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MILLIMETER WAVE ELECTROMAGNETIC MEASUREMENT TECHNIQUES

By

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This report presents the results of studies to develop the rationale for electromagnetic measurement techniques for use in the EMC evaluation of millimeter wave (MMW) communication-electronic equipment and systems. In the development of this rationale, seven basic tasks were performed. Under the first task, the EMC/EMI data requirements for MMW equipments and systems were established to provide a clear definition of the type of data needed, how the data should be used, and who will use the data. The second task was directed

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ABSTRACT (Cont'd.)

to the definition of appropriate measurement philosophy and techniques for obtaining the required data. Because measurements of the EMC characteristics of millimeter wave systems in the 10-300 GHz frequency range impose stringent demands on facilities, test instrumentation, and test methodology, new measurement techniques and configurations for satisfying the demands were recommended as required. Under the third task, the state-of-the-art in EMC/EMI measurement instrumentation and components for the 10-300 GHz frequency band was reviewed to identify the instrumentation which is available, or should be developed, to implement the measurement techniques defined in the previous tasks. The fourth task involved an evaluation of the advantages and disadvantages of manual, semi-automated, and fully automated measurement techniques to determine both the feasibility and cost-effectiveness of these three approaches to data collection and analysis. Under the fifth task, the likely errors associated with EMC/EMI measurements at MMW frequencies were identified. These errors were addressed in terms of errors associated with measurement instrumentation, measurement techniques, and data utilization. The sixth task involved selected experimental measurements to investigate the possible impact of surface wave phenomena on EMI coupling at MMW frequencies, the merits of using the compact range as an EMC/EMI measurement site, and the nonlinear characteristics of MMW mixers. Under the seventh and final task, a method for extrapolating the data from the specific measurement configuration to other configurations which might be employed in practical installations was addressed. This method is based on a statistical rather than deterministic treatment of the measurement data.

FOREWORD

This final report was prepared by the Engineering Experiment Station at Georgia Tech under Contract No. DAAK80-80-C-0569, Georgia Tech Project No. A-2746. The report summarizes the project activities during the 1 September 1980 to 30 April 1982 time period. The work described in the report was directed by Mr. E. E. Donaldson, Project Director, under the general supervision of Mr. H. W. Denny, Chief of the Electromagnetic Compatibility Division.

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1.0 INTRODUCTION

1.1 Program Objective and Scope

This final report summarizes the research activities performed during the period of 1 September 1980 to 30 April 1982 under Contract No. DAAK80-80-C-0569, "Millimeter Wave Electromagnetic Measurement Techniques". The objective of this program is to develop the rationale for electromagnetic measurement techniques for use in the EMC evaluation of millimeter wave (MMW) communication-electronic equipments and systems. The developed rationale will (1) apply to both radiated and conducted emission and susceptibility types of measurements; (2) identify data needs, accuracy requirements, and utilization methods; (3) propose measurement techniques for obtaining the required data; (4) define the measurement instrumentation necessary to implement the proposed measurement techniques; and (5) identify deficiencies in millimeter wave measurement instrumentation and the development efforts required to eliminate these deficiencies.

1.2 Background

Historically, communication-electronic equipments have operated at relatively low frequencies (up to a few thousand MHz), and electromagnetic interference (EMI) problems associated with low frequency equipments have been studied in detail. An extensive amount of literature (standards, specifications, design handbooks, etc.) has been generated which defines the EMC/EMI characteristics of earlier vintage components, circuits, and equipments, identifies reliable measurement techniques and procedures for measuring these characteristics, and provides methods for the reduction or elimination of interference problems. Thus, the causes, effects, and methods for control of EMI in lower frequency equipments and systems are well known to the EMC/EMI community.

In recent years, however, the state-of-the-art in electronic technology has advanced to the point where systems which operate in the 10-100 GHz frequency range are becoming common place, and systems which operate up to 300 GHz are expected to be in use within the next decade. Some fundamental questions thus arise as to the EMC/EMI characteristics of such millimeter wave systems. For example, do the devices and equipments which comprise these systems exhibit different EMC/EMI characteristics than their lower frequency counterparts? What device, equipment, and system parameters influence these characteristics and what data are needed to assess system EMC/EMI performance? Where data needs are defined, what measurement techniques and instrumentation should be employed to assimilate the required data? What measurement accuracy can be achieved at millimeter wave frequencies? What influence do propagation and coupling losses have on the EMC/EMI performance of a system configuration in a field operational environment? Answers to such questions are critical to the design and deployment of millimeter wave systems which will perform satisfactorily in their intended environment. These answers can only be obtained if valid measurement techniques are available for ascertaining the EMC/EMI properties of millimeter wave systems. It was to the development of appropriate rationale for EMC/EMI type measurements on millimeter wave systems that efforts under this program were directed.

1.3 Method of Approach

The approach established to accomplish the program objective involved the following seven basic tasks:

(1) The establishment of EMC/EMI data requirements for millimeter wave equipments and systems;

(2) The definition of measurement techniques for obtaining the required data;

(3) The determination of measurement instrumentation which is available or should be developed to implement the defined measurement techniques;

(4) A tradeoff analysis of manual, semi-automated, and fully automated data collection and analysis techniques;

(5) An error analysis of the proposed measurement techniques;

(6) Selected measurements to experimentally verify program findings; and

(7) The development of methods for extrapolating measured data from the specific measurement configuration employed to other configurations.

The purpose of the first task, the definition of EMC/EMI data requirements for millimeter wave equipments and systems, was to establish a clear definition of the type of data needed, how the data will be used and who will use it, and what data accuracy is required.

Once the data requirements were defined, the second task was to establish the measurement philosophy and techniques which are necessary to obtain the required data. Because measurements of the EMC characteristics of millimeter wave systems in the 10-300 GHz frequency range impose stringent demands on facilities, test instrumentation, and test methodology, new measurement techniques and configurations may be required. To the extent possible, these techniques and configurations should conform to accepted and proven measurement concepts and practices. Where such conformance is not feasible, care must be taken to ensure that new techniques are designed to enable the collection of accurate, repeatable, and reliable data in a cost effective manner.

Under the third task, the state-of-the-art in EMC/EMI measurement instrumentation and components for the 10-300 GHz frequency band was reviewed to identify the instrumentation which is available, or should be developed, to implement the measurement techniques defined in the previous tasks.

Under the fourth task, the advantages and disadvantages of manual, semi-automated, and fully automated measurement techniques were evaluated. The basic purpose of this evaluation is to determine both the feasibility and cost-effectiveness of these three approaches to data collection and analysis.

The fifth task involved an analysis of the individual and collective errors associated with the defined measurement techniques. The utility of EMI data is highly dependent upon the accuracy of the data. Thus, a determination of errors associated with millimeter wave measurements is fundamental to determining the adequacy of the measurement technique as well as the accuracy of the measurement data.

The sixth task was directed to the experimental verification of appropriate phases of the program results. Selected measurements were performed to ensure that the data parameters were correctly defined, that measurement techniques and configurations were valid, or that measurement errors were within the bounds defined by the analyses.

The seventh and final task was the development of methods for extrapolating the data from the specific measurement configuration to other configurations which might be employed in practical installations. The importance of this task is evident when it is recognized that the specific measurement configuration employed in EMI measurements cannot possibly simulate the multiplicity of configurations likely to occur in practical system installations. Thus, a method for extrapolating measurement data between different configurations is essential to valid assessments of system EMC.

1.4 Report Summary and Organization

This final report, covering the period 1 September 1980 to 30 April 1982, documents the results of efforts to define adequate EMC/EMI rationale, measurement techniques, and measurement instrumentation for MMW systems. The material which follows in this report is divided into eight major sections, Section 2 through Section 9. Section 2 reviews the major factors which influence EMC/EMI considerations at MMW frequencies, and Section 3 identifies the basic EMC/EMI data requirements which are necessary to define the interference potential of MMW systems. Section 4 presents a measurement philosophy for MMW systems, Section 5 addresses specific measurement techniques, and Section 6 discusses measurement instrumentation for MMW EMC measurements. Section 7 discusses the utilization of measurement data for assessing MMW system EMC/EMI performance in different deployment configurations. Section 8 provides an assessment of the sources and magnitudes of data errors, and Section 9 presents the major findings and conclusions of the program. The report also contains three appendices which present the results of experimental measurements which were performed.

2. EMC/EMI CONSIDERATIONS AT MMW FREQUENCIES

2.1 General

The purpose of this section is to review the general characteristics of MMW systems, with emphasis given to those characteristics which are unique or different from an EMC/EMI viewpoint with respect to lower frequency systems. Included are considerations of how MMW equipment configurations and construction techniques may influence their EMC/EMI characteristics; the effect of frequency on EMC/EMI interactions in terms of such factors as propagation loss, coupling loss, etc.; the interference potential of MMW antennas; and how a deployed MMW system will interact with its operational environment. These considerations provide the basis for assessing the EMC/EMI characteristics of MMW systems and for determining if EMC/EMI data are needed which are different from those presently required on lower frequency systems.

2.2 Electromagnetic Environment Considerations

Ideally, the EMC design of a system begins with a definition of the specific electromagnetic environment in which the system will operate. Given this environment, the system EMC design is tailored to achieve a system which is electromagnetically compatible with the environment. For Army communication-electronic systems, however, such an approach is not feasible since these type systems may be deployed in many different environments; hence, "tailoring" to a specific environment is not feasible. The approach which is followed by the Army is to design systems to meet fixed EMC/EMI specification requirements. While not providing the optimum EMC design for a given deployment, this approach does provide the best design tradeoff for equipments which must serve different operational needs in a variety of EM environments.

Although the definition of specific environments is not pertinent to the design of Army communication-electronic equipments, a knowledge of the overall characteristics of the environments in which such systems must perform must be known to establish valid system EMC design goals and to develop appropriate data requirements to assure that these goals are met. Specifically, a knowledge of the range of frequencies likely to be encountered and typical power levels to be expected is essential to the initiation of a system design which will perform satisfactorily.

Historically, system EMC designs have been based on environments characterized by a relatively narrow frequency spectrum. In recent years, however, the frequency spectrum has expanded considerably as MMW systems have evolved. This increase in spectrum occupancy brought about a greater need for EMC/EMI measurement data for the resolution of potential EMI problems. This need is evidenced by Figure 1, which is a summary of source frequency coverage based on state-of-the-art component development. Note from this figure that sources are presently available which permit the operation of systems throughout the MMW region of the frequency spectrum (30 to 300 GHz) and beyond. Virtually all of the microwave design and fabrication techniques used at the upper microwave bands, i.e., through K-band (to 30 GHz), may also be readily applied at the lower end of the MMW region (up to 100 GHz). High power sources are available at 35 GHz (TWT's up to 35 kW) and lower power magnetrons are available at 70 and 95 GHz (up to 1 kW). Some magnetrons are tunable while

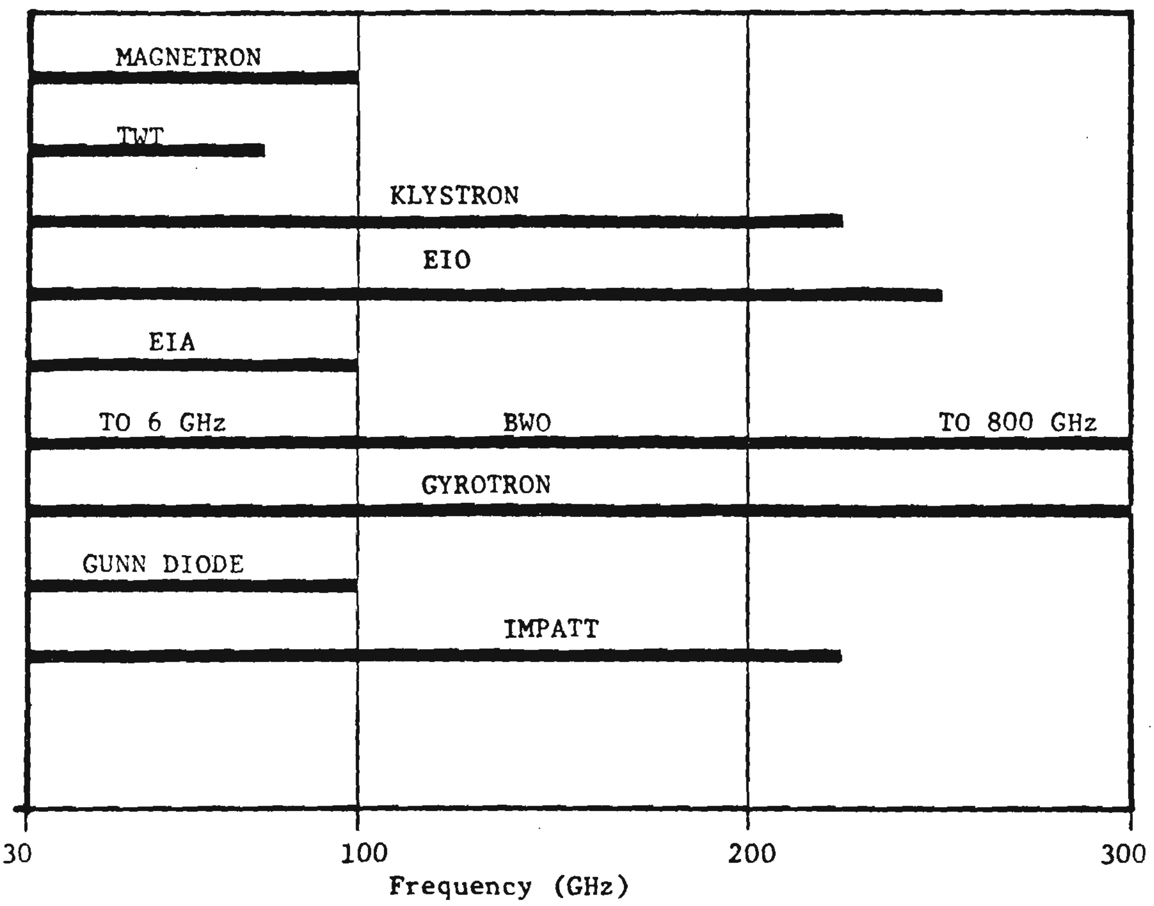


Figure 1. MMW Source Frequency Coverage, State-of-the-Art.

others operate at essentially fixed frequencies. Other types of MMW sources include the klystron, Extended Interaction Oscillator (EIO), Gunn diode source, IMPATT diode source, TWT amplifier, BWO (carcinotron), gyrotron, and relavistic electron beam devices.

As MMW systems evolve and become operational, EMC/EMI data requirements will become even more stringent, for three reasons. One reason is that the frequency range over which data are required will increase. As defined under this program, the current upper frequency of concern is 300 GHz. However, it is expected that systems which operate above this frequency will become operational as MMW technology expands. A second reason is that, for a given system, EMC/EMI data which spans the entire spectrum will likely be required. MMW EMC/EMI data cannot be restricted to the MMW frequency range; the effects of lower frequency signals on MMW system performance must also be measured. Finally, as new MMW sources with higher output power levels evolve, the inherent "isolation" of systems from MMW signals (due to propagation/coupling loss) will decrease, increasing the potential of interference caused by MMW systems. For the above reasons it is felt that the data requirements defined for MMW systems should not be based strictly on current MMW technology, but should reflect technology that can reasonably be projected within the next few years.

2.3 MMW Equipment Characteristics

2.3.1 General

MMW equipments may be classified into three broad categories: (1) radars (pulsed or CW illuminator), (2) radiometers (passive targeting, guidance and imaging systems), and (3) communications systems (transmit/receive, directional or omnidirectional coverage). Within each of these categories the characteristics of individual transmitters and receivers vary widely in the range of transmitted powers, RF signal waveform, receiver sensitivity, and antenna characteristics. On the other hand, some design practices and limitations, such as the use of superheterodyne techniques and the lack of low noise front end MMW preamps, are common among all three MMW equipment categories.

The general characteristics and configurations of typical MMW radar, radiometer, and communications have been documented previously [1]. These characteristics and configurations are summarized briefly in the following paragraph to provide a basis for identifying the EMC/EMI potential of MMW systems.

2.3.2 MMW Radars

The growth of MMW radars has been brought about by the fact that, at MMW frequencies, narrow antenna beamwidths and good target resolution can be achieved with relatively small antenna dimensions. Typical MMW radars include surveillance and instrumentation radars and active radar seekers used in MMW missile guidance, fire control, target acquisition, and missile beamrider applications.

The block diagram of a typical radar (representative of instrumentation or surveillance categories) is shown in Figure 2. In this functional block diagram no apparent difference is seen compared to a microwave radar. The differences

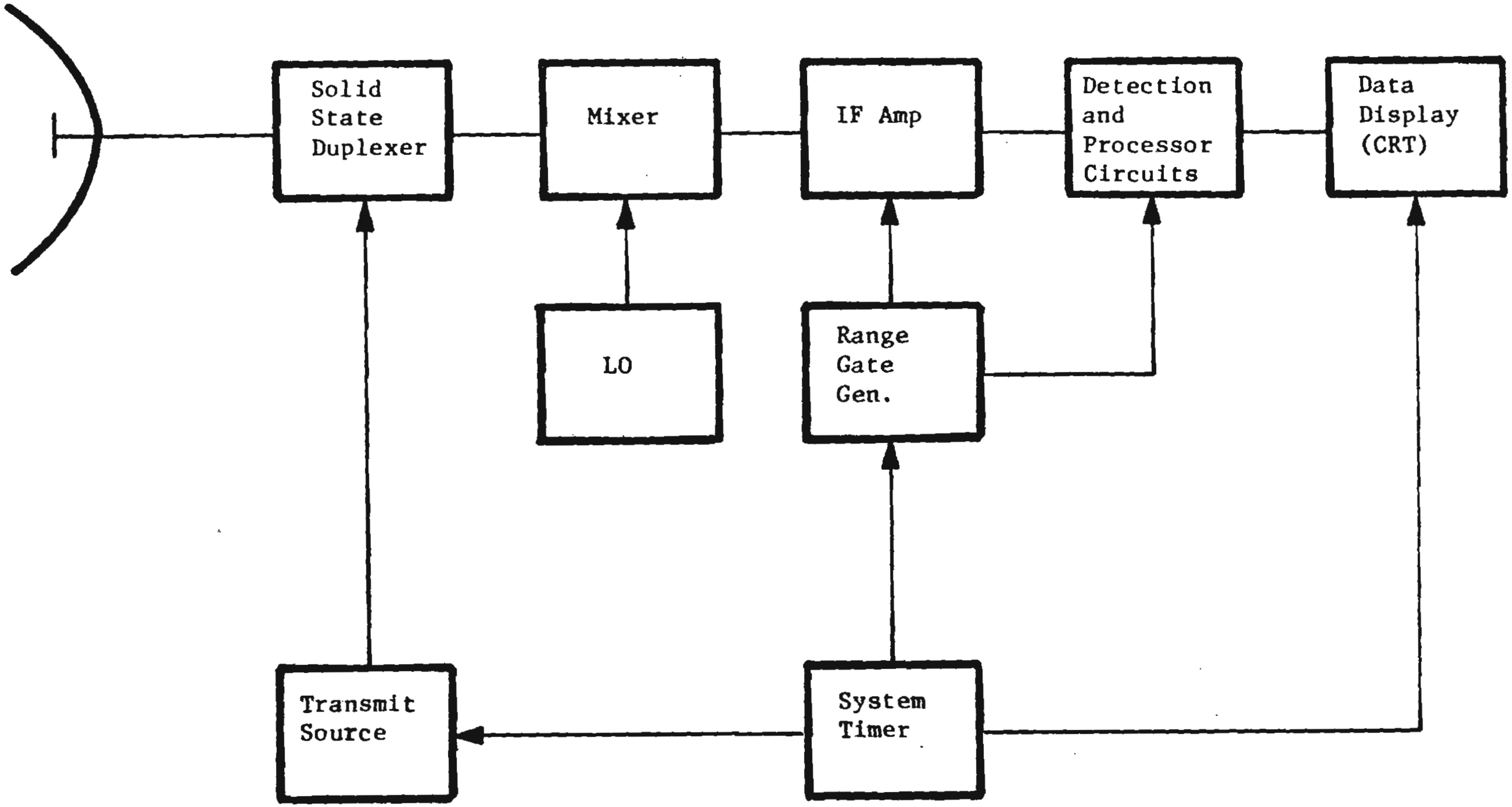


Figure 2. Typical MMW Instrumentation Radar.

that do occur are in the types of components employed. For instance, at the higher MMW frequencies, the duplexer might be a quasi-optical device.

Table I is a summary of the characteristics of radars developed at Georgia Tech which are considered representative of current MMW radars. These MMW radars were designed primarily for use as instrumentation radars, with little thought toward application in intense RF environments. Therefore, these systems could differ considerably in packaging configuration from systems designed for battlefield use. However, these radars are representative of the state-of-the-art in terms of the performance of the high gain antenna, duplexer, mixer, LO, IF amplifier, video detector, etc.

The operating characteristics of a number of MMW radar seekers surveyed is shown in Table II. Note that the characteristics depicted in this table (i.e. low transmit power, relatively large operating bandwidths, high IF center frequencies, etc.) are similar to those of Table I. Hence from an EMC/EMI viewpoint, the MMW seeker from characteristics of concern should be similar to those other MMW radars.

It is difficult to identify in detail the specific interference characteristics of any given MMW radar system. However, some insight into the potential EMC/EMI characteristics of MMW radars can be gained from Figure 2 and Table I. Note from Figure 2 that the configuration of a MMW radar is essentially the same as its lower frequency counterpart (i.e. transmitter, duplexer, superheterodyne receiver, etc.). Hence, in terms of the basic configuration, there should be no significant differences in EMC/EMI problems between low frequency and MMW radar systems. On the other hand, Table I indicates that differences in design parameters between MMW radars and lower frequency types may influence specific EMC/EMI data requirements. First, note that at the present time the transmit power level is generally quite low compared to lower frequency radars. This characteristic, in conjunction with the relatively high propagation/coupling loss at MMW frequencies, would tend to make current MMW transmitters relatively "poor" sources of electromagnetic interference. Second, note that the operating bandwidths (transmit, receive, IF) of MMW systems are relatively broad, which may increase the potential of MMW systems as sources or receptors of interference. Third, note that MMW radars employ very high gain antennas (the antenna is usually designed as an integral part of the system) and waveguide transmission lines, which are similar to the characteristics of many lower frequency radar systems. Finally, note that MMW mixers are highly sensitive components and are probably more sensitive to burnout than lower frequency mixers.

Other MMW radar EMC/EMI characteristics may exist which are unique to particular systems. For example, MMW radars which require phase locked sources for coherent detection may represent an EMC/EMI sensitive area. Undesired energy coupled into the system could break phase lock and, hence, prevent system operation. MMW monopulse radars which utilize additional IF channels for the difference signals and a signal processor to form monopulse error control voltages may be particularly susceptible to erroneous signals. In conical scan radars, the guidance signals are resolved after synchronous detection of the conscan modulation component on the return signal. Antenna coupled EMI, offset in frequency by the conscan frequency, i.e., $f_o + f_m$, is a potential problem. Also, line coupled interference at the IF or conscan frequency may preempt system operation. Note that these types of interference

Table I

GEORGIA TECH MMW RADAR DATA SUMMARY

Item	Radar Group A	B	C	D	E	F	G	H
Type/ Designation	Instrumentation	Instrumentation	Instrumentation	Instrumentation	Surveillance	Fire Control	Beam Rider	Beam Rider
Transmit Power	3W (peak)	1 kW	1 kW	6 kW	500W (Peak)	60W	1.5 kW	250W
Transmit Frequencies	35.24 GHz	95.5 GHz	95.5 GHz	35.0 ± 300 MHz	69 - 71 GHz	225 Gc	94 GHz	140 GHz
Transmit Bandwidths	500 MHz	300 MHz	100 MHz	20 MHz	50 MHz	10 MHz	10 MHz	50 MHz
Transmitter Type	MOPA*	EIO	Magnetron	Magnetron		EIO	EIO	EIO
Receive Frequencies	35.5 - 34.5	94.5 - 96.5 GHz	94.5 - 96.5 GHz	34 - 36 GHz	69 - 71 GHz	225 Gc	94 GHz	140 GHz
Receive Bandwidths	10.00 MHz	2 GHz	2 GHz	2 GHz	100 MHz	100 MHz	100 MHz	100 MHz
Video Bandwidth	40 MHz	20 MHz	20 MHz	20 MHz	50 MHz	5 MHz	5 MHz	5 MHz
LO Frequencies	35.0 GHz	95.3 - 95.8 GHz	95.3 - 95.8 GHz	35.0 GHz	69.6 GHz	224.22 GHz	93.25 GHz	139.25 GHz
IF Frequencies	240 MHz	200 MHz	200 MHz	60 MHz	400 MHz	780 MHz	750 MHz	750 MHz
IF Bandwidths	160 MHz	160 MHz	160 MHz	20 MHz	60 MHz	100 MHz	100 MHz	100 MHz
Antenna Type	Cassegrain	Horn Lens	Cassegrain	Cassegrain	Parabolic Cylinder	Horned Lens	Conescan Cassegrain	Conescan Cassegrain
Antenna Polarization	Dual Linear	Dual Linear	Dual Linear	Dual Linear	Linear	Circular	Variable**	Variable
Output Waveguide	WR-28	WR-10	WR-10	WR-28	--	WR-5	WR-8	WR-8
Input Waveguide	WR-28	WR-10	WR-10	WR-28	--	WR-5	WR-8	WR-8
IF Co-Ax	--	--	--	--	--	RG141	RG141	RG141
Sensitive Components (Burnout Power Levels Estimated)	Mixer 0.3-0.5W	Mixer 0.2-0.5W	Mixer 0.2-0.5W	Mixer 0.3-0.5W	Mixer 0.2-0.4W	Mixer 0.1-0.3W	Mixer 0.3-0.4W	Mixer 0.2-0.3W

*GUNN Oscillator

**Vertical, horizontal, LHC, & RHC polarization

Table II

SURVEY OF MILLIMETER WAVE SEEKERS

Item	Seeker A	Seeker B	Seeker C	Seeker D	Seeker E
Transmit Power	60 mW	10 mW	15 mW	60 mW	60 mW
Transmit Frequencies	35 GHz	94 GHz	94 GHz	94 GHz	140 GHz
Transmit Bandwidths	800 MNz	200 MHz	200 MHz	200 MHz	500 MHz
Transmitter Type	Gunn Diode	Not Available	Not Available	Gunn Diode	Impatt
Receive Frequencies	50-650 MHz	"	"	Not Available	Not Available
Receive Bandwidths	600 MHz	"	"	"	"
IF Frequencies	85 MHz	"	"	"	"
Antenna Type	4.9" lens	Horn lens	Twist reflector	Lens with rotating feed	"

problems are also common to low frequency radar systems. The association of these type problems with a given radar system will depend upon specific knowledge of the functional operation of the system.

2.3.3 MMW Radiometers

A radiometer is a receiver of naturally generated electromagnetic (blackbody) radiation. Its output is a dc signal proportional to the radiometric temperature of the scene that is being viewed. A general block diagram is shown in Figure 3. Table III lists several Georgia Tech instrumentation radiometers with their principal operational parameters. As the table suggests, the majority of MMW radiometers are used at the atmospheric propagation windows. The frequencies 35, 95, 140, and 220 GHz are the most used windows; the 183 GHz radiometer operates on the water vapor absorption line and has been used to measure atmospheric moisture content.

MMW radiometers make use of the most sensitive, lowest noise figure components available. The most critical radiometer component is the front end mixer, which must exhibit a low noise figure and high sensitivity.

MMW radiometers may find tactical applications in battlefield surveillance, targeting, weapon guidance, or passive imaging. Since radiometers are inherently designed for wide RF bandwidths, MMW radars and communication equipments operating in the propagation windows could quite likely be a major source of interference for MMW radiometers. Both direct transmissions from radar sidelobes into radiometer sidelobes and from bistatic radar backscatter into radiometer main beams could be prominent interference mechanisms in certain deployment schemes. Radiometer design measures are commonly taken to reduce antenna sidelobe levels for improved mainbeam sensitivity. This practice may help reduce the susceptibility of radiometers.

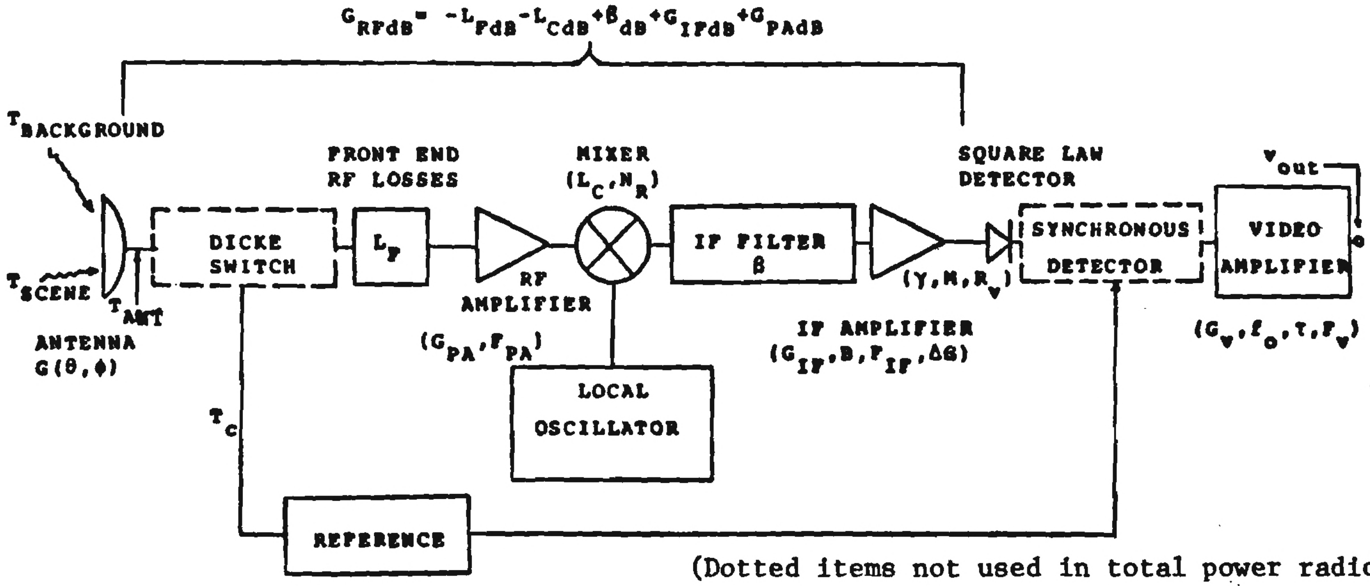
MMW radiometer configurations (and also configurations of MMW radar and communications equipment) may be divided into two categories with respect to MMW EMC/EMI considerations:

1) those with lens antennas and open optical paths within the main electronic enclosure, and

2) those with horn or dish antennas and only waveguide connections between the main electronic enclosure and the external environment.

Systems with open (unshielded) interior RF optical paths may admit undesired MMW radiation through the objective lens which would cause interference with sensitive internal MMW components. Inside the main electronic enclosure, high levels of extraneous MMW RF might conceivably couple to exposed mixer or detector bias leads and lead to interference.

For radiometers in Category 2, the horn and input waveguide offer an entrance path for RF. Frequencies below the waveguide cutoff frequency cannot reach the mixer, and frequencies above the RF pass band are not amplified (strongly) in the IF amplifier. Thus, radiation in the RF pass band which cannot be distinguished from the desired radiation is of prime concern.



(Dotted items not used in total power radiometer)

Figure 3. Generalized Radiometer Block Diagram [4].

Table III

SURVEY OF MMW RADIOMETERS

Item	Radiometer A	Radiometer B	Radiometer C	Radiometer D	Radiometer E
Type/ Designation	Total Power Imaging	Dual Frequency Imaging	Dual Frequency Imaging	Earth Surface Imaging	Earth Surface Imaging
Receive Frequencies	131-133 and 137-139 GHz	31-33 and 37-39 GHz	91-93, 97-99 GHz	89.325 ± .5 93.975 ± .5 GHz	181.05 ± .75 GHz 185.55 ± .75 GHz
Receive Bandwidths	2 GHz	4 GHz	4 GHz	1 GHz	1 GHz
Video Bandwidth	50 Hz	5 Hz	5 Hz	50 Hz	50 GHz
LO Frequencies	135 GHz	35 GHz	95 GHz	91.65 GHz	183.30 GHz
IF Frequencies	2-4 GHz	2-4 GHz	2-4 GHz	1.825-2.825 GHz	1.5 - 3 IF1 4 - 6 IF2 7.5 - 10 IF3 GHz
IF Bandwdiths	2 GHz	2 GHz	2 GHz	1 GHz	1 GHz
Antenna Type	Horn fed lens, 6" lens BW = 1°	Horn fed lens (Cassegrain)	Horn fed lens (Cassegrain)	Horn fed lens 2° at 94 GHz	6" LENS-90° WOBBLE PLATE REFLECTOR
Antenna Polarization	Linear	Dual	Dual	Single linear	Single Linear
Input Waveguide	WR8	WR 28	WR 10	WR 10	WR10
Output Co-Ax	BNC and RG 58	RG141	Semi-rigid	RG141	RG141
Sensitive Components (Burnout Power Levels, Estimated)	Mixer, 0.1-0.3W	Mixers 0.4W	Mixers, 0.3-0.4	Mixers 0.3-0.4	Mixer 0.1-0.3W

Because of their exceptional sensitivity, radiometers are usually designed with internal shielding for discrete components, with shielded bias wires, and with other measures to protect against both external and mutual intercomponent interference. However, in those cases of high power levels that may result from nearby radio or radar transmissions, interference may still occur.

2.3.4 MMW Communication Systems

MMW communication systems offer certain advantages for tactical line-of-sight application: (1) a low probability of intercept resulting from narrow antenna bandwidth; (2) reduced vulnerability to RF jamming, (3) compact physical size, (4) low power requirements, and (5) a very wide frequency spectrum available with low occupancy. Also, another means of achieving a low probability of intercept for short range tactical systems is to use a frequency that is highly attenuated (such as 60 GHz) in the atmosphere oxygen absorption line. Transmitted power density falls off so rapidly with distance that signals are undetectable by any receiver beyond some chosen range of tactical significance, usually in the order of a kilometer or so.

In the last several years, various types of MMW communication systems have been built for field testing and evaluation. Many of these are intended for use with high gain antennas, and all are roughly in the 100 mW transmit power range. Table IV is a survey of the parameters of representative MMW communications equipment. Note from this table that, in addition to superheterodyne receivers, receivers which operate on the homodyne principle are also employed. In a homodyne receiver, the local oscillator frequency is the same as the received frequency (the received signal is converted directly to baseband rather than to an IF frequency). Co-channel interference and receiver overload are prime EMC/EMI concerns for homodyne receivers, although spurious product formations may also occur.

MMW communications system configurations may be somewhat more varied than MMW radar or radiometer configurations. They may range from stationary base-to-base long range, high antenna gain systems to hand held binocular radios. Like MMW radars and radiometers, MMW communication systems may make use of open optical path structures in the front ends; thus extraneous MMW radiation of any frequency may enter the electronic enclosure through the objective lens.

A binocular radio described in a recent article 3 is typical of the state-of-the-art (1981) in MMW line-of-sight communication equipment technology. The system operates near the 60 GHz absorption band and utilizes a Gunn oscillator front-end, FM modulation, and millimeter wave integrated circuit (MMIC) fabrication technology. A block diagram of this system is shown in Figure 4.

MMW communication systems are often designed for data transmissions rather than voice. The inherent wide band IF's associated with high data rate communications systems may represent an EMI vulnerability problem for interfering signals in the IF bandwidth if adequate shielding and suppression are not provided.

While the basic operating principles and functional configurations of MMW communications systems are essentially the same as their lower frequency counterparts, the extremely wide bandwidths and frequency search modes

Table IV

SURVEY OF REPRESENTATIVE MMW COMMUNICATIONS EQUIPMENT

	Communications System Group			
Item	A	B	C	D
Type/ Designation	Base-to-Base	Base-to-Base	1 km Mobile	Binocular Radio
Transmit Power	~ 100 mW	~ 100 mW	60 mW	~ 10 mW
Transmit Frequencies	54-58 GHz	36-38.6 GHz	54.5 GHz	70 GHz
Transmitter Type	Gunn Diode	Gunn Diode	Gunn Diode	Gunn Diode
Receive Frequencies	54-58 GHz	36-38.6 GHz (5 channels)	54.5 GHz	70 GHz
Receive Bandwidths	Not Available	50 MHz	Not Available	150 kHz
Modulation Type	"	Not Available	"	FM
IF Frequencies	"	60 MHz	30 MHz	Not Available
Antenna Type	~ 35 dB gain dish	~ 35 dB dish	10 dB gain 360° azimuth omni*	2" lens
Antenna Polarization	Linear	Linear	Fan Beam	Linear
Sensitive Components (Burnout Power Levels, Estimated)	Mixer 0.3W	Mixer 0.3-0.4W	Mixer 0.3W	Mixer 0.2-0.3W

*Switchable to 30 dB gain vertical.

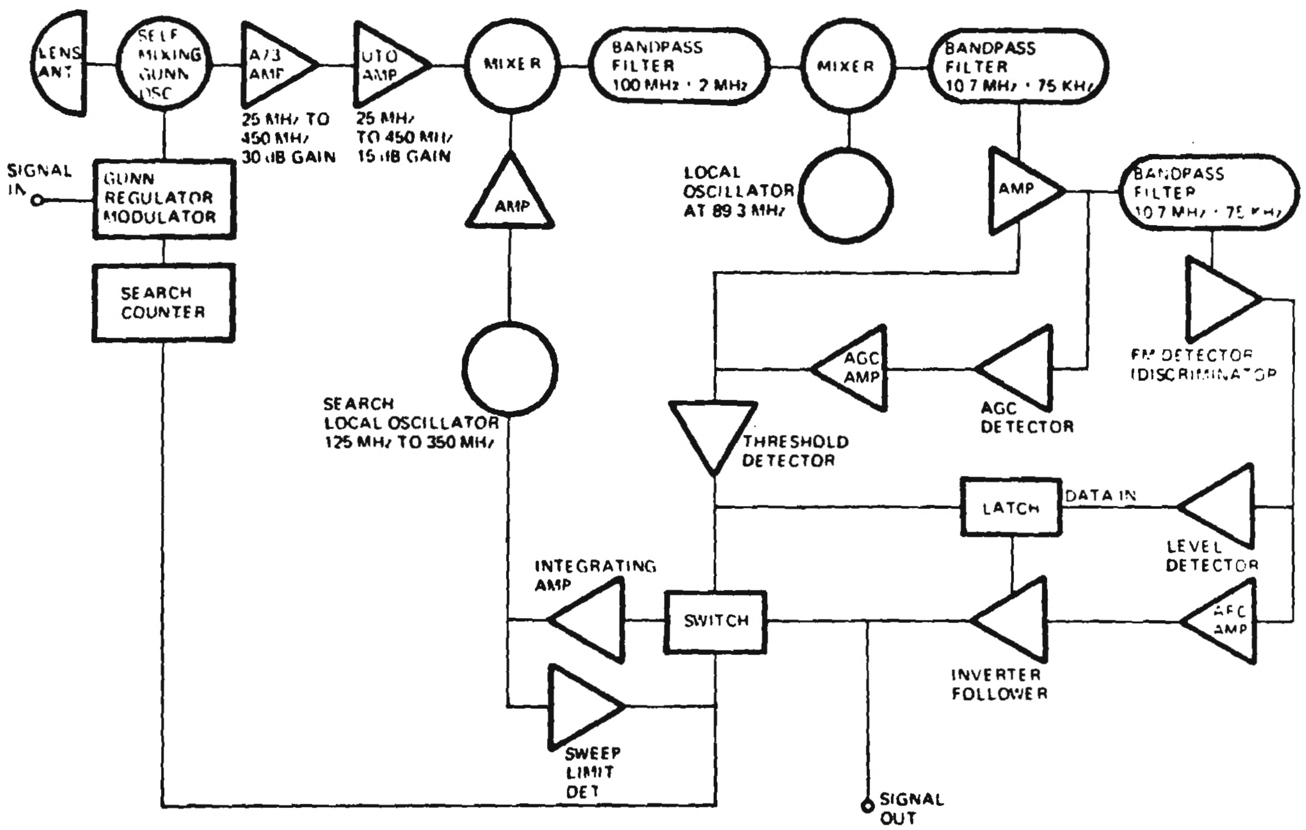


Figure 4. System Block Diagram for Analog Voice Communications [6].

required for their operation make them potentially more susceptible to interference. MMW communications systems utilizing open optical path structures in the front ends (which do not provide the waveguide-below-cutoff filtering characteristics of waveguide transmission lines) appear to be particularly susceptible to interference from lower frequency high power radar systems.

2.3.5 Component Performance/Quality

At the present time, very little information is available which provides a quantitative description of specific EMC/EMI characteristics of MMW components. However, it is expected that the quality of components in the MMW frequency band may influence the EMC/EMI characteristics of MMW systems. Typically, components in the 10-300 GHz range exhibit somewhat poorer performance than their lower frequency counterparts. This poorer performance is largely due to the fact that standard mechanical tolerances, even when closely held, represent increasingly large portions of a wavelength as frequency increases. Thus, it is likely that there will be a greater need for component EMC/EMI data for system assessments and tradeoff studies of emission and susceptibility limits than is currently required at the lower frequencies.

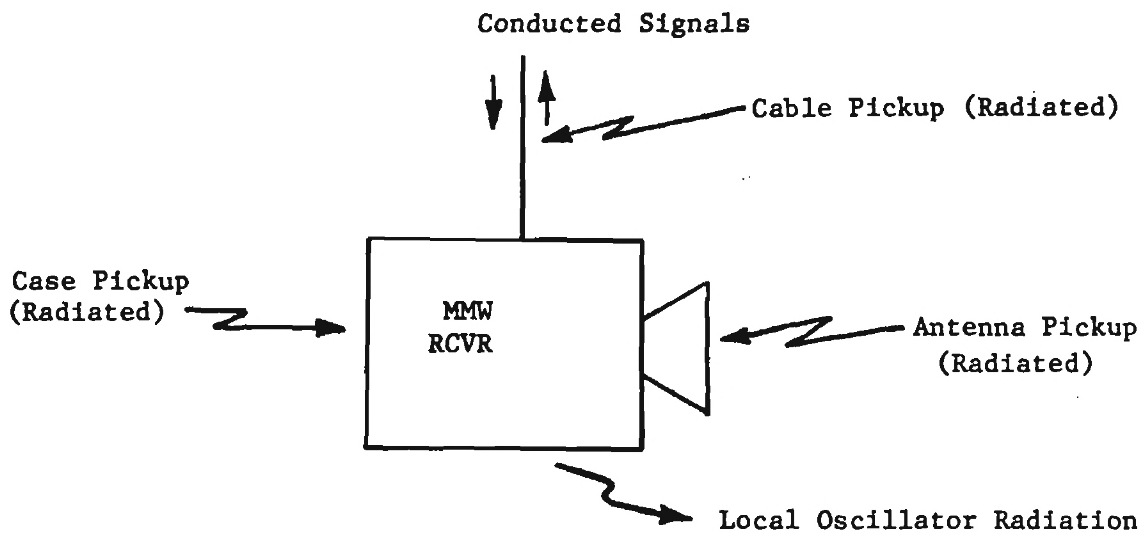
2.3.6 System EMI Potential

As discussed above, MMW equipments are designed and configured as transmitters and receivers for radar, radiometer, and communication system applications. Thus, it is reasonable to assume that the EMC/EMI parameters of concern for MMW systems will be similar to those of lower frequency transmitters and receivers.

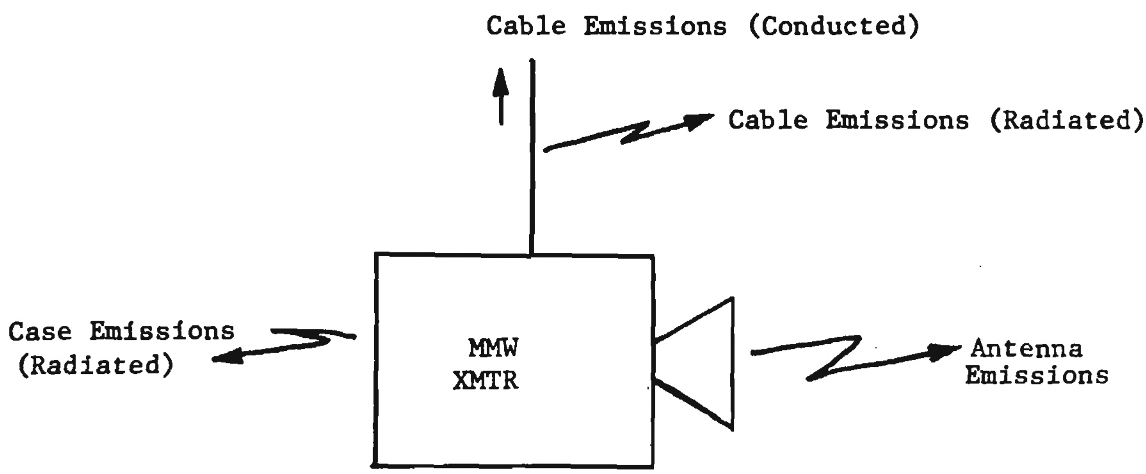
To illustrate the manner in which a MMW system may interact with its operating environment, consider Figure 5. Figure 5 (a) depicts a MMW receiver as a potential receptor of undesired signals whereas Figure 5 (b) depicts a MMW transmitter as a potential source of interference signals. Figure 5(a) shows that undesired signals may be coupled to a MMW receiver via three paths: (1) through the antenna, (2) by direct radiation through the receiver case, and (3) through receiver control leads, power leads, and other cables/wiring connected to the receiver.

Since current MMW receivers are of the same general design as lower frequency receivers, i.e., superheterodyne with RF, mixer, and IF stages (or possibly homodyne), interference problems experienced by a MMW receiver in a field environment should be similar to those experienced by low frequency receivers. Hence, for the typical MMW receiver, the need exists to define such receiver EMC/EMI parameters as sensitivity and selectivity, rejection of receiver spurious responses and intermodulation products, receiver desensitization, receiver dynamic range, and local oscillator radiation. To define these parameters, measurements will be required over the entire spectrum of concern (14 KHz - 300 GHz).

Figure 5 (b) shows that a MMW transmitter may act as a source of interference via three paths: (1) radiation from the antenna, (2) radiation through the transmitter case, and (3) via cables and control leads (conducted and/or radiated). The basic EMC/EMI parameters of concern will be similar to those of



(a) Illustration of MMW Receiver as Receptor/Source of EMI Signals



(b) Illustration of MMW Transmitter as Source of EMI Signals

Figure 5. Illustration of MMW Transmitter and Receiver EMC/EMI Considerations.

low frequency transmitters, except that the parameters must be defined over the 14 KHz -300 GHz frequency range. Such parameters will include transmitter power output, spurious and harmonic outputs, emission bandwidth, and carrier frequency stability. The last two parameters are of particular concern for MMW transmitters since large emission bandwidths can be expected and the frequency stability of MMW sources may be relatively poor.

Since no data are available which describes the specific EMC/EMI characteristics and parameters of MMW transmitters and receivers, the above concepts of potential MMW system EMI/EMC problems and parameters are based largely on the experience which has been gained on lower frequency systems and on current MMW system characteristics. The validation of these concepts will depend upon the development of adequate measurement instrumentation and techniques for performing EMC/EMI measurements at MMW frequencies and the conduct of measurements on representative samples of MMW transmitters and receivers. It is also important to recognize that as the state-of-the-art in MMW technology advances, new and different EMI problems may evolve which will dictate changes or additions to these concepts.

2.4 Frequency Considerations

2.4.1 Propagation Loss

The number of radar, communications, and seeker systems operating in the MMW spectrum (30-300 GHz) is rapidly growing because of the increased antenna spatial resolution relative to their microwave system counterparts. Since MMW system performance is affected by atmospheric transparency, most operate in "windows" between the absorption peaks. However, a number of communications and satellite-to-satellite systems operate near the absorption peaks for security reasons.

In the MMW region, the atmospheric transmission at sea level is dictated by oxygen molecule absorption and by water vapor absorption. The total atmospheric absorptivity, taken as the sum of these two components, is plotted in Figure 6.

In establishing free-space field strengths for possible MMW interfering signals, the atmospheric absorption in addition to the free space loss must be taken into account. For instance, Figure 7 illustrates relative power density versus distance from an emitter when operating at the 35 GHz or 94 GHz "windows," at the 60 GHz oxygen absorption band, or at the 183 GHz water vapor absorption bands. These large atmospheric losses define a major difference between MMW and microwave system operation. Because of these losses, the likelihood of MMW systems acting as sources of interference, or being adversely affected by other MMW systems, is relatively low in these absorption bands.

Attenuation of MMW by foliage is another important issue relating to MMW EMC/EMI when the equipment under consideration is intended for field deployment in foliated areas. Figure 8 shows a plot of foliage attenuation as a function of frequency. These data indicate the rapid increase in RF attenuation with increasing frequency between X-band and 100 GHz.

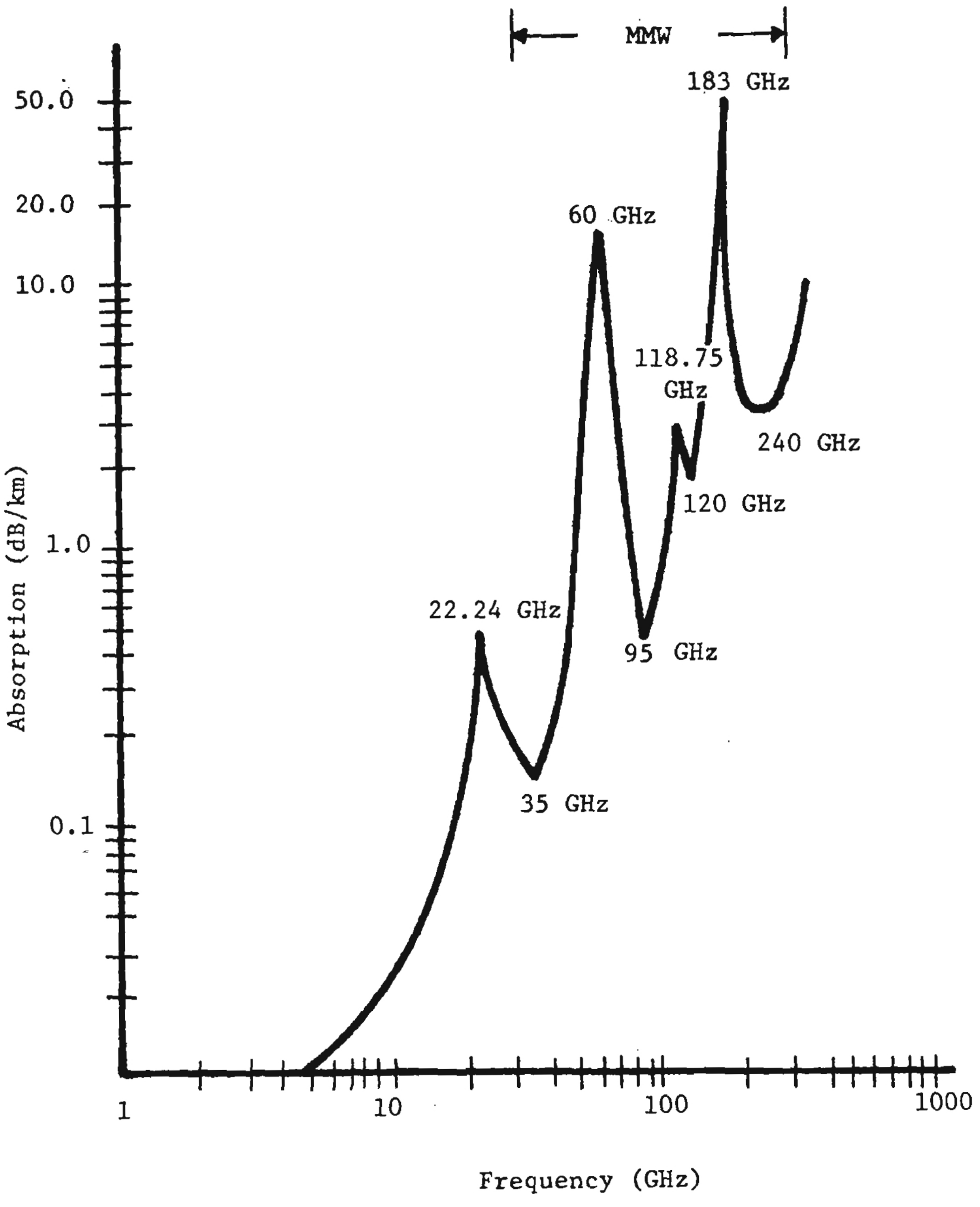


Figure 6. Total Sea Level Atmospheric Absorption. [15].

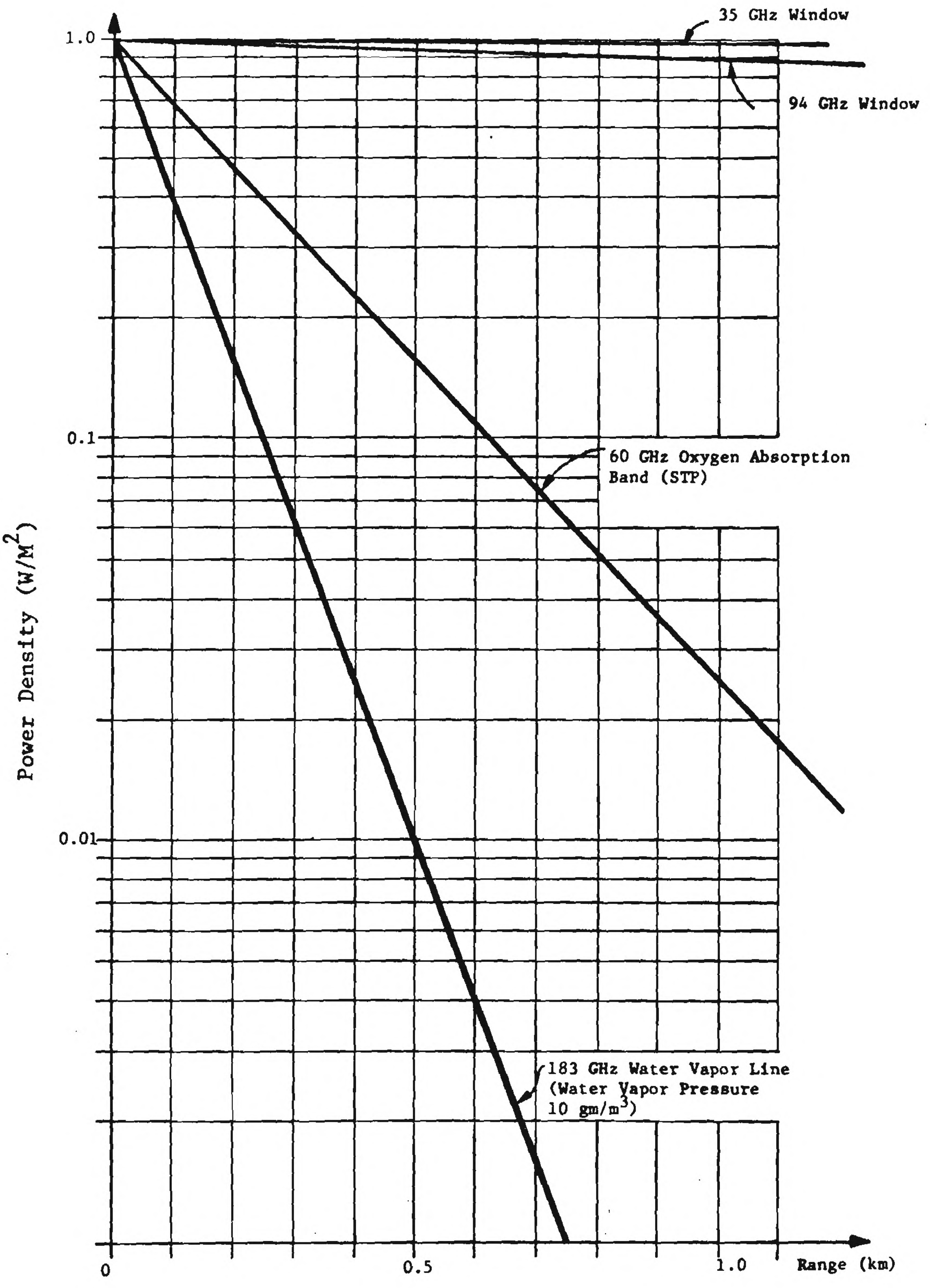


Figure 7. Relative Power Density of 35, 60, 94, and 183 GHz Wavebands Versus Distance (does not include free space loss).

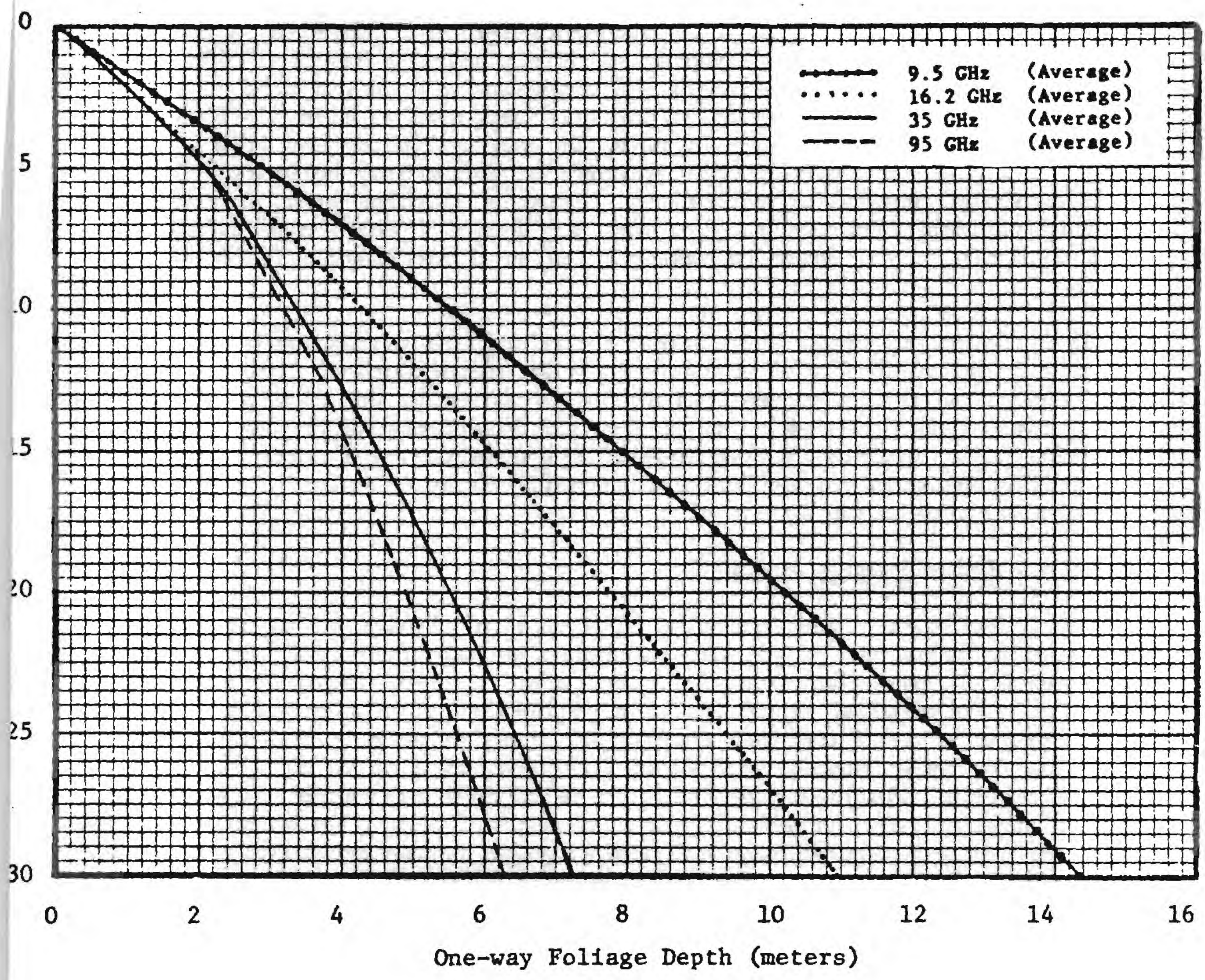


Figure 8. Total Attenuation as a Function of one-way Foliage Depth as Determined by the two-way Experiment [11].

2.4.2 Cable Coupling

Due to the fact that skin depths at MMW frequencies are very small, the coupling and propagation of MMW signals on typical power, signal, and control leads will not occur in the traditional sense. Thus, it is anticipated that EMI problems arising from signal coupling to lines and cables will be less pronounced at MMW frequencies than at lower frequencies. However, the potential for interference to MMW systems when exposed to incident fields cannot be neglected. The coupling of low frequency undesired signals will be no different for MMW systems than for lower frequency systems. Moreover, at MMW frequencies, coupling in the form of a surface wave propagating on dielectric cover cables or wires may occur. This phenomena does not readily occur at the lower microwave frequencies, but may predominate in the MMW region where dielectric thickness on wires is an appreciable portion of a wavelength. As a result of this mechanism, strongly coupled surface waves may propagate on signal, power, or control leads into a shielded box, thus compromising shielding effectiveness. It may be that RFI type feed-thru capacitors, while effective at lower frequencies, may not be effective at MMW frequencies.

The results of an experiment described in Appendix A indicate that surface waves may be a significant EMC/EMI factor at MMW frequencies. However, sufficient information is not presently available to ascertain the EMC/EMI impact of surface wave phenomena, and further studies are needed to define their influence on the interference potential of MMW systems. For this reason, specific EMC/EMI measurement and data requirements related to surface wave phenomena are not addressed in this report.

2.4.3 Reflections and Multipath

Reflections and multipath may present EMC/EMI related problems at MMW frequencies which may complicate measurement techniques and assessments of system/environment interactions. Field operation of transmitters and receivers may be affected by RF reflections from objects such as trees, buildings, terrain obstacles, and vehicles. Many of these objects are more reflective at MMW frequencies than at lower frequencies because their dimensions in terms of wavelength are much larger at MMW frequencies. The reflectivity of objects is also influenced by the polarization, angle-of-incidence, and angle of reflection of the RF signals, as well as by the surface properties of the reflecting objects. In general, the reflectivity of objects increases with frequency. Consequently, mutual interference may take place when reflected signals from one MMW system are incident on another MMW system.

To determine the EMC characteristics of MMW equipments, emission and susceptibility measurements will be required. At lower frequencies these measurements are often performed in an anechoic enclosure. The extrapolation of these anechoic chamber measurement techniques directly to MMW applications will require appropriate absorptive materials for lining the test enclosure. Most absorber materials provide a reflectivity on the order of -40 dB or less when operated at MMW. For corresponding lower frequency microwave absorbers, reflectivity on the order of -50 to -60 dB is readily achievable.

An example of the performance of commercially available materials is the data obtained from the technical literature of Emerson Cuming Pyramidal

Absorber performance at 94 GHz. These data are shown in Figure 9. At Georgia Tech, samples of EHP type absorber obtained from Rantec, Inc. were tested at 140 GHz. A reflectivity level of -40 dB was measured, which is in good agreement with the data observed on the Emerson Cuming materials. Little information was found which describes the performance of absorber material from other manufacturers, or for higher MMW frequencies.

2.4.4 Low Frequency/MMW System Compatibility

It is important to note that since many MMW systems use microwave IF frequencies, interference to MMW equipment from microwave transmissions could be significant. From Tables I-IV, it is seen that MMW systems use IF's ranging from 60 MHz to as high as 10 GHz, with IF bandwidths ranging from around 20 MHz to 6 GHz. Thus, any RF emissions within these bands may serve as interference sources for certain MMW systems.

Even if no direct frequency relationship exists between an interference signal and a victim equipment, a MMW system may experience degradation when exposed to low frequency, high level, RF fields. The possibility of interference is enhanced if the system contains solid-state or integrated circuit devices. Low power, low-signal-level, solid-state devices are generally more susceptible to interference than are their tube-type counterparts. A mitigating factor is the tendency of solid state systems to become less susceptible to high power interference effects with increasing frequency.

2.5 Antenna Characteristics

Antennas used in the millimeter spectrum may be identical in form to those used in the optical portion of the electromagnetic spectrum, i.e., consisting of lenses and mirrors; but the materials used for fabrication of these elements may be different. Lenses are generally made of plastics such as Rexolite, TPX, or Teflon and mirrors are made of high-reflectivity metals such as are used for optical mirrors. Antenna feeds are usually conical or pyramidal horns, except at the shorter wavelengths where direct focusing of radiation is a practical approach to avoiding waveguide losses.

Reflecting antennas for millimeter systems may take the same variety of configurations as has been devised for optical telescopes including Newtonian, Cassegrain, Gregorian, and variations of these types. The secondary mirror of such a reflecting telescope is usually driven with a feed horn.

Horn antennas may be used as feeds for both lens and mirror antenna systems up to a frequency of about 300 GHz. Corrugated horns have been devised which have minimum side lobes in this range of frequencies. Beyond 300 GHz, sources consist mainly of optically pumped or electric discharge pumped lasers, which use partially reflecting mirrors for output coupling.

With respect to EMC/EMI, two characteristics of MMW antennas are of primary concern. First, in contrast to lower frequency systems, MMW antennas are usually designed as an integral part of a system, and, with a few exceptions, are not interchangable. Thus it is unlikely that the antenna will be changed once the system is placed in operation. For this reason, less emphasis needs to be placed on measurements of the EMC/EMI characteristics of individual antennas,

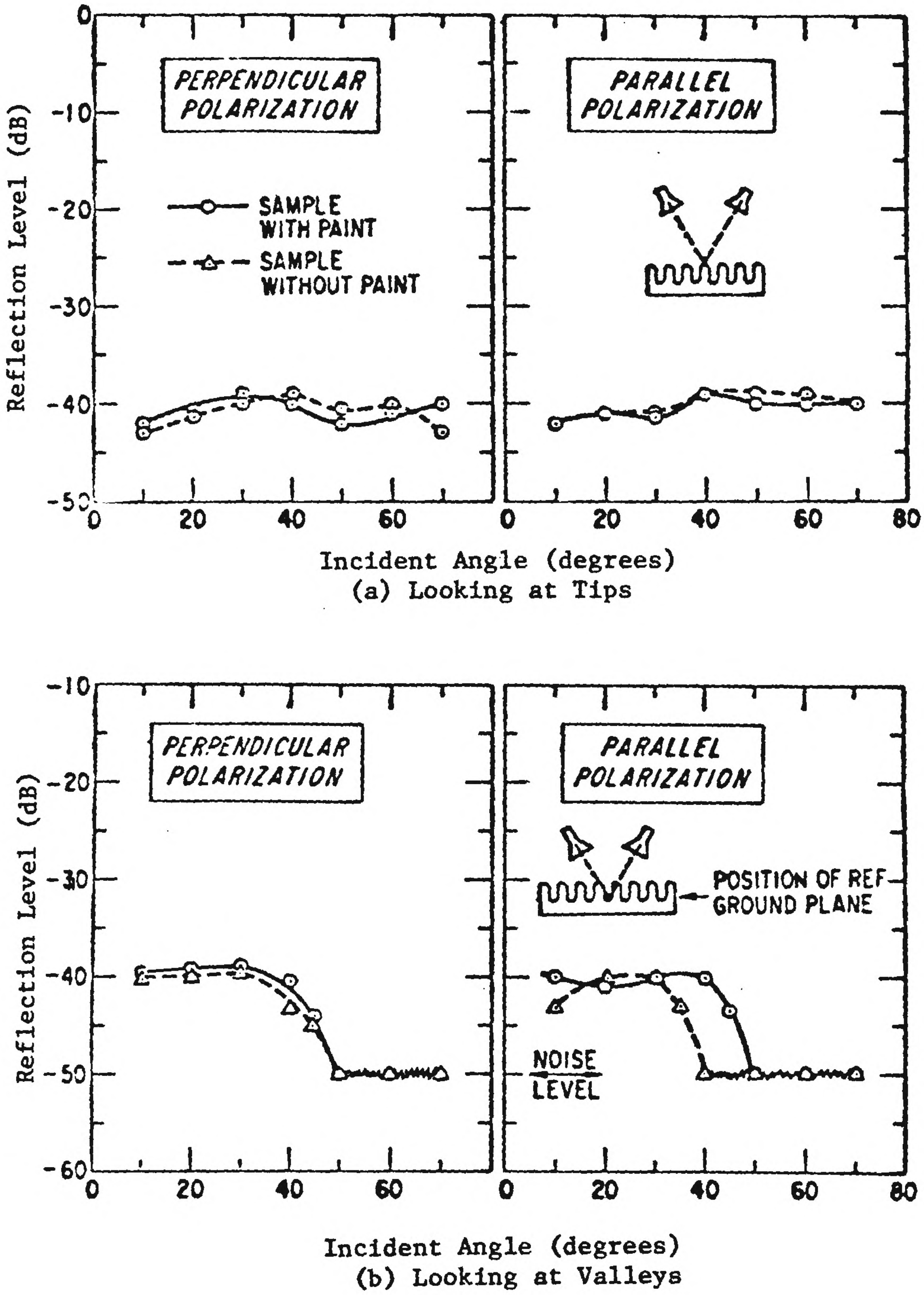


Figure 9. Emerson Cuming CV-4 Pyrimidal Absorber Performance at 94 GHz [17].

except perhaps to establish the relative performance of different antennas. Of primary concern are the EMC/EMI characteristics of the system/antenna combination, i.e., transmitter/antenna or receiver/antenna.

Second, most MMW antennas are characterized by high gains and narrow beamwidths. To predict and/or resolve potential field EMC/EMI problems may require that the "directivity" of transmitter emissions or receiver responses be accurately described. Thus, greater attention must be paid to the accuracy requirements of EMC/EMI measurements performed on MMW systems.

3.0 BASIC MMW EMC/EMI DATA REQUIREMENTS

3.1 General

From the EMC/EMI considerations for MMW systems presented in Section 2, some tentative conclusions can be drawn regarding the basic data requirements for MMW systems. These tentative conclusions are outlined below.

1. When a given MMW system is deployed, the potential for interference to, or caused by, the system will depend upon the operating environment. Whereas a particular system may operate "interference-free" in one environment, the same system may experience significant EMI problems in a different environment. Furthermore, the electromagnetic compatibility of different systems may vary even when operated in the same environment. Thus, in general, EMC/EMI data requirements for MMW systems cannot be limited to specific systems or specific environments. Data must be available which will permit the interference potential of any system/environment to be addressed.

2. The general EMC/EMI concerns for MMW systems are identical to those for lower frequency systems; i.e., (1) will the system act as a source of interference via emissions from the antenna, case, or interconnected cables, or (2) will the system be affected by incident signals which may enter via the antenna, case, or interconnected cables?

3. Although the specific characteristics of MMW components may differ from their lower frequency counterparts, the general configuration of MMW transmitter and receiver circuitry is essentially the same as the configuration of lower frequency systems. It would thus be expected that the generic types of MMW system EMC/EMI problems will be similar to those which have historically been experienced on lower frequency systems.

4. MMW antenna characteristics and configurations may influence EMC/EMI data requirements in two respects. One is that the antenna will typically be designed and configured as an integral part of the system. Thus radiated emission and susceptibility measurements performed on the system-antenna configuration may be more appropriate than conducted emission and susceptibility measurements at the antenna terminal. Another is that the highly directive nature of most MMW antennas may require that particular attention be given to the accuracy of antenna pattern measurements.

5. The relatively large bandwidths (transmit, receiver, IF) of MMW systems may increase the potential of MMW systems as sources or receptors of interference.

6. The EMC/EMI performance of MMW components may be poorer than lower frequency components, which could give rise to EMC/EMI problems heretofore not encountered. There may be a greater need for component EMC/EMI data to perform system EMC/EMI assessments than is currently required at lower frequencies.

7. Because of such factors as propagation and coupling loss and source power capabilities, MMW systems are not as likely to be a cause of interference as are lower frequency systems (this does not imply, however, that the emission characteristics of MMW systems can be neglected). On the other hand, MMW systems may be susceptible to signals other than those at MMW frequencies. In fact, it is likely that lower frequencies may be more of a problem to MMW systems than those frequencies in the MMW spectrum. Thus, data which defines the compatibility of low frequency/MMW systems must be obtained.

8. At MMW frequencies, such factors as propagation loss, coupling loss, and reflections will have a significant influence on interactions between different MMW systems and between MMW systems and other type systems in the environment. A knowledge of these factors is thus highly important to the prediction of field EMI problems and to the "tailoring" of a MMW system to a given environment. However, they will not significantly influence the overall EMC/EMI design requirements for MMW systems since these requirements will be dictated by specifications which are generally independent of any given environment.

9. With the exception of cable conducted emission and susceptibility data, all EMC/EMI data on MMW transmitters and receivers should be derived from radiated measurements. Thus no conducted antenna terminal measurements on transmitters and receivers are indicated at this time, nor are individual antenna measurements likely to be necessary except to establish the relative performance between antennas. This approach is recommended for three reasons. One reason is that radiated EMC/EMI measurements of a system including the antenna should more closely approximate the performance of a system in an actual operating environment. A second reason is that the majority of MMW system designs will include the antenna, and the utilization of different antennas with a given system will be unlikely. The third reason is that radiated measurements should require simpler measurement techniques than conducted measurement over the MMW frequency range. (This is generally not true at lower frequencies where large antenna sizes make radiated measurements difficult).

10. The EMC/EMI data required for MMW receivers can generally be classified as (1) radiated susceptibility data, (2) conducted susceptibility data on each lead/cable connected to the receiver, (3) radiated emission data at the receiver local oscillator (and any other internal source) frequencies, and (4) conducted emission data on each lead/cable connected to the receiver. These data should generally encompass the frequency spectrum of concern, i.e., 14 KHz to 300 GHz. However, the requirements can be further defined based on EMC/EMI experience with low frequency receivers and on anticipated receiver interference characteristics at MMW frequencies.

11. The EMC/EMI data required for transmitters must address emissions from three paths: (1) radiation from the antenna, (2) radiation through the receiver case, and (3) via cables and control leads (conducted and/or radiated). These requirements will generally lead to two basic types of measurements: radiated emission measurements (from case, antenna, and connecting wiring) covering the 14 KHz - 300 GHz spectrum, and conducted emission measurements on cables and wiring at lower frequencies.

12. It is unlikely that signals at MMW frequencies will be coupled to, or conducted along, wiring/cabling connected to the receiver. Thus, it will not be necessary to collect cable conducted susceptibility or emission data over the total 14 KHz - 300 GHz spectrum. Current MIL-STD-461 frequency limits will probably be applicable.

13. Since many MMW receivers use microwave IF frequencies, interference to MMW receivers from microwave transmissions could be significant. Thus, when performing radiated and conducted susceptibility measurements on MMW receivers, emphasis should be given to measurements of receiver susceptibility to signals which fall at the receiver IF frequencies. Note that if the receiver IF frequency falls below the upper frequency limit for cable conducted susceptibility measurements, data which describes the receiver susceptibility to both radiated and conducted signals (at the receiver IF frequencies) can be obtained. If the receiver IF frequencies fall above the limit, only radiated susceptibility measurements will be feasible. However, radiated susceptibility data are considered the most meaningful since these type data will more closely reflect actual interference conditions in an operating environment.

14. Although the need for conducted emission and susceptibility data on wiring and cabling has existed for some time, difficulty has been experienced in implementing a practical measurement technique for obtaining these type data, even for low frequency systems. To circumvent this measurement problem, the approach normally taken is to "tailor" interconnected equipments to prevent conducted interference. Thus, prior to finalizing conducted emission and susceptibility data requirements for MMW systems, further consideration will have to be given to measurement techniques for performing these type measurements.

The above conclusions, although tentative, indicate that while the specific EMC/EMI parameters or characteristics of MMW systems may differ from those of lower frequency systems the overall nature of EMC/EMI problems projected for MMW systems is not significantly different from that which has been historically experienced. For this reason, it is felt that with appropriate modifications, current data requirements for lower frequency systems will also be applicable to MMW systems. Basically, the required modifications will involved the manner in which the data are to be measured and utilized, i.e., for MMW systems, emphasis will be given to radiated rather than conducted measurements, and to specific MMW system design parameters (antenna characteristics, IF amplifier frequencies, etc.) which are significantly different from low frequency systems from an EMC/EMI viewpoint. The modifications will also be influenced by deployment considerations where such factors as propagation and coupling loss will strongly dictate system/environment interactions.

The following paragraphs outline the generic types of data required to establish the EMC/EMI characteristics of MMW systems over the frequency range of 10 to 300 GHz.

3.2 Emission Data

In order to minimize the possibility that a MMW system or subsystem acts as a source of interference, the system or subsystem emission characteristics must be determined. There are three sources of emissions: cable conducted emissions, case radiated emissions, and antenna terminal radiated emissions.

3.2.1 Cable Conducted Emissions

Due to the presence of low frequencies in power supplies, modulators, detectors, etc. in MMW systems, conducted emission tests will be required for MMW equipment. MIL-STD-461 presently requires conducted emission tests to be performed on cables up to 50 MHz. Conducted emission measurements should be performed on the power leads, control leads, signals leads, and interconnecting cables of the MMW system.

3.2.2 Radiated Emissions (Case/Antenna)

Emissions from equipment enclosures may become an increasing problem as MMW system power capabilities increase. Also, leakage from seams and apertures in equipment enclosures becomes a more significant problem for MMW systems because of the extremely short wavelengths of MMW frequencies. The present requirements of MIL-STD-461 for radiated emissions of electric and magnetic fields emanating from cables and equipment enclosures are applicable to MMW systems.

MIL-STD-461 and MIL-STD-469 presently require a number of antenna terminal radiated emission measurements, most of which are performed in a conducted mode. It is recommended (see section 3.1) that all MMW system antenna terminal emission measurements be performed in a radiated mode, i.e., be performed on a transmitter-antenna or receiver-antenna configuration.

Radiated emission measurements (electric field) should be extended to encompass the 10-300 GHz frequency range.

3.2.2.1 Transmitters

Transmitter emission measurements should include measurements of spurious and harmonic outputs, emission bandwidth, frequency tolerance, and power output level.

Spurious and Harmonic Outputs: The spurious and harmonic output test involves a determination of the power versus frequency characteristics of the transmitter, with the exception of that part of the spectrum covered by the necessary emission bandwidth.

Emission Bandwidth: The emission bandwidth test measures the bandwidth of the transmitter around the fundamental frequency. This bandwidth should only be wide enough to accommodate the necessary modulation sidebands but no wider in order to suppress the transmission of spurious outputs.

Frequency Tolerance: The frequency tolerance test determines the frequency stability of the transmitter under test, thus providing a reliable method of determining frequency and equipment assignment.

Power Output Level: The power output test measures the maximum output power of a transmitter throughout the transmitter's frequency coverage.

3.2.2.2 Receivers

Receivers must be tested for undesired radiation from the receiver local oscillator.

Local Oscillator Radiation: The receiver may act as a transmitter by radiating from its antenna or case energy generated by the receiver's local oscillator and other frequency-producing circuits. This energy could be a potential source of interference to surrounding equipment. The local oscillator test measures the energy radiated out of the receiver's antenna or case.

3.3 Susceptibility Data

The susceptibility characteristics of a MMW system or subsystem must be determined in order to minimize the possibility of interference to the system. Susceptibility measurements of concern include: cable conducted susceptibility, case radiated susceptibility, and antenna terminal radiated susceptibility.

3.3.1 Cable Conducted Susceptibility

Due to the extremely short wavelength of MMW frequencies, millimeter waves are not readily coupled to cables. Thus, cable conducted susceptibility testing at millimeter wave frequencies is not of prime concern; however, the present powerline susceptibility test requirements of MIL-STD-461 should be performed to verify interference-free operation of the system with typical power sources. The upper frequency limit of these powerline conducted susceptibility test presently stands at 400 MHz. The conducted susceptibility test, covering the same frequency range as the powerline susceptibility test, also needs to be performed on signal leads, control leads, and interconnecting cables of MMW systems.

3.3.2 Radiated Susceptibility (Case/Antenna)

The case radiated susceptibility test determines the susceptibility of an equipment to radiated fields which can couple into the equipment's circuitry by means other than the equipment's antenna terminal; in particular, energy radiated into the equipment's enclosure through seams and apertures, or energy coupled to exterior cables and conducted into the equipment enclosure. The present requirements of MIL-STD-461 are applicable and should be performed on all MMW equipment.

MIL-STD-461 and MIL-STD-469 require a number of antenna terminal susceptibility measurements, most of which are performed ina conducted mode. It is recommended (see section 3.1) that all MMW system antenna terminal susceptibility measurements be performed in a radiated mode.

Radiated susceptibility measurements should be extended to encompass the 10-300 GHz frequency range.

3.3.3.2 Receivers

Receiver susceptibility measurements should include measurements of spurious responses, intermodulation, sensitivity, selectivity, desensitization, dynamic range, and squelch.

Spurious Responses: The spurious response test determines the receiver's response characteristics to frequencies outside its pass band. Spurious responses are due to internal frequencies combining with an external signal in such a manner to cause a response. The level of these responses indicates the ability of the receiver to discriminate against off-channel signals. The frequency range for this test which is applicable to MMW receivers is from 0.8 f_{co}(where f_{co} is the waveguide cutoff frequency) to 300 GHz.

Intermodulation: Intermodulation characteristics are indications of the interference potential when the receiver is used in the presence of multiple off-channel signals. These signals may mix in the r-f amplifier or the first mixer circuit. If one of the extraneous signals generated in this manner falls at the receiver's tuned frequency and is of sufficient amplitude, intermodulation interference is the result. MMW receivers should be tested for intermodulation products from 0.8 f_{co} up to 300 GHz.

Desensitization: The desensitization test is a measure of the receiver's ability to function despite the presence of on-channel interference. Desensitization measurements are divided into two tests: pulsed desensitization and continuous wave desensitization. The pulsed desensitization test is indicative of the receiver's recovery characteristics following an interfering signal. The continuous wave (CW) test measures the sensitivity of a receiver in the presence of on-frequency CW interfering signals; thus, this test is a measure of the receivers ability to perform its normal function despite the interference caused by the CW signal. This test is of particular importance since it is a measure of the receiver's susceptibility to enemy jamming.

Sensitivity: The sensitivity test determines the weakest signal that can be received to produce a response at the output of the receiver. This test should be performed at several frequencies throughout the receiver's frequency coverage since the sensitivity may vary with frequency.

Selectivity: The selectivity test gives an indication of the overall gain and sensitivity at the receiver's center tuned frequency as well as the response at frequencies slightly removed from the tuned frequency. The selectivity is a measure of the receiver's ability to discriminate against off-channel signals, and in reality is a measure of the receiver's effective bandpass characteristics.

Dynamic Range: The dynamic range test measures the effectiveness of the AVC or AGC system, if one exists, and describes the receiver's linearity between the minimum response level and limiting level.

Squelch: MMW equipment utilizing squelch circuits should be tested to determine whether the circuit characteristics are adequate so as to prevent the opening of the circuit on impulse signals.

3.3.2.2 Transmitters

Transmitters may be susceptible to external energy which is coupled into the transmitter output stage. The coupled energy can cause intermodulation products which act as a source of radiated interference.

Intermodulation: MMW transmitters should be tested to evaluate the intermodulation generating properties of the output stage. The level of intermodulation products obtained when an external signal is coupled into a transmitter output circuit depends on the selectivity of the coupling circuit, the level of interfering signal, and the non-linearity of the output stage.

3.4 Antenna Characteristics

Most MMW systems are designed such that the antenna and transmission line (waveguide) are integral parts of the systems. For these systems, the antenna terminal emissions and susceptibility data should include the effects of the antenna and transmission line on the interference coupling characteristics.

Some MMW systems are designed such that they may be operated with either one of two or three different antennas. For these systems, the antenna terminal emissions and susceptibility data should include the effects of the transmission line and each of the supplied antennas on the interference coupling characteristics.

For MMW antennas that are not an integral part of a system and/or may be used with a number of different systems, the data requirements to define the EMC/EMI characteristics of these antennas are essentially the same as the data requirements for lower frequency antennas and include gain, pattern, and polarization data. The data requirements are similar to the requirements specified in MIL-STD-449 and MIL-STD-469.

Antenna designers are normally concerned about the performance characteristics of an antenna over the frequency range in which it is designed to operate, but there is little or no concern for the performance characteristics outside this frequency range. However, in determining the EMC/EMI characteristics of an antenna, the out-of-band characteristics are usually more important than the in-band characteristics. Since the out-of-band characteristics are normally not measured during the performance tests, they must be measured as part of the EMC/EMI tests.

Antenna gain, pattern, and polarization data are needed to define the EMC/EMI characteristics of an antenna. The EMC/EMI characteristics of antennas must be included in establishing the emission and susceptibility levels at the antenna terminals of equipments. In addition, antenna gain, pattern, and polarization data are extremely useful in siting collocated equipment for minimum interference.

3.4.1 Antenna Gain Characteristics

Theoretically, the gain characteristics of an antenna should be defined over the total frequency range within which interfering signals may be encountered. However, if the antenna is to be used with a waveguide transmission line, the waveguide will act as a high-pass filter and there is no need measuring the gain of the antenna below the cut-off frequency of the waveguide. For transmitting antennas, special attention needs to be given to defining the antenna gain at harmonic frequencies of the transmitter. For receiving antennas, the antenna gain needs to be defined at all frequencies above the waveguide cut-off frequency where radiated interference susceptibilities may be anticipated. The antenna gain data requirements dictate that a capability exist to make antenna gain measurements over the 10 to 300 GHz frequency range.

3.4.2 Antenna Pattern Characteristics

The antenna pattern characteristics of an antenna need to be defined over the total frequency range within which interfering signals may be encountered. Again, if the antenna is used with a waveguide transmission line, there is no need to measure the antenna pattern characteristics below the cut-off frequency of the waveguide. Antenna pattern measurements should be made at the same frequencies where antenna gain mesurements are made. For transmitting antennas, the antenna pattern characteristics define the spatial distribution of the power radiated from the antenna. The antenna pattern at the operating frequency of a transmitter provides several types of data including:

(1) The orientation and beamwidth of the main lobe,
(2) The orientations, relative levels, and beamwidths of the sidelobes, and
(3) The front-to-back ratio.

The antenna pattern characteristics at harmonic and other spurious frequencies may be drastically different than the pattern characteristics at the fundamental operating frequency.

For receiving antennas, the antenna pattern characteristics define the relative response of the antenna as a function of spatial orientation of an incident field. The pattern characteristics of receiving antennas provide the same types of data as the patterns of transmitting antennas and define the susceptibility characteristics of receiving antennas in the same manner that pattern characteristics define the emission characteristics of transmitting antennas.

The antenna pattern data requirements dictate that a measurement capability exist to make antenna pattern measurements over the 10 to 300 GHz frequency range.

3.4.3 Antenna Polarization Characteristics

The polarization characteristics of an antenna need to be defined over the total frequency range within which interfering signals may be encountered. If the antenna is used with a waveguide transmission line, there is no need to measure the polarization characteristics below the cut-off frequency of the waveguide. Polarization data should be obtained at the same frequencies where gain and pattern data are obtained. For transmitting antennas, the polarization characteristics define the polarization parameters of the fields radiated from the antennas. For receiving antennas, the polarization characteristics define the relative response of an antenna as a function of the polarization characteristics of an incident field.

4.0 MEASUREMENT PHILOSOPHY

The EMC/EMI data requirements for MMW systems can be divided into two categories: emission data and susceptibility data. The measurements necessary to obtain this data can be further divided into conducted type measurements and radiated type measurements. The basic measurement philosophies for these two types of measurements are discussed in this section.

Major emphasis for the remainder of this report will be given to radiated measurements with little emphasis being placed on conducted measurements. This approach is being taken for several reasons: (1) the major difference in the EMC/EMI data requirements for MMW systems as opposed to the data requirements for "low frequency" systems is that many of the antenna terminal type of measurements must be performed in a radiated mode rather than in a conducted mode, (2) conducted EMC/EMI problems will usually occur at frequencies well below the MMW frequency range, and (3) maximum use should be made of EMC/EMI test requirements and techniques which already exist and should also be applicable to MMW systems.

4.1 Conducted Measurement Philosophy

In an operational environment, it is likely that radiated interference will be a prime source of concern for MMW systems. However, even if a radiated interference environment did not exist, interference between two or more systems or subsystems could still occur via undesired signals conducted through interconnecting cables or through a common power source. Thus, conducted type EMC/EMI measurements on MMW systems will be required.

Conceptually, conducted EMC/EMI problems should be resolved on all system cabling and wiring over the frequency range of concern, e.g., dc to 300 GHz. Knowledge of the conducted emission and susceptibility characteristics of each cable and wire would then allow potential EMC/EMI problems to be identified and circumvented, either through design/test specification limits or through some form of remedial action.

Practical considerations indicate that the frequency range over which conducted EMC/EMI measurements should be performed can be limited significantly. For example, signal loss on a unit length of cable is generally inversely proportional to wavelength. Therefore, at MMW frequencies, the extremely short wavelengths cause high loss even on relatively short lengths of cable. Also, at MMW frequencies, skin effect losses become significant. Thus, it is not unreasonable to consider an upper frequency limit for conducted measurements which is far below the MMW frequency range. On the other hand, no data has been found which substantiate exactly what this upper frequency limit should be. Moreover, at MMW frequencies, it is possible that conducted interference phenomena may exist which have heretofore not been encountered, such as surface wave propagation which is concentrated within the dielectric covered conductors.

With the exception of surface wave phenomena at MMW frequencies, conducted EMC/EMI problems will likley occur at frequencies much lower than the MMW frequency range. It can thus be argued that the development of conducted EMC/EMI data requirements and measurement techniques should not be a concern of a "Millimeter Wave EMC/EMI Program" if such requirements and techniques already exist. Such an argument leads to the conclusion that current MIL-STD-461 test requirements should be applicable to MMW systems. This conclusion has merit in that maximum use should be made of test requirements and techniques which already exist and are accepted as standard practice. Since the basic measurement requirements and configurations for performing conducted emission and susceptibility type measurements on power leads, signal cables, and control leads are already documented in MIL-STD-461 they are not repeated here.

4.2 Radiated Measurement Philosophy

It is recommended that, with the exception of conducted measurements performed on system cabling, all EMC/EMI data should be derived from radiated measurements. This approach deviates from that employed for lower frequency systems, where a significant amount of EMC/EMI data are derived from conducted measurements at the system antenna terminals. A number of reasons exist for this difference in test philosophy for MMW systems. One reason is that, in contrast to lower frequency systems, most MMW systems will be configured with the transmitter/receiver and antenna as an integral unit. This configuration results from two factors: (1) the short wavelengths at MMW frequencies make it possible to obtain high antenna gain characteristics with small antenna structures which can readily be integrated into the equipment and (2) the high insertion losses encountered in transmission lines at MMW frequencies dictate that the length of the transmission line between equipment and antenna be made as short as possible. This integral equipment/antenna configuration requires that the antenna terminal emission and susceptibility characteristics of MMW equipment include the effects of the antenna and transmission line, which dictates the need for radiated type emission and susceptibility measurements. It is also important to note that where the transmitter/receiver and antenna are configured as an integral unit the antenna terminals may not be readily accessible for performing conducted measurements, even if these type measurements were desired.

Another consideration which supports the conclusion that antenna terminal emission and susceptibility measurements be made in a radiated mode involves the fact that MMW systems typically employ a waveguide transmission line between the transmitter/receiver and the antenna. At frequencies above the dominant mode of the waveguide, the energy may propagate in several different modes, and the accurate sampling of the energy in the transmission lines becomes an extremely difficult and complex process. The magnitude of the problem of accurately sampling a multi-moding transmission line is such that a conducted measurement technique is not considered feasible. Thus,for out-of-band (e.g. spurious emissions) measurements on MMW transmitters, it is not feasible to measure the levels of emissions at frequencies above the dominant mode of the transmission line on a conducted basis. In the same manner, the multi-moding transmission line presents a problem in performing out-of-band (e.g. spurious responses) measurements on MMW receivers at frequencies above the dominant mode of the transmission line. The difficulty of accurately injecting signals into a transmission line at multi-moding frequencies is such that a conducted measurement technique is not recommended. Also, even if data were available which described the system EMC/EMI characteristics at the antenna terminals, the data could not be effectively utilized unless the antenna characteristics (including the out-of-band characteristics) were known, which introduces another significant measurement problem.

The applicable frequency range for the EMC/EMI measurements will obviously be different for MMW systems than they are for lower frequency systems. However, the frequency range cannot be limited only to MMW frequencies due to the fact that MMW systems may be susceptible to signals other than those at MMW frequencies. Similarly, a MMW system may be an emitter of signals other than those at MMW frequencies. As a result, the present EMC/EMI requirements for lower frequency systems may be inadequate to ensure compatibility between MMW and lower frequency systems. For example, MIL-STD-461A presently requires spurious and harmonic emissions to be measured only to 40 GHz; thus, the harmonic emission above 40 GHz of equipment presently employed in today's environment is not known. Similarly, MIL-STD-461A requires radiated susceptibility tests only through 12 GHz. Thus, if a MMW system is deployed in an environment with a lower frequency system which has met the requirements of present military standards, the potential interaction of the two systems cannot be determined.

It is also noted that for MMW systems, case emission/susceptibility tests for MMW systems will not be separate from antenna terminal emission/susceptibility tests as is presently the case for lower frequency systems. Thus, the lower frequency limit of emission/susceptibility tests cannot be limited to the lower cutoff frequency of the waveguide connected to the antenna since the equipment case may emit, or be susceptible to, frequencies below the cutoff frequency of the waveguide.

Although the multimoding problems associated with conducted measurements at MMW frequencies can be circumvented by using a radiated rather than a conducted measurement approach, the radiated measurement approach introduces several additional considerations which must be addressed. Three of the major issues which must be considered in developing radiated measurement techniques for MMW systems are: (1) the separation distance between the system under test and the EMC/EMI test instrumentation, (2) the test antenna size, and (3) the EMC/EMI source power requirements for susceptibility measurements and the EMC/EMI receiver sensitivity requirements for emission measurements. Other physical constraints and limitations which must be considered in the development of measurement techniques are the physical size of the equipment under test and the accuracy required of antenna positioners to measure the extremely narrow bandwidths of many MMW antennas.

4.2.1 Separation Distance

A major consideration in performing radiated measurements involves the separation distance between the system under test and the test source/receiver used in the radiated susceptibility/emission measurement configuration. This consideration leads to the question of whether the measurements should be made in the radiated far-field (Fraunhofer) or the radiated near-field (Fresnel) region. The boundary between these two regions is normally considered to be at a distance of $2D^2/\lambda$, where D is the maximum aperture dimension of the equipment under test or the test antenna (whichever is larger) and λ is the wavelength at the frequency of interest. As seen in Table V, the boundary between the near-field and far-field regions (based on $2D^2/\lambda$) for MMW frequencies can range from less than one-tenth of a meter to thousands of

TABLE V

SEPARATION DISTANCE TO FAR-FIELD BOUNDARY BASED ON $\frac{2D^2}{\lambda}$

Maximum Aperture Dimension (D)	30 GHz	60 GHz	120 GHz	183 GHz	240 GHz	300 GHz
1 cm	.02	.04	.08	.122	.16	0.2
2 cm	.08	.16	.32	.488	.64	0.8
4 cm	.32	.64	1.28	1.952	2.56	3.2
8 cm	1.28	2.56	5.12	7.808	10.24	12.8
15 cm	4.50	9.0	18.0	27.45	32.0	45.0
30 cm	18.0	36.0	72.0	109.8	144.0	180.0
50 cm	50.0	100.0	200.0	305.0	400.0	500.0
100 cm	200.0	400.0	800.0	1220.0	1600.0	2000.0
150 cm	450.0	900.0	1800.0	2745.0	3600.0	4500.0

Note: Separation distance is given in meters

meters depending upon the physical dimensions of the system under test. Most MMW equipment require high gain antennas which require aperture dimensions of the antenna to be many wavelengths; thus, for most MMW equipment it will not be possible to achieve a far-field test configuration in a typical indoor laboratory test environment.

The commonly employed boundary of $2D^2/\lambda$ does not represent a unique or abrupt transition between the near-field and far-field regions, but rather is that distance at which the phase variation of the field over the aperture of the antenna is $\pi/8$, or 22.5 degrees. For distances greater than $2D^2/\lambda$, the phase variation becomes sufficiently small such that the antenna pattern is essentially independent of separation distance. Even for separation distances somewhat less than $2D^2/\lambda$, where the phase variation of the field over the antenna aperture becomes greater than $\pi/8$, measured pattern characteristics may provide an adequate representation of the behavior of the antenna. For most EMC/EMI purposes, adequate representations of antenna behavior are possible with measurements performed within (but reasonably close to) the $2D^2/\lambda$ boundary. Thus, if highly accurate measurements of the radiation patterns of a system are not required, the separation distance between the system under test and the test antenna can be reduced accordingly.

As the separation distance becomes significantly less than $2D^2/\lambda$, measured pattern characteristics will begin to deviate markedly from those obtained in the far-field. When radiation pattern measurements are performed within the near-field of an antenna, the pattern characteristics are highly dependent upon the separation distance employed for the measurements. Thus, near-field measurements are neither useful for describing far-field patterns nor for describing near-field patterns at other distances within the near-field. Moreover, the near-field pattern characteristics of a system will be influenced by the particular test site employed. Thus, near-field test data recorded at a particular separation distance cannot necessarily be translated to another environment, even when the separation distance of concern is the same.

The answer to the question of whether radiated measurements should be made in the far-field or near-field region depends on the type of measurement being performed and how the measured data is to be used. If, for example, the measurement being performed is a spurious emission measurement and the data is to be used to analyze interference conditions at remote locations in the far-field of the equipment under test, the measurements should be made in the far-field region of the equipment under test. These data can be measured at one far-field distance and translated to any other point in the far-field. If the spurious emission data are needed to define or control co-site interference conditions in the near-field of the system under test, the question arises as to how to perform the measurements and utilize the measurement data. Measurements performed in the near-field of a system cannot readily be translated to other points in the near-field. Moreover, measurements performed in the near-field of a system are highly dependent upon the measurement site, configuration, and instrumentation, and are unlikely to represent the emission/susceptibility characteristics of the system when the system is placed in another environment.

Although the applicability of near-field data to EMC/EMI prediction and analysis is questionable, measurements performed in the near-field of a system can be utilized to define and control the relative emission/susceptibility characteristics of a system. For example, assume that emission level measurements were performed on two systems, System A and System B, at a distance of one meter and using the same measurement setup. If the peak emission level recorded on System A was lower than that recorded on System B, then System A would be the "best" system in terms of its potential as a source of interference. Thus, near-field measurements do have application in limiting the potential of a system in serving as a source of, or being susceptible to, electromagnetic interference.

One possible approach to performing EMC/EMI prediction and analysis in the near-field of a system is through the use of statistical techniques. A further discussion of the statistical treatment of system emission and susceptibility levels is given in Section 7.3.

It should be noted that if the measurement being performed concerns frequency only (i.e., frequency tolerance, emission bandwidth), then the measurement could be made either in the far-field or the near-field of the system under test.

4.2.2 Test Antenna Size

A second consideration in performing radiated measurements is the test antenna used to (1) radiate the system under test in susceptibility measurements, or (2) receive the emissions from the system under test in emissions measurements. In general, the test antenna employed needs to be as small as possible while still providing the gain required to perform the measurement. The test antenna needs to be physically small for several reasons. First, in order to minimize the separation distance requirements necessary to satisfy the far-field criterion, the test antenna's maximum aperture dimension (D) should be smaller than the maximum aperture dimension of system under test so that the separation distance required will depend only on the system under test. A small test antenna is also required in radiated emission measurements to ensure that the aperture dimensions of the test antenna do not exceed the beamwidth of any of the emissions which are being measured. An aperture which is larger than this beamwidth will result in erroneous field intensity measurements. A third factor which dictates the need for a small test antenna is the desire to minimize mutual coupling due to scattering and reradiation of energy by the test and system antennas.

An additional consideration in choosing a test antenna is the gain required in order to achieve the required sensitivity in emission measurements or the required field strength in susceptibility measurements. The gain requirement for MMW radiated measurements will generally be higher than that for lower frequency measurements due to the low power levels available from commercially available MMW sources and the poor sensitivity levels of commercially available MMW receivers.

Since gain is proportional to antenna aperture size, the requirement for high-gain test antennas is in conflict with the desire to keep the antenna as small as possible. Thus, the best choice of a test antenna is that antenna which gives the minimum required gain to perform the measurement while still holding the aperture size to a minimum.

4.2.3 Power and Sensitivity Requirements

Performing EMC/EMI measurements in a radiated mode will increase the requirements on the power levels of signal sources and the sensitivity levels of test receivers. This increase in power and sensitivity requirements is due to several factors including the relatively large separation distances which may be required in order to satisfy far-field criteria at MMW frequencies, high absorption losses at MMW frequencies, and the high attenuation effects of the equipment's antenna and transmission line. These factors can be partially circumvented through the use of the high gain test antennas although the use of high gain antennas is only a partial solution because of the need to keep the test antenna aperture as small as possible.

As seen in the Friis transmission formula (including absorption losses due to oxygen (L_o) and water vapor (L_{wv})),

$$P_t = \frac{4 \pi R^2 L_o L_{wv} P_D}{G_T} \quad (1)$$

the power level (P_T) required from a signal source in order to produce a required field strength (P_D) for susceptibility measurements is a function of the separation distance (R), test antenna gain, (G_T), and absorption losses, (L_o and L_{wv}). Table VI gives the transmitter output power required to produce a field intensity of 100 W/m^2 at various separation distances.

It can be seen from Table VI that if a separation distance of a thousand meters is required between the transmitter and system under test (in order to meet the far-field criterion), and if a standard gain horn of 15 or 30 dB is used in the test, then output powers of megawatts will be required. However, for separation distances of a meter or less the required output power will be in the order of watts.

The sensitivity requirements of receivers used in emission measurements is also a function of separation distance, test antenna gain, transmission line loss, absorption loss, and frequency. Table VII gives the receiver sensitivity requirements to detect an effective radiated power level of 1 mW assuming a required signal-to-noise ratio of one. The receiver sensitivity levels given in Table VII were calculated using the equation given below:

$$P_r = \frac{P_{EF} G_r \lambda^2}{(4\pi)^2 R^2 L_o L_{wv}} \quad (2)$$

TABLE VI

TRANSMITTER OUTPUT POWER REQUIRED TO PRODUCE A FIELD INTENSITY OF 100 W/M^2

f (GHz)	30		60		120		183		240		300	
L_o (dB/km)	0.031		14.0		1.5		0.060		0.040		0.031	
L_{wv} (dB/km)	0.11		0.12		0.85		41.0		3.1		5.0	
G_T (dB)	15	30	15	30	15	30	15	30	15	30	15	30
Distance (meters)	Transmitter Output Power (Watts)											
0.5	9.93	0.315	9.95	0.315	9.95	0.315	9.98	0.315	9.94	0.315	9.94	0.315
1	39.8	1.26	39.9	1.26	39.8	1.26	40.2	1.27	39.8	1.26	39.9	1.26
10	$3.98x10^3$	$1.26x10^2$	$4.11x10^3$	$1.30x10^2$	$4.00x10^3$	$1.26x10^2$	$4.38x10^3$	$1.38x10^2$	$4.01x10^3$	$1.27x10^2$	$4.03x10^3$	$1.27x10^2$
100	$3.99x10^5$	$1.26x10^4$	$5.51x10^5$	$1.74x10^4$	$4.19x10^5$	$1.33x10^4$	$1.02x10^6$	$3.24x10^4$	$4.28x10^5$	$1.35x10^4$	$4.47x10^5$	$1.41x10^4$
1000	$4.11x10^7$	$1.30x10^6$	$1.03x10^9$	$3.25x10^7$	$6.83x10^7$	$2.16x10^6$	$5.08x10^{11}$	$1.61x10^{10}$	$8.19x10^7$	$2.59x10^6$	$1.27x10^8$	$4.01x10^6$

Note:

(1) G_T = gain of test transmitting antenna.

(2) L_o = losses due to oxygen absorption.

(3) L_{wv} = losses due to water vapor absorption.

(4) Transmission line losses are neglected.

(5) Values for L_o and L_{wv} are based on standard atmospheric conditions at sea level.

TABLE VII

RECEIVER SENSITIVITY REQUIRED TO DETECT AN EFFECTIVE RADIATED POWER OF 0 dBm

f(GHz)	30		60		120		183		240		300	
L_o (dB/km)	0.031		14.0		1.5		0.06		0.040		0.031	
L_{wv} (dB/km)	0.11		0.12		0.85		41.0		3.1		5.0	
G_r (dB)	15	30	15	30	15	30	15	30	15	30	15	30
Distance (meters)	Receiver Sensitivity (dBm)											
0.5M	-41.0	-26.0	-47.0	-32.0	-53.0	-38.0	-56.7	-41.7	-59.0	-44.0	-61.0	-46.0
1M	-47.0	-32.0	-53.0	-38.0	-59.0	-44.0	-62.7	-47.7	-65.0	-50.0	-67.0	-52.0
10M	-67.0	-52.0	-73.1	-58.1	-79.0	-64.0	-83.1	-68.1	-85.1	-70.1	-87.0	-72.0
100M	-87.0	-72.0	-94.4	-79.4	-99.3	-84.3	-106.8	-91.8	-105.4	-90.4	-107.5	-92.5
1000M	-107.1	-92.1	-127.1	-112.1	-121.4	-106.4	-163.8	-148.8	-128.2	-113.2	-132.0	-117.0

Note:
(1) G_r = gain of test receiving antenna.
(2) L_o = losses due to oxygen absorption.
(3) L_{wv} = losses due to water vapor absorption.
(4) Transmission line losses are neglected.
(5) Values for L_o and L_{wv} are based on standard atmospheric conditions at sea level.
(6) Values for receiver sensitivity assume a required signal to noise ratio of one.

where

P_R = received power,

P_{EF} = minimum effective radiated power which is desired to be detected,

G_R = gain of test antenna,

λ = wavelength at the highest frequency of the test,

R = separation distance, and

L_o and L_{wv} = absorption losses due to oxygen and water vapor

It can be seen from Table VII that at separation distances of 100 meters the required sensitivity using standard gain test antennas is greater than that promised by present commercially available MMW measurement receivers. However, at a separation distance of 1 meter the required sensitivity is achievable. It is noted that for most EMC/EMI measurements the minimum signals required to be measured will be much less than 1 mW, making the sensitivity requirements of the receiver even greater. Table VII also shows that the required sensitivity of a receiver at a given separation distance is proportional to frequency. This is in conflict with the fact that the sensitivity levels of commercially available MMW measurement receivers is inversely proportional to frequency. It should be noted that these figures are for a best case situation and that the actual sensitivity requirements will be greater due to noise added by the receiver.

If EMC/EMI radiated measurements are to be performed at separation distances satisfying the far-field criterion of $2D^2/\lambda$, it is evident that the power and sensitivity levels of MMW test sources and receivers will have to be greatly improved over that presently available or the gain of the test antenna will have to be significantly increased above 30 dB. It is also noted from Tables VI and VII that at large separation distances the power and sensitivity requirements are the most demanding at 183 GHz where atmospheric absorption is the highest.

It is important to recognize that the problem of obtaining sufficient source power and receiver sensitivity for performing radiated emission and susceptibility measurements is strongly indicative of a probable lack of significant EMI problems at MMW frequencies. In other words, if sufficient MMW source power is not available to perform susceptibility measurements, then it is unlikely that MMW transmitters will be a major source of interference in an operational environment. This is not to imply that EMC/EMI problems will not exist at MMW frequencies or that EMC/EMI testing at MMW frequencies is not required. However, it is felt that the nature and extent of EMC/EMI testing should be commensurate with the likelihood of interference at MMW frequencies.

5.0 RADIATED MEASUREMENT TECHNIQUES

This section discusses specific radiated measurement techniques for satisfying the required EMC/EMI data requirements. The first subsection discusses the applicability of various measurement sites for performing radiated EMC/EMI measurements on MMW systems. The three basic measurement sites which offer the greatest promise for MMW system EMC/EMI measurements are: the shielded anechoic chamber, the outdoor range, and the compact range. The second subsection discusses specific EMC/EMI radiated measurement techniques techniques for obtaining the data defined in Section 3.

The radiated test techniques which are presented in this section are in generic form. Although these tests have been extracted from similar tests which are performed currently on a conducted basis, they have not been experimentally verified. Therefore, problems which may exist when these measurements are actually performed are presently not known. Also, much of the equipment required to perform these tests are presently not available as standard off-the-shelf items. Thus, the validation of these test configurations cannot be accomplished until the required test instrumentation and components are developed.

5.1 Measurement Site

A major consideration in performing radiated EMC/EMI measurements is the measurement site/technique to be employed. A review of the various techniques available for performing radiated emission/susceptibility measurements indicates that many of these techniques are unsatisfactory for measurements at MMW frequencies [8]. Those techniques which are considered unsatisfactory are identified below, along with a brief discussion of problems in the utilization of the techniques at MMW frequencies. The three basic measurement techniques which offer the greatest promise for conducting far-field radiated measurements on MMW systems are the open field range, the shielded anechoic chamber, and the compact range. These measurement techniques are discussed in greater detail in the following subsections.

Shielded Enclosures. The shielded enclosure provides a high degree of isolation from the electromagnetic environment and local sources of interference. However, the reflections from the enclosure walls significantly affect any radiated measurements made in the enclosure. Measurement results are extremely sensitive to the size and shape of the enclosure, the location of the test setup in the enclosure, the spacing between the equipment under test and the test antenna, and the presence and location of personnel and test equipment in the enclosure. Thus, large errors can result, which generally make the shielded enclosure unsuitable for radiated measurements of any type at MMW frequencies.

TEM Cell. The TEM Cell is a form of shielded enclosure which provides isolation from the external environment but does not introduce the reflection problems associated with the conventional enclosure. The TEM Cell can be used to establish a relatively uniform TEM field for susceptibility measurements or to couple emissions from a unit under test to the cell's measurement port. However, since the maximum physical dimensions of the cell are inversely proportional to frequency (to prevent multi-moding), the required cell size at MMW frequencies would become so small that its use as a test device would be impossible.

Parallel Plate Structure. The parallel plate structure is another form of TEM transmission line that is commonly employed for radiated measurements. Like the TEM Cell, however, the maximum dimensions of the structure (separation between plates) are inversely proportional to frequency (to prevent multi-moding). The use of the parallel plate structure is thus restricted to relative low frequencies.

Tuned Mode Enclosure. The tuned mode enclosure technique is used primarily as a means of performing shielding effectiveness measurements. This technique involves placing the equipment to be tested inside a multi-moded, tuned shielded enclosure in which paddle wheel tuners are used to redistribute the energy within the enclosure. The tuned mode technique has been incorporated into MIL-STD-1377 as a test method for measuring the shielding effectiveness of cables, connectors, enclosures and filters, and investigations have been performed to determine if it can be utilized to perform radiated emission and susceptibility type measurements. However, it is doubtful that this technique can be extended much beyond its current frequency limit of 10 GHz because of losses which occur in the enclosure walls. Thus, its use for measurements at MMW frequencies is highly questionable.

Near-Field Probe. The near-field probe technique uses a probe antenna to measure the phase and amplitude of the near field at preselected points on a prescribed surface (i.e., plane, cylinder, or sphere) in the near field of the system under test. The far-field radiation patterns can then be calculated after removing the directional effects of the probe antenna. This approach has the advantage over the other measurement techniques in that the complete azimuth and elevation patterns can be determined, not just a few cuts. Unfortunately, this approach presently has serious limitations at MMW frequencies. One limitation is the precise probe positioning accuracy which would be required due to small wavelengths at MMW frequencies. A second limitation is that the large number of sample points required makes the measurement time excessively long and would require extensive computation time and computer requirements. For near-field measurements using a planar surface the sample spacing in both x and y-directions must be less than one-half a wavelength and depends on the distance from the equipment under test to the measurement plane. Thus, at 300 GHz the measurement surface would have to be sampled at points less than one-half of a millimeter. This large number of sample points can be reduced by using a cylindrical or spherical measurement surface. In cylindrical near-field measurements the sample spacing in the z-direction is the same as for a planar surface, but the spacing in the theta direction must be less than $\lambda/2R$ radians (where R is the radius of the smallest cylinder enclosing the equipment under test). In spherical near-field measurements the sample spacing in both the theta and phi directions must be less than λ/R radians (where R is the radius of the smallest sphere enclosing the equipment under test) [9]. Thus, for an equipment which has a largest dimension of 30 cm the required spacing at 300 GHz would be less than 7×10^{-3} radians (0.4 degrees). A third limitation is that this approach would only provide a means for performing emission testing. No equivalent approach is known for susceptibility testing. A final limitation is the large cost associated with a near-field probe system.

5.1.1 Open-Field Range

Open-field measurements are particularly advantageous when systems with high gain antennas are tested since large separation distances can be accommodated. Some MMW systems may require separation distances of several thousand meters in order to meet the far-field criterion of $R = 2D^2/\lambda$. However, open-field measurements do have disadvantages. Large separation distance requirements will place a severe burden on the power and sensitivity requirements of EMC/EMI instrumentation. Also, open-field sites do not provide isolation from the EM environment. In addition, the accuracy of open-field measurements can be hindered due to errors caused by reflections and multipath, and by weather changes.

If open field measurements are required, care should be taken to avoid errors due to ground reflections or reflections from surrounding buildings or terrain. There are several references which discuss the problems involved when making open-field radiated measurements. Various solutions include adjusting the height of the system under test and the test receiver, using a ground plane, or through the use of fences [10],[11],[12]. A simplified open-field test configuration is shown in Figure 10. Care should also be taken to ensure that the test antenna and transmitter used in susceptibility measurements provide sufficient measurement system power output such that the desired field intensity can be produced at the system under test, and that the test antenna and receiver used in emission measurements provide sufficient measurement system sensitivity to allow detection of the minimum desired signal level.

Variations in radiated measurements due to weather and atmospheric conditions may be a particular problem at MMW frequencies because of the significant absorption losses. Thus, repeatability of open-field radiated measurements may be difficult to achieve under some test conditions.

5.1.2 Shielded Anechoic Chamber

If the required separation distance between the system under test and the test antenna to ensure far-field test conditions can be realized in a shielded anechoic chamber, then it is the preferred measurement site. This type chamber minimizes reflections in the test volume, thus simulating open-field conditions while providing electrical isolation from the outside environment.

Typical shielded anechoic chamber configurations used for radiated emission and susceptibility measurements are shown in Figures 11 and 12 respectively. Care should be taken to avoid reflections from metal objects located in the room such as the positioner or other equipment located in the room.

5.1.3 Compact Range

If a compact range is available and the far-field separation distance is not realizable in an anechoic chamber, then the compact range should be used since it eliminates many of the problems involved in making open-field radiated measurements. The compact range can be shielded from the external EM environment, is located indoors, and with the appropriate use of anechoic absorbing material will simulate open-field conditions. Also, the compact range minimizes the power output and sensitivity requirements of test instrumentation

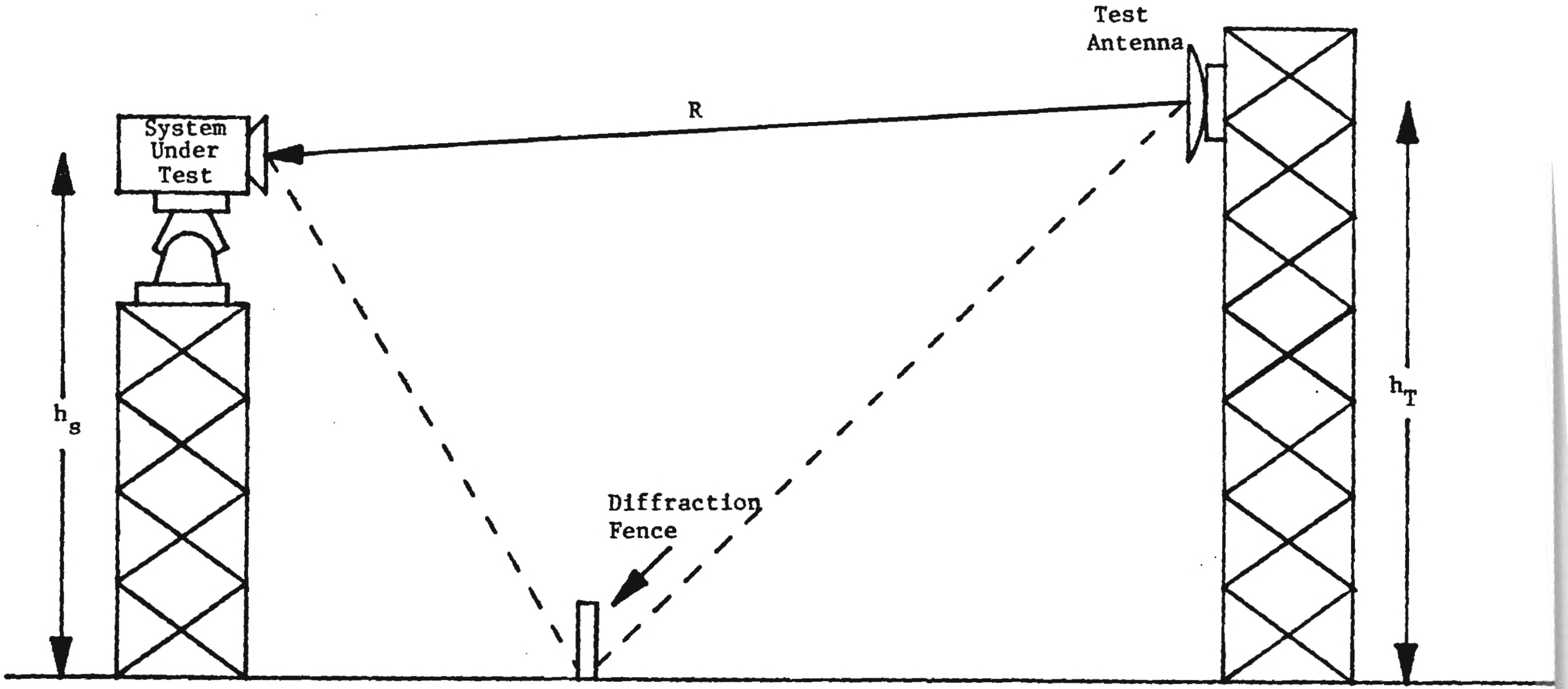


Figure 10. Test Setup for Radiated Emission Measurements Performed on an Open-Field Range.

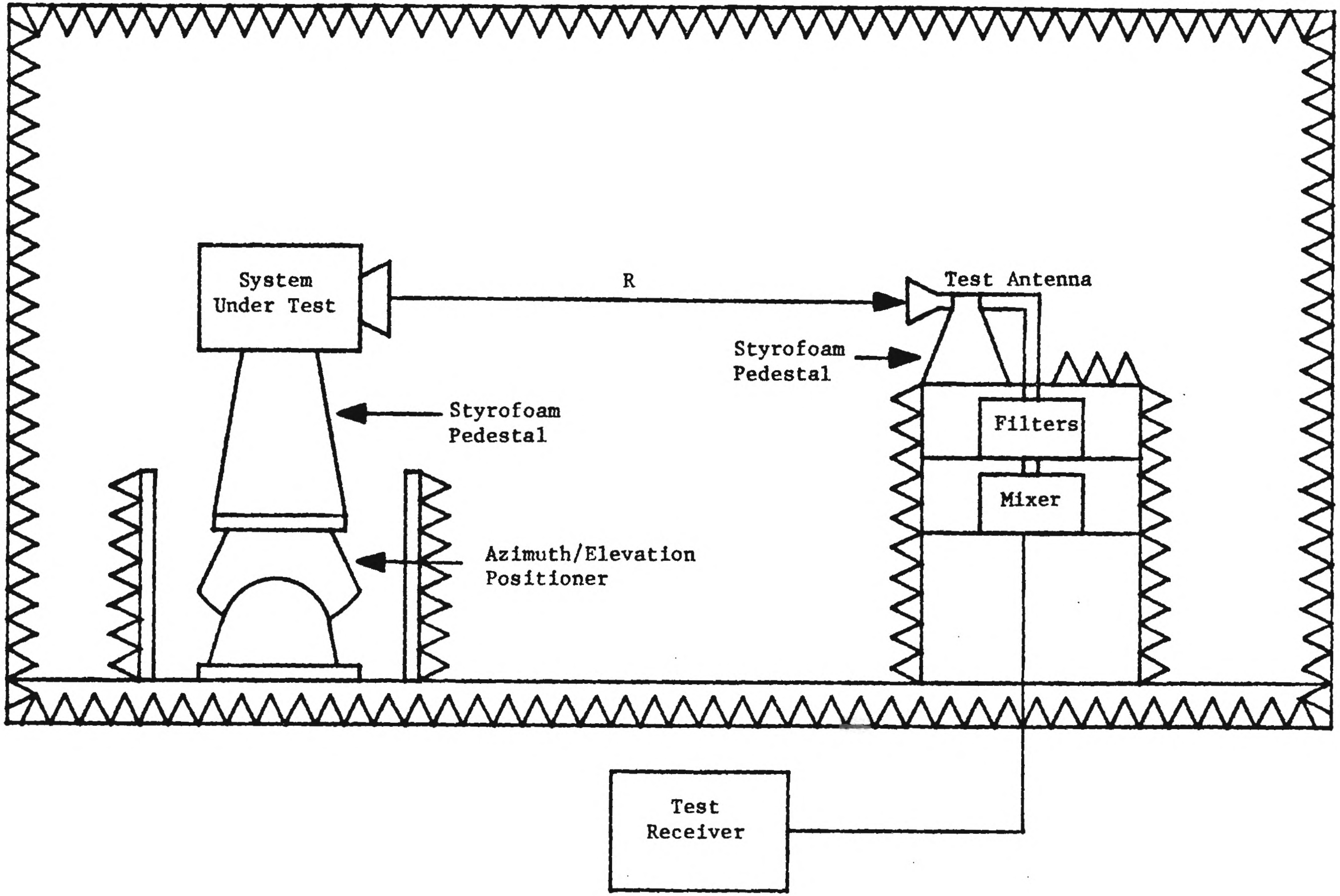


Figure 11. Test Setup for Radiated Emission Measurements Performed in an Anechoic Chamber.

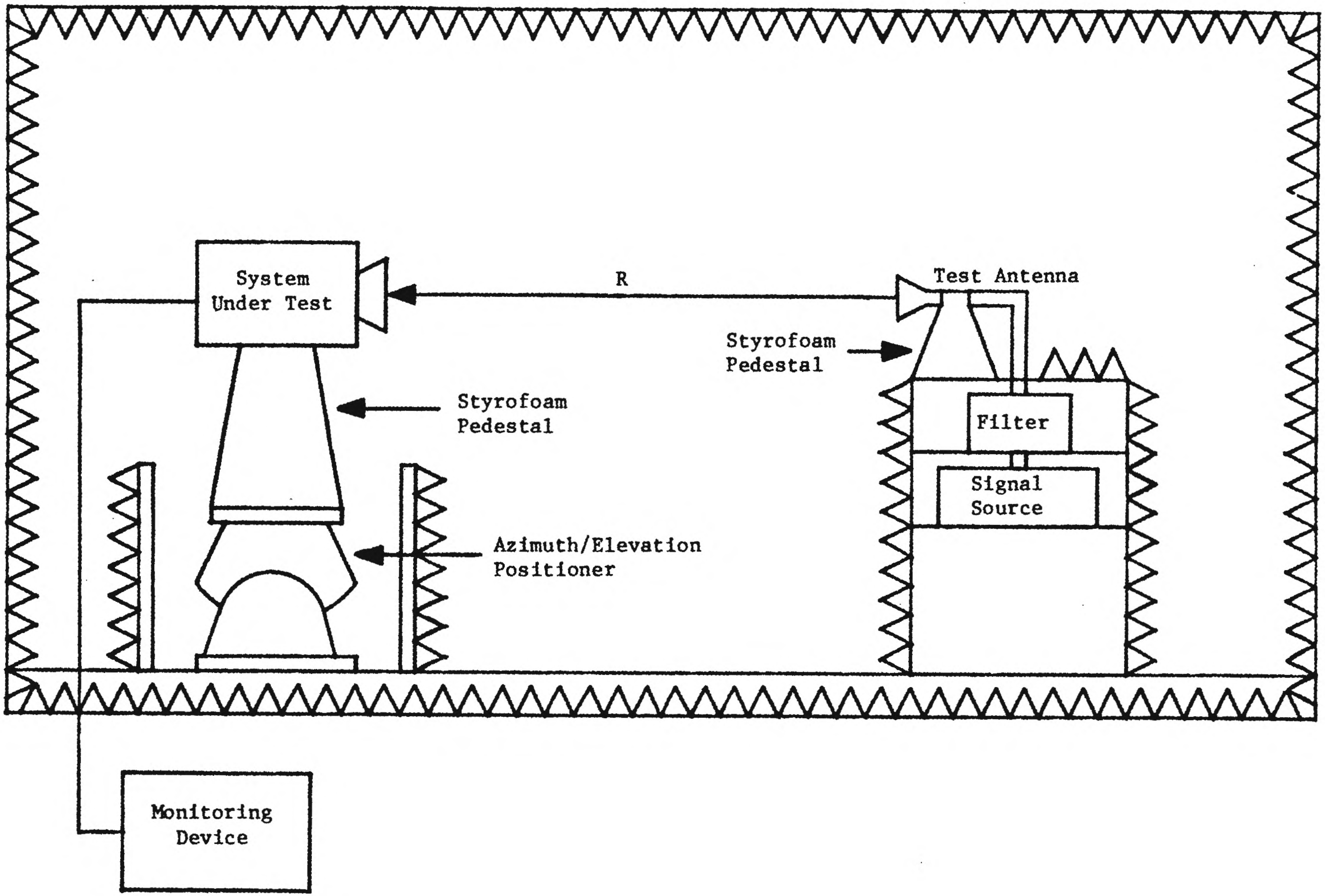


Figure 12. Test Setup for Radiated Susceptibility Measurements Performed in an Anechoic Chamber.

due to the fact that the compact range simulates far-field conditions independent of the dimensions of the system under test.

The compact range involves the use of a large reflector to collimate the beam from a source antenna so as to provide a planar wavefront. A uniform plane electromagnetic wave can be created in a compact range at distances independent of the conventional criterion of $R = 2D^2/\lambda$. The principle of operation is illustrated in Figure 13. The diverging rays from the point-source feed are collimated by the range reflector, and a plane wave is incident on the system under test. The incident wave has a phase variation much less than the $\pi/8$ radians guaranteed by the criterion $R = 2D^2/\lambda$. However, the feed-reflector combination introduces a small amplitude taper across the test zone. Typically, amplitude tapers are less than 2 dB for microwave frequencies and are much better than can be expected at a distance $R = 2D^2/\lambda$.

Two of the main difficulties associated with the use of a compact range at MMW frequencies will be surface tolerance requirements and feed positioning requirements. The surface tolerance requirements of the reflecting antenna are very great at microwave frequencies and will correspondly be much greater at MMW frequencies. The ability to accurately position the feed horn within one-third of a wavelength of the focal point of the range reflector is a demanding requirement on the mechanical tolerances of the probe positioner at MMW frequencies. However, ranges which are useable up to 94 GHz are currently available and it would seem possible to extend extend the frequency range all the way up to 300 GHz if care was taken in the reflector construction and the feed positioner accuracy.

The application of the compact range to EMC/EMI susceptibility type measurements is a simple and straight forward process because the range is being used in its conventional form as a transmitting system. Thus, it would be possible to generate plane waves of relatively high power density at short distances.

Although no documentation has been found which indicates that the compact range has been used as a receiving system, analyses indicate that the compact range can be used as a receiving system for emission measurements. From a simple mathematical description of the coupling between the compact range and the system under test [13], it can be shown that the transmission equation that results from viewing the compact range as the transmitter is identical to the transmission equation that results from viewing the system under test as the transmitter. This derivation is dependent on the concept of a plane wave spectrum, taking the point of view that the compact range acts as an "angle filter" for the plane waves emitted by the system under test.

Figure 14 illustrates the principle of operation of the compact range used as a receiver. It is seen that the plane wave associated with the principal ray will be focused at the focal point of the reflector where the center of the feed horn is located. The plane waves impinging from directions that are slightly off axis will be focused just off the center of the feed horn but will also cause a response provided they are focused within a radius of the focal point equal to the radius of the feed horn's aperture All other plane waves will be focused to other points in the room and will not be received by the horn. It can be shown that the

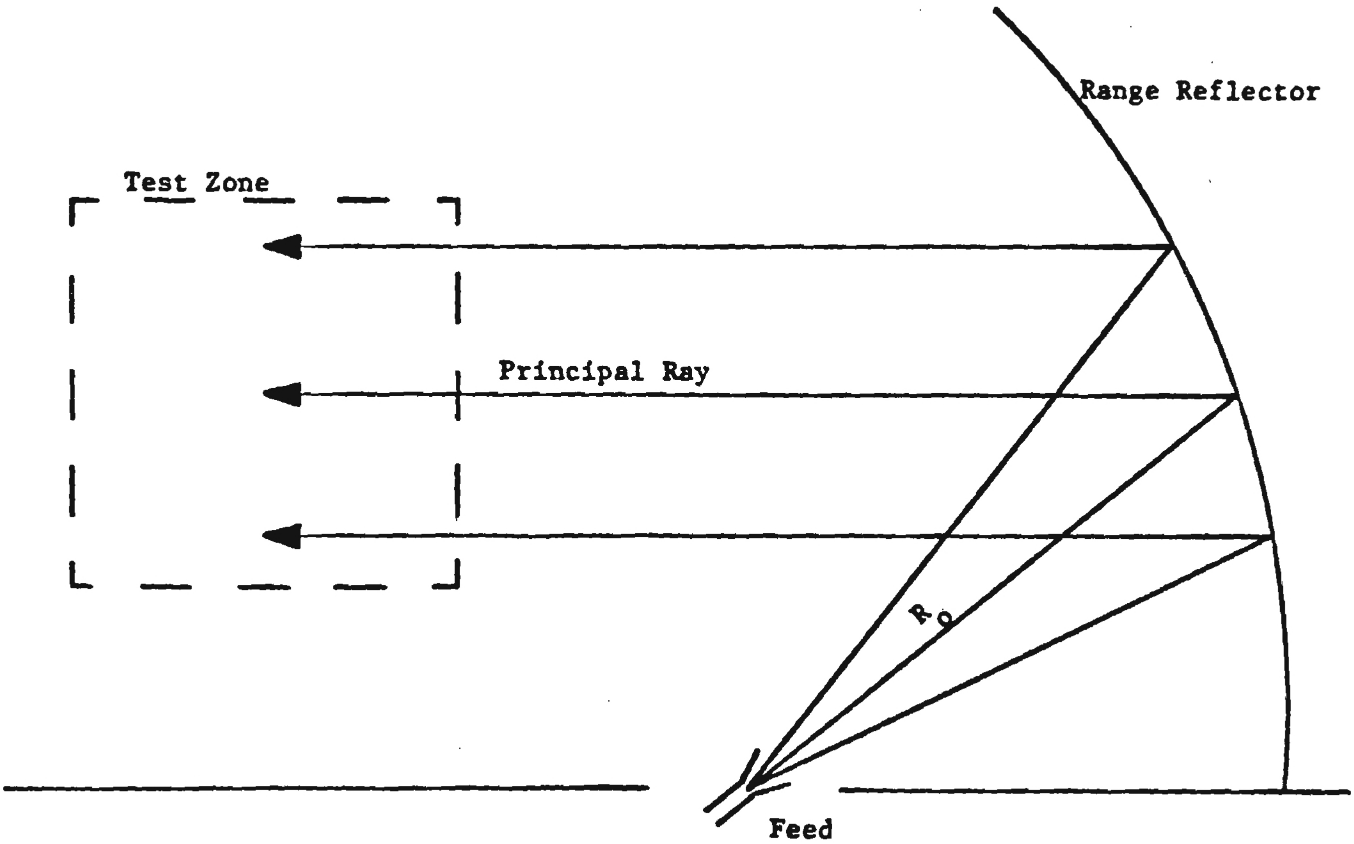


Figure 13. Schematic Representation of Compact Range Employing a Reflector and Feed Horn to Generate a Planar Wave Front. (Rays drawn show concept of equal path distances for all rays)

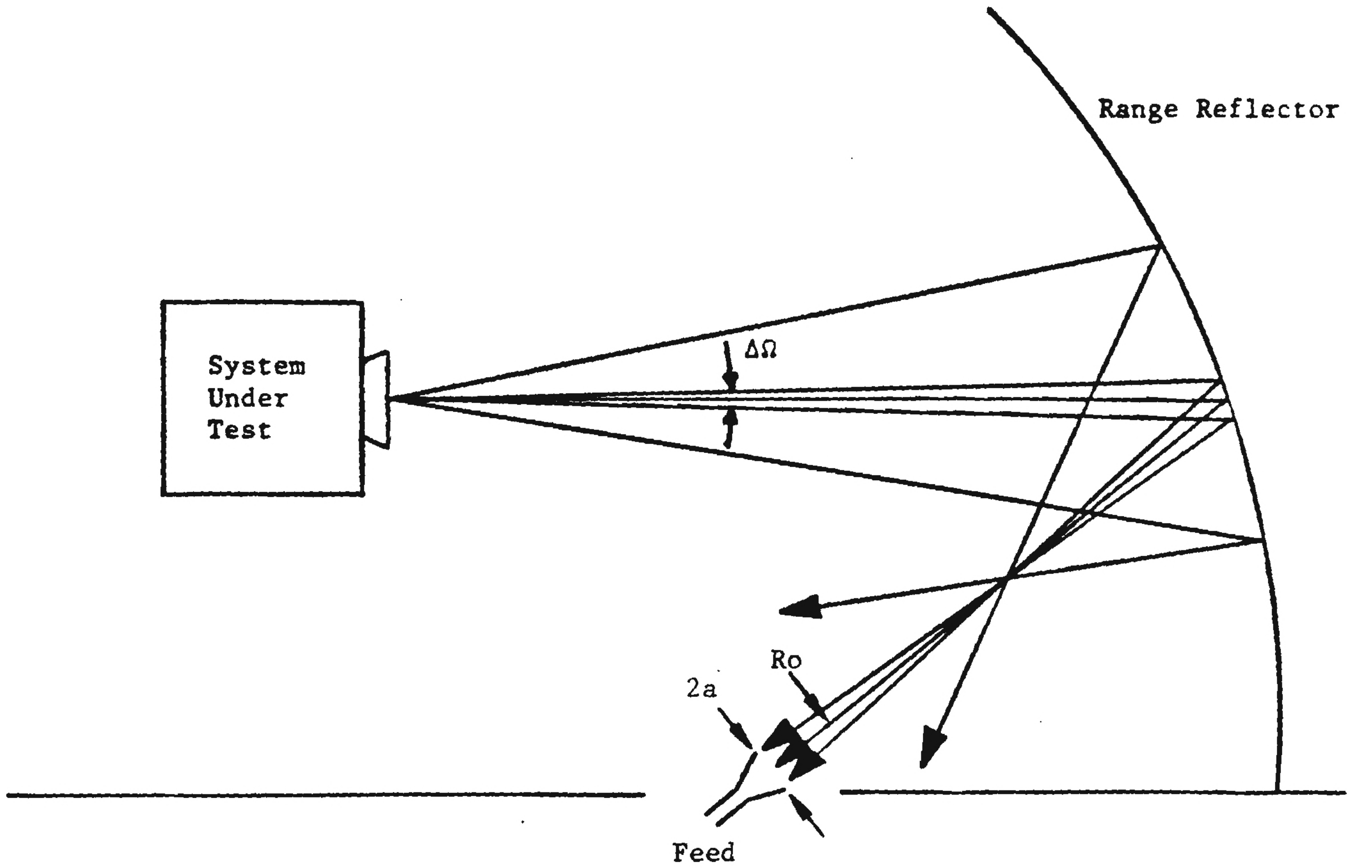


Figure 14. Schematic Diagram of Compact Range Angle Filter Operation in Emission Measurements.

"angular width" (Ω) of the plane wave spectrum that is accepted in the pass band of the compact range is:

$$\Delta\Omega = \left(\frac{a}{R_o}\right)^2 \tag{3}$$

where,

a = physical radius of the feed horn aperture

R_o = distance from feed horn to reflector along the principal ray

This expression for the width of the passband of the compact range angle filter can be utilized to obtain power spectral density in the wave impinging on the reflector from the measured power received by the feed horn.

Experimental measurements were performed on the Georgia Tech compact range to verify the above analysis. A description of these measurements and the results obtained are presented in Appendix B.

Figures 15 and 16 show typical compact range test configurations for radiated emission and susceptibility measurements, respectively. It is noted that the distance between the range reflector and the range feed (R_o) is the distance used in Equations 1 and 2 to calculate the power/sensitivity requirements for the test transmitter/receiver. These equations are independent of the distance from the system under test and the range reflector since the field is a plane wave in this region and the free space losses are not applicable for plane waves. However, the losses due to oxygen and water vapor are applicable for plane waves; thus, the values of L_o and L_{wv} used in Equation 1 and 2 should be the values for the entire transmission path.

Another measurement difficulty which arises on the compact range is that for EMC/EMI measurements which require two test antennas, such as intermodulation measurements, it is not possible to physically locate both test antennas in the focal point of the range reflector. However, if both test antennas are dispaced in the horizontal plane a distance from the focal point as shown in Figure 17, then the field which is impinging on the system under test from one of the test antennas approximates a plane wave which is slightly skewed off axis. Similarly, the plane wave which is being received by a test antenna through the compact range angle filter is also slightly skewed off axis. It can be shown that the skew angle of the plane wave for a displacement Δx is

$$\Delta\theta = \text{Arc tan } \left(\frac{\Delta x}{R_o}\right) \tag{4}$$

If $x \ll R_o$

$$\Delta\theta \simeq \frac{\Delta x}{R_o}$$

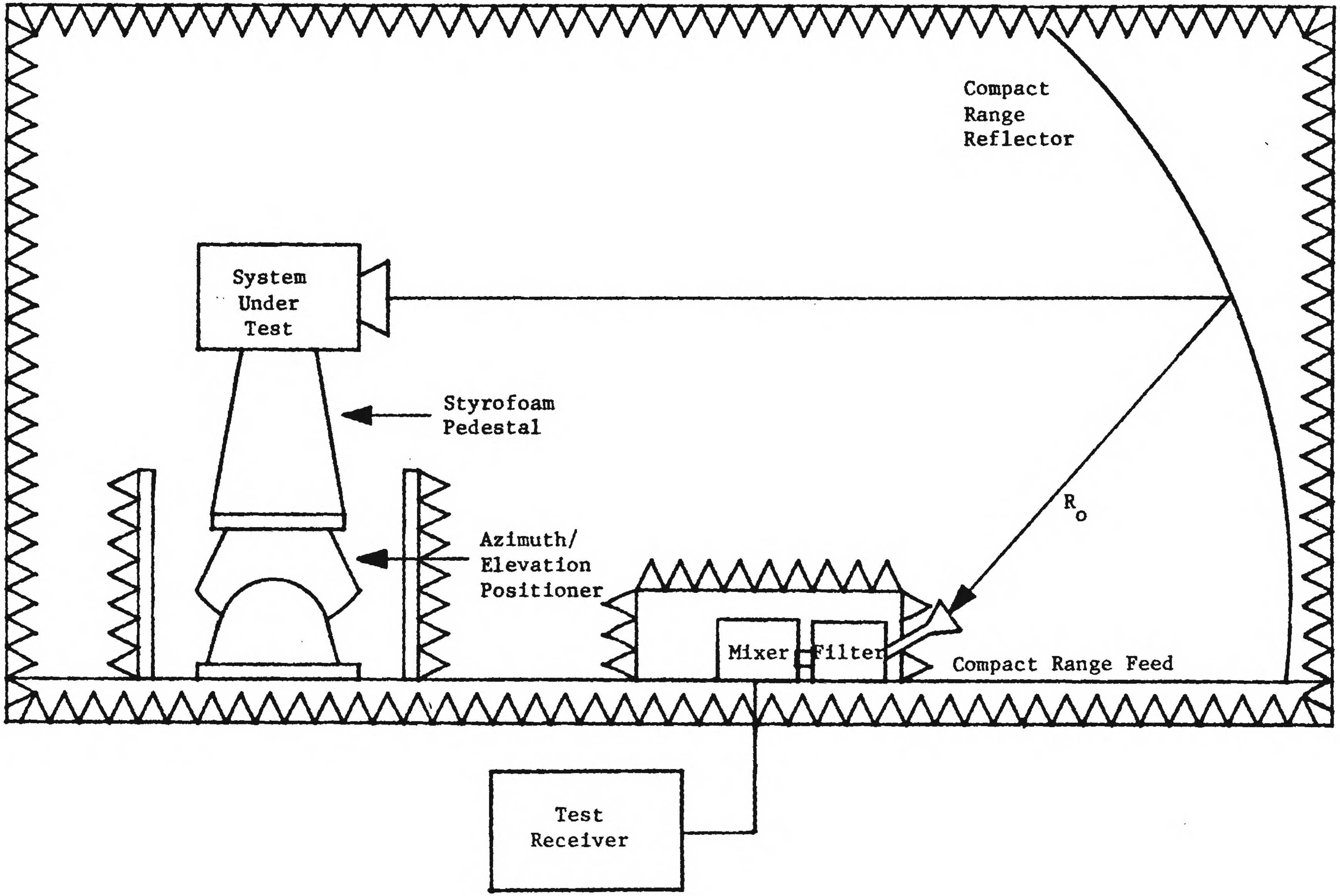


Figure 15. Test Setup for Radiated Emission Measurements Performed on a Compact Range.

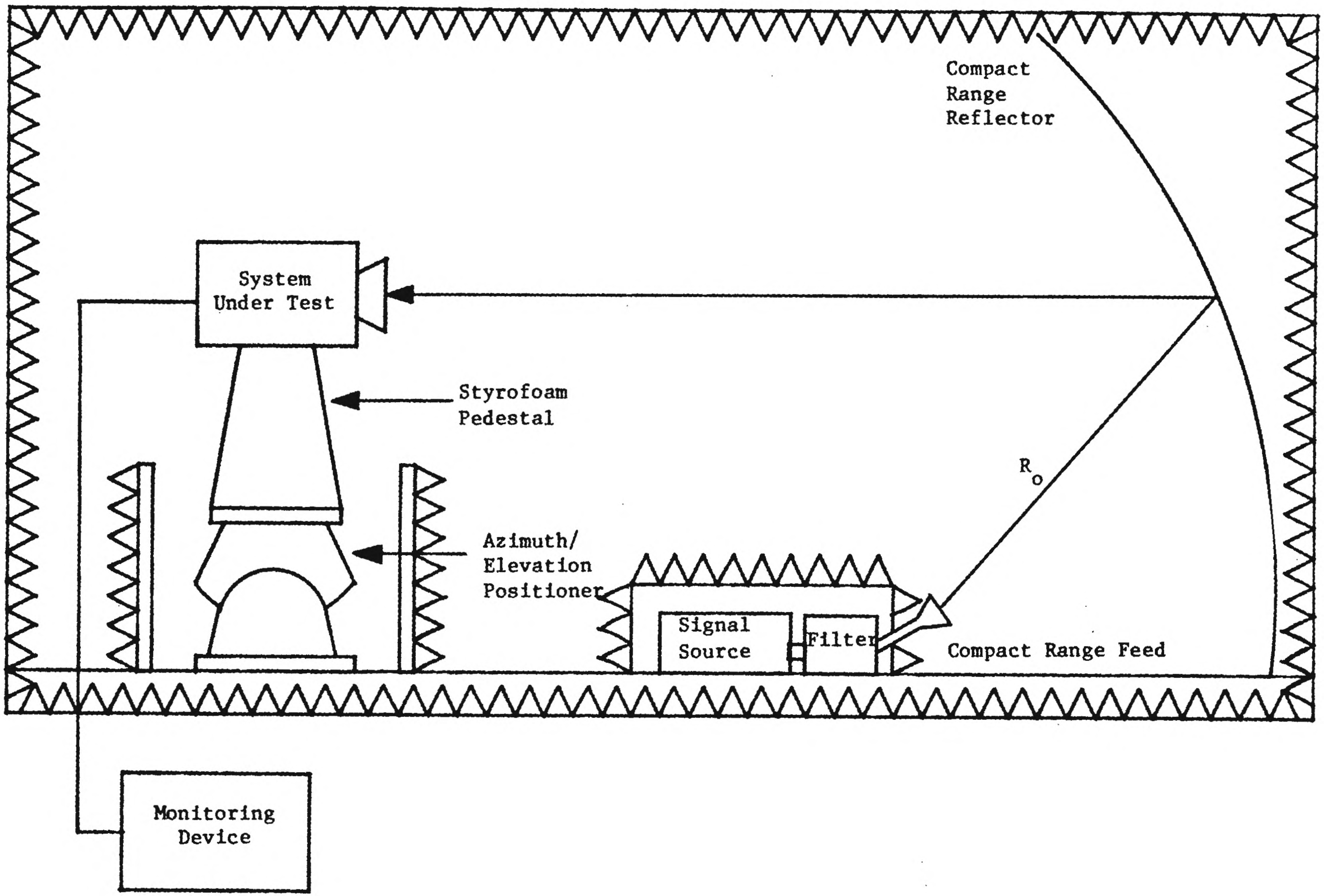


Figure 16. Test Setup for Radiated Susceptibility Measurements Performed on a Compact Range.

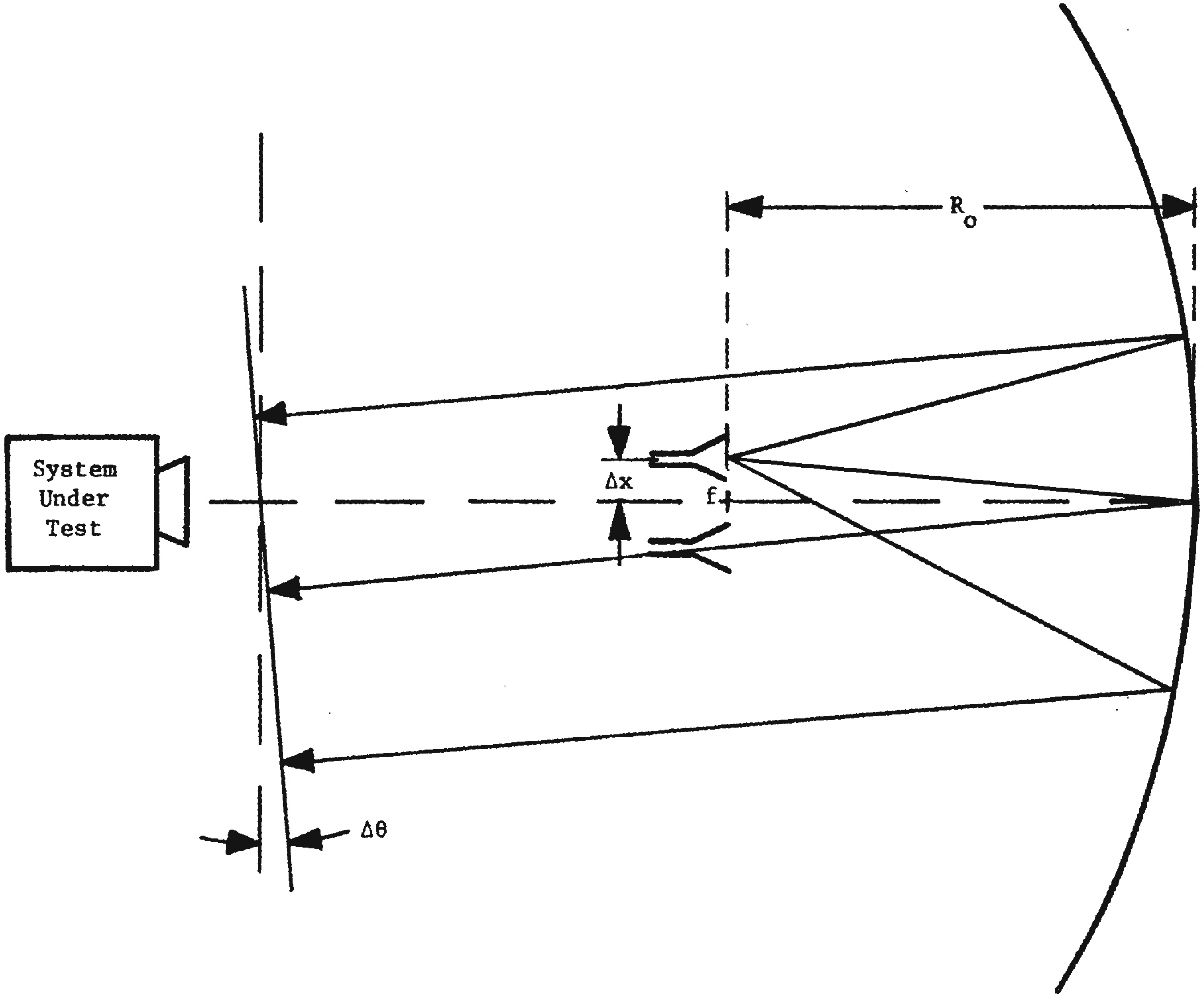


Figure 17. Geometry of Compact Range Test Setup for Two Antenna Intermodulation Test.

Thus, if the test antennas are small, Δx will be small, and errors due to the skew angle will be minimized.

5.2 Specific EMC/EMI Measurement Techniques

It was previously concluded that, with the exception of conducted measurements performed on system cabling, all EMC/EMI measurements on MMW systems should be performed in a radiated mode. It was also concluded that three basic techniques offer the greatest promise for conducting far-field radiated measurements on MMW systems: the shielded anechoic chamber, the open-field range, and the compact range. The shielded anechoic chamber provides an isolated test environment that simulates free space conditions; however, it is limited to those MMW systems for which far field test conditions can be realized within the working space of the chamber. The open-field range allows for measurements at any required separation distance; however, it is subject to environmental influences (extraneous signals, weather, etc.) and is limited by the power and sensitivity characteristics of the available EMC/EMI instrumentation. The compact range provides an isolated test environment and offers the advantage of simulating far-field conditions independent of the dimensions of the system under test. Thus, the compact range will permit far-field measurements to be performed within a relatively small working space and will significantly reduce the power and sensitivity demands of the EMC/EMI instrumentation.

The overall nature of EMC/EMI problems projected for MMW systems is not significantly different from that of lower frequency systems. Thus, the present EMC/EMI data requirements for lower frequency systems will also be applicable to MMW systems. Presently, a significant amount of the EMC/EMI data for lower frequency systems are derived from conducted measurements at the antenna terminals. Although conducted antenna terminal measurements on MMW systems are not feasible, the required EMC/EMI tests will generally be the same as for lower frequency systems except that the transmission path from the system under test to the test instrumentation will be a radiated path rather than a conducted path. There are two types of measurements used for collecting EMC/EMI data requirements: emission measurements and susceptibility measurements.

5.2.1 Emission Measurements

The recommended radiated emission measurements for MMW equipment are: spurious emissions, transmitter intermodulation, transmitter emission bandwidths, transmitter frequency tolerance, and transmitter power output level.

Spurious Emissions Test

The spurious emissions test involves the determination of undesired or spurious outputs from the equipment under test. Since the test is performed on a radiated basis, it will include case-related emissions as well as antenna-related emissions. This approach deviates from present EMC/EMI standards where antenna emissions are measured separately from case emissions. This deviation is due to the fact that MMW equipment will generally be configured with the antenna as an integral part of the equipment case. However, if the emissions of an equipment are to be reduced to a minimum, the case emissions must be reduced to a minimum. It is therefore desirable to know the case-related emissions independent of the antenna-related emissions. Solutions to this problem would be to perform shielding effectiveness measurements on the case alone, or, if possible, to perform case emission tests in the design phase before the antenna is installed (through the use of a dummy load on the antenna port of the equipment).

The applicable frequency range for the spurious emission test should be the same as that already imposed by military standards with the upper frequency limit extended to 300 GHz. MIL-STD-461A Notice 4 presently requires a radiated emission test (RE03) to be performed on all equipment that employs waveguide transmission lines or for an equipment which utilizes an antenna that is an integral part of the equipment under test. This test method will also be applicable for MMW equipment and should be used since it is an already accepted test technique. It is noted that the lower frequency limit of this test for equipment utilizing waveguide transmission lines is 0.8 f_{co} (where f_{co} = waveguide lower cutoff frequency). This lower limit will not be applicable for MMW equipment since the test covers case related emission as well as antenna related emissions. The lower limit should, therefore, be 10 kHz for all equipment. This test requires radiated emission measurements through 40 GHz. Thus, a test method for spurious emissions from MMW equipment must be developed only for the frequency range from 40 GHz to 300 GHz. It is noted that the frequency range applicable for a particular equipment may be modified depending upon the characteristics of the system under test. For example, if the equipment under test is a receiver and its lowest local oscillator frequency is known, then the lower frequency limit of the test can be set at the lowest local oscillator frequency. Also, spurious emission measurements above the fundamental frequency of a transmitter might be limited to frequency regions around the harmonic frequencies.

A block diagram of the recommended equipment configuration for spurious emission measurements is shown in Figure 18. The band-reject filter is used when the equipment under test is a transmitter to reject the transmitter fundamental frequency, and should provide sufficient rejection to prevent overload or saturation of the external mixer or test receiver. The bandpass filter is used to reject all emissions except those surrounding the particular frequency of interest. (It is to be noted that the present state-of-the-art in filter design at MMW frequencies may not support this configuration). The test antenna used should be physically as small as possible while still providing the gain required to achieve the required sensitivity of the test. The test antenna should be small to ensure that its aperture dimensions do not exceed the beamwidth of any of the emissions which are being measured. An aperture which is larger will result in erroneous field intensity measurements. Since the emission levels emanating from the system under test are a function of angular orientation, the system under test is placed on a azimuth over elevation positioner. Thus, the system should be rotated in both azimuth and elevation at each test frequency in order to find the orientation for maximum emissions.

The external mixer employed in the test setup is used to convert the MMW signal down to a lower frequency. The mixer is located as close to the test antenna as possible to eliminate the high attenuation losses at MMW frequencies in the transmission path between the antenna and test receiver. Normally, the receiver provides the local oscillator signal for the mixer, and harmonic mixing

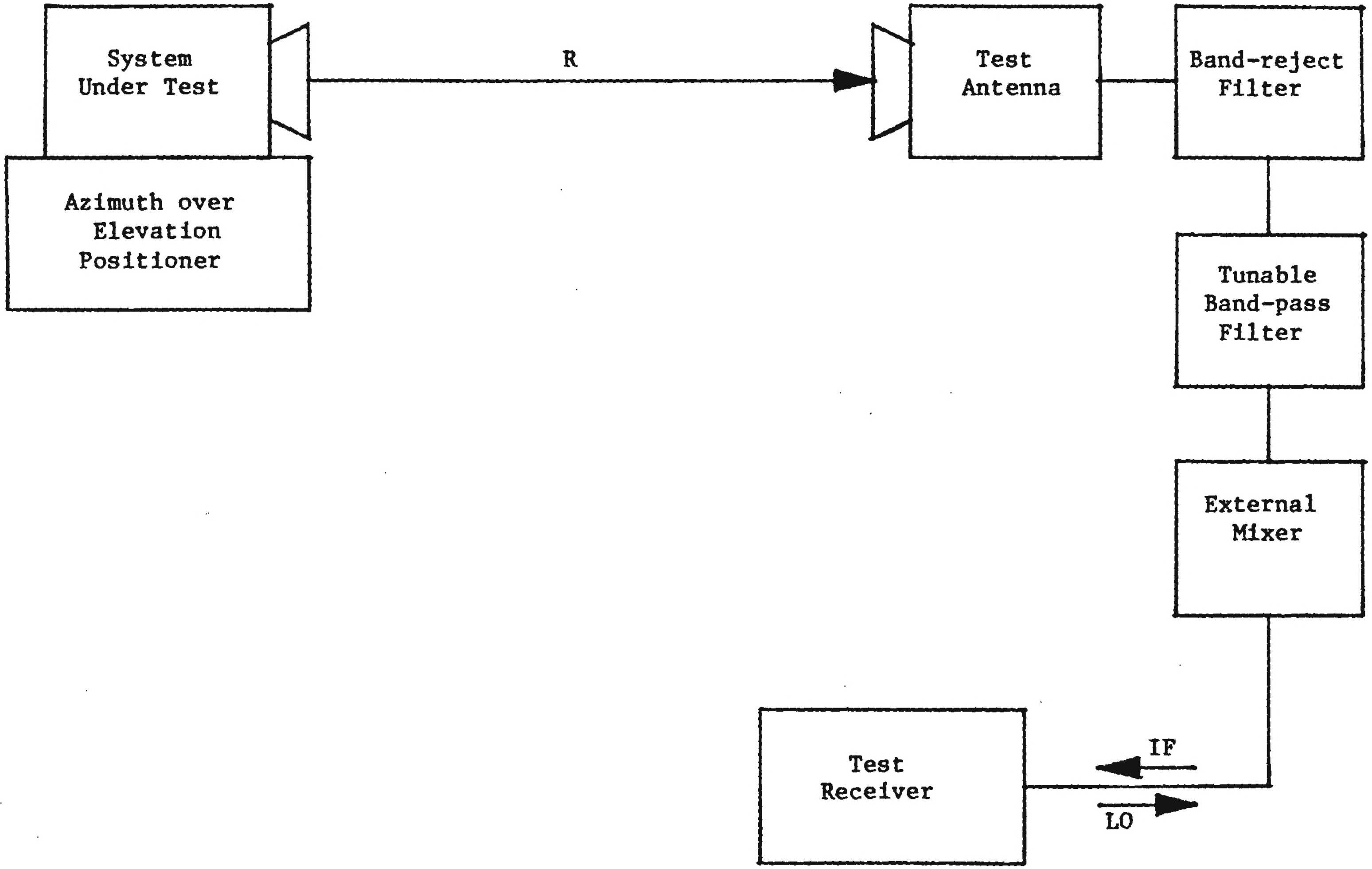


Figure 18. Recommended Equipment Configuration for Spurious Emission Measurements.

is then employed to down convert the received MMW signal. This harmonic mixing technique presents a problem in performing emission measurements if a spectrum analyzer is used as the test receiver. The problem arises due to the large number of spurious responses which are generated in the external mixer, making identification of the "true" response extremely difficult.

If the approximate frequency of the signal to be measured is known, the spectrum analyzer has a signal identifier routine which can be used to verify which particular response is the true response. However, if the frequency of the signal is not known (as is the case if the bandpass filter in Figure 18 is removed in order to look at the entire spectrum characteristics of the system under test), each response must be analyzed through the use of the signal identifier routine in order to identify the true responses. This problem will thus significantly increase the time and cost required to make the spurious emission measurements. Appendix C presents a more detailed discussion of the difficulties associated with the use of spectrum analyzers as EMC/EMI receivers in the MMW frequency band.

It is noted that the above problem is not new, but has existed since spectrum analyzers were first developed. For lower frequency spectrum analyzers, it has been overcome through the advent of electronically tunable bandpass filters which are controlled by the spectrum analyzer to sweep at the same rate as the spectrum analyzers display. Thus, although the spurious responses are generated, they are not seen on the display since the bandpass filter allows the RF signal to get to the mixer only when the spectrum analyzer is tuned to the true response. The use of spectrum analyzers for measurements in the MMW frequency band would be greatly enhanced if electronically tunable bandpass filters were also available in this frequency band.

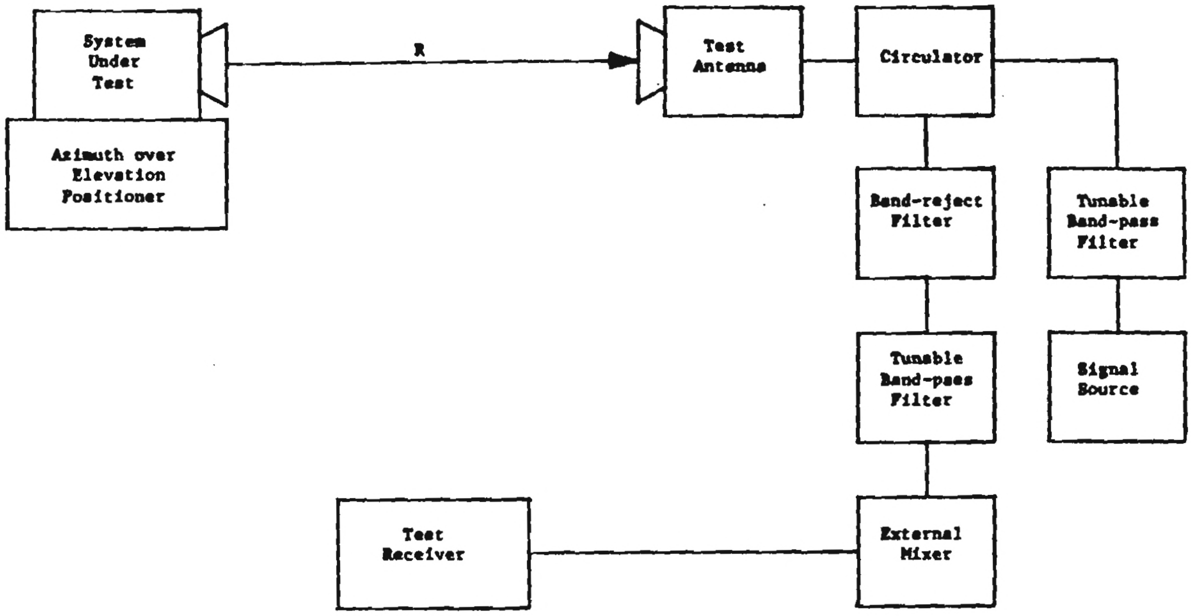
Transmitter Intermodulation Test

If a transmitter output stage is nonlinear, intermodulation (IM) products may be generated by external energy which is coupled into the nonlinear element. The undesired IM product may be radiated and act as a source of interference. The level of the intermodulation product obtained when an external signal is coupled into a transmitter output circuit depends of the selectivity of the coupling circuit, the level of the interfering signal, and the non-linearity of the output stage. Thus, transmitter IM products must be defined in terms of both the power level and frequency of the interfering signal.

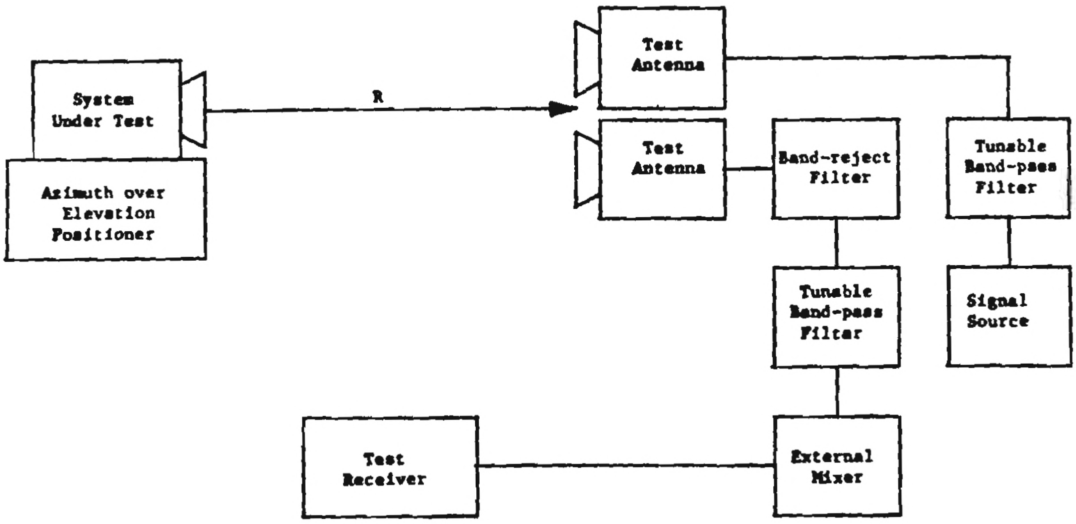
The potential for IM product formations in MMW transmitters is not yet known. If it is determined that tests for such products are required, a block diagram of the recommended equipment configuration for the transmitter intermodulation test is given in Figure 19. Figure 19(a) requires only one test antenna through the use of a circulator which isolates the interference source from the test receiver. Figure 19(b) requires two test antennas to perform the test. The bandpass filter between the interference source and circulator/antenna is used to ensure that the harmonics of the interference source are significantly reduced. All of the other equipment in Figure 19 serves the same purpose as discussed in the spurious emission test (Figure 18).

Intermodulation product frequencies may be generated according to the equation:

$$f_s = mf_o \pm nf_i. \qquad (5)$$



(a) One Test Antenna Method



(b) Two Test Antenna Method

Figure 19. Recommended Equipment Configuration for Transmitter Intermodulation Measurements.

The order of the intermodulation product is defined as (m+n) where m and n are the harmonic number of the transmitter fundamental frequency and interfering frequency as defined in the above equation. Generally, the measurements performed under this test are limited to second order and third order intermodulation products. The frequency range of the interfering source may be limited to the waveguide cutoff frequency on the antenna of the system under test (when applicable) for the lower limit and 300 GHz for the upper limit.

Generally, the interfering signal frequency is set at a frequency a given percentage away from the transmitter fundamental frequency. The interfering source level is then adjusted to obtain a field level at the transmitter under test which is a given number of decibels below the transmitter's fundamental signal level. Measurements are then performed to determine the levels of the various intermodulation products of interest (i.e., $2 f_o - f_i$, $f_o + f_i$, etc.) The above process is then repeated for various power levels of the interfering signal and for various frequencies of the interfering signal.

Transmitter Desired Emissions Test

The desired emissions tests are limited to systems such as transmitters which have desired outputs. Included in the desired emissions test is an emission bandwidth test, a frequency tolerance test, and a power output level test. These tests utilize the same measurement configuration as that shown in Figure 18 with the band reject filter removed. The test receiver used must be capable of accurately measuring frequency as well as power. The angular orientation between the system under test and the test antenna should be adjusted for maximum signal transfer.

The emission bandwidth test measures the bandwidth of the transmitter emission around the fundamental frequency of the transmitter's output. The modulation used in this test should be similar to that employed in an actual operating environment. The frequency tolerance test determines the frequency stability of the transmitter under test, and the power output level test measures the maximum output power of the transmitter throughout the transmitter's frequency coverage.

5.2.2 Susceptibility Measurements

The recommended radiated susceptibility measurements for MMW equipment are as follows: spurious responses, receiver intermodulation, receiver desensitization, receiver sensitivity, receiver selectivity, and receiver dynamic range.

Spurious Responses Tests

The spurious response test determines the receiver's response characteristics to frequencies outside its passband. Since the test is performed on a radiated basis, it will include responses due to energy which is coupled into the equipment circuitry through the antenna port as well as through the case. These responses present the same problem during spurious response tests as they do during the spurious emissions tests. Again, a possible solution is to impose a shielding effectiveness test on the case before the antenna is installed into the equipment under test and, where possible, to perform tests using a suitable dummy load on the antenna port of the equipment.

The spurious response test's applicable frequency range should be the same as that already imposed by military standards with the upper limit extended to 300 GHz. MIL-STD-461A presently requires electric field radiated susceptibility measurements from 10 kHz through 12.4 GHz. Therefore, it will only be necessary to develop a measurement technique for spurious response tests from 12.4 GHz through 300 GHz.

A block diagram of the recommended equipment configuration for spurious response measurements in the MMW band is shown in Figure 20. The bandpass filter is used to suppress the harmonics and other spurious emissions of the interfering source. The entire test sample should be within the 3 dB beamwidth of the transmitted field, and the interfering source/test antenna combination should have sufficient output power/gain to produce the required field intensity at the equipment under test. Since the amount of energy which is coupled into the system under test is a function of angular orientation, the system under test should be placed on a azimuth over elevation positioner and rotated in both azimuth and elevation at each test frequency in order to find the orientation for maximum susceptibility. The output of this test may be monitored with a suitable monitoring device such as an rms voltmeter, power meter, distortion analyzer, or oscilloscope.

Receiver Intermodulation Test

Intermodulation characteristics are indications of the interference potential of a receiver in the presence of off-channel radiation. Intermodulation interference will occur if two off-channel signals are combined in the nonlinear elements of the receiver to produce a new signal which fall at the receiver's tuned frequency or its IF.

The order of an intermodulation product is defined in Equation (5) as m+n, where m and n are the harmonic numbers of the two interfering sources. Normally the most significant intermodulation effects are due to third-order products. In general, odd order products produce spurious signals which lie close to the frequency of the desired signal, while the frequencies of spurious signals associated with even order intermodulation products are far removed from that of the desired signal. Consequently, when appropriate frequency selective filters are available, the signals associated with even order products can be more readily attenuated than those produced by odd order products.

Figure 21 is a block diagram of the recommended equipment configuration for the receiver intermodulation test. The configuration of Figure 21(a) uses a hybrid to combine the two source frequencies at one antenna (this method is only applicable if the test antenna has sufficient bandwidth). Figure 21(b) utilizes two test antennas. The bandpass filters are used to suppress the harmonics of the interfering sources. As discussed for the spurious response tests, the receiver under test should be oriented to maximize the intermodulation product level.

Generally, intermodulation tests are limited to those frequencies whose second and third order products fall at the receiver's tuned frequency and to those frequencies whose second order products fall at the receiver's IF. The two intermodulation test frequencies, f_a and f_b, for third order products are chosen such that their difference, Δf, is equal to $f_a - f_o$, where f_o is the receiver tuned

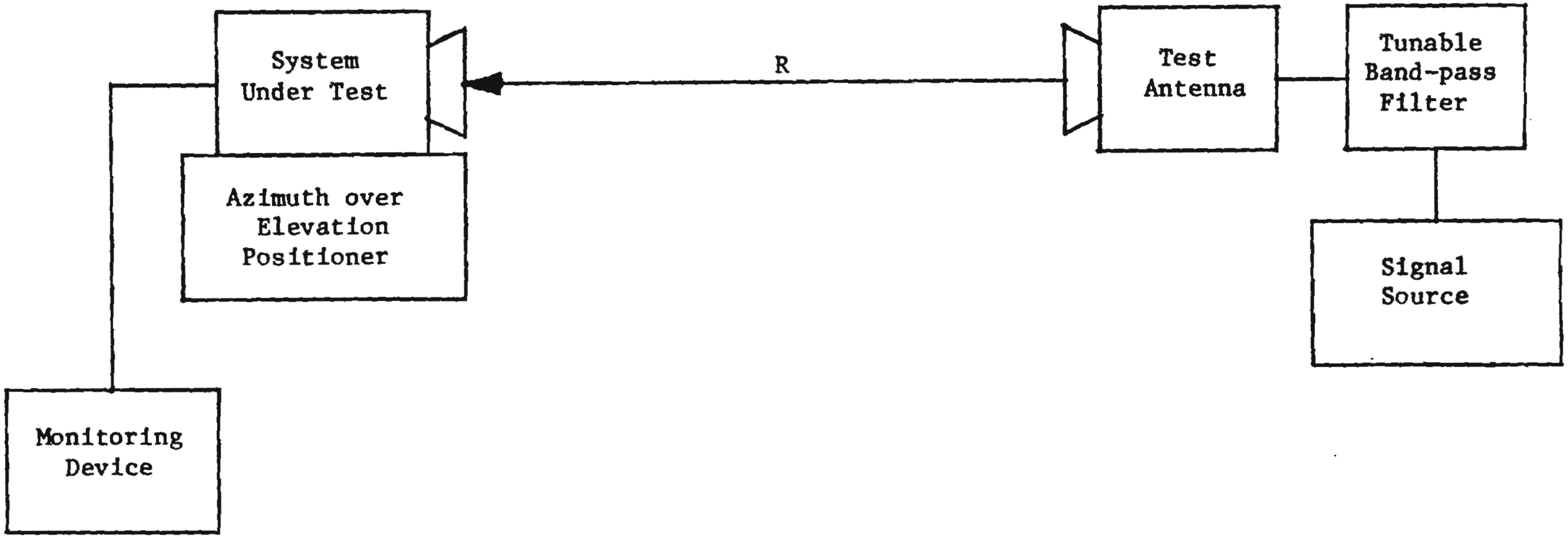
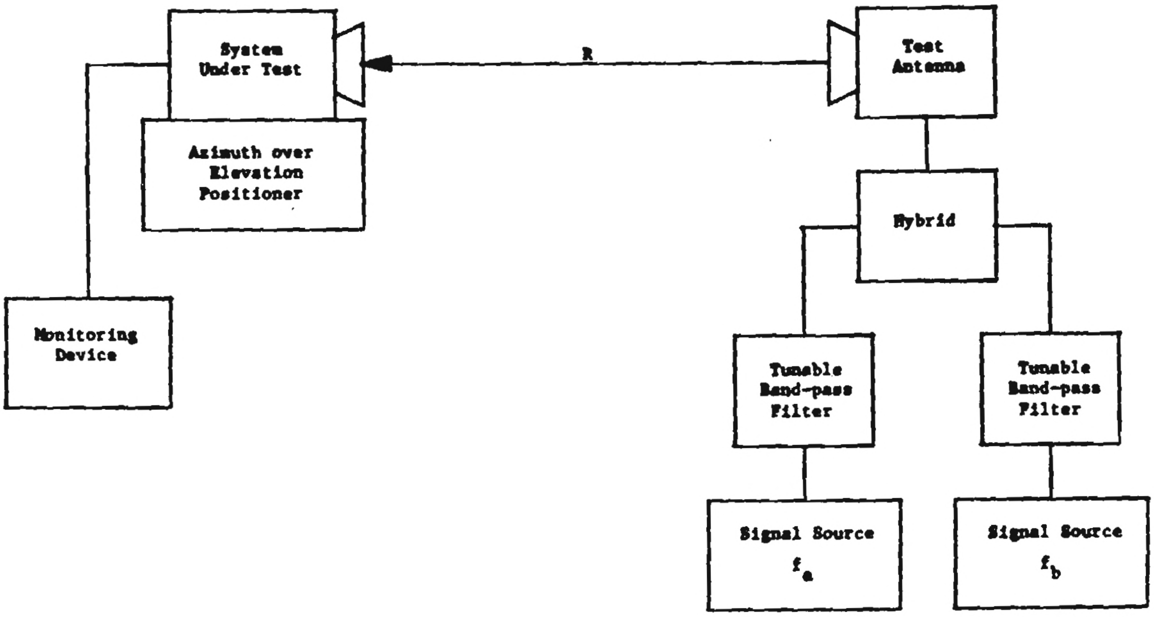
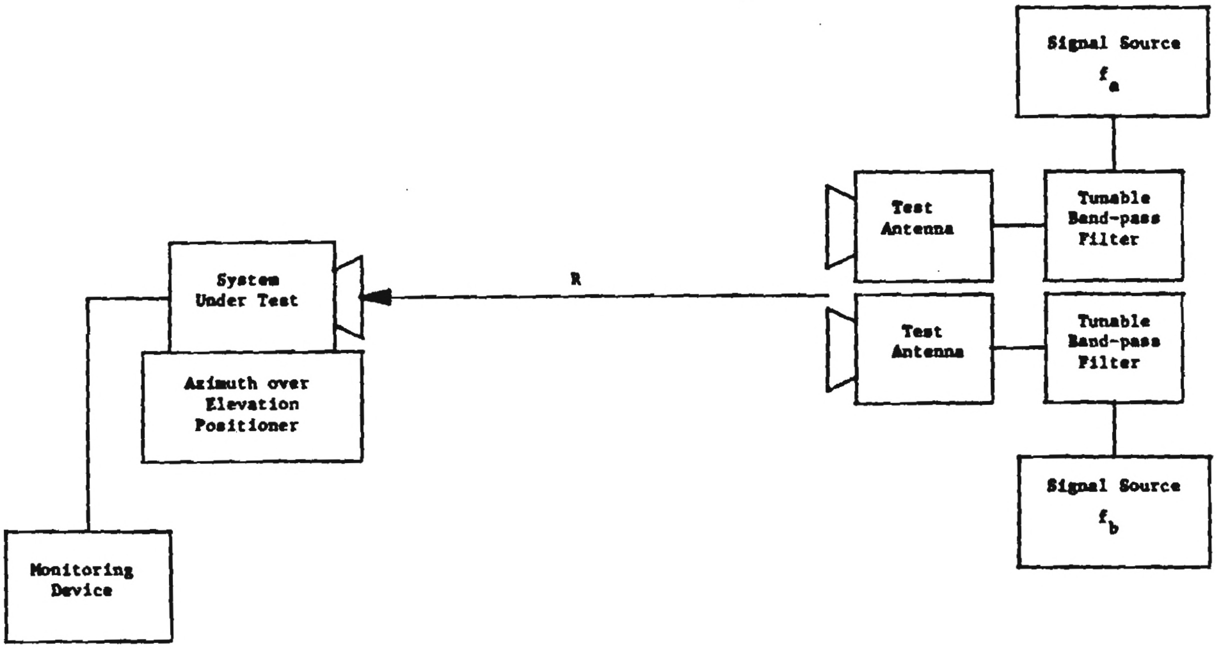


Figure 20. Recommended Equipment Configuration for Spurious Response Measurements.



(a) One Test Antenna Method



(b) Two Test Antenna Method

Figure 21. Recommended Equipment Configuration for Receiver Intermodulation Measurements.

frequency. (f_a is assumed to be the frequency nearest f_o.) The second order test frequencies are chosen such that their sum or difference equals either the receiver tuned frequency or its IF. For MMW receivers, two test frequencies must be greater than the waveguide cutoff frequency and less than 300 GHz.

Generally, f_a is set as close to f_o as possible without causing a close-channel response, and f_b is then set to give the appropriate intermodulation product. While using equal signal levels for the two interfering frequencies, the levels are increased until a given response is measured on the monitoring device. Δf is then increased and the above procedure repeated. This procedure is continued until the frequency range is covered and enough data points are taken to assure that a smooth curve of Δf versus power level is obtained. This test can then be performed for various receiver tuned frequencies.

Receiver Desensitization Test

The desensitization test is a measure of the receiver's ability to function despite the presence of on-channel interference. The desensitization test measures the sensitivity of a receiver in the presence of on-frequency CW interfering signals; thus, this test is a measure of the receiver's ability to perform its normal function despite the interference caused by the CW signal.

The test setup used for the desensitization test is the same as that used for the receiver intermodulation test (Figure 21), except that both signal sources are tuned to the receiver's tuned frequency. One of the sources is used to represent the desired signal and should be modulated similar to that employed in an actual operating environment. The other source represents the interfering signal and should thus be unmodulated. The receiver is monitored to determine the effects of the CW signal for various power levels.

Receiver Desired Response Tests

The desired response tests include a sensitivity test, selectivity test, and dynamic range test. These tests utilize the same measurement configuration as that shown in Figure 20 with the angular orientation between the system under test and test antenna adjusted for maximum power transfer.

The sensitivity test determines the weakest signal that produces a standard response at the output of the receiver. This test should be performed at several frequencies throughout the receiver's frequency coverage. The selectivity test is a measure of the overall gain and sensitivity at the receiver's tuned frequency as well as the response at frequencies slightly removed from the tuned frequency; thus, it is a measure of the receiver's bandpass characteristics. The dynamic range test measures the effectiveness of the receiver's AVC or AGC system, if one exists, and describes the receiver's linearity between minimum response level and saturation level.

6.0 MEASUREMENT INSTRUMENTATION

6.1 State-of-the-Art of MMW Components and Their Availability

Measurement of the EMC characteristics of systems operating in the 10-300 GHz frequency range impose stringent demands on facilities, test instrumentation and methodology. The development and field deployment of communication/radar systems operating in the 10-300 GHz frequency range represent a relatively new field, and the availability of commercial off-the-shelf test equipment and instrumentation for use in this frequency range is currently limited. Furthermore, measurement techniques and approaches which are commonplace at lower frequencies may not be feasible at MMW frequencies, either because of test equipment limitations or because of the time and cost involved in implementing and utilizing a specific technique.

At frequencies greater than 220 GHz the number of components available to the designer decreases rapidly as shown in Table VIII. Many of the components needed to implement an EMC measurement facility, such as directional couplers, attenuators, and mixers, may be procured only on a special order basis. A brief summary of the state-of-the-art of MMW components and instrumentation is presented below.

6.1.1 MMW Sources

Ideally, a MMW radiated test facility should be equipped with an RF source which provides continuous coverage of the entire 10-300 GHz spectrum. Practical considerations limit the maximum tunable bandwidth of sources to the waveguide bands shown in Table IX. This table shows that approximately six waveguide sizes are required to encompass the MMW frequency decade. Waveguide components such as frequency meters and attenuators are available to cover each waveguide band.

There are three basic types of coherent millimeter wave sources: (1) vacuum tube sources including klystrons, magnetrons, and gyrotrons, (2) solid state sources such as Gunn and IMPATT diodes, and (3) laser sources including both discharge and optically pumped devices. Because most of the laser sources operate above 300 GHz, they will be excluded from the following discussion.

Table X gives a summary of existing MMW RF test sources. The general power versus bandwidth trade-off rule applies to MMW sources. Those sources with the desired bandwidths are generally not capable of providing high output powers. For example, the Siemens BWO sources which may be tuned over an entire waveguide bandwidth are limited to about 1 mW (leveled), while the 1-10 watt Hughes IMPATT sources are essentially fixed frequency.

Tube Type Devices. At the lower end of the MMW frequency region, some of the RF power sources used in the microwave frequency region are still applicable, but with decreased power capabilities and reduced tuning range. A summary of state-of-the-art power generation capabilities of MMW tube type devices, both CW and pulsed, is given in Figure 22. Included with these sources is a Litton Industries 35 GHz, 60 kW peak power magnetron, tunable over about a 0.4 GHz range. Above 35 to 40 GHz, the power output of magnetrons drops sharply. The only currently available magnetron at 95 GHz is an English Electric Valve magnetron which provides 1 KW peak. MMW magnetrons are unable to withstand the high anode currents which are necessary for

TABLE VIII

Typical Upper Frequency Limit of Millimeter Wave Components Available

1. Precision Attenuators			
	A. Hughes	Model 4572	To 170 GHz
	B. TRG	Model 510	To 220 GHz
2. Precision Frequency Meters			
	A. Hughes	Model 4571	To 170 GHz
	B. TRG	Model 551	To 110 GHz
3. Precision Phase Shifters			
	A. Hughes	Model 4575	To 170 GHa
	B. TRG	Model 528	
4. Isolators			
	A. Hughes	Model 44607 H	To 110 GHz
	B. TRG	Model 111	To 140 GHz
		Model 112	To 220 GHz
		Model 167	To 110 GHz
	C. Baytron	Model 2D-1	To 325 GHz
		Model 2D-10	To 325 GHz
5. Mixers			
	A. Hughes	Model 4735	To 220 GHz
		Model 4743	To 223 GHz
	B. TRG	Model 9800	To 140 GHz
		Model 922	To 140 GHz
		Model 921	To 140 GHz
		Model 960	To 220 GHz
		Model 967	To 220 GHz
		Model 968	To 220 GHz
6. Directional Couplers			
	A. Hughes	Model 4437X	To 110 GHz
	B. TRG	Model 561	To 110 GHz
		Model 559	To 110 GHz
	C. Baytron	Model 3xx-40	To 325 GHz
7. Local Oscillators			
	A. Hughes	Model Impatt 4717	To 100 GHz
		Model Impatt 41252	To 100 GHz
		Model Impatt 41451	To 100 GHz
8. Receivers			
	A. Textronix Spectrum Analyzer Model 492		To 220 GHz
	B. Scientific Atlanta Receiver Model 1700		To 90 GHz

Table IX

STANDARD WAVEGUIDE BANDS

Waveguide Type	Frequency Range (GHz)
28	26.5 - 40
22	33 - 50
19	40 - 60
15	50 - 75
12	60 - 90
10	75 - 110
8	90 - 140
6	110 - 170
5	140 - 220
4	170 - 260
3	220 - 325

Table X

EXISTING MMW SIGNAL SOURCES

Device	Frequency Coverage (GHz)	CW Power (mW)	Modulation	Approximate Cost
HP8690 sweeper	.0004-50	4	AM	$7K
Siemens	33-50	30	AM/FM	$100K
BWO sweeper	50-75	10		
model 703CL	75-110	4		
	110-170	1		
Hughes	26-40	2	AM/FM	$130K
Model 8350	40-60	2		
sweeper	60-90	2		
	90-110	1		
	110-150	1		
Hughes	26-40	200	AM/FM	$462K (at 100 MHz
CW Impatt	40-60	200		858K bandwidth each,
sources	60-90	200		2277K 840 sources are
	90-96	200		587K needed
	96-110	50		908K ($5,092,000) to cover 26-110 GHz)
Hughes	34-36 each source	10W	Chirp only	$10K each
Pulsed	58-62 at fixed freq.	1W		(useful only at
Impatt	92-96 within given	5W		discrete fixed
Sources	range			frequencies)
Varian EIA	95.0-95.5	30W	May be pulsed (1 kW)	$20K
Varian	58-64	70mW	CW	$4400
Klystron	67-73	70mW	CW	$5600
	80-86	70mW	CW	$5600
	112-120	70mW	CW	$6800
	135-143	70mW	CW	$6800
	162-170	70mW	CW	$9000
	220	70mW	CW	$14,500

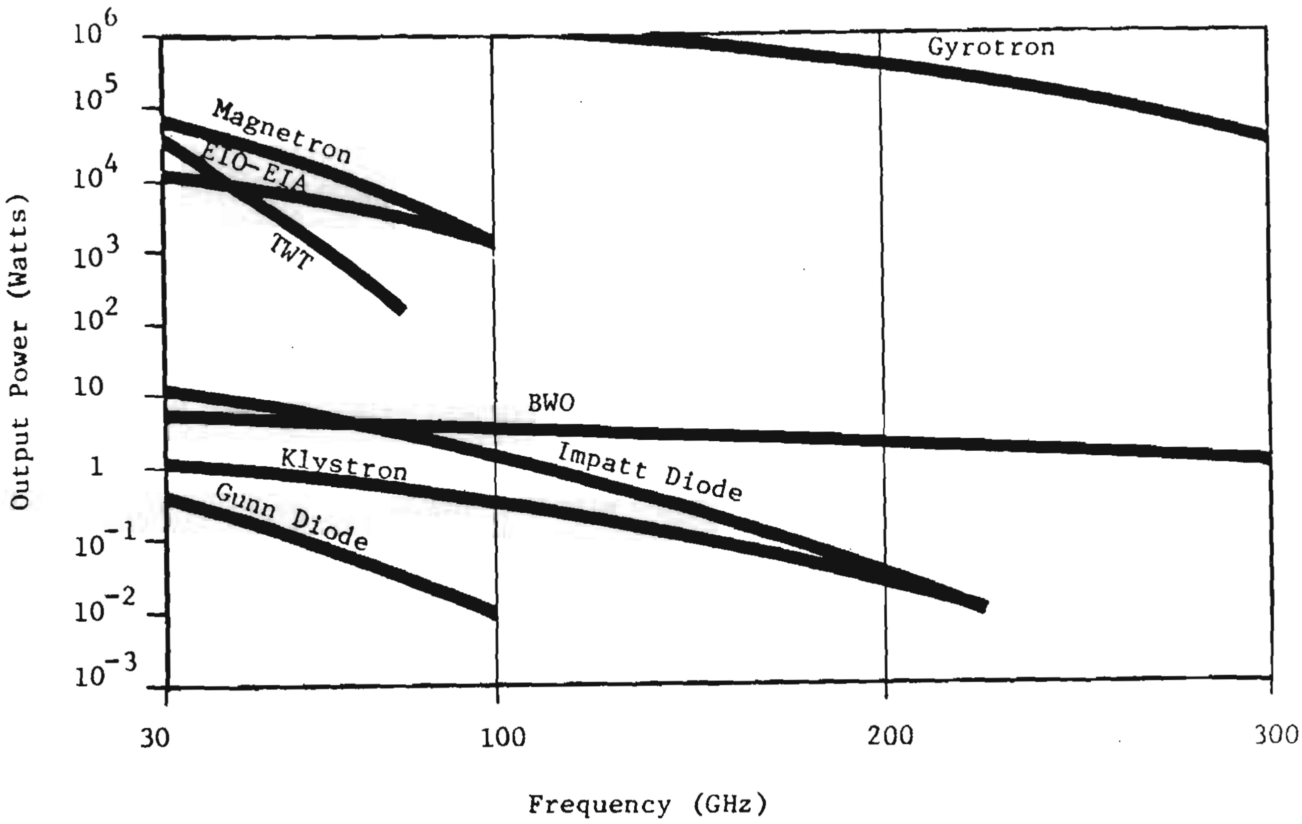


Figure 22. Peak Power Capabilities of Existing MMW Power Sources.

the generation of hundreds of kilowatts of power. The resonant cavity sizes of MMW magnetrons are so small that their frequency determining structures erode under high currents. As the cavities and resonant structures of the magnetron are reduced in size, current densities increase and cooling becomes more difficult. Thus it is unlikely that practical magnetrons above 100 GHz will be available in the near future.

Another useful low power MMW source is the reflex klystron. Klystrons are very stable and have good spectral purity relative to most other MMW sources, may be readily adapted to LO functions, and are readily phase locked. The maximum klystron power available at the present time above 100 GHz is about 100 mW, with several milliwatts available at 220 GHz. As is true with magnetrons, MMW klystrons have cavities and frequency determining structures which are very small. Therefore, klystrons also suffer power handling problems at MMW frequencies. Since klystrons require up to 2000 volts reflector potential, most applications are found in the laboratory.

Another tube type MMW source is the extended interaction oscillator (EIO). In the last few years EIO's have become available at frequencies as low as 40 GHz and as high as 260 GHz. Pulsed outputs of about 100W are available at 220 GHz and pulsed outputs of about 6 kW are available at 30-40 GHz. The EIO output power can be varied by changing the cathode-resonator beam voltage. Narrow frequency tuning is also electronically achieved. Mechanical tuning by motion of the tuning piston is also possible and permits a much broader frequency range than does electronic tuning. There are currently water cooled EIO's capable of 1 kW CW output power between 30 and 40 GHz and some capable of 50 watts CW at around 100 GHz. Some pulsed units provide 2 kW peak power at 10% duty factor between 30 and 50 GHz, and some provide about 1 kW at 1% duty factor at around 100 GHz.

Traveling wave tubes (TWT's) are available up to about 40 GHz, with the highest power being about 30 kW for a new 35 GHz unit intended for radar use. TWT's commonly have wide tuning ranges of 7 to 8% of center frequency.

The gyrotron is another MMW vacuum tube, capable of very high power output. Energy is taken from an electron beam by sending the beam through a magnetic field in such a way that the electrons go into cyclotron resonance. Energy generated by the resonant interaction cavity is coupled into the output waveguide. This type of energy coupling allows the dimensions of the RF coupling stucture to be large relative to the RF wavelength. This large size to wavelength ratio permits the use of much higher powers than could be handled through smaller RF resonant structures. It can therefore be concluded that the gyrotron is the most effective means of generating hundreds of kilowatts of power at MMW frequencies.

Very limited data is currently available which addresses the issue of noise and signal spectral characteristics of MMW active tube devices. Data measured recently by Georgia Tech of the noise characteristics of a 94 GHz klystron indicates there is not any appreciable difference between a MMW and a more conventional microwave CW klystron device [15].

<u>Solid State Sources</u>. MMW solid state power sources are relatively low power compared to tube type devices. Gunn oscillators are capable of about 200 mW output at 40 Ghz and about 10 mW output at frequencies as high as 100 GHz, the upper limit of their frequency coverage. These oscillators are useful only as LO's or as low power transmitters. They can also be phase locked for use in coherent systems. Gunn diodes are relatively low noise devices with narrow spectral distributions.

Impact Ionization Avalanche Transit Time (IMPATT) diodes cover frequencies from about 3 to 230 GHz, with rapid falloff in efficiency with increasing frequency. For instance, efficiencies fall below 1% above 100 GHz. IMPATT's have CW power capabilities to 0.5 W at 40 GHz and 10 mW at 230 GHz; pulsed IMPATTs are capable of 5W pulsed power at 95 GHz. IMPATT's are noiser than Gunn diode devices because of their inherent avalanche generation, and have considerably wider spectral distributions. IMPATT devices can also be phase locked.

Frequency multipliers are available for generating MMW RF from lower frequency solid state sources. These devices are of low efficiency and have low power capability. For example, varactor multipliers used to convert 70 GHz to 140 GHz have about 35% efficiency for a 45 mW input power. Varactor multipliers are available to frequencies up to about 200 GHz.

At the present time, high power MMW sources are not available to sweep across the entire 30-300 GHz spectrum. Therefore, radiated susceptibility testing with currently available MMW sources may be limited to certain frequencies or frequency bands.

Whatever the signal source, measures must be taken to minimize the harmonic content in the test signal. Probably the most viable technique for harmonic suppression is the use of lowpass suspended substrate quartz stripline filters at the generator output. The expected filter insertion loss in its passband would be about 2-3 dB. Such low pass filters are not currently available as off the shelf items but can be designed and built on special order.

Sweeper signal generators usually do not have any RF output filters to suppress harmonics. Harmonic output levels less than 30 dB below the fundamental are not uncommon.

The frequency and amplitude stability of MMW sources is a factor in overall measurement accuracy. Table XI presents typical MMW source stabilities. In general, the frequency stability of unlocked sources is related to power supply voltage stability and temperature control; these parameters are limiting factors in source stability. By use of a "lock box" (frequency stabilizer), frequency stabilities which are orders of magnitude better than unlocked sources can be obtained. However, the tuneability feature of the source is lost, i.e., the source can only be locked at discrete frequencies.

6.1.2 Receivers

An essential piece of equipment for making EMC emission measurements at any frequency is the receiver. At MMW frequencies a typical equipment setup for radiated emission measurements utilizes a spectrum analyzer with suitable down converter mixers.

Representative spectrum analyzer parameters are shown in Table XII. Both the Hewlett Packard (HP) and Tektronix analyzers incorporate programmable control and data bus interfaces. Thus, the ability to proceed toward semi-automated measurement features are inherent in these equipments.

One potential problem with using the spectrum analyzer as the RF receiver in the MMW region is the generation of false signals by the spectrum analyzer itself. When used with external mixers, there is no signal preselector to uniquely identify

Table XI

TYPICAL FREE RUNNING MMW SOURCE STABILITY

Source Type	Frequency Stability	Power Stability
Carcinotron	0.030%/V, approximately 0.001%/°C	~0.5 - 1.0% P-P variation
Gunn	0.15%/V, 0.006%/°C	1%/°C
IMPATT	0.01%/V, 0.005%/°C	1%/°C
Klystron	0.003%/V, 0.0016%/°C	0.6% P-P variation
Lock Box	Zero Drift Aging in Atomic Standard $\pm$ 7 x 10^{-10}% (Atomic Standard Accuracy) 5 x 10^{-8}%/day (EIP 545/548 aging rate, option 05) 1 x 10^{-7}% (short term stability EIP545/548) 2 x 10^{-4}% (temp variation from 0-50°C EIP545/548) 1 x 10^{-6}%/day (standard TCXO aging rate EIP545/548) 5 x 10^{-8}%/day (HP 10811A TCXO aging rate)	N/A

Table XII

SPECTRUM ANALYZER SUMMARY

	Parameter				
MFG	Frequency Coverage	Data Processing Interface	Programmable Feature	Availability	Basic Cost
HP	HP8566A 100 Hz to 22 GHz (plus up to 220 GHz with external mixers)	HP-IB Bus IEEE 488 std	Yes	27 weeks	$54.5K
Tektronix	Model 492P 50 kHz-220 GHz	GP-IB IEEE 488	Yes	6 months	$25K
Polarad	3MHz to 40 GHz	IEEE interface	Yes	2 months	$18K

signal frequencies. The HP 8566A spectrum analyzer makes use of a special microprocessor system to identify the desired signal among the spurious signals.

An alternate concept for radiated measurements is to utilize down converters in conjunction with commercially available broadband microwave receivers. A limitation to this technique is that the useable mixer bandwidth will be limited to the bandwidth of the waveguide used on the RF port of the mixer. Thus a large number of mixer combinations would be required to cover the MMW spectrum, and the growth ability of the system toward semi- or fully automated measurements, would be severely handicapped. Therefore, the spectrum analyzer approach is preferred at this time.

One other type of receiver which can be used to measure the amplitude of MMW signals at a single frequency is a power meter. Table XIII lists four manufacturers of MMW power meters with the frequency coverage and dynamic ranges of their meters. All of the meters are in the 10% accuracy range when using a standard bolometer.

6.1.3 MMW Components

Ancillary components such as mixers, waveguide filters, waveguide switches, dummy loads, isolators, etc., are essential to the physical realization of a viable MMW EMC test setup. It should be noted that MMW components in general have higher losses, higher VSWR's, and lower isolations than their microwave counterparts. Also, many of the components commonly employed at lower frequencies may not be available at MMW frequencies.

Mixers. MMW mixers with a conversion loss and noise figure equivalent to microwave mixers are difficult to achieve. Gallium Arsenide Schottky (GaAs) barrier diodes used between 30 and 140 GHz have noise figures (NF's) ranging from 6 dB at 30 GHz to 13 dB at 140 GHz. GaAs harmonic mixers are available which operate at even harmonics of the LO. Second harmonic and fourth harmonic mixers have been used at 95 GHz and 200 GHz, respectively, with LO's around 45 GHz and 55 GHz.

The different types of mixers include the Schottky barrier diodes, Josephson junctions, and tunnel diodes. Schottky barrier diodes are currently available which will operate at frequencies as high as 2300 GHz. This high frequency operation results from the low resistivity of the diode material and low capacitance of the metal-semiconductor point contact. The Schotttky diode is generally considered to be the best device available for sensitive MMW receiver mixers.

A summary of the state-of-the-art in MMW mixers can be found in Table XIV.

RF Filters. MMW RF filters have recently become available as special order items from Hughes. High pass, low pass, band pass and band stop filters are available from 30-220 GHz. The filters are designed to the purchaser's performance specifications and are priced individually.

Waveguide bends and twists are available from Baytron, TRG and other vendors at all MMW frequencies, at prices ranging from $50 at 30 GHz to $350 at 300 GHz. VSWR's are typically below 1.1 across the waveguide band.

Hybrid Junctions of ring and magic tee configurations are commercially available at all MMW frequencis. Insertion losses range from 0.3 dB at 30 GHz to 1.8 dB at 300 GHz. VSWR's range from 1.2 at 30 GHz to 1.4 at 300 GHz. Ring hybrid costs range from around $400 at 30 GHz to $3,000 at 300 GHz; magic tees are only furnished on special order.

Table XIII

POWER METER FREQUENCY AND DYNAMIC RANGE

MFR	FREQ Range (GHz)	DYNAMIC Range (W)
TRG	26.5 - 325	10^{-4} - 0.5
HP/HUGHES	26.5 - 110	10^{-5} - 10^{-2} (to 75 GHz)
		10^{-5} - 3 x 10^{-3} (60-110 GHz)
C & K	90 - 300	0 - 10 mW } Ranges
		0 - 100 mW } Ranges

TABLE XIV

State-of-the-Art Performance of Millimeter Wave Mixers

HARMONIC MIXERS are available at all frequencies between 30 and 220 GHz. Conversion loss is 30 dB at 220 GHz and less than 10 dB at 30 GHz.

SUBHARMONIC MIXERS are available through 220 GHz.

SINGLE ENDED MIXERS are available to cover the 30 to 220 GHz range. Conversion losses range from about 6.5 dB to 14 dB.

FOURTH-HARMONIC MIXERS to operate at 220 GHz with a 55 GHz LO are currently under development at Georgia Tech with conversion loss under 10 dB.

RF Waveguide Switches. Three and four port waveguide switches are available with VSWR's ranging from around 1.15 at 30 GHz to 1.4 at 300 GHz. Port-to-port isolation is greater than 40 dB. Insertion losses (switch losses) range from about 0.3 dB at 30 GHz to 1.0 dB maximum at 300 GHz. Prices range from $400 (30 GHz) to $3,000 (300 GHz).

Isolators. Ferrite isolators are available from 30 GHz to 220 GHz. Isolations range from 20 dB to 17 dB and insertion losses from 0.6 dB to 2.1 dB over this frequency range. VSWR's range from 1.2 to 30 GHz to as much as 1.5 at 300 GHz. Prices encompass $400 at the low end to more than $1600 at 220 GHz.

Dummy Loads have power handling capacities ranging from 500 W at 30 GHz to about 10 mW at 300 GHz, with VSWR's ranging from 1.05 to 1.15 over this frequency span. Prices may range from $50 (30 GHz) to $400 (300 GHz).

Phase Shifters. Ferrite phase shifters are available from TRG from 30 GHz to 110 GHz with typical insertion losses of 2.5 to 3.0 dB. VSWR's are typically 1.2 - 1.3. Mechanical vane type phase shifters are available up to 220 GHz; insertion loss is in the order of 1 dB.

Waveguide. Standard waveguide stock and hardware is available for waveguides down to WR-3. This includes flanges, alignment pins, and coupling screws. Prices range from $275/ft. for W band guide to $355/ft. for G band waveguide.

Directional Couplers. Directional couplers are available from Hughes, Baytron, Thomson-CSF and other vendors. Coupling variances range from about 0.6 dB at 30 GHz to about 0.8 dB at 300 GHz; 3, 20, 30 and 40 dB couplers are available. VSWR's are typically below 1.2, and insertion losses are slightly greater than corresponding microwave directional couplers. Prices range from roughly $200 at 30 GHz to $1,200 at 220 GHz; units at 220 to 300 GHz are specially priced.

Attenuators. Fixed MMW waveguide attenuators are available over the full MMW spectrum from TRG, Baytron and other vendors with typical accuracies of 0.1 dB. Prices range from about $100 to $300. Maximum VSWR's range from 1.15 to 1.25.

Variable attenuators are also made for use in the MMW region by TRG and Baytron. The maximum VSWR ranges from 1.15 to 1.25 with maximum CW powers of 0.6W at 30 GHz and 0.2W at 300 GHz. Prices range from about $175 at 30 GHz to around $675 at 300 GHz.

PIN attenuators are made to operate at frequencies as high as about 100 GHz.

Ferrite Components. Many ferrite devices used at the low MMW frequency band are nearly as efficient as similar microwave components. Up to 140 GHz, waveguide couplers, tuners, attenuators and ferrite switches are still useful. Ferrite device performance degrades rapidly above 140 GHz; above 220 GHz most components are no longer usable because of high losses. Waveguide is commercially available which is usable up to 325 GHz (WR-3-0.030 x 0.015 inches i.d.) but ohmic losses are over 20 dB/meter, depending on the precision of waveguide machining.

MMW ferrite devices at 140 GHz may work satisfactorily for many applications. A typical ferrite waveguide switch has 20 dB of isolation and an insertion loss of about 2 dB. Diode switches have been used up to 95 GHz, but have high losses (typically as high as 3 dB) and poor isolation (typically 15-20 dB).

Quasi-Optical Components. Still to be considered among MMW components are the quasi-optical devices most useful in the upper MMW frequencies. A quasi-optical attenuator can be made from a rexolite cube. It operates on the principle of frustrated total internal reflection (FTIR). A millimeter wave signal incident on one face of the cube will propagate inward to the diagonal space. The portion of the wave propagated across the diagonal space depends on the width of the space. The FTIR attenuators or switches work only at low switching rates since they require mechanical motion of one half of the block material.

Above 220 GHz, optical transmission techniques are preferable to waveguide because of waveguide losses. Optical techniques are also used at lower MMW frequencies and many optical waveguide hybrid systems have been developed in the transition region between 90 and 220 GHz.

6.1.4 Conclusions

Existing instrumentation will be sufficient to perform basic EMC/EMI measurements over the lower MMW frequency region. However, it is felt that an advancement in the state-of-the-art of practical MMW instrumentation will be necessary in order to cover the upper MMW frequency region.

It is important to recognize that the problem of obtaining sufficient source power and receiver sensitivity for performing radiated emission and susceptibility measurements is strongly indicative of a probable lack of significant EMI problems at MMW frequencies. In other words, if sufficient MMW source power is not available to perform susceptibility measurements, then it is unlikely that MMW transmitters will be a major source of interference in a field environment. This is not to imply that EMC/EMI problems will not exist at MMW frequencies or that EMC/EMI testing at MMW frequencies is not required. However, it is felt that the nature and extent of EMC/EMI testing should be commensurate with the likelihood of interference at MMW frequencies.

In general, the need for EMC/EMI data is not dependent upon the availability of measurement instrumentation or techniques for obtaining the data. In fact, the need, and the establishment of data requirements to fill this need, often gives the necessary impetus for the development of appropriate measurement instrumentation and techniques. For this reason the definition of EMC/EMI data requirements for MMW system is not based on current MMW measurement technology, but rather is based on those identified data needs which are considered significant. It is thus expected that advances in current MMW technology will be required in order to satisfy some of the identified requirements.

Although data needs are considered independent of the means for acquiring the data, it is important to recognize that advances in technology are not automatically brought about by a need. Historically, tradeoffs in EMC/EMI data requirements have been necessary simply because of technology or cost constraints. Thus, the establishment of data requirements for MMW systems must also be based on realistic judgements of the capability of future technology for satisfying these requirements.

In conclusion, it should be noted that even though a particular piece of equipment or component may be available from a vendor it may not be readily available. Since most of these items are not high demand items, they cannot be readily purchased off-the-shelf. One should also consider the fact that most of this equipment is state-of-the-art and it may not be adorned with all of the accessories one may be accustomed to on modern microwave equipment.

6.2 Automated Measurements

6.2.1 Concepts of Automated Measurements

The three basic methods of making measurements are: (1) manual, (2) semi-automated, and (3) fully automated. (Automation is defined as the use of a computer to control or aid in a particular process. With the advent of modern technology in the computer industry, automation has become the norm rather than the exception.)

(1) Manual--Manual measurements are made without the aid of a computer. This type of measurement requires the complete and total attention of a technician to direct the experiment and record the data. Manual measurement techniques are rapidly being replaced with low cost computer controllers and programmable instruments.

(2) Semi-Automated--Semi-automated measurements utilize a computer to control part of the equipment, but operator interaction is required to complete the entire measurement. This type of measurement may be the most common measurement scheme used today, where most of the equipment used in the measurement is controlled by a computer, but the initial calibration and the switching of certain pieces of equipment in and out of the setup at certain times may require operator intervention.

(3) Fully Automated--Fully automated measurements are made totally under the control of a computer. The equipment is calibrated, various pieces of equipment are switched into and out of the setup at the appropriate time, and the final data is collected and stored by the computer. The computer can then manipulate or post-correct the data in any way desired, and produce an output which is of high enough quality to go directly into a report. Throughout this entire process there is no need for any operator intervention except for monitoring; thus this method may be the most cost effective for some applications.

The best way of demonstrating the three measurement methods may be through an example of antenna pattern measurements. A manual measurement would require the operator to set the source of each test frequency, connect the standard gain antenna for calibration, connect the test antenna with all required filters and mixers, start the antenna positioner, and finally document the antenna pattern. A semi-automated antenna measurement might have the source and the receiver/antenna positioner under computer control. Thus the operator might have to connect the calibration antenna, and then the test antenna, but the computer would change the frequency, automatically switch the required filters and mixers, and finally plot the antenna pattern with the required documentation. The semi-automated measurement scheme may be the most practical for EMC/EMI measurements. Finally, the fully-automatic antenna measurement may only require the operator to specify the desired frequency range, and the computer makes the measurement. The computer would change the frequency, switch in the calibration antenna, switch the test antenna along with the required filters, control the antenna positioner and finally plot the antenna pattern along with the required documentation. Note that automated measurements require the development and implementation of appropriate software/hardware for control of the test setup. Thus automation is generally cost effective only for repetitive measurements which do not require a change in the basic software or hardware.

6.2.2 Automated EMC Measurements

EMC/EMI measurements are no different from any other set of measurements. The manual method, semi-automated, and the fully-automated measurement schemes also apply and the tradeoff between automation and manual depends primarily on the number of units to be tested. However, EMC measurements generally require that a large number of different tests be performed. The complexity of test setup and the software required to make the measurement scheme versatile enough to fully automate all of the EMC/EMI measurements on a particular piece of equipment may be impractical. At current state-of-the-art of measurement instrumentation, semi-automation is an attractive alternative. Semi-automation of EMC/EMI measurements requires that the computer perform the following five major functions: (1) Measurement Instrumentation Control, (2) Data Acquisition, (3) Data Processing, (4) Graphic Display, and (5) Report Generation [16].

(1) Measurement Instrumentation Control

The major difference between fully and semi-automated measurement schemes is the function the computer performs in controlling the instrumentation. For a fully automated system every function required would be performed by the computer; with a semi-automated system, however, only the signal level setting and the frequency tuning of the signal source would be done by the computer. The operator would be required to do the switching and initial calibration.

(2) Data Acquisition

The data acquisition process involves the computer reading and storing of the digital output produced by the measurement instrumentation. The data the computer reads contains the actual measurement along with any necessary information that may be required for data processing.

(3) Data Processing

The data processing phase usually consists of applying the initial calibration data and correcting the data for actual interpretation. Once stored, the data may also be used for more elaborate calculations which may put the data in a more usable form. For example, the computer may put the data in a form to be output graphically.

(4) Graphic Display

Computer graphics has become one of the most valuable functions that the computer can perform. It not only allows the operator a chance to continually observe the measurement progress, it also provides an output which is easily interpreted in graphical form and contains the necessary heading and documentation about the measurement.

(5) Report Generation

With the advent of the new computers which provide graphics and word processor features, the computer can generate graphs that are of report quality. The major disadvantage is the additional software required.

The primary advantages of computer controlled instrumentation are speed and accuracy. Each of the major functions described previously are performed more accurately and faster than by manual control. In particular, data acquisition and data reduction are done most effectively by automation.

Automation is most cost effective where large numbers of routine operations are performed. The need for an operator to read a meter, write down data values, and manually perform data reduction is eliminated. This saves time and the possibility of error is eliminated.

The most obvious disadvantage to computer automation is the cost, both of hardware and software. The costs of a computer system is usually a small part of the cost of programmable instrumentation. For example, a frequency synthesizer costs about \$20K and a digitally controlled receiver which tunes to 1 GHz costs between \$100K to \$200K, while an excellent computer system with disk drive, graphic display, and printer can be purchased for \$50K to \$100K. The software development costs are usually the most expensive of all costs. Depending upon the complexity of the system, the software may require several man-years for development. There are also costs associated with the training of personnel, conversion period from manual to automated, and validation of the automated measurements. Costs must also include the support of at least one part-time engineer/programmer to maintain the software system. A programmer is needed to make changes to the programs, to enhance the system capabilities, and design improvements. This process can continue indefinitely.

Automation removes the operator control which tends to remove his sense of responsibility. During a fully automated EMI test the operator has little to do but monitor the test progress. This becomes repetitive and boring and contributes to a loss of attention which is necessary to detect failure which might occur. For this reason, it may be better to avoid over automation in which several lengthy tests are concentrated into a single, fully automated run.

Automation tends to restrict the flexibility of testing each step of a test where computer control must be programmed in the software program. For production testing, flexibility may not be necessary if the same test is repeated over a long time. With development testing, however, each test may require a different schedule of test operations. There are several methods by which the software can provide the flexibility that may be required. A few of the methods are described as follows.

Separate Programs. A separate program is written for each individual test required. Each different program could be chosen from a menu from which the operator selects. Additional options within each program can provide additional flexibility.

Rewrite/Modify Existing Program. This method probably provides the highest degree of flexibility. An existing program is modified or rewritten to provide the required operating sequence for the new test. The major disadvantages are the time required to make the changes and the time and cost of debugging the new program. Due to the lack of flexibility in fully-automated test systems and the large number of different tests required, a semi-automated approach using some form of menu for EMC/EMI testing seems the most practical and cost-effective.

6.2.3 Automated MMW EMC Measurements

The following paragraphs briefly illustrate the concept of performing EMC measurements using an automated test configuration. Unfortunately, the current state-of-the-art of MMW technology will not support this concept, except perhaps at the lower region of the MMW frequency band. It is expected that significant advancements in MMW instrumentation and components will be required before automated EMC measurements over the total MMW spectrum can be a reality.

A simplified test configuration for performing automated emission tests is shown in Figure 23. The heart of the system is a MMW spectrum analyzer which serves as a receiver. Five waveguide mixers are required to encompass the entire 30-330 GHz spectrum, each of which covers a standard waveguide band. (These could be harmonic or subharmonically pumped mixers.) The common IF output bands are switched to the spectrum analyzer via a mechanically driven or multiport PIN switch device.

The IF switch, LO's and device under test (D.U.T.) selection could all be under computer control by the new IEEE 488 interface standard adopted by many OEM's, or by separate parallel or analog interfaces. The calibration factors and tables for receiver power versus field strength at the receiver antenna would be programmed into the microcomputer. A peripheral printer output could represent both a graphic power versus frequency spectrum and numerical analysis/summary of all spurious MMW emissions.

The availability of many high quality, low cost microcomputers such as the HP-85, place total computer costs for this implementation under $5,000. It is presumed that all equipment, including the computer and peripherals, are contained in a MMW anechoic chamber to assure that the results are not influenced by extraneous signals in the test area.

The requirement for automated EMC susceptibility measurements is more difficult to realize. For instance, in the diagram shown in Figure 24, five high power sweepers (1 to 10 Watts) which cover the entire MMW band are shown; however, these devices are not currently available. Developments in state-of-the-art sweepers may make these sweepers available in 3 to 5 years. In this configuration, each sweeper is assumed to include its own leveling loop to assure constant transmit power over the frequency sweep.

If this test setup were used for receiver desensitization measurement, it would be necessary for the computer to control the level of both the desired and interference signal. Parameters of interest at the D.U.T. depend on the particular device. For instance, in the case of a digital receiver, the parameter of interest might be bit-error-rate. For an analog receiver, the quality parameter might be distortion of a test signal in the IF bandpass. In each case, appropriate sensors such as bit error rate detectors (for digital systems), spectrum analyzers (for analog distortion), or A/D's (for line coupled responses), would have to be implemented to interface with the microcomputer.

Once the state-of-the-art has advanced to the point to where all of the instrumentation is available, the tradeoff between full automation versus semi-automation must still be considered to determine which is the most cost effective.

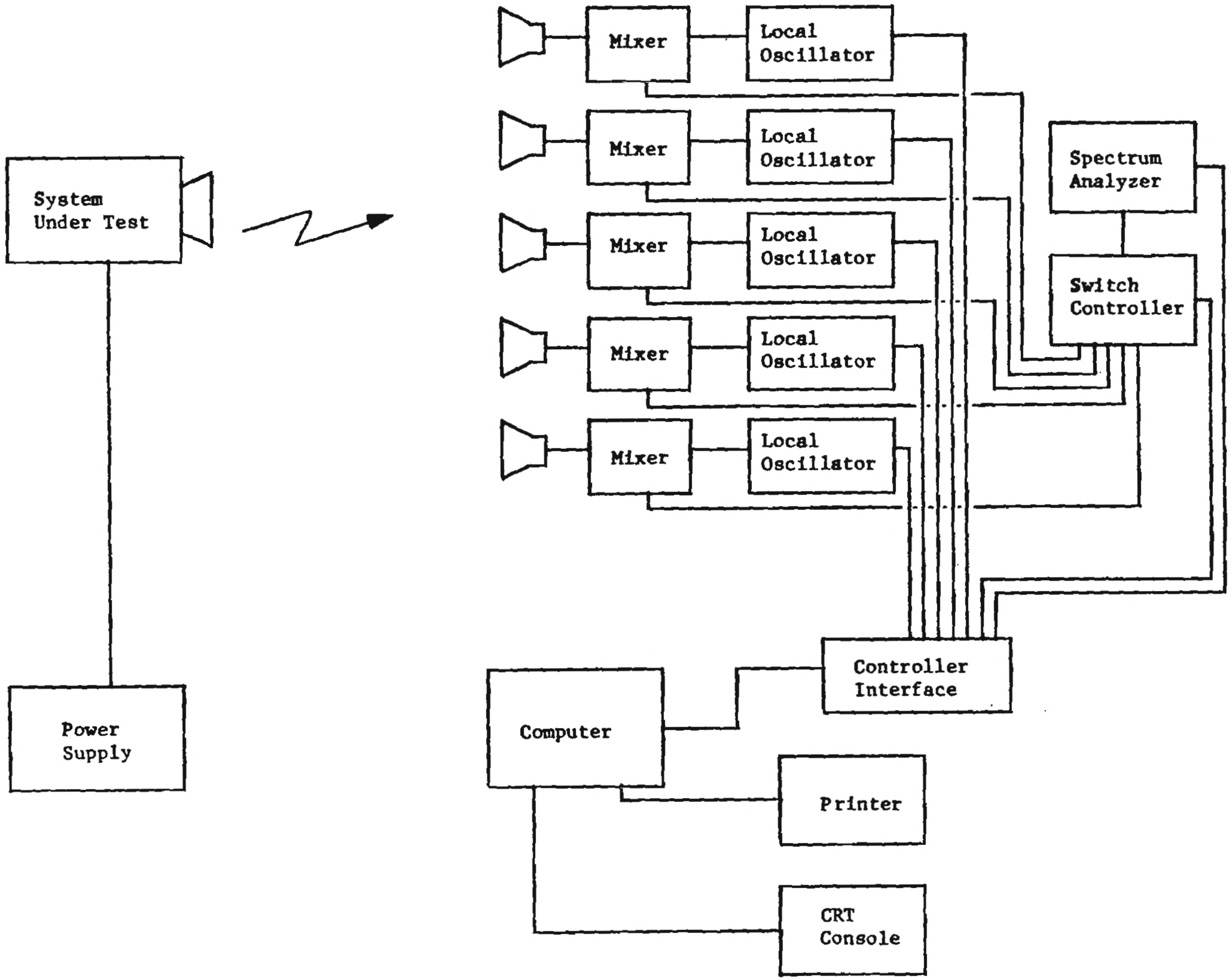


Figure 23. **Automated MMW Emission Analysis.**

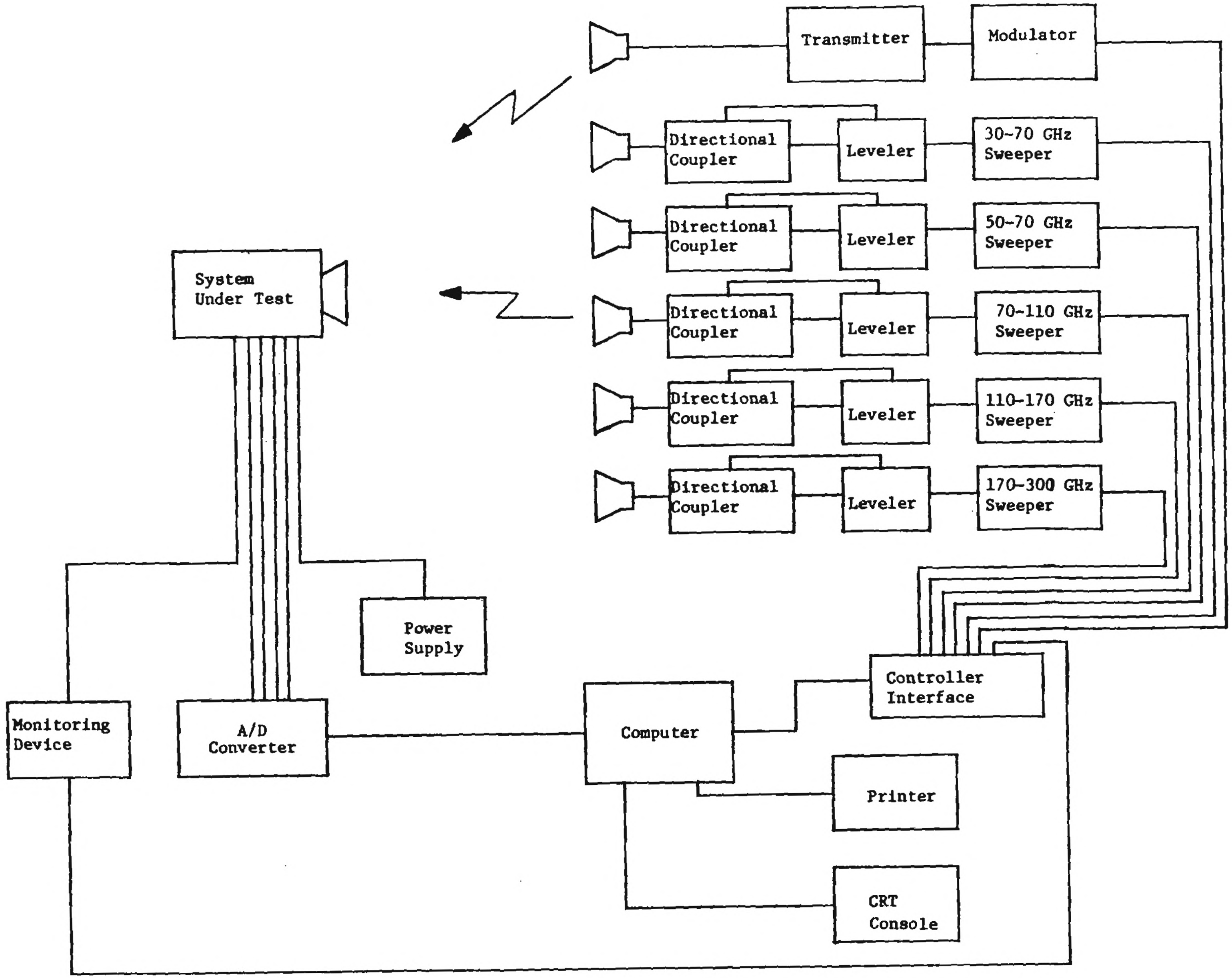


Figure 24. **Automated MMW Susceptibility Analysis.**

6.3 Cost Considerations

The implementation of a typical EMC/EMI test configuration requires a large number of test instruments and ancillary components. At MMW frequencies, the cost of these instruments and components may be an order of magnitude greater than their lower frequency counterparts. For example, consider the sources that would be required to cover the MMW spectrum. In order to cover the range 26-110 GHz, 840 CW IMPATTs sources which supply a relatively low 200 mW CW power would be needed, at a total cost of $5,092,000. (Table IV.) To cover the range 112-220 GHz, the cost of the klystrons alone would be $37,100, which does not include the costs of the power supply and the other support components. Above 220 GHz, the sources are not commercially available. Another system which covers 26-150 GHz, but only supplies a power of 2 mW can be purchased for approximately $130K. However, these low power levels may not be sufficient for all EMC measurements. Since each source is only tunable in a given band, a section of waveguide for that band must be purchased if the source is to be useful in a measurement scheme. This would require the purchase of six different waveguides which range in costs from $275/ft. for W band waveguide to $355/ft. for S band waveguide.

It is evident that EMC/EMI measurements at MMW frequencies would require an investment in instrumentation and facilities which is considerably more costly than that required at lower frequencies. Such an investment is considered unrealistic when compared to the total design and development costs of most MMW systems. Thus, it is felt that significant cost reductions in MMW test instrumentation must be realized before cost effective EMC/EMI measurements can be performed at MMW frequencies.

7.0 DATA UTILIZATION

7.1 General

The ability to design, develop, and deploy an electromagnetically compatible MMW system will depend to a large extent on the proper utilization of EMC/EMI measurement data. In this regard, two major issues of concern are (1) how the data are to be used during the system acquisition process, and (2) how the data are to be extrapolated to permit the assessment of system interference potential in the variety of electromagnetic environments likely to be encountered in practical field installations. These two issues are addressed in the following subsections.

7.2 Life Cycle Considerations

A system life cycle is generally divided into four major phases: (1) concept development, (2) concept validation, (3) full-scale development, and (4) production and deployment. During each of these phases, specific actions must be taken to satisfy the flow of the acquisition process. These actions are highly dependent upon the availability of appropriate data which define the EMC/EMI characteristics of the system of concern; hence the need for accurate and reliable EMC/EMI measurement techniques and instrumentation.

Without regard to specific systems or EMC program requirements, EMC/EMI data requirements during the life cycle of a system can be generally categorized in terms of three major data needs or uses: (1) as an aid in system design, (2) to verify compliance with system EMC/EMI requirements, and (3) for the prediction and circumvention of potential EMC/EMI problems during deployment in a typical field installation.

To achieve the EMC design goal, appropriate EMC/EMI data are needed at various stages of the first three phases of the life cycle, particularly during the full scale development phase. The system designer must have the capability during the design and development stage to perform measurements on components, circuits, and subsystems as necessary to insure that the EMC/EMI characteristics of these system subelements will satisfy the EMC/EMI requirements of the overall system.

During the latter part of the full-scale development phase of the acquisition cycle and possibly during the production/deployment phase, formal EMC/EMI measurements must be performed and data obtained to confirm that the system design conforms to the specified EMC/EMI requirements. A measurement capability must thus exist which will permit an accurate and comprehensive evaluation of system EMC/EMI characteristics. Depending upon the system of concern, this capability may need to encompass both radiated and conducted emission and susceptibility measurements, and may require numerous measurement techniques and configurations.

In terms of life cycle considerations, the need for, and utilization of, EMC/EMI data on MMW systems are no different than for any other system. Data are needed at appropriate points in the acquisition and deployment phases of a system to aid in the design of the system, to verify compliance with the EMC/EMI design requirements, and to permit the prediction and circumvention of potential interference problems in the field. Thus no distinction can be made between MMW and lower frequency systems in terms of what points in the system life cycle that data are needed, what generic types of data are needed, and who will use the data for what purpose.

7.3 Data Extrapolation

The present deterministic techniques for measuring system emission and susceptibility characteristics are limited in that they may not provide all of the EMC/EMI data which may be required throughout the life cycle of a system. For example, deterministic measurements performed in the near-field of a system may be used to adequately predict the EMC characteristics of a similar system; however, they cannot predict the system behavior in a different environment or predict its properties at other distances in the near-field or in the far field. Deterministic measurements made in the far field may be used at other distances in the far field, but they are of little use in predicting near-field interference problems. Therefore, a measurement technique for predicting interference between an emitter and a receptor, which is independent of the separation distance, would significantly enhance current EMC/EMI measurement and analysis capabilities. One such approach which has shown some promise is to use a statistical rather than a deterministic description of the emission and susceptibility characteristics of a system.

Past work done at Georgia Tech [19],[20], has shown that when the gain characteristics of microwave antennas were described statistically, the median gain and standard deviations of the antennas remain essentially constant over a wide range of source and test antenna separations. Only when the range of separation begins to approach the physical dimensions of the antenna does one observe any significant variation 20 . Under another program at Georgia Tech, techniques for statistically describing the emission from a culprit case have been investigated [21],[22],[23],[24]. The results of these programs indicate that statistical descriptions of EMC/EMI emission and susceptibility characteristics can be obtained, and that these descriptions offer promise as a means of translating the measured EMC/EMI characteristics to different environments and deployment configurations.

A discussion of the concept and utility of statistically describing EMC/EMI data will follow, along with a measurement technique for obtaining the data. Although not yet reduced to practice, this measurement technique should be relatively easy to implement with current measurement instrumentation and data processing equipment.

The concept and utility of statistical descriptions of system emission and susceptibility characteristics can be illustrated by reference to Figure 25. Figure 25(a) shows the plot of a probability distribution function statistically describing the strength of the 3-dimensional radiated field at a given frequency which might surround a particular system. The functions show the probability that the field strength at a range R from the center of the system would be less than a given level if the system were randomly oriented. Figure 25(b) shows the corresponding probability distribution statistically describing the susceptibility of a particular system in a radiated field of the same frequency. Here, the function yields the probability that the system will fail in a field of a given level if the case is randomly oriented.

It is possible to predict the probability of mutual interference from the data shown in Figure 25. For example, in Figure 25(b), the probability of failure of a system when exposed to a field strength of -4 dBm/m^2 is 0.3. If the system was located at a distance R from an emitter whose emission characteristics were described by Figure 25(a), then the probability of being exposed to a field

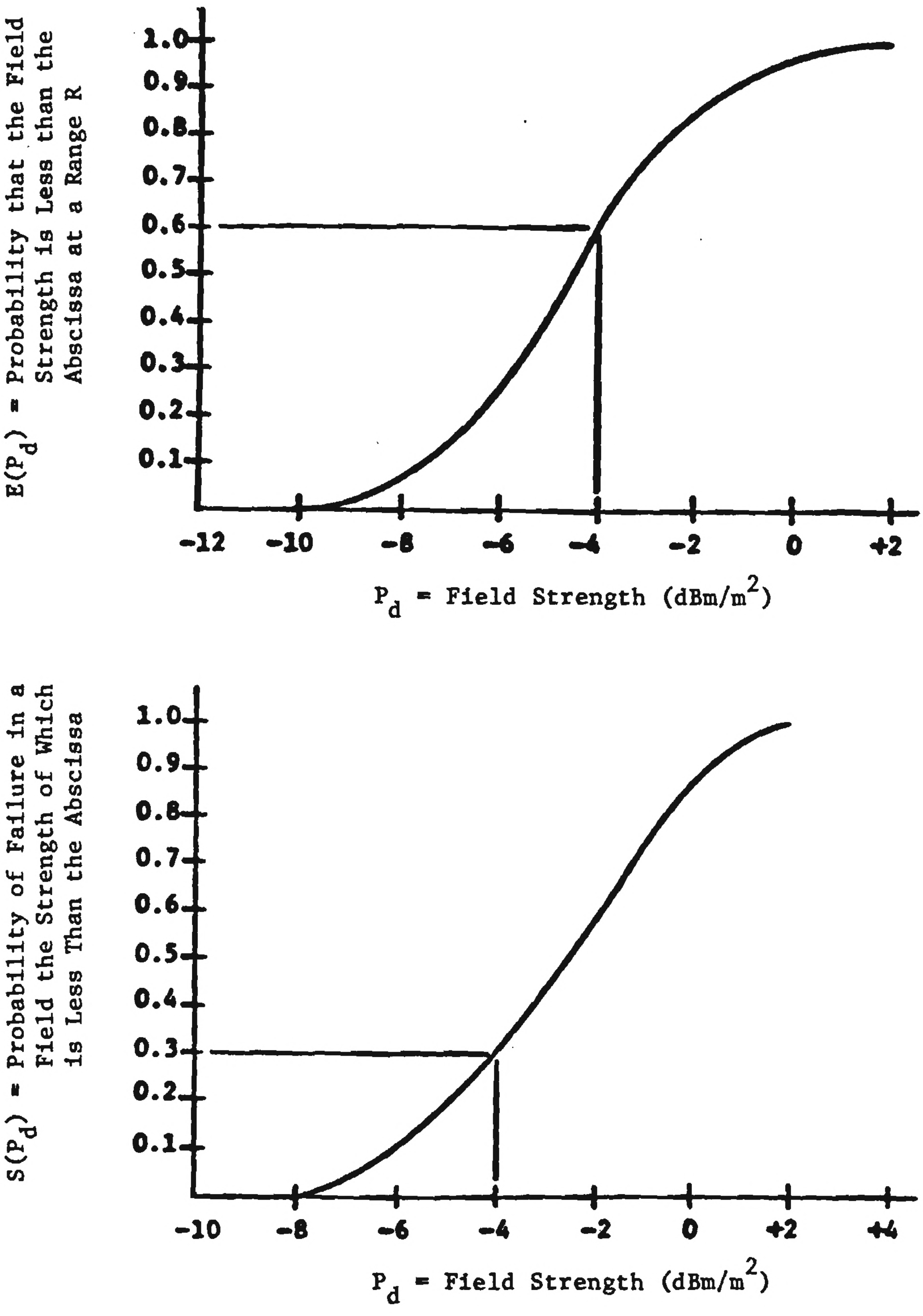


Figure 25. Sample Statistical Description of Case Emissions and Case Susceptibility.

strength greater than -4 dBm/m^2 is 1 - E(4) = 1 - 0.6 = 0.4. Therefore, the joint probability of failure is given by the product (0.3)(0.4) = 0.12. The joint probability of a failure P(F) in a field of any strength at a range R is expressed as

$$P(F) = 1 - \int_{-\infty}^{\infty} S'(P_d)\, E(P_d)\, dP_d \qquad (6)$$

where $S'(P_d)$ is the derivative of $S(P_d)$. This expression can readily be evaluated by numerical integration techniques.

In the example illustrated by the above discussion and by Figure 25, the distance R corresponds to the distance at which case emission data were collected. The probability of mutual interference at other distances can be calculated by appropriately modifying the levels shown on the abscissa of Figure 25(a) by using the distance-inverse-square law applying to radiated fields in conjunction with the absorption losses which are significant at MMW frequencies.

The translation of the power densities at a distance R_1 to a distance R_2 for a MMW system where atmospheric losses are significant can be performed using the following formula, in decibel units:

$$P_d(R_2) = P_d(R_1) + 1000\, L_{AT}(f)\, (R_1 - R_2) + 20 \log (R_1/R_2) \qquad (7)$$

where,

$P_d(R_i)$ = power density at distance R_1 in dBm/m^2

R_i = separation distance in meters

f = frequency in hertz

L_{AT} = atmospheric losses in dB/km

The atmospheric loss term $L_{AT}(f)$ can be obtained from the atmospheric absorption curve shown in Figure 6 at the frequency of operation.

The ability to translate the probability distribution function indicates that the distance used when determining the distribution function can either be a far field distance or a near-field distance referenced to the source.

Since interference doesn't generally occur at only one frequency, the probability of mutual interference may need to be calculated when a number of possible interfering frequencies are involved. The probability of interference for each given frequency must first be calculated individually, then, the mutual interference probability may be determined. For example, if three different frequencies are involved, then

$$P(F) = P(F_1) + P(F_2) + P(F_3) - P(F_1)P(F_2) - P(F_1)P(F_3) - P(F_2)P(F_3) + P(F_1)P(F_2)P(F_3). \quad (8)$$

The quantity Q(F) = 1 -P(F) is the probability that mutual interference will not occur; hence, Q(F) can be termed the figure-of-merit for a pair of cases. Careful use of this term may allow system design decisions to be made relative to one set of components over another set, based on the figure-of-merit comparison.

A method called the power distribution measurement technique has been investigated as a means of statistically describing case emissions. This technique involves the determination of the probability distribution function describing the total field strength of the three dimensional field about a radiating source. The basic measurement setup required to implement the power distribution measurement technique is illustrated in Figure 26. Note that this measurement setup and the instrumentation employed is similar to that typically used to measure case emissions or antenna patterns. The major difference is that a field distribution analyzer is used to determine the distribution of the power levels of the radiated field about the emitter.

The distribution of the radiated power about an emitter was determined by first establishing, at a given elevation and two orthogonal polarizations, the fractional part of an azimuth revolution during which the field level at the probe antenna exceeded each of 13 preselected levels. This was accomplished with the field distribution analyzer, which consisted of 13 digital counters and 13 counting gates, each of which could be set to gate on when the signal at the probe antenna exceeded any predetermined level. The pulsing unit provided pulses to the analyzer for counting.

A probability distribution function, which yielded the probability that the power level at the probe antenna would be less than any given level if the emitter were randomly oriented in azimuth at the given elevation, was determined from the measured data. Measurements were then performed to obtain similar probability distributions for other elevations. The distribution functions obtained were then pooled to define a probability distribution function which statistically described the 3-dimensional radiated field about the emitter. This function gave the probability that the total power density at the probe antenna would be less than any given level if the emitter were randomly oriented in three-space.

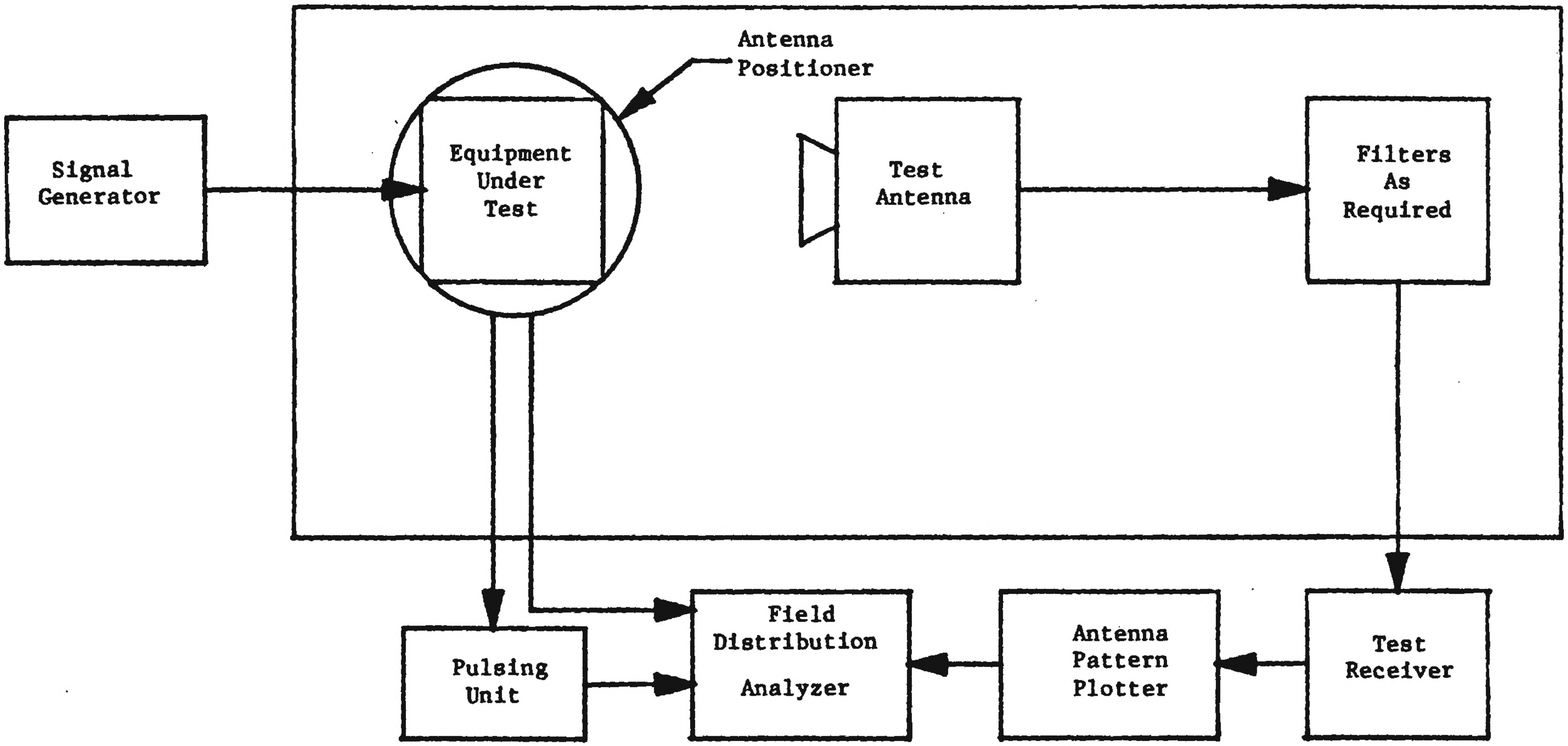


Figure 26. Block Diagram of the Test Configuration Used for Making Power Distribution Measurements.

As was discussed earlier, statistical descriptions of both case emission and case susceptibility characteristics will permit the relative likelihood of mutual interference between two systems to be predicted. As yet, no measurement techniques which permit the susceptibility characteristics of a system to be statistically described have been investigated, i.e., no susceptibility distribution functions have been defined. However, the measurement technique and instrumentation required to determine such functions should be very similar in nature to that used to define the emission power distribution functions.

The power distribution measurement technique requires a relatively large number of measurements to statistically describe the 3-dimensional emission pattern of an emitter. Since it is desirable to keep EMC/EMI measurements as simple as possible, a measurement technique which requires a large number of data points might at first appear to be a disadvantage of the power distribution measurement technique. However, when it is considered that (1) the statistical description of emission (or susceptibility) patterns requires no more data than is needed for a deterministic description, and (2) no other measurement methods appear to offer an adequate means of translating measurement data, then the data requirements for statistically describing the emission and susceptibility characteristics of a system do not appear excessive. Moreover, current computer hardware/software technology should easily support the automation of statistical methods.

In summary, the power distribution measurement technique (and its equivalent for susceptibility measurements) offers promise as a means of translating EMC/EMI data within the near-field of a system and across the near-field and far field boundary. In addition, the measurement technique is not highly sensitive to the test environment. Thus, the choice of measurement site for performing power distribution measurements does not appear to be critical. Finally, statistical methods may be more applicable to describing the EMC/EMI characteristics of a given type of system than deterministic descriptions. In other words, a statistical description of the emission or susceptibility characteristics of a given system should be the same for other systems of the same type, whereas deterministic descriptions are likely to vary between systems of the same type.

8.0 ERROR ANALYSIS

The capability for assessing and controlling the interference potential of a system is highly dependent upon the availability of accurate measurement data which defines the system's EMC/EMI characteristics. Thus, it is important that errors in the measurement and utilization of MMW EMC/EMI data be minimized, and that realistic bounds be established for those errors which cannot be avoided.

For purposes of discussion, it is advantageous to divide the possible errors associated with EMC/EMI data into three general categories: (1) errors associated with measurement instrumentation and components, (2) errors associated with the specific measurement technique employed, and (3) errors associated with the utilization or application of the data. Large or undefined errors in any of these three categories can significantly influence the ability to design, develop, and deploy electromagnetically compatible systems.

The measurement of EMC parameters requires instrumentation with suitable sensitivity, stability and accuracy. The primary factors in characterizing an EMI spectrum are measurements of power level and frequency. The accuracy of state-of-the-art methods for measuring these parameters reflected by the data in Table XV. Here, the calorimeter offers the best accuracy in power measurement, and the frequency counter in frequency measurement. With a suitable amplitude/frequency reference source, calibrated with a calorimeter and frequency counter, there appears no reason why the measurement accuracy of the spectrum analyzer or broadband receiver could not be improved to be near the same accuracy. (A MMW stable amplitude/frequency reference source does not now commercially exist.) However, the current measurement instruments for power level and frequency provide sufficient accuracy for standard EMC/EMI type measurements.

It should be noted that while MMW instrumentation is available which will provide measurement data sufficiently accurate for EMC purposes, it is not implied that adequate EMC/EMI instrumentation exists. When compared to the state-of-the-art of lower frequency measurement instrumentation, it is obvious that significant advancements in MMW instrumentation must occur before efficient and cost effective EMC/EMI measurements at MMW frequencies can be supported.

The measurement technique employed will have a significant impact on the magnitude of measurement errors. Studies have shown that the typical errors encountered in radiated EMC measurements range from 2 dB to 20 dB depending upon the measurement technique employed [25]. As discussed in Section 5, the radiated measurement techniques/sites recommended for MMW systems are the open-field range, anechoic chamber, and the compact range. For measurements at lower frequencies, experience has shown that these three measurement techniques will generally yield measurement errors of less than 4 dB. It is anticipated that the operation of the anechoic chamber and compact range could be extended to the MMW frequency range (up to 300 GHz) without a significant change in the level of measurement errors (obviously dependent upon the quality of the anechoic chamber absorber material and the compact range reflector). However, for open-field measurements at MMW frequencies, the possibility of additional errors caused by atmospheric conditions must also be considered. Figure 27 shows how atmospheric absorption varies with temperature and humidity, and Figure 28 is a plot of attenuation by atmospheric

Table XV

MMW PARAMETER MEASUREMENT METHOD AND STATE-OF-THE-ART ACCURACY

	Device or Related Component					
Parameter	Power Meter/ Calorimeter (1)	Directional Coupler	Detector/ Bolometer Mount	Cavity Type Wavemeter (Frequency Counter)	Spectrum Analyzer	Broadband Receiver (3)
Power	± 0.2% (power meter reading) 5% (calorimeter)	±0.6 dB @ 30 GHz to ±0.8 dB @ 300 GHz	±0.4 dB absolute calibration	NA	±0.3 dB (internal calibration)	±0.11 dB ±0.05 dB/10 dB (Measured with respect to external amplitude reference)
Frequency	NA	NA	NA	0.1-0.2%, 30-110 GHz 0.5-0.7%, 140-220 GHz 1%, 220-325 GHz ($\pm$ 7 x10^{-12}%)	10^{-7}% (2)	±1.0%

Note: (1) Dynamic range of power meter in roughly 10^{-5} to 0.5 W.

(2) Highest accuracy attainable with spectrum analyzer. For normal spectrum analyzer use a formula based on the range of swept frequencies must be used to determine accuracy.

(3) Based on S/A 1770 microwave receiver; maximum frequency 90 GHz.

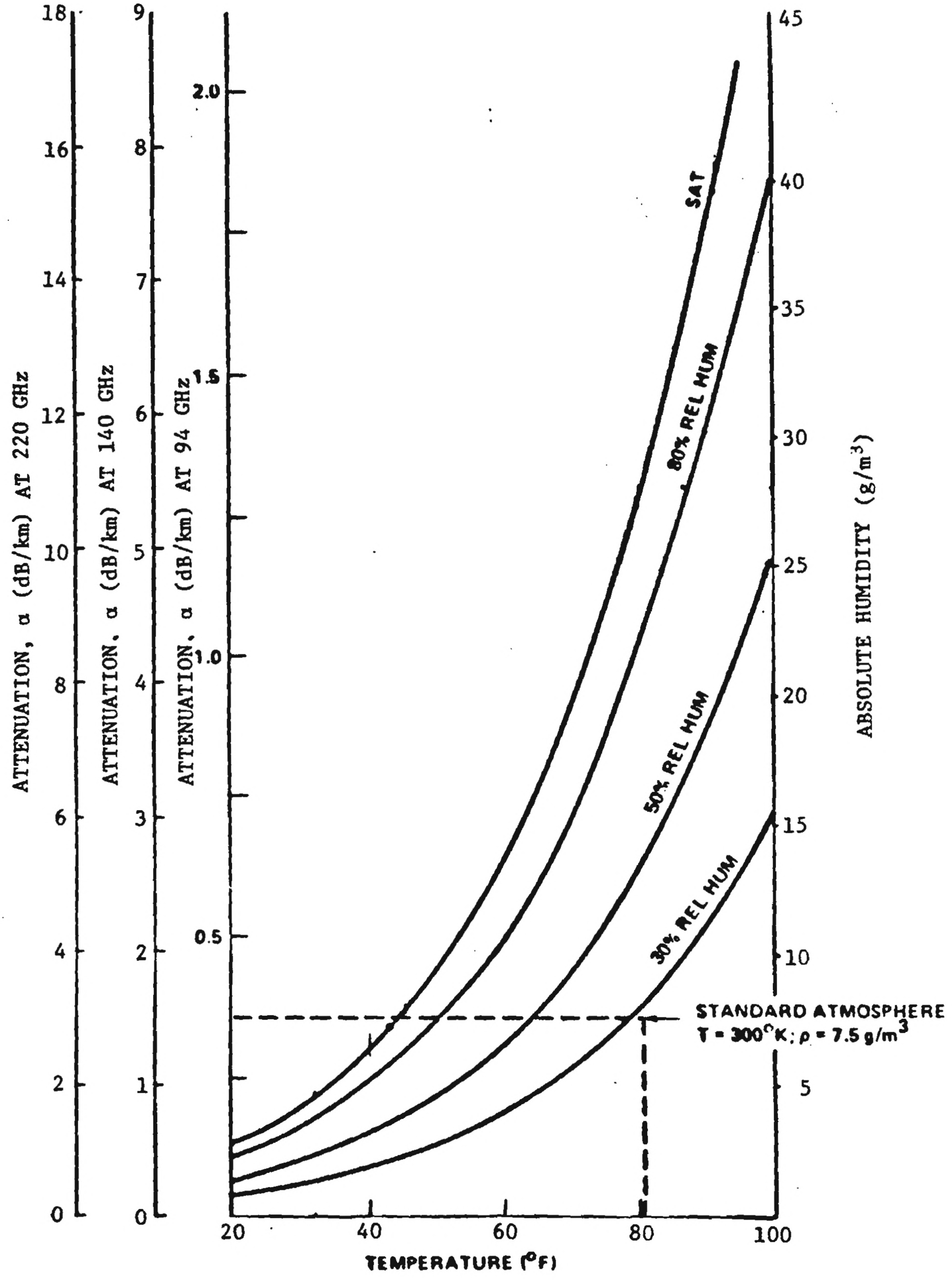


Figure 27. Atmospheric Absorption by Water Vapor.

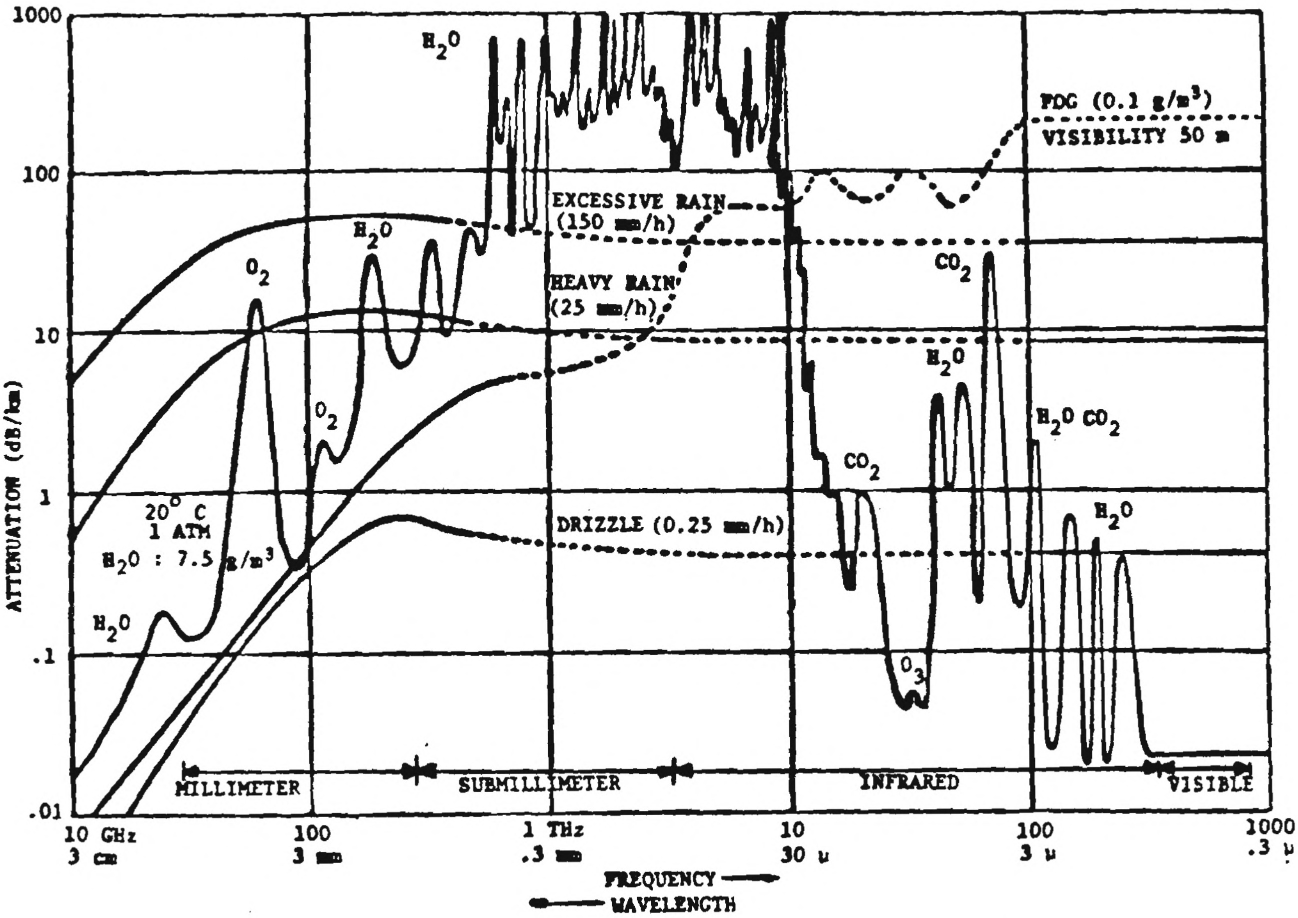


Figure 28. Attenuation by Atmospheric Gases, Rain and Fog.

gases, rain, and fog. From these two figures, it is obvious that open-field measurement results will be heavily influenced by such atmosperhic conditions as temperature, humidity, fog, rainfall, etc.

The third category of errors are related to the utilization of EMC/EMI data for such purposes as prediction and analysis. At MMW frequencies, such errors can arise from two sources. One source simply involves the extrapolation of data from one set of atmospheric conditions to another. For example, assume that data were recorded in an anechoic chamber or on a compact range where atmospheric effects are minimal, or in the open-field under given atmospheric conditions. If these data were then to be used to predict the interference potential of a communications system exposed to a variety of weather conditions, it is likely that the predictions would be in error by orders of magnitude. Such predictions would have to be based on worst case or upper bound estimates to be meaningful.

Errors in the utilization of EMC/EMI data can also arise due to the improper application of the data. Such errors are not unique to the MMW frequency spectrum, but rather are caused by the lack of adequate methods for extrapolating measurement results to different system configurations and environments. In particular, significant errors are likely where predictions are based on near-field measurement results, or predictions of near-field interference conditions are attempted using far-field test data.

In summary, it can be stated that while a critical need exists for more advanced EMC/EMI instrumentation at MMW frequencies, measurements can be performed at MMW frequencies which are comparable in accuracy to that obtainable at lower frequencies. However, when utilizing data to assess potential field interference problems, it may be necessary to resort to worst-case prediction and analysis techniques to account for the effects of atmospheric conditions on MMW signal propagation.

9.0 CONCLUSIONS

This report presents the results of efforts to define appropriate EMC/EMI rationale for MMW systems and to define the measurement techniques, configurations, and instrumentation necessary to accomodate this rationale. The major findings and conclusions drawn from the program investigations are outlined in the following paragraphs.

1. When a given MMW system is deployed, the potential for interference to, or caused by, the system will depend upon the operating environment. Whereas a particular system may operate "interference-free" in one environment, the same system may experience significant EMI problems in a different environment. Furthermore, the electromangetic compatibility of different systems may very even when operated in the same environment. Thus, in general, EMC/EMI data requirements for MMW systems cannot be limited to specific systems or specific environments. Data must be available which will permit the interference potential of any system/environment to be addressed.

2. The general EMC/EMI concerns for MMW systems are identical to those for lower frequency systems, i.e., (1) will the system act as a source of interference via emissions from the antenna, case, or interconnected cables, or (2) will the system be affected by incident signals which may enter via the antenna, case, or interconnected cables?

3. Although the specific characteristics of MMW components may differ from their lower frequency counterparts, the general configuration of MMW transmitter and receiver circuitry is essentially the same as the configuration of lower frequency systems. It would thus be expected that the generic types of MMW system EMC/EMI problems will be similar to those which have historically been experienced on lower frequency systems.

4. Since no data are available which describes the specific EMC/EMI characteristics and parameters of MMW transmitters and receivers, the above concepts of potential MMW system EMI/EMC problems and parameters are based largely on the experience which has been gained on lower frequency systems and on current MMW system characteristics. The validation of these concepts will depend upon the development of adequate measurement instrumentation and techniques for performing EMC/EMI measurements at MMW frequencies and the conduct of measurements on representative samples of MMW transmitters and receivers. It is also important to recognize that as the state-of-the-art in MMW technology advances, new and different EMI problems may evolve which will dictate changes or additions to these concepts.

5. MMW antenna characteristics and configurations may influence EMC/EMI data requirements in two respects. One is that the antenna will typically be designed and configured as an integral part of the system. Thus radiated emission and susceptibility measurements performed on the system-antenna configuration may be more

appropriate than conducted emission and susceptibility measurements at the antenna terminal. Another is that the highly directive nature of most MMW antenna may require that particular attention be given to the accuracy of antenna pattern measurements.

6. The relatively large bandwidths (transmit, receiver, IF) of MMW systems may increase the potential of MMW systems as sources or receptors of interference.

7. The EMC/EMI performance of MMW components may be poorer than lower frequency components, which could give rise to EMC/EMI problems heretofore not encountered. There may be a greater need for component EMC/EMI data to perform system EMC/EMI assessments than is currently required at lower frequencies.

8. Because of such factors as propagation and coupling loss and source power capabilities, MMW systems are not as likely to be a cause of interference as are lower frequency systems (this does not imply, however, that the emission characteristics of MMW systems can be neglected). On the other hand, MMW systems may be susceptible to signals other than those at MMW frequencies. In fact, it is likely that lower frequencies may be more of a problem to MMW systems than those frequencies in the MMW spectrum. Thus, data which defines the compatibility of low frequency/MMW systems must be obtained.

9. At MMW frequencies, such factors as propagation loss, coupling loss, and reflections will have a significant influence on interactions between different MMW systems and between MMW systems and other type systems in the environment. A knowledge of these factors is thus highly important to the prediction of field EMI problems and to the "tailoring" of a MMW system to a given environment. However, they will not significantly influence the overall EMC/EMI design requirements for MMW systems since these requirements will be dictated by specifications which are generally independent of any given environment.

10. With the exception of cable conducted emission and susceptibility data, all EMC/EMI data on MMW transmitters and receivers should be derived from radiated measurements. Thus, no conducted antenna terminal measurements on transmitters and receivers are indicated at this time, nor are individual antenna measurements likely to be necessary except to establish the relative performance between antennas. This approach is recommended for three reasons. One reason is that radiated EMC/EMI measurements of a system including the antenna should more closely approximate the performance of a system in an actual operating environment. A second reason is that the majority of MMW system designs will include the antenna, and the utilization of different antennas with a given system will be unlikely. The third reason is that radiated measurements should require simpler measurement techniques than conducted measurement over the MMW frequency range. (This is generally not true at lower frequencies, where large antenna sizes make radiated measurements difficult).

11. The EMC/EMI data requirements for MMW receivers can generally be defined as (1) radiated susceptibility data, (2) conducted susceptibility data on each lead/cable connected to the receiver, (3) radiated emission data at the receiver local oscillator (and any other internal source) frequencies, and (4) conducted emission data on each lead/cable connected to the receiver. These data should generally encompass the frequency spectrum of concern, i.e., 14 kHz to 300 GHz. However, the requirements can be further defined based on EMC/EMI experience with low frequency receivers and on anticipated receiver interference characteristics at MMW frequencies.

12. The EMC/EMI data requirements for transmitters must address emissions from three paths: (1) radiation from the antenna, (2) radiation through the receiver case, and (3) via cables and control leads (conducted and/or radiated). These requirements will generally lead to two basic types of measurement: radiated emission measurements (from case, antenna, and connecting wiring) covering the 14 kHz - 300 GHz spectrum, and conducted emission measurements on cables and wiring at lower frequencies.

13. It is unlikely that signals at MMW frequencies will be coupled to, or conducted along, wiring/cabling connected to the receiver. Thus, it will not be necessary to collect conducted susceptibility or emission data over the total 14 kHz - 300 GHz spectrum. Current MIL-STD-461 frequency limits will probably be applicable.

14. Although the need for conducted emission and susceptibility data on wiring and cabling has existed for some time, difficulty has been experienced in implementing a practical measurement technique for obtaining these type data, even for low frequency systems. To circumvent this measurement problem, the approach normally taken is to "tailor" interconnected equipments to prevent conducted interference. Thus, prior to finalizing conducted emission and susceptibility data requirements for MMW systems, further consideration will have to be given to measurement techniques for performing these type measurements.

15. Three major considerations must be addressed in performing radiated EMC/EMI measurements on MMW systems. One consideration involves the separation distance between the system under test and the test source/receiver used in the radiated suceptibility/emission test configuration. This distance is critical since it defined whether the measurements are being made in the radiated far-field or radiated near-field. A second consideration involves the characteristics of the test antenna employed. The accuracy of the measurement results will be highly dependent upon the characteristics of this antenna (aperture dimensions, gain, beamwidth, etc.) A third consideration involves the increase in the requirements on the power levels of signal sources and the sensitivity levels of test receivers. This increase in power and sensitivity requirements is due to several factors including the relatively large separation distances which may be required in order to satisfy far-field criterion at MMW frequencies, high absorption losses at MMW frequencies, and the high attenuation effects of the equipment's antenna and transmission line.

16. It is important to recognize that the problem of obtaining sufficient source power and receiver sensitivity for performing radiated emission and susceptibility measurements is strongly indicative of a probable lack of significant EMI problems at MMW frequencies. In other words, if sufficient MMW source power is not available to perform susceptibility measurements, then it is unlikely that MMW transmitters will be a major source of interference in a field environment. This is not to imply that EMC/EMI problems will not exist at MMW frequencies or that EMC/EMI testing at MMW frequencies is not required. However, it is felt that the nature and extent of EMC/EMI testing should be commensurate with the likelihood of interference at MMW frequencies.

17. The three basic measurement sites which offer the greatest promise for MMW system EMC/EMI measurements are: the shielded anechoic chamber, the outdoor range, and the compact range. Other techniques such as the shielded enclosure, TEM cell, parallel plate structure, tuned mode enclosure, and near-field probe are not applicable at MMW frequencies.

18. Several specific test techniques and configurations for performing radiated EMC/EMI measurements have been identified. However, these techniques and configurations have not been experimentally verified, and much of the equipment required to perform these tests are presently not available as standard off-the-shelf items. Thus, the validation of these test configurations cannot be accomplished until the required test instrumentation and components are developed.

19. Existing instrumentation is available to perform very basic EMC/EMI measurements over the lower MMW frequency region. However, it is felt that an advancement in the state-of-the-art of practical MMW instrumentation will be necessary in order to cover the upper MMW frequency region.

20. Even at the lower MMW frequencies, MMW instrumentation and components are not readily available on an off-the-shelf basis, but rather must be "custom-made".

21. MMW instrumentation technology will not presently support semi-automated or fully-automated EMC/EMI measurements. However, the lack of a capability for performing fully-automated or even semi-automated measurements is not considered a serious shortcoming. At this time, what is needed is MMW instrumentation with more fundamental capabilities, i.e., more efficiency and flexibility.

22. In terms of life cycle considerations, the need for, and utilization of, EMC/EMI data on MMW systems are no different than for any other system. Data are needed at appropriate points in the acquisition and deployment phases of a system to aid in the design of the system, to verify compliance with the EMC/EMI design requirements, and to permit the prediction and circumvention of potential interference problems in the field. Thus no distinction can be made between MMW and lower frequency systems in terms of what points in the system life cycle that data are needed, what generic types of data are needed, and who will use the data for what purpose.

23. Data collected using current measurement techniques cannot be readily translated or extrapolated to other interference situations. Thus, a need exists for a method which will permit the prediction of system behavior in different environments. One approach which has shown some promise is to use statistical rather than deterministic descriptions of the emission and susceptibility characteristics of a system.

24. Current measurement instruments for measuring power and frequency at MMW frequencies provide sufficient accuracy for standard EMC/EMI measurements. However, measurement errors on the order of +20 dB may be encountered in radiated EMC/EMI measurements depending upon the measurement technique employed. Also, errors may be caused due to the improper utilization of measurement data or to changes in atmospheric conditions.

25. Experiments performed have shown that surface wave effects at MMW frequencies may significantly influence the interference potential of a system, and that further investigations are needed to define the potential impact of surface wave phenomena.

26. The results of a experiment on the Georgia Tech compact range has verified that the compact range can be used for both emission and susceptibility measurements. The compact range has advantages as a measurement site in that it can be shielded from the external EM environment, is located indoors, and will simulate open field conditions with the appropriate use of absorber material.

27. An examination of MMW mixers indicates that with regard to spurious product formations, MMW mixers are similar to their lower frequency counterparts.

10.0 RECOMMENDATIONS

Based on the program findings and conclusions, it is recommended that additional efforts be directed to:

1. Measurements of the EMC/EMI characteristics of representative MMW systems to ensure that the EMC/EMI data requirements for MMW systems are adequately defined and experimentally verified;

2. An experimental validation of EMC/EMI measurement techniques for MMW systems;

3. An investigation of the EMC/EMI potential of surface wave phenomena at MMW frequencies;

4. The development of methods for extrapolating EMC/EMI measurement data to other interference situations (in particular, the use of statistical methods should be futher investigated);and

5. Studies of conducted measurement techniques to ensure that these techniques are compatible with current EMC/EMI data needs and instrumentation capabilities.

Note that the last two recommendations are not uniquely related to MMW systems. Methods of extrapolating EMC/EMI data and the optimization of conducted measurement techniques are also needed at lower frequencies.

11.0 REFERENCES

1. E. E. Donaldson, D. J. Kozakoff, J. C. Mantovani, W. R. Free, and T. P. Morton, "Millimeter Wave Electromagnetic Measurement Techniques," Quarterly 2, Report CECOM-80-0569-2, Contract No. DAAK80-80-C-0569, Engineering Experiment Station, Georgia Institute of Technology, Atlanta, Georgia, June 1981.

2. L. L. Webb, T. P. Morton and J. M. Schuchardt, "Millimeter Wave Passive Target Signature Measurements; Vol. I," Final Report on Project A-2337, Georgia Institute of Technology, Atlanta, Georgia, June 1980.

3. Y. Chang and L. T. Yuan, "Millimeter Wave Binocular Radio," Microwave Journal, March 1980.

4. A. W. Straiton, "The Absorption and Reradiation of Radio Waves by Oxygen and Water Vapor in the Atmosphere," IEEE Trans. on Antennas and Propagation, July 1975.

5. N. C. Currie, et al, "Radar Foliage Measurements at Millimeter Wavelengths," Final Report on Project A-1485, Georgia Institute of Technology, Atlanta, Georgia, December 1975.

6. H. E. King, F. I. Shinabukuro, and J. L. Wong, 94 GHz Measurements of Microwave Absorbing Material, TR-669(6230-46)-5, Aerospace Corporation, El Segundo, CA, March 1966.

7. E. E. Donaldson, D. J. Kozakoff, J. C. Mantovani, W. R. Free, and T. P. Morton, "Millimeter Wave Electromagnetic Measurement Techniques," Quarterly 3, Report CECOM-80-0569-3, Contract No. DAAK80-80-C-0569, Engineering Experiment Station, Georgia Institute of Technology, Atlanta, Georgia, July 1981.

8. E. E. Donaldson, D. J. Kozakoff, J. C. Mantovani, and T. P. Morton, "Millimeter Wave Electromagnetic Measurement Techniques," Quarterly 4, Report CECOM-80-0569-4, Contract No. DAAK80-80-C-0569, Engineering Experiment Station, Georgia Institute of Technology, Atlanta, Georgia, October 1981.

9. E. B. Joy, "Near-Field Antenna Measurements," Georgia Institute of Technology, Atlanta, Georgia, 1980.

10. J. S. Hollis, T. J. Lyon, and L. Clayton, Jr., "Microwave Antenna Measurements," Scientific-Atlanta, Inc., Atlanta, Georgia, 1970.

11. J. D. Kraus, Ph.D., Antennas, Ohio State University, Mc-Graw-Hill Book Company, Inc., 1950.

12. S. Silver, Microwave Antenna Theory and Design, Office of Scientific Research and Development, National Defense Research Committee, Boston Technical Publishers, Inc., 1964.

13. E. E. Donaldson, J. C. Mantovani, G. B. Melson, "Millimeter Wave Electromagnetic Measurement Techniques," Quarterly 5, Report CECOM-80-0569-5, Contract No. DAAK80-80-C-0569, Engineering Experiment Station, Georgia Institute of Technology, Atlanta, Georgia, December 1981.

14. R. C. Johnson and D. W. Hess, "Conceptual Analysis of Measurement on Compact Range," Engineering Experiment Station, Georgia Institute of Technology, and Scientific-Atlanta, Inc., Atlanta, Georgia, 1979.

15. R. W. McMillan, unpublished data, Georgia Tech, Atlanta, Georgia, Feb. 1981.

16. S. A. Erickson and W. S. Lambdin, "Automating Your EMI Tests - A Realistic Approach," EMC Technology, January 1982.

17. R. C. Johnson, "Mutual Gain of Radar Search Antennas," Proc. 1963 9th Tri-Service Conference on Electromagnetic Compatibility, ITT Research Institute, Chicago, Illinois.

18. R. D. Wetherington, et al., "Analysis of Some Near-Zone Microwave Antenna Patterns Recorded by the Naval Ordnance Test Station," Georgia Institute of Technology, Atlanta, Georgia, Contract NOrd-16189,1958.

19. M. W. Long, "Wide Angle Radiation Measurements," Proc. 1960 6th Tri-Service Conference on Radio Interference Reduction, ITT Research Institute, Chicago, Illinois.

20. F. L. Cain and K. G. Byers, Jr., "Statistical Gain Characteristics of Radar Antennas," Final Engineering Report, Contract No. NObsr-95379, Georgia Institute of Technology, January 1968.

21. C. W. Stuckey, et al., "Statistical Description of Near Zone Spurious Emissions," Georgia Institute of Technology, Atlanta, Georgia, Final Technical Report under Contract AF 33(615)-3329, Air Force Avionics Laboratory, Research and Technology Division, Wright-Patterson Air Force Base, Ohio.

22. J. C. Toler and C. W. Stuckey, "The Power Distribution Measurement Technique-A Method for Measuring Radiated Fields from Equipment Cases," presented at the 20th Meeting of the SAE Electromagnetic Compatibility Committee, Wright-Patterson Air Force Base, Ohio, May 1967.

23. C. W. Stuckey and J. C. Toler, "Statistical Determination of Electromagnetic Compatibility," IEEE Transactions of Electromagnetic Compatibility, September 1967.

24. C. W. Stuckey, J. C. Toler, and O. B. Francis, "Statistical Description of Near Zone Spurious Emissions", Report AFAL-RT-67-37, Contract No. AF-33(615)-3329, Engineering Experiment Station, Georgia Institute of Technology, Atlanta, Georgia, 1967.

25. E. E. Donaldson, J. A. Woody, and J. K. Daher, "Evaluation of Radiated Emission and Susceptibility Measurement Techniques," Final Report, Report CECOM-81-0006-F, Contract No. DAAK80-81-K-0006, Engineering Experiment Station, Georgia Institute of Technology, Atlanta, Georgia, January 1982.

26. J. J. Gallagher, R. W. McMillan, and R. G. Shackelford, "Military Systems Applications at Near-Millimeter Wavelengths," Proceedings of the Society of Photo-Optical Instrumentation Engineers, Volume 197, August 1979.

27. K. G. Heisler, Jr. and H. J. Hewitt, "Interference Notebook," Report RADC-TR-66-1, Contract No. AF 30(602)-3118, Jansky and Bailey Research and Engineering Division of Atlantic Research Corporation, 1967.

28. R. D. Trammell, J., E. E. Donaldson, Jr., and P. T. Spence, "Manuscript of Catalogue, Volume 11, Mixer Interference Characteristics, Project A-678, Electronic Equipment Interference Characteristics-Communication Type, Contract No. DA 36-039 AMC-02294(E), Georgia Institute of Technology, Engineering Experiment Station, August 1964.

29. W. B. Warren, Jr., "Quarterly Status Contract Report No. 6," Contract AF 30(602)-3282, June 1965.

APPENDIX A

EXPERIMENTAL INVESTIGATION OF SURFACE WAVE CONDUCTED EMI PHENOMENA

For dielectric covered conductors, i.e., typical unshielded power and signal cables, it is possible to launch a surface wave which is concentrated within the dielectric. This phenomenon does not readily occur at the lower microwave frequencies, but may predominate in the MMW region where dielectric thickness on wires is an appreciable portion of a wavelength. As a result of this mechanism, strongly coupled surface waves may propagate on signal, power, or control leads into a shielded box, thus compromising shielding effectiveness. It may be that RFI type feed-thrus, while effective at lower frequencies, may not be effective at MMW frequencies. Figure A-1 illustrates how MMW energy may be conducted via surface waves along dielectric wire insulation into a shielded equipment case.

To verify the possibility of surface wave conducted EMI, an experiment was devised to determine the coupling of EM energy on dielectric covered wire into an inner compartment of a test fixture, as illustrated in Figure A-2. A 35 GHz Gunn oscillator of about 20 mW CW power was used to illuminate one end of an insulated wire which went through the enclosure wall as indicated in the figure. A horn-fed crystal detector was positioned at the other end of the wire so as to receive any dielectric-conducted 35 GHz energy which might come from the Gunn oscillator, through the wire insulation, and decouple into the receiving end of the fixture.

In the experiment, the Gunn oscillator was placed on the bench top with its emission directed upward. The absorber-lined cylinder was placed over the source, open end down, so that the source was directed toward the test specimen which was suspended through the ⅛" hole. Several types of dielectric coated wires were used, as well as a bare #12 copper wire for standard reference purposes. For each specimen, the horn-fed crystal detector was held at the same height directly over the upper end of the specimen such that the mouth of the horn was at the level of the upper end of the test specimen.

The results of the experiment are shown in Table A-I. Note that the data in this table show a significant variation in coupling as a function of the type of wire/dielectric employed, which is an indication of surface waves. It is to be emphasized that the experiment was not intended as a rigorous investigation of surface wave phenomena, but rather as a simple means for identifying the possibility of surface waves at MMW frequencies which would influence EMI coupling. The data in Table A-I should not be construed as an absolute measure of coupled energy; the significance of the data is reflected in the differences in coupling for different wires/dielectrics. The fact that these differences exceed 15 dB is a strong indication that surface wave effects at MMW frequencies cannot be ignored. Whether or not these effects will significantly influence the interference potential of MMW systems can only be determined through a more rigorous investigation.

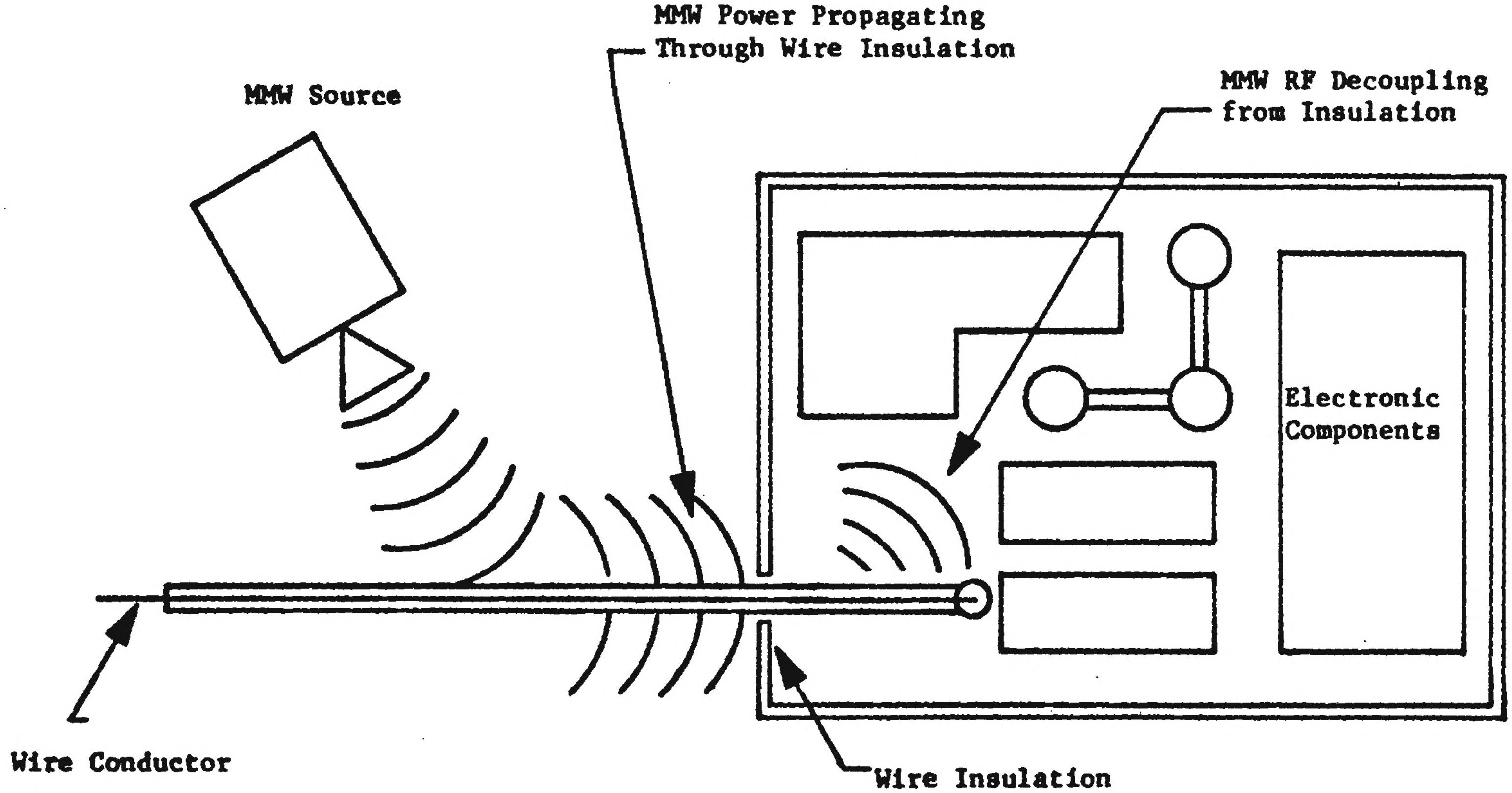


Figure A-1. Surface Waves Propagating Along a Dielectric Coated Wire into the Interior of an Electronic Enclosure.

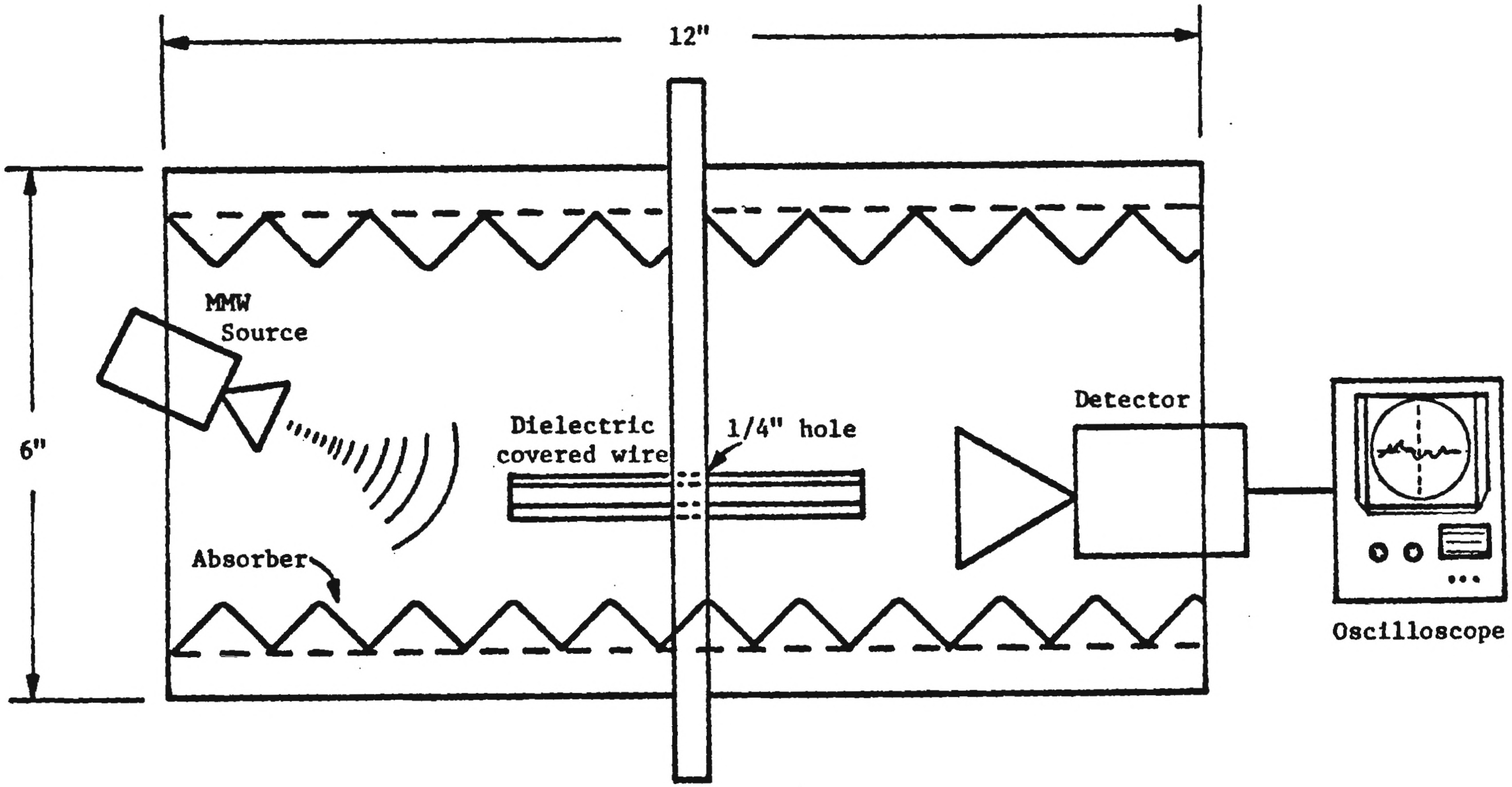


Figure A-2. MMW Surface Wave Conduction Test Fixture.

TABLE A-I

RELATIVE COUPLING ON DIELECTRIC COVERED WIRES

Test Condition	Detector Relative Voltage	Detector Relative dB
Open 1/4" hole with no wire or dielectric	0.05	0
5 1/2" length of RG58 with shield and center conductor shorted at the ends. Co-ax dielectric outer insulation 1/32" thick	0.2	12.04
5 1/2" of 7 conductor cable 1/4" diameter, 1/32" PVC insulation	0.3	15.56
5 1/2" length of RG58, unshorted 1/16" thick co-ax dielectric, 1/32" thick insulation	0.15	9.54
5 1/2" length of #12 copper wire with 1/32" PVC insulation	0.3	15.56
5 1/2" Bake #12 copper wire	0.01-0.05	0
5 1/2" x 1/4" x 1/16" TE flow strip with 1/16" dimension parallel to emitted E field	0.1	6.02

APPENDIX B

INVESTIGATION OF COMPACT RANGE APPLICABILITY TO EMC/EMI MEASUREMENTS

A simple mathematical description of the coupling between the compact range and the system under test, 14 indicates that the transmission equation that results from viewing the compact range as the transmitter is identical to the transmission equation that results from viewing the system under test as the transmitter. This derivation is dependent on the concept of a plane wave spectrum, taking the point of view that the compact range acts as an "angle filter" for the plane waves emitted by the system under test.

Thus, it would appear that the compact range is applicable to both emission and susceptibility measurements. However, no information has been found which indicates that the compact range has been employed in performing emission measurements. Thus, an experimental verification of the applicability of the compact range in performing emission measurements was considered necessary prior to its recommendation as a measurement technique for MMW systems. Therefore, an experimental verification of the application of the compact range for performing emission measurements was conducted on the Georgia Tech compact range. This verification involved measurements to determine if antenna patterns obtained with the compact range operated in the transmitting mode were the same as those obtained with the range operated in the receiving mode. First, the compact range was set up in its conventional form, that is, with the feed horn transmitting. Figure B-1 shows the measurement set up used and the approximate dimensions of the compact range. Figure B-2 is a block diagram of the equipment configuration. After it was verified that the feed horn was properly located in the focal point of the reflector, the test sample was rotated and a 360 azimuth pattern of power received by the test sample was recorded. While maintaining constant gains in the receiver and in the chart recorder and while maintaining a constant output power level from the signal source, the cables connecting the feed horn and test sample were interchanged (points A and B on Figure B-2). The test sample was then again rotated while recording a 360 azimuth pattern of the power received by the feed horn. These two patterns could then be compared to determine if the coupling between the compact range and test sample were, indeed, identical for both cases.

Three different antennas were used as test samples, including a 30-inch Luneberg lens antenna (with a slightly flared open-end waveguide feed), an electrically long dipole antenna, and a standard gain horn. While the test samples used were only antennas and not complete systems, the results should be equivalent to a system test. Two of the test antennas used, the Luneberg lens and dipole, had far field boundaries (based on $2D^2/\lambda$) which were beyond the compact range reflector. Thus, these tests were performed in the near field of these two antennas. The electrically long dipole was tested since it was expected to have a random pattern with many nulls at the frequency of test and thus exhibit results similar to a typical case emissions test. The Luneberg lens was tested since many MMW systems will employ antennas which use a small feed in combination with a reflector or lens. The standard gain horn was tested since it has a symmetrical and known pattern and because it had a small aperture such that the range reflector was located in its far field, based on $2D^2/\lambda$.

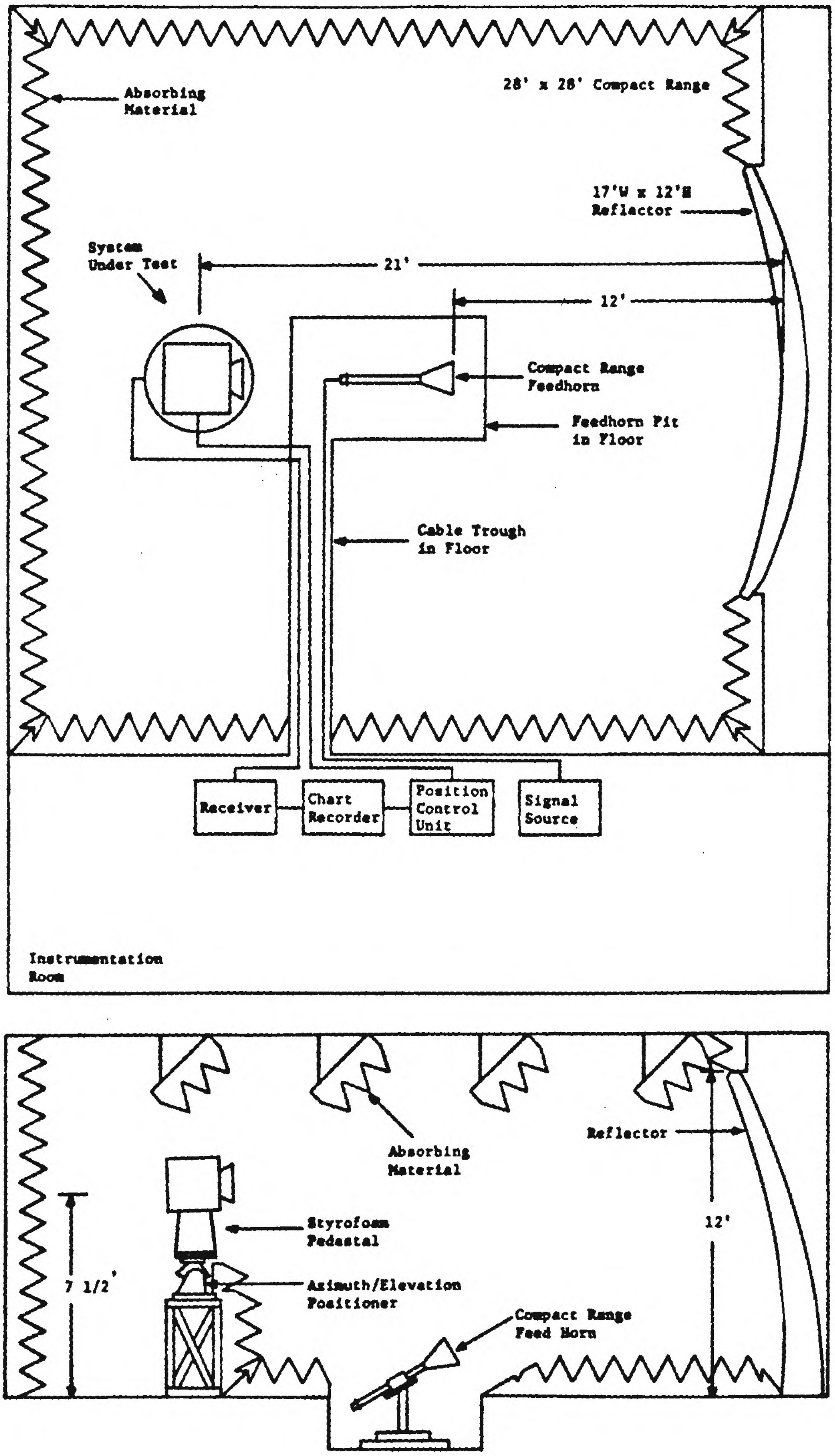


Figure B-1. Measurement Setup used to Confirm the Applicability of the Compact Range for Emission Measurements.

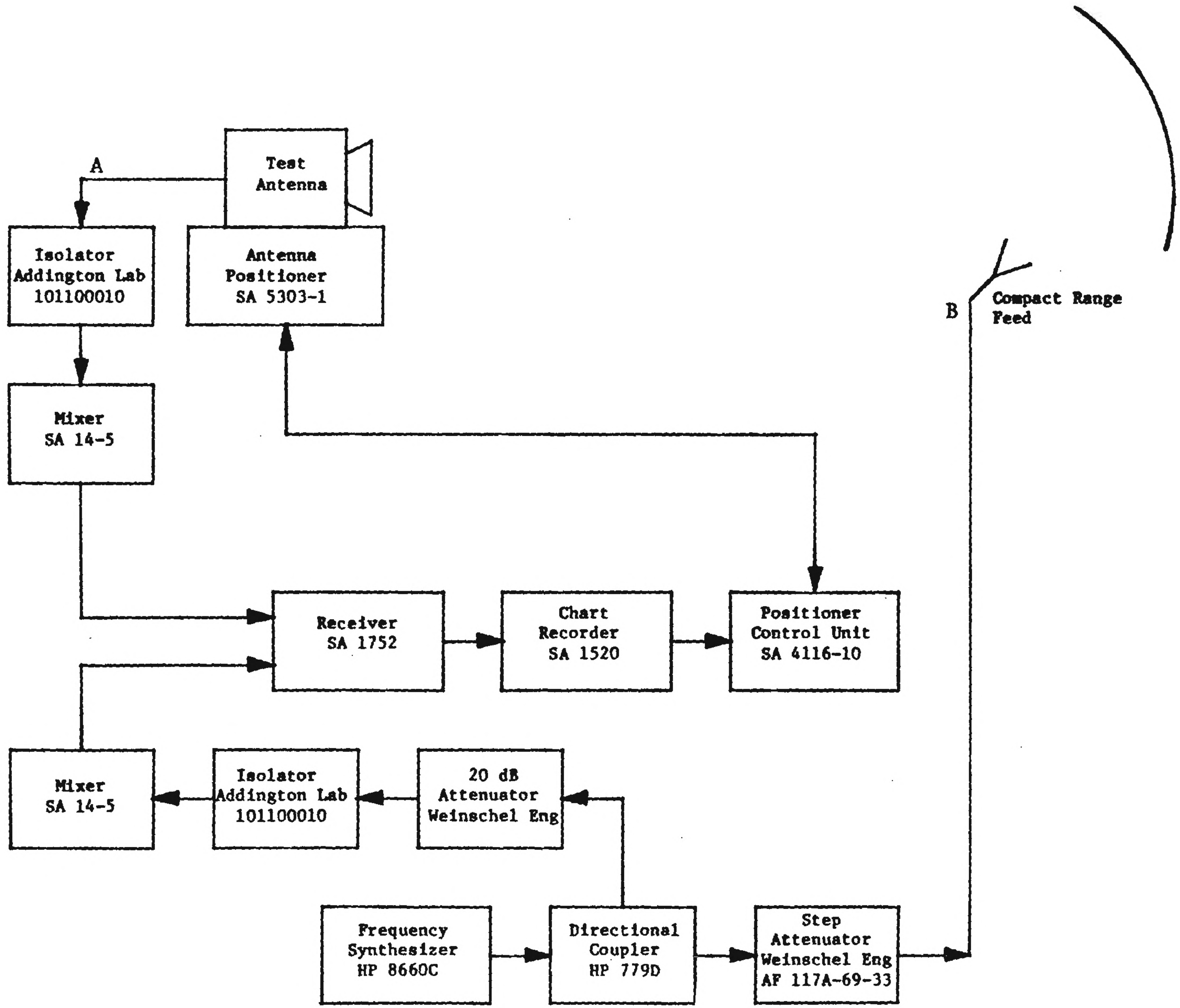


Figure B-2. Equipment Configuration Used to Confirm the Applicability of the Compact Range for Emission Measurements.

Figures B-3 through B-6 show the results from the above experiment. The solid curve on each pattern represents the recorded pattern when the compact range was used as a transmitter, and the dotted curve represents the recorded pattern using the compact range as a receiver. Figure B-3 shows the recorded patterns using the Luneberg lens as the test sample. Figures B-4 and B-5 were both recorded using the dipole antenna at two different test frequencies. Figure B-3 is the pattern recorded using the standard gain horn as the test sample.

As Figures B-3 through B-6 are reviewed, it is seen that the patterns recorded with the compact range transmitting are almost identical to the patterns recorded with the compact range receiving. The maximum variation in Figure B-3 is 1 dB. It is believed that some of the isolated variations in this pattern and in the other patterns are due to reflections off objects located in the compact range and if additional care was taken in the placement of anechoic material these variations could be reduced. A somewhat more constant variation of approximately 0.5 dB is seen in Figures B-4 and B-5. It is believed that these variations are due to VSWR mismatches between the antenna ports and the transmitter/receiver (external mixer) which are different in the two cases. Thus, the power (P_o) accepted by the antenna would be different for the two cases. This fact helps support the above argument since the input impedance of the electrically long dipole is expected to greatly mismatch the output/input impedance of the transmitter/receiver. The two patterns on Figure B-6 are almost identical with maximum variations of 0.25 dB.

The results of this experiment indicate that the coupling between the compact range and system under test is independent of whether the compact range is configured in a transmit or receive mode of operation. These measurements verify that the basic concepts are correct, and it is, therefore, concluded that the compact range can be used to perform both emission and susceptibility measurements.

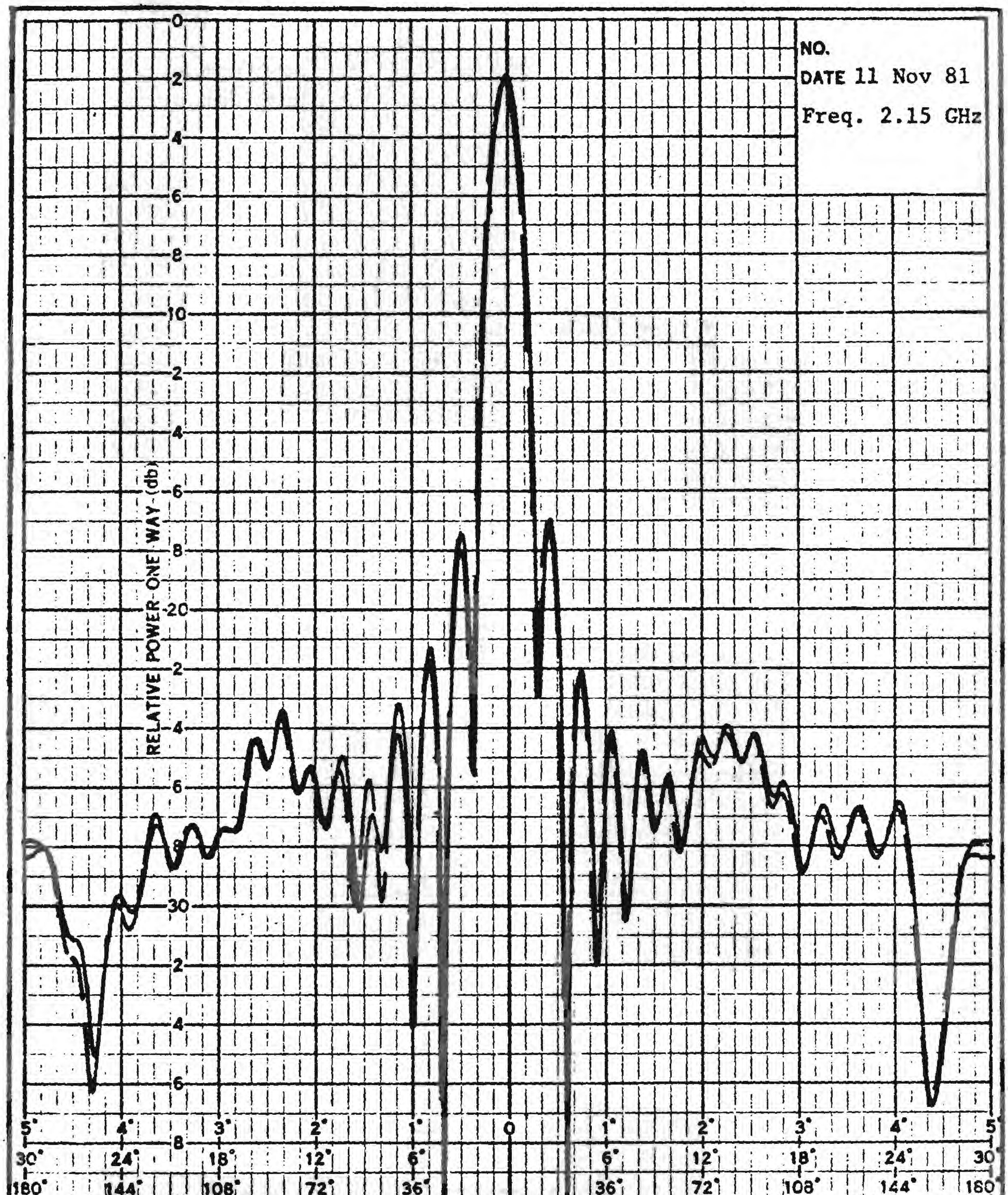


Figure B-3. Recorded Patterns Using Luneberg Lens as the Test Sample. Solid Curve Represents the Compact Range Transmitting; Dotted Curve Represents the Compact Range Receiving.

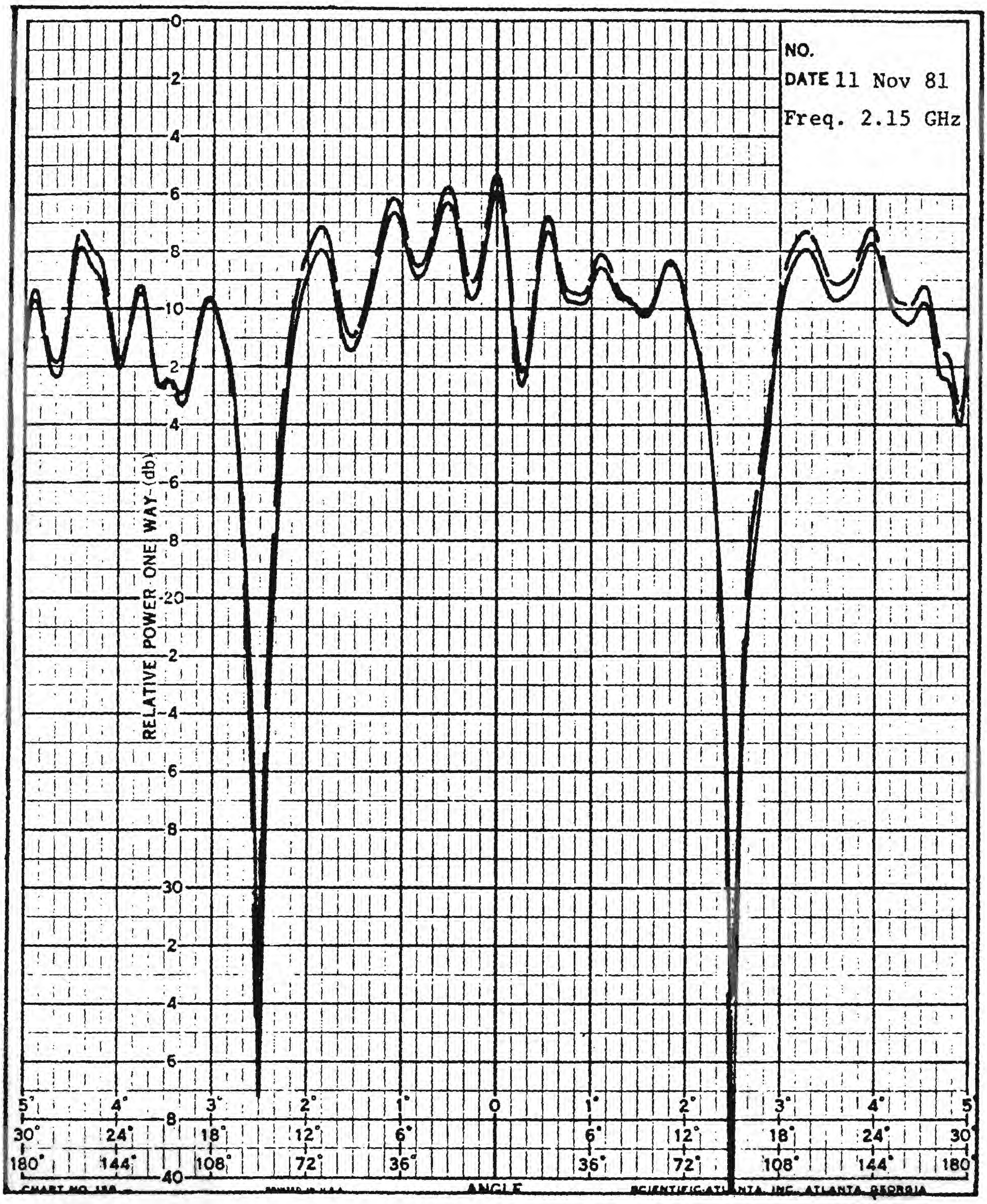


Figure B-4. Recorded Patterns Using the Electrically Long Dipole as the Test Sample. Solid Curve Represents the Compact Range Transmitting; Dotted Curve Represents the Compact Range Receiving.

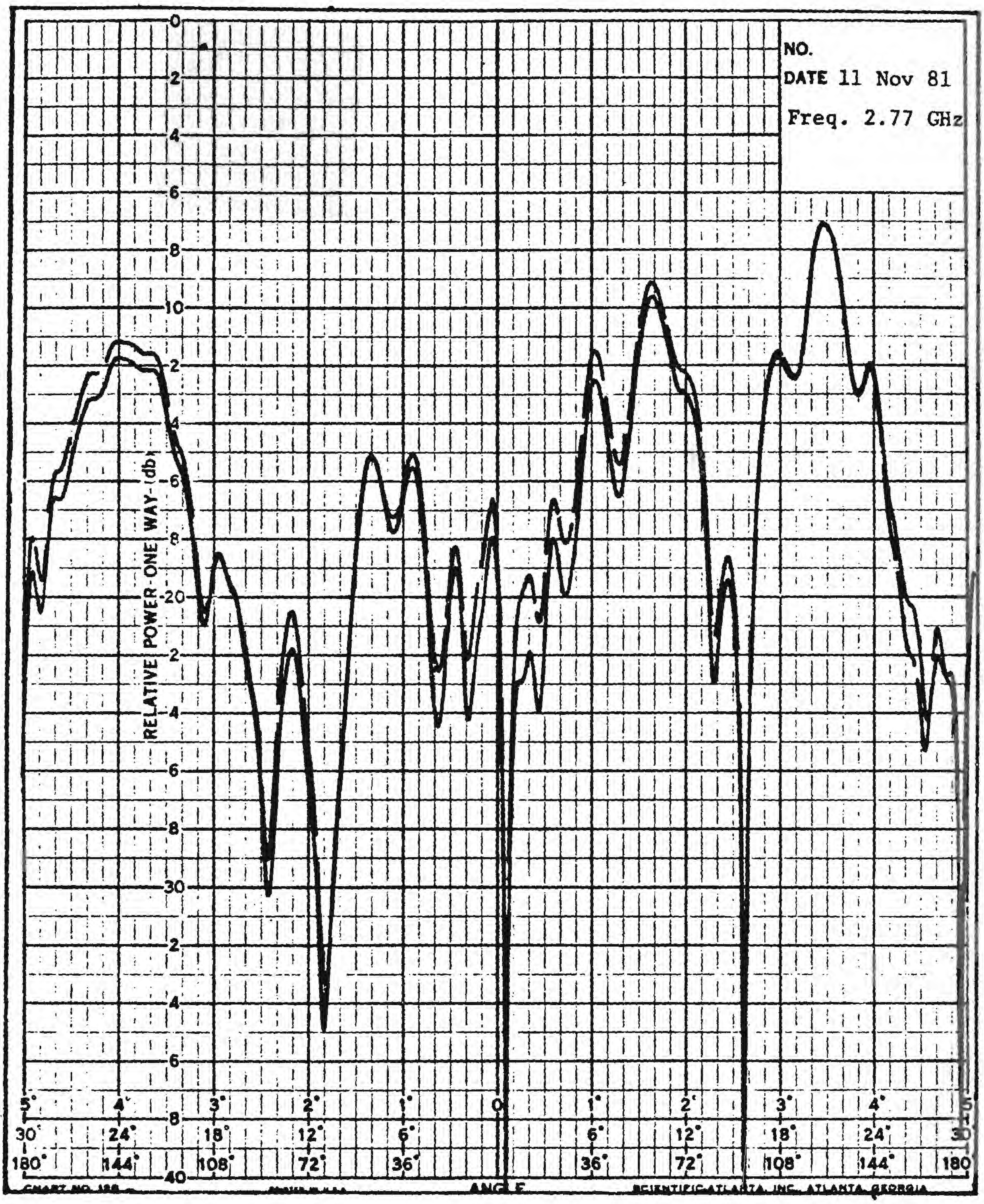


Figure B-5. Recorded Patterns Using the Electrically Long Dipole as the Test Sample. Solid Curve Represents the Compact Range Transmitting; Dotted Curve Represents the Compact Range Receiving.

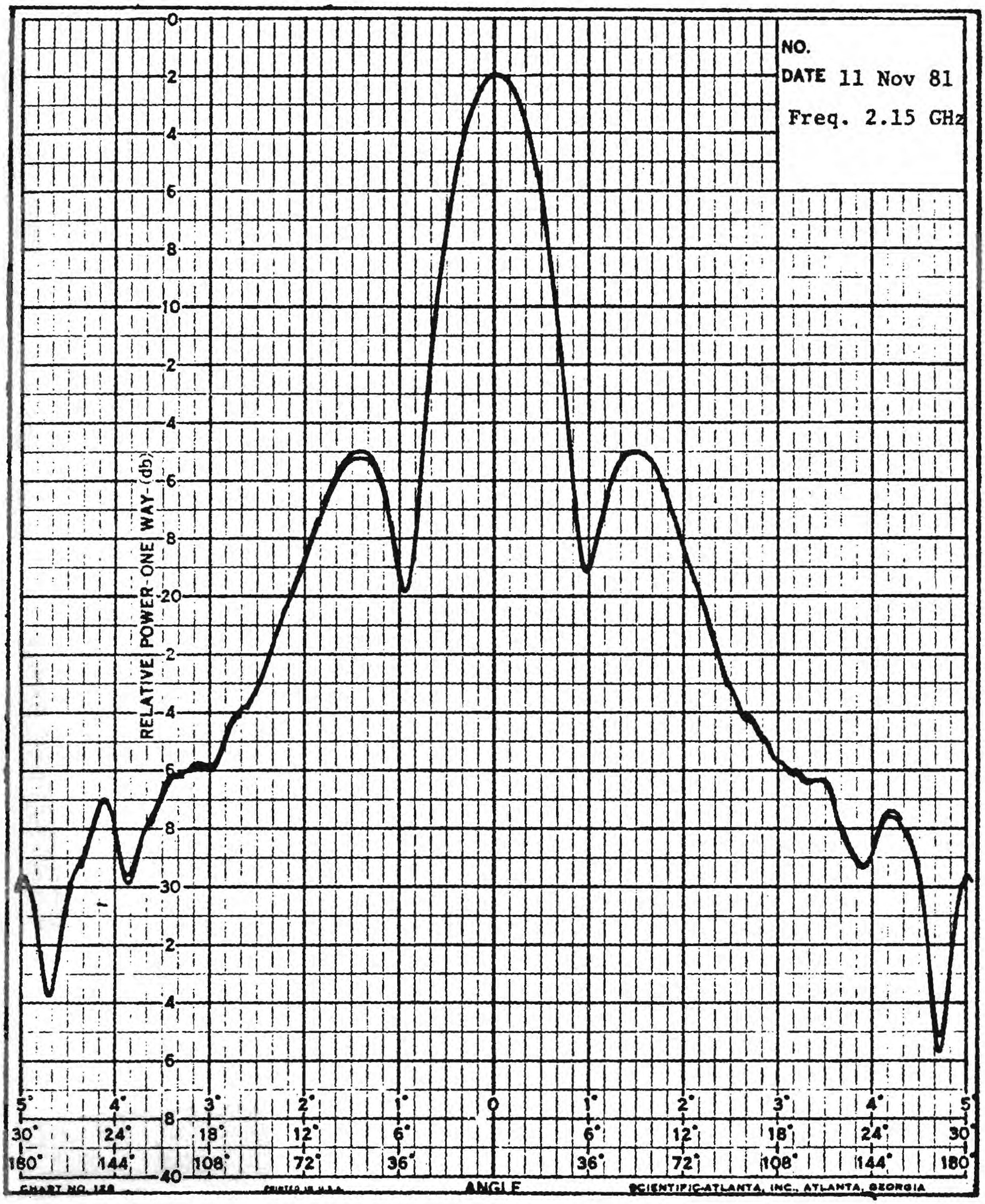


Figure B-6. Recorded Patterns Using the Standard Gain Horn. The Test Sample Solid Curve Represents the Compact Range Transmitting; Dotted Curve Represents the Compact Range Receiving.

APPENDIX C

MMW MIXER MEASUREMENTS

1. General

One receiver element which strongly influences the susceptibility of superheterodyne receivers to extraneous signals is the receiver mixer. The nonlinear characteristics of the mixer which are necessary for its function as a frequency translator (RF to IF) also give rise to undesirable mixer responses in the form of crossmodulation, intermodulation, and spurious responses. Although these undesirable responses are also affected by other receiver elements (RF selectivity, IF selectivity, etc.), a measure of mixer susceptibility to undesired responses will also provide a measure of receiver susceptibility. Thus, a knowledge of the characteristics of MMW mixers relative to their lower frequency counterparts will provide a means of assessing possible differences between the susceptibility characteristics of MMW and lower frequency receivers.

One of the simplest methods of assessing the EMC/EMI properties of a mixer is simply to measure its susceptibility to undesired responses. Since the same mixing action is responsible for the generation of harmonics, spurious responses, and intermodulation (IM) products, a measure of any of these undesired responses will inherently provide an indication of the general susceptibility characteristics of the mixer. For example, a mixer which is highly sensitive to spurious responses would also likely be sensitive to IM product formations, generate relatively large harmonic levels, etc.

The approach followed for evaluating the susceptibility characteristics of MMW mixers was to perform spurious response measurements on a selected MMW mixer. This approach was chosen since spurious responses are one of the most likely causes of receiver interference.

In order for a spurious response to be generated by the mixer, it is necessary that the frequency of the interfering signal be such that the signal or one of its harmonics can mix with the local oscillator (or one of its harmonics) to produce an output at the receiver IF. The frequencies which are capable of mixing with the local oscillator to produce spurious responses can be determined from the equation:

$$f_s = \frac{pf_{Lo} \pm f_{IF}}{q} \qquad \text{(C-1)}$$

where: f_s = spurious response frequency,

f_{LO} = local oscillator frequency,

f_{IF} = intermediate frequency,

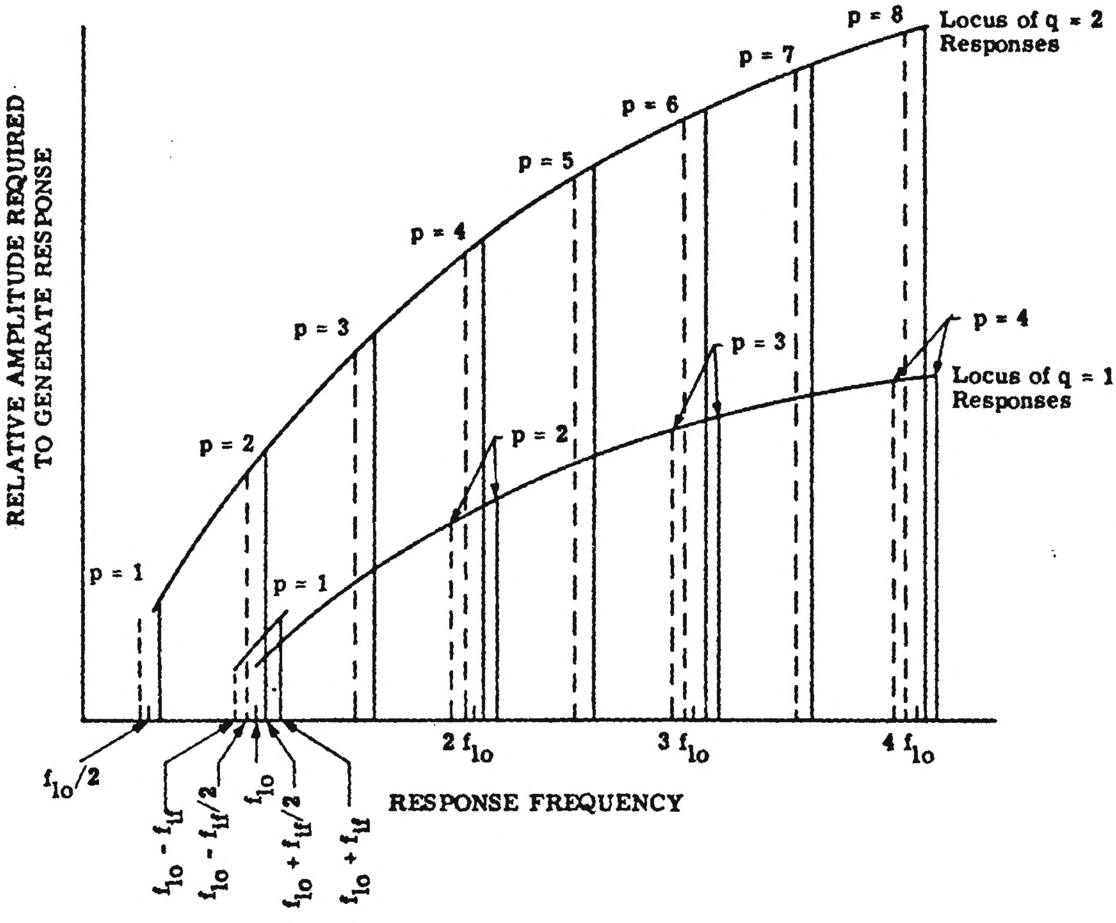


Figure C-1. Relative Amplitude Required to Generate a Particular Spurious Response (Neglecting the Selectivity Characteristics of the Mixer and Assuming Operation in the Nonlinear Portion of the Mixer's Characteristics).

$p = 0,1,2,3,...,$ and

$q = 1,2,3,...$

In Equation C-1 p represents the harmonic of the local oscillator and q represents the harmonic of the response frequency (interfering signal frequency). Specific responses are denoted by the response (p,q) value, as defined in the above equation. Thus, the p = 1, q = 1 response is denoted as the (1,1) response. There are two response frequencies for each value of p and q. The response pairs result from the fact that mixing produces outputs at frequencies corresponding to both the sum and difference of harmonics of the local oscillator and the input signal.

If we neglect the selectivity characteristics of the mixer, the response pairs generated by the mixer will appear as shown in Figure C-1. This figure illustrates the existance of response pairs for each possible combination of p and q. The two members of any given pair are separated in frequency by 2 $f_{IF/q}$. Also, Figure C-1 demonstrates that for a particular value of q, successive pairs of responses are separated by a frequency equal to $f_{LO/q}$. Thus, the q = 2 response pairs are twice as dense as the q = 1 response pairs.

The mixer susceptibility to a particular spurious response depends on several factors including: the mixer conversion ratio; the mixer selectivity characteristics; and the signal level, local oscillator level, and biasing level applied to the mixer. The mixer conversion ratio specifies the portions of the signal that are translated to the intermediate frequency. In general, if we neglect selectivity, the mixer conversion ratio will decrease as the order of p and q increase. This means that the interfering signal level required to produce a spurious response will increase with the order of p and q. Figure C-1 demonstrates the effect of the mixer conversion ratio on the level of signal required to produce a response. In particular, Figure C-1 demonstrates that there is a piecewise linear relationship between the level required to produce a spurious response in a mixer and the logarithm of the parameter p (This relationship does not account for the selectivity characteristics of the mixer and assumes mixing in the nonlinear region of the mixer).

A second factor which influences the signal level required to produce a spurious level required to produce a spurious response is the selectivity characteristics associated with the mixer. The selectivity characteristics associated with the mixer give additional discrimination against signals at spurious response frequencies. In particular, for mixers which utilize waveguide, frequencies appreciably below the cutoff of the waveguide would not be potential spurious response frequencies. Other geometrical or electrical properties of a particular mixer will also add to its selectivity characteristics.

The signal level, local oscillator level, and biasing level applied to the mixer also influence the spurious response amplitude. If the injected local oscillator and signal level are such that the diode is operated primarily within the nonlinear portion of its characteristics, the mixing action can be approximated by a power series representation of the mixer's nonlinear characteristics [28]. When the injected signal or local oscillator levels become large with respect to the nonlinear region of the mixers characteristics, the time spent traversing this region approaches zero, and for sufficiently large inputs,

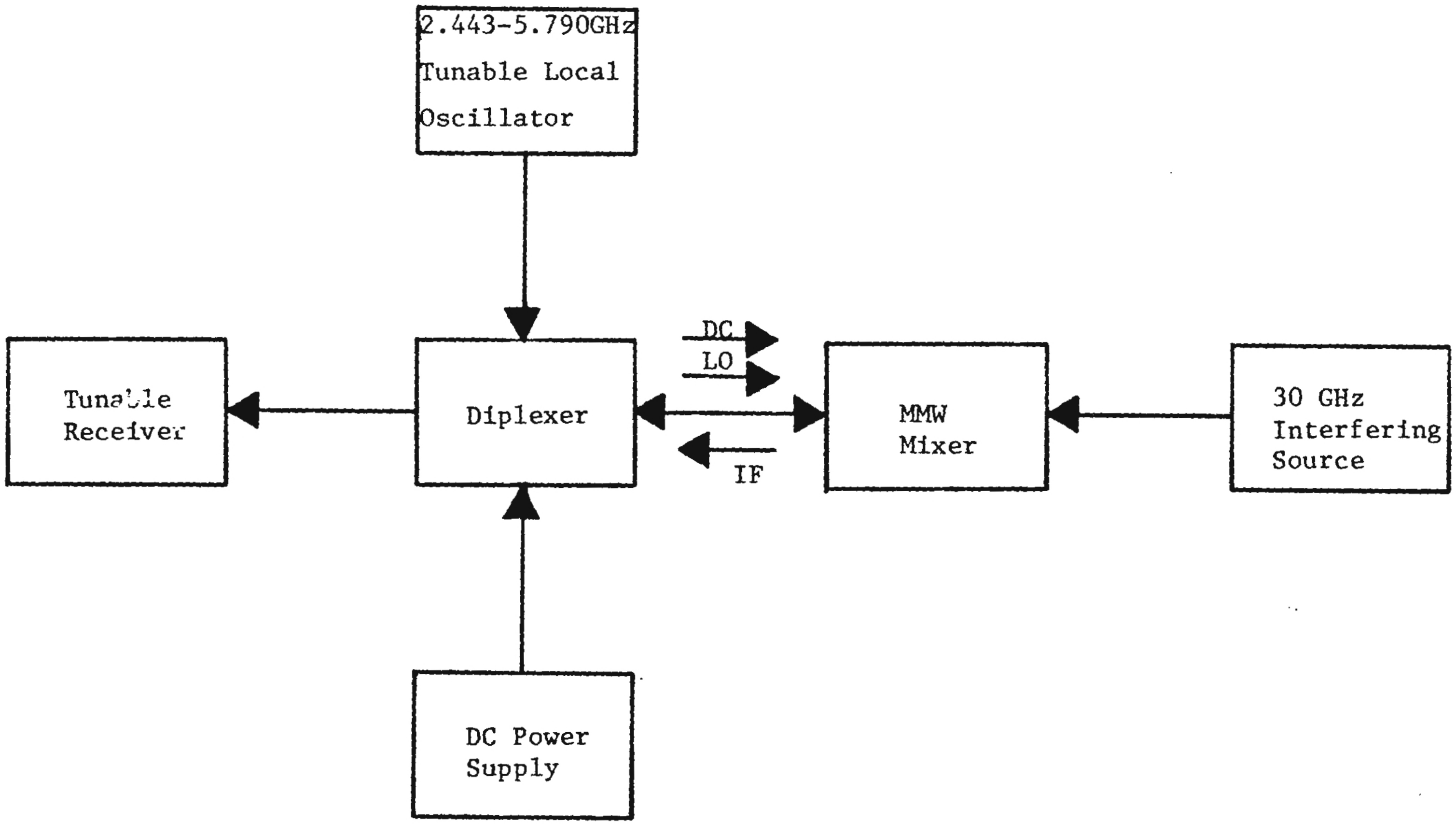


Figure C-2. Equipment Configuration Used for Spurious Response Measurements Performed on a 30 GHz MMW Mixer.

the mixer characteristics may approach that of an ideal "ON-OFF" switching device. Prediction of the mixing action of such a device is also well documented [29]. However, for mixers in general, where a multiplicity of operating conditions may exist, the prediction problem becomes much more complicated. The problem arises in that the range of signal and local oscillator levels, which might be incident on a mixer, could produce responses either by nonlinear mixing, switching, or both. The mixing action in the transition region between nonlinear mixing and switching is not clearly defined.

2. MMW Spurious Response Experimental Measurements

Due to the limited availability of tunable MMW sources and the lack of appropriate MMW components (filters, etc.), it was not feasible to perform MMW mixer spurious response measurements using a conventional test configuration and procedure. In conventional spurious response measurements, the interfering source is tuned to each spurious response frequency of interest (that is the frequency corresponding to a particular p and q in Equation C-1, while the local oscillator frequency is kept constant. MMW sources have extremely limited tunability, with maximum tunability equal to the bandwidth of the particular waveguide band employed in the output port of the source. This limited tunability also limits the number of spurious response frequencies which can be tested using the conventional test procedure.

Conventional spurious response measurements also require filtering between the mixer and the interfering source and between the mixer and the local oscillator; these filters are used to attenuate the harmonics of the interfering source and of the local oscillator. Although several manufacturers sell filters operating in the MMW frequency band, they are sold as special order items, thus causing lengthy delivery periods. Filters ordered by Georgia Tech for these measurements were not delivered in time to include in the test setup.

Conventional spurious response measurements allow for the measurement of fundamental mixer (that is the (1,1) which is the desired response in most "low frequency" mixers. However, MMW mixers generally use a harmonic of the local oscillator frequency to produce the desired response. The local oscillator frequencies of MMW receivers are typically in the microwave frequency band rather than the MMW frequency band for several reasons including: reduction of power loss in the transmission path between the local oscillator and the mixer, limited tunability of the MMW sources which can be used as the local oscillator, and the high cost of MMW sources. Thus, the desired response for a MMW mixer may be the (10,1) response rather than the (1,1) response. For example, the Tektronics 492P spectrum analyzer utilizes the (10+, 1), (15+,1), (23+,1) and (37+, 1) responses for various operating bands in the MMW region. Therefore, the spurious responses which are most likely to be causes of interference for MMW receivers are the higher order p responses (that is for a MMW mixer employing a (10+,1) response as the desired responses the (10-,1), (11+,1), (9+,1) (12+,1), etc. responses will be the responses which will be the most likely sources of interference). While the (1,1) response will not be present since the (1,1) response will require a spurious response frequency which is below the waveguide cutoff frequency on the mixer input port. This consideration of the operational characteristics of MMW mixer and the limitations mentioned in the previous discussion led to following measurement configuration which was used for spurious response measurements on a 30 GHz MMW mixer.

A block diagram of the equipment configuration used for the spurious response measurements performed on the 30 GHz MMW mixer is given in Figure 2. A Tektronics 492P spectrum analyzer was used as the test receiver utilizing its local oscillator which swept from 2.443 GHz to 5.790 GHz. The mixer and diplexer used in the measurement configuration were manufactured by Tektronics and were designed for use especially with the 492 P spectrum analyzer. A Poland Electronics Corporation HU-2A source tuned at 30 GHz was used as the interfering source. In this measurement configuration, a multiple number of spurious responses could be viewed on the spectrum analyzer at one time. Figure C-3 shows typical displays viewed on the 492 P spectrum analyzer set for maximum span (that is full view of the local oscillator sweep). Figure C-3 also shows the increasing number of spurious responses as the interfering source power is increased.

In the frequency band containing 30 GHz the spectrum analyzer display is calibrated for the (10+,1) response. The dot marker in the photographs, in Figure C-3, correspond to the frequency displayed at the center-top of each photograph (30 GHz). Since the interfering signal frequency is known to be 30 GHz, the response at which the marker is the (10+1) response (this can be verified using the signal identification routine on the 492 P spectrum analyzer). Now that desired response has been identified all other responses can be identified using the procedure given below.

The local oscillator frequency corresponding to the desired response can be calculated using Equation (3) with f_s = 30 GHz, P = 10, q = 1, f_{IF} = 2.072 GHz:

$$f_{Lo}^{(10^+,1)} = \frac{30 - 2.072}{10} = 2.7928 \text{ GHz} \qquad \text{(C-2)}$$

Now to identify a particular response first find the local oscillator frequency corresponding to that response as follows:

$$\Delta f_{lo} = \frac{f_{SA} - 30}{10}, \qquad \text{(C-3)}$$

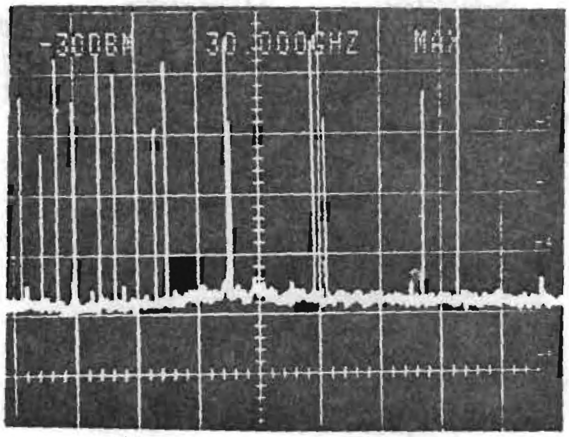
$$f_{Lo}^{(p,q)} = f_{Lo}^{(10^+,\ 1)} + \Delta f_{Lo}$$

where,

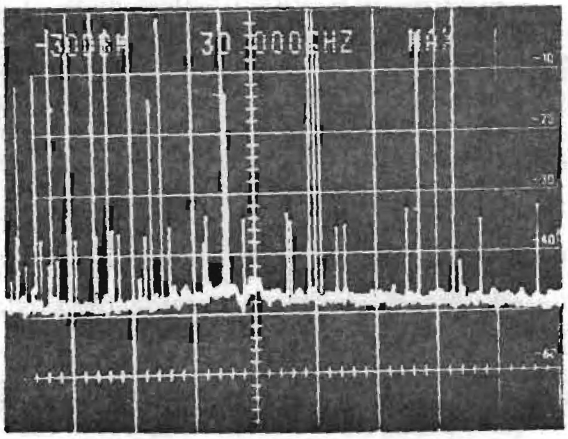
f_{Lo} = the change in the local oscillator frequency from (10+, 1) response to the response under test.

f_{SA} = frequency displayed on the spectrum analyzer for the response under test.

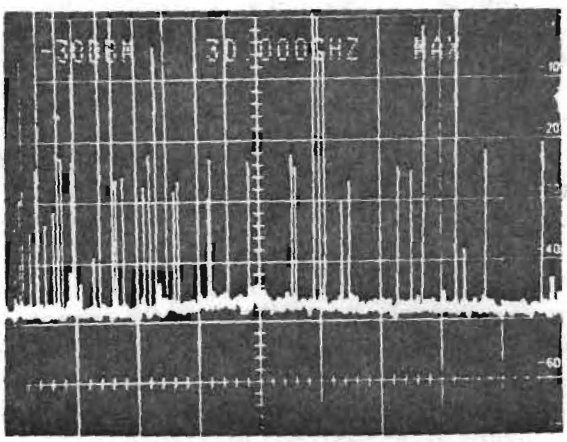
$f_{LO}^{(p,q)}$ = local oscillator frequency at response under test.



(a) -30dBm Interfering Source Output Power



(b) -25 dBm Interfering Source Output Power



(c) -20dBm Interfering Source Output Power

Figure C-3. Spurious Responses Displayed on Spectrum Analyzer's Display Using an External MMW Mixer with an Applied 30GHz Signal. (Figures a-c show the variation in spurious response amplitude with the variation of the applied signal amplitude).

The only two unknowns in Equation C-1 are now p and q. To find q decrease the amplitude of the interfering signal by 10 dB. If the response drops by 10 dB q is equal to one, q is equal to two if the response drops by 20 dB, etc. We can now solve Equation C-1 for the last unknown variable p, as shown

$$p \pm = \frac{q \cdot 30 \mp f_{IF}}{f_{Lo}(p,q)} \tag{C-4}$$

This procedure was used to identify all of the response displayed on the spectrum analyzer for a -20 dBm 30 GHz interfering signal. Figure C-4 shows the results of these measurements for all the responses which were greater than -60 dBm. The q = 2 responses in Figure C-4 are on the average 22 dB below the q = 1 responses. Figure C-4 also demonstrates the fact that only the desired response (10+,1) has its image response (10-,1) separated on the spectrum analyzer scale by $2f_{IF}$ = 4.144 GHz. All other responses pairs are separated on the spectrum analyzer frequency scale by less than $2f_{IF}$ for responses with p greater than 10 and by greater than $2f_{IF}$ for responses with p less than 10. This fact can be used in automated test setups to determine the desired responses if the interfering signal frequency is not known.

Once the responses were identified, the spurious response sensitivity or threshold levels could then be measured. These threshold levels identify the signal input level required to realize a standard response at the mixer output (for these measurements, a standard response of 12 dB (S+N)/N was used). Given these measured spurious response levels, the rejection of the mixer to a particular spurious response is simply the difference between the level of that response and the desired response (10+,1) level.

It is noted here that the 492P spectrum analyzer has a peaking control to adjust the mixer bias in order to maximize the response. This adjustment was used to peak the desired response (10+,1) in the above threshold measurements. All other responses were measured with the peaking adjustment at this setting.

It is also noted that the measurements performed in this test procedure did not reflect the selectivity characteristics of the MMW mixer since all of the responses were measured with the same interfering source frequency. However, spurious response frequencies below the cutoff frequency of input waveguide do not need to be measured due to the lack of signal propagation in the waveguide at these frequencies, and spurious response frequencies above the dominate mode frequency are meaningless due to the multimoding problems. Thus, any frequency variation of the spurious response frequency must be limited to that small frequency band at which the input waveguide only supports the dominate mode. This problem is eliminated in the proposed radiated spurious response test for MMW receivers due to the fact that the effects of the antenna are included in the measurement and the length of waveguide between the antenna and mixer corresponds to that in the actual environment. Thus, even at frequencies above

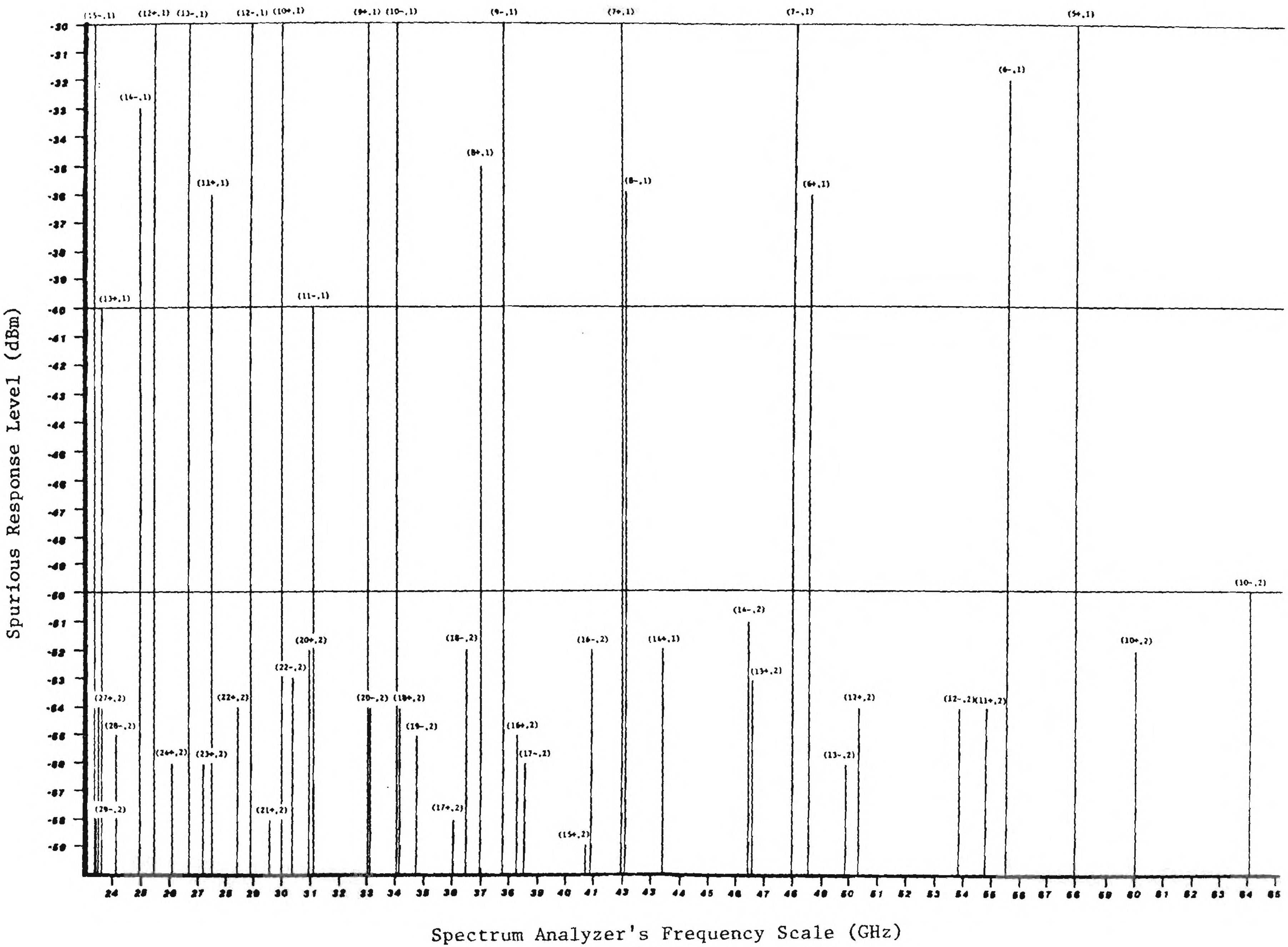


Figure C-4. Identification of all Spurious Responses Greater Than - 60dBm on Spectrum Analyzer's Display for a - 20 dBm 30GHz Interfering Signal.

the dominate mode of the waveguide where multimoding exists the measurement is representative of operating conditions of the receiver in its environment.

Table C-I gives the results of these measurements for q = 1 responses and q = 2 responses. The average rejection for the q = 1 responses is 3.1 dB while the average rejection for the q = 2 responses is 30.1 dB. As Table C-I is reviewed, it is seen that the interfering signal level required to produce a standard response at the mixer output does not increase as the logarithm of the parameter p, as shown in Figure C-1. This is due to the operational characteristics of the MMW mixer rather than the nonlinear characteristics of the MMW mixer. An extremely high level local oscillator signal is applied to the mixer in order to generate the high order harmonics necessary to mix the MMW signal down to the IF of the spectrum analyzer. Thus, the mixer is operating either in the switching state or at a state which is a combination of nonlinear mixing and switching. As seen in Table C-I the level of interfering signal necessary to produce a standard response at some of the q = 1 responses are less than the level required to produce a standard response at the desired response. The results of these measurements indicate that spurious responses may be a particular problem for MMW receivers employing subharmonically pumped mixers without preselection.

MMW receivers using local oscillators in the MMW band, where the desired response is the fundamental response (1,1) will not use as high of a level of local oscillator signal as subharmonic pumped mixers. These mixers will thus generally operate in the nonlinear mixing state and the responses will correspondingly decrease as the logarithm of the parameter p. This will reduce the interference potentials from that a subharmonically pumped mixer.

From the above experimental measurement results it can be concluded that basically MMW mixers have similar characteristics as their lower frequency counterparts. Thus, the susceptibility characteristics of MMW receivers will generally be similar to lower frequency receivers. The two characteristics of MMW mixers which are different from lower frequency mixers are: (1) The input port of MMW mixers will generally use a waveguide transmission path, thus, frequencies below the dominate mode of the waveguide will not be potential spurious response frequencies, and (2) for MMW mixers employing a subharmonically local oscillator signal the desired response will be a high order of responses, therefore, the rejection of other undesired high order of responses will generally be equal to if not less than the desired response.

TABLE C-I

MEASURED SPURIOUS RESPONSE THRESHOLD LEVELS AND CORRESPONDING REJECTION FROM THE DESIRED RESPONSE (10+,1) FOR A MMW MIXER OPERATING AT 30 GHz.

q=1 Responses			q=2 Responses		
P	Threshold	Rejection	P	Threshold	Rejection
15-	-50.0	4.0	29-	-19.5	34.5
14-	-43.0	11.0	28-	-22.0	32.0
13+	-49.0	5.0	27+	-24.0	30.0
13-	-50.0	4.0	24+	-22.0	32.0
12+	-49.5	4.5	23+	-22.5	31.5
12-	-50.0	4.0	22+	-24.5	29.5
11+	-48.0	6.0	22-	-24.0	30.0
11-	-41.0	13.0	21+	-22.0	32.0
10+	-54.0	0.0	20+	-24.5	29.5
10-	-52.0	2.0	20-	-25.0	29.0
9+	-51.5	2.5	19-	-22.0	32.0
9-	-53.0	1.0	18+	-23.5	30.5
8+	-48.5	5.5	18-	-25.0	29.0
8-	-53.0	1.0	17+	-25.5	28.5
7+	-55.0	-1.0	17-	-21.5	32.5
7-	-55.0	-1.0	16+	-25.5	28.5
6+	-51.0	3.0	16-	-20.0	34.0
6-	-54.0	0.0	15+	-24.5	29.5
5+	-60.0	-6.0	14+	-24.0	30.0
			14-	-24.5	29.5
			13+	-25.0	29.0
			13-	-24.5	29.5
			12+	-22.0	32.0
			12-	-26.0	28.0
			11+	-26.0	28.0
			10+	-26.5	27.5
			10-	-28.0	26.0

NOTE:

(1) Threshold levels are measured in dBm and correspond to the input Power required to generate a 12dB $\left(\frac{S+N}{N}\right)$ response.

(2) Rejection levels are in dB and are computed by subtracting the threshold level for a particular response from the desired response's (10+,1) threshold level.

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