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Research and Development Technical Report

ECOM-0171-3

MILLIMETER WAVE SYSTEM ELECTROMAGNETIC COMPATIBILITY STUDY

QUARTERLY REPORT

By
G.G. Sundberg
and
R.F. Marsolais

APRIL 1975

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CONTRACT DAAB07-74-C-0171
GROUND SYSTEMS GROUP
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MILLIMETER-WAVE SYSTEM EMC STUDY

Third Quarterly Progress Report

6 Aug 1974 to 6 Nov 1974

CONTRACT NO. DAAB07-74-C-0171

DA PROJECT NO. 1S7 62701 AH92

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ABSTRACT

This report presents the results obtained from experiments and analysis performed during the third quarter effort of the Millimeter Wave Electromagnetic Compatibility Study. The period covered is from 6 August to 6 November 1974. The major effort in the third quarter consists of performance of experiments which are related to the millimeter wave study, computer analysis of electromagnetic compatibility requirements for typical Army deployments, analysis of modulation effects, analysis of out-of-band antenna characteristics and initiation of the recommended EMC test program for millimeter wave systems.

Experiments ten through fourteen were performed during this quarter. These experiments involved electromagnetic compatibility evaluation of millimeter wave communication and radar systems. Shielding and reflectivity tests were performed to determine the effects of building and equipment enclosures materials on propagation and scattering of millimeter wave emissions.

Computer analysis programs employed during this study were designed to provide assistance in establishing emission and susceptibility parameters which shall be specified to assure electromagnetic compatibility between millimeter wave systems and other collocated systems.

A preliminary test matrix containing a list of EMC tests recommended for millimeter wave systems was developed.

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I. INTRODUCTION AND SUMMARY

This is the quarterly report for the third quarter of the Millimeter Wave Electromagnetic Compatibility Study under ECOM contract number DAAB07-74-C0171. This report documents the work performed during the period of 6 August to 6 November 1974.

Experiments involving electromagnetic compatibility tests performed on millimeter wave communication systems collocated with other millimeter wave communication and radar systems are described. Radiated electromagnetic interference emission and susceptibility evaluations of millimeter wave communication and radar systems are described. A description of an analysis performed to obtain out-of-band characteristics of millimeter wave antennas is included. Difficulties encountered in obtaining viable experimental results in this area proved to be beyond the scope of this contract effort and an analytical approach was decided upon in lieu of performing measurements. Shielding and reflectivity tests performed on typical building and equipment shielding materials are described.

A first cut at a suggested EMC test matrix for millimeter wave systems is included. Further details will be added to this matrix which will be submitted in the final report.

Spectrum measurements of lower frequency systems operating in the frequency range of 1 to 10 GHz was conducted. These systems operate in frequency ranges similar to those being used in typical Army deployments. Harmonics as high as ninth and tenth order were discovered during this survey.

Appendix A contains a complete description of the computer program used for analyzing the interference interactions between collocated millimeter wave systems planned for use in typical Army deployments. Recommendations for specifications limits to be placed on millimeter wave systems to be located within distances of 10 to 100 meters in the deployment configurations supplied by ECOM will be based upon application of this computer analysis and data gathered during this study. This appendix includes a listing of the program in detail to enable the use of this program at a later date for further evaluation of any new deployments which may be considered. The present program however is limited to 100 meters. A future adaptation extending the distance beyond 100 meters would require the addition of atmospheric losses for millimeter-wave frequencies which vary considerably over the frequency range of 10 to 100 GHz. This can be readily accomplished by adding appropriate values of propagation loss from the graph in Figure 20 of the first quarterly report (reference 3).

II. RESULTS OF THIRD QUARTER EXPERIMENTS AND ANALYSIS

A review of the results of the third quarter effort which has included a continuation of experimental and analytical studies indicates that the major portion of the data and information necessary to establish meaningful recommendations has been gathered. A few minor details still remain to be defined further for incorporation into the millimeter wave EMC specification. The experimental portion of this study has been essentially completed. A small number of isolated experiments may be continued into the fourth quarter as required to gather any further data deemed necessary to complete the study.

Computer analysis of the potential interference interactions in typical deployment such as those described by ECOM are being performed and will continue into the fourth quarter. This computer program is proving to be very helpful in establishing parameters of collocated millimeter wave and lower frequency systems. The results obtained to this report indicate that if worst case conditions exist in the deployment configuration then the EMI requirements will be very stringent; however, if some discretion is employed in the deployment configuration the EMI requirements can be relaxed considerably.

Experiments performed during this quarter indicate in some cases that millimeter wave systems exhibit wider transmission bandwidths than those of lower frequency systems. The millimeter wave radar systems, however are still within the emission bandwidth requirements of MIL-STD-469 and MIL-STD-461. The same was found true for receiver acceptance bandwidths. However it must be recognized that the requirements of MIL-STD-461 and MIL-STD-469 allow wider bandwidths as the transmission frequency being employed increases. Frequency allocations in the millimeter wave regions must therefore take into consideration these wider system bandwidths. The new solid state millimeter wave sources were found to exhibit very low harmonic emissions. This is due to the fact that these sources can be operated in a manner that provides highly linear characteristics.

It became evident during the performance of the experiments that further advancement in the state-of-art of millimeter wave EMC equipment is needed. Some of the areas requiring further study and development include built-in calibration provisions for portable equipment, calibrated high gain antennas, receiver sensitivity, receiver spurious responses, portable signal generators and frequency indicating equipment. During the course of performing experiments in this study, it was necessary to calibrate the portable instruments for each specific series of measurements. Highly accurate and sensitive laboratory devices are available for use in performing laboratory experiments. However these components have never been assembled into a portable test equipment system .

The experiment planned to gather experimental data on out-of-band antenna characteristics proved to be beyond the scope of this contract due to unforeseen difficulties encountered in obtaining meaningful data. It was discovered that it is very difficult to simulate an actual situation where a transmitter generates second and higher order harmonics in a specific waveguide and antenna system.

In attempting to use laboratory generators to excite a waveguide and antenna system it is necessary to use transitions to match the generator to the waveguide. This use of waveguide transitions destroys the main intent of the experiment since it does not allow the waveguide to be excited by the complex modes which occur in the actual system. For this reason it was decided that an antenna analysis would provide a more accurate definition of the out-of-band characteristics of an antenna and waveguide system than would be obtained from experimental data.

III. EXPERIMENTAL PROGRAM

A. TYPES OF EXPERIMENTS

Experiments performed during the third quarter constituted a continuation of the experimental program described in the second quarterly report (reference 4). This quarter's effort included experiments 10 through 14. Experiments performed during this quarter included the following:

10. Shielding and Reflectivity Evaluation

    a. Building Materials
    b. Equipment Enclosure Material

11. System Compatibility Evaluation of Collocated Millimeter Wave Radar and Communication Systems.

12. Radiated Interference Evaluation of W-Band Radar System.

13. Evaluation of Radiated Emissions and Compatibility Characteristics of Collocated Ka and V Band Communication Systems.

14. Evaluation of Millimeter Wave Higher Order Harmonic Radiations of 1 to 10 GHz Systems.

B. EXPERIMENT NUMBER TEN

1. Purpose.

The purpose of this experiment was to investigate the shielding and reflectivity characteristics of building and equipment enclosure materials. The need for an experiment of this type became evident during the performance of earlier experiments involving compatibility and emission evaluations of millimeter wave systems. Millimeter waves were found to be shielded and reflected by numerous materials which do not possess these characteristics at lower frequencies. Ordinary building materials such as wood and cement are found to exhibit a considerable amount of shielding and reflectivity at millimeter wave frequencies. Test specimens investigated are listed in Table I.

Consideration of these parameters was considered pertinent to this study since they are the source of adverse or in some instances desirable effects on electromagnetic compatibility aspects of millimeter wave systems. Reflections are a source of considerable confusion during the evaluation of radiated emissions from millimeter wave systems if they are not recognized and controlled. Employment of absorbing material is very important in the performance of radiated emission tests at millimeter wave frequencies. Absorbing material is needed for materials such as wood, brick and cement which are not normally considered to be reflective materials at lower frequencies.

TABLE I. SHIELDING TEST SPECIMENS

Material	Characteristics, Dimensions, Etc
Concrete	High rock density, thickness of 2 inches
Brick	Firebrick building material, thickness of 2 inches
Wood	Hardwood, 2 by 4
Screen	18 by 18 copper mesh
Coated Glass	EMI shielding glass, 14 ohm per square
RF Absorbent Material	Metal impregnated rubber
Panel Honeycomb	Plain metal and coated

Previous studies on terrain backscatter at frequencies between 40 GHz and 90 GHz (reference 1) were employed as guidelines in this experiment.

2. Test Set-Up.

The test set-up for experiment number ten was as shown in Figure 1. The configuration in Figure 1 contains the overall test setup with the arrangement for switching between various generators covering wide frequency ranges. Multiple measurement antenna set-ups are shown. RF absorbent material is shown in the background for prevention of reflections.

Shielding measurements were made by placing the material to be tested in a holder which prevented stray fields from the generator from being picked up by the receiver antenna (see Figure 1). This holder was then placed between the generator and receiver antennas.

Reflectivity measurements were made by bouncing the generator signal off the material being tested into the receiver antenna.

3. Test Procedure.

The shielding measurements were made by adjusting the receiving antenna and EMC receiver controls to a maximum level with the test specimen removed from the path of the radiated beam. Shielding measurements were then performed by comparing levels obtained at the receiver with and without the test specimen located directly in the path of the radiated beam.

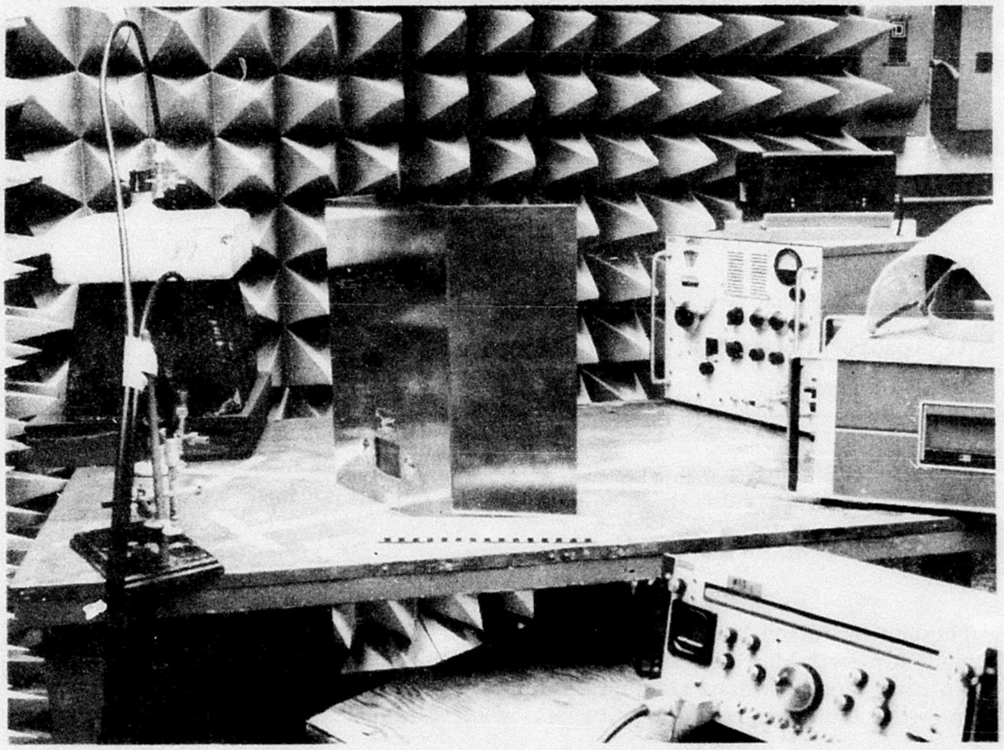

Figure 1. Shielding Effectiveness Test Set Up

Reflectivity measurements were made by inserting a sheet of copper in the generator beam at an angle of 45 degrees. The receiver was then placed directly in the reflected beam. The receiver antenna position was then adjusted for maximum pickup. The copper sheet was then removed and replaced with the specimen. The drop in received signal was compared to the signal reflected from the copper plate.

Measurements of shielding effectiveness in the frequency range of 20 to 60 GHz were performed at Fullerton, Calif. Measurements at frequencies in the 90 GHz range were performed at the radar facilities at Hughes Research Laboratories, Malibu, California. Reflectivity measurements were performed in the 20 to 60 GHz range only.

4. Test Results

The experiment indicated that certain building and enclosure shielding materials exhibit higher shielding effectiveness and reflections at millimeter waves than at lower frequencies. These materials include building materials such as concrete, fire brick and wood. Materials containing many backscattering elements such as concrete heavily laden with gravel exhibit an increasing shielding effectiveness as frequency increases. Enclosure materials such as metal honeycomb and EMI coated glass exhibited very low values of attenuation at millimeter wave frequencies.

Typical building concrete exhibited shielding values of 11 dB at 20 GHz increasing to 45 dB at 90 GHz, fire brick ranged from 7 dB to 40 dB and wood ranged from 4 dB to 29 dB over the same frequency range. Typical enclosure materials such as 18 by 18 mesh copper screen exhibited shielding values of 15 dB at 20 GHz decreasing to 3 dB at 90 GHz, coated glass decreased from 22 dB to 3 dB and plain honeycomb panels indicated a decrease from 10 dB to 3 dB over the same frequency range. One quarter inch thick absorber sheets composed of metal impregnated rubber indicated shielding values ranging from 20 dB at 20 GHz to 14 dB at 90 GHz.

5. Test Equipment

Item	Mfr	Model	Range
Receiver EMI	Micro-Tel	WR200	10-100 GHz
Receiver EMI	Micro-Tel	WR250	10-100 GHz
Signal Generator	HP	628A	12 to 20 GHz
Sweep Osc	HP	8690B	26.5-40 GHz
Sweep Osc Plug In	HP	8697A	26.5-40 GHz
Transceiver (used as RF source)	Hughes	–	60 GHz
Spectrum Analyzer	HP	8551	10-40 GHz
External Mixers	Micro-Tel	1205-7A	18-26 GHz
		1205-8A	26-40 GHz
		1205-9A	40-60 GHz
	Hughes	–	60-120 GHz
Antennas	Micro-Tel	MH-7	18-26 GHz
		MH-8	26-46 GHz
		MH-9	33-50 GHz
		MH-10	50-75 GHz
	Hughes	–	60-120 GHz
Radar (used as RF source)	Hughes	--	90 GHz

6. Conclusions

These tests indicate that many building and equipment enclosure materials which do not provide significant shielding and reflectivity characteristics at lower frequencies can do so at millimeter-wave frequencies.

The main purpose of this experiment was to demonstrate that ordinary building and equipment enclosure materials provide shielding and reflection of millimeter frequencies. This characteristic of millimeter waves is considered important in establishing EMI specification limits for millimeter wave systems collocated within 10 meters in enclosures and in field sites at distances up to 100 meters. The significance of this characteristic indicates that side lobe control of the radiated beam is very important as undesired side lobes can be reflected by materials not normally considered as reflectors. The shielding characteristics of many building materials however can be very helpful in preventing undesired interaction between millimeter wave systems located within enclosures.

C. EXPERIMENT NUMBER ELEVEN

1. Purpose

The purpose of this experiment is to evaluate the interaction between radar and communication systems when the two systems are operated in close proximity. This compatibility test determines the intrasystem electromagnetic interactions between typical communications and radar systems.

2. Test Setup

The test setup is shown in Figure 2. The communications system was operated with its transmission beam both perpendicular to and parallel to the radar beam so that both communications transceivers were in or near the main beam of the radar field.

3. Test Procedure

The communication transceivers were set up in vicinity of the radar system. The transceivers were moved slowly toward the main radar beam. The quality of the communication signal was checked as the transceivers were moved around the area of the radar site. Communications were checked in the side lobes of the radar beam. The communication signals were checked for quality or for reduction of useable range. Amplitudes of the radar fields were measured with the EMC receiver at locations where the communication system was affected.

4. Test Results

The units were operated successfully in the area of the radar system with exception of the area at the edge of the main radar beam. Modulation of the radar was detected in the audio output of the transceiver at this location. The useful communication range of the transciver was reduced at this location due to the radar modulation effects. The field from the radar was measured at

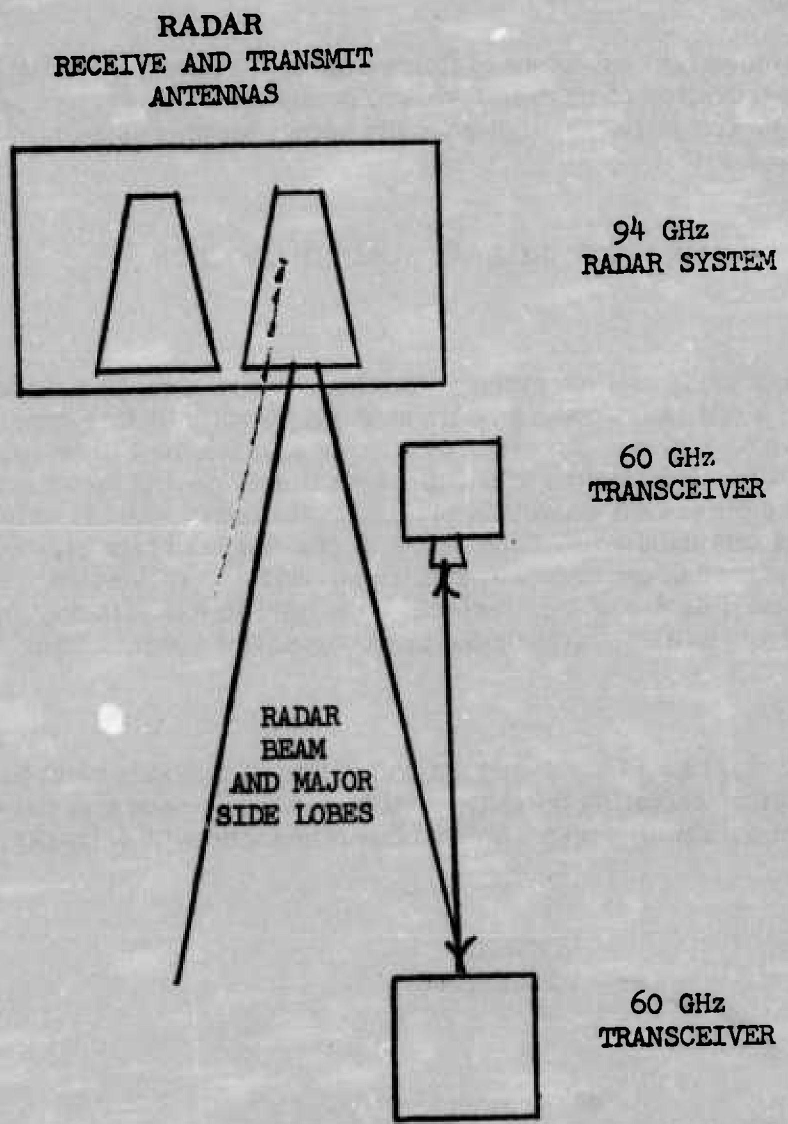

Figure 2. Millimeter Wave Radar/Communications System Compatibility Evaluation

this point and found to be 60.3 volts/meter. This field is equivalent to approximately 60 dB above the minimum useable signal level of the transceivers. The susceptibility condition occurred when the receiving transceiver was directed toward the radar antenna system.

5. Test Equipment

W Band Radar System (94 GHz)
Two (2) 60 GHz Hughes Transceivers
High Gain Mixer and Antenna (Hughes) 70 to 120 GHz
Micro-Tel Receiver, Model WR250, 50 to 100 GHz

6. Conclusions

It was found that out-of-band fields of approximately 60 volts per meter can cause a degradation of millimeter wave communication system performance. The degradation was in the form of an audio output which was related to the radar pulse modulation rate.

D. EXPERIMENT NUMBER TWELVE

1. Purpose

The purpose of this experiment was to measure a typical radiation field pattern around a millimeter wave radar system. Results of this experiment are needed in order to evaluate the electromagnetic environment to be expected in the vicinity of 10 to 100 meters of a typical millimeter wave radar system. There are some classified aspects applying to this radar system which will not be discussed in this document. This test was planned to obtain data which would be helpful in evaluating personnel radiation hazards and collocated system susceptibility areas. Results of this test will be helpful in establishing emission and susceptibility limits to be included in the proposed specification.

2. Test Setup

A block diagram of the test area and points of measurement is shown in Figure 3. A typical radiation measurement test setup is shown in the photograph of Figure 4. The pickup probe was later replaced with a larger, high

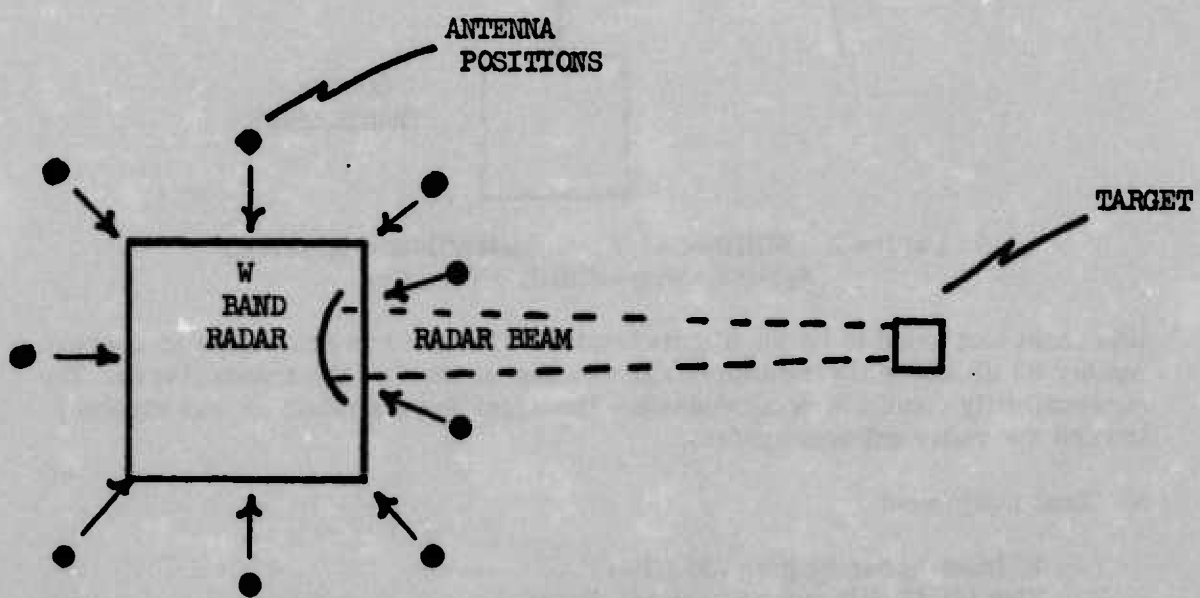

Figure 3. Radiated Emissions Test Setup – W Band Radar System

Figure 4. Radiation Field Measurements of MM-Wave Radar System

gain horn shown in Figure 5. High gain horns were used to improve the overall receiver sensitivity. A close-up view of the radar antenna is shown in Figure 6. The absorbent material between the receive and transmit antennas provides isolation of the receive and transmit signals. Figure 7 shows a view of the radar system with a simulated target. The radar is located on a high cliff overlooking the Pacific Ocean at Malibu, California. This test site provides a very low ambient background with a minimum of reflections and is comparable to

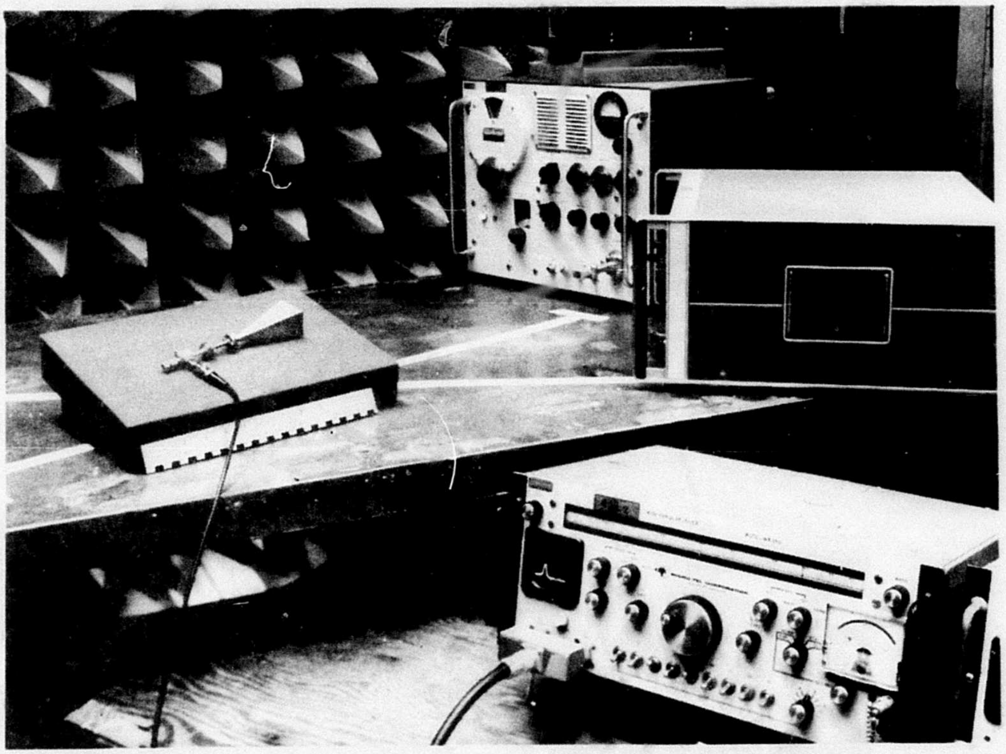

Figure 5. 20 dB Gain Horn Antenna

operating in an anechoic chamber. A frequency search revealed no RF energy was present in the environment in the millimeter wave frequency range below 94 GHz. The search did not go above 94 GHz.

3. Test Procedure

A cursory search between 12 and 94 GHz indicated that no emissions other than the radar fundamental were present. The test measurement horns were positioned at varying distances between 10 and 100 meters from the radar van installation and moved around the perimeter of the test site area. Measurements were made at specific locations where radiated emissions were most likely to occur. These locations included antenna side lobes and areas where leakage from the equipment and waveguides could be present. Caution was exercised when approaching the main beam of the radar. This was because of potential human hazards and potential measurement equipment damage due to high level fields. Radiated emissions were measured and recorded. Any areas approaching radiation hazard limits were noted.

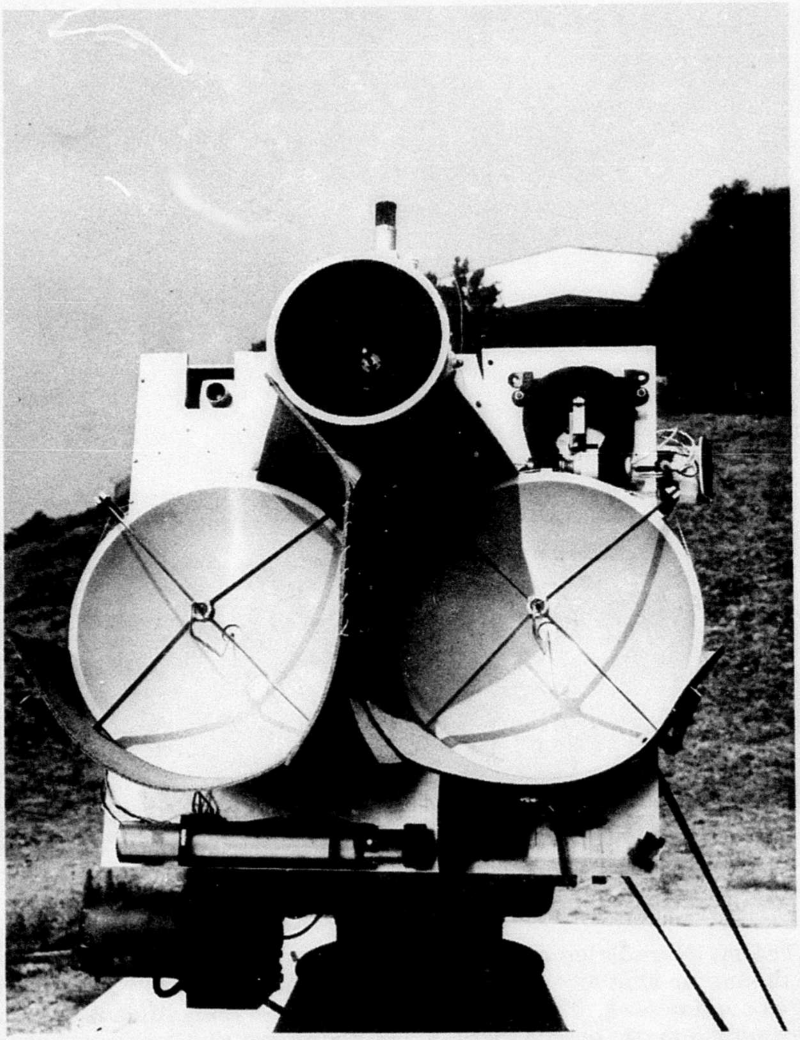

Figure 6. MM-Wave Radar Antenna System

4. Test Results

Radiated emissions from the millimeter wave radar were found to exist in very narrow beams. The radiated main beam is concentrated in a beam of approximately ten centimeters in diameter. The field occurs at a high level, concentrated in a volume measured in centimeters; therefore it should be considered that it may be more meaningful to express millimeter wave fields in terms of volts per centimeter rather than in terms of volts per meter.

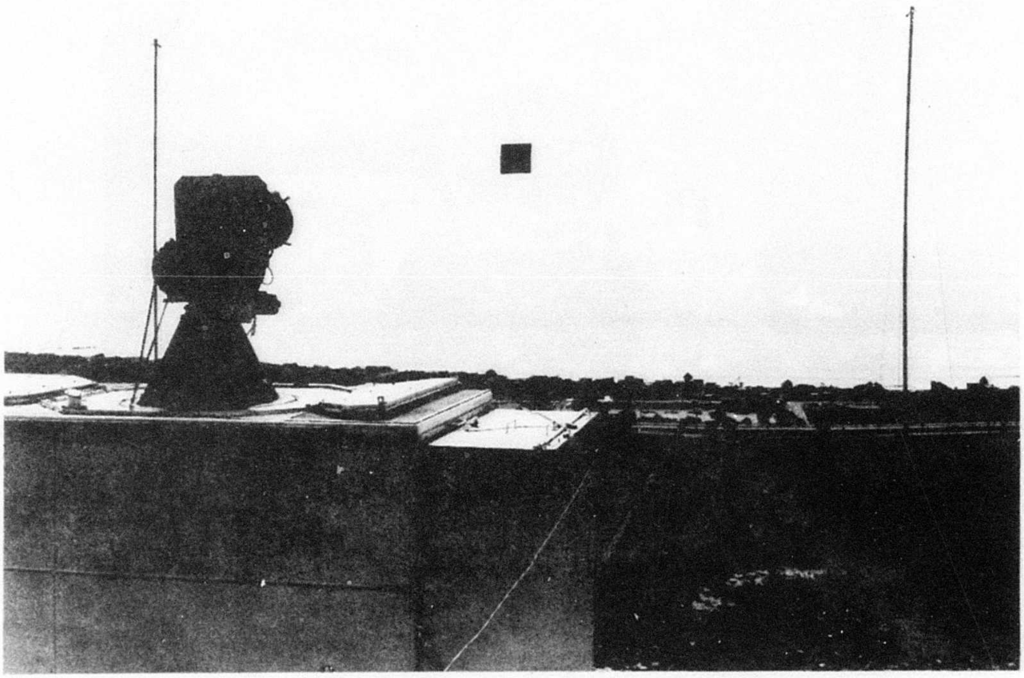

Figure 7. MM-Wave Radar System Test Site

The major radiated emissions aside from the main beam were found to exist in the major side lobes. These beams were very narrow in the order of one or two centimeters. The radiated fields become insignificant in the side lobes beyond the sixth lobe. A field of 155 dB/uv/cm was measured at the edge of the main beam. This level is equivalent to a 60.3 volt/meter field. No attempt was made to measure higher fields due to potential hazardous conditions to the operators and test equipment.

Detection of the radiated emissions required considerable care since the W Band radar beams were of extremely narrow beamwidth. The E and H plane for field antenna patterns for the 90 GHz radar antennas are shown in Figures 8 and 9. Fields in the near field 20 feet from the antenna were found to exist in an area enclosed within angles of ±12 degrees of the main beam. These fields were found to be 0.3 volts per meter at the ±12 degree point. Test data obtained during experiment 12 is shown in Table II.

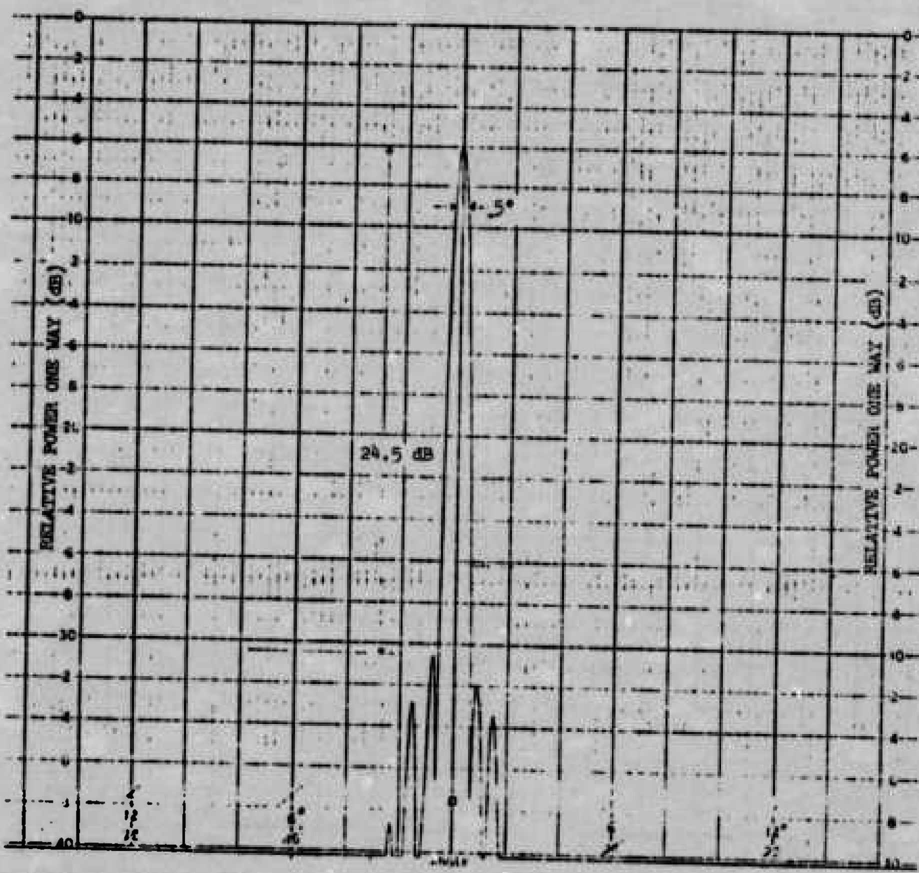

Figure 8. W-Band Radar System Antenna Side Lobes Plotted in E-Plane

TABLE II. TEST DATA OF EXPERIMENT NUMBER TWELVE

Position	Measured Radiated Levels
(40 ft from Radar Antenna)	
Edge of radar main transmit beam	60.3 volts/meter
First major side lobe	3.61 volts/meter
Second major side lobe	2.41 volts/meter
Third major side lobe	0.603 volts/meter
Fourth major side lobe	0.3 volts/meter
Fifth major side lobe	<0.215 volts/meter
(20 ft from Radar Antenna)	
±12 degrees from mid-beam at ground level	0.3 volts/meter
All other positions except above areas	<0.215 volts/meter

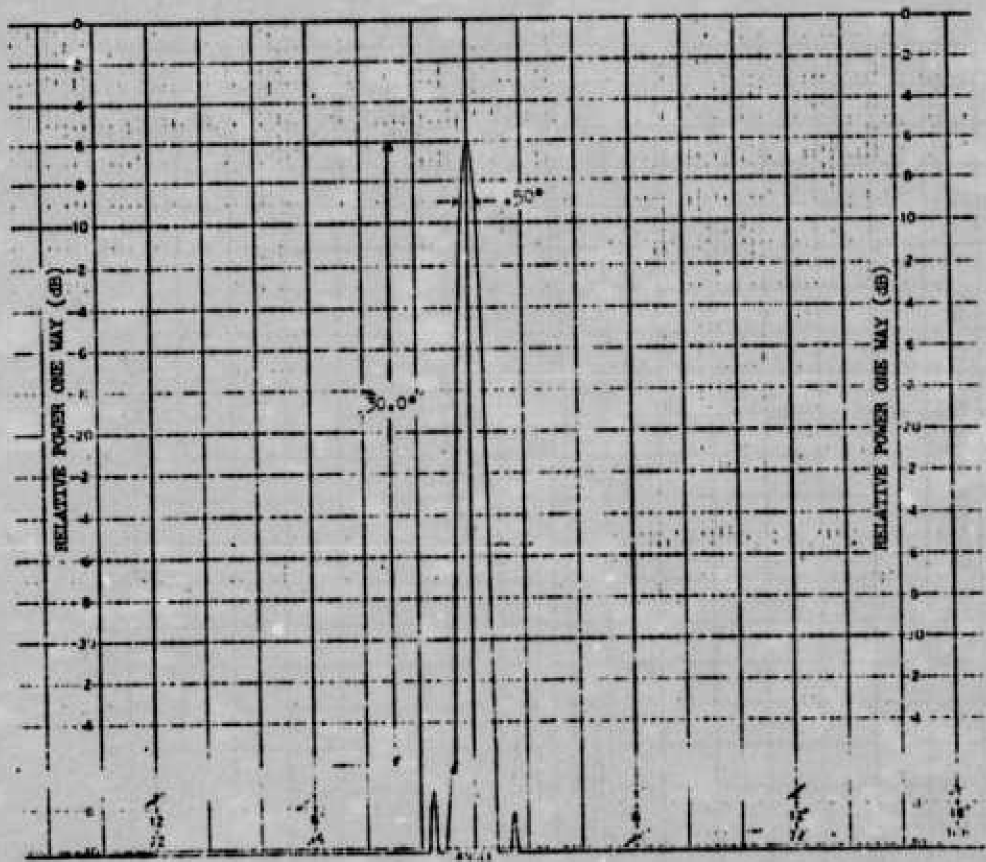

Figure 9. W-Band Radar System Antenna Side Lobes Plotted in H-Plane

The following calculations were performed to obtain the measured fields in terms of dB above one microvolt per meter.

EMI Meter Calibration

Receiver sensitivity $= -50$ dBm

Aperture (A) (Reference 2) $= \frac{G\lambda^2}{4\pi} = \frac{100\,(0.0032)^2}{4\pi}$

$= 8.15 \times 10^{-5}\ m^2$

(Antenna corrected factor (dB) to convert to an aperture of one square meter) $= 10 \log \left(\frac{1}{8.15 \times 10^{-5}}\right) = 40.9$

sensitivity of receiver/antenna system

$$= -50 + 40.9 = -9.1 \text{ dBm/m}^2, \quad -9.1 = 10 \log \frac{P2}{\text{lmw/m}^2}$$

$$P2 = 0.123 \text{ mw/m}^2 = 1.23 \times 10^{-4} \text{ w/m}^2$$

$$\frac{E^2}{377} = 1.23 \times 10^{-4} \text{ w/m}^2$$

$$E^2 = 4.64 \times 10^{-2} \text{ (v/m)}^2$$

$$E = 2.15 \times 10^{-1} \text{ V/M}$$

$$= 0.215 \text{ volts per meter}$$

$$\text{EMI Meter MDS} = 20 \log 215000 \text{ uv/meter}$$

$$= 20\ (5.33)$$

$$= 106.6 \text{ dB/uv/meter}$$

$$= 66.6 \text{ dB/uv/centimeter}$$

This radar system consisted of a backward wave oscillator source operating in the W-Band and a receiver local oscillator operating at a frequency only 70 MHz from the carrier frequency. There were no other intentional signal sources in the system. Emissions from the backward wave oscillator transmitter and waveguide sections were found to be less than 0.215 volts per meter.

5. Test Equipment

Waveguide Mixer and Attached Horn, Model 1205-6A, 12 to 18 GHz
Waveguide Mixer and Attached Horn, Model 1205-7A, 18 to 26 GHz
Waveguide Mixer and Attached Horn, Model 1205-8A, 26 to 40 GHz
Waveguide Mixer and Attached Horn, Model 1205-9A, 35 to 50 GHz
Waveguide Mixer and Attached Horn, Model 1205-10A, 50 to 75 GHz
Waveguide Mixer and Antenna (Hughes) 60 to 120 GHz
Micro-Tel Receiver, Model WR250

6. Conclusions

Relatively high field emissions are present around millimeter wave radar sites. However the major fields outside of the main beam were found to be in the antenna side lobes. Results of this test indicate that millimeter wave systems intended for collocation with millimeter wave radar systems should be specified to meet radiated susceptibility requirements of at least 3 volts per meter to provide a 20 dB safety factor for operation at the fourth major side lobe at a distance of 10 meters from the radar transmitting antenna. These collocated systems should not be expected to operate within the beamwidth of the main radar beam. The bandwidth requirements of the collocated systems will be determined during the fourth quarter analysis. At distances between 10 to 100 meters, the millimeter wave systems should be operated outside of the third major side lobe of the collocated radar systems.

Millimeter wave radar leakage emissions should be limited to 0.1 volt per meter at distances of 10 meters from the transmitter. The first major side lobes should be at least 20 dB down from the main beam. The second lobe should be down 25 dB or greater and all others should be down 30 dB or greater.

Radiated interference fields at millimeter wave frequencies should be evaluated in narrow beams with small aperture antennas as well as with large aperture antennas. The reason for using small aperture antennas is that extremely narrow beams can be evaluated for their potential radiation hazard only by examining the intensity of radiation within the narrow beam. Measurement with the large aperture antenna gives the illusion that the field is spread out over the aperture and does not correctly evaluate the peak beam intensity. Thus it would be possible for personnel to obtain injury due to exposure to narrow beams of energy and still obtain a low intensity field reading on a large aperture antenna. This provides an argument for specifying millimeter wave emission in terms of volts per centimeter or milliwatts per square centimeter.

E. EXPERIMENT NUMBER THIRTEEN

1. Purpose

This experiment was designed to evaluate the interference characteristics of a Ka band communications system. Experiments performed during this experiment included radiated emissions, spectrum evaluation and compatibility tests. Radiated emissions from the case and wave guides were measured. Second and third harmonics of the transmitter were evaluated. Compatibility tests consisted of operation of a collocated 60 GHz communication system during simultaneous operation of the Ka band system. Results of this experiment are beneficial in determining interference requirements for MM-Wave communication systems while operating under worst case conditions with other collocated communication systems.

2. Test Set-up

A block diagram of the radiated emission tests is shown in Figure 10. The same test set-up was employed for the spectrum evaluation with the exception that the test antenna was placed in the main beam of the Ka band transmitting antenna. A filter was required in the test antenna/mixer unit to provide the required isolation of the Ka band system fundamental frequency. This arrangement is shown in Figure 11. The Ka band system configuration is shown in Figure 12. The transmit and receive antenna system is shown in Figure 13.

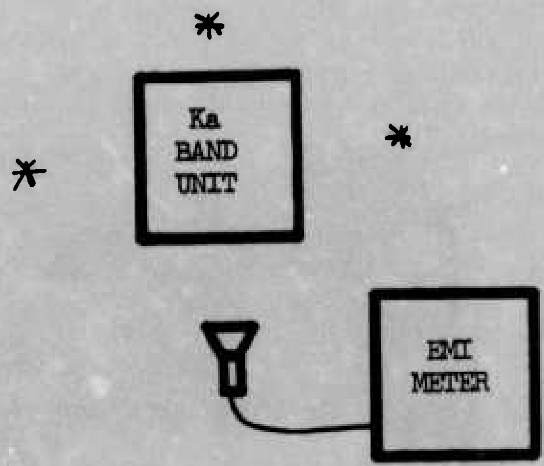

Figure 10. Test Setup for Radiated Emissions

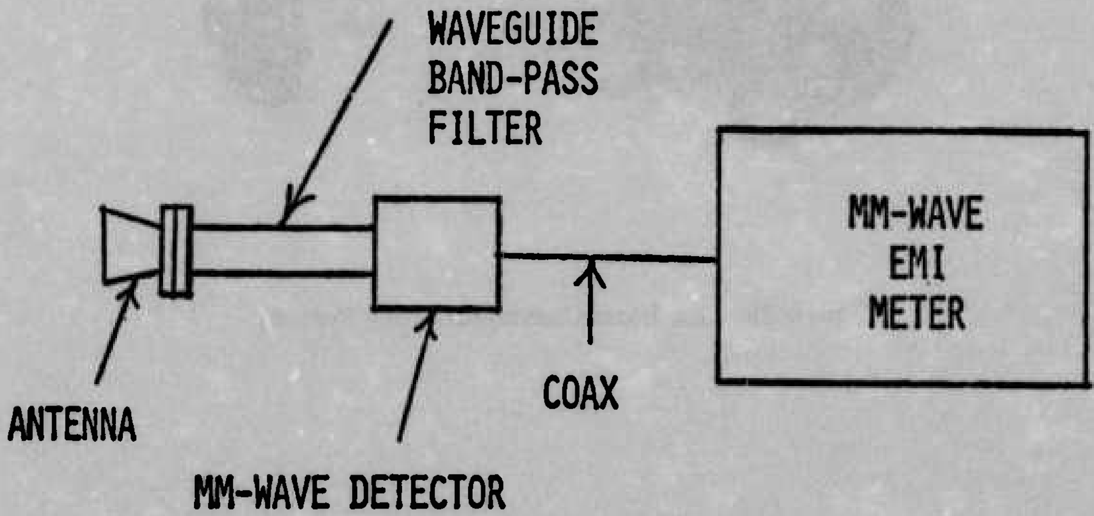

Figure 11. Input Filter for Measurement of MM-Wave Harmonics and Spurious Emissions

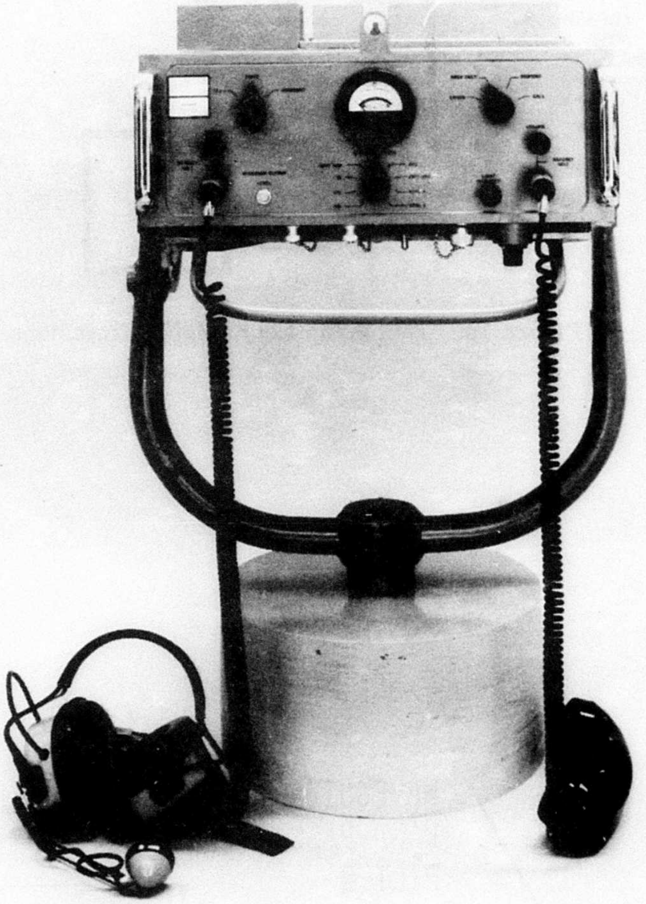

Figure 12. Ka Band Communication System

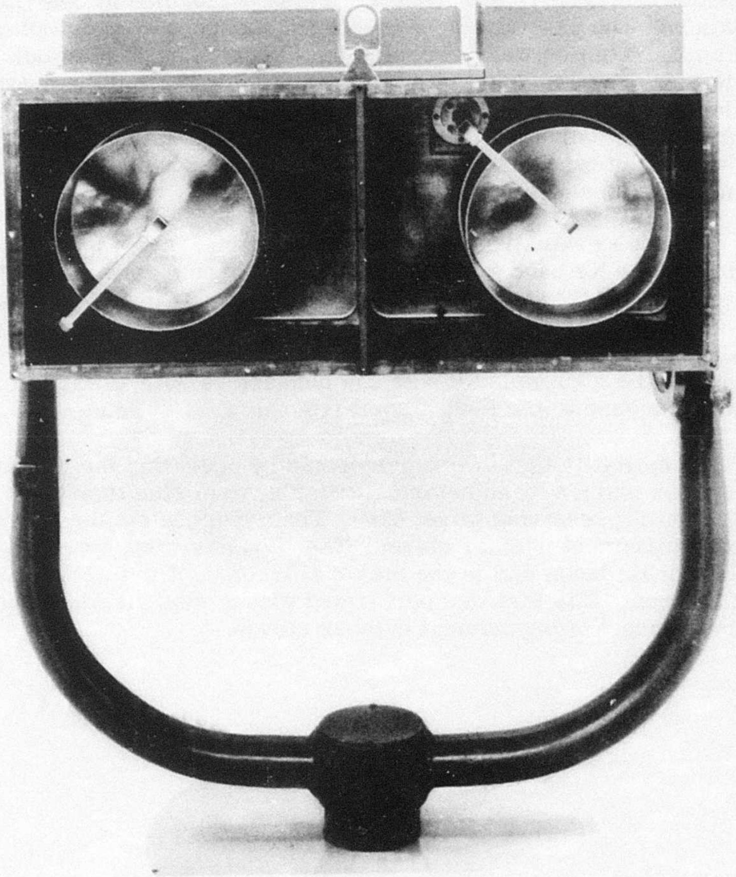

Figure 13. Ka Band Communication Antenna System

3. Test Procedure

The emission measurement equipment was set up to measure the radiated emissions in the 32 to 100 GHz frequency range. The test measurement antennas were positioned around the Ka band system as shown in Figure 10. Tests were performed within a ten meter radius for this test. Tests were performed as close as one meter. Probing tests were also performed to determine the source of radiations. The case was removed to find sources of radiation such as waveguide flanges. Caution was exerted to avoid confusing results due to reflections. These tests were performed in a laboratory area which did not provide an anechoic background and numerous reflections were present. Reflective surfaces were covered with absorptive material wherever possible. When radiations were found the test antenna was moved until the proper source was located to avoid obtaining false measurements due to reflections.

Spectrum evaluation was performed by measuring harmonic and spurious emissions of the Ka band system. These measurements were performed with the test antenna located directly in the main beam of the Ka band system. A filter was installed between the MM-Wave test antenna and the mixer (Figure 11) to eliminate the fundamental frequency. It was also necessary to provide further shielding for the EMI meter mixer and connectors with aluminum foil to eliminate response to the fundamental frequency.

Susceptibility tests were performed by operating the Ka band communication system and a V band communication system simultaneously in a collocated configuration representing worst case. The technique employed was identical to that of experiment number eleven. The V band system was operated at the edge of the main beam and in the major side lobes of the Ka band system transmitting antenna. This test was performed with a configuration much like that shown in Figure 2 of experiment number eleven.

4. Test Results

Radiated measurements indicated that the most significant levels existed in the side lobes of the transmit beam. Radiations were found to originate at waveguide flanges. A level of 0.63 volt per meter was found at a distance of 1 foot from the flange. These radiations were reduced to levels below 0.0714 volts/meter when the system was operated within its enclosed case. Measurements at the major side lobes of the antenna indicated readings of 3.12 volts/meter. The EMI receiver sensitivity was -60 dBm which is equal to 0.0714, 0.139 and 0.207 volts per meter at Ka, V and W bands respectively. The 3.12 volts per meter field at Ka band represented an out-of-band susceptibility threshold on the V band transceiver.

TABLE III. TEST DATA OF EXPERIMENT NUMBER THIRTEEN

Position	Measure Level
Major side lobe of antenna	3.12 volts/meter
At waveguide flanges	0.626 volt/meter
External to case at flange location	< 0.0714 volts/meter
Second side lobe of antenna	< 0.0714 volts/meter
Other locations around enclosed system	< 0.0714 volts/meter

TABLE IV. HARMONICS

Harmonic Number	Measure Level
Second Harmonic $\lambda = 5 \times 10^{-3}$	< 0.139 volt/meter
Third Harmonic $\lambda = 3.3 \times 10^{-3}$	< 0.207 volt/meter

Tables III and IV summarize data obtained in this experiment. A typical calculation performed to obtain the radiated levels in dB above microvolts per meter is shown below:

EMI Receiver sensitivity = -60 dBm (at 31 GHz)

$$\text{Aperture (A)} = \frac{G\lambda^2}{4\pi} = 10\,\frac{(0.0097)^2}{4\pi}$$

$$= \frac{9.4 \times 10^{-4}}{4\pi} = 7.46 \times 10^{-5}\ \text{m}^2$$

$$\text{Receiver/antenna sensitivity} = -60\ \text{dBm} + 10 \log \left(\frac{1}{0.746 \times 10^{-4}}\right)$$

$$= -60\ \text{dBm} + 41.3 = -18.7\ \text{dBm/m}^2$$

$$\text{Sensitivity} = 1.35 \times 10^{-5}\ \text{w/m}^2$$

$$1.35 \times 10^{-5} = E^2/377$$

$$E^2 = 5.1 \times 10^{-3}\ \text{volts/meter}$$

$$E = 7.14 \times 10^{-2}\ \text{volts/meter}$$

$$E = 71400\ \mu\text{volts/meter}$$

$$= 20 \log 71400\ \text{dB/uV/meter}$$

$$= 20\ (4.85) = 97\ \text{dB/uV/meter}$$

5. Test Equipment

Waveguide Mixer and Attached Horn, Model 1205-8A, 26 to 40 GHz
Waveguide Mixer and Attached Horn, Model 1205-9A, 35 to 50 GHz
Waveguide Mixer and Attached Horn, Model 1205-10A, 50 to 75 GHz
Waveguide Mixer and Attached Horn, Model 1205-11A, 60 to 100 GHz
Micro-Tel Receiver, Model WR250

6. Conclusions

The major radiated emissions from the millimeter wave communication systems outside of the main transmit beam were found in the major side lobes, around waveguide flanges and from reflections in the test area. Proper enclosure shielding reduced the waveguide flange emanations to a negligible value.

Radiations at distances of 10 to 100 meters were of relatively low levels and compatible operation of collocated adjacent channel systems can be obtained if the enclosures are shielded and if reflections of the main beam and the major antenna side lobes are avoided. Measurements performed during this experiment indicated that no electromagnetic compatibility problems existed between Ka and V band systems when the V band system was operated outside the major side lobes of the Ka band antenna. This experiment indicates that a value of up to 3.12 volts per meter can be tolerated under these conditions. This would support the recommendation of a value of 0.1 volt per meter as an upper limit for extending RE02 to millimeter meter systems. This would provide a safety factor of approximately 20 dB.

Harmonics and spurious emissions of this system were below the sensitivity of the EMI instrumentation. Analytical estimates of the harmonics indicate the harmonics are at least 60 dB below the fundamental. If operation of collocated communication systems are planned to operate at frequencies harmonically related to other communication systems, a value of 60 dB down from the fundamental should be imposed on millimeter wave systems. An alternate method would be to restrict harmonic radiations to a specific level, which would require greater suppression of harmonics in high power systems. This will be discussed further in the final report.

F. EXPERIMENT NUMBER FOURTEEN

1. Purpose

This test was designed to provide data which would be helpful in establishing susceptibility test criteria for millimeter wave systems intended for operation in the near vicinity of high powered systems in the frequency ranges of 1.0 to 10 GHz. The radiated spectrum characteristics of these systems were evaluated at high order harmonics to determine whether appreciable signal levels would be present at millimeter wave frequencies. Power outputs of the systems which were evaluated ranged from average levels of 0.5 kw to peak values of 1.0 megawatt.

2. Test Setup

A mobile van equipped with a gasoline driven power generator was employed to make these field measurements. Equipment capable of obtaining measurements over the frequency range of 14 kHz to 100 GHz can be operated in the van. A photograph of this van is shown in Figure 14. The measurement antennas were set up in the far field of the systems being evaluated as shown in Figure 15. Caution was taken to avoid areas where radiated fields might approach human hazard limits (10 mw/cm^2).

3. Test Procedure

Measurements were taken at locations indicating worst case conditions. At millimeter wave these frequencies were found to be in areas being radiated by the main beam. Radiations at lower frequencies were found in the immediate vicinity of the system being evaluated at various locations. Millimeter wave radiations however were limited to the higher order harmonic frequencies and were present only in the main beam of the antenna.

A measurement was first made at the fundamental frequency of the system under evaluation. Next the harmonic frequencies were calculated and frequency scans were performed to locate these harmonics on the measurement equipment. Considerable care was required in searching for the harmonic signals since some of the systems employed scanning antennas. The normal frequency tolerance of EMI measurement instruments also does not provide perfect tracking of all harmonic frequencies. Frequencies as high as the tenth harmonic were found to be of a measureable level during this experiment.

A 60 GHz system was also used for communication purposes during these tests. This provided a compatibility evaluation of millimeter wave systems in presence of high fields in the 1.0 to 10 GHz frequence range.

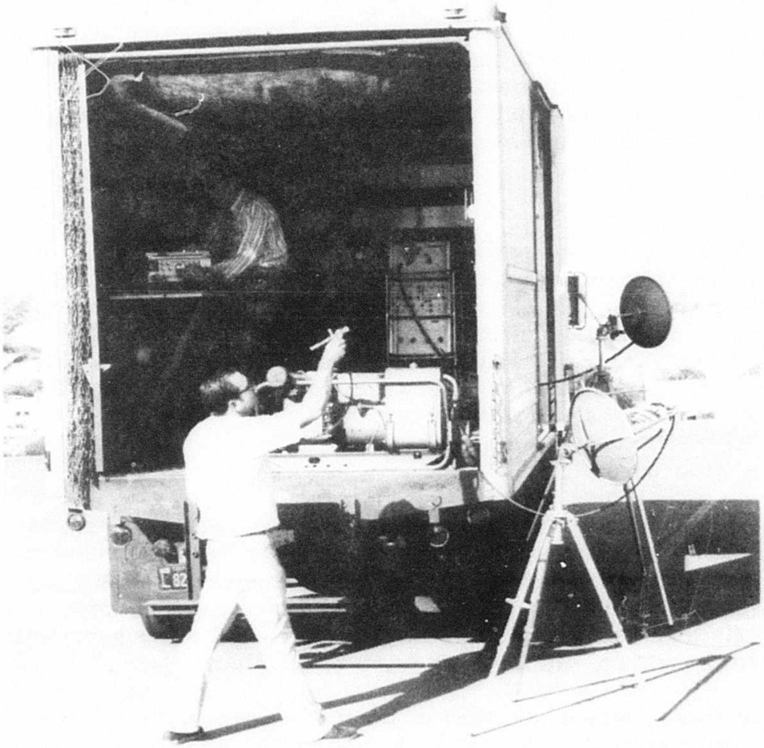

Figure 14. Equipment Van for Experiment Number Fourteen

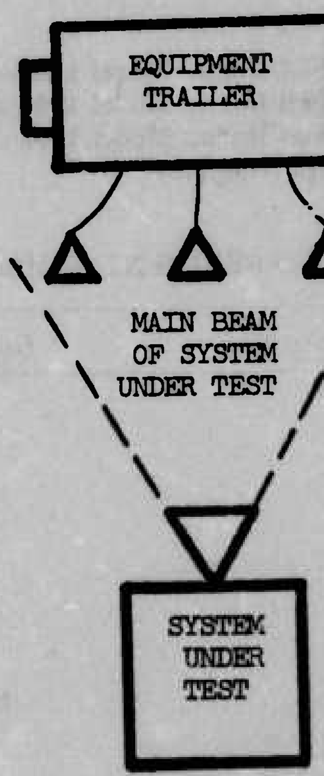

Figure 15. Test Setup for Experiment Number Fourteen

4. Test Results

Radiated measurements performed during this experiment indicated that harmonics as high as the tenth harmonic can exist in systems operating at 1.0 to 10 GHz. This was especially true for systems which had not been designed to meet MIL-STD-461 RE03 or CE06 requirements for harmonic content. Results of the radiation tests are shown in Table V. There were no harmonics from the three systems tested in the 60 GHz range which caused any compatibility problems with the 60 GHz communication system. The systems evaluated for harmonic content were radar systems. Systems A and C operated at approximately 1.0 megawatts. System B was operating at 0.5 kilowatts.

5. Test Equipment

EMI Meters	Frequency Range
EMA 910-10	1.0 to 10 GHz
EMA 910-12	10 to 26 GHz
Micro-Tel WR 25 Antennas	10 to 100 GHz
Empire AT-112	1 to 10 GHz
EMC 910-705	10 to 26 GHz
EMC 1050	10 to 16.5 GHz
EMC 1060	16.5 to 26.5 GHz

Waveguide Mixer and Attached Horn, Model 1205-8A, 26 to 40 GHz
Waveguide Mixer and Attached Horn, Model 1205-9A, 35 to 50 GHz
Waveguide Mixer and Attached Horn, Model 1205-10A, 50 to 75 GHz
Waveguide Mixer and Antenna (Hughes)

TABLE V. TEST DATA OF EXPERIMENT NUMBER FOURTEEN

System	Harmonic No.	Level dB/uV/Meter
System A	2	89
	3	80
	4	93.5
	5	90.5
	6	82
	7	74
	8	65
	9	63
	10	60
	>10	Negligible
System B	2	40
	3	35
	3 to 6	Negligible
	7	70
	9	45
	> 9	Negligible
System C	2	84
	3	65
	>3	Negligible

6. Conclusions

Results of this experiment indicate that systems operating in the 1.0 to 10 GHz range of frequencies can represent a potential source of interference to millimeter wave systems. Frequencies as high as the tenth harmonic can represent a significant source of interference if the millimeter wave system has a receiver response at these harmonic frequencies. Higher order harmonic radiations can be of a higher radiated level than at lower frequencies due to radiation properties of the transmitting antenna system.

Results of this experiment indicate that millimeter wave systems should not be intended for operation in an area where they may be exposed to the main beam of a system which has not been designed to the harmonic suppression requirements of MIL-STD-461 and which has a harmonic frequency which is in the pass band of the millimeter wave system.

Results of this experiment also indicate that millimeter wave systems intended for use in areas where they may be exposed to main beam radiated fields of 1 to 10 GHz systems should be evaluated for out-of-band front end rejection of undesired signals. This experiment indicates that millimeter wave systems planned for collocation with lower frequency systems in the 1 to 10 GHz range should be tested to provide assurance that they can operate in 1 to 10 GHz fields of approximately 110 dB/μv/meter to provide a safety factor of 20 dB.

IV. ANALYSIS PROGRAM

A. ANALYSIS NUMBER THREE – MODULATION EFFECTS

1. Purpose

This analysis is performed for the purpose of describing emission spectrums of millimeter wave systems employing state-of-the-art high data rate modulation processes. Analysis number one which was described in the second quarterly report was designed to describe the emission spectrum of pulsed transmitters with provisions for including systems with frequency modulated signals. This analysis describes the modern modulation method known as continuous phase shift modulation (CPSM). The emission characteristics of CPSM techniques are conveyed in this analysis by relating the principal characterisitics of CPSM to the better known phase shift keying (PSK) modulation technique. A more complete analysis of modulation effects on interference characteristics of millimeter wave systems will be included in the final report.

2. Analysis Procedure

Power spectra emissions were calculated for CPSM, biphase and quadriphase modulation techniques. The spectra envelopes were plotted in terms of dB below the fundamental peak value as a function of data rates. The graph in Figure 16 describes the power spectra lobes from fo to ±5 times the data rate. Millimeter wave systems employ data rates as high as 400 megabits per second. This method of calculating the spectra allows the graph to be employed with any modulation data rates that may be employed by the various systems.

A computer program was devised to plot the chart in Figure 16. The following power spectrum formulas are employed in this program.

$$S(f) \; \alpha \left(\frac{\sin x}{x}\right)^2 \left(\frac{\sin y}{y}\right)^2 \text{ watts/hz}$$

$$x = \pi\tau\left(f - fo - \frac{1}{4\tau}\right)$$

$$y = \pi\tau\left(f - fo + \frac{1}{4\tau}\right)$$

fo = spectrum center frequency

$\frac{1}{\tau}$ = chip rate (= 10 MHz)

S(f) = frequency spectrum

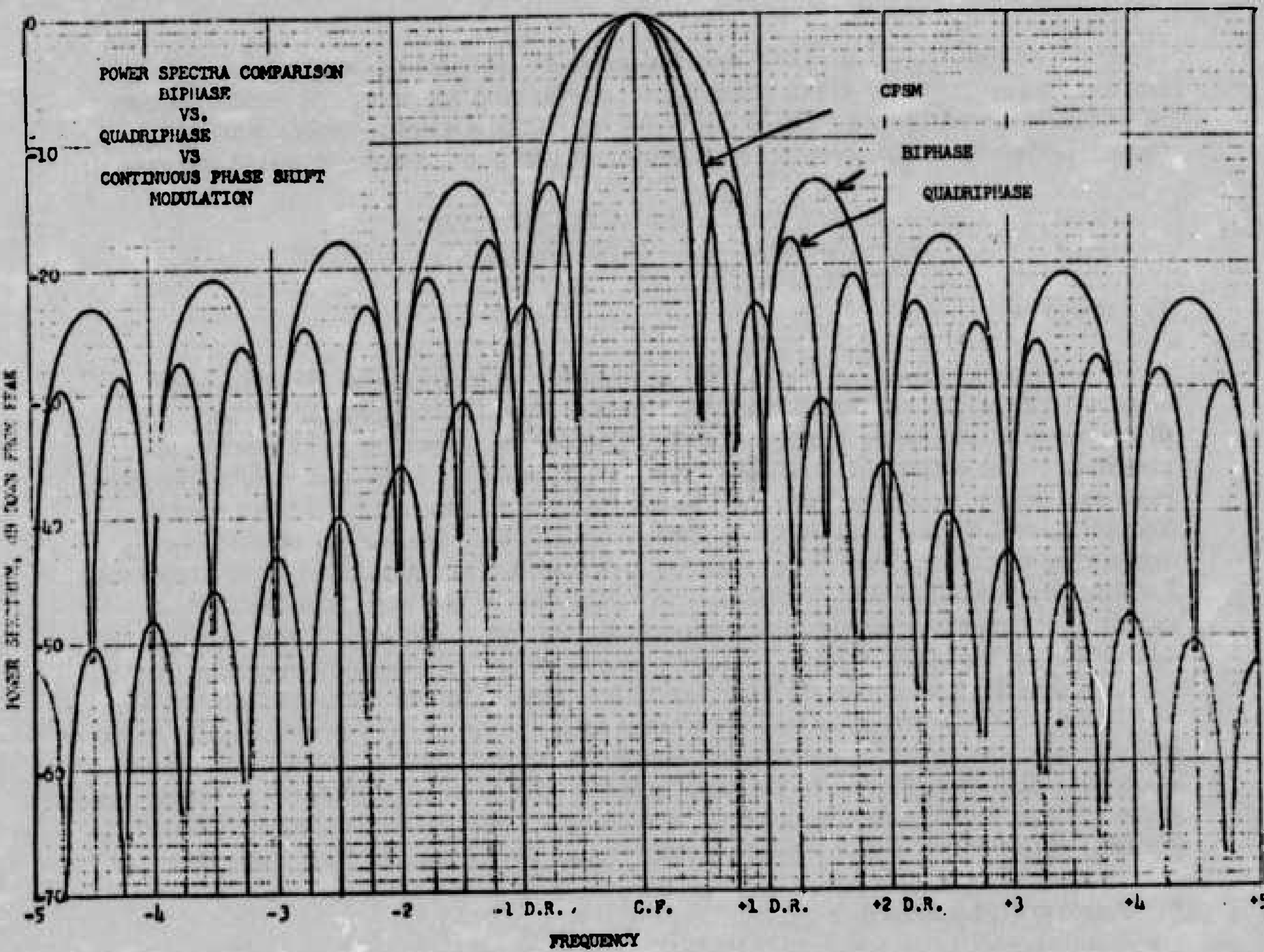

Figure 16. Computer Plot of Modulation Power Spectra
(D.R. = data rate, C.F. = center frequency)

3. Analysis Results

This analysis indicates that the modern state-of-the-art modulation techniques employed in high data rate systems exhibit improvements in interference emission and susceptibility characteristics over the more conventional modulation techniques utilized in earlier system designs. Modern modulation techniques sucn as binary continuous phase shift modulation (2CPSM) exhibit lower spectral side lobe levels.

The Spectra of binary phase shift keying (2PSK) and quadrature phase shift keying have a power spectrum which varies as $(\sin x/x)^2$. The side lobes of 2 CPSM decay as $(\sin x/x)^4$, indicating that 2 CPSM contains less energy in the side lobes. This observation indicated that utilization of 2 CPSM will result in less adjacent channel interference. The first side lobes of the 2 PSM are 23 down, side lobes produced by quadrature phase shift keying 18 dB down and 2 PSK are down 13 dB.

The analysis indicates that the modern modulation techniques exhibit improved rejection of phase shift type interferring signals. The three types of systems investigated in this analysis all exhibited comparable susceptibility characteristics in the presence of centered CW and broadband noise signals.

B. ANALYSIS NUMBER FOUR – ANTENNA OUT-OF-BAND CHARACTERISTICS

1. Purpose

Experimental and analytical approaches for obtaining the out-of-band characteristics of millimeter wave antennas were investigated. It was discovered at the early stages of experimentation, however, that the complexities of an experiment of this type would lead to a less accurate evaluation than that which would be provided by an analytical approach. This problem is brought about by the fact that accurate simulation of the actual conditions occurring in transmitter frequencies, waveguide and antenna system at out-of-band frequencies is very complex. Investigation was made of a method of exciting waveguide and antenna systems by out-of-band generators through the use of waveguide transitions. Closer investigation of this experimental technique indicated that gross errors would be present in the data obtained by this approach. Development of experimental techniques which would provide accurate out-of-band characteristics of the waveguide and antenna system comprises a study in itself and proved to be beyond the scope of this contract. A more complete discussion of antenna out-of-band analysis will be included in the final report. References 8 and 9 were employed as guidelines in this analysis.

2. Analysis Procedure

This analysis is in the process of being completed at the present time and will be described further in the final report. A preliminary treatment of the analysis is presented in this report.

Simulation of the true response of an antenna system at out-of-band frequencies requires an exact duplication of the complex transmission line mode and field distribution that occurs in a transmitter/receiver, waveguide and antenna system. Waveguides propagate several transmission line modes and field distributions. These modes radiate in different patterns and the total radiation pattern is the sum of the radiation fields of the individual modes weighted by the amplitude and phase of excitation of the modes. The use of waveguide transitions for the purpose of connecting out-of-band waveguide to signal generators during performance of antenna system experiments will not permit an accurate simulation of the actual condition which exists in the generation of out-of-band fields.

Radiation patterns and gain characteristics of rectangular waveguide and horn antennas produced by TE_{mn} and TM_{mn} modes were considered in this analysis. Radiation patterns and gain characteristics of conical waveguide and horn antennas produced by the TE^{o}_{11} mode and the multimode (TE^{o}_{11} + TM^{o}_{11}) were also considered.

The most important field component in the rectangular waveguide is E_y:

TE component:

$$E_y^{nm} = C_1 \sin \frac{n\pi x}{a} \cos \frac{m\pi y}{b}$$

TM component:

$$E_y^{mn} = C_2 \sin \frac{n\pi x}{a} \cos \frac{m\pi y}{b}$$

TE waves can exist with either n or m equal to zero, but not both. TM waves can only propagate when both n and m are not equal to zero. The lowest propagating mode is the TE_{10} mode. In this mode

$$E_y^{10} = C_1 \sin \frac{\pi x}{a}$$

with a cutoff wavelength $\lambda_c = 2a$. For both TE_{mn} and TM_{mn} modes, the cutoff wavelength λ_c^{mn} is given by:

$$\lambda_c^{mn} = \frac{2ab}{\sqrt{(mb)^2 + ra^2}}$$

where a = width of waveguide

b = height of waveguide

Analysis of the excitation of waveguide systems by the various modes of transmission will be included in the final report.

The steps employed in determining the out-of-band gain characteristics for a horn antenna are as follows:

1) Find basic gain by using the formula

$$G = \frac{4\pi A}{\lambda^2}$$

where

A = aperture

λ = out of band frequency

2) Find quadratic phase error losses for E and H fields

3) Find cosine aperture distribution

4) Sum all of the above

3. Conclusions

The out-of-band characteristics of the types of waveguide and antennas employed in millimeter wave systems can be determined more accurately by analysis than by experimental methods unless complex experimental test setups are employed. Complete analysis of all of the higher modes of transmission and radiation is also complex; however, close approximations of antenna patterns and gain characteristics have been accomplished in this study. It is recommended that a new study effort be initiated if further investigation is desired for the purpose of obtaining more accurate definition of antenna and waveguide out-of-band characteristics.

C. ANALYSIS NUMBER FIVE – COMPUTER ANALYSIS OF A SIMULATED DEPLOYMENT

1. Purpose

This analysis was performed for the purpose of obtaining potential interference frequencies and amplitudes in a simulated millimeter wave system deployment. Results of this analysis are helpful in establishing radiation emission and susceptibility requirements for the millimeter wave EMC specification.

2. Analysis Procedure

Parameters of millimeter wave transmitting and receiving equipment obtained during the experimental and analytical effort of this study were employed during this analysis. These parameters included bandwidth, transmitter power output, receiver sensitivity, antenna characteristics, receiver rejection of undesired signals, spurious responses and outputs and propagation loss. The computer program described in Appendix A was employed in this analysis. A worst case condition was assumed for this analysis in that the spurious responses of the receiver were assumed to coincide with the harmonic outputs of the collocated transmitter. The harmonic content of the transmitter was also assumed to represent a worst case condition. The second harmonic was assumed to be 50 dB down from the fundamental and the third was assumed to be 60 dB down.

The following parameters were assumed in this simulated millimeter wave system deployment.

Transmitter power output	= 10 watts
Collocated receiver sensitivity	= -90 dBm
Distance between collocated systems	= 10 meters
Collocated receiver spurious response	= 64 and 96 GHz
Transmitter harmonic output	= 64 and 96 GHz
Antenna gain at fundamental frequency	= 24.5 dB
Transmitter emission bandwidth (3 dB)	= 3.6 GHz
Receiver acceptance bandwidth (3 dB)	= 2 GHz
Transmitter center frequency	= 32 GHz
Receiver center frequency	= 60 GHz

3. Analysis Results

The computer run and resulting output is shown on the following pages. Refer to Appendix A for a complete discussion of the computer program.

The computer output data on the following pages shows the results of the above set of parameters. Propagation losses, receiver and transmitter responses and antenna gains are shown under their respective columns. The "Compensated System Response" gives the overall evaluation of the configuration, with positive numbers indicating a receiver response at that particular frequency.

From the output it is evident that system responses occur at 58.6 to 65.8 GHz and 94.6 to 98.2 GHz. These are the first and second harmonic outputs of the transmitter. The system response also peaks at 33.4 GHz, which is the transmitter's fundamental output, however the receiver response at this frequency is so low it was not detected.

The frequencies were offset slightly to obtain maximum program accuracy. This is explained in Appendix A.

RUN

Memory size (program + 1 file buffer) is 12660 words.

This program evaluates the characteristics of a receiver-transmitter-antenna system for interference of desired operation. The data output is given in terms of the frequency at which interference occurs and the total system response. When the total system response is greater than zero, interference is likely to occur.

Units for Data:

Frequency — any units as long as the same units are used throughout the program

Gain and response — dB or dBm as appropriate

Distance - meters

The following information generates data for the RCVR frequency response.

How many frequencies do you want checked for probable interference — maximum = 50 ?50

What is the center frequency of the RCVR and its sensitivity ?60, -90

What are the upper and lower 3 dB frequencies ?61, 59

What are the frequencies at the bottom of the skirt above and below the center frequency and the RCVR

Sensitivity at those frequencies ?70, 50, -20

What are the upper and lower band limits and the RCVR sensitivity at those frequencies ?100, 10, 10

The following information generates data for the XMTR fundamental output.

What is the center frequency of the XMTR and its output ?31.6, 40

What are the upper and lower 3 dB frequencies ?33.4, 29.8

What are the frequencies at the bottom of the skirt above and below the center frequency and the XMTR output at those frequencies ?37, 26.2, -30

What is the XMTR output at the band edges ?-90

The following information generates data for the propogation losses.

What is the distance between the RCVR and XMTR antennas ?10

The following information generates data for the RCVR antenna.

What is the gain at the bottom band edge ?-150

What is the frequency and gain of the first break point ?53.2,-60

What is the frequency and gain of the second break point ?60.4,24.5

What is the frequency and gain of the third break point ?74.3,22.5

What is the frequency and gain of the fourth break point ?94.6,20.5

What is the gain at the upper band edge ?19

The following information generates data for the XMTR antenna.

What is the gain at the bottom band edge ?-100

What is the frequency and gain of the first break point ?28,22

What is the frequency and gain of the second break point ?31.6,24.5

What is the frequency and gain of the third break point ?64,22.5

What is the frequency and gain of the fourth break point ?96.4, 20.5

What is the gain at the upper band edge ?19

The following information generates data for the R. F. environment. The data can concern a neighboring XMTR or any other source of R. F. energy.

How many R. F. signals are there to consider (max = 50) ?2

What is the bandwidth of the R. F. energy ?5

What is the frequency and amplitude of the first signal ?64, -10

What is the frequency and amplitude of the last signal ?96.4,-20

The following data generates RCVR secondary RESP information.

How many secondary responses are there to consider (max = 50) ?2

What is the secondary response bandwidth ?4

What is the frequency and response of the first SPUR RESP ?64,-30

What is the frequency and amplitude of the last SPUR. RESP ?96,4,-30

Do you want a complete listing of all generated data (1 = yes 0 = no) ?1

X	Frequency	Total RCVR RESP.	RCVR ANT RESP
1	10	10	-150
2	11.8	8.65	-146.25
3	13.6	7.3	-142.5
4	15.4	5.95	-138.75
5	17.2	4.6	-135
6	19	3.25	-131.25
7	20.8	1.9	-127.5
8	22.6	0.5499999	-123.75
9	24.4	-0.8000001	-120
10	26.2	-2.15	-116.25
11	28	-3.5	-112.5
12	29.8	-4.85	-108.75
13	31.6	-6.2	-105
14	33.4	-7.55	-101.25
15	35.2	-8.9	-97.50001
16	37	-10.25	-93.75001
17	38.8	11.6	-90.00001
18	40.6	-12.95	-86.25001
19	42.4	-14.3	-82.50001
20	44.2	-15.65	-78.75001
21	46	-17	-75.00001
22	47.8	-18.35	-71.25002
23	49.6	-19.7	-67.50002
24	51.4	-33.1	-68.75002
25	53.2	-46.5	-60.00002
26	55	-59.9	-38.87502
27	56.8	-73.3	-17.75002
28	58.6	-86.7	3.374981
29	60.4	-81.3	24.49998
30	62.2	-67.9	24.24998

X	Frequency	Total RCVR RESP.	RCVR ANT RESP
31	64	-54.5	23.99998
32	65.8	-41.4	23.74998
33	67.6	-27.7	23.49998
34	69.4	-14.3	23.24998
35	71.2	-12.5	22.99998
36	73	-10.7	22.74998
37	74.8	-8.900004	22.49998
38	76.6	-7.100004	22.31816
39	78.4	-5.300004	22.13634
40	80.2	-3.500004	21.95452
41	82	-1.700004	21.7727
42	83.8	0.0999962	21.59088
43	85.6	1.899996	21.40907
44	87.4	3.699996	21.22725
45	89.2	5.499996	21.04543
46	91	7.299996	20.88361
47	92.8	9.099996	20.68179
48	94.6	-30	20.49997
49	96.4	-30	19.99997
50	98.2	-30	19.49997

Frequency	XMTR ANT RESP.	TOTAL R.F. ENVIRONMENT
10	-100	-90
11.8	-87.8	-83.33333
13.6	-75.6	-76.66667
15.4	-63.4	-70
17.2	-51.2	-63.33334
19	-39	-56.66667
20.8	-26.8	-50
22.6	-14.6	-43.33334
24.4	-2.400004	-36.66667
26.2	9.799995	-30
28	22	3.499998
29.8	23.25	37
31.6	24.5	40
33.4	24.38888	37
35.2	24.27777	3.499997
37	24.16666	-30
38.8	24.05555	-31.71429
40.6	23.94444	-33.42858
42.4	23.83333	-35.14286
44.2	23.72222	-36.85715
46	23.61111	-38.57143
47.8	23.5	-40.28572
49.6	23.38888	-42.00001

Frequency	.XMTR ANT RESP.	TOTAL R.F. ENVIRONMENT
51.4	23.27777	-43.71429
53.2	23.16666	-45.42858
55	23.05555	-47.14286
56.8	22.94444	-48.85715
58.6	22.83333	-50.57143
60.4	22.72222	-52.28572
62.2	22.61111	-10
64	22.49999	-10
65.8	22.38888	-10
67.6	22.27777	-59.14286
69.4	22.16666	-60.85715
71.2	22.05555	-62.57144
73	21.94444	-64.28572
74.8	21.83333	-66.00001
76.6	21.72222	-67.71429
78.4	21.61111	-69.42858
80.2	21.49999	-71.14287
82	21.38888	-72.85715
83.8	21.27777	-74.57144
85.6	21.16666	-76.28572
87.4	21.05555	-78.00001
89.2	20.94444	-79.71429
91	20.83333	-81.42858
92.8	20.72222	-83.14287
94.6	20.61111	-20
96.4	20.49999	-20
98.2	19.74999	-20

Frequency	. Propagation Loss.	Compensated System Response
10	-30.99206	-367.6573
11.8	-30.99206	-344.5296
13.6	-30.99206	-321.4017
15.4	-30.99206	-298.2738
17.2	-30.99206	-275.146
19	-30.99206	-252.0182
20.8	-30.99206	-228.8904
22.6	-30.99206	-205.7625
24.4	-30.99206	-182.6347
26.2	-30.99206	-159.5069
28	-30.99206	-110.4849
29.8	-30.99206	-72.02961
31.6	-30.99206	-63.00686
33.4	-30.99206	-61.08758
35.2	-30.99206	-88.6008
37	-30.99206	-116.114

Frequency	Propagation Loss.	Compensated System Response
38.8	-30.99206	-112.954
40.6	-30.99206	-109.794
42.4	-30.99206	-106.6341
44.2	-30.99206	-103.4741
46	-30.99206	-100.3141
47.8	-30.99206	-97.15408
49.6	-30.99206	-93.99409
51.4	-30.99206	-79.20584
53.2	-30.99206	-64.4176
55	-30.99206	-32.86248
56.8	-30.99206	-1.307371
58.6	-30.99206	32.44188
60.4	-30.99206	46.82797
62.2	-30.99206	76.35094
64	-30.99206	62.10819
65.8	-30.99206	47.86544
67.6	-30.99206	-16.07417
69.4	-30.99206	-31.00793
71.2	-30.99206	-34.74769
73	-30.99206	-38.48745
74.8	-30.99206	-42.2272
76.6	-30.99206	-45.90017
78.4	-30.99206	-49.57513
80.2	-30.99206	-53.24909
82	-30.99206	-56.92306
83.8	-30.99206	-60.59702
85.6	-30.99206	-64.27098
87.4	-30.99206	-67.94494
89.2	-30.99206	-71.61891
91	-30.99206	-75.29287
92.8	-30.99206	-78.96683
94.6	-30.99206	20.82319
96.4	-30.99206	20.19069
98.2	-30.99206	18.89693

V. PRELIMINARY EMC TEST MATRIX FOR MILLIMETER WAVE SYSTEMS

A preliminary recommended EMC test matrix for millimeter wave systems is shown in Table VI and VII. Graphs showing proposed limits will be submitted with a final EMC test matrix in the final report. These preliminary recommendations are based upon experimental and theoretical data gathered at this point in time of the study.

The philosophy employed in establishing this matrix takes into consideration the inclusion of all present EMC specifications such as MIL-STD-461 and MIL-STD-469 into the proposed millimeter wave EMC specification. Experiments and analysis performed during this study have indicated that no extension of the present requirements are necessary for millimeter wave systems in certain specific areas. An example of this is the conducted emission and susceptibility requirements. Experiments described in the second quarterly report revealed that millimeter waves are not effectively coupled onto cables. Tests involving radiated E-field emissions and susceptibility must be extended to 100 GHz. Tests involving H-field emissions and susceptibility do not require an extension of frequency over the present requirements since no loop circuits exist which are effective at millimeter wave frequencies. The near field also occurs at very small distances from the radiating source at millimeter wave frequencies, therefore performance of E-field measurements will define the E and H-field characteristics of the radiated fields.

TABLE VI. PRELIMINARY MM-WAVE EMC TEST REQUIREMENT MATRIX FOR ALL SYSTEMS

Test	Modes of Operation				Comments
	Receive	Transmit	Standby	Acquisition	
All Classes of Systems (MIL-STD-461 Type of Tests)					
Power and Signal Lines Conducted Emissions (CE01, CE02, CE03, CE04, CE05)	Test	Test	No Test	No Test	Limit upper test frequency to 50 MHz
Power Line Conducted Susceptibility (CS01, CS02, CS06)	Test	Test	Test	Test	Limit upper test frequency to 400 MHz
Radiated Emissions (RE01, RE02, RE04)	Test	Test	No Test	No Test	Limit upper frequency on RE01 to 30 kHz; RE02 tests over frequency range of 14 kHz to 100 GHz.
Antenna Emissions (CE06, RE03)	Test	Test	Test	No Test	Harmonic emission tests shall be limited to systems operating at 50 GHz and below.
Radiated Susceptibility (RS01, RS02, RS03)	Test	Test	No Test	Test	Upper frequency limit of RS01 shall be limited to 30 kHz; RS03 shall be performed over the frequency range of 14 kHz to 100 GHz.
Receiver Susceptibility (CS03, CS04, CS07, CS08)	Test	No Test	No Test	Test	Tests shall be performed over the frequency range of 0.9 fc. to 100 GHz
Electromagnetic Compatibility Test	Test	Test	Test	Test	Compatible operation of all systems shall be verified

TABLE VII. PRELIMINARY MM-WAVE EMC TEST REQUIREMENT MATRIX FOR RADAR SYSTEMS

Test	Modes of Operation				Comments
	Receive	Transmit	Standby	Acquisition	
Radar Systems (MIL-STD-469 Type of Tests)					
Transmitter Frequency Tolerance	No Test	Test	No Test	No Test	Radar systems shall be subjected to these radar tests in addition to MIL-STD-461 type tests.
Transmitter Emission Bandwidth	No Test	Test	No Test	No Test	
Transmitter Tunability	No Test	Test	No Test	No Test	All of the MM-Wave radar system tests shall cover the entire frequency range up to 100 GHz.
Transmitter Spurious Emissions	No Test	Test	No Test	No Test	
Receiver Acceptance Bandwidth	Test	No Test	Test	No Test	
Receiver Radiation	Test	No Test	Test	No Test	
Antenna Side Lobe Suppression	Test	Test	No Test	No Test	

VI. CONCLUSIONS AND RECOMMENDATIONS

A review of the results of the third quarter effort leads to the following conclusions and recommendations.

A. CONCLUSIONS

1. Millimeter wave signals are attenuated and reflected by numerous types of building materials which do not normally provide shielding or reflection at lower frequencies.

2. Relatively high levels of radiation exist in the far field major side lobes of high power millimeter wave systems. These radiations are concentrated into very narrow beams and are removed from the main beam by a very small distance equivalent to angles to ±3 degrees or less.

3. Radiation fields in the near vicinity of millimeter wave systems are typically of low levels. These fields are limited to an area in front of the radiating antennas and also in the vicinity of waveguide flanges which may not be properly sealed. Interference fields generating from waveguide flanges are of relatively low amplitude and do not generally represent an interference problem at distances of 10 meters or greater.

4. Results of measurements of millimeter wave radiations performed in the vicinity of millimeter wave systems and compatibility experiments performed in conjunction with these systems indicate that radiations of the order of 100 dB/μV/meter can be tolerated at a distance of 1 meter from the source.

5. Systems operating at lower frequencies in the 3 to 10 GHz can act as a source of millimeter wave interference if the harmonics are not adequately controlled. Spurious radiations as high as the 9th or 10th harmonics can be of sufficient signal strength to represent a potential interference problem. Systems designed to meet MIL-STD-461 requirements are found to be relatively free of any significant radiations at millimeter wave frequencies.

6. Millimeter wave horn antennas have a fair amount of gain at frequencies above their operating frequency. They may be down only 3 to 4 dB at the third harmonic. This may be of concern in deployments where there are multiple receivers and transmitters that could interfere with one another.

B. RECOMMENDATIONS

1. Reflection and absorptive qualities of ordinary building materials at millimeter wave frequencies should be taken into consideration in millimeter wave system deployments. The reflective properties of terrain and enclosures which are found in typical deployments should be considered when determining worst-case situations to be employed in interference analysis modeling when establishing specification interference limits.

2. Millimeter wave systems can be successfully deployed in areas located within small angles of main transmit beams of other millimeter wave systems. These angles should be limited to the fourth major side lobe at angles of the order of ±10 degrees. Out-of-band susceptibility limits of millimeter wave receivers should be specified to meet requirements that are compatible with these types of deployments. A typical value of out-of-band susceptibility test levels should be in the area of 130 dB/uV/meter. Rationale for this level is based upon results of experiment number 12 and represents a 20 dB safety factor. This assumes that collocated systems will operate outside the major side lobes, in this case the fourth, which was 0.3 volts per meter.

3. Measurements of random leakage radiations such as those originating at waveguide flanges of millimeter wave systems are recommended at a distance of one meter from the source to permit detection of these radiations with EMI meters of relatively low sensitivity such as are encountered in typical millimeter wave EMI receiver and antenna systems. These measured values can then be extrapolated at greater distances of 10 to 100 meters as desired. A specification limit of 100 dB/uV/meter should be considered for millimeter wave case leakage interference emissions. This value is based upon results obtained in experiment number 13. A value of 3.12 volts/meter was found to cause borderline susceptibility during the compatibility tests. Therefore 100 dB/uV/meter represents a safety value of approximately 20 dB.

4. Measurements should be performed on high order harmonics up to the tenth order on systems operating between 2 and 10 GHz, which are planned for use in collocation with millimeter wave systems. The measurements are necessary, as these higher order harmonics can be present in lower frequency systems and can cause interference to millimeter wave systems.

VII. REFERENCES REVIEWED

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(5) Interference Notebook DOD Document No. AD 484585, Jansky and Bailey, June 1966

(6) Electromagnetic Interference and Compatibility, Vol. 3, Don White Consultants Inc., First Edition 1973

(7) Honeywell 600 Computer Series of Computer Manuals

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APPENDIX A

COMPUTER-AIDED INTERFERENCE ANALYSIS PROGRAM FOR MILLIMETER-WAVE SYSTEMS

This computer program was written as part of the Millimeter Wave EMC study for the purpose of predicting interference interactions occurring between collocated millimeter-wave systems. The program is designed to analyze a total communications system from transmitters to receivers. Positive output numbers represent the amount by which the tolerable interference is exceeded. Negative output numbers represent the interference margin of safety level that is present. The output numbers are listed with the corresponding frequency at which they occur. The program is run on a GE 635 computer with a total memory of 12,660 words. The present program is limited to a study of systems collocated within 100 meters. The program can be adapted at a later date to accommodate deployments involving larger distances. This adaptation would require the programming of atmospheric losses at the various millimeter wave frequencies into the program.

This program is designed to evaluate each section of a communications system and predict what the interference will be. The program design philosophy was to write a separate subprogram for each section and combine the results into one master program. The separate subprograms evaluate the following systems.

1) Receiver desired response
2) Receiver spurious response
3) Transmitter desired output
4) Transmitter spurious output
5) Antenna - receiver
6) Antenna - transmitter
7) Propagation losses

A block diagram follows in Figure A-1. The master program collects all intermediate data and finalizes the output. The frequency control block coordinates all the individual subprograms so they "track" one another. (The numbers in the diagram match the subprogram list above.)

The data generated in each subprogram has the units of db or dbm. This allows us to simply add the intermediate results to obtain the final answer.

(To call each of the sections "subprograms" is a misnomer. The actual design procedure was to write each "subprogram" as a separate program and then combine all the individual programs into one master program.)

Each of these subprograms is described in detail in the following discussion. References 5, 6 and 7 were instrumental in the development of this program.

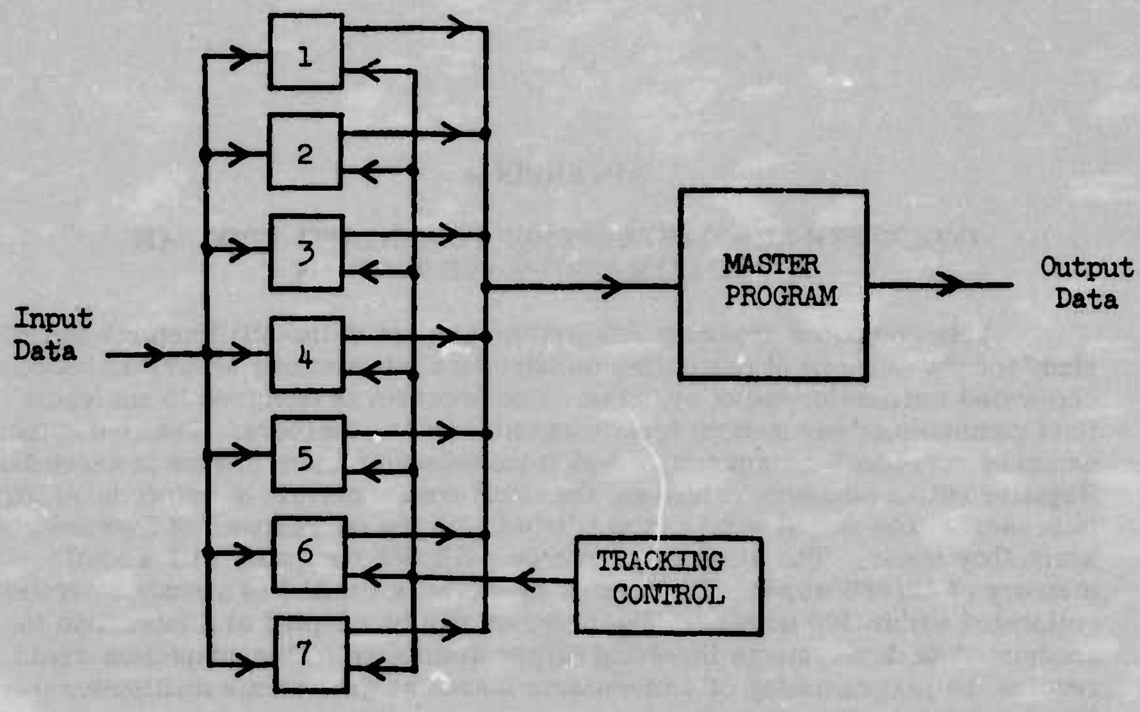

Figure A-1. Block Diagram of Total Program

I. RECEIVER DESIRED RESPONSE SUBPROGRAM

Statements 180 to 760 comprise this part of the total program. Statements 10 to 170 are introductory PRINT statements that preface the program.

The function of statements 180 to 760 is to obtain from the user the required data and internally generate information concerning the desired receiver response. The desired receiver response is defined as the response to the signal that is intended to be received; that is, the fundamental output of the transmitter. Spurious responses, intermodulation products, etc are not included in this subprogram.

1. Data Input

The required data is obtained through a series of INPUT statements. These statements have the effect of stopping the computer until the user supplies the necessary data. When the data is supplied, the computer resumes calculations. The quantity of numbers required depends on the number of variables in the INPUT statement. For example, statement 250,

```
250 INPUT B, C
```

This statement causes the computer to expect two numbers. The first number given by the user will be assigned the variable B, the second, C. When the INPUT statement is combined with a PRINT statement, the computer can be programmed to ask for a number and then wait for it. This is how all input information in the Master program is supplied to the computer. See the sample output starting on page 35 for an example of this combination. NOTE: ALL DATA MUST BE SUPPLIED TO THE COMPUTER IN THE ORDER REQUESTED.

The data supplied to the computer are points from a graph describing the receiver response. The user must take the information he has on his receiver and put it into a graph of the form in Figure A-2. An explanation of the coordinates of Figure A-2 follows.

A = Number of frequencies to be checked.

B = Center frequency of the receiver

C = Receiver sensitivity at frequency A

D, E = The receiver's 3 dB frequencies. The upper 3 dB frequency must be supplied to the computer first, then the lower.

O, G = The frequencies at the low sensitivity end of the skirt, i.e., the frequencies at the "bottom" of the skirt. These frequencies must both have the same sensitivity as specified by G.

H = Receiver sensitivity at the "bottom" of the skirt.

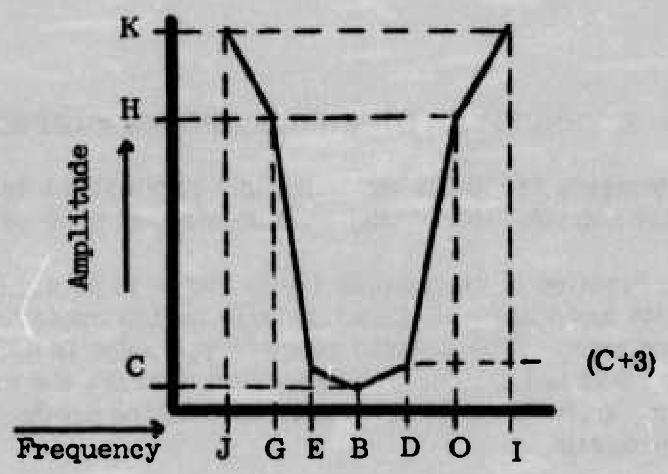

Figure A-2. Graph for Desired Receiver Frequency Response

I, J = The upper and lower band limits of the total program. These values will be internally carried forward so thay must be selected to include all spurious response and output frequencies to be specified in later subprograms. Again observe note on order specified to computer.

K = Receiver sensitivity at the band edges

The units for the amplitude of receiver sensitivity are dBm. For frequency, any units can be used as long as the same units are used throughout the total prŏgram (Master).

2. Internal Data Generation

Once data on the seven graph points is supplied, the computer generates data using an iterative process. This means the following formula is used.

$$730 \quad \text{Let } P(x) = P(x-1) + N \cdot L \cdot U1$$

where

$P(x)$ = amplitude of the x^{th} frequency

$P(x-1)$ = amplitude of the x-1 frequency

X = indexing variable

N = slope of Figure A-3 in the region of the frequency in question

L = the difference, $f(x) - f(x-1)$

U1 = either 0 or 1; this term must be zero for x=1, one for all other x

L is generated using the following formula.

350 Let L = (I-J)/A

where I and H are as specified previously. A is the number of frequencies between I and H to be analyzed for interference.

The value of the slope, N, is generated using statements 360 to 680. This is a more complicated number to calculate as its value depends on the frequency in question. This is done by calculating N1 to N6 (statements 360 to 410) which are the slopes at the various frequencies. N is then assigned the appropriate value in statements 440 to 650. Before we examine the assignment process, let's first examine the action of FOR and NEXT statements.

FOR and NEXT statements allow us to establish a loop. In this loop we have an indexing variable. Each time the computer goes through the loop the indexing variable is increased by a specified amount, which in our case is 1. Also specified is a lower limit (2, supplied by the computer) the number at which the loop starts and an upper limit (A, supplied by the user) the number at which the loop stops. Hence, in our program we generate a series of numbers as follows: 2, 3, 4...A. The FOR statement is the first statement in the loop and the NEXT statement the last.

Between the FOR and NEXT statements other statements can be inserted. These are statements 460 and 730. The assignment process for N and the data generation for the receiver response occurs in these statements.

For the "N" assignment process, see Figure A-3. Note that which value of N1 to N6 gets assigned to N depends on the frequency in question. (The N's are also drawn on the graph.) The following inequalities show which N applies for the frequency range.

$J < \text{Freq} \leq G$, N = N1
$G < \text{Freq} \leq E$, N = N2
$E < \text{Freq} \leq B$, N = N3
$B < \text{Freq} \leq D$, N = N4
$D < \text{Freq} \leq O$, N = N5
$O < \text{Freq} \leq I$, N = N6

In the program, F(1) is set equal to J. (L has been previously calculated.) The loop then starts and statement 460 generates the first frequency at which we check for interference. Note that this value is J.

460 Let F(x) = F(1) + (x-1) * L

This value of F(x) then goes to statement 470. At 470, F(x) is compared to G and found to be smaller. Since it is smaller the computer then goes to statement

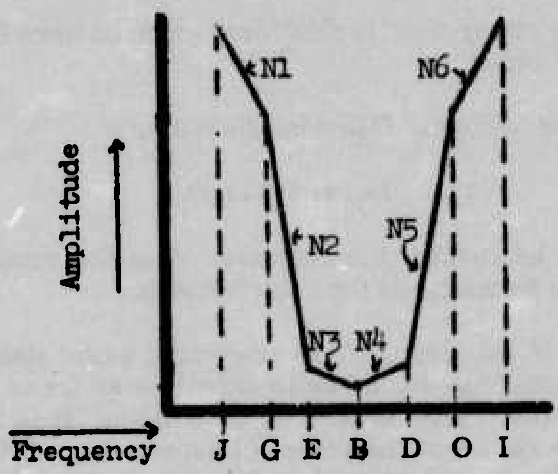

Figure A-3. N Assignment

490, where N is assigned the value N1. The computer then goes to statement 690. Since X=1 in this first case, statements 690 and 700 put U1=0. The computer then goes to 730, where the receiver response, P(x), is calculated. From here we come to our NEXT statement which starts the whole process over.

This preceding example was for X=1. When X is greater than 1 and F is greater than, for example, E, a slightly different process occurs as follows.

A value of X greater than 1 causes a higher frequency than F(1) to be generated. (For this example, our frequency is greater than E but less than B.) The computer than takes this new frequency to 470, where it seems that the new frequency, f(x), is greater than G. Because it is greater, the computer ignores the command to go to 490, and instead goes to the next statement, 480. 480 sends the computer to 510, where it discovers f(x) is greater than E. The computer then goes to 520 where it is told to go to 550. At 550, comparison is made and the inequality is found to be true. The computer goes to 570 where N is set equal to N3. From here the computer is directed to 690 where it calculates the receiver response at this frequency. As the computer calculates each frequency and response, it stores the values, hence we now have two values for frequency and two values for the response. At this point, the NEXT statement is encountered, where the computer returns to statement 450. This process is continued until the indexing variable, X, reaches a value of A.

When X reaches A, the computer exits the loop and goes to the next statement.

At this point, the computer has calculated and stored all the necessary information on the desired receiver response. The next statement is part of the transmitter desired output subprogram.

Note that the subprogram accepted only one center frequency for the receiver. If it is desired to have a receiver that tunes a range of frequencies, it is necessary to run the program for each frequency.

3. Miscellaneous Notes

In multiple receiver environments, the most sensitive receiver response can be considered the desired response. The responses from the other receivers can be described as spurious responses. Whether a response is considered as a desired response or a spurious response makes no difference in the total program. It will still be considered as a response in the total system.

II. TRANSMITTER DESIRED OUTPUT SUBPROGRAM

This program extends from statements 750 to 1290. It is identical to the last program with the following exceptions:

1. Some of the PRINT statements have been changed to clarify the input data needed for each INPUT statement.

2. Statement numbers have been changed.

3. Some of the letters have been changed to assure that no information to be used at a later time will be lost.

a. Data Input

The graph required for this subprogram has the form in Figure A-4. An explanation of the graph coordinates follows:

B = center frequency of transmitter

C = output of transmitter at center frequency

D, E = upper and lower -3 db frequencies of the transmitter spectrum

O, G = upper and lower frequencies at the bottom of the skirt

H = transmitter output at bottom of skirt

K = output at band edges

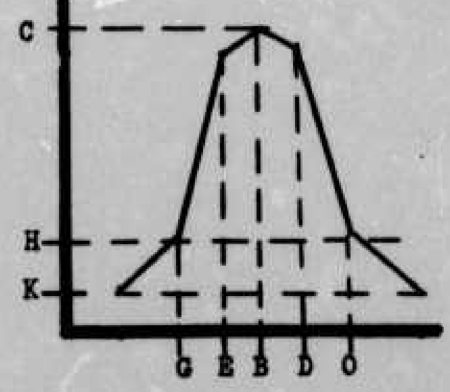

Figure A-4. Transmitter Desired Output Graph

Note that the upper and lower band limits (I, J) and the number of frequencies to be analyzed (A) are not requested in this subprogram. They are carried over from the previous subprogram.

As before, this data will be requested through a series of PRINT and INPUT statements.

b. Internal Data Generation

Data for this subprogram is generated the same way as for the previous subprogram, using L, N1 to N6, and N. Instead of the transmitter data being labeled P(x), it is given a new label, Q(x). If this change was not made, whenever a new value of transmitter data was generated, it would replace the still-needed receiver data.

c. Miscellaneous Notes

Note that, as for the receiver, this subprogram has provision for one center frequency. If it is desired to have a tunable transmitter, the program must be run for each frequency.

It is also possible to describe multiple-transmitter environments using both this program and the transmitter spurious output program. This is done by taking the strongest received signal and considering it as the desired output described in the transmitter desired output subprogram. All other transmitter outputs anywhere in the system, whether fundamental outputs or spurious outputs, are described under the spurious output subprogram. Whether the transmitter outputs are described as spurious or desired outputs, they will still be included in the total system evaluation.

In multiple transmitter environments where the transmitters are at varying distances from the receiver, the output levels of the transmitters should be normalized with respect to the "desired output." The purpose of this normalization is to compensate for the distance effects.

III. PROPAGATION LOSSES SUBPROGRAM

This is the simplest subprogram in the total program. Since only distance effects are considered, this subprogram is frequency independent. There are also no atmospheric absorption losses considered. For purposes of this study, atmospheric losses are negligible since only distances up to 100 meters are considered.

1. Data Input

One parameter of data is required for this program; this is the distance between the transmitting and receiving antennas. This is requested with statements 1350 and 1360.

2. Internal Data Generation

As mentioned previously this subprogram is frequency independent. Therefore, only one value of data need be calculated for the entire subprogram.

The formula (statement 1370) used to calculate this value is

$$\text{Attenuation (dB)} = 10 \cdot \log_{10}\left(\frac{1}{4\pi B^2}\right)$$

where

B = distance between the antennas

The output has the units, dB. See Figure A-5.

3. Miscellaneous Notes

Statements for this subprogram go from 1300 to 1370.

Because no absorption losses are considered, the maximum distance at MMW frequencies should be limited to 100 meters.

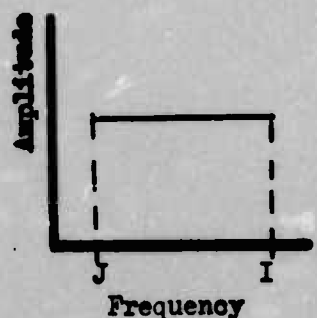

Figure A-5. Output of Propagation Subprogram

IV. THE ANTENNA SUBPROGRAMS

The receiver and transmitter antenna subprograms are identical, with the following exceptions.

1. PRINT statements 1400 and 1950 are worded to fit the appropriate subprogram.

2. The output for the receiver subprogram is labeled S(x), the transmitter-subprogram, X1(x).

See Figure A-6 for a breakdown of the statement numbers. Because of similarities in the two programs, a step-by-step description will be given of only the receiver antenna subprogram.

a) Data Input

The graph for the INPUT statements of these programs has the form of Figure A-7.

The computer will ask for data in terms of bottom and top band edges, and break points. See the graph for an explanation of these terms. As before, this data must be supplied in the order requested. The units for antenna gain are dB. Frequency information is not requested for the upper and lower band limits. This information is carried forward from previous subprograms.

The graph may be of any shape. There are no limitations on the frequency or gain with the exception of the upper and lower band limits. These must be the same throughout the total program.

b) Internal Data Generation

Data concerning the antenna gain is generated in much the same manner as the data for the receiver desired response. An iterative process is also used in this subprogram. The antenna data is generated in statement 1910.

```
1910    Let S1(x) = S1(x-1) + N*O*P
```

	Receiver	Transmitter
Input	1380 - 1550	1970 - 2100
Calculation	1560 - 1920	2110 - 2470

Figure A-6. Breakdown of Subprograms by Statement Numbers

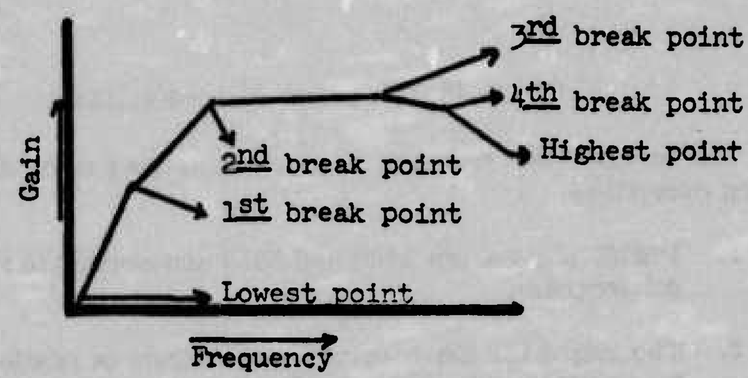

Figure A-7. Antenna Subprogram Input Graph

where

$S1(x)$ = antenna response of x^{th} frequency

$S1(x-1)$ = antenna response of x-1 frequency

X = indexing variable

N = 0, if X = 1; 1, if X > 1

O = difference between test frequencies, f(x) - f(x-1)

P = slope between two frequencies in question

The value of the slope, P, is generated in much the same manner as before. This number has five possible values, the valid value being determined by the frequency. The process involved here is identical with the receiver (and transmitter) desired response (output) subprogram. The statements included are 1560 to 1600 and 1690 to 1850.

As for the receiver response subprogram, the antenna gain calculations are made after the slope, P, has been selected. This gain value is then stored until future use. When the indexing variable X is equal to A, the number of frequencies to be tested, the loop is exited and the transmitter antenna subprogram is entered. The transmitter antenna subprogram exits into the R. F. environment subprogram.

c) **Miscellaneous Notes**

Antenna correction factors and cable losses should be included in this part of the program. Any other losses in the system can also be included.

V. R. F. ENVIRONMENT SUBPROGRAM

The R. F. environment is defined as the signals present in the vicinity of the receiving antenna, and whether or not they came from the desired transmitter neighboring transmitters.

The R.F. environment subprogram block diagram is shown in Figure A-8.

1. Data Input

Statements 2540 to 2730 comprise the input part of the subprogram. The required graph has the form in Figure A-9. Note that the graph locus is not a continuous line, but a series of lines. Each of these lines represents a signal present in the environment. The number of times the loop circulates is determined by the number of signals present. The input PRINT statements must be controlled in such manner as to be printed only as many times as are needed. At the same time, they must be worded generally enough so only a minimum number of statements will be required. This is accomplished by wording the PRINT statements with "first," "last," and "next" signals and putting these in a loop that circulates only the required number of times over the number of times, etc. Statements (2610-2650) are also inserted which direct the computer to the proper PRINT statements. The indexing variable assigns labels and stores each piece of data as it is acquired. This is the action that occurs in statements 2580 to 2730.

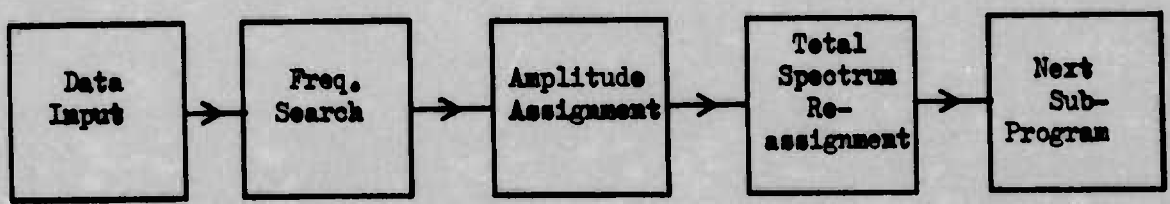

Figure A-8. Block Diagram of R. F. Environment Subprogram

From 2730 we go to the frequency search and amplitude assignment procedure. Note that the input graph has some frequencies where no amplitude is specified. The program must search the entire frequency range in question, but assign values of output only at certain frequencies. This is accomplished in statements 2740 to 2860.

Statement 2740 sets up a loop where X, the indexing variable, goes from 1 to I (formerly A). I represents the number of frequencies to be tested. Statement 2750 uses 2740 and previous information to generate the frequencies to be tested for interference. The next two statements, 2760 and 2770 generate a loop which compares the frequencies from 2750 to the frequencies in the environment (2780 - 2790). If these two frequencies are close enough to each other (i.e., if their difference is less than the bandwidth (2790)), then the output level of the environmental frequency is given to the frequency generated by 2750. The effect of this program so far has been to match the spurious levels to frequencies that are common throughout the rest of the total program. Thus when all the subprograms are brought together, they all have frequencies that will track.

A level must also be supplied to the frequencies where there is no environmental signal. If this is not done, the computer will assign a random number, usually quite large, to this blank information space. This level has been chosen internally to be -120 dBm. If the user desires a different value, only statement 2800 need be changed.

The data from the environment and the fill-in data (mentioned in the last paragraph) are brought together into one final list in 2900. This new list is given the variable, T(x).

At this point in the MASTER program, we have two lists of data concerning the environment. One is from the desired transmitter output subprogram. The other is from this R. F. environment subprogram. These two must be combined into one list that pictures the total R. F. environment. This combined list will then be used for the final calculations. This process takes place in statements 2860 to 2910. Those statements select the stronger signal of the two subprograms as the final value.

The next statement is part of the receiver spurious response subprogram.

2. Miscellaneous Notes

Any R. F. signal or any effect in the system that could be simulated by a transmitted signal can be represented in this subprogram. Examples of this are other nearby transmitters, receiver "birdies," jamming transmitters or background noise levels.

Where multiple transmitters are described, the following consideration must be made if all separation distances are not the same. Varying distances will cause the receiver to "see" a different power level for the transmitter since only one distance can be supplied to the program. To compensate for this, the output levels of the various transmitters should be "normalized" with respect to the desired transmitter output. The reason for the normalization is to allow the transmitters to appear to the receiver as if they were at the specified distance.

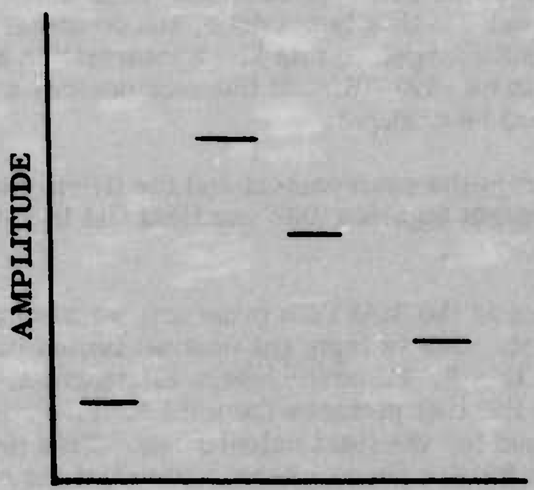

Figure A-9. Bar Graph for Spurious Subprograms

VI. RECEIVER SPURIOUS RESPONSE SUBPROGRAM

The receiver spurious responses are those responses other than the desired response.

This subprogram is identical with the transmitter spurious output subprogram with the following exceptions.

1) The PRINT statements have been reworded to fit their usage.

2) Statement 3300 has been rewritten so the smaller (more sensitive) value instead of the larger (higher output) value is selected as the final value of the total receiver response.

3) Where no spurious response is described at a particular frequency, a value of 100 dBm is assumed.

A. Data Input

This part of the subprogram is the same as the transmitter spurious subprogram with the exception of the PRINT statements.

B. Internal Data Generation

This part of the program is also the same as before. The exception is Note 2 mentioned above with regard to statement 3300.

C. Miscellaneous Notes

This subprogram can be used to describe any spurious response in the system or a multiple receiver environment. In each case, the most sensitive response is described as the desired response. The remaining responses are described on the line graph (Figure A-9). Note that the graph locus is not a continuous line, but a series of lines. Each of these lines represents a spurious response at that respective frequency. If no line is given for a particular frequency, it is assumed there is a spurious response of 100 dBm.

The computer will ask for a bandwidth in each program. This bandwidth is not the 3 dB bandwidth of the receiver or transmitter, but the width of the spurious response or spurious signal.. It can be different for each program but must meet the following restraint:

$$BW > \frac{H-L}{A}$$

where

BW = bandwidth

H = highest frequency to be analyzed

L = lowest frequency to be analyzed

A = number of frequencies to be analyzed

This is to assure that no spurious input can "squeeze" between two test frequencies and not be seen.

The data is generated by seeing if the frequency in question is close enough to the spurious frequency. The bandwidth is used in this comparison. If the frequency in question is in the bandwidth of the system, the amplitude of the spurious signal at the spurious frequency is imputed to the frequency in question.

If the spurious receiver response is more sensitive than the fundamental transmitter output, the spurious output level is substituted for the fundamental output level, resulting in the spurious graph being superimposed on the fundamental graph.

While intermodulation products are not calculated by the program, they can be specified by spurious responses at a specified frequency. The intermodulation analysis program described in the Second Quarterly Report (Reference 6) describes how intermodulation frequencies can be determined. These frequencies can then be inserted into the receiver spurious response subprogram.

VII. PROGRAM ACCURACY

As was explained on page A-5, the frequencies to be tested for responses are generated through an iterative process (Statement 460). By keeping the number of frequencies to be tested large, accuracy is conserved in the overall program. However, if a frequency supplied by the user to the computer falls between and not exactly on one of the frequencies generated by statement 460, inaccuracies will be introduced into the system evaluation. The magnitude of the error depends on the slope of the graph in the region of the frequency in question. These inaccuracies occur because the computer is not allowed to iterate over the entire section of slope (see Figure A-2) before a new slope is used for further calculations. This situation can be prevented and a total program accuracy of ±0.5% or better obtained if the frequencies the user supplies are intentionally chosen to fall on a frequency that will be generated by the computer. This may introduce some error into the data, but this error is usually negligible.

The frequencies that will be generated by the computer are given by statement 460. If the user calculates these frequencies before the program is run and uses these frequencies to supply his data to the computer, the .5% computer accuracy will be obtained.

```
460 Let F(x) = F(1) + (x-1) * L
```

where

F(X) = Frequency computer will generate. The frequency generated by this statement that is closest to the user's data is the frequency the user specifies as his data.

F(1) = Lowest frequency to be analyzed.

L = See page A-5.

X = Indexing variable. This index goes from 1 to n, where n is the number of frequencies to be analyzed for possible interference.

A close inspection of Analysis Number Five reveals this process was used on the transmitter fundamental output data that was supplied to the computer.

VIII. PROGRAM LISTING

```
10 PRINT "THIS PROGRAM EVALUATES THE CHARACTERISTICS OF A
        RECEIVER-"
20 PRINT "TRANSMITTER-ANTENNA SYSTEM FOR INTERFERENCE OF
        DESIRED"
30 PRINT "OPERATION.  THE DATA OUTPUT IS GIVEN IN TERMS OF THE
        FREQ-"
40 PRINT "UENCY AT WHICH INTERFERENCE OCCURS AND THE TOTAL
        SYSTEM"
50 PRINT "RESPONSE.  WHEN THE TOTAL SYSTEM RESPONSE IS GREATER
        THAN ZERO."
60 PRINT "INTERFERENCE IS PROBABLE TO OCCUR."
90 PRINT " "
100 PRINT " "
110 PRINT "UNITS FOR DATA:"
120 PRINT "   FREQUENCY - ANY UNITS AS LONG AS THE SAME UNITS ARE
        USED"
130 PRINT "        THROUGH OUT THE PROGRAM"
140 PRINT "   GAIN AND RESPONSE - DB OR DBM AS APPROPRIATE"
150 PRINT "   DISTANCE - METERS"
160 PRINT " "
170 PRINT " "
180 PRINT "THE FOLLOWING INFORMATION GENERATES DATA FOR THE"
190 PRINT "RCVR FREQUENCY RESPONSE."
200 PRINT " "
210 PRINT "HOW MANY FREQUENCIES DO YOU WANT CHECKED FOR
        PROBABLE"
220 PRINT "INTERFERENCE -- MAXIMUM=50";
230 INPUT A
240 PRINT "WHAT IS THE CENTER FREQUENCY OF THE RCVR AND ITS
        SENSITIVITY";
250 INPUT B, C
260 PRINT "WHAT ARE THE UPPER AND LOWER 3 DB FREQUENCIES";
270 INPUT D, E
280 PRINT "WHAT ARE THE FREQUENCIES AT THE BOTTOM OF THE SKIRT
        ABOVE AND"
290 PRINT "BELOW THE CENTER FREQUENCY AND THE RCVR"
300 PRINT "SENSITIVITY AT THOSE FREQUENCIES";
310 INPUT O, G, H
320 PRINT "WHAT IS THE UPPER AND LOWER BAND LIMITS AND THE RCVR
        SENSITIVITY"
330 PRINT "AT THOSE FREQUENCIES";
340 INPUT I, J, K
341 LET D1=I
342 LET D2=I
350 LET L=(I-J)/A
360 LET N1=(H-K)/(G-J)
370 LET N2=(C+3-H)/(E-G)
380 LET N3=-3/(B-E)
```

```
390 LET N4=3/(D-B)
400 LET N5=(H-C-3)/(O-D)
410 LET N6=(K-H)/(I-O)
420 DIM P(52), F(52)
430 LET P(1)=K
440 LET F(1)=J
450 FOR X=2 TO A
460 LET F(X)=F(1)+(X-1)*L
470 IF F(X)<=G THEN 490
480 GOTO 510
490 LET N=N1
500 GOTO 690
510 IF F(X)<=E THEN 530
520 GOTO 550
530 LET N=N2
540 GOTO 69C
550 IF F(X)<=B THEN 570
560 GOTO 590
570 LET N=N3
580 GOTO 690
590 IF F(X)<=D THEN 610
600 GOTO 630
610 LET N=N4
620 GO TO 690
630 IF F(X)<=0 THEN 650
640 GOTO 680
650 LET N=N5
660 GOTO 690
670 IF F(X)<1 THEN 750
680 LET N=N6
690 IF X<1 THEN 720
700 LET U1=0
710 GOTO 730
720 LET U1=1
730 LET P(X)=P(X-1)+N*L*U1
740 NEXT X
750 PRINT " "
760 PRINT " "
770 PRINT "THE FOLLOWING INFORMATION GENERATES DATA FOR THE
          XMTR"
780 PRINT "FUNDAMENTAL OUTPUT."
790 PRINT " "
800 PRINT "WHAT IS THE CENTER FREQUENCY OF THE XMTR AND ITS
          OUTPUT";
810 INPUT B, C
820 PRINT "WHAT ARE THE UPPER AND LOWER 3 DB FREQUENCIES";
830 INPUT D, E
840 PRINT "WHAT ARE THE FREQUENCIES AT THE BOTTOM OF THE SKIRT
          ABOVE AND"
850 PRINT "BELOW THE CENTER FREQUENCY AND THE XMTR"
860 PRINT "OUTPUT AT THOSE FREQUENCIES";
```

```
870 INPUT O, G, H
880 PRINT "WHAT IS THE XMTR OUTPUT AT THE BAND EDGES";
890 INPUT K
910 LET L=(I-J)/A
920 LET N2=(C-3-H)/(E-G)
930 LET N3=3/(B-E)
940 LET N4=-3/(D-B)
950 LET N5=(H-C+3)/(O-D)
960 LET N6=(K-H)/(I-O)
970 DIM Q(52)
980 LET Q(1)=K
990 LET F(1)=J
1000
1010 LET F(X)=F(1)+(X-1)*L
1020 IF F(X)<=G THEN 1040
1030 GOTO 1060
1040 LET N=N1
1050 GOTO 1240
1060 IF F(X)<=E THEN 1080
1070 GOTO 1100
1080 LET N=N2
1090 GOTO 1240
1100 IF F(X)<=B THEN 1120
1110 GOTO 1140
1120 LET N=N3
1130 GOTO 1240
1140 IF F(X)<=D THEN 1160
1150 GOTO 1180
1160 LET N=N4
1170 GO TO 1240
1180 IF F(X)<=0 THEN 1200
1190 GOTO 1230
1200 LET N=N5
1210 GOTO 1240
1220 IF F(X)<1 THEN 1380
1230 LET N+N6
1240 IF X<1 THEN 1270
1250 LET P=0
1260 GOTO 1280
1270 LETΔ=1
1280 LET Z(X) Q(X)=Q(X-1)+N*L*P
1290 NEXT X
1300 PRINT " "
1310 PRINT " "
1320 PRINT "THE FOLLOWING INFORMATION GENERATES DATA FOR THE"
1330 PRINT "PROPAGATION LOSSES."
1340 PRINT " "
1350 PRINT "WHAT IS THE DISTANCE BETWEEN THE RCVR AND XMTR
          ANTENNAS";
1360 INPUT B
1370 LET U=10*.434294*LOG(1/(4*3.14159*B*B))
```

```
1380 PRINT " "
1390 PRINT " "
1400 PRINT "THE FOLLOWING INFORMATION GENERATES DATA FOR THE
          RCVR ANTENNA."
1410 PRINT " "
1420 PRINT "WHAT IS THE GAIN AT THE BOTTOM BAND EDGE";
1430 LET B=J
1440 INPUT C
1450 PRINT "WHAT IS THE FREQUENCY AND GAIN OF THE FIRST BREAK
          POINT";
1460 INPUT D, E
1470 PRINT "WHAT IS THE FREQUENCY AND GAIN OF THE SECOND BREAK
          POINT";
1480 INPUT G, H
1490 PRINT "WHAT IS THE FREQUENCY AND GAIN OF THE THIRD BREAK
          POINT";
1500 LET M=I
1510 INPUT I, J
1520 PRINT "WHAT IS THE FREQUENCY AND GAIN OF THE FORTH BREAK
          POINT";
1530 INPUT K, L
1540 PRINT "WHAT IS THE GAIN AT THE UPPER BAND EDGE";
1550 INPUT N
1560 LET P1=(E-C)/(D-B)
1570 LET P2=(H-E)/(G-D)
1580 LET P3=(J-H)/(I-G)
1590 LET P4=(L-J)/(K-I)
1600 LET P5=(L-J)/(K-I)
1610 DIM S(51)
1620 LET F(1)=B
1630 LET S(1)=C
1640 FOR X=2TO A
1650 IF X<1 THEN 1670
1680 LET F(X)=F(1)+(M-B)*(X-1)/A
1690 IF F(X)<=D THEN 1710
1700 GOTO 1730
1710 LET P=P1
1720 GOTO 1860
1730 IF F(X)<=G THEN 1750
1740 GOTO 1770
1750 LET P=P2
1760 GOTO 1860
1770 IF F(X)< =1THEN 1790
1780 GOTO 1810
1790 LET P=P3
1800 GOTO 1860
1810 IF F(X)<=K THEN 1830
1820 GOTO 1850
1830 LET P=P4
1840 GOTO 1860
```

```
1850 LET P=P5
1860 IF X<1 THEN 1890
1870 LET N=0
1880 GOTO 1900
1890 LET N=1
1900 LET O=F(X)-F(X-1)
1910 LET S(X)=S(X-1)+N*O*P
1920 NEXT X
1930 PRINT " "
1940 PRINT " "
1950 PRINT "THE FOLLOWING INFORMATION GENERATES DATA FOR THE
        XMTR ANTENNA."
1960 PRINT " "
1970 PRINT "WHAT IS THE GAIN AT THE BOTTOM BAND EDGE";
1980 INPUT C
1990 PRINT "WHAT IS THE FREQUENCY AND GAIN OF THE FIRST BREAK
        POINT";
2000 INPUT D, E
2010 PRINT "WHAT IS THE FREQUENCY AND GAIN OF THE SECOND BREAK
        POINT";
2030 INPUT G, H
2040 PRINT "WHAT IS THE FREQUENCY AND GAIN OF THE THIRD BREAK
        POINT";
2050 INPUT I, J
2060 PRINT "WHAT IS THE FREQUENCY AND GAIN OF THE FORTH BREAK
        POINT";
2080 INPUT K, L
2090 PRINT "WHAT IS THE GAIN AT THE UPPER BAND EDGE";
2100 INPUT N
2110 LET P1=(E-C)/(D-B)
2120 LET P2=(H-E)/(G-D)
2130 LET P3=(J-H)/(I-G)
2140 LET P4=(L-J)/(K-I)
2150 LET P5=(N-L)/(M-K)
2160 DIM S1(51)
2170 LET F(1)=B
2180 LET S1(1)=C
2190 FOR X=2TO A
2200 IF X<1 THEN 2220
2210 GOTO 2230
2220 REM
2230 LET F(X)=F(1)+(M-B)*(X-1)/A
2240 IF F(X)<=D THEN 2260
2250 GOTO 2280
2260 LET P=P1
2270 GOTO 2410
2280 IF F(X)<=G THEN 2300
2290 GOTO 2320
2300 LET P=P2
2310 GOTO 2410
2320 IF F(X)<=I THEN 2340
2330
```

```
2340
2350 GOTO 2410
2360 IF F(X)<=K THEN 2380
2370 GOTO 2400
2380 LET P=P4
2390 GOTO 2410
2400 LET P=P5
2410 IF X<1 THEN 2440
2420 LET N-0
2430 GOTO 2450
2440 LET N=1
2450 LET O=F(X)-F(X-1)
2460 LET S1(X)=S1(X-1)+N*O*P
2470 NEXT X
2480 PRINT " "
2490 PRINT " "
2500 PRINT "THE FOLLOWING INFORMATION GENERATES DATA FOR THE
          R.F."
2510 PRINT "ENVIRONMENT.  THE DATA CAN CONCERN A NEIGHBORING
          XMTR OR ANY"
2520 PRINT "OTHER SOURCE OF R.F. ENERGY."
2530 PRINT " "
2540 PRINT "HOW MANY R.F. SIGNALS ARE THERE TO CONSIDER (MAX=50)";
2550 INPUT B
2551 LET I=A
2555 IF B=0 THEN 2912
2560 PRINT "WHAT IS THE BANDWIDTH OF THE R.F. ENERGY";
2580 INPUT A1
2590 LET A=A1/2
2600 FOR C=1 TOB
2610 IF C=1 THEN 2640
2620 IF C<=B-1 THEN 2680
2630 IF C=B THEN 2710
2640 PRINT "WHAT IS THE FREQUENCY AND AMPLITUDE OF THE FIRST
          SIGNAL";
2650 DIM Z(51), V(51), T(51)
2660 INPUT Z(1), V(1)
2670 GOTO 2730
2680 PRINT "WHAT IS THE FREQUENCY AND AMPLITUDE OF THE NEXT
          SIGNAL";
2690 INPUT Z(C), V(C)
2700 GOTO 2730
2710 PRINT "WHAT IS THE FREQUENCY AND AMPLITUDE OF THE LAST
          SIGNAL";
2720 INPUT Z(C), V(C)
2730 NEXT C
2740 FOR X=1 TO I
2750 LET F(X)=F(1)+(D1-D2)/I*(X-1)
2760 LET R=1
2770 FOR R=1 TO B
2780 LET H1=ABS(F(X)-Z(R))
2790 IF H1<=A THEN 2830
```

```
2800 LET T(X)=-120
2810 IF R=5 THEN 2860
2820 GOTO 2850
2830 LET T(X)=V(R)
2840 GOTO 2860
2850 NEXT R
2860 NEXT X
2870 FOR X=1 TO I
2880 IF T(X)<X(X) THEN 2900
2890 GOTO 2910
2900 LET Q(X)=T(X)
2910 NEXT X
2911 GOTO 2920
2912 FOR X=1 TO I
2913 LET T(X)=-120
2914 NEXT X
2920 PRINT " "
2930 PRINT " "
2940 PRINT "THE FOLLOWING DATA GENERATES RCVR SECONDARY RESP
          INFORMATION. "
2960 PRINT "HOW MANY SECONDARY RESPONSES ARE THERE TO CONSIDER
          (MAX=50)";
2970 INPUT B
2975 IF B=0 THEN 3323
2980 PRINT "WHAT IS THE SECONDARY RESPONSE BANDWIDTH";
2990 INPUT A1
3000 LET A=A1/2
3010 FOR C=1 TOB
3020 IF C=1 THEN 3050
3030 IF C<=B-1 THEN 3090
3040 IF C=B THEN 3120
3050 PRINT "WHAT IS THE FREQ AND RESPONSE OF THE FIRST SPUR RESP";
3060 DIM Y(51)
3070 INPUT Z(1), V(1)
3080 GOTO 3140
3090 PRINT "WHAT IS THE FREQUENCY AND AMPLITUDE OF THE NEXT
          SPUR. RESP";
3100 INPUT Z(C), V(C)
3110 GOTO 3140
3120 PRINT "WHAT IS THE FREQUENCY AND AMPLITUDE OF THE LAST
          SPUR. RESP";
3130 INPUT Z(C), V(C)
3140 NEXT C
3150 FOR X=1 TO I
3160 LET F(X)=F(1)+(((D1-D2)/I)*(X-1))
3170 LET R=1
3180 FOR R=1 TO B
3190 LET H1=ABS(F(X)-Z(R))
3200 IF H1<=A THEN 3240
3210 LET Y(X)=100
3220 IF R=5 THEN 3270
3230 GOTO 3260
```

```
3240 LET Y(X)=V(R)
3250 GOTO 3270
3260 NEXT R
3270 NEXT X
3280 DIM W(51)
3290 FOR X=1 TO I
3300 IF Y(X)<P(X) THEN 3320
3310 GOTO 3321
3320 LET P(X)=Y(X)
3321 NEXT X
3322 GOTO 3326
3323 FOR X=1 TO I
3324 LET Y(X)=100
3325 NEXT X
3326 FOR X=1 TO I
3330 LET W(X)=Q(X)+S(X)+S1(X)+U-P(X)
3350 NEXT X
3355 PRINT " "
3356 PRINT " "
3360 PRINT "DO YOU WANT A COMPLETE LISTING OF ALL GENERATED"
3370 PRING "DATA (1=YES 0=NO)";
3380 INPUT A
3381 PRINT " "
3390 PRINT " "
3400 PRINT " "
3410 IF A=1 THEN 3430
3420 GOTO 3630
3430 PRINT "   X    ,    FREQUENCY   , TOTAL RCVR RESP, RCVR ANT RESP"
3440 PRINT " "
3450 FOR X=1 TO I
3460 PRINT X,F(X), P(X),S(X)
3470 NEXT X
3480 PRINT " "
3490 PRINT " "
3500 PRINT "   FREQUENCY XMTD ANT DESP TOTAL R.F. INVIRONMENT"
3520 FOR X=1 TO I
3530 PRINT F(X),S1(X),Q(X)
3540 NEXT X
3550 PRINT " "
3560 PRINT " "
3570 PRINT "   FREQUENCY   , PROPAGATION LOSS, COMPENSATED SYSTEM
        RESPONSE'
3580 PRINT " "
3590 FOR X=1 TO I
3600 PRINT F(X), U,W(X)
3610 NEXT X
3620 GOTO 3680
3630 PRINT "   X    ,    FREQUENCY   , COMPENSATED SYSTEM RESPONSE"
3640 PRINT " "
3650 FOR X=1 TO I
```

```
3660 PRINT X,F(X),W(X)
3670 NEXT X
3680 END

ready

*:*
```

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1. REPORT NUMBER: ECOM-74-0171-3	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): MILLIMETER WAVE SYSTEM ELECTROMAGNETIC COMPATIBILITY STUDY	5. TYPE OF REPORT & PERIOD COVERED: Quarterly Progress Report 6 Aug 74 - 6 Nov 74
	6. PERFORMING ORG. REPORT NUMBER: FR75-10-238
7. AUTHOR(s): G. G. Sundberg and R. F. Marsolais	8. CONTRACT OR GRANT NUMBER(s): DAAB07-74-C-0171
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Ground Systems Group, Hughes Aircraft Company, Fullerton, California 92634	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 6.27.01.A 1S7 62701 AH92
11. CONTROLLING OFFICE NAME AND ADDRESS: U.S. Army Electronics Command, AMSEL-NL-RY-5, Fort Monmouth, New Jersey 07703	12. REPORT DATE: April 1975
	13. NUMBER OF PAGES: 80
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Distribution limited to U.S. Government Agencies only; Test and Evaluation; April 1975. Other requests for this document must be referred to Commanding General, U.S. Army Electronics Command, ATTN: AMSEL-NL-RY-5, Fort Monmouth, N. J. 07703.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Electromagnetic Compatibility
Millimeter Waves

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents the results obtained from experiments and analysis performed during the third quarter effort of the Millimeter Wave Electromagnetic Compatibility Study. The period covered is from 6 August to 6 November 1974. The major effort in the third quarter consists of performance of experiments which are related to the millimeter wave study, computer analysis of electromagnetic compatibility requirements for typical Army deployments, analysis of modulation effects, analysis of out-of-band antenna characteristics and initiation of the recommended EMC test program for millimeter wave system.

Experiments ten through fourteen were performed during this quarter. These experiments involved electromagnetic compatibility evaluation of millimeter wave communication and radar systems. Shielding and reflectivity tests were performed to determine the effects of building and equipment enclosures materials on propagation and scattering of millimeter wave emissions.

Computer analysis programs employed during this study were designed to provide assistance in establishing emission and susceptibility parameters which shall be specified to assure electromagnetic compatibility between millimeter wave systems and other collocated systems.

A preliminary test matrix containing a list of EMC tests recommended for millimeter wave systems was developed.