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THESIS

COMINT ANALYSIS IN A LITTORAL ENVIRONMENT

by

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September 1996

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13. ABSTRACT *(Maximum 200 words)*

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COMINT ANALYSIS IN A LITTORAL ENVIRONMENT

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LIST OF SYMBOLS, ACRONYMS AND ABBREVIATIONS

λ	Wavelength
ADP	Automatic Data Processing
AM	Amplitude Modulation
AO	Acousto-Optic
AVG	Average
BLOS	Beyond Line-Of-Sight
CD-ROM	Compact Disc - Read Only Memory
COMINT	Communications Intelligence
COMSEC	Communications Security
CW	Continuous Wave
dB	Decibel
DOA	Direction Of Arrival
DTED	Digital Terrain Elevation Data
EC	Electronic Combat
EP	Electronic Protection
EREPS	Engineer's Refractive Effects Prediction System
ERP	Effective Radiated Power
EVD	Evaporation Duct
FM	Frequency Modulation

GHz	Gigahertz
HT	Height
IF	Intermediate Frequency
IFM	Immediate Frequency Measurement
IMOM PD)	Improved Many-On-Many (Program Software Family that includes
K	Effective Earth Radius
kbps	Kilo Bytes Per Second
kHz	Kilohertz
km	Kilometer
LOS	Line of Site
LPI	Low Probability of Interception
MHz	Megahertz
MS	Marden Square
MSL	Mean Sea Level
N/A	Not Available
NATO	North Atlantic Treaty Organization
NCCOSC	Naval Command, Control & Ocean Surveillance Center
NM	Nautical Miles
NSUBS	Surface N-unit Value
OB	Order of Battle
PC	Personal Computer

PD	Passive Detection Software Program
PRI	Pulse Repetition Interval
PW	Pulse Width
RF	Radio frequency
RHCP	Right Hand Circularly Polarized
RLOS	Radio Line-Of-Sight
S/N	Signal-to-Noise Ratio
SATCOM	Satellite Communications
SBD	Surface Based Duct
SDS	Surface Duct Summary (EREPS Module)
SHF	Super High Frequency
SP	Speed
SSB	Single Side Band
TDOA	Time Difference Of Arrival
TIREM	Terrain Integrated Rough Earth Model
TRANSEC	Transmission Security
TRF	Tunable Radio Frequency
UHF	Ultra High Frequency
VGA	Video Graphic Array
VHF	Very High Frequency

I. INTRODUCTION

A. PURPOSE

The purpose of this thesis is to evaluate the performance of selected ship-mounted COMINT systems when collecting against VHF/UHF data/voice signals in a littoral environment with equipment specifications and propagation aspects taken into account. Geolocation will not be considered in this study. The results of this work can be used for purposes of evaluation and comparison by users of either collection or communication systems worldwide. The final product of this thesis could also be a valuable tool in acquisition and deployment decisions.

B. BACKGROUND

"The second major military use of radiated electromagnetic energy is for communication, the sending of messages from one element of the force to another." [Ref. 1] Communication systems are designed to convey information accurately and reliably from the sender to the desired location. When first developed, the communication systems had their terminal stations manned to ensure proper operation and human supervision. Nowadays, this situation has changed with the development of new technologies such as Automatic Data Processing (ADP) and automatic weapon control systems. Therefore, the trend is for communications terminals to be machines; computers in most of cases. A communication system's effectiveness is measured by its efficiency in passing along information. Accuracy, the amount of information conveyed and the speed of transmission dictates the rules. [Ref. 1, Ref. 2]

Despite modern weapons systems and the high degree of readiness of the troops, the command and control capabilities of a battlefield commander would be deeply restricted by the lack of timely and accurate information on the enemy's tactical situation and intentions as well as by the unawareness of his own forces' deployment. [Ref. 3]

Based on the above notion, it is easily seen that intelligence systems play a vital role in the battlefield commander's decision making process of today. Due to the attributes of communications itself, electronic warfare and communications are related in a more complex way than to other uses of electromagnetic radiation. Military communications are conceived for a friendly recipient even though they may be related to the opposing forces sometimes. The presence of the message itself as well as the information being conveyed are meant only for the sender and the receiver. The rules of the EW communications game are clear and the limits well-drawn. While one side attempts to maintain the secrecy of the message, the adversaries try to intercept and compromise the information. [Ref. 2]

Communications Intelligence (COMINT) is the branch of Signal Intelligence (SIGINT) responsible for the collection, location, processing, analysis and reporting of intercepted communications signals by other than the intended recipient. Many COMINT collection systems have been developed by several countries in an attempt to gather as much intelligence information as possible. Conversely, a lot of improvement has been achieved in the Communications Security (COMSEC) area. Many Electronic Protection (EP) techniques were developed to prevent information from either being collected and interpreted or being electronically attacked or jammed. Recent technological development and the increasing use of the RF spectrum represent the main problems faced by COMINT operators nowadays. Signals designed to present a low probability of intercept (LPI) are no longer the exception but the rule. These signals utilize techniques such as fast frequency hopping, short transmission bursts and the pseudorandom coding of the data over a broad spectrum. These techniques, known as spread spectrum, are common devices used to obstruct interception and prevent jamming by an unintended listener. Furthermore, digital compression techniques coupled with signal redundancy can recover bit streams, even when large parts are corrupted, and thus facilitate the task of receiving the correct information. "The challenge is now to recognize that a noise-like signal is actually a man-made artifact rather than naturally occurring noise." [Ref. 4]

Past experiences have also proven that knowing the operational environment is an important and decisive piece in the COMINT puzzle. Geographic location and atmospheric conditions play important roles in the overall scenario by interacting with the electromagnetic radiation either enhancing or degrading its propagation aspects. Knowing the sea and terrain characteristics of the area of interest as well as the reigning propagation phenomena such as trapping and duct formation could lead to a much more reliable intelligence analysis.

II. SCENARIO

The scenario considered in this study is that of a variety of ship-mounted COMINT systems collecting against data/voice signals emitted by VHF/UHF shipborne transmitters in a littoral environment of South America. State of the art equipment from several manufacturers and nationalities were gathered to compose this analysis and they will be described in detail in further chapters. The software program Passive Detection (PD) was used to simulate a hypothetical scenario where the collecting systems and the communication transmitters interact inside a particular geographical area. PD is one of the family of IMOM (Improved Many-On-Many) computer programs developed at the Air Force Information Warfare Center (AFIWC) to model electronic combat (EC) scenarios. Atmospheric propagation effects and phenomena, such as trapping and duct formation for the specific area of interest, were analyzed with the aid of the software program family "Engineer's Refractive Effects Prediction System" (EREPS). EREPS was developed by the Naval Command, Control and Ocean Surveillance Center and is a system of individual stand-alone IBM/PC compatible programs to aid in properly assessing electromagnetic effects of the lower atmosphere.

A. THE GEOGRAPHICAL REGION

The geographical region of interest is the Marden Square (MS) 413. This is a 10-degree by 10-degree square located within the latitudes 30° S to 40° S and the longitudes 050° W to 060° W. This area is approximately 360,000 square nautical miles wide and encompasses the border region of three countries: part of the south littoral of Brazil, the whole shoreline of Uruguay, and a small portion of Argentina's coast. It also includes the mouth of the Plata river. Figure 2-1 is a global perspective map that shows how the Marden square criteria are utilized to map the majority of the world in standard modules of the same dimensions. The square of interest (MS 413) is marked with a cross hair in the bottom part of the figure. To better acquaint the reader with the area of interest, an expanded view of Marden Square 413 is shown in Figure 2-2.

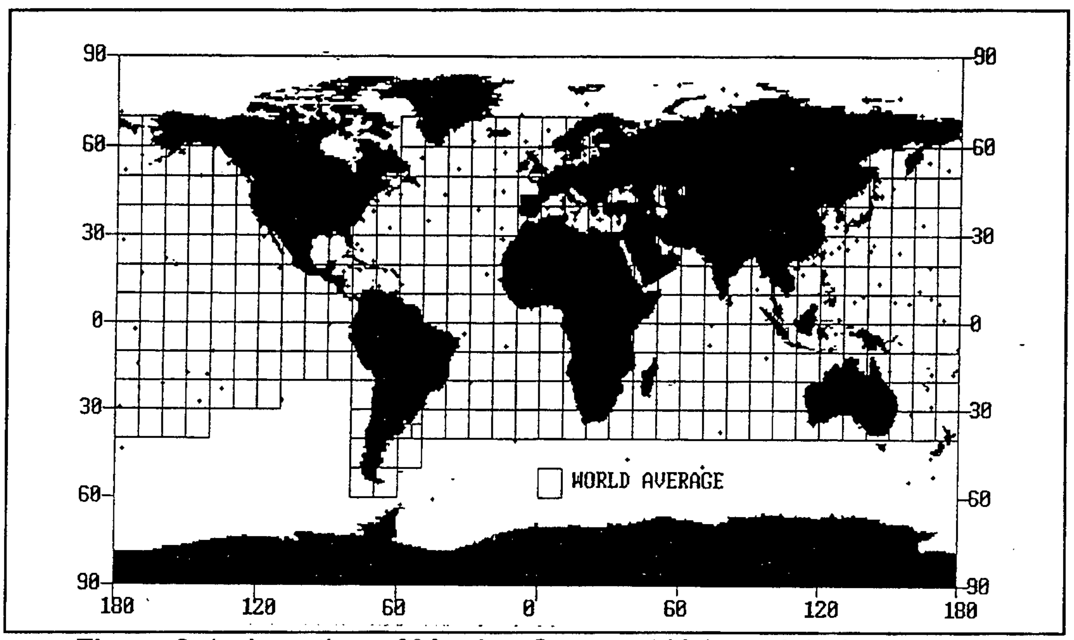

Figure 2-1. Location of Marden Square 413 in a global perspective

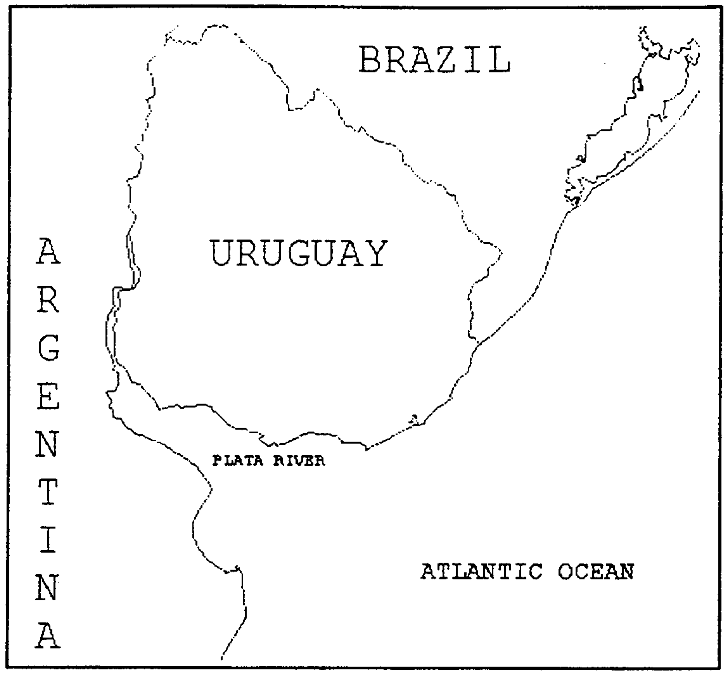

Figure 2-2. Expanded view of Marden Square 413

B. ATMOSPHERIC CONDITIONS

The atmospheric conditions and propagation phenomena such as ducting effects in the area of interest were calculated by the module "Surface Duct Summary" (SDS) of the EREPS family. The statistics displayed within SDS are derived from two meteorological databases; the Radiosonde Data Analysis II assembled by the GTE Sylvania Corporation and the DUCT63 assembled by the National Climatic Data Center. The GTE Sylvania analysis is based on approximately 3 million worldwide radiosonde soundings taken during a 5-year period from 1966 to 1969 and 1973 to 1974. The DUCT63 analysis is a 15-year subset of over 150 years of worldwide surface meteorological observations obtained from ship logs, ship weather reporting forms, published observations, automatic buoys, etc. [Ref. 5]. A duct is a channel in which electromagnetic energy can propagate over great ranges. There are basically three different types of ducts: surface ducts, evaporation ducts and elevated ducts. These phenomena are expounded upon conceptually in Appendix C. Figure 2-3 shows an evaporation duct height histogram and surface-based duct climatology for the selected area expressed in terms of an annual statistical average. The histogram mentioned above describes the evaporation duct height, in meters, versus its percentage of occurrence in that particular area.

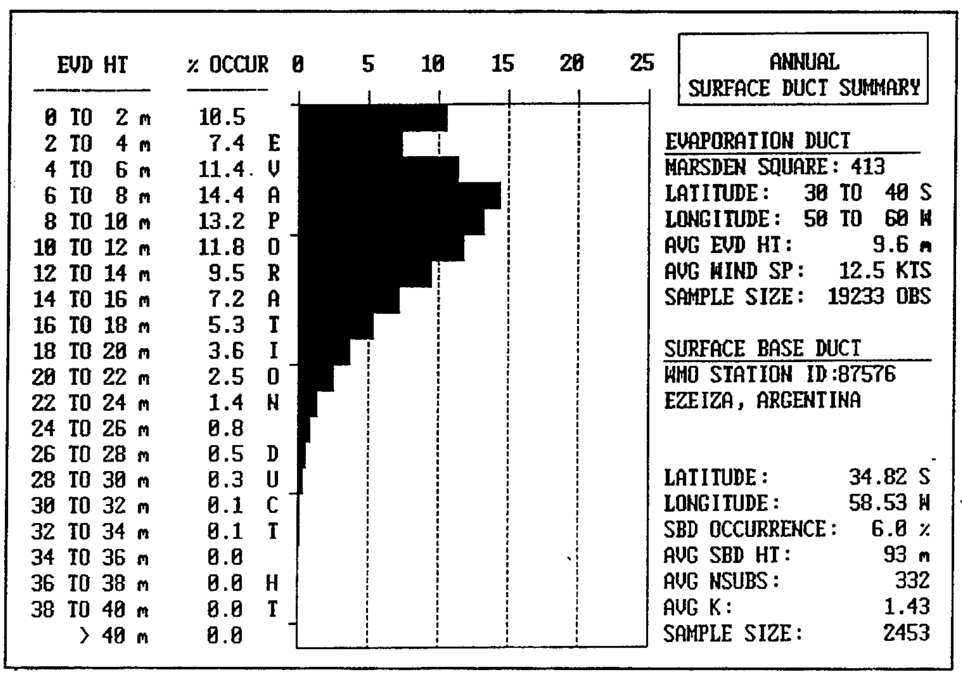

Figure 2-3. Annual Surface Duct Summary

Important data are extracted from the previous graph and listed below. These figures are related to the trapping and ducting phenomena and express the changes in the atmospheric parameters that have to be done in order to better model the propagation effects. This data was used as input for further calculations of propagation loss versus range regarding each combination of transmitter and receiver. For this type of analysis an EREPS module denominated PROPR was employed to provide graphic outputs.

- Average evaporation duct height: 9.6 m
- Average wind speed: 12.5 Kts
- Average surface base duct height: 93 m
- Average surface N-unit value: 332
- Average effective earth radius (K): 1.43
- Surface-based duct occurrence: 6.0 %

III. COMINT COLLECTION SYSTEMS

This chapter focuses on the COMINT collecting systems to be compared by dividing them into the antenna and receiver subsystems. A unique antenna was selected to be operated as a common device for all the collectors with the purpose of narrowing the comparison down to the receiver subsystems themselves. The selected antenna, as well as its performance parameters and characteristics, is described in Section A. Four collection receivers in the VHF/UHF band were selected, among the many available in the market, to be included in this study. The criteria used was the modernity of technology, availability of technical parameters from the manufacturer and literature, and diversity of nationality whenever possible. Section B describes the 6 parameters used to categorize the receivers selected for a comprehensive comparison. This Section also describes the receiver subsystems, stressing their features and capabilities. A comparison table summarizing the receiver's features is provided at the end of the chapter.

A. ANTENNA SUBSYSTEM

The antenna subsystem plays a vital role in the radiolink budget analysis mainly because it is the part of the system where most of the compromise, in terms of meeting system requirements, is done. The system's antenna can be used for COMINT activities or even be shared to accomplish other tasks.

COMINT antennas face conflicting requirements concerning their performance. Primarily, the lack of information on the location, frequency and waveform of the signals to be detected and recorded advocates the use of omnidirectional and wideband antennas. Thus, the probability of detecting signals on any part of the spectrum coming from any direction is increased. On the other hand, the monitoring of potential harmful sectors is compromised due to the low gain of such ideal omnidirectional antennas. Eventually weaker emissions would not be sensed in those directions. Therefore, the antenna to be chosen to perform better monitoring is a two step task. First, an omni antenna is deployed to detect the presence of the signal and roughly find the direction of a source. Then more directional antennas, with higher gains, are used to narrow and determine the direction of arrival (DOA) of the emissions. [Ref. 4]

Since geolocation will not be considered in this study, the evaluation will be restricted to the first part of the detection problem and therefore an omni direction antenna will be considered for this purpose.

1. Antenna Parameters

The antenna parameters necessary to conduct the evaluation are described in the following sub-subsections. As mentioned earlier, a common antenna will be utilized for all the COMINT systems. These parameters will be later used as input data for each collecting system evaluated in the PD simulation.

a. Antenna Gain

The antenna gain is a measure of the its ability to concentrate in a particular direction the power accepted. The maximum antenna gain is usually given in decibels relative to an isotropic radiation pattern (dBi).

b. Beamwidth Azimuth

It represents the horizontal antenna beamwidth measured in degrees (deg.). It is basically the angle between the half power points (3 dB point) of the antenna main lobe on the radiation pattern. For an omnidirectional radiation pattern, the azimuthal beamwidth is 360° . "Omni-directional" refers to the uniform horizontal beam pattern but does not consttrain the vertical pattern. An antenna pattern may be omni-directional but not isotropic.

c. Beamwidth Elevation

Like the previous item, the elevation beamwidth represents the vertical antenna beamwidth, which is again related to the half power points. The value of the vertical beamwidth is also measured in degrees (deg.).

d. Antenna Polarization

This parameter indicates the direction of the oscillation of the electric field vector of the emitter's transmitted energy. In radiolink systems, antennas use linear polarization that can be either Vertical (VER) or Horizontal (HOR). Other types of polarizations such as Right Hand Circular (RHC) and Left Hand Circular (LHC) can be used depending on the desired deployment.

2. Antenna Specifications

The antenna selected to be used with all the collection systems is the model OWB-30, manufactured by Electro-Metrics, Inc. Among others, the OWB-30, an omni-directional antenna, was selected because of the suitability of its performance parameters for the imposed task. In order words, the capability is to first detect the presence of the signal in any incoming direction despite the compromise in gain due to its non-directivity nature. The following table describes in detail the antenna's parameters considered in the analysis.

Manufacturer	Electro-Metrics,Inc.
Model	OWB-30
Frequency	60-1000 MHz
Pattern	Omni
Gain	9.5 dBi
Beamwidth (H x V)	360 x 13 Degrees
Polarization	Vertical
Size	8.1 x 27.5 inches
Application	ECM / COMINT /COMMS
Platform	Ship / Ground

Table 3-1. Antenna's Performance Parameters. After [Ref. 6]

B. RECEIVER SUBSYSTEMS

COMINT receivers also face contradictory constraints regarding their performance, thus, making the choice of the perfect system dependable on trade-offs that have to be made by the user.

Wideband crystal video receivers (CVR) are a typical example of this situation. They are inexpensive and quite easy to implement. They also offer a high probability of intercept within the frequency band. On the other hand, some compromise has to be made regarding their sensitivity and frequency resolution. [Ref. 4]

The tunable RF (TRF) receiver technology is accomplished by placing narrow bandpass filters in the receiver front end. By doing so, an improvement in the frequency selectivity is achieved whereas the probability of interception decreases.

Instantaneous frequency measurement (IFM) receivers utilize a different technique. Phase differences proportional to frequency are created by routing the incoming signal into two or more paths of varying electrical lengths. These receivers present accurate frequency resolution while simultaneously covering a broad RF bandwidth. Therefore, spectral scanning is not required. As to drawbacks, IFM receivers present relatively poor sensitivity as well as an inability to discern incoming simultaneous signals. Crystal video and IFM receivers employ direct detection technology.

A different approach, which is widespread, is the frequency conversion receiver. This category is basically composed of superheterodyne circuits, channelized, microscan, and acousto-optics approaches.

Superheterodyne receivers are by far the must frequently used type in COMINT systems. The technology is well developed and quite simple to implement. By mixing the received high-frequency RF signals with a generated signal from a local oscillator (LO), an intermediate frequency (IF) signal is recovered. This resulting signal still maintains the exact same modulation characteristics of the incoming signal. Good frequency resolution and high sensitivity are achieved by scanning the LO signal. This technique, however, presents a rather slow response time that can be improved by using wideband local oscillators.

In the Channelized receiver approach a much more complex and therefore expensive technology is involved. A series of filters divide the incoming RF spectrum into discrete channels with each one having its own detector. Thus, wideband is achieved with short response time.

Microscan receivers, also known as "microsweep" or "compressive" receivers, are a special category of the scanning superheterodyne technique. The RF bandwidth in this case is swept in a very small time interval which is normally less than the duration of the incoming pulses. The time relationship of the output pulses is related to the input frequencies. The advantages of these type of systems are a nearly instantaneous operation allied to good resolution, wide dynamic range and simultaneous signal capability. Conversely the complexity of the system implies high cost and a rather limited bandwidth.

Acousto-optic (AO) receivers introduce relatively new technology. The signal processing is achieved with the use of Bragg cells. The key here is to convert the electromagnetic signals into acoustic waves which are then sampled with light beams. AO receivers and the microscan approach, in addition to having a high signal probability of intercept, also have positive aspects in common. Hybrid approaches can offer advantages in attempting to combine the desirable properties of more than one type of receiver. [Ref. 4]

1. Receiver Performance Parameters

The following performance parameters concerning the receivers were considered relevant to the research and therefore included in the comparison evaluation. These parameters will also be used in the scenario simulation generated by PD in order to evaluate the detection ranges for each pair of collectors and emitters.

a. Modulation Types Receivable

This parameter is related to the type of modulation used by the transmitted signal that the receivers are able to receive. Such modulation schemes include AM, FM, SSB among others.

b. Frequency Range

This is the system's operational frequency range described in terms of its minimum and maximum receivable frequency, stated in megahertz (MHz).

c. Receiver Sensitivity

This parameter specifies the minimum receivable signal power taking internal noise into consideration. Sensitivity is expressed in decibels referenced to power in miliwatts (dBm) and its expression is derived by the Equation A-10 in the Appendix A. The sensitivity value provided by the system manufacturers in this simulation were given in terms of IF bandwidth, Noise Figure and Signal-plus-Noise-to-Noise ratio ((S+N)/N). Notice that Equation A-10 was derived in terms of Signal-to-Noise ratio (S/N) instead of (S+N)/N ratio. Therefore a conversion is mandatory prior to calculating the sensitivity value. The conversion is given by this identity

$$(S/N)_{dB} = 10 \cdot \log \{ [10 \wedge 0.1 \cdot [(S+N)/N]_{dB}] - 1\} \qquad (1)$$

When the Signal-to-Noise ratio is much higher compared to the unity, the (S+N)/N ratio can be approximated to the S/N ratio.

d. IF Bandwidth

IF bandwidth represents the intermediate frequency bandwidth in kilohertz (kHz). The IF is generated after a frequency down conversion in the demodulation process. The IF bandwidth limits the receiver internal thermal noise and therefore plays a vital role in the sensitivity of the receiver.

e. *Signal-to-Noise Ratio*

The Signal-to-Noise ratio (S/N) expresses in decibels the amount by which a signal level exceeds the competing noise.

f. *Noise Figure*

The Noise Figure is a measure of the noise produced by an actual receiver compared to an ideal receiver (i.e., one that is noiseless). It simply relates the signal-to-noise ratio of the output signal from the network to the signal-to-noise ratio of the input signal. It can be interpreted as the degradation of the signal-to noise ratio by the network. [Ref. 7]

2. Receiver Description

The following collecting systems were selected among several others to compose this evaluation.

a. *VHF-UHF Search Receiver ESMA*

ESMA is a processor-controlled search receiver designed by the German Company Rohde & Schwarz for fast radiomonitoring in the VHF/UHF spectrum. A standard stand-alone configuration consists of Search Receiver ESMA including control software and an IBM-compatible PC, which is operated via keyboard, mouse and VGA monitor. The PC communicates with the receiver via a high-speed transputer link and a link adapter which is to be installed in the PC. The control software operates under MS-Windows™ 3.1. The scope of ESMA applications ranges from statistical channel monitoring and dialog-based searching and identifying to continuous scenario monitoring of frequency bands. The monitoring of frequency-agile systems or burst transmissions is also possible thus allowing ESMA to detect emitters using Electronic Protection techniques. The receiver itself is a double-heterodyne receiver. The tuners are provided with a tracking selection so as to reduce the total signal load. The stand-alone configuration can be upgraded to a standard monitoring system including extracting tools for off-line analysis and linking of several standard systems to form a multi-position system. Figure 3.1 shows a view of the receiver and the controller as well. [Ref. 8, Ref. 9, Ref. 10]

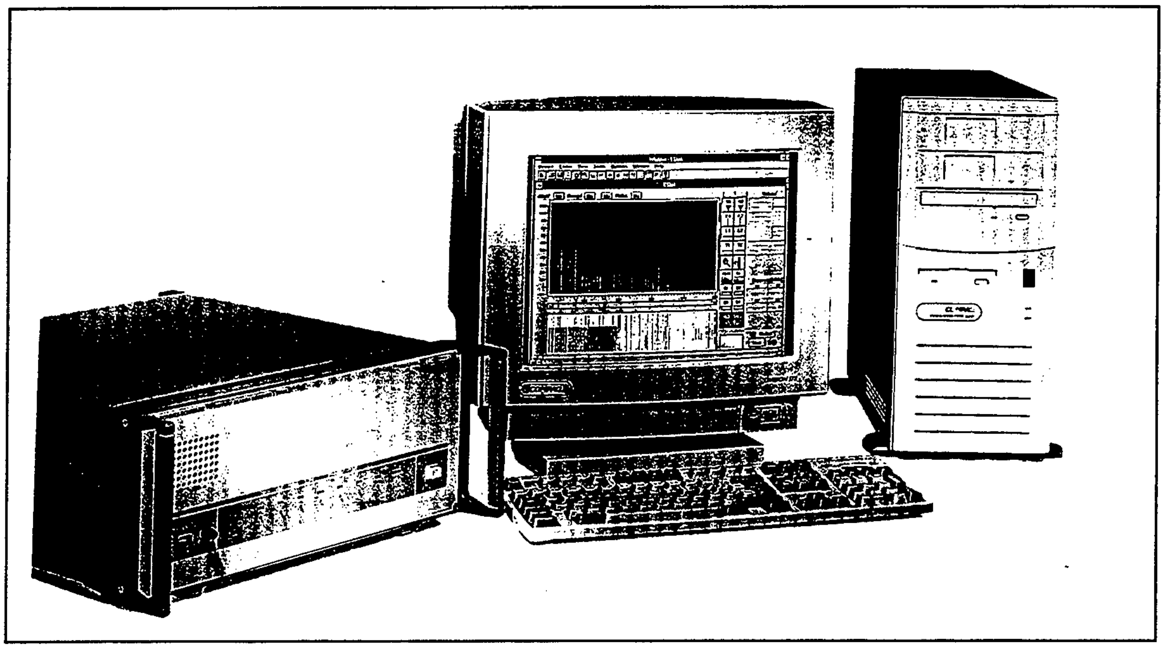

Figure 3-1. VHF/UHF Search Receiver ESMA and Controller

b. RA3720 VHF/UHF Receiver

The RA3720 series of COMINT receivers is manufactured by the British company RACAL Radio and is suitable for use in many types of surveillance and monitoring systems in the frequency range of 10 kHz to 1 GHz. It uses digital signal processing and microprocessor technologies to give claimed improvements in configurability and flexibility allowing the system to operate in crowded electronic signal environments. Comprehensive channel and frequency scanning facilities are built into the basic receiver. These include the ability to scan multiple frequency ranges and to set up mixed frequency/channel scan routines. Specific channels or frequency ranges within a scan range may be omitted from the scan. RA 3720 features AM, FM and SSB/CW demodulation facilities. The IF signal display provides the operator with a visual display of the signal environment. The receivers include a remote control capability which allows control of all receiver functions. The receivers are easily integrated into computer controlled systems and a dedicated control unit is also available. Comprehensive Built-in-Test-Equipment (BITE) locates any faults to module level and may be controlled remotely as well as from the front panel. The equipment is also suitable for operation in fixed and transportable applications. Figure 3-2 displays the RA 3721 receiver layout. [Ref. 8, Ref. 9, Ref. 11]

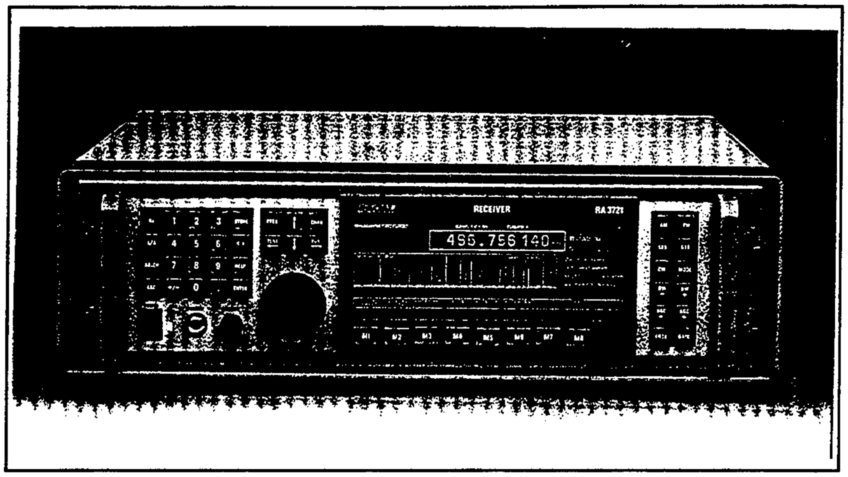

Figure 3-2. RA 3721 VHF/UHF Receiver

c. WJ-8615P VHF/UHF Compact Receiver

The WJ-8615P VHF/UHF compact receiver is a microprocessor-controlled receiver designed by the American company Watkins-Johnson and is intended to monitor or search the 20 MHz to 1600 MHz frequency range. Three IF bandwidths, ranging from 3.2 kHz to 8 MHz are provided with the unit. Two additional bandwidths are readily accepted giving a total of five selectable bandwidths. AM, FM, CW, and pulse detection modes are provided with the standard receiver. Independent sideband (ISB), for upper, lower, or simultaneous upper and lower sideband detection, is available as an option. The Scan-Step-Lockout function of the WJ-8615P provides the capability of stepping through a sequence of preprogrammed discrete frequencies in search of signal activity. Associated with the scan mode, the lockout feature permits an operator to exclude portions of the frequency segment from the scan to prevent undesired signals from interrupting the scan. Logging is a standard WJ-8615P feature which provides a permanent record of signal activity without host supervision and with a minimum of external equipment. When enabled, a serial port sends detailed information about each intercepted signal to a compatible printer or terminal. The printer shows the date and time a scan or step sequence is initiated and provides a description of the new sequence. Each acquired signal is then logged by date, time, RF frequency, and signal strength in dB. The WJ-8615P also outputs the logged data in Frequency Shift Keying format for direct recording onto audio tape. [Ref. 8, Ref. 9, Ref.12]

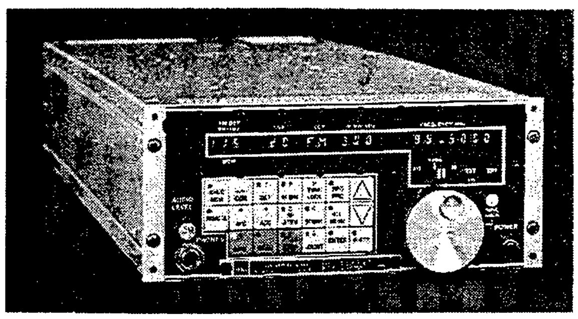

Figure 3-3. WJ-8615P VHF/UHF Compact Receiver

d. TRC 622 Interception Receiver

TRC 622 is an interception receiver manufactured by the French company Thomson-CSF. It is designed to meet new EP threats, particularly frequency-hopping or free channel search transmissions and burst transmissions. The scanning rate is designed to provide a (claimed) high detection probability on brief transmissions and short frequency-hopping dwell times. It belongs to the TRC 620 family of receivers. The family includes three receivers to cover all or part of the HF/VHF/UHF frequency range. The TRC 622 itself covers from 20 to 1350 MHz. Integrated as system front end components, these sensors provide a view of phenomena occurring in the spectrum and then allow fine analysis of the detected transmissions in categories such as occupation rate and activity per sub-range. The receivers can be remotely controlled via standard serial and parallel interfaces. The equipment is designed for all types of strategic and tactical applications for army, air force, navy, and paramilitary units. Figure 3.4 shows the receiver layout. [Ref. 8, Ref. 9]

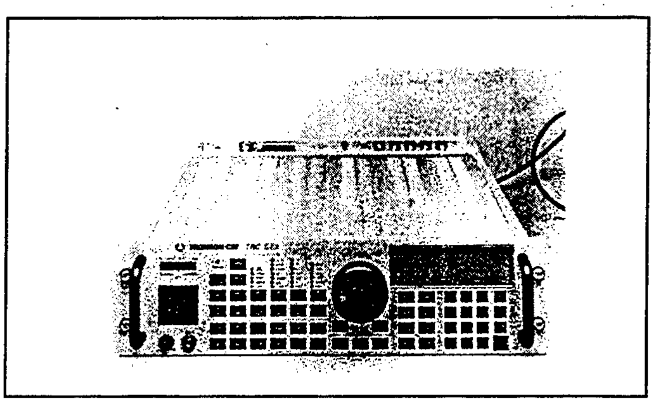

Figure 3-4. TRC 622 Interception Receiver

3. Summary Comparison Table

Table 3.2 provides a comparison table summarizing the important parameters considered in this study, thus allowing a better visualization of each system's features.

Receiver	ESMA	RA 3720	WJ-8615P	TRC 622
Manufacturer	Rohde & Schwarz	RACAL Radio	Watkins-Johnson	Thomson
Nationality	Germany	UK	USA	France
Modulation Type	AM/FM	AM/FM/CW SSB/FSK	AM/FM CW/Pulse	AM/FM
Frequency Band	20 to 1300 MHz	20 to 1000 MHz	20 to 1600 MHz	20 to 1350 MHz
Sensitivity	-97 dBm	-113 dBm	-107 dBm	-107 dBm
IF Bandwidth	15 kHz	3 kHz	6.4 kHz	10 kHz
Signal to Noise Ratio - (S+N)/N	25 dB	13 dB	17 dB	N/A
Noise Figure -NF	10 dB	13 dB	12.5 dB	N/A

Table 3-2. Receiver Summary Comparison Table

IV. COMMUNICATION SYSTEMS

The comparative evaluation was based on four data/voice communication systems, including a SATCOM radio and a cellular phone in the VHF/UHF band, selected from the many available on the market. These transmitters are representative of the potential emitters that the COMINT systems, described in the previous chapter, have to collect against. Since the emitters in question utilize different types of propagation, such as LOS and satellite, specific antennas have to be associated with each particular case. The selected antenna subsystems as well as their performance parameters and characteristics are described in Section A. Section B gives an insight into the transmitter subsystems, specifying the performance parameters needed for the evaluation and exploring the system capabilities as well as their current deployment status in the world military environment.

A. ANTENNA SUBSYSTEMS

In the case of the communication systems, the role of the antenna subsystem differs quite a bit from the COMINT case seen in the previous chapter. The intent is no longer to monitor a broad spectrum but, instead, to ensure the known signal is transmitted efficiently from emitter to receiver. Depending on the transmission frequency band and the type of propagation path (e.g., LOS, troposcatter, meteorburst), specific designs have to be achieved in order to make the antennas capable of accomplishing the task. Tactical situations sometimes demand low probability of interception. Therefore, higher directivity is required as in the case of satellite transmissions. Trade-offs between performance parameters are still key to a successful design.

1. Performance Parameters

Although a different type of antenna is required for each particular propagation method used by the emitters, the performance parameters of interest remain the same for all the antennas. These parameters were already described in subsection A.1 of the previous chapter.

2. Antennas Specifications

Considering the propagation methods involved and the associated parameters requirements, the following antennas were selected to operate with the transmitter subsystems.

a. Line-of-Sight (LOS) Propagation

Due to the nondirectivity criteria, the antenna selected to be used with the LOS transmitter/transceiver subsystems is the same one chosen to be used with the collection systems. The model OWB-30, manufactured by Electro-Metrics, Inc. is also suitable for VHF/UHF LOS communication links. Even though cellular phones have their own portable antennas, the OWB-30 was used as the phone antenna in the current evaluation. This simplified the modeling process. The antenna specifications and features were provided in Chapter III.

b. Satellite Propagation

The model SAT-100 manufactured by Electro-Metrics, Inc. achieves the requirements necessary to establish a UHF communication satellite link and therefore was selected to perform that task in the current evaluation. The characteristics of this model are described in the table below.

Manufacturer	Electro-Metrics,Inc.
Model	SAT-100
Frequency	240-400 MHz
Pattern	Steerable Beam
Gain	6.8 dBi
Beamwidth	N/A
Polarization	RHCP
Size	N/A
Application	COMM/COMINT/ESM
Platform	Ground/shipborne

Table 4-1. SAT-100 UHF Satellite Antenna . After [Ref. 6]

B. TRANSCEIVER/TRANSMITTER SUBSYSTEMS

The technology of broadcasting radio signals through the atmosphere in order to establish a communication channel has been well-dominated by man since the early years. However, with the advent of state-of-the-art monitoring systems and jamming devices, such areas had to be revisited to counter the imminent threat. The trend of Information Warfare imposes high demands on low probability of interception and electronic protection features (i.e. Anti-Jamming) for the emerging systems. Techniques such as spread-spectrum transmissions are very widely deployed nowadays, thus making the intelligence tasks even harder to accomplish. To combat signal fading and multipath interference, communication systems designers must utilize diversity techniques.

1. Performance Parameters

For the transceivers/transmitters subsystems, the parameters taken into consideration in this analysis are described in the following subsections. As in the previous chapter, these parameters also were used as input data for a range prediction simulation, run with the aid of the program PD.

a. Frequency Range

This is the equipment's operational frequency range described in terms of its minimum and maximum transmittable frequency, stated in megahertz (MHz).

b. Transmitter Power

This is the average signal power transmitted by the transceiver/transmitter measured in watts (W) at the antenna feed.

c. Modulation Capability

This parameter defines the types of modulation that the equipment is able to perform when transmitting the information.

2. Transceivers/Transmitters Description

The following transceivers/transmitters were selected among several others to compose the potential emitters database. The criteria used was modernity of technology, availability of technical parameters from the manufacturer and literature, and diversity of nationality whenever possible.

a. ERM 9000 VHF/UHF Shipborne Transceiver

The ERM 9000 transceiver is designed by the French company Thomson-CSF. It has been used for tactical links aboard ships or land stations. The ERM 9000 operates in the AM mode in the VHF band, or AM and FM in the UHF band. It has capabilities for fixed frequency or low, fast frequency-hopping applications, voice, crypto-voice, telegraphy, data and NATO links. It has a modular design using microprocessor hardware. The ERM 9000 and its external central unit are designed with a variety of digital or other interfaces for integration within any communication system or to operate jointly with existing earlier generation equipment. It was introduced in 1986 as the standard equipment in the French Navy, but it is also in service in the Dutch Navy. [Ref. 8]

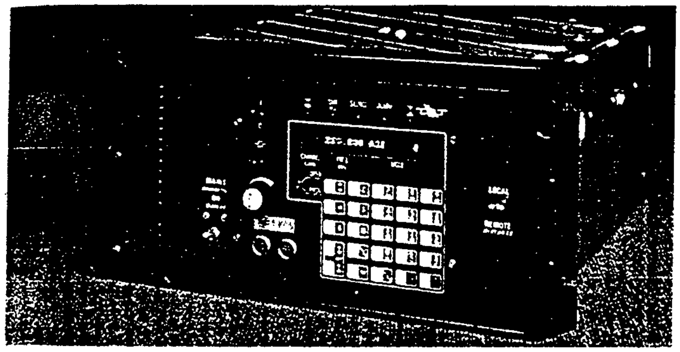

Figure 4-1. ERM 9000 VHF/UHF Shipborne Transceiver

b. SECOS 400 VHF/UHF ECCM Radio

SECOS 400 is designed by the German company Rohde & Schwarz for stationary, land-mobile or shipboard use. The radio integrates COMSEC and TRANSEC, digital encryption, medium speed frequency-hopping, collision-free operation of a large number of networks and COMSEC/TRANSEC interoperability with SECOS 610 UHF transceivers for airborne use. The SECOS 400 product line comprises: transceivers, transmitters, receivers (VHF, UHF or combined VHF/UHF), control units, a data processor and a key entry device. Have Quick ECCM versions of this generation type of radio are being used by NATO. [Ref. 8]

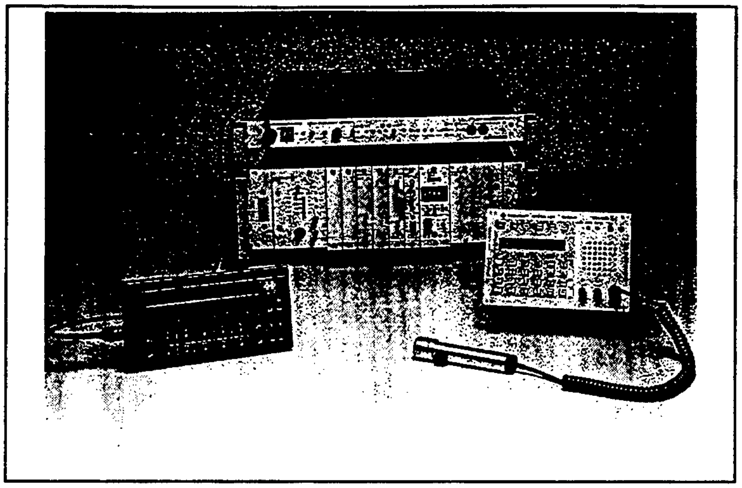

Figure 4-2. SECOS 400 VHF/UHF ECCM Radio

c. AN/WSC-3 UHF SATCOM/LOS Transceiver

The AN/WSC-3 is designed by the American company E-Systems, Inc. and is the US Navy's standard UHF Satellite terminal and Line-Of-Sight (LOS) transceiver. It was developed to serve as the US Navy's new generation ship/submarine terminal for Fleet Satellite Communication System. The system has several LOS and SATCOM versions. The US Navy has contracted with E-Systems to upgrade the WSC's anti-jam capability to a Have-Quick II capability as well as to add DAMA compatibility to the SATCOM version. The AN/WSC-3(V) is currently in use by all US armed services and by the armed forces of many countries such as Australia, Brazil, Canada, and the UK.

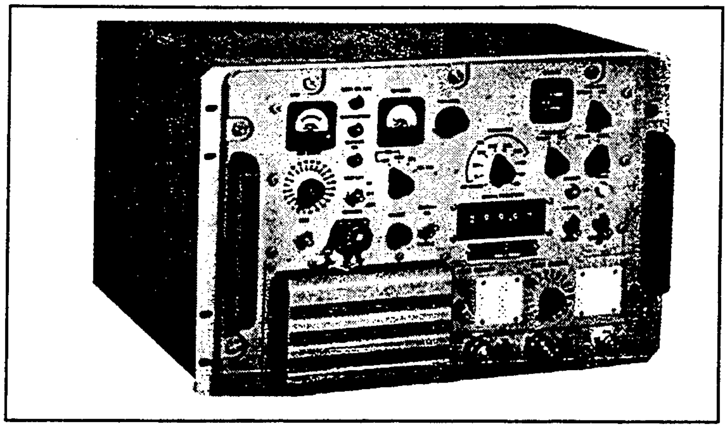

Figure 4-3. AN/WSC-3 UHF SATCOM/LOS Transceiver

d. QCP 800 Cellular Phone

QCP-800 is a dual mode Cellular Phone system manufactured by the American company Qualcomm. It operates in the digital mode using code division multiple access (CDMA) but it is also analog capable when traveling in areas without CDMA. The CDMA technique for commercial cellular phones, first developed by Qualcomm, is one step beyond the wide spread TDMA digital mode. CDMA eliminates most causes of background noise, hand-off and reception noise. Besides, this technology ensures that conversations are always coded for privacy, thus, eliminating cross-talks. CDMA is a form of spread spectrum that increases the channel capacity and allows more users to benefit from the entire spectrum. Moreover, it offers a higher jam resistance and low probability of interception (LPI) which makes the task of monitoring even harder for surveillance systems.

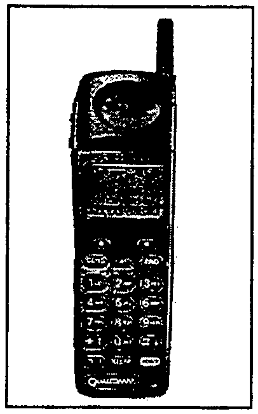

Figure 4-4. QCP-800 CDMA Cellular Phone

3. Summary Comparison Table

Emitter	ER 9000	SECOS 400	WSC 3	QCP 800
Manufacturer	Thomson	Rohde-Schwarz	E-systems	Qualcomm
Nationality	France	Germany	USA	USA
Propagation	LOS	LOS	Satellite	Cellular
Frequency Range	100-400 MHz	100-400 MHz	225-400 MHz	824-848 MHz
Transmitter Power	40 W	300 W	100 W	0.6 W
Modulation Type	AM/FM	AM/FM	AM/FM	PSK

Table 4-2. Summary Comparison Table

V. ANALYSIS AND CONCLUSIONS

A. DETECTION RANGES

Probably one of the most efficient ways to evaluate the selected COMINT systems is by comparing their detection ranges when collecting against several types of communication systems. The detection range is intimately related to the sensitivity of the COMINT receivers as well as to the transmitted power and antenna gain. Appendix A describes how these parameters are related in a LOS communication link. Sometimes atmospheric phenomena such as trapping and ducting occur and enhance or degrede the detection range. Therefore, two distinct situations were considered to evaluate the systems: Detection without Ducting and Effects of Ducting in the Detection Ranges.

1. Detection Without Ducting Effects

Passive Detection (PD) was used to evaluate the detection capability of the COMINT systems, presented in Chapter III, when collecting against the communication systems described in Chapter IV. However, PD does not account for ducting and trapping in its propagation modeling routines. Other limitations and assumptions apply and they are specified in Appendix D. PD uses several calculation routines to determine whether a signal can be passively detected by a receiver. These routines are described in detail in Appendix E. The calculations utilize the systems' performance parameters described earlier in

Chapters III and IV. These parameters are defined and input by the user in appropriate files throughout the simulation. Several databases are created with these files and are sorted by function such as collectors, emitters, antennas and platforms. Thus, all sorts of deployment combinations are made available to the user to allow the creation of any desired order of battle (OB). The geographical area -- Marden Square 413 -- described in Chapter II is created by extracting the map from a built-in library. This is done by defining the coordinates (latitude and longitude) of the NE and SW corners of the area of interest. Relief and terrain data can be inserted in the simulation if available. For this evaluation, the terrain data for the area of interest was available in CD-ROM in Digital Terrain Elevation Data (DTED) format. Although PD has successfully input the CD-ROM data at the AFIWC computer facility, the PD version installed at the Naval Postgraduate School was incompatible. The difficulty may be do to different versions of the computer operating system and could not be resolved within the budget for this research. Therefore, relief contour was not considered in the study and multipath interference from the terrain nearby was not taken into account. However, this effect turned out not to be a significant problem since most of the propagation occurred over the ocean body.

Each COMINT system was evaluated separately but positioned in the same physical location in the area of interest --Marden Square 413 -- described in Chapter II. A hypothetical route was created simulating an approaching platform (ship) carrying one emitter at a time. Figure 5-1 illustrates the scenario considered.

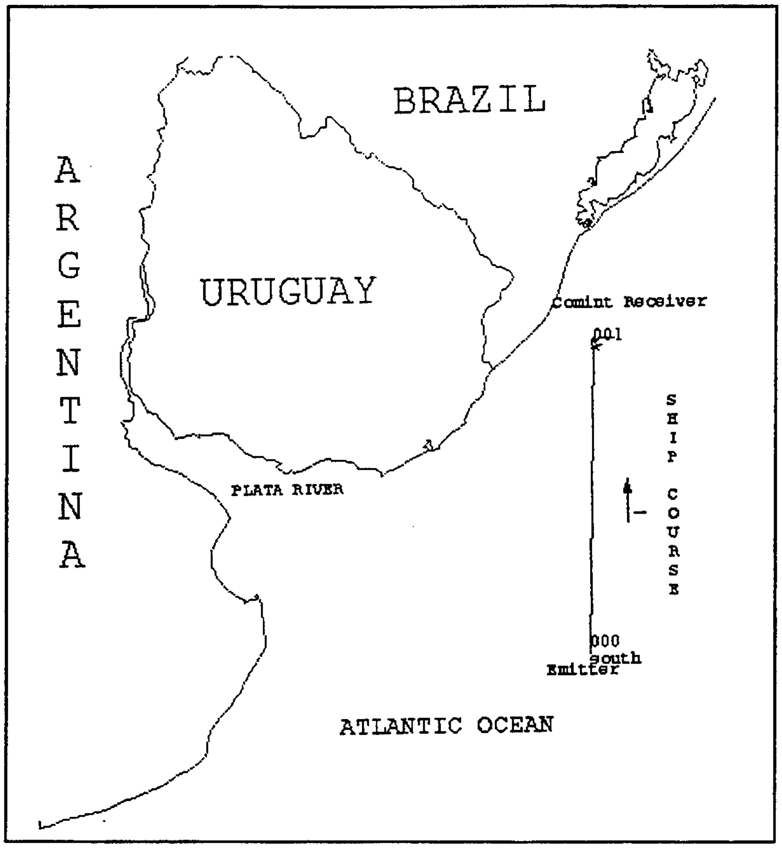

Figure 5-1. Detection Range Scenario

PD then conducted a route analysis and calculated whether detection was possible for each position defined in the route. The occurrence of detection was calculated by PD by comparing the receiver's sensitivity to the power received by the receiver at each position. When the latter matches or exceeds the first, detection is then possible. See Appendix E. The intervals between points on the route are user-defined and are directly related to the precision required. In this evaluation a space of one nautical mile was selected to enhance the quality of the evaluation. Two different types of propagation loss models, the Freespace loss model and Terrain-Integrated-Rough-Earth-Model (TIREM), are available to be defined by the user. The first takes into account only the wave spreading factor as it varies with distance and considers both emitter and receiver as isotropic sources. The latter takes into consideration irregular terrain features. These two propagation loss models are described better in Appendix E. In this study only the TIREM model was taken into account.

After running the evaluation for the specified route, PD allows the user to have the entire simulation translated into a summary file. This file provides output data for each position considered in the route, including emitter latitude and longitude, relative position to the receiver (azimuth, distance and elevation), received power, and position status (detected or not detected). Other parameters such as the receiver's coordinates and sensitivity and the emitter's ERP and frequency are also displayed. To provide an easy and efficient comparison among the COMINT receivers, the summary files for each individual receiver, related to the same emitter, were compiled in a common and condensed table. Only the parameters related to the furthest detection range possible were selected to be compared. The following results were obtained for each emitter separately.

a. ERM 9000

The table below shows the results obtained for the ERM 9000 transceiver when collected by all the receivers under evaluation.

Group Status	Receiver Name	Rcvr Type	Receiver Location	Rcvr Sens (dBm)	Power (dBm)	Band/ Beam	Emt Rcv'd	Emt Freq (Mhz)	ERP (dB)	Dist (km)	Az (deg)	Elev (deg)
Detected	ESMA	DOA	333000S 0520000W	-97.000	-96.814	1/1	1	100.0	22.510	82	0	0
Detected	RA 3720	DOA	333000S 0520000W	-113.000	-112.921	1/1	1	100.0	22.510	193	0	1
Detected	WJ-8615P	DOA	333000S 0520000W	-107.000	-106.850	1/1	1	100.0	22.510	130	0	0
Detected	TRC-622	DOA	333000S 0520000W	-107.000	-106.850	1/1	1	100.0	22.510	130	0	0

Table 5-1. Emitter: ERM 9000

b. SECOS 400

The table below shows the results obtained for the SECOS 400 transceiver when collected by all the receivers under evaluation.

Group Status	Receiver Name	Rcvr Type	Receiver Location	Rcvr Sens (dBm)	Power (dBm)	Band/ Beam	Emt Rcv'd	Emt Freq (Mhz)	ERP (dB)	Dist (km)	Az (deg)	Elev (deg)
Detected	ESMA	DOA	333000S 0520000W	-97.000	-96.841	1/1	1	100.0	31.261	119	0	0
Detected	RA 3720	DOA	333000S 0520000W	-113.000	-112.791	1/1	1	100.0	31.261	317	0	-1
Detected	WJ-8615P	DOA	333000S 0520000W	-107.000	-106.979	1/1	1	100.0	31.261	230	0	-1
Detected	TRC-622	DOA	333000S 0520000W	-107.000	-106.979	1/1	1	100.0	31.261	230	0	-1

Table 5-2. Emitter: SECOS 400

c. AN/WSC-3

The table below shows the results obtained for the AN/WSC-3 transceiver , when collected by all the receivers under evaluation.

Group Status	Receiver Name	Rcvr Receiver Type Location	Rcvr Sens (dBm)	Power (dBm)	Band/ Beam	Emt Rcv'd	Emt Freq (Mhz)	ERP (dB)	Dist (km)	Az (deg)	Elev (deg)
Detected	ESMA	DOA 333000S 0520000W	-97.000	-95.952	1/1	1	100.0	16.990	67	0	0
Detected	RA 3720	DOA 333000S 0520000W	-113.000	-112.845	1/1	1	100.0	16.990	106	0	0
Detected	WJ-8615P	DOA 333000S 0520000W	-107.000	-106.608	1/1	1	100.0	16.990	84	0	0
Detected	TRC-622	DOA 333000S 0520000W	-107.000	-106.608	1/1	1	100.0	16.990	84	0	0

Table 5-3 Emitter: AN/WSC-3

d. QCP-800

The table below shows the results obtained for the QCP-800, when collected by all the receivers under evaluation.

Group Status	Receiver Name	Rcvr Receiver Type Location	Rcvr Sens (dBm)	Power (dBm)	Band/ Beam	Emt Rcv'd	Emt Freq (Mhz)	ERP (dB)	Dist (km)	Az (deg)	Elev (deg)
Detected	ESMA	DOA 333000S 0520000W	-97.000	-95.584	1/1	1	824.0	4.271	39	0	0
Detected	RA 3720	DOA 333000S 0520000W	-113.000	-112.857	1/1	1	824.0	4.271	54	0	0
Detected	WJ-8615P	DOA 333000S 0520000W	-107.000	-105.944	1/1	1	824.0	4.271	48	0	0
Detected	TRC-622	DOA 333000S 0520000W	-107.000	-105.944	1/1	1	824.0	4.271	48	0	0

Table 5-4. Emitter: QCP 800

e. Summary Range Detection Table for the TIREM Model

The maximum detection ranges calculated by PD for the COMINT systems are summarized in the table below.

Emitters / Receivers	ER 9000	SECOS 400	AN/WSC-3	QCP 800
ESMA	82 km	119 km	67 km	39 km
RA3720	193 km	317 km	106 km	54 km
WJ-8615P	130 km	230 km	84 km	48 km
TRC 622	130 km	230 km	84 km	48 km

Table 5-5. Summary Range Detection Table for the TIREM Model

2. Effects of Ducting in the Detection Ranges

Ducting can increase the detection range by the COMINT receivers by several tens or even hundreds of miles, depending on the intensity of the phenomena, because the electromagnetic energy is trapped within the duct layers. Of course both the transmitter and collector must be in the same duct, otherwise ducting will degrade or even prevent collection capability.

PD does not account for ducting in its calculation routine. Therefore, the module PROPR of the EREPS software program family was utilized to extend the PD evaluation by modeling the atmospheric conditions for such phenomena. As shown previously in Chapter II, these conditions are not present all the time in the selected area but instead they are proven to have a statistical occurrence of

6% of the time. The atmospheric data for the area (Marden Square 413), calculated by SDS and presented in Chapter II, were then utilized as input for the PROPR module, allowing the program to account for ducting. One of the outputs provided by PROPR, and the one selected in this evaluation, is a "Propagation Loss" by "Range" graph. The propagation loss is expressed in terms of decibel (dB) and the range in terms of nautical miles (NM). By default, this graph presents a Freespace propagation loss and a No-ducting propagation loss as well. However, a third option can be overlaid on the graph to display a ducting propagation loss, if the atmospheric parameters are modified according to the statistical data obtained by SDS previously. To better assess the effects of ducting, all three types of propagation losses were calculated for each receiver, in both the VHF and UHF band separately. A propagation threshold for the collecting system related to each emitter is also displayed in the graph as dashed lines. These thresholds are calculated as the decibel difference between the effective radiated power of the emitter and the COMINT receiver's sensitivity. Thus, propagation losses less than the threshold represent intercept capability. Conversely, when the propagation losses exceed the threshold level, the receiver is unable to detect the presence of a signal. The following results were obtained for each specific system:

a. *VHF/UHF Search Receiver ESMA*

Figure 5.2 reveals the performance of the ESMA receiver when collecting against emitters in the VHF band. The Freespace Loss curve represents the simplest and ideal case of electromagnetic wave propagation. Free space is defined as a region whose properties are isotropic, homogeneous, and loss-free. That means that the earth's atmosphere influences are not taken into account. In this situation the electromagnetic wave front spreads uniformly in all directions from the transmitter and its energy level decreases inversely with the square of the distance. The No Ducting case takes into account effects such as sea-surface reflection, atmospheric refraction, scattering from inhomogeneties in the atmosphere, and diffraction from the bulge of the earth's surface. [Ref. 5] The detection thresholds for the two emitters, the ERM 9000 and the SECOS 400 are respectively 150 dB and 160 dB of allowable propagation loss. These thresholds intercept the actual No-ducting propagation loss curve at 35 (65 km) and 45 NM (83 km). This is the detection range calculated by EREPS for this specific receiver. A substantial decrease in propagation loss can be observed, on the order of 50 dB, when ducting is taken into account. This represents a tremendous increase in detection range; the Ducting propagation loss curve does not intercept the two emitters' thresholds in the 100 NM (185 km) range considered.

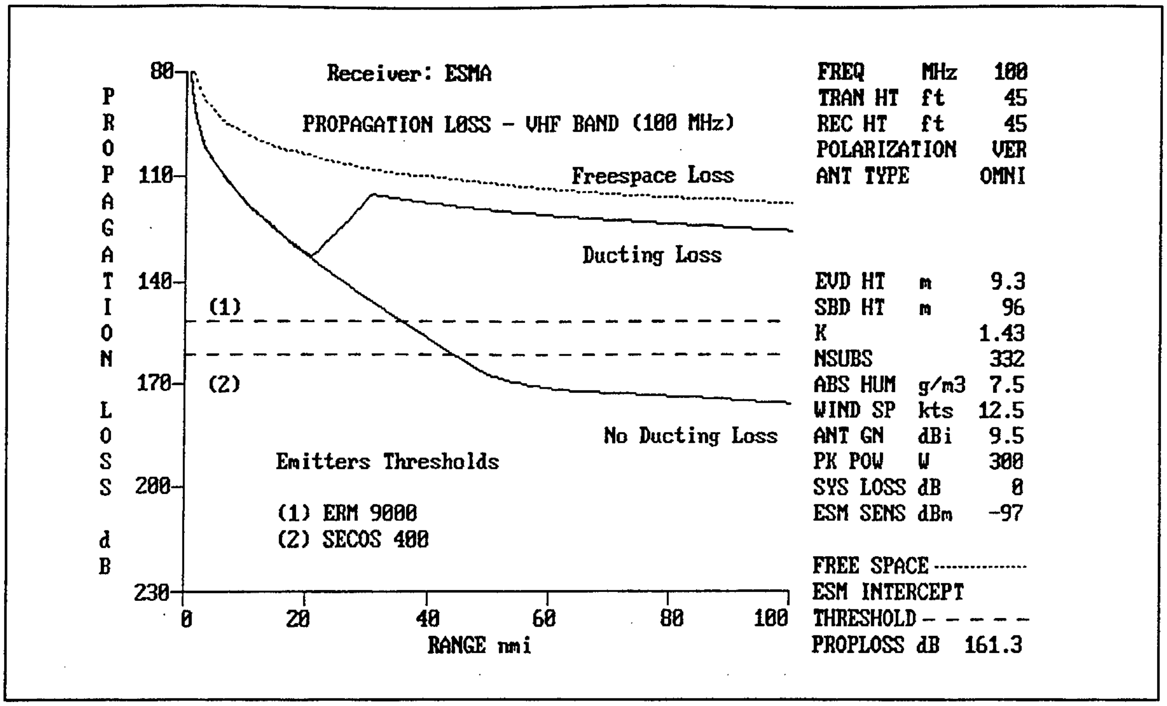

Figure 5-2. Propagation Loss Versus Range in the VHF Band (100 MHz) for the ESMA Receiver

For the UHF case, two different frequencies were analyzed: 400 MHz for the AN/WSC-3 UHF Transceiver and 880 MHz for the QCP-800 cellular phone. In the first case, as shown in Figure 5-3, the AN/WSC-3 Threshold intercepts the "No Ducting" propagation loss curve at 28 NM (52 km). This is distance is shorter than in the VHF case due to the increase in frequency . When ducting is taken into consideration again the detection range extends beyond 100 NM (185 km) due to a reduction in propagation loss of up to 65 dB.

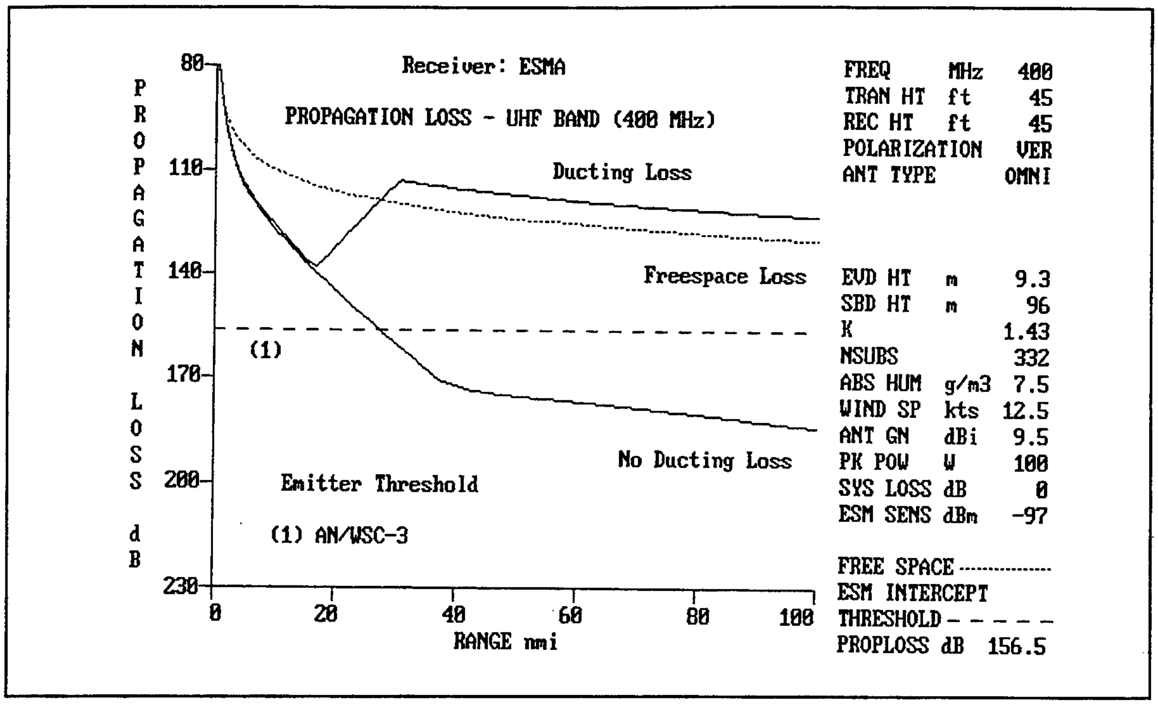

Figure 5-3. Propagation Loss Versus Range in the UHF Band (400 MHz) for the ESMA Receiver

In the second case, since the transmitted power of the cellular phone is much smaller and the operational frequency (880 MHz) is higher than the values used in the VHF scenario, the emitter thresholds intercept the "No Ducting" propagation loss curve in a much shorter distance: 15 NM (28 km). Between 15 NM (28 km) and 22 NM (41 km) detection is no longer possible even if ducting is considered and creates then a shadow zone. This is caused by the propagation loss being greater than the emitter threshold which is calculated to be on the order of 135 dB. However, for distances longer than 22 NM (41 km), detection is again made possible if ducting effects are considered. It might be noticed that the difference in propagation loss is rather small in the first 20 NM (37 km) for the Ducting and No-ducting scenarios. However, the difference increases with range and the Ducting propagation loss reaches values of 50 dB greater than the No-ducting case. This rather low value of propagation loss extends the detection ranges out to more than 100 NM (185 km). Figure 5-4 illustrates the phenomena.

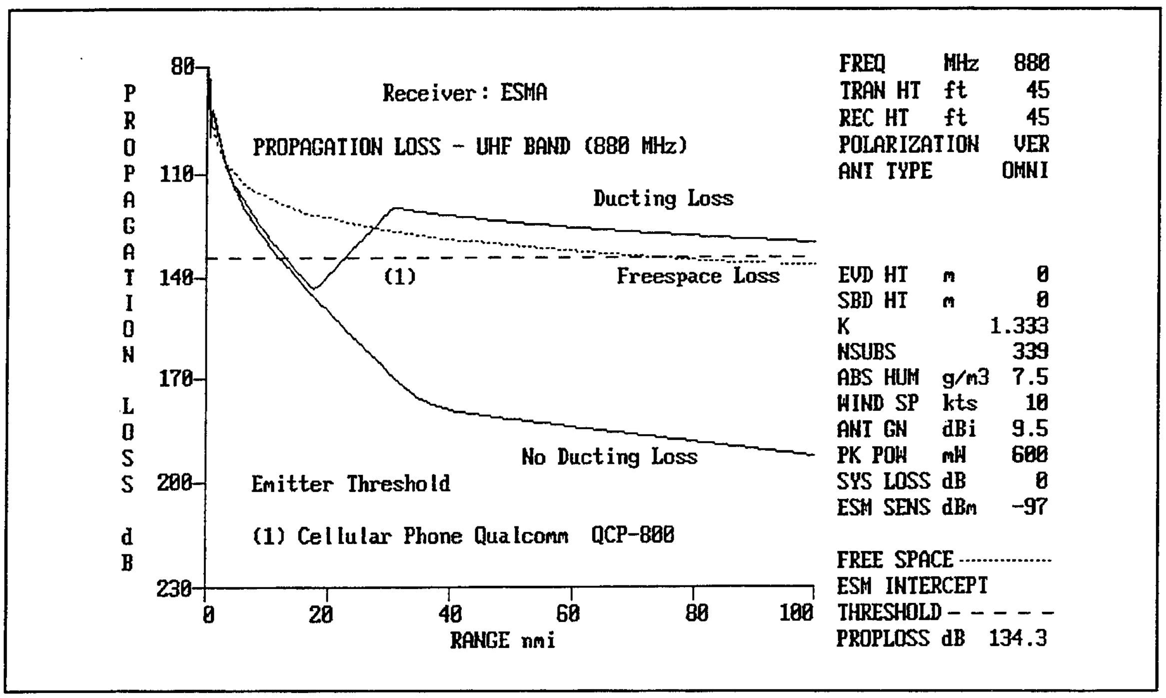

Figure 5-4. Propagation Loss Versus Range in the UHF Band (880 MHz) for the ESMA Receiver

b. RA 3720 VHF/UHF Receiver

Figure 5.5 displays the performance of the RA 3720 receiver when collecting against emitters in the VHF band. The detection thresholds for the two emitters, the ERM 9000 and the SECOS 4000 are respectively 170 dB and 180 dB of allowable propagation loss. The related detection ranges for these thresholds are 50 NM (93 km) for the ER 9000 and 100 NM (185 km) in the case of SECOS 400. As observed before in the previous receiver, the greater decrease in propagation loss occurs when ducting is considered. In this case, it reaches values of 60 dB, allowing long range detection as well.

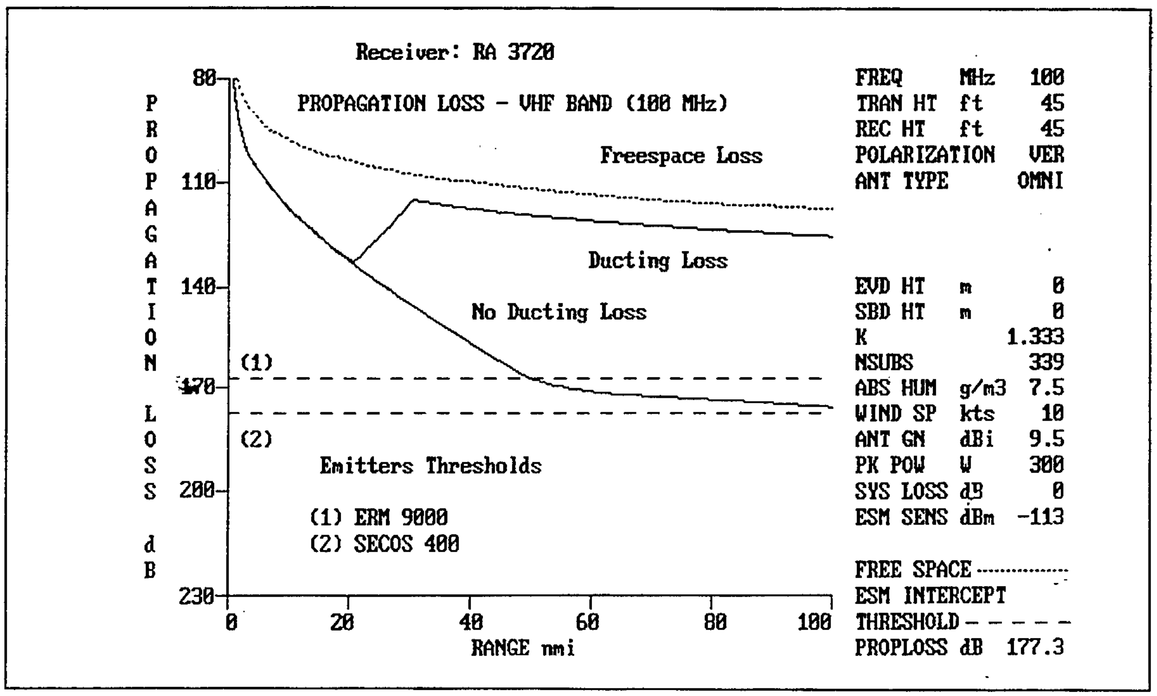

Figure 5-5. Propagation Loss Versus Range in the VHF Band (100 MHz) for the RA 3720 Receiver

For the UHF band, the AN/WSC-3 presents a threshold of 172 dB of permissible propagation loss translating into a detection range of 40 NM (74 km) when ducting is not taken into consideration. However, when such phenomena is considered the detection range increases considerably reaching values far beyond the 100 NM. This occurs because the propagation loss is extremely reduced by values up to 60 dB. Figure 5.6 illustrates the phenomena.

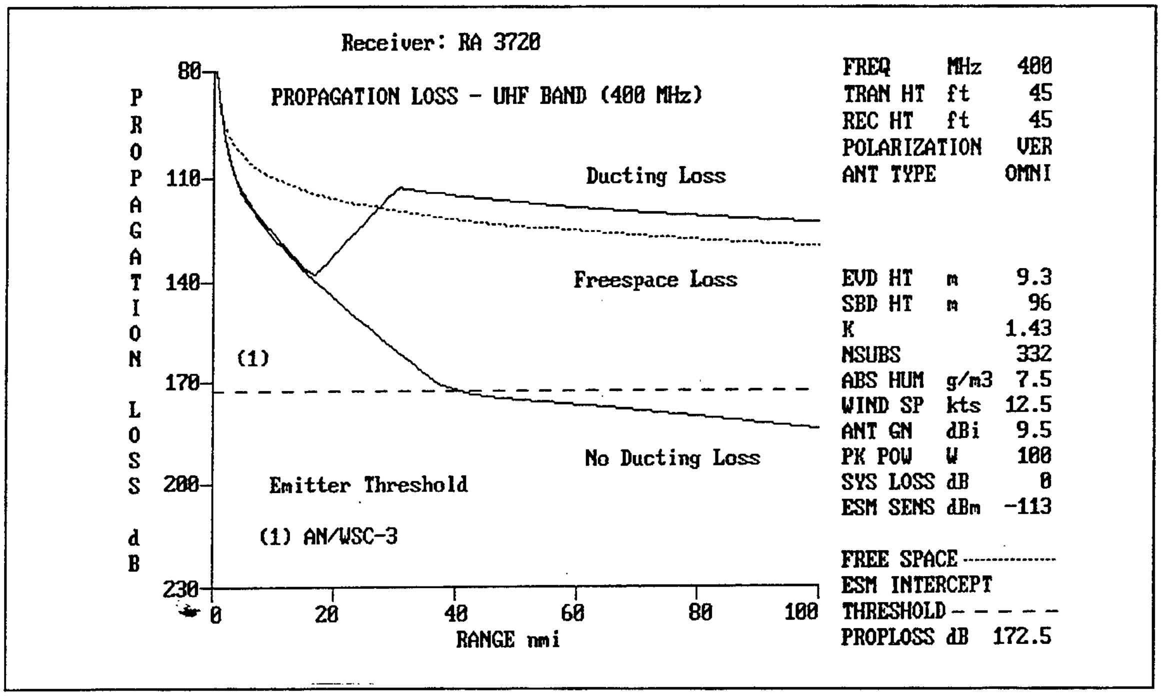

Figure 5-6. Propagation Loss Versus Range in the UHF Band (400 MHz) for the RA 3720 Receiver

In the case of the QCP 800, also in the UHF band, the threshold is 150 dB of allowable propagation loss. This limit translates into a detection range of 20 NM (37 km), where the threshold intercepts the actual no-ducting propagation loss curve. If ducting is taken into consideration the detection ranges extend far beyond that. It might be noticed in Figure 5-7 that the Ducting propagation loss curve does not intercept the emitter threshold at any range, which is contrary to what happened in the UHF case of the ESMA receiver.

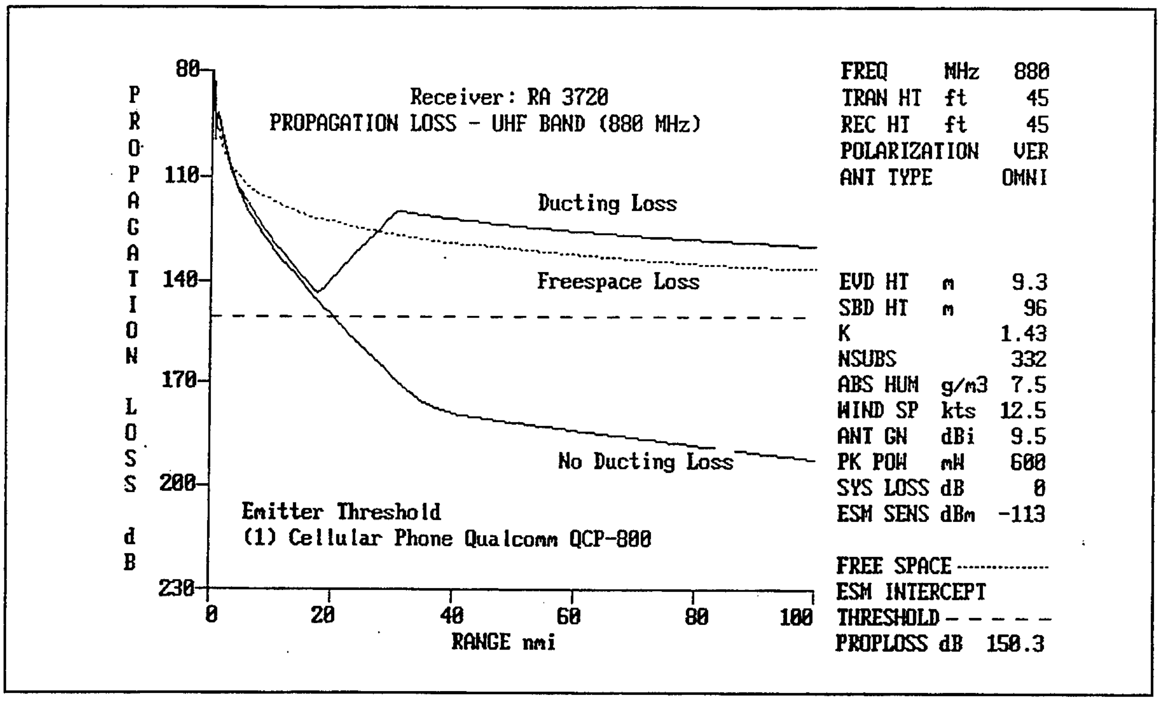

Figure 5-7. Propagation Loss Versus Range in the UHF Band (880 MHz) for the RA 3720 Receiver

c. WJ-8615P VHF/UHF Compact Receiver

In the VHF band, the emitters threshold of admissible propagation loss are 160 dB for the ERM 9000 and 172 dB for the SECOS 400. For the no ducting propagation scenario, the detection ranges are 45 NM (83 km) in the ERM 9000 case and 65 NM (120 km) in the SECOS 400 example. As occurred with the previous receivers, the ducting effects again extend the detection ranges far away by reducing the propagation losses by up to 55 dB for ranges greater than 50 NM (93 km). Figure 5-8 illustrates the results.

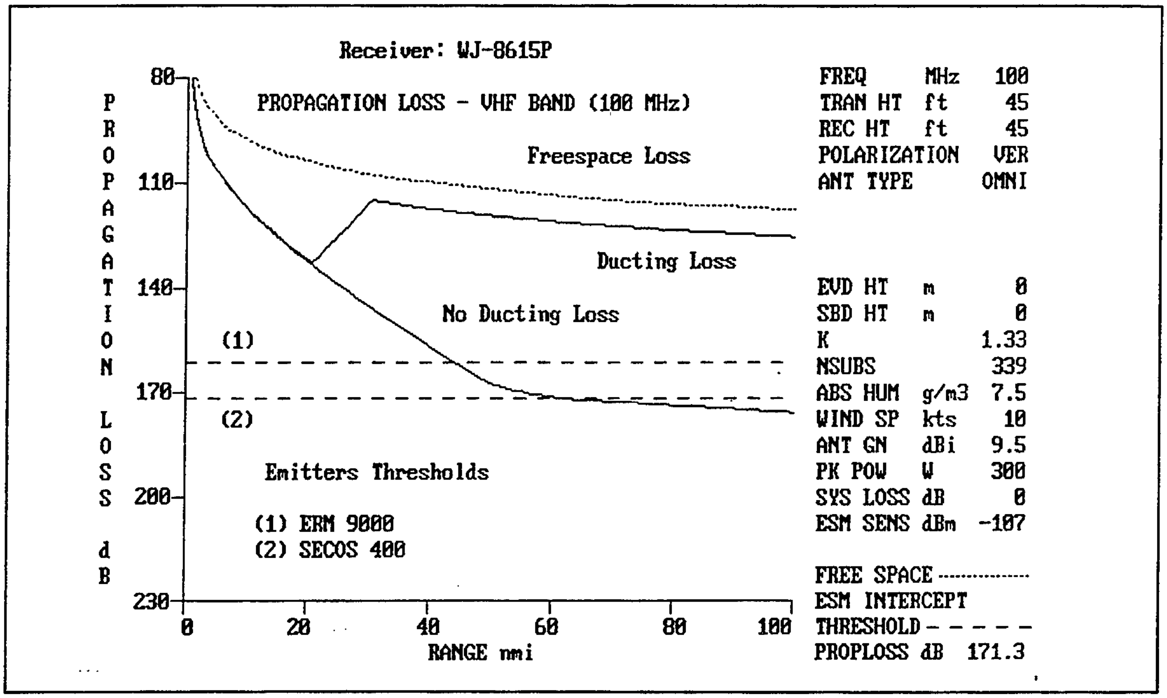

Figure 5-8. Propagation Loss Versus Range in the VHF Band (100 MHz) for the WJ-8615P Receiver

In UHF band, for the AN/WSC-3 case the threshold of permissible propagation loss reaches 168 dB indicating a detection range of 35 NM (65 km) when ducting is not considered. When the ducting effects are taken into account, once again the detection range is pushed to an extreme limit, far beyond the 100 NM (185 km) as shown in Figure 5.9.

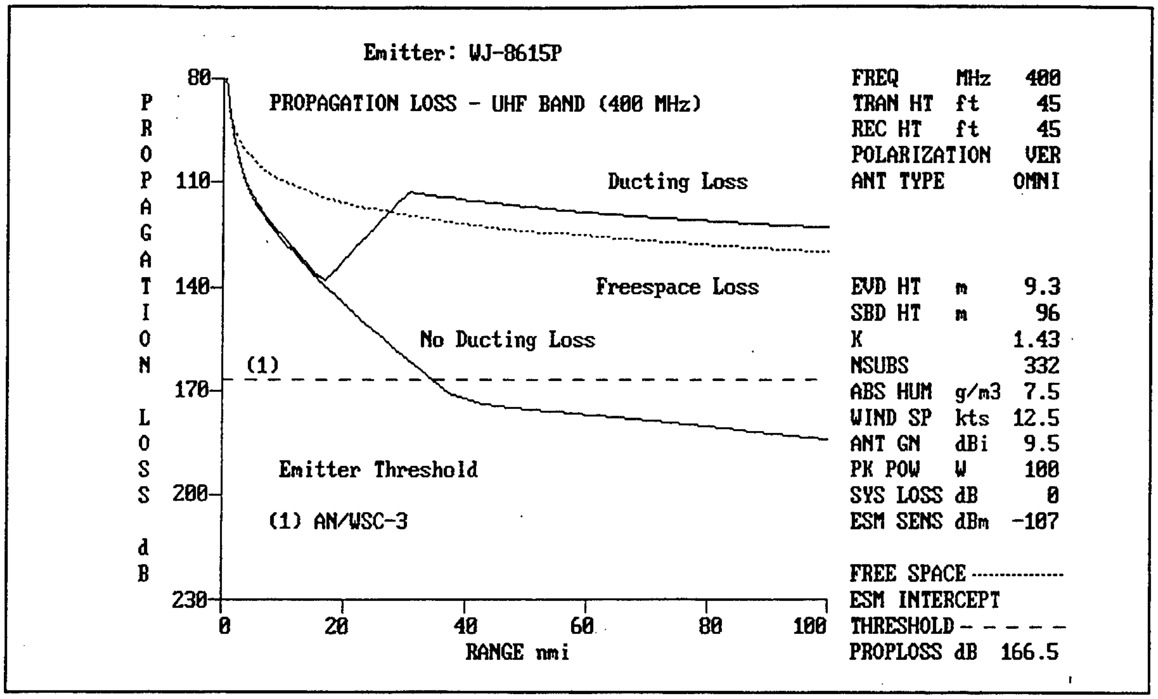

Figure 5-9. Propagation Loss Versus Range in the UHF Band (400 MHz) for the WJ-8615P Receiver

The QCP 800 cellular phone presents a threshold of 144 dB of allowable propagation loss with respect to the WJ-8615P receiver. By not considering ducting effects, the detection range is up to 19 NM (35 km). If ducting is taken into account the same pattern observed earlier repeats itself. Detection ranges increase remarkably due to a reduction in propagation loss of up to 65 dB. Figure 5-10 shows that the Ducting propagation loss curve again does not intercept the emitter threshold at any range.

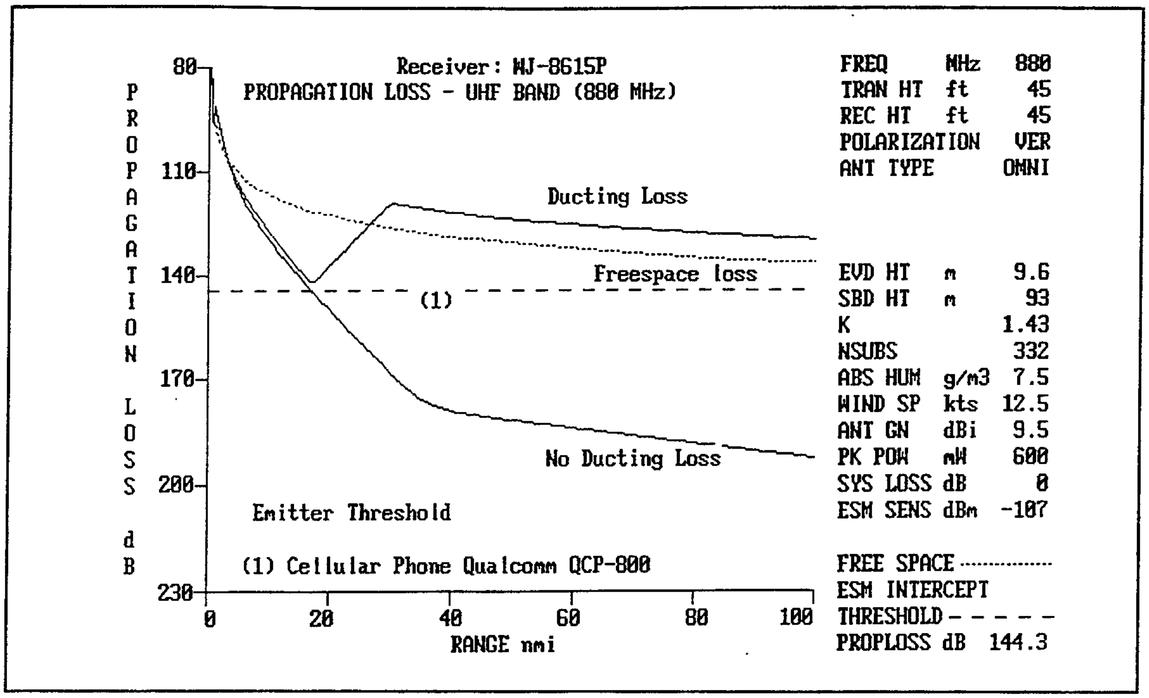

Figure 5-10. Propagation Loss Versus Range in the UHF Band (880 MHz) for the WJ-8615P Receiver

d. TRC 622 Interception Receiver

Since the TRC 622 interception receiver and the WJ-8615P receiver have the same sensitivity value (-107 dBm), the propagation results calculated by EREPS are the same for both systems, in the VHF and in the UHF band. The same observations made for the WJ-8615P apply in the case of the TRC 622.

B. FEATURES AND CAPABILITIES COMPARISON

There are other aspects besides detection range that should be considered when evaluating COMINT systems.

As mentioned in earlier chapters, advances in communications technology have diminished the probabilities of interception of communications signals by the collecting systems. The use of modulation schemes such as spread spectrum, for satellite and LOS radio communications, and more powerful access techniques such as CDMA, for cellular telephones, has made collection even harder to accomplish. Therefore, it is worth comparing the COMINT systems' capabilities to overcome such techniques. The scan rate of the receiver determines the capability for detecting short-burst frequency hopping transmissions. However, an increase in scan speed should not compromise the sensitivity of the receiver. Therefore, a trade-off has to be made depending on the threat to counter.

Another feature that has to be considered is the user-friendliness of such systems, including whether the man-machine interface is designed to permit the user to rapidly digest the information and make decisions. The speed of threats nowadays no longer allows for delayed, off-line analysis, but instead demands a rapid and immediate response. Computer-controlled receivers seem to fit this mold more appropriately.

The capabilities of the receivers to interface with recording systems is also an issue that must be evaluated. Mostly, signal collection recording is done for strategic purposes leading to a subsequent and more detailed analysis in more capable evaluation centers.

To allow better comparison, Table 5-6 summarizes and emphasizes the features and capabilities of the systems under evaluation.

Receiver	Scan Rate	Computer Controlled	Data Recording	User Friendly
ESMA	5 GHz/sec	YES	NO	YES
RA 3720	10 kHz/sec	NO	YES	YES
WJ-8615P	N/A	NO	YES	YES
TRC 622	1 GHz/sec	NO	UNK	YES

Table 5-6 - COMINT Systems' Features and Capabilities

C. CONCLUSIONS AND RECOMMENDATIONS

In the geographical area evaluated, the RA 3720 receiver, manufactured by RACAL, had the best performance in detection range due to its higher sensitivity. However, its scan rate is rather low and good performance when collecting against modern communications systems utilizing spread spectrum techniques is negated.

The fast scan rate of the TRC 622 receiver, manufactured by Thomson and the ESMA receiver, manufactured by Rohde & Schwarz, enable them to perform well against modern systems, even though they did not have the best detection range. The fast scan rates available in these systems allow them to counter and intercept the stealthy spread spectrum signals. As mentioned earlier, this capability is a "must have" in monitoring systems nowadays. The ESMA receiver is computer controlled and very resourceful in terms of man-machine interface, causing this system to have a considerable advantage over the remaining ones.

In conclusion, as an eventual deployment and/or acquisition suggestion , for the specific area studied, regarded that no cost constrains are imposed, the author would recommend the following systems in order of preference:

- VHF-UHF Search Receiver ESMA (Rohde & Schwarz)
- TRC 622 Interception Receiver (Thomson-CSF)
- RA 3720 VHF/UHF Receiver (RACAL)
- WJ-8615P VHF/UHF Compact Receiver (Watkins-Johnson)

APPENDIX A. LOS COMMUNICATION LINKS

This appendix summarizes the theory behind Line-of-Sight (LOS) communication links. Equations relating transmitter and receiver power, as well as other parameters intrinsically related to the propagation aspects, are derived.

Consider a simple transmit-receive LOS communication link where the transmitter power P_T is known. It is of primary interest to be able to calculate how much of this power the receive antenna can pick up at a specific distance from the emitter. An assumption is made that in the far field of the transmit antenna the waves are essentially plane and of uniform amplitude over any small region. The total power P_R incident on the receiving antenna is found by summing up the incident power density (Poynting vector) over the area of the receive antenna following the relationship

$$P_R = S_{av} A_{em} \qquad \text{(A-1)}$$

where P_R is the time-average available power at the antenna terminals for a lossless antenna aligned to pick up maximum power, and S_{av} is the time-average power density of the incoming wave. The effective area A_{em} (in square meters) is a measure of how effectively the antenna converts incident power density S_{av} (in watts per square meter) into received power P_R (in watts) and is given by

$$A_{em} = \frac{D_R \lambda^2}{4\pi} \qquad \text{(A-2)}$$

where λ is the signal wavelength and D_R is the directivity or directive gain of the receive antenna. If the transmit antenna were isotropic it would have power density at distance r of

$$S_{av} = \frac{U_{ave}}{r^2} = \frac{P_T}{4\pi r^2} \tag{A-3}$$

where P_T is the time-average radiated power from the transmit antenna. For a transmit antenna that is not isotropic but has directivity D_T and is pointed for maximum power density in the direction of the receiver the relationship is then expressed by

$$S_{av} = \frac{D_T U_{ave}}{r^2} = \frac{D_T P_T}{4\pi r^2} \tag{A-4}$$

Using Equation A-1, the receive power becomes

$$P_R = \frac{D_T P_T A_{em\,R}}{4\pi r^2} \tag{A-5}$$

where $A_{em\ R}$ is the effective aperture area of the receive antenna that is assumed to be pointed and polarized for maximum response. Combining Equations A-2 and A-5 the following relationship is obtained for P_R.

$$P_R = \frac{P_T D_T D_R \lambda^2}{(4\pi r)^2} \tag{A-6}$$

In practical cases, antennas are not lossless. The power available at the terminals of a transmitting antenna is not all transformed into radiated power, but rather the fraction *e* (radiation efficiency) of the available power. The power received by a receiving antenna is also reduced by the fraction *e* from what it would be if the antenna were lossless. The concept of gain was introduced to account for losses on an antenna and is defined as

$$G = e\,D. \tag{A-7}$$

The power transfer Equation (Equation A-6) is then modified to include lossy antennas just by replacing directivities by net gains leading to

$$P_R = \frac{P_T\, G_T\, G_R\, \lambda^2}{(4\pi\, r)^2} \tag{A-8}$$

This formula is very useful for calculating signal power levels in communication links. It assumes that there are no impedance mismatches at the transmit and receive antennas terminals, and that the transmit and receive antennas have identical polarization and are aligned for polarization match. It also assumes that the antennas are pointed toward each other for maximum gain. [Ref. 13]

Adapting Equation A-8, it can then be determined that the range that a receiver will detect a signal sent by a specific transmitter is

$$r = \sqrt{\frac{P_T\, G_T\, G_R\, c^2}{(4\pi)^2 f^2 P_R}} \tag{A-9}$$

where *c* is the speed of light and *f* is the operating frequency. The received power P_R can be expressed by:

$$P_R = K\, T_0\,(NF - 1)\, B\,(S/N) \tag{A-10}$$

where K is the Boltzmann's constant (1.3803 * 10^{-23} J/K), T_0 is the room temperature (17 ° C or 290 K), B is the IF bandwidth in Hz of the receiver, NF is the Noise Factor of the receiver (or Noise Figure when expressed in dB), and *(S/N)* is the Signal-to-Noise Power Ratio at the receiver. Line losses in the receiver can also be accounted for in this model by introducing a new factor L_{line} in Equation A-9. Finally, the maximum range that a particular signal will be received at a specific receiver can be calculated by introducing the minimum value of the receiver's Signal to Noise Ratio -- $(S/N)_{min}$. When S/N is minimum, Equation A-10 represents the smallest amount of signal power necessary to detect the signal in the presence of noise or, in other words, the receiver sensitivity. The results can be expressed in terms of Equation A-11.

$$r_{max} = \sqrt{\frac{P_T\, G_T\, G_R\, c^2}{(4\pi)^2 f^2 L_{line}\, K\, T_0 (NF + 1)\, B\, (S/N)_{min}}} \qquad \text{(A-11)}$$

APPENDIX B. ATMOSPHERIC PROPAGATION

There are four general categories of propagation associated with the atmosphere: ground wave propagation, space wave propagation, and scatter propagation.

Space wave is the type of propagation considered in this thesis since it occurs in the VHF, UHF, SHF ranges. The region in which this occurs is not "freespace" but rather the lower atmosphere (troposphere) where wave speed gradients can exist due to varying properties of the air, excluding free electron densities. Space waves usually travel in straight paths and are also called direct Line-of-Sight waves (LOS). Such signals can be reflected off objects such as buildings and are then called reflected waves.

The primary loss of signal strength for space waves, is due to the spreading of the wave front. The spreading loss varies as the inverse of the square of the distance ($1/r^2$). Unlike ground and sky waves, space waves are not affected by the ionosphere but instead, by the pressure, temperature and humidity of the troposphere; all of which affect the wave speed. The rate of change of these variables with respect to altitude determines the degree of refraction of the wave space.

The most severe degree of refraction occurs in a trapping layer, which bends the waves back toward the earth. A trapping layer produces a duct within which the electromagnetic waves are trapped. A duct's lower boundary can be either at the surface (surface duct) or above the surface (elevated duct). The transmitter must be in the layer for trapping to occur. Under such conditions a signal can propagate hundreds and sometimes thousands of miles. A duct is a "waveguide" so its influence on propagation is frequency dependent, and not all frequencies are "ducted".

The trapping phenomenon is most prevalent over or near large bodies of water where there is cold moist air at low levels and a rapid increase in temperature and decrease in humidity with increasing altitude. Ducting can be beneficial or harmful, depending on the application.

Terrestrial Microwave/(spacewave) Frequencies

Terrestrial microwave frequencies allow Line-of-Sightcommunications commonly used for long-distance voice communications. The path is illustrated in Figure B-1. The propagating wave loss is proportional to the square of distance; repeater spacing of 10 to 100 km are typical.

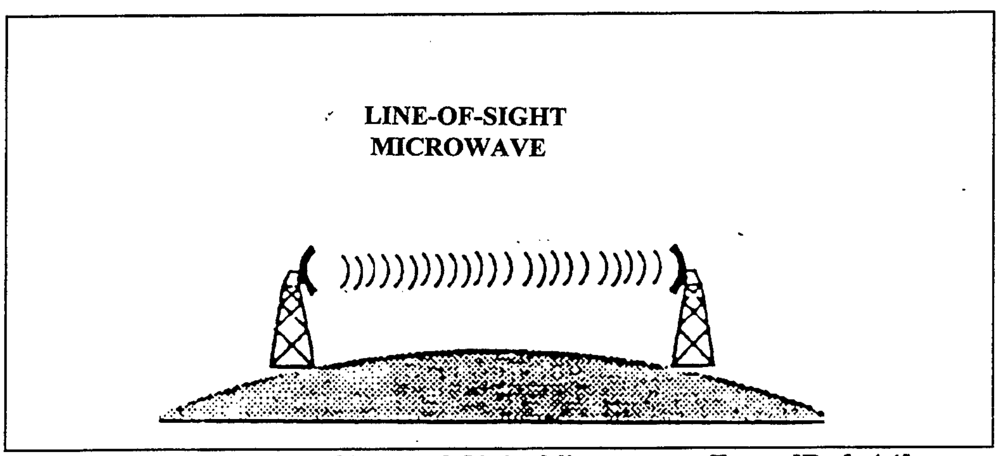

Figure B-1. Path of Line-of-Sight Microwave. From [Ref. 14]

Satellite Microwave (Spacewave) Frequencies

Satellite is the optimum medium for high usage international trunks and is competitive with terrestrial microwave and coax for many long distance international links. The path is illustrated in Figure B-2. The optimum frequency range is 1 to 10 GHz. Below 1 GHz, noise is a factor from natural noise (galactic, solar, atmospheric) and man-made noise (from electronic devices) sources. Above 10 GHz, they are severely attenuated by atmospheric absorption.

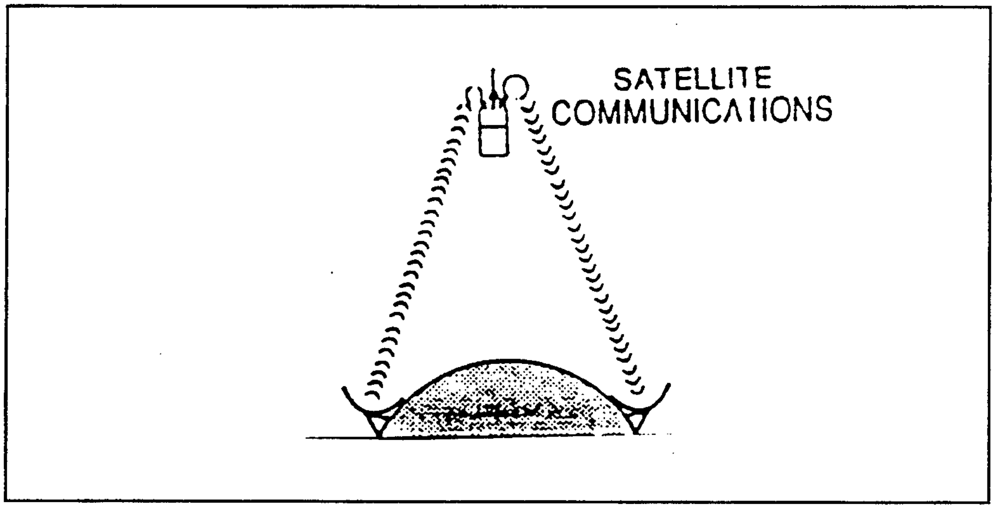

Figure B-2. Path for Satellite Communications. From [Ref. 14]

Radio (spacewave) Frequencies

Radio is usually associated with broadcast communications. Typical frequencies are from 30 MHz to 1 GHz. They support kilobit transmission rates rather than the megabit rates required for digital transmission. Their primary impairment is multipath interference, in which reflection from natural or man-made objects create multiple paths. An example of multiple path interference is ghosting on TV images. [Ref. 14]

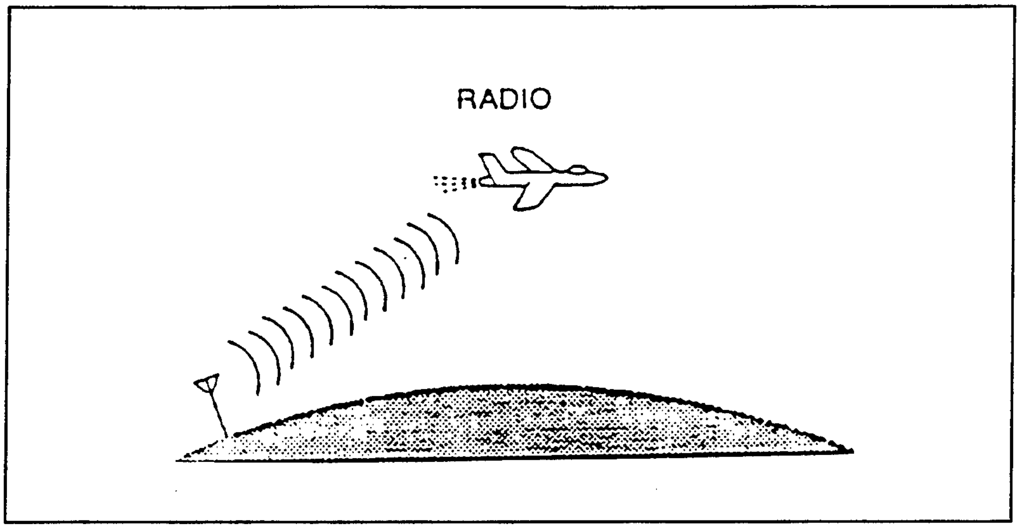

Figure B-3. Path for Radio frequencies. From [Ref. 14]

APPENDIX C. ATMOSPHERIC DUCTS

A duct is a waveguide in which electromagnetic energy can propagate over great ranges. To propagate energy within a duct, the angle the electromagnetic system's energy makes with the duct must be small; usually less than 1 degree. Thicker ducts in general can support trapping for lower frequencies. The vertical distribution of refractivity for a given situation must be considered as well as the geometrical relationship of transmitter and receiver to the duct in order to access the duct's effect at any particular frequency.

Ducts have dramatic effects upon transmitter/receiver systems that transcend duct boundaries. For example, a signal that would normally be detected may be missed if the receiver is within or just above the duct and the transmitter is just above the duct. This area of reduced coverage is known as shadow zone.

Although the duct acts like a waveguide for the energy, this waveguide does not have rigid and impenetrable boundaries, except for the earth's surface in cases where the duct's bottom lies at the surface. Therefore, energy is continually leaking from the duct. While the energy level within a shadow zone may be insufficient for receiver detection, it may be sufficient for a COMINT receiver intercept the signal.

SURFACE DUCTS

Several meteorological conditions will lead to the creation of ducts. If these conditions cause a trapping layer to occur, such that the base of the resultant duct is at the earth's surface, a surface duct is formed. There are three types of surface ducts based on the trapping layer's relationship to the earth's surface. These are a surface duct created from a surface-based trapping layer, referred to as a surface duct; a surface duct created from an elevated trapping layer, commonly referred to by EREPS as a surface-based duct; and a surface duct created by a rapid decrease of relative humidity immediately adjacent to the air-sea interface. Since the latter duct is a nearly permanent worldwide feature, it is referred to as an evaporation duct. EREPS allows for separate inputs for the surface-based duct and the evaporation duct. EREPS models do not allow for a surface duct created from a surface-based trapping layer. [Ref. 5] EREPS is being gradually replaced by another model called Radio Physical Optics (RPO), also developed by NCCOSC.

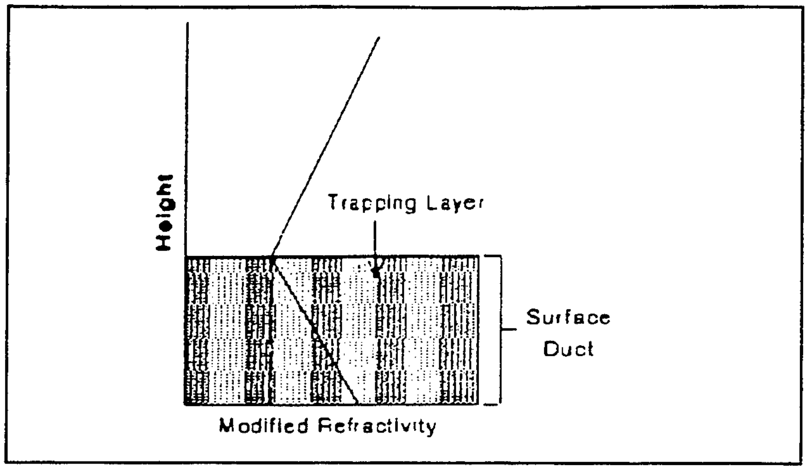

Figure C-1. Surface Duct. From [Ref. 5]

Surface-based ducts occurs when the air aloft is exceptionally warm and dry compared with the air at the earth's surface. Several meteorological conditions may lead to the formation of surface-based ducts.

Over the ocean and near land masses, relatively warm and dry continental air may be advected over the cooler water surface. This differential advection will lead to a temperature inversion at the surface. In addition, moisture is added to the air by surface evaporation, producing a moisture gradient to strengthen the trapping gradient. This type of meteorological condition routinely leads to a surface duct created by a surface-based trapping condition, a surface duct type not modeled within EREPS. However, as one moves from the coastal environment into the open ocean, this trapping layer may well rise from the surface, thereby creating the surface-based duct known by EREPS. Surface-based ducts tend to be on the leeward side of land masses and may occur both during the day or at night. in addition, surface-based ducts may extend over the ocean for several hundred kilometers and may be very persistent (lasting for days).

Surface-based ducting is associated with fair weather, with increased occurrence of surface-based ducts during the warmer months and in more equatorial latitudes. Any time the troposphere is well-mixed, such as with frontal activity or with high wind conditions, surface-based ducting is decreased. An interesting feature of surface-based ducts is the skip zone near the normal horizon, in which the duct has no influence.

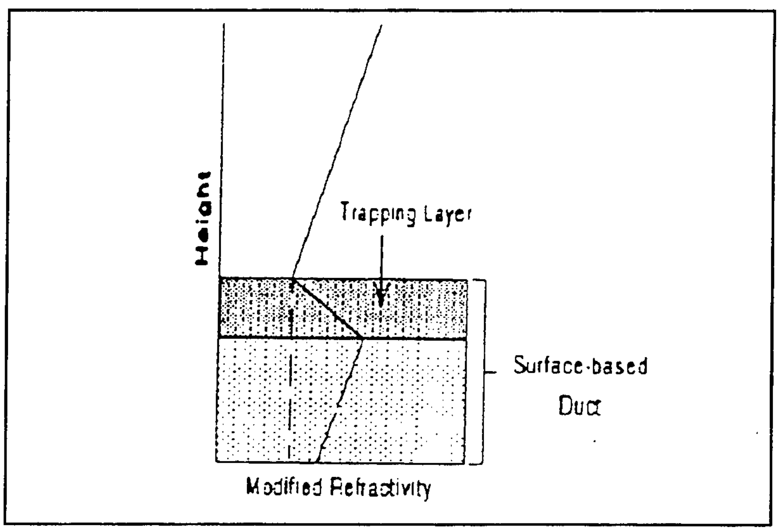

Figure C-2. Surface-Based Ducts. From [Ref. 5]

EVAPORATION DUCTS

A change in moisture distribution without an accompanying temperature change can also lead to a trapping refractivity gradient. The air in contact with the ocean's surface is saturated with water vapor. A few meters above the surface the air is not usually saturated, so there is a decrease of water vapor pressure from the surface to some value well above the surface. The rapid decrease of water vapor initially causes the modified refractivity, M, to decrease with height, but at greater heights the water vapor distribution will cause M to reach a minimum and, thereafter, increase with height. The height at which M reaches a minimum is called the evaporation duct height.

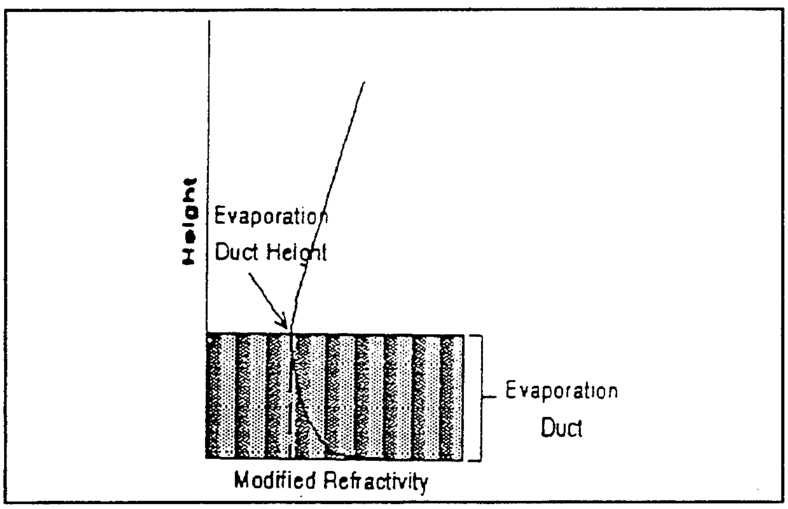

Figure C-3. Evaporation Duct. From [Ref. 5]

Evaporation ducts exist over the ocean, to some degree, almost all of the time. The duct height varies from a meter or two in northern latitudes during winter nights to as much as 40 meters in equatorial latitudes during summer days. On a world average, the evaporation duct height is approximately 10-15 meters. It should be emphasized that the evaporation duct "height" is not a height below which an antenna must be located in order to have extended propagation but a value that relates to the duct's strength or its ability to trap radiation. The duct strength is also a function of wind velocity. For unstable atmospheric conditions, stronger winds generally result in stronger signal strengths (or less propagation loss) than do weaker winds.

Since the evaporation duct is shallower than the surface-based duct, its ability to trap energy is highly dependent on frequency. Generally, the evaporation duct is only strong enough to affect electromagnetic systems above 3000 MHz.

The proper assessment of the evaporation duct is best performed by making surface meteorological measurements and inferring the duct height from the meteorological measurements and the meteorological processes occurring at the air/sea interface. The evaporation duct height cannot be measured using a radiosonde or microwave refractometer. With the advent of newer, high-resolution sondes that may be lowered to the surface from a ship, the impression is given that the evaporation duct may be measured directly. For practical applications, however, this impression is false and a direct measurement should not be attempted due to the unsteady nature of the troposphere at the ocean surface. A refractivity profile measured at one time would most likely not be the same as one measured at another time, even when the two measurements are seconds apart. Therefore, any measured profile would not be representative of the average evaporation ducting conditions. These conditions must be considered for an assessment system.

ELEVATED DUCTS

If meteorological conditions cause a trapping layer to occur aloft, such that the base of the duct occurs above the earth's surface, the duct is referred to as an elevated duct. Semipermanent surface high-pressure systems, centered at approximately 30 degrees north and south latitude, cover the ocean areas. These are more intense in eastern parts of ocean. Poleward of these systems lay the mid-latitude westerly winds and, equatoward, the tropical easterlies or the tradewinds. Within these high-pressure systems, large-scale subsidence of air causes heating as the air undergoes compression. This leads to a layer of warm, dry air overlaying a cool, moist layer of air which is often called the marine boundary layer. The resultant inversion is referred to as the tradewind inversion and may create a strong ducting condition at the top of the marine boundary layer. Elevated ducts may vary from a few hundred meters above the surface at the eastern part of the tropical oceans to several thousand meters at the western part.

It should be noted that the meteorological conditions necessary for an elevated duct are the same as those for a surface-based duct . In fact, a surface-based duct may slope upward to become an elevated duct as warm, dry continental air glides over cool, moist marine air. The tradewind inversion may also intensify, thereby turning an elevated duct into a surface-based duct. [Ref. 5]

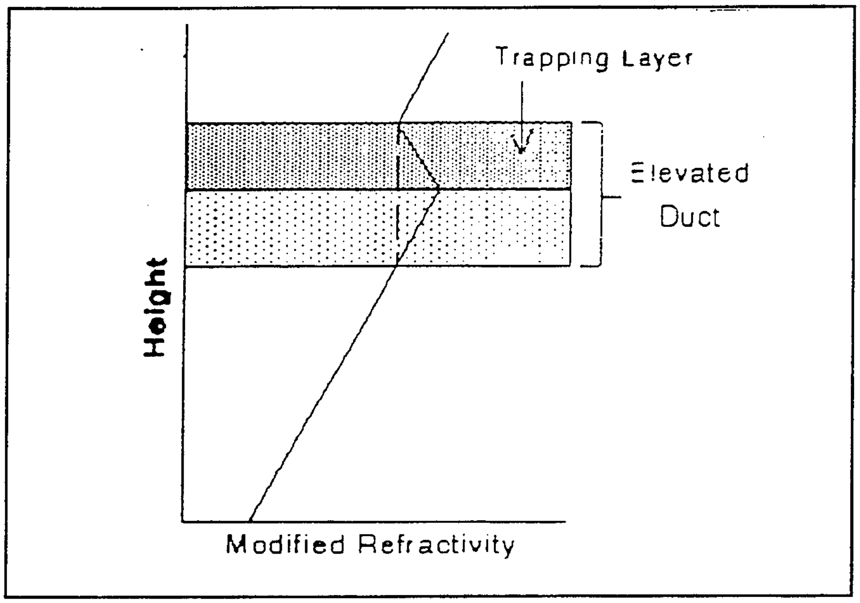

Figure C-4. Elevated Duct. From [Ref. 5]

APPENDIX D. PD SOFTWARE PROGRAM PURPOSE, ASSUMPTIONS AND LIMITATIONS

PURPOSE

PD is one of the family of IMOM computer programs developed at the Air Force Information Warfare Center (AFIWC) to model electronic combat (EC) scenarios. A two-dimensional, graphically oriented analyst aid for tactical mission planning and analysis, PD is primarily designed to predict the ability of a passive detection receiver network to detect and locate targets.

PD evaluates the capability of passive detection receiver systems to detect and locate airborne or ground-based emitter platforms. The passive detection systems are of the time-difference-of-arrival (TDOA) or the direction-of-arrival (DOA) receiver types. Detection is based on the collection of the emitter platform's intentional and unintentional radio frequency (RF) emissions.

MODEL ASSUMPTIONS

PD operates under several assumptions. The user is advised to adhere to the guidelines.

- Receiver IF bandwidth:

  CW - Use largest known value or 10 kHz.

  Pulsed - Use largest known value or assume $\leq$ 1.2/PW (μsec).

- Use frequency-dependent receiver sensitivities or antenna gain if given. Use lowest frequency of receiver/emitter overlap as frequency of concern for each receiver/emitter pair.
- Use largest PW and shortest PRI for pulsed emitters (within the limits of detection system).
- Match antenna polarization if possible. If mismatch is unavoidable, minimize losses by choosing a mismatch other than VER/HOR, RHC/LHC, or SLL/SLR. If unknown, assume a polarization match.
- Assume receiver sensitivity includes S/N ratio and noise considerations, but not receiver antenna gain, unless specifically stated otherwise. Enter a value of O dB for S/N and noise factor fields.
- Use 0 degrees for elevation boresight angle, unless exploring specific limitations of an elevated beam.
- Emitter power:

  CW - Use peak power if available, otherwise use average value

  Pulsed - Use peak power at antenna feed port if it is known. Otherwise, use the transmitter value. If frequency is greater than 1 GHz, subtract 2 dB.
- If emitter ERP is given, set antenna gain to 0.
- Frequency range and sensitivity are minimum elements necessary to characterize a receiver.

- If intelligence information indicates a similarity with a known system, use the parameters of the known system.
- If intelligence information indicates an upgrade relationship with a known system, add 6 dB to the receiver sensitivity and use the other parametrics from the known system.
- If antenna gain for the receiver is not known, or if gain given is not appropriate for the frequency of interest (common for systems with a wide frequency range), uses value listed below. Frequency of interest is lowest frequency of receiver/emitter overlap.

Frequency (MHz)	Equal To (dBi)
30 - 500	30
500 - 1000	6

- Use best DF accuracy given.
- If antenna height is unknown, assume 12 feet for mobile systems or 30 feet for fixed or unknown systems.

MODEL LIMITATIONS

PD limitations include the following:

- The maximum number of emitters per platform is 26.
- The maximum number of receiver bands is 15.
- Doppler effect is not considered in determining probable emitter location.

- Weather conditions, during phenomena, and ionospheric bouncing are not considered in the propagation loss calculation.
- The TIREM propagation model does not consider attenuation due to rain, foliage, or man-made obstacles. [Ref. 15]

APPENDIX E. PD SOFTWARE PROGRAM CALCULATION ROUTINES

PD uses several calculation routines to determine whether airborne and ground-based targets can be passively detected and the level of confidence with which they can be located.

SIGNAL POWER AT RECEIVER

The signal power at receiver routine determines whether a target's emitter signal at a receiver station has sufficient power to be detected by that receiver. If the signal can be detected by a sufficient number of receivers, PD estimates the probable location of the target using TDOA or DOA analysis. PD sums transmitted power, transmitter antenna mainbeam or side lobe gain, receiver antenna gain, and propagation and polarization losses to calculate received power, $\mathbf{P_R}$. Received power is then compared to the sensitivity of the receiver as specified in the receiver database file to determine if the receiver can detect the target's signal. The following calculation is used to determine the power of the emitter signal at the location of each receiver capable of receiving the signal.

$$\mathbf{P_R = P_T + G_T - L_P - L_{POL} + G_R}$$

Where:

$\mathbf{P_R}$ = Signal power in decibels (dB) at receiver

$\mathbf{P_T}$ = Transmitter signal power in dB

G_T = Transmitter gain in dB

L_P = Propagation Losses in dB

L_{POL} = Losses due to polarization mismatch between transmitted signal and receiver Antenna, in dB

G_R = Receiver gain in dB

PD reads the parameters set by the user in the receiver data file to determine whether the emitter antenna is within the receiver antenna's azimuth (Figure E-1) and elevation field of view (Figure E-2). Based on this determination, PD calculates a value for received power $\mathbf{P_R}$.

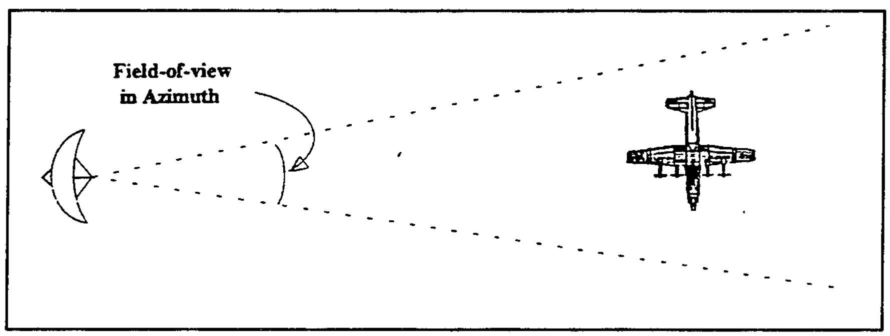

Figure E-1. Receiver Antenna Azimuth Field-of-View. From [Ref. 15]

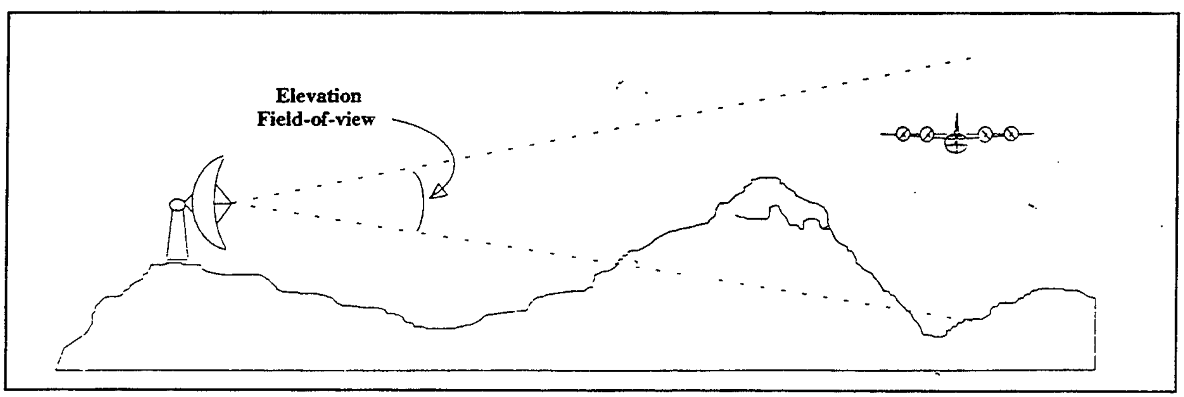

Figure E-2. Receiver Antenna Elevation Field-of-View. From [Ref. 15]

The transmitter power, $\mathbf{P_T}$, and antenna gain $\mathbf{G_T}$, are user-specified parameters in the emitter data base file. PD determines whether the receiver antenna is within the emitter antenna's mainbeam or sidelobe. If the receiver antenna is within the emitter antenna's mainbeam, PD uses the mainbeam gain from the emitter file as the transmitter gain value. If the receiver antenna is within the emitter antenna's sidelobe, PD uses the sidelobe gain for this value (Figure E-1).

The receiver gain $\mathbf{G_R}$, is a user-specified parameter in the receiver file. PD determines the polarization loss, $\mathbf{L_{POL}}$, by comparing the polarization of the transmitting and receiving antennas, as specified in the emitter and receiver file, respectively.

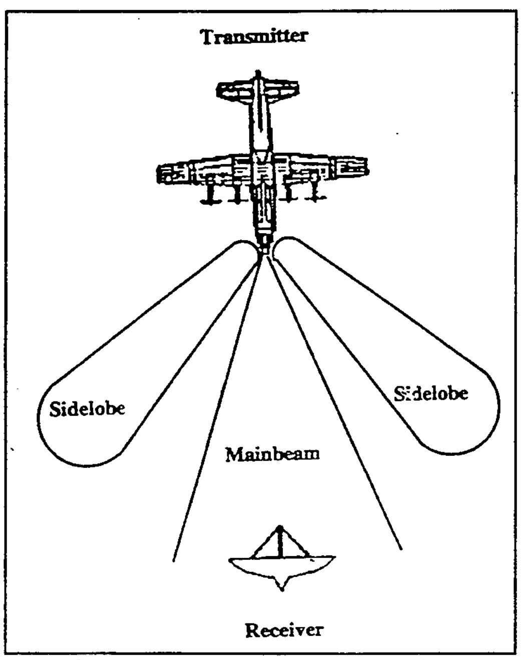

Figure E-3. Emitter Antenna Mainbeam and Sidelobes. From [Ref. 15]

Propagation Loss, $\mathbf{L_P}$, is determined by PD based on which propagation loss model the user selects, either the freespace propagation loss model or TIREM propagation loss model.

FREE SPACE PROPAGATION LOSS MODEL

The Freespace model determines propagation loss using either the Radio Line-of-Sight (RLOS) distance or slant range distance from emitter to receiver. The basic free-space transmission loss is that loss that would occur if the emitter and receiver antennas were replaced by isotropic antennas located in a perfectly dielectric, homogeneous, isotropic, and unlimited environment. It can be expressed by:

$$L_d = 20 \log 4\pi d/\lambda \text{ dB},$$

where d (RLOS or slant range distance) and λ (signal wavelength) are expressed in the same units. Simply put, the free space loss is the amount of attenuation caused solely by the propagation of the signal through standard atmospheric conditions.

PD assumes, with the Freespace model, that an emitter's signal cannot be detected by a receiver if the signal from emitter to receiver is terrain-masked -- i.e., there is terrain in the LOS (assuming a curved earth) that can block the signal (Figure E-4).

For receiver to emitter distances less than RLOS, *d* used to calculate free space loss is calculated using the geometric slant range distance. For longer distances, however, the earth curvature and the effects of atmospheric refraction become considerations. The greater the distance between emitter and receiver, the greater the angle of curvature of signal toward earth. This is due to changes in index of refraction of the atmosphere with altitude.

Because the atmosphere is inhomogeneous, the index of refraction versus height curve varies for different points on the earth's surface. PD uses a simplifying assumption for calculating RLOS, known as an effective earth model, or the 4/3 (four thirds) earth model. In the effective earth model, the inhomogeneous atmosphere of the actual earth is replaced by a homogeneous atmosphere of a slightly large earth -- one having a radius approximately 4/3 times the actual earth radius. With this simplification, the *d* in the propagation loss calculations is found by the formula:

$$d = (2kah_t)^{1/2},$$

Where a=6370 Km (actual earth radius), k=4/3, and h_t is the height of the emitter.

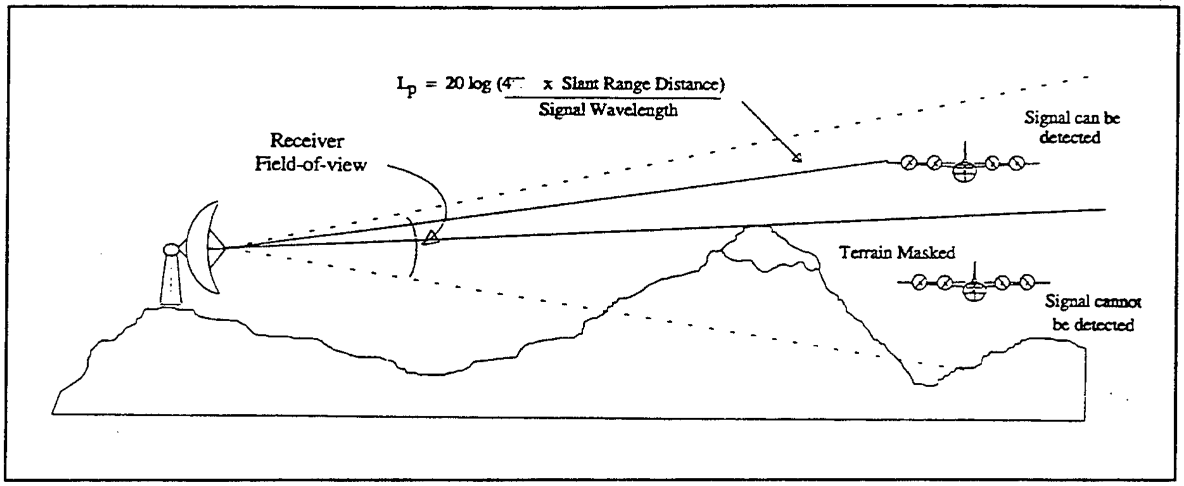

Figure E-4. Line-of-Sight detection - Free Space Propagation Loss Model. From [Ref. 15]

TIREM PROPAGATION LOSS MODEL

The TIREM model bases propagation loss on effects caused by irregular terrain features. The model inputs a terrain profile described by a set of discrete points, where each point is defined as a distance from the transmitter and an elevation above mean sea level (MSL). Other parameters influencing the model are: emitter frequency, emitter antenna height and antenna polarization, receiver antenna height, standard atmospheric constants -- refractivity, and ground constants -- permissivity and conductivity.

TIREM examines the terrain profile between the two antennas (using the effective earth radius geometry) to determine whether the signal from the emitter to receiver is within LOS or beyond line-of-sight (BLOS) (see Figure E-5).

If the signal is within LOS, L_p is the sum of the free-space loss and the loss due to atmospheric absorption when frequency exceeds 10 GHz.

If the signal is beyond line-of-sight, PD sums the following losses to calculate L_p - the total diffraction loss, the free-space loss, the total diffraction loss above free-space, and, if the frequency exceeds 10 GHz, the atmospheric absorption. The tropospheric scatter loss is also calculated and, if the frequency exceeds 10 GHz, the loss due to atmospheric absorption is added to it. The path loss is set to the smaller of the total diffraction loss and the total tropospheric scatter loss.

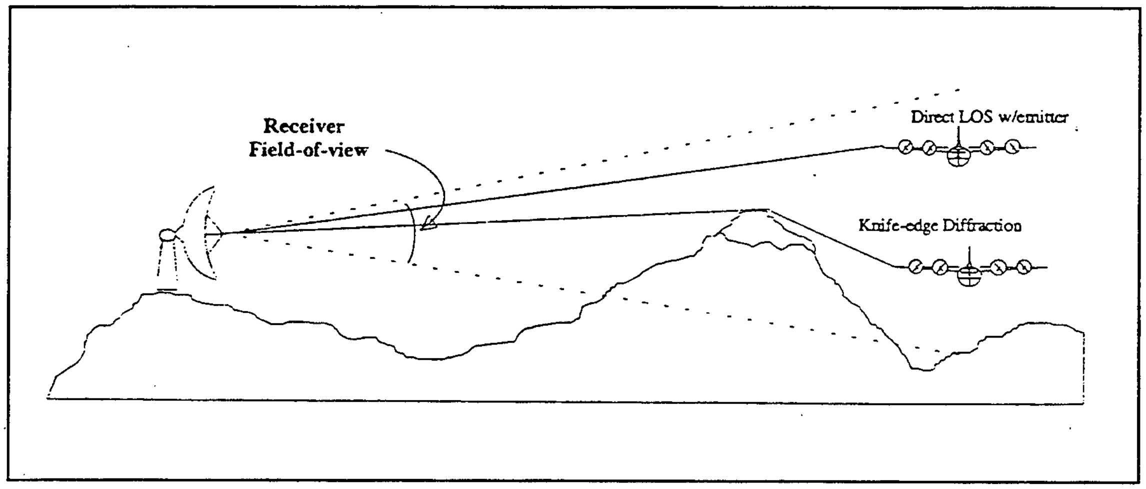

Figure E-5. Determination of LOS vs. BLOS. From [Ref. 15]

In areas where terrain intrusion into the Fresnel zone above the top edge of the barrier and into the barrier "shadow" causes diffraction (bending) of the emitter beam, the total diffraction loss above free-space is computed as the sum of the individual knife-edge losses, when this loss is greater than 7 dB and the terrain is considered rough, and the reflection losses are due to terrain intrusion.

If diffraction occurs on sea water along the profile, spherical-earth losses for the segments of water around which diffraction occurs is included.

If the average knife-edge loss is less than 7 dB, the terrain is regarded as smooth and a spherical-earth model is approximated using the spherical-earth model with land ground constants. If there is any sea water along the path, the spherical-earth model is used again, but this time with sea water ground constants.

The total spherical-earth loss is the combination of the land and sea spherical-earth losses weighted by the proportion of land and sea segments along the entire path.

The diffraction loss is set to the minimum of the spherical-earth loss and the rough earth loss.

The TIREM model does not consider ducting phenomena or ionospheric (skywave) propagation. It does not perform calculations of performance improvement that would result from angle, space, or frequency diversity. Lastly, the model does not consider attenuation due to rain, foliage, or man-made obstacles. [Ref. 15]

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