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ANALYSIS OF FACTORS AFFECTING ELECTROMAGNETIC COMPATIBILITY OF RADARS OPERATING IN THE 2700 TO 2900 MHz BAND

Michael A. Maiuzzo

IIT Research Institute

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of
IIT Research Institute
Under Contract With
DEPARTMENT OF DEFENSE
Electromagnetic Compatibility Analysis Center
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16. Abstract

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The effect of selected technical and operational considerations on the electromagnetic compatibility of present and projected deployments of radars in the 2.7 to 2.9 GHz frequency band is analyzed. The spectrum channel width relationship to transmitter power amplifier characteristics and pulse waveform parameters is explored. The results of assigning discrete channels for individual radars are presented.

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PREFACE

The Electromagnetic Compatibility Analysis Center (ECAC) is a Department of Defense facility, established to provide advice and assistance on electromagnetic compatibility matters to the Secretary of Defense, the Joint Chiefs of Staff, the military departments and other DOD components. The Center, located at North Severn, Annapolis, Maryland 21402, is under executive control of the Director of Defense Research and Engineering and the Chairman, Joint Chiefs of Staff or their designees who jointly provide policy guidance, assign projects, and establish priorities. ECAC functions under the direction of the Secretary of the Air Force and the management and technical direction of the Center are provided by military and civil service personnel. The technical operations function is provided through an Air Force sponsored contract with the IIT Research Institute (IITRI).

This report was prepared for the Systems Research and Development Service of the Federal Aviation Administration in accordance with task assignment 10, subitem c, of the Interagency Agreement DOT-FA70WAI-175 as part of AF Project 649E under Contract F-19628-71-C-0221 by the staff of the IIT Research Insitute at the Department of Defense Electromagnetic Compatibility Analysis Center.

To the extent possible, all abbreviations and symbols used in this report are taken from American Standard Y10.19 (1967) "Units Used in Electrical Science and Electrical Engineering" issued by the United States of America Standards Institute.

Persons making significant contributions to the work contained in this report were M. Massaro, G. Imhoff, M. Aasen, W. Carter, R. Turton and J. Pierzga.

Users of this report are invited to submit comments which would be useful in revising or adding to this material to the Director, ECAC, North Severn, Annapolis, Maryland 21402, Attention ACV.

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SECTION 1

INTRODUCTION

BACKGROUND

The frequency band between 2.7 and 2.9 GHz is allocated on a primary basis for the aeronautical radionavigation and meteorological aid services. Within the U.S. and its possessions, the Federal Aviation Administration has the administrative responsibilities for this band (Reference 1). The FAA uses the band to provide an airport surveillance function in the vicinity of airfields, and coordinates the use of the band with other users. The FAA relies on radars operating in this band to provide accurate and continuous information on the location of aircraft in the terminal area regardless of weather or traffic conditions. To meet the requirements for increased air traffic, more airfield facilities, and all-weather operations, new radar equipment is being developed and procured.

In order to promote efficient use of the frequency spectrum allocated to the Aeronautical Radionavigation Service, the Spectrum Plans and Programs Branch of the FAA requested ECAC to perform an investigation of the feasibility of establishing equipment standards which would lead to discrete channel assignments and improved utilization of the 2.7-2.9 GHz radar band.

OBJECTIVES

The basic objective of this task is to determine practical methods which could be used to improve utilization of the 2.7 to 2.9 GHz radar band, including the application of frequency assignment techniques and evaluation of the influence of equipment characteristics and equipment standards.

APPROACH

The approach taken in the accomplishment of the tasks is as follows:

1. The ECAC data files were used to determine the equipment types and technical characteristics, types of service, and system operational characteristics common to the 2.7 to 2.9 GHz band in the continental United States. These files were augmented for the Los Angeles region by additional information obtained from the Western Regional Frequency Management Office of the FAA. The locations and operating frequencies of

systems operating in a sample dense environment, the Los Angeles area, were also established. An analysis of the interference potential using the current operating frequencies in the sample environment was performed. The results are given in APPENDIX A and SECTION 2.

2. Two files of reported interference cases were explored. These were case reports from the U.S. Air Force Ground Electronic Engineering Installation Agency (GEEIA, now a part of the U.S. Air Force Communications Services) and the interference report file maintained by the FAA headquarters. A summary of these cases was made indicating areas where interference was reported, the cause of interference, how often it occurred, methods used to alleviate interference, and the success of these methods (see APPENDIX B).

3. The relationships between system performance and minimum emission and receiver bandwidths were extracted from the literature. These were analyzed to determine what factors had the primary influence in determining system bandwidths. The information gathered, when coupled with performance requirements and characteristics of hardware to be implemented, would determine the minimum achievable bandwidths. This analysis is presented in APPENDIX C, subsection RELATIONSHIP OF PULSE PARAMETERS TO SYSTEM PERFORMANCE.

4. Data concerning the emission characteristics and specifications for radar output devices was collected from manufacturers, from the literature, and from spectrum signatures. The theoretical relationship between pulse characteristics obtainable with the several output devices and the consequent emission spectrum was developed. The results of this investigation are contained in APPENDIX C, subsection RADAR TRANSMITTER EMISSIONS.

5. An analysis was performed of selected design features, making use of measured data and computerized Fourier analysis techniques, to ascertain their electromagnetic compatibility implications.

6. Frequency assignment techniques were examined for applicability to the problem. The assignment technique identified as applicable to this study is described in APPENDIX D. Off-frequency rejection curves were prepared for the environmental equipment based on measured data; these are reported in APPENDIX E. An automated frequency assignment technique was used to analyze the effects of dual frequency diversity, improved equipment characteristics, and sub-allocation of certain portions of the frequency band, using the Los Angeles area as a test environment. The Radar Spectrum Engineering Criteria of the Office of Telecommunications Policy (OTP) were examined to determine if they would support various frequency channelization considerations.

SECTION 2

ANALYSIS SUMMARY

UTILIZATION OF THE 2.7 TO 2.9 GHz BAND

To establish the background upon which to assess the value of frequency assignment techniques, a survey of the utilization of the 2.7 to 2.9 GHz band was conducted. Considerations of primary interest were the allocation rules governing the band; the principal services accommodated in the band; the population, nomenclature, and technical characteristics of equipments employed to provide these services (current and future); and deployment factors. The survey consisted of a summary of the overall CONUS environment and a detailed study of a test environment, the latter representing a high equipment density condition. (See APPENDIX A).

The following paragraphs present a summary of this topic.

The CONUS Environment

The primary services allocated for this band are aeronautical radionavigation and meteorological aids. The band is used by the FAA for airport surveillance radars (ASR's). The United States military uses this band to support the ASR function of their ground controlled approach systems. The U.S. military-operated ASR's will be referred to as GCA's. Other constituents of the band provide meteorological and radiolocation services. All of the radars are ground-based except for one type of airborne radiolocation (surveillance type) radar, of which several hundred exist.

TABLE 2-1 summarizes data for the radars in CONUS. Certain operations of the radiolocation service will operate temporarily in the 2.7-2.9 GHz frequency band (Reference 2). Electronic countermeasure (ECM) missions (both air and seaborne) are conducted in the band, primarily against the Military (Aerospace Defense Command) radars.

Conventional magnetron oscillators are the most commonly used output devices. These devices offer far less spectrum economy than do coaxial magnetrons and klystrons, both of which are available and are capable of providing the required power.

A coaxial magnetron has been developed for use in the AN/APS-20 airborne acquisition radars. Comparison of Figures 2-1 and 2-2 illustrates an advantage of employing

TABLE 2-1

USERS OF THE 2.7-2.9 GHz BAND IN CONUS

SERVICE	AGENCY	FUNCTION	DEPLOYMENT	NO OF NOMENCLATURES	TYPICAL PEAK POWERS (kW)	NO. OF EQUIPMENT ESTIMATED OPERATIONAL
Aeronautical Radionavigation	FAA and Military	Airport Surveillance (search)	ground	33	500	337
Meteorological	Weather Bur and others	Weather (search)	ground	7	50 & 500	98
Radiolocation	Military	Height Finding	ground	2	5000	154
		Tracking	ground	2	250-2000	92
		Acquisition	ground	2	750	22
			airborne	1	2000	several hundred

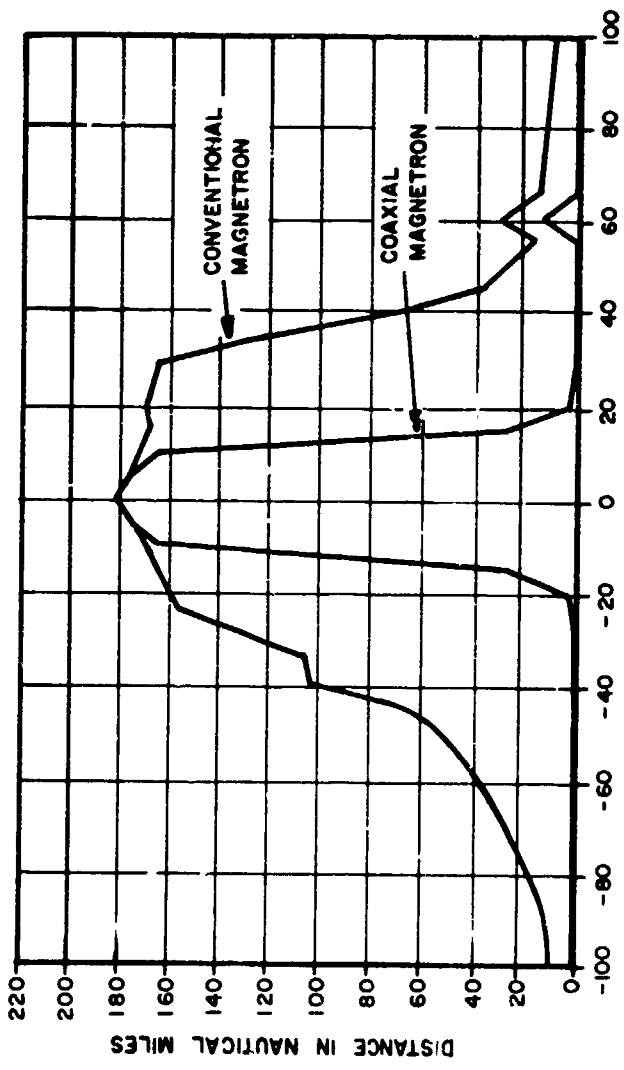

Figure 2-1. Frequency-Distance Curves AN/APS-20 Transmitter vs. ASR-7 Receiver for $I/R'_s = 0$ dB at −10 dB Mutual Antenna Coupling

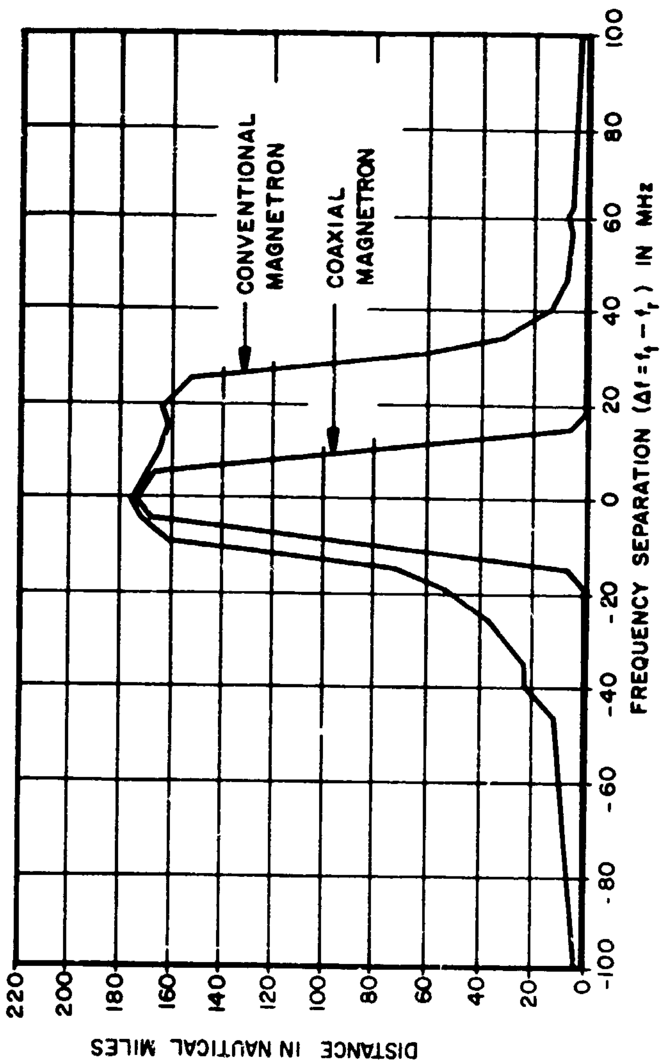

Figure 2-2. Frequency Distance Curves AN/APS-20 Transmitter vs. ASR-7 Receiver for I/R'_s = 10 dB at −10 dB Mutual Antenna Coupling

this new type of magnetron in these radars. Shown on these figures are frequency-distance (F-D) curves for both conventional and coaxial magnetrons. The figures are plots of the minimum frequency-distance separation an ASR-7 radar must maintain so that peak interference from the AN/APS-20 ( ) radar is kept below a specified interference threshold. To illustrate the difference between the characteristics of the magnetrons, consider an AN/APS-20 situated approximately 40 nautical miles from an ASR-7, and a peak interference to single-pulse sensitivity ratio (I/R'_s) threshold of 10 dB for mutual antenna coupling of −10 dB (Figure 2-2). The AN/APS-20 ( ), with its current conventional magnetron, would be required to operate at least 35 MHz above the ASR-7. However if a coaxial magnetron were used, the frequency separation could be reduced to 14 MHz, thus gaining an additional 20 MHz or 10% of the 2700-2900 MHz band. This estimate is conservative, since the increased frequency stability provided by the coaxial magnetron was not considered in the example.

The Test Environment

To study in detail the frequency utilization of the 2700 to 2900 MHz band, a specific test environment was chosen. With the concurrence of the FAA an area within 200 miles of Los Angeles, California was selected. The area was considered a good test sample because of the relatively high density of users in the band.

The number of ground-based radars found to be operating within 200 nautical miles of nine major cities are shown in Figure 2-3. It is seen that within the New York, N.Y. or Philadelphia, Pa. areas the number of radars is greater than in Los Angeles. However, within the New York and Philadelphia areas the radars are distributed more evenly within the environment than in the Los Angeles area. The Atlanta, Ga. area also has a number of radars comparable to Los Angeles including a relatively high density of meteorological radars.

Within the Los Angeles area there were found to be 28 ground-based radars operating in the frequency band under study. Their locations and current operating frequencies (Figure 2-4) as well as other pertinent characteristics were established.

The degree of interference between the 28 systems was estimated by calculating the ratio of received interference power to single-pulse receiver sensitivity (I/R'_s).

In making the calculations, the following assumptions were made:

1. Radars operating at the primary frequencies ("Operating Frequency A" in Figure 2-4).
2. Antenna gains of −5 dB for each antenna.

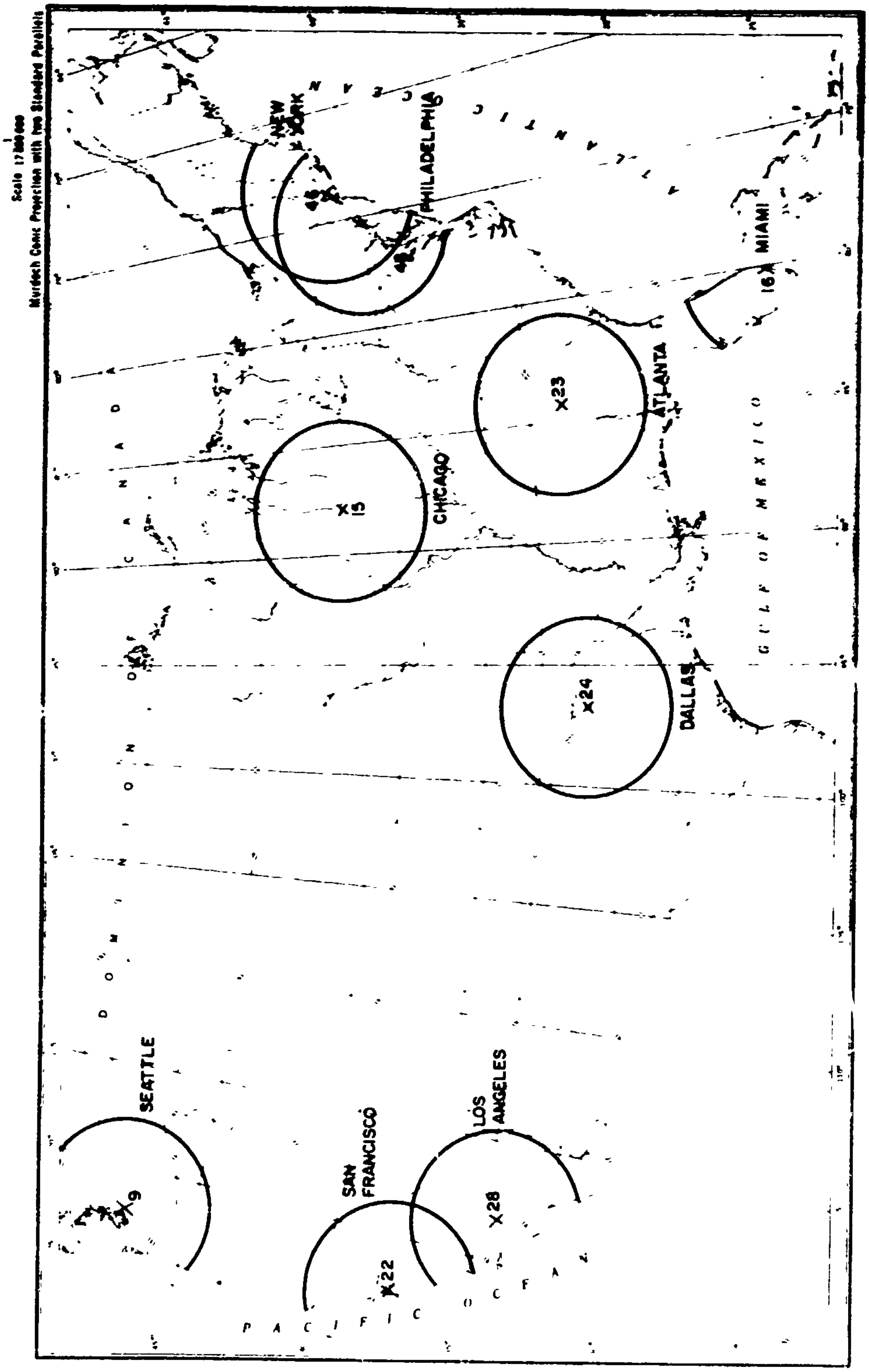

Figure 2-3. 2.7-2.9 GHz Band Radars Within 200 nmi of Nine Cities

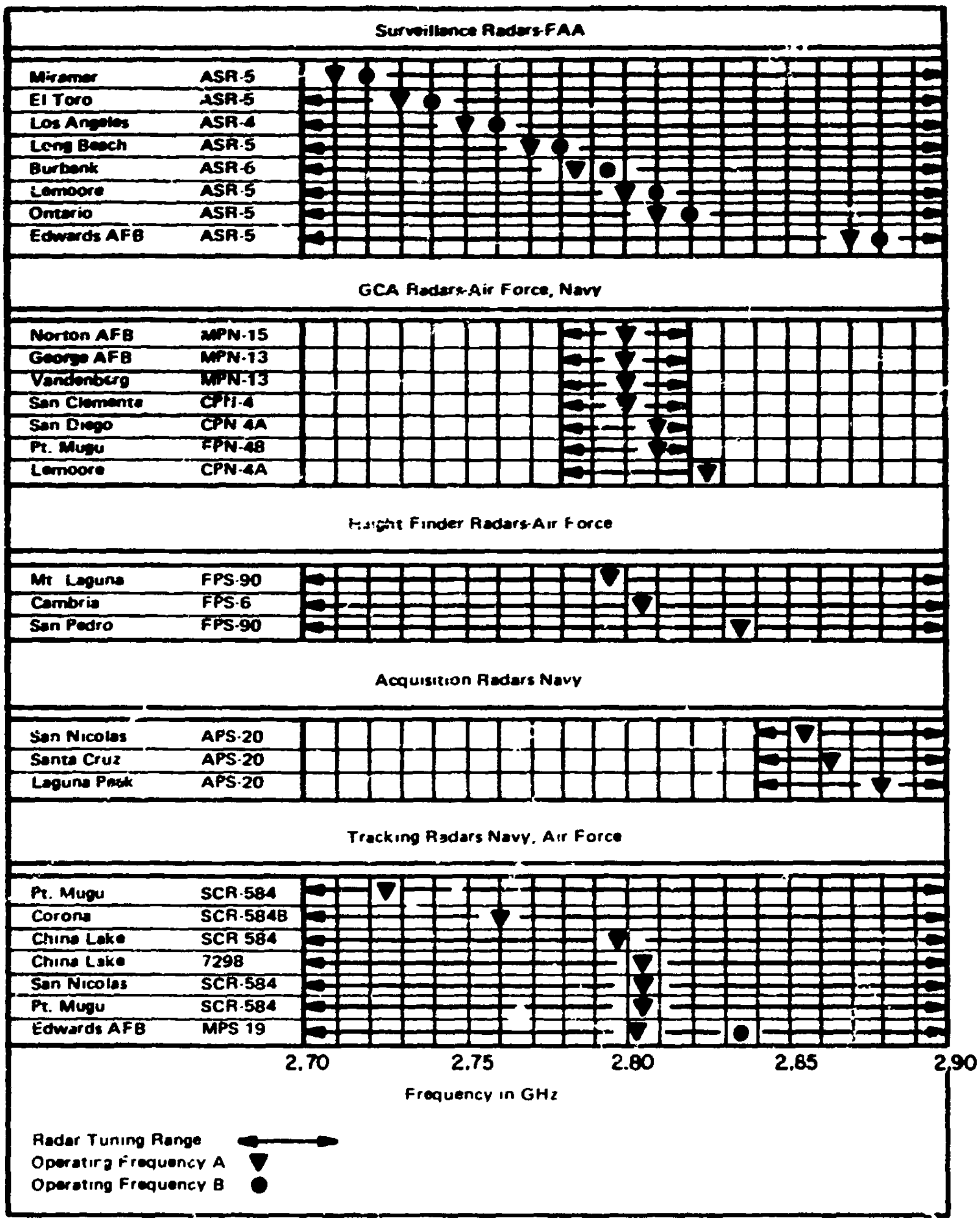

Figure 2-4. Frequencies Of Ground Radars In The Los Angeles Area

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3. Rough earth propagation loss conditions, using the 95% reliability hourly median loss.
4. Other losses, such as polarization loss, transmission line losses, negligible.
5. No frequency drift.

The results, shown in TABLE 2-2, list 35 cases where the interference threshold of $I/R'_s = 0$ dB was exceeded for an assumed mutual antenna coupling of −10 dB.

The results of calculations indicate that most of the FAA ASR's should operate without significant interference. This situation was confirmed by the area frequency coordinator.

However, calculations resulted in a prediction of significant interference for the Lemoore ASR-5 radar (TABLE 2-2, case 11). The Western Area Frequency Coordinator stated that the two radars at Lemoore did not operate simultaneously; in fact the AN/CPN-4A has not been used for some time. Time sharing or joint use of radars has eliminated some of the more serious problems that have been experienced in the past, e.g., the case of the Lemoore radars and the case of the WSR-57 weather radar formerly at Catalina Island. The compatible operation of other military radars is being accomplished through time sharing also. Some of the more serious potential interference situations involve tracking radars. These radars are operated infrequently and are required to coordinate before doing so.

Experience has shown that interference occurring only occasionally and for short durations is commonly not resolved and to that extent tolerated by the operator. Some of the factors that cause interference to occur in an apparently random fashion are:

1. *Frequency drift or frequency error.* This is an important consideration, especially in the case of transmitters employing conventional magnetrons, which can drift significantly.
2. *Prolonged main-beam illumination.* Narrow-beam tracking radars or narrow-scanning height-finders can occasionally illuminate a victim for an extended period.
3. *Nonadherence to designated operating frequencies.* The operating frequency of a previously compatible system may change because of a malfunction or be changed intentionally for operational purposes. Frequency changes may be tried to eliminate interference. Changing frequency without consulting the appropriate FAA Regional Frequency Management Officer (Reference 1, Annex D) will often compound the interference problem.
4. Coupling combinations of antenna mainbeams, sidelobes and backlobes, when suitably oriented, can cause wedges of relatively intense interference.

TABLE 2-2

INTERFERENCE TO SENSITIVITY THRESHOLD RATIO COMPUTATIONS FOR POTENTIAL INTERFERENCE COUPLETS IN THE LOS ANGELES AREA FOR THE 2.7 TO 2.9 GHz BAND

Case No.	Victim Receiver	Interfering Transmitter	I/R_s'* (dB)
1.	China Lake (7298)	China Lake (SCR-584)	32
2.	China Lake (7298)	Edwards AFB (AN/MPS-19)	1
3.	China Lake (7298)	George AFB (AN/MPN-13)	21
4	China Lake (SCR-584)	China Lake (7298)	27
5	Edwards AFB (ASR-5)	Edwards AFB (AN/MPS-19)	4
6	Edwards AFB (ASR-5)	Santa Cruz (AN/APS-20)	13
7	Edwards AFB (AN/MPS-19)	China Lake (7298)	15
8.	El Toro (ASR-5)	Burbank (ASR-6)	3
9	El Toro (ASR-5)	Long Beach (ASR-5)	1
10	George AFB (MPN-13)	China Lake (7298)	30
11	Lemoore (ASR-5)	Lemoore (AN/CPN-4A)	26
12	Long Beach (ASR-5)	Corona (SCR-584B)	9
13	Long Beach (ASR-5)	San Pedro Hill (FPS-90)	4
14	Miramar (ASR-5)	El Toro (ASR-5)	5
15	Norton AFB (AN/MPN-15)	Ontario (ASR-5)	3
16	Ontario (ASR-5)	San Pedro Hill (AN/FPS-90)	4
17	Pt. Mugu-II (SCR-584)	Pt. Mugu (AN/FPN-48)	54
18	Pt. Mugu (AN/FPN-48)	Pt. Mugu (SCR-584)	59
19	Pt. Mugu (AN/FPN-48)	San Diego (AN/CPN-4A)	1
20	Pt. Mugu (AN/FPN-48)	San Nicolas II (SCR-584)	10
21	Pt. Mugu (AN/FPN-48)	Pt. Mugu I (SCR-584)	6
22	San Clemente (AN/CPN-4)	Corona (SCR-584B)	10
23	San Clemente (AN/CPN-4)	San Nicolas (SCR-584)	20
24	San Clemente (AN/CPN-4)	San Pedro Hill (AN/FPS-90)	11
25	Santa Cruz (AN/APS-20)	Edwards AFB (ASR-5)	4
26	Santa Cruz (AN/APS-20)	Laguna Peak (AN/APS-20)	10
27	San Diego (AN/CPN-4A)	Mt. Laguna (AN/FPS-90)	13
28	San Nicolas (AN/APS-20)	Laguna Peak (AN/APS-20)	5
29	San Nicolas (AN/APS-20)	San Nicolas (SCR-584)	29
30	San Nicolas (SCR-584)	Pt. Mugu II (SCR-584)	4
31	San Nicolas (SCR-584)	San Nicolas (AN/APS-20)	47
32	San Nicolas (SCR-584)	San Pedro Hill (AN/FPS-90)	1
33	Vandenberg AFB (AN/MPN-13)	Cambria AFB (AN/FPS-6)	29
34	Pt. Mugu I (SCR-584)	Pt. Mugu (AN/FPN-48)	7
35	Pt. Mugu (AN/FPN-48)	Laguna Peak (AN/APS-20)	18

* Peak interference to single pulse sensitivity ratios for −10 dB mutual antenna coupling

Summary of RFI Cases

A survey was made of documented interference reports in the 2.7 to 2.9 GHz band in order to gain insight into the most common causes of interference, and into the methods used to alleviate them. A tabulation of the reported information is given in APPENDIX B, along with a discussion of the sources, the extent of the interference, and of the methods used to combat interference. However it should be noted that since most cases surveyed covered a short time frame, and since a small percentage of the actual interference experienced in the field is usually documented (Reference 3), the severity of the problem may not be indicated by the number of documented cases.

The most frequently reported cause of interference was from ECM, both active and passive (chaff), directed against ADC radars in the band. Relegating the ADC radars to a separate part of the band would help alleviate the active jamming threat. Apart from ECM, the high-powered ADC height finders appear to be the most frequent cause of interference.

Changing the operating frequency was the method most frequently used to reduce the interference problems encountered. As could be expected, this was seldom effective for the ECM interference problem, or for the situation where the source of interference had not been identified. In radar-to-radar interference, for all cases involving a height-finder, the height-finder frequency was changed.

A small minority of the cases involved interactions between occupants of other bands and the 2.7 to 2.9 GHz band radars. In all of these cases, the radars in the 2.7 to 2.9 GHz band were the sources of the interference and the victim was in a lower frequency band.

EQUIPMENT FACTORS AFFECTING COMPATIBILITY

System Performance and Pulse Parameters

The signal characteristics of a radar system are selected to achieve certain performance requirements. Radar compatibility within the spectrum is directly related to the signal characteristics, since they also determine the amount of spectrum used by the system and susceptibility characteristics of the system. Therefore, relationships among pulse signal parameters, system performance, and the EMC characteristics of a system must be understood. System performance characteristics such as range resolution, range accuracy, detection in white Gaussian noise, detection in clutter, and signal bandwidth are related to the signal parameters. The detailed relationships are presented in APPENDIX C.

The signal parameters directly affecting system performance are pulse width, pulse rise time and fall time, and signal energy. The range resolution achievable with a rectangular pulse, as determined by examining its autocorrelation function, is equal to the range represented by one pulse width. For a Gaussian pulse, the resolution is approximately the range represented by 1.5 times the pulse width. Therefore, for a given resolution, a Gaussian pulse would need to be narrower than a rectangular pulse by a factor of 2/3. However, for identical pulse widths, the 3-dB bandwidth of the spectrum produced by a Gaussian pulse is narrower than that produced by a rectangular pulse by the ratio of 2/3. Therefore, the range resolution is proportional to the reciprocal of the 3-dB spectrum bandwidth. This statement is also true for compressed pulse systems where the compressed pulse width must be considered.

The overriding pulse parameters affecting range error are the rise/fall times of the received waveform. For trapezoidal or Gaussian type pulses with comparable rise/fall times, the range accuracy is a function of receiver bandwidth and not of pulse type. It can also be shown (APPENDIX C) that with a given spectral bandwidth, a pulse compression system can achieve better range accuracy than can a conventional pulse system.

For targets not obscured by clutter, maximum theoretical detection range is proportional to the fourth root of the signal energy. To optimize system performance, considering targets obscured by stationary clutter, systems commonly employ MTI processing. The shape of the pulse does not appear to be a significant factor in target detection in clutter when employing MTI processing. Improvement in target detection in certain forms of volume clutter can be realized through the use of pulse compression. Without pulse compression, shorter pulse widths (needed for detection in clutter) with the same peak power result in less transmitter energy and smaller detection range.

System Performance and Receiver Selectivity

The receiver 3-dB bandwidth requirement is also influenced by the system performance requirements. The acceptance bandwidth is usually designed to be larger than the emission bandwidth to allow for pulse-width jitter, frequency instability, and other factors, as discussed in APPENDIX C. A review of the performance requirements for new ASR's revealed that, in order to meet the range accuracy requirement, a theoretical minimum receiver bandwidth on the order of 1 MHz was required. Range resolution dictates a slightly greater emission bandwidth. However, for systems not limited by stringent range accuracy requirements, the use of the longest practical rise times would be most beneficial.

Pulse Shape and Spectra

Fourier transforms of several waveforms were examined. The waveforms produced by magnetrons are essentially trapezoidal waveforms. Systems employing other waveforms such as Gaussian and cosine-squared would require use of klystrons. When comparing the spectra of various waveforms to determine which is the most beneficial with respect to EMC, the comparison must consider system performance. That is, the spectra being compared should represent waveshapes having equal pulse widths, rise times, and energy. However, for systems not limited by stringent range accuracy requirements, use of the longest practical rise time would be most beneficial.

Shown in Figure 2-5 are the relative spectral levels for five waveforms. The parameter K is the ratio of pulse width to rise time; τ is the half-amplitude pulse width in microseconds. As an example, consider the case where pulse width, rise time and energy have been set by performance requirements, and K is assumed to be ten. Comparing the trapezoid waveform with the cosine-squared trapezoid*, an improvement of approximately 20 dB may be realized at a frequency separation equal to $30/\tau$ from the carrier.

Figure 2-6 indicates some of the benefits that can be realized by using pulse compression. The curve labeled (τ = 6, D = 12), where τ is the transmitted pulse width and D is the compression ratio, indicates the same range accuracy, detection and resolution capabilities as does the trapezoid (τ = 0.5, K = 10), but shows an improvement in spectral levels of up to 30 dB. The (τ = 6, D = 50) pulse yields a better than four-to-one improvement in range resolution compared to that of the trapezoid waveform, as well as improvements in detection in volume clutter (at the same energy levels) and in range accuracy. In addition, spectral levels beyond a few MHz from the carrier are greatly reduced. From this, it can be seen that a narrow-band receiver requiring 22 dB rejection from a radar could be tuned as close as 4 MHz if that radar employed pulse compression, while a 7-MHz separation would be required with the trapezoid. (Twenty-two dB was the amount of attenuation required to eliminate interference in 50% of the interference paths in the test environment requiring some off-frequency rejection in order to achieve $I/R'_s \leq 0$ dB for −10 dB mutual antenna coupling.)

The sharper fall-offs exhibited by pulse compression emissions are a function of the compression ratio; the higher the compression ratio (D), the sharper the roll-off. This effect is illustrated in Figure 2-7, where spectra of two waveshapes providing the same performance are given, but with differing compression ratios.

Emission Characteristics of Output Devices

The emission characteristics of the output devices available for use in this frequency

* A cosine-squared trapezoid is defined here as a flat-topped time waveform whose leading and trailing edges are characterized by cosine-squared curves

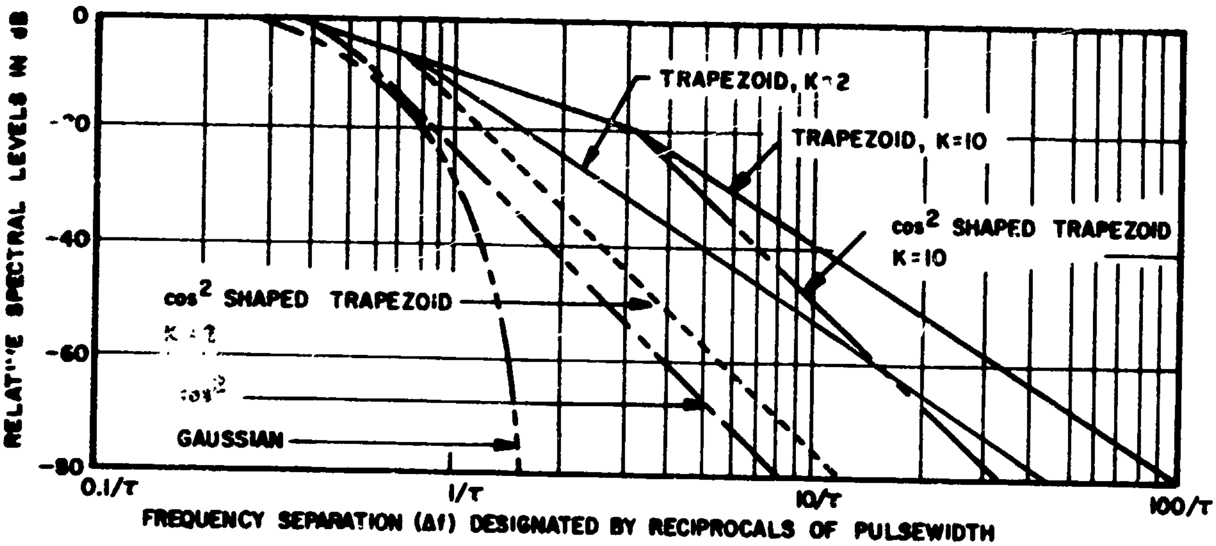


Figure 2-5. Fourier Transforms of Waveshapes

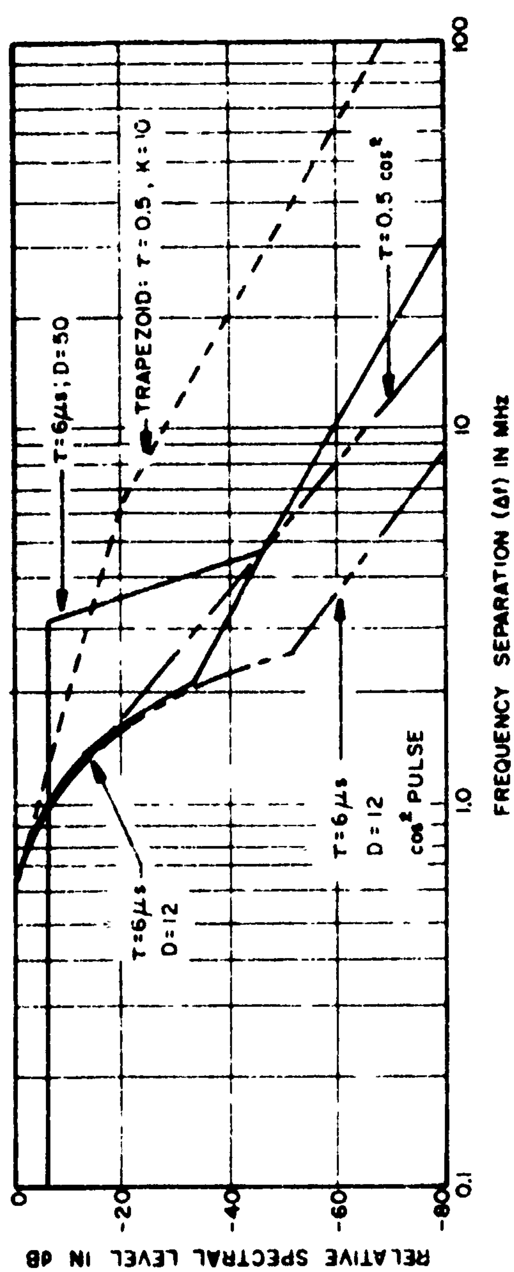


Figure 2-6. Spectra of Pulse Compression and Trapezoid Waveforms

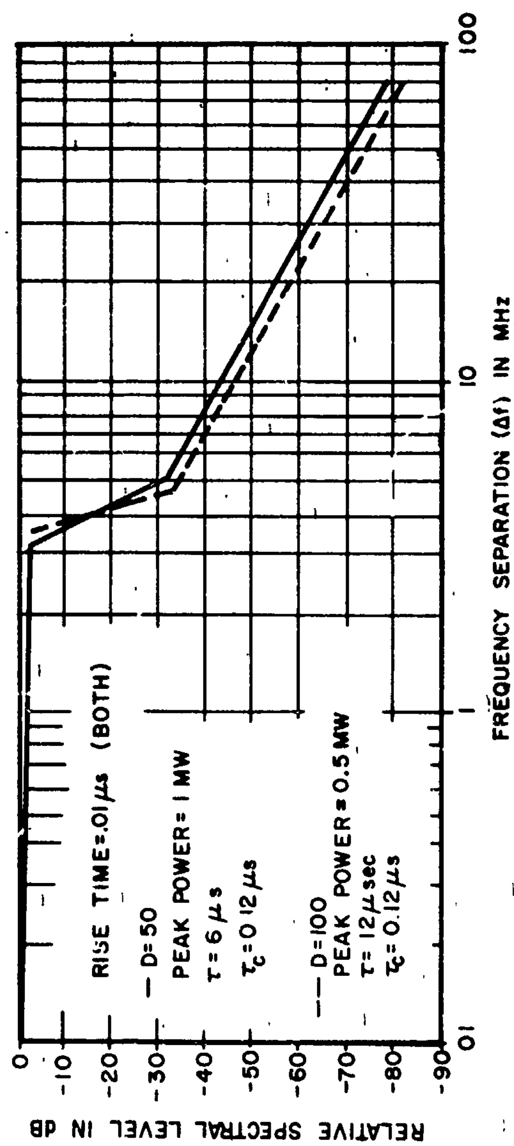


Figure 2-7. Pulse Compression Spectra with Dispersion Ratio As Parameter

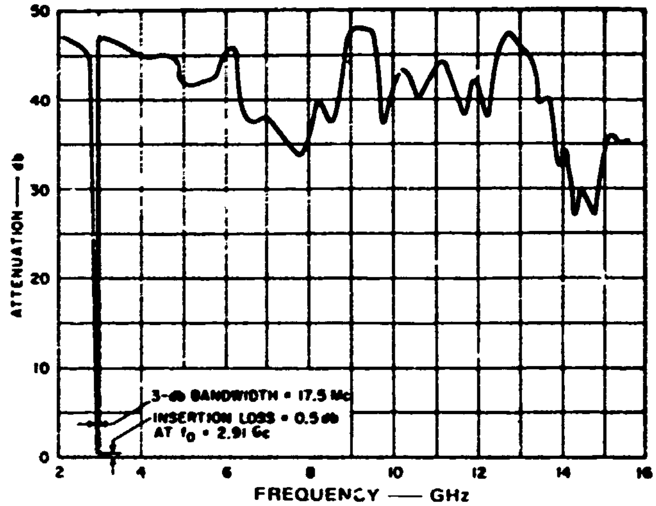
band are controlling factors in establishing the spectrum bandwidth occupied by a system. The equipments presently operating in the band are equipped with conventional magnetrons. The relatively poor stability and asymmetric bandwidth characteristics of these tubes require relatively broad channels, resulting in less than desirable utilization in dense environments. The recent development of the coaxial magnetron for use in this frequency band offers substantial improvements in frequency utilization due to its improved emission spectral characteristics. The frequency stability of the coaxial magnetron tube shows improvement over the conventional magnetron by a factor of ten. The coaxial magnetron also provides a reduction of sideband energy by a factor of ten, the results of a higher Q cavity.

Systems employing klystron amplifiers have emission characteristics significantly different from those employing either type of magnetron. The use of a klystron amplifier permits RF signal generation, modulation and filtering at low power levels. The frequency stability for this type of transmitter can be more accurately maintained, through use of precision crystal oscillators, providing excellent long-term and short-term stability. Pulse waveforms can be shaped through the use of low-power pulse-forming circuitry.

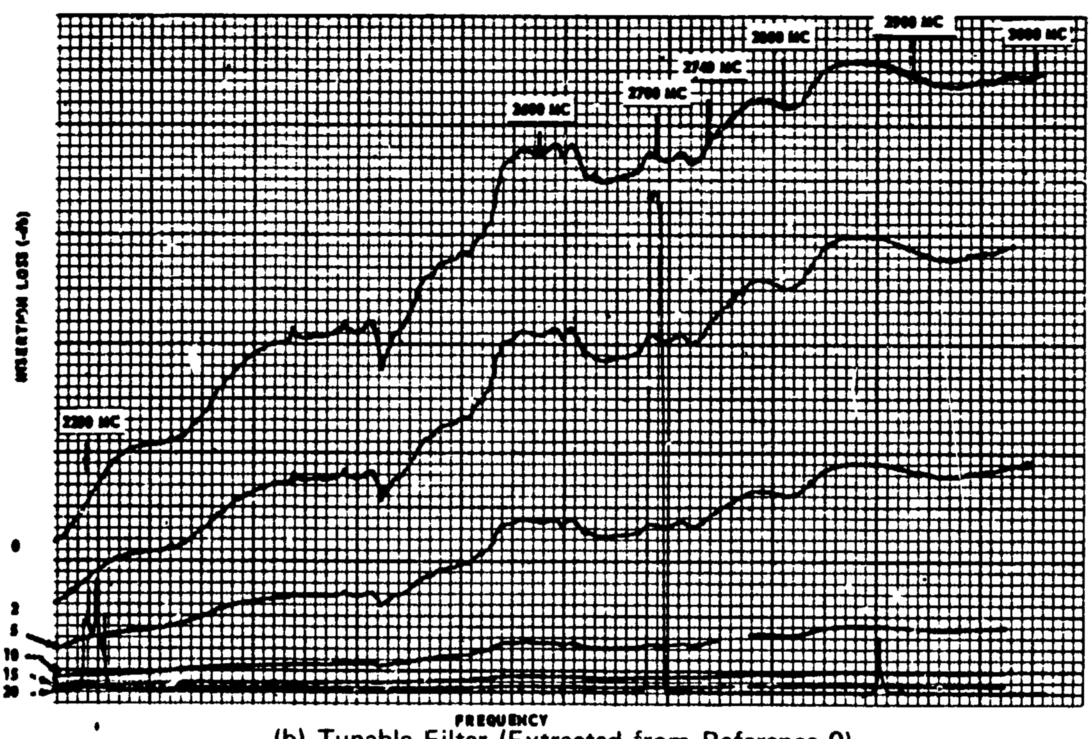
The spurious emission characteristics associated with each type of output tube are given on TABLE 2-3. (See also References 4, 5, 6 and 7, and APPENDIX C.) The klystron is superior in all respects, with the exception of the harmonic levels. Unless the 2nd harmonic is attenuated in the transmitter path between the output device and the antenna output, introduction of klystrons to the 2.7 to 2.9 GHz band may result in interference to equipments in the 5.4 to 5.8 GHz frequency range.

The frequency selectivity characteristics of two bandpass filters that can be used in the 2.7 to 2.9 GHz band are described in Figure 2-8. Used with a conventional magnetron, these filters could provide sideband and spurious-rejection characteristics similar to those of a coaxial magnetron.

Reference 8 describes (also Figure 2-8a) a nontunable filter constructed of two resonators with open walls. A low power version of this filter has been constructed. The power-handling ability of this filter is nominally the same as that of corresponding filters using conventional cavity resonators. The reference indicates that the measures used to increase the power-handling ability of filters with conventional resonators are also feasible with this filter.



(a) Fix-tuned Filter (Extracted from Reference 8)



(b) Tunable Filter (Extracted from Reference 9)

Figure 2-8. Attenuation Characteristics of 2.7-2.9 GHz Frequency Band Filters

TABLE 2-3

ESTIMATED SPURIOUS EMISSION LEVELS, RELATIVE TO FUNDAMENTAL, IN dB

	Separation from Center Frequency				
Tube Type	20 MHz	200 MHz	2nd Harmonic	3rd Harmonic	Non-Harmonic Spurious Level (>200 MHz)
CONVENTIONAL MAGNETRON	−25 to −45	−60 to −70	−65	−60	−80
COAXIAL MAGNETRON	60 to −80	−100	−70	−80	110
KLYSTRON	(Dependent on Pulse Shape)	−100	−30 to −35	−40	100

Reference 9 describes (also Figure 2-8b) a tunable nonreflecting bandpass filter. It includes two identical 3-dB sidewall couplers, two high power RF terminations and a pair of identical 4-cavity bandpass filters – these filters are being used in some 2.7 to 2.9 GHz band radars.

More detailed treatments on filters suitable for use in high power microwave transmitting systems are contained in References 6, 10 and 11. See APPENDIX C also.

Radar Standards and Emissions of Output Devices

Radar standards (spectrum engineering criteria) were adopted by the Office of Telecommunications Policy (OTP) in July, 1971 (APPENDIX F). These standards apply to emission spectral levels, antenna patterns, frequency stability (tolerance), tunability, receiver selectivity, and field frequency measurement capability.

Standards on radar emission spectral limits are established by calculating two-slope lines which describe upper bounds relative to the maximum power spectral level of the radar. For an 0.8 μs pulse width (K = 10), a typical pulse employed in the band, the maximum 40-dB bandwidth is 30 MHz. The minimum suppression at ± 150 MHz from the carrier must be such that the absolute average power spectral level does not exceed –31 dBm/kHz (a minimum of 40 dB suppression must be maintained however). For a typical ASR (1200 pps) the suppression is 58 dB with respect to the maximum spectral level.

Data applicable to radars in the environment (exclusively conventional magnetron radars) were examined to determine the spectral emission levels exhibited. The spectra shown in Figures 2-9 through 2-12 present the most comprehensive sets of data available for the radars in the test environment. They were extracted from spectrum signatures and are estimated to approximate radars common to this study, which employ the same magnetron and pulse characteristics. For further discussion of this data, see APPENDIX E.

Also plotted on the figures are the minimum allowable suppression levels set by the standard. The standard limits are a function of duty cycle; as a result some radars are indicated on the figures twice, due to their ability to operate at various pulse-repetition frequencies. It is seen that, due to the emission characteristics of conventional magnetrons below the tuned frequency, none of the radar emissions examined complies with the standards. The difference-frequency of the spectrum at the 40-dB level exceeds the value required by the standard The slope of these magnetron spectra below the 40 dB level, however, does approximate closely the fall-off required by the standard. If the reference frequency and the bandpass were to be shifted off center to compensate for the asymmetry of the spectra, the 40 dB difference-frequency criteria of the standard could be met. The

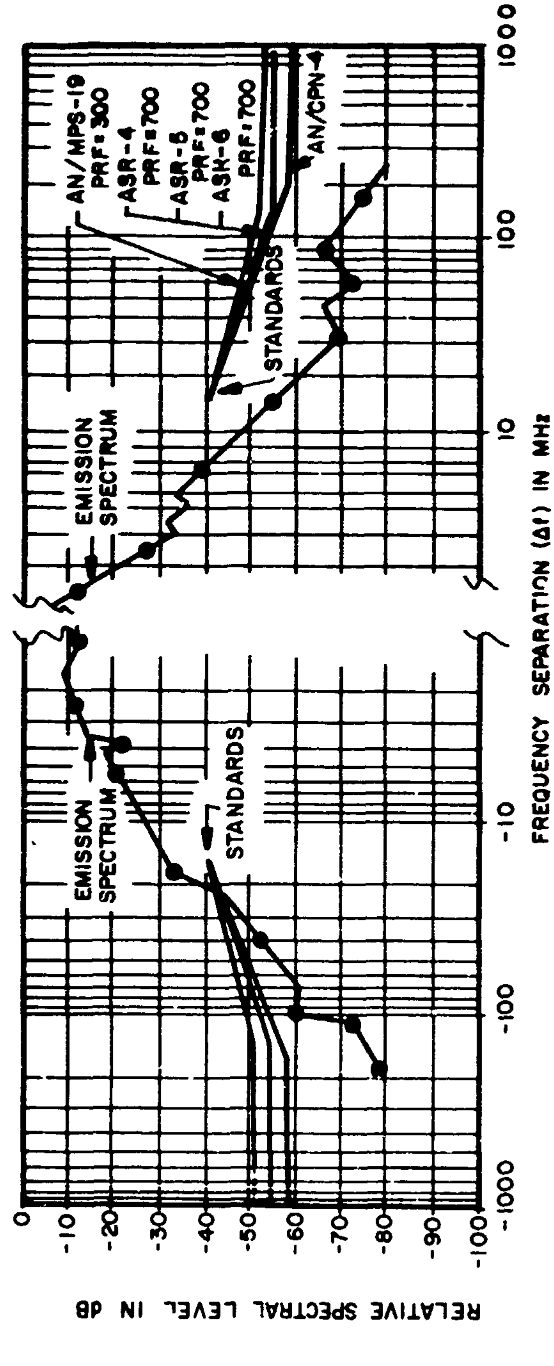


Figure 2-9. Representative Spectra of AN/MPS-19, ASR-4, ASR-5, ASR-6, and AN/CPN-4

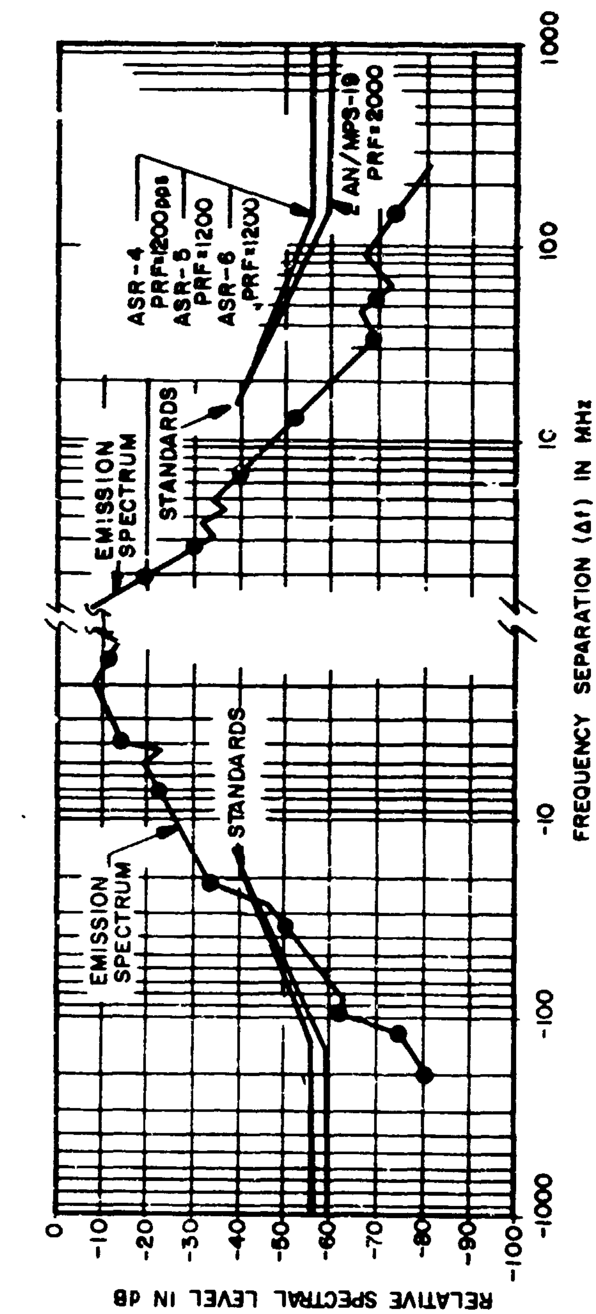


Figure 2-10. Representative Spectra of the ASR-4, ASR-5, ASR-6, and AN/MPS-19

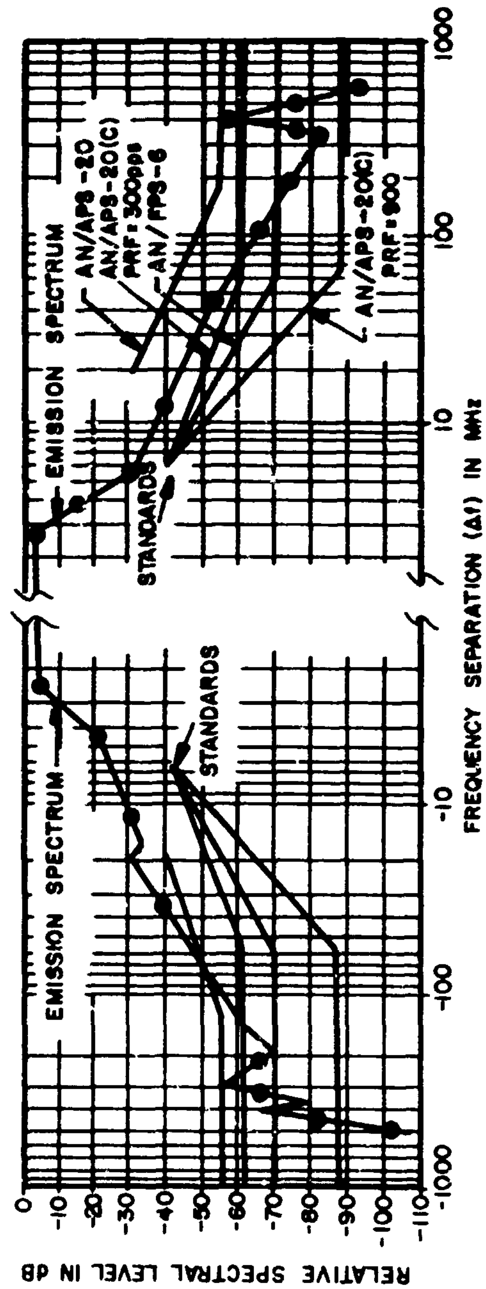


Figure 2-11. Representative Spectra of the AN/APS-20, AN/APS-20 (C) and AN/FPS-6

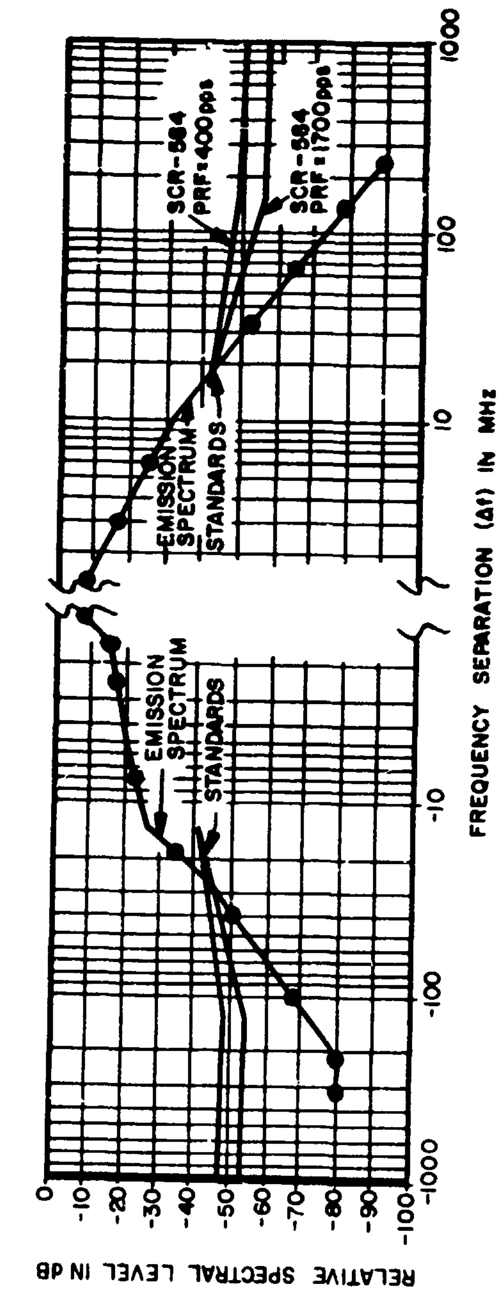


Figure 2-12. Representative Spectra of the SCR-584

effect of not centering the spectrum in the middle of the standard bandpass is shown in Figure 2-13; this manipulation has been applied in the past with MIL-STD-469. It can be seen that some magnetrons may be made to meet requirements if this "sliding" is allowed. This practice would imply that the asymmetry of a magnetron spectrum is unimportant in terms of EMC; this, of course, is not true.

To illustrate the effect of this asymmetry on spectrum management, consider the problem of assigning the closest possible frequencies to two identical conventional magnetron radars (Figure 2-14). The receiver of each radar is tuned to the frequency corresponding to the peak of the emission spectrum. As frequencies F_1 and F_2 are made to approach each other, receiver R_1 reaches its interference threshold, establishing the minimum frequency separation. At this separation, interference in receiver R_2 is still well below threshold. The minimum frequency separation would be unchanged if the high spurious levels below the carrier appeared on both sides of the carrier frequencies. For frequency management purposes, it is equivalent to having to tolerate wider bandwidths, which consume more spectrum space.

Figure 2-15 compares the emission spectrums of three tube types with the OTP standard. It is seen that the conventional magnetron does not meet the standard. Klystrons and coaxial magnetrons have been manufactured for use in this band. Though measured data were not available for these devices operating in this band, data on similar devices using other bands show that the klystron and coaxial magnetron can comply with the standard. Calculated spectra, based on manufacturers' data (APPENDIX E), indicate levels well within the proposed standard. Enforcement of the standard may require the use of these tubes in this band.

Emission Standards and the Environment

The effectiveness of changes in spectrum standards can be examined by evaluating their influence on deployment considerations as for example the effect of emissions of varying levels on required rejection. Cosite, near-site, line of sight (LOS), and beyond line of sight (BLOS) deployments were evaluated. Assuming 400 kW peak transmitted power, trapezoidal (0.5μs K = 10) pulse, mutual antenna gain of −10 dB, receiver single-pulse sensitivity of −99 dBm, PRF = 1000 pps, antenna heights of 30 ft., and separation distances of 1/6, 1, 10, 20 and 30 nautical miles over smooth earth, required off-frequency rejection values and minimum frequency separations were calculated. The results are presented in TABLE 2-4 and are discussed in the following paragraphs.

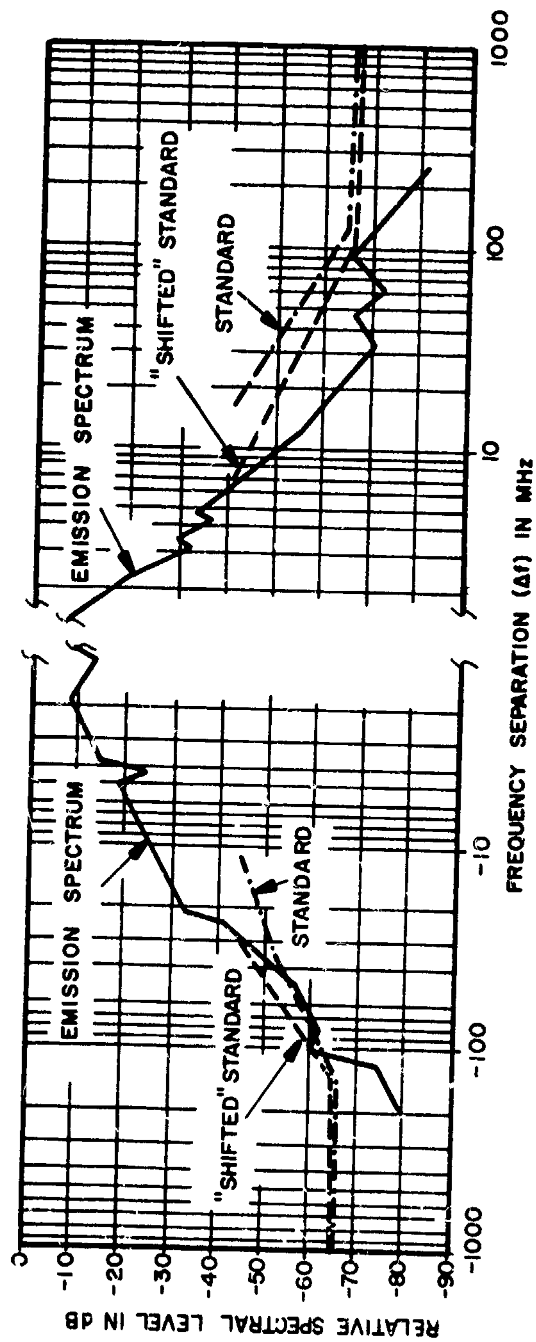


Figure 2-13. Effect of not Centering Standard on Emission Carrier Frequency

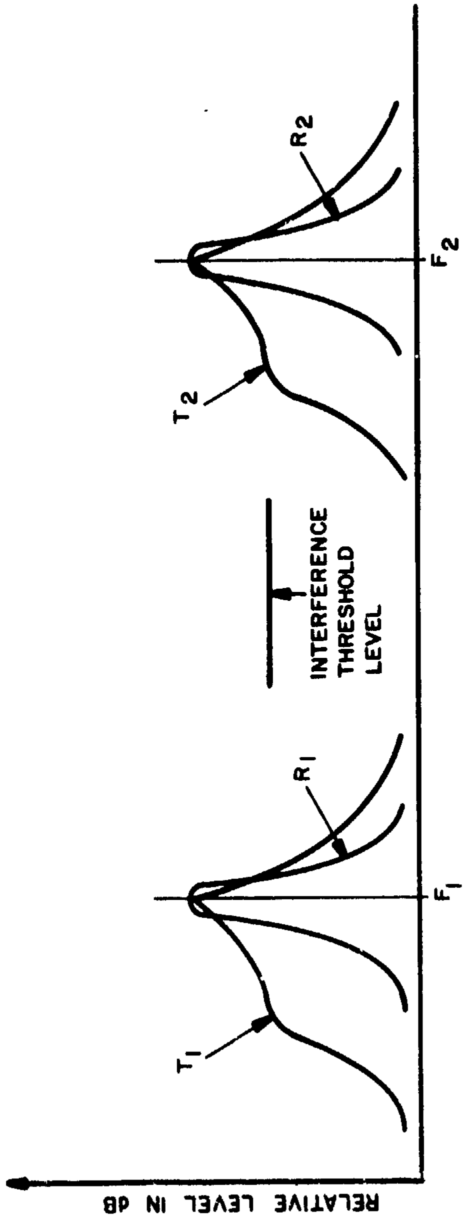


Figure 2-14. Emission Spectra and Receiver Selectivities of Two Conventional Magnetron Radars

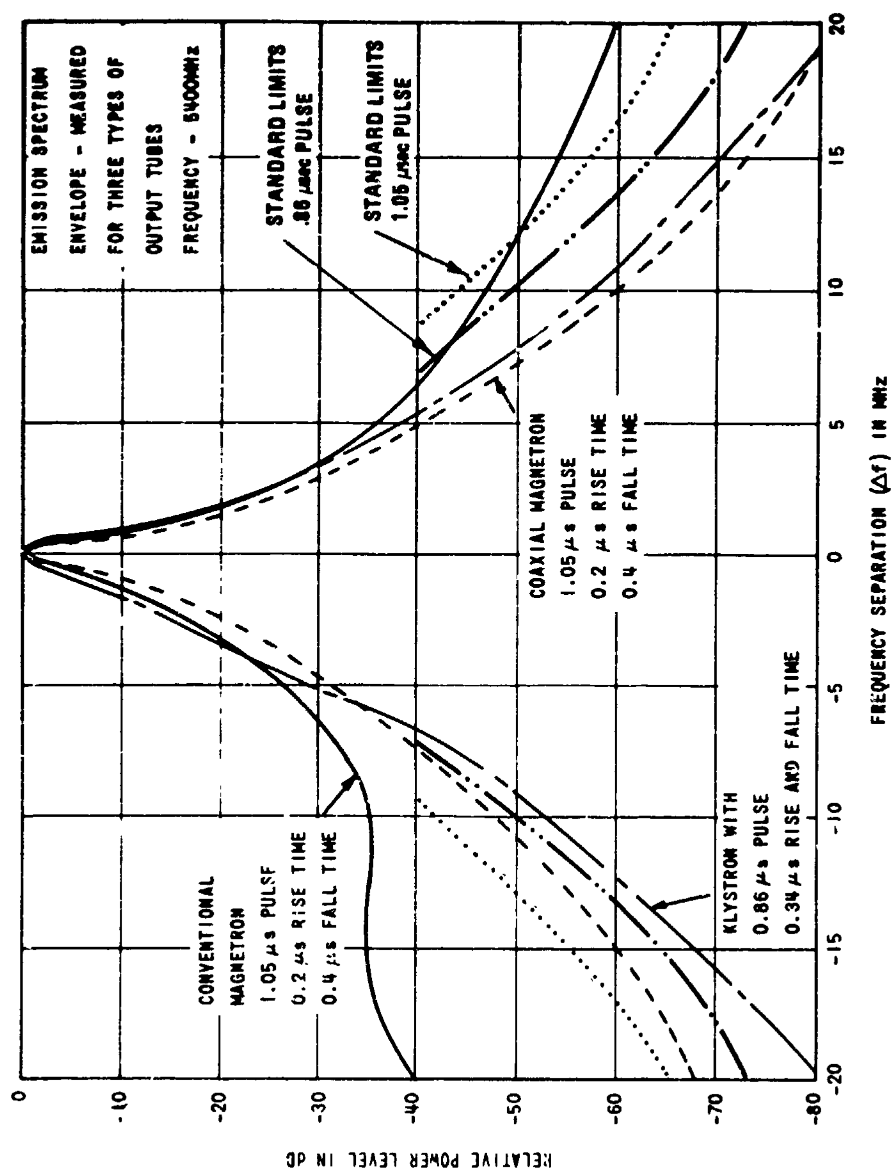


Figure 2-15. Emission Spectrums

TABLE 2-4

ESTIMATED OFR AND ΔF FOR VARIOUS SEPARATIONS

		MINIMUM ΔF (MHz)		
SEPARATION	REQUIRED OFR *	EQUIP. MEETING MIN. REQS. OF OTP STANDARD	CONVENTIONAL MAGNETRON	KLYSTRON **
COSITE (1/6 nm)	85 dB	impossible	>200	>50
NEAR-SITE (1 nm)	70 dB	>150	>100	25-30
LOS (10 nm)	50 dB	50-100	30-40	20-25
BLOS (20 nm)	20-40 dB	21	10-30	7-20
BLOS (30 nm)	5-20 dB	21	3-10	3-10

* The required OFR is that rejection required to reduce I/R'_s to $\leq$ 0 dB for mutual antenna coupling of −10 dB.

** Minimum ΔF assumes klystron with trapezoidal waveform, K = 10. Smaller ΔFs could be achieved with slower rise times or additional waveform shaping, e.g. cosine-squared trapezoid.

The distribution of the OFR requirement to reduce the I/R's at each of the radar receivers in the Los Angeles sample environment is shown in Figure 2-16. Of the 784 transmitter-receiver couplets comprising the 2700-2900 MHz radar environment only the 252 which had I/R's greater than zero, at a mutual antenna coupling level of −10 dBi, are represented on the histogram in Figure 2-16.

The following discussion relates the OTP standard and the emission characteristics of improved output devices to the siting situations in TABLE 2-4 and their relative occurrence in the test environment. The discussion is reflected in the suggestions contained in the paragraph RADAR STANDARDS at the end of SECTION 2.

BLOS Separations. Approximately 88% of the interactions in the test environment require OFR's of less than 40 dB to achieve $I/R'_s \leq 0$ dB for mutual antenna coupling of −10 dB. The standard identifies the frequency limit for the 40 dB rejection level. The frequency limit is a function of the pulse width and rise time. Because of the high percentage of interactions in this range of OFR requirements, advantages in increasing spectral roll-off down to at least 40 dB are obvious. The most desirable limit can be realized by employing the smallest pulse-width-to-rise-time ratio that will support system performance requirements. The OTP standard is such for the 40 dB frequency limit, however, that increased spectral roll-off can be achieved only through pulse shaping, or equivalently, transmitter filtering.

LOS Separations. Twenty-six cases of LOS interactions are present in the test environment requiring on the order of 50 dB rejection by off-tuning to achieve $I/R'_s \leq 0$ dB for mutual antenna coupling of −10 dB. Were the typical ASR to just meet the standard, 50 to 100 MHz frequency separations would be required. Some degree of interference would then be expected if more than 2 or 3 of these radars were located within one another's LOS. The addition of dual frequency diversity systems to the environment will also be affected by this permissive requirement. This may be pessimistic, however, since measured emission data on conventional magnetrons indicate that 30 to 40 MHz is the maximum frequency separation required to achieve this level of OFR. Employing klystrons will enable even smaller frequency separations.

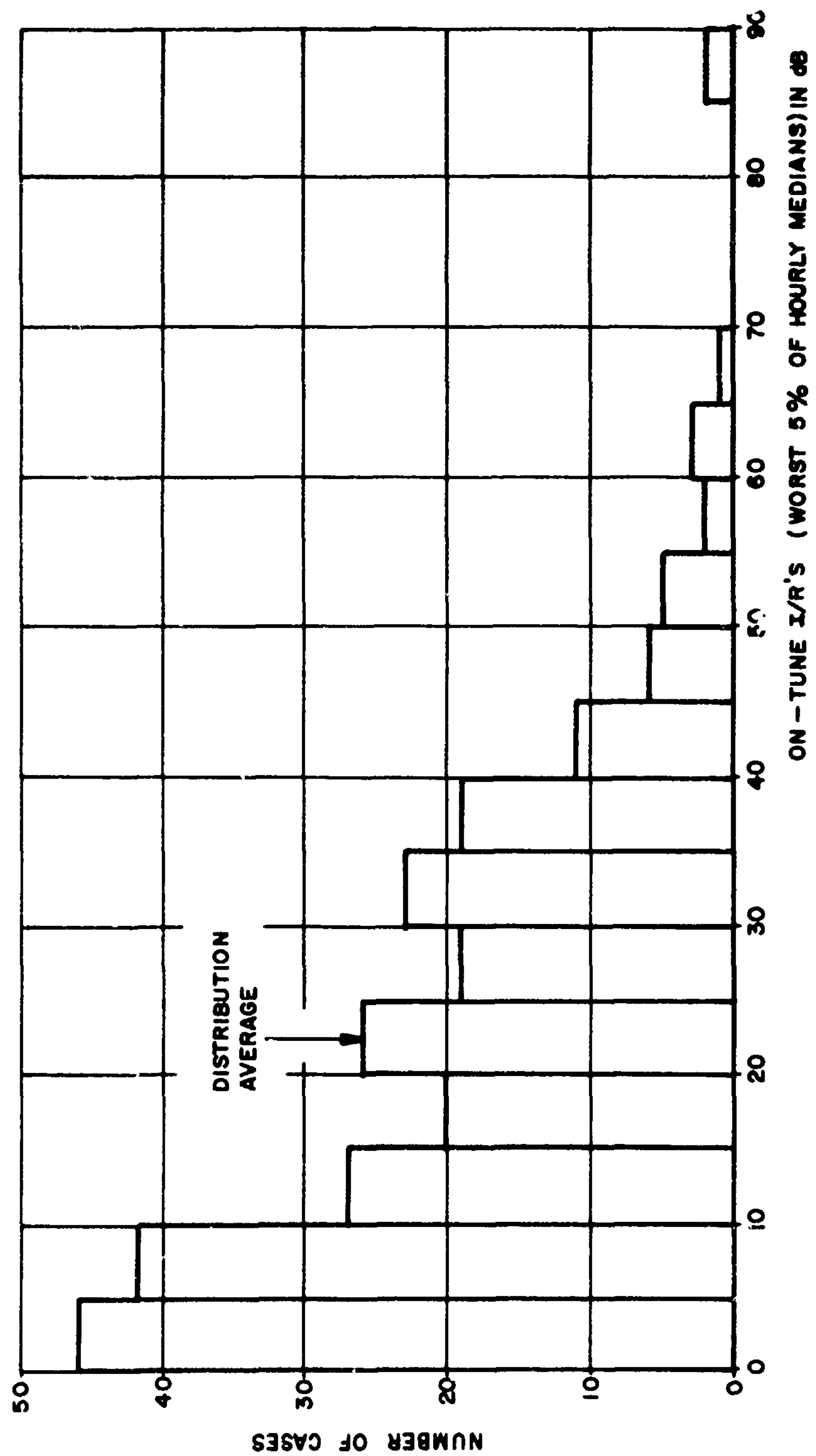


Figure 2-16. Distribution of On-Tune I/R's Relative to Mutual Antenna Coupling of –10 dB for Test Environment

Near-Site and Cosite Separations. It can be seen that near-site and cosite separations represent a small minority of the siting situations. The OFR requirements, to achieve $I/R'_s \leq 0$ dB for mutual antenna coupling of −10 dB, however, are high, suggesting that agreements should be made that equipments in this band should not be situated within 1 to 2 nmi. of each other. If such a requirement exists, special techniques such as time sharing or pulse synchronizing could be instituted. The inconvenience of employing these changes could be avoided if the standard was designed in such manner as to require emission spectra characteristics to conform to expected klystron (or coaxial magnetron) performance specifications. Either bandpass or notch filtering at the victim frequency could also be employed. Notch filtering may be a preferred method should protection such as $I/R'_s \leq 0$ dB under 27 dB mutual antenna coupling be desired. For such protection, 122 dB OFR would be required (85 dB + 37 dB); 37 dB is the difference between −10 dB (coupling used in TABLE 2-4) and 27 dB.

Tuning Capacity and Tuning Increments

An important advantage in the frequency management of a congested radar band is the capability of the radars to tune throughout the band in as unrestricted a fashion as possible. Both the number and the size of the increments attainable are important, since they serve to establish practical channel widths.

Channel Widths. Several factors enter into determination of practical channel widths. One of these factors is whether the band will support the present and projected demands of the users. To estimate the impact of channel width on the spectrum demand of a number of radars, the following analysis was performed. Eight FAA ASR's were selected from the test environment. Their current operating characteristics were assumed, except for the substitution of klystron output tubes, and of a 0.5μs cosine-squared trapezoidal waveform with 50% rise time (K = 2). Figure 2-17 shows the effect of channel width on required spectrum occupancy for the chosen equipment.

It is seen that a minimum of approximately 11 MHz is required to accommodate these systems in the test environment, disregarding frequency drift. If 20 MHz channels are employed, a 60 MHz band is required.

Estimation of Channel Widths. A method of establishing channel width is to identify the frequency separation required to achieve a specified off-frequency rejection including an allowance for carrier frequency inaccuracy.

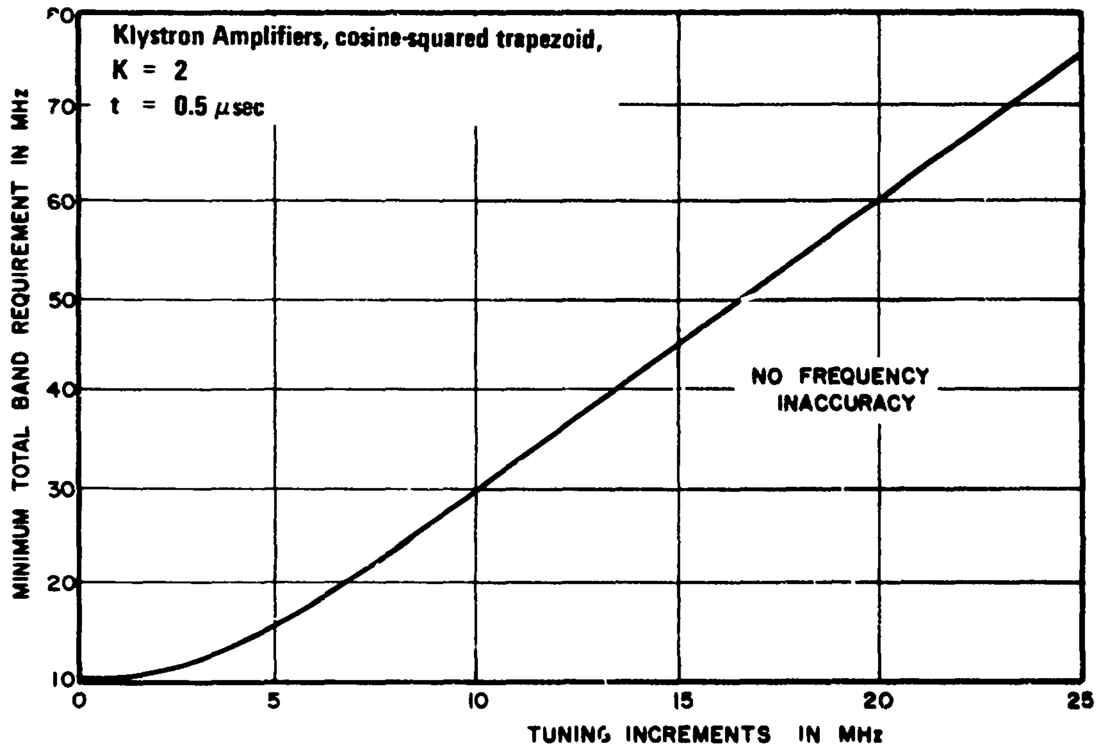


Figure 2-17. Band Occupancy and Tuning Increments for Eight FAA Radars in Los Angeles Environment

Using 22 dB, the average off-frequency rejection requirement in the test environment (a reasonable compromise between unnecessary spectrum utilization and ease of frequency management efforts), as the criterion for a channel width, conventional magnetron radars in this band would require 10 MHz channels while klystrons with trapezoid shaping would require on the order of 7 MHz. Coaxial magnetrons and klystrons employing pulse shaping (cosine-squared trapezoid) would require less than 5 MHz. These estimates were arrived at through the use of Figures E-1 and E-8 (sheets 1, 2 and 3) in APPENDIX E, and assumptions of ± 2 MHz drift for conventional magnetrons and ± 250 kHz drift for coaxial magnetrons and klystrons.

Spectral Roll-Off

A limited analysis was performed that estimated the degree of improvement, in spectrum occupancy, to the eight FAA Los Angeles area radars (see APPENDIX A) realized by the increased spectral roll-off of klystrons as compared to conventional magnetrons. It was specified that a radar would not be assigned a frequency unless $I/R'_s \leq 0$ dB for mutual antenna coupling of −10 dB for all radar pairs. The FAA radars were first assumed to have the improved characteristics of Figure 2-17 (i.e., klystron, cosine-squared trapezoid pulse, K = 2). The frequencies were reassigned employing 1 MHz tuning increments until the minimum total band occupancy was achieved. As indicated on Figure 2-17, this minimum was 11 MHz. The process was then repeated with the assumption that the radars had the emission and reception characteristics of the ASR-6 (see APPENDIX E). The result (not indicated on the figure) was that 43 MHz is the minimum total band required to accommodate these radars, a ratio of four-to-one. A further check indicated that the result was independent of whether the klystron exciter pulse was cosine-squared trapezoid or plain trapezoid. This ratio would be even greater if the relative instabilities of two different types of transmitters were considered; i.e., the klystron provides greater frequency stability. Employing node-coloring techniques developed in Reference 12, it can be shown that the minimum band is approximately proportional to the geographic density of radars. Thus, it can be concluded that if klystrons were used in the eight FAA radars instead of conventional magnetrons, about a four-fold increase in the number of users could be accommodated.

Long Term Frequency Instability and Tube Characteristics

Long term frequency instability can play an important role in the frequency management problem; experience has indicated that certain high-power radars drift over a frequency range that is considerably larger than the emission bandwidth over long periods of time. The OTP radar standards, however, restrict long term frequency drift to 2.2 MHz for radars in this band. Also, the radar specification for the ASR-7 (conventional magnetron oscillator) requires a long-term drift of no more than 2 MHz. As previously stated the coaxial magnetron is capable of frequency stability of up to a ten-fold improvement over the conventional magnetron tube, and klystrons are capable of even better stability performance.

Frequency inaccuracy (due to drift or error in estimated tuned frequency) has essentially an additive effect in terms of the amount of spectrum necessary to support system operation. Figure 2-18 provides some additional insight by translating frequency inaccuracy into dB-rejection uncertainty for three different emission spectra.

The average rejection requirement in the test environment is 22 dB. From the figure it is seen that a frequency inaccuracy of ± 2 MHz translates into a 3 dB rejection inaccuracy for a 20 dB/decade fall-off, a 22 dB inaccuracy for a 40 dB/decade fall-off, and a 38 dB inaccuracy for a 60 dB/decade fall-off. Thus it is seen that in order to take optimum advantage of the much higher fall-off rates afforded by the klystrons, more stringent requirements on frequency stability and frequency accuracy are required. For example, in order to maintain a 6 dB rejection accuracy, a frequency accuracy of ± 250 kHz must be maintained for 60 dB/decade fall-off. (This fall-off is that of a cosine-squared pulse.)

THE TEST ENVIRONMENT AND CHANNEL ASSIGNMENTS

Previous paragraphs in Section 2 described the effects on frequency/distance separation relationships of system performance requirements, pulse shape, transmitter output devices, tuning capacity and increments, and frequency instabilities. This paragraph discusses the results of an analysis whose objective has been to ascertain the effects of changing radar characteristics pertaining to:

1. Pulse shape,
2. Transmitter output device,
3. Conversion to dual frequency diversity.

Analysis has been directed at establishing the frequency band necessary to accommodate radars in a typical dense environment (Los Angeles area). Other parameters dealt with in previous paragraphs are held constant as noted.

Another factor that affects the frequency bandwidth is the amount of interference that is considered to be intolerable (the assignment threshold). This amount is discussed and results presented for two, differing assignment thresholds.

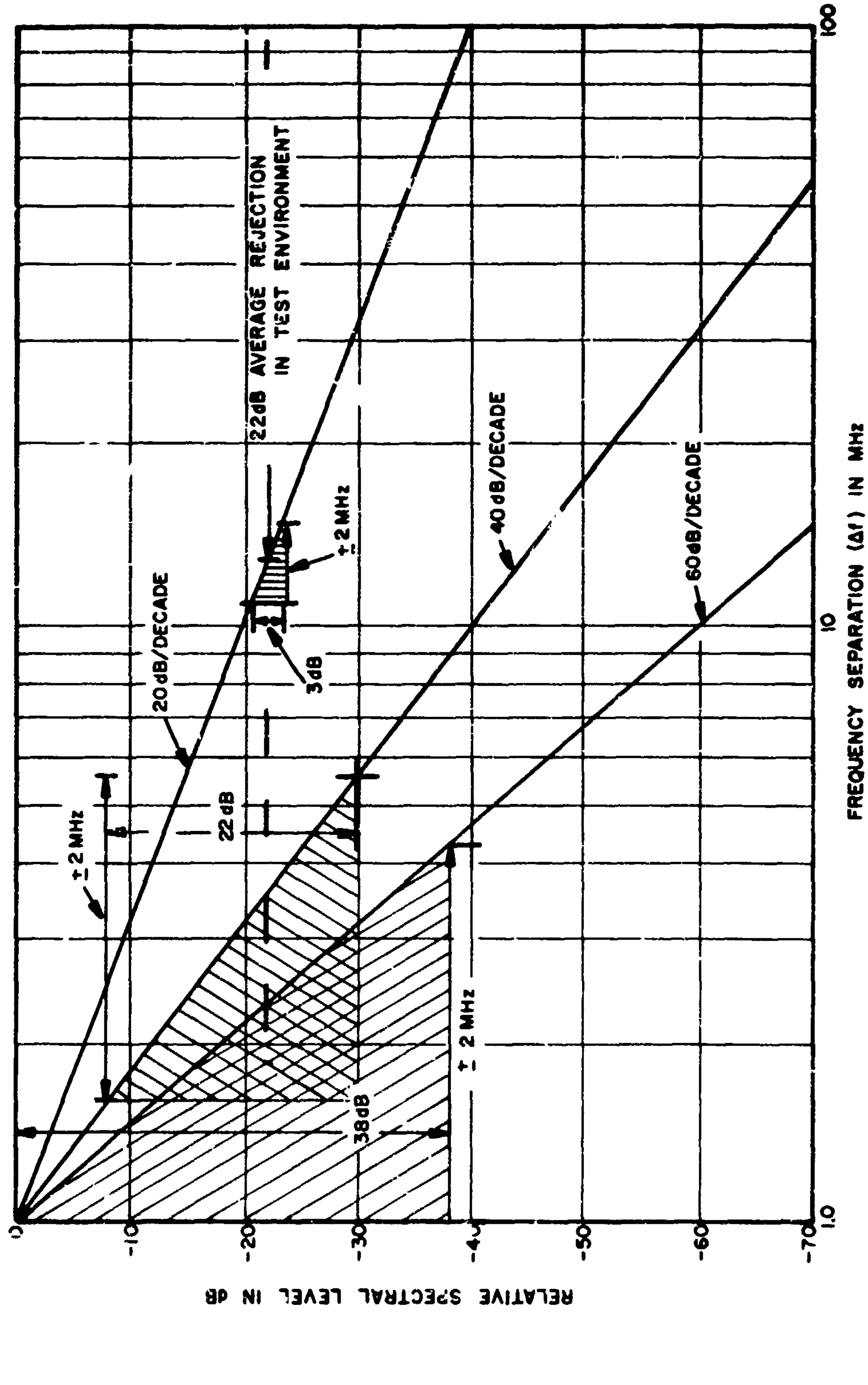


Figure 2-18. Frequency Inaccuracy In Terms of dB Rejection

The first threshold is defined by Equation (2-1) and will be hereafter referred to as the "less stringent interference criterion" threshold.* The second is defined by Equation (2-2) and will hereafter be referred to as the "stringent interference criterion" threshold.**

Assignment Threshold

Two thresholds have been used in the frequency assignment algorithms. The first threshold represents a situation where a radar will not be assigned to a channel unless the following inequality, Equation (2-1), is satisfied for each radar pair:

$$\frac{I_i}{R'_{sj}}(0.95,0.95) = P_{ti} + G_m(0.95) - L_p(0.95) - OFR_{ij} - R'_{sj} \leq 0\,\text{dB} \qquad (2\text{-}1)$$

where;

$\frac{I_i}{R'_{sj}}(p, q)$ = the ratio of peak pulse interference power from the ith radar received by the jth radar to the single-pulse sensitivity of the jth radars, which is not exceeded over p of the cumulative antenna pattern for at least q of hourly median path losses.

P_{ti} = the peak transmitter power of the ith radar

$G_m(0.95)$ = that level on the mutual antenna gain cumulative distribution which is not exceeded with a probability of 0.95, relative to the mutual gain of two isotropic antennas in free space (Figure 2-19). This level was estimated to be −10 dB for antennas in this analysis (Reference 13).

$L_p(0.95)$ = that hourly median path loss exceeded 95% of the time. Standard terrain profile dependent propagation loss prediction methods developed by the National Bureau of Standards were employed.

OFR_{ij} = the off-frequency rejection between the ith transmitter and the jth receiver.

*Interfering pulses above the single pulse sensitivity will be sprinkled in around the radar display via backlobe to-backlobe coupling. Coupling combinations of antenna mainbeams, sidelobes and backlobes when suitably oriented can cause wedges of relatively intense interference

**Mainbeam-to mainbeam and mainbeam to sidelobe interactions will occur when antennas become suitably oriented Slight violation of second criterion will permit interference from the mainbeams through the peaks of the backlobe structures, resulting in some interference on each antenna revolution

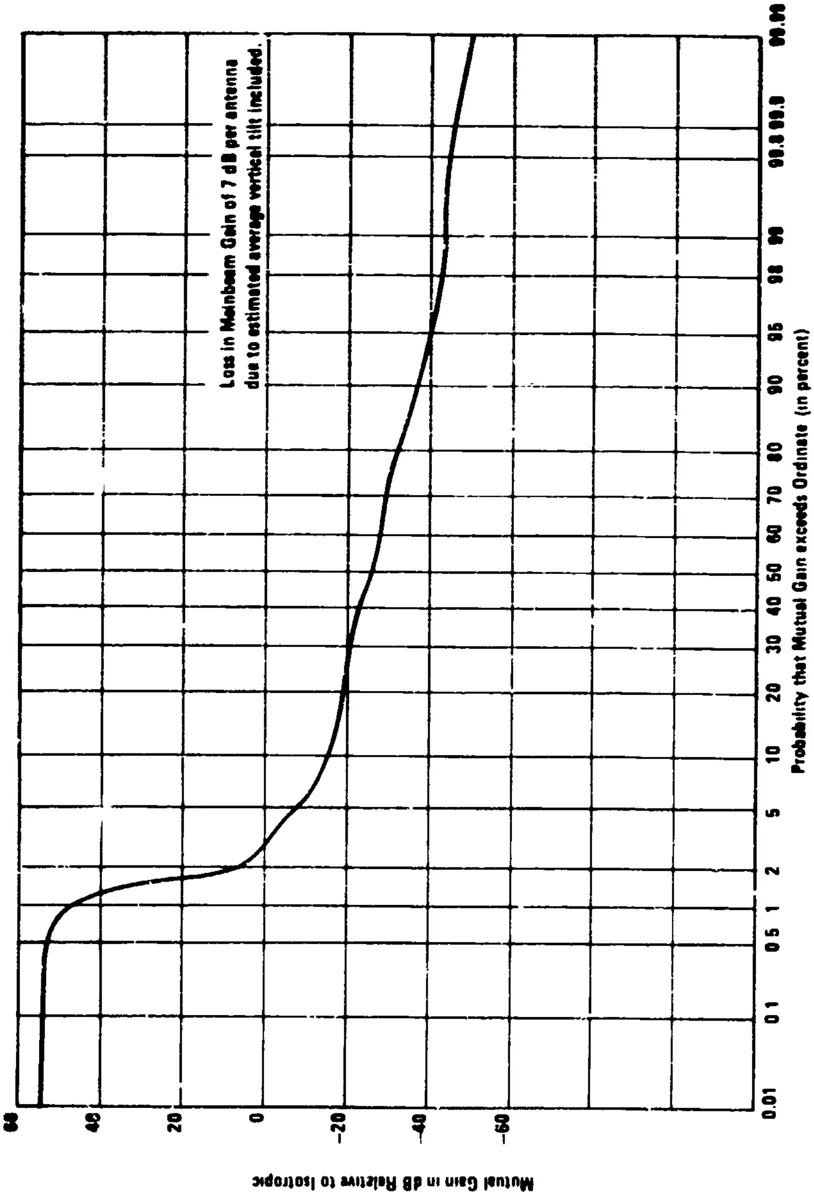


Figure 2-19. Mutual Antenna Gain Cumulative Distribution

R'_{sj} = the sensitivity of the jth receiver to a single uncorrelated pulse. The receiver is assumed to be 10 dB less sensitive to the interference pulse than the nominal value, R_{sj}.

There are several ways that the inequality of Equation (2-1) could be written, but, in summary, it means that no assignment would be made unless at least −10 dBi mutual gain is required for the interference level, I_i, to exceed R'_s. This means that 95% (at a minimum) of the transmitted pulses would be undetected.

The second threshold represents a situation where a radar will not be assigned to a channel unless the following inequality, Equation (2-2), is satisfied for each radar pair:

$$\frac{I_i}{R'_{sj}}(0.984, 0.95) = P_{ti} + G_m(0.984) - L_p(0.95) - OFR_{ij} - R'_{sj} \leq 0 \text{ dB} \qquad (2\text{-}2)$$

where:

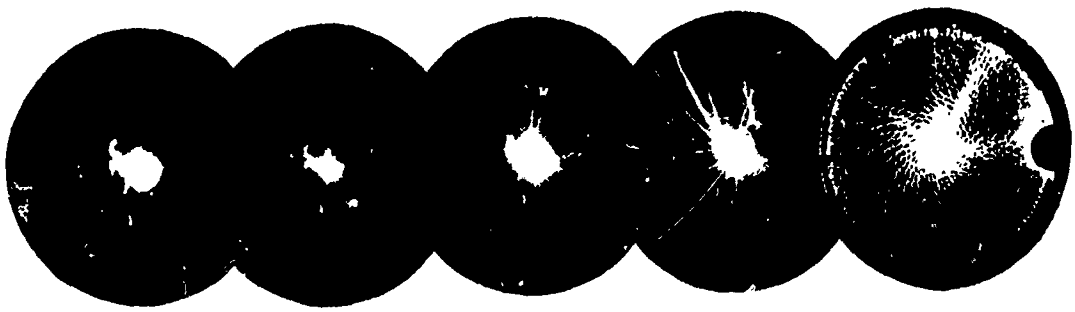
G_m (0.984) = That level on the mutual antenna gain cumulative distribution which is not exceeded with a probability of 0.984 (Figure 2-19). This level corresponds approximately to the mutual coupling when the mainbeam of one antenna (34 dB gain minus 7 dB for the estimated average vertical tilt loss) intercepts the peak of the backlobe structure of the other antenna (estimated as 0 dB gain).

Scope Condition, A Method of Evaluating the Assignments

A method is presented to evaluate the results contained in the following subparagraph of the channel assignments. This method is termed scope condition.

The concept of scope condition (Reference 14) has been employed here as an analytical method to obtain a quantitative prediction of interference displayed on a radar PPI. The pulse signal distribution input to the display is related to the resulting interference on the PPI by means of the intermediate parameter "N".

Within the U. S. Air Force, the Aerospace Defense Command has standardized a five-level classification of interference which is used for reporting interference experienced on a PPI (Reference 15). These five levels, illustrated on Figure 2-20, range from condition 1, having little or no interference pulses on the scope, to condition 5, which has heavy interference clutter over most of the scope face. TABLE 2-5 shows the relationship of the intermediate parameter N to scope conditions.



Condition 1 Condition 2 Condition 3 Condition 4 Condition 5

Figure 2-20. Example A. D. C. Scope Conditions

TABLE 2-5

RELATIONSHIP OF N TO SCOPE CONDITION

N Range	Scope Condition
0–3.7	1
3.8–9.4	2
9.5–14.7	3
14.8–23.2	4
25.3 & over	5

Determining Intermediate Parameter N. The intermediate parameter N must be calculated in order to predict a scope condition. The calculated value of N per interference source (the total N at the victim is the sum of the N from each interference source) is a function of the number of interfering pulses arriving at the victim which exceed receiver threshold during each victim antenna rotation, and is therefore also a function of the mutual-antenna-gain cumulative distribution of Figure 2-19. More specifically,

$$N \text{ (per interference source)} = Q_i \, (P_i - R'_s) \times 10^{-4} \qquad (2\text{-}3)$$

where:

Q_i = number of pulses per victim antenna rotation (scan) at power level P_i,

P_i = power level category of received interfering pulse signals expressed in dBm (P is used instead of I to avoid a double subscript),

R'_s = single pulse threshold of victim PPI, $(P_i - R'_s)$ has maximum value of PPI video dynamic range, estimated at 20 dB. Estimated $R'_s = -100$ dBm.

In Figure 2-21 are the results of many calculations of the intermediate parameter N. The values of N were calculated based on these assumptions:

1. Antenna rotation rate of 15 RPM,
2. Pulse repetition frequencies of 1000 pps,
3. Mutual-antenna-gain cumulative distributions as shown in Figure 2-19.

Two interference situations were considered for the calculations. In one, represented in the lower curve on Figure 2-21, interference pulses were assumed to arrive along a single propagation path. In the other curve, three reflected paths of pulses arriving at a level of −40 dB, relative to pulses arriving along the more direct path, were considered in addition to the direct path. This consideration represents an average rough terrain condition (Reference 16).

In summary, when the inequality of Equation (2-1) is employed as the assignment threshold, the intermediate parameter N per interference source will not exceed 0.25 for one path and 0.56 for four paths which corresponds to a maximum value of $I/R'_s = 0$ dB, for a mutual antenna gain of −10 dB. When the inequality of Equation (2-2) is employed as the assignment threshold, the maximum value of intermediate parameter N per source is 0.11 for one propagation path and 0.18 for four paths.

Sample Calculation of Intermediate Parameter N. The curves of Figure 2-21 were derived from many iterations of Equation (2-3). The curves render unnecessary further consideration of Equation (2-3) in this analysis. A sample calculation, using Equation (2-3), will show that use of data from an arbitrary siting situation produces points on the curves; it will also reveal how the many iterations of Equation (2-3) resulted in the curves.

Consider the siting/frequency situation where two radars comprise the environment. These two radars are positioned in space and frequency such that:

$$L_p = 147 \text{ dB}$$

and

$$OFR = 50 \text{ dB}.$$

Assuming that $R'_s = -100$ dBm and $P_t = 87$ dBm, it may be calculated that the two antennas must be oriented such that at least +10 dBi mutual gain is experienced in order for the interference pulses to be detected.

Equation (2-3) will now be computed for this siting/frequency situation from the above information and from Figure 2-19. From Figure 2-19 it may be deduced that only 0.15% of the pulses per antenna rotation arrive at the receiver at levels between R'_s (where

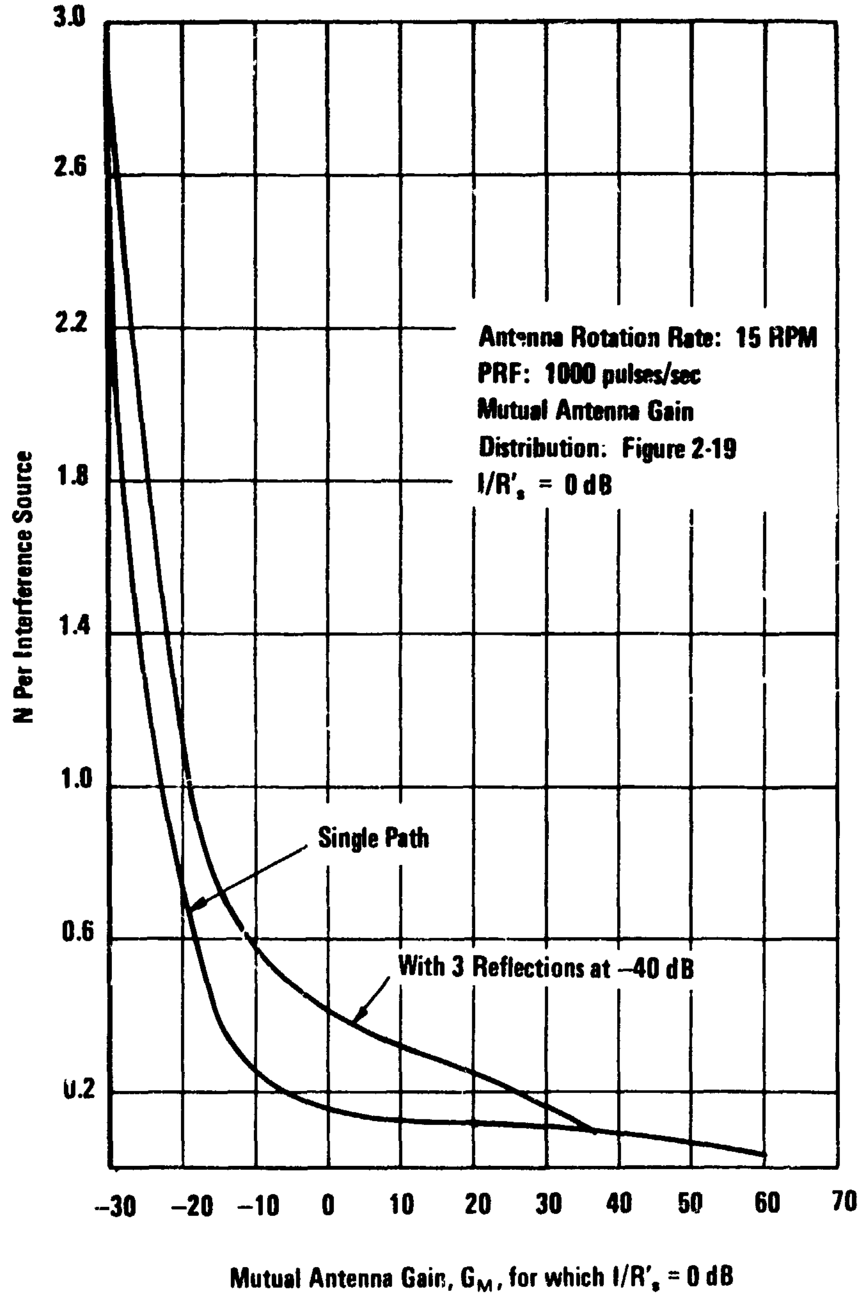


Figure 2-21. N per Interference Source

G_m = 10 dBi) and R'_s + 10 dB (where G_m = 20 dBi). This 0.15% is the difference between 1.8% (from G_m = 10 dBi) and 1.65% (from G_m = 20 dBi). Note that power levels are being categorized into 10 dB "bins".

Q_1 is the number of pulses in bin No. 1 and constitutes the number of pulses arriving at the receiver at power levels between R'_s (−100 dBm) and R'_s + 10 dB (−90 dBm). The quantity P_1 is defined as the midpoint of this bin, −95 dBm, or 5 dB above R'_s; P_2 is defined as the midpoint of bin No. 2, −85 dBm, or 15 dB above R'_s, etc. Steps in calculating intermediate parameter N per source are shown in Equations (2-4) through (2-7).

TABLE 2-6 shows the results of the steps in calculating the intermediate parameter, N, for this siting/frequency situation of two radars. Equations (2-4) through (2-7) are given as a guide through the first few steps in TABLE 2-6.

$$Q_1 \quad = \quad 0.0015 \times 1000 \text{ pps} \times 4 \text{ sec/rotation} = 6 \tag{2-4}$$

where:

0.0015 is that part of the mutual antenna gain cumulative distribution falling in bin No. 1, as described earlier.

$$\therefore Q_1\ (P_1 - R'_s) \times 10^{-4} \quad = \quad 6 \times 5 \times 10^{-4} = .0030 \tag{2-5}$$

The next step is to consider power level category (or bin) No. 2, $10 \leqslant P - R'_s \leqslant 20$. It is seen from Figure 2-19 that (1.65 − 1.55) 0.1% of the mutual pattern falls in this range.

$$\therefore Q_2 \quad = \quad 0.001 \times 1000 \times 4 = 4, \tag{2-6}$$

$P_2 - R'_s$ = 15 dB (midpoint of range), and

$$Q_2\ (P_2 - R'_s) \times 10^{-4} \quad = \quad .0060 \tag{2-7}$$

Continuing on as in TABLE 2-6, it is seen that the total N is 0.13, corresponding to the lower curve on Figure 2-21 for a G_m of + 10 dB.

From this one could say that if an environment consists of two radars situated such that a mutual antenna gain of + 10 dBi were required in order that the interference levels exceed R'_{sj}, then the N at the PPI scopes would be 0.13. Comparing this number with TABLE 2-5 would indicate a "low" scope condition 1. In order to indicate a scope

TABLE 2-6

STEPS TO INTERMEDIATE PARAMETER N, SINGLE SOURCE*

i (BIN No.)	P (dBm) BIN	P_i (dBm) (Midpoint of BIN)	Midpoint**, $P_i - R'_s$ (dB)	Q_i Pulses in BIN	$Q_i (P_i - R'_s) 10^{-4}$
1	−100 to −90	−95	5	6	.0030
2	−90 to −80	−85	15	4	.0060
3	−80 to −70	−75	20	10	.0200
4	−70 to −60	−65	20	20	.0400
5	−60 to −50	−55	20	32	.0640

Total N for this single sourve $= \sum_i Q_i (P_i - P_{MDS}) 10^{-4} = 0.1330$

* PRF = 1000 pulses/sec, Victim Scan rate = 15 RPM, $R'_s = -100$ dBm

** Limited to maximum value of PPI Video Dynamic Range estimated as 20 dB.

condition resulting from multiple sources of interference, the N's of each source require adding before comparing with numbers on TABLE 2-5.

Assignment of Primary Emitters

The eight ASR's and six operational GCA's make up the primary emitters in the Los Angeles test environment (See APPENDIX A). Channels were assigned to the environmental radars for each of various combinations of equipment parameters and assignment thresholds. In some assignments only the ASR's were considered to comprise the environment. In others, the environment was expanded to include the GCA's. A further expansion, to include assignments of secondary emitters is considered in the next subsection.

The assignment threshold was either Equation (2-1) or Equation (2-2). Equipment characteristics that were considered fixed for all equipments included: channel spacing = 5 MHz, transmitter power = 500 kW, pulse width = 0.5 μsec, pulse rise time = 0.25 μsec, R'_{t} = −100 dBm, frequency drift negligible. Also considered fixed was the GCA emission spectra as that of a coaxial magnetron (see Figure 2-22). Equipment characteristics that were varied include: emission spectra for the eight ASR's assumed to be that of a klystron with a 34 MHz cavity bandpass and either a trapezoidal pulse (see Figure 2-23) or a trapezoidal pulse with modulator shaping to provide a cosine-squared rise and fall (see Figure 2-24), and either single channel or dual frequency diversity operation. Where dual frequency diversity was considered, a minimum of 80 MHz separation between channels was maintained.

TABLE 2-7 summarizes the results of the estimated channelizations of the Los Angeles area primary emitters. These results are presented in terms of the minimum frequency band required to support the radars and an estimate of the degradation which would be experienced by the Long Beach ASR, picked as an illustration.

Figure 2-25 is also presented to illustrate the channels which would be occupied by the radars for the estimated channelizations.

Consider the case where 14 ASR's and GCA's using dual frequency diversity operation make up the environment. The procedures selected make assignments in terms of Equation (2-2): if assignment of a radar to a channel would result in detectable interference from/to any other radar at mutual antenna gains of 27 dBi, that radar was not assigned that channel. Trapezoid waveforms are considered in the example; τ = 0.5 and K = 2. From TABLE 2-7, the minimum frequency band necessary to accommodate these dual-diversity radars is 205 MHz which exceeds the 200 MHz frequency allocation between 2.7 and 2.9 GHz. The intermediate parameter N at the Long Beach ASR lower channel ranges from

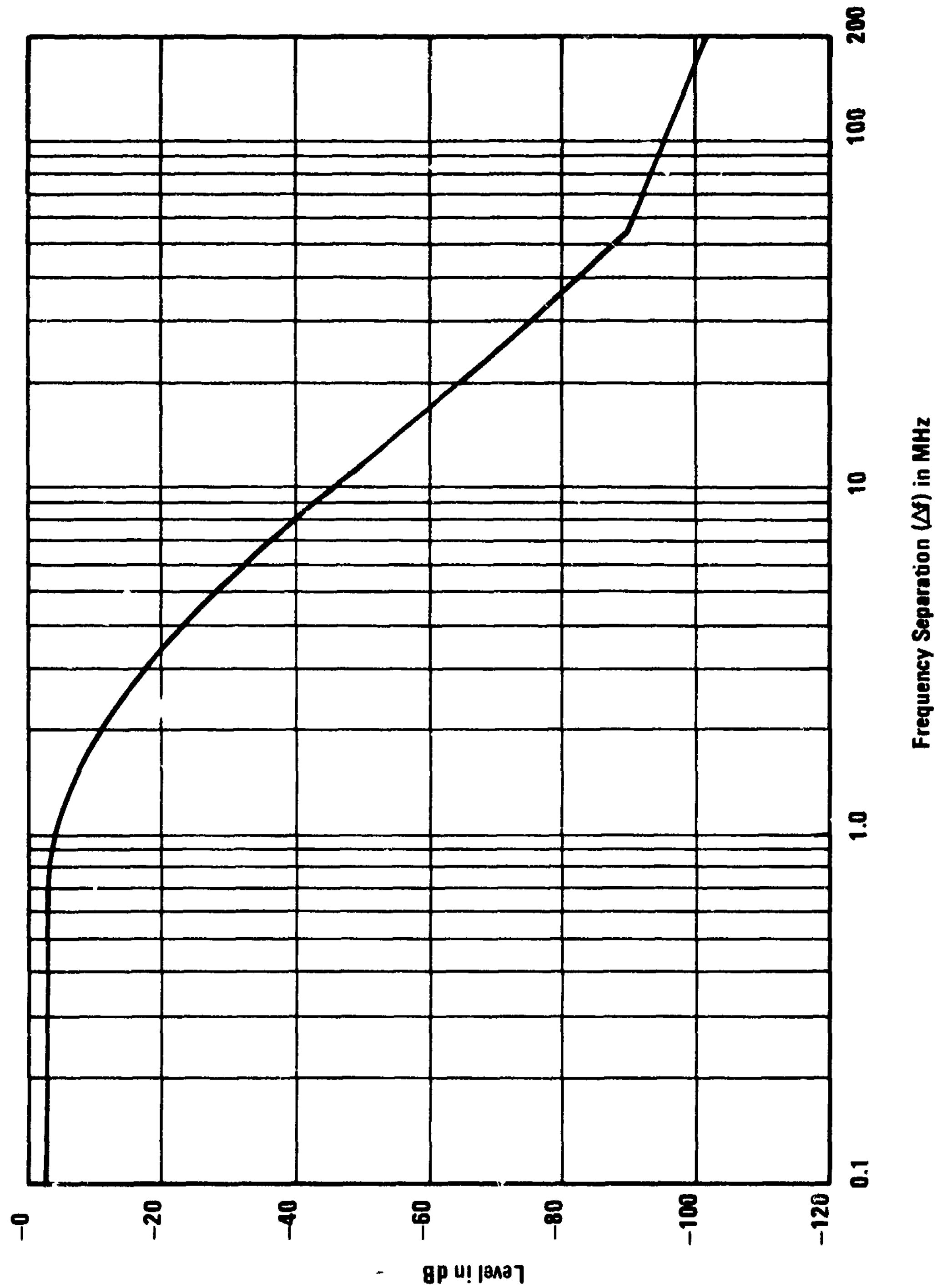


Figure 2-22. Coaxial Magnetron Emission, $\tau = 0.5\ \mu s$, K = 2

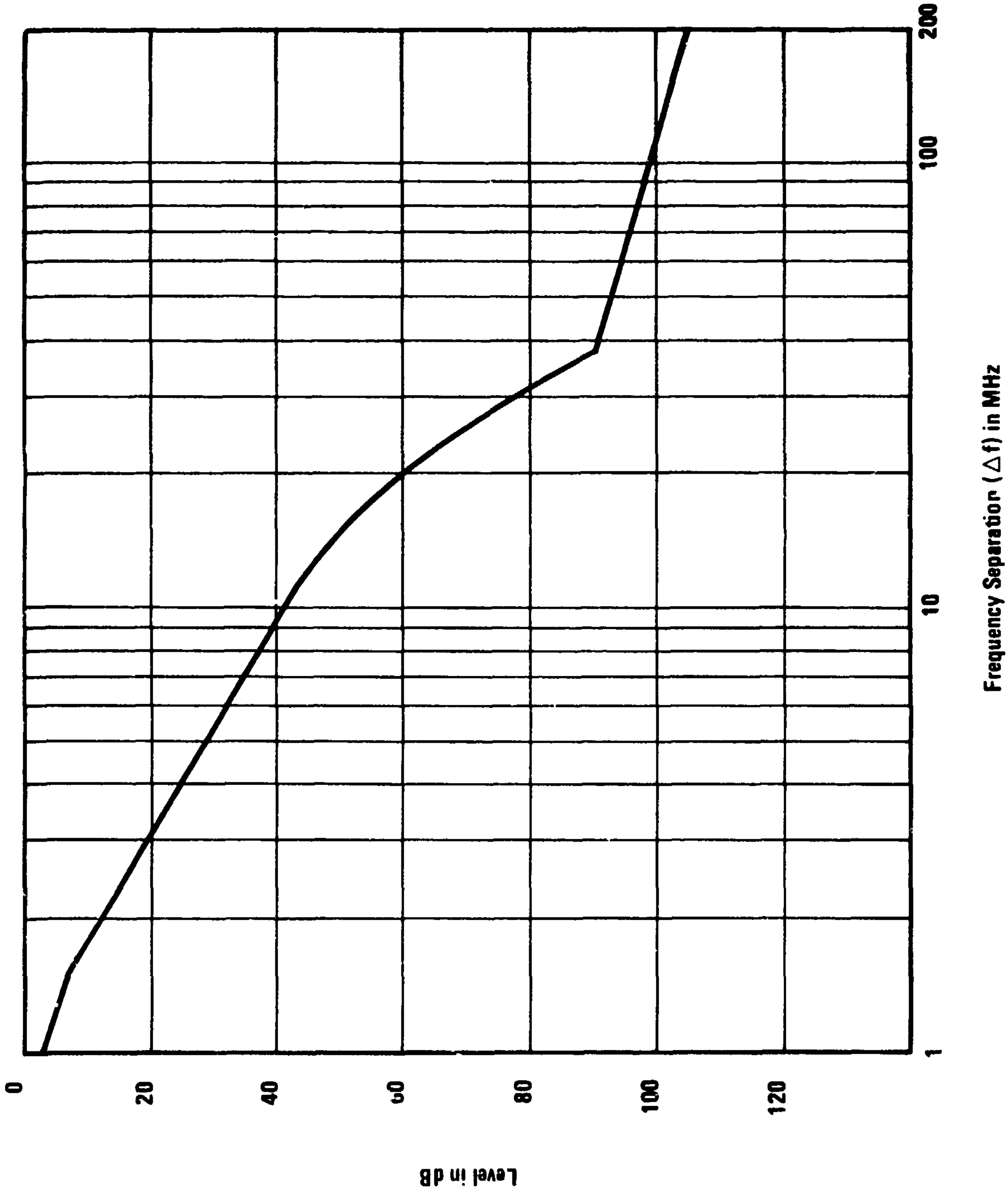


Figure 2-23. Klystron Emission, Trapezoidal Waveform, $\tau = 0.5\ \mu s$, K = 2

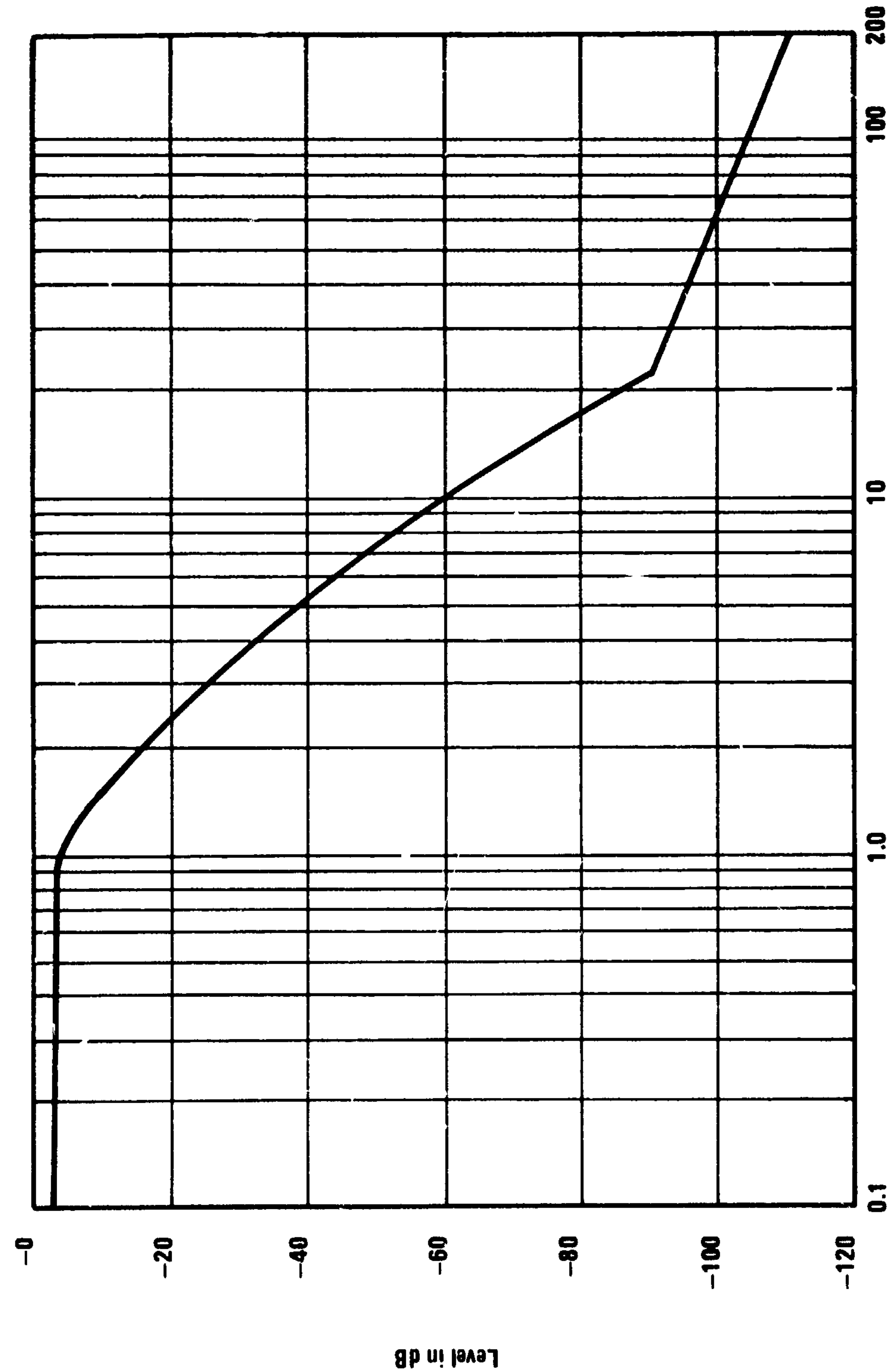


Figure 2-24. Klystron Emission Trapezoidal Waveform with Cosine-Squared Rise and Fall, τ = 0.5 μs, K = 2

TABLE 2-7

2.7-2.9 GHz BAND CHANNELIZATION DATA, PRIMARY EMITTERS

Selected Procedures		Single channel Operation						Dual Frequency Diversity Operation							
		Environment of ASR s only			Environment of ASR s and GCA's			Environment of ASR's only				Environment of ASR's and GCA's			
Assignment Threshold	Pulse type†	Minimum band (MHz)	N‡	Scope condition	Minimum band (MHz)	N‡	Scope condition	Minimum band (MHz)	Lower channel N‡	Upper channel N‡	Scope condition	Minimum band (MHz)	Lower channel N‡	Upper channel N‡	Scope condition
EQ (2 1) G_m (0 95) = - 10 dBi*	Trapezoid	15 MHz	1 03 to 2 49	1	25	1 47 to 3 23	1	95	1 03 to 2 49	1 03 to 2 49	1	105	1 47 to 3 23	1 47 to 3 23	1
EC (2 2) G_m (0 984)= 27 dBi*	Trapezoid	65	0 45 to 0 50	1	90	0 42 to 0 49	1	165	0 65 to 0 73	0 59 to 0 64	1	205	0 67 to 0 81	0 42 to 0 49	1
EQ (2 1) G_m (0 95) = -10 dBi*	Cosine squared Trapezoid	15	0 73 to 1 64	1	20	1 05 to 1 95	1	95	0 86 to 1 77	0 86 to 1 77	1	100	1 19 to 2 09	1 19 to 2 09	1
EQ (2 2) G_m (0 984)=27 dBi*	Cosine-squared Trapezoid	40	0 45 to 0 52	1	65	0 48 to 0 55	1	120	0 65 to 0 74	0 53 to 0 60	1	155	0 60 to 0 67	0 57 to 0 64	1

* Assignments were made such that antenna orientations yielding mutual antenna gains less than that given would not result in interference levels exceeding R's

† Pulse width = 0 5 μs, rise time = 0 25 μs (K = 2) for both pulse types

‡ Resulting N, summed for all sources in environment at Long Beach ASR.

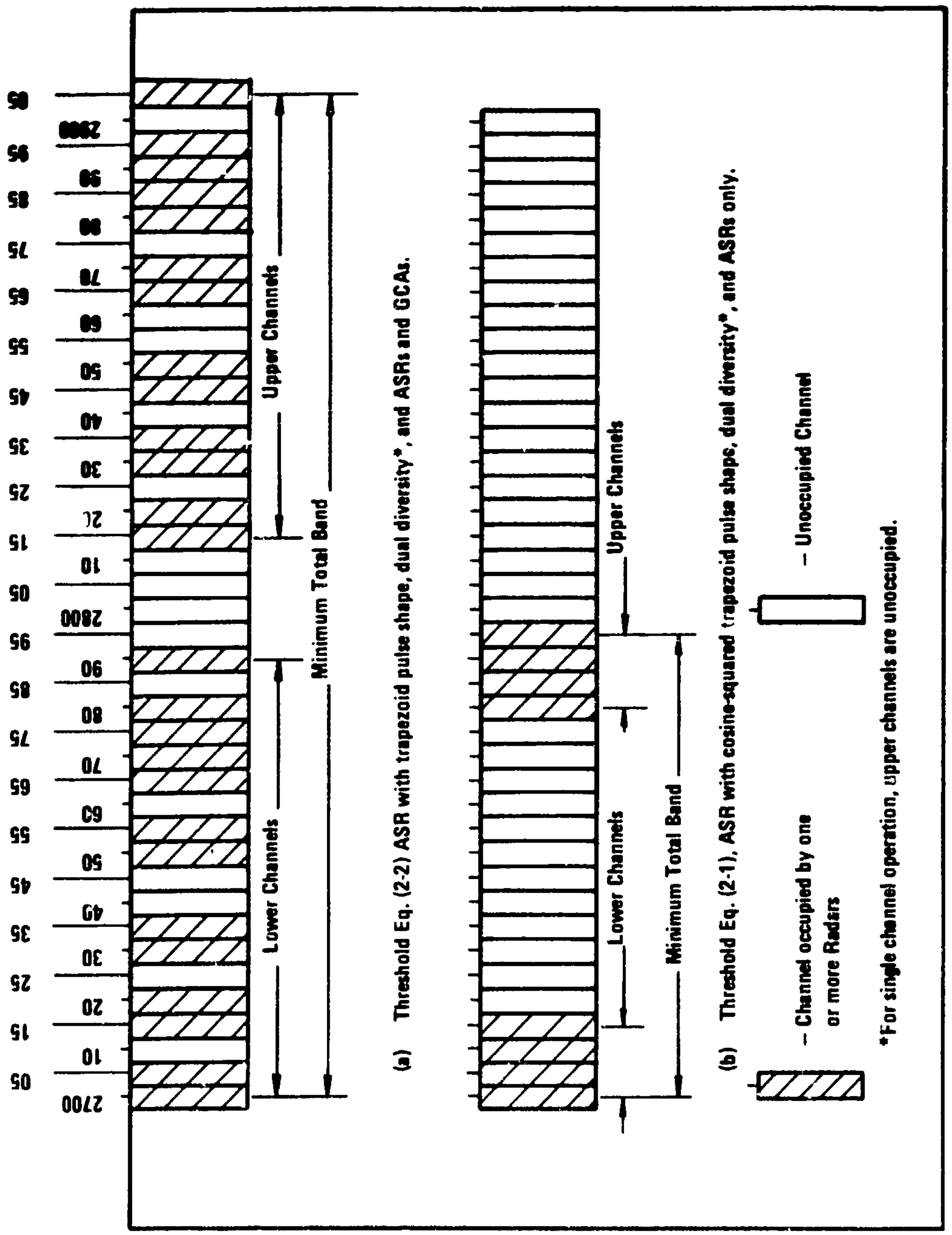


Figure 2-25. Illustrations of Frequency Assignments (Sheet 1 of 4)

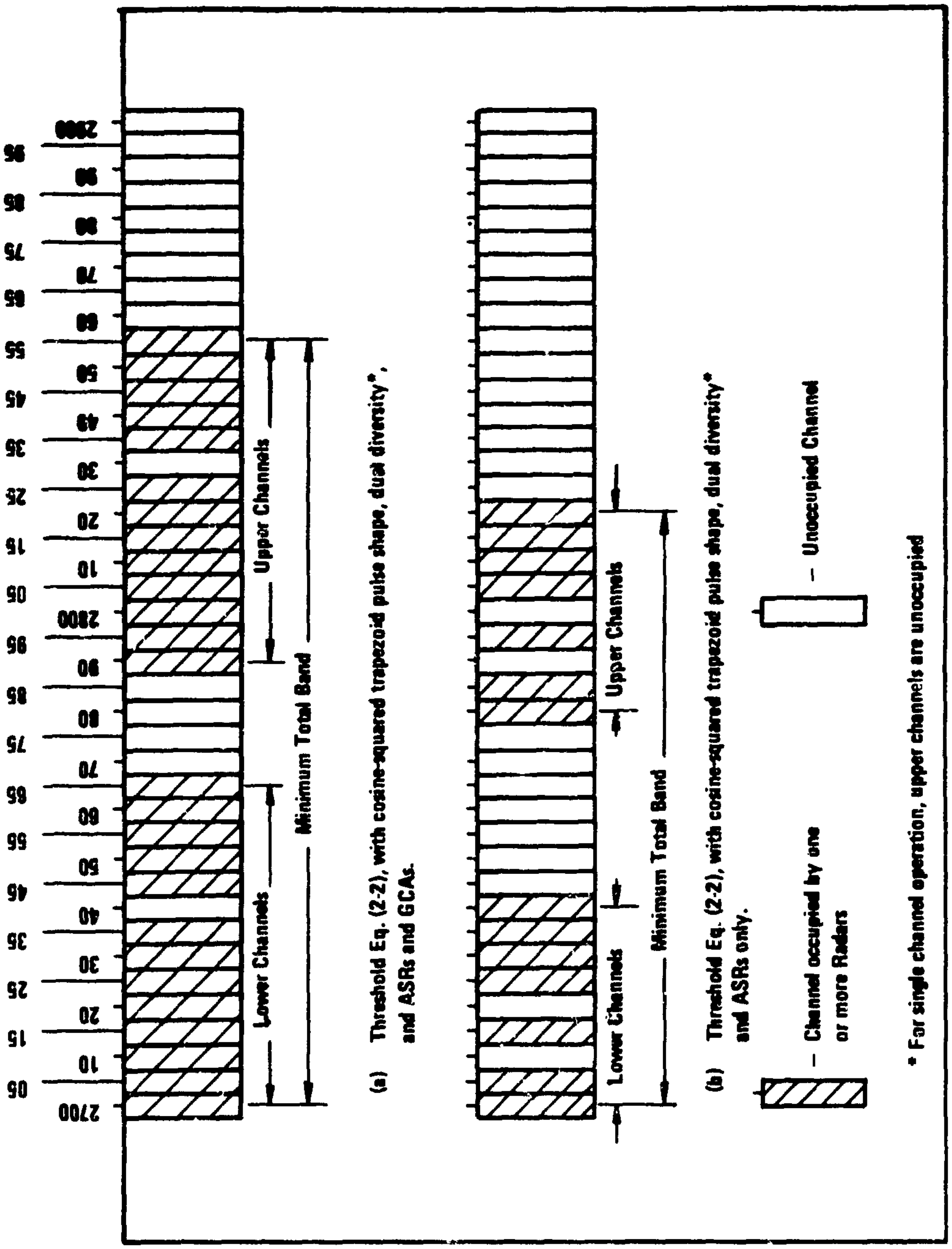


Figure 2-25. (Sheet 2 of 4)

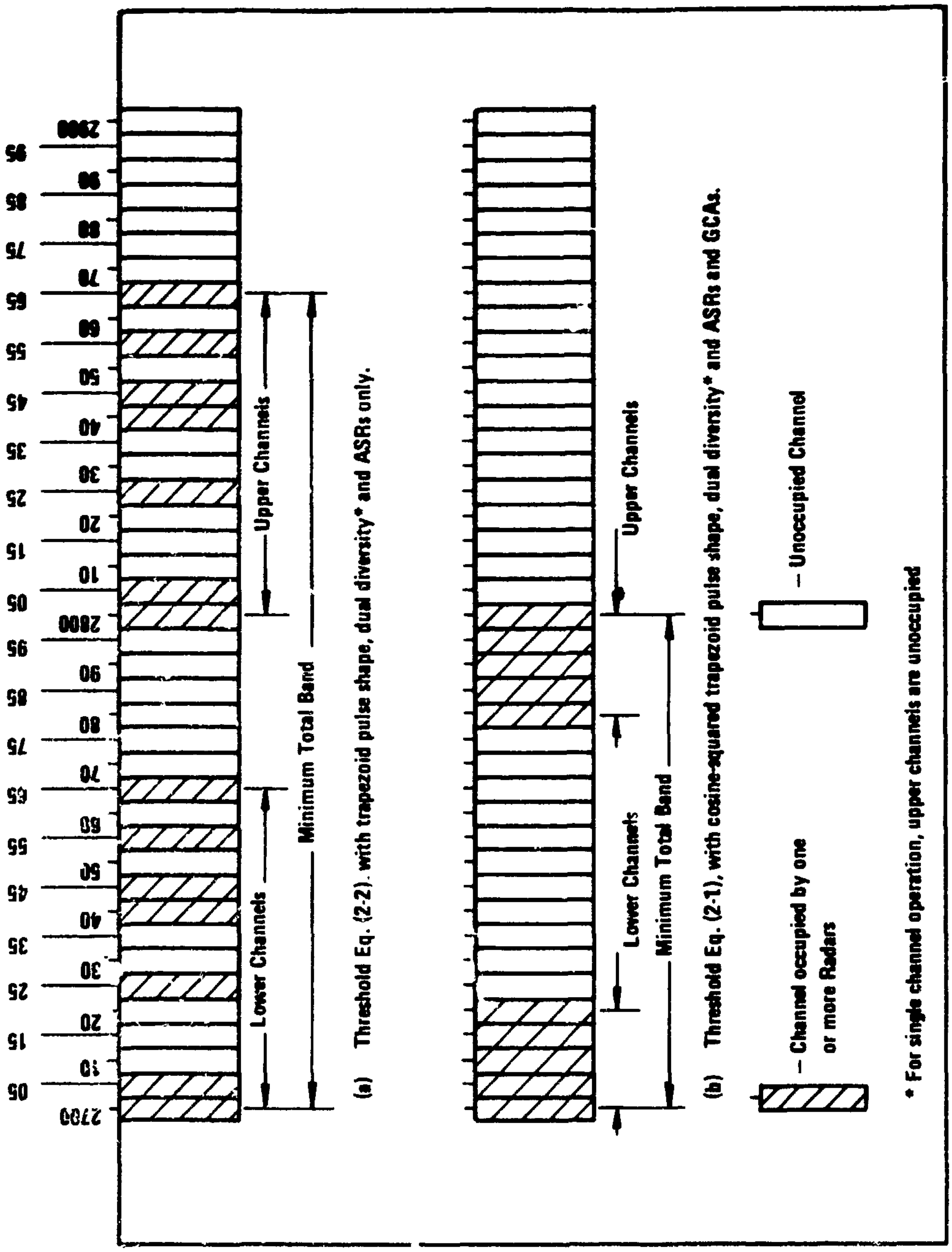


Figure 2-25. (Sheet 3 of 4)

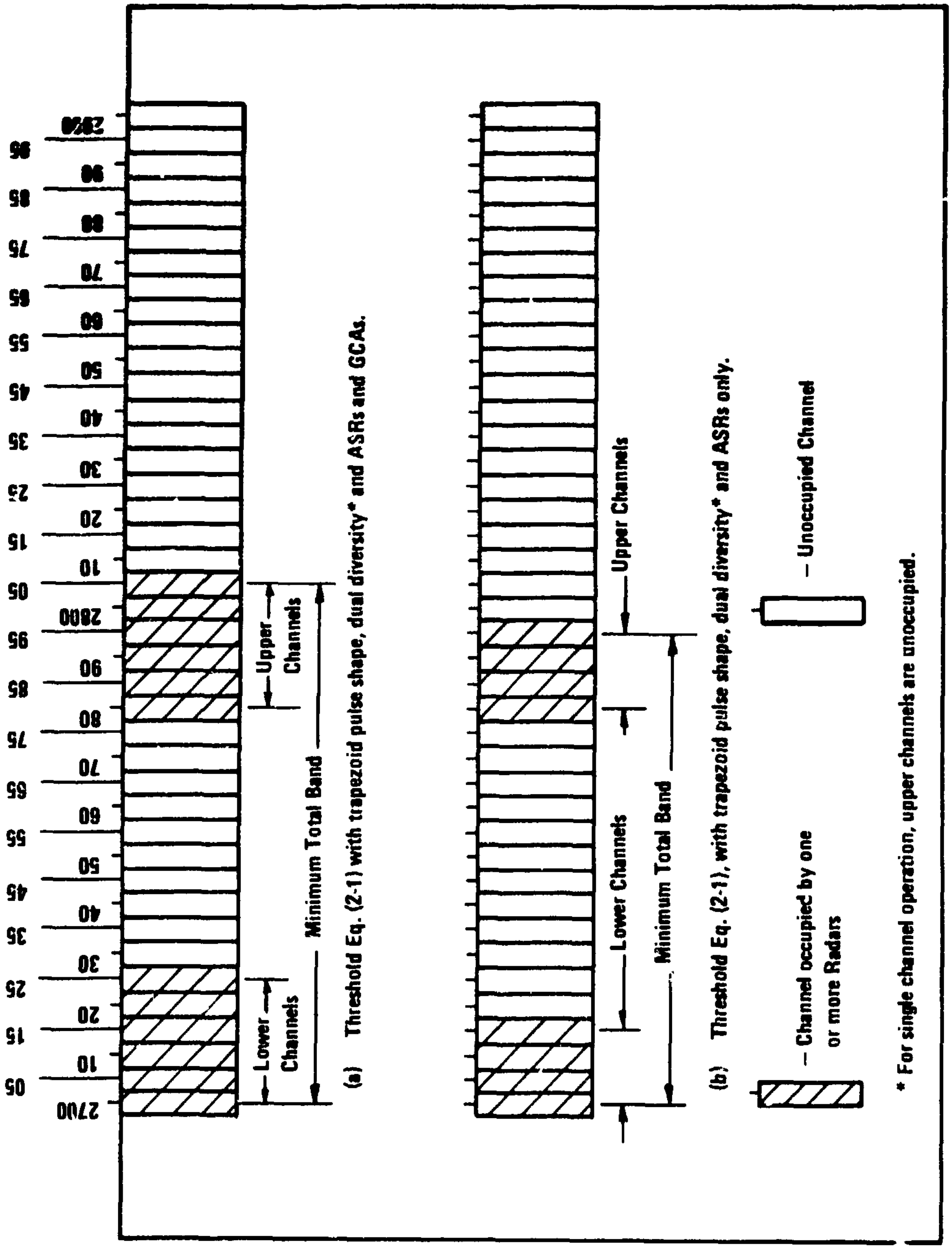


Figure 2-25. (Sheet 4 of 4)

0.67, considering direct paths from all sources, to 0.81, considering reflected paths from all sources, and the N range falls within scope condition No. 1 (see also TABLE 2-5). Intermediate parameter N for the upper channel ranges from 0.42, considering direct paths from all sources, to 0.49, considering reflected paths from all sources; the N range also falls within scope condition No. 1. Figure 2-25 [sheet 1 (a)] shows this assignment in terms of occupied channels.

As a second example, consider the case where the eight ASR's operate single channel. The procedures selected make assignments in terms of Equation (2-1): if assignment of a radar to a channel would result in detectable interference from/to any other radar at mutual antenna gains of −10 dBi, that radar was not assigned that channel. Cosine-squared trapezoid waveforms are considered in the examples, $\tau = 0.5$ and $K = 2$. From TABLE 2-7, the minimum frequency band needed to accommodate these single channel radars is 15 MHz; the intermediate parameter N for the Long Beach ASR ranges from 1.03, considering direct paths from all sources, to 2.49, considering reflected paths from all sources; and the N' range falls within scope condition No. 1 (see also TABLE 2-5). Figure 2-25, (sheet 1 b) shows this assignment in terms of occupied channels. As indicated on the figure, upper channels are considered unoccupied for this single channel operation situation.

Figure 2-25 (sheets 2 through 4) describe frequency assignments, in terms of occupied channels, for the other selected procedures shown on TABLE 2-7.

Assignment of Secondary Emitters

Several analyses were performed in order to determine:

1. The degree of supportability of the secondary emitters under the restrictions of the selected procedures concerning the primary emitters given in TABLE 2-7, and
2. The feasibility of segmenting the band, i.e., reserving portions of the band for radars with improved output tubes (klystrons or coaxial magnetrons), while allocating any remaining spectrum to secondary emitters.

In the course of the analysis, secondary emitters were assumed to have their present emission characteristics as found in APPENDIX A and APPENDIX E, i.e., characteristics of conventional magnetron transmitters. Frequency inaccuracy of ± 2 MHz was also assumed. The results were strongly dependent on the assignment threshold employed. That is, employing the terms of Equation (2-1) as assignment criteria, secondary emitters could be accommodated in the 2.7 to 2.9 GHz band to the extent described in the examples which follow. On the other hand, if the terms of Equation (2-2) were employed, every secondary emitter would interact with at least one primary emitter such that none could be accommodated in the band.

TABLE 2-8 lists some of the more significant interactions which would be unresolved by off-frequency rejection. The level of on-tune I/R', (0.984, 0.95) are all greater than the maximum realistic off-frequency rejection that could be realized by a conventional magnetron transmitter. The victims listed are all primary radars.

Segmentation of the band, as discussed in the following examples, is also feasible under the terms of Equation (2-1) but not under Equation (2-2).

The following results concern the degree of supportability of the secondary emitters and segmentation of the band under the requirements of Equation (2-1).

Segmented Band and Single Channel ASR's. In order to determine whether the 2.7 to 2.9 GHz band would support the establishment of discrete channel assignments over portions of the band, the following calculation was made. The eight ASR's in the test environment were selected for possible segmentation, since they were considered the most likely to employ improved radar EMC design in the near future. Klystron amplifiers with 0.5 μs cosine-squared trapezoidal output pulses having a 50% rise time ($K = 2$) were also assumed, consistent with determination feasibility. It was then found that 15 MHz would be sufficient to accommodate these radars with 5 MHz tuning increments (Figure 2-16). The MCAS (APPENDIX C) algorithm was then applied to see whether a satisfactory assignment of frequencies would be accomplished under the following constraints:

1. The eight ASR's restricted to a 15 MHz segment at the lower end of the band.
2. The three AN/APS-20 acquisition radars allowed exclusive use of the 2850-2910 MHz portion of the band. (This is the current procedure, as confirmed by the cognizant frequency managers.)*
3. The rest of the radars, seventeen in number, restricted to the remaining portion of the band.

The result was that all radars would be easily accommodated. This procedure was then repeated, except that the seven GCA surveillance radars (part of the seventeen) were restricted to their nominal tuning range, 2780 to 2820 MHz. The result in this case was that small increases in levels of interference would be introduced. This was due to a height-finder radar situated physically between an ASR and GCA. This factor, combined with the restricted and widely separated tuning ranges of the ASR and GCA, required smaller frequency separations between the height finder and these radars.

* Figures 2-1 and 2-2 illustrate the impact of the airborne AN/APS-20 ( ) radars and thereby a rationale for this procedure.

TABLE 2-8

SOME OF THE MORE SIGNIFICANT ON-TUNE I/R's AT PRIMARY RECEIVERS DUE TO SECONDARY EMITTERS RELATIVE TO G_m (0.984)

Offending Transmitter (Secondary)	Victim Receivers (Primary)	On-tune* I/R'$_s$ (0.984, 0.95) in dB
Cambria (AN/FPS-6)	Vandenberg AFB (AN/MPN-13)	89
China Lake (SCR-584)	George AFB (AN/MPN-13)	78
China Lake (7298)	George AFB (AN/MPN-13)	71
Corona NTC (SCR-584B)	Long Beach (ASR-5)	73
Edwards (AN/MPS-19)	Edwards (ASR-5)	95
LaGuna Peak (AN/APS-20)	Point Mugu (AN/FPN-48)	99
Mt. Laguna (AN/FPS-90)	Miramar (ASR-5)	90
Mt. Laguna (AN/FPS-90)	San Diego NTS (AN/CPN-4)	91
Point Mugu (SCR-584)	Point Mugu (AN/FPN-48)	112
San Cruz Isl. (AN/APS-20)	Point Mugu (AN/FPN-48)	83
San Nicolas (SCR-584)	El Toro (ASR-5)	71
San Nicolas (SCR-584)	San Clemente (AN/CPN-4)	76
San Nicolas (AN/APS-20)	El Toro (ASR-5)	76
San Nicolas (AN/APS-20)	San Clemente (AN/CPN-4)	82
San Pedro (AN/FPS-90)	El Toro (ASR-5)	89
San Pedro (AN/FPS-90)	Long Beach (ASR-5)	96
San Pedro (AN/FPS-90)	Los Angeles Int. (ASR-4)	95
San Pedro (AN/FPS-90)	San Clemente (AN/CPN-4)	93

* The on-tune I/R'$_s$ (0.984, 0.95) is the minimum amount of OFR in dB which must be satisfied (Equation 2-2) with less than 200 MHz frequency separation More than 70 dB is not a realistic expectation with these equipments.

Segmented Band and Dual Frequency Diversity ASR's. An analysis was performed to determine whether employment of dual diversity operation by the ASR's would be supportable under the same procedure. The process described above was repeated with the exception that the ASR's were allotted two separate 15 MHz portions of the band and the GCA's were allowed to violate their nominal tuning range. In this case, the answer was again affirmative, although the height finder mentioned previously would cause small increases in interference levels.

Unsegmented Band and Dual Frequency Diversity ASR's. Another analysis was performed, identical to the one above with the exception that the ASR's did not have exclusive use of any portions of the band. The result indicated no change in the interference potential.

Dual Frequency Diversity with Conventional Magnetrons. During the course of the project, the question was raised as to the possible effect of dual frequency diversity operation of both the ASR's and GCA's, with more than 80 MHz separation between diversity channels, and employing conventional magnetrons. This subject was addressed by conducting several analyses of the test environment.

In the first analysis, the eight FAA ASR's were assumed to employ dual diversity. It was found that this arrangement could, with difficulty, be accommodated; interference levels slightly greater than 10 dB above sensitivity (at a mutual antenna gain of −10 dBi) would apparently be unavoidable in several ASR or GCA receivers. Should the GCA's be restricted to their nominal tuning range, however, this procedure would not be possible.

A second analysis was performed assuming that the ASR's and GCA's both employ dual diversity. In this case no apparent accomodation could be expected in the test environment. As a check on this result, a third analysis was performed, permitting assignments of tracking radars when interference was 45 dB above sensitivity, and with 10 dB above sensitivity for all others. The result was again negative; even with these permissive factors, at least four of the 28 radars could not have been permitted to operate.

EVALUATION OF DESIGN FEATURES

The introduction of various design features to enhance performance of radar systems raises the question of the effects that these features may produce on the electromagnetic compatibility of the system and on spectrum utilization. Some of these designs, by intention or as by-products, result in the reduction of interference. Their effect on system EMC has been evaluated. Design features falling into this category include sidelobe suppression, pulse width and PRF discriminators, Dicke Fix receivers, and pulse integrators. A number of current radar design developments for improvement of airport surveillance-radar performance are evaluated in this study from a spectrum compatibility standpoint. Design features considered are phased array antennas, pulse compression radars, orthogonal antenna polarizations, and signal coding.

Phased Array Antennas

The directivity and required bandwidth of phased array antennas differ markedly from conventional aperture antennas. The theoretical discussion presented in APPENDIX C relates the required system bandwidth to beamwidths and scan-angle widths. The relationships developed indicate that bandwidth necessary to support beam angle accuracy and sector width do not increase the system bandwidth required to support current system functions.

Those characteristics of phased array antennas that can cause interference problems in some configurations are expanded upon in the analysis presented in APPENDIX C. The antenna can be highly directive toward an undesired signal source and in an undesired direction. A common example of this phenomenon is the grating lobe, which is formed at an angle other than that of the directed lobe. The grating lobe angle (or angles, if multiple lobes occur) is a function of element spacing, steering angle, and tuned frequency.

The susceptibility to undesired high-power signals of the amplifiers connected to elements, or clusters of elements, of a phased array antenna must also be considered. Undesired signal levels could be experienced which would be damaging to the amplifier.

Pulse Compression

Receivers employing pulse compression processing offer more range resolution than do conventional radars which have the same 40 dB bandwidth. The effective narrow-pulse capability realized through this technique improves system performance against volume clutter, such as rain, making it of particular interest for use in ASR systems.

APPENDIX C discusses two basic interactions: (1) between two PC radars employing linear FM pulse compression, and (2) between a radar employing linear FM pulse compression and one employing constant frequency pulses. For a situation involving an environment of pulse compression radars, the employment of negative and positive FM slopes, respectively, in adjacent radars would enable reusable channels at smaller distances not otherwise obtainable.

It is yet to be determined whether the use of pulse compression in conjunction with MTI will provide the clutter rejection and detection requirements of FAA airport surveillance function.

Antenna Polarization Diversity

In a dense environment of surveillance radars and other radars employing rotating antennas or wide-sector-scanning antennas, the most likely cases of interference coupling are through antenna orientations other than the mainbeam (s). Thus, because of depolarization off the mainbeam, the use of polarization diversification would have little effect in this environment. In addition, beam scattering from terrain causes further depolarization. Therefore, any EMC benefits derived from antenna polarization differences would be limited to specific situations where mainbeam or close-in sidelobe (within 10 degrees of the mainbeam) couplings are a factor. Where two radars operating with the same antenna polarization experienced only mainbeam-to-mainbeam interactions, the conversion of one of these radars to an opposite polarization *may* eliminate all interactions.

Radars currently under consideration, when operating with dual frequency diversity, may radiate one channel in horizontal and the other in vertical when linear polarization is selected, and left and right when circular polarization is selected.

The Coding of Radar Signals

The technique of signal coding offers radars in a common environment an effective interference-reduction device. Coding of the desired signal in time, frequency, phase, or combination of these, has the effect of decreasing or eliminating response to other signals. This discrimination allows a measure of interference rejection and, thereby, more efficient spectrum utilization. That is, systems normally required to maintain wide frequency guardbands to avoid coupling would not be so restricted. In a dense environment of such systems, the increased spectrum utilization could be substantial. APPENDIX G discusses the techniques of signal coding in detail.

Disadvantages of signal coding techniques are increased design complexity and a potential increase in the signal bandwidths. Further, the technique is most effective when every system in the common band and in the common environment is so designed. Since the frequency band in question is currently occupied by uncoded systems, the practicality of employing signal coding may be limited. However, a study of such employment would be useful on the premise that one specific portion of the band could be dedicated to systems using signal coding exclusively.

RADAR STANDARDS

The recently adopted radar standard (APPENDIX F) of the Office of Telecommunications Policy (OTP) was examined with regard to ne effect that its specifications would have on the sample environment under study. It was found that if all the radar equipments just meet the standards, the anticipated expansion of the use of this band would be inhibited in dense environments such as Los Angeles. However, transmitter output devices and radar design techniques are available that could satisfy this new demand through improvement of basic radar characteristics. In this context the following comments on the OTP standard are made.

1. The standard's 40 dB bandpass requirement, that is, 40 dB of rejection with respect to the fundamental, cannot be reduced without pulse shaping or equivalently, transmitter filtering.
2. The limit on spurious emission levels described by the standards, that is, average spurious power $\leqslant -31$ dBm/kHz, as applied to ASR's, is significantly higher than that which can be realized through the use of coaxial magnetrons, klystrons, or filtered conventional magentrons. The use of these devices can permit a reduction of non-harmonic spurious emissions by 35 dB, i.e., to -66 dBm/kHz. However, a 20 dB reduction of the in-band spurious emissions (to -51 dBm/kHz) would be sufficient for most radar siting situations to achieve a condition of $I/R'_s \leqslant 0$ dB for mutual antenna coupling of -10 dB.
3. Significant increase in the standard's requirement for minimum spectral roll-off may be achieved through use of the improved output devices, in light of the average power levels common to this band. A practically achievable level that satisfies spectral occupancy requirements can be represented by the substitution of the relationship $\Delta F_2 = 3\Delta F_1$, for the relationship $\Delta F_2 = 10\Delta F_1$ that now appears in the OTP standard.
4. With this increase in spectral roll-off, better frequency control will be indicated.

In order to fully realize the benefits of the increased spectral roll-off, the long-term frequency stability requirement would have to be reduced from the present ± 2.2 MHz to approximately ± 250 kHz, which is estimated to be achievable in klystron and coaxial magnetron radars.

5. The OTP standard for search radars provides that the median antenna gain in the horizontal plane shall not exceed -10 dB, relative to an isotropic antenna. Measurements show (Reference 13) that search radar antennas in the 2 to 6 GHz frequency range have median gains in the horizontal plane of -11 to -22 dB. Therefore, the standard can be readily complied with. But, as this factor is highly significant from a compatibility standpoint, the standard could be improved substantially in new antenna designs without forcing sidelobe reduction techniques to be employed.

6. The OTP standard on radar receivers requires 50 dB of rejection for the image response and 60 dB of rejection for other spurious responses. In light of the spurious emission comments above (item 2), an additional 20 dB rejection would be desirable that is, 70 dB for the image and 80 dB for other spurious responses.

7. The OTP standard allows radars to be tunable in discrete increments no greater than 2% of the nominal carrier frequency. For this frequency band, these increments would be approximately 56 MHz. This could place a severe constraint on the efficient use of the band; if radars were designed to the maximum 56 MHz allowance, the 2.7 to 2.9 MHz band could only accommodate four distinct channels. Sitings in the test environment are such that a minimum of at least 10 and up to 27 distinct channels are required to accommodate all the systems in the band.

SECTION 3

FINDINGS

Several factors contribute to the overall problem of accommodating present and future needs involving the 2.7-2.9 GHz band. These are:

1. The emission spectrum characteristics of existing components, particularly conventional magnetrons.
2. Poor frequency stability and tolerance characteristics of the devices.
3. High density of equipments using the band.
4. Planned requirements for use of dual-frequency diversity, which will tend to add to spectrum congestion.
5. Lack of adequate susceptibility reduction in radar receivers.

ACTUAL UTILIZATION OF THE 2.7-2.9 GHz BAND IN A DENSE ENVIRONMENT

An area within 200 miles of Los Angeles was selected as a sample dense environment to be studied. Results of calculations indicated that most FAA ASR's should operate without significant interference. Predictions of significant interference to a number of other radars were investigated. It was learned that some of the more serious problems are being eliminated through time-sharing and operational coordination procedures.

Occasional interference experienced by FAA could be caused by (1) frequency drifts, tuning errors or uncoordinated changes in operational frequencies, (2) mainbeam illumination by tracking or height-finding radars for extended periods of time, and (3) combinations of backlobe, sidelobe and mainbeam couplings occurring when antennas become suitably oriented during rotation to cause wedges of more intense and pronounced interference.

EQUIPMENT FACTORS AND SELECTED DESIGNS AFFECTING COMPATIBILITY

Pulse parameter and receiver selectivity relationships to system performance are presented in the report. Maximum emphasis for achieving compatibility is given to improved emission spectrum characteristics. It is apparent that coaxial magnetrons and, to an even greater extent, klystrons, are far superior to conventional magnetrons. Their emission spectra are "cleaner"; drift and tolerance characteristics are considerably improved. The study suggests that a drift/tolerance level of ± 250 kHz is achievable.

The use of pulse shaping techniques with klystrons can provide superior spectral fall-off characteristics. It was theoretically indicated for the conditions described on page 2-33 under "Spectral Roll-off" that if klystrons were used instead of conventional magnetrons, about a four-fold increase in the number of users could be accommodated.

Channelization procedures are feasible, particularly if equipment with improved radiation characteristics are employed. With the use of klystrons, five MHz channelization is practicable. However, it would be necessary to assign any remaining radars using conventional magnetrons to more than one channel and to maintain continuing surveillance of their frequencies and emission spectra.

In order to assure minimal interference conditions for all radars in the high density area projected for the future, equipment with improved radiation characteristics would be required. These improved radiation characteristics must be more stringent than the requirements of the OTP Radar Spectrum Engineering Criteria. Transmitter output devices and radar design techniques are available for achieving the required improvement in radar characteristics.

Pulse compression techniques can be used to achieve resolution obtainable by narrower pulses without their associated broad spectrum effects. Pulse coding techniques could also be used to reduce interference levels. The use of orthogonal polarization would tend to reduce mainbeam-to-mainbeam interactions, but the probability of this type of interaction is very small.

THE EFFECTS OF IMPROVED EQUIPMENT CHARACTERISTICS AND CHANNELIZATION ON SPECTRUM UTILIZATION

The study was concerned primarily with the feasibility of establishing equipment standards which could lead to discrete channel assignments and improved utilization of the 2700-2900 MHz band. Toward this aim, analyses were conducted using improved equipment characteristics consistent with the above objective. The improved emission spectra of the GCA's were that of a coaxial magnetron. The ASR emission spectra were that of a klystron with a ratio of pulse duration to pulse rise time of two and either a trapezoid pulse shape or a cosine squared rise and fall trapezoid pulse shape.

The amount of spectrum required to accommodate operation of all primary emitters in the test environment (eight ASR's and six operational GCA's operating in the aeronautical radionavigation service) was determined. The assignment of all primary emitters operating with dual-frequency diversity in accordance with an FAA specified "stringent" threshold criterion, with the ASR's utilizing only trapezoid pulse shaping, required the entire 200 MHz band. Under the same conditions, if the ASR's only operated with dual-frequency diversity, 165 MHz was required. With the ASR's employing cosine squared trapezoidal pulse shaping, 155 MHz was required when all operated with dual-frequency diversity. TABLE 2-7 contains these results and the results of other analyses for single channel and dual-frequency diversity operation of ASR's and GCA's assigned in accordance with two different interference threshold criteria. If secondary emitters utilize conventional magnetrons, assignment in accordance with the FAA specified "stringent" threshold criterion would not permit accommodation of a single secondary emitter (operating in the radiolocation service), since every secondary emitter would interact with at least one primary facility. Secondary emitters could be accommodated in the 2.7-2.9 GHz band to the extent described in the examples discussed on pages 2-55 through 2-57 when assigned in accordance with the less stringent interference threshold criteria.

The feasibility of initially segmenting the band for radars with improved characteristics was also explored in accordance with the less stringent interference threshold criterion. The eight ASR's were assigned exclusively to one segment of the band providing them with klystrons with cosine squared trapezoidal output pulses. When the GCA's were restricted to their nominal tuning range, some interference was caused by a height finder for both single channel and dual-frequency diversity operation of the ASR's. This analysis was repeated without restricting the ASR's to any portions of the band. There was no change in the interference potential. On the basis of this limited analysis, it is concluded that segmentation of the band would be feasible in the test environment at the possible cost of restricting assignment flexibility.

On the basis of additional analyses in accordance with the less stringent interference threshold, it is concluded that (1) the 2700-2900 MHz band will not support dual-frequency diversity operation of the 14 primary emitters in the sample Los Angeles test environment analyzed when they employ conventional magnetrons; and (2) if only the eight ASR's, using conventional magnetrons, employ dual-frequency diversity, they could not be accommodated. If the GCA's were restricted to their nominal tuning-range the interference levels were even more severe.

APPENDIX A

USE OF THE 2.7 TO 2.9 GHz BAND

The 2.7 to 2.9 GHz frequency band is allocated for use by the radars of three radio-determination services. These are the aeronautical radio-navigation and meteorological aid services, which with certain restrictions are given primary allocation in the frequency band, and the radiolocation service, which has a secondary allocation.

Special purpose use by the military services is also accommodated on occasion, but this use must be fully coordinated with the service that has primary allocation. According to OTP regulations, stations of secondary service:

1. Shall not cause harmful interference to stations of primary or permitted services to which frequencies are already assigned or to which frequencies may be assigned at a later date;
2. Cannot claim protection from harmful interference from stations of a primary or permitted service to which frequencies are already assigned or may be assigned at a later date;
3. Can claim protection, however, from harmful interference from stations of the same or other secondary service (s) to which frequencies may be assigned at a later date.

FREQUENCY BAND RULES AND EQUIPMENT DESCRIPTIONS

Rules laid down by the governing bodies concerning the services using or planned for use in the 2.7 to 2.9 GHz band are given in the following paragraphs; descriptions of typical equipments are also included.

Aeronautical Radionavigation

Rules. Rules for the aeronautical radionavigation service restrict the 2.7 to 2.9 GHz frequency band to ground-based radars and, in the future, to associated airborne transponders only when actuated by radars operating in this frequency band. Nongovernment land-based radars in the aeronautical radionavigation service may be authorized in the 2.7 to 2.9 GHz frequency band, subject to the conclusion of appropriate arrangements between the Federal Communications Commission and Government agencies concerned, and upon special showing of need for service, which the government is not yet prepared to render. (References 2 and 17, footnotes 43 and 346 respectively.)

Equipment Types and Functions. TABLE A-1 lists the equipment types used by the aeronautical radionavigation service. They are all ground-based search (surveillance) radars. When used by the military services they are usually part of a ground controlled approach system. Only those nomenclatures for which at least one is estimated operational or for which future deployments are planned are shown in the table. Information is from ECAC Environmental Files.

TABLE A-1

AERONAUTICAL RADIONAVIGATION RADARS ESTIMATED OPERATIONAL

Nomenclature	Number Estimated Operational
ASR-1	2
ASR-2	6
ASR-3	8
ASR-3B	5
ASR-3M	4
ASR-4	45
ASR 4B	3
ASR-5	38
ASR-6	35
ASR-7	13
ASR-8	Future Deployment
AN/CPN 4	12
AN/CPN-4A	24
AN/CPN-18	3
AN/CPN-18A	4
AN/CPN-18C	3
AN/FPN-28	4
AN/FPN-28A	3
AN/FPN-47	31
AN/GPN 6	2
AN/MPN-5	4
AN/MPN-5A	2
AN/MPN 5B	3
AN/MPN-11	2
AN/MPN 11B	4
AN/MPN 11D	2
AN/MPN-11E	1
AN/MPN-13	40
AN/MPN 14	18
AN/MPN-15	10
AN/MPN-16	3
AN/MPN 17A	3
AN/TPN 19	Near Deployment Date

The Meteorological Aids Service

Rules. Ground-based meteorological-aids radars are authorized to operate on a basis of equality with the aeronautical radionavigation service in the 2.7 to 2.9 GHz band. (Reference 17 footnote 366.)

Equipment Types and Functions. TABLE A-2 lists the nomenclatures of weather radars presently in use and the number estimated operational. They are all ground-based search radars. This information is also from the ECAC Environmental Files.

TABLE A-2

WEATHER RADARS ESTIMATED OPERATIONAL

Nomenclature	Number Estimated Operational
AN/FPS-41	7
MRT-2	4
WSR-1	17
WSR-1A	2
WSR-3	35
WSR-4	3
WSR-57	30

The Radiolocation Service

Rules. Additional restrictions have been placed on the development of new equipment for use in other than the primary function of the frequency band. [MCEB 445/33, Dec. 1963, revised Aug. 1970 (CONFIDENTIAL document]. Use of the 2.7 to 2.9 GHz band by military fixed and shipborne air defense radiolocation installations are required to be fully coordinated with the primary users, the meteorological aids and aeronautical radionavigation services.

> Temporarily, and until certain operations of the radiolocation service in the band 2700-2900 Mc/s can be transferred to other appropriate frequency bands, the aeronautical radionavigation and meterological aids services may, in certain geographical areas, be subject to receiving some degree of interference from the radiolocation service (Reference 2, footnote 42).

Equipment Types and Functions. A search of ECAC's Environmental Files revealed the operation of both ground-based and airborne radiolocation service radars in this band. The ground-based radars consist of height-finding, tracking, and acquisition radars. The airborne radars consist of the AN/APS-20 radars. Of significance is the fact that all of the radars but the AN/APS-20 have tuning ranges confined to this band; the AN/APS-20 type radars have an upper bound at 2910 MHz. This, in general, precludes tuning the secondary users outside the band to avoid interference.

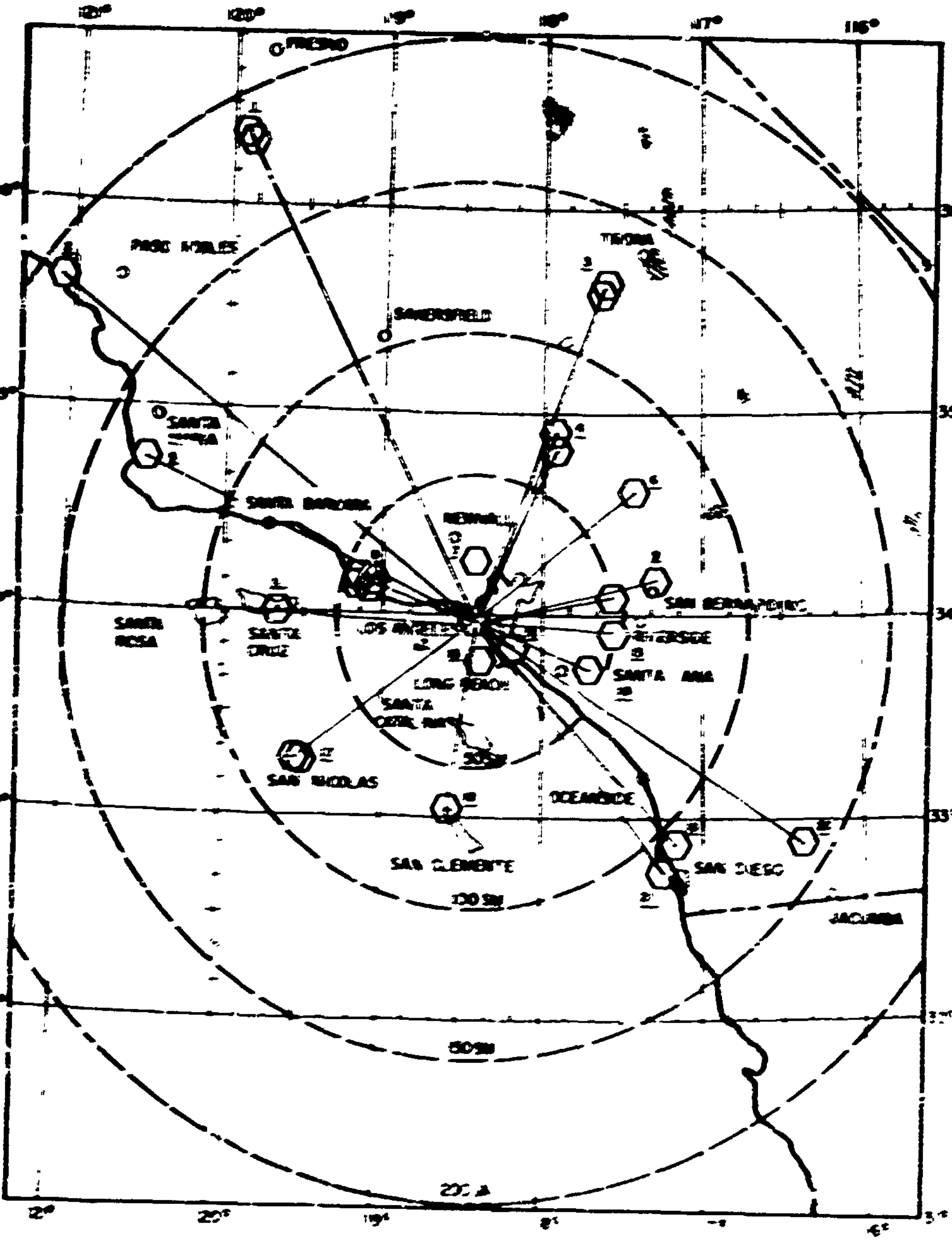
There are 154 height finders in operation and are typically AN/FPS-6's or AN/FPS-90's. The acquisition radars number 22 and are AN/FPS-18's or ground-based AN/APS-20's. The tracking radars number 92 with numerous types and characteristics.

There are several hundred airborne AN/APS-20 ( ) radars in use presently. These radars were built with two modes of possible operation, search and beacon. The low power beacon mode is generally not used, and no new beacon development shall be permitted in the band (See Reference 18).

ENVIRONMENT OF THE 2.7 TO 2.9 GHz FREQUENCY BAND AT LOS ANGELES

ECAC Data Base sources indicated that in the 2.7 to 2.9 GHz band, there are a total of 28 radars, located at 21 different sites, within 200 miles of Los Angeles. These are depicted on the Los Angeles area map, Figure A-1, and identified in TABLE A-3. (It was determined that several tracking radars of the SCR-584 type are installed at Point Mugu, but only two have been shown on the listing since it is not likely that more than two would operate simultaneously.)

The locations shown in Figure A-1 depict fixed equipments. A study of the mobile environment indicates that only two equipments pose a major interference threat: the AN/APS-20C and the AN/APS-20E. An investigation has shown that the AN/APS-20C radars are used in two types of Navy aircraft. The AN/APS-20E radars are used in six types of aircraft. It is expected that some of these aircraft will be deployed periodically in the Los Angeles area. The characteristics of the radars in the chosen environment are shown in TABLE A-4.



Note: See TABLE A-3 For identification of Radar Types

Figure A-1. Location of Radars in the Los Angeles Area 2.7 to 2.9 GHz

TABLE A-3

LIST OF RADARS LOCATED BY NUMBER ON LOS ANGELES AREA MAP

Location No.	Location	Radar	Operating Agency and Function
1	Lemoore NAS	AN/CPN-4 ASR-5	Navy, GCA FAA, Airport Surveillance
2	Cambria AFS	AN/FPS-6	AF, Height Finder
3	China Lake NTC	SCR-584 SCR-729B	Navy, Tracking Navy, Tracking
4	Edwards AFB	AN/MPS-19 ASR-5	AF, Tracking FAA, Airport Surveillance
5	Vandenberg AFB	AN/MPN-13	AF, GCA
6	George AFB	AN/MPN-13	AF, GCA
7	Burbank, California	ASR-6	FAA, Airport Surveillance
8	Point Mugu NTC	SCR-584 SCR-584 AN/FPN-46	Navy, Tracking Navy, Tracking Navy, GCA
	Laguna Peak	AN/APS 20	Navy, Surveillance
9	Norton AFB	AN/MPN-15	AF GCA
10	Ontario, California	ASR-5	FAA, Airport Surveillance
11	Santa Cruz Isle	AN/APS-20	Navy, Surveillance
12	Los Angeles Int.	ASR-4	FAA, Airport Surveillance
13	Corona NTC	SCR-584B	Navy, Tracking
14	Long Beach, California	ASR-5	FAA, Airport Surveillance
15	San Pedro AFS	AN/FPS-90	AF, Height Finder
16	El Toro	ASR-5	Marine GCA & FAA
17	San Nicolas Isle	SCR-584 AN/APS-20	Navy, Tracking & Surveillance Navy, Tracking & Surveillance
18	San Clemente Isle	AN/CPN-4	Navy, GCA
19	Mirimar, California	ASR-5	FAA, Airport Surveillance
20	Mt. Laguna	AN/FPS-90	AF, Height Finder
21	San Diego NTS	AN/CPN-4A	Navy, GCA

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TABLE A-4

CHARACTERISTICS OF RADARS IN THE LOS ANGELES AREA

Radar	Lo fo MHz	Hi fo MHz	Oper Func	Po Peak kW	P. W. μs	PRF PPS	Output Tube	Rec Sens dBm	Rec BW MHz	Ant Gain dB	Ant Beam Width	Ant Pol	Ant Scan Info
Fixed Equipments													
AN/APS 20	2850	2910	Surv	750	2	295-315	QK428	-102	1	31	3.5x8	H	10R
AN/CPN4 & 4A	2780	2820	GCA	600	.5	1500	5586	-106	2.25	33	2.2x3.6	V-C	20R
AN/FPS 6 & 90	2700	2900	HF	3000	2	360	QK327A QK338	108	.8	38	3.1x8	V	1R
AN/MPN 13 & 15	2780	2820	GCA	750	.7	1100	5586	-106	2.25	32	2.3x18	H-C	15R
&AN/FPN 48													
AN/MPS 19	2700	2900	Track	500	.8	2000	5586	-110	3	33	3x3	V-C	0-20R
ASR 4	2700	2900	Surv	425	.8	700-1200	5586	-102	2.4	34	1.5x4	V-C	15R
ASR 5 & FPS 47	2700	2900	Surv	400	.8	700-1200	5586	-109	2.7, 5	34	1.5x30	V-C	12, 15R
ASR 6	2700	2900	Surv	400	.8	.71-1.2K	5586	-109	2.7, 5	34	1.5x30	V-C	12, 15R
SCR 584 & 584A	2700	2900	Track	210	.8	365-1707	2J31-34	95	2	33	4x4	Rot	Track
AIRBORNE													
AN/APS 20C & E	2850	2910	Search	2000	.67, 2	300-900	QK428	-107	1.2	34	3.5x6.5	H	2, 5, 15R

SPECTRUM USAGE

A study of the present use of the 2.7 to 2.9 GHz frequency band in the Los Angeles area resulted in the list of frequencies shown in TABLE A-5. The operating frequencies were obtained from ECAC's automated electronics equipment file (E-file) and their use confirmed by the appropriate frequency coordinators. Use of frequencies shown for the tracking radars could not be confirmed. These radars are used by the Navy test centers and operate only on frequencies which are assigned for specific test periods; they are coordinated with all other agencies prior to the test. Many of the frequencies shown for the other radars are assigned permanently and, in the case of the ASR, have not been changed for five years.

Figure A-2 illustrates graphically the frequency usage in the Los Angeles area related to the type of service being performed by the radar.

EQUIPMENT USAGE AND INTERFERENCE POTENTIALS

Airport Surveillance Radar-FAA

The FAA ASR radars shown in Figure A-2 are required to operate continuously. To maintain continuous operation, it is necessary that these radars have two interference-free operating channels available at all times. In this way they can immediately change from one channel to the other in the event of equipment malfunction in the operating channel. This is necessary to assure that regularly scheduled air traffic can be controlled satisfactorily and without interruption. Essentially any degree of interference is unacceptable for this type of service; the mission is such that even a few minutes loss of use of the ASR cannot be tolerated.

Functions. The function of the FAA surveillance radars requires that the moving target indicator (MTI) receiver be in continuous use. Use of the MTI with staggered PRF makes it difficult to use many of the common interference-reduction techniques. The existence of interference is more noticeable on FAA ASR radars, in that they are being monitored by operators at all times and scan a full 360°.

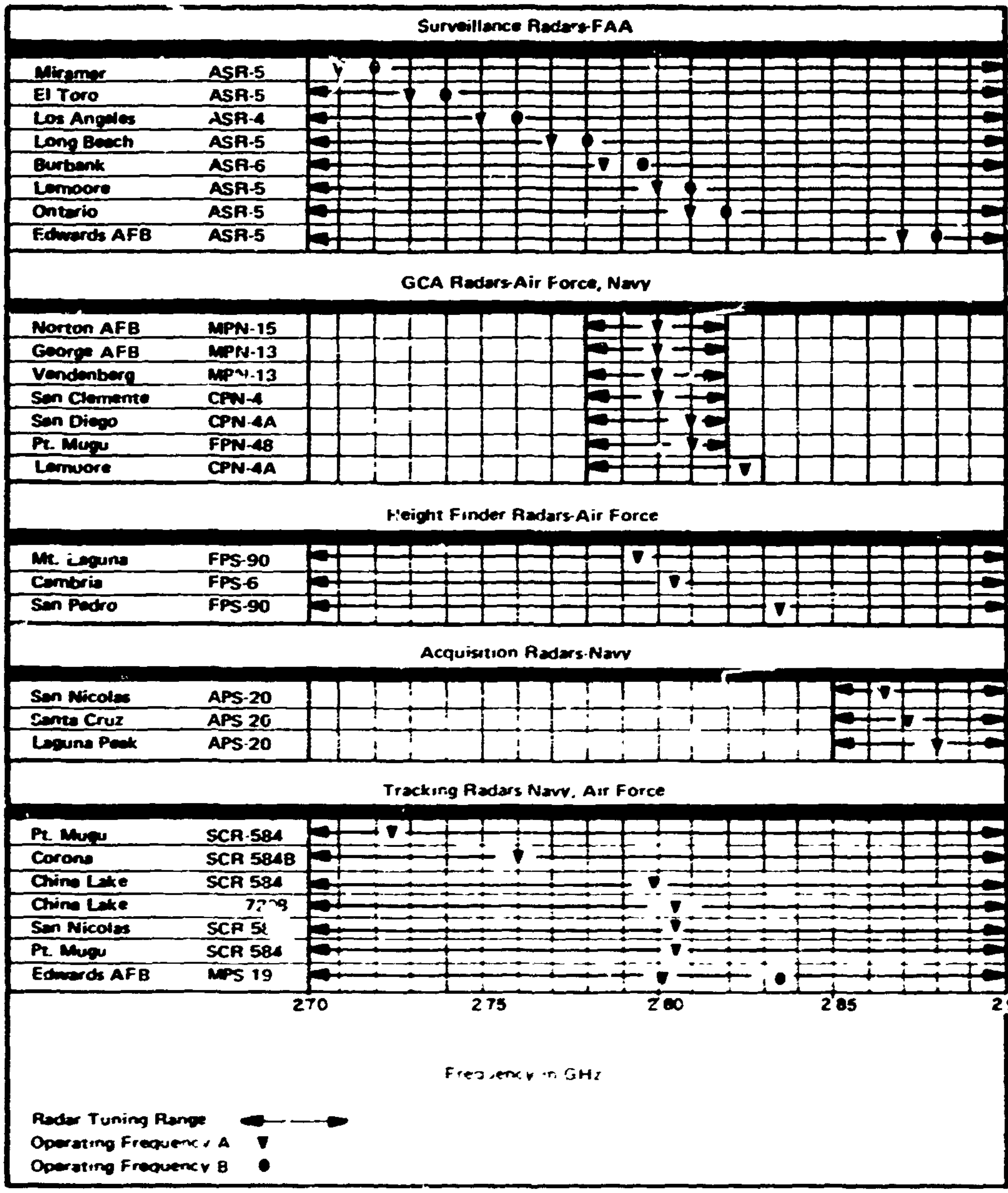
Another characteristic of the ASR operation is that frequencies are generally fixed, once a frequency has been assigned, there is little requirement for changing to another frequency except to avoid persistent interference of a high level.

TABLE A-5

LOS ANGELES AREA FREQUENCIES

Location	Nomenclature	Function	Agency	Freq., MHz
Miramar	ASR-5	AS*	FAA-N‡	2710, 2720
El Toro	FPN-47	AS	FAA-MC‡	2730, 2740
Los Angeles Int.	ASR-4	AS	FAA	2750, 2760
Long Beach	ASR-5	AS	FAA	2770, 2780
Burbank	ASR-6	AS	FAA	2785, 2795
Lemoore	ASR-5	AS	FAA-N‡	2800, 2810
Ontario	ASR-5	AS	FAA	2810, 2820
Edwards A.F.B.	ASR-5	AS	FAA	2870, 2880
Norton A.F.B.	MPN-15	GCA	AF	2800
George A.F.B.	MPN-13	GCA	AF	2800
Vandenberg A.F.B.	MPN-13	GCA	AF	2800
San Clemente Isle	CPN-4	GCA	Navy	2800
San Diego	CPN-4A	GCA	Navy	2808
Pt. Mugu	FPN-48	GCA	Navy	2808
Lemoore	CPN-4A	GCA	Navy	2825
Mt. Laguna	FPS-90	HF	AF	2793
Cambria A.F.B.	FPS-6	HF	AF	2809
San Pedro Hill	FPS-90	HF	AF	2834
San Nicolas Isle	APS-20	SURV†	Navy	2866
Santa Cruz Isle	APS-20	SURV	Navy	2871
Laguna Peak	APS-20	SURV	Navy	2880
Pt. Mugu	SCR-584	Track	Navy	2724
Corona	SCR-584B	Track	Navy	2760
China Lake	SCR-584	Track	Navy	2800
China Lake	7298	Track	Navy	2805
San Nicolas Isle	SCR-584	Track	Navy	2805
Pt. Mugu	SCR-584	Track	Navy	2805
Edwards A.F.B	MPS-19	Track	AF	2801, 2833

* Airport Surveillance
† Surveillance
‡ Joint Use


Surveillance Radars-FAA
Miramar ASR-5
El Toro ASR-5
Los Angeles ASR-4
Long Beach ASR-5
Burbank ASR-6
Lemoore ASR-5
Ontario ASR-5
Edwards AFB ASR-5
GCA Radars-Air Force, Navy
Norton AFB MPN-15
George AFB MPN-13
Vandenberg MPN-13
San Clemente CPN-4
San Diego CPN-4A
Pt. Mugu FPN-48
Lemoore CPN-4A
Height Finder Radars-Air Force
Mt. Laguna FPS-90
Cambria FPS-6
San Pedro FPS-90
Acquisition Radars-Navy
San Nicolas APS-20
Santa Cruz APS 20
Laguna Peak APS-20
Tracking Radars Navy, Air Force
Pt. Mugu SCR-584
Corona SCR 584B
China Lake SCR 584
China Lake
San Nicolas
Pt. Mugu SCR 584
Edwards AFB MPS 19
2.70
2.75
2.80
2.85
2.90
Frequency in GHz
Radar Tuning Range
Operating Frequency A
Operating Frequency B

GCA Radars-Air Force and Navy

The second part of Figure A-2 lists GCA radars (airport surveillance function) used by the Air Force and Navy. These radars are located in close proximity to metropolitan areas and would display a high density of aircraft. The large number of target displays makes any level of interference undesirable.

Functions. Unlike the ASR's, the GCA radars have only single-channel capability and cannot automatically tune to a clear frequency in the event of interference. For this reason a clear frequency should always be made available for this type of service. The GCA radars tune in a 40 MHz band and must be able to move to channels over their band (2780-2820 MHz) whenever necessary to minimize prolonged interference or to follow frequency assignment agreements.

Changing Operations. Future equipments for GCA service are likely to be equipped with two transmitters operating simultaneously. The channels will operate with a frequency separation of at least 80 MHz, thus requiring that two clear channels be available and that their operating band be considerably increased to allow for the separation between channels.

Height Finder Radars-Air Force

There are three height finder radars in the Los Angeles area. Only one of these is in close proximity to the center of the area: the AN/FPS-90 on San Pedro Hill. The other two are at Cambria and Mt. Laguna. These radars are capable of generating severe interference even at considerable distances. The power output of the AN/FPS-90 is approximately 5000 kW peak as compared to 500 kW peak for the ASR and GCA radars.

Functions. These radars are maintained and operated by the Aerospace Defense Command. The mode of operation allows the height finder to scan in azimuth and elevation. Under certain circumstances a height finder antenna may be stopped at a critical azimuth, illuminating other systems in the band for various periods of time depending on the amount of traffic being monitored by the height finder. These height finders are normally tuned to a frequency which does not cause significant interference to other radars in the area (assuming the other radar is not illuminated by its main beam). However, operation of the height finder may change. When it becomes necessary to replace a magnetron, a height finder transmitter may be tuned to a new frequency, which can cause an unacceptable level of interference.

Acquisition Radars-Navy

There are three radars shown on Figure A-2 used by the Navy for range surveillance at Point Mugu. These are AN/APS-20 radars, normally used in aircraft but which have been adapted for fixed use. These radars, at Laguna Peak, Santa Cruz Island and San Nicolas Island, provide weather and traffic information in the range area and make possible the coordination of testing being carried on by the missile ranges. The radars are operating on fixed frequencies but are capable of being tuned from 2850 to 2910 MHz. There is a requirement for adequate frequency separation between the three systems because of possible simultaneous use. Also, they must be capable of tuning to frequencies provided by the area frequency coordinator. It is not likely that all three of these radars would be required to operate 24 hours a day, every day. However, there may be times when operation for extended periods is required, and extremely close coverage is of the utmost importance for assurance of range safety.

Tracking Radars-Navy, Air Force

The last group of radars shown in Figure A-2 are tracking radars used by Point Mugu, Corona, Edwards Air Force Base and China Lake test centers. These are used for tracking specific test vehicles and it is very unlikely that they would ever be used continuously or even for long periods of time. For most cases the frequency and time of operation would be planned well in advance of the test so that no interference would be experienced by any of the agencies sharing the band. The tracking radars for most operational requirements could satisfactorily operate on fixed frequencies, but the capability is required to tune to frequencies over a considerable portion of the band in order to avoid interference between tracking systems and to comply with frequency assignment plans.

Airborne Radars-Navy

The AN/APS-20C and -20E radars are used on several types of Navy aircraft, as noted at the beginning of this section. The "location" of the tuning range of these radars at the very end of the band (2850-2910 MHz) helps mitigate the interference situation. This has been further aided by planning the frequencies for the ASR and other services for use in the lower 75 percent of their tuning range. In the case of the GCA radars, for example, they cannot be tuned much above 2820 MHz. Therefore, interference should not be experienced unless distance separation becomes small or there is an image response problem. See SECTION 2, Figure 2-1.

SUMMARY OF ENVIRONMENTAL DESCRIPTION

The description of the environment based on computerized files and updating material shows that there are presently six types of service being provided by 28 radars in the 2.7-2.9 GHz frequency range in the Los Angeles area. These are FAA Air Traffic Control, Military Air Traffic Control, Air Force Height Finding, Navy Range Surveillance, Military Tracking and Navy Airborne radars.

A frequency assignment plan has been in effect in the area for several years. This plan has been effective in reducing interference, but does not allow for much flexibility in frequency changes and will not be adequate in the event that some of the radars are converted to frequency diversity operation. (See SECTION 2.)

Careful direction of spectrum usage for the services in the Los Angeles area might provide more flexibility in the present operation and reduce incidences of interference. Selection of blocks of frequencies for the various types of service might aid in eliminating the number of cases of interference in general and those cases from electronic countermeasures (ECM), which have been experienced in the past.

By selecting radars for joint usage, the total usage of the spectrum in the Los Angeles area might be decreased, thus reducing the crowded spectrum condition which exists at this time. Alleviating this crowding is important when considering that a number of frequency-diversity radars may be introduced into Los Angeles in the future.

APPENDIX B

SUMMARY OF RFI CASES IN THE 2.7 TO 2.9 GHz FREQUENCY BAND

GENERAL

A review of information relative to past and current cases of interference in the 2.7 to 2.9 GHz radio frequency band has been made. Three sources of information were explored. These sources are as follows:

1. Interference cases reported to and analyzed by the Air Force Communications Service (AFCS) and by the Ground Electronics Installation Agency (GEEIA), former elements of which are now part of AFCS;
2. The file of case histories maintained by the FAA in Washington, D.C. for the period 1964-1966.
3. A search of the Defense Documentation Center's collection of reports.

From the GEEIA information, 18 cases were found of which 14 reports and 4 were message requests for assistance in resolving interference cases experienced by Air Force operational commands. These are by no means all the cases of this GEEIA reported interference which have been experienced. These are only the cases where sufficient information has been recorded.

From the FAA files, a number of cases have been reviewed, and the pertinent characteristics of the cases are summarized in tabular form.

A comprehensive search of interference information in DDC did not identify any specific cases of interference in the desired 2.7 to 2.9 GHz frequency band. However, several reports on the subject of interference reduction and on research in the desired frequency range were identified. (See References 19, 20 and 21.)

GEEIA AND AFCS CASES

TABLE B-1 summarizes pertinent information extracted from the 18 AFCS and GEEIA interference cases found in ECAC files of interference reports. Some remarks are appropriate here with respect to the information contained in TABLE B-1. Of the 18 cases listed there were 14 which involved, in one way or another, Air Force

TABLE B-1

SUMMARY OF GEEIA AND AFCS CASES

Offending Radar Function	Victim Receiver Function	No. of Cases	Resolution Technique				
			Frequency Separation	Filter	Synchronize PRF	Receiver Processing	Sector Blank
Height Finder	GCA	5	4		1		
GCA	Height Finder	4	2			2	
Height Finder	Microwave	2		1			1
Height Finder	ASR (FAA)	2	1	1			
GCA	GCA	1	1				
GCA	TROPO	1	1				
Height Finder	Navy Test Facility	1		1			
GCA	Microwave	1		1			
Search	ASR (FAA)	1			1		
TOTALS		18	9	4	2	2	1

height-finder radars of the AN/FPS-6 type. These height finders radiate an extremely high power level and a pattern, essentially a pencil beam, which is periodically directed toward the horizon at various azimuths. The AN/FPS-6 is a magnetron radar with high sideband energy. This type of radar is capable of operating anywhere within the same frequency range as the FAA ASRs and is involved in a high percentage of other cases of interference reviewed.

Nomenclatures of the height-finders that have been noted in the reports are the AN/FPS-6, AN/FPS-90, and the AN/MPS-14. For the purposes of analysis of interference to other radars, these systems all generate a similar spectrum.

TABLE B-1 shows that out of the 18 cases, 9 solutions (or 50 percent) involved separation of frequencies between the interfering systems. In all of the cases involving a height-finder, the height-finder frequency was changed to try to eliminate the interference. This was true even when the height-finder was the radar being interfered with.

The normal sequence of steps to eliminate interference, set forth in these reports, is straightforward:

1. The first step after optimizing victim receiver adjustments is to try to identify the offending system.
2. If the offending system can be identified, determine which system can most easily change frequency.
3. Change frequency and note possible improvement in performance.
4. If frequency change does not provide a satisfactory improvement, some method of time sharing or sector blanking may be worked out between the two systems to temporarily eliminate interference.
5. Resolution of interference involving filtering, synchronizing PRF, or receiver signal processing is sometimes set forth.

The GEEIA interference cases summarized in TABLE B-1 are all situations where an interference problem had existed for some time and the site had requested assistance in eliminating the problem. The reports contained information as to identification of the interference source and signal characteristics. In all cases a technique to resolve the problem was either recommended or implemented.

FAA CASES

TABLE B-2 summarizes interference cases that were taken from one-page interference report forms filled out as each case of interference was experienced in the FAA western region from 1964 to 1966. In many of the cases reported, the interference source was not identified. The final column shows that in 57 percent of the cases essentially no action was taken. This was due mainly to the fact that the radar was still usable in 35 percent of the cases reported, and usable with difficulty for 54 percent of the cases. Other cases where no action was taken involved configurations where techniques for interference reduction could not be employed. Some of the cases were those of single-channel radars where to change frequency would require a considerable effort and would only be undertaken in the event of severe interference.

As shown in TABLE B-2, the actions to reduce interference involved frequency change, turning off the offending source, sector blanking, and reduction of receiver gain. It should be noted that the nature of the interference reduction actions is temporary and does not resolve the interference problem permanently as was the intent in the AFCS and GEEIA problems.

From AFCS, FAA, and GEEIA reported interference, it is evident frequency changes are sometimes made to eliminate the interference. It is probable that new interference will occur should any systems begin changing frequency without sufficient coordination with other users.

A significant point to stress from the TABLE B-2 summary is that the high percentage of cases of interference to ASRs comes from ECM missions being performed against other 2.7 to 2.9 GHz radars operating in the same frequency range as the ASRs. Fifty percent of the interference came from ECM. Of the 11 percent where it was reported that the ASR was unusable, 9 percent were caused by ECM missions. Furthermore, in 15 percent of the cases, chaff dropped by aircraft involved in ECM interfered with ASR operations.

FREQUENCY CHANGE AS AN INTERFERENCE REDUCTION TECHNIQUE

From the AFCS, GEEIA, and FAA reported interference it was determined that changing the frequency of one of the systems in an interference pair was the most commonly attempted method to reduce interference. In the 18 AFCS and GEEIA reports this technique was attempted 9 times out of the 18, or 50 percent. In the

TABLE B-2

SUMMARY OF FAA RFI CASES

Victim Location and Nomenclature	Type Int. Source	Percent of Cases	RFI Level			Interference Reduction					
						Frequency Change					
			1*	2†	3‡	Improvement	No Improvement	Turn Off	Sector Blank	Reduce Gain	None
Los Angeles	Radar	1	1								1
ASR-4	ECM	30	8	14	8	3	2	2			23
	Chaff	14	10	4							14
Palmdale	Radar	4	1	2	1						4
ASR-4	ECM	3		2	1						3
	Chaff	1	1					1			
Long Beach	Radar	10	2	8		3	6	1			
ASR-3	ECM	4		4			4				
March A.F.B.	Radar	5	3	2					2		3
CPN-18	ECM	5	2	3				2			3
McClellan A.F.B.	Radar	4	1	3		3					1
ASR-4	ECM	1		1				1			
El Toro	Radar	4	2	2		3					1
FPN-28	ECM	2	2				1				1
Salt Lake City	Radar	1	1						1		
ASR-4	ECM	1		1						1	
Hill A.F.B.	Radar	4	1	3			1	2	1		
CPN-18											
Seattle	ECM	4		4			1				3
ASR-2											
Spokane	Radar	1		1					1		
CPN-18											
Beale A.F.B.	Radar	1			1	1					
TOTALS		100	35	54	11	13	15	9	6	1	57

* Usable † Usable with Difficulty ‡ Unusable

FAA reports, 28 percent involved frequency change. In TABLE B-1, the first column under "Resolution Technique" is "Frequency Separation." For these cases, the frequency of the interference source was known, and the frequency chosen provided a greater separation between the victim and source systems.

In the FAA cases shown in TABLE B-2 the first column under "Interference Reduction" is headed "Frequency Change." For most of these cases, the interference-source frequency was not known and changing to the other frequency might have resulted in a worse separation just as easily as a better separation.

Analysis of the nine AFCS and GEEIA cases of interference where the technique of frequency separation was attempted to reduce interference, has revealed only limited success in the use of this technique. Distance separation between interference pairs in these cases ranged from .5 to 30 miles. The reports indicate that if a line of sight propagation path exists between the interference source and the victim, it is impossible to completely eliminate interference by frequency separation alone when the interference source illuminates the victim receiver with its mainbeam at these ranges. As much as 90 MHz frequency separation was used for a 22-mile distance between sites without success. In other cases of about a 10-mile distance between sites and where a line of sight propagation path did not exist, it was possible to reduce interference to an acceptable level with 20-to-25-MHz frequency separation between the interference source pair and the victim. For situations where distance was about 1 mile or less between radars, frequency separation was of little use in eliminating interference. In one case, of a distance separation of about one mile, a marginal level of operation was obtained by a combination of frequency selection and use of the video integrator to reduce interference. In another case, where distance separation was 22 miles, it was necessary to resort to temporary sector blanking and eventually install a high-power filter on the interference source.

Figure B-1 illustrates the results of frequency change for the purpose of interference reduction in the cases reported by the FAA western region. There are 12 cases of interference from ECM missions and 16 cases attributed to other radars. In most of the latter cases, it appears that the existence of the interfering radars and their locations were not known. Probably, they were at some distance from the victim receivers, so interference resulted from a change in frequency or possibly an anomalous propagation condition. In 12 of those 16 cases, improvement in reception was achieved by changing to the alternate channel. However, in four of the cases no improvement was noted. For the 12 cases of interference due to ECM, only four

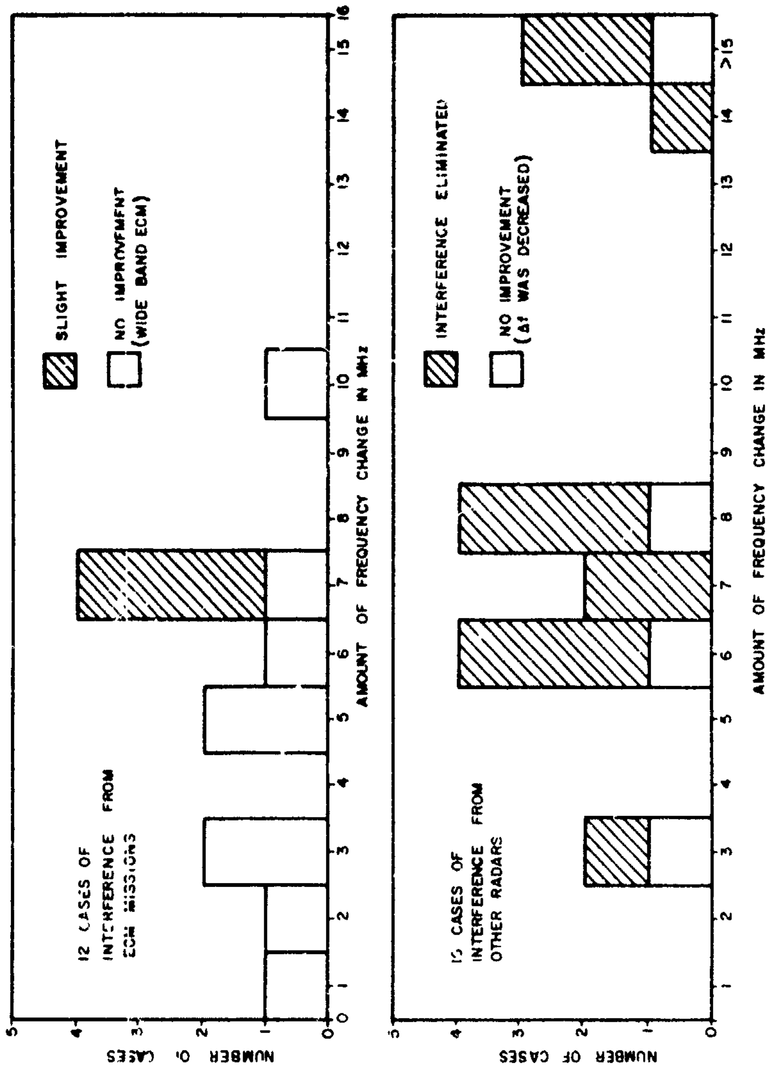


Figure B-1. Results of Frequency Change for Interference Reduction showed improvement when switching to the alternate channel. The ECM interference here is probably of the barrage type and covers the entire tuning range. It is not expected that changing frequency by any amount would reduce barrage interference significantly. It appears that for very severe barrage interference, the only successful solution was to turn off the ECM transmitters.

CHANNEL FREQUENCY SEPARATIONS USED BY FAA

In Figure B-2, 31 radar-channel frequency separations are plotted. Ten MHz is the most common separation. Two other radars show a 110 and 115 MHz separation. However, if these two wide separations are not considered as part of the normal situation, the remainder of the separations are less that 60 MHz. Source of the information of frequency separation is the environmental file maintained at ECAC.

SOME CONCLUSIONS RELATING TO SITUATIONS THAT MAY RESULT IN INTERFERENCE

In addition to the review of the interference cases discussed previously, more detailed reports of problems encountered in the 1968, 69, 70 period have been studied. Considerable correspondence relevant to the evaluation of interference-reduction devices and techniques has been reviewed as have letters which concern FAA operational procedures to be followed when interference is experienced.

From the review of these reports and letters, it appears that many problems of the type reported previously, still occur and that there are still significant periods of time where harmful interference is encountered.

Frequency Separation, ASR's

The ASR's normally operate on a frequency or frequencies which provide good performance and reliability. The systems are required to operate at all times at a performance level to insure public safety. When two channels are available, they are normally separated by 10 to 20 MHz. Some records show that both channels were tuned to the same frequency or to frequencies separated by only 3 or 4 MHz. In these cases, the frequency separation is not large enough to be of much use in eliminating or reducing interference. Normal procedures require alternating channels during periodic performance checks, maintenance periods, or for emergencies such as interference.

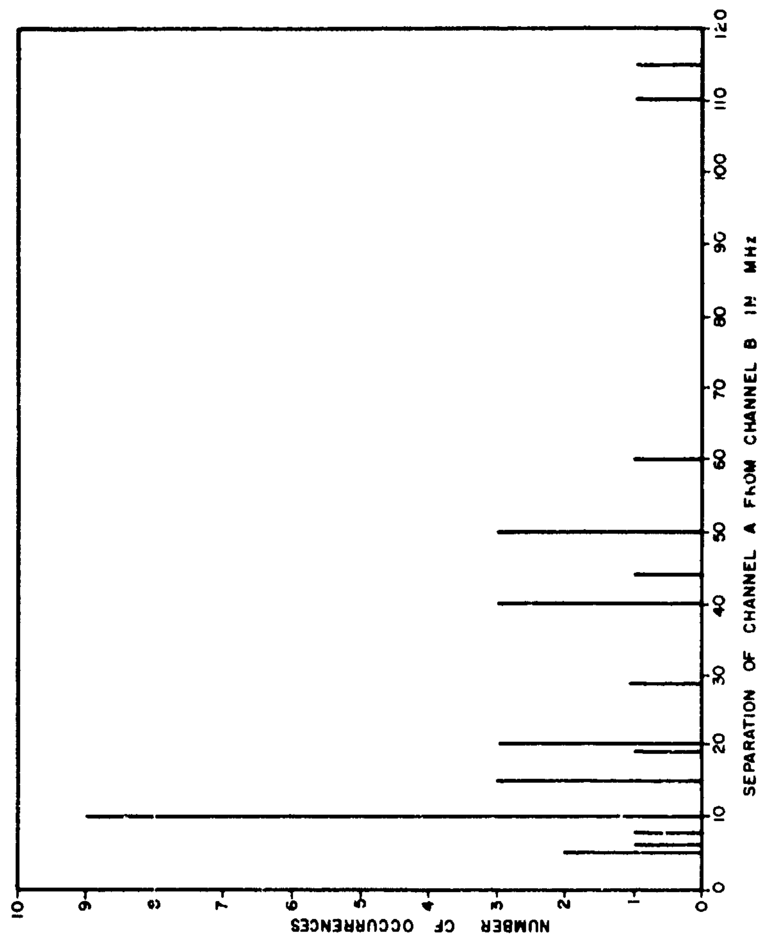


Figure B-2. ECAC Environment File Information On Frequency Separation For FAA Radars With Two Channels

Considering the need for reliability, tuning, and normal procedures described above, some of the situations which may result in interference to the ASR are:

1. Another nearby radar which operates in the same band changes to a new frequency indiscriminately and begins to cause interference;
2. A new emitting device which radiates in the same band deployed (possibly airborne) or installed in the vicinity of the ASR radar with no previous coordination;
3. The operational characteristics of a previously compatible system may change because of a malfunction or be changed intentionally without coordination with the ASR unit;
4. Unusual propagation conditions such as temperature inversions may occur which may cause signal strength from distant radars to increase and cause interference;
5. ECM training missions against radars in the same frequency range as the ASR radars may cause interference.

Interference Reduction Circuitry

A number of interference reduction techniques were discussed in the GEEIA, AFCS, FAA, and DDC interference reports (See Reference 22). Some of these reports indicate that elimination or reduction of interference was accomplished. However, many of these techniques are not compatible with features used on the ASR systems. Further study of them may indicate where improvements are required and under what situations they would be most useful.

Operational Procedures

There are operational procedures which cover the actions that should be taken when a station experiences interference. However, it appears that operational instructions to avoid causing interference during normal operation are needed. These instructions are particularly needed at the time plans are made to operate a radar set on a new frequency or in a new mode or in a new area. An inexpensive, continuously monitoring receiver for those radars which have capability to operate over a frequency range may be desirable. This monitoring receiver would allow each site to observe the spectrum occupancy and maintain optimum frequency separation when changing to a new frequency.

APPENDIX C

FACTORS AFFECTING SPECTRUM ENGINEERING

In this appendix factors are discussed affecting spectrum engineering; these factors are pertinent to the types of systems presently operating in the 2.7 to 2.9 GHz frequency band and to some possible designs of future systems.

Spectrums generated by three types of radar transmitter output tubes are given and compared. These are: a conventional magnetron, a coaxial magnetron, and a klystron. The magnetron spectrums are presented on the basis of a trapezoidal CW driving waveform. Because a klystron is capable of generating a wider variety of waveforms and modulations, klystron emissions are presented on the basis of various pulse shapes and both CW and linear FM (pulse compression) modulation driving waveforms. System performance is dependent on the pulse shape and modulation of the driving waveform. Therefore this appendix begins with a presentation of the relationships between pulse shape and system performance in terms of range resolution, range accuracy, detection in white Gaussian noise, and detection in clutter. Spectrum comparisons are then made in terms of Fourier transforms of different pulse-shape and modulation combinations. Finally comparisons of the three output tubes mentioned above are made in terms of spectra and frequency stability. An absorptive filter suitable for use in the 2.7 to 2.9 GHz frequency band is also discussed.

The appendix concludes with a discussion of phased array antennas and the effect of their use on system performance and on EMC in general and a discussion of compressed pulses and their implications on band channelization, and a discussion on dual antenna-polarization diversity.

RELATIONSHIP OF PULSE PARAMETERS TO SYSTEM PERFORMANCE

The performance categories which have major significance in the pulse parameters contributing to the spectral characteristics of the waveforms are range resolution, range accuracy, and the detection range.

Range Resolution

The range resolution achievable with a particular waveform can be determined by examining the autocorrelation function of the waveform. The autocorrelation functions of three types of pulses, i.e., Gaussian, cosine-squared, and trapezoidal are shown in Figure C-1. The curves illustrated can be approximated for application to other pulse shapes. For example, a trapezoidal pulse with cosine-squared leading and trailing edges will have an autocorrelation function that lies between the curves of the cosine-squared and trapezoidal pulses shown in Figure C-1. Moreover, the function for a chirped pulse can be represented by the function for the chirped pulse waveform when the chirped pulse has been compressed. The major finding obtained from Figure C-1 is that the range resolution of a pulsed waveform is approximately equal to the range represented by one pulse width. In other words, the resolution obtained with a pulsed waveform is essentially independent of the shape of the pulse for all practical shapes and consequently for the pulse shapes that can be designed for radars of the 2.7 to 2.9 GHz band.

Range Accuracy

The range accuracy does depend on the shape of the pulse. As shown in Reference 23, the RMS time delay error is:

$\delta_{T_r} \approx [\tau/4B\ (E/N_o)]^{1/2}$ for a bandwidth limited rectangular pulse (C-1a)

$\delta_{T_r} = \tau/[5.63\ (E/N_o)]^{1/2}$ for a Gaussian pulse* (C-1b)

$\delta_{T_r} \approx \tau/[6\ (E/N_o)]^{1/2}$ for a cosine-squared pulse* (C-1c)

where:

δ_{T_r} = the RMS time delay error, in microseconds

τ = the pulsewidth between half-amplitude points, in microseconds

B = the acceptance bandwidth and is approximately equal to the reciprocal of the rise time of the resulting pulse, in MHz

E = the signal energy in watt-seconds

N_o = the noise density in watts per hertz

* Minimum obtainable error.

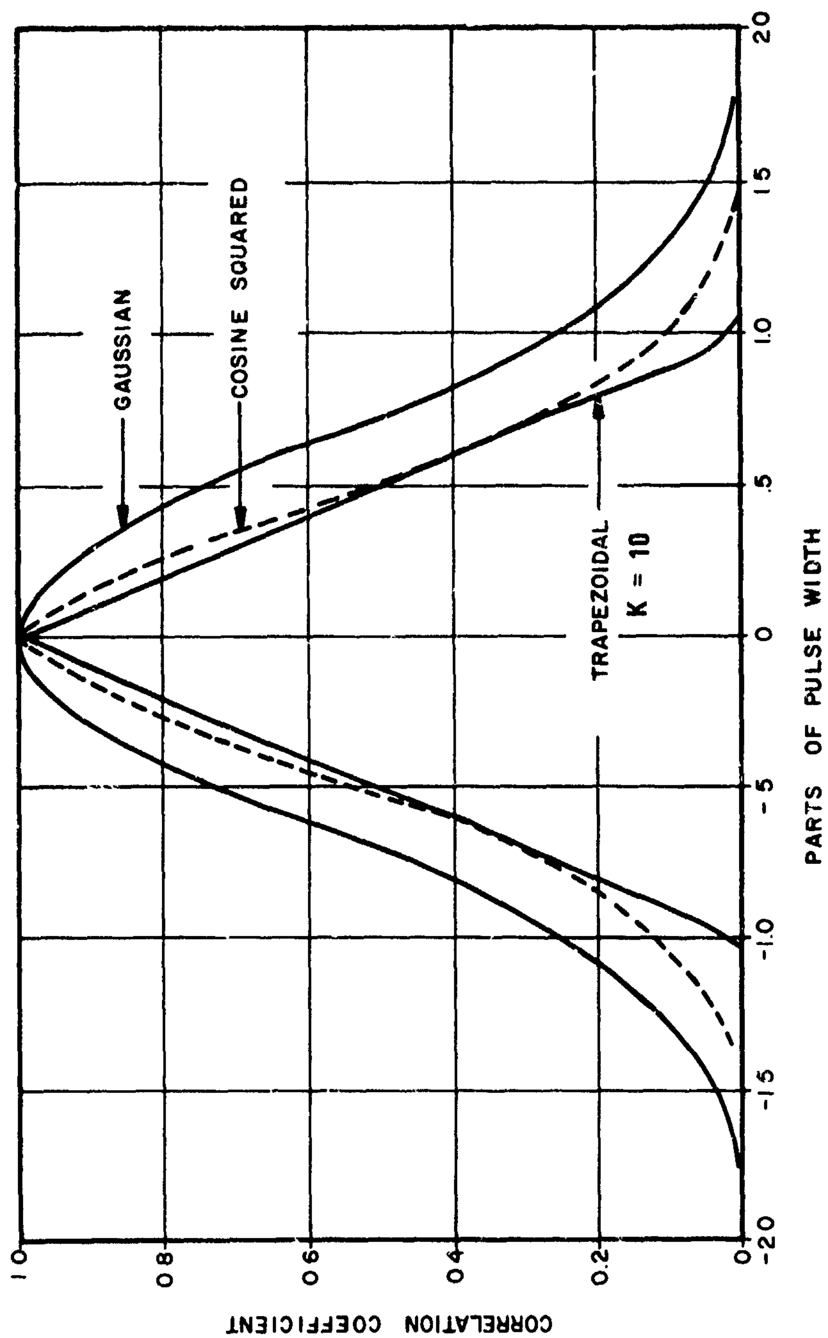


Figure C-1. Autocorrelation Function Of Pulse Shapes

In order to make a reasonable comparison of the range resolution achievable with the different pulse shapes a substitution in Equation C-1a of $B = \frac{9}{\tau}$ is made to approximate the matched filter case. Rigorous techniques described in Reference 23 were used to estimate the errors for the Gaussian and cosine-squared pulse. Comparing these errors with the error for the rectangular pulses yield:

$$(\delta_{T_r})\text{ rectangular} \cong 0.94\ (\delta_{T_r})\text{ Gaussian}$$

$$\cong 0.99\ (\delta_{T_r})\text{ cosine-squared}$$

The range error, δR, is merely $(C/2)\ \delta_{T_r}$, where C is the velocity of light. Accordingly, the RMS range error observed with the bandwidth limited rectangular pulse is approximately the error observed with the bandwidth limited cosine-squared shape pulse.

The RMS time-delay error for a pulse compression waveform consisting of a rectangular pulse of width τ whose carrier frequency is linearly modulated in frequency over the frequency band B is given by:

$$\delta_{T_r} = \frac{\sqrt{3}}{\pi\ B\ (2\ E/N_o)^{1/2}} \tag{C-2}$$

Pulse compression can affect an improvement in range accuracy of a long pulse (narrow emission spectrum). A means of comparing the RMS error obtained with a linear FM pulse compression waveform with a limited "rectangular" pulse occupying the same bandwidth and of the same pulse duration is by finding the ratio R_1 of Equation C-1a to Equation C-2.

$$R_1 = \frac{\text{Rectangular Pulse RMS time delay error}}{\text{FM pulse compression RMS time delay error}}$$

$$R_1 = \frac{\pi}{\sqrt{6}}\ (B\ \tau)^{1/2} \tag{C-3}$$

Ratio R_1 is plotted as a function of the product of effective bandwidth and pulse width and shown in Figure C-2. Note from Figure C-2 that at the $B\tau$ product increases, the ratio increases significantly. At low $B\tau$ products, little differences exist in accuracy performances versus waveshape.

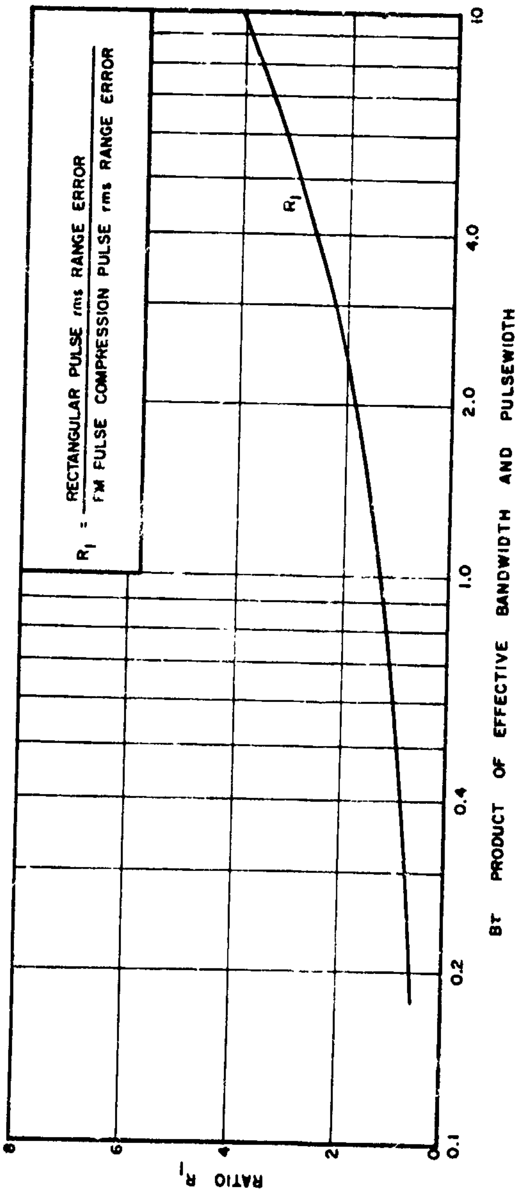


Figure C-2. Range Error Comparisons

Detection in White Gaussian Noise

In white Gaussian noise the familar detection range equation for a single pulse is given as:

$$R^4 = \frac{P_t\, G_t\, A_e\, \sigma_t\, \Sigma L}{(4\ \pi)^2\ K\ T_s\ B_N\ (S/N)} \tag{C-4}$$

where:

R = range

P_t = peak transmitted power

A_e = effective aperture area

G_t = antenna gain

σ_t = target cross section area

K = Boltzman's constant

T_s = system noise temperature

S/N = signal to noise ratio for a given probability of detection

ΣL = sum of system losses such as transmitter loss, receiver loss, collapsing loss, atmospheric loss, etc.

B_N = noise bandwidth

With respect to pulsewidth (and shape) the above equation reflects maximum detection range in two principal ways: first that of power transmitted and second that of matching the receiver to the emission waveform.

In the first way detection is actually related to the energy transmitted in each pulse rather than to the transmitted power as given in Equation C-4. If it is assumed that the receiver is matched to the pulse waveshape then:

$$\tau = \frac{k}{B_N} \tag{C-5}$$

Where k is a function of the pulse shape and ranges from 0.632 for Gaussian pulses to 0.89 for rectangular pulses (an apparently insignificant range), and hence, replacing the terms:

$$\frac{P_t}{B_N} \rightarrow P_t \tau k \rightarrow \text{energy} \qquad \text{(C-6)}$$

Thus,

$$R^4 \propto P_t \tau$$

The maximum detection range is directly proportional to the 4th root of the pulsewidth of the waveshape. (For detection in the presence of clutter, this relationship is not restricted to the 4th power. See paragraphs in subsection Detection In Clutter.)

The assumption has been made that a matched-filter receiver is utilized by all radars in the 2.7 to 2.9 GHz frequency band. The term L_m, for a receiver-filter matching-loss, must be included in the range Equation C-4 if a matched filter is not utilized by a receiver. The characteristics of a matched filter in frequency response is the complex conjugate of the received spectrum of the signal. With a rectangular pulse and a $\frac{\sin x}{X}$ filter response, the equivalent noise bandwidth is:

$$B_N = \frac{1}{\tau} \qquad \text{(C-7)}$$

Barton (See Reference 24) based upon the work of North has illustrated the performance of various filters (e.g., receivers) as compared to a matched filter. Their results are shown in Figure C-3. Figure C-3 shows the receiver-filter matching-loss for various pulse waveshapes and receiver filters as a function of the product of receiver-filter bandwidth and pulsewidth. Note that the matched-filter loss is zero at the pulse/bandwidth product one. This is the reference point of the curves.

The curves of Figure C-3 illustrate the dependence of detection range upon pulsewidth, upon receiver bandwidth, and upon waveshape and filter shape. For waveshapes such as cosine-squared and cosine-squared trapezoid, similar curves can be constructed. Generally, curves based upon those waveshapes will lie somewhere between curves 1 and 2 of Figure C-3.

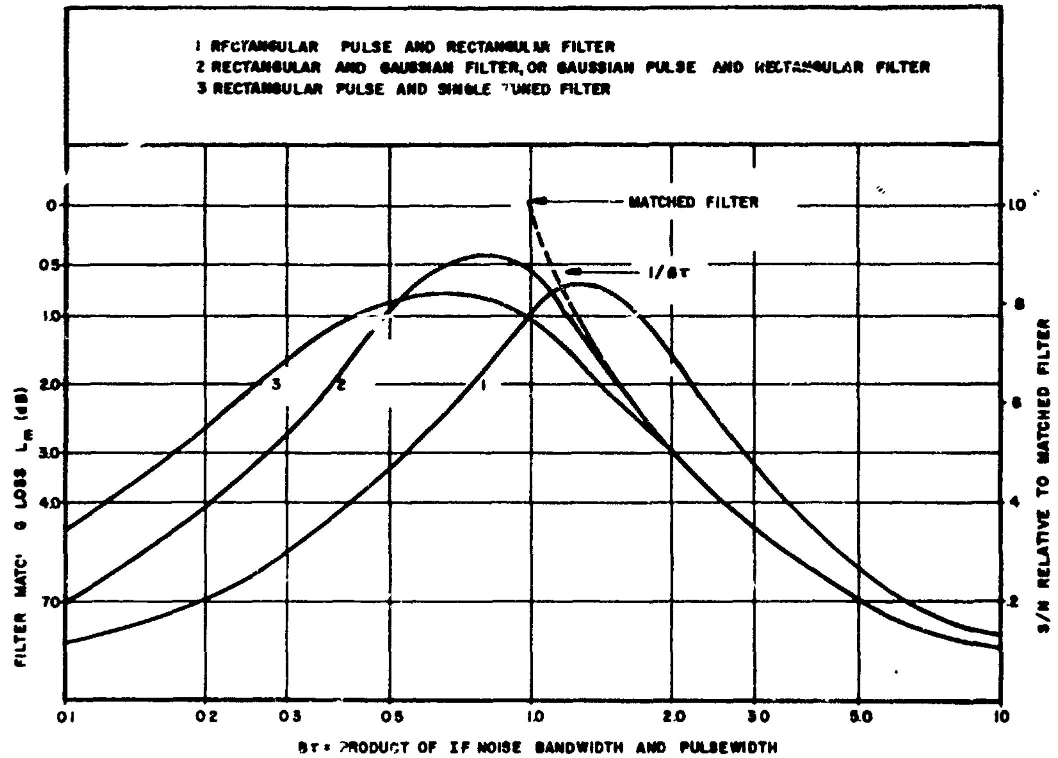


Figure C-3. Filter Matching Loss, L_m

Detection in Clutter

The environment of the 2.7 to 2.9 GHz frequency band, in terms of clutter, for which a radar is intended to operate is not well defined. In general, clutter exists in various forms. First there is volume clutter as seen from rain, snow, and chaff. This form of clutter is usually considered in the form of a large number of finely divided and randomly distributed reflectors. Analysis usually approximates this form of clutter as additive Gaussian noise. Volume clutter may be stationary or nonstationary and is highly dependent on wind and turbulence. Also, the extent of the clutter (e.g., rain) must be considered in design. The second type of clutter is due to terrain (or area clutter). Terrain clutter is not a large number of finely divided and randomly distributed backscatter reflectors, but has large point scatterers such as hills, buildings, watertowers, etc. which is, in most cases, not well defined. Terrain clutter does not have the characteristics of large relative doppler velocities that volume clutter may have. In considering the best waveform and receiver design all these factors that make up volume and terrain clutter should be considered.

The optimization of waveforms and receiver signal processor designs for operation in a clutter environment has been studied by numerous investigators (See References 25, 26, 27, 28 and 29).

The most common design in optimizing performance in clutter where there is a known significant doppler shift is the MTI processor (moving target indicator canceller). In this processor a null in the spectrum of the received echo is placed at the mean doppler velocity of the clutter. Hence, the MTI processor is a clutter-rejection filter. For such a processor, Nathanson (See Reference 30) has developed radar detection range equations for targets in both volume and area clutter. Included in these equations is the clutter improvement factor due to use of the MTI. In the case of volume clutter, two special cases exist. In one case, the wind shear effect is dominant (as when the radar antenna points downwind at distant ranges); in the other case the wind turbulence effect is dominant (as when the radar antenna points crosswind or for short ranges). For area clutter, the range equations are dependent on the angle at which the beam grazes the terrain surface. Two special cases exist for area clutter also. Both cases are dependent upon whether the radar pulse packet is pulsewidth or beamwidth limited. These detection range equations show that the power law of a single canceller MTI may vary between one and four, depending on the condition of the clutter (for a given signal-to-clutter S/C ratio at the input to the detector that is required for a given probability of detection):

$$R^n \propto \frac{1}{(S/C)} \tag{C-8}$$

where n varies from 1 to 4.

In each of the MTI detection-range equations, except for the case where the area clutter is beamwidth limited, the detection range is inversely proportional to the length of the pulse (or pulse packet).

$$R^n \propto \frac{1}{(S/C)\ [(c\ \tau)/2]} \tag{C-9}$$

where:

S/C = signal to clutter ratio

τ = pulsewidth

c = speed of light

Therefore, the width of the pulse waveform is directly related to the detection range of a target, or:

$$R^n \propto \frac{1}{\tau} \tag{C-10}$$

The improvement in detection range resulting from a waveform change in pulsewidth (or emission spectrum broadening) depends upon the clutter.

The shape of the pulse in the MTI processor does not appear to be a significant factor in target detection in clutter. In receiver design it is necessary that the receiver bandwidth be greater than the received spectrum. The degree or receiver widening depends upon the clutter improvement ratio desired, the pulsewidth jitter and PRF jitter allowable, inherent propagation delays, etc.

Improvement in target detection in certain forms of volume clutter is gained through the use of a coded waveform or pulse compression. Manasse (See Reference 26) assumed clutter of a large randomly distributed stationary ensemble of very small independent scatters and no doppler separation of target in clutter. Using this clutter model, Manasse arrived at the S/N for an optimum receiver.

$$\frac{S}{N} = A^2 \int_{-\infty}^{\infty} \frac{|U(f)|^2}{\tfrac{1}{2} N_o + k\ |U(f)|^2}\ df \tag{C-11}$$

where:

$\frac{1}{2} N_o$ is the receiver noise power per cycle

U (f) is the signal spectrum

K is a constant dependent on intensity of clutter

A is an amplitude of the signal

In this expression it is of interest to determine the dependence of S/N on U (f), the transmitted signal waveform. Manasse analyzed the shape of the transmitted waveshape in maximizing S/N subject to the requirements that the pulse energy and pulse bandwidth are fixed. The optimum pulse energy spectrum was shown to be:

$$|U(f)|^2 = E/(2\Delta F) \text{ for frequency within } \Delta F \qquad \text{(C-12)}$$

$$= 0 \text{ otherwise}$$

Hence, with this waveshape

$$S/N = \frac{2A^2 E}{N_o + k\ E/\Delta F} \qquad \text{(C-13)}$$

where E is the energy in the pulse and ΔF is the maximum frequency deviation of the pulse compression waveform.

This expression shows that for this type of clutter the use of a wide bandwidth or the use of a chirped, pulse compression waveform will reduce the clutter and improve the S/N or target detection in clutter.

The waveform in the above is a rectangular spectrum which is flat over the bandwidth. The question arises as to what loss from this optimum will other waveshapes have. All other waveshapes will have part of the pulse energy in their skirts outside the bandwidth. Rihaczek (See Reference 25) has indicated that, in practical terms, the choice of the waveform should be to facilitate detection based upon concentration of the energy in the acceptance bandwidth rather than try to extract much from the outskirts of the transmitted waveform. Therefore waveshapes can be graded (under the constraints of equal pulse energy and bandwidth) dependent upon the relative energy in the spectrum skirts. For pulse compression (or pulse coded) waveforms, then, the following waveforms are graded in descending order of goodness in detection:

1. Gaussian
2. Cosine-squared
3. Cosine-squared-shaped trapezoidal
4. Trapezoidal (10 percent rise and fall)

Receiver Bandwidth Considerations

Previously in this appendix, receiver bandwidth was treated as for either the matched filter case or as a variable. In this subsection consideration is given to selection of the parameters. The minimum emission bandwidth and receiver acceptance bandwidth selected in design depend upon numerous factors. Among these are frequency stability, target characteristics, display techniques, and waveform design. In a surveillance radar, the minimum values of these bandwidths are basically determined theoretically by the specified requirements for target range resolution and range accuracy. Actual design will require the deviation of these theoretical values to compensate for the factors as mentioned above.

Target range resolution in a pulse surveillance radar is determined by the pulsewidth; i.e. resolution = τ. The emission bandwidth is given by:

$$B_{TX} = \frac{0.9}{\tau} \text{ for trapezoidal pulses } (k = 10) \qquad \text{(C-14)}$$

$$B_{TX} = \frac{0.63}{\tau} \text{ for Gaussian} \qquad \text{(C-15)}$$

Figure C-4 is a plot of the two above relationships in terms of resolution in feet as a function of emission bandwidth in MHz. From C-4 it is seen that for a given specified system range resolution a wider emission bandwidth is required for a rectangular or trapezoidal (K = 10) waveform than with a Gaussian waveform. Other waveforms such as the cosine-squared pulse and cosine-squared trapezoidal pulse will lie between the two curves as indicated in the figure. Reference 31 indicates 360 feet of range resolution for minimum range. With this specification, it is noted that for a trapezoidal waveshape an emission bandwidth of 1.2 MHz is the minimum permissible. For a Gaussian waveshape, 0.82 MHz is the minimum.

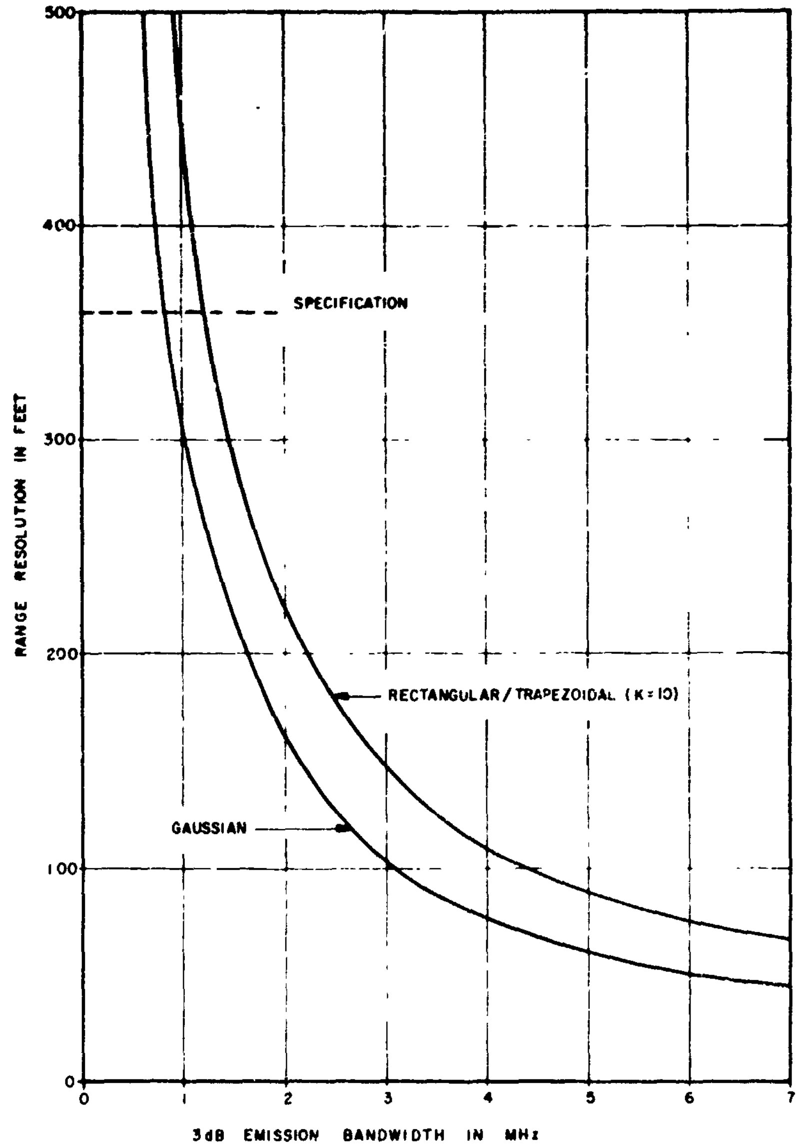


Figure C-4. Range Resolution vs. Emission Bandwidth

Range accuracy depends upon the *viewing* of the emission waveform. The larger the viewing window of the emission spectrum, the better accuracy obtainable. The receiver bandwidth is the viewing window or the acceptance bandwidth for the emission spectrum. Thus, in actuality range accuracy is a function of receiver bandwidth. Equations C-1a, C-1b, and C-1c give the relationships for range accuracy. Figure C-5 is a plot of this relationship for the case of a trapezoidal pulse (K = 10) for various S/N ratios.* From Figure C-5 it is seen that as the receiver bandwidth is increased an improvement in range accuracy is obtained. It is to be noted that the accuracy obtainable for a given bandwidth is dependent upon (S/N)''. Reference 31 specifies that the range accuracy shall be within 3 percent of the range. For a scope range of 6 miles and setting the minimum usable display range at 10 percent of the total or 0.6 miles, the specified range accuracy is 108 feet. From Figure C-5 this accuracy sets a minimum acceptable receiver bandwidth of approximately 0.7 MHz for a $(S/N) \geq 10$ dB. A further requirement being that in all cases the product of receiver bandwidth and pulsewidth be equal to or greater than one.

RADAR TRANSMITTER EMISSIONS

Among the factors having major significance in the decision whether or not to divide the 2.7 to 2.9 GHz frequency band into assignable channels are the spectral characteristics of the emissions of the transmitters being used. The emissions of the ASRs, AN/APS-20s, etc., at least from the standpoint of electromagnetic compatibility, include unintentional emissions and intentional emissions. This subsection sets forth both types and discusses output devices in relation to them.

The spectral characteristics of the intentional emissions have been evaluated by performing a Fourier analysis of the transmitted waveform. The nature and characteristics of the unintentional emissions, which include harmonics, undesired frequency modulation, and extra-spectral noise, depend on the modulation techniques used to generate the waveform and the output devices and filtering employed in the transmitting equipment.

Intentional Emissions

Many authors have described the methods needed to perform an analysis of the various waveforms that can be used in radar applications. In this subsection, the results of such analyses on a few selected waveforms will be presented and references will be quoted where appropriate. It appears impractical to consider any of the selected waveforms in conjunction with magnetron oscillators except

* In the non matched receiver case, as considered herein, the relationship E/N_0 in Equation III 1 is substituted by $E/N_0 = n\tau$ (S/N).

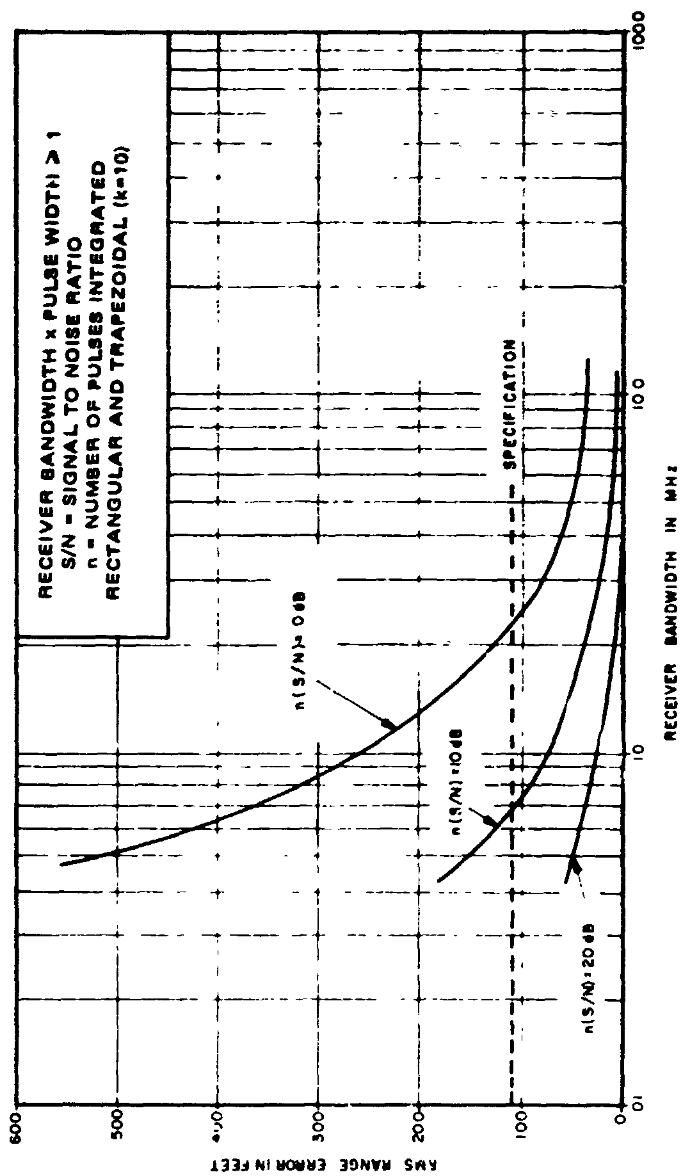


Figure C-5. Range Accuracy as a Function of Acceptance Bandwidth trapezoidal. Klystrons can be used as power amplifiers in the generation of any of the waveforms under consideration. The waveforms examined during the work discussed here include normal trapezoidal, cosine-squared, and Gaussian pulses, and trapezoidal pulses with cosine-squared leading and trailing edges. Included also are frequency modulated pulses having trapezoidal and cosine-squared waveforms.

Spectral Emission Envelopes

Normalized spectrum emission envelopes as a function of pulsewidth for the waveforms discussed here are shown in Figures C-6 and C-7. In Figure C-6, envelopes are shown for a trapezoidal pulse with linear leading and trailing edges trapezoidal pulses with cosine-squared shaped leading and trailing edges, a cosine-squared pulse, and a Gaussian pulse. The parameter K, used in conjunction with the trapezoidal pulses, represents the ratio of the pulsewidth to the rise time of the waveform.

The envelope of the trapezoidal, cosine-squared, and Gaussian pulses represent the loci of points at the lobes predicted by the Fourier transform of the waveforms. The envelopes of the shaped trapezoidal pulses were developed using the methods described by Newhouse (See Reference 32).

The effects of pulse compression techniques are illustrated in Figure C-7. The envelopes of the pulse compression waveforms were developed using the methods described in Reference 33. In this instance, however, the baseline used for comparison is the 0.5 microsecond trapezoidal pulse with K = 10. This spectral emission is then compared with chirp pulses that give the same overall performance relative to the trapezoidal waveform. For illustrative purposes, a pulse compression waveform with a dispersion ratio of 50 is also shown.

Unintentional Emissions

Unintentional generation of energy at frequencies removed from the desired operating frequency always occurs in practical transmitters. The nature of these spurious emissions depends on the modulation techniques employed to obtain the desired waveform and the devices used in the final stages of the transmitters. Three principal types of devices are used in the 2.7 to 2.9 GHz frequency band which enable the output power levels needed; these devices are power-amplifier klystrons, conventional magnetrons, and coaxial magnetrons.

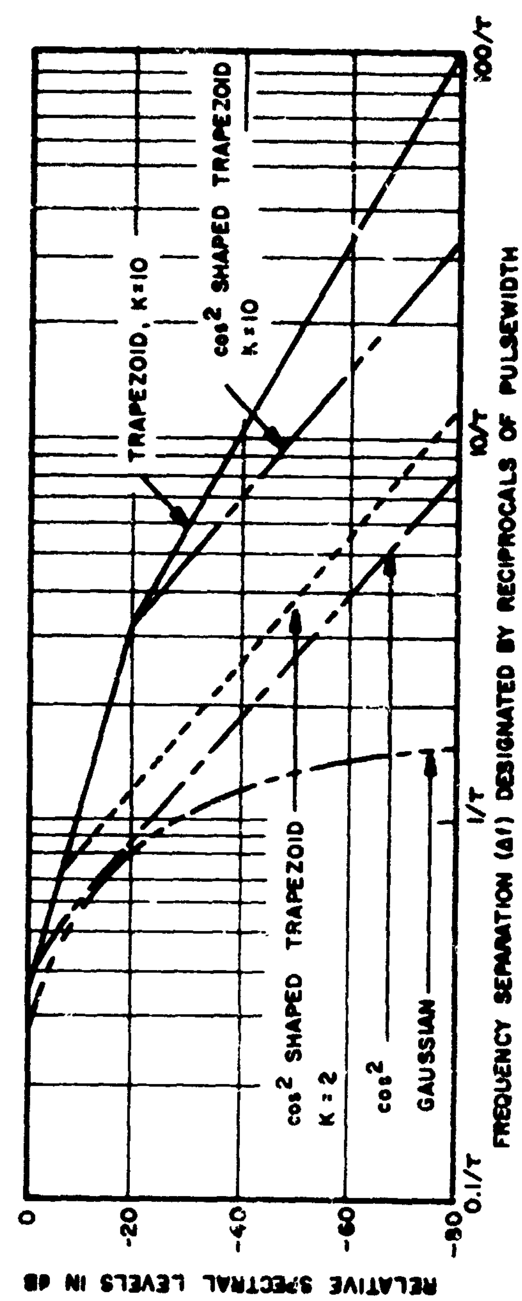


Figure C-6. Fourier Transforms of Waveshapes

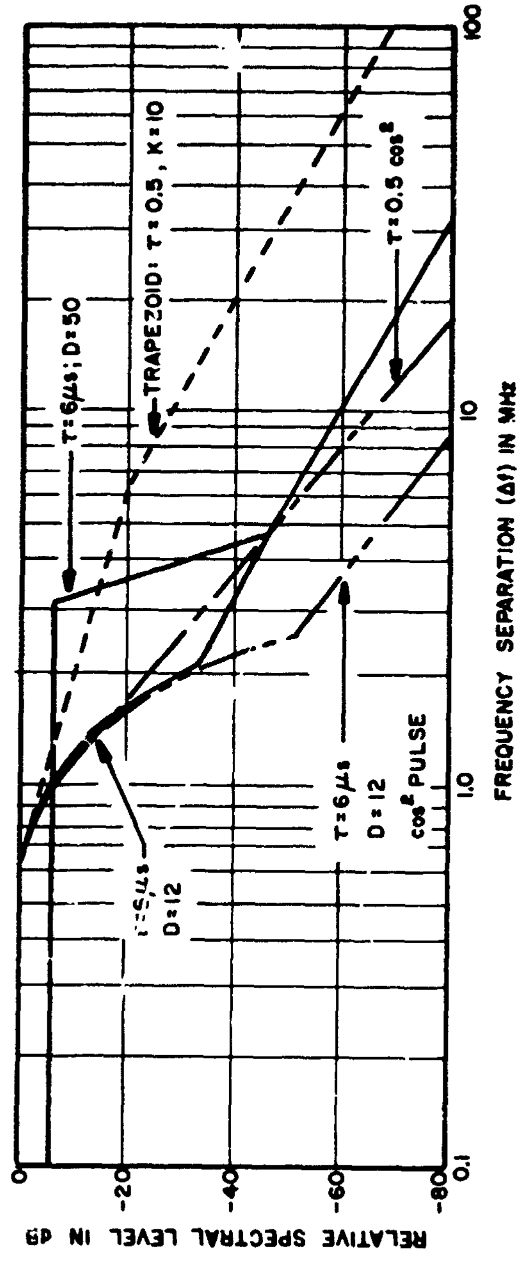


Figure C-7. Effects of Pulse Compression

Conventional Magnetrons

Conventional magnetrons are used extensively in the 2.7 to 2.9 GHz frequency band, although little flexibility is afforded toward spectrum conservation.

Conventional magnetrons generate emission spectrums that are not well confined because of the low Q of the resonant cavity

The operating frequency of a magnetron is determined by cavities integral to the device and significant changes in the operating frequency occur if the amplitude of the modulation pulses is not controlled. Typically the magnetron's frequency during the rise and fall time is lower than the carrier frequency; this instability causes an assymetrical spectrum with excessive power on the low frequency side of the carrier. In addition to this stability problem, magnetrons can also emit high levels of spurious RF energy at frequencies very close to the desired operating frequency. These spurious outputs result from the excitation of undesired operating modes. The frequency separation between these undesired and desired modes depends on the construction of the magnetron (See Reference 34) and the excitation of these modes occurs when the modulator pulse rise and fall times are too slow (See Reference 35). The spurious emissions will generally be removed from 2 to 10 percent from the desired operating frequency and will be at a level of 10-25 dB below the fundamental power output of the transmitter in a 1 kHz bandwidth.

Figure C-8 illustrates the response of a receiver to the spectrum of an AN/FPS-6 height-finder using a conventional magnetron, as measured in a 4 MHz bandwidth. The emission including noise and spurious outputs is shaped by the output tube selectivity and the selectivity of the couplers, transmission line, and antenna. Only a few radars had their emissions measured to this degree of dynamic range, and data of this type is very difficult to obtain. However, all the magnetron systems that have been measured show similar emission spectrum and spurious outputs.

For the analysis at hand, the discussion is concentrated on transmitter emissions within ± 200 MHz of the tuned frequency because the total band extends from 2.7 to 2.9 GHz and the best separation which could be obtained is 200 MHz. Of principal interest is the region ± 20 MHz from the carrier. The irregular shape of the receiver response to a conventional magnetron spectum in this region is shown in Figure C-9. At ± 20 MHz from the operating frequency there is a difference in emission level. Arrow indicates 20 MHz below the tuned frequency where the

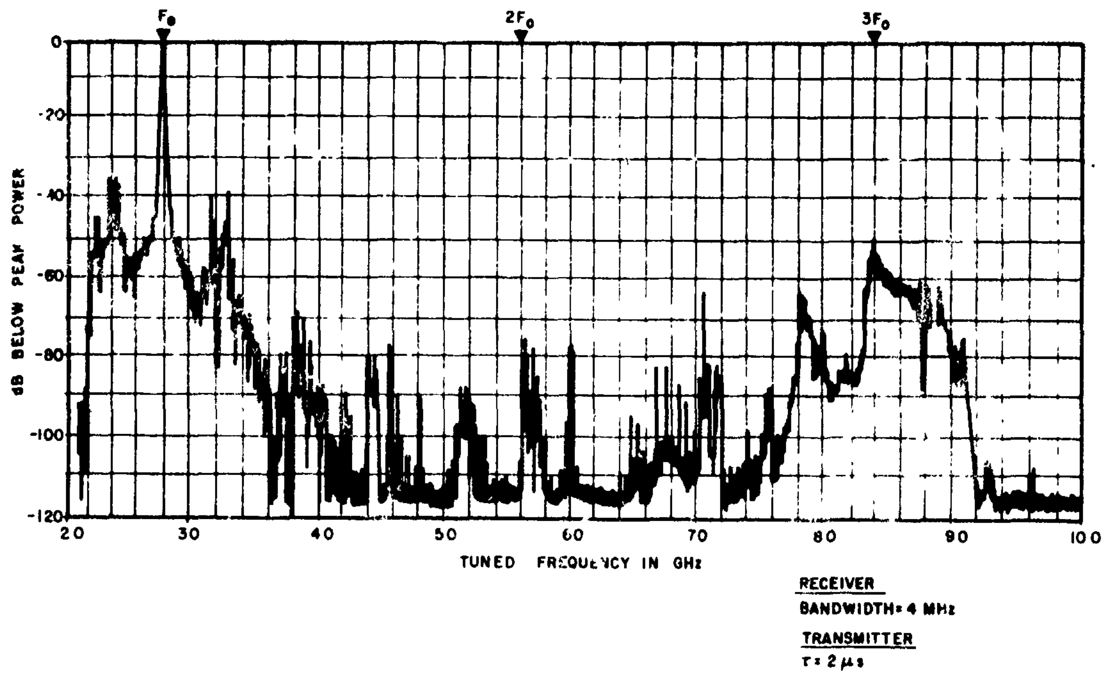


Figure C-8. Response of Receiver to Magnetron Transmitter

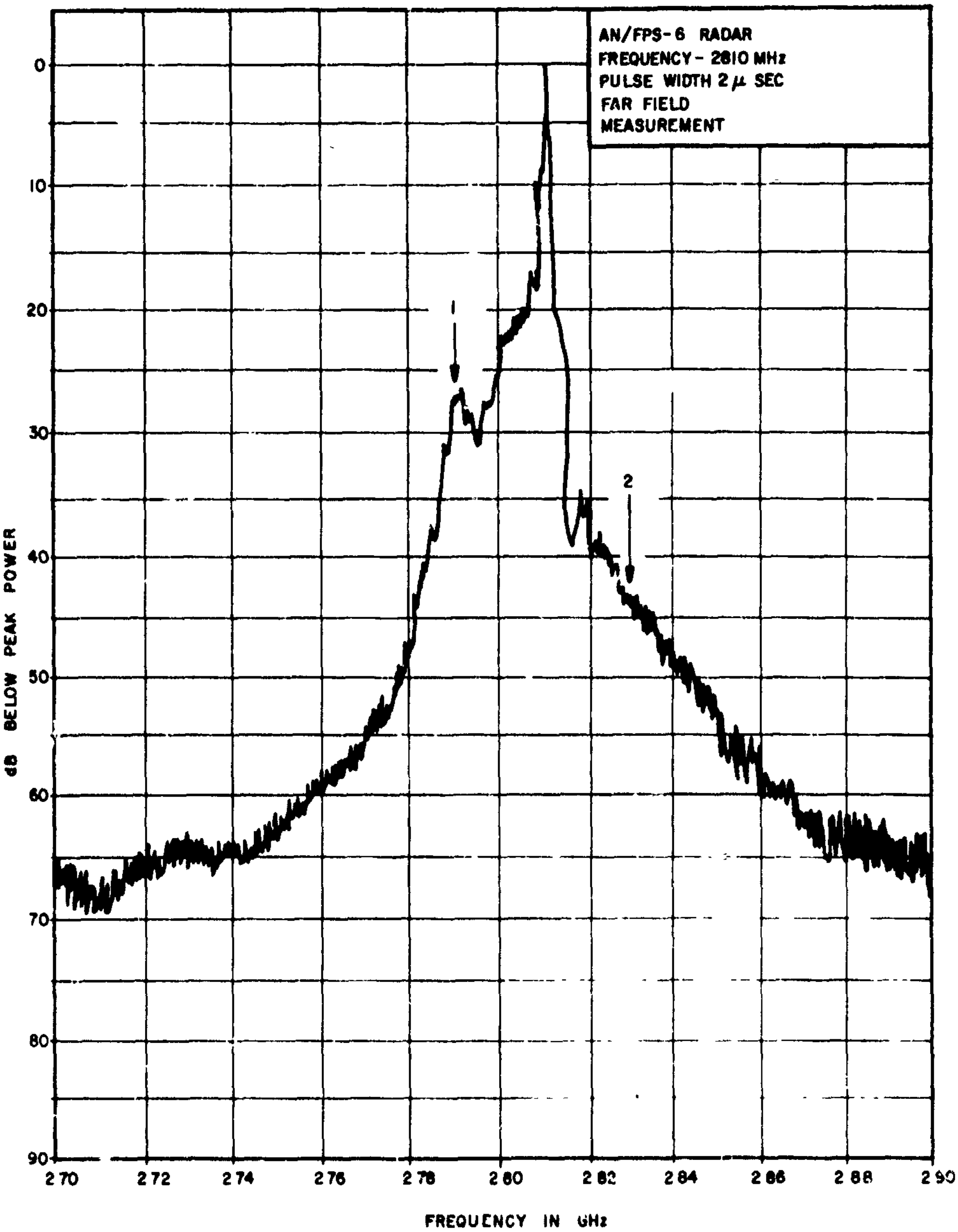


Figure C-9. Response of 0.5 MHz BW Receiver to a Magnetron Spectrum (Extracted from Reference 40.)

response level is down from the peak by about 27 dB. Arrow 2 indicates 20 MHz above the tuned frequency where the response level is down by about 44 dB or a difference in emission levels of 17 dB. The receiver response level falls off to approximately 65 dB below the tuned-frequency response level at ± 90 MHz from the carrier.

Coaxial Magnetrons

Recent advances in the development of tubes have resulted in the availability of coaxial magnetrons. The limited information available on these tubes indicates that there is an improvement in all of the areas where problems exist with the conventional magnetrons. Of special importance is the improvement in the emission spectrum of the coaxial tube. Achievable improvement in the Q of the cavity is on the order of 5 to 1 when compared with a conventional magnetron. This means that the cavity bandpass can be on the order of the emission bandwidth for most pulsewidths presently being used in the 2.7 to 2.9 GHz band.

One of these tubes, the SFD-371, has been developed for the frequency range being analyzed in this report. Available information on this tube indicates that the nominal temperature coefficient for this tube is 50 kHz per degree centigrade as compared to 70 kHz per degree centigrade for the 8798, a conventional magnetron. The coaxial magnetron's higher Q provides frequency pushing reduced by a factor of approximately 10 and frequency pulling reduced by a factor of approximately 5. The frequency in the coaxial magnetron is determined by the stabilizing cavity rather than the resonators as in a conventional magnetron. Temperature coefficient, higher Q, and the stabilizing cavity combine to proved better frequency stability, available measurements indicating ten times better or more. (See Reference 36.)

Klystron Amplifiers

Klystron amplifiers provide flexibility in designing pulse waveshapes. The design of the transmitter pulse however, must recognize the objectives, transmitter efficiency and minimal spectral sidelobes. If klystron amplifiers operate in a linear fashion the Gaussian and cosine-squared waveforms can be approximated. A flat-topped pulse provides for efficient klystron operation. A disadvantage of operating in a linear fashion is that transmitter efficiency is low. On the other hand, efficient channelization of the frequency spectrum requires low sidelobe levels. Raytheon has investigated (References 37 and 38) a reasonable compromise achieved by shaping the rise and fall times of a flat-topped pulse at low power levels and driving the klystron somewhat into its nonlinear region of operation.

When klystron amplifiers are used, the spurious, or unintentional emissions, consist of harmonics and extra-spectral noise. As shown in Reference 6, the harmonic emissions of klystrons range from 30 to 40 dB below the fundamental power output. The extra-spectral noise spurious emission is shown to be down approximately 130 dB as measured in a 1 kHz bandwidth. For a receiver nearly matched for the baseline, 0.5 microsecond trapezoidal wave, these noise sidebands would be approximately 97 dB below the fundamental power emission. However, there will also be a noise contribution at the output of the transmitter because of amplified-noise attributable to the stages preceeding the klystron amplifier; frequency stability is determined primarily by the exciter, which may be crystal controlled.

Spectrum Comparisons of Output Tubes

Curves illustrating the differences between spectra generated by the three tubes considered are shown in this subsection.

Figure C-10 shows the effect of the frequency selectivities of the three tube's cavities on the theoretical spectrum (Fourier transform) of a 0.5 μs CW trapezoidal pulse with 0.05 μs rise and fall times. Also shown is the estimated envelope of spurious emissions. The level of the envelope for the klystron represents the limit of available data. The level may be lower and will vary with the number of cavities and their bandpasses.

The klystron and coaxial magnetron envelopes were produced by multiplying (dB addition) the normalized transform of the pulse by the measured cavity selectivities of the VA87E (6 cavity klystron being considered for ASRs) and the SFD-356 coaxial magnetron. The cavities' 3 dB bandpasses are 34 MHz and 4 MHz respectively – The conventional magnetron cavity was assumed to have a very low Q, thereby not affecting the transform.

Figure C-11 presents measured emission spectrum data on a conventional magnetron, a coaxial magnetron, and a klystron. The type of measured data necessary for a comparison of the three types in the 2.7 to 2.9 GHz frequency band is not presently available, so the comparison has been made for the 3.9 to 6.2 GHz tubes where some limited measured data in coaxial magnetrons is available. The information was extracted from References 4 and 39. Figure C-11 clearly illustrates the low frequency pushing characteristics of the magnetron tubes. However, a considerable improvement can be noted, particularly on the low frequency side of the coaxial magnetron.

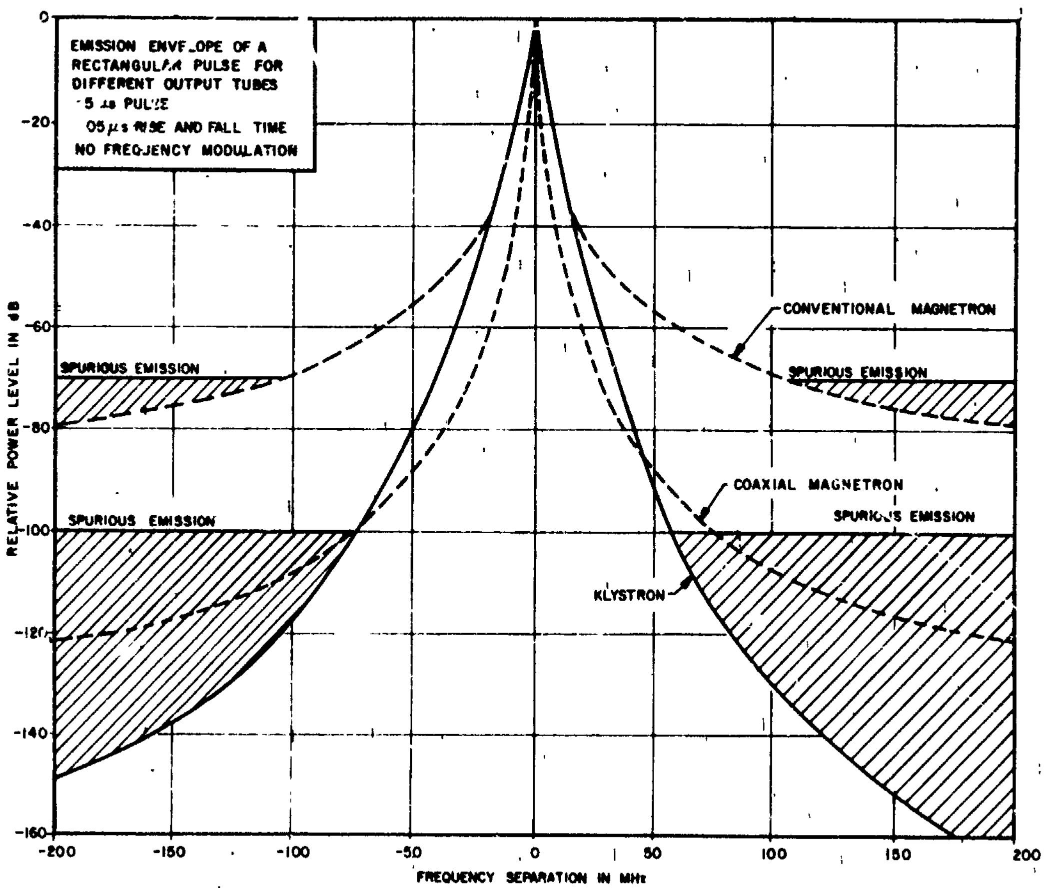


Figure C-10. Emission Envelopes of Output Pulses Resulting from Indicated Trapezoidal Input Pulse

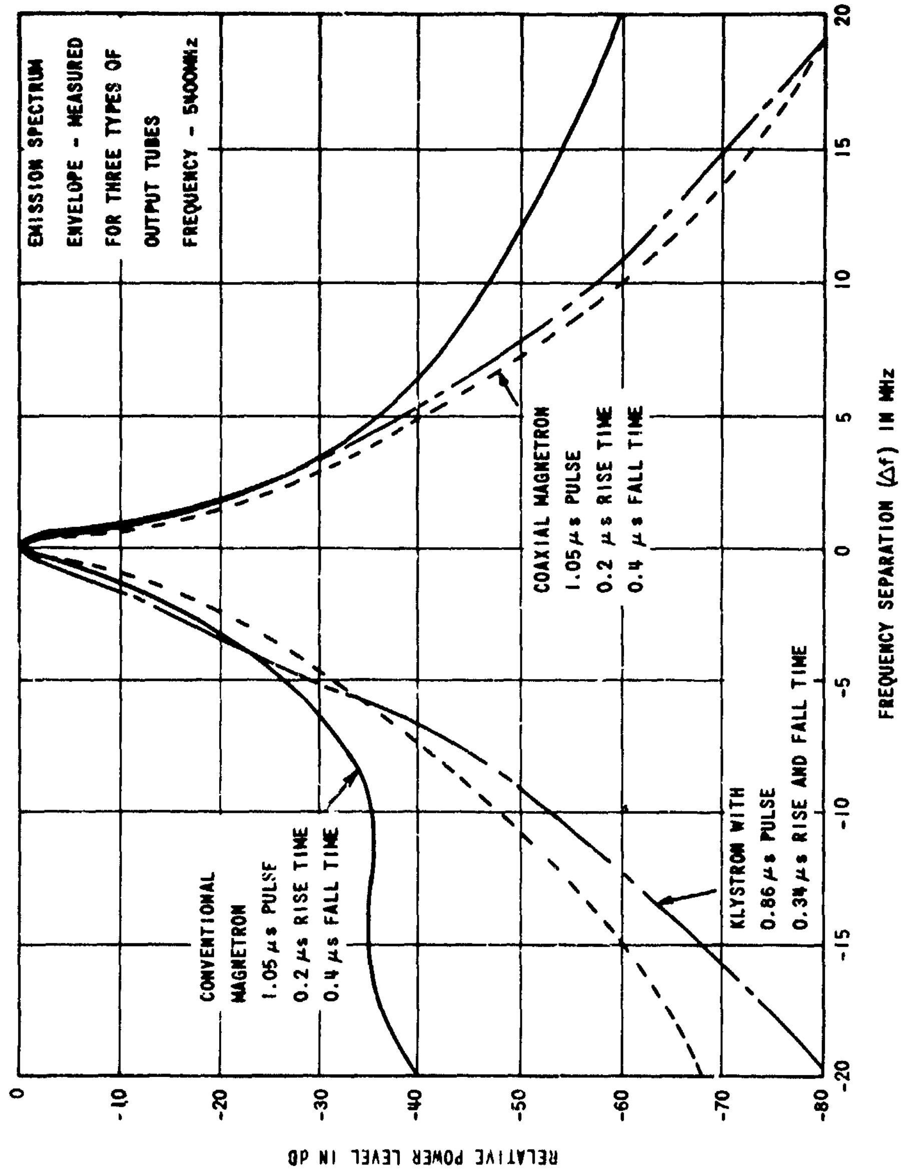


Figure C-11. Emission Spectrums

Filters

Most of the narrow-band dominant-mode filters used in the past were constructed of one or more cavity resonators. These filters have two disadvantages: they are reflective, and undesired resonances (spurious passbands) occur when attenuation degrades to intolerable levels.

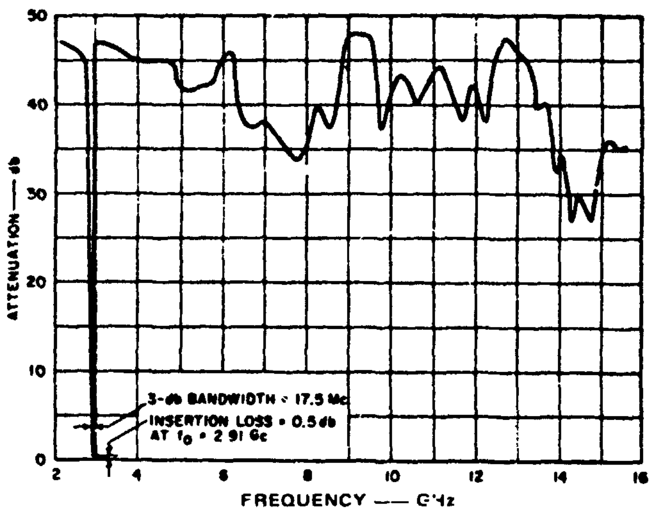
The impact of the power reflected from these filters depends on two conditions: the type of device used in the output of the transmitters and the power level of unwanted emissions that are rejected by the filter and reflected back into the transmitter. Because of these conditions, the impact of the reflected power may be unnoticed, may result in oscillation of the final transmitter stage, or may result in damage to the final stage.

The spurious passband problem can be overcome by using high-pass or low-pass filters in conjunction with the bandpass filter.

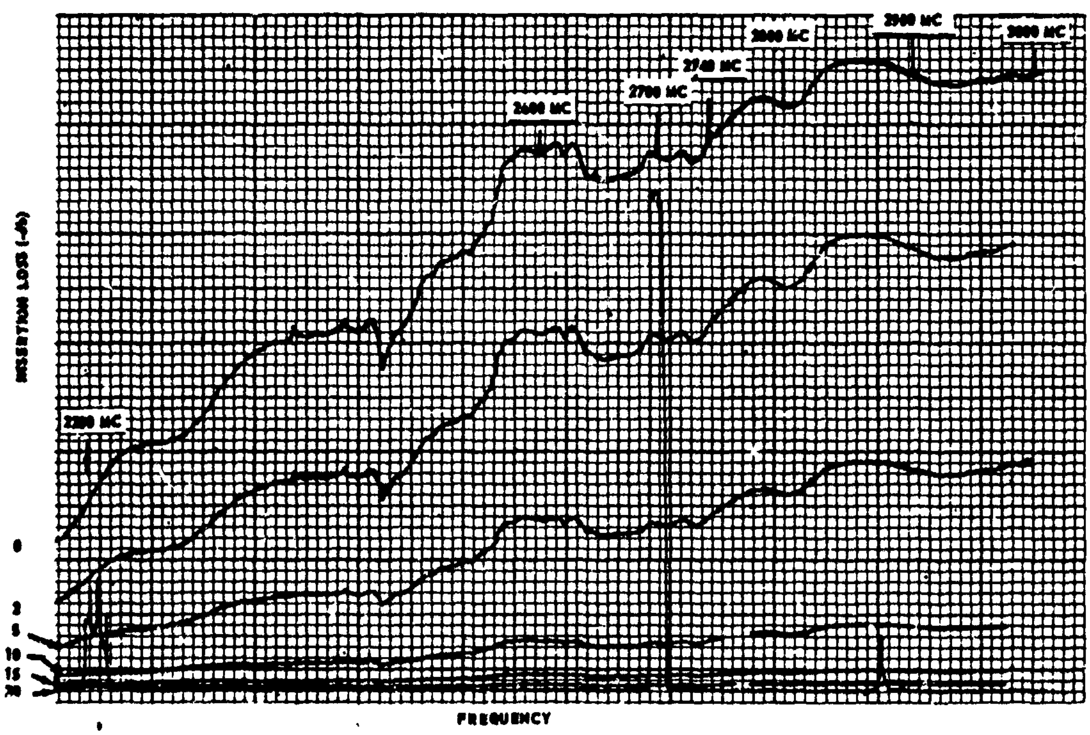
One advantage of these filters is that they are tunable over reasonable frequency ranges.

The first disadvantage of the reflective filters has been overcome in recent years with the development of absorptive filters. Two of these filters designed for use in the 2.7 to 2.9 GHz band are described in References 8 and 9. Their attenuation characteristics are shown in Figure C-12. As an illustration, the effect of the fix-tuned filter on the Fourier transform of a 0.5 μs trapezoidal pulse with a K of 10 is shown in Figure C-13. The spectral characteristics of a 0.5 μs trapezoidal pulse with cosine-squared-shaped leading and trailing edges is also shown for comparison.

The fix-tuned filter of Reference 32 is a rectangular-waveguide filter using two trapped-mode (open-walled) resonators. Although the power handling ability of this filter is low, conventional methods used to increase the power handling ability of conventional resonators apply to this filter (Reference 8). The design of this filter is such that the open-walled resonators damp out the higher order resonances, resulting in a stop band free of additional pass bands (Reference 10). This filter also isolates the input from the output by coupling orthogonally from the direction of normal power flow. The fundamental TE_{101} mode is trapped in the resonator structures to give high-Q resonances such as are typical of conventional solid-wall resonators. In summary the filter reacts as a conventional cavity resonator to the fundamental mode, but damps out other, unwanted, modes over an extremely wide frequency range.



(a) Fix-tuned Filter (Extracted from Reference 8)



(b) Tunable Filter (Extracted from Reference 9)

Figure C-12. Attenuation Characteristics of 2.7-2.9 GHz Frequency Band Filters

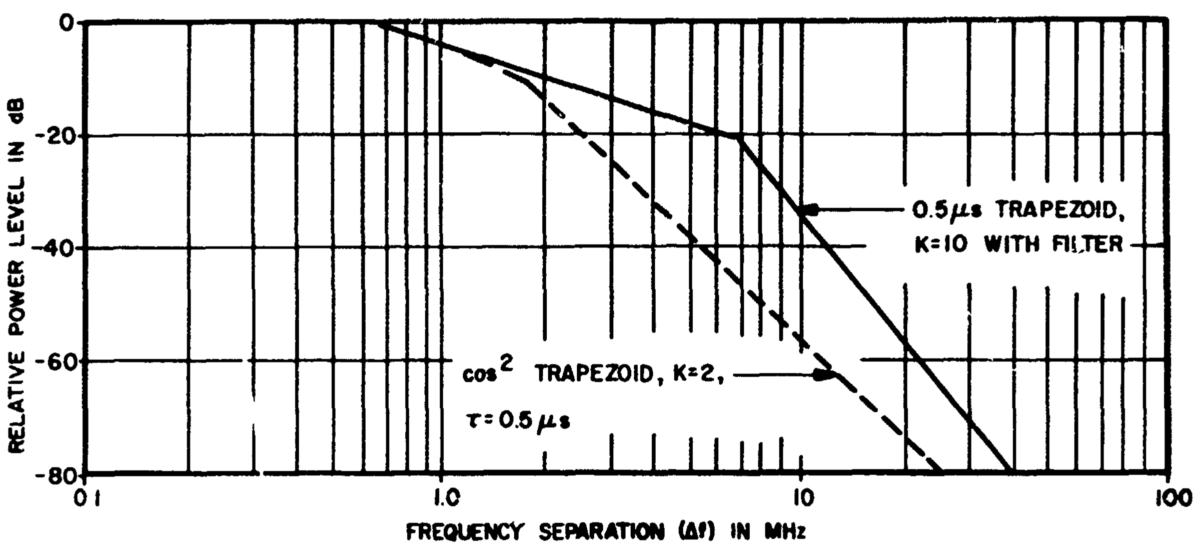


Figure C-13. Estimated Response of Fix-tuned Filter to a K = 10, 0.5 μs Trapezoidal Pulse as Compared to the Spectral Characteristics of a K = 2, 0.5 μs Cosine-Squared Trapezoidal Pulse

The filter described in Reference 9, and in use in some 2.7 to 2.9 GHz band radars, is tunable and nonreflecting. It includes two identical 3-dB sidewall couplers, two high power RF terminations and a pair of identical 4 cavity bandpass filters. The phase properties within the hybrid and the identical settings of the cavities are such that reflected energy is absorbed in the input RF load. More detailed treatments on filters suitable for use in high power microwave transmitting systems are contained in References 6, 10 and 11.

CONSIDERATIONS FOR SELECTED DESIGNS

Signal Bandwidth in Phased Arrays

The usable spectrum, or bandwidth, of the signal waveform is limited in systems that utilize phased-array antennas because the beam of the antenna disperses as bandwidth increases. Generally, the limitations of bandwidth can be separated into at least two classes: a phase approximation to time delay and the transient effects. Phased arrays can take on many different design configurations such as frequency scanning, phase scanning, sub-arrays, different feed type (end, center, parallel), etc. Each array configuration will require a specific analysis to determine what maximum signal bandwidth is permissible. General and approximate bandwidth limitations have been developed by several investigators. (See References 41 and 42.) Beam position error, beam shape, sidelobe, and gain loss limit the usable signal bandwidth. Contained in this subsection are summarized mathematical relationships for maximum signal bandwidth (and maximum pulsewidths) for phase-array antennas.

Scanned arrays operaging over a wide signal bandwidth require that the aperture excitation of the individual radiators be advanced or delayed in time to form a desired inclined equiphase signal front. This time delay has to be achieved with absolute precision. In phased arrays the desired scanned phase front is obtained by adjusting the delay up to a maximum value of one period of oscillation-modulo 2π in phase. This limits the signal bandwidth since a change in frequency changes the beam pointing direction.

For parallel-feed phased arrays it has been shown (See Reference 42) that for a 60° scan angle (from broadside), a reasonable maximum transmission (and receiving) bandwidth is given by:

$$\frac{BW}{f_c} = \frac{\theta_B}{100} \qquad \text{(C-16)}$$

where:

BW = transmission (or receiving) signal bandwidth

f_c = carrier frequency

θ_B = beamwidth (at boresight)

This relationship is based on the criterion that it is desired to limit the bandwidth so that the beam never scans by more than ± ¼ of a beamwidth with frequency, or:

$$\left|\frac{\delta\theta}{\theta_B \text{ (scanned)}}\right| = \frac{1}{4} \tag{C-17}$$

where:

$\delta\theta$ = angle change due to different frequencies

θ_B = (scanned) normalized scanned beamwidth

As an example, let f_c = 2700 MHz and θ_{AZ} = 1.5°, then the maximum signal bandwidth permissible is:

$$BW = \frac{1.5 \times 2700}{100}$$

$$BW = 40.5 \text{ MHz} \tag{C-18}$$

Larger signal bandwidths will give unacceptable angle positional error, antenna gain losses, and higher sidelobes.

Likewise, assuming a matched receiver $\tau = \frac{1}{BW}$, the minimum pulsewidth τ is:

$$\tau \approx \frac{1}{40.5 \times 10^6} = 0.025\ \mu s \tag{C-19}$$

If the phased array utilizes a monopulse technique for determining angle, then the difference pattern null is altered and the stated criterion of ¼ of a local beamwidth error will yield a null increase up to −9 dB relative to the peak sum pattern.

The bandwidth factor, defined in terms of the broadside beamwidth is given as:

$$K = \frac{\text{signal bandwidth in percent}}{\text{beamwidth (degrees)}} \qquad \text{(C-20)}$$

The factor K may be expressed in terms of equivalent pulse length. If all of the allowable bandwidth were used, a pulse could have the duration $\tau = \frac{1}{\text{bandwidth}}$. The length of this pulse is given by:

$$L = c\tau \qquad \text{(C-21)}$$

where:

c = speed of light

The relationship, as developed by Frank in Reference 41 between pulse length and aperture size (a) is given as:

$$L \approx \frac{2}{K} a \qquad \text{(C-22)}$$

when K = 1

(min) pulse length = twice aperture size

The array elements may be grouped into-subarrays. Of concern in this form of array is loss in gain and the magnitude of grating lobes as a result of the change in frequency of a broadband signal. The referenced literature indicates that if the bandwidth factor K is kept below one ($K \leqslant 1$) then the loss in gain is restricted to 1 dB or less and that the relative amplitude equal grating lobes is restricted to within 10 dB. At beam-scanned angles closer to broadside (less than 60°) these values become less. If scan angles less than 60° are specified in the system design, then a larger K could be tolerated.

EMC Aspects of Phased Array Antennas

Phased-array antennas used in radar systems present features of concern to EMC that are not present in the more conventional (e.g., parabolic dish) antennas. Discussed herein are two principal aspects of phased arrays that appear to warrant considerations in surveillance radars. These two considerations are;

1. The antenna pattern for non-design frequencies can take on different shapes;

2. When used in conjunction with certain receiver design configurations, potential degradation to the receiver may be experienced. In all cases, as mentioned previously in subsection Signal Bandwidth in Phased Arrays, the degree to which these effects will be experienced depends upon a specific design.

In any array antenna the elements are spaced, located, taper fed, phased, etc., to achieve the desired beam pattern and positioning. The spacing of elements must be done carefully to avoid creating grating lobes as the beam is scanned. (Grating lobes are due to the radiation from the elements adding in phase in those directions for which the relative path lengths are integral multiples of 2π radians.)

At non-design frequencies, however, apparent grating lobes may result. This effect is illustrated through the consideration of a linear, N-element, isotropic array. The normalized (one-way) pattern is given by the following relationship (See Reference 23).

$$E(\theta) = \frac{\sin\left[\frac{N\pi d}{\lambda}(\sin\theta - \sin\theta_o)\right]}{N\sin\left[\frac{\pi d}{\lambda}(\sin\theta - \sin\theta_o)\right]} \qquad \text{(C-23)}$$

where:

$E(\theta)$ = one-way voltage pattern

N = number of elements

d = element spacing

λ = wavelength

θ_o = angle to which beam is steered

θ = angular coordinate

Grating lobes will occur whenever both the numerator and denominator of the above equation are zero, or when;

$$\frac{\pi d}{\lambda}(\sin\theta - \sin\theta_o) = k\pi \qquad \text{(C-24)}$$

where:

$$k = 0, \pm 1, \pm 2, \ldots$$

Using this relationship, and letting $\sin \theta = 1$ (the angle at which a grating lobe first becomes real) and $k = 1$ (the first appearing grating lobe), the curves of Figure C-14 are constructed. Figure C-14 illustrates the maximum angle to which a beam can be steered before appearance of a grating lobe as a function of undesired signal wavelength (λ_u), and for two different element spacings. At the desired-signal frequency, $\frac{\lambda_u}{\lambda} = 1.0$, the beam can be scanned to 40° with a spacing of 0.6λ before the appearance of a grating lobe. However, for a higher frequency signal, say for $\lambda_u = 0.8\lambda$ an "apparent grating lobe," as responding to this frequency, may appear even when the phase shifters steer the beam only to an angle of approximately 20°. Hence, as a receiving antenna responding to frequencies, the array pattern may have gains approaching that of the mainbeam gain at positions other than the desired mainbeam position. The degree to which this condition exists will depend upon the particular array design, spacing tolerances, tapering, phase shifters, type feed, etc.

Certain receiver designs associated with array antennas can affect special EMC cases. To illustrate the need for EMC analysis in a phased-array/receiver interface the following illustration is presented. A receiver design which incorporates a separate low noise amplifier attached to each element of the array is considered. These amplifiers may see undesired signal power levels from an interfering transmitter that are at significantly different levels than those normally expected from the composite array pattern. In effect, the element receiver is directly fed by a dipole. In many cases the gain of the element dipole, as shown in Figure C-15 (a) is much higher than the sidelobes of the composite antenna. Hence, potentially stronger interference signals reach the element receiver. Also, in cases where the array beam is steered far from the normal, an interfering transmitter operating at a frequency different from the designed frequency may cause an apparent grating lobe (as previously discussed) at this frequency as illustrated in Figure C-15 (b). These phenomena, in such designs which use subarrays, may well result in a high antenna gain acting on several receivers in a cluster as shown in Figure C-15 (c). In this case, potentially high undesired power is fed to these element receivers. Saturation of the receivers may well be of concern in this instance.

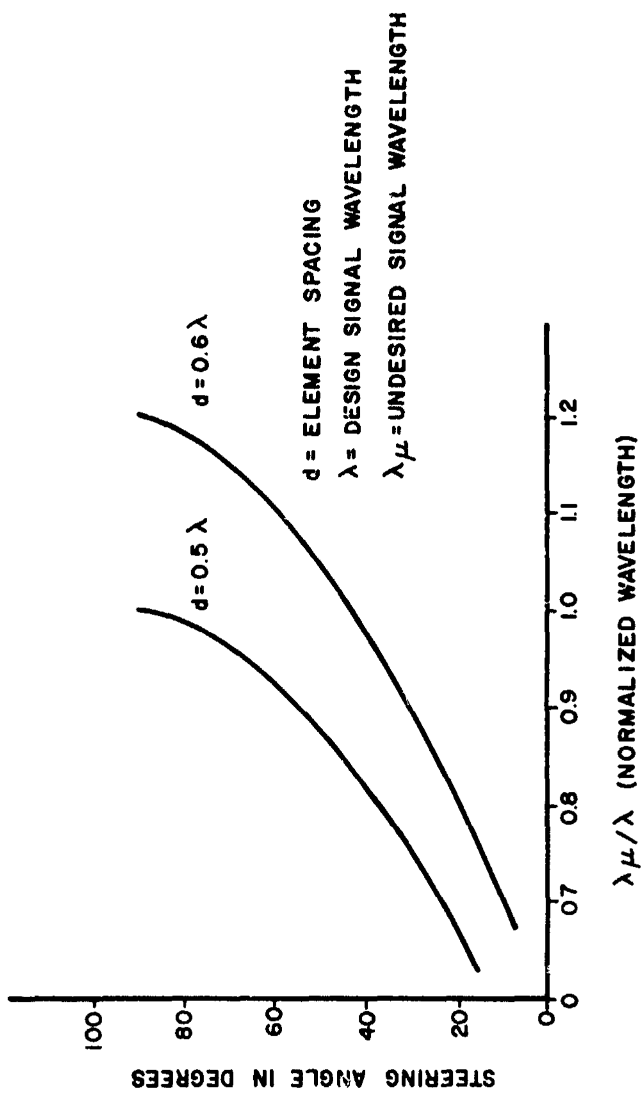
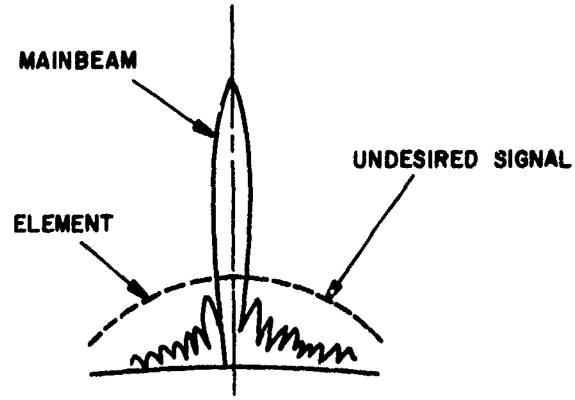
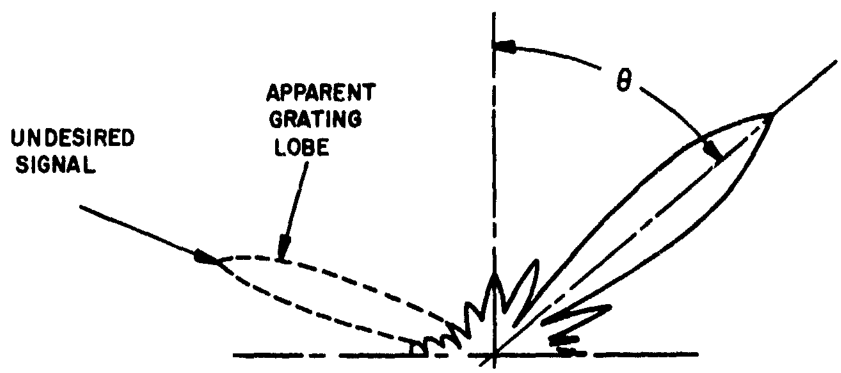


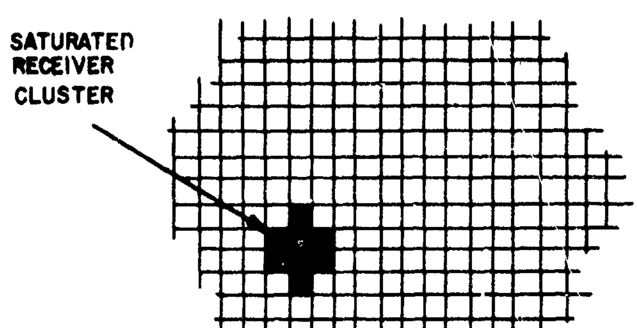
Figure C-14. Steering Angle at which a Grating Lobe will appear



(a) Antenna Patterns



(b) Antenna Pattern For Receiver Cluster



(c) Element/Receiver Matrix

Figure C-15. Receiver/Antenna-Element Aspects

LINEAR FM PULSE COMPRESSION

Presented in this subsection is a discussion of the interaction between two radars employing linear FM pulse compression and the interaction between a radar employing linear FM PC and a radar employing CW pulses. Considered first is the case of a CW pulse radar interfering with an FM PC radar.

CW Pulse Interference to PC Receiver

Results of a computerized discrete Fourier analysis are shown. Figures C-16 and C-17 show the response of a filter matched to a particular FM rate and pulsewidth to a constant carrier frequency, on-tuned pulse. These figures show that for large pulsewidth, the input pulse is virtually unaffected by the filter. For smaller pulsewidths the output of the filter has a loss in peak amplitude and a spread in pulsewidth when compared to the input pulse. Other, as yet unpublished, data, which analyzes the effects of off-tuning, show the same trends and an additional loss in peak amplitude due to this off-tuning.

PC Interference to CW Receiver

Considered next is the response of a constant-carrier-designed radar receiver to a linear FM PC signal described as follows (See Figure C-18). Given an FM pulse, the response of an IF filter is given by Equation C-25.

$$\tau_o \approx \frac{BW_{IF} \times T_u}{F_{max}}, \; \tau_o > \frac{1}{BW_{IF}} \tag{C-25}$$

$$\tau_o \approx \frac{1}{BW_{IF}}, \; \tau_o < \frac{1}{BW_{IF}}$$

where:

τ_o = IF response pulsewidth

BW_{IF} = IF bandwidth

T_u = uncompressed input pulsewidth

F_{max} = maximum frequency sweep of the input pulsewidth

As can be seen from Figure C-18 the approximation holds for the on-tune or slightly off-tune cases only.

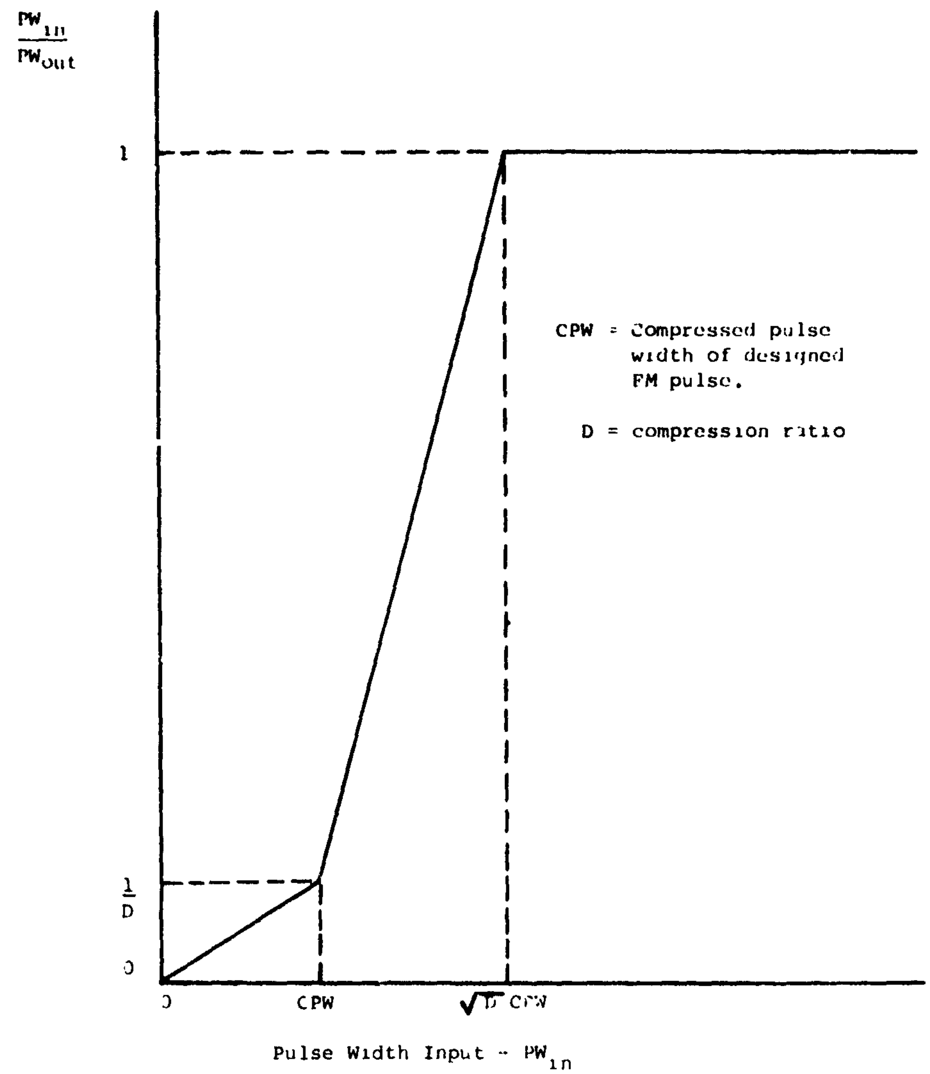


Figure C-16. Pulse Compression Model for Ratio of Input to Output Pulsewidth as a Function of Width of Constant Carrier Frequency Input Rectangular Pulse $f_d = 0$
(Extracted from Reference 43)

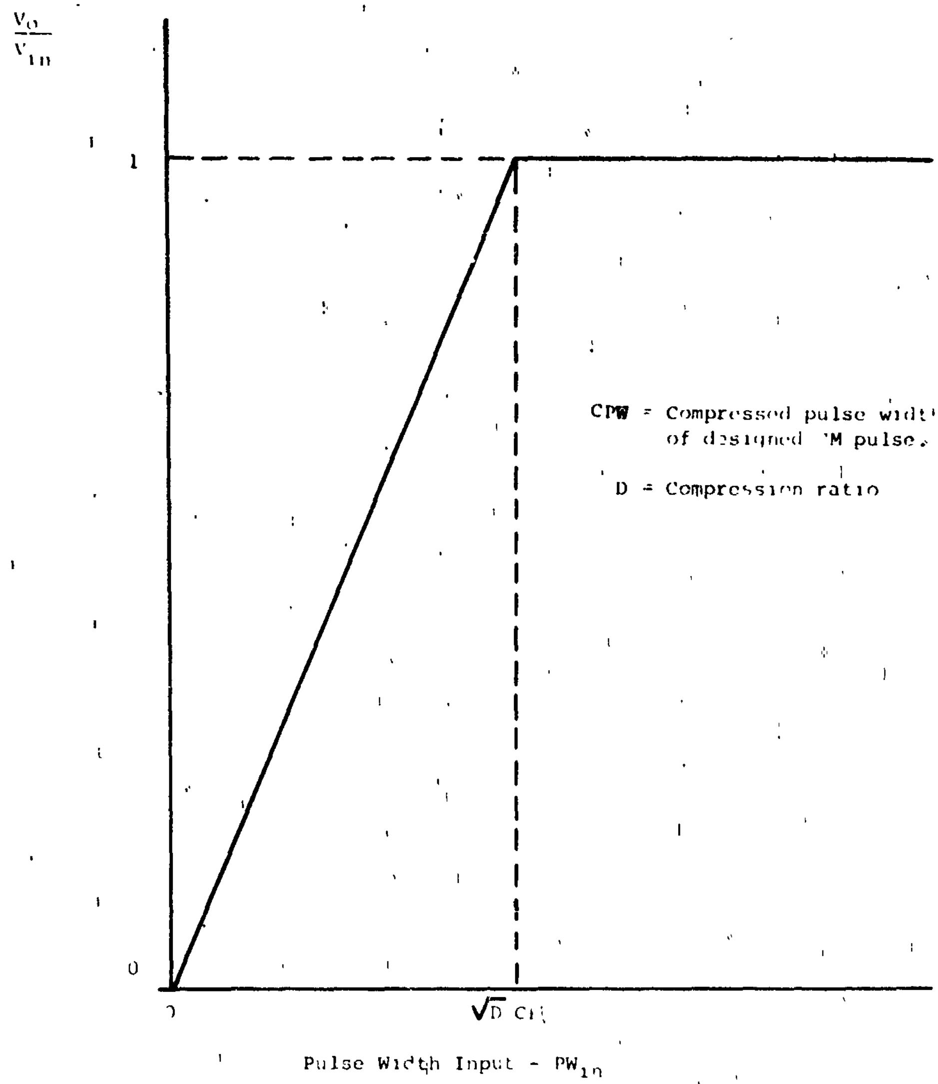


Figure C-17. Pulse Compression Model for Ratio of Peak Output Voltage to Input Voltage of Constant Carrier Frequency On-tuned, Input Rectangular Pulse
(Extracted from Reference 43)

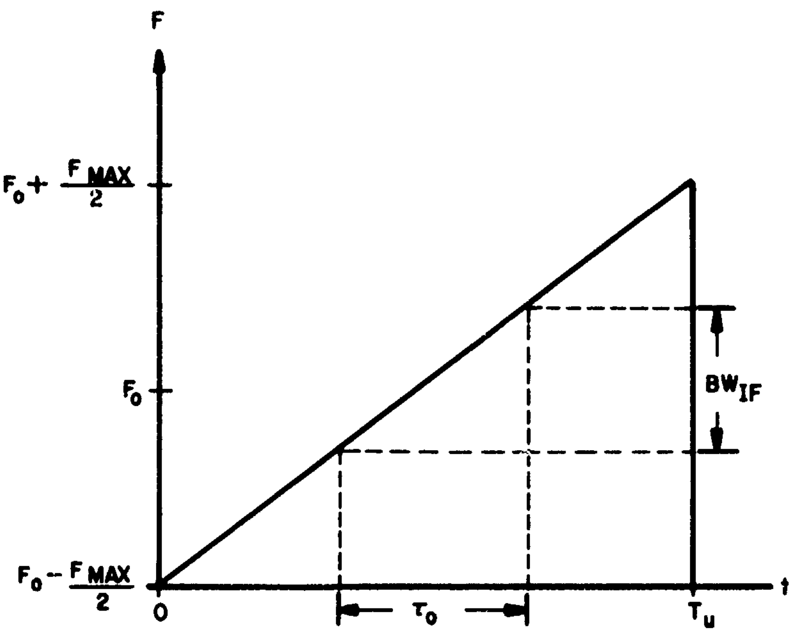


Figure C-18. Frequency Variation vs Time of a Pulse Compression Waveform

The total average power contained in the output pulse is given by;

$$P_{oaver} \approx P_{iaver} \times \frac{BW_{IF}}{F_{max}}, \quad BW_{IF} < F_{max} \tag{C-26}$$

$$P_{oaver} \approx P_{iaver}, \quad BW_{IF} > F_{max}$$

where:

P_{iaver} = the average input pulse power

A more detailed analysis of PC interference as a function of off-tuning is available through the use of a discrete Fourier computer algorithm programmed at ECAC.

PC Interference Pulse to PC Receiver

Reference 37, describes the response of a matched filter for a linear FM PC for varying degrees of off-tuning, differences of pulsewidths, compression ratios and peak amplitudes.

As can be expected, losses are experienced when the input pulse to the receiver is not the designed pulse. An important point to note in the reference, however, is that when the input pulse is matched to the filter in all respects save that the FM rate is in the opposite direction, then the output of the filter is a pulse twice the width and one half the amplitude of the input pulse. This amplitude reduction and pulse spreading (instead of compression) when placing two or more PC radars in the same environment may be an important consideration in frequency management.

USE OF ANTENNA POLARIZATION AS AN EMC REDUCTION TECHNIQUE

The use of different polarizations is a congested environment yields some limited advantages in interference rejection. Data of Reference 44 illustrates the change in the pattern of a high gain antenna when the measurement antenna goes from the same polarization to orthogonal (cross linear or opposite handedness in circular polarization) polarization. Other unpublished measured data show essentially the same effects. The data indicates that the patterns are relatively the same except for the elimination of the main beam. Some of the unpublished data, however, indicates that improvements in sidelobes are possible on the order of 10 dB. This sidelobe reduction does not appear to be an automatic result of cross polarization and care in design should be taken to realize this benefit.

In the case of search radars, mainbeam to mainbeam coupling is a situation that rarely occurs.

Where two radars, operating with the same antenna polarization experience only mainbeam-to-mainbeam interactions, the conversion of one of these radars to an orthogonal polarization may eliminate most interactions.

The mainbeam to sidelobe coupling is not expected to improve unless there is a crossed-polarized sidelobe reduction; this improvement being equal to the sidelobe reduction of one antenna. In the case of sidelobe to sidelobe reduction, however, the improvement is equivalent to the sum of the sidelobe reductions of the two antennas.

A possible major drawback to the use of orthogonal polarization as considered from an interference rejection, is the effect of terrain. The depolarization due to foreward scatter reflections from terrain, buildings, vegetation and hills may wipe out any expected improvement. This effect is probably even more pronounced for beyond-the-horizon paths. Some data is presently available in the literature and an analysis of such data is presently under way at ECAC, although intermediate results are not conclusive.

APPENDIX D

FREQUENCY ASSIGNMENT ALGORITHMS

INTRODUCTION

The basic purpose of a frequency assignment alogrithm is to identify a set of frequencies within a given range of frequencies at which a predetermined group of equipments can successfully operate.

There are several frequency assignment algorithms available at ECAC. These algorithms were examined in order to determine the one most suitable for application to the radar assignment problem in the 2.7 to 2.9 GHz frequency band. The criteria used for selecting the algorithm were ease of implementation, accuracy, and feasibility of assigning frequencies to a predetermined group of equipment, called the environment.

Some of the major factors that influence operations of frequency assignment algorithms are discussed in the following paragraph. This is followed by a description of the frequency assignment algorithm applied in this study and a computer flow diagram of the algorithm.

INTERFERENCE PARAMETERS AND CRITERIA

Interference Parameters

A number of interference parameters are used in the determination of interference between two equipments. Some of the more important terms that are relevant to the subject of frequency assignment algorithms are the following:

1. The pulse repetition frequency (PRF). This is the rate per second at which radar pulses are generated and transmitted.

2. The antenna gain. The mainbeam or sidelobe antenna gain may be used. If the antenna is rotating, the antenna gain can be expressed as a distribution using the horizontal antenna pattern.

3. The pulsewidth.

4. The long-term hourly median transmission loss distribution.

5. The peak or average transmitter power.

6. The receiver noise threshold, or sensitivity threshold. This is the minimum amount of received power at which signal detection will occur.

7. The off-frequency rejection curve (OFR). The off-frequency rejection curve is a graph of the interference peak power produced by the spectrum of an interfering transmitter in a victim receiver as a function of the transmitter and receiver tuned frequencies. When normalized with respect to the power received when both transmitter and receiver are tuned to the same frequency, the curve is considered as the loss due to the difference of the tuned frequencies of the transmitter and receiver, i.e., the off-frequency rejection loss.

8. The image rejection loss. This is the loss of the image frequency response with respect to the fundamental tuned frequency response of the receiver.

Interference Criteria

The algorithms applicable to search radars employ two different interference criteria —blip intensity number, BIN, also referred to as "N" (See Reference 14), and received interference levels.

Blip Intensity Number

The BIN is a measure of the ability of the surveillance radar scope observer to properly identify targets in the presence of blips caused by nearby radars. In a sense, it is an EMC operational degradation or performance measure. The number is proportional to the average value of the combined received pulse rates generated by nearby interfering radars. The BIN is also proportional to the peak power of interfering pulses, up to the point of saturation of the victim receivers.

BIN ranges have been assigned to five scope-display conditions, ranging from no degradation to intolerable degradation.

Correlation of BIN values to the five conditions has been accomplished on the basis of field and laboratory tests (See Reference 14).

A BIN criterion for maximum tolerable degradation is established, forming the basis for deciding whether the combined effects of all of the potentially interfering radars will or will not cause unacceptable operation.

Minimum Interference Levels

This criterion is simply the condition that frequency assignments be made such that the peak interference power from any radar in any other radar's receiver divided by the noise level in (or the sensitivity of) that radar's receiver is less than a specified threshold. These ratios are written as INR and I/R_S' in this report. The selection of the threshold is usually based on a knowledge of relative pulse repetition frequencies and receiver processing, and on an estimate of the resulting BIN.

THE FREQUENCY ASSIGNMENT ALGORITHM

Frequency Assignment Parameters

Some of the more important factors that can affect a frequency assignment are the following:

1. Fixed-tuned equipment in the problem environment.

2. The tuning range of the equipments to which frequencies are to be assigned, i.e., discrete or continuous, overlapping tuning bands, and, the number of tuning frequencies available.

3 Relative location of equipment, i.e., collocated or remotely located.

4. The existence of intermodulation interference. The frequency assignment techniques to be discussed in the following subsections consider only adjacent and co-channel interference, i.e., those interfering signals within the 80 dB bandwidth and the 3 dB bandwidth, respectively. Only one of the ECAC assignment techniques suggests possible ways of modifying the 2.7 to 2.9 GHz frequency assignment to include the effects of intermodulation interference.

Intermodulation presents a more severe problem with extremely high duty cycle and collocated equipment conditions. These conditions do not exist in the band under study.

Of the five ECAC frequency assignment procedures reviewed, the Radar Assignment Model (RAM) (See Reference 45), Communications-Electronics Frequency Assignment System (CEFAS) (See Reference 46), Channel Assignment Model (CHAM) (See Reference 47), Multiple Channel Assignment Technique (MCAS) (See Reference 12), and Node Coloring Algorithms and Computer Implementations (NODE) (See Reference 48), the MCAS technique was employed.

Multiple-Channel Assignment Technique

The Multiple-Channel Assignment Technique is a frequency assignment algorithm that employs the channel separation matrix of the fundamental frequency responses. Using the interference parameters set forth under INTERFERENCE PARAMETERS AND CRITERIA, the OFR needed to attain a specific BIN or I/R_S' is determined for each equipment and formed into a matrix. There is a row and a column for each equipment and the elements of the matrix represent the off-frequency rejection loss needed between the equipment corresponding to the row number and the equipment corresponding to the column number. If the off-frequency rejection loss needed between a victim and interferer is different than the off-frequency rejection loss needed when their roles are reversed, the larger of the two values is entered into the matrix. The matrix is now symmetrical. After the channel frequency spacing is specified by the user, the off-frequency rejection loss matrix is converted to a channel separation matrix using the off-frequency-rejection loss characteristic. The process of assigning channels is based mainly on the channel separation matrix of the fundamental tuned frequencies. As an example of the above process, let us assume that we are given the off-frequency rejection loss matrix shown in Figure D-1 for three equipments and an off-frequency rejection characteristic for all three equipments shown in Figure D-2. If the curve is not symmetrical, it is converted to a symmetrical curve by associating the higher worst case value of frequency separation Δf with each value of loss. The term Δf represents the frequency difference, or separation, between the tuned frequencies of the transmitter f_t and the receiver f_r. The frequency separation matrix shown in Figure D-3 indicates the frequency separation between the transmitter tuned and the receiver tuned frequency required to achieve the corresponding loss, given by Figure D-1. The frequency separation matrix is converted to the channel separation matrix by dividing each of the elements of the matrix by the specified bandwidth of a channel. If the specified bandwidth is 5 MHz, the channel separation matrix will be given by Figure D-4.

The initial frequency assignment sequence is based on the number of discrete frequencies that the equipment can tune to, the equipment with the smallest number of available frequencies being assigned first and the equipment with the largest number of frequencies being assigned last. Thus, equipments with fewer tunable frequencies are given greater assignment priority. First, one of the tunable frequencies of the first equipment of the assignment sequence is selected and assigned to that equipment. Second, one of the tunable frequencies which is available to the second equipment in the sequence and which meets the channel separation requirements from the first equipment is selected and assigned to that equipment. This process continues until an assignment is achieved for all equipments on the list. If some of the equipments were not able to be assigned and were deleted, the assignment process is repeated and the deleted equipments are given a higher assignment priority in the assignment sequence, i.e., a higher position in the order of assigning frequencies. The repetition of the assignment process is continued until either all

RADAR	1	2	3
1	0 db	25 db	20 db
2	25 db	0 db	15 db
3	20 db	15 db	0 db

Figure D-1. OFR Loss Matrix

RADAR	1	2	3
1	0 MHz	15 MHz	10 MHz
2	15 MHz	0 MHz	5 MHz
3	10 MHz	5 MHz	0 MHz

Figure D-3. Frequency Separation Matrix

RADAR	1	2	3
1	0 Channels	3 Channels	2 Channels
2	3 Channels	0 Channels	1 Channels
3	2 Channels	1 Channels	0 Channels

Figure D-4. Channel Separation Matrix

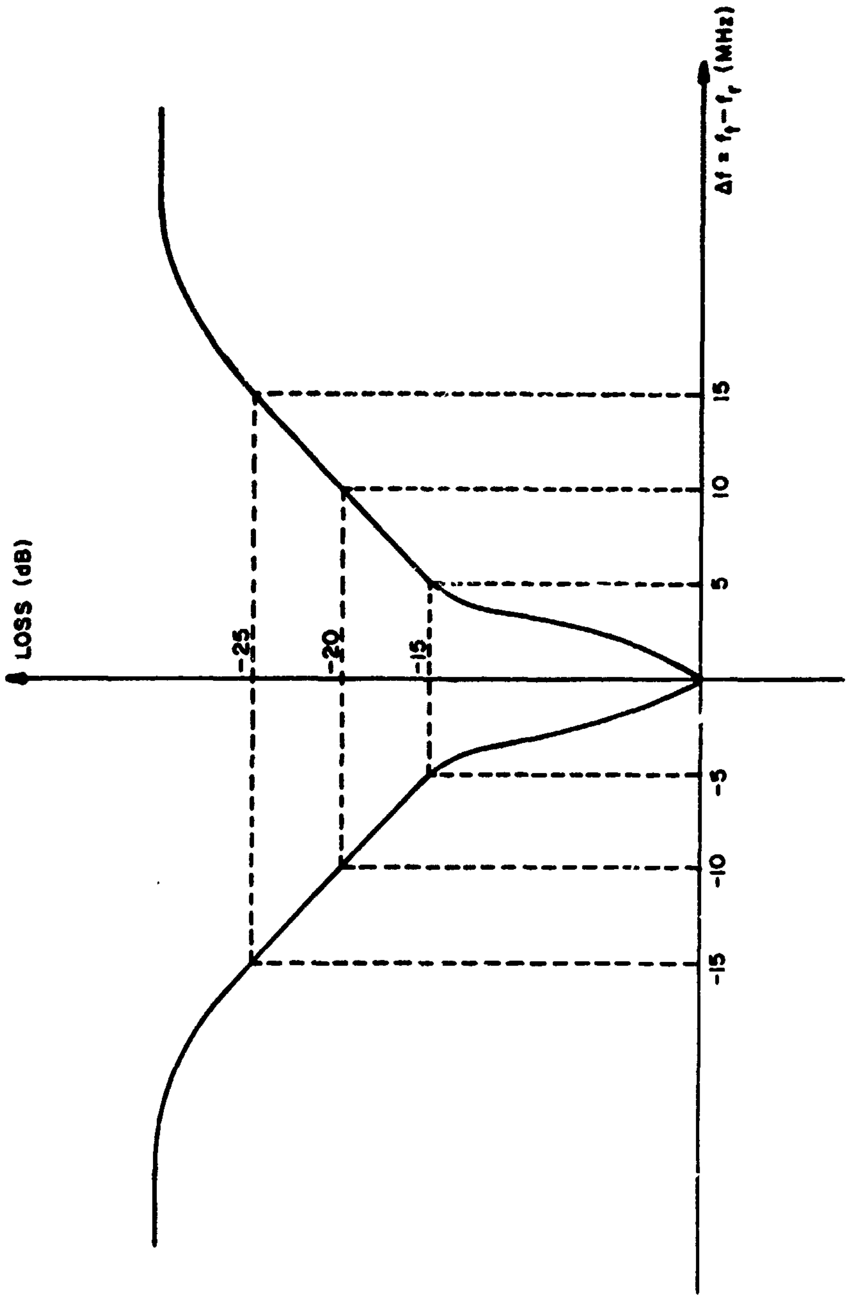


Figure D-2. OFR Characteristics

equipments have been assigned frequencies or the maximum alloted computer run-time has been exceeded. If run-time is exceeded, either a longer run-time is specified and the program rerun, or the interference criteria are made less stringent. A functional block diagram is given in Figure D-5. The channel separation matrix can be generated independently using the transmission loss, the off-frequency rejection curve, the transmitter powers, the interference criteria (BIN or I/R'_s), and the receiver sensitivity, or the channel separation matrix can be generated by the computer program using the above parameters in conjunction with the channel distance curve. The channel distance curve is a graph of the number of channels of separation required between a transmitter and receiver as a function of geographic separation.

If one or more equipments have not been assigned and are deleted, the results are printed only if the present assignment has deleted less equipments than any of the previous assignment attempts. This is a major advantage of MCAS in the sense that those equipments that are the most difficult to assign are determined. The user has the option of accepting the present assignment and giving the deleted equipments special consideration. Also, MCAS can easily consider fixed tuned background equipment and equipments with overlapping and non-overlapping and discontinuous frequency tuning bands.

The disadvantages of the MCAS assignment procedures are:

1. The assignment may not be optimum in the sense of minimum interference or minimum bandwidth occupied.

2. Only a subset of all the possible combinations of frequency assignments is considered.

3. Only symmetrical off-frequency rejection characteristic curves can be considered.

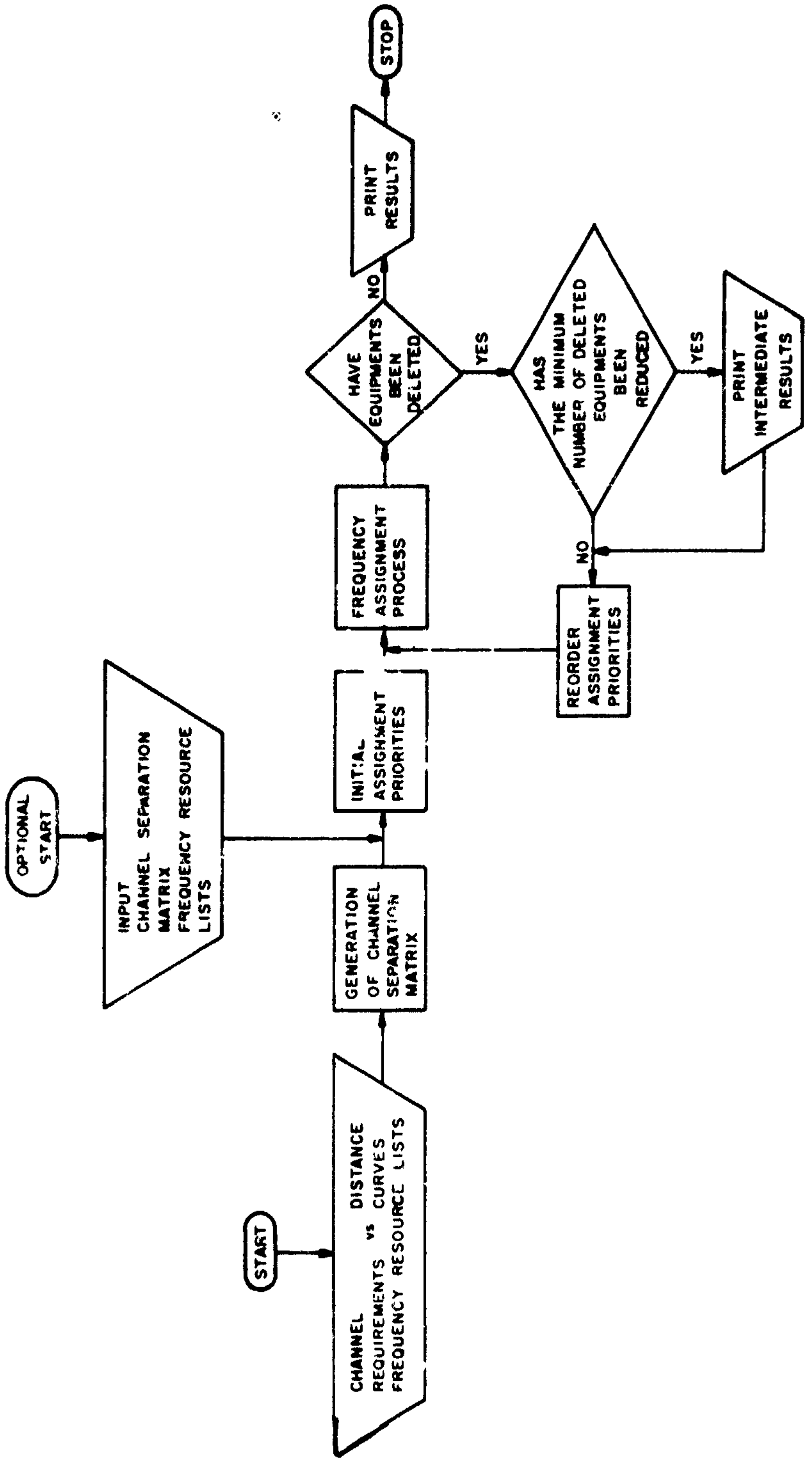


Figure D-5. MCAS Block Diagram

APPENDIX E

OFF-FREQUENCY REJECTION DATA AND CALCULATIONS

OFF-FREQUENCY REJECTION (OFR)

Values of off-frequency rejection (OFR) are required as input to the Multiple Channel assignment technique. OFR is the rejection (in dB) of a given transmitter's signal caused by the selectivity characteristic of a given receiver as the transmitter and receiver are separated in frequency.

By definition, off-frequency rejection is

$$OFR = \frac{1}{\int_{-\infty}^{+\infty} P(f)\, R(f)\, df} \int_{-\infty}^{\infty} P(f)\, R(f+\Delta f)\, df \qquad \text{(E-1)}$$

where

$P(f)$ = transmitter relative power density

$R(f)$ = receiver relative selectivity

Δf = frequency separation (transmitter minus receiver frequency)

As these are relative functions; transmitter power and receiver sensitivity do not enter the calculations.

In order to perform the required OFR calculations, it was necessary to obtain the power density and selectivity functions for all the equipments in the Los Angeles area. These were divided into two classes – the present environment and a projected (selected radars assumed to have improved characteristics) environment.

INPUT FOR PRESENT-ENVIRONMENT OFR CALCULATIONS

Measured data for most of the equipments of the present environment exists in the form of spectrum signature reports, technical manuals, JF-12 applications for frequency allocations, etc. Data selected from these documents provides the input to the OFR calculations. It is assumed that equipments having similar operational functions, modulation characteristics and output tubes have similar emission spectrums and selectivities. TABLE E-1 lists the sources of data for each of the equipments. In some cases, spectrum signature

TABLE E-1

DATA SOURCES

Equipment	Spectrum Signature	JF-12 Number	Similar Radar
AN/APS-20	References 40, 49	A-2210	AN/FPS-6
AN/CPN-4	Reference 50	409	AN/MPN-13
AN/FPS-6	References 40, 49	193	
AN/MPN-13	References 50, 51	2215	
AN/MPN-15	Reference 50		AN/MPN-13
AN/MPS-19	Reference 50	2588	PRELORT
SCR-584	Reference 52	3127	AN/MPQ-10
WSR-57	Reference 53	459	AN/FPS-41
7298	Reference 50		PRELORT
AN/FPN-48	Reference 50		AN/MPN-15
ASR-4	References 50, 54		AN/FPN-51
ASR-5	References 50, 54	2198	AN/FPN-47
ASR-6	Reference 50		
ASR-7	Reference 50	2747	

reports did not exist; but cross-referencing among JF-12 applications, technical manuals, and the Communications and Electronics Equipment Directory yielded equipments that are similar or, in some cases, identical. Examining the measured data for each equipment yielded groups which had nearly identical emission spectrums or selectivities. These groups were given the category letters shown in TABLE E-2. Transmitter power and receiver sensitivity were not considered in the grouping for OFR purposes.

An example of the method for grouping into categories is shown by Figure E-1, a plot of the emission spectrums of four of the transmitters from category A. The similarity of the spectrums is evident. For three of the four, however, data exists only for frequencies within 30 MHz of the carrier frequency, while the PRELORT had a complete measured spectrum. For this reason, the PRELORT spectrum was used for all category A transmitters.

Figures E-2 through E-5 are plots of transmitter categories A, B, C, and D and corresponding receiver categories 1, 2, 3, 4 and 5. There are only four transmitter categories for five receiver categories because some equipments had nearly identical transmitters, but not receivers. Care should be taken with these figures because the log scale on the abcissa has been reversed to display the negative values of Δf.

The receiver image response is included on the selectivity curves. *In all cases, the local oscillator frequency was chosen to be above the receiver tuned frequency.* However, some of the receivers have the capability to have the local oscillator frequency either above or below the receiver-tuned frequency. Moving the oscillator frequency below the tuned frequency would also move the image response below the tuned frequency. If MCAS should make a frequency assignment that falls on the image response frequency, a possible solution would be to change the local oscillator frequency if the particular equipment has the capability.

SAMPLE OFR CALCULATION

OFR calculations depend only on the shape of the emission spectrums and the selectivity of receivers. Therefore, OFR calculations were performed only for the categories in TABLE E-2, and not for each equipment, since similar shapes will give the same results.

Figures E-6 and E-7 are samples of OFR plots. Figure E-6 is a category A transmitter versus a category 2 receiver. Figure E-7 is a category B transmitter versus the same category 2 receiver. It can be seen that the sharper skirt on the category A transmitter (Figure E-2) results in a sharper skirt on the OFR for negative values of Δf in Figure E-6 compared with the category B transmitter for the same receiver (Figure E-7). This occurs because the transmitter sidebands are of a higher level than the receiver selectivity resulting in the OFR at large values of Δf being transmitter dependent. Improving the transmitter then improves the OFR, which permits closer frequency assignments.

TABLE E-2
CATEGORIES FOR OFR CALCULATIONS

Category	Equipments	Spectrum Used
Transmitter		Emission
A	AN/MPS-19, 7298, AN/MPN-13, AN/MPN-15, AN/FPN-48, ASR-4, ASR-5, ASR-6, ASR-7, AN/CPN-4	PRELORT
B	AN/FPS-6, AN/APS-20	AN/FPS-6
C	SCR-584	AN/MPQ-10
D	WSR-57	AN/FPS-41
Receiver		Selectivity
1	AN/FPS-6, AN/APS-20	AN/FPS-6
2	ASR-4, ASR-5, ASR-6, ASR-7	ASR-7
3	AN/MPN-13, AN/MPN-15, AN/CPN-4, AN/FPN-48	AN/MPN-13
4	AN/MPS-19, 7298	PRELORT
5	SCR-584, WSR-57	AN/MPQ-10

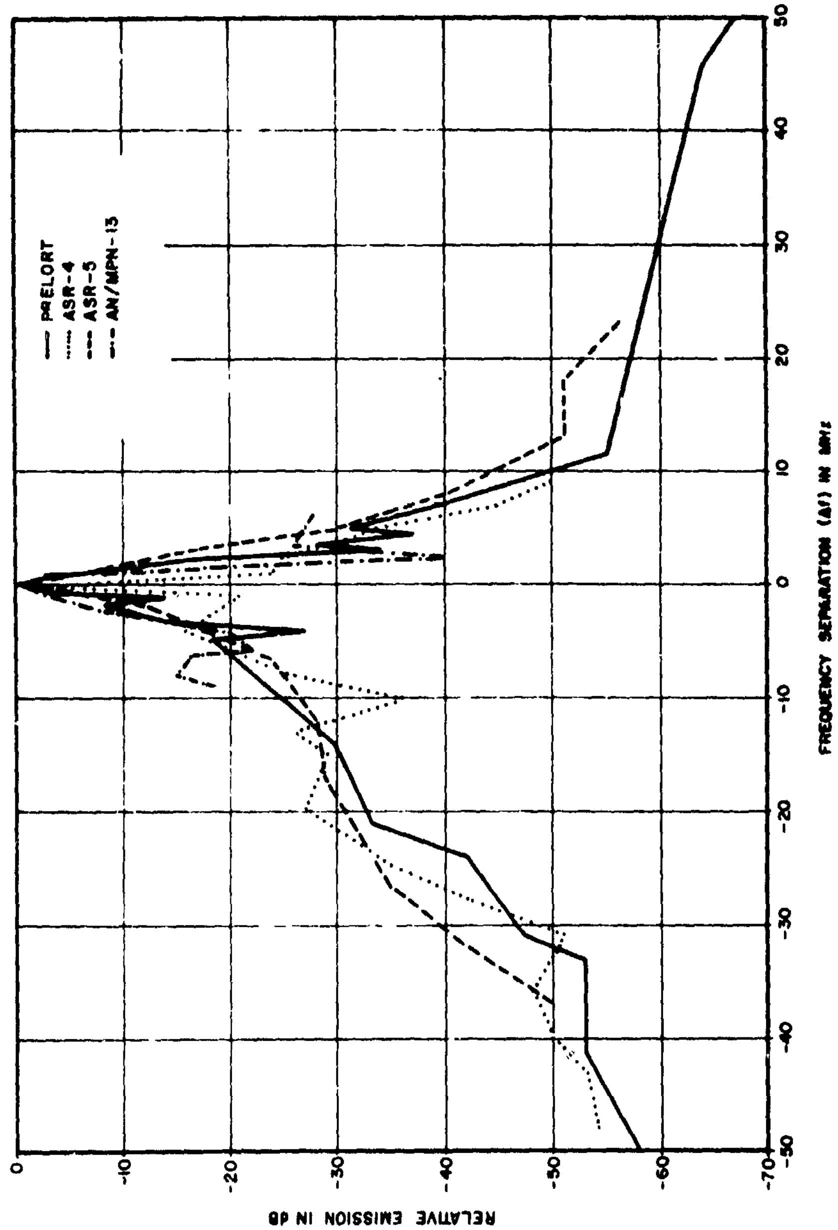


Figure E-1. Comparison of Radar Transmitter Spectrum for Category A Radars

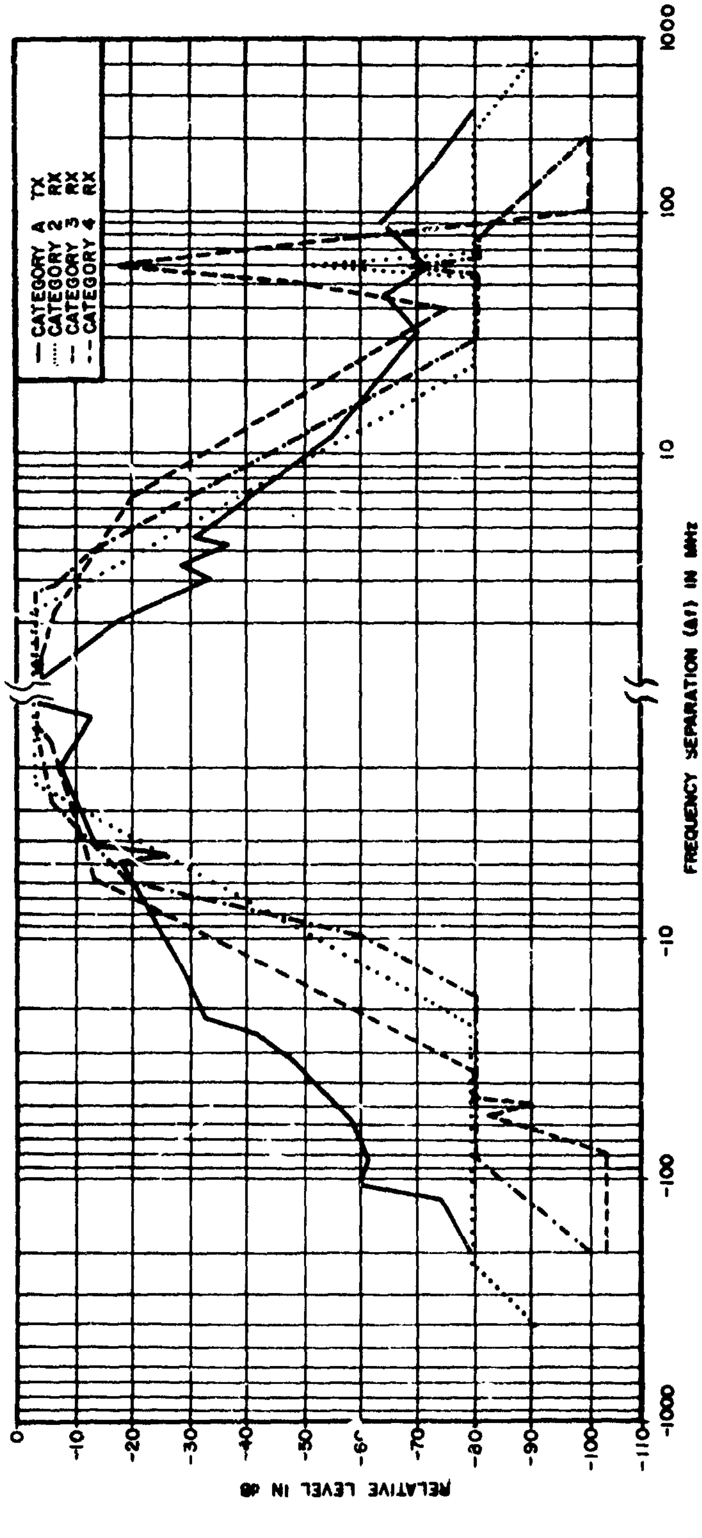


Figure E-2. Normalized Emission Spectrum and Receiver Selectivity Data

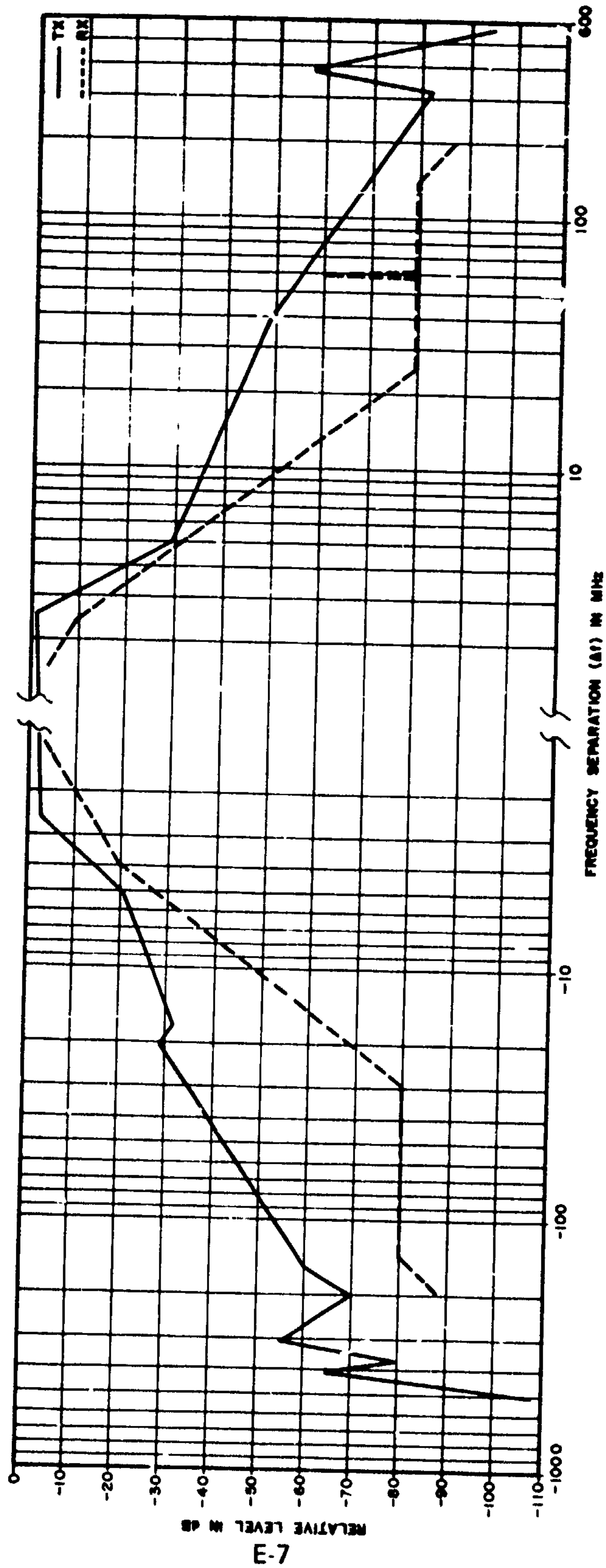


Figure E-3. Category B Transmitter Normalized Emission Spectrum and Category 1 Receiver Selectivity Data

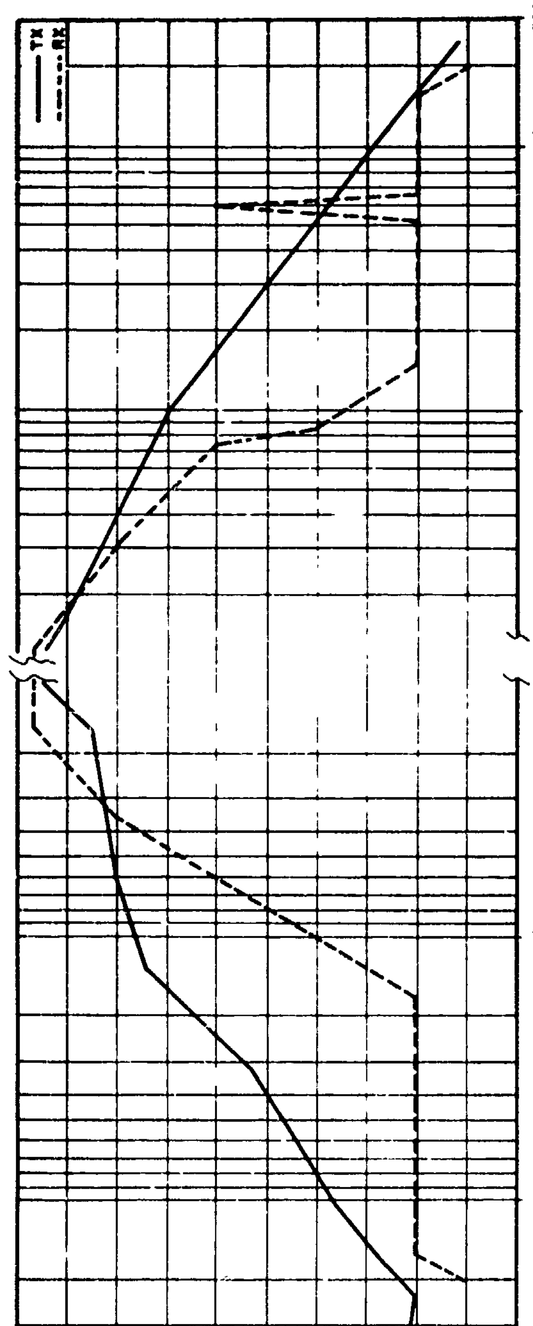


Figure E-4. Category C Transmitter Normalized Emission Spectrum and Category 5 Receiver Selectivity Data

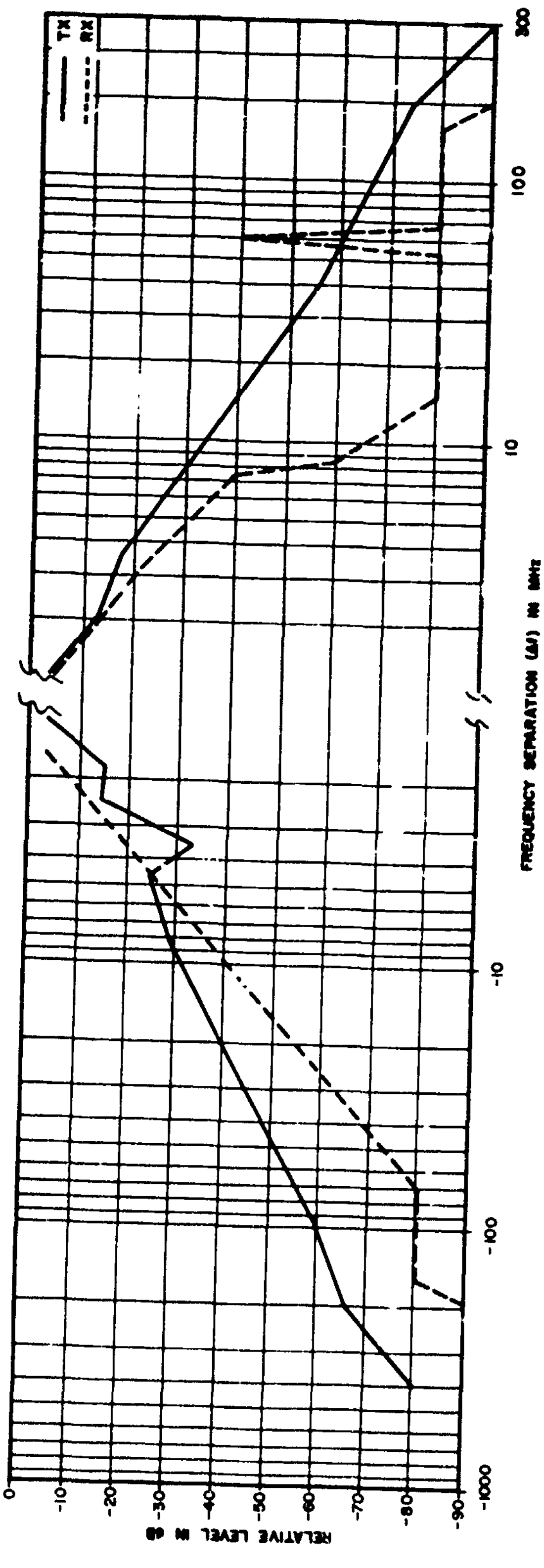


Figure E-5. Category D Transmitter Normalized Emission Spectrum and Category 5 Receiver Selectivity Data

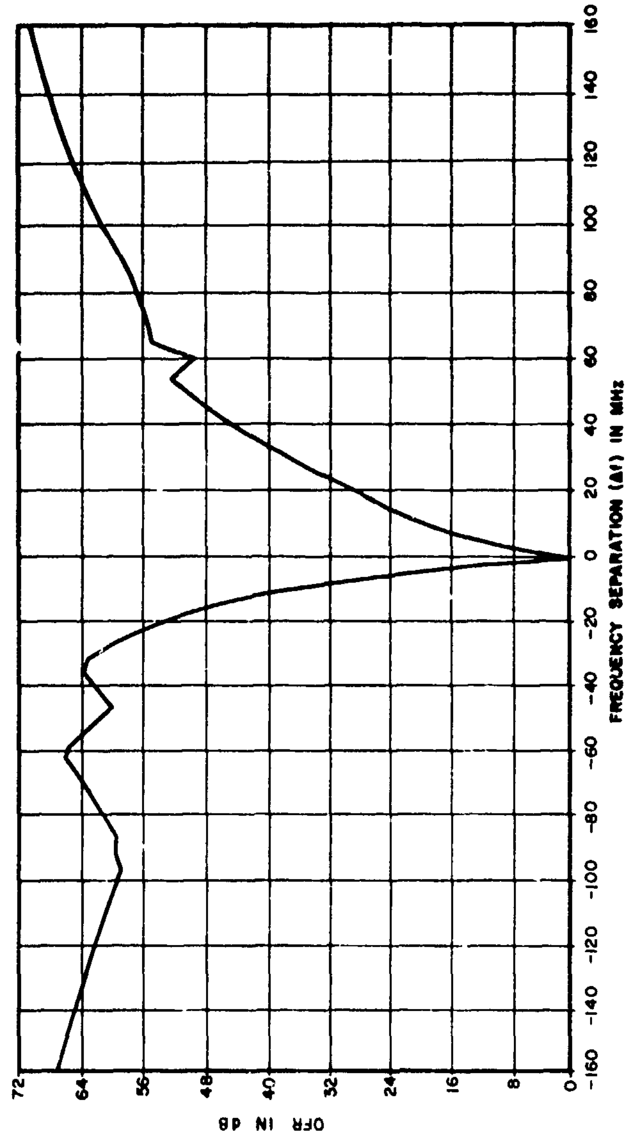


Figure E-6. OFR For Category A Transmitter vs Category 2 Receiver

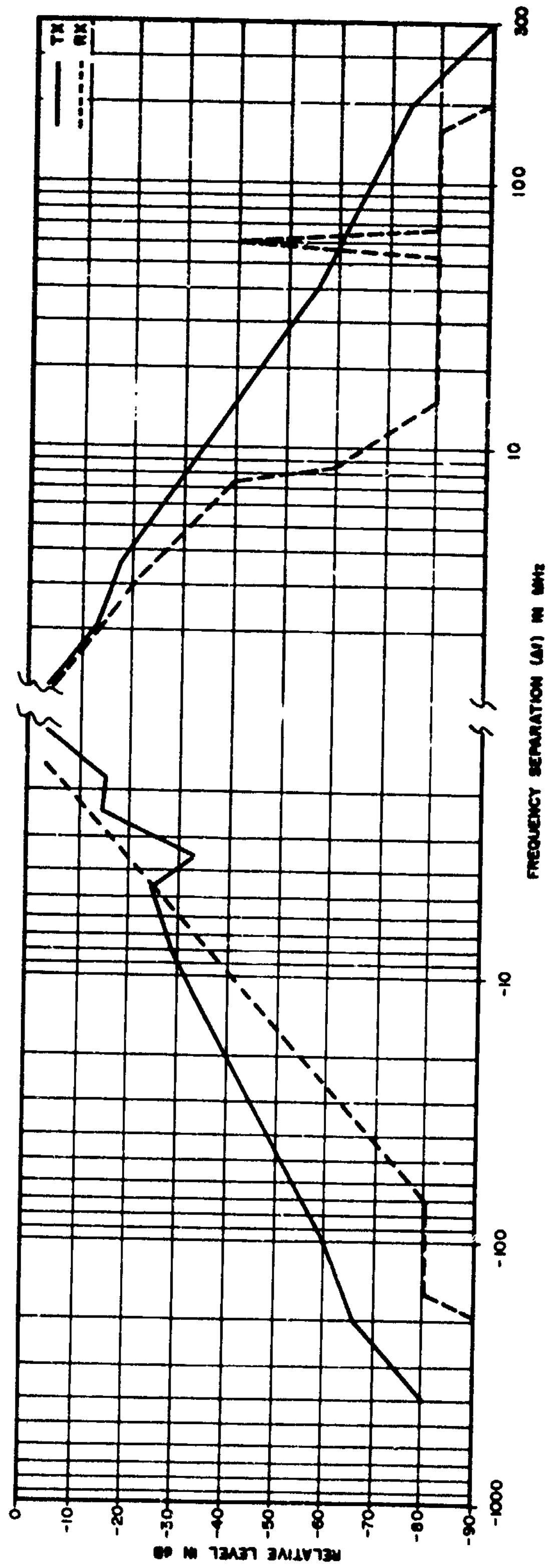


Figure E-5. Category D Transmitter Normalized Emission Spectrum and Category 5 Receiver Selectivity Data

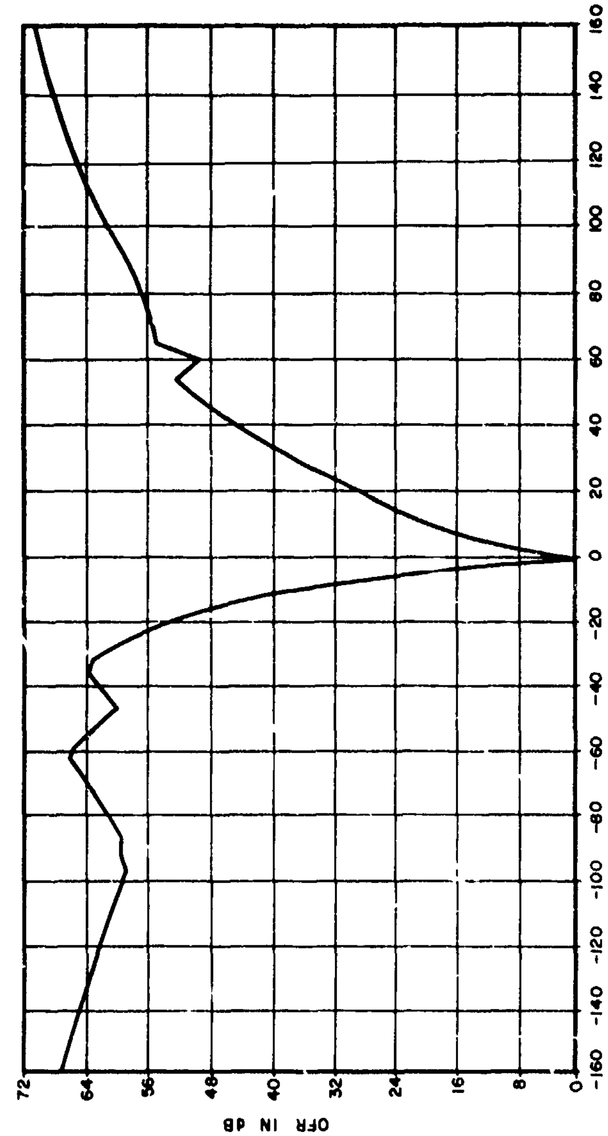


Figure E-6. OFR For Category A Transmitter vs Category 2 Receiver

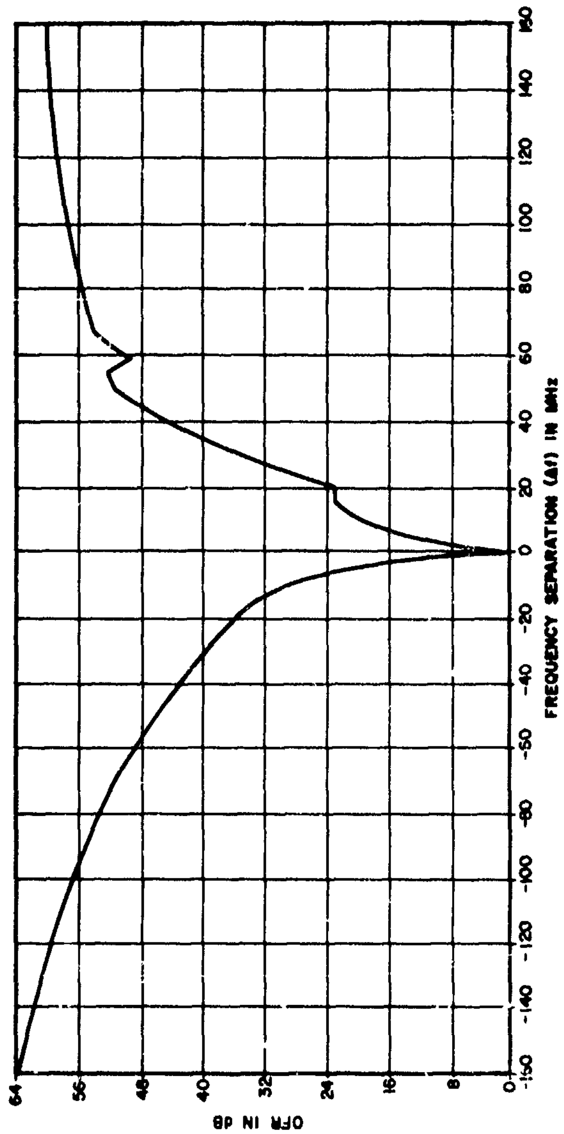


Figure E-7. OFR For Category B Transmitter vs Category 2 Receiver

The OFR routine used for this analysis performs the integration for Δf equal to transmitter frequency minus receiver frequency. Thus, the OFR for *positive* values of Δf are influenced by the *negative* values of the transmitter emission spectrum and the *positive* values of the receiver selectivity.

OFR CALCULATIONS FOR THE PROJECTED ENVIRONMENT

Since spectrum signatures do not exist for future equipment, it was necessary to synthesize their transmitter emission spectrums and receiver selectivities. Correspondence with FAA personnel and design specifications for new radars were used to determine which modulation types to examine and what the ranges of the system parmeters are.

From this data it was decided to look at two pulsewidths – 0.15 and 0.50 microseconds. The modulation types and output tube types were:

1. Trapezoidal pulse (K = 10) – coaxial magnetron transmitter
2. Trapezoidal pulse (K = 10) – klystron transmitter
3. Trapezoidal pulse (K = 2, K = 10), cosine-squared rise and fall, klystron transmitter
4. Gaussian shaped pulse, klystron transmitter
5. CHIRP pulse (dispersion of 12 and 50), klystron transmitter

where K = the ratio of pulsewidth to rise and fall time as explained in Appendix C.

The conventional magnetron was not included in the analysis of the projected environment. Klystron and coaxial magnetron design specifications were derived from various data sources.

The envelope of the spurious emissions and extraspectral noise (noise floor) is (reference 5) −90 to 110 dB below the carrier level. For this analysis, a noise floor of −90 dB was used. After the noise floor was reached, the output was assumed to fall off at the attenuation rate of a single cavity, which is 20 dB/decade. The spectrum data for the coaxial magnetron was obtained from an assumption of a single cavity Q equal to 700. The results were compared with spectrum analyzer photographs of a 2.7 to 2.9 GHz band one MW coaxial magnetron and were found to agree within ± 3 dB out to 20 MHz separation from the carrier (the limit of the data).

The frequency response for a four cavity klystron (VA-878B/C) was obtained from Varian Associates References 5 and 56. The extraspectral noise level given was

-130 dB in a 1 kHz bandwidth, relative to fundamental peak power, at a frequency far off-tune (frequency deviation around 500 MHz). Converting this measurement to radar bandwidths of 1 to 2.5 MHz raises the noise level to -100 dB or -95 dB at large values of Δf. The addition of some amplified noise sideband from the modulator should give a noise level of about -90 dB for small values of Δf.

In keeping with current design capabilities, the synthesized receiver selectivities were assumed to have a fall-off of 80 dB/decade beyond the -3 dB points and a spurious response envelope of -100 dB. A fall-off of 80 dB/decade was chosen as this is easily attainable with four tuned stages, and although a steeper slope could be obtained, all anticipated transmitters have slopes less than 80 dB/decade. Thus, OFR calculations will be transmitter limited and a steeper selectivity skirt would yield no improvement in the OFR. No image response was shown as it was assumed the future receivers of the projected environment would have an IF frequency of at least 100 MHz. This IF places the image response out of band where it would be attenuated by RF selectivity.

Figure E-8 illustrates the design specifications and the resultant emission spectrums and selectivities. The transmitter emission spectrum for each of the modulation types mentioned above is shown as a solid curve. On the same figure, several receiver selectivities are shown as dashed curves.

The same type of representation is shown in Figure E-9.

After a value of B_T has been chosen, the plot of the emission spectrum for that transmitter is compared with the selectivity of the receiver for another radar of the same type. The OFR curve is a composite approximated by the larger of the emission spectrum or the selectivity. As an example, note the emission spectrum of the transmitter from Figure E-8, sheet 4, and a receiver with $B_T = 3$. The OFR is then the receiver curve up to a Δf of 4.6 MHz and the transmitter curve for Δf larger than 4.6 MHz. Figure E-10 is a plot of the transmitter, the receiver, and the OFR.

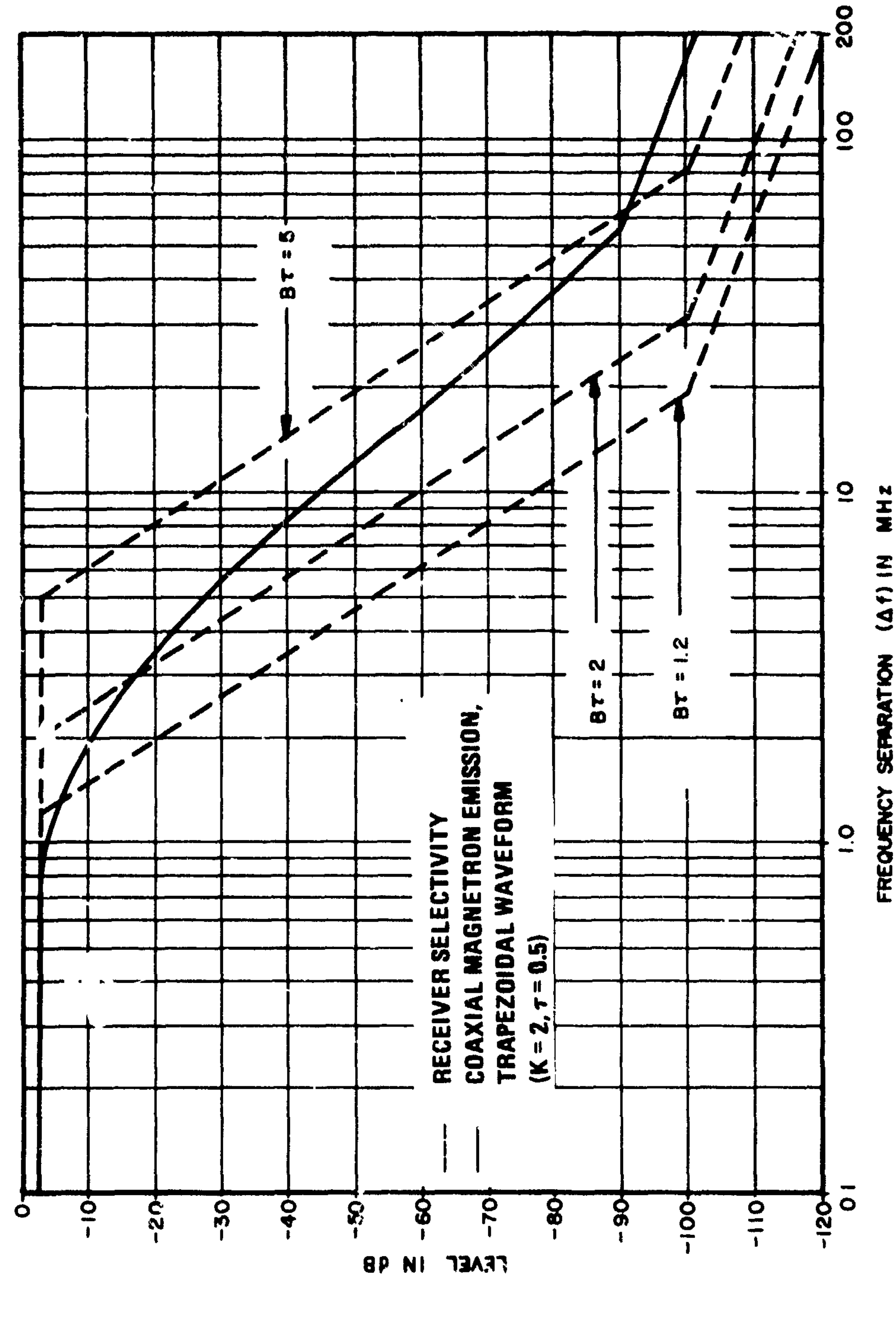


Figure E-8. Normalized Emission Spectrum (τ = 0.5 μs or 6 μs) and Possible Associated Receiver Selectivities (Sheet 1 of 6)

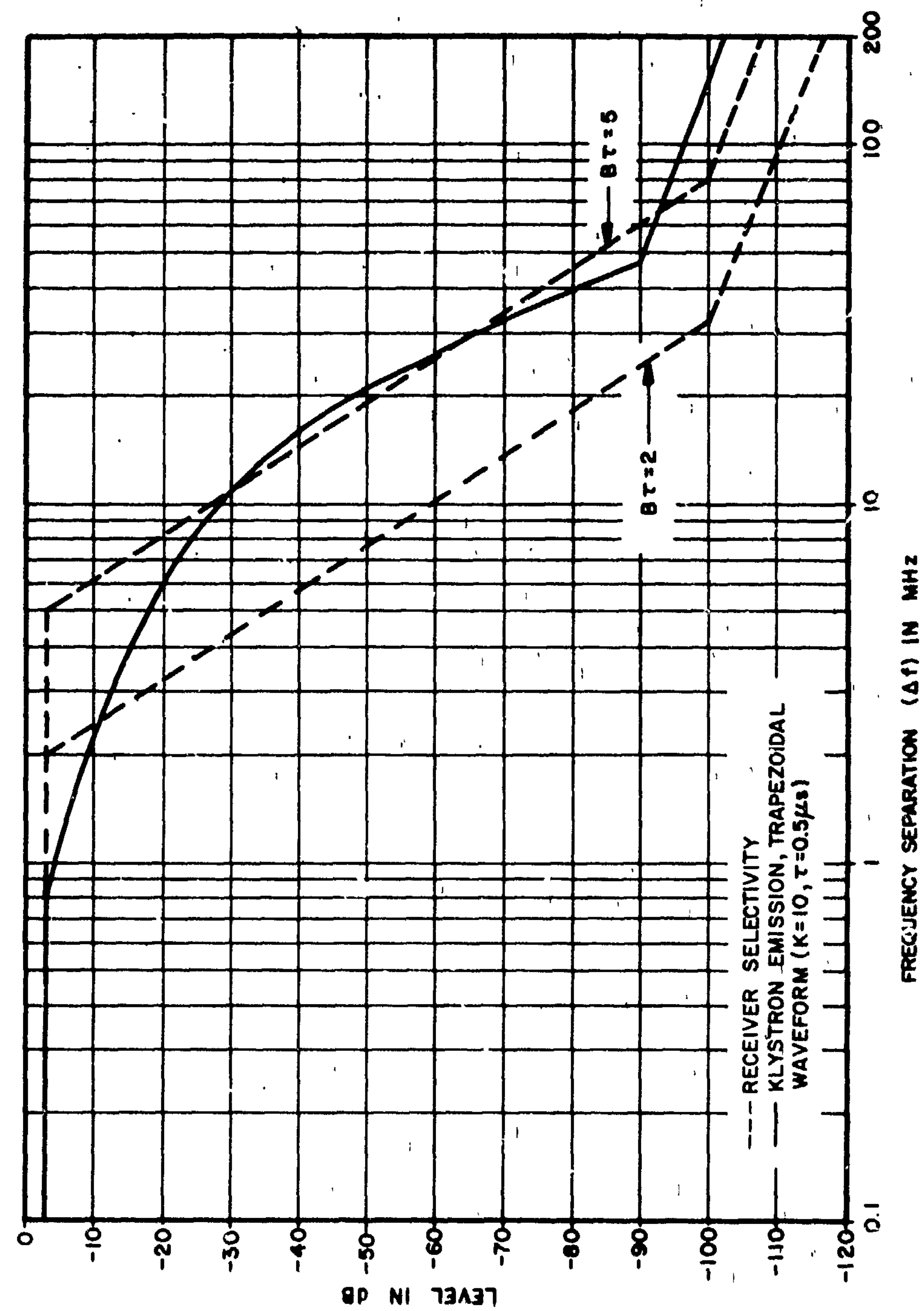


Figure E-8. (Sheet 2 of 6)

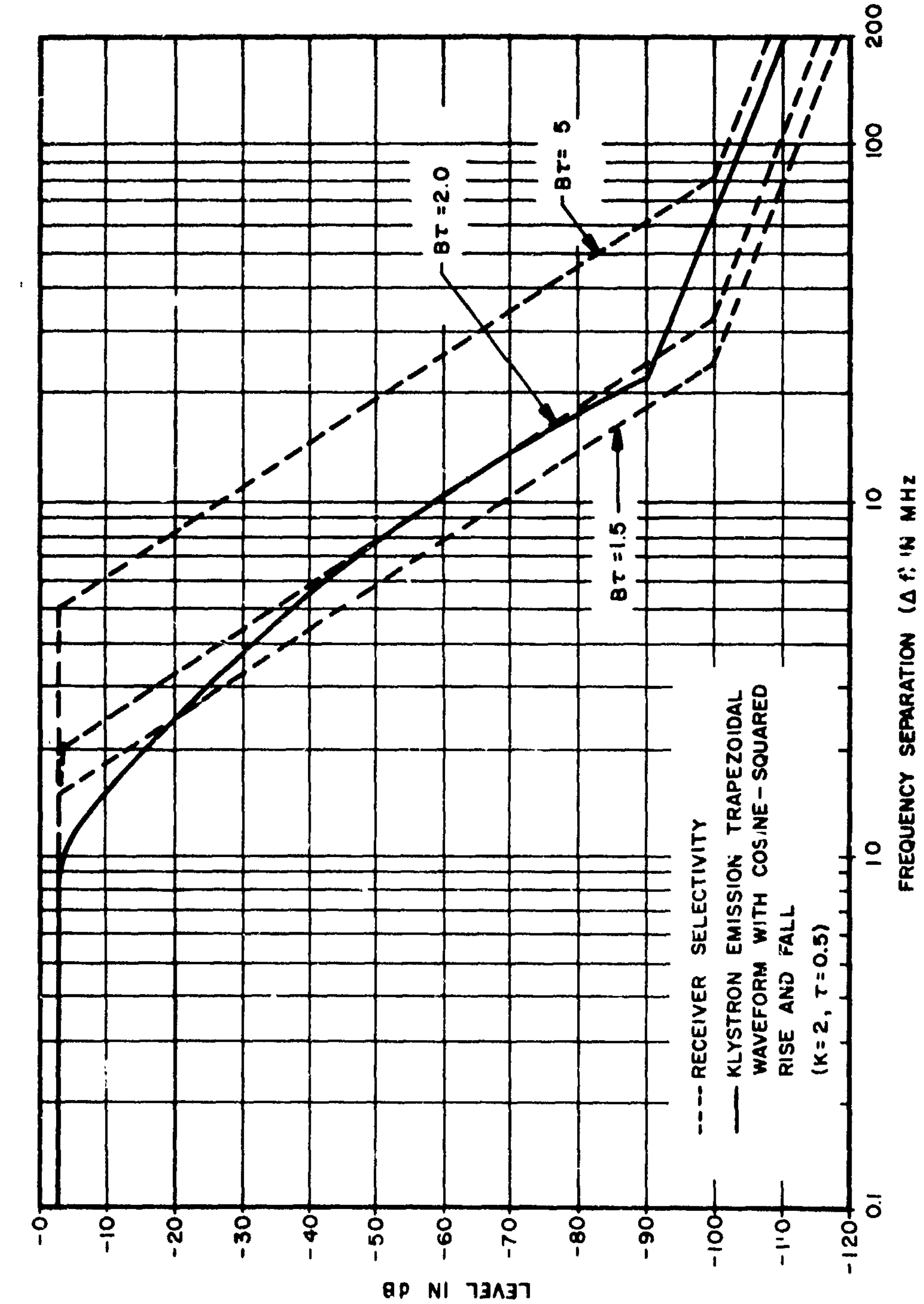


Figure E-8. (Sheet 3 of 6)

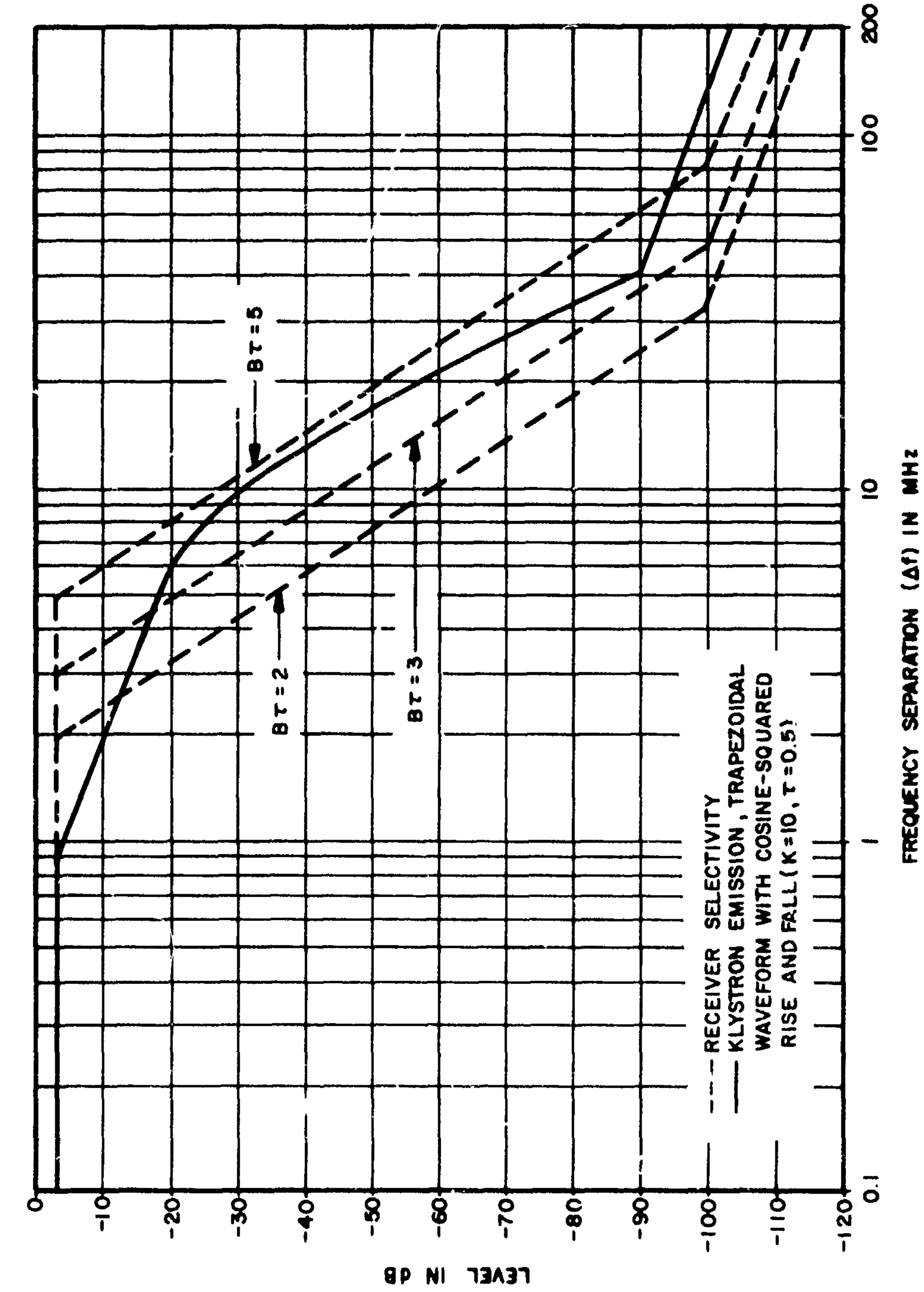


Figure E-8. (Sheet 4 of 6)

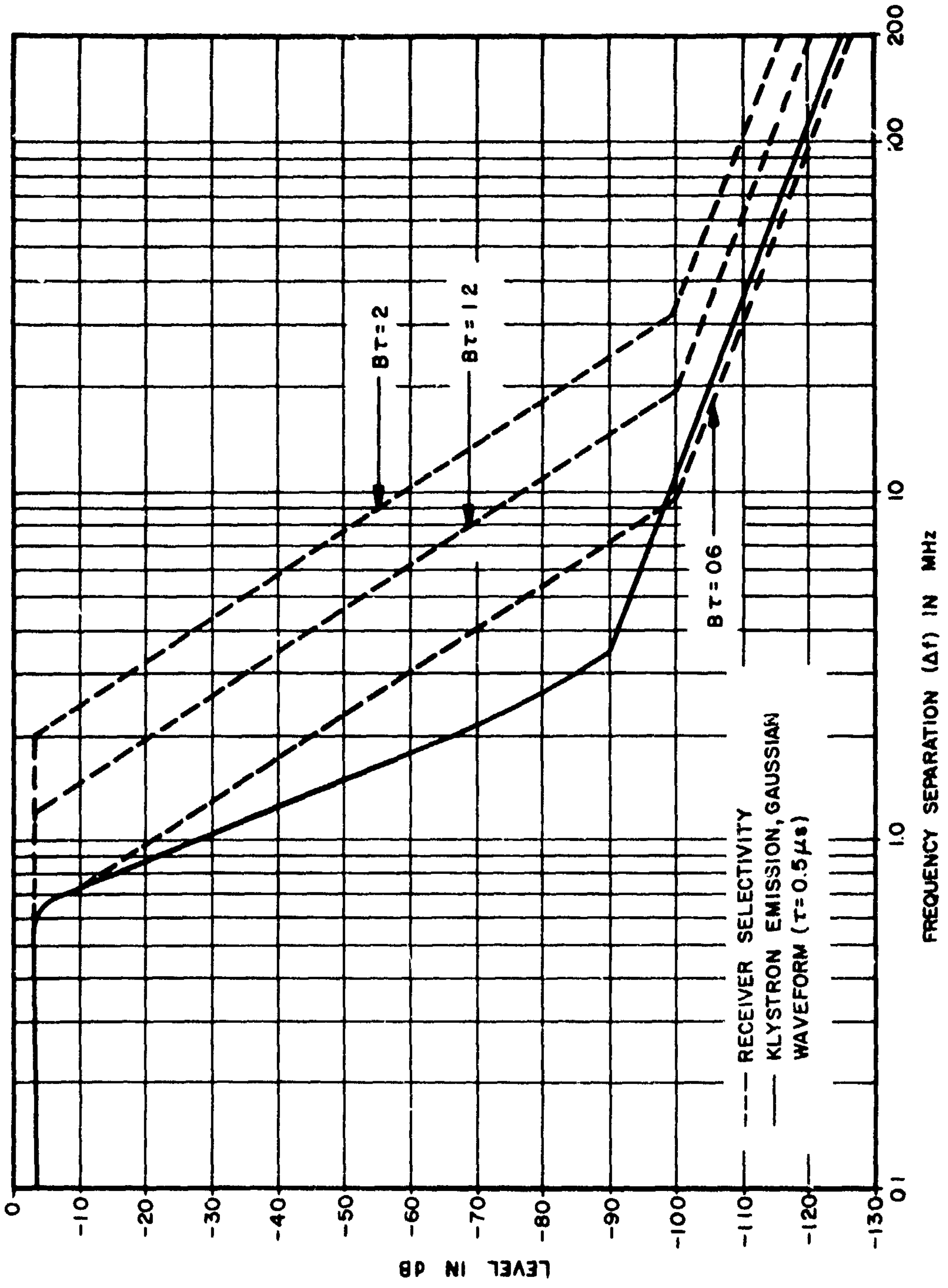


Figure E-8. (Sheet 5 of 6)

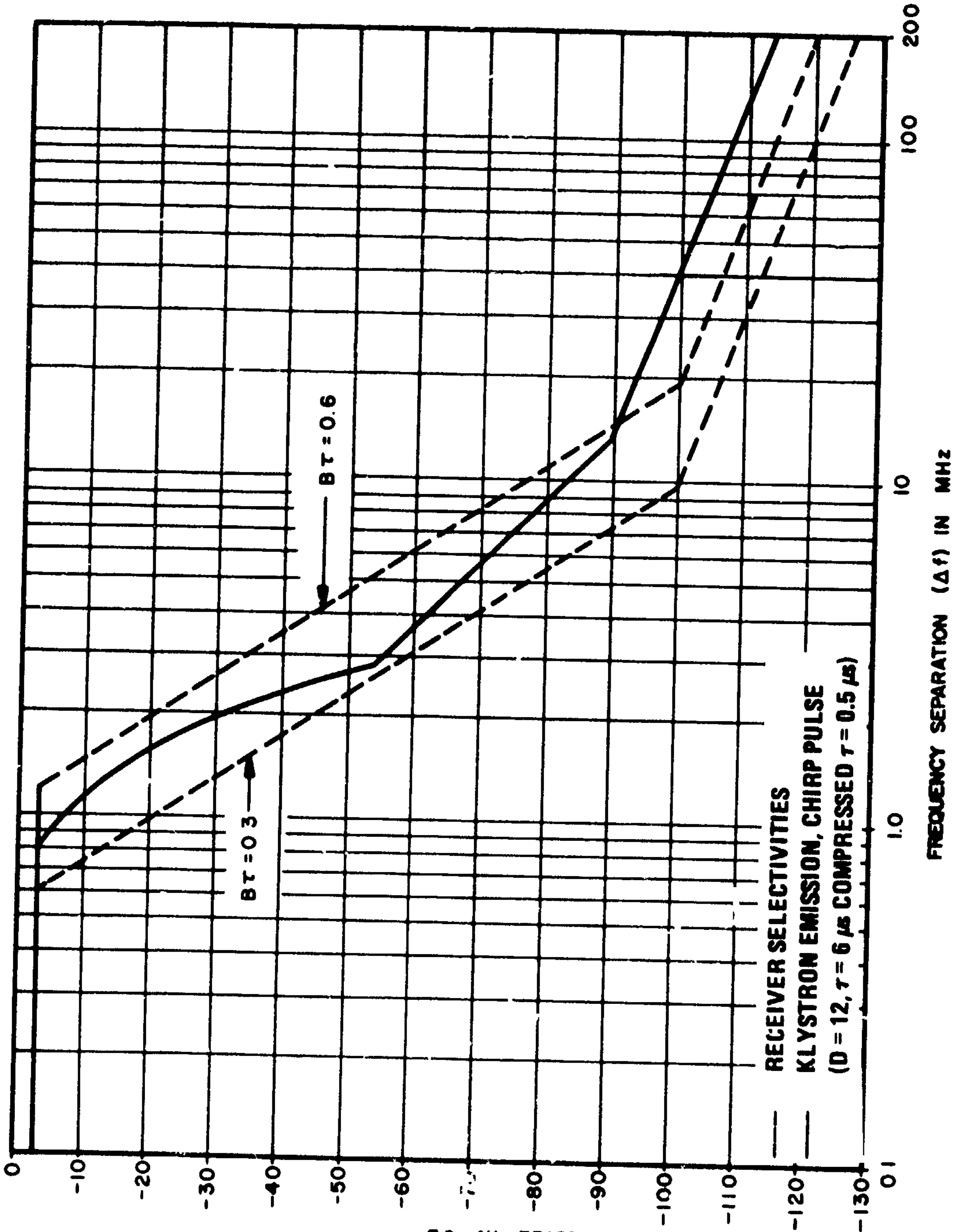


Figure E-8. (Sheet 6 of 6)

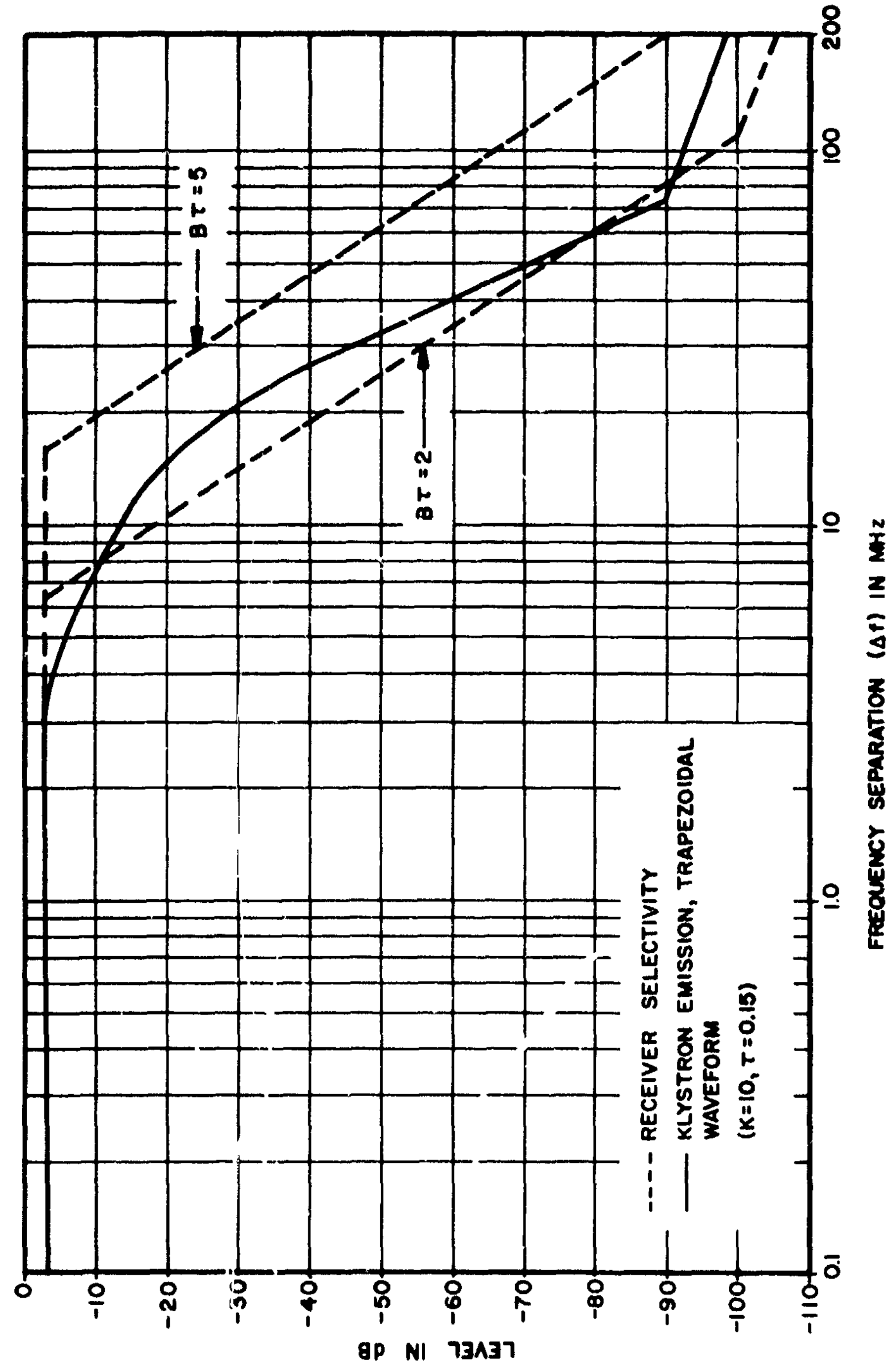


Figure E-9. Normalized Emission (τ = 0.15 or 6 μs) and Possible Associated Receiver Selectivities (Sheet 1 of 4)

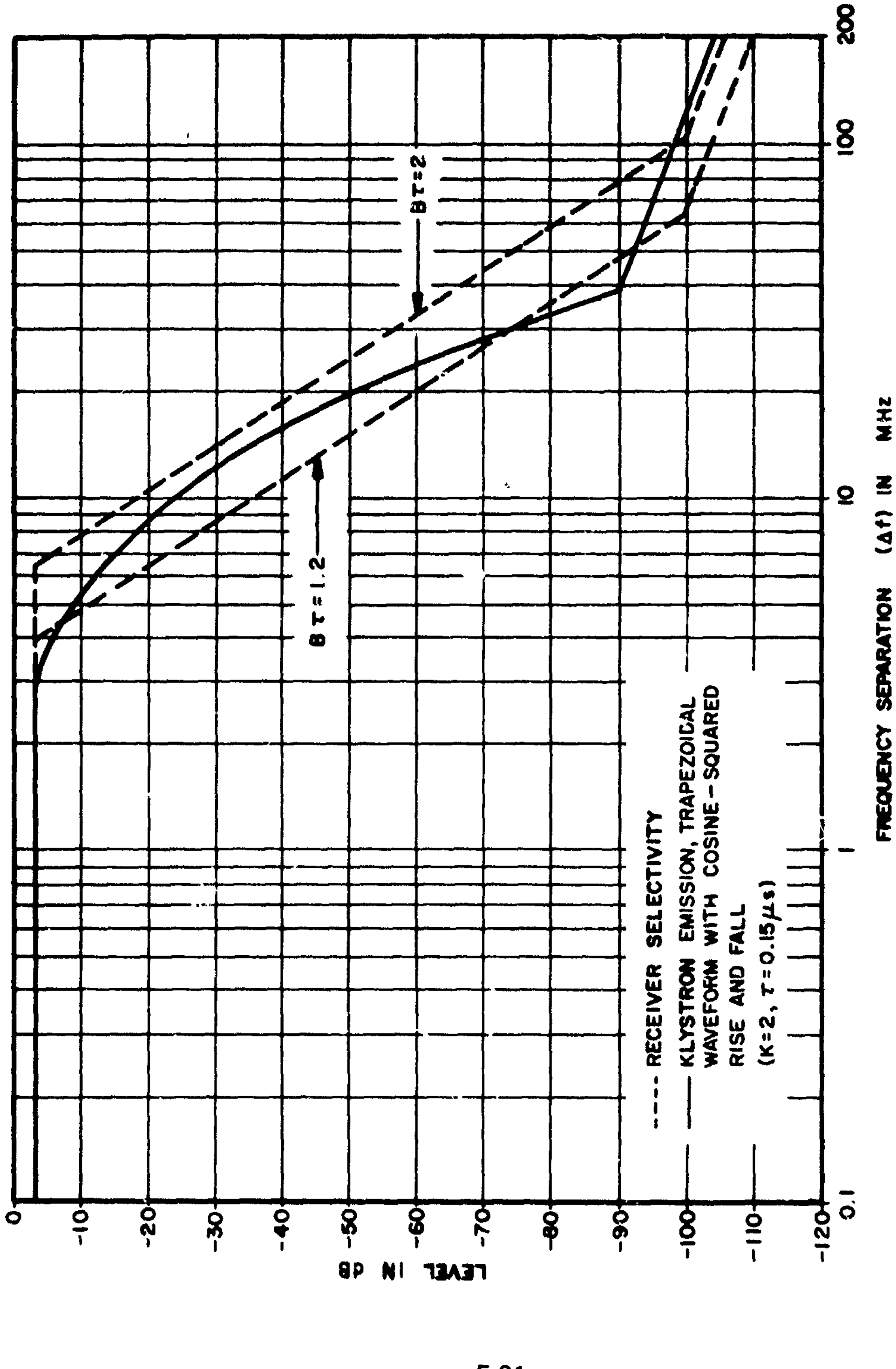


Figure E-9. (Sheet 2 of 4)

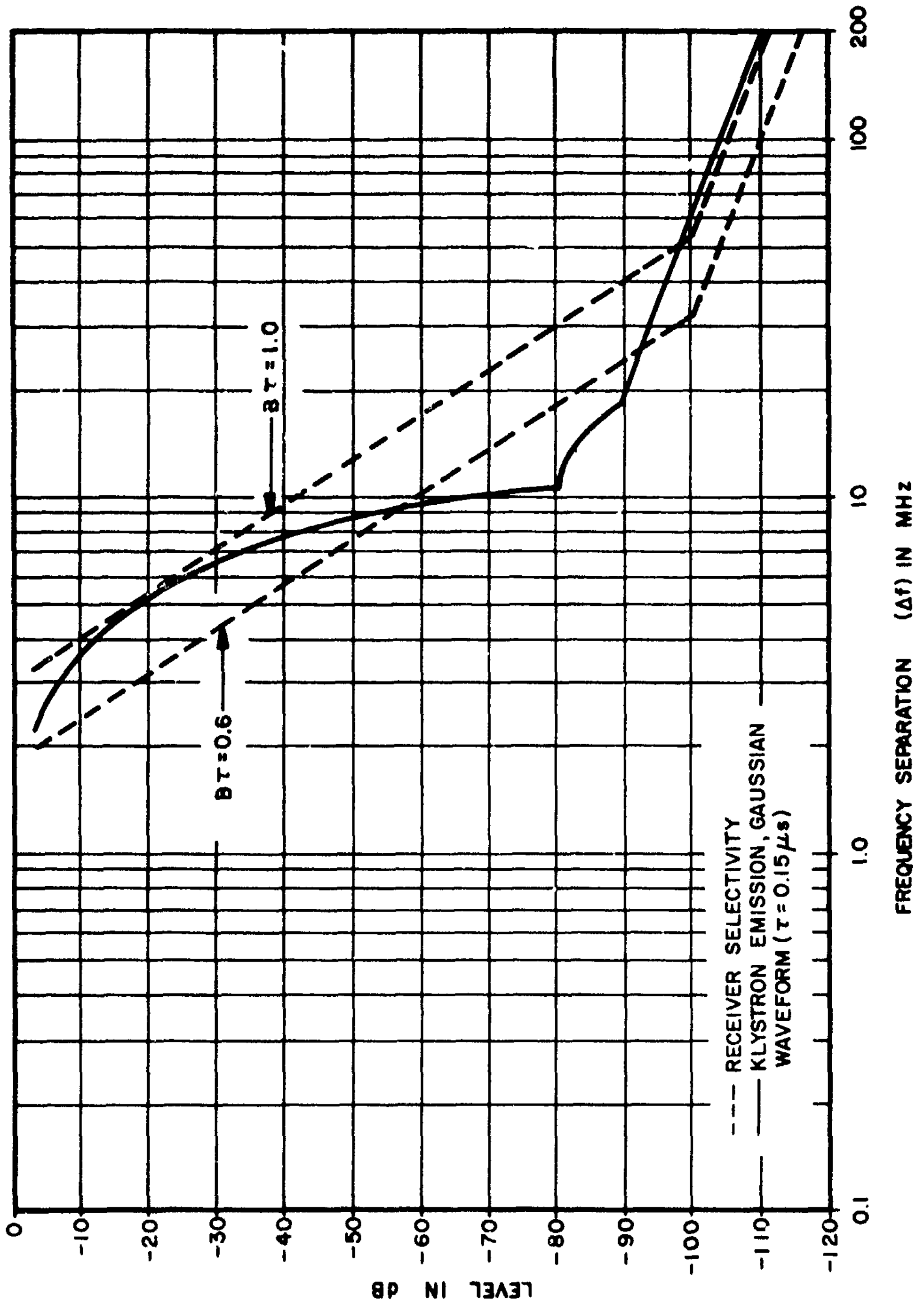


Figure E-9. (Sheet 3 of 4)

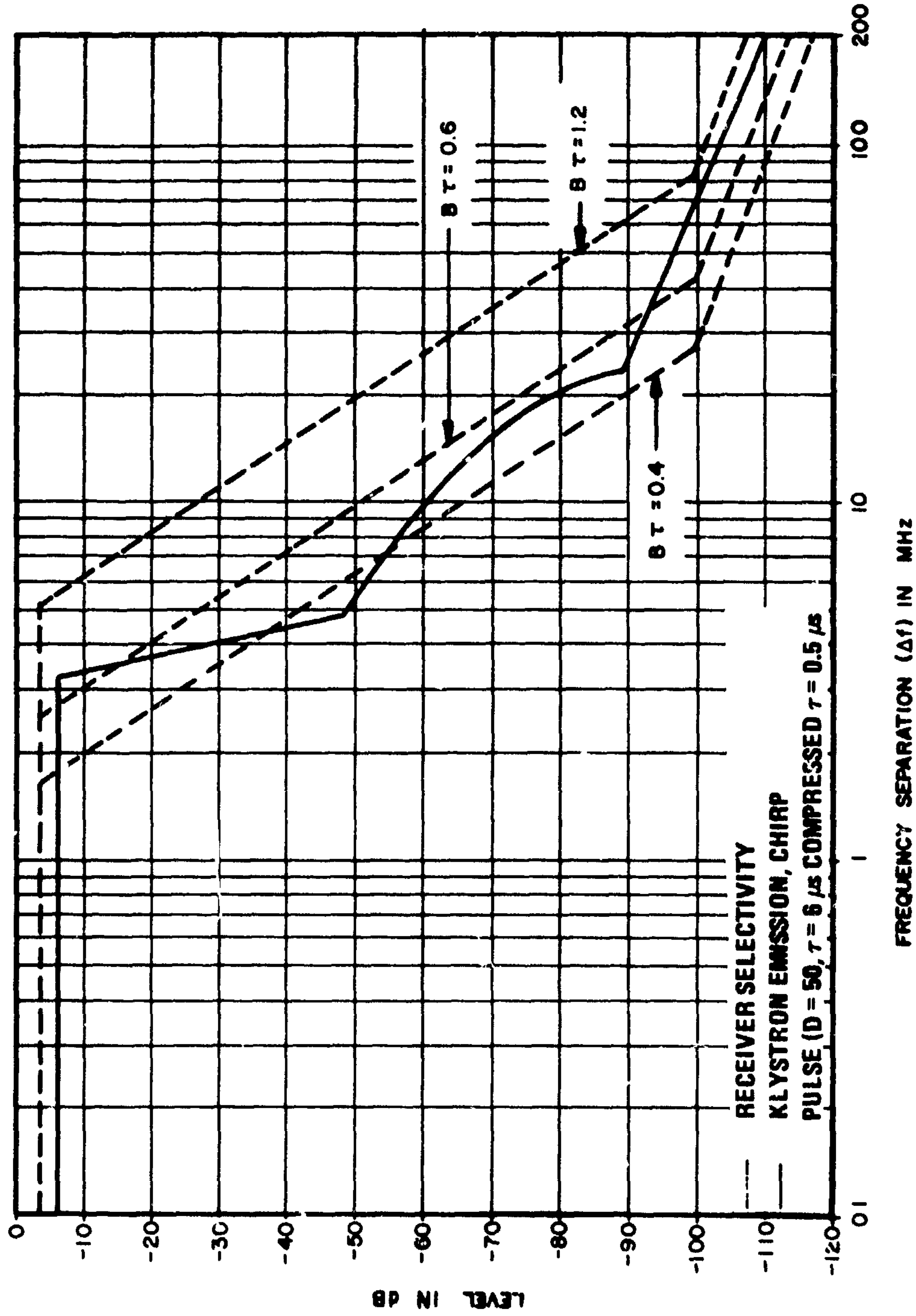


Figure E-9. (Sheet 4 of 4)

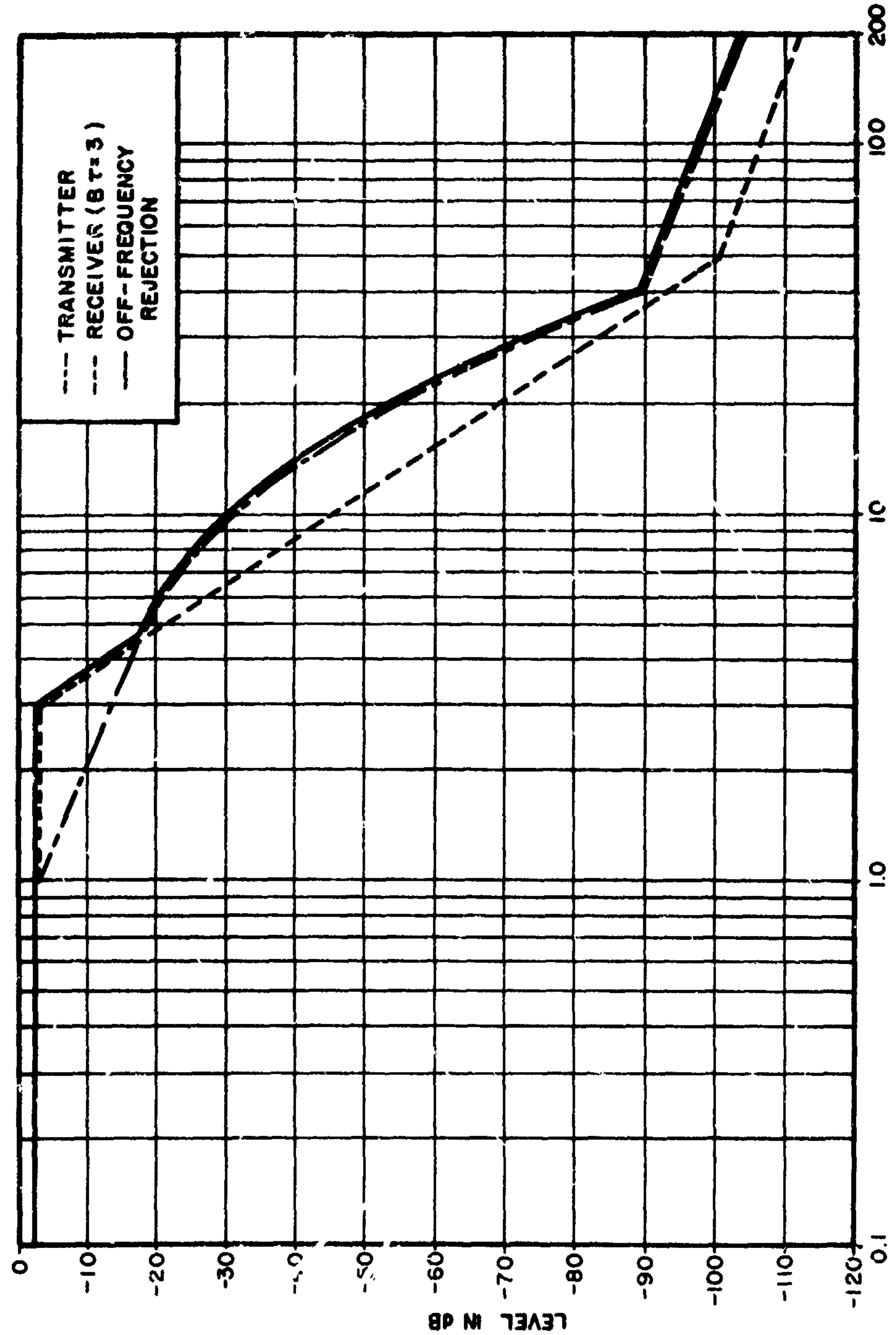


Figure E-10. Off Frequency Rejection for a Klystron Transmitter (COS^2 Shaped Trapezoidal Pulse, K = 10, τ = 0.5 vs Proposed Receiver with B_τ = 3)

APPENDIX F

RADAR SPECTRUM ENGINEERING CRITERIA

The information in this appendix is supplied directly from the *Manual of Regulation and Procedures for Radio Frequency Management* (Reference 1). Its purpose is to provide the standards information used in this report.

5.3.2 RADAR SPECTRUM ENGINEERING CRITERIA

General

The wide application of radar for various functions makes large demands on the radio spectrum, and requires the application of effective frequency management measures for the equipment and systems involved. Criteria for certain equipment characteristics are specified herein to ensure an acceptable degree of electromagnetic compatibility among radar systems, and between such systems and those of other radio services sharing the frequency spectrum.

These criteria are concerned with promoting efficient use of the spectrum, and in specifying them there is no intent to require particular numerical values from the standpoint of the radar's mission. For example, characteristics such as power, sensitivity, pulse repetition rate, pulse duration, pulse rise time, and the range of radio frequency emission are closely related to operational requirements. Accordingly, where limits for some of these characteristics are specified herein, the criteria have been chosen to avoid undue degradation of operational effectiveness. Moreover, the specification of these criteria is compatible with the policy of encouraging a free and unrestricted approach in further research looking toward more effective radars. Nevertheless, any proposals for new approaches and new system concepts involving radar must be reviewed from a frequency management viewpoint prior to development of new equipment.

Useful receiver techniques are available for reduction of the susceptibility of radars to low-duty-cycle pulsed interference. The applicability of such devices as video integrators, correlators, PRF and pulse width discriminators varies with factors such as cost, availability, and their adaptability to specific equipments and environmental situations. While the mandatory incorporation of such devices is not specified herein, their application is recommended for low-duty-cycle radars intended for operation in congested frequency bands and geographic areas.

Effective Dates

The Radar Spectrum Engineering Criteria shall become effective on January 1, 1973, for all new radars developed under the sponsorship of agencies of the Federal Government. On July 1, 1978, the provisions of paragraph 2 of part 5.0 become applicable for all non-conforming radars for which waivers have not been granted.

Applicability

The Radar Spectrum Engineering Criteria apply to all radars that operate below 40000 MHz except:

a) man-portable radars;

b) pulsed radars that have a rated peak power of less than 1 kW; and

c) pulsed radars designed to be used aboard a mobile platform (e.g. ships, aircraft or spacecraft), and whose operating frequencies are equal to or greater than 2900 MHz, and whose rated peak power is no greater than 100 kW.

Waivers

Waiver of the requirements herein may be requested when supported by reasonable justification. When technical and engineering data are supplied in support of a request for waiver or in evaluating the performance of equipment pursuant to provisions of paragraph 2 of part 5.0, an explanation of the non-conforming parameters and any measurement methods employed shall be furnished. Manufacturer's data may be used where deemed appropriate and adequate.

Symbols Used

B = emission bandwidth, in MHz.

B_c = compression bandwidth, in MHz

B_s = bandwidth of the frequency shift ("modified" radar systems) in MHz.

B_d = bandwidth of the frequency deviation (peak difference between instantaneous frequency of the modulated wave and the carrier frequency) -- (FM/CW radar systems), in MHz.

F_o = nominal operating frequency, in MHz.

M = bandwidth due to modification of pulse or to deviation from carrier frequency, in MHz.

t = pulse duration in μsec. (time between 50% amplitude points of pulse).

t_r = pulse rise time in μsec. (time required for instantaneous amplitude to rise from 10% to 90% of the peak value).

Δf_1 = value of one half the emission bandwidth (B/2).

Δf_2 = ten times value of Δf_1 ($10\Delta f_1$).

P_t = maximum power spectral level of the radar in dBm/kHz.*

S = suppression below P_t in dB.

K = t/t_r (ratio of pulse duration to pulse rise time).

k = weighting factor for K.

Radar Emission Bandwidth

The bandwidth of the radar emission spectrum is obtainable from the following relationships:

1. For conventional pulse radars and pulse doppler radars:

   $$B = \frac{2kK^{**}}{t} \le \frac{64}{t}$$

2. For "modified" pulse radars, including chirp, matched filter, pulse compression, and pulse stretch:

   $$B = \frac{2kK^{**}}{t} + M \le \frac{64}{t} + M$$

   (where $M=B_c$ or B_s)

   } or ½% of F_o (whichever is greater)

3. For CW radars:

   $$B = 0.0003\ F_o$$

4. For FM/CW radars:

   $$B = 0.0003\ F_o + 2M$$

   (where $M=B_d$)

---

* P_t may be measured or may for the purposes of these Criteria be calculated from the following:

$$P_t = P_p + 20 \log D_c + 10 \log (1000\ \text{Hz}/PRR) \quad \underline{\text{(Conventional pulse)}}$$

$$P_t = P_p + 20 \log D_c + 10 \log (1000\ \text{Hz}/PRR) - 10 \log d \quad \underline{\text{(Compressed pulse)}}$$

where: P_p = peak power in dBm

D_c = duty cycle

d = pulse compression ratio

PRR = pulse repetition rate in pulses per second.

** Values of the weighting factor "k" vary from unity upward according to the relationship in Figure 2. Its value is unity for values of K = 14.44 and higher. Values of K are commonly 10 or less. Bandwidths resulting from values of K greater than 14.44 (t/t_r in excess of 14.44) require justification based upon technical system requirements.

The radar emission levels outside the above bandwidth at the antenna input shall be no greater than the values obtainable from the curve in Figure 1.* At plus or minus the frequency Δf_1 from F_o the level shall be at least 40 dB below the maximum value. At and beyond plus or minus Δf_2 from F_o, the level shall be at least the value below the maximum which is given by the formula:

$$S = P_t - 20 \log F_o + 100 \geq 40 \text{ dB}$$

or, in absolute level,

$$P_{\Delta f2 \text{dBm/kHz}} = P_t - S$$

Between Δf_1 and Δf_2 values, the level shall be at least the value below the maximum which is obtainable from the straight line drawn between the Δf_1 and Δf_2 values.

Allowable Radar Antenna Patterns

Since electromagnetic compatibility considerations involve phenomena which may occur at any angle, the allowable antenna patterns for many radars may be usefully described by "median gain" relative to an isotropic antenna.** Antennas operated by their rotation through 360° of the horizontal plane shall have a "median gain" of -10 dB or less, measured in the principal radiation plane. For other antennas, suppression of lobes other than the main antenna beam shall be provided to the following levels, referred to the main beam:

major sidelobes -- 20 dB;

all other lobes -- 30 dB.

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* For radars employing more than a single emitter, including certain phased-array radars, special methods may be required in establishing the maximum level of emission and determining levels outside the bandwidth B. Pending adoption of standardized procedures for such radars, values submitted for these parameters shall be accompanied by an explanation of their derivation.

** Median gain is defined as that level over an angular region at which the probability is 50% that the observed or measured gain at any position of the antenna will be less than or equal to that level.

Frequency Stability (Tolerance)

Based on practical electromagnetic compatibility considerations, such as those involving the selection of usable frequencies, all radar transmitters shall have a long term stability no larger than those noted in the following table:

Frequency Range (in MHz)	Tolerance (parts/million)
Below 960	400
960 to 4000	800
4000 to 10000	1250
10000 to 30000	2500
30000 to 40000	5000

Frequency shift radars shall meet the above tolerance requirements as appropriate at the upper and lower extremes of the shift frequency.

Radar Tunability

Maximum capability for tunability supports operational flexibility and promotes electromagnetic compatibility. A minimum requirement is that the radar be tunable either over the allocated bands for which it is designed to operate or over a band which is 10% of the tuned frequency. Radars may be continuously tunable, or have the capability to tune in discrete steps of no more than 2% of the operating frequency.

Radar Receivers

In general terms, the overall receiver selectivity characteristics shall be commensurate with the transmitter bandwidth, as portrayed in Figure 1. Receivers shall be capable of switching bandwidth limits to appropriate values whenever the transmitter bandwidth is switched (pulse shape changed). Receiver image rejection shall be at least 50 dB; rejection of other spurious responses shall be at least 60 dB. Radar receivers shall not exhibit any local oscillator radiation greater than -40 dBm at the receiver input terminals. Frequency stability of receivers shall be commensurate with, or better than, that of the associated transmitters.

Measurement Capability

In order to coordinate radar operations in the field, an accurate measurement of the center frequency is necessary. An accuracy of ± 1 part in 10^6 is desirable, although, for most radars, ± 1 part in 10^4 is adequate. Accordingly, a frequency measurement capability of at least ± 1 part in 10^4 shall be available for use by every fixed radar installation and for every service facility responsible for maintenance and adjustment of mobile radars not exempt from these criteria.

Of comparable importance is the capability to measure pulse rise time and spectrum occupancy. Accordingly, every fixed radar installation and every service facility responsible for maintenance and adjustment of mobile radars not exempt from these criteria shall have access to a suitable oscilloscope and spectrum analyzer to measure pulse rise time and spectrum occupancy.

RADAR EMISSION BANDWIDTH AND EMISSION LEVELS

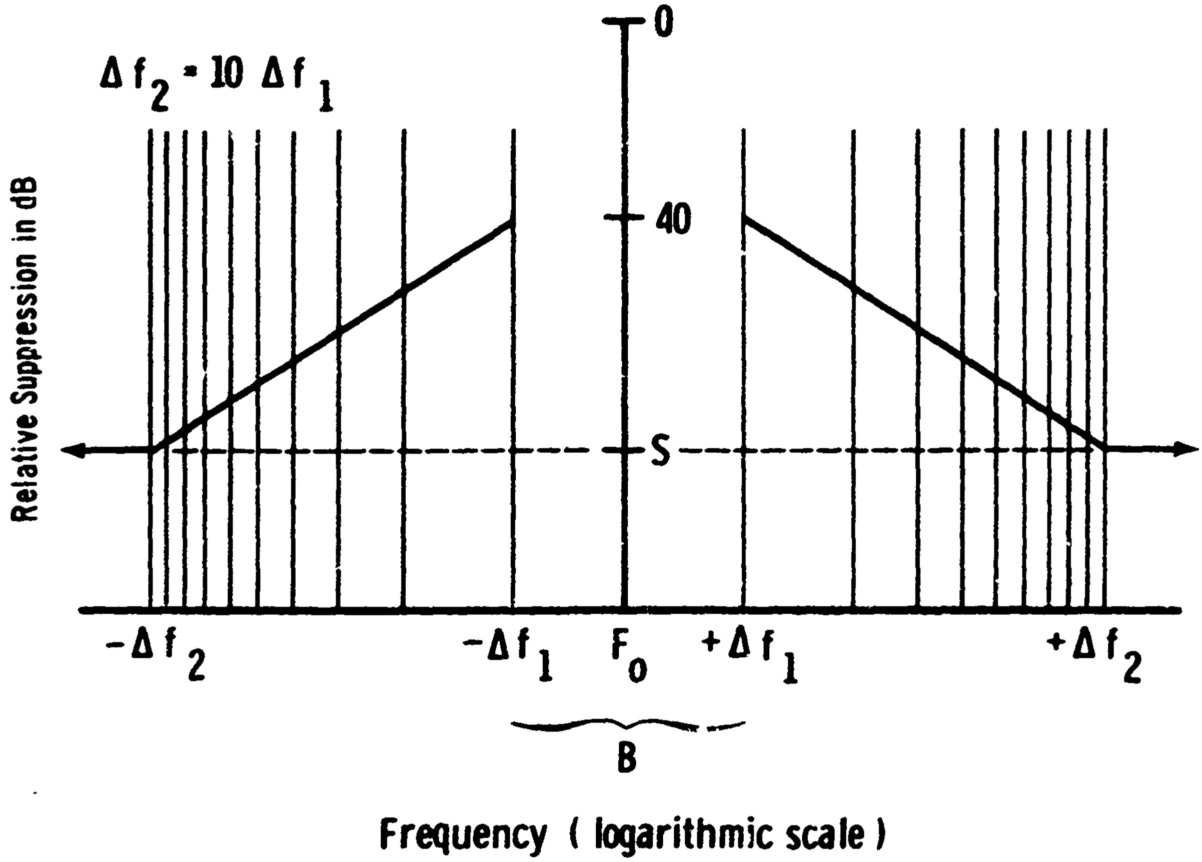

FIGURE 1

DEPENDENCE OF WEIGHTING FACTOR k UPON K

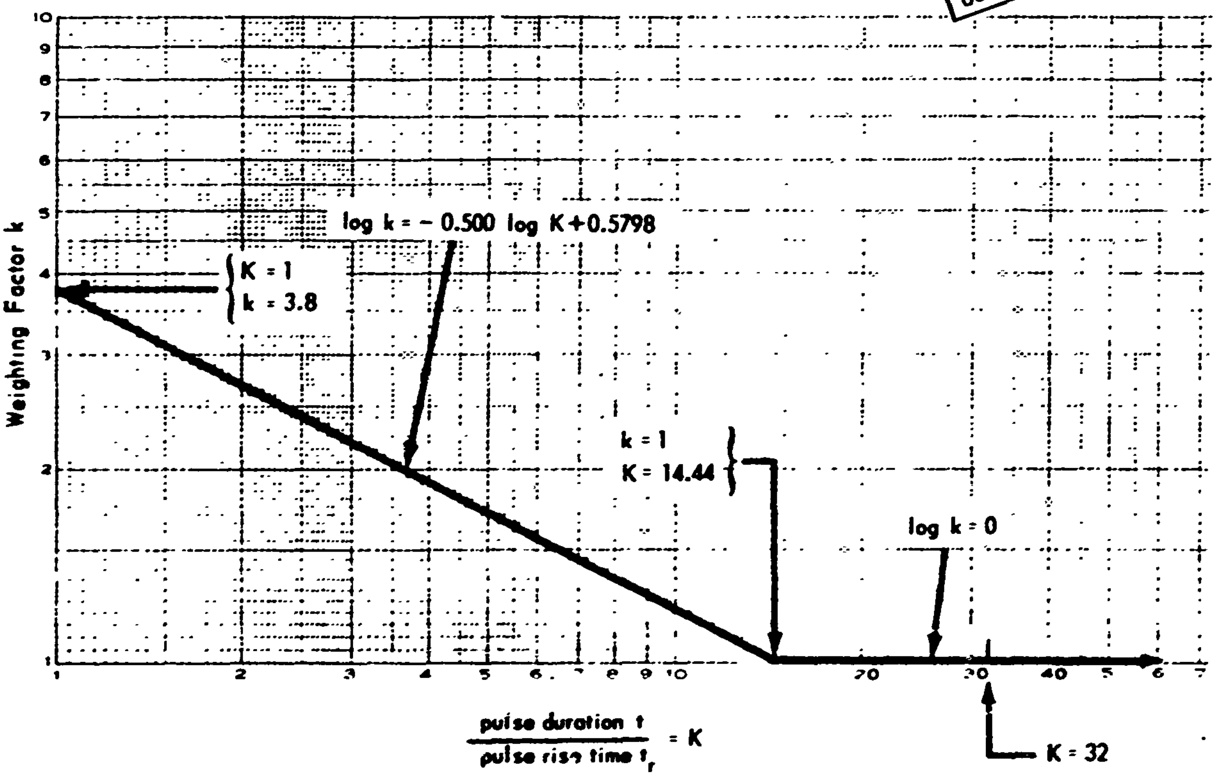

FIGURE 2

APPENDIX G

CHANNELIZATION WITH CODING

Radar systems utilizing coded waveforms appear to possess great potential to provide interference-free operation when large numbers of radars must be operated in a limited frequency band. In addition, many of these coding techniques provide excellent clutter rejection. Examples discussed here are binary phase coding, frequency coding, frequency agility and pulse compression techniques.

In evaluating such coding techniques (pulse compression is also covered in Appendix C), the properties of the received waveforms (in the absence of a doppler shift) can be discussed in terms of the autocorrelation function since use is generally made of a matched filter. (When there is a doppler shift the complete ambiguity function must be discussed.) For evaluation of radar-to-radar interference effects, the interfering signals from one radar being received by the other system will also appear as "target signals" on the second radar, with varying range and velocity characteristics. Thus, in any EMC analysis good use can be made of both the autocorrelation and ambiguity function (or diagram).

BINARY PHASE-CODING

Binary Phase-Coding consists of a transmission of a constant-amplitude sinusoidal carrier which is divided in time into N equal segments of duration τ. Each segment will correspond to the nominal carrier phase (0°) or to a 180° shift. (Polyphase waveforms may also be implemented where each segment can have any one of M possible codes.) Such waveforms are generally classified as random, binary periodic sequences pseudo-random sequences, maximum-length coded words, or perfect codes. Many good references exist in the literature on waveform coding techniques, among which are noted References 29,30, 57 58 and 59. The principal concept behind the coding techniques is that the received signal code must be matched to a stored code (i. e., the matched filter). The transmitted code (which is subsequently also stored) is, when received, matched segment by segment. If the codes are compared in a time axis, the resulting code yields a maximum output from the receiver. A received signal with a different code will be either completely rejected by the processor or greatly reduced in level. The degree of rejection of an undesired code depends upon many factors in the waveform design and processing techniques of the system. Coding techniques must be selected to give suppression of time sidelobes and/or velocity sidelobes, depending upon desired clutter and interference rejection. For example, it may be desirable to have a "thumbtack" ambiguity surface in which the low-value sidelobe levels are smeared throughout the range-velocity plane equally and have only a maximum response at the target signal (in this case clutter is averaged over the range-velocity plane). The amount of rejection of an unmatched received coded signal depends upon the coding technique and the processing. Theoretically in some cases, total rejection of a wrong code is possible. Practically, with time and frequency varying signals rejection values between $\sqrt{N}$ and N^2 may be realized.

The binary-phase coding technique is simple, and flexible coding/decoding units can be built. This flexibility could be an important factor in providing interference free operation, or optimum band usage of a number of radars restricted to a given operating frequency band. A particular code can easily be changed from radar to radar to reduce or eliminate an interference problem or when, say, a new radar is added, thus further crowding the band. The coding change would require no redesign or modification of equipment. If digital techniques are used, possibly only a control adjust would be necessary to re-adjust a shift register. Coding thus can offer an additional rejection, allowing much closer frequency operation between systems. Nathanson (See Reference 30) has pointed out that with a maximum-length code (with the use of a digital pulse-compression processor) transmission by one radar will not cause false alarms to appear on another radar using a different code.

FREQUENCY CODING

Frequency coding techniques include the familiar linear FM or "chirp" modulation and discrete frequency coding modulation. These forms of coding likewise offer an interference rejection capability between radars operating in a limited band and in close proximity. Also, the analysis techniques of autocorrelation and ambiguity functions provide a useful tool in interference analysis. In the case of linear FM pulse waveform a degree of isolation can be obtained between two radars by having one modulated up in frequency and the other down in frequency; the degree of rejection is dependent on the compression ratios and time bandwidth products involved. In addition, the linear FM pulse offers subclutter visibility improvement in some forms of clutter (See Appendix III, Detection in Clutter). The linear FM pulse can be approximated by a discrete stepped frequency -- for example, an increasing stepped frequency in each τ segment of the transmitted pulse. Digital processing may then be used to provide the matched compression filter.

FREQUENCY AGILITY

Yet another frequency coding technique is to transmit a scrambled frequency code. Each τ segment of the pulse would be at a different discrete frequency. A system using this type of modulation will not respond to interfering FM-like signals generated by other radars.

Higher pulse repetition frequencies may be necessary when operating a narrow beamwidth surveillance radar in an environment where the locations of clutter and/or interference are not known but a large amount of clutter reduction and interference rejection is desired. However, there may be insufficient dwell time to do this. Use of frequency-agile pulse train coding can be used to accomplish these desired results. Frequency-agile pulse consists of pulses on several different carriers. There are various classes of this waveform and each class requires a different processing configuration. Reference 60 presents some of the properties of this type of waveform guide.

Coding techniques offer rejection capability of radar systems to undesired signals. The use of such coding techniques to augment or even replace the usual method of channelization when operating a number of radars in a limited band offers great potential. The potential exists to operate more systems in a given band, change assignments more flexibly or introduce additional systems. However,. the techniques of coding generally require greater signal bandwidth than noncoded techniques. Therefore, a study to compare the advantage of receiver rejection gained with coding techniques to the disadvantages of additional transmitter bandwidth needed with coding techniques would be useful. Such a study would show the relationships to channelization of receiver rejection, coding type, frequency band limits, and numbers of radar systems in the frequency band.

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