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A simplified model of the single channel communication system with interference is developed. The various parameters of this model which affect the quality of communications is then discussed. Specifically, performance data for the VRC-12 radio for various signal-to-interference ratios is introduced and a message quality indicator is developed for various received friendly and jamming signal strengths.

The results of the analysis show that it is possible to develop a realistic computerized model for tactical communications in a jamming environment. Comparisons of the propagation portion of the model with actual field tests show the results to be an accurate indication of "real-world" conditions while the integration of actual equipment performance under co-channel interference adds a realism to the model which enhances its usefulness as a training or planning device.

FM Tactical Communications Under Intentional Interference

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A thesis presented to the faculty of the U.S. Army Command and General Staff College, Fort Leavenworth, Kansas 66027

FM TACTICAL COMMUNICATIONS
UNDER INTENTIONAL
INTERFERENCE

A thesis presented to the Faculty of the U.S. Army
Command and General Staff College in partial
fulfillment of the requirements of the
degree

MASTER OF MILITARY ART AND SCIENCE

by

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The opinions and conclusions expressed herein are those of the individual student author and do not necessarily represent the views of either the U.S. Army Command and General Staff College or any other governmental agency. (Reference to this study should include the foregoing statement.)

ABSTRACT

This study is undertaken to determine whether it is possible to develop a realistic computerized mathematical model for FM tactical radios operating under the influence of enemy jamming.

A simplified model of the single channel communication system with interference is developed. The various parameters of this model which affect the quality of communications is then discussed. Specifically, performance data for the VRC-12 radio for various signal-to-interference ratios is introduced and a message quality indicator is developed for various received friendly and jamming signal strengths.

Next, mathematical relationships for signal propagation over various terrain is introduced. The specific communication links considered were those for air-to-ground, line-of-sight (LOS), and single and multiple obstacle paths. Consideration was also given to the moisture content of the soil as this is an important consideration at the frequencies involved in the analysis. A comparison is then made between the path losses predicted by the various mathematical relationships and actual field tests. It is shown that the developed expressions produce realistic results. These tested signal propagation relationships are then integrated with the VRC-12 radio's

performance under interference to produce the final computerized model.

In addition to the terrain between friendly transmitter and receiver and enemy jammer and receiver, several other variables are incorporated in the model. The additional variables of the model include frequency, transmitter and jammer output power, antenna height and directivity and jammer location with relationship to the receiver antenna.

The completed model explains various interrelationships in this type of communication problem while answering the "what would happen if ...?" question. This is done without actually constructing an operating system.

The actual output of the computerized model tells the user whether he has excellent, good, fair, poor or unsuitable communications for various battlefield deployments. By changing various characteristics of the problem, i.e., antenna gain, power output, obstacle between jammer and receiver, etc., a means of changing unsuitable communications to acceptable communications is developed.

In summary, the results of the analysis show that it is possible to develop a realistic computerized model for tactical communications in a jamming environment. Comparisons of the propagation portion of the model with actual field tests show the results to be an accurate indication of "real-world" conditions while the integration of actual equipment performance under co-channel interference adds a realism to the model which enhances its usefulness as a training or planning device.

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INTRODUCTION

Rapid and reliable communications are essential to the commander of a modern, mobile military force. As a result of its flexibility, radio has traditionally been used to meet the tactical commander's communication requirements. However, some of the same characteristics of our tactical frequency modulated (FM) radios which make them so desireable also make them especially susceptible to intentional electronic interference. Specifically, the use of pretuned channels and the idiosyncrasies of frequency modulation provide inherent advantages to the enemy jammer when compared with amplitude modulated (AM) communications. As a result of these limitations, it is of paramount importance that the tactical communicator understand the vulnerabilities of his FM equipment and how best to use his radios so as to reduce the effectiveness of enemy interference.

BACKGROUND

During World War I amplitude modulated (AM) sets furnished the only radio communications available to the American Forces. It was not until just prior to World War II that frequency modulated (FM) sets were developed.[1] Frequency modulation proved to be far superior to amplitude modulation for the majority of the required army radio nets. The reliance on this means of communications has grown rapidly in the intervening years until the Vietnam Conflict, during which the U.S. Army relied extensively upon FM radios for tactical communications.

During this same time period, Electronic Warfare (EW) gradually emerged as a threat to our FM nets. The first use of FM radio jamming was employed by the British against Rommel's Afrika Korps in North Africa in November of 1941.[2] The British accomplished this by mounting a number of FM transmitters in their bombers. Each of these radios were redesigned to transmit random FM noise. By flying over the German Tanks, the British were able to cause effective disruption of the enemy radio communications until the German Fighters finally shot down the jammer aircraft.

During our most recent combat experience in Vietnam there were occasional attempts by our relatively unsophisticated enemy to interfere with our tactical radio communications.[3] However, virtually all of the enemy's sophisticated EW means were located outside the Army's area of operations and were encountered mostly by the Air Force and Navy in their sorties over North Vietnam.

However, the recent mid-east war has shown that this may well not be the case in any future conflict.[4] The EW threat to the Army's operations is likely to be much greater than it has been in the past. As a consequence, it is essential that the Army move to improve its posture in this area.

The basic characteristic of FM communication that makes it particularly vulnerable to enemy jamming is the threshold effect of frequency modulation. This effect is graphically displayed in figure 1 where an FM system is compared with those systems referred to as being linear.[5] What this illustrates is that FM systems require the carrier power to be above the noise power in order to detect the transmitted signal. In other words, unless the received signal exceeds a certain signal level the detected signal is unusable. FM is therefore essentially a "go" or "no go" system, while amplitude-modulated systems are soft. Soft systems are those in which the signal-to-noise ratio improves gradually in proportion to the carrier.

This threshold effect consequently reduces the jamming-to-signal ratio that is required to completely jam an FM or threshold system. This characteristic has given rise to the term "FM Capture Effect" as the receiver output signal will be dominated by the strongest signal once a certain threshold is exceeded.

STATEMENT OF THE PROBLEM

This is the specific question which this study will address -- is it possible to develop a computerized mathematical model for FM tactical radios operating under the influence of enemy jamming so as to optimize communications for particular battlefield terrain and various equipment configuration?

The completed model should do several things for the communication planner or student of Electronic Warfare.

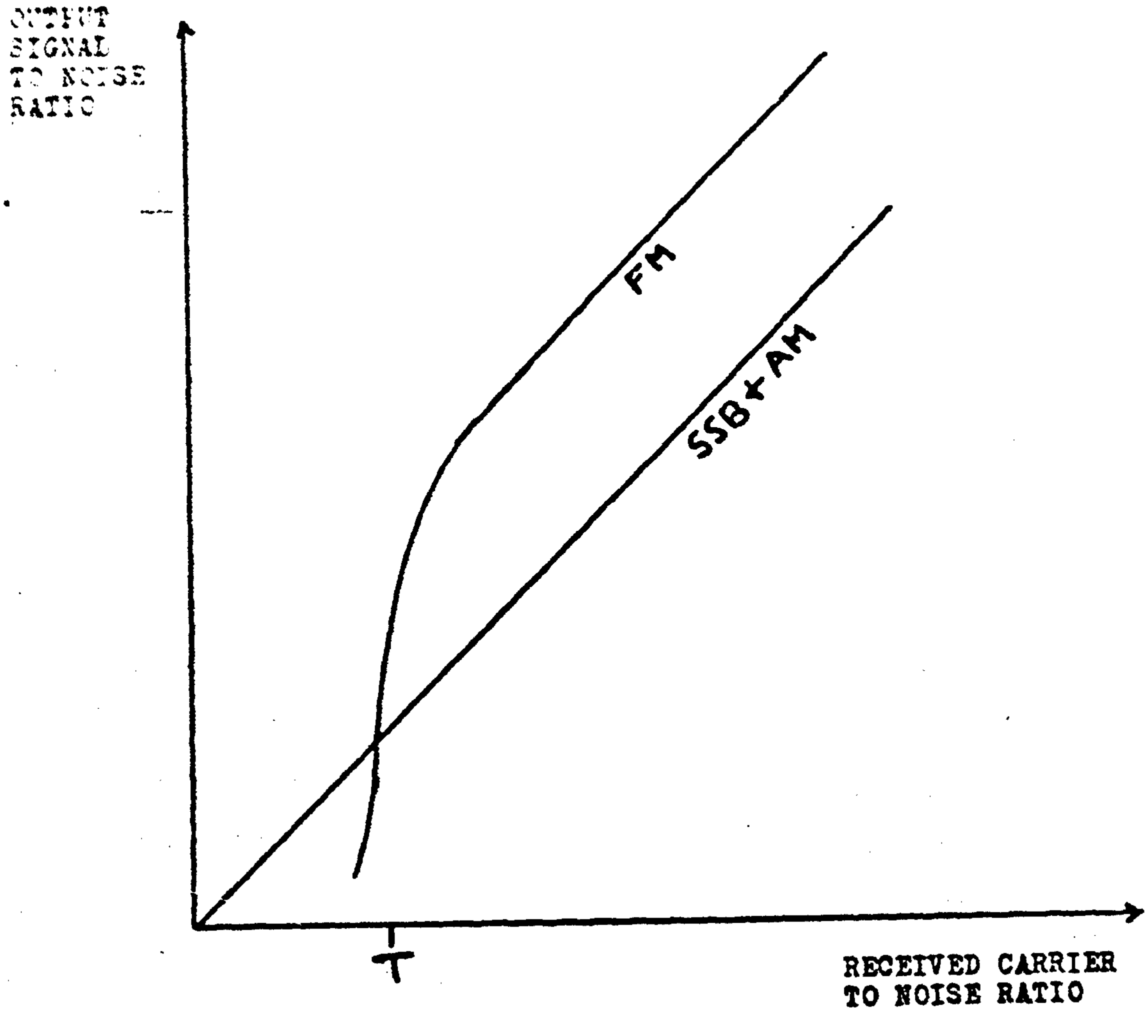


Figure 1. Threshold Systems

It should explain the various interrelationships in this type of communication problem while answering the "what would happen if ...?" question. This would be done without the requirement for actually constructing an operating communication system. In addition, it should indicate what steps could be taken to reduce the effectiveness of enemy jamming.

METHOD OF INVESTIGATION

Figure 2 best illustrates the components of the problem. It shows in graphic form a model which represents a tactical radio communication system under intentional jamming. The friendly FM transmitter radiates a frequency modulated electromagnetic (EM) wave of some predetermined power rating from a suitable antenna with a directivity determined by the operator. Some of this EM wave, after experiencing a transmission loss dependent on distance and terrain, will be received by the intended receiver. The signal strength of this received signal will also be a function of the gain of the receive antenna used. In addition to the desired EM wave, the receiver will pick up jamming signals intentionally transmitted to prevent the desired signal from being received in a useable condition. The strength of this jamming signal will be a function of the jammer output, antenna directivity, transmission loss, distance and receive antenna orientation. If the received friendly signal is sufficiently larger than the jammer signal, the friendly receiver will provide an intelligible output.

It can be seen from this discussion that the variables

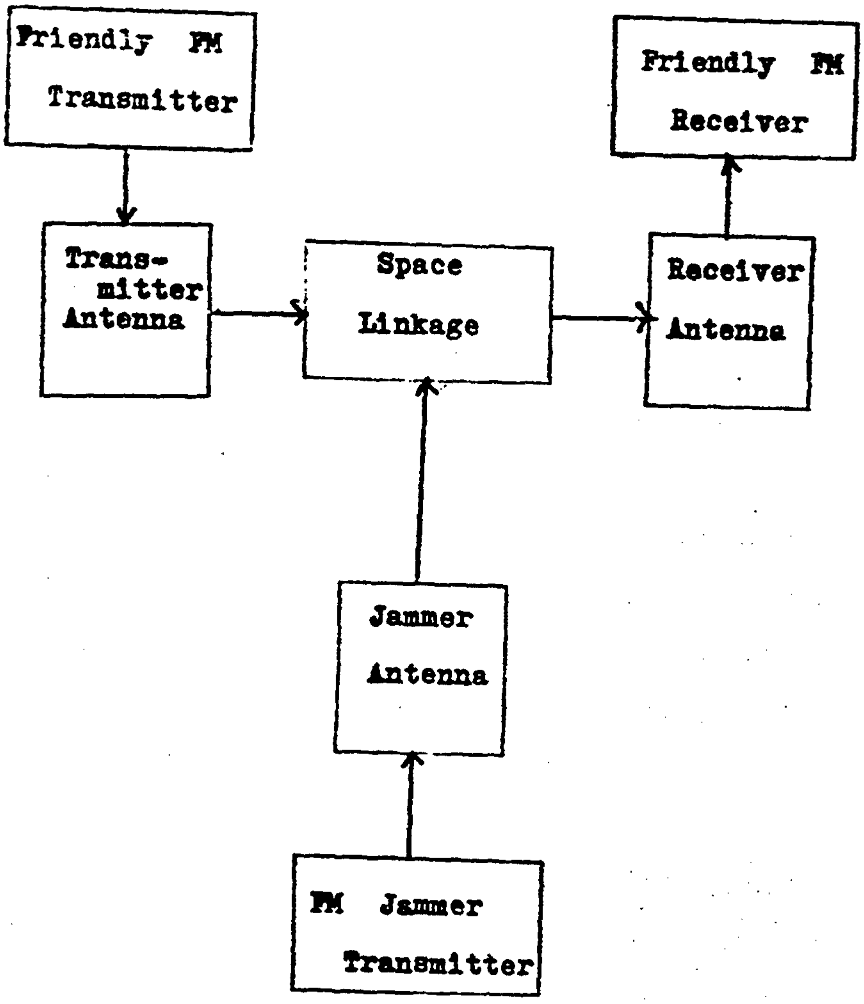


Figure 2.Block Diagram of a FM Radio Link under Intentional Jamming

of this problem are frequency, transmitter and jammer output power, antenna configuration, transmission loss as a function of various terrain configurations and distance, and the signal-to-interference ratio as a function of intelligibility. In order to solve the problem it will be necessary to develop the mathematics which relate these parameters and then compare the results of the model with actual field tests.

As with any theoretical model, it is important to make some assumptions. The most basic to this problem is that the enemy has determined what our transmission frequency is and is jamming our communication channel. This is a reasonable assumption as our radio's detent tuning prevents us from detuning to discourage co-channel interference.

Another important assumption is that the transmitting and receiving antennas are clear of all obstructions in the immediate site areas. This is important as obstructions immediately adjacent to an antenna can seriously distort its radiation pattern and unnecessarily complicate the system analysis. In addition, it can be safely assumed that any good communicator will locate for optimum performance.

The terrain over which the signals are analyzed is assumed to be that of the central part of western Germany. Not only is this an area in which the U.S. Army could experience a future conflict, but there are no rugged mountains or extremely flat plains to complicate the analysis. It is in fact typified by rolling farmland spotted with forested areas.[6] It is assumed, for the purpose of the present model, that any ground reflections from transmitters within line-of-sight (LOS) will either be from a freshly plowed field or a field with a small crop. This negates the importance of ground reflections as a source of interference. Since there are no large water areas, these are neglected. In addition, the conditions are assumed to be the summer, spring or fall so that no ice or snow will be involved.

Each computed value of path loss will be considered to be the median value for that particular path. The actual received signal strength varies with time because of changing conditions in the media. However, short-term variations are not significant for the distances involved and may be neglected.[7]

Another important assumption is the type of signal used by the jammer. A well known principle states that the jammer, to be most effective, must employ the same type of signal and modulation as the signal it intends to jam.[8] The most effective jamming signal and the one which will be assumed is a FM signal modulated with random audio noise.[9] Since random noise has no periodically recurring frequency, it cannot be filtered out or otherwise eliminated without also removing the desired signal.

The effect of these assumptions is believed to be second order and will not have a significant effect on the model's accuracy.

Chapter II

REVIEW OF RELATED LITERATURE

From the discussion in the previous chapter, it can be seen that the model development can be separated into two major components. These are; the effects of terrain on the transmitted signal and the interaction of the received friendly and jammer signal at the receiver. This chapter will review some of the more significant studies which have addressed these two major areas of concern.

VERY HIGH FREQUENCY (VHF) PROPAGATION STUDIES

Many studies have been conducted in an attempt to predict the behavior of radio signals when transmitted over different terrain. The most significant studies, as far as FM tactical communications are concerned, were those concerned with the very high frequency (VHF) range (30-300MHz). One of the most important was the work undertaken by Egli.[10]

In many cases, such as with mobile communications and other systems involving movable equipment, one may not know in advance the nature of the terrain over which transmission will be requested. In such situations, information concerning the propagation loss association with a particular hill or grove of trees is of little value in determining the amount of attenuation which should be assumed in the design of the system. Egli's approach to this type of problem was to analyze a large number of measurements involving propagation over a great variety of terrain in order to determine the mean and standard deviation of the distribution of the losses which are attributable to terrain and other obstructions. This would allow one to predict the probability that various amounts of attenuation would be encountered.

The results of the various measurements were then expressed in terms of the percentage of locations at a specified distance from the transmitter at which the field strength can be expected to equal or exceed a specified value. For example, if a five-mile circle with the transmitter at the center is divided into 100 equal parts, with each division represented by a receiver location, 75 percent coverage would mean that at 75 of the locations the median value of the field strength in the immediate vicinity would be equal to or greater than the specified value.

The primary weakness with Egli's method is that it is primarily suited to the problem of estimating the attenuation caused by irregular terrain when the system is to operate in an unknown or variable environment. If, however, any information concerning the region in which the system is to operate is available, it must be considered in predicting path attenuation. Otherwise, Egli's method would probably lead to unduly pessimistic results.

This same method has been used to report on the effectiveness of one of the most widely used computer models for propogation over irregular terrain, the Longley and Rice model.[11] This model is used to predict long-term median transmission losses over irregular terrain and is intended for use in the 20 to 40,000 MHz range and for distances of up to 2,000 kilometers. Using this rather complicated model, transmission loss may be calculated for specific paths where detailed profiles are available, but this prediction method is particularly useful when little is known of the details of terrain for actual paths. This analysis is facilitated by classifying different types of terrain with a certain terrain parameter which is used along with the carrier frequency, path distance and transmitting and receiving antenna heights to predict the signal loss for the particular area of communication.

Area predictions of transmission loss over irregular terrain using the Longley and Rice model were compared with measurements made with low antennas in Colorado, Ohio, Virginia, Wyoming, Idaho and Washington.[12] These tests showed excellent agreement for over-the-horizon communications. However, for known line-of-sight (LOS) and single-horizon paths, the predicted attenuation proved greater than actually observed.

A review of these studies has shown that most computer models now in use are far more complicated than required for my analysis. In addition, I will be working with particular terrain profiles such as a communicator could derive from a map analysis. As previously discussed, the models presently in use are designed primarily for use in an area analysis using Egli's method of probability of coverage. Consequently, I have decided to use the classical relations for line-of-sight (LOS), plane-earth, free-space and single and multiple obstacle propagation loss. The development of these relationships and their use will be discussed in chapter 4. When these relationships are used in conjunction with the simplifying assumptions of chapter 1, the result will be a model of sufficient accuracy so as to realistically simulate actual field conditions.

One of the most useful field tests for the purpose of testing the propagation portion of my communication model was done in 1967 by the Institute for Environmental Research.[13] The purpose of this report was to present tabulations of transmission loss data resulting from propagation experiments over arbitrary terrain in the 20 to 100 MHz range. The three terrain types over which the measurements were taken were the Colorado Plains, the Colorado Mountains and the Ohio Hills. The data for these tests consists of terrain profiles, photographs, power levels, basic transmission loss, frequencies, and antenna heights for each of the propagation paths selected.

FREQUENCY MODULATION (FM) INTERFERENCE RESEARCH

Laboratory tests have been conducted at the U.S. Army Proving Ground at Fort Huachua, Arizona to collect data on the effects of Electronic Counter-Measure (ECM) jamming on AM and FM type communication equipment in an attempt to develop a model to predict the effects of jamming on various communication systems.[14] By employing a number of different jamming levels, a set of curves were developed which graphically displayed the ratio of the jammer to desired signal levels versus a relative intelligibility score. These results were then used to predict what might be the performance of an idealized communication receiver when a certain level of jamming and friendly signal were present at its input terminals.

The major failings of this particular model are due to its highly idealized nature. As the model is presently formulated, it represents several idealized jamming mechanisms that might be utilized by friendly and enemy forces. How adequately these mechanism represent actual jamming equipments can not be realistically determined without knowledge of specific communication equipments and their response to various inputs. In addition, such a model is of little use to the tactical communicator without integrating it into one of the previously discussed propagation models.

To accurately display the degradation of friendly communications by an enemy jammer, some measure of communication intelligibility must be used. For many years the most popular method was to state the degradation factor in terms of a more-than-normal delay in the message delivery time. However, most recent communication analysis has been in terms of a signal-to-noise (S/N) or a signal-to-interference (S/I) ratio and an Articulation Index (AI).[15] The value of the AI is that it is a numerical value which can be calculated by a communication engineer from a knowledge of the power level of the received desired signal and the received noise or interference. These calculations then allow him to predict performance using the known relationships which exist between the AI rating and the percent of intelligibility. AI ratings will be used in this study to evaluate the effectiveness of enemy jamming.

Laboratory tests have also been conducted to investigate the on-channel capture effect in the Army's FM tactical radios.[16] These tests were undertaken with the intention of studying the interference effects of one U.S. Army FM radio upon another when operating on the same frequency. However, the results of these unintentional interference tests are essentially the same as would be obtained by employing intentional interference (jamming) against the Army's FM radios. The specific ECM jamming that is duplicated is that referred to as "spot" jamming in which the enemy operates only on one or two communication channels at any instant of time.

The actual laboratory tests required three radio sets. Two identical sets comprised the desired communication link while a third set acted as an interference source. The interference set was modulated with an audio noise signal so as to simulate the most destructive mode of interference to voice communications.

The results of the FM on-channel capture effect tests are presented in the form of curves of AI versus S/I for each of the test links and interference combinations. The curves for the AN/VRC-12 series radios are of particular significance to this study as they will used to predict the interaction of desired and jamming signals at the receiver.

SUMMARY

As a review of the related literature has shown, the major contribution of the proposed model will be as a realistic simulation which integrates actual equipment performance under jamming with realsitic but simplified signal propagation relationships.

Chapter III

FM CAPTURE EFFECT

As previously mentioned in Chapter I, the basic characteristic of FM Communication that makes it particularly vulnerable to enemy jamming is the threshold effect of frequency modulation. It is the purpose of this chapter to explain this characteristic and the rapid degradation of the desired signal which occurs when that signal is approached in relative strength by any form of interference. Actual test results will then be introduced and their significance in the model development.explained.

A real-world example that would be of assistance in understanding the difference in performance between AM and FM receivers is the case of a mobile receiver traveling from one transmitter toward another, all operating on the same frequency. With AM transmitters and receiver, the performance of the receiver would be very straightforward. The nearer transmitter would always predominate, but the other one would be heard as quite significant interference although it might be very distant.

The situation is far more interesting with FM. While the signal from the second transmitter is less than about half of that from the first, the second transmitter is virtually inaudible, causing practically no interference. After this point, the transmitter towards which the receiver is moving becomes quite audible as a background and eventually predominates, finally excluding the first transmitter; the moving receiver has been "captured" by the second transmitter. If a receiver is between the two transmitters and fading conditions prevail, first one signal, and then the other, will be the stronger, so that the receiver will be captured alternatively by one transmitter and then the other.

THEORY OF FM CAPTURE

In my analysis of the FM "Capture" effect I will treat the interfering signal as being a noise signal with uniform density across the communications channel. This is a realistic assumption for my purposes as this type of interferance or jamming is the most destructive and most probable type of jamming that would be used against FM noise.communications.[17] The input signal to the receivers demodulator could then be represented by

$$Y(t) = X_c(t) + n(t)$$
$$= A_c \mathrm{Cos}[\omega_c t + \phi(t)] + r_n(t)\mathrm{Cos}[\omega_c t + \phi_n(t)].$$

Where A_c and $r_n(t)$ represent the amplitude of the received FM signal and noise envelope respectively and $\phi(t)$ and $\phi_n(t)$ their associated phases. ω_c is the carrier frequency expressed in radians per second.[18]

After a little manipulation, y(t) can be written in the form

$$Y(t) = r(t)\ \mathrm{Cos}[\omega_c t + \psi(t)]$$

where

$$\psi(t) = \arctan \frac{A_c\ \mathrm{Sin}\,\phi(t) + r_n(t)\mathrm{Sin}\,\phi_n(t)}{A_c\ \mathrm{Cos}\,\phi(t) + r_n(t)\mathrm{Cos}\,\phi_n(t)}.$$

Physically, we can expect noise to modulate the carrier in both amplitude and phase. However, a demodulator having perfect limiting will respond only to the latter and will remove the envelope variations represented by r(t), so we are concerned only with the relative phase $\psi(t)$. Specifically, the detected signal is proportional to the time derivative of $\psi(t)$.

In view of the complexity of $\psi(t)$ as shown above, it is helpful to make some simplifying approximations. Let us therefore assume that the signal is either very large or very small compared to the noise, such that $A_c \gg r_n$ or $A_c \ll r_n$. This is the same as saying that the predetection signal-to-noise ratio, $(\frac{S}{N})_T$, is much greater or much less than one. The phasor representations of these signals can be illustrated as shown in Figure 3.[19] From these illustrations the following approximations can be made:

$$\psi(t) \approx \phi(t) + \frac{r_n(t)}{A_c}\sin\varphi(t) \qquad \text{for} \quad (\tfrac{S}{N})_T \gg 1 \quad (3a)$$

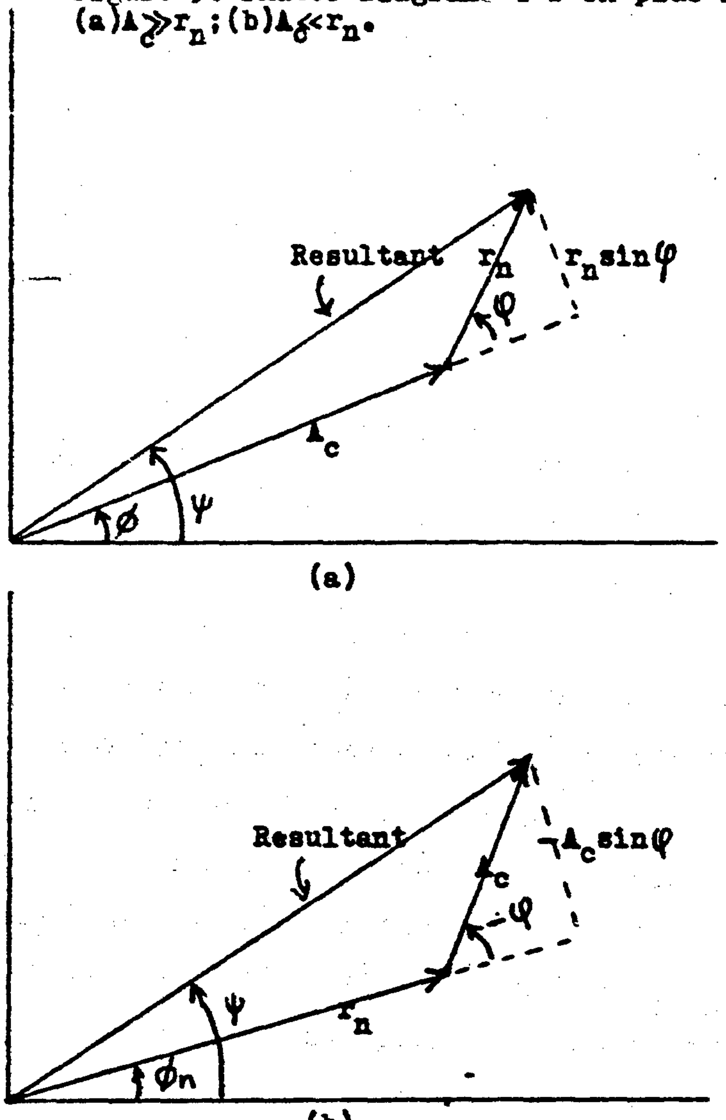
$$\psi(t) \approx \phi_n(t) - \frac{A_c}{r_n(t)}\sin\varphi(t) \qquad \text{for} \quad (\tfrac{S}{N})_T \ll 1 \quad (3b)$$

where

$$\varphi(t) = \phi_n(t) - \phi(t).$$

An examination of the above equations reveals that the leading term is the phase of the dominant component alone, whether signal or noise. This becomes particularly important in the case where the noise dominates. A careful examination of eqn. 3b reveals that the message appears only as a part of

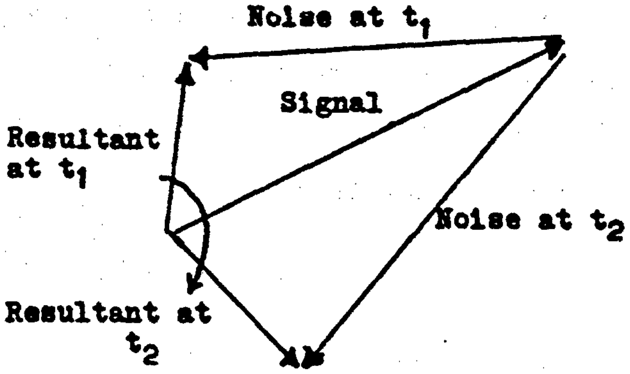
Figure 3. Phasor Diagrams for FM plus Noise.
(a)$A_c \gg r_n$; (b)$A_c \ll r_n$.



(a)

(b)

Figure 4. Effect of Phase Fluctuations when $(\frac{S}{N})_T \ll 1$.



Sin $\varphi(t)$, which also includes $\phi_n(t)$ and in turn is multiplied by the random variable $1/r_n(t)$. This means the message is mutilated by noise and cannot be recovered. The resulting "threshold effect" was graphically displayed in figure 1.

Equation 3b was approximated by assuming that $(S/N)_T \ll 1$. However, significant mutilation begins to occur when $(S/N)_T \approx 1$, for then $A_c^2 \approx r_n^2$, and the signal and noise phasors are of equal length. If they are also of nearly opposite phase $[\phi_n(t) = -\phi(t)]$, the resultant is quite small, and a small change in the phase difference $\phi_n(t) - \phi(t)$ yields a large phase deviation of the resultant, as diagramed in figure 4.[20] As the condition $\phi_n(t) = -\phi(t)$ comes and goes intermittently, the output changes in a sporadic fashion from signal to crackling.

Although the above discussion might leave the impression that capture effect is the sudden take-over of the stronger signal in FM receivers, this is not the case. Capture by an interfering signal is in fact a gradual degradation of the received Signal-to-noise ratio until $(\frac{S}{N})_T \approx 1$ is reached. Because of this a check will be made early in the analysis of the friendly transmitter to receiver link to insure that $(\frac{S}{N})_T \geq 12$dB. In this case the noise present would only be that due to background and internal receiver noise. The value 12dB has been determined to be a signal-to-noise ratio which is required by FM receivers to ensure negligible mutilation of the desired signal at the output.[21]

If a check by the computer program reveals that the received signal-to-noise ratio is appreciably less than 12dB even without jamming, the program analysis will cease as we obviously have designed a poor communications link.

FM CAPTURE TEST RESULTS

In chapter two it was mentioned that unclassified interference tests had been conducted by the Army on its FM radios.[22] The results of these tests are particularly significant in the development of this model as they offer actual equipment performance when subjected to co-channel interference by a transmitter whose carrier is modulated by audio noise. This is directly analogous to an enemy jammer employing the most effective form of "spot" jamming against FM voice. By integrating these laboratory tests into an accurate propagation model, the result will be a model which will accurately predict the performance of FM communications under noise jamming.

Figure 5 shows a plot of the performance of the AN/VRC-12 radio set when subjected to interference from another AN/VRC-12 radio whose carrier is modulated by audio noise.[23] The results are presented as a plot of the articulation index versus the signal-to-interference ratio in decibels. During the laboratory tests it was assumed that "capture" by an interfering signal could be considered to have occurred when the ratio of desired signal strength to interfering signal strength resulted in a corresponding articulation index (AI) less than or equal to 0.7 measured at the output of the test link receiver.[24] An examination of figure 5 will reveal the justification for such an assumption. It can be seen that the articulation index deteriorates rapidly with only a relatively small drop in the signal-to-interference ratio. This illustrates that while total capture is a gradual process, it still occurs relatively rapidly once the signal-to-interference ratio drops below about

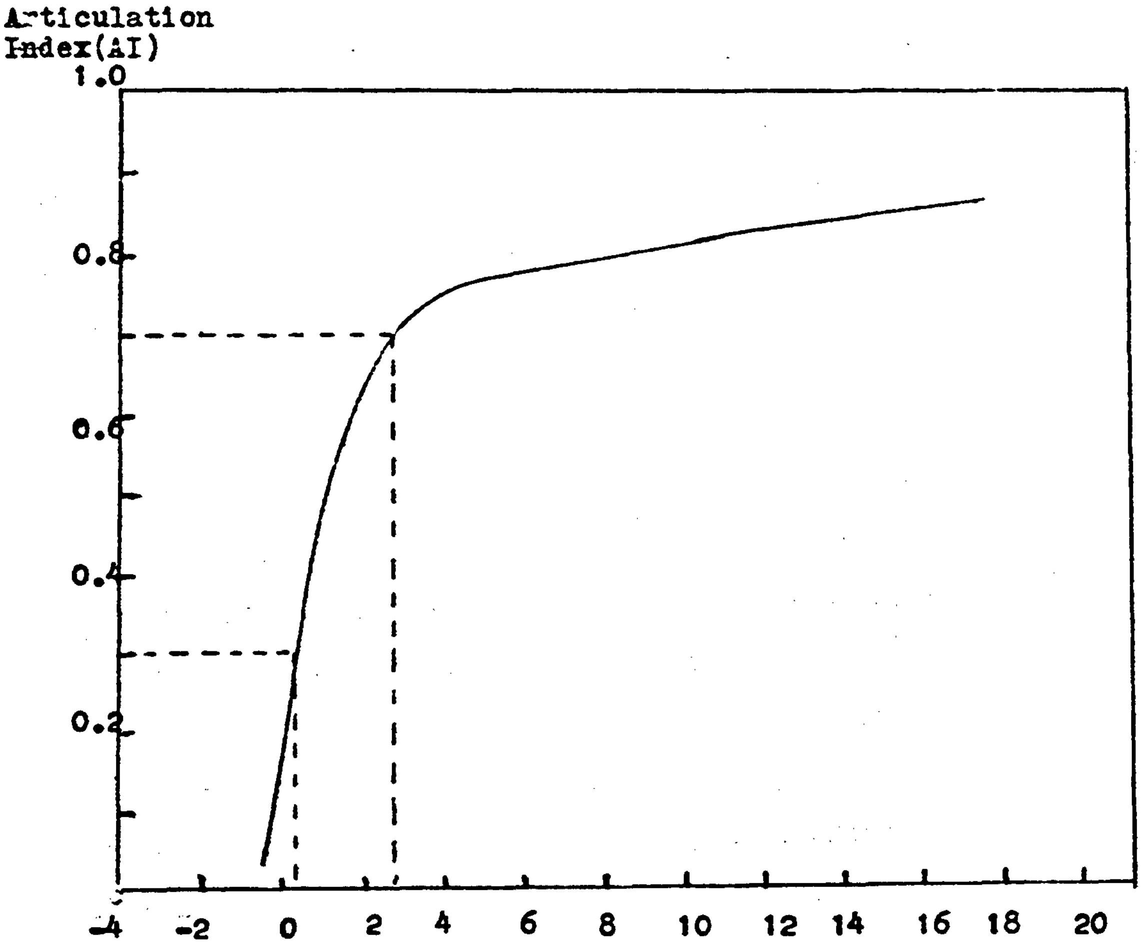


Figure 5. AI versus S/I for AN/VRC-12

2.5dB. This deterioration continues until S/I=0dB which is equivalent to the previously discussed predetection signal-to-noise ratio $(S/N)_T$ when it is equal to unity. At this point the communication link can be considered to be worthless.

Before using the test results in the computer model it is necessary to relate the signal-to-jammer (S/J) ratio to some measure of communication link quality more useful than the articulation index (AI). Such a parameter is the intelligibility (I) of the received signal. The relationship between the articulation index and intelligibility for the AN/VRC-12 radio set is shown in figure 6.[25] By combining figures 5 and 6 one obtains the result shown in figure 7 where the intelligibility is plotted versus the signal-to-interference ratio. The extremes of useful intelligibility extend from 40% upward. Any communication link with a S/I such that I is less than 40% can be considered inoperable. For intelligibility levels higher than this, the link is considered to be operable, but the message transmission time is increased to allow for the repetition necessary to raise intelligibility to a satisfactory level. Intelligibility of 90% or greater can be treated as original message length while an I of 40% would require repetition of the transmission 4 or 5 times to ensure correct reception of the message.[26]

In an attempt to make the scoring of the communication link's quality more meaningful to the tactical commander and the equipment operator, the intelligibility scale has been divided into a 5- interval scale. The 5 intervals were selected on a purely rational basis. Their designations and the related approximate message repetitions required to insure message

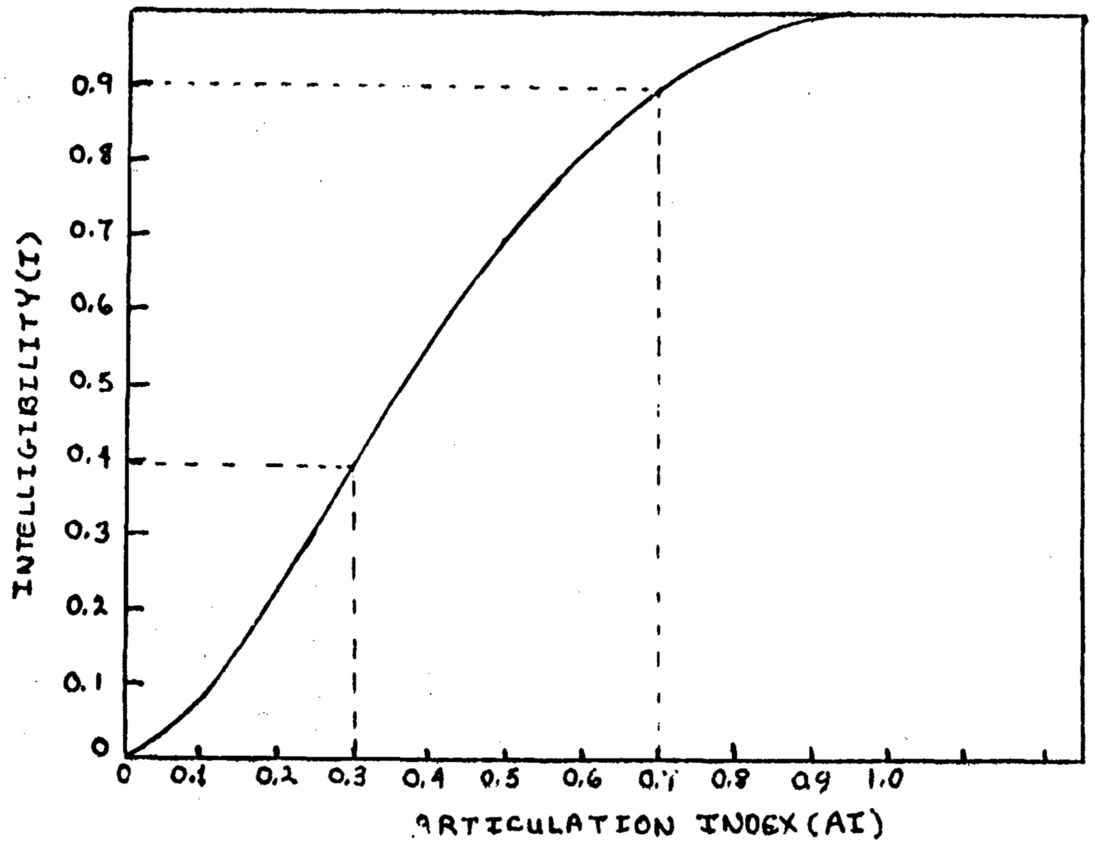


FIGURE 6. Relation Between AI and Intelligibility
For Radio Set AN/VRC-12

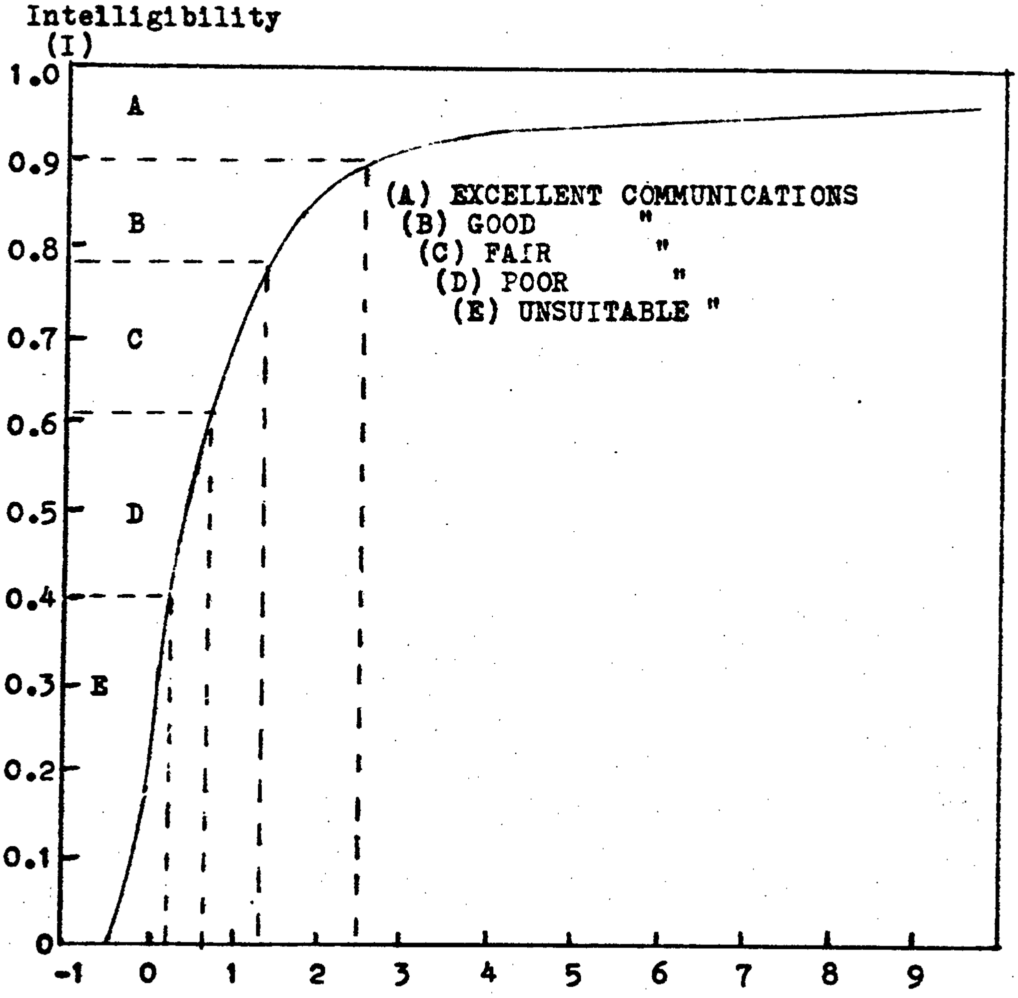


Figure 7. I versus S/I for AN/VRC-12 versus AN/VRC-12

reception are as follows:[27]

Excellent	1
Good	1 - 1½
Fair	1½ - 2½
Poor	2½ - 4½
Unsuitable	greater than 4½

These intervals will be employed in the computer model to inform the user of the quality of the proposed communication link once the related signal-to-interference ratio at the receiver has been calculated.

Chapter IV

MODEL DEVELOPMENT

In chapter three the relationship between the received signal and intelligibility was developed. It is now necessary to develop the relationships for the remainder of the system illustrated previously in figure 2. The most critical component of the actual communication link are the equations for signal loss over different types of terrain. In this chapter various equations will be developed to express propagation losses for various terrain configurations. These equations will then be integrated into the entire system so a value for the friendly signal and jamming signal at the receiver can be calculated.

VHF COMMUNICATIONS

Very High Frequencies (VHF) cover the frequency range from 30 to 300 MHz. The portion of this band that we will be concerned with for military FM communications is limited to the 30 to 80 MHz range. For this range we will be concerned only with ground-wave propagation as VHF waves are not reflected from the ionosphere.

The ground wave is made up of two components, a surface wave that follows the contours of the earth and a space wave that moves through the atmosphere either directly, by reflection from the ground obstacles, or by refraction and diffraction occuring within a few miles of the earth's surface.[28] For radio frequencies above approximately 20 MHz, the surface wave portion of the ground wave attenuates rapidly, becoming negligible at a few hundred feet for a frequency of 30 MHz. Successful transmission therefore depends on a propagation of the space wave between the transmitting and receiving antennas. It is this space wave that is so greatly attenuated by obstacles, either natural or manmade.

COMMUNICATION LINKS

The signal power, S, at the received end of a communication link will be considerably affected by propagation conditions and the uncertainties introduced by natural and human elements in the operation of the link. The exact form of the signal power equation can be assumed to obey the equation:[29]

$$S(dB) = P + G_{11} + G_{12} - L(d) \qquad (1)$$

where P = transmitter power in decibels

G_{11}, G_{12} = the transmitter and receiver antenna gains in db, respectively

L = the signal path loss in db which is primarily a function of the path length, d, in kms.

In general, all these parameters may be variable. Propagation conditions will always introduce uncertainties in L, and the antenna gain factors G_{11}, G_{12}, and P are a function of the antenna configurations and transmitter power output respectively.

The decibel (db) is the preferred unit for expressing power in communication analysis because it is logarthmic. Two values can be multiplied or divided by adding or subtracting their logarithms. Since amplification and attenuation are multiplication and division processes, the decibel provides a handy means of expressing changes of power by simple addition and subtraction.

For example, if a signal is transmitted at a certain power and is received at $1/1{,}000 = 10^{-3}$ that power, it has suffered a 30 dB loss ($= 10 \log_{10} 10^{-3}$). If this reduced signal is transmitted again and undergoes similar attenuation, the final signal is $1/1{,}000{,}000 = 10^{-6}$ its original strength ($1/1{,}000 \times 1/1{,}000$). It is simpler to add 30 dB and 30 dB to get 60 dB as the total attenuation of the signal.

It is inevitable that the signal expressed in equation 1 will deteriorate during the process of transmission and reception as a result of some distortion in the system such as jamming or because of the introduction of noise, which is unwanted energy, usually of a random character, present in a transmission, due to any cause. Since noise will be received together with the signal, it obviously places a limitation on the transmission system as a whole; in a severe case, it may mask a given signal to such as extent that the signal becomes unintelligible and therefore useless. The signal-to-noise ratio (S/N) expresses the ratio, in decibels, of signal power to total noise power in a channel and is consequently an indicator of received signal quality. In chapter 3 it was stated that high quality FM voice communications are assumed to require a signal-to-noise ratio of about 12 dB. It is therefore important that some means of calculating background noise be introduced.

The noise present at a receiver when no intentional interference is present is a function of environmental noise and internal receiver noise. The equations for computing these noise values are as follows:[30]

$$N_r = kt_oB_rF_r = \text{internal receiver noise}$$

$$N_a = kt_oB_rF_a = \text{environmental noise} \qquad (2)$$

$$N = N_a + N_r = \text{equivalent receiver input noise}$$

where F_r = receiver noise figure (= 15 dB for mobile vehicular VHF)

F_a = environmental noise figure (= 20 dB for Central Europe suburban noise)

k = Boltzman's constant = 1.38×10^{-23} joules/°K

t_o = reference temperature = 290°K

B_r = receiver banswidth (= 32 KHz for military FM).

Making the computations indicated in equations 2 reveals an equivalent receiver input noise for Central Europe of -128dB. Consequently, the computer model will check each communications link before jamming to ensure the received signal at the receiver input is a least -116 dB (= 12 dB - 128 dB). This will ensure that an operational communications link is being analyzed. The ability to make this check will also give the model the ability to plan the coverage of FM voice communications when no jamming is present.

During the jamming analysis, the equivalent receiver input noise (N) is neglected as N is seldom as large as the

Jamming signal (J). The model computer program will use the S/J ratio with the data from figure 7 to determine the quality of the communications link. If N was appreciable compared to either J or S, then the S/J ratio should be modified to a S/(J+N) ratio.

PROPAGATION LOSS

Free Space Path Loss

A free space transmission path is a straight - line path in an ideal atmosphere. As no interference or obstacles are present, the relationship between transmitted and received power may simply be stated as:[31]

$$P_r = \frac{g_t g_r \lambda^2}{(4 \pi d)^2} P_t \qquad (3)$$

where P_r = received power in watts

P_t = transmitted power in watts

g_t and g_r = the respective directivity gains (in terms of power ratios) of the transmit and receive antennas with respect to an antenna radiating uniformily in all directions

λ = the wavelength in km

d = the separation between antennas in km.

By substituting the relationship between wavelength and frequency ($\lambda = 300/f(\mathrm{MHz})$) into equation 3 and simplifying the results we obtain the relationship:

$$\frac{P_t}{P_r} = \frac{(41.87\ df)^2}{g_t g_r} \ .$$

The expression for free space path loss is then:

$$L = 20 \log_{10} (41.87\ df) \qquad (5)$$

where f is the frequency in MHz.

Equation 5 will be used in the model to determine path loss when either the friendly transmitter or jammer are airborne and the receiver is on the ground.

Plane Earth Path Loss

The theoretical received power for transmission over plane earth is given approximately by the relationship:[32]

$$P_r = g_t g_r \frac{(h_t h_r)^2}{d^4} P_t \qquad (6)$$

where P_r, P_t, g_t, g_r and d are as defined for equation 3.

h_t, h_r = the transmit and receive antenna heights in kilometers.

The expression for plane earth path loss can then be computed from the formula

$$L = 20 \log_{10} d^2/h_t h_r \quad . \qquad (7)$$

The equation given above is limited to transmission over water and flat, barren land. In addition it is independent of the particular frequency of operation. A form of this equation has been adapted by Egli in his work to predict losses for mobile communications when little is known about specific terrain obstacles and an estimate of area coverage of a radio signal is required.[33] Unfortunately, comparisons with actual terrain losses showed eqn. 7 to be unduly pessimistic in its predictions. The actual comparisons between predicted and measured losses will be given in chapter 6.

A more accurate equation for field strength calculations over smooth ground takes into consideration the moisture content of the soil near the antennas. For a smooth ground path, the influence of the ground constants on field strength is determined by the value of the effective dielectric constant (ϵ) which is determined mainly by the water content of the ground.[34]

For vertically polarized VHF ground wave propagation at low heights, the equation for the total received field strength as a function of ground moisture is:[35]

$$E_r = \sqrt{\frac{30 P_t g_t}{d^2}} \cdot \frac{\lambda}{\pi} \cdot \frac{\epsilon^2}{\epsilon - 1} \cdot \sqrt{1 + \frac{\epsilon - 1}{\epsilon^2}\left(\frac{2\pi h_t}{\lambda}\right)^2} \cdot \sqrt{1 + \frac{\epsilon - 1}{\epsilon^2}\left(\frac{2\pi h_r}{\lambda}\right)^2} \qquad (8)$$

In order to calculate an expression for path loss from this expression it is first necessary to determine the power (P_r) at the input to the receiver. Consequently, a relation is needed between the field intensity at the receivers antenna and the power into the receiver. The Poynting relation between the field intensity E_r and power P_r is

$$E^2_r = \frac{480\ \pi^2}{gr\ \lambda^2}\ P_r \qquad (9)$$

where E_r is in volts per meter, P_r is in watts.[36] By combining equation 8 and 9 the expression for path loss over smooth earth is derived:

$$L = -10\log_{10}\left[\frac{5.21 \times 10^{-6}}{(df)^4} \cdot \left(\frac{\epsilon^2}{\epsilon - 1}\right)^2 \cdot \left(1 + 438\left(\frac{\epsilon - 1}{\epsilon^2}\right) h_t^2 f^2\right)\left(1 + 438\left(\frac{\epsilon - 1}{\epsilon^2}\right) h_r^2 f^2\right)\right] \qquad (10)$$

where ϵ = relative dielectric constant

f = frequency in MHz

d = separation between antennas in km

h_t, h_r = transmit and receive antenna heights in km.

The values for the relative dielectric constant for ground conditions in central Germany have been found to vary from 4 for very dry earth to 30 for wet ground with a median value of 13.[37] This range of values along with equation 10 will be used in the model to calculate propagation losses for flat earth communication links.

Obstacle Path Loss

Egli's statistical approach[38] for determining propagation loss is appropriate for situations in which the actual terrain is unknown and an average terrain must be assumed. However, in my analysis the profiles are known or may be extracted from a map analysis. Therefore, propagation losses may be estimated for the particular terrain in the communication path.

Obviously, the equations previously introduced for air-to-ground and line-of-sight (LOS) communications are not sufficient to cover all possible terrain conditions that could occur. Two additional terrain categories are shown in figure 8, the single-obstacle path (SOP) and the multiple-obstacle path (MOP). The single-obstacle path is a terrain obstacle so situated that a LOS path exists from a single obstacle to each terminal, as shown in figure 8a. In the case of a multiple-obstacle path, more than one terrain obstacle exists such that no LOS path exists from any single obstacles to both terminals, as shown in figure 8b.

The basic general equation to compute propagation losses for these terrain profiles is [39]

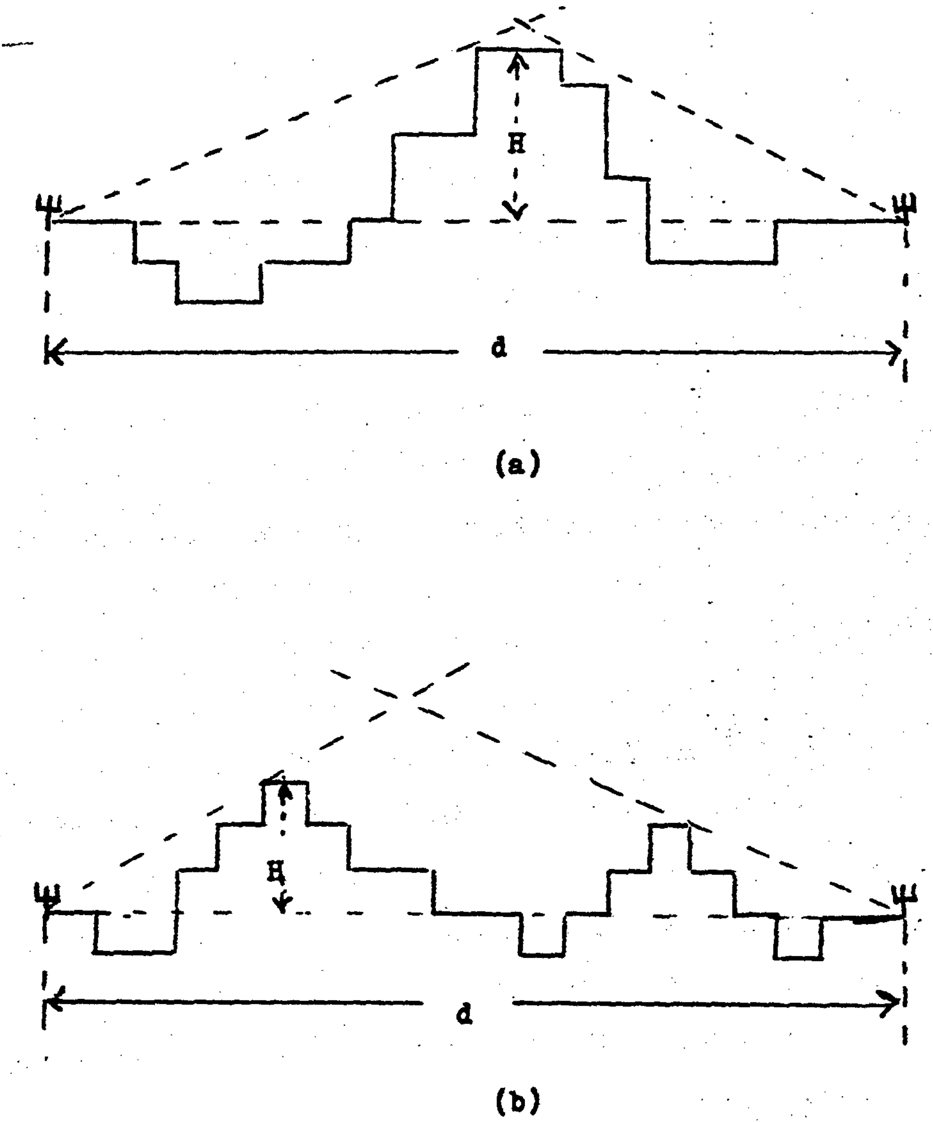
$$L = C_1+F_1(H/d)+F_2(H/d)^2+C_2f+C_3\log f+C_4d+C_5d^2 \quad (11)$$

where L = path loss (attenuation in dB)

d = total path length, in kilometers

H = maximum obstacle height in kilometers above a line

Figure 8. Propagation Paths.(a)SOP;(b)MOP



joining the path terminals

f = operating frequency in megacycles per second.

The C's are constants and the F's indicate functions. The specific equations for the non - LOS paths are:

SOP:

$$L = 46.2 + 1070\ (H/d) - 7500\ (H/d)^2 + 0.00268\ (f) + 28.34 \times \log (f) + 0.879\ (d) - 0.00378\ (d)^2 \qquad (12)$$

MOP:

$$L = 119.9 + 287\ (H/d) - 11000\ (H/d)^2 + 0.00425\ (f) + 14.98 \log(f) + 0.541\ (d) - 0.00159 d^2 \qquad (13)$$

Equations 12 and 13 are for obstructed paths when relatively ideal local-site conditions exist at both path terminals. Such conditions exist when transmitting and receiving antennas are clear of all obstructions in the immediate site areas. These equations will be used in the model for any communication link where one or more obstacles exist.

Profiles representing terrain configuration paths for West German terrain were drawn and classified according to whether the paths were LOS, SOP, or MOP.[40] In a sample of 128 profiles, 27 were LOS, 53 SOP and 48 MOP. For a somewhat larger sample, it was found that approximately one-third of the single-obstacle and multiple -obstacle paths had obstacles between 20 and 40 meters high. Approximately one-third of the multiple-obstacle paths had obstacle heights greater than 60 meters, while no single-obstacle paths were found to fall into this category.

EQUIPMENT CONSIDERATIONS

Antennas

In order to couple the output of a radio transmitter to space, it is necessary in each case to use some type of structure capable of radiating electromagnetic waves or receiving them, as the case may be. An antenna is such a structure and may be described as a metallic object, often a wire or a collection of wires, used to convert high-frequency current into electromagnetic waves which then travel and behave as described by the equations in the preceding sections, and are finally picked up by the receiver antenna. Apart from their different functions, transmitting and receiving antennas behave identicall

Since all practical antennas concentrate their radiation in some direction, to a greater or lesser extent, the power density in those directions is greater than it would have been had the antenna not concentrated its radiation in this manner. Accordingly, antennas may be said to have gain. The term most frequently used with respect to an antenna's gain is "directive gain".

Directive gain, in a particular direction, is the ratio of the power density radiated in that direction by the antenna to the power density that would be radiated by an isotropic antenna.[41] An isotropic antenna is an antenna that cannot exist in practice, but since its radiation pattern is perfectly omni-directional, or spherical, its properties are very easy to visualize, calculate, and use for reference. To compare the antenna to be tested with an isotropic antenna, both power densities are measured at the same distance, and both antennas must be assumed to radiate the same total power.

While directive gain refers to any particular direction, the direction of the maximum directive gain is usually that which concerns us most. The correct name for maximum directive gain is directivity and refers to the gain in the direction of the major lobe of the radiation pattern.[42]

The importance of antenna gain to communication links is that it increases the effective power of a transmission just as surely as does amplifier gain. A distant observer located along the main beam would receive as much signal power from an antenna with a gain of 30 dB, radiating 1 watt, as he would from an isotropic radiator at the same distance with an output of 1,000 watts. The effectiveness of the transmission is similarly increased by the gain of the receiving antenna. This ability of a directional antenna to increase the effectiveness of transmission is not only important for the improvement of communications but can also be used to decrease the effectiveness of an enemy jammer. If the major lobe of a receiving antenna is pointed away from the jammer and directly toward the friendly transmitter, the desired signal will be greatly enhanced while the jamming signal is degraded.

The omnidirectional whip antenna presently used by the Army with its mobile FM radios is essentially a center-fed half-wavelength antenna and therefore has a directive gain of 1.64 or 2.15 dB broadside to the radiator. While this omnidirectional antenna makes mobile communications simpler, it also makes the receiver susceptible to jamming. Fortunately, the army is presently developing a directional antenna which will enhance communications while reducing susceptibility to interference. This antenna is a broadband log-periodic designed to cover the range from 30 to 80 MHz without the requirement to change elements while still being portable enough for tactical use.[43] The radiation pattern for this antenna in comparison with that of an isotropic antenna is shown in figure 9. The main beam offers a gain of 6 dB above isotropic, while the antennas backlobe in 8 dB below isotropic. A jammer or transmitter located broadside to such an antenna would be subjected to an antenna gain of only about 2 dB. These will be the three categories of receiver gain used in the computer model when computing the jammer to receiver link. Since the enemy's jammers will normally be operating from his side of the FEBA, the jammer signal will usually be subjected to a -8 dB gain at the receiver, while the friendly signal will receive the benefit of the major lobes 6 dB gain.

It can be assumed that the jammer antenna will either be a half-wave whip or a directional log-periodic antenna. While there are antennas with greater gain, the log-periodic offers the flexibility of being relatively frequency independent while still providing significant directive gain. Therefore, the values of jammer antenna gain suggested in the model will vary from approximately 2 to 8 dB, depending on the antenna configuration.[44]

Transmitters

The transmitter assumed to be used in this analysis

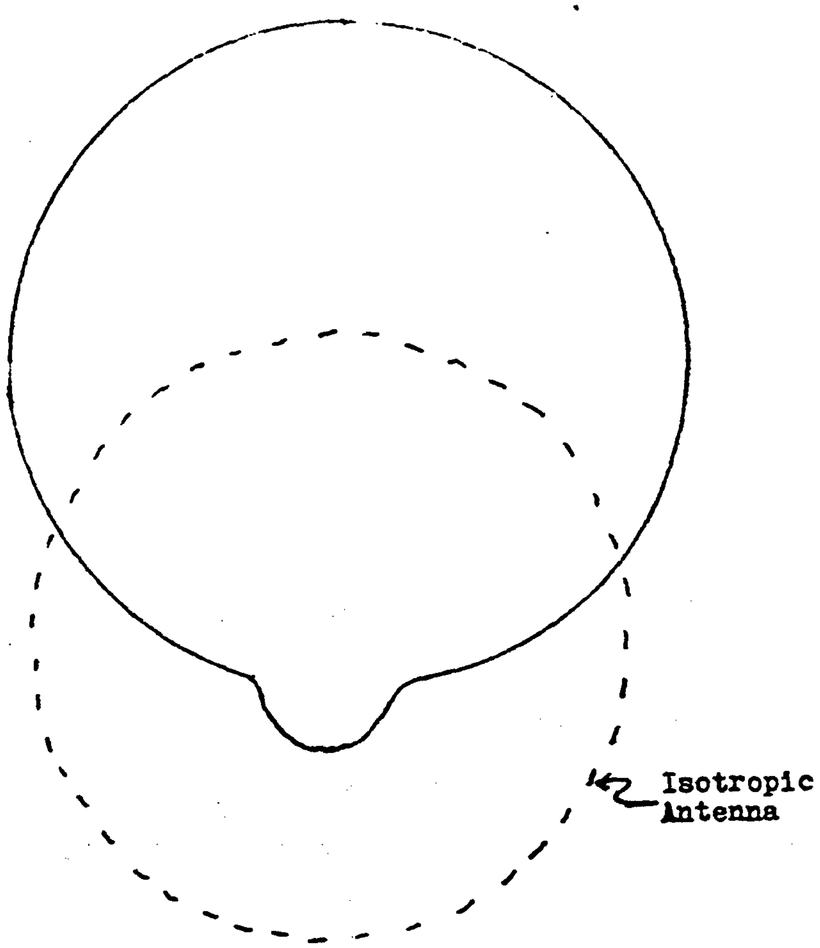


Figure 9. Field Strength Radiation Pattern for VHF Log-periodic Antenna

is the one used in the army's mobile configuration of the AN/VRC-12 radio. The basic receiver-transmitter is the RT-524 which has a rated output of 35 watts for high power and approximately 2 watts for low power.[45]

While exact jammer transmitter charactertics are difficult to predict in advance, we can assume that the enemy will use noise modulation against FM voice and that typical FM jammer transmitter power outputs will fall anywhere from 500 to 2,000 watts.[46]

Chapter V

MODEL COMPUTERIZATION

In the preceding chapters the parameters of the problem and the justification for their development was presented. To facilitate their use in a real-time analysis and to reduce the tedious mathematics involved, it is advisable to computerize the model.

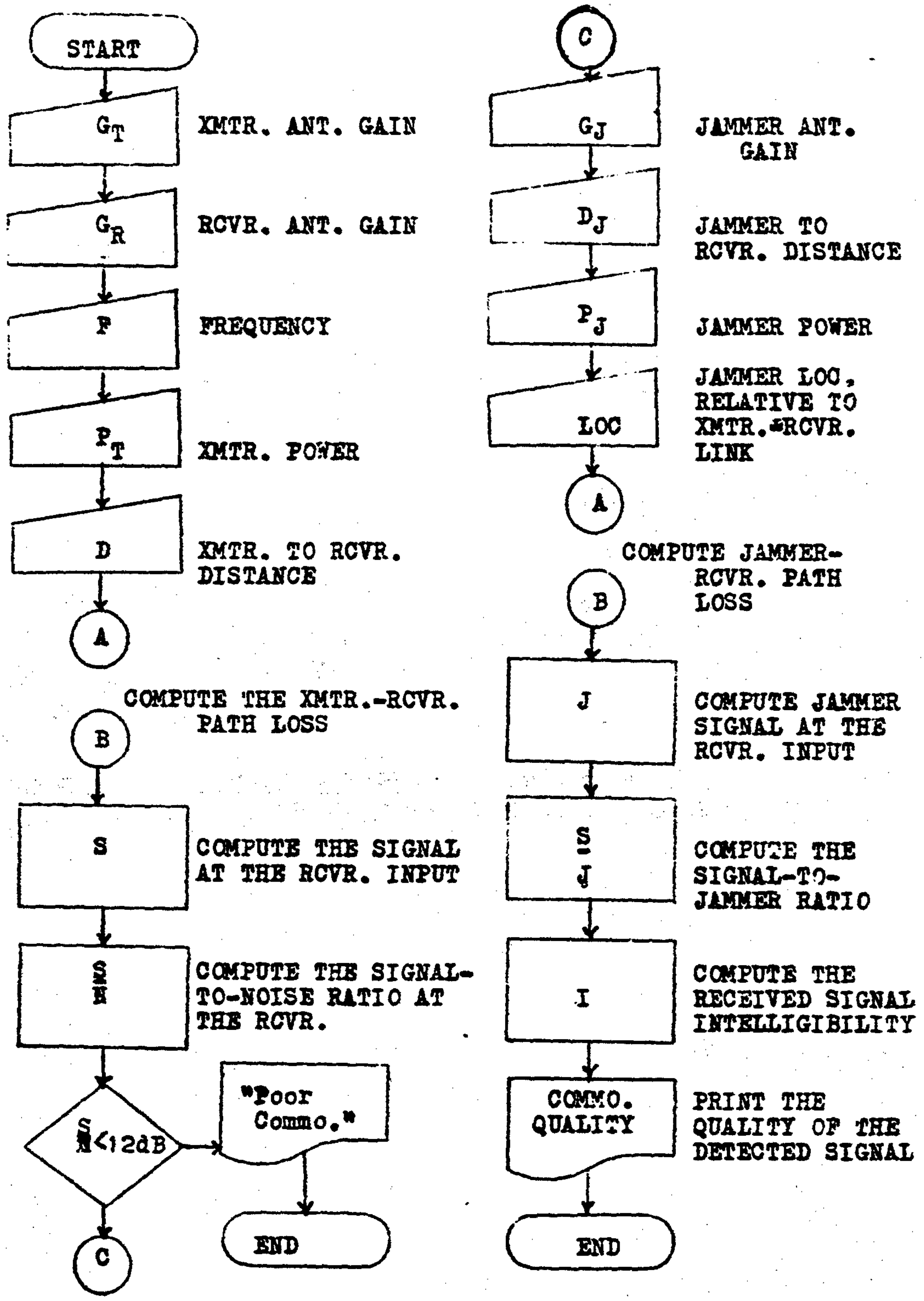
FLOW CHART

The first step in developing a computer program is the development of a flow chart so as to graphically illustrate the interrelation of the problem's parameters. The flow chart for this problem is shown in figure 10. Note that the path-loss subroutine (figure 11) is used twice during the run of the problem. The first use of this subroutine is in the calculation of the desired signal at the receiver input. This same subroutine is then used to calculate the level of the jamming signal at the receiver input.

COMPUTER PROGRAM

The complete computer program which implements the flow chart shown in figure 10 is shown in figure 12. Examples of different computer runs are presented in the appendix for different terrain and equipment configurations.

Figure.10. Flow Chart



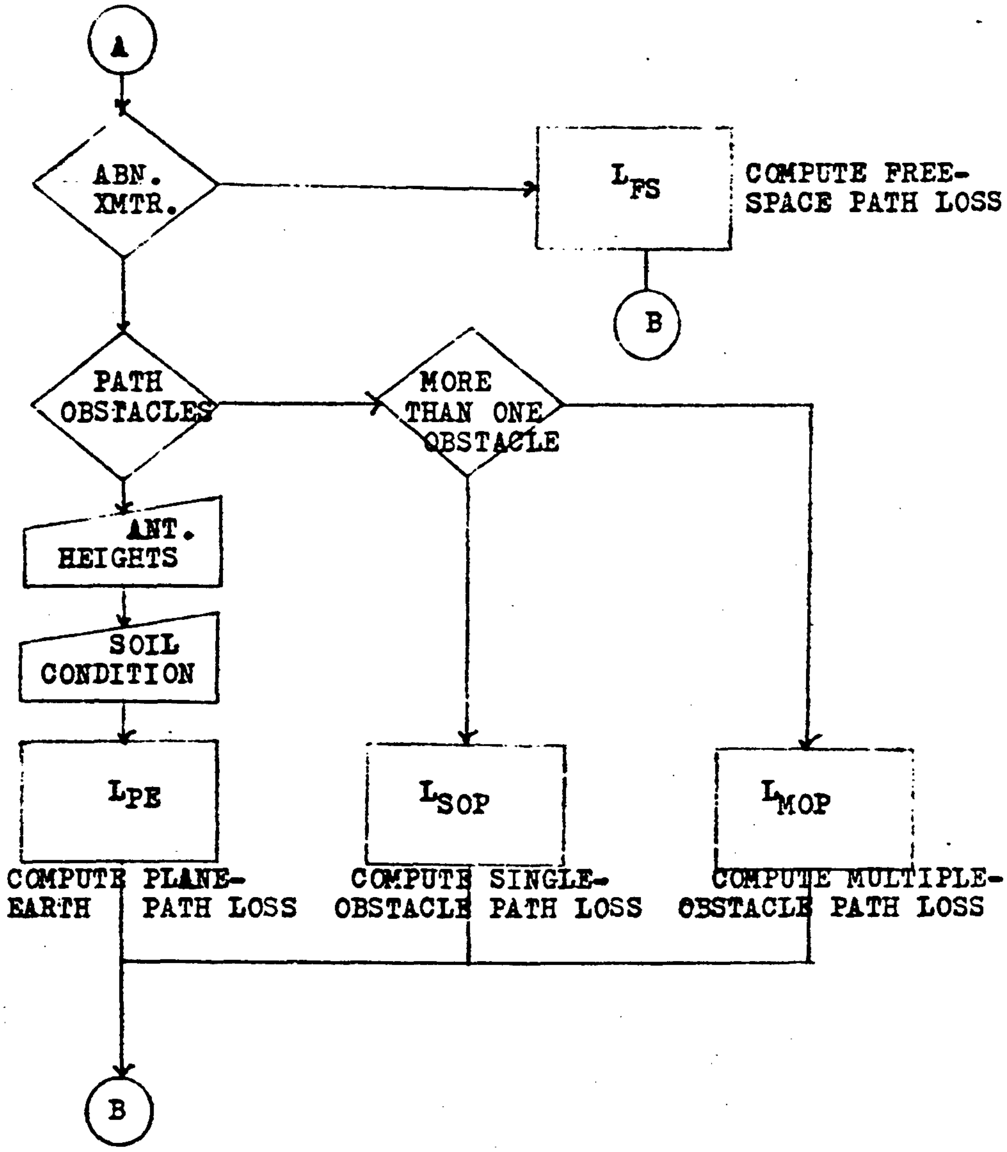


Figure 11. Path Loss Subroutine

Figure 12. Tactical FM Jamming Program

```
01 PRINT"TACTICAL FM JAMMING ANALYSIS PROGRAM"
02 PRINT"[illegible]--------          "
03 PRINT"INPUT XMTR ANT. GAIN;2.15 FOR WHIP ,6 FOR DIRECTIONAL"
04 INPUT G1
05 PRINT"INPUT RCVR ANT. GAIN ;2.15 FOR WHIP,6 FOR DIRECTIONAL"
06 INPUT G2
10 PRINT"INPUT FREQ. IN MHZ"
11 INPUT F
15 PRINT"INPUT XMTR TO RCVR DISTANCE IN KM"
16 INPUT D
20 PRINT"INPUT XMTR PWR. OUTPUT IN WATTS;2.0 FOR LOW POWER,"
21 PRINT"35 FOR HIGH PWR."
22 INPUT P
30 PRINT "INPUT RCVR ANT. HT. IN KM"
32 INPUT H2
37 PRINT"THE FOLLOWING IS A CALCULATION OF XMTR TO RCVR PATH LOSS"
38 PRINT"----------------------------------------"
39 PRINT"     "
40 GOSUB 500
43 LET L1=L
44 PRINT"XMTR/RCVR PATH LOSS IN DB IS="L1
45 PRINT"----------------------------------------"
46 LET P1=10*LGT(P)
50 LET S1=P1+G1+G2-L1
51 PRINT"RECEIVED SIGNAL WITHOUT JAMMING IN DB="S1
55 LET S2=S1+128
56 PRINT"RECEIVED SIGNAL-TO-NOISE RATIO IN DB="S2
57 PRINT"     "
58 PRINT"     "
60 IF S2<12 THEN 455
65 PRINT"INPUT JAMMER ANT. GAIN;USE A VALUE FROM 2 TO 6"
67 INPUT G3
70 PRINT "INPUT JAMMER TO RCVR DISTANCE IN KM"
72 INPUT D
75 PRINT"INPUT JAMMER PWR. IN WATTS;USE A VALUE IN THE"
76 PRINT "RANGE FROM 500 TO 2000"
77 INPUT P2
80 PRINT"INPUT JAMMER LOCATION; IF A DIRECTIONAL RCVR. ANT. IS USE
81 PRINT"USE 6 FOR A JAMMER BETWEEN THE RCVR/XMTR LINK,2 FOR A"
82 PRINT"JAMMER BROADSIDE TO THE LINK,AND -6 FOR THE JAMMER TO THE
83 PRINT"REAR OF THE XMTR. IF A WHIP RCVR ANT. IS USED,ENTER 2.15"
85 INPUT G4
91 PRINT"THE FOLLOWING IS A CALCULATION OF JAMMER TO RCVR PATH LOS
92 PRINT"-------------------------------------"
93 PRINT"     "
100 GOSUB 500
101 LET L2=L
103 PRINT"JAMMER/RCVR PATH LOSS IN DB IS="L2
104 LET P2=10*LGT(P2)
105 LET J=P2+G3+G4-L2
106 PRINT"THE JAMMER SIGNAL AT THE RCVR IN DB="J
107 PRINT"-------------------------------------"
108 PRINT"     "
110 LET S3=S1-J
111 PRINT"THE SIGNAL-TO-JAMMER RATIO AT THE RCVR IN DB="S3
115 IF S3<=0.2 THEN 405
120 IF S3>2.5 THEN 415
125 IF S3<=0.7 THEN 425
```

```
130 IF S3<=1.5 THEN 435
135 IF S3<=2.5 THEN 445
405 PRINT "UNUSABLE COMMO. LINK"
410 GO TO 490
415 PRINT"EXCELLENT COMMO."
420 GO TO 490
425 PRINT "POOR COMMO."
430 GO TO 490
435 PRINT "FAIR COMMO."
440 GO TO 490
445 PRINT "GOOD COMMO."
450 GO TO 490
455 PRINT"UNSUITABLE COMMO. LINK EVEN WITHOUT JAMMING"
460 GO TO 490
462 PRINT"     "
463 PRINT"     "
490 PRINT"IF YOU WISH TO EXECUTE ANOTHER PROBLEM, INPUT A 7"
493 INPUT E
494 PRINT"----------------------------------------------------------------"
496 IF E=7 THEN 03
499 STOP
500 PRINT"INPUT XMTR\JAMMER ANT. HT. IN KM"
501 INPUT H1
502 PRINT"IF THE XMTR\JAMMER IS ABN.,INPUT A 1;IF A FLAT EARTH COMMO."
503 PRINT"PATH, INPUT A 2;IF A SINGLE-OBSTACLE PATH,INPUT A 3;"
504 PRINT"IF A MULTIPLE-OBSTCLE PATH,INPUT A 4"
506 INPUT A
510 IF A=1 THEN 530
515 IF A=2 THEN 545
520 IF A=3 THEN 560
525 IF A=4 THEN 585
530 LET B=41.67*D*F
535 LET L=20*LGT(B)
540 GO TO 995
545 PRINT"INPUT GROUND CONDITIONS; USE 4 FOR DRY OR SANDY SOIL,"
546 PRINT"30 FOR WET GROUND ,OR 13 FOR AVERAGE GROUND"
548 INPUT E
549 LET B=(5.21E-6/(D*F)**4)*(E**2/(E-1))**2
551 LET B=B*(1+436*(H1*F)**2*((E-1)/E**2))
552 LET B=B*(1+436*(H2*F)**2*((E-1)/E**2))
553 LET L=10*LGT(B)
554 LET L=-L
555 GO TO 995
560 PRINT"INPUT OBSTACLE HT. IN KM ABOVE A LINE JOINING THE PATH"
561 PRINT"TERMINALS"
565 INPUT H
570 LET C=28.34*LGT(F)
575 LET L=46.2+1070*(H/D)-7500*(H/D)**2+.00266*F+C+.679*D-.00376*D**2
576 LET L=L+20
580 GO TO 995
585 PRINT"INPUT MAX. OBSTACLE HT. IN KM ABOVE A LINE JOINING"
586 PRINT"THE PATH TERMINALS"
590 INPUT H
595 LET C=14.98*LGT(F)
600 LET L=119.9+287*(H/D)-11000*(H/D)**2+.00425*F+C+.541*D-.00159*D**2
605 GO TO 995
995 RETURN
999 STOP
..
```

The instructions to the user in the computer printout are designed as typical values for equipment presently in the field. Future developments in hardware operating in the VHF range (30-300 MHz) can be easily adapted for use with this program as long as the signal-to-interference performance of the receiver is known.

Chapter VI

EVALUATION OF RESULTS

To determine the validity of this computer program it is necessary to compare the predicted values with actual field tests. As the performance of the receiver was based upon actual laboratory tests when subjected to various signal-to-interference ratios, the only portion of the model which requires analysis are the equations used to calculate propagation losses.

PREDICTED VERSUS MEASURED

As previously mentioned in chapter 2, the most useful field tests of VHF propagation losses were performed in 1967 by the Institute for Environmental Research.[47] These tests are particularly useful for the purposes of testing this model because terrain profiles were drawn for each of the measured communication links. Figures 13.a. and 13.b. show the results of tests for several line-of-sight paths for different frequencies and distances. It should be understood that each propagation path had varying amounts of vegetation and buildings, even though there were no actual terrain obstacles in the LOS paths. In addition, the test measurements were subjected to a ±3 dB error due to faulty antenna gain measurements. Two measurements were taken at each test site. An initial measurement was followed

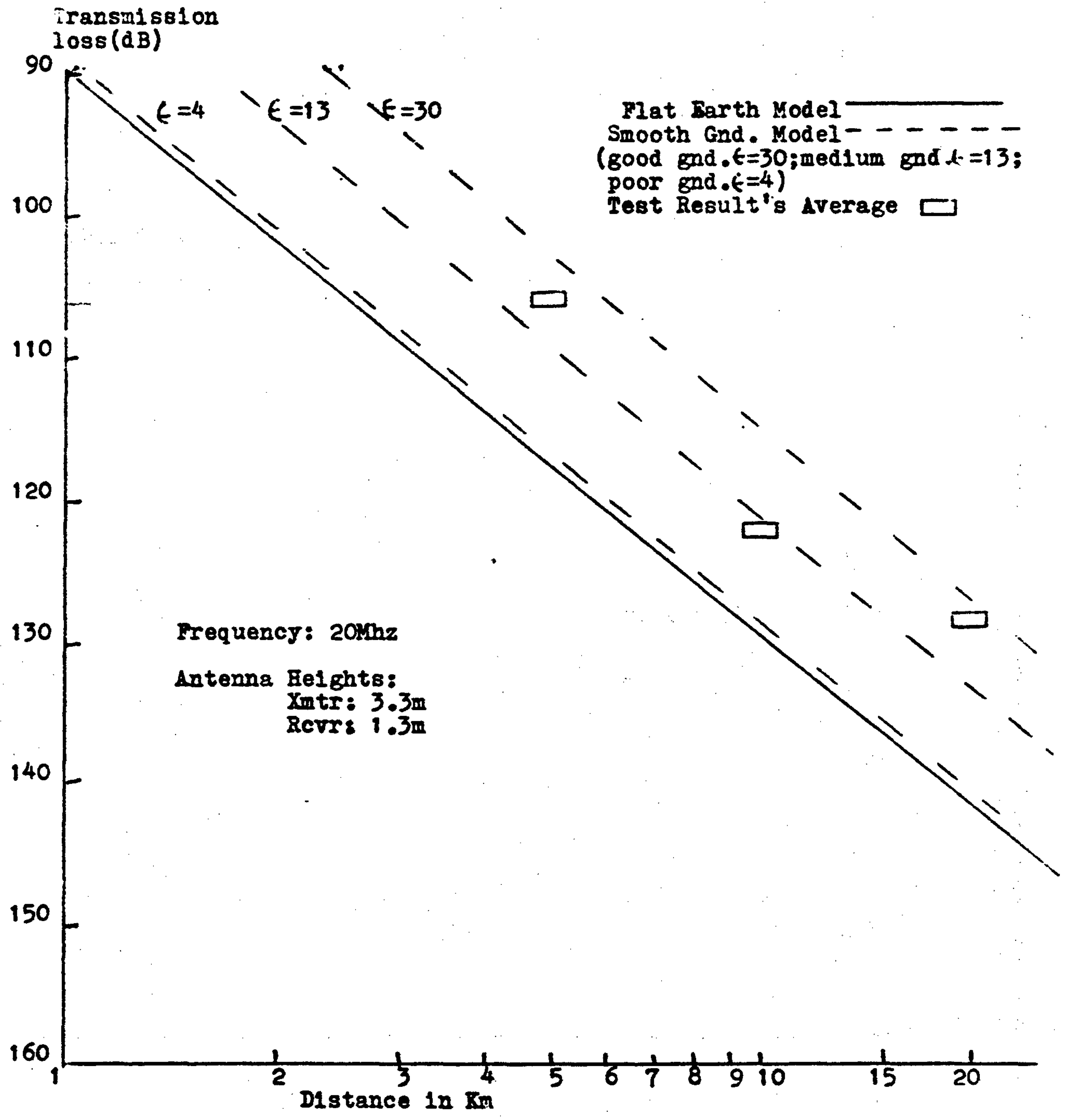


Figure 13.(a) Comparison of Line-of-Sight Losses(predicted) with Data derived from Measurements(field tests)

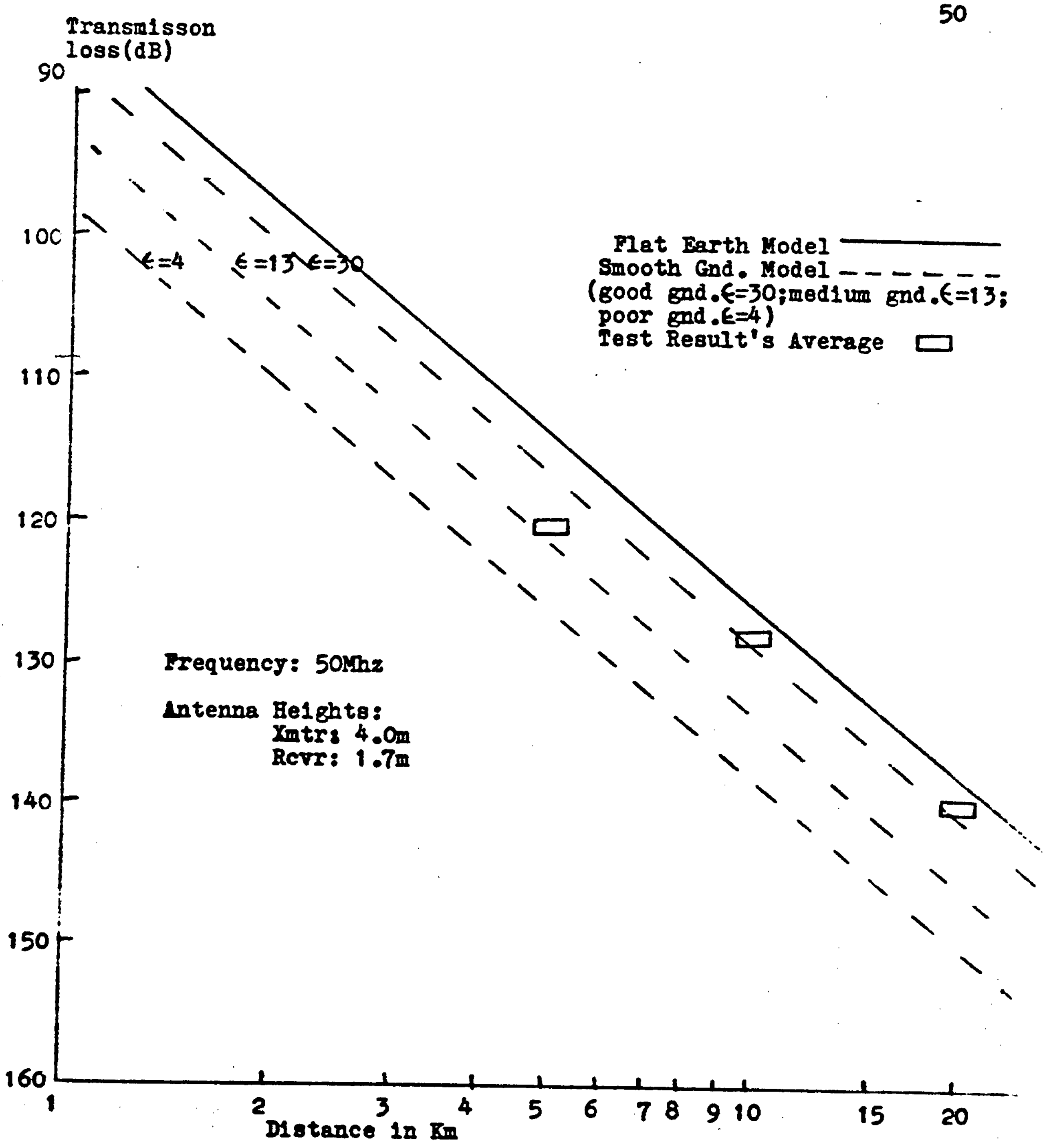


Figure 13.(b) Comparison of Line-of-Sight Losses(predicted) with Data derived from Measurements(field tests)

by a measurement from the optimum location found within 100 meters of the first.

Figure 13 compares these measured propagation losses with a modified version of Egli's equation (eqn. 7, chapter 4) denoted as the flat earth model and with equation 10 (chapter 4) referred to as the smooth ground model. In an attempt to make Egli's equation fit the data, the predicted loss was reduced by 17.7 dB. This modification was fairly successful for a frequency of 50 MHz, but failed to adapt to a frequency change such as illustrated for 20 MHz. However, the smooth ground model covers the range of test results fairly well within its range of variation for different dielectric constants, particularly for the lower frequency of 20 MHz. Therefore, the smooth ground model was chosen to be used for line-of-sight communication links.

Figure 14 compares the results of the single-obstacle and multiple-obstacle propagation equations with actual field test results. The test site variations are due to different measurements taken at the same site all within a 100 meter radius of the original one. When the measurement errors previously discussed are taken into consideration, the comparison proves to be quite good and consequently justifies the use of these equations in the model.

CONCLUSIONS

The specific question which this study has attempted to answer is - - is it possible to develop a computerized mathematical model for FM tactical radios operating under the

	SINGLE-OBSTACLE PROPAGATION MODEL				MULTIPLE-OBSTACLE PROPAGATION MODEL			
DISTANCE(Km)	5	10	20	20	30	30	30	50
OBSTACLE HEIGHT(Km)	.03	.03	.07	.08	.05	.100	.130	.07
TEST SITE VARIATIONS(dB)	127.8 to 122	127.7 to 122.7	135.4 to 131.2	138.2 to 133.8	160.5 to 158.6	165.6 to 161.4	167.2 to 165	172.9 to 164.7
PREDICTED LOSS(dB)	124.9	126.1	134.2	134.7	160.8	161.2	161.4	169

Figure 14. Comparison of Field Test Results with Predicted Propagation Path Losses for SOP and MOP

influence of enemy jamming so as to optimize communications for particular battlefield terrain and various equipment configurations?

The answer is yes, it is possible. Comparisons of the propagation portion of the model with actual field tests have shown the results to be an accurate indication of "real-world" conditions while the integration of actual equipment performance under co-channel interference adds a realism to the model which enhances its usefulness as a training or planning device.

By inserting the characteristics of actual FM communications equipment and the terrain over which it is expected to operate, the user will receive as an output not only the vulnerability of a particular communication link to jamming, but also an indication of what steps should be taken to reduce the effectiveness of enemy jamming.

APPENDIX

COMPUTER RUN EXAMPLES

Figure 15 illustrates the output of the computerized model for varying battlefield configurations. For example, figure 15.a. is a link where the received signal-to-noise ratio is inadequate even without jamming. The remainder of the examples illustrate links which produce varying signal-to-jamming ratios and consequently a varying quality of received signal. These links are respectively an unusable, fair and an excellent communication link.

```
INPUT XMTR ANT. GAIN;2.15 FOR WHIP ,6 FOR DIRECTIONAL
?
        6

INPUT RCVR ANT. GAIN ;2.15 FOR WHIP,6 FOR DIRECTIONAL
?6

INPUT FREQ. IN MHZ
?50

INPUT XMTR TO RCVR DISTANCE IN KM
?30

INPUT XMTR PWR. OUTPUT IN WATTS;2.0 FOR LOW POWER,
35 FOR HIGH PWR.
?35

INPUT RCVR ANT. HT. IN KM
?.01

THE FOLLOWING IS A CALCULATION OF XMTR TO RCVR PATH LOSS
--------------------------------------

INPUT XMTR\JAMMER ANT. HT. IN KM
?.01

IF THE XMTR\JAMMER IS ABN.,INPUT A 1;IF A FLAT EARTH COMMO.
PATH, INPUT A 2;IF A SINGLE-OBSTACLE PATH,INPUT A 3;
IF A MULTIPLE-OBSTCLE PATH,INPUT A 4
?4

INPUT MAX. OBSTACLE HT. IN KM ABOVE A LINE JOINING
THE PATH TERMINALS
?.120

XMTR/RCVR PATH LOSS IN DB IS= 161.334
--------------------------------------
RECEIVED SIGNAL WITHOUT JAMMING IN DB=-133.893
RECEIVED SIGNAL-TO-NOISE RATIO IN DB=-5.89339

→ (UNSUITABLE COMMO. LINK EVEN WITHOUT JAMMING)
IF YOU WISH TO EXECUTE ANOTHER PROBLEM, INPUT A 7
?7
```

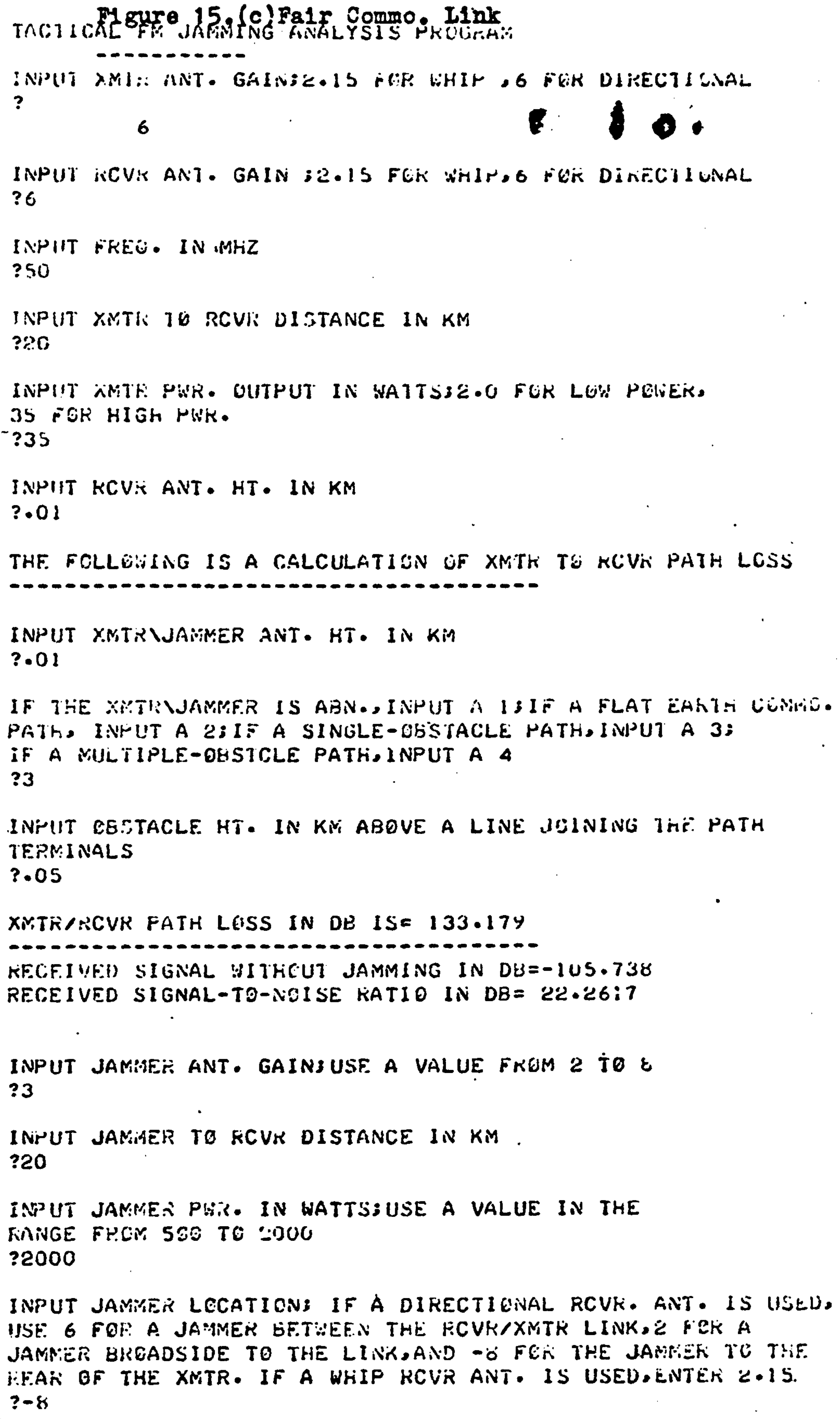
Figure 15. Sample Computer Runs.(a)Unsuitable Commo. Link

Figure 15.(b) Unusable Commo. Link

```
INPUT XMTR ANT. GAIN;2.15 FØR WHIP ,6 FOR DIRECTIONAL
?
          6

INPUT RCVR ANT. GAIN ;2.15 FOR WHIP,6 FØR DIRECTIONAL
?6

INPUT FREQ. IN MHZ
?50

INPUT XMTR TØ RCVR DISTANCE IN KM
?20

INPUT XMTR PWR. ØUTPUT IN WATTS;2.0 FØR LØW PØWER,
35 FØR HIGH PWR.
?35

INPUT RCVR ANT. HT. IN KM
?.01

THE FØLLØWING IS A CALCULATIØN ØF XMTR TØ RCVR PATH LØSS
----------------------------------------

INPUT XMTR\JAMMER ANT. HT. IN KM
?.01

IF THE XMTR\JAMMER IS ABN.,INPUT A 1;IF A FLAT EARTH CØMMO.
PATH, INPUT A 2;IF A SINGLE-ØBSTACLE PATH,INPUT A 3;
IF A MULTIPLE-ØBSTCLE PATH,INPUT A 4
?3

INPUT ØBSTACLE HT. IN KM ABØVE A LINE JØINING THE PATH
TERMINALS
?.08

XMTR/RCVR PATH LØSS IN DB IS= 134.711
----------------------------------------
RECEIVED SIGNAL WITHØUT JAMMING IN DB=-107.27


RECEIVED SIGNAL-TØ-NØISE RATIØ IN DB= 20.7299
INPUT JAMMER ANT. GAIN;USE A VALUE FRØM 2 TØ 8
?2

INPUT JAMMER TØ RCVR DISTANCE IN KM
?20

INPUT JAMMER PWR. IN WATTS;USE A VALUE IN THE
RANGE FROM 500 TO 2000
?2000

INPUT RELATIVE JAMMER LØCATIØN; IF A DIRECTIØNAL ANT. IS USED
USE 6 FOR A JAMMER BETWEEN THE RCVR/XMTR LINK,2 FØR A
JAMMER BROADSIDE TØ THE LINK,AND -8 FØR THE JAMMER TØ THE
REAR OF THE XMTR. IF A WHIP RCVR ANT. IS USED,ENTER 2.15
?-8

THE FØLLØWING IS A CALCULATIØN ØF JAMMER TØ RCVR PATH LØSS
---------------------------------------
```

```
INPUT OBSTACLE HT. IN KM ABOVE A LINE JOINING THE PATH
TERMINALS
?.07

JAMMER/RCVR PATH LOSS IN DB IS= 134.204
THE JAMMER SIGNAL AT THE RCVR IN DB=-107.194
.-----------------------------------

THE SIGNAL-TO-JAMMER RATIO AT THE RCVR IN DB=-7.64945E-2
→(UNUSABLE COMMO. LINK )
IF YOU WISH TO EXECUTE ANOTHER PROBLEM, INPUT A 7
?0
```

Figure 15.(c)Fair Commo. Link



```
TACTICAL FM JAMMING ANALYSIS PROGRAM
-----------
INPUT XMTR ANT. GAIN;2.15 FOR WHIP ,6 FOR DIRECTIONAL
?
        6

INPUT RCVR ANT. GAIN ;2.15 FOR WHIP,6 FOR DIRECTIONAL
?6

INPUT FREQ. IN MHZ
?50

INPUT XMTR TO RCVR DISTANCE IN KM
?20

INPUT XMTR PWR. OUTPUT IN WATTS;2.0 FOR LOW POWER,
35 FOR HIGH PWR.
?35

INPUT RCVR ANT. HT. IN KM
?.01

THE FOLLOWING IS A CALCULATION OF XMTR TO RCVR PATH LOSS
------------------------------------------

INPUT XMTR\JAMMER ANT. HT. IN KM
?.01

IF THE XMTR\JAMMER IS ABN.,INPUT A 1;IF A FLAT EARTH COMMO.
PATH, INPUT A 2;IF A SINGLE-OBSTACLE PATH,INPUT A 3;
IF A MULTIPLE-OBSTCLE PATH,INPUT A 4
?3

INPUT OBSTACLE HT. IN KM ABOVE A LINE JOINING THE PATH
TERMINALS
?.05

XMTR/RCVR PATH LOSS IN DB IS= 133.179
------------------------------------------
RECEIVED SIGNAL WITHOUT JAMMING IN DB=-105.738
RECEIVED SIGNAL-TO-NOISE RATIO IN DB= 22.2617


INPUT JAMMER ANT. GAIN;USE A VALUE FROM 2 TO 6
?3

INPUT JAMMER TO RCVR DISTANCE IN KM
?20

INPUT JAMMER PWR. IN WATTS;USE A VALUE IN THE
RANGE FROM 500 TO 2000
?2000

INPUT JAMMER LOCATION; IF A DIRECTIONAL RCVR. ANT. IS USED,
USE 6 FOR A JAMMER BETWEEN THE RCVR/XMTR LINK,2 FOR A
JAMMER BROADSIDE TO THE LINK,AND -8 FOR THE JAMMER TO THE
REAR OF THE XMTR. IF A WHIP RCVR ANT. IS USED,ENTER 2.15.
?-8
```

```
THE FOLLOWING IS A CALCULATION OF JAMMER TO RCVR PATH LOSS
-------------------------------------

INPUT XMTR\JAMMER ANT. HT. IN KM
?.01

IF THE XMTR\JAMMER IS ABN.,INPUT A 1;IF A FLAT EARTH COMMO.
PATH, INPUT A 2;IF A SINGLE-OBSTACLE PATH,INPUT A 3;
IF A MULTIPLE-OBSTCLE PATH,INPUT A 4
?3

INPUT OBSTACLE HT. IN KM ABOVE A LINE JOINING THE PATH
TERMINALS
?.06

JAMMER/RCVR PATH LOSS IN DB IS= 134.711
THE JAMMER SIGNAL AT THE RCVR IN DB=-106.701
-------------------------------------

THE SIGNAL-TO-JAMMER RATIO AT THE RCVR IN DB= .962255
→(FAIR COMMO.)
IF YOU WISH TO EXECUTE ANOTHER PROBLEM, INPUT A 7
?7

-----------------------------------------  ---------------
```

```
INPUT XMTR ANT. GAIN;2.15 FOR WHIP ,6 FOR DIRECTIONAL
?6
```

Figure 15.(d) Excellent Commo. Link

```
INPUT RCVR ANT. GAIN ;2.15 FOR WHIP,6 FOR DIRECTIONAL
?6

INPUT FREQ. IN MHZ
?50

INPUT XMTR TO RCVR DISTANCE IN KM
?50

INPUT XMTR PWR. OUTPUT IN WATTS;2.0 FOR LOW POWER,
35 FOR HIGH PWR.
?35

INPUT RCVR ANT. HT. IN KM
?.01

THE FOLLOWING IS A CALCULATION OF XMTR TO RCVR PATH LOSS
-----------------------------------------

INPUT XMTR\JAMMER ANT. HT. IN KM
?2

IF THE XMTR\JAMMER IS ABN.,INPUT A 1;IF A FLAT EARTH COMMO.
PATH, INPUT A 2;IF A SINGLE-OBSTACLE PATH,INPUT A 3;
IF A MULTIPLE-OBSTCLE PATH,INPUT A 4
?1

XMTR/RCVR PATH LOSS IN DB IS= 100.397
-----------------------------------------
RECEIVED SIGNAL WITHOUT JAMMING IN DB=-72.9562
RECEIVED SIGNAL-TO-NOISE RATIO IN DB= 55.0438


INPUT JAMMER ANT. GAIN;USE A VALUE FROM 2 TO 8
?8

INPUT JAMMER TO RCVR DISTANCE IN KM
?50

INPUT JAMMER PWR. IN WATTS;USE A VALUE IN THE
RANGE FROM 500 TO 2000
?2000

INPUT JAMMER LOCATION; IF A DIRECTIONAL RCVR. ANT. IS USED,
USE 6 FOR A JAMMER BETWEEN THE RCVR/XMTR LINK,2 FOR A
JAMMER BROADSIDE TO THE LINK,AND -8 FOR THE JAMMER TO THE
REAR OF THE XMTR. IF A WHIP RCVR ANT. IS USED,ENTER 2.15
?2

THE FOLLOWING IS A CALCULATION OF JAMMER TO RCVR PATH LOSS
----------------------------------------

INPUT XMTR\JAMMER ANT. HT. IN KM
?.01

IF THE XMTR\ IS ABN.,INPUT A 1;IF A FLAT EARTH COMMO.
PATH, INPUT A 2;IF A SINGLE-OBSTACLE PATH,INPUT A 3;
IF A MULTIPLE-OBSTCLE PATH,INPUT A 4
?4
```

```
INPUT\MAX. OBSTACLE HT. IN KM ABOVE A LINE JOINING
THE PATH TERMINALS
?.07

JAMMER/RCVR PATH LOSS IN DB IS= 169.018
THE JAMMER SIGNAL AT THE RCVR IN DB=-126.006
--------------------------------------

THE SIGNAL-TO-JAMMER RATIO AT THE RCVR IN DB= 53.0518
→ (EXCELLENT COMMO.)
IF YOU WISH TO EXECUTE ANOTHER PROBLEM, INPUT A 7
?0

------------------------------------------------------------
SAVE,R00D3

..STORE,R00D3,CGSC

..
..BATCH,ROOD3,PUNCH,CGSC

..LOGOUT
```

FOOTNOTES

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