be sufficient unless a site is located in close proximity to a transmitting site or the site itself contains transmitters.
- Avoid the use of any component in an RF path prior to a band-pass filter that contains elements that can saturate from the total signal power applied to them. This includes items such as line amplifiers, multicouplers, directional couplers and signal splitters. Ensure that all such items are rated to handle the maximum signal, noise, and interference power applied to them. All signal splitters and other components that contain ferrite components or nonlinear capacitors should be able to handle at least 1-Watt of total power and maintain linear operation. Avoid the use of small and inexpensive line amplifiers and multicouplers.
- In general, avoid line amplifier and multicouplers whose amplifying component use less than 12 to 15 watts of d.c. power. In some cases even high dynamic-range line amplifiers and multicouplers will not meet site needs, and site operators must be aware of their adverse impact of signal reception.
- For maximum equipment life, provide sufficient cooling for line amplifiers, multicouplers and other heat generating devices.

7.5 Cable Leakage

Examples of signal and noise leakage into coaxial cables are provided in Section 5.3, and Figure 11 in that section provides measured values of cable-to-cable isolation for typical flexible coaxial cables. Note that a 0-dBm signal in a single-shielded cable with only 80 dB of isolation to another similar nearby cable will result in a -80 dBm signal in the second cable. If a receiver connected to the second cable has a noise floor of -130 dBm for a 3-kHz bandwidth, the leakage signal will be 50-dB above the noise floor of the receiver.

The following procedures will eliminate emission leakage problems in RF paths.

- For long coaxial cable runs, use low-loss and solid-shielded coaxial cable such as Times LMR series or Andrew Corporation Heliax cable. Carefully check the total attenuation for the length needed from the manufacturer's literature, and use an appropriate size cable.
- Never use single-shielded coaxial cable for any application in a receiving site, even for very short coaxial cables.
- Always use double-shielded coaxial cable. Where flexible cable is needed for short 50-Ohm runs, use a cable such as MI7/84-RG-223/U or one with equivalent shielding.

7.6 Shielded Rooms

Examples of problems found with shielded rooms are provided in Section 5.5. Additional information about shielded enclosures to control radio interference is provided in Section 6.1.1.

General guidelines for the use of shielded rooms are provided below.

- Shielded rooms are required only for highly critical applications where their cost can be justified. Most sources of radio interference can be controlled and isolated using standard metal enclosures provided the barrier, filter and ground techniques described in this handbook are properly used.

- Never allow a conductor or a pipe to penetrate a shielded room or a shielded enclosure without bonding it to both the external and internal surfaces of the shield wall with electrically-short bonding conductors.

- If a shielded signal cable or a coaxial cable is allowed to penetrate a shielded room or a shielded enclosure, its shield must be terminated on both the inside and the outside surface of the shield wall. Standard non-insulated coaxial feed-through connectors provide an excellent means to terminate a coaxial cable shield to both surfaces.

- Shielded rooms provide excellent attenuation of electric fields from internal and external sources. However, they provide only partial isolation from near-field sources magnetic fields located inside a shielded enclosure at frequencies below about 50 kHz, and near-zone techniques can be used to detect, measure, and receive such sources outside an enclosure. External sources of magnetic fields at frequencies below about 50 kHz also penetrate a shielded enclosure and can be detected inside such an enclosure with near-zone techniques. This is because the skin depth of current flowing in shielded material is often larger than the thickness of the material at low radio frequencies. Thus, caution must be used in locating a shielded room and in its applications.

- The conducting strips around doors deteriorate with use and age thus decreasing the effectiveness of a shielded room. If a full shielded room is required to prevent an internal source from escaping the room or an outside source from entering the room, then ongoing maintenance is necessary.

7.7 Buildings Issues

A number of building issues have been noted at receiving sites. Among these are numerous cases of incidental contacts, and examples are shown in Figures 52 and 53. For example Figure 52 shows an MC cable touching a floor support and a conduit. If potential differences exist between the cable and the other metal items and movement occurs, the thin layer of oxide on the floor support and on the conduit can be penetrated with a resulting electrical transient. The transient will be propagated along the conducting objects, be inductively and/or capacitively coupled to other conductors and can eventually reach sensitive equipment. Such transients have been observed to disrupt computers and can enter the RF paths to radio receivers.

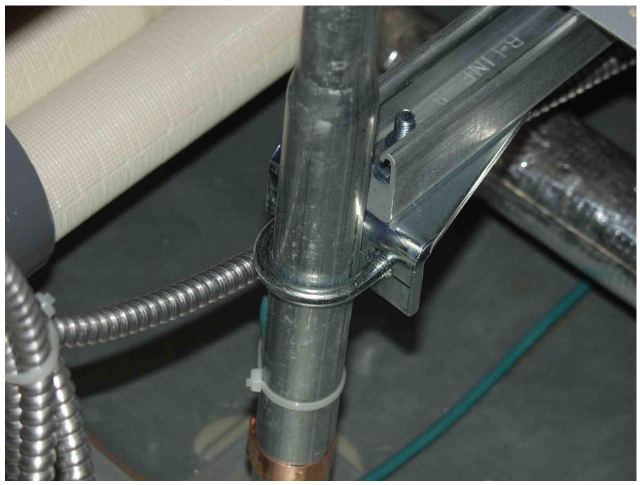


Figure 52 Incidental Contact, Example 1

Figure 53 shows another example where a loose coil of BX cable touches other metallic items under a raised floor. Other conductors are supported or bonded to avoid incidental contacts.

Figure 53 Incidental Contact, Example 2

Figure 54 shows an example of a weld on galvanized angle material used to support electrical and electronic equipment. Current flowing in the welded joints can produce intermodulation products and intermodulation noise which is conducted away from the source by the nearby metal conductors. While the welds have been painted, this has no impact on the production of these unwanted products.

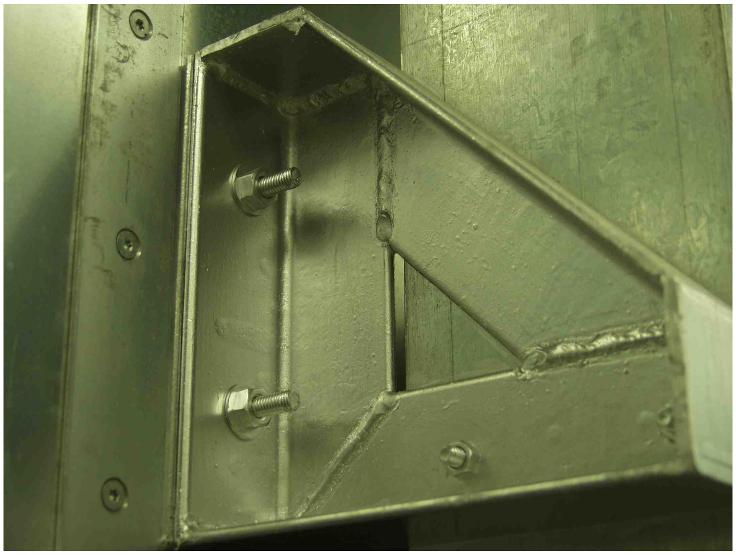


Figure 54 Welds on Galvanized Metal Supports

7.8 Other Site Issues

Many receiving sites contain other buildings for a variety of purposes and uses. Emissions from all electrical and electronic equipment and devices in these buildings must also be sufficiently low that they do not adversely affect the reception of low-level signals. As a general rule, all such devices should be required to meet the Federal Commission (FCC) Class B emission limits described later in Section 8.

Figure 55 shows an example of a site issue that caused harmful levels of radio noise to appear at the input terminals of radio receivers. The security camera shown in the example was powered by a switching power supply that did not meet FCC Class B emission limits and was not modified in accordance with the barrier-filter techniques described in Section 7.1. Radiation from noise current flowing on the camera mount and its associated cables was intercepted by the nearby antennas. In this case the solution was to implement a field modification by replacing the switching power supply with an analog type of power supply.

Figure 55 Security Camera Powered by a Noisy Switching Power Supply

Sometimes power cables will be buried under an antenna field. In such cases care must be taken to ensure that high-frequency noise-current levels carried by such buried power cables is sufficiently low that inductive and capacitive coupling of harmful levels of noise current into antenna counterpoise systems and/or directly into antenna elements does not occur. A good rule is to limit the high-frequency noise current flowing on such cables to the maximum values provided in Table 1.

Communications cables are sometimes routed under antennas, and in such cases the high-frequency shield current carried by such cables must be limited to the values provided in Table 1.

8. SPECIFICATIONS AND STANDARDS

8.1 General Comments

A large and often confusing variety of standards and handbooks exist which are related to the control of electromagnetic noise and interference. Many of them have portions that can be applied to radio-receiving sites and facilities, but none fully cover the specific needs of such facilities and sites. Most of the existing standards and handbooks have old and out-of-date information that can mislead site planners and operators. Some contain technically inaccurate and incorrect information, especially with regard to grounding.

A comprehensive review of available standards and handbooks as they apply to radio-receiving facilities and sites is badly needed, but it is beyond the scope of this document. This document is limited to the presentation of the technical aspects of noise and interference encountered by its authors over several decades of investigations at receiving sites. A partial listing of these documents is provided in this section.

8.2 National Electric Code

All electrical and grounding aspects of buildings at a receiving facility or site should be required to fully meet the requirements of the National Electric Code (NEC). This includes all aspects of electrical power at a receiving site that supply electricity to equipment. Full compliance with the NEC is required by a DoD directive, and each facility or site should have available the latest edition of the NEC as well as one or more individuals trained in its use.

Of special interest is that while compliance with the NEC is required of all U.S. Department of Defense facilities, the NEC is not a government produced or sponsored document. It is a document produced and provided by the National Fire Protection Association (NFPA) for the protection and safety of personnel, equipment, and buildings from electrically-related causes. The document is updated periodically by the NFPA.

Copies of the NEC can be ordered on-line at nominal cost from the web site for the NFPA at nfpa.org.

An earlier section (Section 4.3) describes one limitation of the NEC green-wire ground as it applies to radio-receiving and data-processing facilities or sites. The NEC does not include the specific aspects or implications of sources of radio-noise and radio-interference that might be generated by equipment and devices using electric power. The aspects of equipment and devices that are sources of radio-noise and radio-interference are at least partly covered by other standards and handbooks such as the FCC Class B requirements described in the next section and also by this document.

8.3 Federal Communications Commission Part 15, Class B

Compliance with the Federal Communications Commission (FCC) Class B[13] noise limits is often required for equipment purchased for use in radio-receiving facilities, and this should be a requirement for all electrical and electronic equipment and devices procured for use in such facilities. The FCC Class B requirement is currently the most practical and most effective reference available for the procurement of low-noise-emission electronic and electrical equipment.

However, the FCC Class B noise requirement has one limitation that must be considered when conducting measurements to ensure that a device is suitable. The Class B noise requirement is based on the measurement of noise-voltage levels, and suitable instruments are available for such measurements from a number of instrument manufacturers. One needs to ensure that the frequency range and measurement bandwidths of such instruments realistically describe noise and interference conditions. However, voltage measurements are valid only at the exact source of a noise or interference where a zero-voltage-reference exists. Unfortunately, sources can inject harmful levels of noise and interference into many source-associated conductors (including ground conductors), and the impedance of even short lengths of any conductor will result in invalid noise and interference voltage reference except at the source. Any noise-voltage measurement made at even a short distance from a source will be suspect and probably will not be valid. Also, all voltage measurements made at a location with multiple sources, no matter where made, will be suspect since a zero-voltage reference will not be present.

While the level of discrete-frequency spectral components of noise can be accurately measured with many instruments, the amplitude of broadband impulsive noise is dependent on the bandwidth of the measuring device. Thus, considerable care must be taken in voltage-measurement procedures of impulsive noise to ensure compliance with the FCC Class B limits. These aspects of noise measurements are discussed further in Appendix A.

Of interest is that current measurements of both discrete-frequency spectral components of noise and interference, and also of broadband cases, can be measured with a broadband current probe. A reference point is not required for current measurements or for multiple sources. All examples of the measurement of noise and interference in this document injected onto conductors are based on current measurements, and Table 1 provides recommended maximum values of noise current generated by equipment for radio-receiving sites.

The FCC Class B measurement procedures need to be updated to include maximum tolerable values of discrete-frequency and broadband noise current, a measurement that is independent of the need for a zero-reference point.

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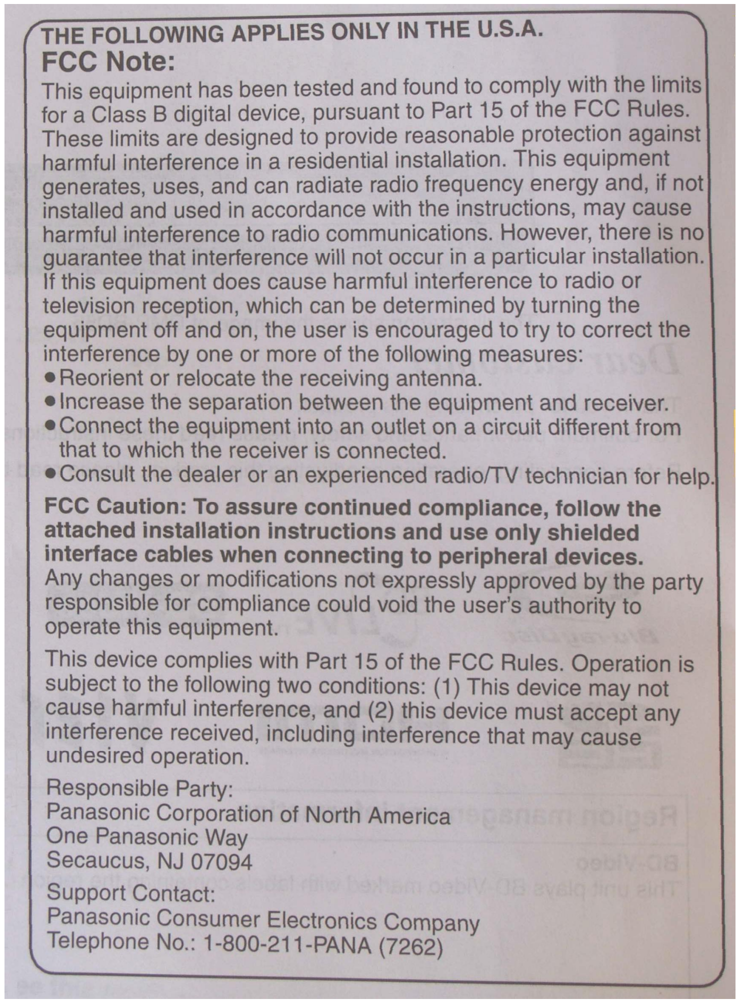
[13] 47 CFR part 15, Rules and Regulations, Federal Communications Commission, Washington D.C.

Electronic devices and equipment sold for use in a residential installation must be in accordance with FCC Class B requirements and must contain a label indicating its compliance with the requirements. The instruction manuals of all equipment complying with the FCC Class B noise emission standard also contain this information. An example of such a label is provided in Figure 56.



THE FOLLOWING APPLIES ONLY IN THE U.S.A.

FCC Note:

This equipment has been tested and found to comply with the limits for a Class B digital device, pursuant to Part 15 of the FCC Rules. These limits are designed to provide reasonable protection against harmful interference in a residential installation. This equipment generates, uses, and can radiate radio frequency energy and, if not installed and used in accordance with the instructions, may cause harmful interference to radio communications. However, there is no guarantee that interference will not occur in a particular installation. If this equipment does cause harmful interference to radio or television reception, which can be determined by turning the equipment off and on, the user is encouraged to try to correct the interference by one or more of the following measures:

- Reorient or relocate the receiving antenna.
- Increase the separation between the equipment and receiver.
- Connect the equipment into an outlet on a circuit different from that to which the receiver is connected.
- Consult the dealer or an experienced radio/TV technician for help.

FCC Caution: To assure continued compliance, follow the attached installation instructions and use only shielded interface cables when connecting to peripheral devices.

Any changes or modifications not expressly approved by the party responsible for compliance could void the user's authority to operate this equipment.

This device complies with Part 15 of the FCC Rules. Operation is subject to the following two conditions: (1) This device may not cause harmful interference, and (2) this device must accept any interference received, including interference that may cause undesired operation.

Responsible Party:
Panasonic Corporation of North America
One Panasonic Way
Secaucus, NJ 07094

Support Contact:
Panasonic Consumer Electronics Company
Telephone No.: 1-800-211-PANA (7262)

Figure 56 Example of a FCC Class B Label

Electronic and electrical devices rated for the FCC Class A noise and interference requirement must not be tolerated in radio-receiving or data-processing facilities since this requirement allows unacceptable levels of high-frequency noise and interference to be emitted by electrical and electronic devices and be injected into power, ground, and other conductors of a facility. The Class A noise and interference limits are intended only for the procurement of equipment to be used in industrial facilities where high radio-noise levels can be tolerated. Examples of the FCC Class A label required for all electronic devices marked in the United States are provided earlier in Figures 20 and 24.

8.4 Coaxial Cable Designations

In the WWII era, coaxial cable was designated as RG- (Radio Guide) followed by one, two, or 3 numerals, and then /U for universal. This system was replaced in 1976 by the new ćrevision Eô of MIL-C-17 which introduced the M17/ system. Note that cables manufactured after 1976 and bearing only RG/U nomenclature are essentially unregulated and should be avoided. Only M17/ coaxial cables must be manufactured to meet any standard. Cables mentioned in this document by their old designations cross reference to current nomenclature as follows:

Old	Current	Low smoke/halogen
RG8/U	M17/74-RG213	M17/189-0001
RG58/U	M17/28-RG58	M17/183-0001
RG214/U	M17/75-RG214	M17/190-0001
RG223/U	M17/84-RG223	M17/194-0001

Appendix A INSTRUMENTATION

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A.1 Instrumentation for the Definition of Signals, Noise and Interference

The instrumentation used for field measurements of signals, noise, and interference is described in this appendix. An understanding of both the capabilities and the limitations of the instrumentation is necessary to fully evaluate the implications of the examples of data provided.

The purpose of the instrumentation is to provide a visual presentation of the primary properties of time- and frequency-varying signals, radio noise, and interference in any portion of the radio spectrum. This includes a means to portray both the temporal and spectral structures of signals, radio noise and radio interference in selected bands where the both the frequency span, the time of observation, and other instrumentation parameters can be rapidly changed to best describe the conditions encountered. One further requirement was included. The amplitude, frequency span, and time of observation must be calibrated and presented in commonly accepted engineering terms.

Figure 57 shows a block diagram of the primary components of the instrumentation used for most measurements. The input is usually connected directly to the actual antenna used for signal reception or to a current or voltage probe. This enables the instrumentation to observe the actual signal, noise and interference conditions applied to a receiver or to examine the broadband current and voltage on cables and grounds.

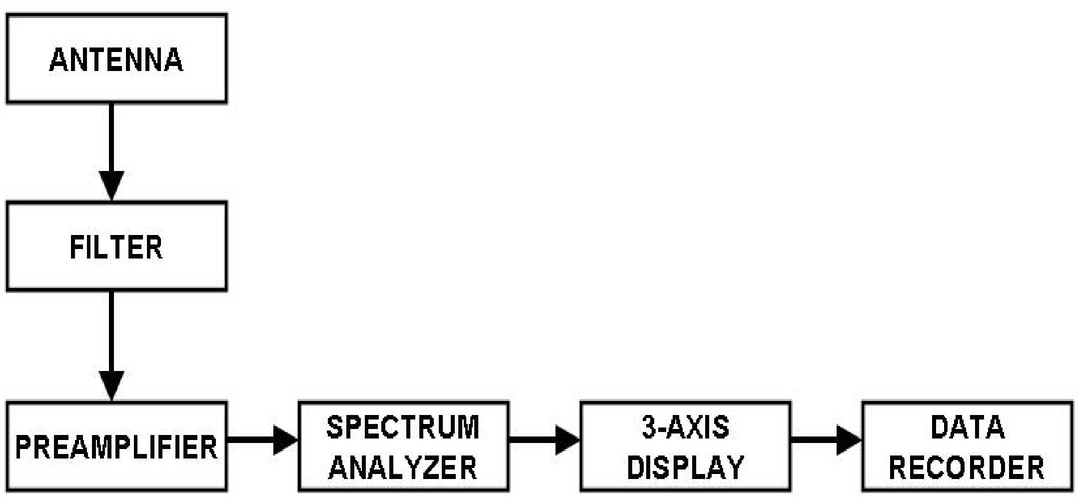

Figure 57 Block Diagram of the Instrumentation

Figure 58 is a photograph of a typical instrumentation configuration used to investigate signals and noise appearing at the input of a receiver, signals carried on cable shields and ground conductors, or other uses. The instrumentation is mounted on a wheeled cart to allow moving it to any desired location, and only the primary instrumentation is shown. Auxiliary instrumentation such as filters, probes, and additional preamplifiers are shown in other figures.

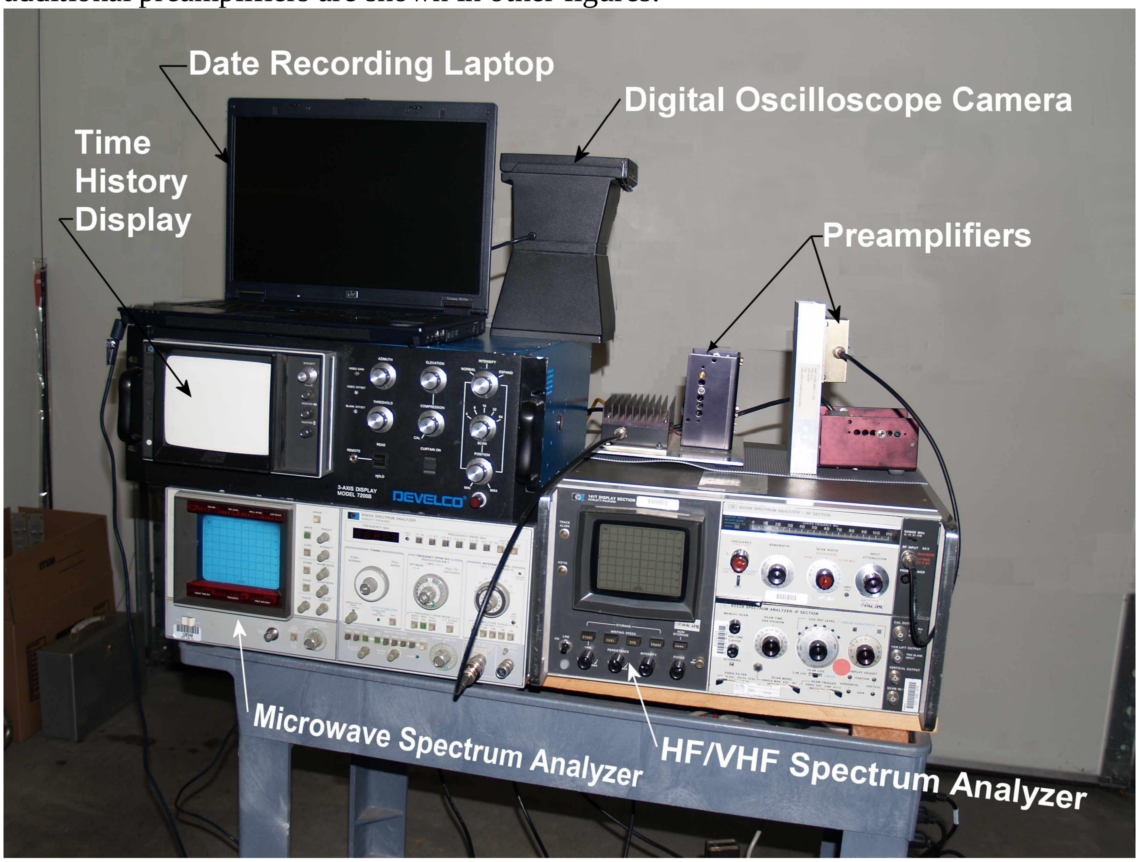

Figure 58 Typical Instrumentation configuration

A.1.1 Filters

A band-pass filter is provided for each portion of the radio spectrum to be observed. The filters are used to avoid strong out-of-band signals that might cause overloading of the preamplifier and/or the spectrum analyzer. Care was taken in the design of each filter to ensure that its dynamic range was sufficient to avoid saturation of its internal components. Many kinds of small commercially-available filters were found to be unsuitable for the measurement program because of component saturation.

Figure 59 shows a photograph of two sets of filters often used to examine signals, noise and interference in the HF, VHF and the lower part of the UHF bands. The top set consists of a bank of eight filters covering portions of the HF band. This particular set shows band-pass filters covering portions of the HF spectrum between allocations for the International Broadcast Service. The bottom set shows four band-pass filters covering portions of the VHF and UHF bands. A number of additional single filters are used for special measurements.

Figure 59 Example of Band-pass Filters

Figure 60 shows a photograph of the filters used for measurement in the 915-MHz and the 2.4-GHz bands. These filters are physically large to provide linear operation for the maximum total signal power imposed onto their input terminals.

Figure 60 Example of Special Purpose Filters for the UHF Band

Many additional special-purpose high-dynamic range filters were designed, fabricated and used for special-purpose measurements in portions of the radio spectrum.

A.1.2 Preamplifiers

Since the noise figure of most commercially available spectrum analyzers is considerably higher than that of radio receivers, a preamplifier is used between the filter and the spectrum analyzer. Unfortunately, the low-cost preamplifiers that are commonly available have insufficient dynamic range to cope with total signal power applied to them during signal reception under the conditions encountered at most receiving facilities. The saturation of such amplifiers always results in the generation of intermodulation products and broad-band intermodulation noise. To avoid this problem, high-dynamic-range preamplifiers were provided for each radio band. The maximum total signal power at the input to each preamplifier is carefully examined prior to recording data to ensure that linear operation is achieved.

Figure 61 shows an example of a preamplifier and its power supply that is used for measurements in the HF band. The components are mounted on a large heat sink to dissipate the heat generated by the preamplifier.

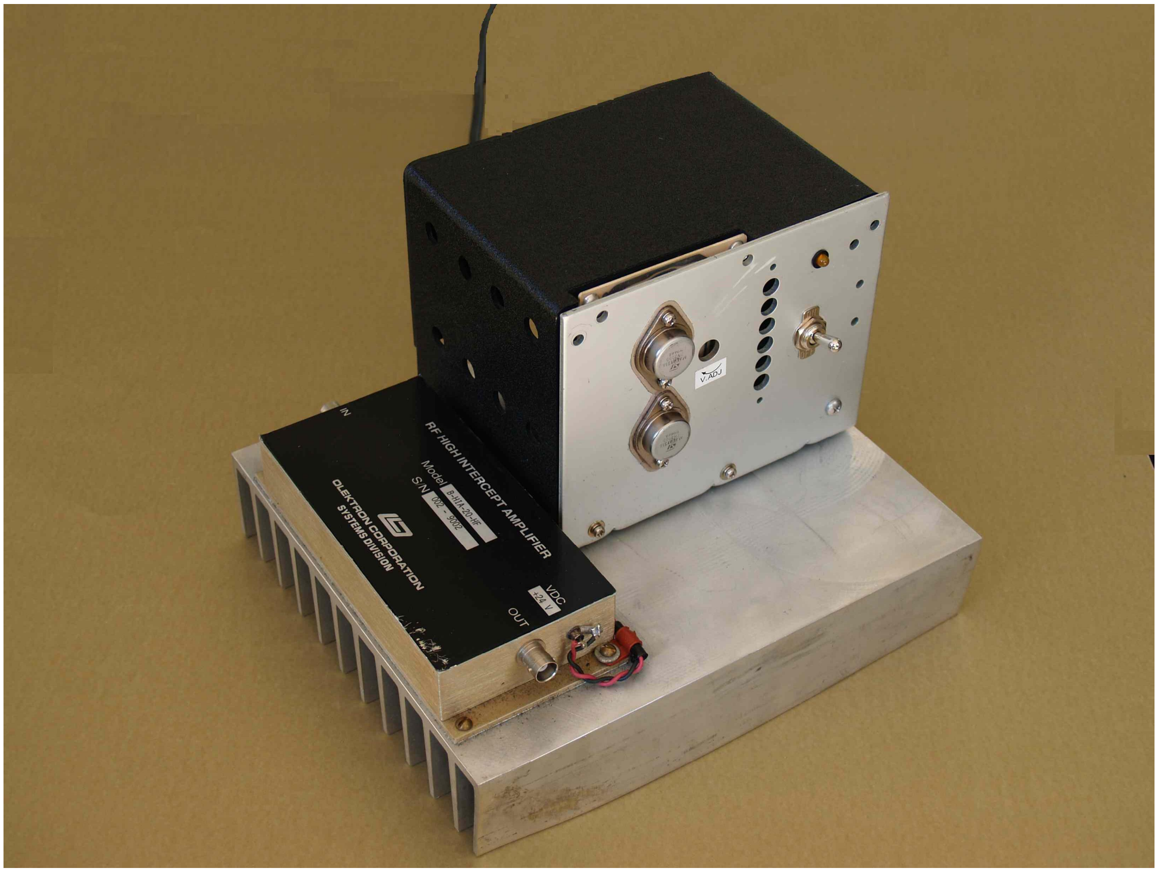

Figure 61 Example of a Preamplifier for the HF Band

Figure 62 shows an example of a preamplifier and its power supply used for the examination of signals, noise and interference in the UHF band. In this particular case sufficient heat dissipation from heat generated by the preamplifier was achieved by its heat sink and the aluminum mounting plate.

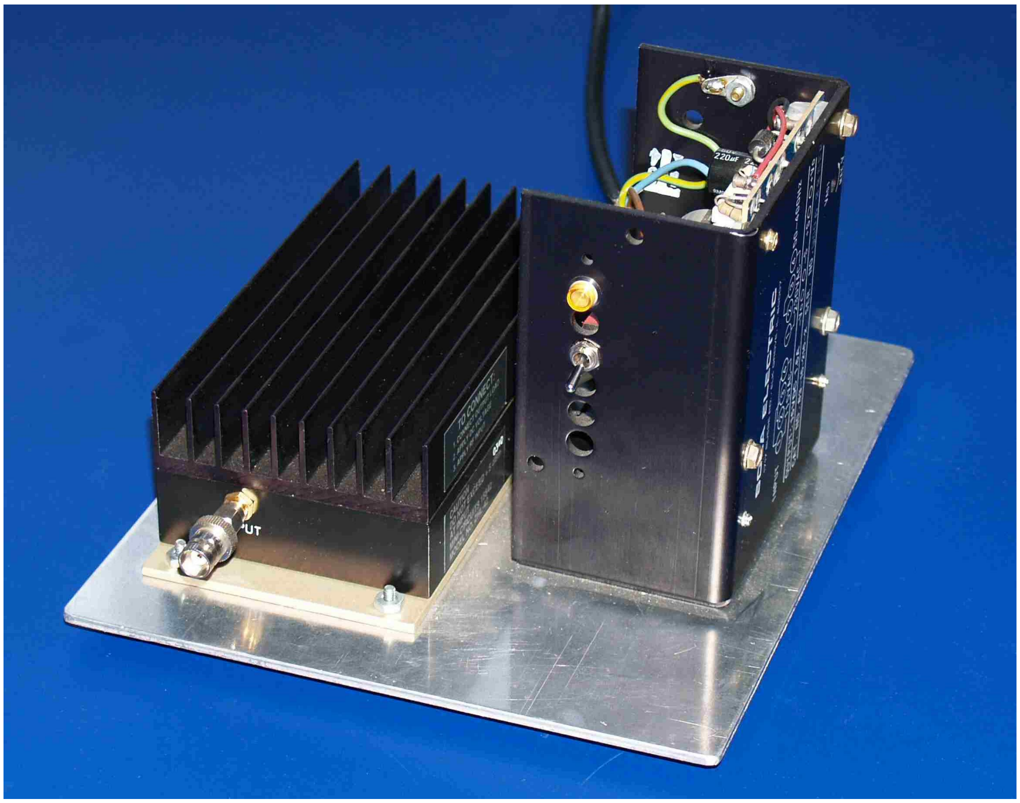

Figure 62 Example of a Preamplifier for the UHF Band

Some sacrifice in the noise figure for all preamplifiers was necessary in order to achieve a sufficiently high dynamic range for practical measurements. Noise figures of 6 to 12 dB are provided by the preamplifiers normally used compared to the approximately 2-dB noise figures achieved by low-dynamic-range units. Additional low-noise preamplifiers were provided for special measurements, but extreme care was taken in their use to avoid intermodulation problems.

The signal environment frequently contained a mixture of random impulses, signals with various formats, impulsive noise, and impulsive radio interference along with a few discrete-frequency signals. High-level impulsive signals, noise, and interference can result in the production of impulsive and broadband intermodulation noise. Precautions to identify instances of strong impulsive signals, noise, and interference are essential to avoid contamination of recorded data and the misleading results from such contamination.

A.1.3 Spectrum Analyzers

Two types were used to collect data in the field. The first type was the popular scanning spectrum analyzer commonly used to examine radio signals. The second type was the FFT type of spectrum analyzer, although all of the available FFT analyzers required the use of a linear frequency translator due to their base-band operation. Both types of spectrum analyzers were employed for field measurements, although most measurements were made with the scanning type.

The selection of an appropriate model of a scanning spectrum analyzer was a major matter, and a number of models were used over past years. While excellent modern digitally-controlled scanning spectrum analyzers are available, they were seldom used during field measurements for a variety of technical reasons. First, their dead time between scans (not specified by any of the manufacturers) was far too long to cope with the rapidly-changing signal and noise conditions found in real life. The dead time also significantly reduces the ability of a spectrum analyzer to receive and define the properties of intermittent signals, noise, and interference. In addition, the use of keypad or keyboard controls resulted in unacceptable time delays for changing the analyzer operating parameters to cope with time-varying signal, noise, and interference conditions. However, the newer digitally-controlled analyzers are preferred for the laboratory measurement of time-stable signals and noise or other similar special purpose measurement tasks.

The older knob-controlled spectrum analyzers were found to be more suitable for field-measurement purposes. The time delay between spans of the older scanning-type analyzers is considerably lower than that for the newer digitally-controlled units thus increasing their ability to detect and define intermittent and frequency varying emissions. The knob controls permit the rapid adjustment of instrumentation parameters to cope with the need to define time- and frequency-changing signal and noise conditions.

The old Hewlett Packard Model 141 Spectrum Analyzer with RF heads covering the frequency ranges of 0 to 110 MHz and 0 to 1250 MHz was found to be the best available model for measurements within its frequency-coverage ranges. The Hewlett Packard Model 8565A Spectrum Analyzer was found to be the best available analyzer for the measurement of time- and frequency-changing and intermittent emissions in the microwave bands. While the signal-handling dynamic range of these two models was somewhat lower than for newer models, the short dead times between spans and the ability to rapidly alter operating parameters outweighed the dynamic-range considerations. These analyzers were often modified for specific measurement tasks to improve dynamic range, provide an external synchronizing capability, and further reduce their dead time between scans.

Both spectrum analyzer models provide the ability to quickly change operating parameters such as the center frequency of a band under observation, the frequency span of that band, the scan time, and the measurement bandwidth. In addition, the analyzers could be quickly switched to operate in a zero-span mode similar to that of a fixed-tuned receiver. The scanning process could be synchronized to external synchronizing sources to aid in the fine-scale definition of the temporal structure of some repetitive signals.

The dead time between scans was carefully measured and documented for each spectrum analyzer prior to its use in the field. This was done for two reasons.

First, transients and intermittent signals can, and will, occur during the dead time of a scanning analyzer, and such transients and intermittent signals will not be received. Also, portions of repetitive impulsive signals and noise will occur during the dead time and not be received. The probability of receiving an unknown transient is the quotient of the ratio of the scan time to the scan time plus dead time. Because of this the magnitude of the dead time compared to the scan time is a significant disadvantage of a scanning spectrum analyzer. It is essential that this ratio be known and be as low as possible to properly understand and interpret the results of field measurements.

Second, the dead time between scans influences the duration of the time-history axis used to define the temporal properties of signals and noise. This will be described in more detail in the following section.

A.1.4 Time-History Display

A Model 7200B 3-Axis Display is used to portray the time-history properties of signals and noise in real time. It has been used by students and staff of the Naval Postgraduate School for a number of thesis projects and other tasks. The display is completely slaved to the operation of a spectrum analyzer, thus only visually-related adjustments are provided on the instrument. The easiest way to demonstrate its presentation and capabilities is to review an example. Figure 63 shows an example of the presentation provided by a Model 7200 display. Two views of the same data are provided. The top view shows amplitude vs. frequency in a presentation similar to that provided by most spectrum analyzers. The bottom view provides a time-history presentation of the same data as shown in the upper view.

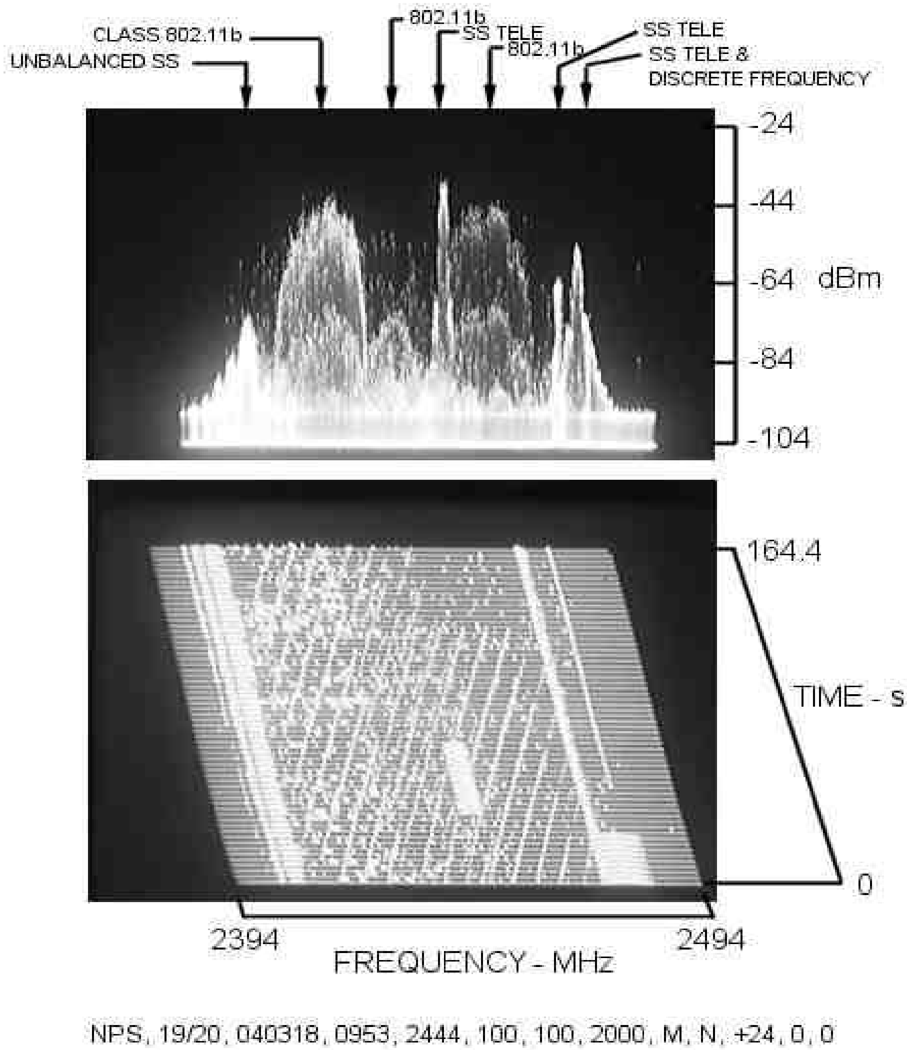

Figure 63 Example of Signals, Noise and Interference in the UHF Band

Information from each new scan of the spectrum analyzer is shown on the bottom line of the time-history presentation. Each new scan bumps all older scans up one line, and the oldest line at the top of the time-history presentation is discarded. This process occurs in real time. Prominent aspects of emissions in the example are identified by the annotation at the top of the amplitude-vs.-time view.

Several ways are available to enhance the time-history presentation of signals, noise, and interference. For example, the time axis can be slewed (or rotated); the time axis is slightly skewed to the left in the example to better show the slanting lines across the time-history view. The amplitude can be compressed; it is almost fully compressed in the time-history view and not compressed in the upper amplitude-vs.-frequency view of the same data. The elevation of the time-history view can be varied from 0 to 90 degrees; it is at zero degrees in the time-history view and at 90 degrees in the amplitude-vs.-frequency view. In addition, any set of 4, 8, 16, or 32 lines of the time-history view can be selected for a detailed line-by-line analysis of an emission. The amplitude threshold can be varied to minimize visual interference from low-level emissions. These features can be altered in real time to aid in portraying any desired feature. Any view can be frozen for a detailed examination or to photograph the two presentations, and the viewing enhancement controls also operate with a frozen view.

The slanting lines across the time-axis presentation are a result of receiving the broadband synchronizing pulses from an 802.11b access point as the spectrum analyzer scans across the bandwidth of the pulses. The scan time of the spectrum analyzer must be longer than the repetition period of the pulses, and the analyzerôs IF bandwidth must be less than the spectral width of the pulse emission for this type of presentation. Since the data is obtained from a scanning filter, the time between impulses can be scaled from the horizontal axis which is a combination of frequency and scan time. The scan time of this axis is provided for each item of data, but it is not always added to the bottom horizontal axis to avoid excess material in the presentation.

The amplitude scale on Figure 63 refers to the amplitude of received signals at the output terminals of the antennas. The impact of receiver bandwidth on the amplitude of received signals is discussed later.

Synchronizing pulses from three 802.11b access points are shown in the time-history view. The clutter between the synchronizing pulses is from the 802.11b emissions of laptop computers using the networks as well as a few random pulses from other sources. Other signal formats are also shown in the two views such as the relatively narrow-band spread-spectrum signals from portable telephones..

The data in Figure 63 was obtained during a classroom session at the Naval Postgraduate School where wireless radio was extensively used as a classroom aid. Only the signal identified as ñClass 802.11bò was associated with the classroom. All other signals came from other sources on the campus.

A.1.5 Data Recording

Until a few years ago, data was recorded by freezing the operation of the 7200B display and photographing the frozen view with a Tektronix Model C-5C Oscilloscope Camera using Polaroid film. Operating parameters were then written onto the back of each photograph. The pictures were trimmed and pasted onto white cardboard, and scales were manually added to the frequency, amplitude, and time axes. The resulting paste-ups were then scanned and recorded as a computer file. While this manual process was tedious, it provided excellent examples for the documentation of the results of field measurements.

The increasing price of Polaroid film in recent years eventually became a major cost of conducting field measurements. This resulted in the modification of the Tektronix camera enclosure to incorporate a small digital camera into the C-5C case. A USB cable connection between the digital camera and a laptop computer now provides a means to place examples of the two views from the time-history display directly onto the hard drive of a laptop in a standard .jpg format. The two views are subsequently combined into a single file, and the frequency, amplitude, and time scales are added to each set of views along with any desired annotation using a standard photo-processing program. The end result is a compressed .jpg file ready for direct insertion into the text of a report. This process eliminated the high cost of film and the cost of the manual graphics effort needed to format the Polaroid pictures.

A digital recording capability is built into Model 7200B display. This capability was seldom used since useful and effective digital data-processing techniques could not be applied to much of the data accumulated for this effort.

A.1.6 Data Calibration and Scaling

Comprehensive records are maintained for each item of data collected in the field. These records include the following items about each item of data.

Measurement Location
Picture Number
Date in yymmdd Format
Local Time
Center Frequency of Data
Frequency Span
Measurement Bandwidth
Scan Time in ms
Signal Source (Usually an Antenna ID)
Filter ID
Preamp Gain
RF Attenuator Setting
Signal Reference Level
Comments
Additional Special Comments

An abbreviated version of the above parameters is added below each item of formatted data as shown by the line of text at the bottom of Figure 63. Sufficient information is provided in this line to add amplitude, frequency, and time scales to the data and to reference each item of data to its source.

The amplitude scales in this document are calibrated in dBm to provide a convenient means to relate recorded data to commonly accepted spectrum analyzer calibration terms. Noise temperature has not been used as a measure of interference to the reception of a desired signal. This is because the term has not yet been defined sufficiently to describe the erratic time and frequency-varying conditions found in the wireless bands as well as the measurement bandwidth considerations.

The amplitude scales in this document show the peak level of signals, noise, and interference as received within the measurement bandwidth of the spectrum analyzer. The peak amplitude of any emission whose bandwidth is equal to or smaller than the measurement bandwidth can be determined directly from the amplitude scale shown on the right edge of the amplitude-vs.-frequency view. Impulsive signals and broadband signals with spectral content wider than the measurement bandwidth are always higher in amplitude than shown by the amplitude scale. This is because some of the spectral content is outside the measurement bandwidth.

An empirical curve has been generated by Hodge[14] to provide an approximate means to scale the amplitude of wide-band emissions to other than the measurement bandwidth. Figure 64 shows this curve along with a second curve for wideband Gaussian noise.

---

[14] James W. Hodge, ***A Comparison between Power-Line Noise Level Field Measurements and Man-Made Radio Noise Prediction Curves in the High Frequency Radio Band***, MS Thesis, Naval Postgraduate School, Monterey, CA, December 1995

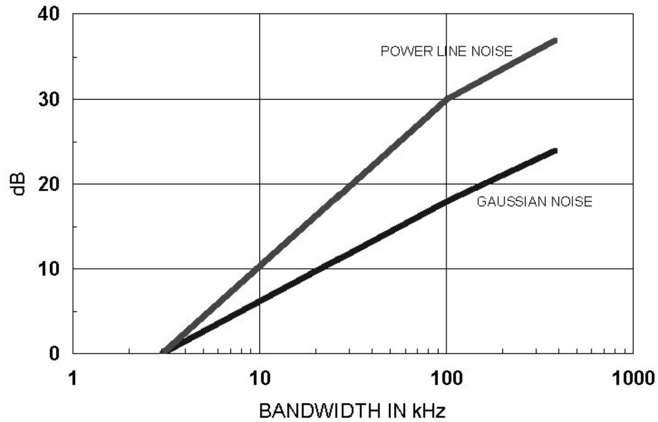

Figure 64 Bandwidth Compensation Plot

While the above Hodge curve was derived primarily from measurements of impulsive power-line noise in the HF and VHF bands, it has been shown to provide reasonable estimates for pulse emissions and impulsive noise and interference in the wireless bands. The curve is valid for receivers using Gaussian-shaped measurement bandwidths such as the bandwidth shapes used by many models of spectrum analyzers. To our knowledge similar curves have not been obtained for receivers with more rectangular IF bandpass filters.

Since the temporal structure of emissions in the wireless bands change significantly over brief intervals of time and with frequency, and are clearly non-Gaussian, one cannot provide a universal and acceptable way to define the average, root-mean-square, or other measures of amplitude other than at a selected time and for a specific small frequency band.

Finally, the duration of the time-history axis must also be determined to understand the variations of the emissions received over time and frequency. For a 60-line time-history display, the duration of the time axis, T(s), is determined by:

T(s) = [(Scan Time in ms + Blanking Time in ms) x 60] / 1000

For a 120-line time-history display the duration of the time axis is:

T(s) = [(Scan Time in ms + Blanking Time in ms) x 120] / 1000

The scan and blanking times are measured prior to each field use, and they are recorded along with other operating and site parameters. Tables 2 and 3 show the measured blanking times and the resulting duration of the time-history axis for two examples of instrumentation configurations. Since multiple sets of instrumentation are available, a similar chart is provided for each field measurement instrumentation configuration.

Table 2 Typical Calibration Data – NPS HP 141 #5

Scan Time/div ms	Total Scan Time ms	Free Run Scan + Blank ms	Free Run T(s) s	Line Sync Scan + Blank ms	Line Sync T(s) s
1	10	15.1	0.91	16.5	0.99
2	20	25.1	1.51	33.7	2.02
5	50	67.9	4.07	65.6	3.94
10	100	183.0	11.0	183.0	11.0
20	200	283.0	17.1	299.0	17.9
50	500	582.0	34.9	594.0	35.6
100	1000	1,082	64.9	1,096	65.8
200	2000	2,626	157.6	2,641	158.8
500	5000	5,628	337.7	5,632	337.9
1000(1 s.)	(10 s.)	10,624	637.4	10,632	637.9

Table 3 Typical Calibration Data – WRV HP 140

Scan Time/div ms	Total Scan Time ms	Free Run Scan + Blank ms	Free Run T(s) s	Line Sync Scan + Blank ms	Line Sync T(s) s
1	10	14.7	0.88	19.9	1.2
2	20	24.7	1.48	33.7	2.03
5	50	54.7	3.28	65.8	3.95
10	100	185.0	11.1	199.0	12.0
20	200	285.0	17.1	285.0	17.1
50	500	584.0	35.1	587.0	35.2
100	1000	1,084	65.0	1094	65.7
200	2000	2,084	125.0	2092	125.5
500	5000	5,084	305.0	3088	185.2
1000(1 s.)	(10 s.)	10,090	605.4	10,090	605.4

A.2 Instrumentation for Source Location and Identification

A variety of instrumentation and devices have been used to locate sources of noise and interference within the borders of a receiving site. For example, the instrumentation described in Section A1.1 can also be used with small probes to investigate on-site sources of noise and interference. In addition, additional instrumentation has been found to be highly useful, and examples of these are provided in this section. Some of these additional items are also used to investigate and identify sources of noise and interference external to a receiving site and their use is shown in reference 1 listed on page 1.

Figure 65 is a photograph of the Radar Engineers Model 242 portable noise receiver. It is tunable over the frequency range of 100 kHz to 1000 MHz, and it contains a small display of the temporal structure of examples of noise that is especially useful to portray the temporal structure of noise and interference that is synchronized to the power-line frequency. Data from this device is highly useful in relating and comparing the temporal structure of impulsive noise at a source location to that observed at the input terminals of a receiver.

Figure 65 Radar Engineers Noise Receiver with Probe

The noise receiver is battery powered and can be carried to any convenient location. It can be used with a small whip antenna for general purpose or any other convenient source device. The above photograph shows it with a small probe that is used to pinpoint sources of unwanted emissions within a receiving or data-processing site.

The temporal structure of noise and interference observed on the Model 242 Noise Receiver can be recorded by photographing the display with a small conventional digital camera.

Figure 66 shows a Model F-70 Current Probe made by Fischer Custom Communications. It is used to examine and measure the level of spectral components of current flowing in any conductor up to about two inches in diameter. The probe provides a flat frequency response from 100 Hz up to 100 MHz, and its response can be calibrated down to about 30 Hz. The probe is matched to the 50-Ohm inputs of many amplifiers and spectrum analyzers. Spectral components of currents as low as 2μA can be measured with the use of a suitable low-noise preamplifier and a spectrum analyzer. This probe provides a means to make measurements of current to the low levels required to meet the limits provided in Table 1.

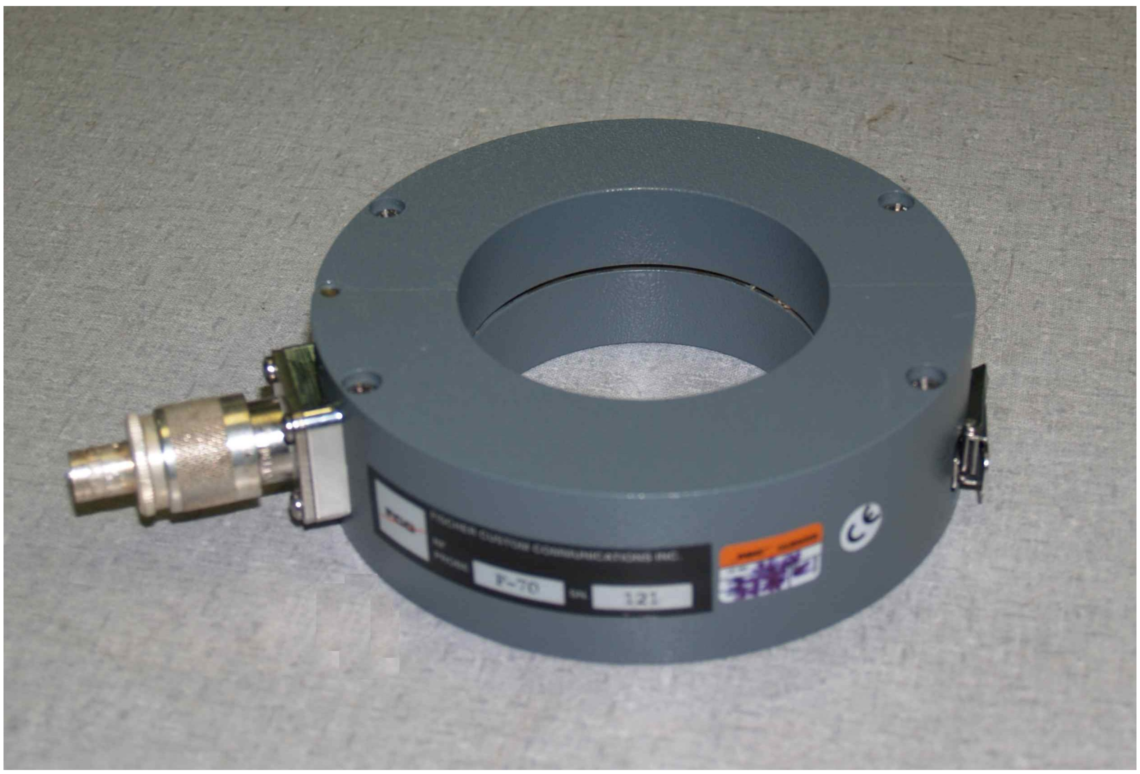

Figure 66 Model F-70 Current Probe

Caution must be employed with the use of the probe since many cases of noise and interference current are non-stationary. Thus, the amplitude of spectral components of current cannot always be accurately described with conventional measures of amplitude.

Figure 67 shows a Radar Engineers Model 245 Circuit Sniffer. This device is useful to detect the location of devices emitting unwanted broadband noise and interference from power-conversion sources. It is shown with its small whip antenna for general probing. It also contains a small magnetic-field sensor on the upper right corner of its case. This sensor is highly useful when scanning the circuit breakers of a power panel to identify which breaker feeds electric power to a power-conversion device or other noise source.

Figure 67 Circuit Sniffer Used to Locate On-Site Sources

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Mr. Fred Horning 1
Radar Engineers, Inc.
9535 N.E. Colfax St.
Portland, OR 97220

Mr. Werner Graf 1
SRI International
333 Ravenswood Ave.
Menlo Park CA 94025

American Radio Relay League 225 Main Street Newington, CT 06111-1494 Attention: Mr. Ed Hare	1
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Bristow, VA 20136

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