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PRACTICAL CONSIDERATIONS OF THE TOPOLOGICAL APPROACH TO ELECTROMAGNETIC INTERFERENCE CONTROL

by

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Practical Considerations of the Topological Approach to Electromagnetic Interference Control

by

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Lieutenant, United States Navy
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ABSTRACT

The topological approach to electromagnetic interference control is described and explained for background. Some of the issues concerning the implementation of an equipment-level topological barrier at electronics facilities are discussed. Experiments are conducted on a common 19-inch equipment rack to investigate and evaluate topological grounding techniques and the proper connection of a penetrating conductor filter. Additional experiments are conducted to evaluate the use of double-shielded coaxial cable.

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I. INTRODUCTION

Over the years, the electromagnetic interference problem has been dealt with in a wide variety of ways, with varying degrees of success. Satisfactory control of interference to a single, given electronic circuit in a well-defined electromagnetic environment, or of electromagnetic interference emanating from a single source, can almost always be achieved in relatively short order, even if by trial and error. At the level of even the simplest system, however, the problem is exceedingly complex and calls for a logical, fundamental approach which can be applied in a general manner.

From a practical point of view, what is required is a means of simultaneously satisfying the great number of interference control requirements and standards which has grown along with the variety and number of potential electromagnetic interference sources and victims. These differing standards have often been considered to be mutually conflicting, but only because the practices which have evolved to meet each individual requirement have not been consistent with any one set of fundamental principles.

Vance, Graf and Nanevicz [1] have concluded that the "topological approach" is a fundamental, physical approach to broadband interference control which does indeed allow for the simultaneous application of numerous requirements concerning the electromagnetic pulse (EMP), lightning, electromagnetic interference/electromagnetic compatibility (EMI/EMC), communications security (COMSEC), and safety in a communications facility. The concept calls for simply separating the circuit to be protected from the source of interference with a barrier, or set of barriers, which is "effectively impervious" to electromagnetic waves. Such imperviousness is, of course, a function of frequency, but broadband control throughout a significant frequency range of interest can be achieved. Immunity and compatibility requirements are met simultaneously if the barrier is bilaterally effective.

It is the practical implementation of such a barrier that is dealt with in this thesis. Various elements can be utilized in meeting the central requirement of the concept: that the barrier be "topologically closed." Certain of these elements will be discussed and investigated here, specifically with regard to a practical, equipment-level barrier. While the initial motivation for this research was in the area of interference control at high frequency (HF) (2-30 MHz) communications receiver facilities, the concept is, as stated earlier, broadband in scope and efforts will be made to generalize where possible.

In Chapter II, the topological approach is explained in greater detail in order to provide a good fundamental background. Chapter III discusses, from a more practical point of view, some of the issues concerning the actual implementation of an equipment-level topological barrier.

In Chapter IV, significant instrumentation elements and data presentations utilized in experimentation supporting this study are described. Chapters V and VI describe, and present the results of, specific experiments done involving a practical equipment rack and coaxial cables, respectively. Previous relevant experiments and field studies conducted by others are also referred to.

Chapter VII summarizes the work and provides conclusions.

II. THE TOPOLOGICAL APPROACH

A. INTRODUCTION

Electromagnetic interference can be generally defined as the introduction of electromagnetic energy into an electronic circuit or system which causes a detrimental, or at least unintentional, response in that circuit or system. Such energy may be originated by a source external to the circuit or system, or it may be internally generated. To reach the exact components or circuitry at which the desired signal or process is affected, the undesired energy may propagate by conduction (more generally, a guided path), induction, or radiation.

Electromagnetic compatibility involves the presence of electromagnetic interference mechanisms between all of the various circuits or systems in some given environment. Each circuit or system is a potential interference source and each is a potential interference "victim"; compatibility is achieved only when each can nevertheless operate correctly.

While in the analysis of existing systems or the design of new systems an interference process in a given component or circuit may be readily understood, the overall problem is nearly always one of multiplicity and complexity. That is, the sheer number and the complicated configuration of circuits, signal paths, connections, supporting structures, etc., in any system make complete, exact solutions impossible. Even if the configuration of all such elements in a practical environment such as a communications building, a ship, or an aircraft could somehow be accurately modeled and the set of electromagnetic sources somehow correctly defined, the multiplicity and complexity would still preclude, say, the solution of Maxwell's equations at every point in the system.

Addressing that complexity, Baum [2] analyzed ways of decomposing the specific problem of electromagnetic pulse (EMP) interaction into smaller pieces. The analysis of the smaller problems could then not only lead to solutions of the smaller problems, but also to additional benefits owing to increased understanding. One important decomposition which he proposed is that on a physical or geometrical basis, more generally a topological decomposition. This topological decomposition of the system into various pieces would be followed by the determination of transfer functions for each of the pieces and then a recombination of these into an overall system transfer function.

Baum further addressed specifically the idea of topological decomposition into layers of shielding. That is, protection against external EMP signals would be provided by layers of topological shields surrounding the circuit to be protected and then each other successively. At each layer, analysis would include the coupling of current and charge densities to the outside of the shield and then the penetration of energy through the shield via the usual distributed penetration (e.g., diffusion) as well as discrete penetrations. In a practical sense, Baum identified the shield layers with physical system features such as aircraft skin, cable shields, and black boxes and the discrete penetrations with such items as antennas, apertures, and conductor penetrations and connections.

Tesche [3] also utilized these concepts in his analysis of the internal interaction part of the EMP problem but additionally stated that they were general concepts which could be utilized in electromagnetic interference problems other than EMP. Indeed, Baum [4] did generalize the ideas. Within general scattering theory, he discussed a hierarchical scatterer topology, based on surfaces and their enclosed volumes, as one means (among a variety) of decomposing any complicated electromagnetic interference problem into a set of smaller problems. His primary interest was in problem decomposition for analysis simplification. He did, however, also discuss the application of hierarchical scatterer topology to actual system design and maintenance for reduction of electromagnetic interference. An effective design concept utilizing a set of shields, control of penetrations of the shields, and a theoretically consistent grounding scheme was possible.

This latter use of topology as not just an aid to analysis, but as an actual means to practical, effective, general electromagnetic interference control has been pursued in various quarters. Vance, Graf, Nanevicz, and Hamm [1,5] utilized and comprehensively developed the concept specifically to serve as a single, fundamental basis for evaluating a broad range of standards and specifications concerning EMI/EMC, safety, EMP, lightning, and TEMPEST. It is thereby a unified approach; any technique which is consistent with these basic physical principles will be compatible with any other technique which is likewise consistent with them. It is these latter authors' development of the topological approach, as described in References 1 and 5, that serves as a basis for this background chapter.

B. A BARRIER VERSUS A SHIELD

The topological approach as developed begins with the more basic concept that a circuit can be protected from electromagnetic interference by separating the circuit from the offending source(s) of energy by a barrier which is effectively impervious to electromagnetic waves, whether in space or guided. This barrier may consist of primarily a conducting shield but also a number of other elements which contribute to the central requirement of this approach: that the barrier form a topologically closed surface.

The distinction between barrier and shield in this context is critical. A closed Faraday shield made of perfectly conducting material will completely isolate its interior volume from any exterior electromagnetic energy (and vice versa) and therefore is the ideal impervious barrier. In any practical situation, however, such a shield would necessarily be violated in order for the system inside to function. For an electronic system, signal and control lines must enter and leave, power must be supplied to the circuit, and items such as ventilation and maintenance access must be provided for.

For such a system, the shield is then only one element of the required barrier, the latter term defining the more general concept. Additional elements of this barrier will include those treatments of conductor penetrations, apertures, etc., needed to reduce or eliminate the propagation of interference through them, that is, to achieve a topologically closed, effectively impervious barrier. A barrier need not, in fact, involve a metal shield surface at all. However, the use of such a shield as the primary barrier element does allow for easier identification and control of the barrier topology and therefore can be expected to be common.

Considering, then, a barrier which does utilize a conducting shield as its primary element, the shield itself may generally turn out to be the least critical element of the barrier, except at very low frequencies. Even a non-ideal, i.e., finitely conducting, metal shield would offer significant isolation to electromagnetic waves if it were completely closed. An untreated conductor, on the other hand, penetrating through a hole in that shield would provide a path for the nearly unattenuated propagation of electromagnetic waves through the barrier over a broad range of frequencies, making that path much more critical in terms of barrier effectiveness. Perhaps in-between in degree of importance would be the impact of other apertures in general. This order of importance of interference "paths" through the barrier is, of course, dependent upon frequency, physical sizes and geometries, etc., but may be considered to be typical.

The interference control problem, then, reduces to the identification and rigorous control of a barrier topology. A topologically closed, effectively impervious boundary around a protected circuit may be comprised of various elements, including shields, penetrating conductor treatments such as filters and limiters, and aperture treatments such as meshes and covers. While this imperviousness is certainly a function of frequency, the approach is a fundamental, physical approach which, if employed properly, can allow for effective broadband control throughout a significant frequency range of interest. Figure 1 is a generic, simplified representation of the use of a topological barrier.

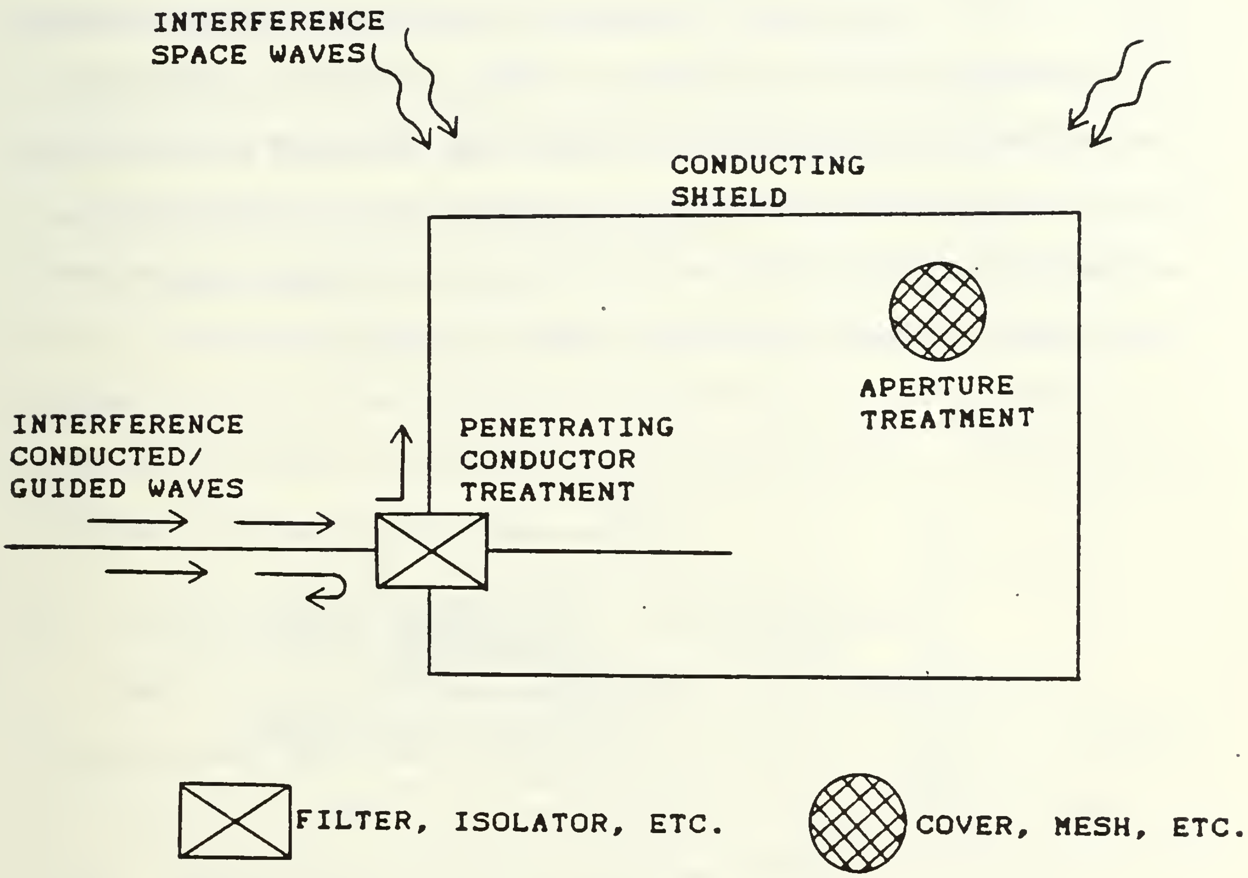


Figure 1. Generic Topological Barrier

C. BARRIER EFFECTIVENESS

The ultimate measure of barrier effectiveness is the level of "stress," realized in current and charge densities, which a protected circuit on one side of the barrier is subjected to due to interference generated on the other side.

The threshold below which that stress must be is determined by at least the damage level of components, if known, and further by the malfunction rate, subjectively arrived at, which can be tolerated. However, a practical barrier should only be required to be effective enough that the effect of the external interference is below the internal stress level due to interference normally generated within the protected volume anyway. This is what is meant by "effectively impervious." Figure 2 illustrates the idea.

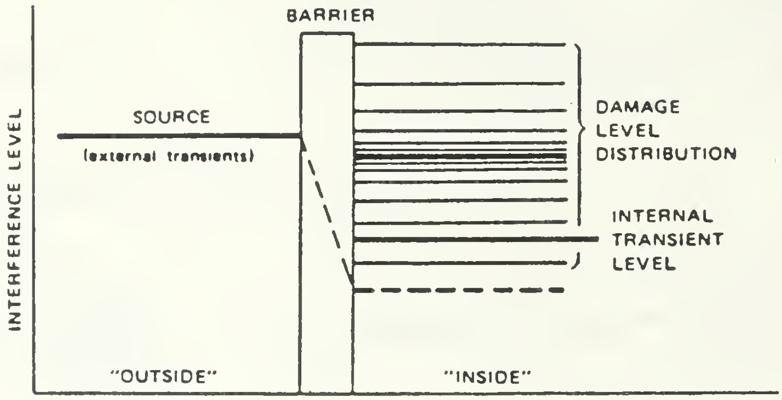


Figure 2. Effectively Impervious Barrier [5]

It is often required in practice, and fortunately quite natural in theory, to provide control of electromagnetic interference both ways across a barrier. That is, it is desirable to have the topological barrier function bilaterally. While a circuit inside a topologically closed barrier is protected from external interference, a bilateral barrier will similarly control the influence of the internal circuit on the external environment. This is especially useful in the case of extremely noisy equipment or when requirements for secure communications exist. More importantly, however, compatibility in general between circuits in separate barriers is achieved in this manner.

Fortunately, many practical barrier elements and treatments generally are, or can be made to be, bilateral. If so, "outside" and "inside" are simply swapped. The guideline for being effectively impervious is followed in both directions and susceptibility and emission criteria are thereby simultaneously met.

D. ALLOCATION OF CONTROL

Under the topological approach, electromagnetic interference control is normally allocated between a number of levels, or layers of topologically closed, effectively impervious barriers. In this manner, the interference control requirements, or responsibilities, imposed on any one barrier are not overly demanding.

While any number is always possible, two levels can typically be readily identified and utilized. One is at the facility or system level and the other is at the equipment or subsystem level. Figure 3 shows, again in a simplified, generic manner, the use of two such levels of barriers.

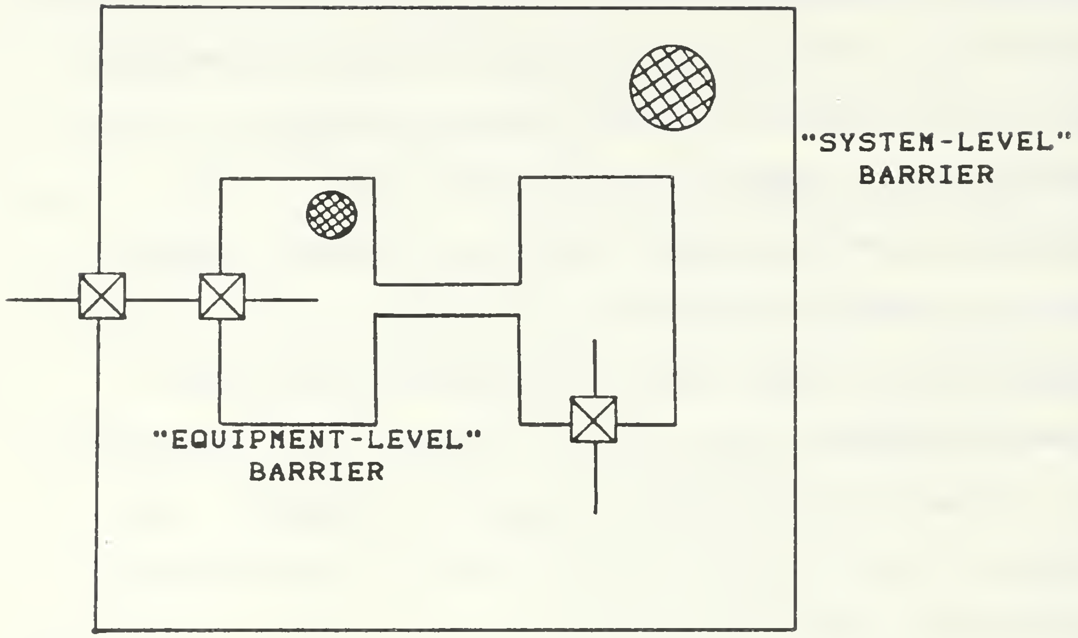


Figure 3. Two Layers of Topological Barriers

The physical realization of these levels can be as varied as the many types of electronics installations themselves. In a communications building, for instance, a facility-level barrier may indeed be at the building structure itself. In this case, metal structural elements may form the primary part of the barrier as shielding and then treatments would be provided for penetrations such as power, communications, and antenna lines and for apertures such as doors, windows, and ventilation, thereby forming a topologically closed barrier. Completely enclosed within that barrier, an equipment-level barrier may coincide with equipment cabinets (each containing a number of individual equipment cases) and their interconnecting ducts or cable trays, again including required treatments of penetrations, apertures, etc. Alternatively, the individual equipment cases and their interconnecting shielded cabling may be the level at which the equipment-level barrier is formed. In yet another option, the system-level barrier can coincide with the equipment cabinets and the equipment-level barrier with the individual equipment cases.

Once again, more than two levels could very likely be utilized. For example, all of the physical boundaries mentioned, i.e., the building, the cabinets, and the equipment cases, as well as others, such as various rooms, could be used as the bases for multiple levels, or layers, of topological barriers.

The possibilities are, of course, endless. The question also arises of whether, or perhaps how, to separate subsystems (or systems depending on definition) into separate barriers at the same level. If forming an equipment-level barrier at the individual equipment case, for instance, the circuitry in one case is likely to be required to interface with circuitry in another case or cases. In that event, it would be beneficial to extend the barrier using, for example, shielded cabling so that the barrier includes all those cases and their interconnecting cable shields. Doing so is likely to be much easier than closing the barrier around each case and then, at each case, providing treatments for each conductor penetration or pin connection involved in the interface. On the other hand, circuits or components which do not interface, and are therefore not likely to be compatible (each may interfere with the other), would probably not be included in the same extended barrier because circuit design protection from each other (which amounts to barrier separation) would then be required and a degree of flexibility would be lost. As a result, a typical scenario may include the use of a single facility-level barrier and inside of that, a number of separate barriers corresponding to separate systems (subsystems), each at the equipment level and each independently providing a topologically closed, effectively impervious boundary. Again, it is stressed that all of the various barriers may normally be required to function bilaterally in order to achieve overall compatibility (and perhaps fulfill security requirements.) Protection of a circuit "inside" a closed barrier from "outside" interference is not a general description of the problem; typically, a circuit "inside" a barrier is also a source whose effects "outside" that barrier must be controlled.

Chapter III will further discuss, from a practical standpoint, many of the above issues with regard to equipment-level barrier design.

In any event, the benefits of allocating the protection between more than one level are clear. As already mentioned, it is desirable to ease the interference reduction requirements imposed on any one barrier. A prime example of this is protection of circuitry from the effects of large-scale, large-area external sources such as lightning or the nuclear EMP. While sometimes it is necessary to do so, it would normally be unreasonably difficult and extremely costly to design a single barrier at the circuit level to handle the tremendous electromagnetic field levels which can be expected, particularly in terms of critical items such as the treatment of required conductor penetrations. Instead, enough effort could be put into a facility-level barrier to reduce the interior stress level due to such external sources to just below the facility's normal interior stress level due to power and regulator switching transients, computer and other circuit noise, etc. Then, equipment-level barriers would only be required to reduce that more easily-manageable facility environment to below the small-signal stress levels inside of those barriers. (Indeed, since the basic principles involved are the same for either, the differences between a facility-level and an equipment-level barrier in this scenario would lie primarily in the types of penetration and aperture treatments required for the vastly different impressed voltage and current levels involved).

It must be remembered that the concepts here certainly do not just apply to buildings or to any other specific type of electronics facility. For instance, in an aircraft system, the skin of the aircraft can coincide with a facility-level barrier and, completely enclosed within that barrier, the individual equipment cases and their interconnecting shielded cabling may be utilized in an equipment-level barrier.

E. GROUNDING CONSIDERATIONS

While the proper grounding scheme to use is an integral part of the overall topological approach, it is mentioned separately due to its critical importance combined with the fact that the role of grounding in interference control is generally misunderstood.

While often credited with the qualification, grounding is not, in fact, an interference control technique at all. One cannot "ground out" interference. On the other hand, an improper grounding scheme can enhance interference. The goal is to simply utilize a grounding scheme which is compatible with the fundamental, physical concepts of the topological approach.

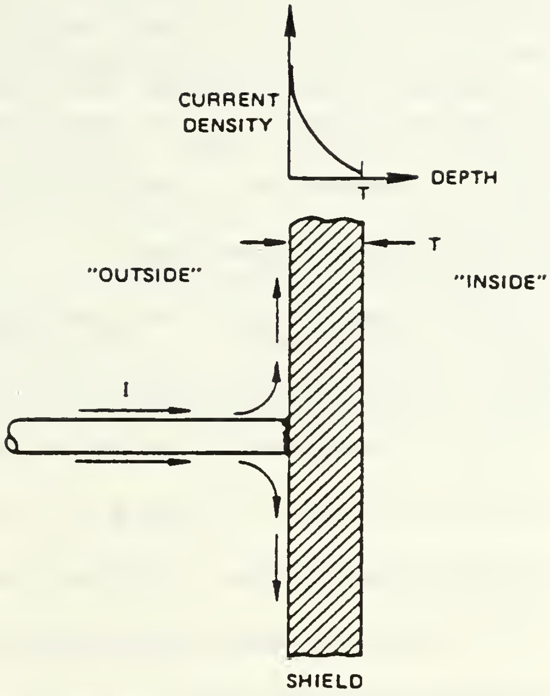
The term "grounded" is defined by the National Electrical Safety Code (NESC) to be "connected to or in contact with earth or connected to some extended conductive body which serves instead of the earth." [6] According to the NESC, the purpose of grounding is the safety of personnel. To that end, it must provide a continuous conducting path through which electrical fault currents may flow, thereby allowing fuses and circuit breakers to trip, clearing the fault.

For example, if the hot lead of an ac power line supplying an equipment were to accidentally become shorted to the metal equipment chassis, a severe shock hazard would be created. However, a proper safety ground bonded to the chassis (a bond is simply a good electrical connection) would follow a continuous path back to the service entrance where it would be tied to the transformer secondary neutral (as well as to earth ground although the earth should not be part of a fault clearance path on the consumer side of the service entrance). This would allow for a large current flow, sufficient enough to immediately trip breakers located in line, thereby disconnecting the hazardous circuit, or clearing the fault. In additional roles (although not unrelated to safety), grounding can also prevent the accumulation of electrostatic charge and allow for the equalization of potential between nearby objects.

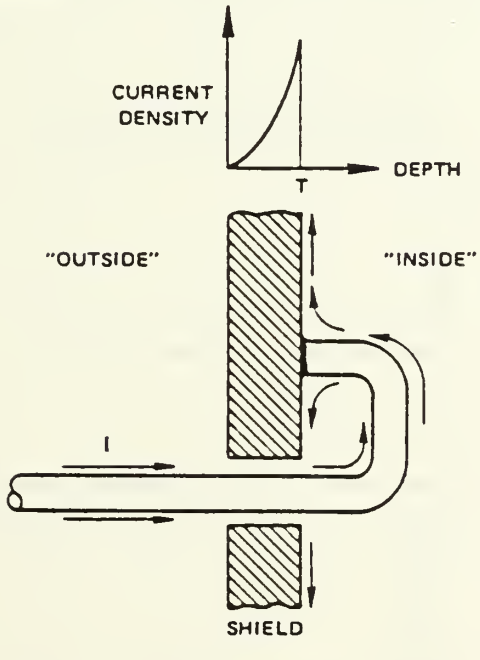
From an electronic circuit point of view, a ground can also provide a common reference potential, to the extent that the impedance of the ground conductor at the signal frequency will allow it to be so. This is the well-known signal common. This purpose, however, has no direct relationship with the safety goals already mentioned.

Under the topological approach, in which an impervious barrier is imposed between the source of interference and the protected circuit, grounding is in no way an element of that barrier. Grounding can, however, violate the barrier if a ground conductor is allowed to freely penetrate it. The compatible approach is to provide the required continuous ground path from any metal cabinet back to the service entrance, but without penetrating any topological barrier layers along the way. The method would be to terminate (bond) the ground conductor on one side of the metal shield portion of a barrier (i.e., the metal wall of the box, cabinet, room, or whatever structure that layer's barrier coincides with), and then continue the path with a ground conductor similarly bonded at another spot <u>on the other side</u> of the barrier.

The important principle is that at low power frequencies, such a ground path is effectively continuous and therefore can do its safety job. At high frequencies, however, skin effect forces current to the outside of conductors and current flowing on one side of a closed shield is confined to that side. This, of course, depends on the shield thickness versus skin depth at the interference frequency as well as effects due to openings in the shield, but empirical evidence shows that the effects can be dramatic throughout a significant frequency range. Interference currents at high frequencies which are, by whatever mechanism, injected on a properly (topologically) connected ground conductor in one zone would not be allowed to propagate freely through a barrier into another zone as they would be on a ground conductor which simply penetrates through a hole in the



CONFINEMENT OF CONDUCTOR CURRENT TO "OUTSIDE" SURFACE BY SKIN EFFECT



CONDUCTOR CURRENT INJECTED ON THE "INSIDE" OF A SHIELD

Figure 4. Ground Conductors and Skin Effect [1]

barrier. Figure 4 illustrates this principle. If, for whatever reason, it became physically necessary to allow such a penetration, the ground conductor would need to be treated as would any other type of conductor, generally presenting a harder task than inside/outside connection.

In a system of layered topological boundaries, then, each zone, or enclosed volume, effectively has its own ground system and, again, no ground conductor would normally ever be permitted to penetrate any barrier. Figure 5 illustrates the compatible system grounding technique. As far as signal common is concerned, the ground system interior to any topologically closed barrier could serve as signal common for circuitry in that zone.

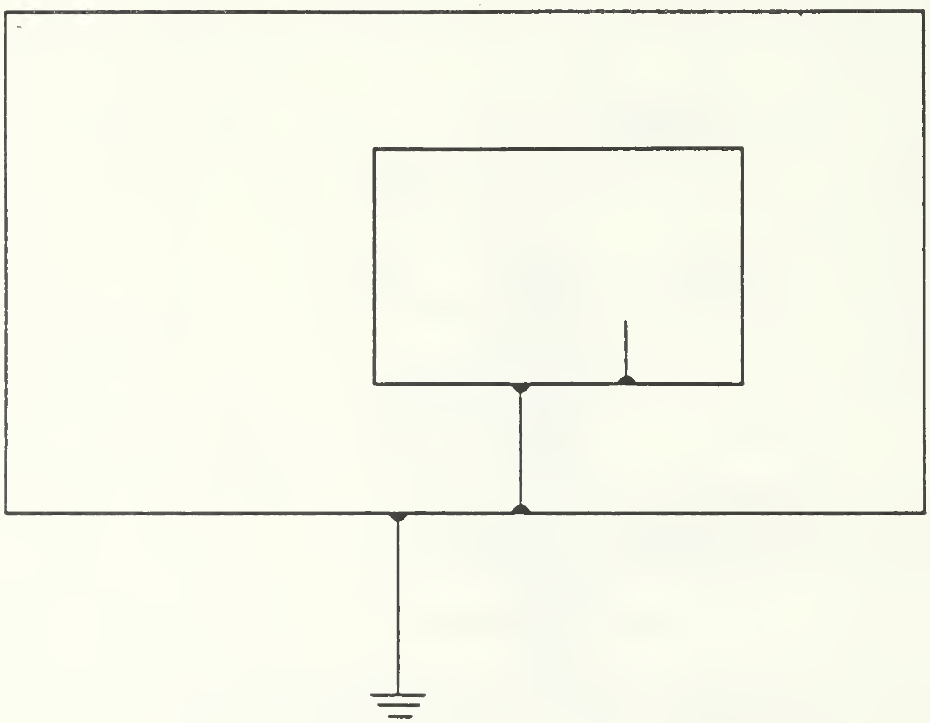


Figure 5. Compatible System Grounding Technique [1]

The practical details involved in setting up a proper ground system will surely vary somewhat with each particular system application. The approach outlined, however, is a simple one to follow and significant benefits can be gained with relatively little effort by simply applying the principles correctly. These benefits were specifically evaluated in the experiments which will be reported on in Chapter V.

III. IMPLEMENTATION

A. BASIC APPROACH

There exists a need to evaluate a number of items concerning the practical implementation of the topological approach at electronics facilities. One very important, basic question is whether, realistically, the concepts can be applied at all at an already existing facility.

Heavy expenditures in time (including operational time) and money could be required to bring a facility completely in line with the proposed concepts. The level of difficulty encountered would, of course, depend on the existing system architecture. Particularly important would be items such as the type of grounding system in place, the equipment layout, the use of equipment enclosures, and the inevitable existing accumulation of a number of different interference control techniques.

On the other hand, it would normally be extremely difficult to justify the primary alternative, that is, the construction of a replacement facility which follows the topological approach. The benefits of such a move could be extensive and long-lasting, but the costs could easily be prohibitive.

Further cost and benefit analyses concerning these alternatives will be required, but such analyses will naturally rely heavily upon additional practical study and experimentation. It is in the interest of such study that these remaining chapters were developed. An examination of some aspects of the first option, that is, implementing the concepts at an already existing facility, was conducted since this is considered to be the more realistic option in most cases. Specifically, the subject of equipment-level barriers was pursued.

B. LOCATION OF THE EQUIPMENT-LEVEL BARRIER

In the previous chapter, various "physical" boundaries were discussed as possibly serving as the bases for equipment-level topological barriers. Consistent with the above goal of implementation at existing facilities, the use of physical boundaries which are inherent to or easily available to such facilities is desirable. For instance, the physical structure of an individual equipment case is a prime candidate since the metal enclosure would provide a semi-closed shield as the primary element of the barrier. But is it the best choice? As already discussed, there are a number of options.

1. The Equipment Case

Equipment such as individual radio receivers, amplifiers, test instruments, computer components, recording devices, etc. are generally individually and independently enclosed or cased. Such equipment cases serve several obvious purposes, e.g., basic packaging, but can also play an important role in the topological approach. While for packaging purposes alone, a manufacturer could use various materials for a case, the use of some sort of metal enclosure is by far the most common approach. Strength, durability, the use of modern construction techniques, etc. are factors supporting the use of metal, but certainly the shielding properties of metal have played no small role in the design of electronic equipment cases.

Indeed, numerous standards and specifications exist which detail the required construction of metallic equipment cases for shielding purposes. These specifications may not completely comply with the basic physical principles of the topological approach. Some may, in fact, promote ineffective or counter-productive practices. The fact remains, however, that most individual electronic equipment items are provided by the manufacturer with cases which provide a conducting shield which is closed to a significant degree. Such a shield alone is not sufficient but, as stated in Chapter II, its use as the primary <u>element</u> in a topological barrier may allow for relatively easy barrier implementation.

Again, in addition to the case as a shield, treatments of conductor penetrations (e.g., power, signal, and control lines) and apertures (e.g., ventilation ports, hardware accesses, and any extraneous holes) would be required to achieve a topologically closed barrier.

The question of equipment interconnection was also previously raised. If barriers were implemented to coincide with the physical boundaries of equipment cases, extending the barrier between cases containing appropriately compatible equipment would preclude the need to provide treatments, at each barrier, for every conductor involved in the interconnection. Because the barrier is at this "black box" level, such extension could possibly be easily implemented through the use of shielded cabling which is relatively common in such interconnection situations anyway. Various types of shielded cabling are available, including shielded multiconductor cable, twisted shielded pairs, coaxial cable and many others. The proper topological connection of a shielded cable at each equipment case requires that the cable connector provide a 360-degree, circumferential continuation of the cable shield with the equipment case shield. The use of high quality cable, properly connected at the individual boxes as described, could ensure a continuation of the barrier which is topologically sound but mechanically flexible. This is a major advantage to implementing the barrier at the case level to begin with. Of course, even this extended, larger barrier is likely to enclose equipment which must interface with equipment outside the extended barrier, as well as receive power, and each conductor in those interfaces must be treated.

Shielded cable will be addressed again in Chapter VI, where the results of various experiments and field investigations concerning coaxial cable will be reported.

2. <u>The Equipment Rack</u>

Another important option to investigate is the use of a typical equipment cabinet, or "rack," as part of an equipment-level barrier. This is a structure which is commonly, almost assuredly, available in nearly any electronics facility.

While numerous different styles exist, the rack is in general a metal box or enclosure to begin with. Its primary (non-interference control) purpose is to provide a supporting structure in which to mount various smaller pieces of equipment, that is, a number of individual equipment cases. The individual equipments in a given rack are normally related to each other, that is, all part of one system or sub-system, but this is not necessarily so. The rack may also contain ancillary equipment which services the installed equipment in a common manner, such as ventilation, cooling, or power distribution.

Typically, the common "open" rack can be found, in some form, in abundance at almost any electronics facility. It is, in fact, built to accommodate "standard" 19-inch wide equipment cases with relatively simple mounting hardware. The front is initially open and is only ultimately covered by either the front panels of installed equipment or, when equipment does not fill all the space available, some sort of blank metal plates. A door in the back allows personnel access to the inside of the rack, including, of course, the back panels of installed equipment. The bottom of the rack is typically open except for some minimal framework for mounting and support. The top and the sides are usually solid, closed metal, although the top may be louvered (as well as, perhaps, the back door) for ventilation. Again, various styles of racks are in use.

A typical modern "RFI (radio frequency interference) cabinet" functionally serves the same equipment-mounting purposes as the open rack, but it is further designed so that all equipment is housed entirely inside of the cabinet, allowing for complete closure of the cabinet with solid doors on front and back. In fact, the doors are typically gasketed with "RFI gaskets" (usually a metal mesh material) to attempt to maintain a continuous shield. A ventilation port in an otherwise closed top is usually provided but is likewise designed in some way to attempt to maintain shielding. The bottom is generally closed except for some facility for the passage of required wires and cables.

While the RFI cabinet would obviously provide a better starting point for use in a topologically closed barrier, it is typically not used to its fullest advantage. The primary reason for this is the continued use of untreated penetrations by power, signal, control, and ground wiring.

However, since the manufacturer of the rack has already provided for excellent closure of the shield element as well as treatment of the non-conductor apertures, implementing a topologically closed barrier may require only the treatment of those conductors.

The open rack, on the other hand, could require a great deal of work to be used correctly according to the topological approach. Open bottoms could be closed with ease and an effort made to ensure that equipment or blanking plates cover the front as completely as possible. However, small spaces will generally remain between those front panels and open ventilation provisions such as large areas of louvering would be difficult to treat. The lack of attention to continuous shielding in general results in cracks and spaces inherent in the cabinet construction. The back door may not make metal-to-metal contact around its entire perimeter and the rack may (even rather loosely) piece together. These apertures and discontinuities in shielding may be difficult or impossible to treat by cost-effective means. Finally, treatment of penetrating conductors must still be accomplished afterwards.

Unfortunately, the open rack is simply more common, as well as a great deal less expensive. To follow the practical route to implementation of the topological approach at existing facilities, the usefulness of the open rack despite serious imperfections must be investigated. In support of such investigation, various simple experiments using a rack were conducted and will be reported on in Chapter V. For that experimentation, an open rather than an "RFI" rack was purposely used in the interest of being as practical as possible.

In any case, when the barrier is made to coincide with the physical boundaries of the equipment rack, the question of how to extend the barrier, when it is desirable to do so, must again be answered. It turns out that such an extension can be made in a rather simple manner using metallic ducting. That is, a closed metallic duct would simply join two or more cabinets into one continuous volume. Then, all required interconnection wiring could simply be run in the ducts and remain within, when fully implemented, the closed topological barrier.

While simple, the duct approach does have an element of permanence to it, perhaps reducing flexibility in a dynamic, or even semi-portable, environment. Shielded cabling could provide that flexibility, as it did in the black box scenario previously described, but is less physically compatible with the rack scenario. A large number of shielded cables may be required between racks, each of which contains numerous individual equipments. A few connections may be made right to the front panels of equipment in the case of an open rack. Otherwise, some other facility must be provided to maintain continuity of the barrier's shield element at the metal wall of the rack. In other words, in order to continue the same type of cable on into the individual boxes in the rack, as would be typically desired, topologically correct feed-thru connections, providing 360-degree circumferential shield connections on both sides of the rack wall, would have to be provided for each cable.

In fact, this inability in general to utilize the quickness and flexibility of common shielded cabling, such as coaxial, between individual boxes in different racks without providing feed-thru's at the rack walls could be considered to be a major disadvantage of placing the barrier at that rack wall level. On the other hand, the grouping of individual equipments into a common barrier when possible does reduce the overall amount of interconnection treatments needed and/or the complexity of interconnecting shielded cabling required if the equipment case scenario were used as in the last section. Therefore, the tradeoffs must be considered carefully.

3. Other Choices

Considering the points outlined above, the equipment case and the equipment cabinet, or rack, may be the most natural candidates for physical boundaries along which to implement topological barriers. (They are, in fact, the most commonly used devices in presently configured shielding schemes.) Other options, however, can be put to excellent use under various circumstances.

One option is to implement the topological barrier at the individual circuit level. Such an approach is not likely to be practical as a general means to implement topology in an entire facility. The complexity of the scheme could quickly become overwhelming and the requirements to provide treatments at all of the required conductor interconnections could be virtually impossible to meet. On the other hand, the use of topology at the circuit level could be extremely useful in specific cases involving particularly rigorous emission standards, such as with local oscillators or secure communications circuitry, or susceptibility requirements, such as with sensitive radio receiver circuits. In such scenarios, the best use of a barrier at the circuit level would still likely be as an additional layer of barrier, that is, in conjunction with a barrier at the equipment case or other level.

Another possible location for the implementation of an equipment-level barrier is along the structure of an entire room. As in the cabinet-level scheme, the primary benefit would be a degree of simplification in that one effort in barrier design and construction could provide the necessary barrier for a number, perhaps a very large number in this case, of individual equipments. The number of interconnection treatments and extensions of barriers could be greatly reduced. However, the basic assumption, as it was with the equipment cabinet, is that since the individual equipments enclosed are not individually provided with barriers, they all must be mutually compatible to a satisfactory degree. Although that assumption may be valid in certain specific cases, it would be difficult to meet in general and much could be lost in terms of equipment interchangability and flexibility using this approach. Therefore, except for such special cases, a barrier coinciding with the confines of a room would most likely be used, when required, as an additional layer to barriers coinciding with equipment cabinets or cases.

In these last two schemes, at the circuit level and at the room level, the topological barrier would still normally be expected to utilize as its primary element a conducting metallic shield which is inherently closed to the degree possible. While this might be a considerable task at the room level, it is far from impossible and the treatments of conductors with which the enclosed equipment communicates to the outside, and of apertures arising from such items as ventilation and accesses, are likely to impose the more difficult problems.

While a topological barrier is not fundamentally required to utilize a shield element at all, its use, as discussed in Chapter II, as the primary element is rather natural in practice and leads to easier implementation and control of the barrier. Therefore, while physical boundaries which are not basically comprised of a metal box (or made to be so) could be added to the list of options, it would be hard to imagine the practical use of any other elements which could, on a large but simple scale, contribute towards a barrier as effectively as those metal structures used as shields.

Once again, while all of the options mentioned, as well as other such structures, must be considered, combinations of any number of them in layers really comprise additional options. Allocation between the layers can be utilized to meet the interference control requirements in the best practical manner. An additional consideration concerning the open type rack comes to mind here, for instance. If it was desired to implement two layers of barriers at both the rack and the equipment case levels, the open rack does not easily allow for it since, inherently, the front shield wall of the barrier at the rack level is provided by the front panels of the equipment cases themselves. That is, the two levels of barriers would actually share one shield wall instead of one barrier being completely enclosed within the other. While it is possible that the actual configuration could be nearly as effective as the ideal one anyway, further analysis or experimentation would be needed to confirm that.

IV. INSTRUMENTATION

A. INTRODUCTION

In the following two chapters, the results of various experiments conducted for this thesis are presented. A brief description of some of the more important instrumentation elements which were utilized in those experiments is offered here first.

The primary thrust of the experimentation was frequency domain analysis. Specifically, in attempting to obtain a qualitative and quantitative appreciation for the interference control "performance" of practical devices, such performance as a function of frequency was observed. In support of the initial motivation for this thesis as stated in Chapter I, and in an attempt to limit the scope of the investigation, the experiments were primarily limited to frequencies within the HF range.

B. MEASUREMENT PACKAGE

The main instrumentation set-up included a scanning spectrum analyzer and an accompanying 3-axis display as configured in numerous previous Naval Postgraduate School studies [7,8]. This allowed frequency domain analysis with the additional benefits of time variance observation and the direct comparison of successively different hardware configurations.

1. Analyzer

The spectrum analyzer which was utilized for the measurements is the Hewlett-Packard Model 141T Display Section operated with a Model 8553B RF Section and Model 8552B IF Section. The resulting configuration is a scanning superheterodyne receiver with a frequency range of 1 Khz to 110 Mhz. In its basic operation, a single IF (Gaussian) filter repeatedly scans up linearly through its assigned frequency range, or scan width. The scan width, scan center frequency, scan time, IF bandwidth, and IF gain are all selectable as is the analyzer input attenuation.

2. 3-D Display

For data presentation, the 141T analyzer output was sent to a synchronized Develco Model 7200B 3-Axis Display. As each analyzer scan output is displayed on the 7200B, it is moved up in a rising raster manner as shown in Figure 6. The last 120 scans are thereby always displayed with the most recent at the bottom. The display provides a unique opportunity to observe the time variation of signals and noise. Since the input to the display is only that energy within a scanning IF bandwidth, however, the horizontal axis is both a frequency and time axis and this must be carefully considered in the interpretation of the data.

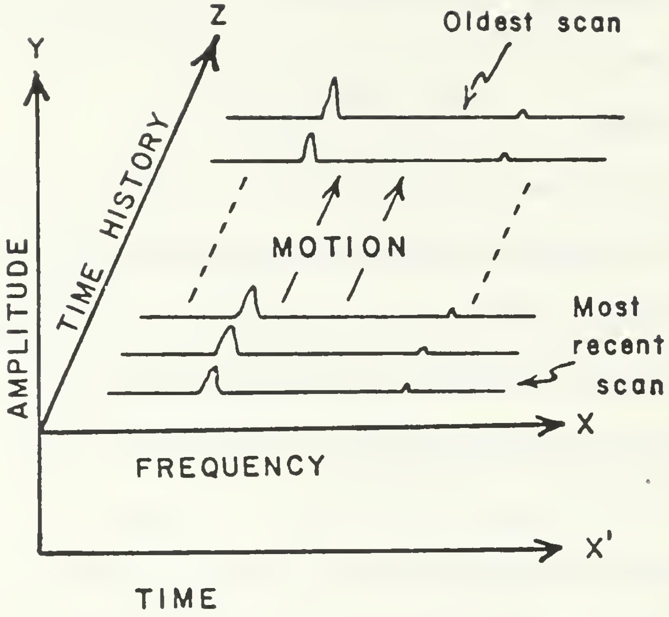


Figure 6. 3-Axis Display

The aspect angle, the amplitude threshold, and the height of the signal or noise presentation (called compression) can be varied to highlight various features of the information. The display may run continuously as desired or be stopped for photographic recording. Also when desired, a smaller number of consecutive lines out of the 120 may be displayed exclusively to investigate a particular span in time. For this thesis, this last feature was used extensively to display only 64 lines in a given view for greater visual resolution between lines.

A typical final data presentation consists of two photographs. One is a 3-D view as described and for the other, the elevation of the display is dropped down to baseline and the azimuth vertically aligned so that what is observed is all of the displayed scans overlaying one another. The compression is raised to its highest position, which has been previously calibrated against the 141T. This provides a calibrated, 2-D amplitude-versus-frequency presentation.

For each of the photographic presentations which follow, only the most important measurement parameters are included in the figures. The complete list of measurement parameters and calibration data for each can be found in the Appendix in the following standard format [7]:

Line 1 -- Local time of day, date of measurement

Line 2 -- Organization code, measurement site, measurement location

Line 3 -- Sensor or probe, line amplifier gain, analyzer input attenuation, analyzer IF gain

Line 4 -- Center frequency, frequency scan width, IF bandwidth, scan time

3. <u>Current Probe</u>

In the majority of cases for this thesis, the primary measured parameter was current flowing in conductors. For those measurements, a Tektronix Model P6021 Current Probe with passive termination was utilized. The P6021 is clipped onto a conductor and thereby measures the current through the conductor without interrupting or connecting to the circuit.

The measurement bandwidth is from 450 Hz to 60 Mhz with its passive termination and with a 2 mA/mV sensitivity.

With its passive termination, the P6021 is designed for use with 1-megohm input impedance devices, while here it was used with the HP141T analyzer, and the HP8447A line amplifier in front it, which are 50-ohm input impedance devices. The dominant effect of the resulting mismatch, however, is a loss in measured signal power and since the experiments were all concerned with <u>comparisons</u> of measurements between configurations, the power loss was an acceptable alternative to a more complicated measurement set-up and a matching amplifier was not utilized.

C. NOISE SOURCES

The experiments primarily involved the response of a hardware configuration to injected signals which represented externally generated noise and interference. The signals used included white noise, discrete sinusoids, and switching transients associated with a silicon controlled rectifier (SCR) device.

1. White Noise Generator

The Marconi Type 2091B Noise Generator was utilized for a source of white noise. The output of the generator is approximately flat from about 12 Khz to 12.5 Mhz. The output level can be adjusted through the use of attenuators working in various 5 and 10-db steps. The bandwidth of the white noise can also be limited through the use of installed filters if desired.

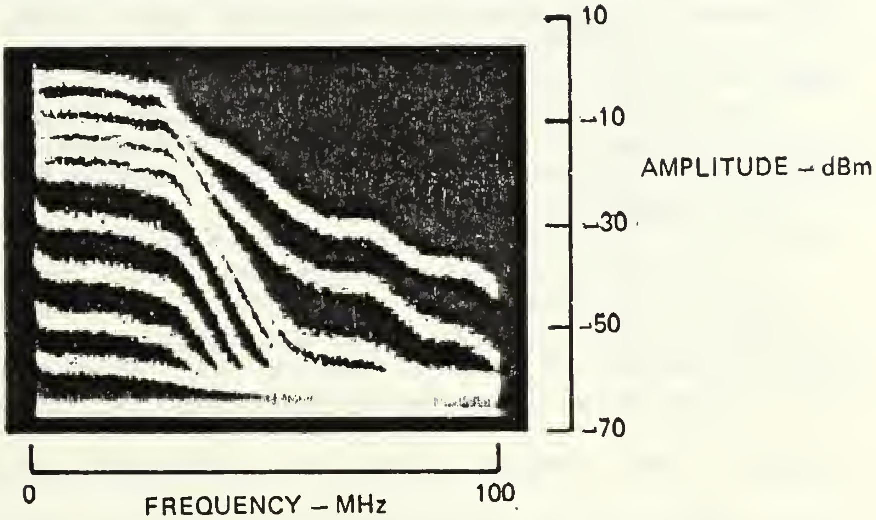


Figure 7. White Noise Generator Output

Figure 7 shows the output of the 2091B with no filters in line and at its various attenuator settings, as measured by the HP141T with a 100-Khz IF bandwidth. Displayed is a 2-D amplitude-versus-frequency presentation taken off the 3-axis display as previously described. It can be seen that at the highest (least attenuation) settings, the spectrum of the noise beyond the design rolloff is increased. While this is probably due to intermodulation products (a result of non-linearity when an active device is overdriven) created in one of the generator's amplifier stages, it is not clear how the output attenuators would affect such a process (the HP141T was checked and was found to not be causing the effects.) However, since the important consideration in the experiments which follow is, once again, the comparison of different configurations with the same input noise, the absolute spectrum of the noise is not of concern and the above phenomenon was not further investigated.

2. Function Generator

The Hewlett-Packard Model 3325A Synthesizer/Function Generator was utilized when a sinusoidal source was called for, although the generator provides for other signal shapes as well. The output level is selectable over a wide range of values and the sinusoidal signal can be produced at frequencies up to 20 Mhz. The frequency may be swept up or down with a variety of sweep modes and rates.

3. SCR Control Device

To provide a simple but "real world" source of noise, a standard commercial light dimmer was used. The dimmer utilizes an SCR to control power to a load, usually lighting. While the SCR device provides a relatively efficient means of controlling power, the switching transients associated with the basic operation of the device are so fast, or narrow in time, that their frequency spectrum runs well into the megahertz range. The transients can easily be measured with a current probe on any of the hot, neutral or ground leads associated with the circuit and, as well as being conducted elsewhere, these currents give rise to strong radiated fields.

Because of this, a commercial dimmer is normally equipped with a filter to reduce these transients above a frequency cutoff corresponding roughly to the lower end of the AM radio broadcast band (540 to 1600 Khz). For the experiments here, however, the filter was removed to provide a more broadband source of noise. With a 120-ohm (therefore approximately 1-amp) resistive load, the transients were subsequently measured at significant levels throughout the HF frequency range.

V. CABINET PENETRATING CONDUCTOR EXPERIMENTS

A. BASIC APPROACH

While theoretical analysis is indispensable, the value of empirical evidence in the appraisal of new concepts cannot be overstated. In the case of concepts which are expressly simple in nature, it is often further expected that the validity of the concepts should be able to be demonstrated in a simple, straightforward manner.

It is from this perspective that the motivation was formed to conduct a number of experiments concerning the practical implementation of the topological approach. As stated earlier, a need exists for such experiments to address the feasibility of using available, practical hardware elements in the approach. In support of this, the experiments described in this chapter investigated the use of a common, open equipment rack taken from the field.

In Chapter II, it was submitted that for a barrier using a conducting shield as the primary barrier element, the order of importance of interference "paths" through the barrier may be considered to be: penetrating conductors, apertures in general, and, lastly, the shield itself. That is, untreated conductors penetrating the shield would allow the greatest amount of interference energy to pass through the barrier while the passage of that energy through the shield itself is of the least amount. While dependent upon frequency, sizes, etc., this order typically holds in many practical cases up through the HF frequency range and higher.

Considering a common equipment rack, the construction and configuration of the rack are likely to be far from ideal in terms of shielding material, shield continuity, and apertures. Nevertheless, sufficient closure ability is likely to be provided that untreated penetrating conductors would still present the greatest potential violation of the barrier which the rack is intended to implement. These conductors may include power, signal, control, and ground conductors.

The experiments conducted on the test rack addressed two aspects of penetrating conductors. First, concerning ground conductors, a number of experiments sought to demonstrate the benefits of not allowing a ground to penetrate the barrier at all, but instead making a proper topological inside/outside connection. Secondly, conductors which are required to penetrate the barrier must be treated, e.g., while allowing desired signals to pass, a filter may be required to eliminate, or rather reduce, energy outside some desired frequency range, a limiter may be needed to reject energy above some amplitude level, etc. In the experiments here, the proper connection of a filter from a topological viewpoint was investigated for simple wire penetrations. While the filter was designed for use as a power line filter, the principles involved should apply in general to other such wire penetrations and filters.

B. SOME PREVIOUS RELEVANT EXPERIMENTS

A number of earlier experiments by others are of interest here. While not involving an actual equipment cabinet, they provide, in more typical laboratory scenarios, invaluable insight into the same basic problem. Their clear and sometimes striking results provide strong motivation to continue the work on more practical devices.

1. Group I

In Part I of the report by Vance et al., which was referenced at length in Chapter II, an experiment conducted with a large shielded chamber was reported on [1: Appendix C]. The outside of one wall of the chamber was driven with a double exponential high-voltage pulse in order to excite the chamber over a wide range in the frequency domain. Time domain measurements were made of the peak open-circuit voltage and short-circuit current induced in large (the largest which could be installed) loops inside the chamber under various ground return configurations. In the first, basic configuration, the return conductor was connected to the outside of the wall opposite the driver and then to the ground plane below (which the chamber was insulated from.) In this manner, the chamber remained closed. In each of the remaining configurations, a penetrating ground conductor was simulated by passing the return conductor through a hole in the wall and connecting it, with various lengths, to various spots inside the chamber.

The results indicated that the induced loop voltages and currents were 6 to 50 db greater for the penetrating ground configurations than they were for the basic, topologically proper, configuration. While the results were dependent on specific geometries and resonances of the experimental set-up, they do provide a representative view of the superiority of a topological ground.

The same chamber was utilized for a number of other experiments. One concerned the proper mounting of a surge arrestor/filter combination at a shield interface. Another demonstrated that, at least in one particular example, the degradation due to a penetrating conductor was worse by 14 db than the degradation due to an aperture cut in a wall of the chamber, supporting the order of importance discussed earlier. An additional experiment involved penetrating pipes and conduits.

In Part II of the same report [5], another experiment was conducted to evaluate the topological ground at lower frequencies. Using a continuous wave current source and a small instrumentation box, the open-circuit voltage induced inside the box by the outside source was measured under two different configurations. Once again, a penetrating ground was simulated in one configuration and in the other, a proper topological ground. Between 2 kHz and 100 kHz, the voltage measured in the topological ground configuration was always at least 100 db below that in the penetrating ground configuration, even when the lid of the box was removed to present a large aperture. The trend of the data indicated even greater effectiveness of a proper topological ground at higher frequencies.

2. Group II

Another set of experiments specifically aimed at evaluating the performance of topological grounding techniques was conducted by Bly and Tonas [9]. While the experiments were performed with a small experimental box in a controlled laboratory environment, the nature of the set-ups and measurements resulted in a comprehensive data set of great practical significance. It is worthwhile to present the results here at some length.

The tests were conducted on a ground plane inside a room-size shielded enclosure. A small brass test enclosure (box) was bonded to the plane and an exterior signal source used to drive an excitation loop in a number of different configurations, each using a different method of "ground" conductor terminations. Various configurations which were tested are illustrated in Figure 8. Current probes measured the current in the exterior and interior wire segments as shown. With a tightly sealed box under test, data was taken across a wide range of frequencies for each of the

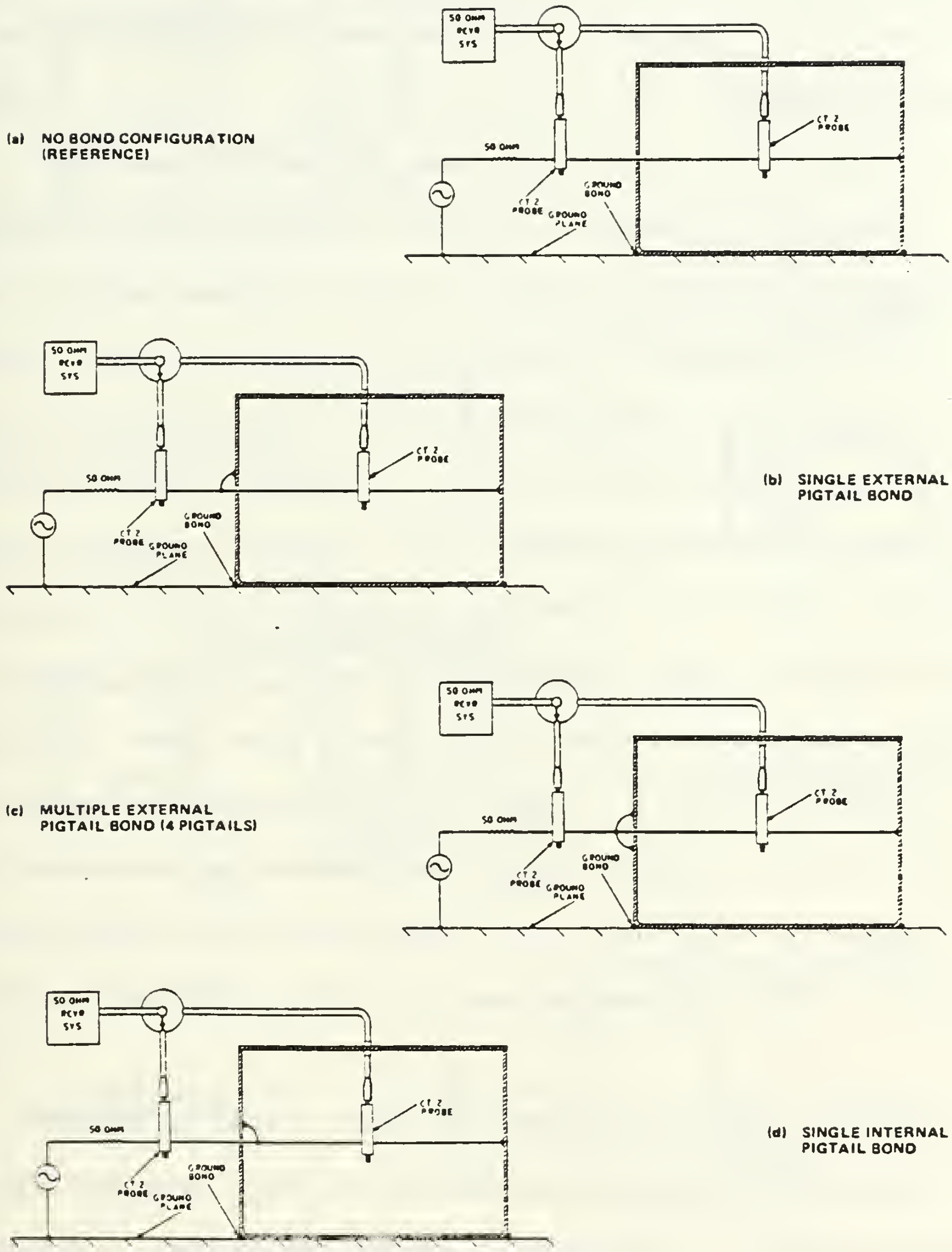
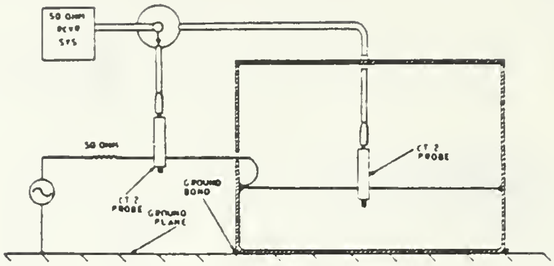
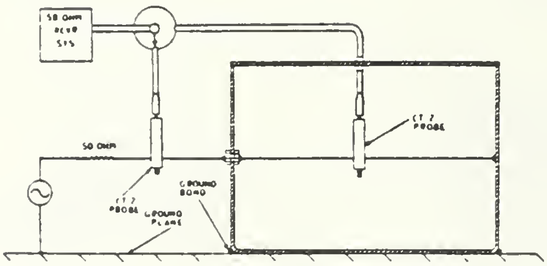


Figure 8. Test Configurations for Bly and Tonas Ground Termination Tests [9]

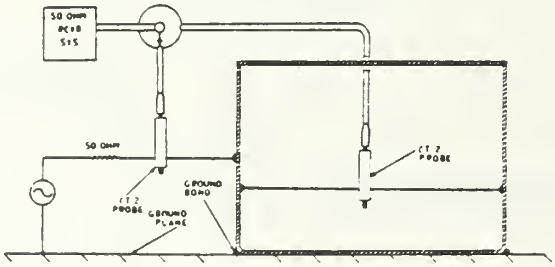
(e) INTERNAL "GREEN WIRE" GROUND CONFIGURATION

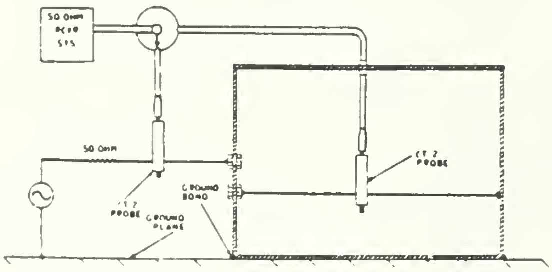




(f) COMMON PENENTRANT GROUND

(g) SEPARATED GROUND TERMINATION WITH SOLDER





(h) SEPARATED GROUND TERMINATION WITH SCREWS

Figure 8. (Continued)

configurations. Additionally, the measurements were repeated for a few of the configurations using an open enclosure in the form of a simple, U-shaped (a bottom and two sides) brass chassis.

The results showed dramatic differences between the measurements for different ground termination methods. Figure 9 shows the data for the tightly sealed enclosure. Relative interior wire current in db is plotted versus frequency. While the various pigtail-type terminations (configurations b through e) provided some degree of isolation between "inside" and "outside", the important observation is the tremendous increase in isolation realized (40-75 additional db) when topological, i.e., inside/outside, terminations were made (configurations f through h). The data further show that the best cases (g and h) call for the inside and outside connections to be made at separate spots but that those connections can just as well be properly made with common hardware (nuts and bolts), a practical benefit indeed.

Figure 10 shows data for both the open, U-shaped enclosure and the tightly sealed enclosure for configurations b,d,f and h. Comparing curves, the amount of improvement in isolation which can be realized with topological grounding even when the enclosure is very poorly sealed (in fact, wide open) is rather startling. When topologically correct schemes (f and h) were used for both the open and closed

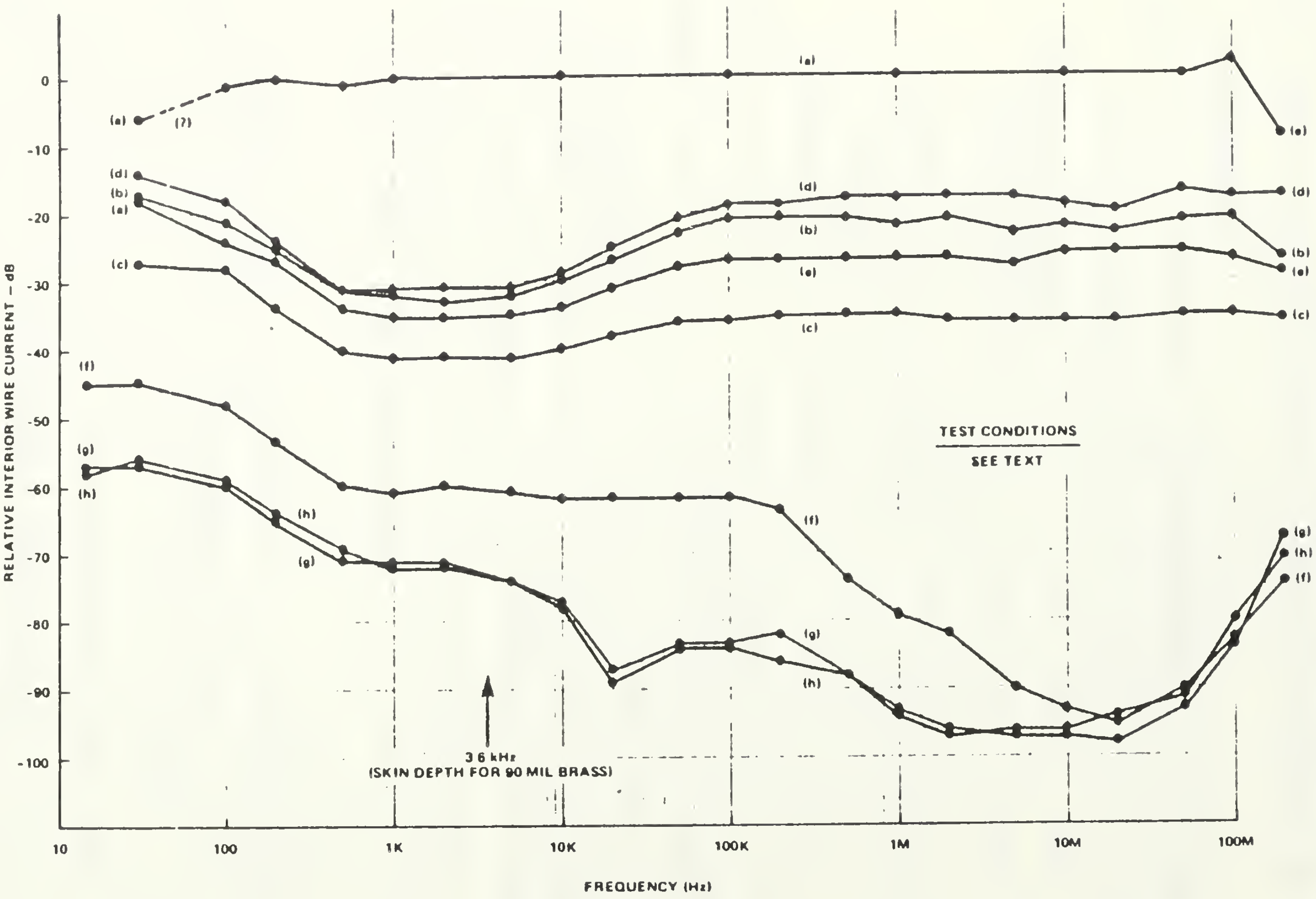


Figure 9. Relative Interior Wire Current vs. Frequency for Closed-Style Enclosures for the Various Test Configurations Shown in Figure 8 [9]

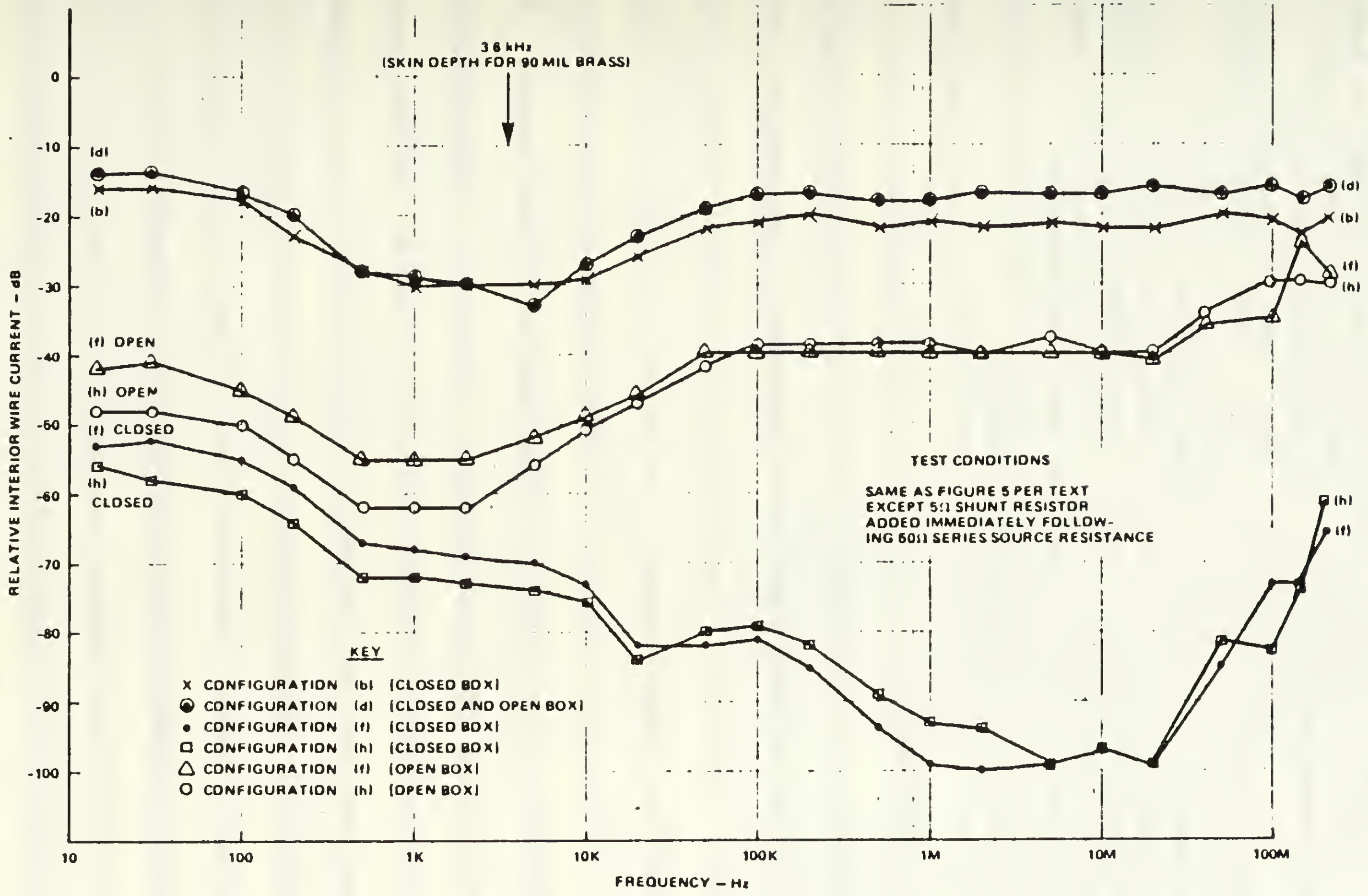


Figure 10. Relative Interior Wire Current vs. Frequency for Closed and Open-Style Enclosures for the Test Configurations Defined in Figure 8 [9]

boxes, the isolation measured with the open box was not nearly as good as with the closed box, especially in certain frequency ranges. However, the isolation provided by the topological schemes with the open enclosure was still significantly better, by 20 db or so, than non-topological configurations (b and d) for closed <u>or</u> open enclosures. This is an important practical result, considering the wide use of rather poorly shielded enclosures and the ease of implementation of a topological ground.

C. THESIS EXPERIMENTS

The penetrating conductor experiments performed for this thesis will now be described and the results presented and analyzed.

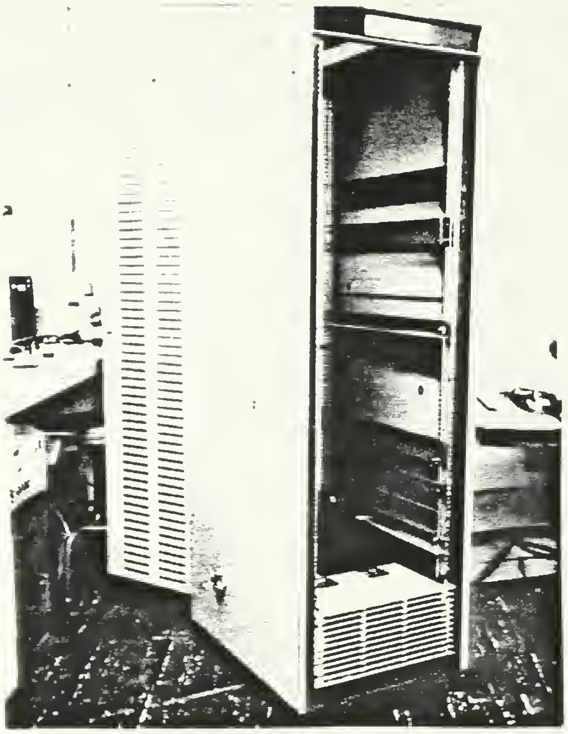
1. <u>The Test Rack</u>

As previously stated, the enclosure chosen for experimentation was a common, open-type equipment rack. Such a rack has already been described in general in Chapter III. This specific rack was removed from service in a digital electronics laboratory. Side by side with another identical rack, it had been used to house a multi-user microprocessor-based computer system. Besides the system itself, additional ancillary devices were removed prior to the experiments. These included a rack "power supply," which merely distributed electrical power received on a long power cord to a power strip inside the rack and two auxiliary outlets at the front, as well as two sets of "muffin"-type cooling fans shelved at two different levels. A larger ventilation fan at the base of the rack was kept in but was not used; its power cord was coiled up and taped to its casing.

Figure 11 contains photographs of the rack utilized. Figure 11a shows the rack with no equipment installed and Figure 11b shows it with a single radio receiver installed, primarily as a token piece of equipment, and with the remaining space covered with standard blank plates.
The latter configuration is the one in which the final data collection was done.

The basic skeleton of the rack is composed of ribs of approximately 0.08-inch thick steel. The top, back door, and sides of the rack are made of approximately 0.05-inch steel sheet.

Overall, the continuity of shielding is very poor. Numerous seams and spaces are inherent in the rack construction. Metal-to-metal contact throughout is somewhat limited in that the various surfaces are painted and/or coated, although DC continuity between any two bare metal points was indicated with an ohmmeter. The sides are held in place only by simple clips, so that they could easily be removed for joining two racks together in one larger enclosure. The back door is louvered as is the top of the rack. The back door hangs by three metal hinges and closes against rubber stoppers and simple roller latches. While a



(a) No Equipment Installed

(b) Receiver and Blank Plates Installed

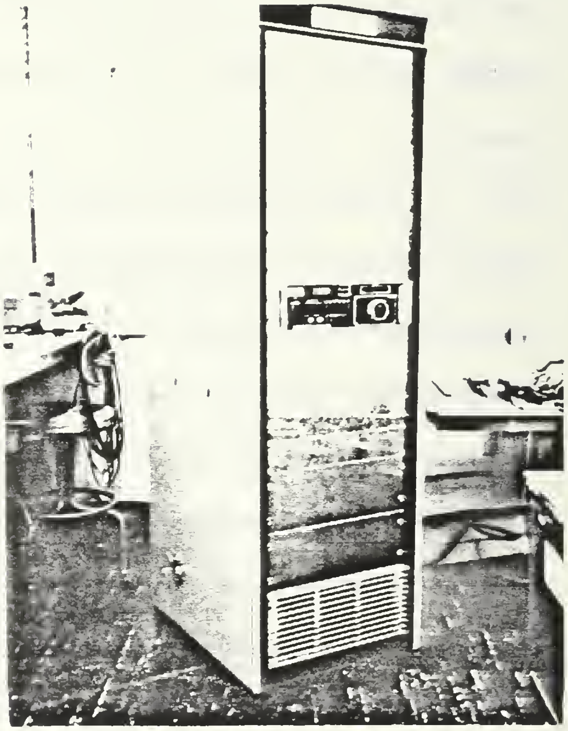


Figure 11. Test Rack for Thesis Experiments

thin aluminum sheet had been placed loosely in the rack bottom at one time, it was not an actual part of the rack and was removed for the experiments, leaving the bottom open (as is typical) except for corner framework pieces.

In the test configuration as in Figure 11b, the front panel of the radio receiver and the remaining blank plates cover the front of the rack, although cracks remain between the various plates. The plates are constructed of approximately 0.12-inch thick aluminum.

Although the continuity of the rack shielding is described as poor, it is still useful at this point to address the wall thickness of the rack in terms of conventional skin depth calculations. Since the 0.05-inch thick steel walls, top, and door provide the largest surfaces involved, they are of primary interest.

Skin depth refers to the depth of penetration of an electromagnetic wave in a conductor. It is a function of the frequency of the wave and of the conductivity and permeability of the conductor. For a perfect (ideal) conductor, the depth of penetration would be zero, that is, the wave could reside only at the surface. In non-ideal but very good conductors, the depth of penetration is finite but small. This "skin effect" (the energy resides primarily near the "skin" of the conductor) plays an obviously important role in shielding and in the topological approach.

Normally, the term skin depth is further defined specifically to mean the depth at which the magnitude of the wave is reduced to 1/e (about 0.37) times its value at the surface. For a good conductor, the skin depth equation is:

$$\delta = (\pi f \mu \sigma)^{-1/2}$$

where

δ = 1/e depth in meters

f = frequency in hertz

μ = permeability in henrys/meter

σ = conductivity in mhos/meter

For typical steel, at 1 MHz the skin depth is evaluated to be approximately 0.016 mm (0.0006 in.); therefore the 0.05-in. steel rack material is over 80 skin depths in thickness! Similarly, the 0.12-in. aluminum blank plates are around 45 skin depths in thickness. While the rack is not completely closed with these materials, that high an attenuation supports the earlier hypothesis that diffusion through the shield itself is a much lesser problem than penetrating conductors and apertures, at least in this high frequency range (the attenuation is even greater above 1 MHz). Certainly, the use of skin effect in the concept is valid.

2. Simple Simulated Ground Experiment

The set-up for this first experiment is shown in Figure 12. The Marconi generator delivered a white noise

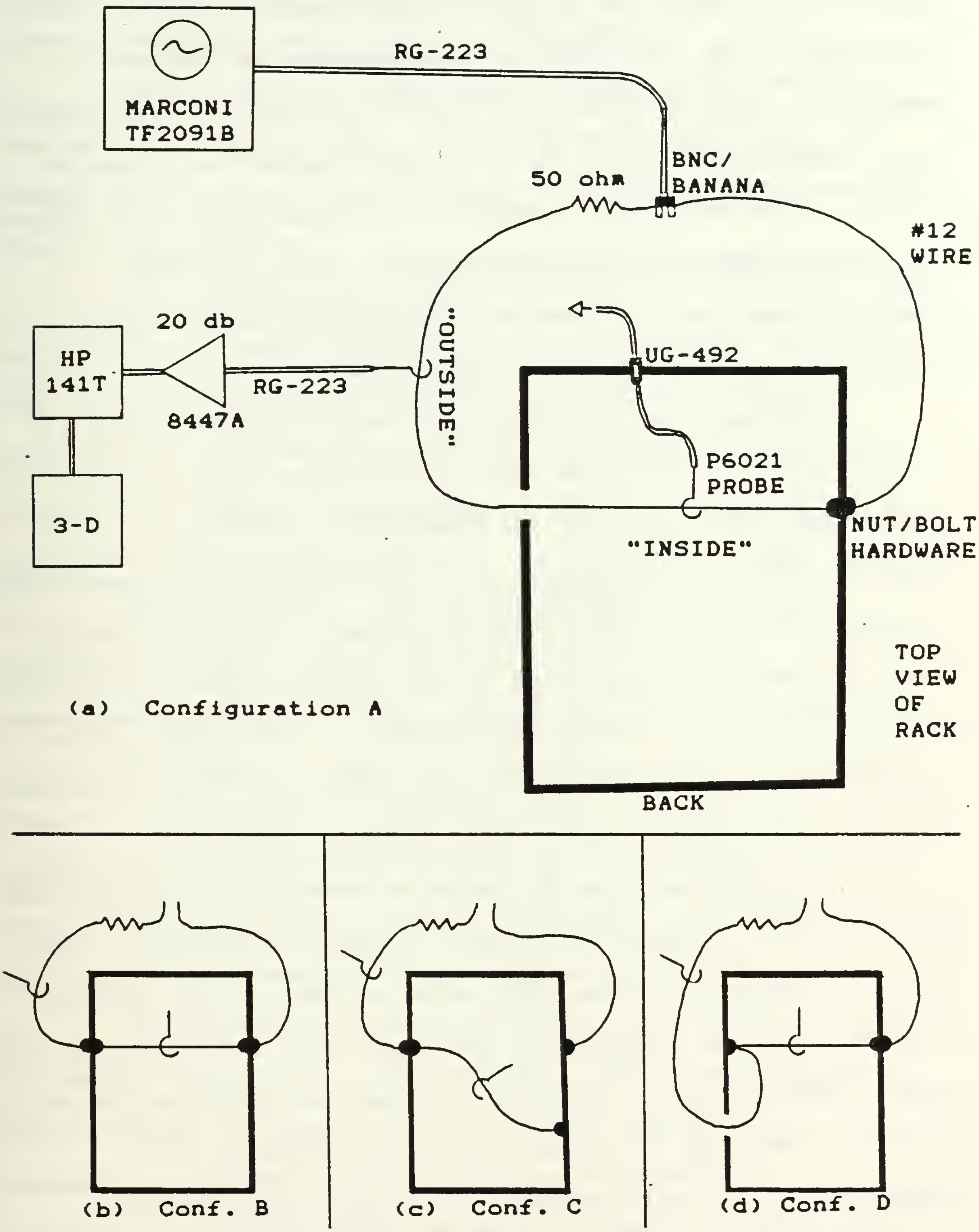


Figure 12. Test Set-up Configurations for Simple Simulated Ground Experiment

output via a length of RG-223 double-shielded coaxial cable (the quality of which will be demonstrated in the next chapter.) Just outside the front of the rack, a BNC/Banana-Plug adapter at the end of the cable enabled the noise to drive a wire loop which simulated a ground "circuit." Common 12 AWG stranded wire was used for the loop. A 50-ohm resistor was placed in series to provide a load for the generator, especially at low frequencies.

Configurations A through D varied in the way the simulated ground wire was terminated at the rack. These differences are reflected in Figures 12a through d, respectively. In Configuration A, the wire simply penetrated a small hole (just big enough for later use of a #10 bolt) about halfway up on one side of the rack in order to simulate a non-topological, penetrating ground. On the other side, it was returned via an inside/outside connection which remained the standard return for all the configurations.

In Configuration B, the wire penetration was replaced with a proper, topological inside/outside connection. That is, the outside wire was terminated on the outside of the rack wall and an inside wire continued from the inside of the wall. Standard nut and washer hardware on a common through-bolt was used for the bonds. (For all bonds in the experiments, the wall surface was locally prepared by removing the paint.) In Configuration C, the topological connection was changed to terminate the outside and inside wires at separate spots about 1 foot apart.

Configuration D simulated another common method of terminating a ground wire. The wire penetrated, then was bonded to an inside spot, in this case about 1 foot away, and finally continued on.

For each configuration, the current in the wire loop was alternately measured at one location outside the rack and then at another inside the rack. These test points are indicated by the locations of the P6021 current probe in Figure 12. Another short length of RG-223 cable connected the probe to a HP8447A amplifier (with 20 db of gain) which fed the HP141T analyzer and 3-axis display. A 100-kHz bandwidth was used on the HP141T. For the inside measurement, the probe cable connected to the outside cable via a UG-492 coaxial feed-thru mounted in one of the rack front's blank plates. Such a feed-thru provides the necessary circumferential connection of the cable shield on both sides of the metal plate so that the instrumentation for the inside measurement was topologically correct.

To compare the inside current to the outside current for each configuration, both 3-D and 2-D views from the 3-axis display, as described in the last chapter, are presented. For the 2-D amplitude-vs.-frequency presentations, the amplitudes would normally be calibrated values; power measured by the HP141T in dbm could be converted to rms voltage in 50-ohms and then to rms current using the 2mA/mV conversion per the probe's passive termination. In this case, the amplitudes are not in calibration because of the probe/analyzer mismatch cited in the last chapter. Once again, however, only comparisons between inside and outside and between different configurations are important so the lack of absolute calibration is not a problem. On the 2-D views, the highest value shown is arbitrarily designated as a 0-db reference and the db scale is used for comparisons.

Additionally, the emphasis throughout all the experiments was on the observation of gross effects rather than on fine grain analysis. The desire to keep the experiments simple and "real-world" in nature led to a level of experimental control which would make such fine grain analysis unsuitable. The gross effects observed, however, were generally quite descriptive and convincing in nature.

The results for Configuration A are shown in Figure 13a. In the bottom, 3-D view, the top half of the total time span (i.e. the earlier scans) displays the measurement of the outside current and the lower half shows the inside current. As can be seen from this view and from the fact that the amplitude lines merged on the 2-D view, there is virtually no difference between the inside and outside currents for the 0 to 20-MHz frequency range measured. As expected, the penetrating ground provides effectively no isolation between

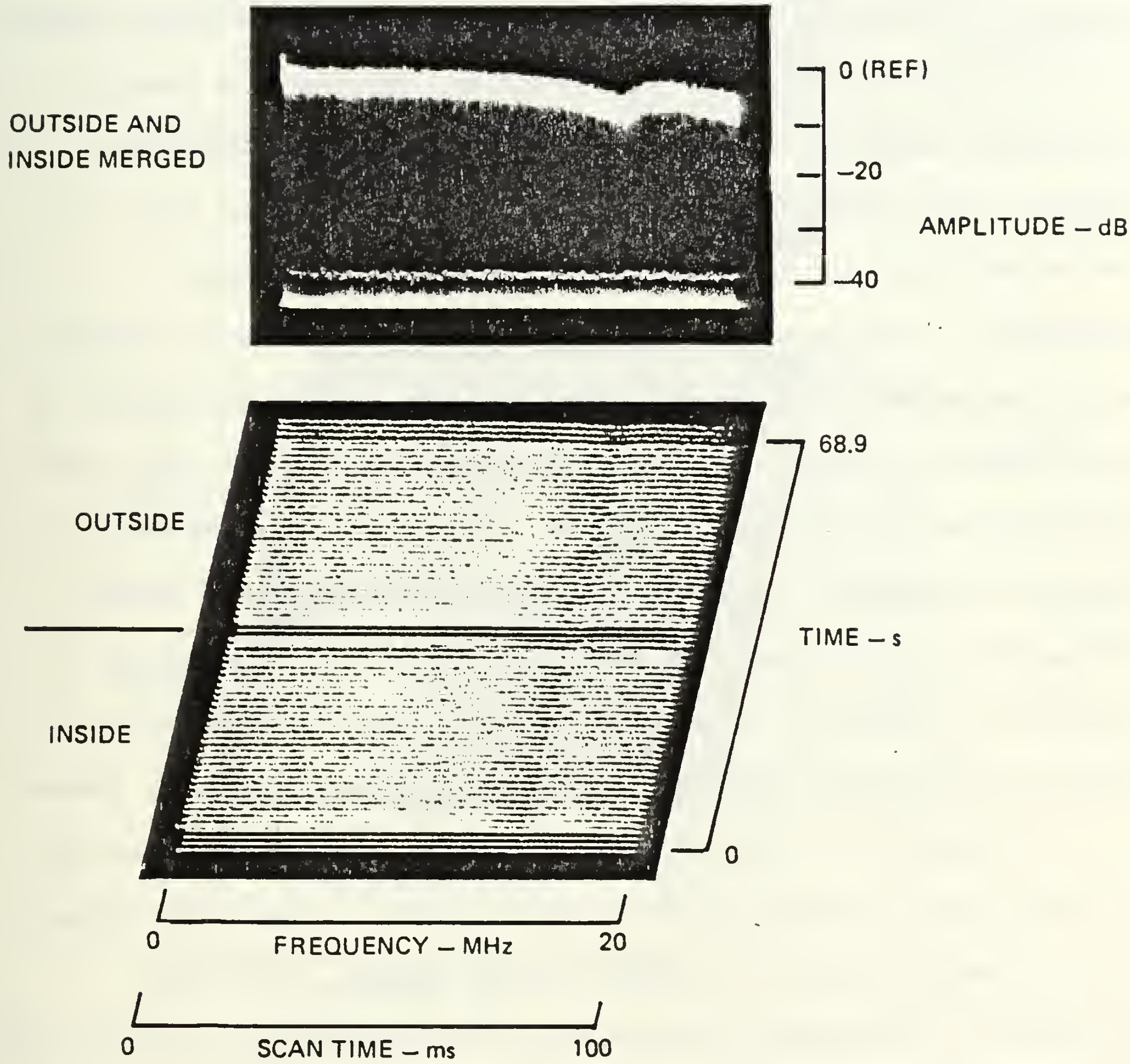


Figure 13a. Outside and Inside Currents for Configuration A

inside and outside. Any interference currents flowing on the ground system outside the rack could pass freely to the inside and vice-versa. At much higher frequencies, wire-to-wall capacitance and the increased importance of apertures might make a difference, but none can be seen here.

The results for Configuration B (Figure 13b) show a dramatic difference between inside and outside current when the topological ground is implemented. While the exact difference depends on the effects of various resonances present, the difference in the magnitude lines in the 2-D view show as great as a 30-db difference. At lower frequencies, the difference approaches its smallest amount; the difference which exists even at very low frequencies is due simply to current division between the inside wire path and other paths through the rack structure. As frequency increases, however, the isolation improves as skin effect enables the inside/outside connection to work according to topological theory. The trend at the upper frequency end indicates continued improvement above the measurement range.

Figure 13c indicates that the effect of separating the locations of the inside/outside bonds is negligible for this enclosure and in this frequency range. The only noticeable difference between this configuration and the last is a sharpening of a resonance at 7 MHz. While the separation technique is recommended under the topological approach and Bly and Tonas [9] saw significant improvements

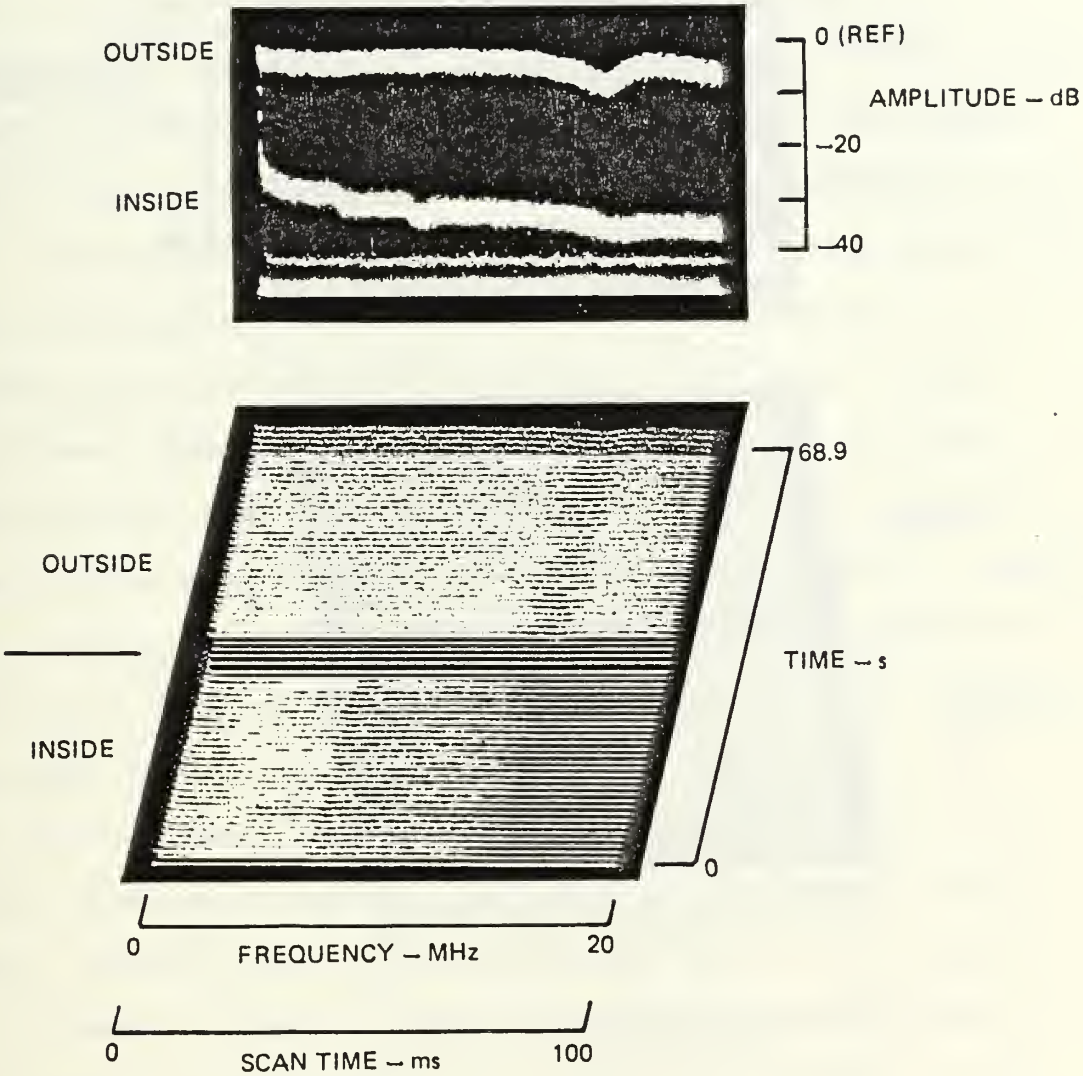


Figure 13b. Outside and Inside Currents for Configuration B

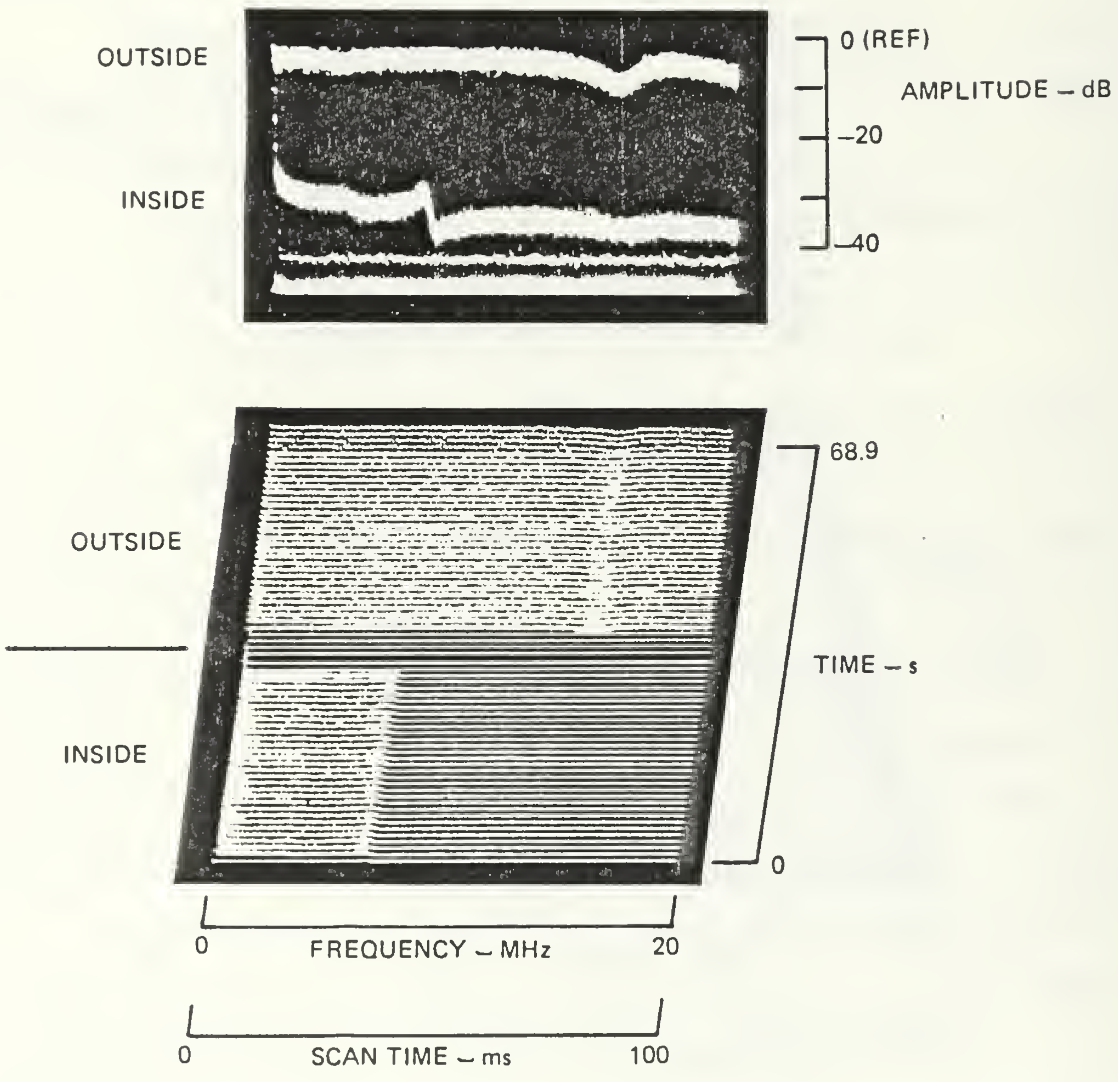


Figure 13c. Outside and Inside Currents for Configuration C

below 20 MHz when it was done on a tightly sealed box, they found little improvement in the HF range for their open box. The rack here is a much closer approximation to their open box.

In Figure 13d, the results for the final Configuration D are seen to be highly dependent on the actual geometry of the wires. When the penetrant wire was passed into the hole and then run flat along the inside wall to its bond, the current measured on the inside wire continuing from there was roughly the same as that in Configuration B. Although the configuration is clearly a bad one in that interference current may be directly "injected" onto the interior wall, that surface current is not being measured here and some mechanism is favoring the passage of the energy back outside the rack for return to the source without significant coupling to the measured interior wire. However, the danger of letting the wire penetrate at all is demonstrated when just about 12" of the penetrant wire is loosely paralleled against the interior wire before being bonded, allowing good coupling between them. The interior wire current is greatly increased in that case as shown in the figure. The injection of interference current on the inside wall and the coupling of interference by any mechanism to interior wires must be simply avoided by utilizing skin effect to advantage with proper inside/outside bonds.

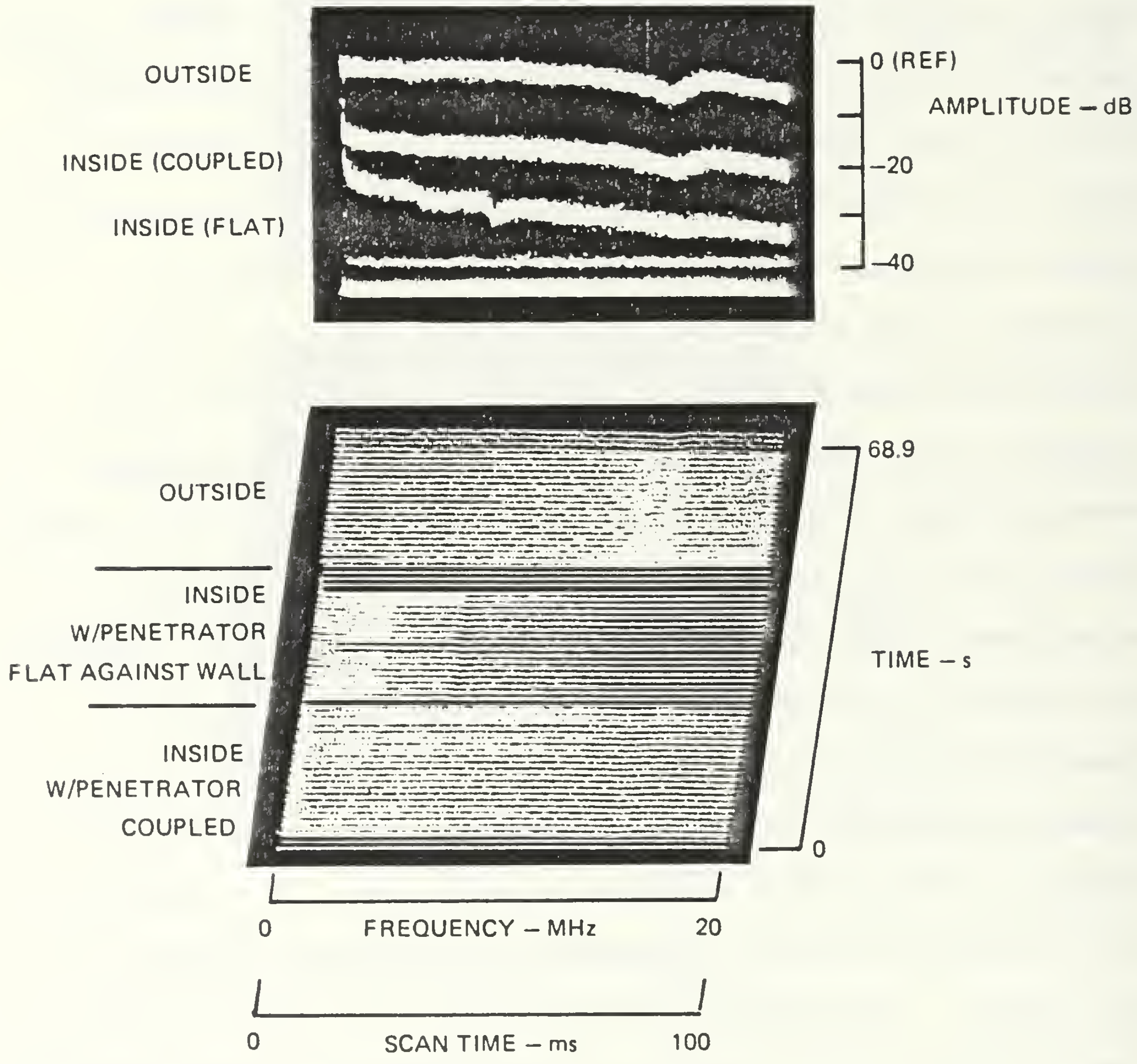


Figure 13d. Outside and Inside Currents for Configuration D

As an additional note, it was found here that opening or closing the back door of the rack made no noticeable difference in the measurements for any configuration. This stands to reason because, as noted earlier, the door is louvered and it makes no continuous metal contact around its perimeter when closed anyway. Its contribution to shielding continuity is minimal, at least at the observed frequencies.

3. Penetration Treatment Experiment: Line Filter

The intent of this experiment was to show the effect of topology on the effectiveness of one particular type of filter, a basic pi-type filter. Such a filter, a two-pole device using two capacitors and an inductor, is illustrated in Figure 14. The details of design, including the formula for the 3-db cutoff frequency, are not important here. Rather, an attempt was made to correlate quantitative measurements with a qualitative analysis of the filter's operation under changes in topology.

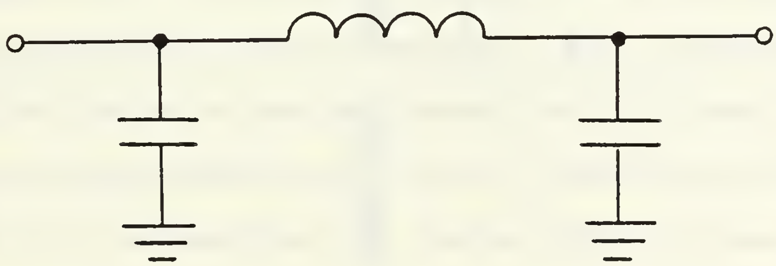
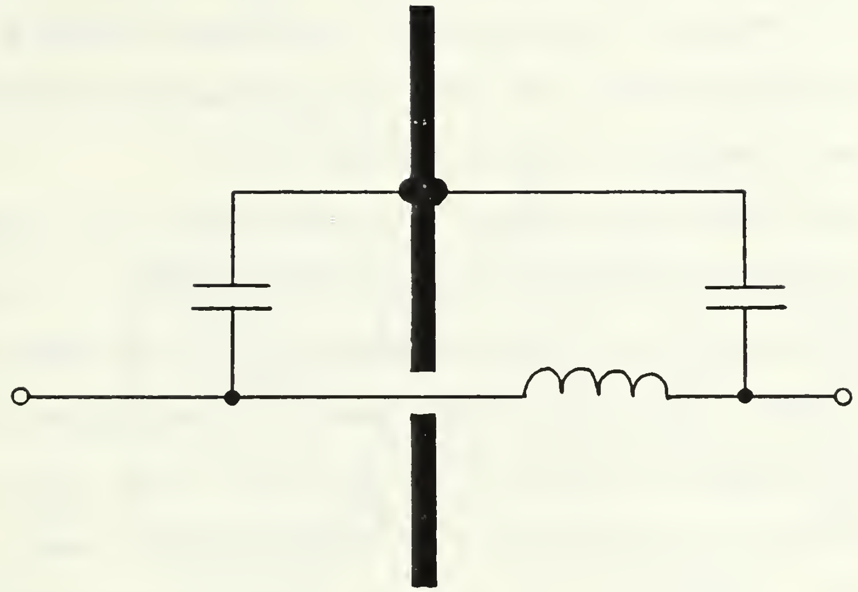


Figure 14. Pi-Type Filter

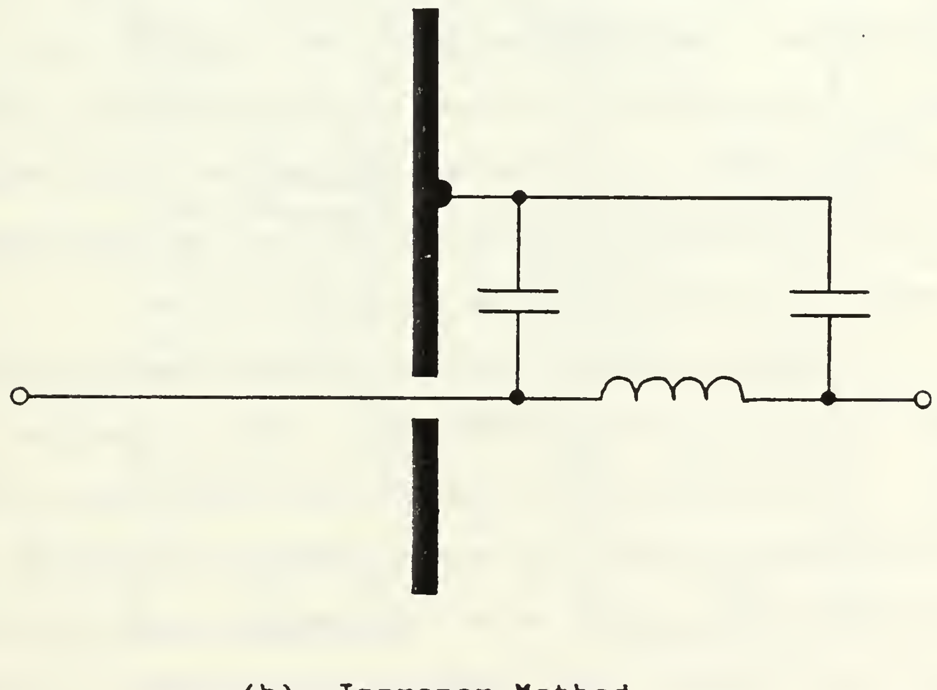
It is proposed that for a pi-type filter, its proper connection at a barrier wall in order to treat a wire passing through the barrier is with one capacitor tied to the outside of the wall and the other tied to the inside instead of both being tied to one side. Figure 15 illustrates this concept. The theory is that if the capacitors are connected outside and inside, interference currents flowing on the outside can be diverted to the outside surface of the barrier wall and returned without entering the inside, and similarly, currents on the inside will be confined inside. If both capacitors are on one side, say, the inside, interference from outside of the barrier will be allowed to pass through and be injected on the inside wall. The location of the inductor may be on either side; the important variable here is the location of the capacitors.

Unfortunately, the improper configuration, with all elements on one side, is the configuration which can typically be expected in a constructed filter. Although the proper configuration requires no change in the design for filter operation, e.g. component choice for cutoff, it would require a change in the packaging and mounting of the filter.

Two equivalent filters were constructed so that they could be used for both sides, hot and neutral, of an AC line. Each utilized two 0.01-microfarad capacitors and an inductor made using about 64 turns of enameled wire around a ferrite core. The resultant filter was swept, while mounted on a



(a) Proper Method (Inside/Outside Connection)



(b) Improper Method

Figure 15. Pi-Type Filter Connection at Barrier Wall

breadboard not the rack, using the HP3325A synthesizer and the HP141T spectrum analyzer and was found to have a 3-db cutoff at approximately 95 kHz. This is a satisfactory cutoff for a general AC line filter.

For this experiment, only one filter was tested in a simple wire loop circuit. Figures 16a through c describe the set-up. For each of three different configurations, proper outside/inside connections were made for the return wire but at three different locations on the rack. The filter and penetration it was treating were located low on one side wall of the rack. The return termination was made inside/outside on the same wall (halfway up), inside/outside on the opposite wall, and inside on the same wall and outside on the opposite wall for Configurations A, B, and C, respectively. For each configuration, two different cases were tested; one had both capacitors tied inside the rack and the other had them connected inside and outside as recommended. The same noise input and measurement instrumentation set-up were used as in the last experiment except as described below.

A general instrumentation dynamic range problem proved to exist for this experiment. Well above its cutoff at HF, the filter provided significant attenuation of the current inside the rack for either form of capacitor connection. While there were differences in that current between the "proper" and "improper" connections, in order to measure both, either the measuring device needed to be made

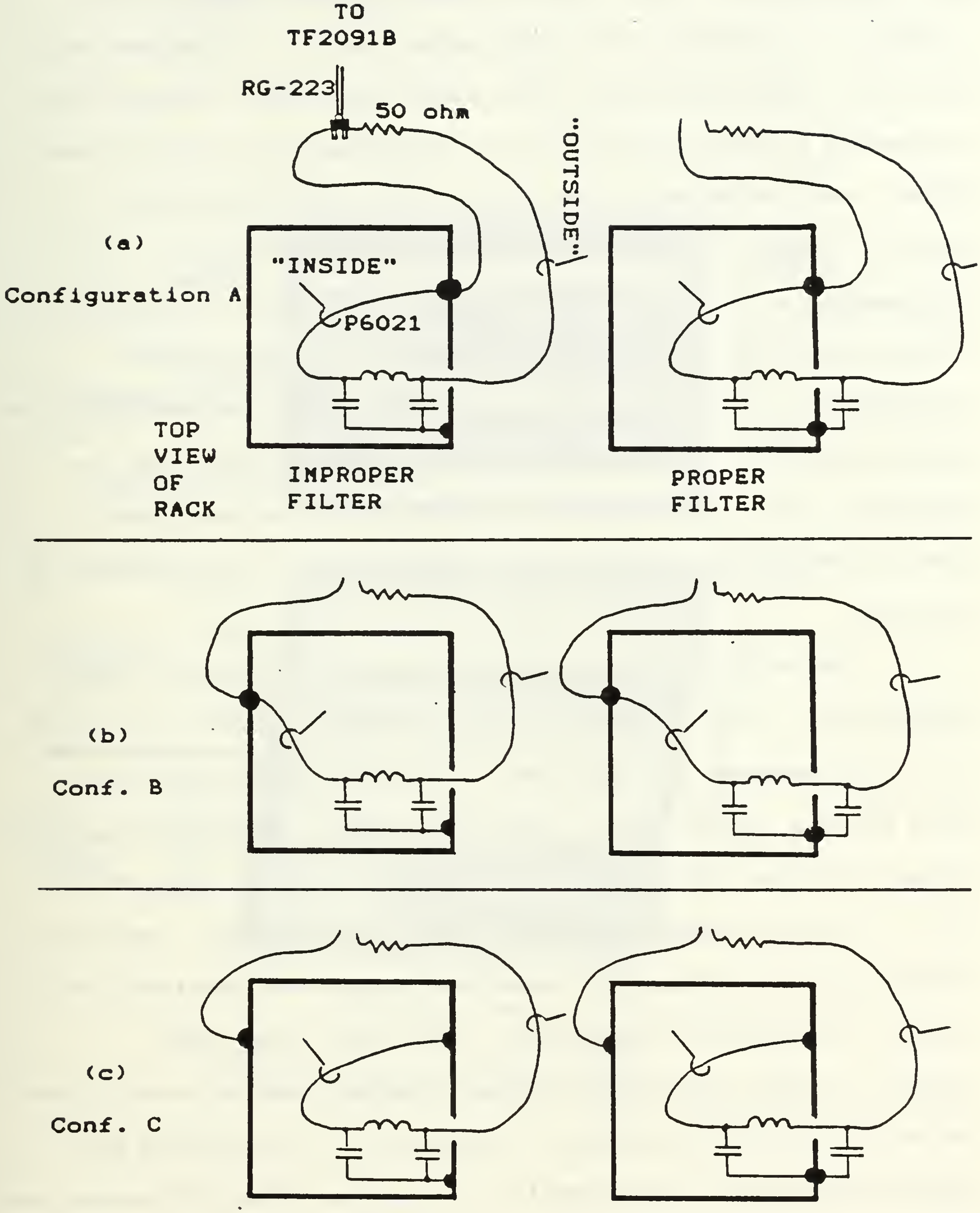


Figure 16. Test Set-up Configurations for Filter Experiment

more sensitive or the level of that current needed to be raised by increasing the input noise level. It turned out that both techniques were required; the Marconi output was increased to its maximum and the amplifier in front of the HP141T was increased to 40 db in gain. Increasing the Marconi output, however, caused undesirable effects. It appeared that a larger than expected increase in radiated fields from the wires and surfaces changed the problem considerably. The measurements became much more sensitive to cable lengths, wire lengths and geometries, etc., and the radiated fields interacted much more with the less than ideally-shielded current probe, affecting its measurement of current.

Nevertheless, measurements were taken which were descriptive. The frequency range measured was cut down to 0 to 10 MHz because the greatest ill effects with the probe were evident above that. The results for Configuration A are shown in Figure 17a. In this simplest scenario, the results are in obvious agreement with the proposed theory. When the capacitors were properly connected inside and outside, the current inside was dramatically lower than when both capacitors were connected inside. Current was allowed to be passed by the outside filter capacitor to the outside rack surface and easily returned to its source. The difference is shown to be about 20 db just above the 2-MHz resonance (which was evidently an effect of the rack.) However, the

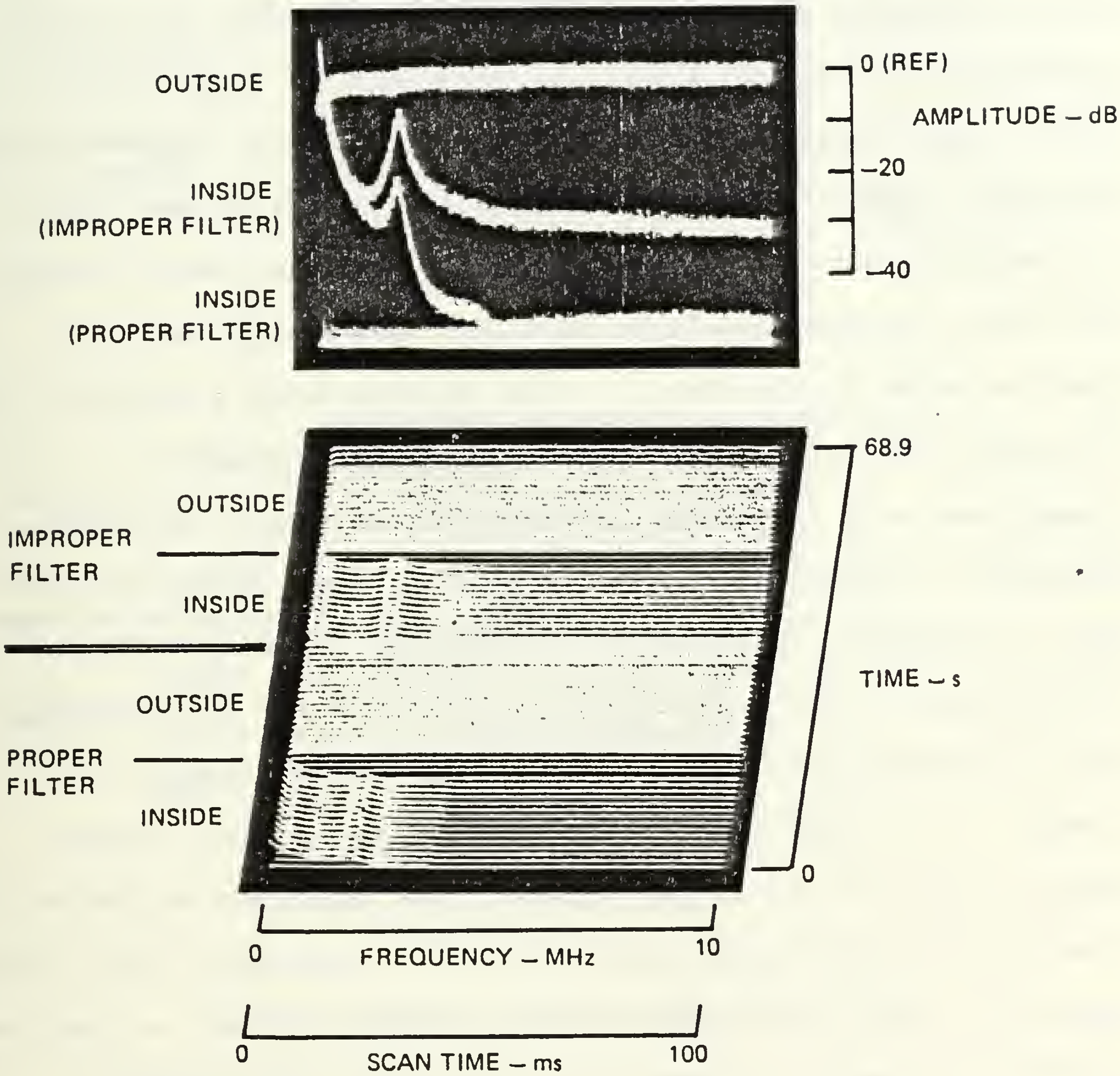


Figure 17a. Outside and Inside Currents for Configuration A

difference beyond that can only be called at least 20 db in that the measurement for the proper case falls below the instrumentation noise floor.

For Configurations B and C, the results are not consistent with A. For B (Figure 17b), in which the return outside/inside bonds were moved to the other side of the rack, there appears to be no difference in the inside current when the capacitors were connected the two different ways. In Configuration C (Figure 17c), in which the inside return bond and outside return bond are on opposite walls, the results actually reversed. That is, the inside current, and therefore the isolation realized, was worse when the capacitors were connected "properly" than when they were connected "improperly." The causes of these latter effects are not readily explainable. When both capacitors filter the current to the inside surface of the rack, the coupling path of energy from inside to out for circuit return is likely a very complex one. Separating the circuit return points far from the filter allowed that coupling to change in a way that counteracted the benefits of connecting the filter properly. One consideration which surely applies is that the separation simply allowed for current flow over greater surface areas, which in turn may have allowed for greater diffusion through the shield and, more importantly, greater interaction with apertures to occur. Preventing such current flow across large areas of the barrier surface by

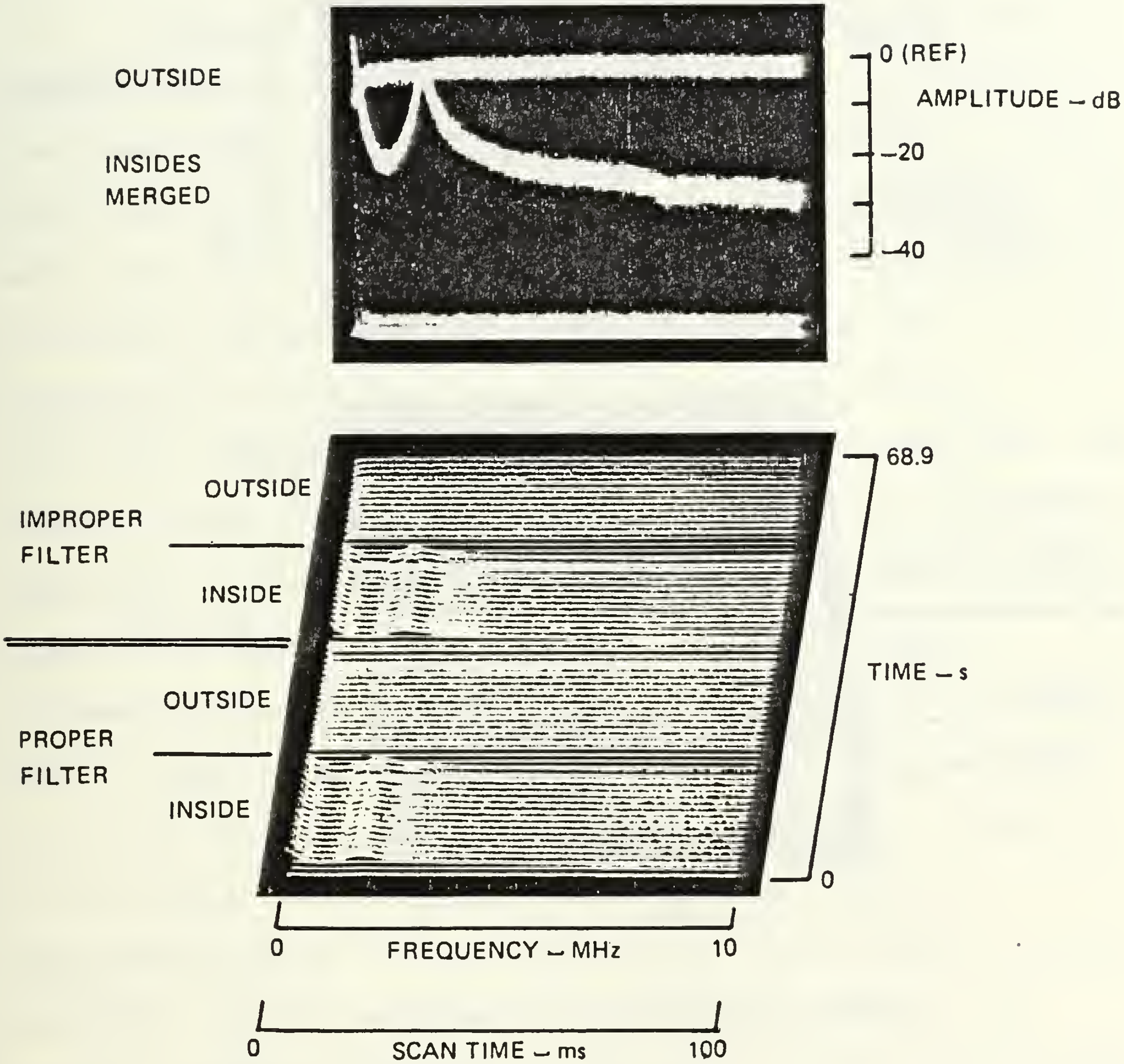


Figure 17b. Outside and Inside Currents for Configuration B

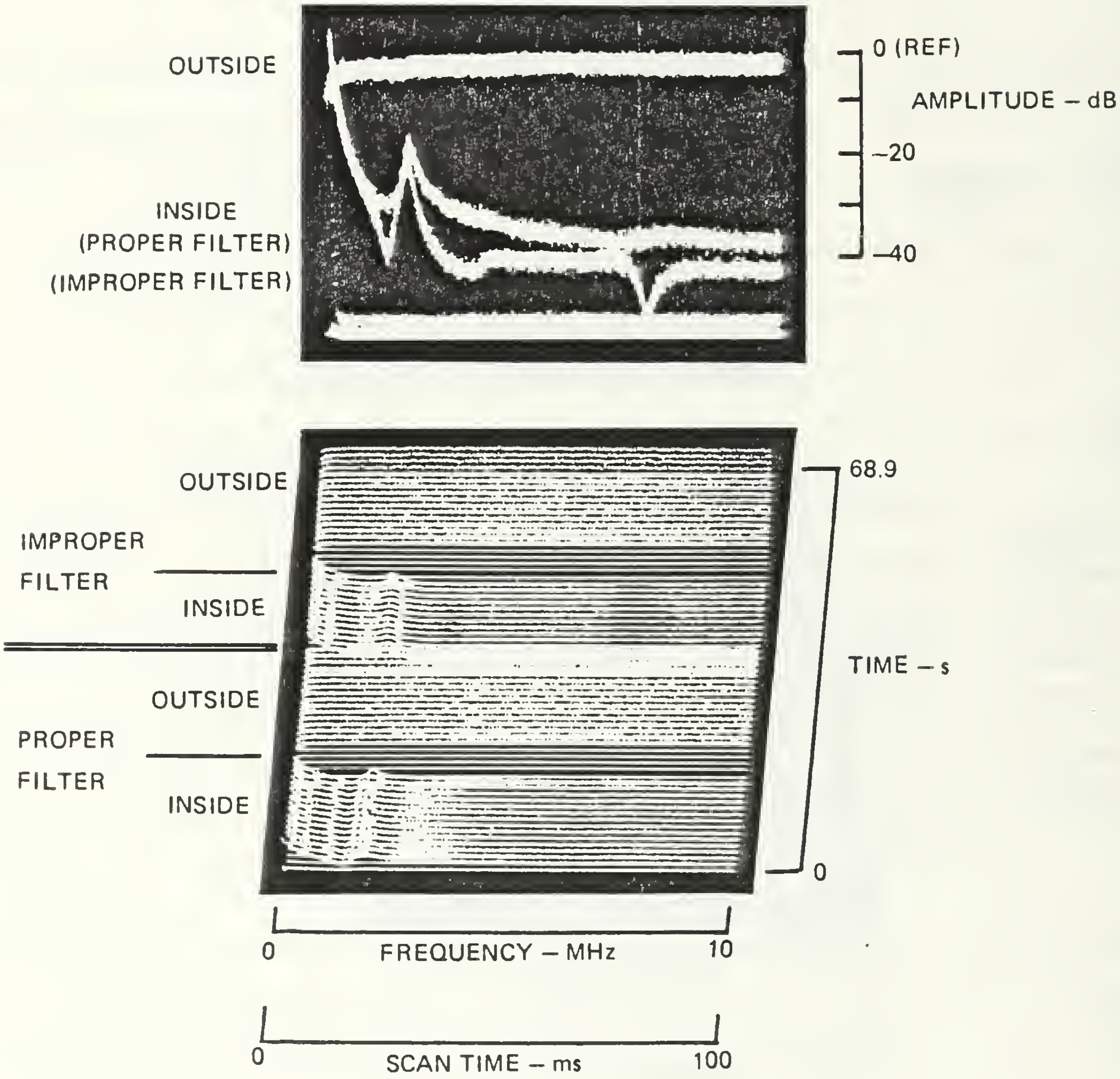


Figure 17c. Outside and Inside Currents for Configuration C

concentrating external conductors in one small area, and thereby allowing interference currents to enter and return in that small area, is a recommended approach referred to as the "single entry panel concept." [1]

In all of these experiments, the results can only be interpreted with a mixture of circuit theory, transmission line theory, and field theory. In this experiment, in which noise levels throughout the rack "circuit" were purposely set very high, many coupling modes were likely to be excited and the results became even harder to quantify. It is interesting to note that earlier in the study when an experiment like this was initially done from 0 to 20 MHz, the results were not the same. Proper connection of the capacitors had at that time held at least a small performance edge for all configurations, but it is perhaps more interesting that the number of difficult variables involved made the results simply unrepeatable. Once again, however, fine grain analysis is not of interest here and the results of the simple Configuration A indicate that there is considerable merit in the connection of the pi-type filter as proposed. Further work may be required to evaluate the effects of varying the path by which the current diverted by the capacitors is allowed to return to its source.

4. <u>Real-World Ground Experiment</u>

This next experiment returned to the issue of topological grounds, but did so with an experimental set-up which was more "real-world" in nature. The set-up is shown in Figure 18. The radio receiver mounted in the rack was energized to serve as a representative piece of operational equipment. It was powered via a two-wire line; the green safety ground wire was removed from its cord. The two-wire line was passed through the pi-type line filter described in the last experiment (both filters were used), which was connected throughout this experiment in its proper manner, i.e. with an outside capacitor tied to the outside wall and an inside capacitor tied to the inside wall. From the filter, a two-wire cord continued to a lab bench outlet.

The normal green wire ground was then replaced with one of three configurations. In Configuration A, a wire was bonded to the outside of the metal receiver casing then passed through a small hole in the rack wall and on to a ground receptacle in the same outlet pair that the two-wire power cord was plugged into. In Configuration B, the ground wire from the receiver was instead bonded to the inside of the rack wall and the ground path was continued from the outside in the proper topological manner, where it continued on to the outlet ground. In Configuration C, the topological inside/outside terminations were at separated spots in the wall. (In all of the configurations, the receiver casing made other metal-to-metal contacts with the rack by virtue of its mounting, as is normal.)

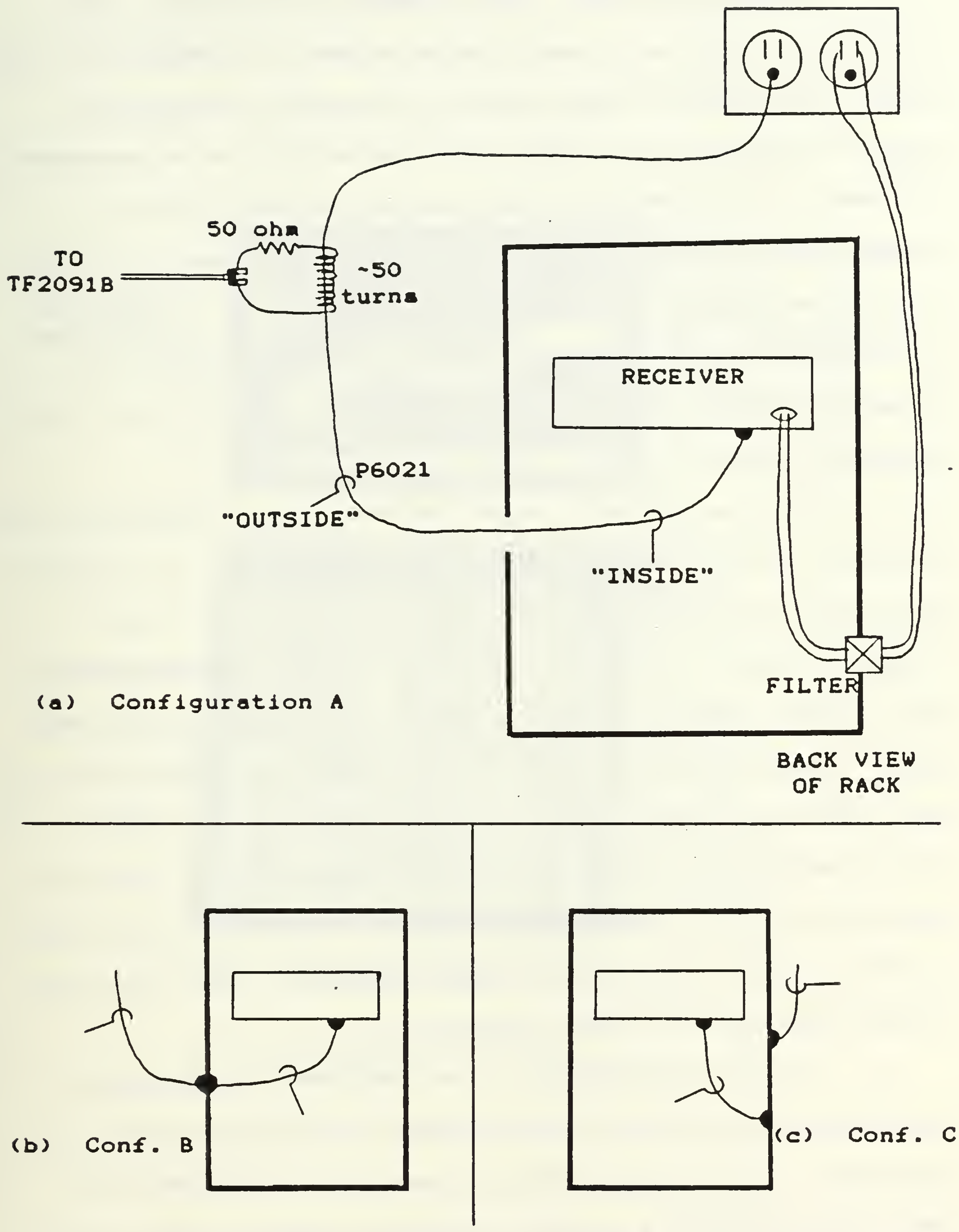


Figure 18. Test Set-up Configurations for Real-World Ground Experiment

Outside the rack, approximately 50 turns of light-gauge, insulated wire were wrapped around the ground wire and then, with a 50-ohm load resistor, connected (BNC/Banana plug) to the end of a cable from the Marconi noise generator as shown. This coupled noise into the ground wire in a simple but effective manner to simulate interference on the real-life exterior ground system. The current in the wire outside and inside the rack was then measured using the standard HP141T and 3-axis display set-up with 40 db of line amplifier gain.

Figures 19a and b show the results for Configurations A and B, respectively, from 0 to 20 MHz. In A, it is easily seen that the outside current is basically equal to the inside current, i.e., there is no isolation between outside and inside provided by this scheme. The upward-going shape of the spectrum is due simply to the increasing efficiency of the simple wire-wrap coupling with frequency. At the low end of the spectrum, signals in the AM broadcast band are also seen to be very strong, as the power distribution and ground system of the laboratory building provided a very efficient receive antenna at those frequencies.

In Configuration B, it is seen that the effect of implementing a proper inside/outside topological ground is dramatic. In fact, the measured current inside the rack under this scheme is entirely below the noise floor of the instrumentation, except for a minimal amount at the lowest

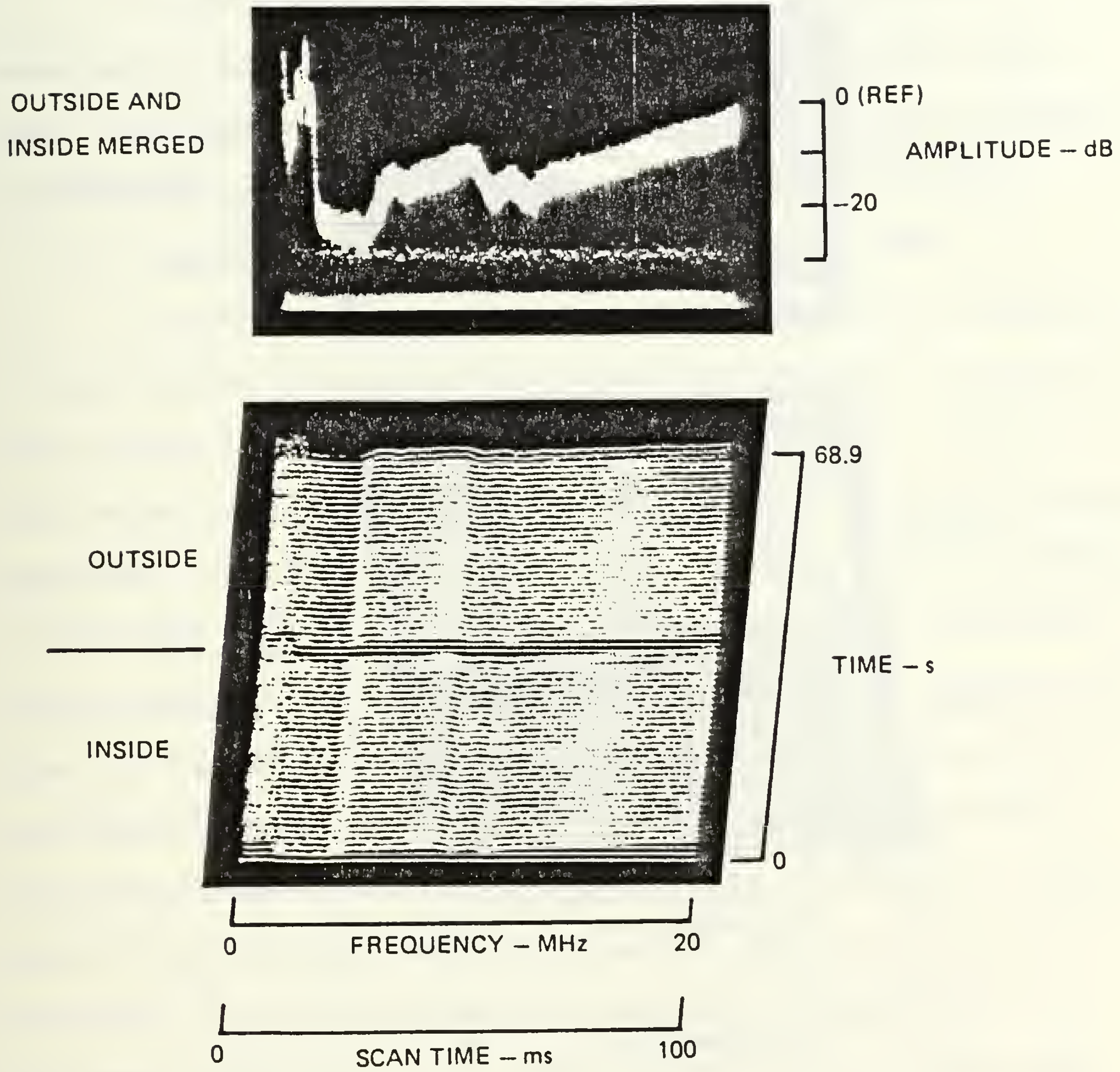


Figure 19a. Outside and Inside Currents for Configuration A

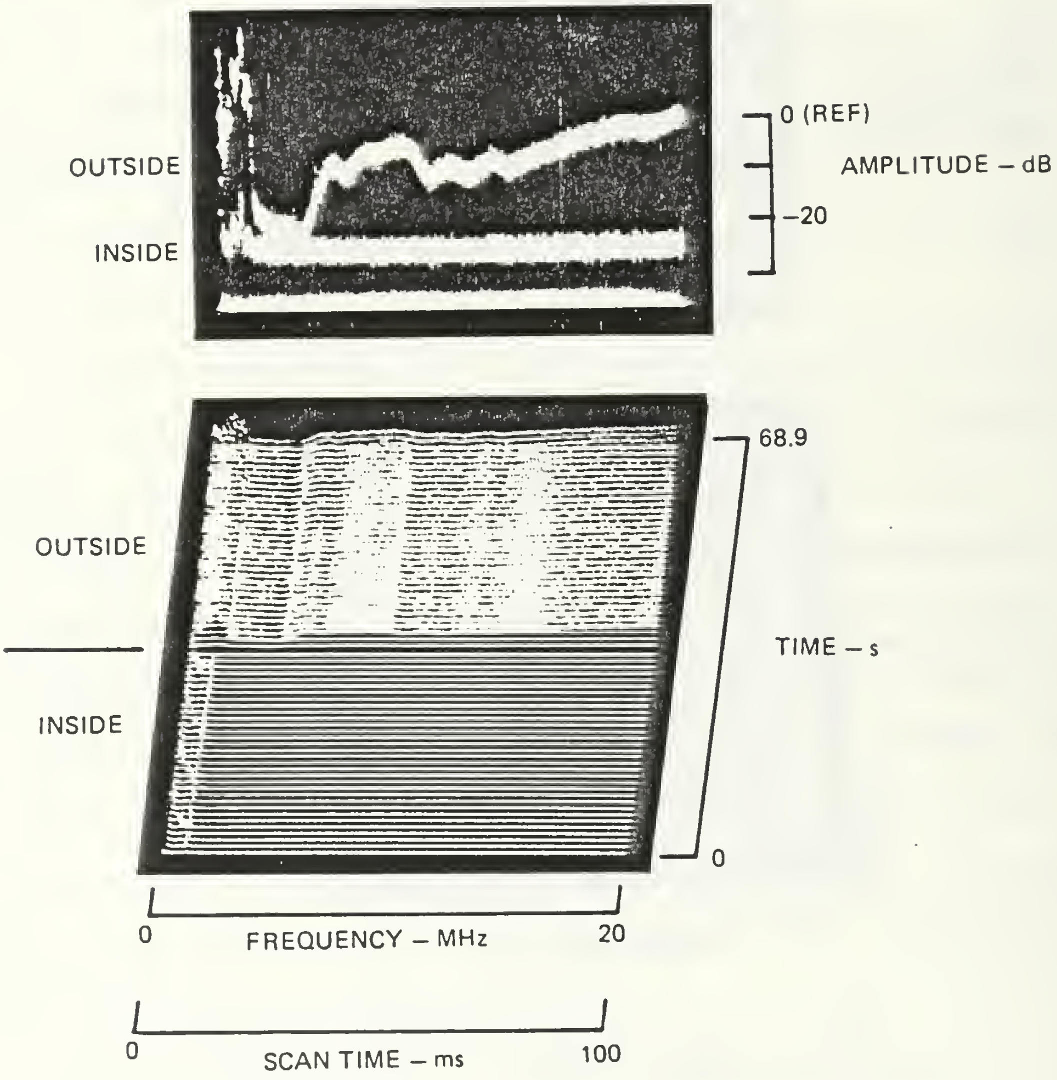


Figure 19b. Outside and Inside Currents for Configuration B

frequencies. Therefore, actual isolation cannot be stated except that it is greater than the spread shown. For example, at 20 MHz it is greater than the 25 db seen between the outside current and the noise floor.

In Configuration C, with the inside/outside termination points separated, the measurements were also below the noise floor, therefore no statement about further improvement can be made. The data has not been shown.

5. Inside-to-Outside Ground Experiment

In the last experiment of this series, the benefits of topological grounding were again investigated, this time with a more realistic noise source and with the coupling of that noise from the inside of the rack to the outside being measured. The SCR dimmer device and 120-ohm load described in the last chapter, which simulate an equipment such as a noisy computer, were placed inside the rack and energized as shown in Figure 20. The hot and neutral leads at the end of the dimmer's power cord were once again run through the topologically correct pi-type line filter. The cord's green ground wire, though, was broken out at that point and completed its path to the outlet ground through three different configurations: penetrating a hole in the rack wall; inside/outside terminated at the same spot in the wall; and inside/outside terminated at different spots in the wall. Inside and outside ground wire currents were measured

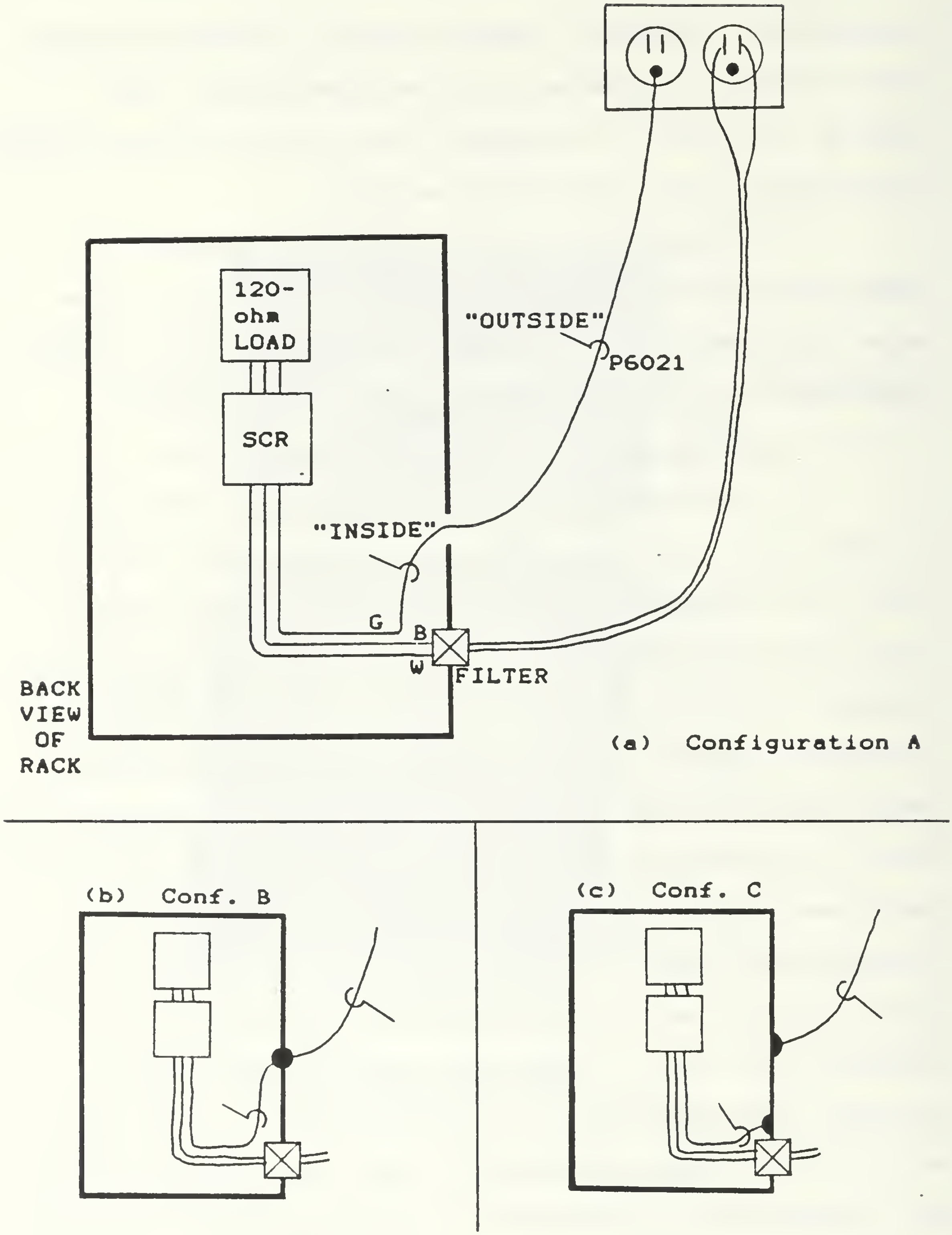


Figure 20. Test Set-up Configurations for Inside-to-Outside Ground Experiment

as before but the levels required only a 20 db line amplifier gain.

Figure 21a shows the results for Configuration A, the penetrating ground. Two 2-D magnitude presentations are used to show only those scans in the upper or lower half of the 3-D time span for the inside and outside currents, respectively, in order to provide better visual resolution of the SCR transients. Again, it is readily seen that no isolation between inside and outside is provided with a penetrating ground. The shape of the transients' spectrum is complex and the presence of a number of separate envelopes for the transients can be noted, indicating more than one noise coupling mechanism associated with the SCR. The presence of the AM broadcast band is again seen to be strong.

The results for Configuration B (Figure 21b) again show a dramatic isolation between inside and outside when a topological ground is implemented. Besides the drop in the coupling of the inside noise source to the outside, the broadcast band and a weak signal at 10 MHz which are seen on the outside are attenuated on the inside. The Configuration C results (Figure 21c) show negligible further improvement when the outside/inside bonds are separated, although a definitive statement is difficult to make since even the inside current changed somewhat with the change in configuration.

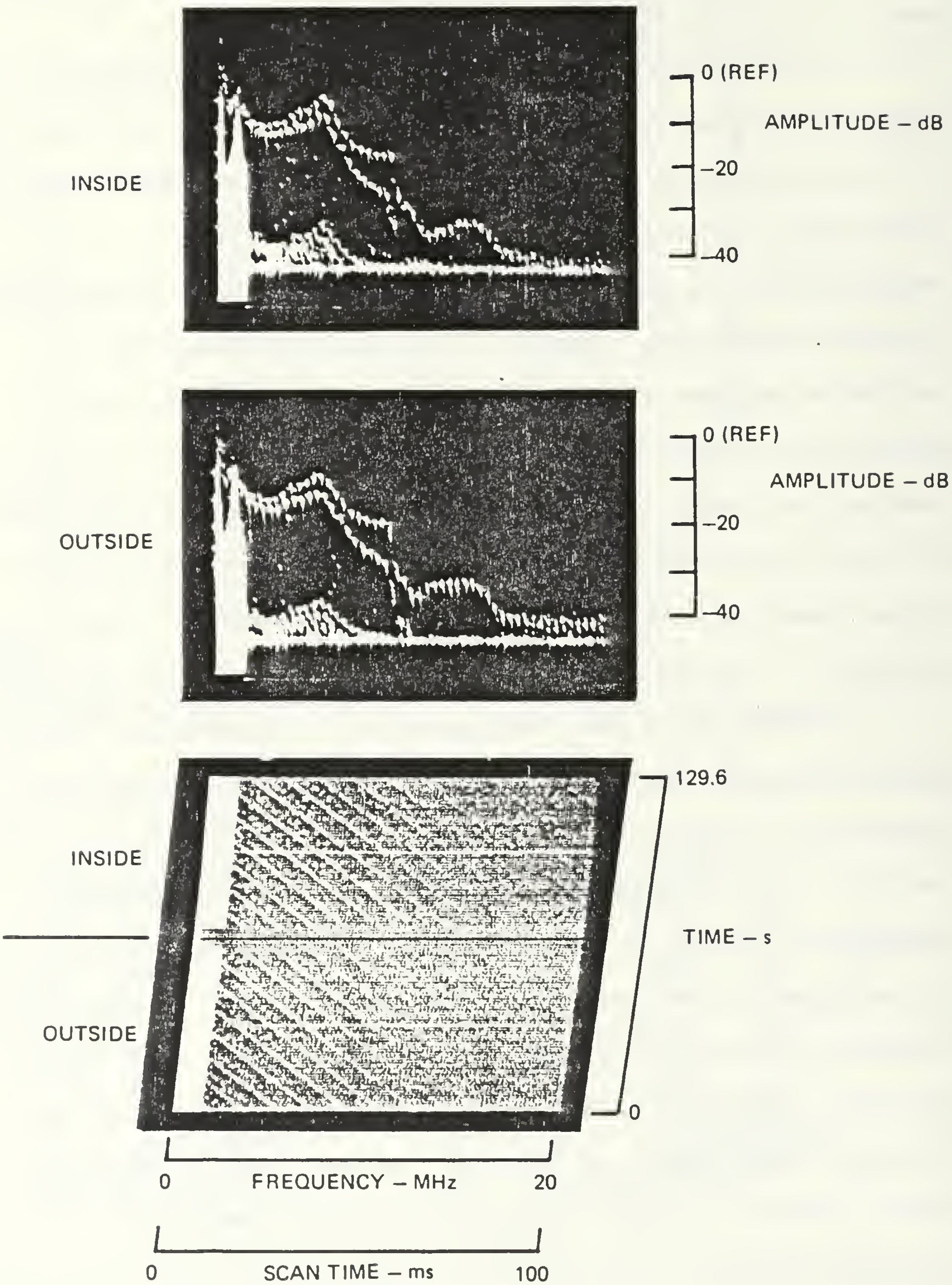


Figure 21a. Inside and Outside Currents for Configuration A

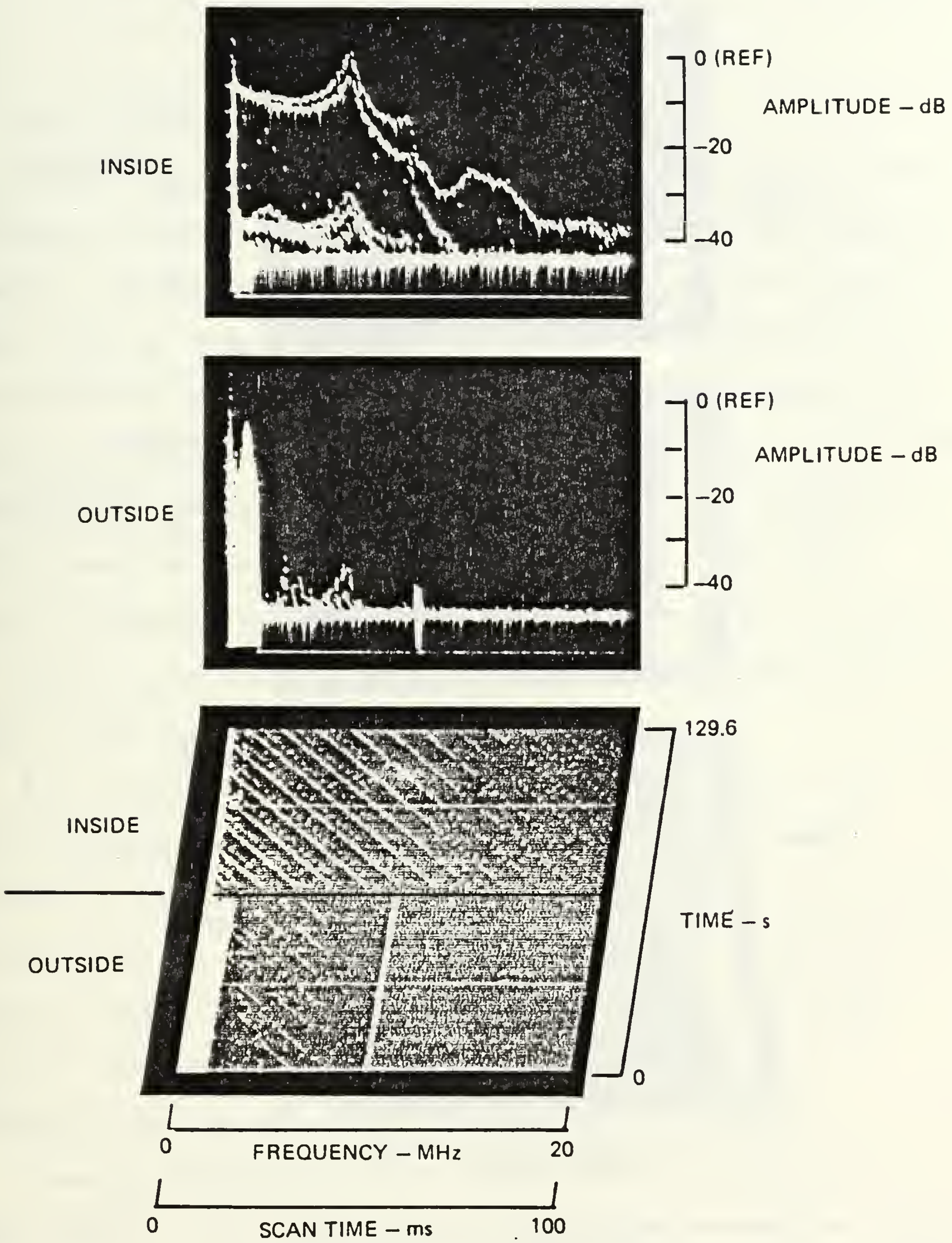


Figure 21b. Inside and Outside Currents for Configuration B

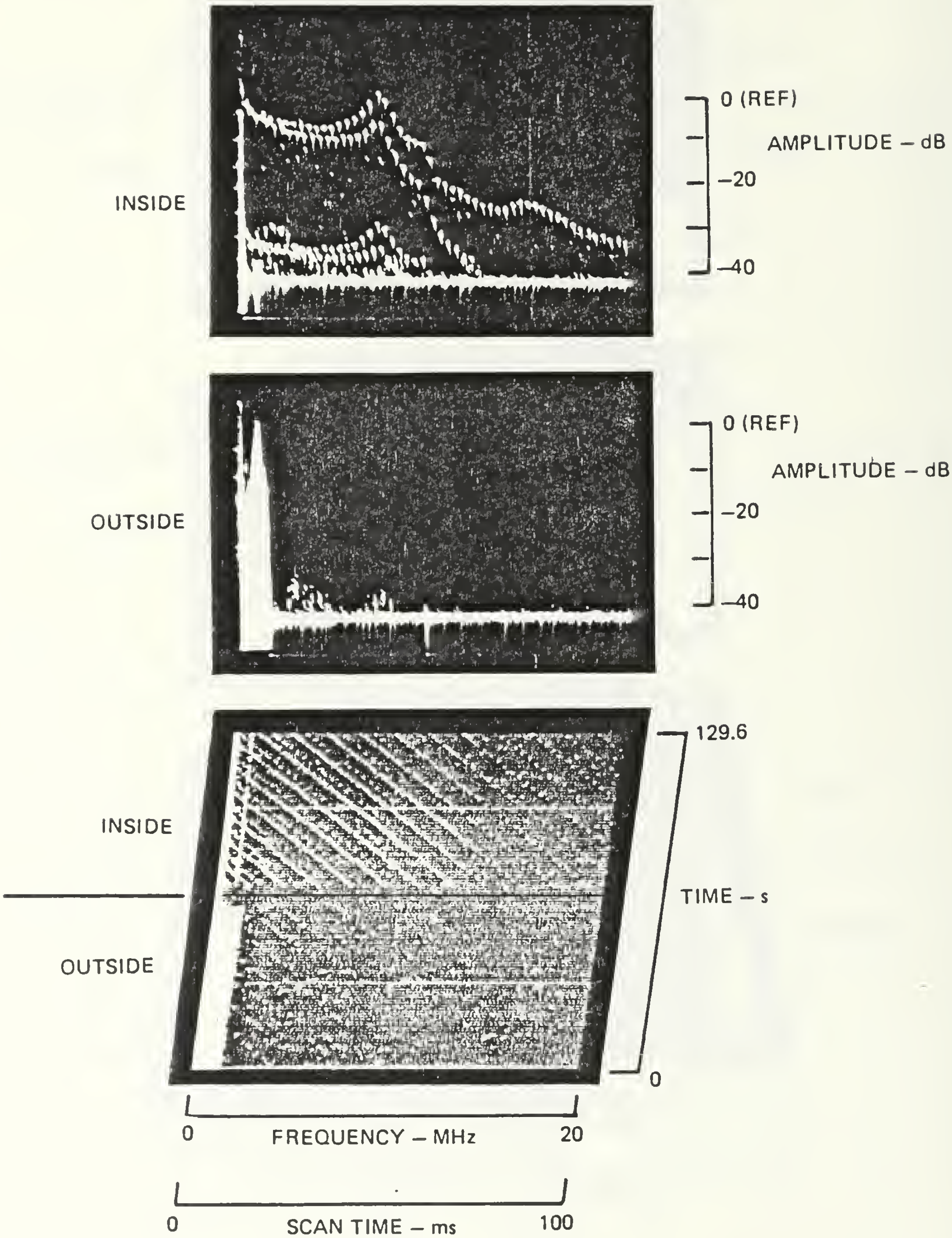


Figure 21c. Inside and Outside Currents for Configuration C

VI. COAXIAL CABLE EXPERIMENTS

A. BASIC APPROACH

In earlier chapters, the idea of extending the barrier between two otherwise independent barriers was discussed at length. The advantages of doing so in certain cases were clear and, at some levels, the use of shielded cabling to implement the extension was suggested to be effective, yet relatively simple and flexible. While many types of shielded cables could be involved in such a scheme, e.g., shielded multiconductor, twisted shielded pair, etc., the use of coaxial cable is highly prevalent in the field for a number of applications and needs to be looked at in a practical manner with regards to the topological approach.

For a typical coaxial cable above about 1 MHz, skin effect causes the signal current to flow on the inside surface of the cable shield and noise current to flow on the outside surface. [10] This fits in very nicely with the barrier extension idea above, but the shield must remain closed. This requirement includes the circumferential connection of the shield at the barriers at its ends.

Numerous techniques exist which violate the closure requirement. For instance, the cable shield is often opened at one of two interconnected cabinets to break an undesirable ground loop composed of the cable shield, the cabinets, and a ground connection between the cabinets. Practices such as this defeat the barrier, however, and simple experiments on a coaxial cable and on a shielded twisted pair were conducted by Vance et al., to show that closing the shield with circumferential terminations at both ends, i.e., maintaining the topological barrier, is the correct procedure at all frequencies [5]. They proposed interrupting the ground loop current by some other means if necessary, but without interrupting the shield.

If the cable shield is to maintain the barrier, then, its effectiveness as a shield must be addressed. In practice, the quality of a cable shield and the length of the cable run are often such that significant leakage through the shield may occur. In coaxial cable applications, the most common cable shield in use seems to be a single layer of metal braid and experience has shown that in many cases such a shield may be wholly inadequate. The use of coaxial cable in general need not be abandoned, however, because alternatives in shields exist.

While other alternatives, such as solid shields, are available, increased effectiveness can be obtained, and many of the advantages of braid kept, by using double-shielded coaxial cable. The high frequency performance increase obtained by an additional layer of braided-wire shield can usually be 20 to 30 db in reduced coupling through the shield. [11] Similar to single shielding except that two layers of braid are layed concentrically and in contact with each other, the cable can directly replace single-shielded cable with no other hardware considerations.

After a discussion of some earlier studies by others concerning coaxial cable coupling, the results of experiments conducted for this thesis evaluating the benefits of double-shielded coaxial cable will be presented.

B. EARLIER STUDIES

1. A Field Investigation

A team from the Naval Postgraduate School was recently involved in the investigation of a serious interference problem at a Navy HF communications receiver facility. [12] Interference from 5-MHz frequency reference signals appearing in the RF signal distribution system was the major problem and severe degradation of operations had been experienced in one room of equipment in particular. It was determined that two primary mechanisms existed for the coupling of the high-level reference signals into the RF signal distribution system. First, significant leakage of the 5-MHz reference out of the RG-58/U single-shielded coaxial cables used for its distribution led to high interference field levels around the cables, in the cable runs, and throughout the building. These fields were then coupled, in numerous locations, into RG-58 cables used for RF signal distribution. Secondly, a patch panel in the room contained both reference cables and signal cables and insufficient isolation between adjacent jacks allowed strong coupling between them.

At that time, the 5-MHz interference to one particular critical receiving system was eliminated by replacing the RG-58 signal cable feeding it with RG-223/U double-shielded cable and rerouting it away from the patch panel. However, replacing the cable supplying the 5-MHz tone to that room with RG-223 did not significantly reduce the overall field level in the room because so many other RG-58 runs existed in the building with that high-level tone on them.

A return was made to the facility to implement more thorough improvements to, among a variety of items, the RF signal and reference signal distribution systems. [13] Specifically, the completed work included: the replacement of all RG-58 feed cables for RF signals and high-level reference signals from the RF distribution room to the room of interest with RG-223 cable; the rerouting of signal, reference, control, and power wiring into separate cable trays for each category; and the reconfiguration of the offensive patch panel to provide the same separations.

The team concluded that the new cabling had completely solved the internal noise and reference signal RFI problem in the room. All signals and noise found afterwards in the room's RF distribution system were from sources external to the facility.

As an example of the effectiveness of the RG-223 replacement, after the tasks were completed a comparison was made between the signal and noise pickup on, alternatively, a newly-installed RG-223 cable and an old RG-58 cable (left in for the comparison), which ran from the RF distribution room to the newly-improved room. Both were terminated in their 50-ohm characteristic impedance in the RF distribution room. Figure 22 shows the results. It is seen that the reduction in pickup with the RG-223 was at least about 40 db for the 1-MHz reference tone shown and about 30 db for the 5-MHz tone. The reduction is <u>at least</u> these values because the RG-223 pickup is below the instrumentation noise floor across the spectrum. The same effect is seen with all the other background signals and noise picked up on the cables.

2. Single-Shielded Cable Coupling

To more fully investigate RG-58 adjacent cable coupling, a set of experiments was concurrently done at the Naval Postgraduate School. [14] Two variable lengths of RG-58 C/U cable were laid next to each other on an insulated surface and one, designated the drive cable, was connected to either a Marconi TF2091B noise generator, for a white noise signal, or a HP3325A Function Generator, for sinusoidal signals. The other cable, called the pickup cable, was connected to an HP141T spectrum analyzer to measure the

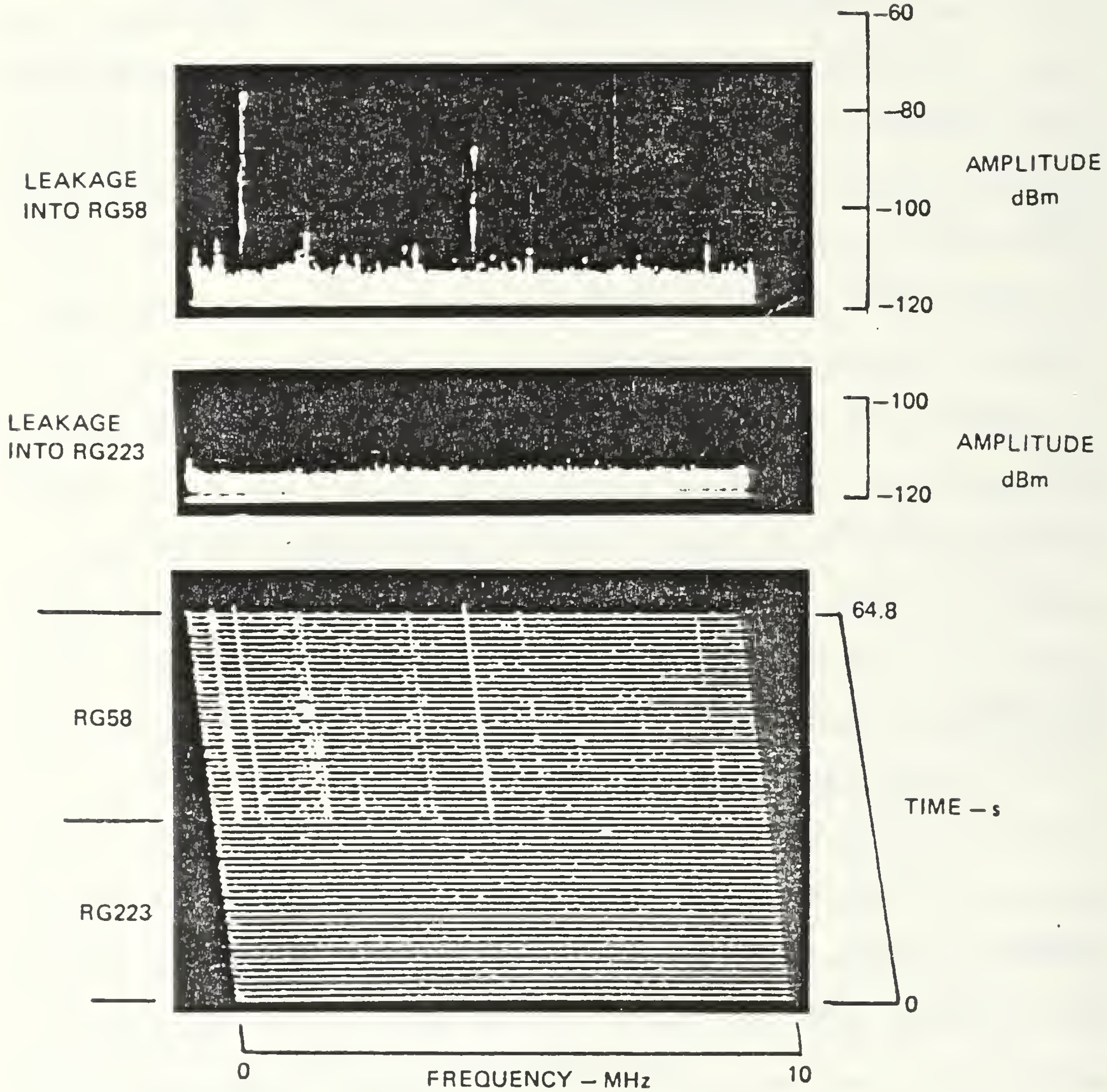


Figure 22. RG-223 vs. RG-58 Pickup

pickup. A coupling ratio (power measured on the pickup cable over power input to the drive cable) of -78 db was initially measured using a 5 MHz tone and two 200-ft. lengths of cable, both terminated in 50 ohms. Local AM broadcast signals were also measured on the pickup cable at a level of -40 dbm.

The white noise generator was then used as a source and measurements from 0 to 50 MHz were taken with various cable lengths and conditions of the drive/pickup cables being terminated/unterminated. Figure 23 shows both the white noise input (as measured directly by the HP141T) to the drive cable and the measured pickup on the pickup cable for, again, two 200-ft. lengths of terminated cables. It is readily seen that the coupling between the two cables was a complex function of frequency. Resonance peaks and nulls less than 1 MHz apart resulted in a spread of coupling ratios from as great as about -65 db to as little as about -90 db.

Using the same noise input, a comparison was made between both cables terminated and both unterminated. The results in Figure 24 show that although the coupling was perhaps a few db greater when the cables were unterminated (the maximum coupling is greater by around 3 db), the predominant effect was to change the shape of the resonance and null structure.

Measurements were also taken from 0 to 10 MHz for all four cases of pickup/drive cable terminated/unterminated. The results are in Figure 25. In all cases, the measured

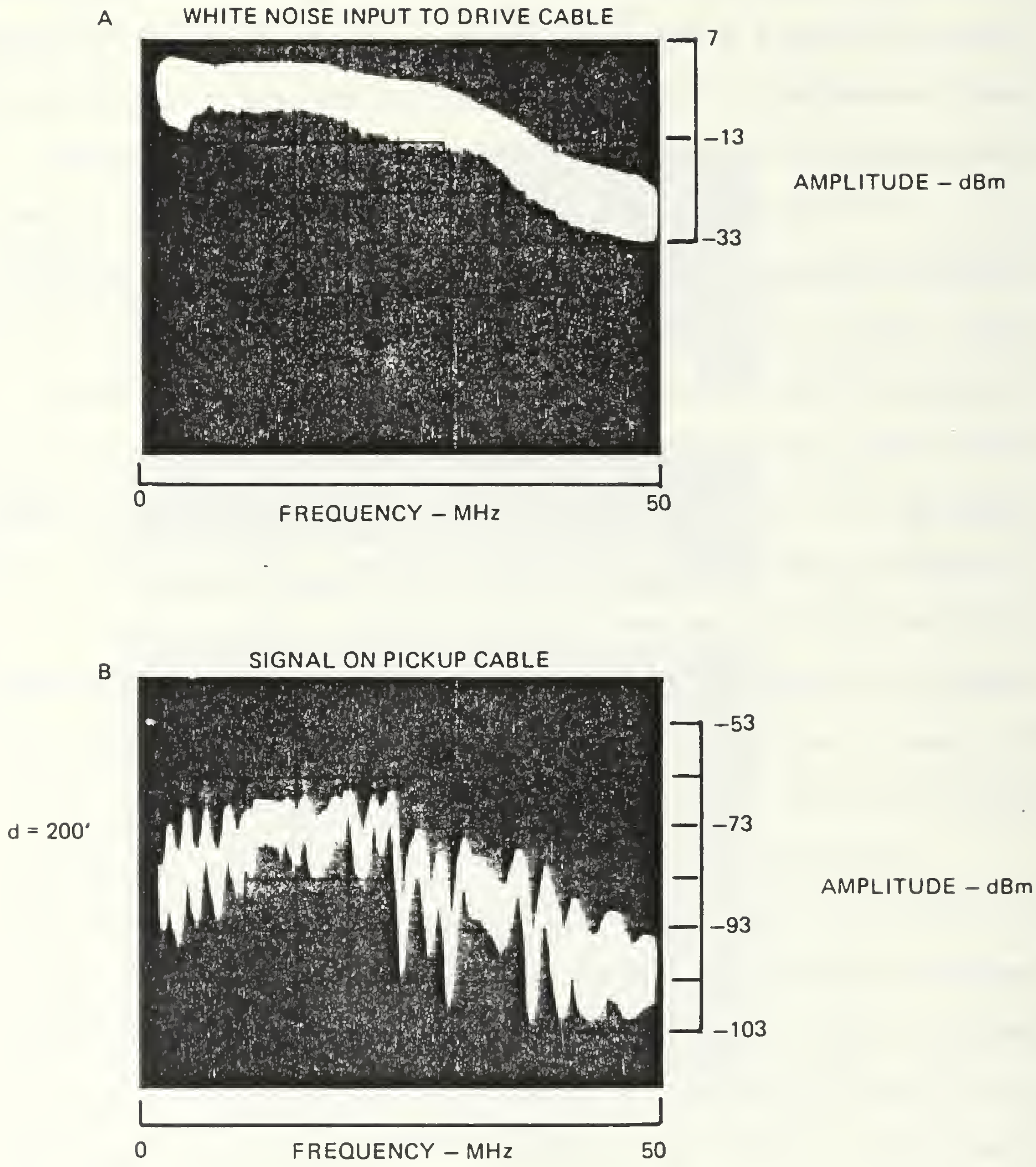


Figure 23. Coupling for Two 200 ft. Terminated Cables

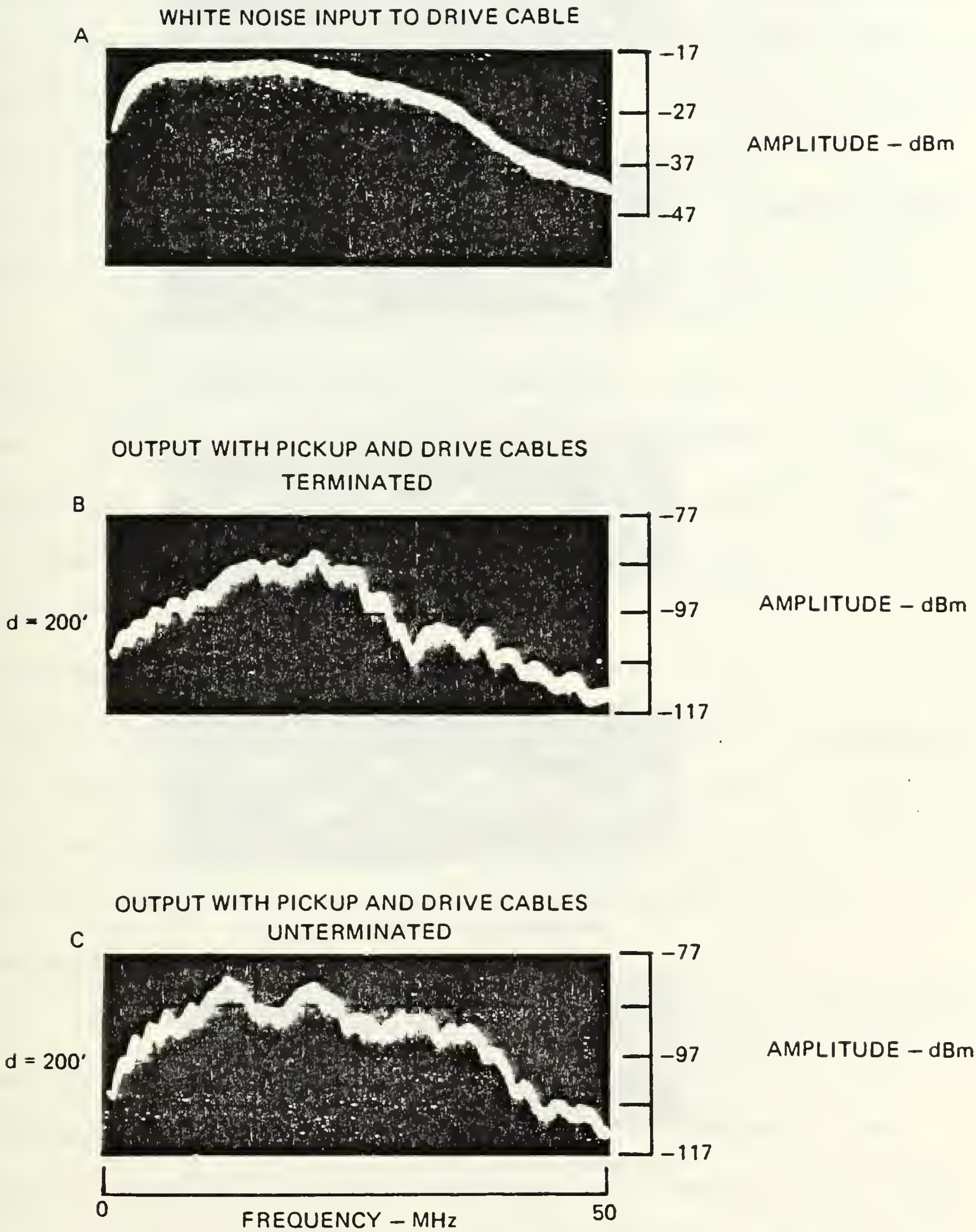


Figure 24. Coupling With Changes in Termination

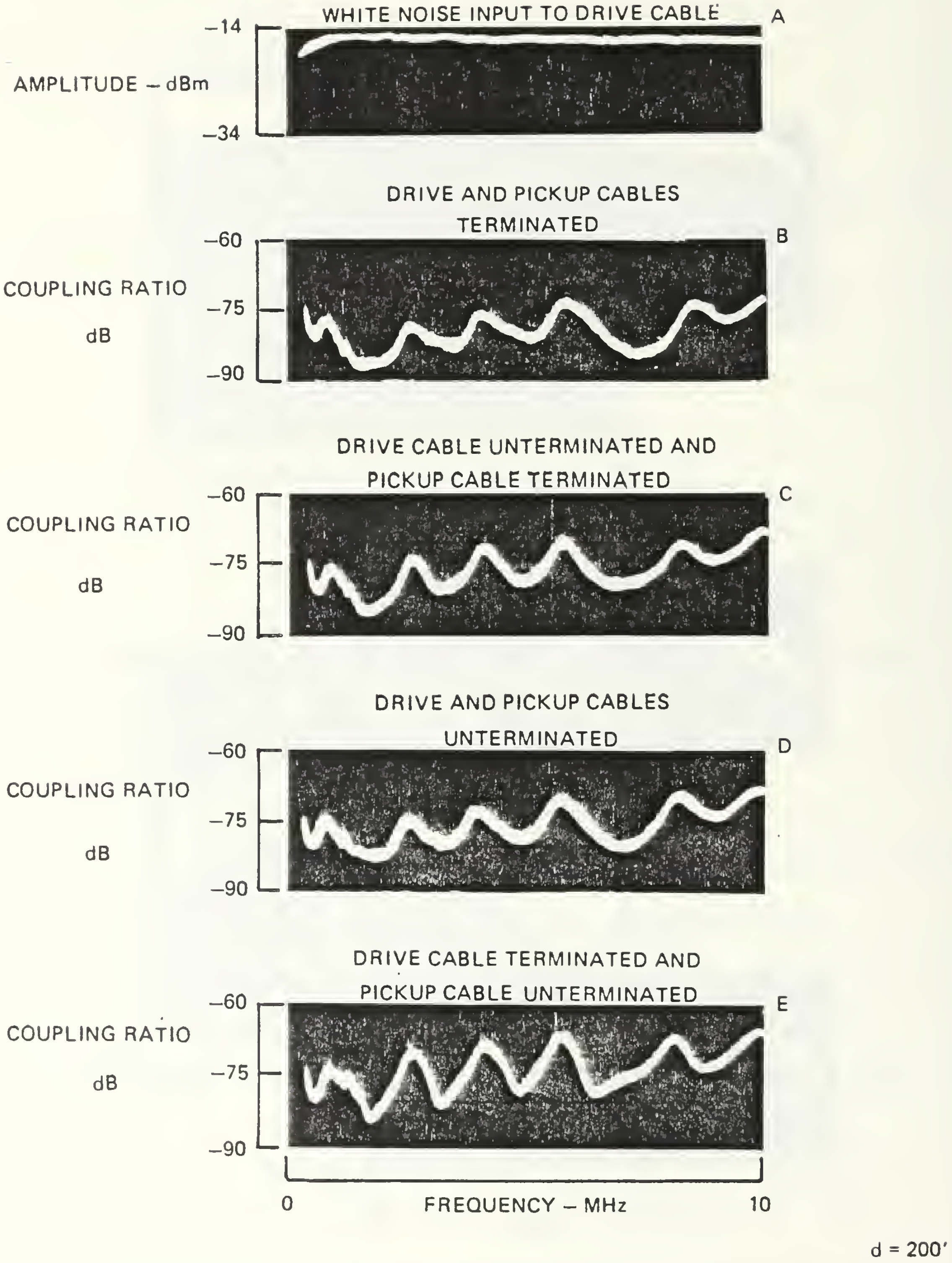


Figure 25. Coupling With Changes in Termination

coupling ratios varied over an approximately 15-20 db range. The smallest maximum coupling ratio was again with both cables terminated and the case with the drive cable terminated and the pickup cable unterminated showed the largest maximum coupling ratio overall. Unlike the 0 to 50 MHz measurements, the shape of the resonance and null structure seemed to remain fairly consistent between cases here.

Figure 26 shows the effect, from 0 to 10 MHz, of changing the lengths of the cables (both terminated in each case). These can also be compared to the 200-ft. (both terminated) case in Figure 25. The general effects seem to be closer spacing of the resonances and increased overall coupling as the cable lengths increase. This must be interpreted carefully, however, since the lengths of the cables in wavelengths are under one wavelength for many of the length/frequency combinations involved. The results may be quite different for very long lengths of cables, i.e., when all lengths are multiples of wavelengths at the frequency of interest.

Overall, the results show that although the exact coupling between two random lengths of RG-58 at a given frequency would be impossible to predict reliably, the general levels of coupling would be sufficiently high that strong signals or noise in one cable could be expected to couple at undesirably high levels into other cables going to

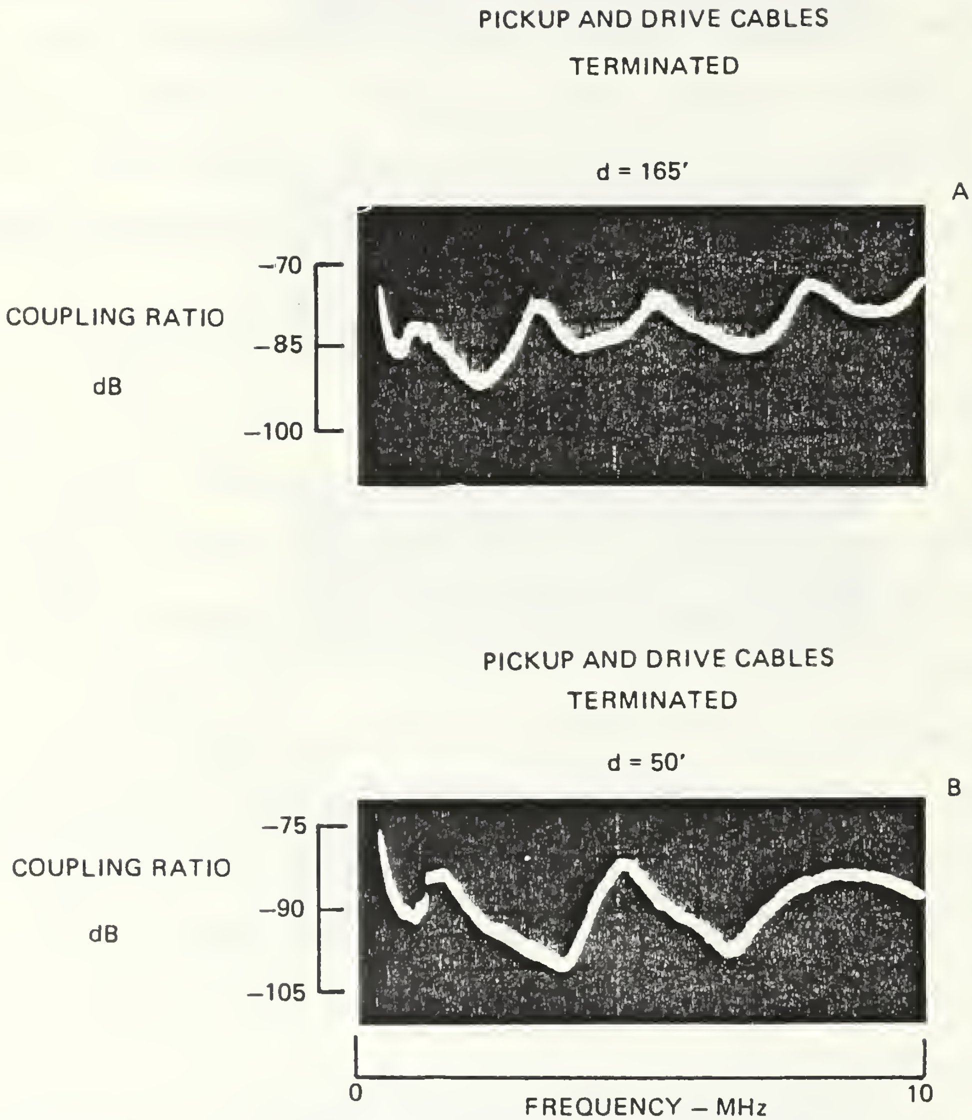


Figure 26. Coupling With Changes in Lengths

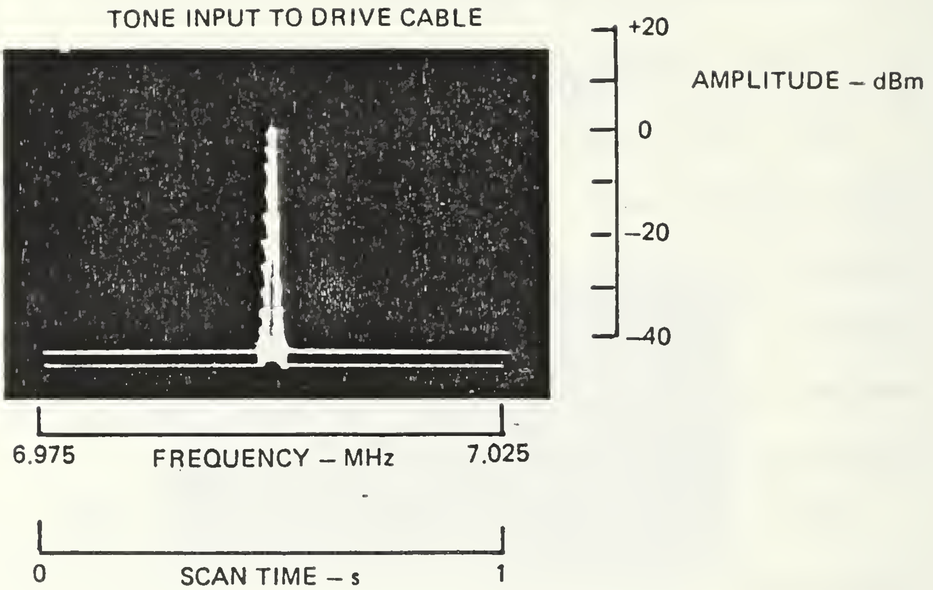
sensitive receivers. This is exactly the situation described in the preceding field study.

C. THESIS EXPERIMENTS

For this thesis, a number of experiments similar to those just reported were conducted to provide a direct comparison between single-shielded RG-58 and double-shielded RG-223 cables in a controlled environment. Both laboratory noise sources and "real-world" noise and signals were used for the comparison.

Since the primary purpose was comparison, the parameters which were varied in the previous experiments were held constant here. All lengths of cable used were 100 ft. and all cables were terminated at their ends in 50 ohms. Effects qualitatively similar to those realized in the previous experiments could be expected if the same parameters were varied here.

For the first experiments, the laboratory noise sources utilized were again the Marconi TF2091B, for white noise, and the HP3325A synthesizer, for sinusoids. The outputs which they were set to, as measured directly by the HP141T, are shown in Figure 27. The levels were set to 0 dbm for easy calculation of coupling ratios. A 2-12 MHz measurement range was used for the white noise cases in order to utilize the flat portion of the generator's spectrum and to avoid, for



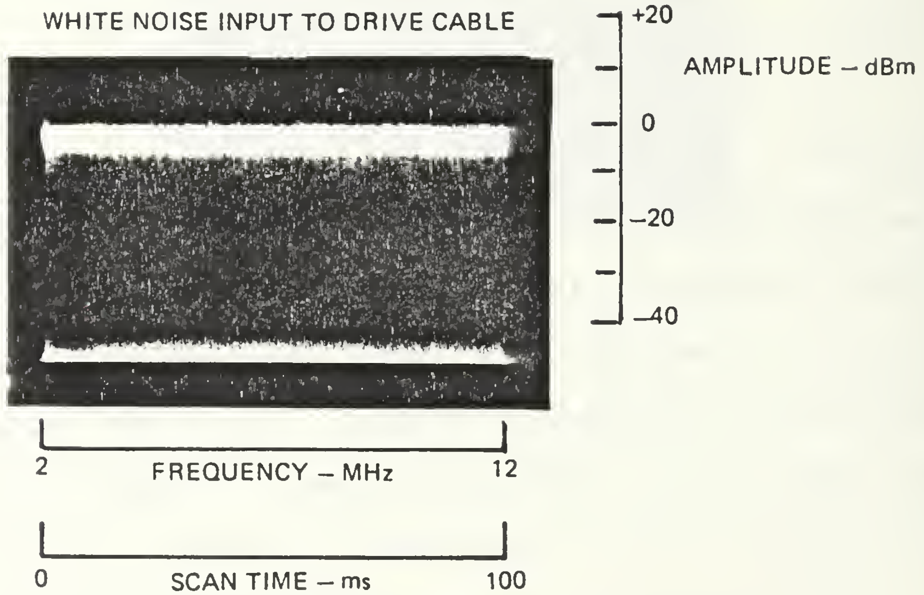


Figure 27. Inputs to Drive Cable

the time being, the strong AM broadcast signals which were able to be picked up.

First, a 100-ft. RG-58 drive cable was connected to the synthesizer sinusoidal (7 MHz) output and another 100 ft. length of RG-58 was layed directly alongside of it as a pickup cable. The pickup cable was connected to the 20-db gain line amplifier, HP141T analyzer and 3-axis display set-up described earlier. The measured pickup was displayed on one-third of the 3-axis display's time span and then two other configurations were similarly measured. The second had an RG-58 drive cable and an RG-223 pickup and the last had RG-223 drive and pickup cables. The results are shown in Figure 28. Since the input to the drive cable was 0 dbm, the measured value from the pickup cable corresponds directly to a coupling ratio. The RG-58 to RG-58 coupling is the greatest, as expected, at a value of -80 db. The RG-58 to RG-223 coupling is measured at -110 db, therefore a 30 db improvement is realized with one changeover of a single to a double shield. The pickup in the case of RG-223 to RG-223 coupling is seen to be below the instrumentation noise floor at -123 dbm so all that can be said is that the coupling is less than -123 db. That level of isolation between cables is likely to be satisfactory under almost any circumstances.

Next, the same configurations were used except with the white noise generator driving the drive cable. Figure 29 shows the results. Resonance peaks and nulls are observed as

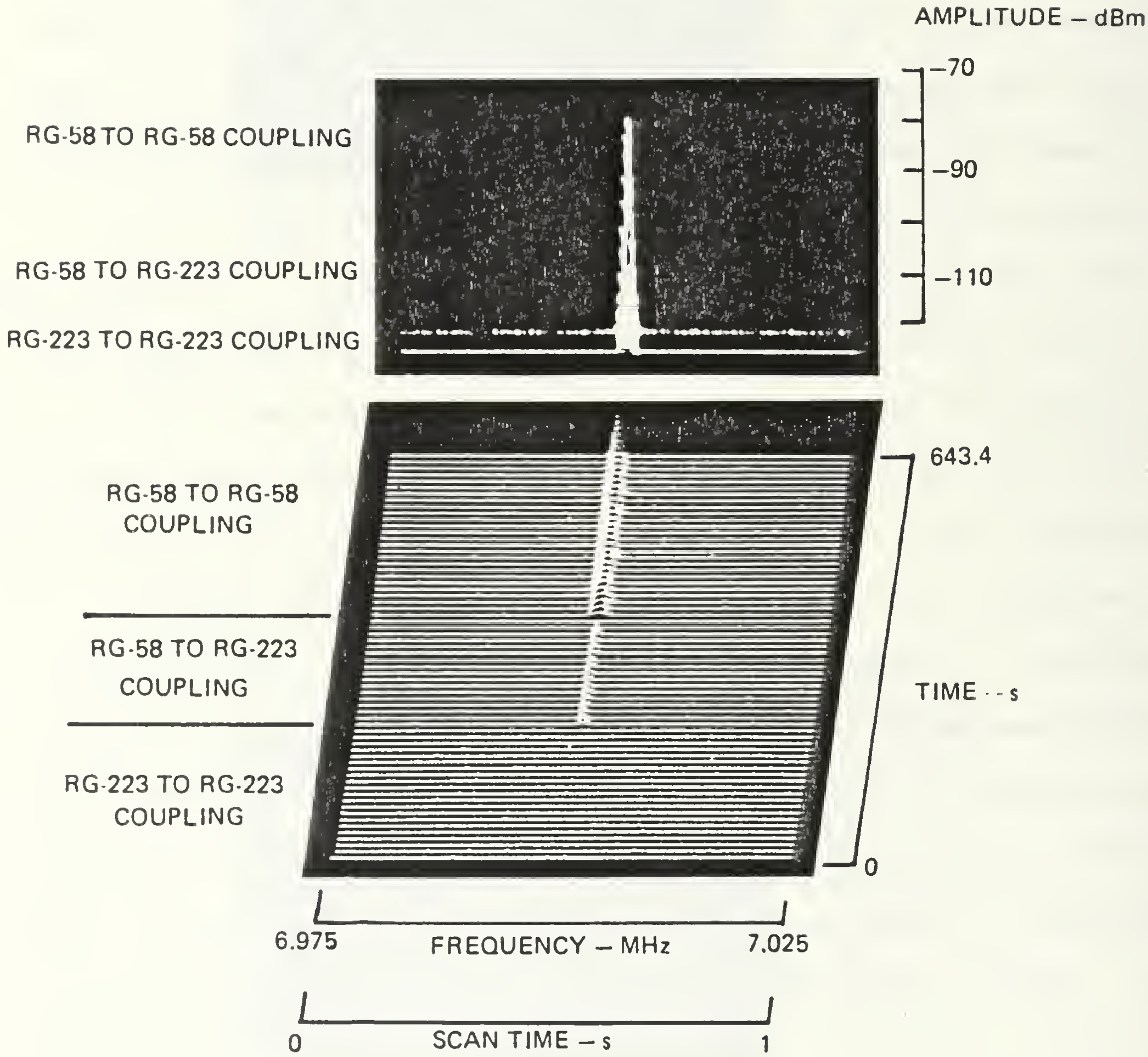


Figure 28. Coupling With Various RG-58/RG-223 Pair Changes

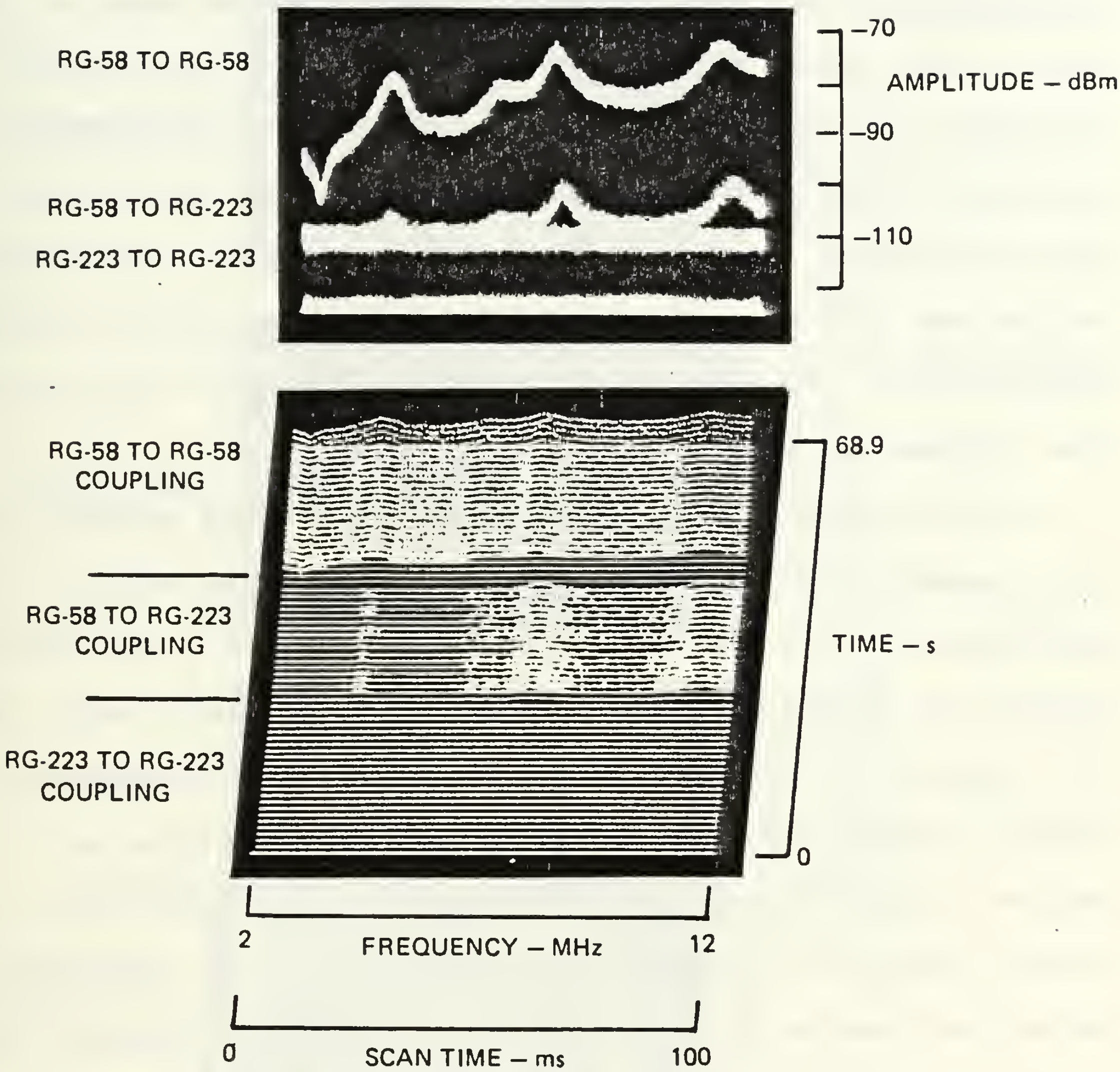


Figure 29. Coupling With Various RG-58/RG-223 Pair Changes

expected and the RG-58 to RG-58 coupling is again the greatest, ranging from -72 db to -105 db. While for the RG-58 to RG-223 coupling case, some of the response is below the noise floor, the improvement in coupling can be seen at the peaks to be around 27 db, although the peaks also shifted slightly in frequency for this case. The RG-223 to RG-223 coupling cannot be determined as the response is totally below the noise floor, which is higher here at -110 dbm due to the use of a much higher measurement bandwidth with the white noise. The coupling is simply less than -110 db at all the frequencies measured.

For the next experiment, a real-world noise source was used, namely the SCR device used earlier in the cabinet experiments. The SCR device, with its 120-ohm load, was plugged in at the end of a 100-ft. standard power cord. 100-ft. lengths of RG-58 and RG-223 were alternately laid directly alongside it and the cable pickup measured as before. While a coupling ratio cannot be defined here, a direct comparison of pickup can still be made. Figure 30 shows the results from 0 to 20 MHz. Only the measured scans corresponding to each cable are shown in each of two amplitude pictures. While more than one SCR noise mechanism is again present, comparing peaks of the maximum transient envelopes shows an average improvement of about 22 db with the RG-223. The pickup of the AM broadcast band is also decreased by about 20 db with the RG-223.

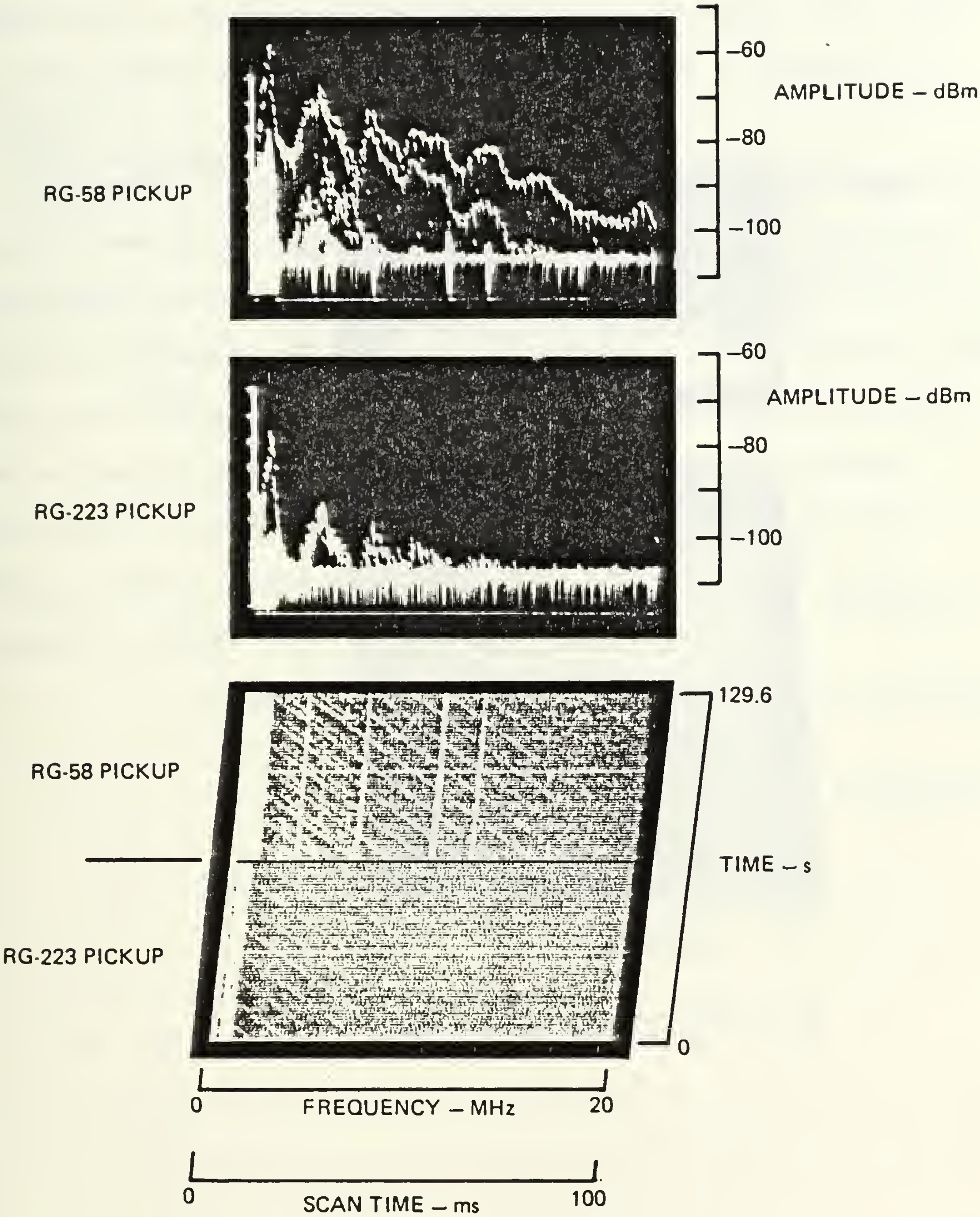


Figure 30. RG-223 vs. RG-58 Pickup

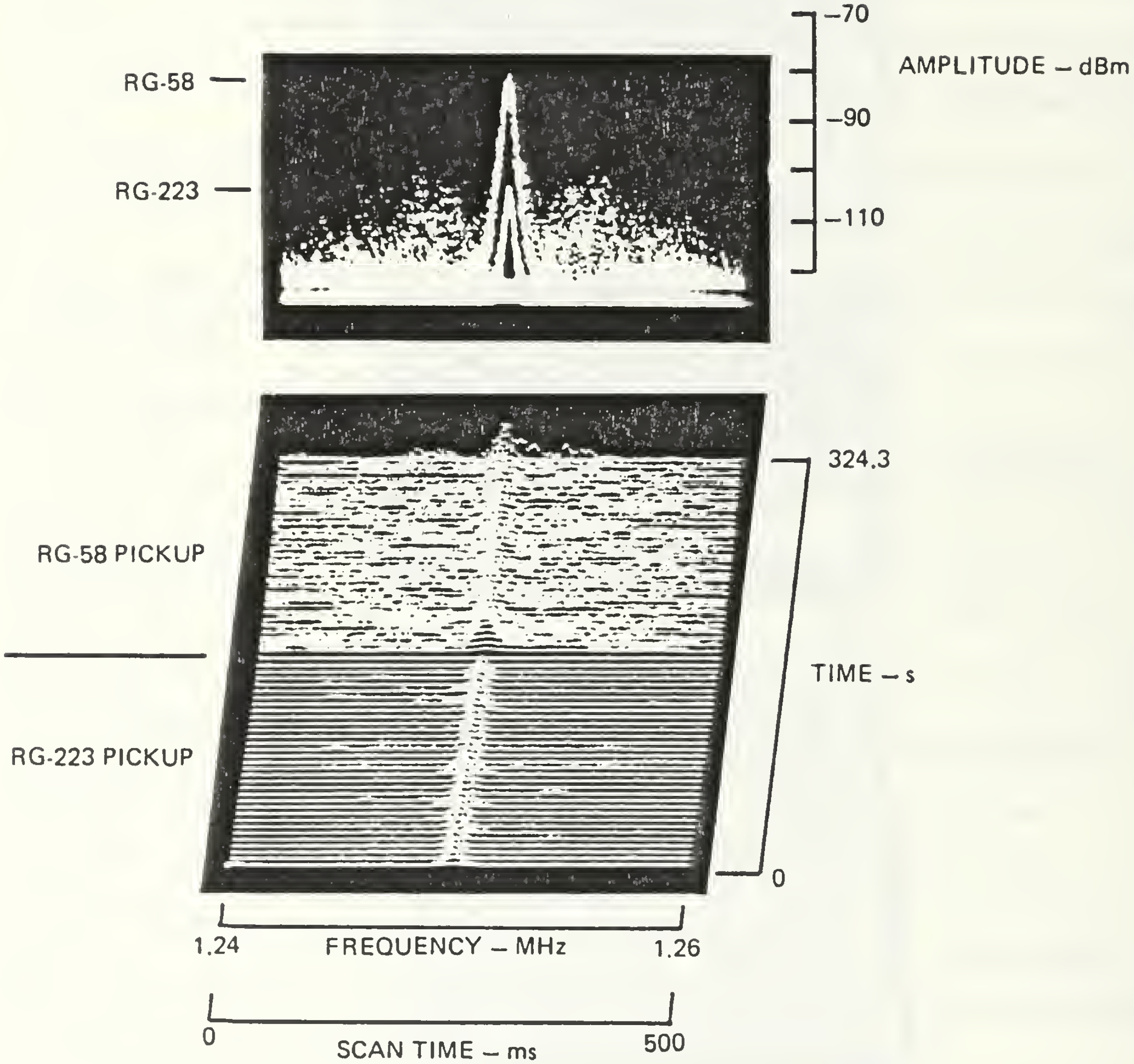


Figure 31. RG-223 vs. RG-58 Pickup

In Figure 31, a closer look is taken at the cable pickup of one particular local AM radio station. While it is difficult to state anything about the sidebands, the pickup of the carrier shows a clear improvement of 21 db with the RG-223.

The above results clearly demonstrate the superiority of RG-223 over RG-58 cable in terms of interference coupling. A changeover of just one shield in the coupling problem from single to double resulted in improvements of from 20 to 30 db for a wide range of frequencies and signal and noise types. The exclusive use of double-shielded cables in a given environment would result in exceptionally good isolation between cables and a high degree of protection from any external fields.

VII. CONCLUSION

The topological approach to electromagnetic interference control has been described in this thesis as being based on relatively simple concepts which are broadband in scope. It was proposed that control in a complex electronic system or facility can be achieved in a general manner within this one fundamental framework. The approach would thereby provide a desirable alternative to past application-specific methods and field-fixes which often resulted in confusing, ineffective, or incompatible configurations.

In a discussion of the implementation of the proposed approach at an already existing facility, in particular with regard to an equipment-level barrier, it was seen that implementation strategies can be developed in a rather straightforward manner. Existing hardware and architectures can often be effectively utilized with the application of a few simple rules.

The experiments which were conducted provided strong empirical support for the proposed concepts, at least in the HF frequency ranges studied. The important conclusion which can be drawn from the grounding investigation is that it appears to be quite beneficial to implement the proposed topological grounding techniques even on common, open-type equipment racks which are widely in use but which are not even intended by design to possess significant interference control attributes. Relatively simple, straightforward changes to present grounding schemes are all that would be required and safety would not be compromised in the least. The investigation of filter connections similarly demonstrated the significant potential benefits which could be realized by applying very simple topological concepts to treatment implementations.

In additional experiments investigating the use of double-shielded coaxial cable instead of single-shielded in the extension of a topological barrier, the data was clear and consistent in demonstrating the considerable quantitative improvements which could thereby be realized. Because of double-shielded cable's physical compatibility with existing system architectures, it too represents a source of potential benefit with minimal cost.

Continued research in the areas addressed in this thesis would be invaluable, especially with regard to practical topological grounding techniques and penetrating conductor treatments. Such research must, however, strive for realism. Empirical evidence will be most useful when it has been gathered in practical, realistic experiments which approximate operational equipment and scenarios as closely as possible.

APPENDIX

MEASUREMENT PARAMETERS

Following are the measurement parameters corresponding to each of the HP141T spectrum analyzer data presentations in this thesis. The format is described in Chapter IV, page 43. All data photographs were taken from the 3-axis display except for those in Figures 23 through 26, which were taken directly from the HP141T CRT.

Figure 7
1455, 11 Feb 86
NPS, SP219 Lab, TF2091B Output
Direct, 0, -30, +10
50 MHz, 100 MHz, 100 kHz, 100 ms

Figure 13a
0955, 8 Feb 86
NPS, SP219 Lab, Rack Exp.
P6021(2), +20, 0, -20
10 MHz, 20 MHz, 100 kHz, 100 ms

Figure 13b
1020, 8 Feb 86
NPS, SP219 Lab, Rack Exp.
P6021(2), +20, 0, -20
10 MHz, 20 MHz, 100 kHz, 100ms

Figure 13c
1035, 8 Feb 86
NPS, SP219 Lab, Rack Exp.
P6021(2), +20, 0, -20
10 MHz, 20 MHz, 100 kHz, 100 ms

Figure 13d
1100, 8 Feb 86
NPS, SP219 Lab, Rack Exp.
P6021(2), +20, 0, -20
10 MHz, 20 MHz, 100 kHz, 100 ms

Figure 17a
1540, 8 Feb 86
NPS, SP219 Lab, Rack Exp.
P6021(2), +40, 0, 0
5 MHz, 10 MHz, 100kHz, 100ms

Figure 17b
1555, 8 Feb 86
NPS, SP219 Lab, Rack Exp.
P6021(2), +40, 0, 0
5 MHz, 10 MHz, 100 kHz, 100 ms

Figure 17c
1610, 8 Feb 86
NPS, SP219 Lab, Rack Exp.
P6021(2), +40, 0, 0
5 MHz, 10 MHz, 100 kHz, 100 ms

Figure 19a
1752, 8 Feb 86
NPS, SP219 Lab, Rack Exp.
P6021(2), +40, 0, -10
10 MHz, 20 MHz, 100 kHz, 100 ms

Figure 19b
1745, 8 Feb 86
NPS, SP219 Lab, Rack Exp.
P6021(2), +40, 0, -10
10 MHz, 20 MHz, 100 kHz, 100 ms

Figure 21a
1315, 9 Feb 86
NPS, SP219 Lab, Rack Exp.
P6021(2),+20, 0, -20
10 MHz, 20 MHz, 100 kHz, 100 ms

Figure 21b
1210, 9 Feb 86
NPS, SP219 Lab, Rack Exp.
P6021(2), +20, 0, -20
10 MHz, 20 MHz, 100 kHz, 100ms

Figure 21c
1247, 9 Feb 86
NPS, SP219 Lab, Rack Exp.
P6021(2), +20, 0, -20
10 MHz, 20 MHz, 100 kHz, 100 ms

Figure 22
1212, 22 Aug 85
E, 46, RF Patch
Direct, 0, 0, -40
5 MHz, 10 MHz, 1 kHz, 100 ms

Figure 23a
1350, 27 Jun 85
NPS, SP219 Lab, RG-58 Coupling Exp.
Direct, 0, -50, +7
25 MHz, 50 MHz, 300 kHz

Figure 23b
1345, 27 Jun 85
NPS, SP219 Lab, RG-58 Coupling Exp.
Direct, 0, 0, -43
25 MHz, 50 MHz, 300 kHz

Figure 24a
1325, 27 Jun 85
NPS, SP219 Lab, RG-58 Coupling Exp.
Direct, 0, -50, -17
25 MHz, 50 MHz, 10 kHz, 100 Hz Video Filter

Figure 24b
1335, 27 Jun 85
NPS, SP219 Lab, RG-58 Coupling Exp.
Direct, 0, 0, -67
25 MHz, 50 MHz, 10 kHz, 100 Hz Video Filter

Figure 24c
1328, 27 Jun 85
NPS, SP219 Lab, RG-58 Coupling Exp.
Direct, 0, 0, -67
25 MHz, 50 Mhz, 10 kHz, 100 Hz Video Filter

Figure 25a
1310, 27 Jun 85
NPS, SP219 Lab, RG-58 Coupling Exp.
Direct, 0, -50, -14
5 MHz, 10 MHz, 10 kHz, 100 Hz Video Filter

Figure 25b
1315, 27 Jun 85
NPS, SP219 Lab, RG-58 Coupling Exp.
Direct, 0, 0, -64
5 MHz, 10 MHz, 10 kHz, 100 Hz Video Filter

Figure 25c
1320, 27 Jun 85
NPS, SP219 Lab, RG-58 Coupling Exp.
Direct, 0, 0, -64
5 MHz, 10 MHz, 10 kHz, 100 Hz Video Filter

Figure 25d
1321, 27 Jun 85
NPS, SP219 Lab, RG-58 Coupling Exp.
Direct, 0, 0, -64
5 MHz, 10 MHz, 10 kHz, 100 Hz Video Filter

Figure 25e
1322, 27 Jun 85
NPS, SP219 Lab, RG-58 Coupling Exp.
Direct, 0, 0, -64
5 MHz, 10 MHz, 10 kHz, 100 Hz Video Filter

Figure 26a
1250, 27 Jun 85
NPS, SP219 Lab, RG-58 Coupling Exp.
Direct, 0, 0, -64
5 MHz, 10 MHz, 10 kHz, 100 Hz Video Filter

Figure 26b
1252, 27 Jun 85
NPS, SP219 Lab, RG-58 Coupling Exp.
Direct, 0, 0, -64
5 MHz, 10 MHz, 10 kHz, 100 Hz Video Filter

Figure 27a
1740, 9 Feb 86
NPS, SP219 Lab, RG-58/RG-223 Exp.
Direct, 0, -50, +30
7 MHz, 50 kHz, 300 Hz, 1 sec

Figure 27b
1605, 9 Feb 86
NPS, SP219 Lab, RG-58/RG-223 Exp.
Direct, 0, -50, +30
7 MHz, 10 MHz, 100 kHz, 100 ms

Figure 28
1615, 9 Feb 86
NPS, SP219 Lab, RG-58/RG-223 Exp.
Direct, +20, 0, -30
7 MHz, 50 kHz, 300 Hz, 1 sec

Figure 29
1630, 9 Feb 86
NPS, SP219 Lab, RG-58/RG-223 Exp.
Direct, +20, 0, -30
7 MHz, 10 MHz, 100 kHz, 100 ms

Figure 30
1825, 9 Feb 86
NPS, SP219 Lab, RG-58/RG-223 Exp.
Direct, +20, 0 -20
10 MHz, 20 MHz, 100 kHz, 100 ms

Figure 31
1945, 9 Feb 86
NPS, SP219 Lab, RG-58/RG-223 Exp.
Direct, +20, 0, -30
1.25 MHz, 20 kHz, 300 Hz, 500 ms

LIST OF REFERENCES

1. Defense Nuclear Agency Report 5433F-1, Unification of Electromagnetic Specifications and Standards, Part I-Evaluation of Existing Practices, by E.F. Vance, W. Graf, and J. E. Nanevicz, pp. 1-63, 31 October 1980.

2. Baum, C. E., "How to Think About EMP Interaction," Proceedings of the 1974 Spring FULMEN Meeting, Air Force Weapons Laboratory, Kirtland AFB, New Mexico, pp. 12-23, 16-17 April 1974.

3. Tesche, F. M., "Topological Concepts for Internal EMP Interaction," IEEE Transactions on Electromagnetic Compatibility, Vol. EMC-20, No. 1, pp. 60-64, February 1978.

4. Baum, C. E., "The Role of Scattering Theory in Electromagnetic Interference Problems," Uslenghi, P. L. E., ed., Electromagnetic Scattering, pp. 471-502, Academic Press, 1978.

5. Defense Nuclear Agency Report 5433F-2, Unification of Electromagnetic Specifications and Standards, Part II-Recommendations for Revisions of Existing Practices, by W. Graf, J. M. Hamm, and E. F. Vance, pp. 1-34, 28 February 1983 (rev. 15 April 1983).

6. National Electrical Safety Code, 1984 Edition, American National Standard ANSI C2-1984, p. 52, The Institute of Electrical and Electronics Engineers, Inc, 1983.

7. O'Dwyer, J. M., Electromagnetic Noise and Interference at High Frequency Communications Receiver Facilities, Electrical Engineer Thesis, Naval Postgraduate School, 1984.

8. Technical Memorandum, Brief Description of Instrumentation, by W. R. Vincent, pp. 1-17, 31 January 1985.

9. Bly, R. T. and Tonas, E., "The Inside and the Outside Are Not the Same--Experimental Investigations of Ground and Shield Topology," 1982 IEEE International Symposium on Electromagnetic Compatibility, Santa Clara, CA, pp. 53-60, 1982.

10. Ott, H. W., Noise Reduction Techniques in Electronic Systems, pp. 49-50, John Wiley and Sons, 1976.

11. Vance, E. F., Coupling to Shielded Cables, pp. 6-7, John Wiley and Sons, 1978.

12. Naval Electronics Systems Command PDE 107-6 Technical Memorandum, Signal-to-Noise Enhancement Investigation at the Edzell, Scotland CDAA, by E. J. Cummins, S. Jauregui, O. A. Larson, and W. R. Vincent, pp. 1-14, 13 May 1985.

13. Space and Naval Warfare Systems Command PDW 107-6 Report, Final SNEP Team Report for NAVSECGRUACT EDZELL, 4-30 August 1985, by E. J. Cummins et al., 3 September 1985.

14. Technical Note, Adjacent Cable Coupling, by J. M. O'Dwyer and W. R. Vincent, pp. 1-4, June 1985.

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