Image Cover Sheet

CLASSIFICATION UNCLASSIFIED	**SYSTEM NUMBER** 70181

TITLE

COMMUNICATIONS ELECTRONIC COUNTERMEASURES: AN OVERVIEW

System Number:

Patron Number:

Requester:

Notes:

DSIS Use only:

Deliver to: JR

National Defence Défense nationale

COMMUNICATIONS ELECTRONIC COUNTERMEASURES: AN OVERVIEW (U)

by

Janette D. Hooper

DEFENCE RESEARCH ESTABLISHMENT OTTAWA

REPORT NO. 1074

Canada

December 1990
Ottawa

National Defence Défense nationale

COMMUNICATIONS ELECTRONIC COUNTERMEASURES: AN OVERVIEW (U)

by

Janette D. Hooper
Communications Electronic Warfare Section
Electronic Warfare Division

DEFENCE RESEARCH ESTABLISHMENT OTTAWA

REPORT NO. 1074

PCN
041LK11

December 1990
Ottawa

ABSTRACT

This report presents a review of the requirements and methods for technically effective communications jamming.

An equation to determine technical jamming effectiveness is introduced. The equation allows calculation of the jammer–to–signal (J/S) ratio at the target receiver. The equation requires knowledge of the jammer power and the power of the target transmitter, the antenna gains over the jammer–receiver link and the transmitter–receiver link, and the path loss between the jammer and receiver and the transmitter and receiver. There is an overview of the methods to determine path loss. If the J/S ratio required to jam a link is calculated, the technical effectiveness of a particular jamming scenario can be determined because thresholds of J/S ratio required for jamming are tabulated.

An overview of the types of communications electronic countermeasures, their implementations, and their problems is also included. Both jamming and deception techniques are discussed.

RESUME

Ce rapport examine les besoins en matière de brouillage des communications et la technologie pour parvenir efficacement à cette fin.

On formule d'abord une équation permettant de déterminer l'efficacité technique du brouillage. Cette équation permet de calculer le rapport brouillage/signal (B/S) à l'entrée du récepteur cible. Pour ce faire, on doit connaître la puissance du brouilleur et celle du transmetteur cible, de même que les gains de l'antenne réceptrice et les pertes de signal sur les trajets brouilleur–récepteur et transmetteur–brouilleur. On revoit les méthodes permettant la détermination de ces pertes de signal en fonction de la distance de propagation. Une fois calculé le rapport B/S requis pour le brouillage d'une communication radio, on peut procéder à l'évaluation de l'efficacité d'un scénario particulier de brouillage grâce à une table des valeurs minimums du rapport B/S.

Finalement, on couvre les différentes contre–mesures électroniques disponibles pour le brouillage des communications et on décrit leur mise en application et les problèmes qui en découlent, tant du point de vue brouillage que déception.

EXECUTIVE SUMMARY

Electronic countermeasures (ECM) represent the active portion of electronic warfare. ECM is used to disrupt the communications of an opposing force and thus affect the outcome of a battle, much like a weapon system. ECM can work using either jamming (active suppression of communication) or deception (using communications to confuse the enemy) techniques. Jamming is the usual form of ECM, since deception requires high level planning to be successful. Jamming requires planning to be technically effective, but can be employed tactically as targets of opportunity arise.

The jammer–to–signal (J/S) ratio equation developed in this paper allows determination of jamming effectiveness by comparison of the calculated J/S ratio with known thresholds required at victim receivers to overcome the intended communication signal. The equation for J/S ratio depends on the following variables: transmitter and jammer power, gain between transmitter and receiver antennas in both directions, gain between jammer and receiver antennas in both directions, the differences in bandwidth between the receiver input and the jamming signal, and the path losses between transmitter and receiver and jammer and receiver.

Since jamming effectiveness depends to a large extent on the amount of path loss encountered, methods of determining path loss are investigated. In general, estimates of path loss vary widely depending on the technique used to calculate it and the type of terrain considered. It is necessary to first determine the type of terrain being considered, then to choose the path loss model that best fits the situation under study. The estimates for path loss can then be used knowing that 10 dB variation in the estimated path loss is not uncommon. This 10 dB variation is equivalent to about a 2 to 1 variation in range for jamming effectiveness.

Methods of determining technical jamming effectiveness are applied before the jammers are used operationally because it is difficult to determine jamming effectiveness against enemy links. These a priori methods include measuring the error rates in digital signals and measuring the intelligibility of voice signals. Once effectiveness has been measured, the effective techniques can be used operationally with confidence that they are the most effective against the target.

The techniques for jamming depend on the technical characteristics of the target signal. Fixed frequency targets are the easiest to jam. The target must be located in time and frequency, and when known to be active, jammed. Wideband signals such as frequency hopped or direct sequence spread spectrum targets are more difficult to jam because they are more difficult to locate in time and in frequency. The frequency agile signals are difficult to track in both time and frequency, and the spread spectrum signals have an innate anti–jamming capability at the receiver in that the jamming signal is compresessed by the same amount that the signal is spread over the spectrum when demodulated by the receiver.

The techniques discussed in the report include barrage, comb, and narrow–band jamming against fixed frequency targets. Also discussed are sequential, follower, and repeater jamming against wideband targets. Against wideband targets, jamming transmitters are restricted in location relative to the target in order for repeater and follower jamming to be effective. Of course, the fixed frequency jamming techniques can be used against wideband targets, but they are not optimum.

The effectiveness of jamming relies to a large part on the height of the emitter since an increase in height reduces the path loss between the jammer and receiver. Various airborne platforms are discussed which would allow the jammers to achieve increased effectiveness. The proximity to the target receiver is also a factor in path loss, so several methods of delivering jammers to locations near targets are discussed as well.

The conclusion of the report indicates that to determine effectiveness of a particular jamming technique, the J/S ratio calculated from the equation developed should be compared to a threshold, T, of required signal level over noise at the target receiver. The following relationships are then applied to determine whether the signal is jammed:

a. If $J/S + \sigma < T$ then the signal is not jammed.
b. If $T - \sigma < J/S < T + \sigma$ then the signal may be jammed.
c. If $J/S - \sigma > T$ then the signal is jammed.

Note that σ is the error on the predicted J/S ratio.

Recommendations include suggestions for future research to develop the ECM expertise at DREO. Suggested work includes validating the threshold values currently used, defining measures of performance for military digital and voice links, and studying the technical feasibility of airborne jammers.

TABLE OF CONTENTS

TABLE OF CONTENTS (cont)

PAGE

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AWGN	Additive White Gaussian Noise
B	Receiver to Jammer Bandwidth Ratio in dB
c	Speed of light: 3E+8 m/s
D	Emitter to receiver distance
dB	Decibel
dBi	Decibels relative to an isotropic radiator
dBW	Decibels relative to one Watt
DREO	Defence Research Establishment Ottawa
DRFM	Digital Radio Frequency Memory
ϵ	Dielectric constant
ECM	Electronic Counter Measures
ESM	Electronic Warfare Support Measures
f	Frequency
FFT	Fast Fourier Transform
G_{tr}	Transmitter–receiver antenna gain
G_{rt}	Receiver–transmitter antenna gain
G_{rj}	Receiver–jammer antenna gain
G_{jr}	Jammer–receiver antenna gain
h	Minimum antenna height
H	Obstacle distance below path
h_t	Transmitter antenna height
h_r	Receiver antenna height
h_j	Jammer antenna height
h_{eff}	Effective antenna height
HF	High Frequency
jr	Jammer to receiver distance
J/S	Jammer to signal
K	Ratio of effective to mean earth radius
km	Kilometre
L	Loss
L_{tr}	Path loss from transmitter to receiver
L_{jr}	Path loss from jammer to receiver
MHz	Megahertz
ns	Nanosecond
π	Mathematical constant: 3.14159...
P_t	Transmitter power in dBW
P_j	Jammer power in dBW
R	First Fresnel Zone Radius
RF	Radio Frequency
R–T	Receiver to transmitter
σ	Conductivity
S/N	Signal–to–Noise ratio
SCI	Speech Communication Index
STI	Speech Transmission Index
tr	Transmitter to receiver distance
T–J–R	Transmitter to jammer to receiver distance

UAV	Unmanned Aerial Vehicle
UHF	Ultra High Frequency
μs	Microsecond
VHF	Very High Frequency
λ	Wavelength

1.0 INTRODUCTION

1.1 Aim

This report will give the reader an overview of communications electronic countermeasures (jamming and deception), and provide an equation for calculating the jammer–to–signal ratio which can be achieved at a target receiver. The report is also a vehicle to develop ideas as to the direction for research into communications electronic countermeasures.

1.2 Background

Electronic countermeasures (ECM) represent the active portion of electronic warfare. ECM is used to disrupt the communications of the opposing forces and put them at a disadvantage. If communications are disrupted, all phases of the battle can be affected. Information about the battle is prevented from reaching higher echelons, so decisions requiring time–critical information may be poorly made.

ECM can prevent the enemy from carrying out its full battle plan, since coordination can be hard to achieve while operating during the ECM. ECM also helps the friendly forces hide their own intentions.

Effective jamming requires that the jamming itself be technically successful to prevent communications over the link. The jamming must also be tactically effective so that the communications prevented were important to the battle. If the jamming was both technically and tactically effective, the jamming was effective. Deception must also be both technically and tactically effective to achieve its purpose.

To achieve technical effectiveness requires planning. The required jammer–to–signal ratio at the target receiver must be above a defined threshold, which depends on the modulation type of the jammer and receiver. The jammer–to–signal ratio depends on the power, antenna gains, and path loss over the jammer–to–receiver and transmitter–to–receiver links. The success of the jamming also depends on the types of jamming techniques used. These techniques define the time and frequency description of the jammer. Another requirement for successful jamming is that the jammer's center frequency must occur within the bandwidth of the target receiver so the jamming power is used most effectively.

Tactical effectiveness is also required for successful jamming but it is hard to determine in practice. The targets must be carefully chosen, first to technically be able to jam them and second to jam critical communication links and affect the flow of the battle. ECM as a weapon must be considered carefully before employment. There is a risk that the jamming will affect friendly communications links, so the commander must be aware of the possibilities and weigh the possible results against the consequences. Because of the unpredictability of technical effectiveness, jamming does not provide reliable suppressive fire power, but can be used as harrassment and against targets of opportunity as they arise.

1.3 Scope

This report discusses some aspects of technical jamming effectiveness. Section 2 discusses the requirement to develop a certain jammer–to–signal ratio at the target receiver, including the calculation of path loss. Section 3 discusses measures of jamming effectiveness. Section 4 discusses some jamming techniques available and their implementations. The last section describes further work to be done in the area of communications electronic countermeasures. Appendix A contains, for reference, a table of the jammer–to–signal ratio thresholds required for different modulation types. The other appendices contain detailed calculation methods to analytically determine the propagation loss over a particular path and programs developed to calculate empirical path loss and resulting jammer–to–signal ratios for the chosen scenarios.

2.0 JAMMING EQUATION

The aim of this chapter is to define an equation which expresses the relationship between a jammer and its target communications link. The equation should reflect the jammer's technical effectiveness by determining the jammer–to–signal power ratio at the target receiver.

2.1 Jammer–to–Signal Ratio

The equation used to determine the jammer–to–signal (J/S)[1] ratio at the receiver is referred to as the jamming equation. There are a large number of variables in the equation, many of which can only be characterized statistically. The jamming equation can thus only approximate the jammer–to–signal ratio at the receiver.

To develop a formula for jammer–to–signal (J/S) ratio, the signal power at the receiver is calculated as is the jamming power at the receiver. The two power formulas are then taken in ratio. The formulas for signal and jammer power at the receiver follow, (assuming jamming power >> other noise power at receiver) :

$$S = P_t + G_{tr} + G_{rt} - L_{tr} \qquad \text{(dBW)}$$

$$J = P_j + G_{jr} + G_{rj} - L_{jr} \qquad \text{(dBW)}$$

P_t :	output transmitter power	(dBW)
P_j :	output jammer power	(dBW)
G_{tr} :	antenna gain from tx to rx	(dB)
G_{rt} :	antenna gain from rx to tx	(dB)
G_{jr} :	antenna gain from jammer to rx	(dB)
G_{rj} :	antenna gain from rx to jammer	(dB)
L_{tr} :	path loss from tx to rx	(dB)
L_{jr} :	path loss from jammer to rx	(dB)

---

[1] J/S is used instead of the more correct J–S (dB) since it better indicates the idea of a ratio

The jammer–to–signal ratio is the ratio of the jammer power arriving at the receiver to the transmitter power arriving at the receiver (intended signal).

$$\begin{aligned} J/S &= (P_j + G_{jr} + G_{rj} - L_{jr}) - (P_t + G_{tr} + G_{rt} - L_{tr}) \\ &= (P_j - P_t) + (G_{rj} + G_{jr} - G_{tr} - G_{rt}) + (L_{tr} - L_{jr}) \end{aligned}$$

where J/S is in dB.

The jammer–to–signal ratio depends on the differences (in dB) between the transmitter powers, the antenna gains, and the losses over the two paths (the transmitter–to–receiver and the jammer–to–receiver paths). If the intended signal is stronger than the jamming signal then the J/S ratio is negative, and communication will likely be successful (but success depends on modulation type). The jammer tries to make the J/S ratio positive, or as large as possible, by making the jamming signal stronger than the intended signal to be sure to disrupt communications.

The relationship between the J/S ratio and the success of communications is not as clear cut as indicated. Depending on the jammer and signal modulation types used, a certain threshold of signal over noise and interference is required to maintain communications. This noise+interference margin is tabulated in Appendix A (from [4, p. 8.16], giving values of signal over noise required to provide a specified performance level. For example, if both the target transmission and the jamming signal are AM voice with 6 kHz bandwidth, then the required threshold is –5 dB. An interpretation of the threshold says that if the jamming signal is more than 5 dB above the desired signal at the receiver, the victim will start to be jammed. The signal man's interpretation of the threshold says that if the signal is up to 5 dB below the level of the jamming signal (or if it is higher than the jamming signal) then the receiver can achieve a 1 percent probability of error on a 1000 word vocabulary.

It is possible that noise alone will prevent communications so jamming is not required. Both environmental and receiver front end noise can prevent communication. Environmental noise includes both man–made and atmospheric noise. Receiver front end noise is the thermal noise within the receiver that is produced by its components. This noise depends on the temperature and the bandwidth. In the VHF bands and lower, atmospheric noise is the limiting noise factor, but as frequencies increase, the receiver noise becomes the limiting factor. If noise alone prevents communication, there is no need to jam the link.

The differences in power and gain over the transmitter–receiver and jammer–receiver paths are calculated directly from the equipment specifications. The differences in the path losses over the two paths depend both on the system antenna heights and on the environment. Each loss term includes factors to account for path, cable, polarization and any other losses. The path loss values are calculated using equations dependent on the frequency, the locations of the equipment and the interposing terrain. These equations predict the losses as the signals propagate over their respective paths.

Another factor which should be included in the definition of the J/S ratio is the amount of jammer power transmitted which was not in the receiver bandwidth. This factor can reduce the jammer power at the receiver, but will never increase the intended signal power. When the receiver–to–jammer bandwidth ratio B_r/B_j is greater than one, it can be arbitrarily set to one since all jammer power is within the receiver bandwidth. The bandwidth difference (in dB) is thus always negative, with a maximum value of zero. The jammer bandwidth, when larger than the target bandwidth, reduces the J/S ratio because the jammer is wasting power on the frequencies where there is no target. When the jammer bandwidth is smaller than the target bandwidth, there is no effect on the J/S ratio as reflected by the 0 dB bandwidth ratio when B_r/B_j is set to one.

If this difference is included in the equation for jammer power at the receiver, the following equation results for the J/S ratio:

$$J/S = (P_j + G_{jrj} - L_{jr} + B) - (P_t + G_{trt} - L_{tr})$$

where J/S is in dB

$B = 10\log(B_r/B_j)$ in dB
B_r is the receiver bandwidth in MHz
B_j is the jammer bandwidth in MHz

2.2 Propagation Losses

Propagation losses depend on the nature of the environment near and between each antenna, and the propagation mode of the radio waves. These modes depend on the frequency of the transmission, the terrain, the antenna height, and, in the case of skywave HF propagation, the state of the ionosphere.

2.2.1 HF (3–30 MHz) Propagation

HF transmission is supported by sky wave and ground wave modes. Skywave is the mode in which reflection from the ionosphere causes bending of the electromagnetic wave back toward the earth. Ground wave is the mode covering all transmissions not reflected from the ionosphere.

Surface wave is a ground wave mode where the wave travels along the surface of the earth, the maximum depth of penetration depending on the frequency. The wave is increasingly attenuated as the distance between emitter and receiver increases, but is often strong enough to allow communication to occur over short ranges, (tens of kilometres).

Ground wave propagation losses in the HF range are tabulated for specific frequencies and path lengths [4, pp. 6.14–6.23]. Sky wave losses are computed using a statistical prediction of the ionospheric height and electron density or by actual measurements of the ionosphere using a sounding technique. References [14] and [15] discuss an HF signal strength computation method using a computer (program available).

Losses vary as fading occurs. Fading is due to multipath reflections off different and changing layers of the ionosphere. The losses can vary by more than 30 dB. The transmitted signal level must thus be increased by the expected amount of variance to ensure reliable communications even at maximum loss [7].

2.2.2 VHF/UHF (30–3000 MHz) Propagation

The ground wave propagation mode is used by most VHF/UHF transmissions. Propagation loss at the VHF/UHF frequencies depends on how close the path between transmitter and receiver is to radio line of sight (LOS). Line of sight at any frequency means the transmitter and receiver have a path free of obstacles between them. Radio line of sight may not exist over a path even if stations are within optical sight of one another. As frequency increases, radio line of sight approaches optical line of sight since optical frequencies are higher than radio frequencies. The radio line of sight can be assumed to exist between two antennas (height in metres) if the obstacle–free distance between them is less than:

$$\text{distance} = 1.6[(6.1h_t)^{\frac{1}{2}} + (6.1h_r)^{\frac{1}{2}}] \qquad \text{(km)}.$$

The following table contains some values of the maximum separation between antennas of several antenna heights using this equation. Note that for these tactical antenna heights, the obstacle–free separation may be achievable in relatively smooth terrain because the distances are fairly short. These distances, while short, are in common tactical use.

TABLE 2.1: MAXIMUM ANTENNA SEPARATION (km) FOR RADIO LOS

Transmitter Antenna Height h_t (m)	Receiver Antenna Height h_r (m)	Maximum LOS Separation (km)
3.0	3.0	13.7
5.0	5.0	17.7
10.0	10.0	25.0

If an obstacle exists in the path of the radio wave, radio line of sight cannot be assumed. There are two steps used to determine if an obstacle exists in the path of the radio wave. The first step determines whether the surface of the earth will interfere with propagation, as explained in Appendix B. The radius of the earth is corrected for tropospheric refraction effects by a factor denoted by K. The K value changes the assumed radius of the earth so that the surface of the earth between the endpoints may be at a different height than that specified for the usual smooth spherical earth. The K factor usually used is 4/3. This is applied to the earth's radius so that the increased radius comes between the communication path's endpoints as indicated in Figure 2.1. The path between antennas can now be drawn as a straight line over the adjusted radius. If the first Fresnel zone around the straight line path does not intersect the earth's corrected radius, then the surface of the earth is not an obstacle, as explained in Appendix B.

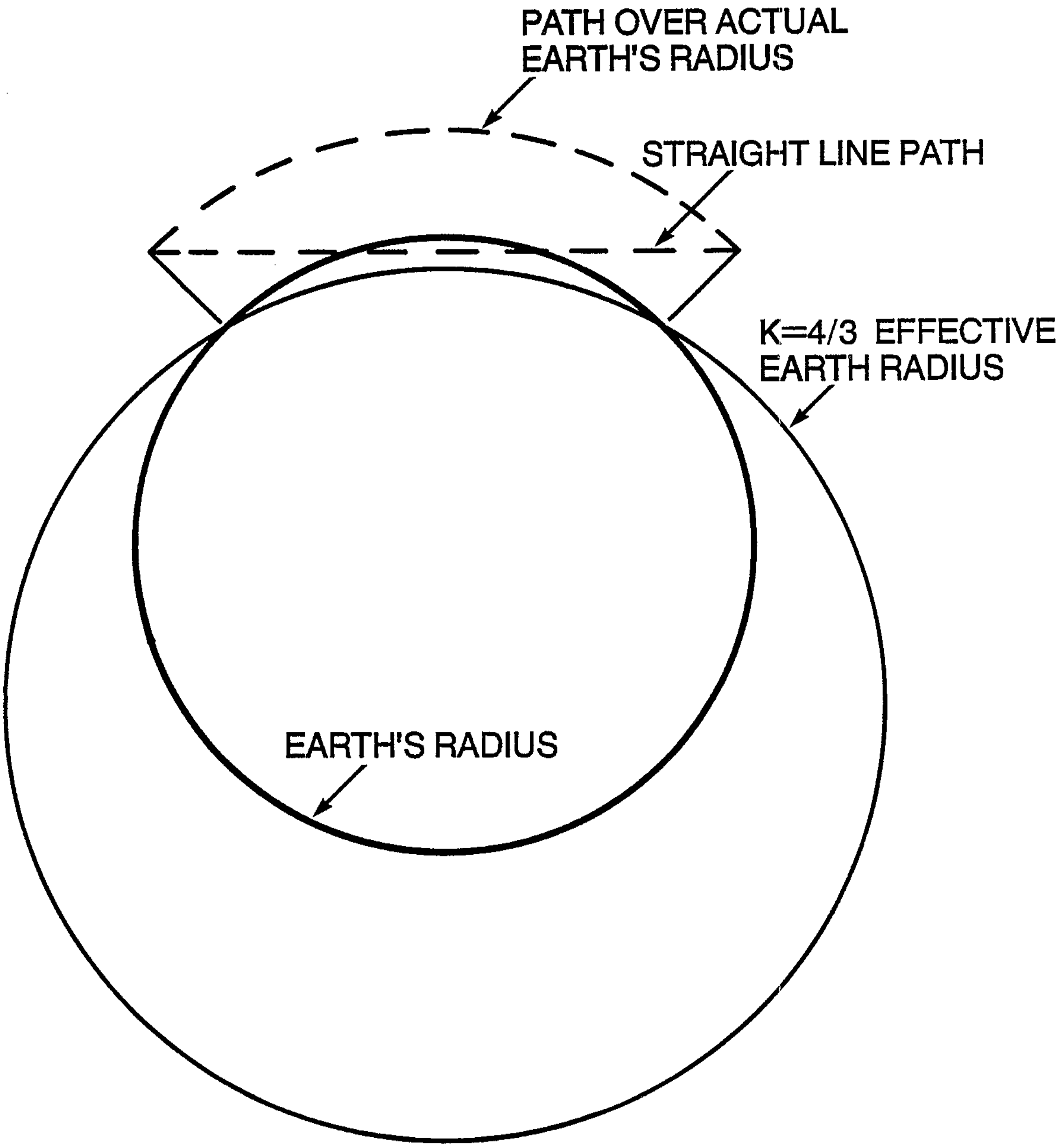

FIGURE 2.1: EFFECTIVE RADIUS

Tactical path lengths of 50 km represent 0.125 percent of the earth's circumference. If the radius is increased by K = 4/3, then the path represents 0.094 percent of the earth's adjusted circumference. The amount of curvature between path endpoints (antennas) is negligible to start with and when the earth's radius is adjusted, the amount of curvature is reduced. It is thus assumed that at tactical path lengths of up to 100 km the path between antennas can be taken as a straight line. The distance of the earth's surface from the straight line path can thus be taken as the antenna height, and if the earth's surface does not fall into the first fresnel zone, the surface is not an obstacle.

The second step is to determine if each terrain feature in the path between receiver and transmitter is in fact an obstacle. It is called an obstacle if it comes within a certain distance of the straight line path between the transmitter and receiver, called the first Fresnel zone, which is frequency dependent. The required distance from the path, the Fresnel radius, is usually taken as 0.6 of the Fresnel zone. The calculation of the Fresnel radius is outlined in Appendix B. The first Fresnel zone indicates the area in which diffraction losses occur if any obstacles are present. If an obstacle is present the wavefront gets distorted because the propagating wave does not have a clear path. The distortion occurs in a fashion known as diffraction. Figure 2.2 shows the first Fresnel zone for a 1 km path between 50 m antennas for several values of frequency. Note that as frequency increases, the first Fresnel zone approaches the straight line path.

The frequency of operation and the terrain feature's distance from the midpoint of the path determine whether a terrain feature between transmitter and receiver is to be considered an obstacle. Terrain features below the direct path between transmitter and receiver are more likely to be obstacles as the frequency decreases because the Fresnel radius increases and encompasses features at lower heights. Table 2.2 shows the minimum distance from the path an obstacle at the midpoint between the transmitter and receiver must be in order not to affect the propagation of the radiation between them.

TABLE 2.2: MINIMUM OBSTACLE DISTANCE FROM Tx–Rx PATH (in metres)

frequency(MHz)	Path Length (km)		
	2	10	20
30	42.4	94.9	134.2
300	13.4	30.0	42.4
3000	4.2	9.5	13.4

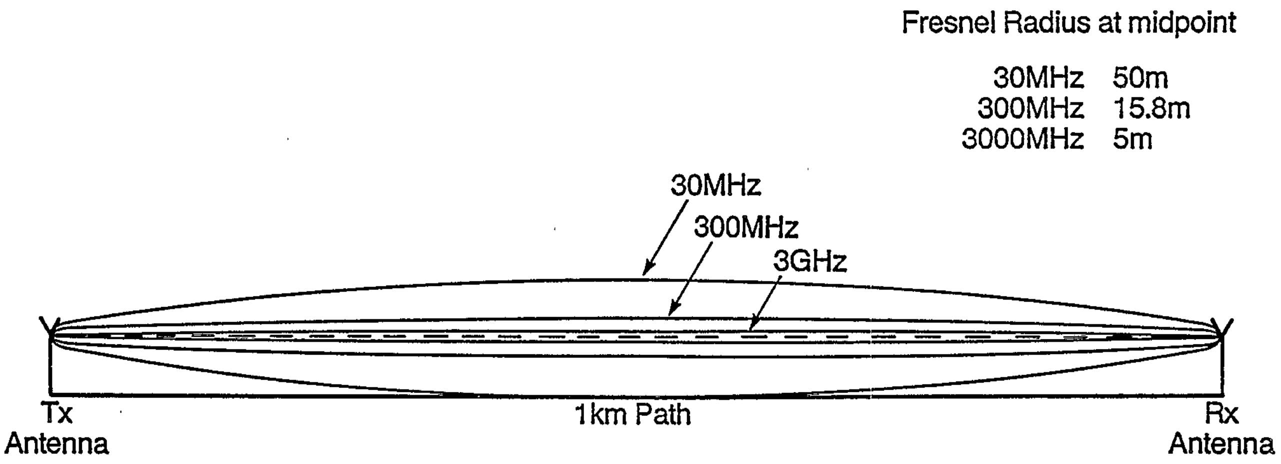

FIGURE 2.2: FRESNEL RADIUS

To make proper use of the theory, it would be necessary to know all terrain features and to evaluate each one as to its effect on the propagation. If the obstacle is not of a theoretically convenient shape, and not many are, the theoretical equations to calculate the propagation effects of the obstacle, if available at all, are complicated.

In summary, the two line of sight considerations in determining obstacles in the path are:

(a) the earth's radius, (and thus the height of all terrain features), must be adjusted using the K factor and,

(b) all terrain features including the surface of the earth must be evaluated to see whether they come within 0.6 of the Fresnel zone.

If there are obstacles in the path, the analytic equations assuming line of sight cannot be used and the most efficient propagation prediction models to use are the empirical or statistical models.

2.2.3 VHF/UHF Path Loss Summary

The various detailed propagation models are included in Appendix B, section B3. In summary, there are many ways to arrive at a figure for the path loss between a transmitter and receiver. The actual method chosen to calculate the loss will depend on the amount of computing power available to the jammer operator, and the environment of the transmitter and receiver. There are many factors affecting the validity of the number generated as the path loss. A specific value of path loss can only be stated with a certain probability of occurring, over time and over space.

2.2.3.1 Estimating Path Loss

Table 2.3 shows the variation in answers to the question "What is the path loss?" when different formulas are used to calculate the answer. A program, included in Appendix C, was used to calculate the path loss for a particular situation using each of the empirical equations as well as the free space and plane earth equations for comparison. Path loss predicted by the empirical equations varies from 120 to 164 dB, depending on the defined terrain. The dielectric constant of the earth is used in some of the more complicated empirical equations. It depends on the moisture content of the earth. The dielectric constant used in the calculations is that for average terrain, (not over water).

The situation used was as follows:

Transmitter antenna gain (dB):	6.0
Receiver antenna gain (dB):	6.0
Transmitter antenna height (m):	3.0
Receiver antenna height (m):	3.0
Frequency (MHz)	250.0
Transmitter to Receiver distance (km):	10.0
Dielectric constant:	13.0

TABLE 2.3: PATH LOSS PREDICTIONS

Method	Path Loss (dB)	σ (dB)
Free Space	100	
Plane Earth	141	
Egli, h < 10 m	150	9
Murphy, Mountainous	144	17
Murphy, Level	121	13
Rood, LOS	140	
Rood, one 100 m obstacle	153	
Rood, obstacles < 100 m	164	
ECAC, LOS	127	
ECAC, non–LOS	147	
ECAC, mountainous	134	
Palmer, Trees/Vertical	126	
Palmer, Trees/Horizontal	120	
Palmer, Bare/Summer	128	
Palmer, Bare/Winter	136	

2.2.3.2 When to Use Each Model

The models make certain assumptions about the terrain over the path of the emitter–receiver link. Each modelling equation is thus used under specific circumstances:

a. The free space model is only used when terrain is not a factor in the link, such as between airplanes in an air–air link, or in ground–air–ground links in which the angle of incidence between aircraft and ground station is such that the link never grazes the earth.

b. The plane earth model can be used in situations where the terrain is smooth and flat and the paths are limited to several kilometres. Examples include prairie and ocean environments which are smooth (bumps or waves of size no greater than the wavelength of the emitted signal).

c. Egli's model is a widely used predictor of propagation loss. It produces valid, if pessimistic loss values for paths of up to 80 km over the frequency range 30 MHz to 1 GHz. The original equation was developed using measurements in an urban environment so appropriate situations include paths through cities. There are two equations, one applies to situations with receive antennas of less than 10 m, and the other with receive antennas of greater than 10 m.

d. Murphy repeated Egli's experiment in a rural environment, once in mountainous terrain and once in level terrain. Thus:

(1) Murphy mountainous equation is valid in mountainous areas with path lengths of less than 80 km and over the 30 MHz to 1 GHz VHF band.
(2) Murphy level equation is valid in flat areas with scattered trees with path lengths of less than 80 km and over the 30 MHz to 1 GHz band.

e. The model developed by Rood is valid for irregular terrain and with path lengths less than 100 km over the 20 to 100 MHz band. The three equations have the following specific conditions:

(1) Rood, LOS is used when the emitter and receiver are in nominal line of sight and there are no obstacles in the first Fresnel zone.
(2) Rood, one obstacle is used when there is one obstacle less than 100 m high in the path between emitter and receiver.
(3) Rood, many obstacles is used when there is more than one obstacle in the emitter–receiver path.

f. The ECAC model requires that the path be less than 50 km long and not be over water. Antenna heights are also assumed less than 6 m. The following specific conditions also apply to each of the three equations:

(1) ECAC, LOS requires that there be radio line of sight between emitter and receiver and no obstacles in the first Fresnel zone.
(2) ECAC, non–LOS equation applies to any relatively level or slightly hilly terrain paths.
(3) ECAC, mountainous is applied to paths through mountainous terrain.

g. Palmer did specific studies in summer and winter over barren and treed terrain in the Arctic. The model requires that the effective antenna heights be calculated using a dielectric constant of 45 and a conductivity of 0.01 S/m. The model is valid over the frequency range 30 to 100 MHz and with paths up to 100 km long.

(1) The Palmer, trees model is applied to paths through terrain with relatively sparse trees that are less than 5 m high, and during either summer or winter conditions.
(2) The Palmer, bare/summer model applies to paths over barren terrain in the summer when there is no snow.
(3) The Palmer, bare/winter applies to paths over barren terrain which are snow–covered.

2.2.3.3 Terrain Determination

In order to make use of the proper equation, the terrain type must be known to some extent. As indicated in the discussion of models in Section 2.2.3.2, there are some relatively general models that require only limited knowledge of the target terrain, but there are also some more sophisticated models that require knowledge of the details of the terrain. Several require that the application know whether there are obstacles in the path of interest and even how many there are. The terrain details can be determined analytically, or statistically.

To obtain the required terrain information analytically, the path must be analyzed. If the terrain information is stored digitally, a computer can be used to provide terrain information about the path. If the terrain information is not available in this form, then a manual method must be used, such as studying a map.

A statisical determination of the likelihood of the type of terrain occurring can also be done. Studies such as one done of terrain in West Germany [19] to determine the statistics of the number of obstacles on paths of various lengths can be used to provide a basis for statistical prediction of the number and type of obstacles in a path of a particular length in a specific area. The study in [19] determined probabilities for communicating over poor, average and good ground in a selected West German area as shown in Figure 2.3. The type of transmitter being used as an example was a 30 W FM voice radio with a 3 metre (10 foot) antenna using a frequency of 60 MHz. The required S/N at the receiver was 12 dB. Low suburban noise level was also assumed.

Another study looked at the probability of communicating with radio relay equipment [18]. The distribution of path lengths used in the study are shown in Figure 2.4, and the calculated number of LOS links as a function of frequency is shown in Figure 2.5. This type of information can be used to qualify the use of a particular empirical model for calculating path loss. For example, if it is known that most of the links of a particular length are LOS, the ECAC LOS model can be used with confidence. It would be necessary to carry out such studies of the terrain in the particular areas of tactical interest so that when deployed to these areas, units could operate using the predefined average link characteristics.

2.3 Jamming

The objective of jamming is to increase the J/S ratio until the jamming signal dominates the intended signal and denies communications between the transmitter and receiver. There are two ways to jam a link: either prevent the front line sets from receiving their orders from higher echelons or prevent the higher echelons from receiving reports from the front. It is desirable to jam both sides of the transmission, but jamming will be limited by the distance to the higher echelon receivers (and the increased path loss) and will likely only affect the reception at the front.

2.3.1 Jamming Equations Using Empirical Path Loss

The equation introduced in Section 1 determines the jammer–to–signal (J/S) ratio achieved by the jammer at the target receiver. That equation, reproduced below, includes a term for path loss difference between the path from jammer to receiver and that from transmitter to target receiver. As introduced earlier in Section 2, path loss is a highly variable quantity, and exact figures are impossible to determine without actual measurement at the time in question. The value for J/S ratio is thus similarly variable when the estimates for path loss are included. The most convenient and not inaccurate equations for the path loss are the empirical equations summarized in Section 2.2.3 and detailed in Appendices A and B. These will be used in the equations that follow to determine complete equations for the jammer–to–signal ratio.

$$J/S = (P_j - P_t + B) + (\text{Gains}) - (L_{jr} - L_{tr})$$

where

P_j:	jammer power	(dBW)
P_t:	transmitter power	(dBW)
B:	B_j/B_r bandwidth ratio	(dB)
Gains:	$G_{jr} + G_{rj} - G_{tr} - G_{rt}$	(dB)
G_{jr}:	jammer to receiver antenna gain	(dBi)
G_{rj}:	receiver to jammer antenna gain	(dBi)
G_{tr}:	transmitter to receiver antenna gain	(dBi)
G_{rt}:	receiver to transmitter antenna gain	(dBi)
L_{jr}:	jammer to receiver path loss	(dB)
L_{tr}:	transmitter to receiver path loss	(dB)

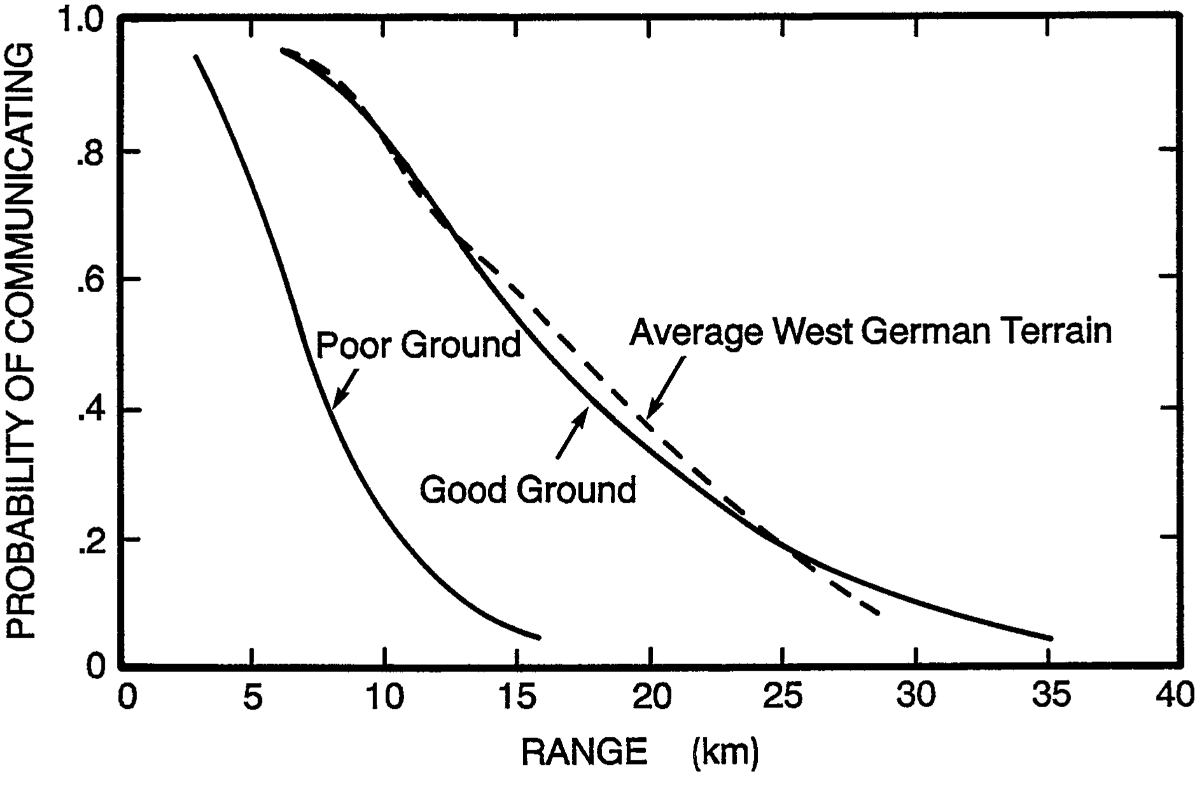

FIGURE 2.3: PROBABILITY OF COMMUNICATING OVER VARIOUS TERRAIN

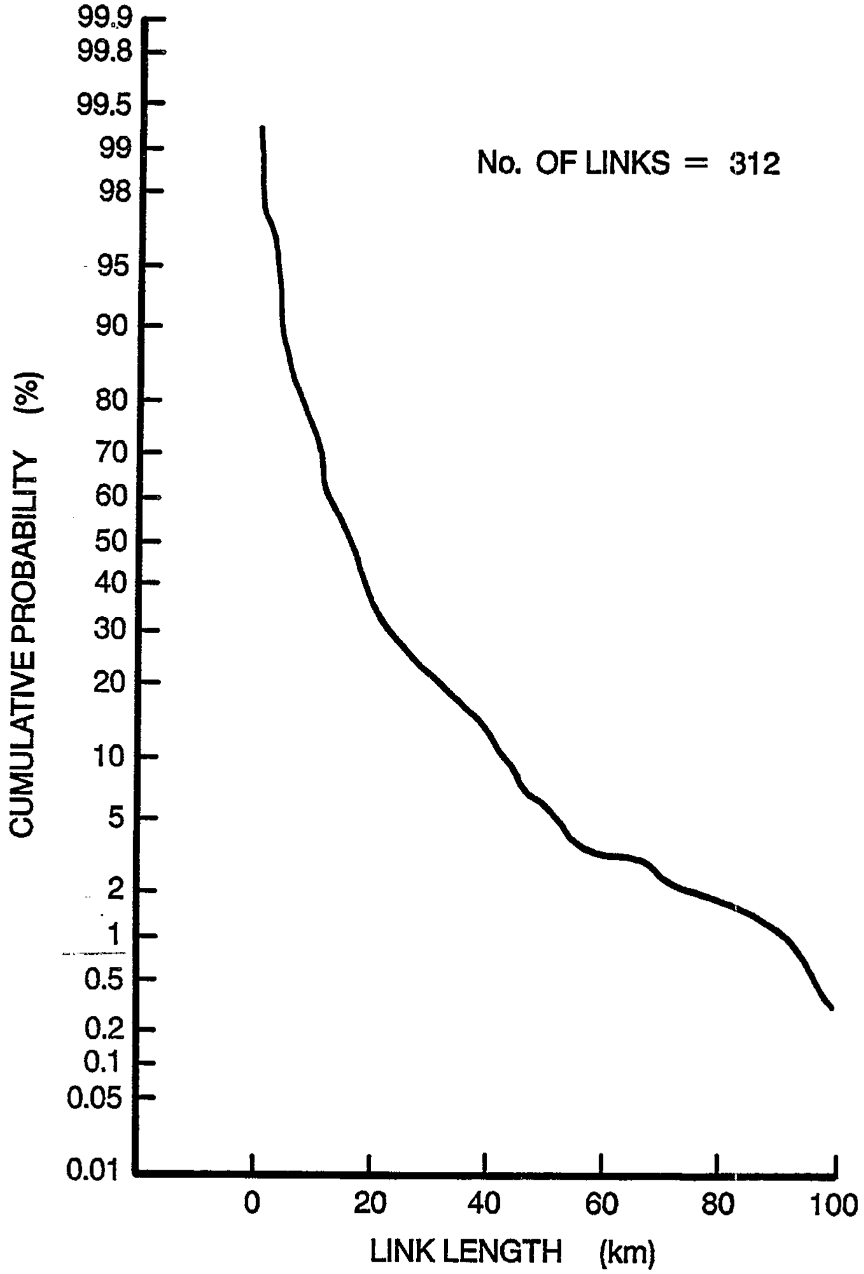

FIGURE 2.4: DISTRIBUTION OF LINK LENGTHS

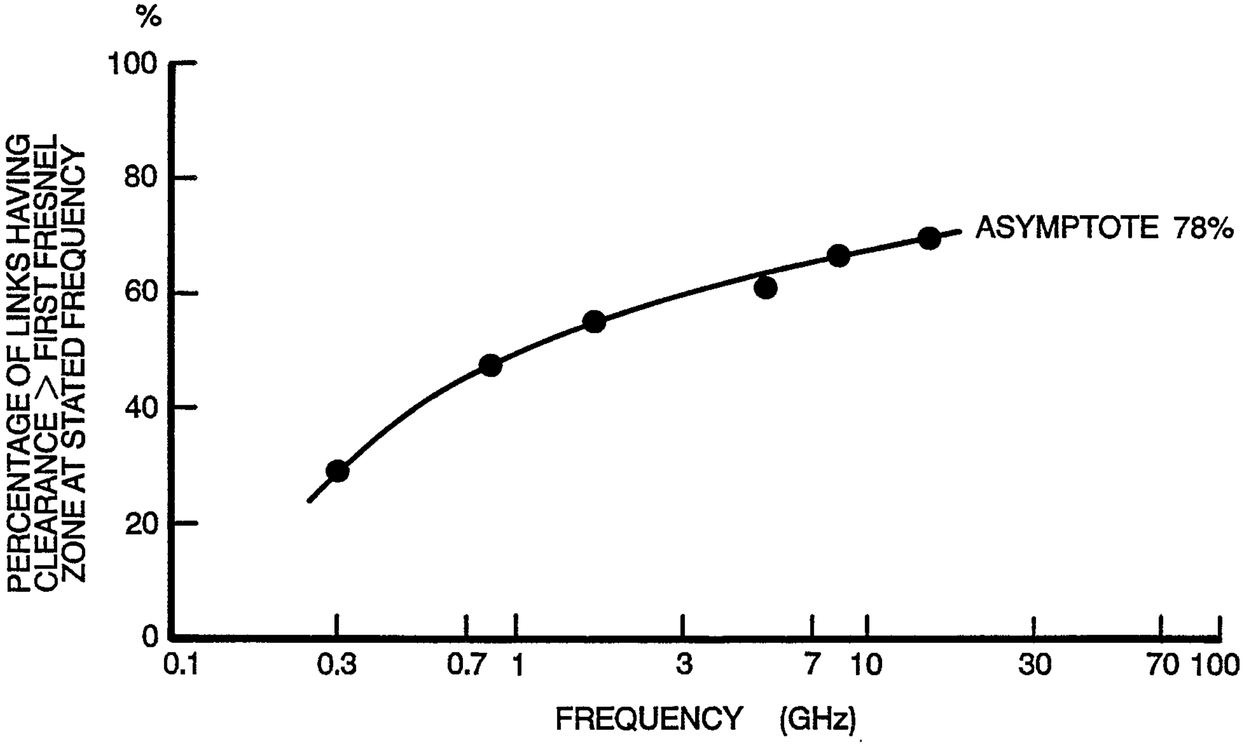

FIGURE 2.5: INCIDENCE OF LINE OF SIGHT LINKS

In order to calculate the jammer–to–receiver distance at which a certain jammer–to–signal ratio will occur or vice versa, the equation repeated above for J/S ratio can be solved. Since the path losses vary with the ratio of the transmitter to receiver and the jammer–to–receiver distances, the equation can give a line relating J/S ratio to the distance ratio. The equation will look different for each empirical equation used to determine the path loss.

The equations for $(L_{tr} - L_{jr})$ in each of the empirical cases is given below.

Egli and Murphy:

$$(L_{tr} - L_{jr}) = 40\log\left[\frac{D_{tr}}{D_{jr}}\right] + 20\log\left[\frac{h_j}{h_t}\right]$$

Rood LOS:

$$(L_{tr} - L_{jr}) = 40\log\left[\frac{D_{tr}}{D_{jr}}\right] + 10\log\left[\frac{\epsilon^2}{438(\epsilon-1)} + (fh_j)^2\right] - 10\log\left[\frac{\epsilon^2}{438(\epsilon-1)} + (fh_t)^2\right]$$

Rood one obstacle:

$$(L_{tr} - L_{jr}) = \frac{1070H}{D_{tr}-D_{jr}} - \frac{7500H^2}{D_{tr}^2-D_{jr}^2} + 0.879(D_{tr}-D_{jr}) - 0.00378(D_{tr}^2-D_{jr}^2)$$

Rood many obstacles:

$$(L_{tr} - L_{jr}) = \frac{287H}{D_{tr}-D_{jr}} - \frac{11000H^2}{D_{tr}^2-D_{jr}^2} - 0.541(D_{tr}-D_{jr}) - 0.00159(D_{tr}^2-D_{jr}^2)$$

ECAC non–LOS:

$$(L_{tr} - L_{jr}) = (26 + 4\log f)\log\left[\frac{D_{tr}}{D_{jr}}\right]$$

ECAC LOS:

$$(L_{tr} - L_{jr}) = (31.5 + 4\log f)\log\left[\frac{D_{tr}}{D_{jr}}\right]$$

ECAC mountainous:

$$(L_{tr} - L_{jr}) = (22\log f - 9)\log\left[\frac{D_{tr}}{D_{jr}}\right]$$

Palmer Treed:

$$(L_{tr} - L_{jr}) = 44.8\log\left[\frac{D_{tr}}{D_{jr}}\right] + 6.6\log\left[\frac{h_j}{h_t}\right]$$

Palmer Barren:

$$(L_{tr} - L_{jr}) = 31.3\log\left[\frac{D_{tr}}{D_{jr}}\right] + 6.5\log\left[\frac{h_j}{h_t}\right]$$

For comparison, the free space and plane earth loss difference can also be calculated:

Free Space:

$$(L_{tr} - L_{jr}) = 20\log\left[\frac{D_{tr}}{D_{jr}}\right]$$

Plane Earth:

$$(L_{tr} - L_{jr}) = 40\log\left[\frac{D_{tr}}{D_{jr}}\right]$$

The J/S can thus be calculated with different $\frac{D_{tr}}{D_{jr}}$ ratios and plotted to give the graphs shown in Figures 2.6 through 2.9 for the baseline situation expressed below.

Jammer Power (P_j) and Transmitter Power (P_t):	100W,20 dBW
Bandwidth Ratio (B):	0 dB
All Antenna Gains (G_{jr}, G_{rj}, G_{tr}, G_{rt}):	6 dB
All Antenna Heights (h_t, h_r, h_j):	3 m
Jammer and Transmitter Frequency (f):	250 MHz
Dielectric Constant:	13

The graphs can thus be used to determine the J/S ratio at a victim receiver if the distance between the jammer and receiver and the distance between the transmitter and receiver are known or can be estimated. The important factor is the ratio of the two distances; if the jammer operator is estimated to be three times as far from the victim receiver as the intended transmitter is, then the J/S ratio is found as follows. The ratio one–third is used with the graph (one of figures two through six) by looking up –0.5 (log of one–third is –0.5) on the distance ratio axis and finding the corresponding J/S ratio on the other axis. Some of the graphs include dotted lines indicating the extent of the error possible on the J/S ratio.

Antenna heights are adjusted to include not only their physical height above ground, but also a factor to deal with the electrical properties of the earth on which they transmit if the main propagation mode is via surface wave. Surface wave is dominant until the antennas reach a height on the order of a wavelength over land or 5 to 10 wavelengths over the sea. The effect of the electrical properties of the earth is frequency dependent but after antennas reach a certain minimum height, only the physical height is used. The formula to calculate the minimum height is given in Appendix B, Section B3.2.

Note that the baseline case is not generally realistic in that simplifying assumptions such as equal antenna heights, gains, bandwidths, and powers are made. Thus in the baseline case described in the graphs, the J/S ratio can be equated to the differences in path losses alone. In order to use the curves for other than this simple baseline case, the curve can be adjusted on the J/S ratio axis directly by an amount equal to the differences (in dB) between the parameters and the baseline. Thus if there is a power difference, a gain difference, or a bandwidth ratio other than 1 (0 dB), then these differences in dB are added to the J/S ratio. Note that the correct difference must be taken (the subtraction must be done with the arguments in the order described below) and the resulting sign must be respected when adding the difference to the J/S ratio. Thus if the subtraction results in a negative number, then the negative number must be added to the J/S ratio, which reduces it. Use the following equations for the differences:

$P_j - P_t$:	(subtract transmitter power (dBW) from jammer power (dBW))
$10\log B_j/B_r$:	(take the ratio of jammer bandwidth to transmitter bandwidth)
$G_{jr} + G_{rj} - (G_{tr} + G_{rt})$	(subtract the sum of transmitter/receiver and receiver/transmitter gains from the sum of jammer/receiver and receiver/jammer gains).

A program, jscalc, to calculate the jammer–to–signal ratio for all of the empirical equations using a given situation is included in Appendix C. Results for the baseline case are given in Table 2.4 and are plotted in Figures 2.6 through 2.9.

TABLE 2.4: Jammer–to–Signal Ratio Baseline for Different Path Loss Formula

Path Loss Method	$\frac{D_{tr}}{D_{jr}}$	J/S Ratio (dB)	σ (dB)
Egli	0.1	–40.	±14.
Murphy level	0.1	–40.	±19.
Murphy mountainous	0.1	–40.	±24.
Rood LOS	0.1	–40.	
Rood one obstacle	0.1	14.	
Rood many obstacles	0.1	–87.	
ECAC LOS	0.1	–33.	
ECAC non–LOS	0.1	–36.	
ECAC mountainous	0.1	–44.	
Palmer treed	0.1	–45.	
Palmer bare	0.1	–32.	

2.3.2 Jammer–to–Signal Ratio Illustration: Egli Path Loss

The J/S equation is rewritten to include the path loss difference equation found when the Egli or Murphy model is used.

$$J/S = (P_j - P_t) + (\text{Gains}) - (L_{tr} - L_{jr})$$

$$= (P_j - P_t) + (\text{Gains}) - 40\log\left[\frac{D_{tr}}{D_{jr}}\right] + 20\log\left[\frac{h_j}{h_t}\right]$$

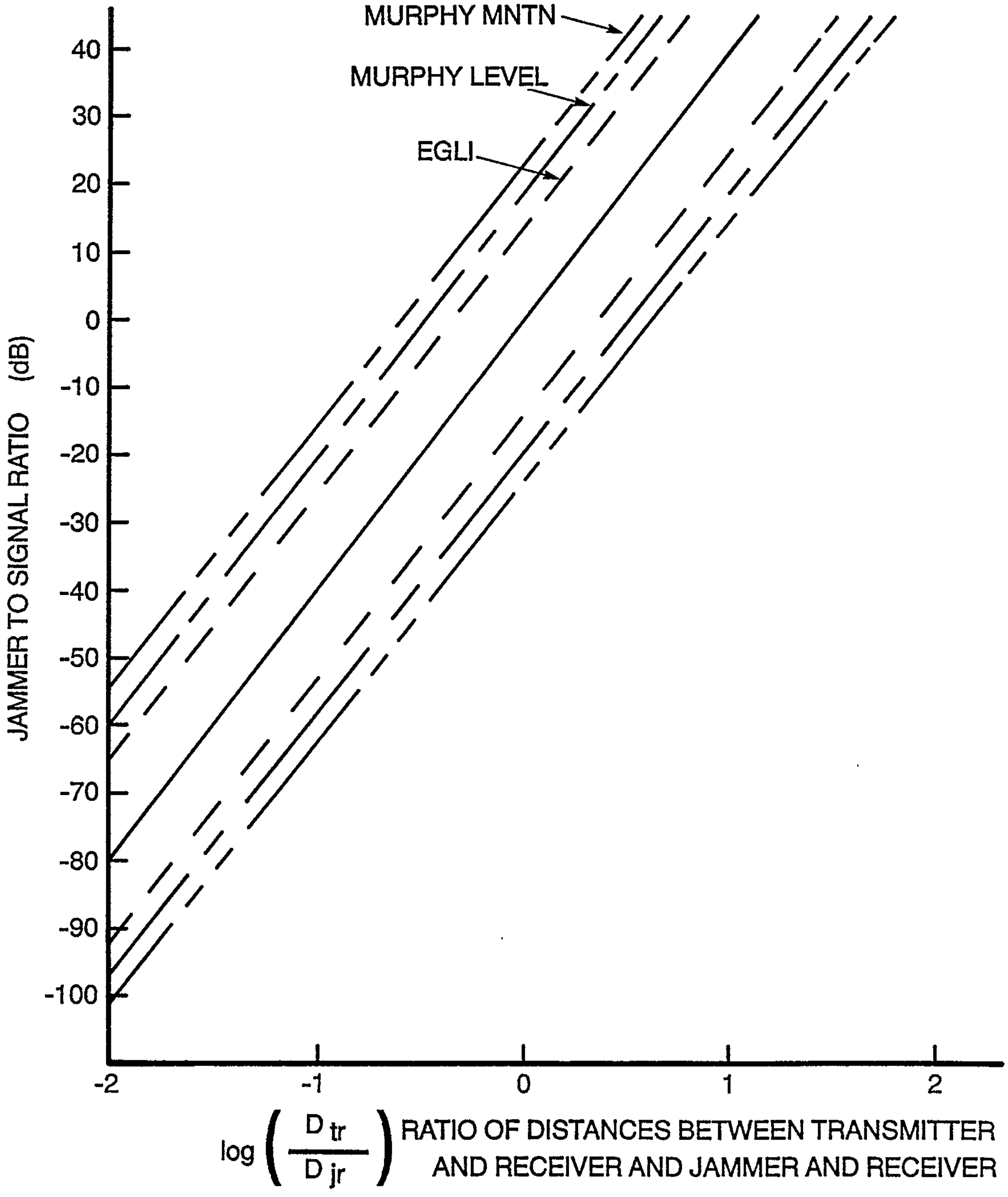

FIGURE 2.6: MODEL WITH EGLI AND MURPHY PATH LOSS

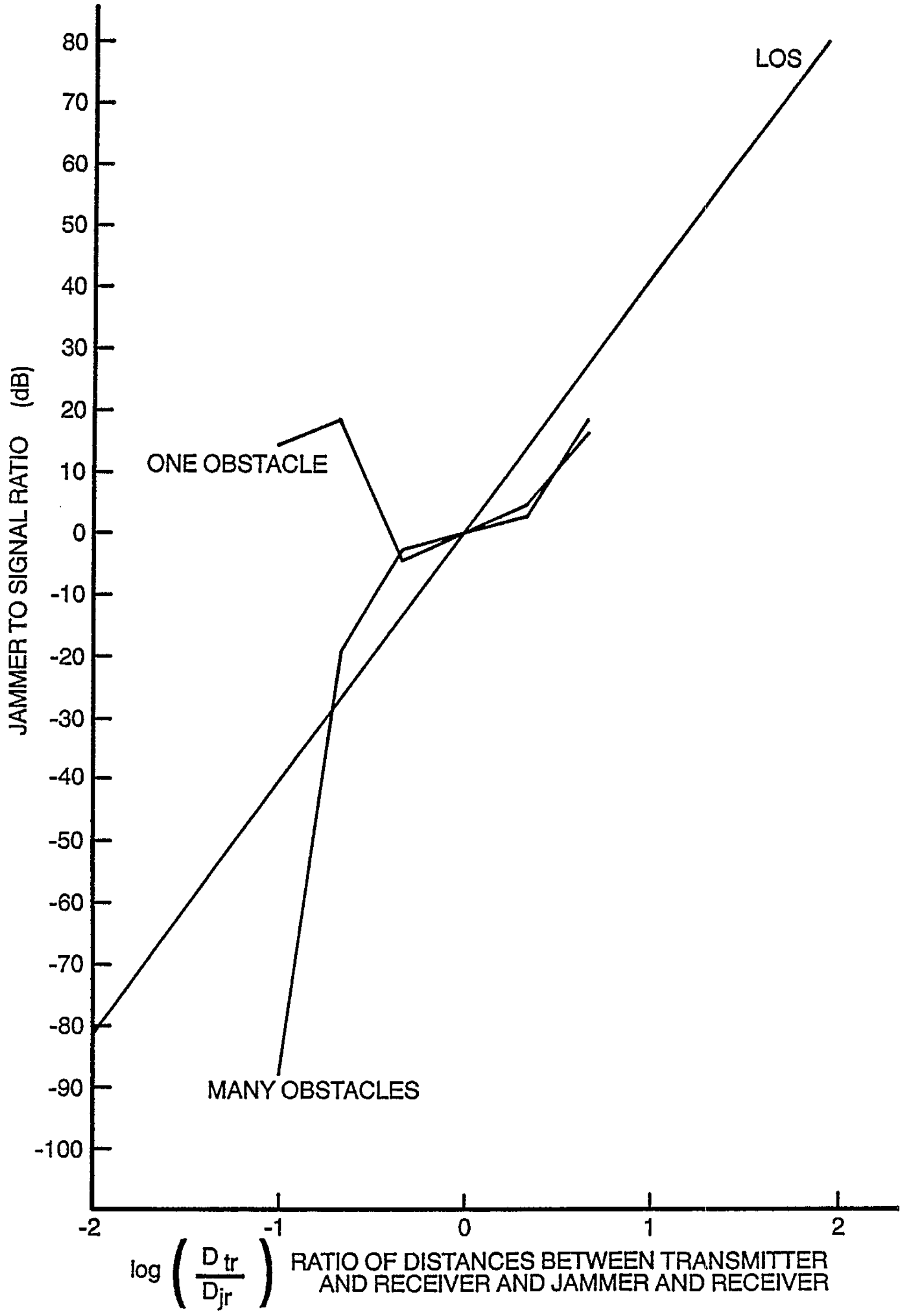

FIGURE 2.7: MODEL WITH ROOD PATH LOSS

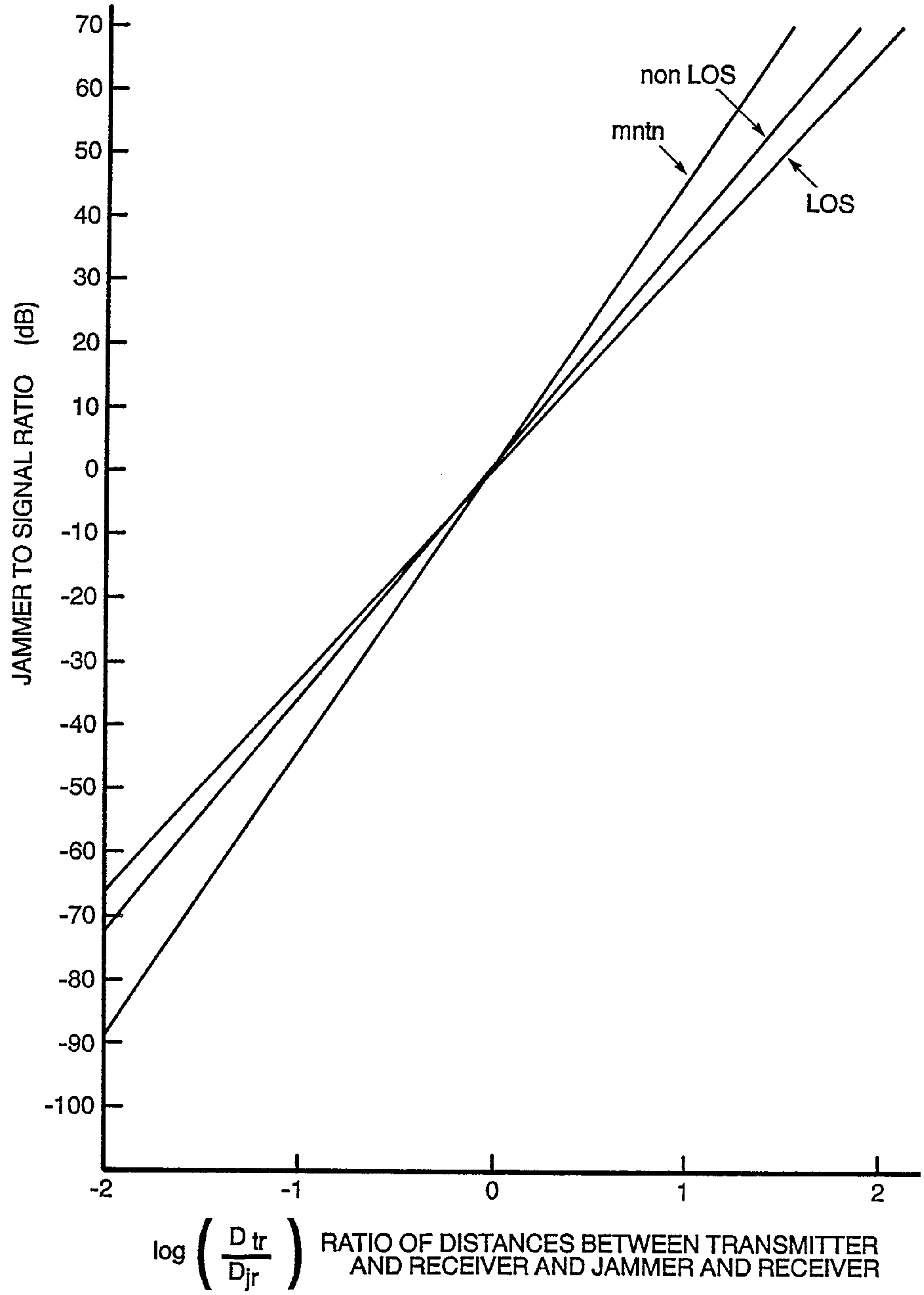

FIGURE 2.8: MODEL WITH ECAC PATH LOSS

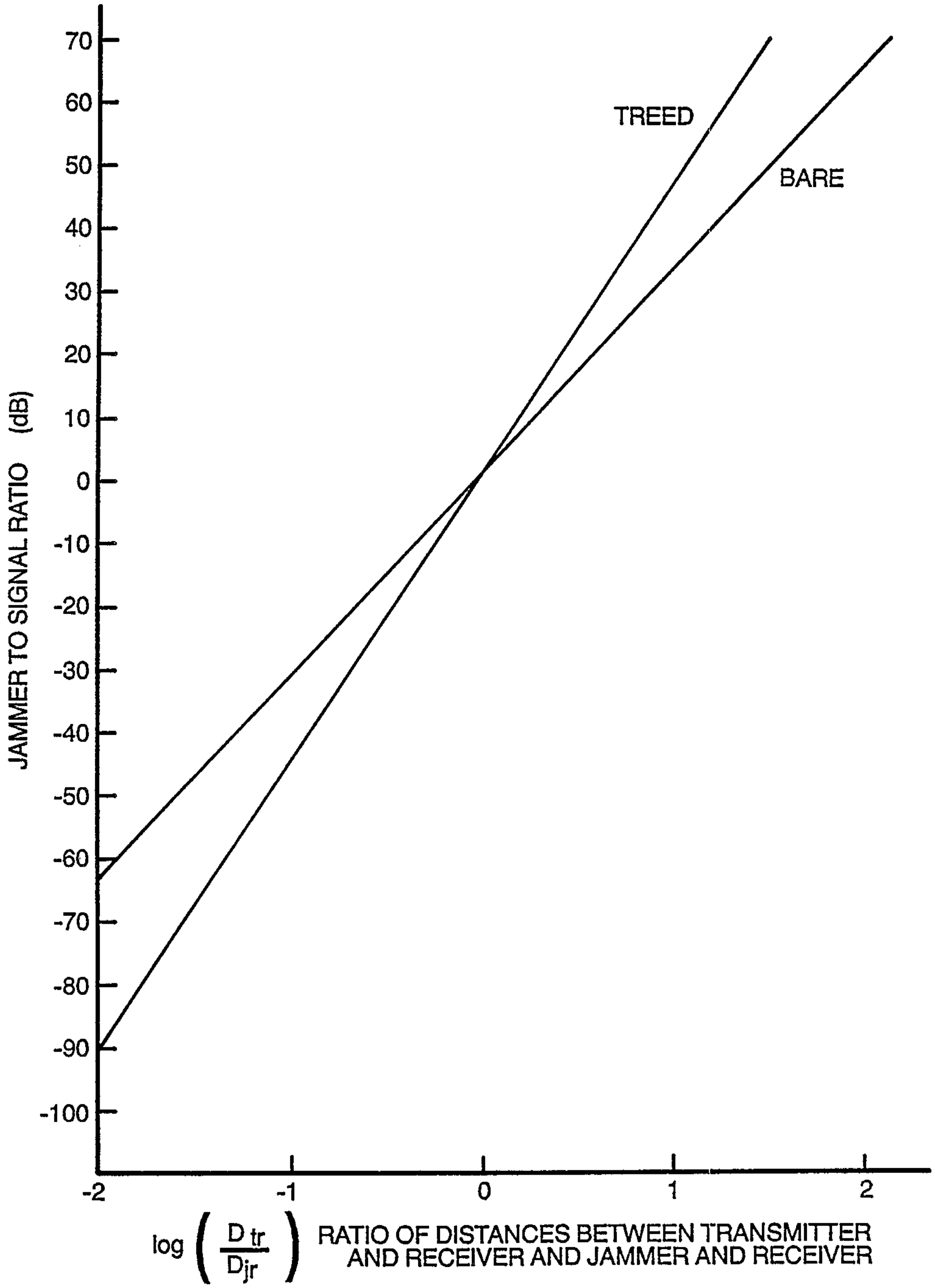

FIGURE 2.9: MODEL WITH PALMER PATH LOSS

The term in the J/S equation with the most effect is the path loss difference (dB) between the intended signal and the jamming signal paths ($L_{tr} - L_{jr}$). The path loss difference consists of powers of the ratio of the path lengths, and of the emitter antenna heights: $40\log\left[\frac{D_{tr}}{D_{jr}}\right] + 20\log\left[\frac{h_j}{h_t}\right]$ (where D_{jr} is jammer to receiver and D_{tr} is transmitter to receiver distance, and h_j and h_t are jammer and transmitter antenna heights, respectively).

In the ground based environment, the loss varies with the fourth power of the ratio of path lengths. If the jammer is closer to the receiver than the transmitter is, the distance ratio becomes a fraction and the J/S ratio is increased by the influential 40log factor. Having the jammer further from the receiver than the transmitter will decrease the J/S ratio by the same factor. If the transmitter is more than approximately three times closer to the receiver than the jammer is, the link will not be jammed (if there are reasonable limits on the power available). It is not jammed because 19.1 dB (40log3) is too large to be countered by any of the other terms in the J/S equation. The jammer antenna height would have to be 9 times (20log9 = 19.1) higher than the transmitter's, or the sum of jammer power and jammer–to–receiver antenna gain would have to be 19.1 dB greater than the transmitter's power and antenna gain.

The other factor in the path loss is the square of the ratio of antenna heights. It is desirable from the jamming standpoint to have the jamming antenna higher than the transmitting antenna so L_{jr} (path loss between jammer and receiver) is reduced and the J/S ratio is increased. The height ratio contributes to the change as 20log of the ratio.

The other factors in the J/S equation are the power difference between transmitter and jammer, and the difference in antenna gains. These differences affect the J/S ratio directly. For instance, increasing the power difference increases the J/S ratio by the same amount in dB. Proper placement of the jammer is a more effective way to increase the J/S ratio than increasing the power used (or the antenna gain), since there is a practical limit on power and gain available in a particular situation.

The other models for path loss will give slightly different interpretations to the jamming requirements, but the overall requirements remain unchanged; the jammer must have the advantage at the receiver to overcome the intended signal and it can achieve this by reducing its path loss relative to the transmitter–to–receiver path loss, by increasing its power, or by increasing its gain in the direction of the receiver.

3.0 JAMMING EFFECTIVENESS

Each type of jamming must be evaluated to determine if it has been successful. This section discusses some measures of technical jamming effectiveness. It is difficult to determine jamming effectiveness while the jamming is being used tactically. Operators must rely on such outward signs as changes in frequency or increases in power by the victim link to determine success. The technical measures discussed in this section are a priori measures that are used to determine the theoretically most effective jamming signals. When applied in the field, these jamming techniques must be evaluated by the operators as to their actual effectiveness.

3.1 Digital Target Signals

The term 'digital signals' refers to those signals which are converted to binary or m–ary bit streams for interpretation at the receiver. Jamming these signals can occur in two ways: disrupting the incoming information, and disrupting the synchronization between the receiver and transmitter or the receiver and the bit stream; in the first case, the message may have to be repeated, as in voice communications. In the second case, the receiver cannot receive any information from the transmitter until it reestablishes a lock on the incoming signal.

The bit error rate (BER) measures the number of bits in error out of the total sent. The measurement allows the jammer to determine what percentage of the target transmission bits are being jammed. A bit error rate of 0.02 or 2 per 100 can be considered jammed, and the message will likely have to be repeated. At a 0.5 bit error rate (half the bits in error), the receiver will likely lose synchronization, and be totally jammed.

The error–free seconds (EFS) measurement gives the percentage of time that the victim link had no errors. This measurement is inversely related to the BER measurement.

The block error rate (BLK) indicates the number of blocks of a predetermined length (corresponding to message length) that are corrupted by the jamming. BLK thus indicates how many messages will have to be repeated.

3.2 Analog Target Signals

The most effective determination of jamming effectiveness against voice targets is to carry out listener studies in which trained operators listen to the jammed transmissions and report what they hear. There are many variables which affect such studies, including the age and sex of listeners, the mental and physical condition of the listeners, and the acoustic properties of the signal being listened to. A method of automatically classifying the analog signals as to their intelligibility has been developed [20], but it is a relatively crude measure. The articulation index, as it is called, gives a number between 0 and 1. Anything less than 0.3 can be considered unintelligible, and anything over 0.7 can be considered intelligible, but the middle region is inconclusive and listener trials would be required to make conclusive statements about intelligibility.

There are several newer methods that attempt to simplify the automatic measurement of intelligibility. These are the Speech Transmission Index (STI), the Speech Communication Index (SCI), and the Pattern Correspondence Index (PCI) [21]. The PCI provides a comparison between a speech signal at the input and output of the communication channel based on physical measurements of the signals going in and coming out. The SCI depends only on analysis of the communication channel itself. The physical characteristics of the channel are used to determine how the channel will affect the signal traversing it. The STI is a simpler method. It determines how well the differences between two signals passed through the channel are preserved from input to output. The STI value determined from a simple test can be related directly to the standard phonetically – balanced word score indices, giving a measure of intelligibility.

4.0 ECM TECHNIQUES

The aim of this section is to describe the techniques used to implement communications electronic countermeasures, both jamming and deception.

4.1 Jamming

The techniques for jamming can be used against different types of targets. The easiest to jam are the fixed frequency transmissions. The target must be located and, for maximum efficiency, known to be active. Once located in time and frequency, the target can be jammed. Wideband signals are more difficult to jam because it is difficult to locate them in time (low probability of intercept) and in frequency (special receivers are required). Frequency agile targets are most difficult to jam because locating them in time and frequency requires that they be tracked with two degrees of freedom (time, frequency) both of which are variable.

4.1.1 Jamming Fixed Frequency Targets

Broadband barrage jamming is a brute force jamming technique. Jammer bandwidth is equal to the range of target frequencies, so jamming power is spread over all possible channels. This technique, shown in Figure 4.1, requires the jammer to have a very large power output or the target to have a limited frequency range to ensure that the effective jamming power in each channel is sufficient to interrupt communications.

Comb jamming is a modified barrage jamming technique in which the jamming occurs only on specific channels in the range of target frequencies. The jamming power is concentrated in equal amounts at regular intervals over the target frequency range. Figure 4.2 shows comb jamming. One method of producing comb jamming is to use a pulsed signal. The pulse duration and duty cycle determine the location of the frequencies in the comb. For example, 1 microsecond pulses repeated every 50 microseconds results in the pattern shown in Figure 4.2: a 2 MHz wide comb with each frequency separated by 25 kHz. The pulsing produces a signal with the envelope of a $\sin(x)/x$ function in the frequency domain, centered around 0 Hz. The signal can then be mixed and filtered to move it to the desired center frequency. Note that since the envelope is a $\sin(x)/x$ function, the amplitudes of the combs are smaller at the frequencies away from the center frequency.

If an on/off technique is used with any jamming technique, the comb–type signal will be produced. It is necessary to be aware of such noise being generated because if the on/off period of the jamming signal is regular, significant interference can occur on unexpected frequencies.

Narrowband, partial–band, or spot jamming is a more directed technique than broadband jamming. Jammer bandwidth covers a small portion of the possible target frequency range, usually one channel bandwidth for narrowband targets. All the jamming power is concentrated over a small part of the target frequency range, as shown in Figure 4.3. The jammer requires precise knowledge of the center frequency and bandwidth of the target channel. A problem arises when the receiver to be jammed is not channelized but is continuously tunable in frequency. The jamming power, which covers a fixed part of the spectrum, may not exactly cover the part of the spectrum in use by the target. The receiver would thus be only partially jammed. The receiver may also be tuned up or down in frequency so that the bandwidth in use is out of the jammed bandwidth and communications are still possible.

Swept spot or sequential jamming is a compromise between barrage and spot jamming and is shown in Figure 4.4. The jammer bandwidth equals the target channel bandwidth so the jammer power is concentrated in a small frequency range, but the jammer sweeps sequentially through all channels in the frequency range of the target. This compromise allows the full jammer power to be visited on all channels at least part of the time. Swept spot or sequential jamming can also be thought of as a generalization of on/off jamming. Each time the jammer is on, it jams a different frequency, using narrowband jamming; while off, it changes frequency.

'Simultaneous' jamming is a time–share jamming technique using sequential jamming. A fixed number of predetermined targets are jammed sequentially at a rate such that, effectively, all are jammed simultaneously. The re–visit rate on a channel is the rate at which the jammer returns to that channel. It is determined by the number of targets and the time spent jamming each target. If the re–visit rate is high enough and the dwell time is long enough, the targets are all jammed. The targets are the active emitters so the jammer should be able to jam only frequencies containing active emitters. The interference generated by the fast switching between targets must be accounted for so that friendly communications are not compromised.

4.1.2 Jamming Frequency Agile and Wideband Targets

As more complicated target transmission types arise, more complex jamming strategies are required to defeat them.

Follower jamming is a cyclic technique with applications in spread spectrum jamming (frequency hopped spread spectrum systems), and in push–to–talk situations where target emissions occur randomly on different frequencies. Each cycle of the follower technique has a period of search and a period of jamming. During the search period, the jammer identifies the target signal. During jamming, the jammer tunes to the target frequency and transmits the modulated jamming signal.

A follower jammer will use a target identification system in order to be sure the target is appropriate (approved non–friendly target) before jamming it. Discussion of the basics of such a system in the context of frequency hopper jamming follows.

When trying to defeat frequency hopping systems with speeds of 3 to 300 hops/sec and with the frequency difference between hops a large percentage of the available system bandwidth, more than a fixed spectrum (partial band or barrage) jammer is required. A fixed spectrum jammer radiates power over a certain range of frequencies. To be certain of jamming the hopping target signal, the jammer would have to spread its power over all possible target frequencies. To ensure effective jamming, a large percentage of the time transmitting on a frequency should be jammed; however jamming 10 to 20 percent of the band may be sufficient to induce bit error rates of about 0.05 to 0.1. In any case, spreading the jamming power over a large bandwidth lowers the average power per channel, assuming a limited amount of available power.

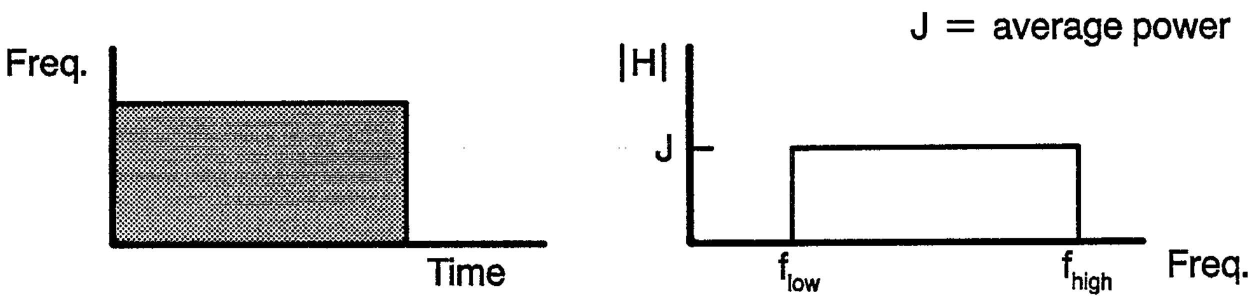

FIGURE 4.1: BARRAGE JAMMING

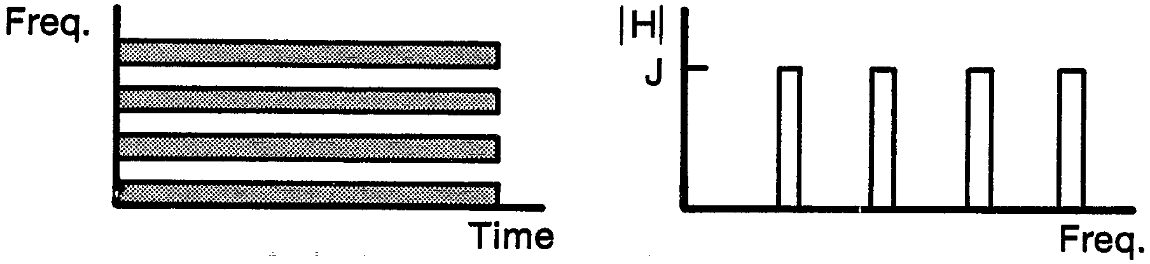

FIGURE 4.2(a) COMB JAMMING

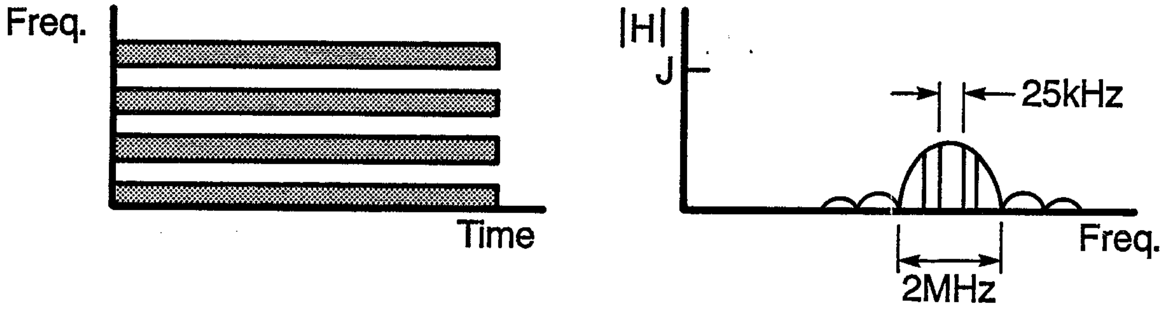

FIGURE 4.2(b): COMB PRODUCED BY PULSED SIGNAL

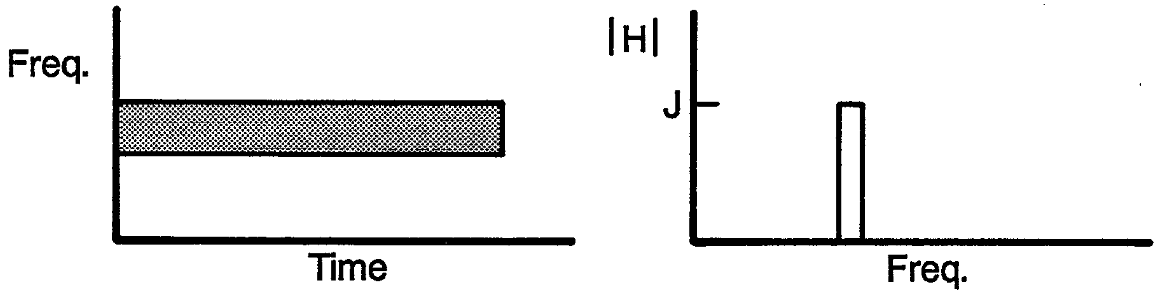

FIGURE 4.3: NARROWBAND JAMMING

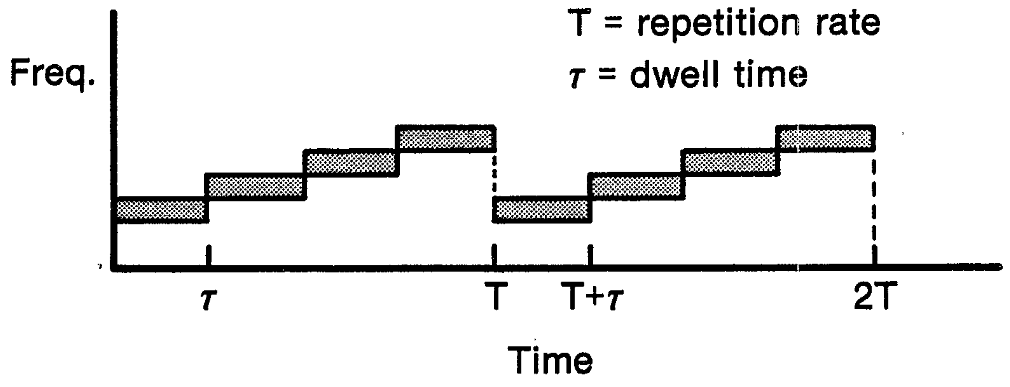

FIGURE 4.4: SEQUENTIAL JAMMING

To be more efficient, the jammer requires support equipment to track the target frequency changes and to ensure that most of its power is radiated on the target channel. A possible support system includes a high speed signal processor and a wideband receiver. The wideband receiver is required to intercept all possible hops of the target emitter. There are several types of wideband receiver available, including microscan receivers using surface acoustic wave techniques, acousto–optic receivers, and channelized or multiple superheterodyne receivers. The signal processor is required to correlate frequency information with another parameter, such as bearing, signal phasing (signal going off one frequency and reappearing on another), amplitude, hop rate, or duty cycle (transmit time vs. frequency change time). The correlation allows the system to deinterleave hoppers and to isolate the frequency stationary emissions.

Once the hoppers have been intercepted and the targets identified, jamming can proceed. The overall system response time must be faster than the target hop time so that once the new target frequency is determined, jamming can take place before the target frequency changes.

A block diagram of the required functions for jamming a frequency hopper is shown in Figure 4.5. The incoming waveform must be sampled for a finite period which depends on the required resolution of the channels. For example, sampling for 50 μs gives a maximum frequency resolution of 20 kHz. Following the sampling, a Fourier transform is required to resolve the sampled waveform into its component parts. The highest frequency component available is, by Nyquist's theorem, half of the sampling frequency.

Following the sampling and the Fourier transform, the signal must be processed to determine the value of bearing or other parameters in use to sort targets. Table 4.1 lists the approximate time required by the various methods for all three steps, assuming a 15 MHz possible target bandwidth and 20 kHz channel resolution.

TABLE 4.1: TIMES REQUIRED FOR JAMMING SUPPORT

	Type	Sample time μs	FFT time μs	Process (each signal) ns
1.	Microscan	50	50	500
2.	Acousto–optic	50	n/a	500
3.	Digital	50	2000	500
4.	4 Channel	10000	n/a	500

The jamming support equipment must distinguish the target emitter from all others present in the received bandwidth. The correlation processing using the chosen parameter does this. An example of the total time required for this step follows, assuming the identification of a signal and determination of the parameter takes 500 ns.

If the received bandwidth is 15 MHz, there are 750 channels (20 kHz) with possible signals. Of these, there will likely be one–quarter active (200) in the worst case. If it takes 500 ns per signal to determine the correlation parameter, a total time of 100 μs

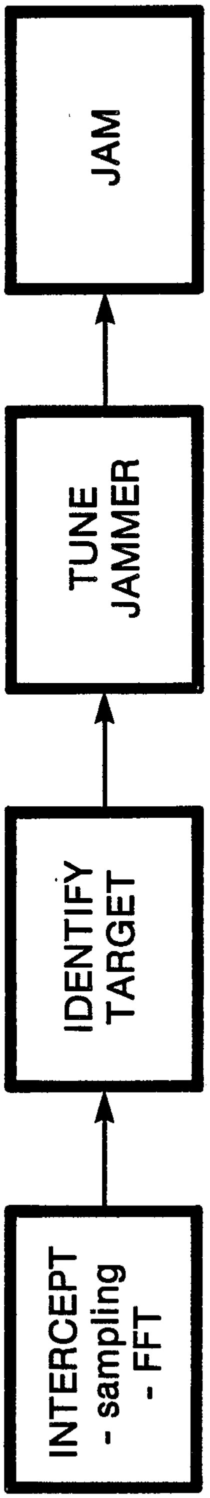

FIGURE 4.5: JAMMING A FREQUENCY HOPPER

results. Following the determination of the parameters, emitters can be sorted and targets determined. Specific targets can then be jammed. Frequency synthesizers can be tuned in approximately 50 μs. Faster synthesizers (<20 μs) are in development.

Using the microscan receiver as an example, the best performance to be expected out of a following jammer over 15 MHz is computed.

Sample	50 μs
FFT	50 μs
Correlate	100 μs
Tune	20 μs
Total	220 μs

Thus, the jammer can acquire and start to jam the chosen target in 220 μs. The 220 μs period translates to a frequency of 4.55 kHz, so the jammer can defeat hoppers with hop speeds up to about 4 kHz. At a hop speed of 4 kHz the transmitter is only jammed for 14 percent of his transmission, which may not be enough to disable communications. Multiple receiver/processor pairs would allow more rapid scanning or a larger spectrum scan in the same time.

Note that if the transmitter could hop at a rate exceeding 20 kHz (once every 50 μs) his signal would be acquired in the sampling but the amplitude may be too small to detect. The receiver would have to go to a coarser channel resolution bandwidth in order to sample for a shorter time and acquire the target signal. With the coarser resolution, two targets separated by less than the resolution frequency will not be distinguished and the target detection capability will be impaired because of an increased noise level.

Another possible method to defeat complex signals is to use repeater jamming to simulate multipath at the target receiver. Digital RF memories (DRFM) have been suggested as hardware to implement repeater jamming [25]. This repeater jamming can be thought of as a sophisticated barrage jamming technique, and may have applications against direct sequence spread spectrum signals. A scenario for repeater jamming is summarised in the following paragraph.

Repeater jamming is a type of follower jammer but the repeater jammer retransmits the received signal instead of transmitting a modulated jamming signal. The received signal goes through a delay line (sampling). After the delay, when the sample is reaching the transmit antenna, the sampled RF signal (exactly that which was received) is transmitted for the remaining time in the cycle. This technique relies on simulating multipath interference at the intended receiver. In the repeater technique, each cycle has a period of sampling and a period of jamming. During the sampling period, the target signal is received and replicated. During jamming, the replicated target signal is retransmitted.

There are several ways to condition the received spectrum for use with the repeater to be sure only the target of interest is jammed. First, tunable band reject filters, either adaptive or preset, can be used to clear the band of the outgoing jamming signal of all but the predetermined signal of jamming interest. Second, the band can be channelized and predetermined bands containing no jamming targets can be turned off before the jamming signal is transmitted. The system must use a target identification system in order to be an efficient jammer. Targets can then be jammed as they are determined to be active by the system. Since a target identification system is to be used in conjunction with the repeater jammer, the system may be used against any signal including frequency hoppers if the target identification system is responsive enough to allow the hop to be identified and the output jamming signal to be conditioned and transmitted before the hopper changes frequency.

Direct sequence spread spectrum communication has an implicit anti–jamming feature: repeater jamming and multipath signals which arrive at the receiver more than one chip time after the actual data are reduced in amplitude by an amount equal to the number of chips per bit. It is the despreading process in the spread spectrum receiver that produces this effect known as processing gain. Since the number of chips per bit is large (to achieve a small chip time, T_c, because the spread bandwidth is equal to $1/T_c$ and is expected to be large), any interference arriving at the receiver after one chip time can be neglected [30]. Note the similarity to frequency agile signals whereby if the interference reaches the target more than one hop time later than the intended signal, it is ineffective.

Thus, if the target transmission is a direct sequence spread spectrum transmission, the interference must reach the receiver within one chip time (period of the clock used to generate the pseudonoise code) of the target transmission. A similar requirement exists for jamming frequency hopped spread spectrum systems in that the jammer must intercept and jam within one hop time in order to jam the transmission. These requirements severely limit the placement of repeater jammers in relation to the target spread spectrum transmitter–receiver pair.

Calculations for the minimum chip time which can be jammed at various receiver–transmitter, D_{rt}, and transmitter–jammer–receiver, D_{tjr}, link distances follow. Assume a processing delay at the jammer of 1 μs. This is representative of a DRFM repeater jammer without jammer signal conditioning. Assume also that the transmission must be jammed for half of each chip (hop) duration. Note that $c = 3*10^8$ m/s is the speed of light used.

The time to travel from transmitter to receiver is:

$$t_{tr} = \frac{D_{tr}}{c} \qquad \text{(seconds)}$$

The time to travel from transmitter to jammer to receiver is:

$$t_{tjr} = \frac{D_{tjr}}{c} + \text{processing delay} \qquad \text{(seconds)}$$

The minimum chip or hop time, t_{min}, the jammer can defeat is:

$$t_{min} = 2.0\,(t_{tjr} - t_{tr}) \qquad \text{(seconds)}$$

TABLE 4.2: MINIMUM DEFEATABLE CHIP OR HOP TIMES

D_{tr} (km)	D_{tjr} (km)	t_{tr} (μs)	t_{tjr} (μs)	t_{min} (μs)
1	4	3	14	22.0
2	4	6	14	16.0
3	4	10	14	8.0
4	4	13	14	2.0

The hop or chip time the jammer can defeat by jamming a hop (chip) for at least 50 percent of its duration decreases as the link distances become closer, so faster hoppers (larger spread bandwidth) can be defeated. The physical limit occurs when the links are equal in distance (the jammer is between the transmitter and receiver). Note that as the transmitter and receiver get further apart but the transmitter–jammer–receiver distance stays the same, the jammer must be physically closer to the transmitter–receiver link (due to geometry).

The D_{tjr} link distance must be 300 m shorter for every μs of jammer processing delay than the D_{tr} link distance in order that both transmitted and interference signals arrive at the receiver at the same time. Since having the transmitter–jammer–receiver link shorter than the transmitter–receiver distance is physically impossible, for every 300 m that the T–J–R link is longer than the T–R link, the interference signal will arrive 1 μs, plus any processing delay, later than the transmitted signal.

The following equation gives the transmitter–jammer–receiver distance required for the jammer to jam the frequency for 50 percent of the hop time.

$$D_{tjr} \quad = \quad c\left[\frac{t_{hop}}{2} - t_{delay}\right] + D_{tr}$$

Table 4.3, calculated using $D_{tr} = 4$ km and $t_{delay} = 1$ μs in the above equation, shows that as the hop time decreases, the total T–J–R distance at which jamming can occur decreases, until the transmitter–jammer–receiver distance is the same as the transmitter–receiver distance. This situation requires that the jammer be between the transmitter and receiver.

Table 4.3. TRANSMITTER–JAMMER–RECEIVER PATH LENGTH vs HOP RATE

t_{hop} (μs)	D_{tjr} (km)
100	18.7
50	11.2
20	6.7
10	5.2
5	4.5
2	4.0

In summary, in order for repeater jamming to be effective against spread spectrum signals, either frequency hopped or spread spectrum, the jammer must be close to the target link in order to minimize the time delay of the jamming signal arriving at the target receiver. The jamming signal must arrive at the target receiver within one hop time for frequency hopped systems and within one chip time for direct sequence systems. In fact, the jamming will likely only be effective if at least 50 percent of the hop/chip is jammed. This limitation is more severe in the spread spectrum case, because chip times are generally shorter than hop times. Note that this discussion assumes, optimistically, that the jammer can differentiate its target from the crowded spectrum.

4.1.3 Jamming Enhancements

To complement the jamming waveform, a scheme called lookthrough is used to ensure jamming is only used when a target is active. The jammer has a dedicated receiver which is used to determine if targets are active before trying to jam them. The jammer output is turned off and the antenna switched to receive (if only one antenna is being used) before the receiver scans the spectrum either in a general search for targets or to check if a specific channel or channels are active.

Lookthrough in the general search must be used in conjunction with follower jamming. The combined follower jamming and lookthrough is often called set–on or transponder jamming. Jamming occurs when the general search finds an active target. The jamming must be interrupted periodically to check that activity remains on that channel. If activity has stopped, the general search for targets is resumed.

Another use of lookthrough is when channels to be jammed are determined before jamming activity starts. Each of the channels is then checked in sequence, and jammed if active. Again, the channel must also be checked for activity during jamming.

Lookthrough can be employed in conjunction with any jamming waveform including broad and narrow band, sequential, pulsed, and simultaneous jamming. Lookthrough is inherent in the jamming systems required to jam frequency agile and other complex transmission types. Targets are only jammed if they are active, preventing wasted effort and keeping jammers from becoming unnecessary targets.

Target activity is one parameter used to determine which targets to jam. Target priority is another. When lookthrough finds a large number of active targets, the jammer can have some logic to determine which to jam first.

The simplest logic is to jam sequentially, depending either on frequency or time of activity. Sequential jamming in order of frequency means the jammer chooses the next target as that which has the next highest (using modulo arithmetic) frequency. Sequential jamming in order of time of activity means the next target will be that frequency which most recently has had activity. In order to cover the case where more than one target fits the 'next target' criteria, the above selection criteria are often combined.

More complex logic allows targets to have predetermined priorities. The target, with or without lookthrough, can be jammed according to an algorithm which ensures the amount of time jammed depends on assigned priority. The highest priority targets can be set up so that they are immediately jammed when they are determined active.

4.1.4 Jamming Modulations

Jamming waveforms have so far been described only in terms of their power distribution over frequency. Any combination of RF and baseband modulation can be used if it provides the power distribution required by the chosen technique. There is not necessarily an advantage gained by matching the jamming modulation to the target modulation unless deception is to be used. Reference [26] discusses this point.

Baseband signals can be used to modulate either the amplitude, the frequency, or the phase of the RF carrier of the jammer. The following are some common examples of baseband jamming modulation.

Noise of various bandwidths can be used to modulate the RF carrier. The noise approximates additive white Gaussian noise (AWGN) as closely as possible across the required frequency range. AWGN is used because it has a uniform power spectral density (power dissipated per unit bandwidth). Hence, time averaged power at each frequency is equal.

Two basic approaches to produce the required uniform power spectral density of AWGN at RF are direct noise amplification and pseudonoise generation. Direct noise amplification takes noise in the appropriate bandwidth and amplifies it. Pseudonoise generation involves modulating the carrier with a pseudorandom or random waveform chosen so the waveform appearing in the victim receiver has Gaussian noise qualities.

There are several tones which can also be used, in either sine or square wave form; a single tone (one frequency), and swept tones where tones of different frequencies are produced sequentially (usually in a sawtooth fashion).

There are also a number of imitative modulations that are used to confuse or annoy the target operator. Sparks or short high intensity bursts of noise repeated rapidly sound like an engine ignition and may lead to the operator suspecting faulty equipment. Similarly, sounds like high speed electric machinery and receiver noise can cause confusion. Annoying modulations include randomly stepped tones (which sound like bagpipes) and taped audio noises, music, or equipment sounds. Another baseband modulation used is a delayed version of the audio on the channel itself, a form of repeater jamming.

Syllabic rate repetition of the baseband modulation causes a chatter in the jamming which can sound like garbled speech. The operator then has difficulty distinguishing the transmitted voice from the periodic interference. The length of an average syllable is 1/8 of a second (0.125). Using this average, the syllabic rate of speech can be estimated at 8 syllables per second or 8 Hz. To achieve a realistic sounding 'voice', the rate can be varied, but the average syllable length should be 0.125 seconds over the length of the jamming.

Studies have shown, [31], [32], [33], that concentration (short term memory of visually presented information), is disrupted more by the presence of another voice (including singing) than by pure noises such as tones and instrumental music or by white noise. The level of interference was not a factor in performance, but the type of interference was. In the study, subjects were required to memorize a series of 9 digits while listening to different sounds. Those who studied in the presence of voices did more poorly at recall than those in the presence of no noise or of pure noise. This study indicates that potentially the most damaging form of jamming would be that of voices superimposed on the victim transmission. The victim operator would have more dificulty remembering the message he is trying to hear.

4.1.5 Jamming Platforms

Stand–off jammers are jammers which are remotely controlled or preprogrammed and work while standing off (at a different location) from the operator. They allow different tactics to be used to maximize jamming effectiveness. Several examples are discussed.

Unmanned Aerial Vehicles (UAV) allow jamming at close range to the target without endangering either the operator or the command post. Jammers remote from the command post provide protection to the command post from home–on–jam missiles and artillery steered by radio–location on the jammer.

Another advantage of using UAV's for VHF jamming is improved effectiveness provided by a better line of sight to the target. The height of the jammer is one of the critical parameters in the jamming equation as are losses due to terrain factors. If the UAV has significant height the terrain has very little effect on its signal.

The jammer–to–signal ratio at the receiver becomes a function of the square of the ratio of transmitter–receiver link distance to jammer–receiver link distance as the propagation path approaches that of free space. With ground–based jammers, the J/S ratio is a function of that ratio to the fourth power. The UAV jammers can thus be as successful as groundbased jammers while using only a fraction of the power, or they can be more effective than ground–based jammers using the same power. The same advantage can be gained for elevated ESM (Electronic Warfare Support Measures) equipment.

Airplanes, or any manned aerial vehicles, can also carry electronic warfare equipment, including communication and radar jammers. They have the same characteristics as the UAV but are not expendable and are likely to be available only for special missions as a battalion jamming resource. Higher echelons control the employment of air assets as such employment is a joint force coordination effort. Generally the air force uses their assets to support their own missions, in which case the ground forces should be informed that jamming may be occurring at a particular time and place.

Hand–emplaced or expendable jammers can be clandestinely placed near the target or left in place during a retreat and remotely triggered to jam enemy communications at a critical time. They can be triggered using either wire or radio connection, or by using a timer. Due to the strong relationship of the J/S ratio to the distance the jammer is from the target, having the jammers in close proximity to the target greatly reduces the amount of power required for effective jamming. The power of four works in favour of the jammer when the jammer is closer to the receiver than the transmitter is. The antenna of the unit is generally very low however, so the proximity advantage is reduced somewhat.

Artillery–delivered jammers are an alternative to the hand–emplaced jammers. They are simple and in order to survive delivery, rugged. The jammers can be timed and they have a short, predetermined life. They can self–destruct once they reach the end of their power supply (battery). They are generally used in conjunction with a fire mission as the final volley. That way, the enemy communications are disrupted at a critical time;

when they are trying to regroup following a barrage. The jammers are, however, another type of ammunition to be stocked, and the chain of command for deploying the jammers (when, where, how many, what priority) is not well defined.

4.2 Deception

There are three types of deception: manipulative, simulative and imitative. Using manipulative deception involves altering friendly emissions so the enemy receives misleading information. Simulative deception involves creating friendly emissions to pass wrong information. The third type of deception is imitative, where friendly operators enter an enemy net to cause confusion.

In general, deception is hard to do successfully and must be coordinated at the highest levels. It generally encompasses all arms and thus all participants must be aware of their role in the deception so as not to be fooled by the deception or ruin the deception inadvertently. Thus low level deception is not generally practiced. Deception also generally requires a large amount of resources, which means that these resources are not available for other operations. To minimize the draw on scarce communications resources, expendable or hand emplaced jammers can be used as decoy transmitters when mounting a radio deception mission.

4.2.1 Imitative Deception

Imitative deception includes entering the enemy net and imitating one of the enemy outstations, and presumably passing bad information or giving incorrect orders. Imitative deception also includes such methods as passing annoying or frustrating messages and sounds on the link to reduce the efficiency of the radio operators. These include women's voices, monotone recitations, bagpipes, popular music, and reports of misfortune. Another method to cause confusion is imitating the skip echelon commander and giving orders to the enemy troops.

In FM transmission links, a stronger signal than the transmitted signal at the intended receiver will cause the receiver to lock on to the stronger jamming signal. This will cause the link to be completely jammed, and provides a good time to enter the enemy net.

4.2.2 Simulative Deception

One method in simulative deception is the creation of dummy networks. Enemy intelligence analysts can then be fed information which is totally different from the actual situation. The dummy nets are generally used in conjunction with radio silence so a unit's actual plans are not available to the enemy analysts. They can also be used as an apparent manpower multiplier, since more nets can be interpreted as more units in an area.

There are other non–electronic techniques used in conjunction with the dummy nets to make the deception plan realistic to all enemy sensors. Dummy encampments can give the impression of strength or of intentions.

4.2.3 Manipulative Deception

Manipulative deception requires altering friendly emissions to give an impression different from the actual state of affairs. Traffic levels can be changed, specific tests associated with a certain phase of battle can be performed at different times, and planned security breaches can occur to give false information.

5.0 CONCLUSIONS

The following equation for jammer–to–signal ratio was determined:

$$J/S = (P_j + G_{jrj} - L_{jr} + B) - (P_t + G_{trt} - L_{tr})$$

where J/S is in dB
$B = 10\log(B_r/B_j)$ in dB
B_r is the receiver bandwidth in MHz
B_j is the jammer bandwidth in MHz
P_t : output transmitter power (dBW)
P_j : output jammer power (dBW)
G_{trt} : sum of antenna gains from transmitter to receiver and from receiver to transmitter (dB)
G_{jrj} : sum of antenna gains from jammer to receiver and from receiver to jammer (dB)
L_{tr} : path loss from transmitter to receiver (dB)
L_{jr} : path loss from jammer to receiver (dB)

The loss term can be determined many ways using analytical and/or empirical methods. In general, over land, loss varies with the fourth power of the jammer–receiver distance to transmitter–receiver distance ratio. Since all the loss equations depend on terrain type, it is assumed the correct one for a particular situation can be chosen. Uncertainties in predicted path loss in the range of 10 dB can be expected. A default path loss equation to use is Egli, which is empirical and has been tested in several terrain types. The loss will be pessimistic, but this is desired in a worst case analysis. With Egli, the J/S ratio is:

$$\begin{aligned} J/S &= (P_j - P_t) + (\text{Gains}) - (L_{tr} - L_{jr}) \\ &= (P_j - P_t) + (\text{Gains}) - 40\log\left[\frac{D_{tr}}{D_{jr}}\right] + 20\log\left[\frac{h_j}{h_t}\right] \end{aligned}$$

In order to improve jamming effectiveness, one method is to reduce the path loss. The most efficient way to reduce path loss is to increase the antenna height. This change requires no fundamental equipment redesign, it just requires some logistics to allow the antenna to have a higher mast, or otherwise be raised.

To determine effectiveness, the J/S ratio resulting at the target receiver is compared to the threshold, T, for each modulation type (given in Appendix A). If:

$J/S + \sigma < T$ then signal is not jammed
$T - \sigma < J/S < T + \sigma$ then signal may be jammed
$J/S - \sigma > T$ then signal jammed.

Note that for voice signals the threshold is higher (more J/S ratio is required to jam a voice link) than that for a digital link. The digital link jammer only has to defeat the circuitry of the receiver (induce a bit error rate), whereas the voice link jammer has to defeat the human ear.

6.0 RECOMMENDATIONS

The aim of the recommendations is to detail investigations in the area of communications electronic countermeasures that DREO could do to further develop the ECM expertise available to the Canadian Forces.

1. Define measures of performance for both digital and voice links in a military setting. The links must be evaluated for quality when jammed and when not, so there should be guidelines indicating what constitutes a good link, and when the quality is poor enough that the link is jammed. For military service, the voice link will operate until the operator can not distinguish even messages spelled out with a known word for each letter of the alphabet. The digital link will operate until the error rate is such that it is uncorrectable. These limits should be investigated and related to the required J/S ratio at the target.

2. The technical effectiveness of jamming should be investigated for all target links with all jamming modulations (both baseband and RF). The J/S ratio required at the target receiver for effective jamming, as determined with the measures of performance defined in the study proposed in 1, would be determined by this report. These results should be compared to the standard J/S thresholds for jamming effectiveness included in Appendix A.

3. The technical feasibility of expendable unmanned aerial vehicle jammers should be investigated.

4. The terrain of interest to the CF should be characterized statistically so that the proper path loss equation can be used to estimate path loss, in each link scenario.

5. The calculation of jammer–to–signal ratio should be automated in a pocket–sized package. The calculator can be of any form, from a nomograph adjusted to fit the parameters of the situation, to a computer which asks what the parameters are. Operators will have to determine the probability that the predicted J/S ratio will in fact be realized at the target.

6. The probability of jamming effectiveness should be determined against each type of target military communication network, including combat net, fixed link, push–to–talk and spread spectrum tactical, radio relay, strategic, satellite, and submarine communications.

7.0 REFERENCES

[1] Follis, L., "Evaluating Tactical Jamming Effectiveness", Slides and Text of Presentation, US Army CACDA, Fort Leavenworth, KS.

[2] Follis, L., "Jamming Calculations for FM Voice Communications", EW Magazine, Nov/Dec, 1976, pp. 33–40.

[3] Friedman, H., "Jamming Susceptibility", IEEE Transactions on Aerospace and Electronic Systems, Vol.AES–4, No. 4, July 1968, pp. 515–528.

[4] White, D., "EMI Prediction and Analysis Techniques", EMI Handbook (Electromagnetic Interference and Compatibility), Volume 5, 1972, Germantown, Maryland, pp. 6.1–6.45.

[5] Palmer, F., "VHF and UHF Propagation Studies in the Canadian Arctic", CRC Report #1327, Ottawa, Oct. 1979.

[6] Stark A., "Propagation of Electromagnetic Waves (1)", News from Rohde & Schwarz, No. 112, 1986/1, Vol. 26, pp. 28–33.

[7] Freeman, R., "Telecommunication Transmission Handbook", 2nd Edition, John Wiley and Sons Inc., Toronto, 1981.

[8] Attwood, S., ed., "Radio Wave Propagation", Consolidated Summary Technical Report of the Committee on Propagation of the National Defense Research Committee, Academic Press Inc., New York, 1949.

[9] "Atlas of Ground Wave Propagation Curves for Frequencies between 30 and 10 000 Mc/s", CCIR Resolution No. 22, Geneva, 1959.

[10] Palmer, F., "Ground Wave Propagation Characteristics of Interest to the Tactical Communicator", AGARD Lecture Series No. 120, Electromagnetic Propagation Problems in the Tactical Environment, 1982.

[11] Palmer, F.H., "The Communications Research Centre VHF/UHF Propagation Prediction Program: An Overview", CEEJ, 6, #4, pp. 3–9, 1981.

[12] Rood, R. D., "FM Tactical Communications Under Intentional Interference", Masters Thesis, US Army Command and General Staff College, Ft. Leavenworth, Kansas, June, 1975.

[13] Johnson, M. E., "Tabulations of VHF Propagation Data Obtained Over Irregular Terrain at 20, 50, 100 MHz", Institute for Environmental Research, Technical Report IER 38–ITE/A38, May 1967.

[14] Ott, R. H., "Theories of Ground Wave Propagation over Mixed Paths", AGARD Conference Proc. 269, 10–14 Sep 1979.

[15] Ott, R. H., "Ground Wave Propagation over Irregular Inhomogeneous Terrain: Comparisons of Calculations and Measurements at Frequencies from 121 kHz to 50 MHz", AGARD Conference Proc. 269, 10–14 Sep 1979.

[16] Thersley, G. B., "Some of the Problems in Digital Terrain Model Construction", AGARD CP269, Sep 1979.

[17] Dadson, C. E., "Radio Network and Radio Link Surveys Derived by Computer from a Terrain Database", AGARD CP269, Sep 1979.

[18] Fitzsimmons, T. K., "E.M. Propagation Problems for Tactical Radio Relay Systems", AGARD Lecture Series 120, pp. 7–1/7–14.

[19] Heverly, J. R., Russell, J. E., "Range, Mobility, and Transmission Reliability Factors for Division Communications (U)", Research and Analysis Corp., Information and Control Systems Division, Technical Memorandum RAC(ORO)–T–408, June 1962.

[20] Methods for the Calculation of the Articulation Index, ANSI standard S3.5–1969.

[21] Houtgast, T., Steeneken, H., J., M., "Evaluation of Speech Transmission Channels by Using Artificial Signals", Acoustics 25, 1971, pp. 355–367.

[22] Robertson, Arthur D., "Tactical Communications Jamming", Report from ECM Systems Dept., SSE Division, Watkins Johnson.

[23] Schlesinger, Robert J., "Principles of Electronic Warfare", Prentice–Hall, Inc., Englewood Cliffs, NJ, 1961.

[24] Van Brunt, Leroy B., "Applied ECM, Volume 1", EW Engineering Inc., P.O. Box 28, Dunn Loring, VA 22027, 1978.

[25] Schneider, W.J., "Application of the Digital RF Memory to Communication Jamming", RF Expo Jan 23–25 1985, Sponsored by Paradigm Technologies, 2680 Montery Rd, San Marino, Calif.

[26] Torrieri, J., "Communication Warfare", 1978.

[27] Miller Communications, "Communication Jamming Techniques Study".

[28] Proakis, J.G., "Digital Communications", McGraw–Hill Book Co., 1983.

[29] Knorr, J., Karantanas, Maj. D., "Simulation Optimizes Noise Jammer Design", Microwave Journal, May 1985, p. 273.

[30] Simon, M.K., et al, "Spread Spectrum Communications", Volume 1, Computer Sciences Press, U.S.A., 1985, pp. 32, 35.

[31] Salame, P., Baddeley, A., "Noise, Unattended Speech, and Short–Term Memory", Ergonomics, Vol. 30, No. 8, 1987, pp. 1185–1194.

[32] Dornic, S., "Effect of a Specific Noise on Visual and Auditory Memory Span", Scandinavian Journal of Psychology, Vol. 8, 1967, pp. 155–160.

[33] Salame, P., Baddeley, A., "Effects of Background Music on Phonological Short–Term Memory", The Quarterly Journal of Experimental Psychology, Vol 41, No. 1, 1989, pp. 107–122.

Appendix A: J/S RATIO THRESHOLD FOR EFFECTIVE JAMMING

	A1	A2	A3	A3'	A3B	A3J	A4	A5C	A9	F1	F2	F3	F3'	F4	F9	F9'	PO	P9D	P9E	P9F	P9G	P9	P9'
A1	8	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	8	7	7	8	7	7	7
A2	9	6	0	0	11	7	6	11	11	5	6	6	11	11	11	11	9	6	6	6	9	6	6
A3	–23	–13	–1	–5	4	0	–13	0	2	–23	0	0	2	0	2	2	–23	–13	–13	–13	–23	–13	–13
A3'	–19	–10	0	–4	7	3	–10	3	5	–19	3	3	5	3	5	5	–19	–10	–10	–10	–19	–1	–10
A3B	–36	–24	–7	–7	–7	–7	–24	3	3	–36	–7	–7	3	–7	3	3	–36	–24	–24	–24	–36	–2	–24
A3J	–36	–24	–7	–7	–7	–7	–24	3	3	–36	–7	–7	3	–7	3	3	–36	–24	–24	–24	–36	–2	–24
A4	10	10	5	2	12	8	10	12	10	10	10	10	12	10	12	12	10	10	10	10	10	12	10
A5C	41	41	36	32	45	41	41	45	41	41	41	41	45	41	45	45	26	41	41	41	41	45	41
A9	10	10	5	2	12	8	12	8	10	10	8	8	10	8	10	10	10	10	10	10	10	10	10
F1	6	–6	–12	–16	16	16	–6	16	16	6	–6	–6	16	–6	16	16	6	16	16	16	6	16	16
F2	6	16	16	16	16	16	16	16	16	6	16	16	16	16	16	16	6	16	16	16	6	16	16
F3	0	3	3	3	2	2	3	2	3	0	3	3	2	3	2	2	0	0	0	0	0	0	0
F3'	0	0	0	0	–4	–4	0	–4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F4	12	12	10	10	10	10	10	10	12	12	12	12	12	12	10	10	0	12	12	12	12	12	12
F9	22 +n	22 +n	22 +n	22 +n	25	25	22 +n	25	25	22 +n	22 +n	22 +n	25	22 +n	25	25	15	15	15	15	15	15	22 +n
F9'	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10

	A1	A2	A3	A3’	A3B	A3J	A4	A5C	A9	F1	F2	F3	F3’	F4	F9	F9’	PO	P9D	P9E	P9F	P9G	P9	P9’
PO	5	7	7	4	10	10	7	7	7	7	7	7	7	7	7	7	10	10	10	10	10	10	5
P9D	18 +n	18 +n	18 +n	18 +n	18 +n	18 +n	18 +n	18 +n	18 +n	18 +n	18 +n	18 +n	18 +n	18 +n	18 +n	18 +n	18 +n	18 +n	18 +n	18 +n	18 +n	18 +n	18 +n
P9E	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
P9F	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
P9G	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
P9	10 −n	10 −n	10 −n	10 −n	10 −n	10 −n	10 −n	10 −n	10 −n	10 −n	10 −n	10 −n	10 −n	10 −n	10 −n	10 −n	10 −n	10 −n	10 −n	10 −n	10 −n	10 −n	10 −n
P9’	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13

The following describes the modulation types used in the table of thresholds for communications:

A1: AM Pulse, Bandwidth = 6 kHz, $\delta_s = 0.5$, $P_{fa} = 10^{-4}$, $P_{fd} = 10^{-1}$
Performance at threshold: $P_e = 1\%$

A2: AM Pulse/2–tone FSK, BW = 6 kHz, $m_s = 1$, $P_{fa} = 10^{-4}$, $\delta_{ms} = 0.5$
Performance at threshold: $P_e = 1\%$

A3: AM Voice, BW = 6 kHz, $m_s = 0.5$, 1000 word vocabulary
Performance at threshold: Articulation Score = 50%

A3': AM Voice, BW = 20 kHz, $m_s = 0.3$, 1000 word vocabulary
Performance at threshold: Articulation Score = 50%

A3B: Ind. DSB–SC voice/analog, BW = 6 kHz, 1000 word vocab.
Performance at threshold: Articulation Score = 50%

A3J: SSB–SC voice/analog, BW = 3 kHz, 1000 word vocab.
Performance at threshold: Articulation Score = 50%

A4: AM Facsimile, BW = 6 kHz, $m_s = 1$, $(S/I)_q = 10$ dB
Performance at threshold: 90% passable

A5C: TV Video, BW = 6.25 MHz, $m_s = 0.7$, $(S/I)_q = 33$ dB
Performance at threshold: 90% passable

A9: AM analog, BW >> 6 kHz, $m_s = 0.7$, $(S/I)_q = 10$ dB
Performance at threshold: 90% passable

F1: FSK Pulse, BW $\leq$ 12 kHz, $B_s = 1$, $(S/N)_i = 14$ dB
Performance at threshold: probability of error = 1%

F2: FM Pulse/2–tone FSK, BW $\leq$ 12 kHz, $B_s = 1$
Performance at threshold: probability of error = 1%

F3: FM Voice, BW = 12 kHz, $B_s = 1$, 1000 word vocab.
Performance at threshold: Articulation Score 50%

F3': FM Voice, BW = 60 kHz, $B_s = 1$, 1000 word vocab.
Performance at threshold: Articulation Score 50%

F4: FM Facsimilie, BW $\leq$ 12 kHz, $B_s = 1$, $(S/N)_o = 10$ dB
Performance at threshold: 50% passable

F9: FDM, n = number of channels, $n \geq 2$, n in dB
Performance at threshold: 90% passable

F9': PM/analog, BW $\geq$ 12 kHz, $B_s = 1$, $(S/N)_o = 10$ dB
Performance at threshold: 90% passable

P0: Pulse Wideband, BW >> 12 kHz, $\delta = 1/30$, $P_{fa} = 10^{-4}$, $P_{fd} = 5$
Performance at threshold: probability of error = 1%

P9D: PAM, n = no. of channels and $n \geq 2$ where n is in dB
Performance at threshold: 90% passable

P9E: PWM, Threshold criteria is Single Edge detection
Performance at threshold: 90% passable

P9F: PPM, Threshold criteria is $(S/N)_o = 12$ dB
Performance at threshold: 50% passable

P9G: Pulse Compression, Threshold criteria is $(S/N)_o = 12$ dB
Performance at threshold: 50% passable

P9: Matched Filter, $(BW_i/BW_o) = n$, n in dB, $(S/N)_o = 10$ dB
Performance at threshold: 90% passable

P9': Phase Lock, Threshold criteria is 22.5°
Performance at threshold: 50% passable

Appendix B: DETAILED VHF/UHF PROPAGATION CALCULATIONS

B1. Calculation of Fresnel Zone Radii

There are two considerations when calculating whether or not an obstacle affects the propagation of a signal. First, between the transmitter and receiver an ellipsoid can be defined which outlines the area of influence that the obstacle in question has over the propagating electromagnetic wave. The volume of the ellipsoid is called the first Fresnel zone. Obstacles must be outside of the first Fresnel zone or the signal will incur diffraction loss due to the obstacle. In standard practice, any obstacles outside of 0.6 of the radius of the ellipsoid are not considered to be contributing diffracting obstacles.

The ellipsoid has its focal points at the transmitter and the receiver. A wave reflected at the surface of the ellipsoid has an indirect path 1/2 wavelength longer than the direct path so it will be exactly out of phase with the direct path wave at the receiver but the reflection coefficient is about –1. There will be repeated zones where this cancellation occurs but only the first zone is considered (the first Fresnel zone), and all activity is assumed to occur within it. An illustration of the Fresnel zone is included as Figure B1.

The formula to calculate the radius of the first Fresnel zone and hence the clearance required at any point along the path between antennas is:

$$R = \left[\frac{\lambda * d_1 * d_2}{d_1 + d_2}\right]^{\frac{1}{2}} \qquad \text{(m)}$$

d_1 (m) : distance from transmitter to obstacle
d_2 (m) : distance from obstacle to receiver
λ (m) : wavelength of transmission

B2. Calculation of the earth's effective radius

The second consideration when determining line of sight is the so–called "bulging of the earth" between the receive and transmit antennas [7]. As the wave travels through the troposphere, the vertical gradient of the refractive index causes it to bend. A linear gradient of the refractive index makes the wave refract so that it can follow the curvature of the earth. The effect of refraction in the atmosphere can thus be represented mathematically by introducing an effective earth radius and treating the atmosphere as homogeneous [8]. For example: $a_{eff} = K \cdot a_{actual}$ where a is the earth's radius.

$$\frac{1}{a_{actual}} + \frac{\delta n}{\delta h} = \frac{1}{K \cdot a_{actual}}$$

$$K = \frac{1}{1 + a_{actual} * \frac{\delta n}{\delta h}} \qquad \text{and } K = a_{eff}/a_{actual}.$$

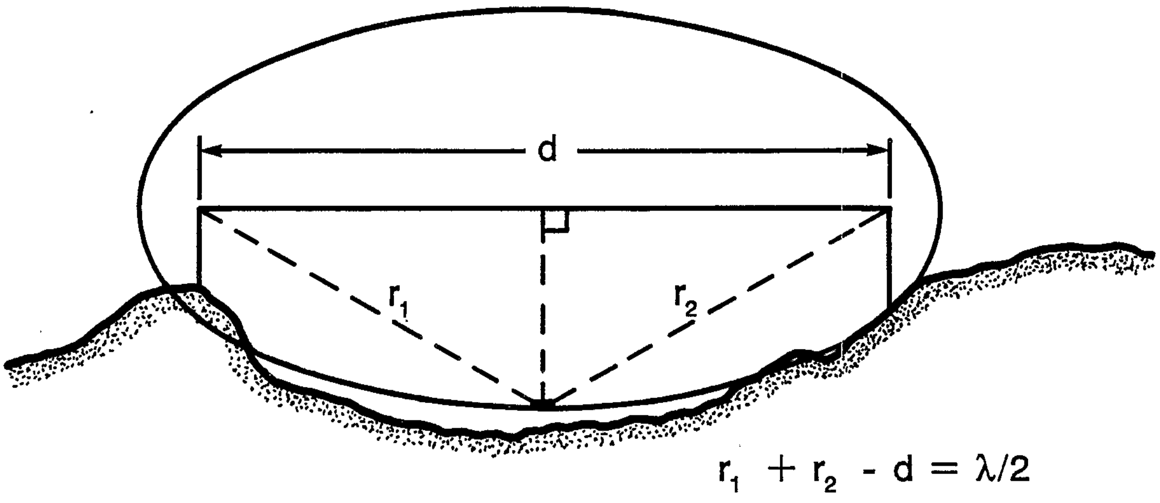

FIGURE B1: FIRST FRESNEL ZONE

a_{eff} : effective earth radius (m)
a_{actual} : actual earth radius ($6.37*10^6$ m)
n : refractive index
h : height into atmosphere (m)
K : ratio of effective to actual earth radius

Usually, the rate of change of refractive index with respect to height of the atmosphere ($\delta n/\delta h$) is $-0.039*10^{-6}$ per metre. This leads to a K equal to 4/3. When the earth's curvature is corrected by the K factor in a path diagram, the ray between the transmitter and receiver may be drawn as a straight line, called the straight line path. The surface of the earth will thus appear further from the straight line path than it was when the actual curved path was drawn.

The radio horizon is defined as the point where the path of the propagating wave grazes the surface of the earth. This defines the length of the maximum possible line of sight path achievable if no obstacles are present out to this horizon. Radio horizons of the transmitter and receiver depend on the height of each antenna, and the effective earth curvature compensates for the gradient of refractive index.

The combined distances of the transmitter and receiver to the radio horizon define the maximum possible separation and can be calculated as:

$$D_{tr}\,(\mathrm{km}) = \left[\frac{51}{4} * K * h_t\right]^{\frac{1}{2}} + \left[\frac{51}{4} * K * h_r\right]^{\frac{1}{2}}$$

D_{tr} (km) :maximum unobstructed path between transmitter and receiver
h_t (m) :height of transmitter antenna above a smooth earth radius
h_r (m) :height of receiver antenna above a smooth earth radius
K :ratio of effective to actual earth radius

B3 Detailed Propagation Models

There exist some specific cases for which the behaviour of propagating electromagnetic waves has been determined. Each method can only be used to produce valid results for real situations when the restrictions applied to the generation of the analytic calculation also apply to the physical circumstances.

B3.1 Free Space Propagation: No Obstacles

Analytical solutions are available to calculate the free space path loss between two antennas. These solutions rely on a large number of assumptions which must be verified as representative of the situation.

The free space case is limited to situations where there are no obstacles within 0.6 of the first Fresnel zone and the direct wave is the only incident wave. This is the environment where there is no diffraction and there are no reflections.

Two instances which can be modelled as free space are the cases of air–ground or air–air links, links using high gain directive antennas over unobstructed paths, and links which are at sufficiently high elevation angles that the earth does not intersect the first Fresnel zone. In these instances, reflections from the ground or other conductors are minimal as is diffraction over obstacles.

The formula to calculate the free space loss in dB between two isotropic antennas a distance D apart is:

$$L = 32.4 + 20\log f + 20\log D \qquad (\mathrm{dB})$$

f : frequency of transmission (MHz)
D : straight line transmitter to receiver distance (km)

B3.2 Plane Earth Propagation

Another case where an analytical solution can be used is that in which reflection occurs from the earth but where there is no diffraction over obstacles. The calculation depends on the assumption that the reflected wave is perfectly reflected from the surface, (assumed to be flat and smooth). The reflected wave and the direct wave are to be the only waves incident at the receiver. These assumptions are valid for prairie and ocean environments which are smooth on the order of wavelengths, and have path lengths limited to several kilometres. Note that at frequencies less than VHF, even houses look smooth at grazing incidences. Figure B2 illustrates the scenario.

Other assumptions are that antennas are short compared to the path length so the reflection angle is small.

The plane earth environment uses the following modelling equation :

$$L = 120 + 40\log D - 20\log h_t - 20\log h_r$$

h_t : height of Tx antenna above a uniform smooth earth (m)
h_r : height of Rx antenna above a uniform smooth earth (m)

Note that the plane earth model lacks a frequency dependence.

As antenna heights decrease, a minimum height is reached at which the path loss levels off and does not continue increasing as the equation predicts due to the existence of the otherwise ignored "surface wave" mode. When the antenna is below this ‘minimum height’, h, the height used in calculations is assumed to be the effective height, h_{eff}. The minimum antenna height in metres is:

For vertically polarized antennas:

$$h = \frac{\lambda \left[(\epsilon + 1)^2 + (60\,\sigma\,\lambda)^2 \right]^{\frac{1}{4}}}{2\,\pi}$$

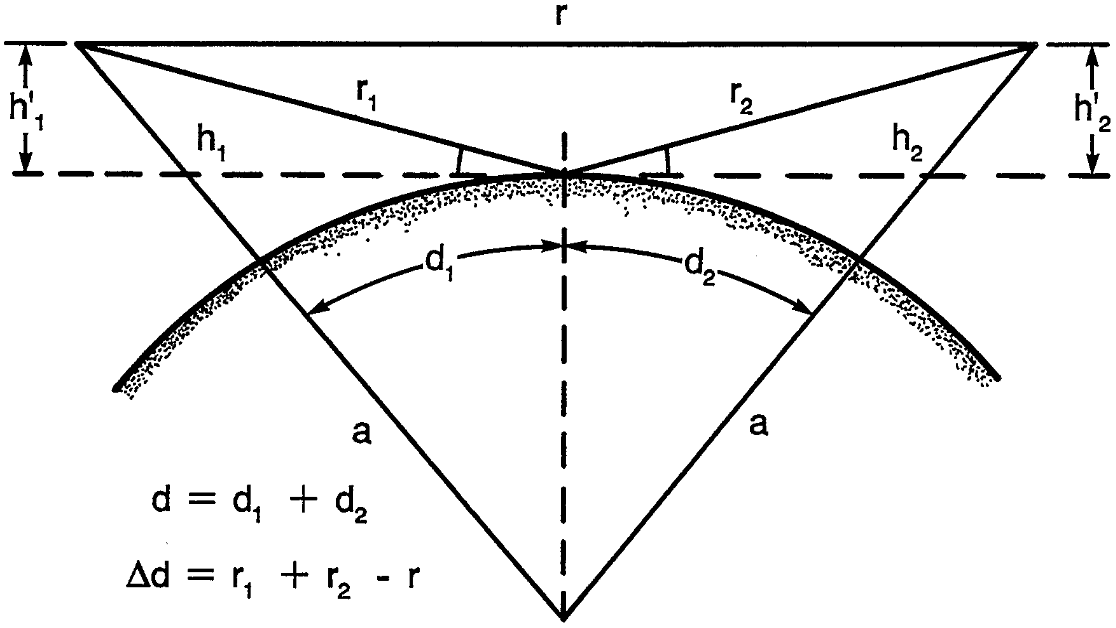

FIGURE B2: SMOOTH EARTH PROPAGATION

For horizontally polarized antennas:

$$h = \frac{\lambda \left[(\epsilon + 1)^2 + (60\,\sigma\,\lambda)^2 \right]^{\frac{1}{4}}}{2\,\pi}$$

where:

ϵ : dielectric constant
σ : conductivity (S/m)
λ : wavelength (m)

The minimum effective height that is used in the path loss equation is:

$$h_{eff} = \left(h^2 + h_{actual}^2 \right)^{\frac{1}{2}}$$

The minimum effective height for the antenna depends on the dielectric constant and the conductivity of the ground over which it is operating. Terrain cover, the type of material covering the ground to a depth depending on frequency, determines both the dielectric constant and the conductivity of the earth. The dielectric constant defines the capacitance of the earth. It can vary from 4.0 for very dry earth to 30.0 for very moist earth. The dielectric constant is higher over water. Sea water has a dielectric constant of near 80. Higher values of dielectric constant result in less path loss. The conductivity varies from 4 S/m for sea water to $3*10^{-4}$ S/m for dry land. Average land conductivity is $3*10^{-2}$ S/m.

Table B1 contains some calculated minimum antenna heights, h, for vertically polarized antennas for typical ground cover cases. (The minimum effective height can be calculated from h if the actual antenna height is known). A minimum effective height, h_{eff}, will likely only be required in calculations when the path is over sea water or very wet ground (such as marsh), and at low frequencies.

TABLE B1: MINIMUM ANTENNA HEIGHT h (m), VERTICAL POLARIZATION

Type of Land	ϵ	σ (S/m)	Frequency (MHz)		
			30	300	3000
sea	80.0	4.0	78.0	2.5	0.146
wet (a)	30.0	3.0	67.6	2.15	0.095
wet (b)	30.0	1.0	39.0	1.31	0.089
fresh water	80.0	0.01	14.4	1.43	0.143
average land	13.0	0.03	6.1	0.60	0.059
swamp land	10.0	0.01	5.64	0.529	0.053
dry:snow	1.0	0.001	2.3	0.225	0.0225

B3.3 Propagation by Diffraction Over Obstacles

The third possible method of propagation is via diffraction over obstacles in the path. Diffraction allows communications to occur between antennas even if there is an obstacle in the interposing terrain. Signal strength will be degraded from the free space case, but communications are possible at lower frequencies (typically less than VHF). At higher frequencies, communications become increasingly difficult in the presence of obstacles.

The amount of diffraction occurring depends on the ratio of the obstacle's distance below the straight line path, H, to the Fresnel radius, R at that point. The diffraction losses increase with frequency and as the ratio of H to R increases (since the Fresnel radius decreases as frequency increases). As obstacles approach and become higher than the straight line path, H becomes negative, and diffraction losses continue to increase. Diffraction losses have been tabulated for some idealized propagation paths (over smooth earth and knife–edge obstacles).

The smooth earth calculations assume the earth is a smooth sphere with homogeneous electrical properties, there are no reflections from the ionosphere, path lengths are non–optical, and $K = 4/3$. The calculations are presented in graphical form in the CCIR Atlases [9]. An example of the available graphs is included as Figure B3. These graphs do not include troposcatter which is the dominant mode of propagation in the far diffraction region.

Each graph shows field strength as a function of the great circle distance between two vertical dipoles at various receiver heights. There are different graphs for each combination of transmitter height and ground condition. The graphs in the second atlas cover a frequency range of 30 to 10 000 MHz, antenna heights of 0 to 20 km above the spherical earth, and an average sea and an average land ground condition.

Calculations of diffraction losses in the case of a knife–edged obstacle between transmitter and receiver are made using classical optical diffraction methods which require the following assumption. The obstacle is a knife–edge which is long compared to the Fresnel ellipsoid in the plane transverse to the propagation path. Figure B4 shows the knife–edge scenario. The graph in Figure B5 from reference [8] (page 6) illustrates the field in the shadow behind such a diffracting ridge.

Most obstacles have some rounding of the knife–edge and also surface irregularities so the knife edge assumption does not apply. Losses are higher over actual obstacles than those predicted using the idealized knife–edged obstacle. There is a method to take the radius of an obstacle into account outlined at reference [10]. The losses for obstacles with radii are in between the extremes of smooth earth (radius very large, high losses) and knife–edge (radius zero, low losses) diffraction. Figure B6 is a graph which can be used to determine losses over obstacles. In this graph, β is the ratio of the obstacle's distance below the straight line path, H, to the Fresnel radius, R at the point in question, and α is a ratio involving the wavelength λ, the radius of curvature of the obstacle r, and R.

It is a mistake to use the knife–edge diffraction model for calculating path loss over the sea when the straight line path between the transmit and receive antennas is such that the path is grazing the sea. There is not the predicted diffraction which depends on the obstacle being a knife–edge; losses are instead much higher, and the smooth earth model is more appropriate.

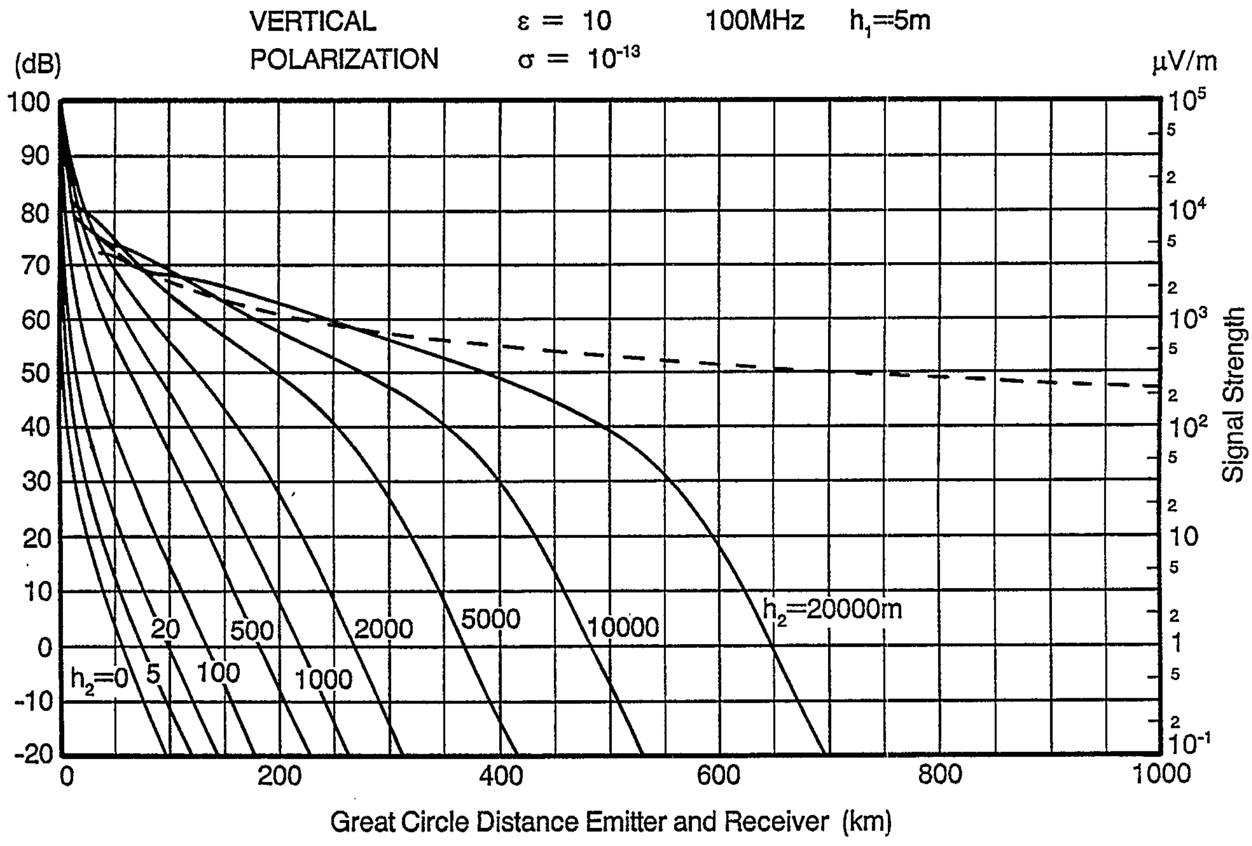

FIGURE B3: CCIR SMOOTH EARTH PATH LOSS GRAPHS

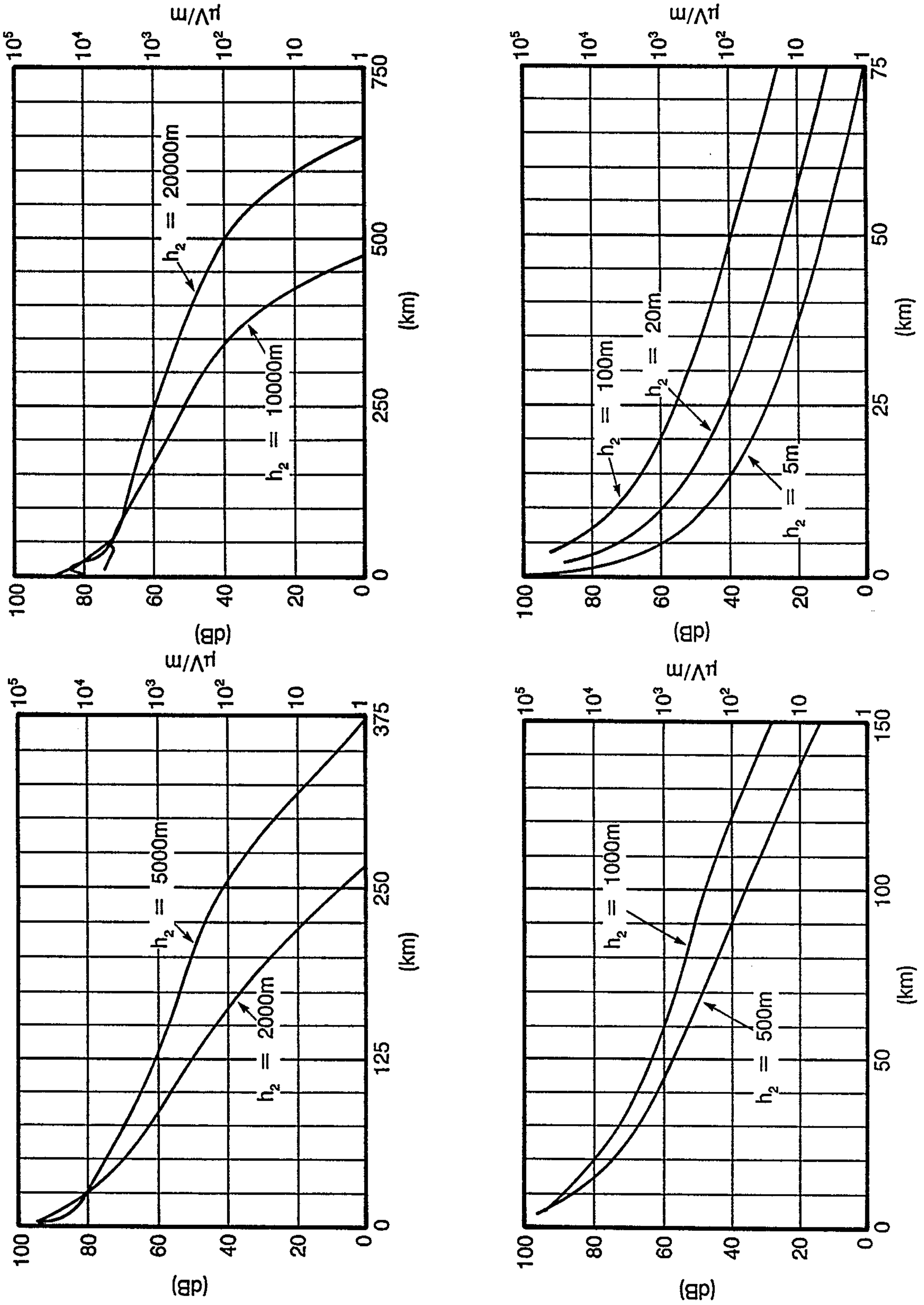

FIGURE B3 (cont'd): PATH LOSS GRAPHS

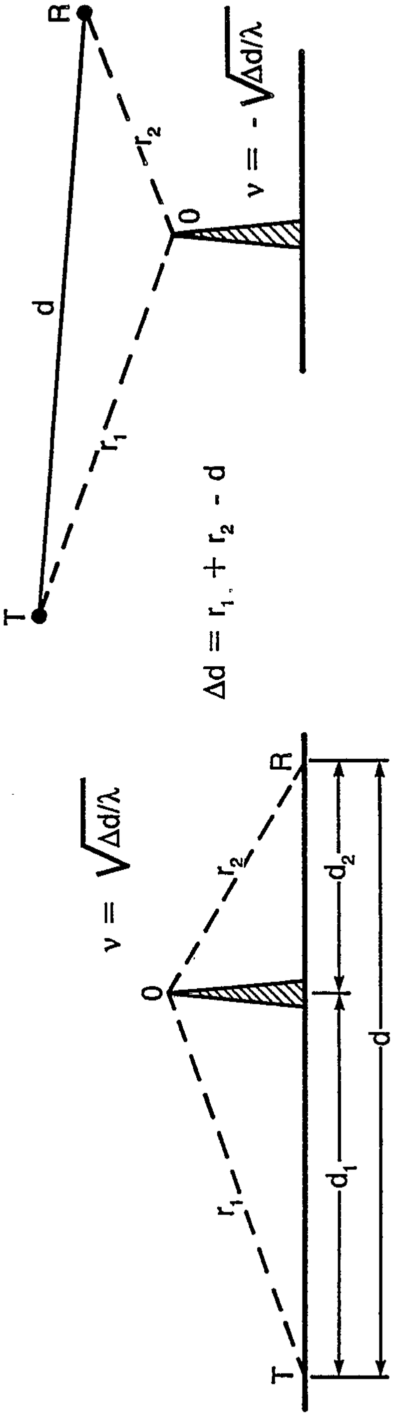

FIGURE B4: KNIFE–EDGE DIFFRACTION SCENARIO

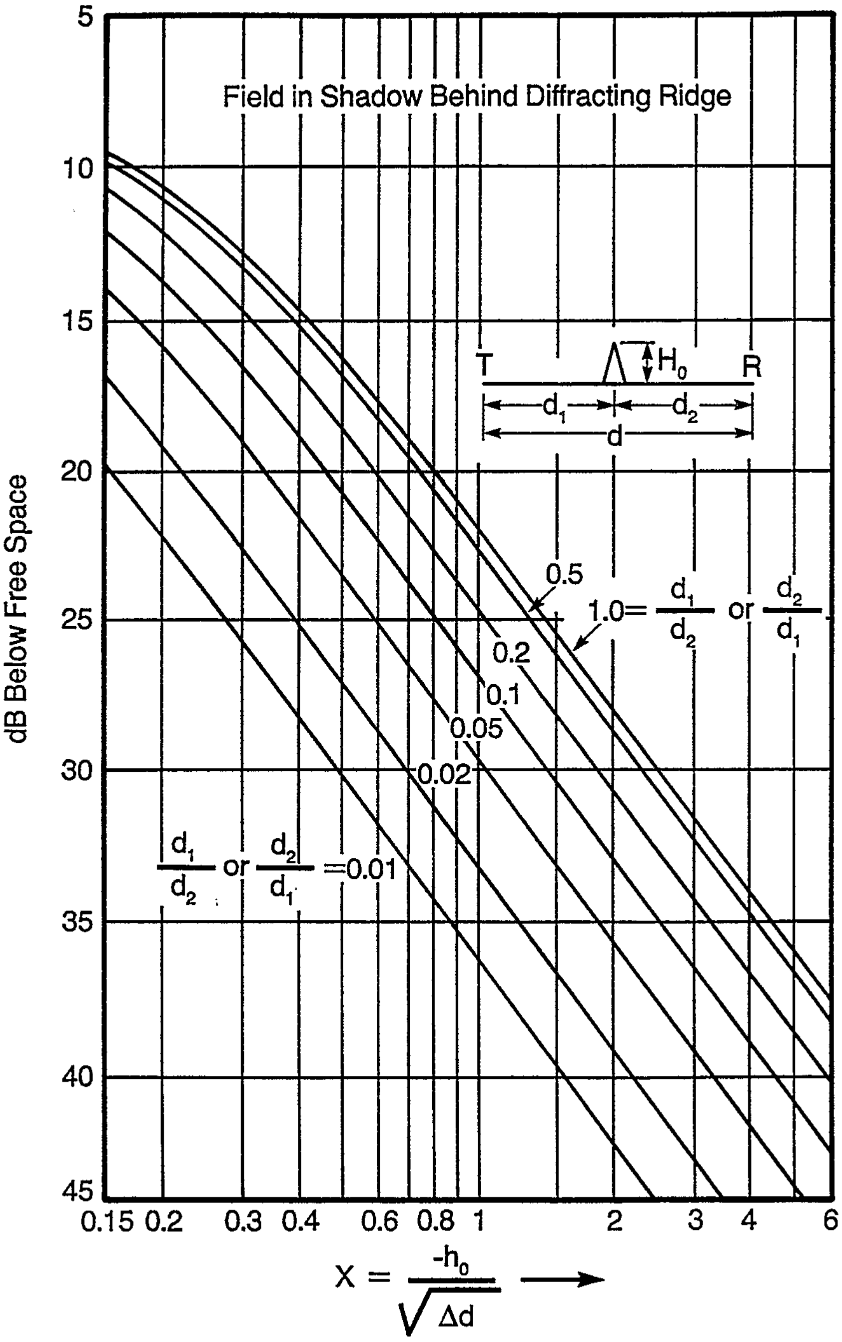

FIGURE B5: FIELD IN THE SHADOW BEHIND A DIFFRACTING RIDGE

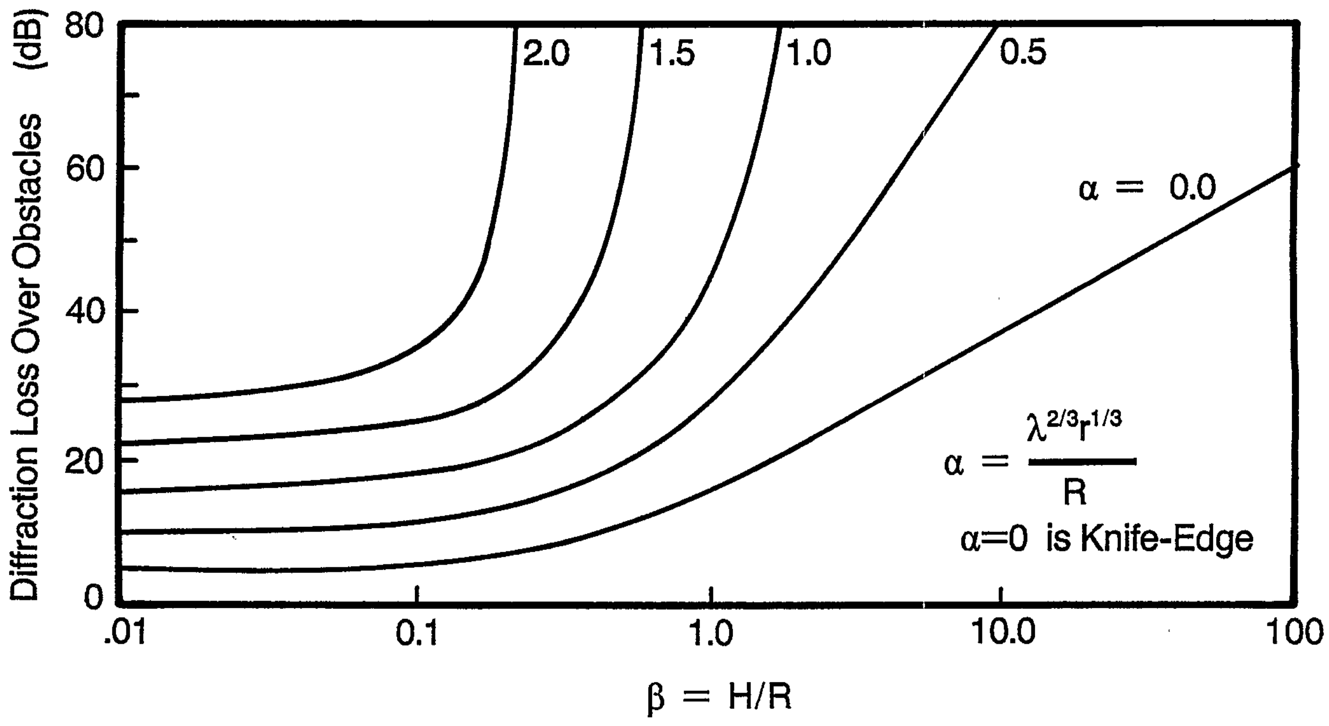

FIGURE B6: DIFFRACTION LOSSES OVER ROUNDED OBSTACLES

B3.4 Propagation by Both Diffraction and Reflection

Both diffraction and reflection are included in the more thorough computations of path loss. Obstacles must be defined and possible reflective surfaces must be picked out. These computations are highly involved and a computer is required if efficient computation is desired.

There are computer propagation prediction programs available to do thorough calculations of path loss. The Communications Research Centre of the Dept. of Communications developed a computer model using a database of actual terrain data for the prediction of path loss, signal strength, field intensity or signal to noise ratio. The CRC program can also use an empirical algorithm for statistical predictions. This program is detailed at reference [11].

B4 Empirical or Statistical Models

Analytical solutions in the more complicated situations involving both diffraction and reflection are very complicated so empirical equations can be used instead to statistically predict the path loss. The equations are based on measured data, and have an associated standard deviation.

B4.1 Propagation Modelling Equations

J. Egli developed the following equation to describe data collected for the propagation losses using ground based antennas (fixed and mobile) in an urban environment. It produces valid results at frequencies from 30 MHz to 1 GHz and at distances to 80 km. The equation is taken from reference [10] and gives the median value for path loss in dB. The median value is the value exceeded 50 percent of the time and at 50 percent of the locations in the area of interest. Units used are MHz for frequency, km for distance, and m for antenna heights.

For receive antenna heights h_r greater than 10 m :

$$L = 86 + 20\log f + 40\log D - 20\log h_t - 20\log h_r$$

For receive antenna heights h_r less than (or equal to) 10 m :

$$L = 76 + 20\log f + 40\log D - 20\log h_t - 10\log h_r$$

Standard deviation (large–scale encountered by a moving terminal) is :

$$\sigma = 5.5 \log f - 3.2 \ (\mathrm{dB})$$

The following equations developed by Murphy give path loss in dB and associated standard deviation for a rural environment in the same frequency range [10] as the Egli equation.

Mountainous terrain:

$$L = 21.4 + 39.4\log f + 40\log D - 20\log h_t - 5.3\log h_r$$
$$\sigma = 17.3 - 0.019h_r + 0.0012f$$

Level terrain:

$$L = 99.2 + 0.016\log f + 40\log D - 20\log h_t - 18.5\log h_r$$
$$\sigma = 13.7 - 0.11h_r + 0.002f$$

The following equations are taken from [1] and represent formulas chosen by R. Rood for the Dept. of the Army in the US as the most representative for path loss in the tactical FM situation. They are based on data from [13].

If the emitter–receiver pair are both on the ground but have nominal line of sight then the following equation is used:

$$L = \frac{5.21^{-6}}{(fD)^4} * \left[\frac{\epsilon^2}{(\epsilon-1)}\right]^4 * \left[1 + 438(fh)^2 * \frac{(\epsilon-1)}{\epsilon^2}\right] * \left[1 + 438(fh_r)^2 * \frac{(\epsilon-1)}{\epsilon^2}\right]$$

ϵ: dielectric constant
h: emitter antenna height (km)
h_r: receiver antenna height (km)
D: antenna separation distance (km)
f: frequency of transmission (MHz)

If the emitter–receiver pair are both on the ground and there is one obstacle between them, the following equation is used to characterize the path loss.

$$L = 66.2 + 1070(H/D) - 7500(H/D)^2 + 0.00268f + 28.34\log f + 0.879D - 0.00378D^2$$

H: maximum obstacle height above straight line path (km)
D: distance between receiver and emitter (km)

If there is more than one obstacle between the emitter and receiver on the ground, then the equation for path loss becomes the following.

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

Another model for the path loss was developed by the U.S. Electromagnetic Compatibility Analysis Centre (ECAC). This model assumes that path lengths are less than 50 km (not over water), and that antenna heights are less than 6 metres. The following equations describe the models [10]:

For a line of sight (LOS) path:

$$L = 95.6 + 2.5\log f + (31.5 + 0.5\log f)*(\log D - 0.21)$$

For a non–LOS path:

$$L = 92.6 + 11.0\log f + (26.0 + 4\log f)*(\log D - 0.21)$$

For a 'mountainous' path:

$$L = 107.6 - 3.5\log f + (22.0\log f - 9)*(\log D - 0.21)$$

Another model was developed by Palmer [5] using data collected at sites in the Canadian arctic, near Inuvik and Resolute Bay. The equations start to produce similar results as the path length increases from 10 to 100 km. Antenna heights are the effective heights, h_{eff}, calculated using a dielectric constant of 45 and a conductivity of 0.01 S/m.

Area with trees < 5m, antenna with vertical polarization:

$$L = 72.9 + 7.7\log f + 44.8\log D - 6.5\log h_t - 15.6\log h_r$$

Area with trees < 5m, antenna with horizontal polarization:

$$L = 66.8 + 7.7\log f + 44.8\log D - 6.5\log h_t - 15.6\log h_r$$

Barren area in the summer:

$$L = 88.7 + 7.7\log f + 31.3\log D - 6.5\log h_t - 15.6\log h_r$$

Barren area in the winter:

$$L = 96.3 + 7.7\log f + 31.3\log D - 6.5\log h_t - 15.6\log h_r$$

B4.2 Statistical Properties

There are time–dependent and time–independent random variables inherent in the propagation process. Time independent random variables include roughness of reflecting surfaces, number and spatial distribution of diffracting objects, local environment of the antennas, and uncertainty of effective antenna heights. These variables lead to a variability in the predicted path loss of approximately 2 to 14 dB. The average amounts of variability to be expected for different propagation conditions are tabulated in Table B2 [4, page 6.45].

TABLE B2: TIME INDEPENDENT SIGNAL VARIABILITY

Propagation Mode	Condition	Standard Dev. σ_d (dB)	σ_i (dB)	σ_t (dB
Reflection Region	Smooth Earth	5	5	7
	Rough, VHF	5	8	9
	Rough, UHF	5	12	13
Diffraction Region	Smooth, VHF	4	2	4
	Smooth, UHF	8	2	8
	Rough, VHF	4	8	9
	Rough, UHF	8	12	14
Knife–Edge	VHF	3	8	8
	UHF	6	12	14
Transhorizon	VHF	4	8	9
	UHF	8	12	14

The term σ_d is the time–dependent propagation loss variable, while σ_i is the time–independent propagation loss variable. The term σ_t is the total variation derived by taking the square root of the sum of the squares of the time–dependent and independent variables.

Time–dependent random variables include temperature, humidity, and wind velocity which affect atmospheric refractive index, both its gradient and structure. Others are the amount of foliage along the propagation path, and the moisture content of the ground. Time dependence is only important for paths greater than about 50 km when the transmission frequency is in the VHF/UHF range.

The time–dependent variables lead to a time variability in the path loss which is predictable in the statistical sense. A graph detailing the required correction to the median path loss, in a temperate climate, is included as Figure B7 [10] Other plots in [10] are relevant to other conditions. The graph B7 shows the path loss correction (in units of dB below calculated path loss) as a function of path length for specific percentages of time. For example, over a path of length x km, the graph indicates how much path loss variability over the median amount is expected y percent of the time. If a percentage of time greater than 50 (long term median) is specified such as 90 percent, more variability is experienced as the correction value moves from 0 dB for the median (50 percent) to –10 dB below (or 10 dB above) the calculated path loss value at a path length of 200 km. The graph changes with the general climate, and similar graphs for other climates are available.

As the receiver is moved, a spatial variability in the path loss is observed because the time–independent variables, such as the obstacles, affect the propagating wave differently. If the receiver is moved about in an area on the order of wavelengths in size, a small–scale spatial variability is found. The signal strength at the different locations varies as maxima and minima occur between interfering wave components. The small–scale space variation is usually Rayleigh distributed.

If the median values of the small scale spatial variability are recorded for a number of the small areas over a larger area, a large–scale spatial variability is found to be log–normal distributed with a standard deviation depending on the receiver's environment. Hence, for a specified percentage of receiving locations, the path loss will be larger or smaller than the median path loss by a fixed amount. This is the standard deviation, σ, specified for the empirical equations. A graph detailing this large scale variability is shown in Figure B8 [10]. The graph shows the correction required to the median path loss calculated at a fixed time. It indicates the path loss over the median that is exceeded at a specified percentage of locations measured at a fixed time.

The path loss can be specified for any given reliability (percent of time system is operational) and at any given percentage of locations. The following equation used in conjunction with the graphs in Figures B7 and B8 will yield this path loss.

$$L(t, x) = L(50, 50) + \Delta L(t) + \Delta L(x)$$

where $\Delta L(t)$ is the value from Fig. B7
$\Delta L(x)$ is the value from Fig. B8
$L(50,50)$ is the median path loss

The maximum path loss variation is thus determined for that reliability and that percentage of locations. The transmitted signal must then be large enough to overcome the median path loss plus the maximum variation in loss.

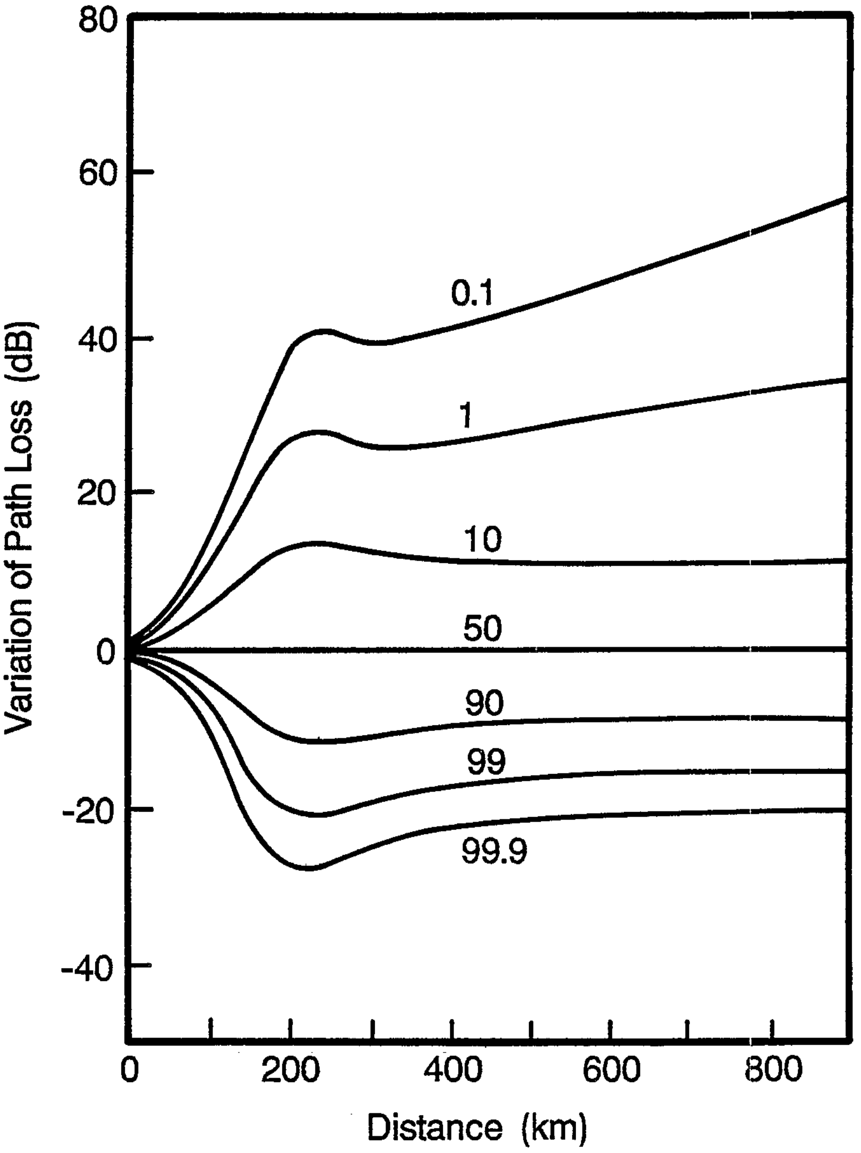

FIGURE B7: VARIATION OF PATH LOSS WITH DISTANCE AND TIME IN TEMPERATE CLIMATE

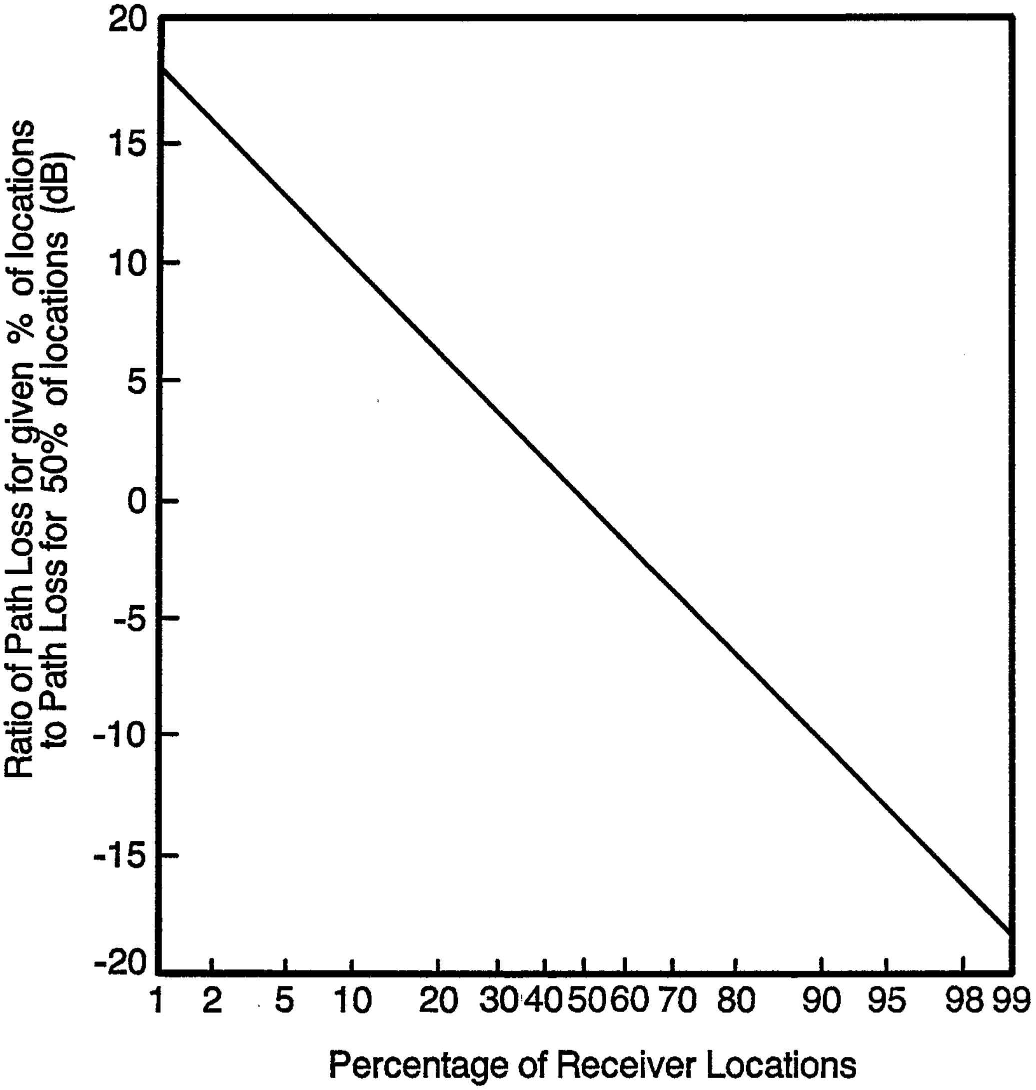

FIGURE B8: LARGE SCALE SIGNAL VARIABILITY

APPENDIX C: PROGRAMS FOR PATH LOSS CALCULATION

C1 Path Loss calculation for Empirical Equations

```
program pathloss;  { program to calculate path loss with a number of }
                   {  different equations }

function Log(real_var:real): Real;
  begin
    Log := (Ln(real_var)/Ln(10));
  end;

function Raise(value,power: Real): Real;
  begin
    Raise := Exp(power*Ln(value));
  end;

function Antilog(real_var: Real): Real;
  begin
    Antilog := Raise(10.0,real_var);
  end;

var     tpow,trgain,rtgain : Real;
        jpow,jrgain,rjgain : Real;
        tr,jr,jt,freq,jtos : Real;
        tloss,jloss,R,J,S,T: Real;
        theight,rheight,H  : Real;
        epsilon,sigma      : Real;
        i,k                : Integer;
        outfile            : Text;

begin
{open file to write results into}

Assign(outfile,'PLOSS.DAT');
Rewrite(outfile);

{Initialize variables to indicate scenario}

trgain := 6;   {6 dB Tx antenna gain}
rtgain := 6;   {6 dB Rx antenna gain}
freq   := 250; {250 MHz frequency}
theight := 3;  { 3 metre tx antenna height}
rheight := 3;  { 3 metre rx antenna height}
epsilon := 13; {average land dielectric constant}
tr := 10;      {tx to rx distance is 10 km}

{put scenario into file}

Writeln(outfile,'Path loss calculated for the following situation:');
Writeln(outfile,'Transmitter antenna gain  (dB): ',trgain:6:2);
Writeln(outfile,'Receiver antenna gain     (dB): ',rtgain:6:2);
Writeln(outfile,'Transmitter antenna height (m): ',theight:6:2);
Writeln(outfile,'Receiver antenna height    (m): ',rheight:6:2);
Writeln(outfile,'Frequency                (MHz): ',freq:6:2);
Writeln(outfile,'Tx to Rx Distance         (km): ',tr:6:2);
Writeln(outfile,'Dielectric constant           : ',epsilon:6:2);
writeln(outfile);

{Calculate loss using free space model}

tloss := 32.4+20*Log(freq)+20*Log(tr);

{put answer in file}

Writeln(outfile,'Free Space Path Loss ');
Writeln(outfile,'Loss  (dB): ',tloss:6:2);
Writeln(outfile);

{Calculate loss using plane earth model}
```

```
tloss := 120+40*Log(tr)-20*Log(theight)-20*Log(rheight);

{put answer in file}

Writeln(outfile,'Plane Earth Path Loss ');
Writeln(outfile,'Loss  (dB): ',tloss:6:2);
Writeln(outfile);

{Calculate loss using Egli for heights less than 10 m}

tloss := 76.3+20*Log(freq)+40*Log(tr)-20*Log(theight)-10*Log(rheight);
sigma := 5.5*Log(freq)-3.2;

{Put answer in file}

Writeln(outfile,'Egli Path Loss for heights < 10 m');
Writeln(outfile,'Loss  (dB): ',tloss:6:2);
Writeln(outfile,'sigma (dB): ',sigma:6:2);
Writeln(outfile);

{Calculate loss using Murphy mountainous}

tloss := 21.4+39.4*Log(freq)+40*Log(tr)-20*Log(theight)-5.3*Log(rheight);
sigma := 17.3-0.019*rheight+0.0012*freq;

{Put answer in file}

Writeln(outfile,'Murphy path loss for Mountainous terrain');
Writeln(outfile,'Loss  (dB): ',tloss:6:2);
Writeln(outfile,'sigma (dB): ',sigma:6:2);
Writeln(outfile);

{Calculate loss using Murphy level}

tloss := 99.2+0.016*Log(freq)+40*Log(tr)-20*Log(theight)-18.5*Log(rheight);
sigma := 13.7-0.11*rheight+0.002*freq;

{Put answer in file}

Writeln(outfile,'Murphy path loss for level terrain');
Writeln(outfile,'Loss  (dB): ',tloss:6:2);
Writeln(outfile,'sigma (dB): ',sigma:6:2);
Writeln(outfile);

{Calculate loss using Rood for nominal LOS}

J := Raise(freq*tr,4.0);
T := Raise(freq*theight/1000,2.0);
S := Raise(freq*rheight/1000,2.0);
R := Raise(epsilon,2.0);
tloss := (0.00000521/J)*(Raise((R/(epsilon-1)),2))*(1+(438*T*((epsilon-1)/R)));
tloss := tloss*(1+(438*S*((epsilon-1)/R)));
tloss := -10*Log(tloss);

{put answer in file}

Writeln(outfile,'Rood path loss assuming nominal line of sight');
Writeln(outfile,'Loss  (dB): ',tloss:6:2);
Writeln(outfile);

{Calculate using Rood with one obstacle .1 km above path}

H := 0.1;
tloss := 66.2+1070*(H/tr)-7500*Raise(H/tr,2)+0.00268*freq+28.34*Log(freq);
tloss := tloss+0.879*tr-0.00378*Raise(tr,2);
```

```
{put answer in file}

Writeln(outfile,'Rood path loss with one obstacle 100 m above path');
Writeln(outfile,'Loss  (dB): ',tloss:6:2);
Writeln(outfile);

{calculate path loss using Rood with more than one obstacle, highest .1 km}

H := 0.1;
tloss := 119.9+287*H/tr-11000*Raise(H/tr,2)+0.00425*freq+14.98*Log(freq);
tloss := tloss+0.541*tr-0.00159*Raise(tr,2);

{put answer in file}

Writeln(outfile,'Rood path loss with many obstacles, max height .1 km above');
Writeln(outfile,'Loss  (dB): ',tloss:6:2);
Writeln(outfile);

{Calculate using ECAC LOS equation}

tloss := 95.6+2.5*Log(freq)+(31.5+0.5*Log(freq))*(Log(tr)-0.21);

{put answer in file}

Writeln(outfile,'ECAC path loss assuming LOS');
Writeln(outfile,'Loss  (dB): ',tloss:6:2);
Writeln(outfile);

{calculate using ECAC non-LOS equation}

tloss := 92.6+11*Log(freq)+(26+4*Log(freq))*(Log(tr)-0.21);

{put answer in file}

Writeln(outfile,'ECAC path loss assuming non-LOS');
Writeln(outfile,'Loss  (dB): ',tloss:6:2);
Writeln(outfile);

{Calculate using ECAC mountainous terrain}

tloss := 107.6-3.5*Log(freq)+(22*Log(freq)-9)*(Log(tr)-0.21);

{put answer in file}

Writeln(outfile,'ECAC path loss in mountainous terrain');
Writeln(outfile,'Loss  (dB): ',tloss:6:2);
Writeln(outfile);

{Calculate loss using Palmer,trees,vertical polarization}

tloss := 72.9+7.7*Log(freq)+44.8*Log(tr)-6.5*Log(theight)-15.6*Log(rheight);

{put answer in file}

Writeln(outfile,'Palmer Path Loss, Treed, Vertical pol. ');
Writeln(outfile,'Loss  (dB): ',tloss:6:2);
Writeln(outfile);

{Calculate loss using Palmer,trees, horizontal polarization}

tloss := 66.8+7.7*Log(freq)+44.8*Log(tr)-6.5*Log(theight)-15.6*Log(rheight);

{put answer in file}

Writeln(outfile,'Palmer Path Loss, Treed, Horizontal pol. ');
```

```
Writeln(outfile,'Loss  (dB): ',tloss:6:2);
Writeln(outfile);

{Calculate loss using Palmer, bare, summer}

tloss := 88.7+7.7*Log(freq)+31.3*Log(tr)-6.5*Log(theight)-15.6*Log(rheight);

{put answer in file}

Writeln(outfile,'Palmer Path Loss, Bare, Summer ');
Writeln(outfile,'Loss  (dB): ',tloss:6:2);
Writeln(outfile);

{Calculate loss using Palmer, bare, winter}

tloss := 96.3+7.7*Log(freq)+31.3*Log(tr)-6.5*Log(theight)-15.6*Log(rheight);

{put answer in file}

Writeln(outfile,'Palmer Path Loss, Bare, Winter ');
Writeln(outfile,'Loss  (dB): ',tloss:6:2);
Writeln(outfile);

Close(outfile);
end.
```

C2 Jammer–to–Signal Ratio Calculations

Appendix C

C2 Jammer-to-Signal Ratio Calculations

```
program jscalc;     {program to calculate jammer to signal ratio when path loss}
                    {is calculated with a number of }
                    {different equations }

function Log(real_var:real): Real;
  begin
    Log := (Ln(real_var)/Ln(10));
  end;

function Raise(value,power: Real): Real;
  begin
    Raise := Exp(power*Ln(value));
  end;

function Antilog(real_var: Real): Real;
  begin
    Antilog := Raise(10.0,real_var);
  end;

var     tpow,trgain,rtgain : Real;
        jpow,jrgain,rjgain : Real;
        tr,jr,jt,freq,jtos : Real;
        tloss,jloss,R,J,S,T: Real;
        theight,rheight,H  : Real;
        jheight,jserr      : Real;
        epsilon,sigma      : Real;
        i,k                : Integer;
        outfile            : Text;

begin
{open file to write results into}

Assign(outfile,'JS.DAT');
Rewrite(outfile);

{Initialize variables to indicate scenario}

trgain := 6;   {6 dB Tx to Rx antenna gain}
rtgain := 6;   {6 dB Rx to Tx antenna gain}
freq   := 250; {250 MHz frequency}
theight := 3;  { 3 metre tx antenna height}
rheight := 3;  { 3 metre rx antenna height}
epsilon := 13; {average land dielectric constant}
tr := 10;      {tx to rx distance is 10 km}
jr := 20;      {jammer to rx distance is 20 km}
jheight := 3;  {jammer antenna height is 3 metres}
jrgain := 6;   {jammer to receiver antenna gain is 6 dB}
rjgain := 6;   {receiver to jammer antenna gain is 6 dB}

jpow := 10*Log(100); {jammer power is 100 Watts}
tpow := 10*Log(100); {transmitter power is 100 Watts}

{put scenario into file}

Writeln(outfile,'Path loss calculated for the following situation:');
Writeln(outfile,'Transmitter-Rx antenna gain  (dB): ',trgain:6:2);
Writeln(outfile,'Receiver-Tx antenna gain     (dB): ',rtgain:6:2);
Writeln(outfile,'Jammer-Rx antenna gain       (dB): ',jrgain:6:2);
Writeln(outfile,'Rx-Jammer antenna gain       (dB): ',rjgain:6:2);
Writeln(outfile,'Transmitter antenna height    (m): ',theight:6:2);
Writeln(outfile,'Receiver antenna height       (m): ',rheight:6:2);
Writeln(outfile,'Jammer antenna height         (m): ',jheight:6:2);
Writeln(outfile,'Frequency                   (MHz): ',freq:6:2);
Writeln(outfile,'Tx to Rx Distance            (km): ',tr:6:2);
Writeln(outfile,'Jammer to Rx distance        (km): ',jr:6:2);
Writeln(outfile,'Dielectric constant              : ',epsilon:6:2);
```

```
Writeln(outfile,'Jammer Power                 (dBW): ',jpow:6:2);
Writeln(outfile,'Transmitter Power            (dBW): ',tpow:6:2);

writeln(outfile);

{Calculate loss using free space model}

tloss := 32.4+20*Log(freq)+20*Log(tr);
jloss := 32.4+20*Log(freq)+20*Log(jr);

{Calculate J/S}

jtos := (jpow-tpow)+(jrgain+rjgain)-(trgain+rtgain)+(tloss-jloss);

{put answer in file}

Writeln(outfile,'Free Space Path Loss ');
Writeln(outfile,'Transmitter Loss  (dB): ',tloss:6:2);
Writeln(outfile,'Jammer Loss       (dB): ',jloss:6:2);
Writeln(outfile,'Jammer-to-Signal  (dB): ',jtos:6:2);
Writeln(outfile);

{Calculate loss using plane earth model}

tloss := 120+40*Log(tr)-20*Log(theight)-20*Log(rheight);
jloss := 120+40*Log(jr)-20*Log(jheight)-20*Log(rheight);

{Calculate J/S}

jtos := (jpow-tpow)+(jrgain+rjgain)-(trgain+rtgain)+(tloss-jloss);

{put answer in file}

Writeln(outfile,'Plane Earth Path Loss ');
Writeln(outfile,'Transmitter Loss  (dB): ',tloss:6:2);
Writeln(outfile,'Jammer Loss       (dB): ',jloss:6:2);
Writeln(outfile,'Jammer-to-Signal  (dB): ',jtos:6:2);
Writeln(outfile);

{Calculate loss using Egli for heights less than 10 m}

tloss := 76.3+20*Log(freq)+40*Log(tr)-20*Log(theight)-10*Log(rheight);
jloss := 76.3+20*Log(freq)+40*Log(jr)-20*Log(jheight)-10*Log(rheight);
sigma := 5.5*Log(freq)-3.2;

{Calculate J/S}

jtos := (jpow-tpow)+(jrgain+rjgain)-(trgain+rtgain)+(tloss-jloss);
jserr := Raise(2*Raise(sigma,2),0.5);

{Put answer in file}

Writeln(outfile,'Egli Path Loss for heights < 10 m');
Writeln(outfile,'Transmitter Loss  (dB): ',tloss:6:2);
Writeln(outfile,'sigma             (dB): ',sigma:6:2);
Writeln(outfile,'Jammer Loss       (dB): ',jloss:6:2);
Writeln(outfile,'Jammer-to-Signal  (dB): ',jtos:6:2);
Writeln(outfile,'J/S Error         (dB): ',jserr:6:2);
Writeln(outfile);

{Calculate loss using Murphy mountainous}

tloss := 21.4+39.4*Log(freq)+40*Log(tr)-20*Log(theight)-5.3*Log(rheight);
jloss := 21.4+39.4*Log(freq)+40*Log(jr)-20*Log(jheight)-5.3*Log(rheight);
sigma := 17.3-0.019*rheight+0.0012*freq;
```

```
{Calculate J/S}

jtos := (jpow-tpow)+(jrgain+rjgain)-(trgain+rtgain)+(tloss-jloss);
jserr := Raise(2*Raise(sigma,2),0.5);

{Put answer in file}

Writeln(outfile,'Murphy path loss for Mountainous terrain');
Writeln(outfile,'Transmitter Loss  (dB): ',tloss:6:2);
Writeln(outfile,'sigma             (dB): ',sigma:6:2);
Writeln(outfile,'Jammer Loss       (dB): ',jloss:6:2);
Writeln(outfile,'Jammer-to-Signal  (dB): ',jtos:6:2);
Writeln(outfile,'J/S Error         (dB): ',jserr:6:2);
Writeln(outfile);

{Calculate loss using Murphy level}

tloss := 99.2+0.016*Log(freq)+40*Log(tr)-20*Log(theight)-18.5*Log(rheight);
jloss := 99.2+0.016*Log(freq)+40*Log(jr)-20*Log(jheight)-18.5*Log(rheight);
sigma := 13.7-0.11*rheight+0.002*freq;

{Calculate J/S}

jtos := (jpow-tpow)+(jrgain+rjgain)-(trgain+rtgain)+(tloss-jloss);
jserr := Raise(2*Raise(sigma,2),0.5);

{Put answer in file}

Writeln(outfile,'Murphy path loss for level terrain');
Writeln(outfile,'Transmitter Loss  (dB): ',tloss:6:2);
Writeln(outfile,'sigma             (dB): ',sigma:6:2);
Writeln(outfile,'Jammer Loss       (dB): ',jloss:6:2);
Writeln(outfile,'Jammer-to-Signal  (dB): ',jtos:6:2);
Writeln(outfile,'J/S Error         (dB): ',jserr:6:2);
Writeln(outfile);

{Calculate loss using Rood for nominal LOS}

J := Raise(freq*tr,4.0);
T := Raise(freq*theight/1000,2.0);
S := Raise(freq*rheight/1000,2.0);
R := Raise(epsilon,2.0);
tloss := (0.00000521/J)*(Raise((R/(epsilon-1)),2))*(1+(438*T*((epsilon-1)/R)));
tloss := tloss*(1+(438*S*((epsilon-1)/R)));
tloss := -10*Log(tloss);

J := Raise(freq*jr,4.0);
T := Raise(freq*jheight/1000,2.0);
S := Raise(freq*rheight/1000,2.0);
R := Raise(epsilon,2.0);
jloss := (0.00000521/J)*(Raise((R/(epsilon-1)),2))*(1+(438*T*((epsilon-1)/R)));
jloss := jloss*(1+(438*S*((epsilon-1)/R)));
jloss := -10*Log(jloss);

{Calculate J/S}

jtos := (jpow-tpow)+(jrgain+rjgain)-(trgain+rtgain)+(tloss-jloss);

{put answer in file}

Writeln(outfile,'Rood path loss assuming nominal line of sight');
Writeln(outfile,'Transmitter Loss  (dB): ',tloss:6:2);
Writeln(outfile,'Jammer Loss       (dB): ',jloss:6:2);
Writeln(outfile,'Jammer-to-Signal  (dB): ',jtos:6:2);
Writeln(outfile);
```

```
{Calculate using Rood with one obstacle .1 km above path}

H := 0.1;
tloss := 66.2+1070*(H/tr)-7500*Raise(H/tr,2)+0.00268*freq+28.34*Log(freq);
tloss := tloss+0.879*tr-0.00378*Raise(tr,2);

H := 0.1;
jloss := 66.2+1070*(H/jr)-7500*Raise(H/jr,2)+0.00268*freq+28.34*Log(freq);
jloss := jloss+0.879*jr-0.00378*Raise(jr,2);

{Calculate J/S}

jtos := (jpow-tpow)+(jrgain+rjgain)-(trgain+rtgain)+(tloss-jloss);

{put answer in file}

Writeln(outfile,'Rood path loss with one obstacle 100 m above path');
Writeln(outfile,'Transmitter Loss  (dB): ',tloss:6:2);
Writeln(outfile,'Jammer Loss       (dB): ',jloss:6:2);
Writeln(outfile,'Jammer-to-Signal  (dB): ',jtos:6:2);
Writeln(outfile);

{calculate path loss using Rood with more than one obstacle, highest .1 km}

H := 0.1;
tloss := 119.9+287*H/tr-11000*Raise(H/tr,2)+0.00425*freq+14.98*Log(freq);
tloss := tloss+0.541*tr-0.00159*Raise(tr,2);

H := 0.1;
jloss := 119.9+287*H/jr-11000*Raise(H/jr,2)+0.00425*freq+14.98*Log(freq);
jloss := jloss+0.541*jr-0.00159*Raise(jr,2);

{Calculate J/S}

jtos := (jpow-tpow)+(jrgain+rjgain)-(trgain+rtgain)+(tloss-jloss);

{put answer in file}

Writeln(outfile,'Rood path loss with many obstacles, max height .1 km above');
Writeln(outfile,'Transmitter Loss  (dB): ',tloss:6:2);
Writeln(outfile,'Jammer Loss       (dB): ',jloss:6:2);
Writeln(outfile,'Jammer-to-Signal  (dB): ',jtos:6:2);
Writeln(outfile);

{Calculate using ECAC LOS equation}

tloss := 95.6+2.5*Log(freq)+(31.5+0.5*Log(freq))*(Log(tr)-0.21);
jloss := 95.6+2.5*Log(freq)+(31.5+0.5*Log(freq))*(Log(jr)-0.21);

{Calculate J/S}

jtos := (jpow-tpow)+(jrgain+rjgain)-(trgain+rtgain)+(tloss-jloss);

{put answer in file}

Writeln(outfile,'ECAC path loss assuming LOS');
Writeln(outfile,'Transmitter Loss  (dB): ',tloss:6:2);
Writeln(outfile,'Jammer Loss       (dB): ',jloss:6:2);
Writeln(outfile,'Jammer-to-Signal  (dB): ',jtos:6:2);
Writeln(outfile);

{calculate using ECAC non-LOS equation}

tloss := 92.6+11*Log(freq)+(26+4*Log(freq))*(Log(tr)-0.21);
jloss := 92.6+11*Log(freq)+(26+4*Log(freq))*(Log(jr)-0.21);
```

```
{Calculate J/S}

jtos := (jpow-tpow)+(jrgain+rjgain)-(trgain+rtgain)+(tloss-jloss);

{put answer in file}

Writeln(outfile,'ECAC path loss assuming non-LOS');
Writeln(outfile,'Transmitter Loss  (dB): ',tloss:6:2);
Writeln(outfile,'Jammer Loss       (dB): ',jloss:6:2);
Writeln(outfile,'Jammer-to-Signal  (dB): ',jtos:6:2);
Writeln(outfile);

{Calculate using ECAC mountainous terrain}

tloss := 107.6-3.5*Log(freq)+(22*Log(freq)-9)*(Log(tr)-0.21);
jloss := 107.6-3.5*Log(freq)+(22*Log(freq)-9)*(Log(jr)-0.21);

{Calculate J/S}

jtos := (jpow-tpow)+(jrgain+rjgain)-(trgain+rtgain)+(tloss-jloss);

{put answer in file}

Writeln(outfile,'ECAC path loss in mountainous terrain');
Writeln(outfile,'Transmitter Loss  (dB): ',tloss:6:2);
Writeln(outfile,'Jammer Loss       (dB): ',jloss:6:2);
Writeln(outfile,'Jammer-to-Signal  (dB): ',jtos:6:2);
Writeln(outfile);

{Calculate loss using Palmer,trees,vertical polarization}

tloss := 72.9+7.7*Log(freq)+44.8*Log(tr)-6.5*Log(theight)-15.6*Log(rheight);
jloss := 72.9+7.7*Log(freq)+44.8*Log(jr)-6.5*Log(jheight)-15.6*Log(rheight);

{Calculate J/S}

jtos := (jpow-tpow)+(jrgain+rjgain)-(trgain+rtgain)+(tloss-jloss);

{put answer in file}

Writeln(outfile,'Palmer Path Loss, Treed, Vertical pol. ');
Writeln(outfile,'Transmitter Loss  (dB): ',tloss:6:2);
Writeln(outfile,'Jammer Loss       (dB): ',jloss:6:2);
Writeln(outfile,'Jammer-to-Signal  (dB): ',jtos:6:2);
Writeln(outfile);

{Calculate loss using Palmer,trees, horizontal polarization}

tloss := 66.8+7.7*Log(freq)+44.8*Log(tr)-6.5*Log(theight)-15.6*Log(rheight);
jloss := 66.8+7.7*Log(freq)+44.8*Log(jr)-6.5*Log(jheight)-15.6*Log(rheight);

{Calculate J/S}

jtos := (jpow-tpow)+(jrgain+rjgain)-(trgain+rtgain)+(tloss-jloss);

{put answer in file}

Writeln(outfile,'Palmer Path Loss, Treed, Horizontal pol. ');
Writeln(outfile,'Transmitter Loss  (dB): ',tloss:6:2);
Writeln(outfile,'Jammer Loss       (dB): ',jloss:6:2);
Writeln(outfile,'Jammer-to-Signal  (dB): ',jtos:6:2);
Writeln(outfile);

{Calculate loss using Palmer, bare, summer}

tloss := 88.7+7.7*Log(freq)+31.3*Log(tr)-6.5*Log(theight)-15.6*Log(rheight);
```

```
jloss := 88.7+7.7*Log(freq)+31.3*Log(jr)-6.5*Log(jheight)-15.6*Log(rheight);

{Calculate J/S}

jtos := (jpow-tpow)+(jrgain+rjgain)-(trgain+rtgain)+(tloss-jloss);

{put answer in file}

Writeln(outfile,'Palmer Path Loss, Bare, Summer ');
Writeln(outfile,'Transmitter Loss  (dB): ',tloss:6:2);
Writeln(outfile,'Jammer Loss       (dB): ',jloss:6:2);
Writeln(outfile,'Jammer-to-Signal  (dB): ',jtos:6:2);
Writeln(outfile);

{Calculate loss using Palmer, bare, winter}

tloss := 96.3+7.7*Log(freq)+31.3*Log(tr)-6.5*Log(theight)-15.6*Log(rheight);
jloss := 96.3+7.7*Log(freq)+31.3*Log(jr)-6.5*Log(jheight)-15.6*Log(rheight);

{Calculate J/S}

jtos := (jpow-tpow)+(jrgain+rjgain)-(trgain+rtgain)+(tloss-jloss);

{put answer in file}

Writeln(outfile,'Palmer Path Loss, Bare, Winter ');
Writeln(outfile,'Transmitter Loss  (dB): ',tloss:6:2);
Writeln(outfile,'Jammer Loss       (dB): ',jloss:6:2);
Writeln(outfile,'Jammer-to-Signal  (dB): ',jtos:6:2);
Writeln(outfile);

Close(outfile);
end.
```

```
Path loss calculated for the following situation:
Transmitter antenna gain  (dB):   6.00
Receiver antenna gain     (dB):   6.00
Transmitter antenna height (m):   3.00
Receiver antenna height    (m):   3.00
Frequency                (MHz): 250.00
Tx to Rx Distance         (km):  10.00
Dielectric constant          :  13.00

Free Space Path Loss
Loss  (dB): 100.36

Plane Earth Path Loss
Loss  (dB): 140.92

Egli Path Loss for heights < 10 m
Loss  (dB): 149.95
sigma (dB):   9.99

Murphy path loss for Mountainous terrain
Loss  (dB): 143.81
sigma (dB):  17.54

Murphy path loss for level terrain
Loss  (dB): 120.87
sigma (dB):  13.87

Rood path loss assuming nominal line of sight
Loss  (dB): 140.43

Rood path loss with one obstacle 100 m above path
Loss  (dB): 153.19

Rood path loss with many obstacles, max height .1 km above
Loss  (dB): 163.90

ECAC path loss assuming LOS
Loss  (dB): 127.43

ECAC path loss assuming non-LOS
Loss  (dB): 147.09

ECAC path loss in mountainous terrain
Loss  (dB): 133.77

Palmer Path Loss, Treed, Vertical pol.
Loss  (dB): 125.62

Palmer Path Loss, Treed, Horizontal pol.
Loss  (dB): 119.52

Palmer Path Loss, Bare, Summer
Loss  (dB): 127.92

Palmer Path Loss, Bare, Winter
Loss  (dB): 135.52
```

DOCUMENT CONTROL DATA

(Security classification of title, body of abstract and indexing annotation must be entered when the overall document is classified)

1. ORIGINATOR (the name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g. Establishment sponsoring a contractor's report, or tasking agency, are entered in section 8.)

NATIONAL DEFENCE HEADQUARTERS
DEFENCE RESEARCH ESTABLISHMENT OTTAWA
SHIRLEYS BAY
OTTAWA, ONTARIO, K1A 0Z4 CANADA

2. SECURITY CLASSIFICATION (overall security classification of the document. including special warning terms if applicable)

UNCLASSIFIED

3. TITLE (the complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S,C,R or U) in parentheses after the title.)

COMMUNICATIONS ELECTRONIC COUNTERMEASURES: AN OVERVIEW (U)

4. AUTHORS (Last name, first name, middle initial)

HOOPER, JANETTE D.

5. DATE OF PUBLICATION (month and year of publication of document)

DECEMBER 1990

6a. NO. OF PAGES (total containing information. Include Annexes, Appendices, etc.)

95

6b. NO. OF REFS (total cited in document)

33

7. DESCRIPTIVE NOTES (the category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

DREO REPORT

8. SPONSORING ACTIVITY (the name of the department project office or laboratory sponsoring the research and development. Include the address.)

NATIONAL DEFENCE
DEFENCE RESEARCH ESTABLISHMENT OTTAWA
SHIRLEY BAY, OTTAWA, ONTARIO K1A 0Z4 CANADA

9a. PROJECT OR GRANT NO. (if appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant)

014LK11

9b. CONTRACT NO. (if appropriate, the applicable number under which the document was written)

10a. ORIGINATOR'S DOCUMENT NUMBER (the official document number by which the document is identified by the originating activity. This number must be unique to this document.)

DREO REPORT 1074

10b. OTHER DOCUMENT NOS. (Any other numbers which may be assigned this document either by the originator or by the sponsor)

11. DOCUMENT AVAILABILITY (any limitations on further dissemination of the document, other than those imposed by security classification)

(X) Unlimited distribution
( ) Distribution limited to defence departments and defence contractors; further distribution only as approved
( ) Distribution limited to defence departments and Canadian defence contractors; further distribution only as approved
( ) Distribution limited to government departments and agencies; further distribution only as approved
( ) Distribution limited to defence departments; further distribution only as approved
( ) Other (please specify):

12. DOCUMENT ANNOUNCEMENT (any limitation to the bibliographic announcement of this document. This will normally correspond to the Document Availabilty (11). However, where further distribution (beyond the audience specified in 11) is possible, a wider announcement audience may be selected.)

UNLIMITED ANNOUNCEMENT

13. ABSTRACT (a brief and factual summary of the document. It may also appear elsewhere in the body of the document itself. It is highly desirable that the abstract of classified documents be unclassified. Each paragraph of the abstract shall begin with an indication of the security classification of the information in the paragraph (unless the document itself is unclassified) represented as (S), (C), (R), or (U). It is not necessary to include here abstracts in both offical languages unless the text is bilingual).

50|| This report presents a review of the requirements and methods for technically effective communications jamming.

An equation to determine technical jamming effectiveness is introduced. The equation allows calculation of the jammer-to-signal (J/S) ratio at the target receiver. The equation requires knowledge of the jammer power and the power of the target transmitter, the antenna gains over the jammer-receiver link and the transmitter-receiver link, and the path loss between the jammer and receiver and the transmitter and receiver. There is an overview of the methods to determine path loss. If the J/S ratio required to jam a link is calculated, the technical effectiveness of a particular jamming scenario can be determined because thresholds of J/S ratio required for jamming are tabulated.

An overview of the types of communications electronic counter-measures, their implementations, and their problems is also included. Both jamming and deception techniques are discussed. ||

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus. e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus-identified. If it is not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title.)

ELECTRONIC WARFARE
ELECTRONIC COUNTERMEASURES
JAMMING
JAMMER-TO-SIGNAL RATIO
RADIO PROPAGATION
COMMUNICATIONS
PATH LOSS
JAMMING EFFECTIVENESS
COMMUNICATIONS ELECTRONIC WARFARE

NO. OF COPIES NOMBRE DE COPIES 1	COPY NO. COPIE Nº 1	INFORMATION SCIENTIST'S INITIALS INITIALES DE L'AGENT D'INFORMATION SCIENTIFIQUE JUN 19 1991 DAG
AQUISITION ROUTE FOURNI PAR ▶	DREO	
DATE ▶	10 JUNE 1991	
DSIS ACCESSION NO. NUMÉRO DSIS ▶	91-02987	

DND 1158 (6-87)

#10181

National Defence Défense nationale

~~PLEASE RETURN THIS DOCUMENT~~
~~TO THE FOLLOWING ADD~~RESS:

DIRECTOR
SCIENTIFIC INFORMATION SERVICES
NATIONAL DEFENCE
HEADQUARTERS
OTTAWA, ONT. - CANADA K1A 0K2

PRI~~ERE DE RETOURNER CE DOCU~~MENT
~~À L'ADRESSE SUIVANTE:~~

DIRECTEUR
SERVICES D'INFORMATION SCIENTIFIQUES
QUARTIER GÉNÉRAL
DE LA DÉFENSE NATIONALE
OTTAWA, ONT. - CANADA K1A 0K2