FINAL REPORT

EXPLORATION OF ELECTROMAGNETIC FIELDS AND SYSTEM APPLICATIONS RELATING TO THE PORTED COAXIAL CABLE SENSOR (PCCS)

VOLUME II
INVESTIGATION OF THE FEASIBILITY OF A LONG LINE INTRUSION SENSOR SYSTEM

Report No. INS-RD-1008

FUNDED BY
RESEARCH AND DEVELOPMENT
IMMIGRATION AND NATURALIZATION SERVICE

JULY 1987

By

James R. Harrison and Larry C. Schooley
Department of Electrical and Computer Engineering
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Tucson, Arizona 85721

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FOREWORD

This is the final report for Task II, entitled Investigation of the Feasibility of Long Lines, of the Evaluation of the Ported Coaxial Cable Sensor (PCCS), U.S. Department of Justice Grant No. 85-IJ-CX-ØØ18.

The support and input of Harry D. Frankel and George A. Van Horn of the Immigration and Naturalization Service Research and Development Program, throughout the length of this project, is greatly appreciated.

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LIST OF ABBREVIATIONS

A/D	Analog to Digital
AWG	American Wire Standard
bps	Bits per Second
°C	Degrees Celsius
CATV	Cable Television
CSMA/CD	Carrier Sensed Multiple Access with Collision Detection
cw	Continuous Wave
db	Decibels
dc	Direct Current
dia	Diameter
EPROM	Erasable Programable Read Only Memory
°F	Degrees Fahrenheit
FCC	Federal Communications Commission
FMCW	Frequency Modulated Continuous Wave
ft	Feet
Gbps	Gigabits per Second (1 X 10^9 bps)
GHz	Gigahertz (1 X 10^9 hertz)
Hz	Hertz
IFRB	International Frequency Regulation Board
in	Inches
Kbps	Kilobits per Second (1 X 10^3 bps)

LIST OF ABBREVIATIONS--Continued

KHz	Kilohertz (1 X 10^3 hertz)
KV	Kilovolts (1 X 10^3 volts)
KVA	Kilovolt amps (1 X 10^3 watts)
mA	Milliamps (1 X 10^{-3} amperes)
M-ary	Multiple Array
Mbps	Megabits per Second (1 X 10^6 bps)
MHz	Megahertz (1 X 10^6 hertz)
m/s	Meters per Second
mW	Milliwatts (1 X 10^{-3} watts)
NBTDR	Narrow-band Time-Domain Reflectometer
ns	nanoseconds (1 X 10^{-9} seconds)
PCCS	Ported Coaxial Cable Sensor
prf	Pulse Repetition Frequency
QPSK	Quadrature Phase-shift Keying
RAM	Random Access Memory
RF	Radio Frequency
SCPC-FDMA	Single Channel per Carrier Frequency Division Multiple Access
TM	Transceiver Module (Sentrax System)
TMS	Texas Instruments
TWP	Twisted Wire Pair
uF	Microfarads (1 X 10^{-6} farads)
us	Microseconds (1 X 10^{-6} seconds)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS--Continued

ABSTRACT

In this project, the feasibility of constructing a long line ported coaxial cable intrusion detection sensor, PCCS, is studied. Long line PCCS systems are necessary to assist Border Patrol agents in providing information on the number and location of intrusions along remote areas of international borders. Two commercially available PCCS sensor systems, GUIDAR and SENTRAX, are analyzed to determine their practicality for use as long line sensors. The various candidate long line sensor system configurations are derived from three primary engineering considerations: network topology, distribution of processing and type of transmission media. The advantages, disadvantages and approximate cost of the technically feasible and practical candidate systems is presented. Also, the approximate cost per mile of a complete long line sensor system, including the cost of communications equipment, power distribution and sensor equipment, is given.

EXECUTIVE SUMMARY

1 Introduction

The purpose of this study is to determine the feasibility of constructing a long line ported coaxial cable sensor system (PCCS) of up to 100 miles in length which could be installed along an international border such that the presence of intruders can be displayed at a remote central base station. Long line PCCS systems are necessary to assist Border Patrol agents in providing information on the number and location of intrusions along remote areas of international borders. Long line PCCS systems could also be used at official border ports-of-entries, traffic check points and storage and detention facilities.

Two commercially available PCCS systems, GUIDAR and SENTRAX, are analyzed to determine their suitability for use as long line sensors. The GUIDAR system has a total length of two miles and the SENTRAX system has a total length of 3 miles. Fifty GUIDAR systems and about thirty three SENTRAX systems would be required for a sensor system 100 miles in length. The receiver electronics of the GUIDAR system is analyzed in detail to determine if any portion can be remotely located at the central base station or an intermediate node. If distributed processing is possible, the cost and complexity of the GUIDAR equipment required at each two mile segment could be reduced. This idea also applies to the SENTRAX system.

The various candidate long line sensor systems are derived from three primary engineering considerations: network topology, distribution of processing and type of transmission media. A preliminary evaluation of all possible candidate systems will eliminate those systems which are not technically or physically realizable. A second evaluation will eliminate the remaining noncompetitive systems. Finally, the advantages, disadvantages and approximate cost data is presented for the feasible long line sensor systems and an estimate of the total system cost per mile, including communications equipment, power distribution, sensor equipment and installation is given.

2 Conclusions

The major conclusions are:

2.1 Distribution of Processing

A long line intrusion detection sensor is technically feasible. However, because of the large bandwidth requirements and the use of centralized timing and control circuitry, the only practical place to divide the GUIDAR receiver is after all intrusion signal processing has been completed. Only the appropriate display data would be sent to a remote base station. A complete GUIDAR system, less display, would have to be located at every two mile section of a long line sensor system. The same conclusion applies for the SENTRAX system. A complete SENTRAX system, less the operators terminal, would have to be located at every three mile section of a long line sensor system.

2.2 Transmission Media

There are four technically feasible and physically practical transmission media capable of relaying the display data from each sensor to the base station. These four transmission media are: twisted wire pair, broadband coaxial cable, fiber optic cable and power line carrier. These four transmission media were selected from a list of nine candidate transmission media (see Figure 3.3). One of the major evaluation criteria in choosing a transmission media was vulnerability to deliberate sabotage. The advantage of the four selected transmission media is that they all can be completely buried underground and therefore are less vulnerable to intentional damage then the other transmission media which would require some type of an above ground antenna.

2.3 Topology

The four remaining transmission media would all be employed in a bus topology. With twisted wire pair, fiber optic cable and power line carrier, each sensor would share the same channel. A simple access protocol, such as carrier sensed multiple access or token passing, could be used to relay the display data to the base station. With broadband coaxial cable, it might be possible to assign each sensor a unique carrier frequency and therefore each sensor would have its own dedicated channel to communicate with the base station.

2.4 Power Requirements

The distribution of power is a significant economic factor in the construction of a long line sensor system. Power does not exist along most remote areas of the international borders. It is estimated that each GUIDAR system and the additional communications equipment would require 3.Ø amperes of current at 12Ø volts. A 1ØØ mile system, requiring 5Ø GUIDAR systems, would require 18 KW (18,ØØØ watts) of power. The distribution of this power would necessitate the installation of a major power distribution system. An additional study would be necessary to accurately determine the cost of an optimal power distribution system and to explore the possibilities of using alternative power sources such as solar energy and batteries. Possibly, the optimal power distribution system might consist of a specially designed cable which cable which could be used for both power distribution and sensor communications. Instead of using off-the-shelf power line cable carrier cable and equipment, the cable and associated equipment would be specifically designed for the power requirements and data rates of a 1ØØ mile long line sensor.

2.5 Cost

The total cost per mile of a complete long line sensor system, using the GUIDAR system, including communications and power distribution equipment costs as well as installation costs, is estimated to be $59,5ØØ. The cost of the power distribution system is estimated by assuming that all of the power is distributed form one end of the 100 mile long sensor system. The actual power distribution costs will vary depending upon the optimal design, location and the overall length of the sensor system. The cost of communications equipment will vary slightly depending upon the type and overall length of the sensor system. The largest expense of a 100 mile sensor system is the cost of the GUIDAR equipment. However, the installation costs assume that the GUIDAR, communications and power distribution equipment are installed over flat terrain and in soil which is easily excavated. The true installation costs will vary depending upon the location, terrain and type of soil where the sensor system is installed and may increase 5 or 10 fold and become comparable to the cost per mile of the GUIDAR equipment.

3 Possible Improvements

3.1 GUIDAR System

There are several ways of improving the GUIDAR system to provide better performance for use as a long line sensor. One improvement, which has already been demonstrated for use with other types of sensors, is called the adaptive learning technique. With the adaptive learning technique, the cell thresholds are constantly updated with changing soil conditions. Both frequency and time domain features of the intrusion signals are processed. The adaptive learning technique declares an alarm when the intrusion data is within the range of a human target and declares an alert when a cell threshold is exceeded but the intrusion data is not within the range of a typical human target. Either an automatic or remote cell threshold adjustment system would have to be designed into the GUIDAR system before it could be used as a long line sensor. Improvements in the quantization process, which would lower the false alarm rate and increase the probability of detection, are possible by using 12 or 16 bit quantizers, companding circuitry and adaptive digitization techniques. The limiting factor on the implementation of any new signal processing algorithm is the total time required to perform a single intrusion detection. At least one intrusion detection must be performed in the time it takes an intruder to cross the detection zone. The more computations required to implement a detection algorithm, the longer the total intrusion detection time. An additional study would be necessary to implement any of these suggested changes and to redesign any of the hardware in the GUIDAR system.

3.2 SENTRAX System

The improvements suggested for the GUIDAR system also apply to the SENTRAX system.

The SENTRAX system is ideally suited for border areas which do not require the fine range resolution of pulsed systems. Currently, the maximum separation distance between transceiver modules of the SENTRAX system is 300 meters. The separation distance between transceiver modules is limited to 300 meters because both the intrusion data and power distribution is transmitted over the leaky coaxial cables. If separate data communication and power distribution lines were used, a greater separation distance between transceiver modules could be achieved. For large separation distances, line amplifier units would be needed to maintain a high signal to noise ratio. The overall system cost could be reduced because the cost of the additional line amplifier units would probably be less than the cost the required number of transceiver modules. For large detection cells, the recommended 3 to 1 intrusion response ratio should be maintained.

CHAPTER 1

INTRODUCTION

1.1 Purpose

The objective of this study is to determine the feasibility of constructing a long line ported coaxial cable sensor (PCCS) system of up to 100 miles in length which could be installed along an international border such that the presence of intruders can be displayed at a remote central base station. Long line PCCS systems are necessary to assist Border Patrol agents in providing information on the number and location of intrusions along remote areas of international borders, official border ports-of-entries and other important areas such as traffic check points and storage and detention facilities. The candidate long line PCCS systems will be derived from three primary engineering considerations: network topology, distribution of processing and the type of transmission media. A preliminary evaluation of all possible candidate systems will eliminate those systems which are not technically or physically realizable. A second evaluation will eliminate the remaining noncompetitive systems. Finally, the advantages, disadvantages and approximate cost data is presented for the feasible long line sensor communication systems and an estimate of the total system cost per mile is given.

1.2 Development of PCCS Technology

Guided electromagnetic detection sensors were originally developed to provide a means of obstacle detection along the track or pathway of ground transportation systems such as high-speed railways (Beal et al. 1973). The major components of a high-speed railway guided radar system include a transmitter/receiver set and coupler (antenna) on each side of the lead railway car to launch electromagnetic energy on to the buried leaky transmission lines and to process received echoes. The leaky transmission lines can be buried on each side of the track or a single line can be buried in the center of the track. The detection range, system sensitivity and the zone width depended upon such factors as frequency, line attenuation, coupling loss an receiver sensitivity. Although zone widths of five meters and ranges of several kilometers were achieved, initial experiments showed that the dynamic range between the obstacle response and the fixed profile, caused by the surrounding environment and cable discontinuities, was so large that only obstacles within a few inches of the leaky cables could be detected consistently (Sentrax, Perimeter Intrusion Detection System 1985).

In the early 1970's, researchers at Queen's University of Kingston, Ontario, Canada, developed several prototype intrusion detection sensors which enabled the detection of human targets walking in the vicinity of the leaky coaxial cables. The detection of human targets was made possible by improved leaky coaxial cable design and the development of inexpensive microprocessors which are used for highspeed digital signal processing. Some of these prototype systems are described in articles by Mackay and Mason 1975, Mackay and Beattie 1976, Vinnins et al. 1976 and Patterson and Mackay 1977.

The basic signal processing components of the GUIDAR system were developed from narrow-band time-domain reflectometry (NBTDR) equipment. NBTDR equipment is used to test discontinuities in transmission lines and fiber optic cables. The signal processing algorithms used in NBTDR equipment enabled the detection of very small changes in the reflection coefficient of distributed cable systems versus time. An extension of these signal processing techniques led to the development of a very sensitive prototype obstacle detection system which was able to detect metallic objects within two feet of a leaky coaxial cable (Mackay and Penstone 1974). One of the first commercially available intrusion detection sensors, using buried leaky coaxial cables, was developed by the Computing Devices Company of Ottawa, Ontario, Canada. This system, called GUIDAR, was first described at the 1976 Carnahan Conference on Crime Countermeasures (Harman and Mackay 1976).

The Guidar system consists of a pair of parallel, buried, leaky coaxial cables which define a detection zone along which an intrusion can be sensed. A radio frequency modulated pulse of electromagnetic energy is sent down a length of a ported coaxial transmit cable. A portion of this electromagnetic energy leaks out into the surrounding environment and is coupled onto the receive cable. Part of this coupled electromagnetic energy travels back to the Guidar receiver where signal processing algorithms perform target detection. A basic GUIDAR system block diagram is shown in Figure 1.1 (Guided Intrusion Detection and Ranging System 1981). General descriptions of the GUIDAR system can be found in: Harman and Mackay 1976, Guided Intrusion Detection and Ranging System 1981 and in Clarke et al. 1977. Results of performance tests can be found in Ball and Levett 1980 and Frankel, et al. 1984. A more detailed analysis of the GUIDAR system is given in Chapter 2.

Recently, several more cost effective intrusion detection sensors systems have been developed for short perimeter applications. These systems use continuous wave (CW) transmission as an alternative to the pulse transmission of the GUIDAR system. The signal processing electronics of CW systems can be simplified and are therefore less expensive. Two types of commercially available CW systems are SPIR, manufactured by Computing Devices Company, and SENTRAX, which is manufactured by Senstar Corporation of Kanata, Ontario, Canada. Since continuous wave sensors can not discern target location, they are generally installed in block sectors where an intruder can be detected anywhere within each sector. A description of the SPIR system can be found in Clarke and Sims 1984. The SENTRAX system is described in: Harman and Siedlarz 1982, Harman 1983a, Harman 1983b, Harman 1983c, Harman 1983d, and in the SENTRAX users manual (SENTRAX, Perimeter Intrusion Detection System 1985). A block diagram of the SENTRAX system

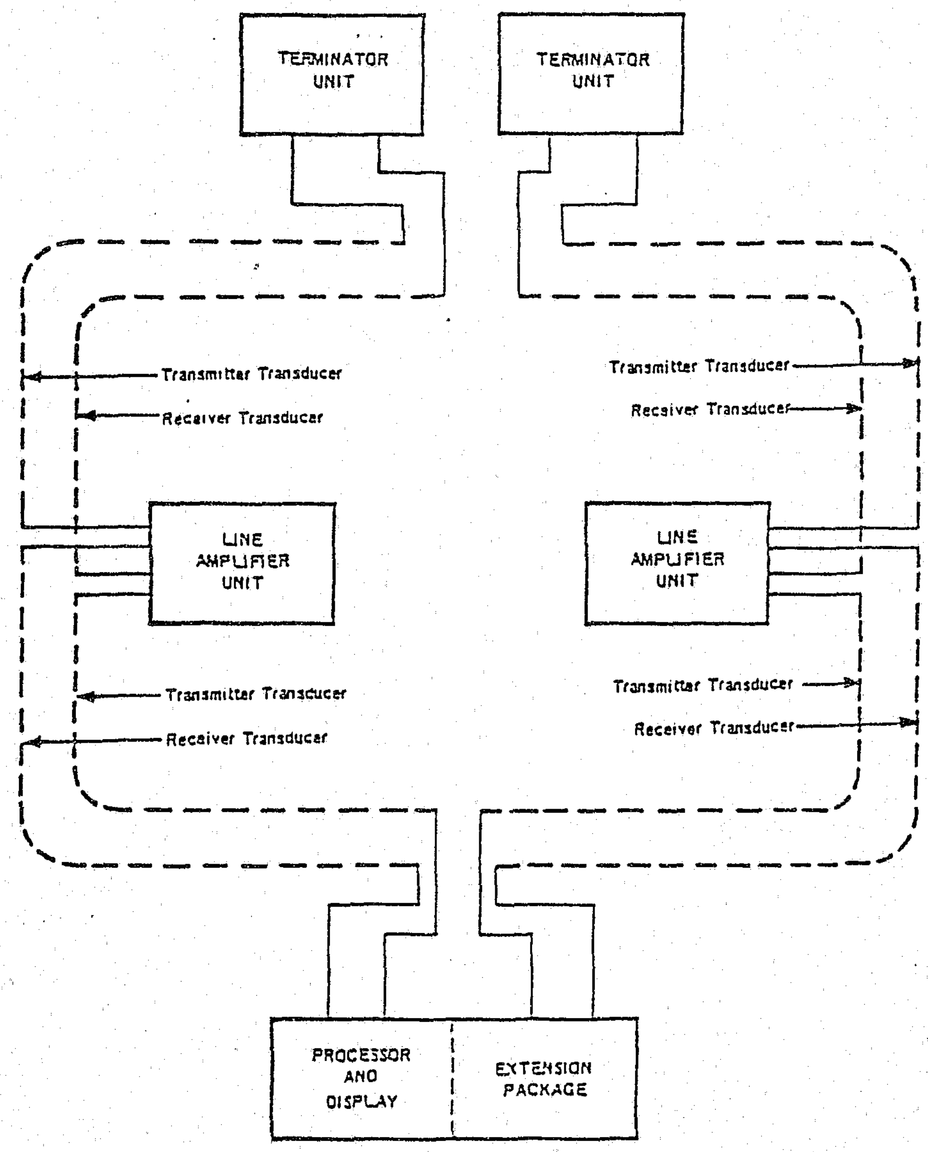


Figure 1.1 GUIDAR System Block Diagram

is shown in Figure 1.2 (Harman. 1983d). The SENTRAX system will be described in greater detail in Chapter 2.

1.3 Report Outline

This report is organized into seven chapters and an executive summary.

The executive summary consists of a introduction containing a statement of the report objective, a brief description of PCCS technology and an explanation of the engineering method used to reach the conclusions of this study. Section 2.Ø of the executive summary lists the general conclusions of this study. Section 3.Ø is entitled possible improvements. This section suggests some possible improvements for both the GUIDAR and SENTRAX systems.

Chapter 2 consists of a detailed description of two commercially available long line PCCS systems, GUIDAR and SENTRAX.

Chapter 3 discusses the three variables of the long line sensor communications problem. The three variables are network topology, distribution of processing and transmission media. A brief description of the different types of topologies is given. Distribution of processing is divided into three categories centralized, decentralized and hybrid. A description of the various transmission media is also given.

In Chapter 4, the preliminary evaluation of all possible candidate systems is conducted. Each candidate system is derived from a combination of the three variables of the communications problem.

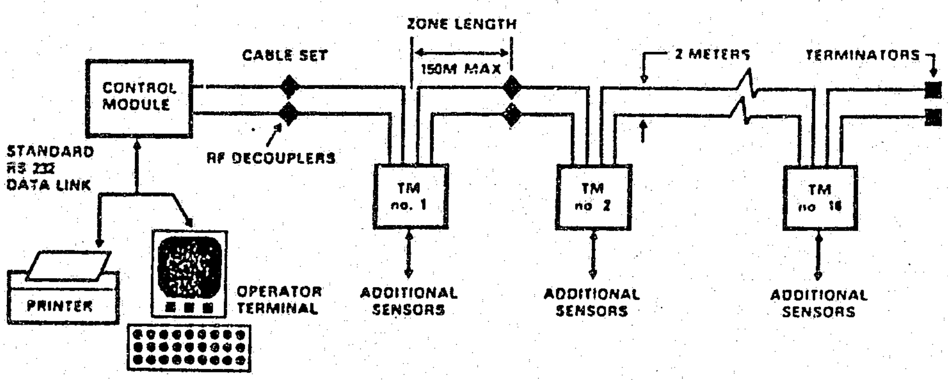


Figure 1.2 SENTRAX System Block Diagram

After the preliminary evaluation, the surviving systems will be further evaluated in Chapter 5. The preliminary evaluation criteria are transmission bandwidth and system timing and control.

Chapter 5 is a second evaluation of those remaining systems which were not eliminated in the preliminary evaluation. The evaluation criteria at this stage are current technological considerations, vulnerability considerations and installation requirements. In this chapter, some of the candidate systems from the preliminary list of systems in Chapter 4 will be eliminated.

Chapter 6 consists of a detailed evaluation of the remaining long line sensor systems which were not eliminated in Chapters 4 and 5. For each surviving system, the advantages and disadvantages will be discussed and approximate cost data will be presented.

Chapter 7 contains the summary and conclusions.

CHAPTER 2

DETAILED DESCRIPTIONS OF THE GUIDAR AND SENTRAX SYSTEMS

2.1 Introduction

This chapter consists of a detailed technical description of two commercially available long line PCCS sensor systems. A technical description of the GUIDAR system will be presented in section 2.2 and a technical description of the SENTRAX system will be given in section 2.3.

A full understanding of the GUIDAR signal processing is necessary in order to make accurate judgments on the potential feasibility of each of the candidate long line sensor systems. A technical description of the SENTRAX system will be given because it offers an alternative to the pulse mode of operation of the GUIDAR system. It is possible that a 100 mile long sensor system could consist of a combination of continuous wave and pulse type sensor systems. This idea will be discussed in Chapter 7.

The majority of the information presented in this chapter originates from the technical manuals for each system (Guided Intrusion Detection and Ranging System 1981 and Sentrax, Perimeter Intrusion Detection System 1985). Additional information was obtained from published articles and general reference material. Some specific information, such as the exact target detection algorithm utilized by the GUIDAR system, or the signal multiplexing technique which allows power distribution and data communication over the leaky sensor cables in the SENTRAX system, are considered as proprietary information by each company (Chalmers 1985 and Harman 1985) and, therefore, will only be described qualitatively. This details are not relevant to the conclusions reached in this study.

2.2 General Theory of Operation--GUIDAR System

A pictorial diagram highlighting the main features of operation of the GUIDAR PCCS system is shown in Figure 2.1 (Frankel et al. 1984).

The transmitter sends a pulse of RF energy down the transmit side of the pair of buried leaky cables. As the pulse travels down the cable, electromagnetic energy continually leaks out and is coupled, through the surrounding environment, onto the receive cable. A portion of the electromagnetic energy which is coupled onto the receive cable travels back to the receiver. After bandpass filtering, the received signal is coherently demodulated using the transmitter RF generator as a reference signal. The received signal envelope will typically look like signal S1 of Figure 2.1. Signal S1 is known as the profile of the system. Over short time periods, the profile will not vary significantly. An intruder crossing the cables perturbs the electromagnetic field between the transmit and receive cables. This disturbance will cause a rapid change in amplitude of the profile which

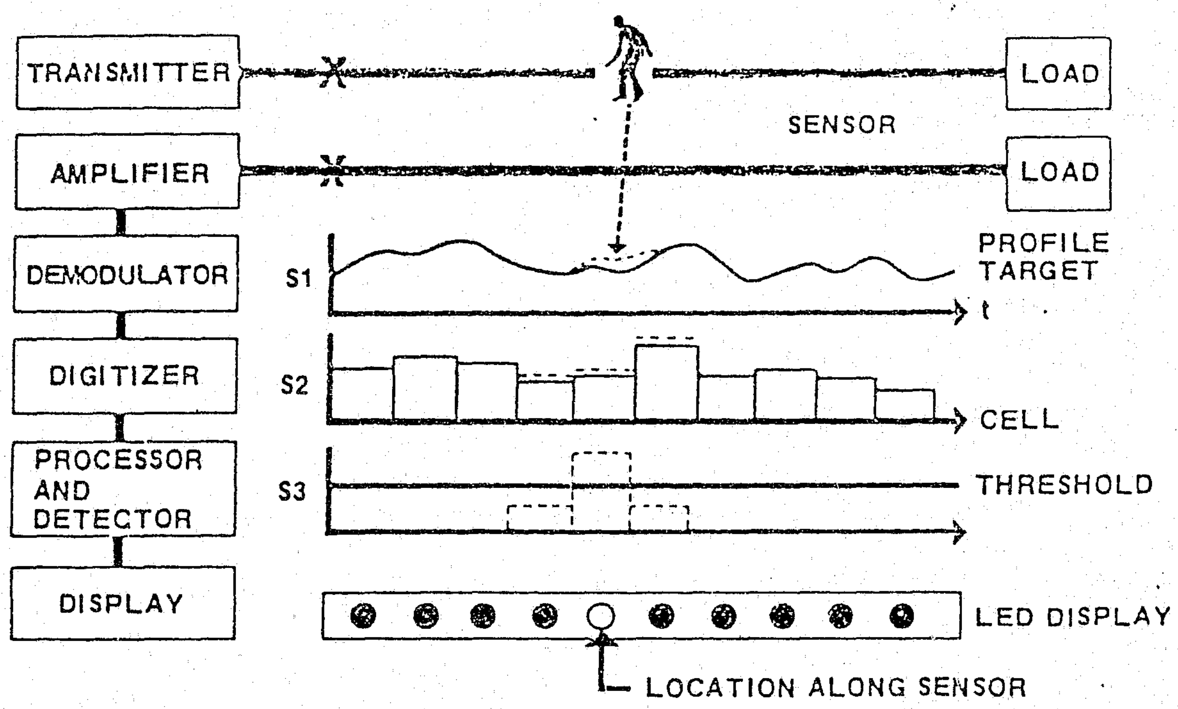


Figure 2.1 Operation of the GUIDAR PCCS System

can be detected with additional signal processing. Signal S1 is divided electronically into separate range cells and each cell is quantized into discrete levels. This range division and digitization process is represented by signal S2 of Figure 2.1.

The change in magnitude of signal S2, caused by an intruder, for a single transmitted pulse is not large enough to be reliably distinguished from the quasi-stationary profile. Several thousand pulses must be integrated, or added, over time in order to distinguish a true target from a false alarm. Pulse integration greatly enhances the signal to noise ratio because the magnitude changes of the returned signal caused by an intruder are correlated from pulse to pulse where the noise is uncorrelated from pulse to pulse.

After pulse integration, the magnitude of each range cell is compared against the weighted average of previous cell magnitudes. The difference, signal S3 of Figure 2.1, is compared against a predetermined threshold. If this value exceeds the threshold, an intrusion is declared.

Sections 2.2.1 through 2.2.6 will describe each part of the system block diagram shown in Figure 2.2 (Guided Intrusion Detection and Ranging System 1981). Sections 2.2.7 through 2.2.9 are entitled power consumption, operating temperature range and and possible improvements.

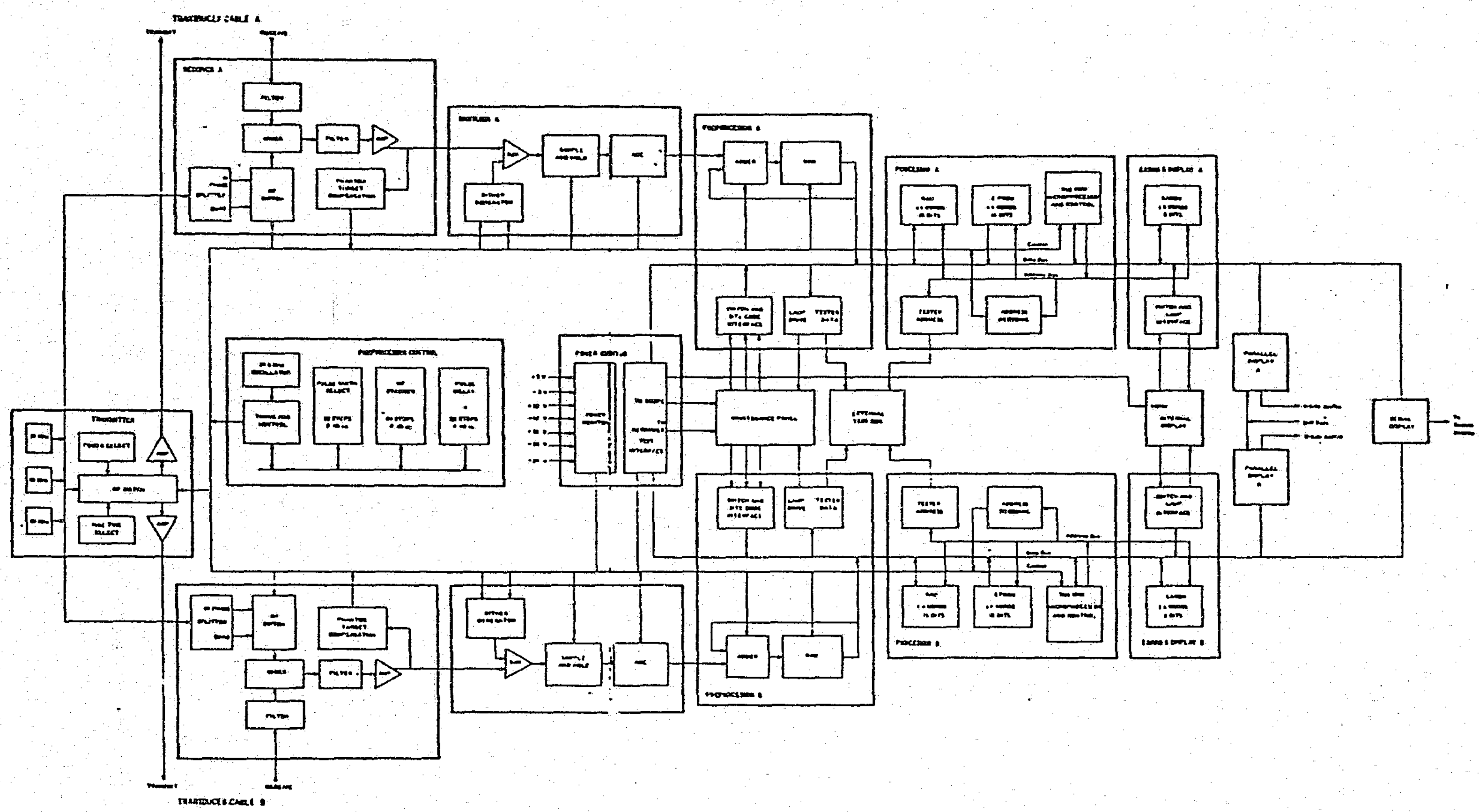


Figure 2.2 GUIDAR Transmitter/Receiver Block Diagram

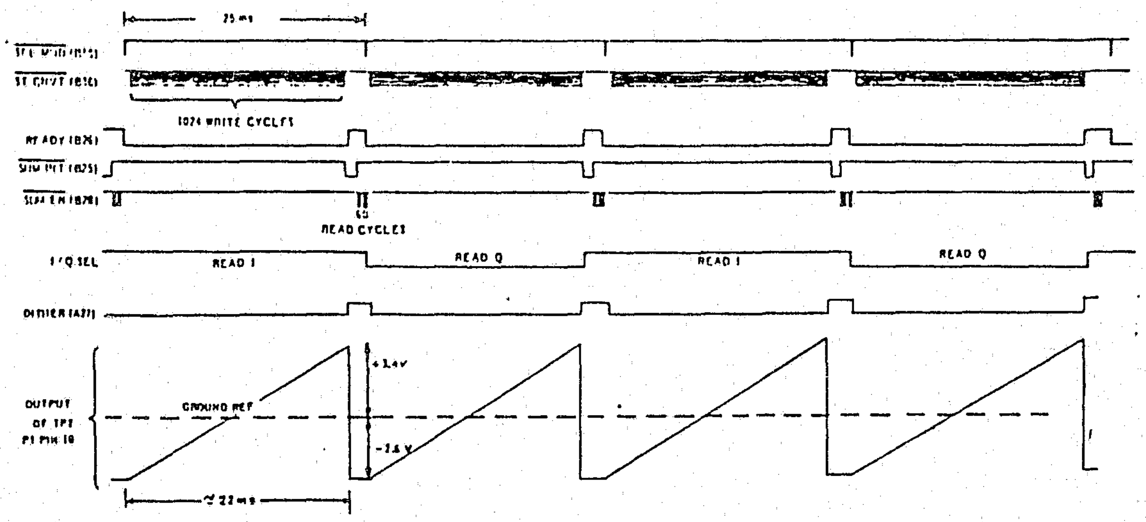
2.2.1 Preprocessor Control

A 24.491 MHz crystal oscillator provides the basic 40.8 ns timing interval used throughout the GUIDAR system. Specific timing diagrams can be found in the GUIDAR technical manual. One timing and control unit provides timing and synchronization to the transmitter, receiver, digitizer, preprocessor and the TMS 9900 microprocessor. The received signal is demodulated, digitized, integrated and processed using common timing signals. This centralized timing design has a significant impact on the ability to easily separate the different signal processing stages. This topic will be elaborated upon during the preliminary evaluation of the candidate systems in Chapter 4.

The four phase timing necessary for the TMS 9900 microprocessor is generated from the 24.491 MHz oscillator. This timing consists of four 61 ns clock pulses with a 326.7 ns period. The basic clock rate of the TMS 9900 microprocessor is 3.3 MHz (TMS 9900 Microprocessor Data Manual 1978). The TMS 9900 microprocessor, which was state of the art in the 1970's, operates significantly slower than most modern microprocessors. Today, 16 bit microprocessors operate in the 10 MHz range. The possibility of using a faster microprocessor will be explored in section 2.2.9.

Both sides of the GUIDAR system operate simultaneously. Each side is synchronized at the start of a pulse transmission by waiting until their respective processors have completed the previous cycle. The transmission of an RF pulse is initiated by the TMS 9900 microprocessor by the setting of the SELMOD timing signal to a low. An overview of the timing signals used in the GUIDAR system is shown in Figure 2.3 (Guided Intrusion Detection and Ranging System 1981). The TMS 9900 microprocessor also acts as a controller for the receiver demodulator and digitizer. In addition, it performs self testing routines and provides alarms for system malfunctions, cable breaks and component failure (Harman and Mackay 1976). This centralized control inhibits easy separation of the different signal processing stages.

The width of the transmitted pulse is manually set by switches located on the processor control board. At the beginning of the pulse transmission cycle, the pulse width switch settings are parallel loaded into the pulse width counter. The pulse width counter is incremented by the basic clock cycle every 40.8 ns until the terminal count is reached. The minimum pulse width setting is 40.8 ns and the maximum pulse width setting is 1264.8 ns. The pulse width determines the resolution accuracy of the system. A smaller pulse width provides better target resolution but increases the bandwidth. Wider bandwidth processing allows more noise power at the receiver which lowers the signal to noise ratio and reduces the probability of detection. A reduction in pulse width should correspond with an increase in peak pulse transmitted power. Too wide of a pulse will cause range ambiguities. The recommended pulse width setting is 450 ns (Guided Intrusion Detection and Ranging System 1981). At this setting, using a pulse propagation velocity of 2.37×10^8 m/s (Vinnins et al. 1976) the transmitted pulse will be approximately 106 meters long.



Figures 2.3 Overview of the GUIDAR Timing Signals

The RF stagger counter works together with the Pulse Delay Counter to vary the repetition frequency of the transmitted pulse in a pseudo random fashion. This is an antijamming technique which can prevent an intruder with electronic monitoring equipment to from locking onto the pulse repetition frequency (Chalmers 1985). The RF stagger counter is reset at the start of each read cycle and is incremented on each iteration through 1024 pulses. The seven bit output, which will be a number between 192 and 255, is used as a preset input to the Delay Timer. When the RF stagger counter is disabled, it increments to terminal count and loads a value of 255 into the Delay Counter. This will provide a constant delay between read cycles.

The received signal is demodulated and electronically divided into 60 range bins. Recently, a variable zone feature has been added which permits the operator to define the number and length of each of the range bins (Clarke and Sims 1984). When the end cell counter reaches 60, the Pulse Delay Counter is reset to zero. This counter is then incremented at the basic clock rate of 40.8 ns until a count of 96 is detected by the decode gates. This delay, 40.8ns X 96, generates the 4.0 us clock phantom which occurs at the end of every pulse cycle. Phantom target compensation lasts for 4.0 us after the return of each transmitted pulse. This provides dc restoration and eliminates the possibility of ghost targets caused by multiple reflections from within the cable and from the surrounding environment. During the 4.0 us phantom target generation, the value in the frequency agility counter is loaded into the pulse delay counter. This will correspond to an maximum additional delay of 2.74us (Guided Intrusion Detection and Ranging System 1981).

The timing breakdown for one target detection cycle is listed below. This timing breakdown parallels the flow chart shown in Figure 2.4 (Guided Intrusion Detection and Ranging System 1981).

Sample rate 285.8 ns X 60 cells	=	17.1 us
Phantom Target Compensation	=	4.0 us
Jitter Delay (prf jitter off)	=	0.1 us
Time per iteration	=	21.2 us
Preprocessor output 1024 iterations	=	21.7 ms
Read cycle 16.4 us X 60 cells	=	1.0 ms
Single cycle time	=	22.7 ms
2 X I + 2 X Q	=	90.8 ms
Processor computation	=	9.0 ms
Total cycle time	=	99.8 ms

The total cycle time of 99.8 ms equates to about 10 target detection cycles per second. The pulse repetition frequency is of the order of 40,960 pulses per second. The maximum speed of a human target is considered to be 10 meters per second and the average minimum detection zone width is of the order of 2.5 meters (Frankel et al. 1983, pp. 55-58). A person crossing the detection zone at 10 m/s will only be detected twice. Any redesign or separation of the signal

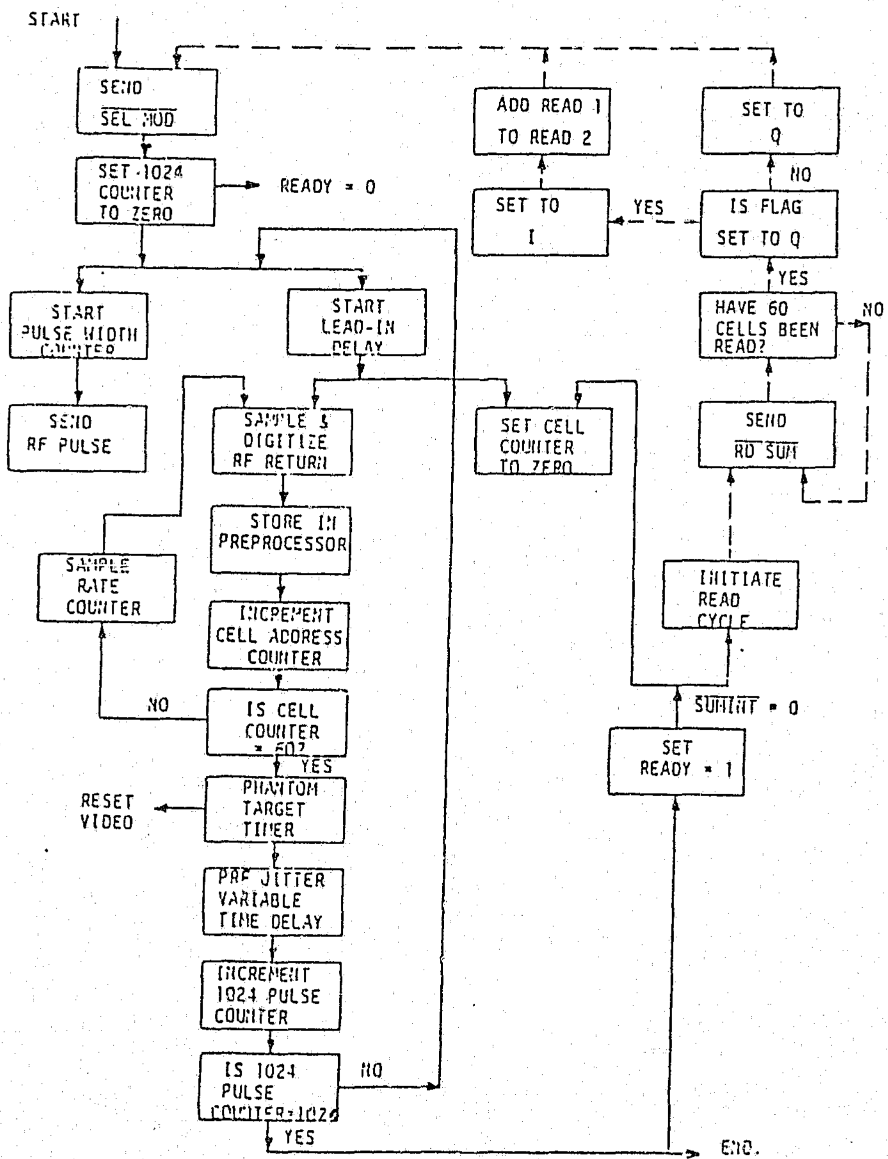


Figure 2.4 GUIDAR Signal Processing Flow Chart

processing stages will have to maintain the same cycle time in order to insure the same probability of detection. This fact affects the total bandwidth required to transmit any of the partially processed signals. This topic will be discussed further in Chapter 4.

2.2.2 Transmitter

Since leaky coaxial cable sensors produce electromagnetic fields, they must comply with the Federal Communications Commission (FCC) regulations. For the GUIDAR system, three carrier frequencies are possible: 57 MHz, 63 MHz, and 69 MHz. These frequencies are located along the fringe, or unused channel space, of television channels 2, 3 and 4 respectively. The use of this channel space has been approved by the FCC. The most favorable operating frequency should be determined experimentally at each location where the GUIDAR system is installed.

An optimal carrier frequency depends both on the line loss, due to cable attenuation, and on the coupling loss between the transmit and receive cables. The effective operating range of leaky coaxial cables has determined to be between 30 and 200 MHz (Clarke and Sims 1984). As the carrier frequency increases so does the signal attenuation. Therefore, cable attenuation loss favors the use of the lowest frequency possible. The line losses of various types of leaky coaxial cables have been documented and typical values at a 60 MHz carrier frequency range from 0.6 db per 100 ft to as high as 1.4 db per 100 ft. (Patterson and Mackay 1977 and Cree and Giles 1975). Calculation of the coupling loss between the transmit and receive cables is more complex (Maki 1984 and Harman 1983a). This loss can depend on the cable construction, the cable spacing, soil parameters and other environmental affects. One theoretical study suggest a minimum working frequency of 30 MHz (Martain 1975). Another study, based on experimental data collected from the SENTRAX system, suggest that the optimal operating frequency is in the range of 40 MHz (Harman 1983d). A third study suggest that the optimal frequency range is between 40 and 75 MHz (Poirier 1982). In general, the overall probability of detection depends more on the system coupling loss, receiver sensitivity and signal processing then the precise operating frequency.

The peak pulse transmitted power is set manually by switches located on the transmitter circuit card. Four settings are possible 200, 400, 600, and 800 mW. The normal setting is 800 mW (Guided Intrusion Detection and Ranging System 1981). The more signal power the higher the signal to noise ratio and the higher the probability of detection.

2.2.3 Receiver

The GUIDAR system uses synchronous or coherent detection to demodulate the returning pulse. The pulses taken from the receive transducer cable are first passband filtered to eliminate some of the noise and then mixed alternately with the inphase and quadrature components of the original carrier. When the received signals frequency is known, but not its amplitude or phase, this type of receiver is optimal (Whalen 1971, pp. 205-207). The signal is then lowpass filtered to get the baseband portion. The resulting signal is represented by signal S1 of Figure 2.1.

Synchronous detection allows the returned pulse to be integrated for the entire pulse duration, thereby increasing the overall signal to noise ratio (Mackay and Penstone 1974).

2.2.4 Digitizer

The baseband output is mixed with a ramp waveform, called dither, to minimize linearity errors and increase dynamic range. The ramp waveform is continuous over an entire 1024 pulse cycle and is reset during each write cycle. Dither acts to eliminate the harmonic distortion caused by the quantizer clipping low level signals (Bloom 1985).

From the dither circuit, the signal is sent into a zero order sample and hold circuit. The sample and hold circuit is necessary to reduce the aperture effect created by the narrow sampling pulses and allow the analog to digital converter to operate slowly compared to the sampling rate. Since impulses can not be realized, the received signal is sampled with a series of narrow flat top pulses. This process imparts a sinx/x roll-off factor on the frequency spectrum of the sampled signal. When the ratio of the pulse width to the pulse period (duty cycle) is less then ten percent, the roll-off effect is negligible. However, when the duty cycle is high, the sinx/x weighting factor on the sampled signal can cause decision uncertainties in the

A/D converter (Transmission Systems for Communication 1982, Chapter 28).

After the sample and hold circuit, the time width of each pulse is now equivalent to the distance of one cell or 33 1/3 meters. Next, the analog to digital converter quantizes each cell into an 8 bit digital word. An 8 bit A/D converter will detect changes in the fixed profile as low as Ø.4 percent. Since the original development of the GUIDAR system, the digitizer module has been replaced with a newer integrated circuit capable of 8 bit A/D conversion at the 15 MHz rate (Clarke and Sims 1984). With the 8 bit flash converter, the sample and hold circuit is not necessary. Considerably better linearity and reliability has been obtained through the use of this module. Increased linearity results in lower quantization noise and hence lower false alarm rates. The improvement factor for a 8 bit A/D converter is about 5Ø db (Bloom 1985). Other possible methods to improve linearity and decrease quantization noise are the use of 12 or 16 bit quantizers, companding circuitry and adaptive digitalization techniques (Bloom 1982).

2.2.5 Preprocessor

To provide an acceptable rate of incoming data to the TMS 99ØØ processor, the preprocessor sums 1Ø24 eight bit samples for each of the 6Ø range cells into separate 18 bit random access memory locations. This summing process is known as pulse integration. Pulse integration consists of adding N successive pulses together and comparing their sum against a predetermined threshold. When adding N pulses of voltage V, the total signal voltage is NV. The noise voltage, however, will fluctuate about its average value. Due to the random nature of noise, the voltage of the sum is only $\sqrt{N}$ times the voltage of a single pulse. Therefore, the signal to noise ratio of the sum provides an improvement factor of $\sqrt{N}$ db (Marcum 1960). Since the GUIDAR system integrates a total of 2048 pulses per range cell, the total improvement factor will be about 45 db. The more pulses integrated, the higher the signal to noise ratio and the greater the probability of detection, but, at the expense of longer detection times. There is a trade-off between pulse integration time and the probability of detection.

After a block of 1024 samples has been collected, the most significant 16 bits of each cell is passed to the processor. After the processor has received two inphase and two quadrature blocks of data from the preprocessor, target detection is performed before starting a new cycle.

2.2.6 Processor

The TMS 9900 microprocessor acts as command and control for the entire system. It controls the transmit pulse generator, receiver demodulator and the digitizer (Harman and Mackay 1976).

The processor first takes the two inphase blocks of data from the preprocessor and sums them together to get a total pulse integration of 2048 pulses. The processor also does this with the quadrature blocks of data. Next, the processor performs recursive filtering to remove the profile. The exact filtering algorithm is proprietary information of Computing Devices Company (Chalmers 1985).

The TMS 9900 processor realizes a second order recursive filter. The exact filter coefficients are not known. The recursive filter could be acting as a delay line canceler. In radar applications, delay line cancelers are widely used as a means of separating moving targets from fixed clutter. A delay-line canceler filters out the small portion of noise around the dc component of the returning signal. Also, the filter could be used smooth-out the magnitudes of the integrated cell values. Each new cell magnitude would be compared against a running average of previous cell magnitudes. In addition to filtering, the processor might perform some cable equalization algorithms (Mackay and Mason 1975).

After filtering, the resulting magnitudes of the inphase and quadrature channels are summed together to determine the peak cell values (Figure 2.5, Patterson and Mackay 1977). The peak value for each cell is then compared against the threshold value, which was established during calibration, for that cell. If the peak value exceeds the threshold value, an intrusion is declared for that cell. The threshold value for each of the cells is stored in the EPROM memory located on the EPROM circuit card assembly.

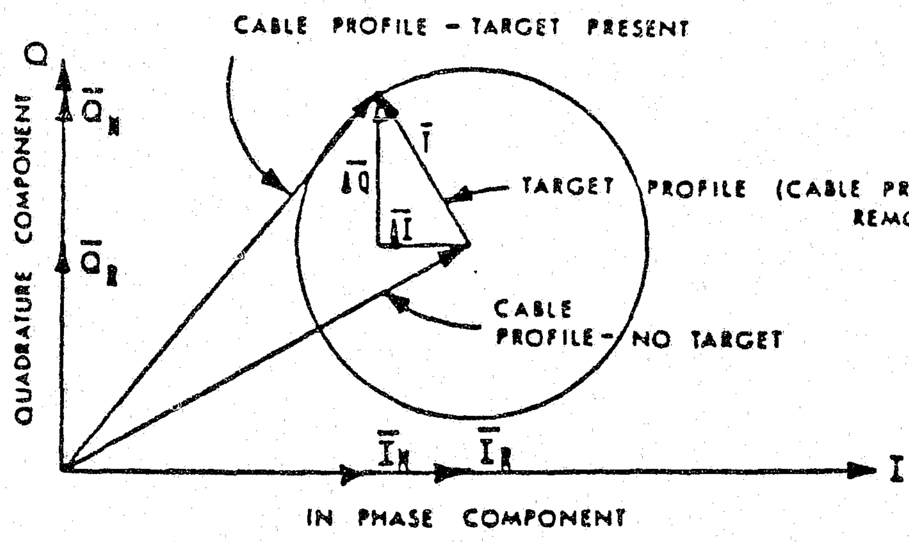


Figure 2.5 Vector Subtraction of the Inphase and Quadrature Phase Components to Determine the Target Profile

2.2.7 Power Consumption

Power requirements will be a significant factor in determining the feasibility of a 100 mile long-sensor system. The GUIDAR system draws 2.4 amps of current at 115 volts AC fully loaded. The display portion of the GUIDAR system would not be required at each two mile segment. It is estimated that each two mile segment would require 2.0 amperes of current to power the GUIDAR system less display and the additional transmitter equipment. A hundred mile system involving 50 sensors would require 100 amps at 115 volts or 11,500 watts of power. The allocation of this power would involve the installation of a major power distribution system. An additional study would be required to collect the cost data for the optimal power distribution system and explore the possibilities of using alternative power sources such as photovoltaic cells and batteries.

2.2.8 Operating Temperature Range

The GUIDAR systems normal operating temperature range is from 0 to 35 degrees Celsius (32-95 degrees Fahrenheit). This temperature range should be sufficient for a long line sensor system provided each sensor is buried underground below the soil freezing level. Since the GUIDAR system requires environmental protection, each system would have to be buried in a specialized weather proof container. This container would have to protect against moisture condensation and provide some type of heat sink to dissipate any excess heat generated during operation. Additional performance data should be collected determine the reliability of the GUIDAR system when operating near either of its temperature extremes for extended periods of time. If an all-weather system is not available from the manufacturer, the design and manufacture of a environmentally controlled container system will add additional cost to the overall system design.

2.2.9 Possible Improvements

Recent improvements incorporated into the GUIDAR system include the implementation of variable zone boundaries, the replacement of the digitizer module with an 8 bit flash A/D converter and the application of more powerful signal processing algorithms (Clarke and Sims 1984).

It has been demonstrated that a significant reduction in false and nuisance alarms can be obtained by applying an adaptive learning technique. With the adaptive learning technique, the signal processing algorithms are continually adapted to the changing soil conditions and nuisance alarm rates (Hunt 1984 and Hunt et al. 1983). The adaptive learning technique declares an alarm when the processed signal parameters are within the range of a human target and it declares an alert when a cell threshold is exceeded but the processed signal parameters are not within the range of a human target. The adaptive learning algorithm processes both the time and frequency domain features of the sensor signal and then applies a target recognition technique to distinguish true targets from false alarms. The frequency domain features are processed using the fast fourier transform algorithm. The limiting factor on the implementation of any new signal processing algorithm is the total time required to perform target detection. At least one target detection must be performed in the time it takes an intruder to cross the detection zone. The more complex the target detection algorithm, the more computations necessary for each target detection. A faster microprocessor would be required to implement additional target detection schemes. An additional study would be necessary to test any changes in the signal processing algorithms or hardware design of the GUIDAR system.

2.3 General Theory of Operation--SENTRAX System

The SENTRAX system differs from the GUIDAR system in that it is a continuous wave sensor which operates at a frequency of 40.68 MHz. The SENTRAX system consists of the following main components: transceiver modules, cable sets, control module, printer and an operators terminal (Figure 1.2). Since the SENTRAX system transmits a continuous frequency along the sensor cables, it can only detect an intrusion that has occurred anywhere between two transceiver modules. The maximum spacing between two transceiver modules is 300 meters. The maximum number of transceiver modules that can be linked together is 16. A complete SENTRAX system has a total length of 4.8 kilometers. Target detection is performed at each transceiver module. The central control module uses the leaky cable sets to collect intrusion detection data from each transceiver. The central control module also distributes power to each transceiver through the leaky cable sets. The SENTRAX system has the ability to interface with other sensor systems through the use of specially designed interface units. These interface units allow additional sensors to communicate to the control module or directly to the operators terminal via standard RS232 data links. The operator terminal provides the system operator with a means to communicate to the control module or any of the transceiver modules. Alarm acknowledge and threshold settings are set from the operators terminal. Other alarms such as cable fault, test failure, tamper detection and rf jamming are detected at the operators terminal. The printer furnishes a hard copy of all alarms, operator actions and maintenance events. A long line sensor system would only require the transceiver modules, control modules and cable sets at each 4.8 kilometer segment. The printer and the operators terminal would be located at the remote central base station.

Sections 2.3.1 and 2.3.2 will describe the operation of the transceiver module and control module in more detail. Sections 2.3.3 and 2.3.4 are entitled operating temperature range and power consumption. Section 2.3.5 will discuss possible system improvements and design changes.

2.3.1 Transceiver Modules

Each transceiver module, TM, can detect targets in two separate detection zones. Each detection zone has a maximum length of 150 meters. Normally, the TM modules are connected in cascade with one detection zone located on each side. T-couplers can be used to permit branching of the TMs at any point along the detection zone. Rf decoupler units are buried with the leaky cables to isolate detection zones from adjacent TMs. Each TM alternatively checks its left and right detection zones a number of times per second. Target detections are performed using signal processing algorithms similar to those used in the GUIDAR system. The exact nature of the signal processing algorithms is considered proprietary information by the manufacturer.

The TM provides the operator with five different types of alarms: intrusion, tamper, cable fault, self test failure and RF jamming. If the TM casing is opened, a tamper alarm is generated. If one of the cable sets is damaged, a cable fault alarm is produced. Each TM is equipped with a self test capability with an associated test failure alarm.

Specialized transceiver modules have the ability to interface with additional sensor systems. These TMs can provide 12 volts dc at 100 mA to external sensors. Different types of sensors might be useful in some sectors of a long line system.

2.3.2 Control Modules

The control module uses both time and frequency division multiplexing to distribute power to and collect data from each transceiver module. Each control module can incorporate up to 16 transceiver modules for a total of 32 detection zones. Centralized timing and synchronization is provided by the control module to each transceiver module to avoid collision during intrusion data collection.

After intrusion data is collected from the transceiver modules, it is passed to the operators terminal through a standard RS232 data link. A long line sensor system would require the output of the control module to be passed to the central base station or an intermediate node. Additional transmitter equipment and storage logic would be required every 4.8 kilometer segment of a long line sensor system.

2.3.3 Operating Temperature Range

The transceiver modules and cable sets have an operating temperature range of -40 to +60 degrees Celsius (-40 to +140 Fahrenheit). The control module is normally located indoors and has an operating temperature range of 0 to 40 degrees Celsius (32 to 104 Fahrenheit). If an all-weather control module is not available from the manufacturer, each control module would have to be adapted for outdoor use or placed in a specialized weather proof container.

2.3.4 Power Consumption

Each transceiver module requires 8.5 watts of power and the control module requires 60 watts of power. A 4.8 kilometer system, using 16 transceiver modules and one control module would require a total power of 196 watts. A 161 kilometer system (100 miles), including the overhead for transmitter equipment, would need a minimum of 7,000 watts of power. This estimate is 3,500 watts less than then the estimate for the GUIDAR system. As with the GUIDAR system, distribution of this power over a hundred miles would require the installation of a major power distribution system. An additional study would be necessary to determine the most feasible power distribution system.

2.3.5 Possible Improvements

CW systems are ideally suited for areas which do not require the high range resolution of pulsed systems. Over long border areas, there may be sections where intrusion detection to the nearest one forth or one half mile would be adequate.

The transceiver modules of the SENTRAX system can only be separated a maximum distance of 300 meters. This is because both the intrusion data and power are transmitted over the leaky cable sets. If separate power and data distribution lines were employed, a greater separation distance between each transceiver module could be achieved. This would reduce the number of transceiver modules needed for each 3 mile (4.8 kilometer) segment and therefore the overall cost of a 100 mile system. The maximum separation distance between each transceiver module would be directly proportional to the pulse transmit power. Similar to the GUIDAR system, as the separation distance between transceiver modules increased, line amplifier units would be necessary to maintain a high signal to noise ratio. However, the cost of a additional line amplifier units would most likely be less than the cost of the transceiver modules.

Large separation distances between transceiver modules would only be practical if the intrusion response ratio remained within the recommended 3 to 1 ratio (Frankel et al. 1984). The 3 to 1 intrusion response ratio would enable the system to distinguish actual intrusions from small animals.

Frequency modulated CW systems have the ability to detect target range, but, more expensive electronics are necessary at both the transmitter and receiver. FMCW systems have been successfully built for distributed fiber optic sensors (Davies 1984). At this time, there are no CWFM ported coaxial cable sensors manufactured. The potential use of this technology should be explored further.

CHAPTER 3

THREE VARIABLES OF THE COMMUNICATIONS PROBLEM

3.1 Introduction

The design of a long line sensor system can be separated into three unique divisions. These three divisions, labeled the three variables of the communications problem, are network topology, distribution of processing and type of transmission media.

Network topology refers to the method by which each sensor is connected to the remote base station. Common network topologies are the star, bus, tree, ring and mesh networks (Figure 3.1). Each sensor can communicate directly or indirectly to the base station. The communications channel can be shared by part or all of the sensors, or each sensor can have its own dedicated communications channel. The three topologies being considered for this long line sensor project are the bus, star and tree topologies.

The choice of the best topology is dependent upon the degree of distributed processing and the type of transmission media. For example, a multilevel distributed processing system would require the use of a tree network. Tree topologies would require the use of line of sight radio for transmission media. Star topologies would have to use nonline of sight radio systems and satellite communication links for transmitting the sensor data to the base station. Bus topologies favor

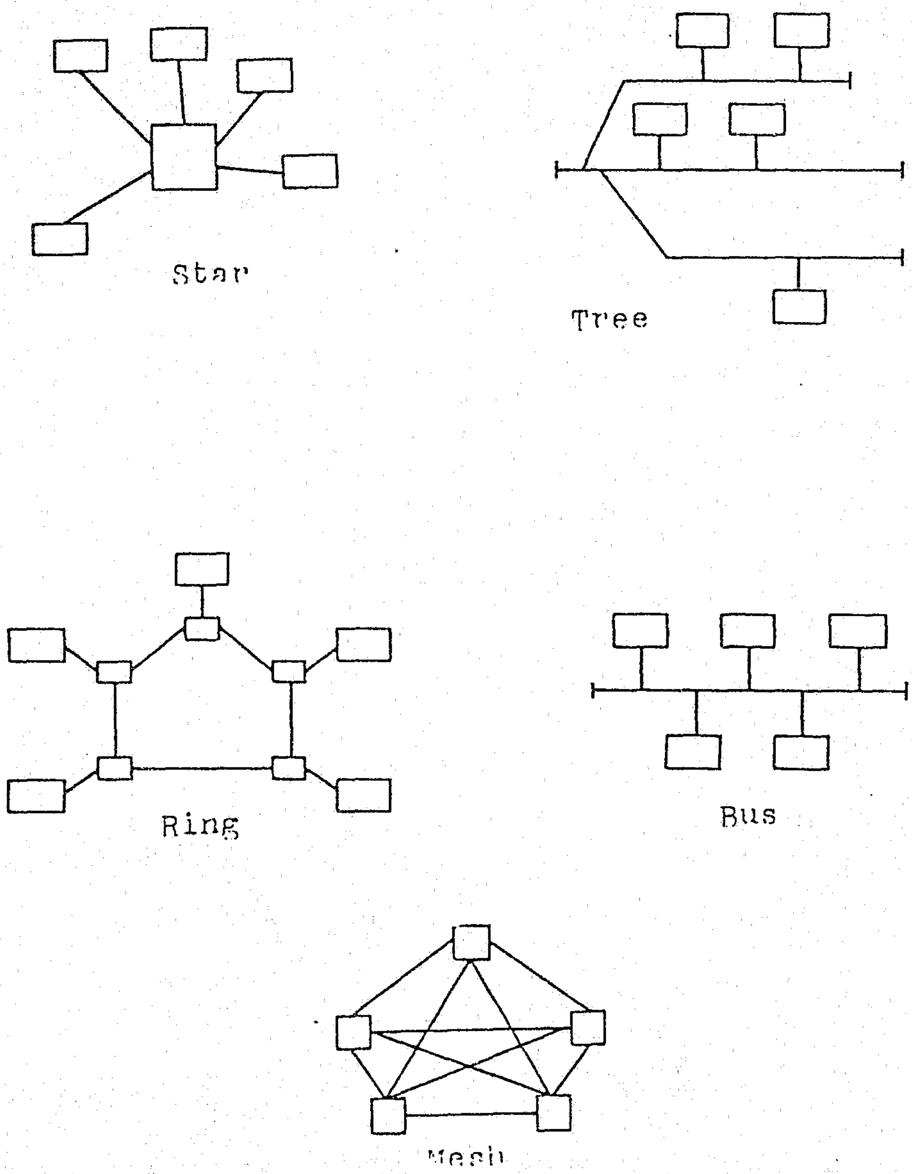


Figure 3.1 Network Topologies

the use of cable and power line carrier systems for transmission media. A detailed description of the different types of network topologies will be given in section 3.2.

Distribution of processing is defined as the degree in which the sensor data signals are processed at each node in the network. On one extreme, unprocessed sensor data would be sent directly to the base station for complete processing. On the other extreme, all signal processing would be done at each sensor site. With this scheme, only the essential intrusion data, such as the cell threshold and target location, would be sent to the base station. For bus and star networks, all of the different signal processing stages would be performed at each sensor site or at the remote base station because there are no intermediate nodes in these network designs. Several different signal processing distributions designs are possible with tree networks. A functional block diagram of the different signal processing stages of the GUIDAR system is shown in Figure 3.2. Distribution of processing will be discussed in more detail in section 3.3.

The various types of transmission media under consideration range from simple twisted pair wire to sophisticated satellite transmission systems. A list of the candidate transmission media is shown in Figure 3.3. The bandwidth required to send the sensor data signals to the base station is the primary consideration when choosing a transmission media. In general, the more bandwidth required, the

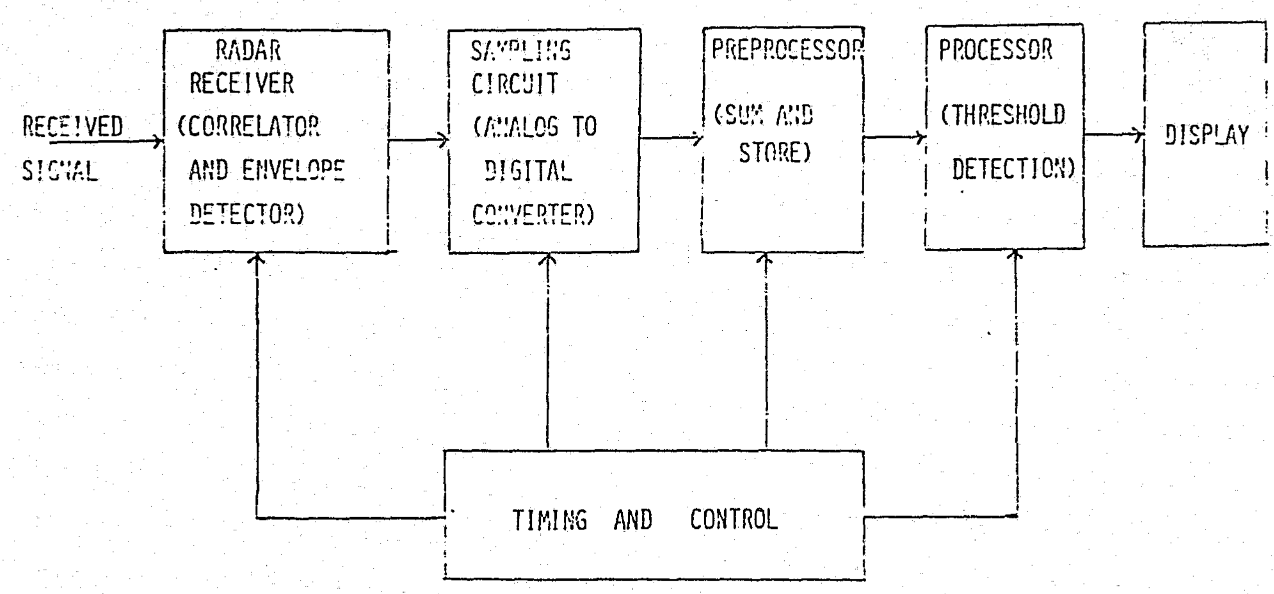


Figure 3.2 Functional Block Diagram of GUIDAR Receiver

--- twisted pair wire

--- baseband coaxial cable

--- broadband coaxial cable

--- fiber optic cable

--- power line carrier

--- low, medium and high frequency band radio

--- very-high and ultra-high frequency band radio

--- microwave radio

--- satellite

Figure 3.3 Candidate Transmission Media

greater the cost of the associated transmission media. For example, twisted pair wire has lowest cable cost per kilometer but it also has the least bandwidth of all of the candidate cable transmission media. Microwave, fiber optic and satellite systems offer the greatest amount of bandwidth but are also the most expensive transmission media. Usually, once the required transmission bandwidth is set, the transmission medium that most closely matches the required bandwidth is selected. Also, if future expansion is required, a transmission medium that provides excess bandwidth can be chosen. A derivation of the required sensor signal bandwidth for several distributed processing arrangements is given in Chapter 4.

Other important factors which influence the choice of transmission medium are attenuation versus repeater spacing for cable systems and the ability to obtain approval from the Federal Communications Commissions (FCC) for radio, microwave and satellite systems. The specific advantages and disadvantages for each transmission medium will be discussed in section 3.4.

3.2 Topology

Distributed processing systems are frequently characterized by their topology. Network topology, as applied to long line sensor systems, can be defined as the physical arrangement and interconnection between each sensor and the base station. The five common topologies are: star, bus, tree, ring and mesh (Figure 3.1).

In a star network, each sensor communicates directly to the base station. For a short sensor system, less than a few kilometers, it would be possible to install a separate cable communications link from the base station to each sensor. This process is impractical for a one hundred mile long sensor system. Therefore, star network designs are limited to using nonline of sight radio and satellite communications systems for transmission media. Greater then line of site radio communications can be achieved by using the low, medium and high frequency radio bands. The feasibility of using low, medium and high frequency band radio systems and satellite systems as a transmission media will be discussed further in sections 3.4.5 and 3.4.8.

The major advantages of star networks are terrain independence, ease of expansion and the fact that a single sensor failure does not affect the remainder of the network. The main disadvantage of star topologies, as well as all radio systems, is the requirement for an antenna to be collocated with each sensor. The vulnerability of exposed antenna systems is a subjective matter. An above ground antenna system could easily be seen and possibly damaged by an intruder.

With bus networks, each sensor is located along a single transmission path called a bus. The base station could be located at either endpoint of the one hundred mile system or anywhere in between the endpoints. For this study, the base station will be assumed to be located at one of the end points of the one hundred mile system. This is essentially a worst case assumption and would require the most distant sensor to communicate a minimum of one hundred miles to the base station. Bus topologies are limited to using twisted pair wire, coaxial cable, fiber optic cable and power line carrier as transmission media.

Numerous access protocols (Stallings 1985, Chapter 11 and Tobagi et al. 1984) have been developed which will allow any number of sensors to communicate over a common bus. The most commonly used access protocol for bus topologies is carrier sense multiple access with collision detection (CSMA/CD). With this protocol, each sensor listens to the bus, before transmitting, for the presence of data traffic. If traffic is present, the sensor normally waits a random amount of time before trying to retransmit. While transmitting a data packet, the sensor continues to listen to the bus in order to detect a possible collision with another data packet. If a collision occurs, the sensor again waits a random amount of time before trying to retransmit. CSMA/CD performs well when the data being transmitted is bursty in nature (Local Area Networks 1985). The specific performance of CSMA/CD and other access protocols depends on the total number of sensors and data rate of each sensor.

Two way communications between the sensors and the base station is desirable. Two way communications would allow the base station to interrogate each sensor for information such as operating status, fault detection and data verification.

With broadband coaxial cable, it would be possible for each sensor to have a unique channel to communicate to the base station by assigning a different carrier frequency to each sensor. The number of possible subchannels depends on the bandwidth of each channel.

The principle advantage of bus networks is that the entire 100 mile sensor system could be completely buried. This is assuming that the power distribution system will be buried underground. Installation costs could be saved by burying the data communications cable in the same trench as the power distribution cable.

In a tree network, each sensor is connected to the base station through a series of intermediate nodes or branches. For distributed processing networks, each node can be used to compute one or more signal processing stages. For nondistributed processing systems, each node can act as a signal multiplexing and relay station. Error correction algorithms can be used on digital signals and analog signals can be filtered and amplified.

The main advantage of tree networks is the option to manipulate the sensor data signals before they arrive at the base station. The disadvantage is the additional installation cost of building the the intermediate remote relay stations.

Mesh and ring topologies are not compatible with the design of this type of long line sensor system. Ring topologies are similar to bus topologies except the endpoints are connected together to form a closed loop. The advantage of using a ring topology is that if the communications cable is damaged at any point, each sensor would still be able to communicate to the base station. For a 1ØØ mile sensor system, a ring topology would require 2ØØ miles of cable and this would not be cost effective. Mesh topologies can be eliminated since it is not necessary for a sensor to communicate to another sensor.

3.3 Distribution of Processing

Distribution of processing can be described as the degree in which the sensor data signals are processed at each node in the network. A long line sensor system using a distributed processing scheme might have several advantages over nondistributed processing networks. First, it might be possible to reduce the amount and complexity and, therefore the cost, of the GUIDAR signal processing equipment at each two mile segment. The second advantage of distributed processing is that it can allow the basic signal processing stages to operate at a faster rate as compared to the remaining more time consuming signal processing stages (Hunt 1983). For example, with the GUIDAR system, the next pulse integration cycle does not start until the TMS 99ØØ microprocessor has completed all intrusion detection computation. With a distributed processing scheme, it might be possible to separate the the TMS 99ØØ microprocessor from the rest of the GUIDAR system. This would allow the intrusion detection computation of the previous cycle and pulse integration of the present cycle to take place simultaneously.

Figure 3.2 shows a function block diagram of the major components of the GUIDAR receiver. A detailed description of each of these components can be found in Chapter 2.

There are five places where the signal processing components of the GUIDAR receiver can be divided to enable distributed processing. First, the signal taken directly from the receive cable can be sent to the base station or some intermediate node. This signal still contains the original carrier frequency. This carrier frequency could be translated to another carrier frequency before transmission. The second point where the GUIDAR receiver can be divided is after the correlator and envelope detector. At this point, the signal is either the inphase or quadrature phase envelope of the sensor profile. This signal is equivalent to signal S1 in Figure 2.1 and is called the baseband envelope. Since the carrier frequency has been removed, the envelope would have to be remodulated to an appropriate carrier frequency for transmission. With additional hardware, this signal could be digitalized and then transmitted as a digital signal. The third place were the GUIDAR receiver can be divided is after the analog to digital converter. This signal consists of 60 eight bit data words. Each data word represents one detection cell. This digital signal could be transmitted directly or converted to an analog signal using using any M-ary signaling scheme. The next place where the GUIDAR receiver can be divided is after the preprocessor. The signal at this point consists of 60, 18 bit data words. Each 18 bit word is the sum of 1024 values of either the inphase or quadrature components of the received signal. These 18 bit words can be transmitted digitally or converted to an analog signal before transmission. The last place to divided the GUIDAR receiver is after all signal processing and target detection has been completed. At this point, only the display data would be sent to the base station.

The bandwidth calculations for each of these distributed processing stages will be given in the next chapter. An important factor to be considered when separating any of the GUIDAR receiver components is timing and control. The GUIDAR receiver uses a centralized timing and control process. The centralized timing and control logic is used to synchronizes all of the signal processing stages. There are only two places in the GUIDAR receiver that do not operate from the centralized clock. The first place occurs prior to any signal processing. This signal is the unprocessed sensor profile taken directly from the receive cable. The second place occurs after all signal processing has been completed. The signal at this point is just the sensor display data.

3.4 Transmission Media

This section describes the advantages and disadvantages of each of the candidate transmission media listed in Figure 3.3.

3.4.1 Twisted Wire Pair

Each wire pair of a multipair twisted pair cable consists of two insulated conductors of copper or aluminum twisted together. The purpose of the twisting is to reduce the electromagnetic interference or crosstalk between each pair. Usually, the wire pairs are twisted at a variable pitch rate and then the entire cable is twisted throughout its length. Although aluminum conductor twisted pair cable is lighter in weight, copper conductors have less attenuation per unit length at a given frequency (Freeman 1985, p. 231) and are preferred for long distance communications. The conductors may be either solid or stranded with solid conductors recommended for long haul communications systems. Typical insulating material consists of a polyethylene compound. For direct burial cable, the outer shell is either foam or jelly filled to provide an all weather protective coating. Shielding is an effective means to further reduce electromagnetic interference. Each wire pair can be individually shielded, the entire cable can be shielded or both the wire pairs and the cable can be shielded. For long distance communications, individually shielded pairs and one overall shield is recommended. Common conductor sizes are 16 through 26 gauge (AWG) where the smaller the AWG, the larger the conductor size. Cable pair sizes range from 2 to over 3600 pairs per cable. Twisted pair wire is the least expensive of the transmission media at a cost of 25 to 30 cents per foot for 3 pair, 19 AWG, direct burial cable (Standard Materials List 1986).

Twisted pair wire (TWP) has the least bandwidth of all of the candidate cable transmission media. Although transmission rates of 1 Mbps can be achieved for a few thousand feet, the exponential attenuation rate at higher frequencies limits long distance communications to the 4 or 5 kilohertz bandwidth range. This bandwidth can support data rates up to 9,600 bps with relatively few errors. Attenuation in db per mile versus frequency for 19 AWG TWP is shown in Figure 3.4 (Freeman 1985, p. 235). At 5,000 hertz, the attenuation rate is 2.2 db per mile.

Attenuation and distortion can be counteracted by the use of a smaller AWG conductor size, narrower spacing of amplifiers, repeaters and line conditioning equipment and by the use of inductive loading. Inductive loading is a method to obtain dramatic decreases in attenuation for frequencies less then about 5,500 hertz. The effects of loading on 19 AWG TWP and the nominal cut-off frequencies for various loading systems is shown in Figure 3.5 (Hamsher 1967, pp. 11-16). For B-88 loading, the attenuation rate at 5,000 hertz is only about 0.3 db per mile compared to 2.2 db per mile for the nonloaded cable. A detailed analysis of the effects of inductive loading can be found in: Freedman 1981, pp. 63-65; Hamsher 1967, Chapter 11 and Transmission Systems for Communication 1983, Chapter 10.

One advantage of TWP is that it can easily be tapped. Bridge taps and line build out units are common components used throughout the telephone industry and are readily available. Each bridge tap adds about 2 to 3 db of attenuation to the overall link loss calculation (Transmission Systems for Communication 1985, Chapter 10).

Information can be sent over TWP wire in a digital or analog format. The advantage of digital transmission is that regenerative

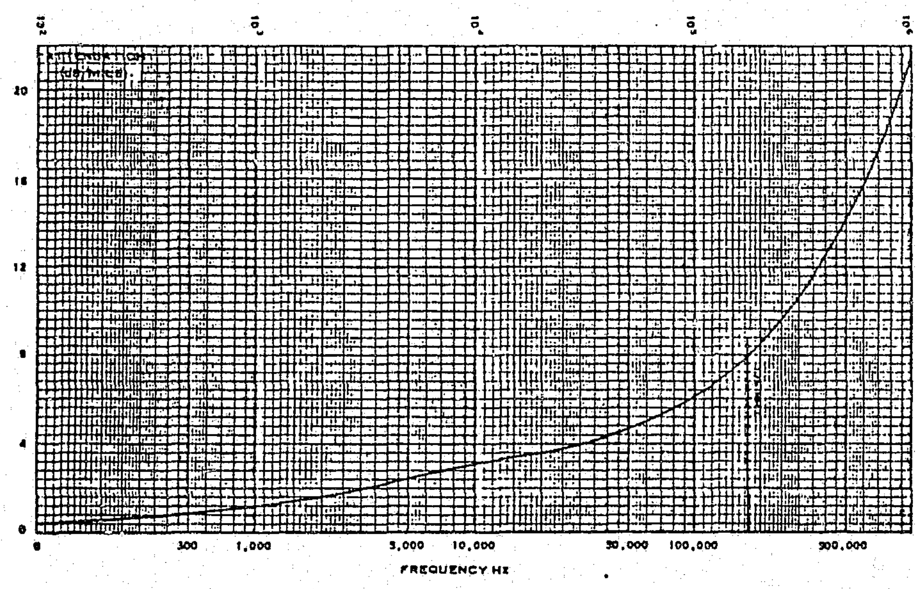
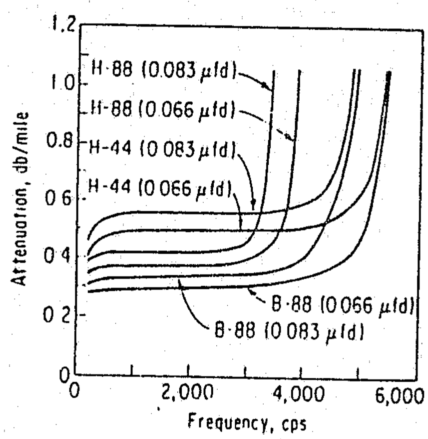


Figure 3.4 Attenuation Versus Frequency for a Typical 19 AWG Twisted Wire Pair Cable



Loading system	Mutual capacitance, μf/mile	Nominal cutoff frequency, cps
B-88	0.066	5,500
B-88	0.083	4,900
H-88	0.066	3,900
H-88	0.083	3,500
H-44	0.066	5,500
H-44	0.083	4,900
D-88	0.083	4,000

Figure 3.5 Effects of Inductive Loading on 19 AWG TWP Cable and Nominal Cut-Off Frequencies for Various Loading Systems

repeaters can be used and, therefore, the signal to noise ratio is restored after each repeater. Conversely, analog amplifiers amplify both the signal and the noise. With analog ampliers, the signal to noise ratio decreases with the log of the number of repeaters in the system (Transmission Systems for Communication 1985, pp. 385-386).

Intersymbol interference is another major factor in limiting the transmission distance of digital signals. Figure 3.6 (Guidelines for Engineering U.S. Army Satellite Terminals Interconnect Facilities 1984) shows the effects of both attenuation limits and intersymbol interference limits for a typical 19 AWG TWP cable. For a baud rate of 2.4 kilosymbols per second (9.6 Kbps QPSK) distances of around 10 miles can be achieved before line conditioning equipment is necessary. Low data rate modems have manufactors recommended ranges of 5 to 25 miles depending upon the line quality and data rates (Data Sources 1984).

3.4.2 Coaxial Cable

Coaxial cable consists of an inner conductor completely surrounded by a second conductor and a jacket material. The inner and outer conductors are separated by a continuous solid dielectric or by air and dielectric spacers. The inner conductor is either solid or stranded and the outer conductor is either solid or braided. The jacket material usually consists of a polyvinylchloride or polyurethane compound. Direct burial coaxial cable, in addition to having a waterproof jacket, uses a solid, tubular outer conductor. A specific list of the different types of dielectrics, conductors and

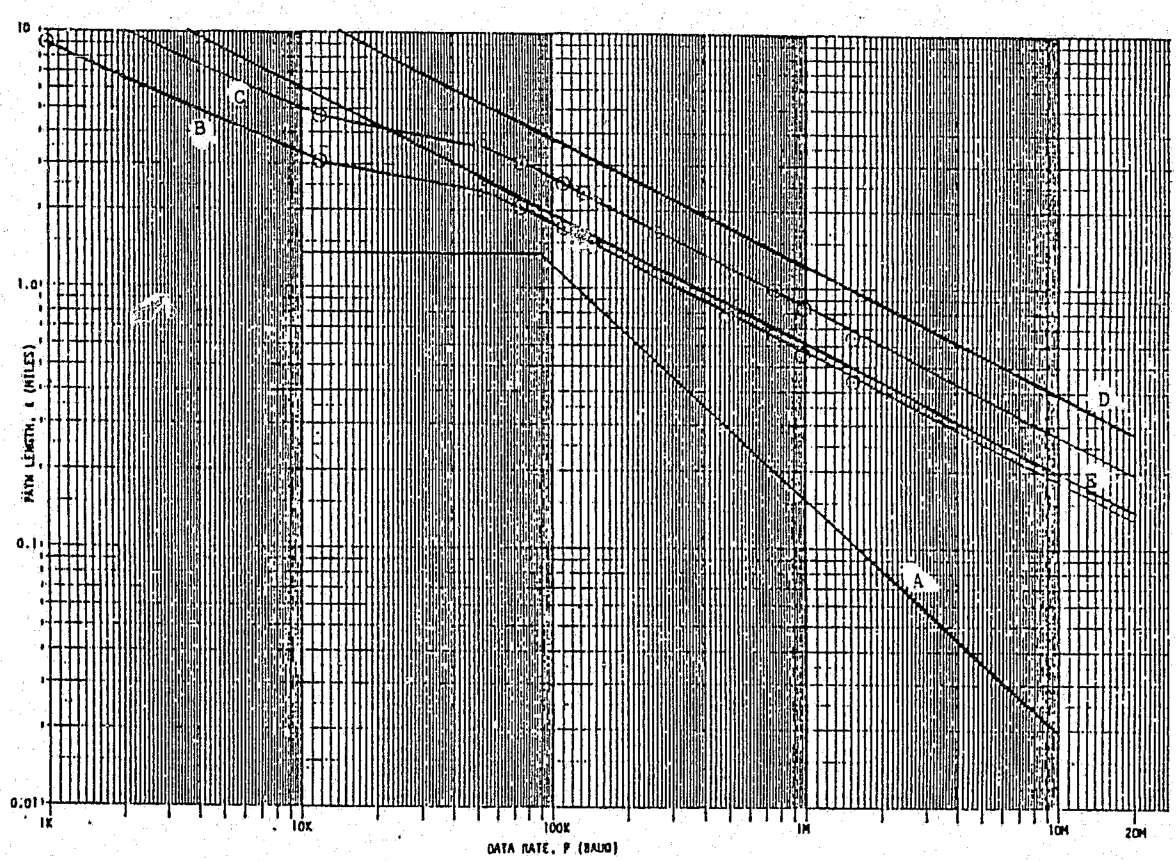


Figure 3.6 Attenuation Limited and Intersymbol Interference Limited Performance for a Typical 19 AWG TWP Cable

A - Recommended
B - 10 db insertion loss
C - 14 db insertion loss
D - 10% distortion
E - 5% distortion

jacket materials can be found in Guidelines for Engineering U.S. Army Satellite Terminals Interconnect Facilities 1984, p. 5-41.

Coaxial cable can operate in two modes, baseband and broadband. In baseband operation, data is transmitted digitally and, in broadband operation, data is transmitted in an analog format. In the baseband mode, the full bandwidth of the coaxial cable is made available to each device attached for a short period of time. Therefore, only one sensor at a time could communicate to the base station. In a the broadband mode, the total bandwidth of the coaxial cable can be divided into unique subchannels. Depending upon the data rate of each sensor, it might be possible to assign each sensor its own channel.

Common impedances of coaxial cable are 50, 75, and 125 ohms. By carefully choosing the size of the conductors and the type of dielectric, coaxial cables can be made to match any impedance within this range. Normally, 50 ohm cable is used for baseband networks and 75 ohm is used for broadband communication networks.

At normal operating frequencies, 1 MHz to 1 GHz, the outer conductor of the coaxial cable provides excellent shielding against electromagnetic interference. At lower frequencies, below 1 MHz, the skin depth of the transmitted signal is comparable to the thickness of the outer conductor and shielding becomes ineffective (Transmission Systems for Communication 1982, p. 81). At frequencies above 1 GHz, discontinuities in the cable caused by the manufacturing process begin to affect the attenuation rate. Bandwidths and mode cut-off frequencies for common size 50 and 75 ohm coaxial cable can be found in Freeman 1985, p. 256.

Coaxial cable can be used as a transmission medium when the bandwidth or carrier frequency of the signal to be transmitted ranges from about 1 MHz to 1 GHz. For baseband systems, the bit rate should exceed 1 M bit. Broadband coaxial cable systems can be used to transmit lower data rates. A 9.6 K bps signal can easily be modulated by a high frequency carrier that is within the operating range of a broadband cable.

The main disadvantage of baseband transmission is the limited distance the signal can travel before repeaters are required. Figure 3.7 (Guidelines for Engineering U.S. Army Satellite Terminals Interconnect Facilities 1984, p. 5-56) shows a typical manufacturers guideline chart of baseband transmission distance versus bit rate for different types of coaxial cables. At 1 Mbps, the maximum recommended transmission distance is 5,000 feet or about 1 mile. With baseband transmission, a 100 mile sensor system would require a repeater every mile.

Figure 3.8 (Guidelines for Engineering U.S. Army Satellite Terminals Interconnect Facilities 1984, p. 5-56) shows a typical manufactors guideline chart of attenuation versus frequency for various types of broadband coaxial cables. Figure 3.9 (Freeman 1985, p. 258) shows attenuation versus frequency for 0.375 inch diameter long haul broadband coaxial cable. An attenuation rate of 4 db per mile at 1 MHz

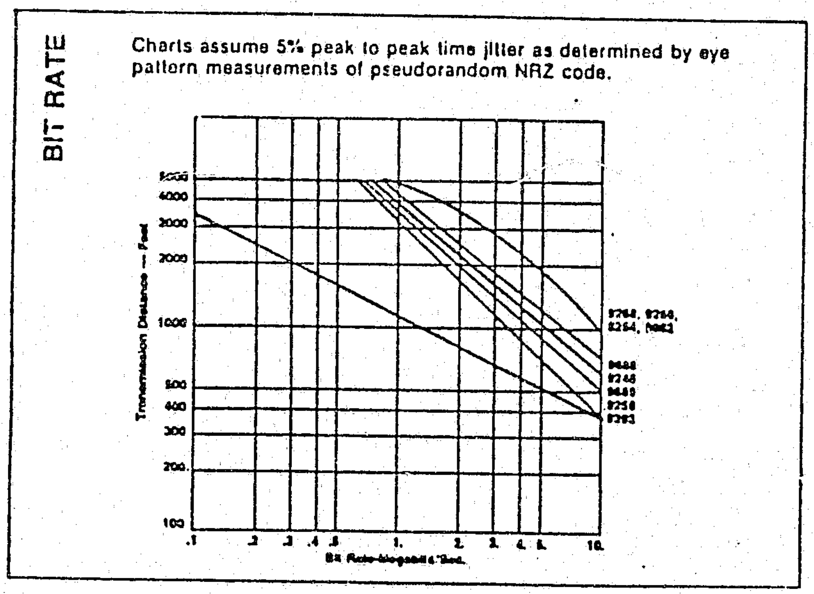


Figure 3.7 Typical Manufacturers' Guidelines for Baseband Coaxial Cable Transmission

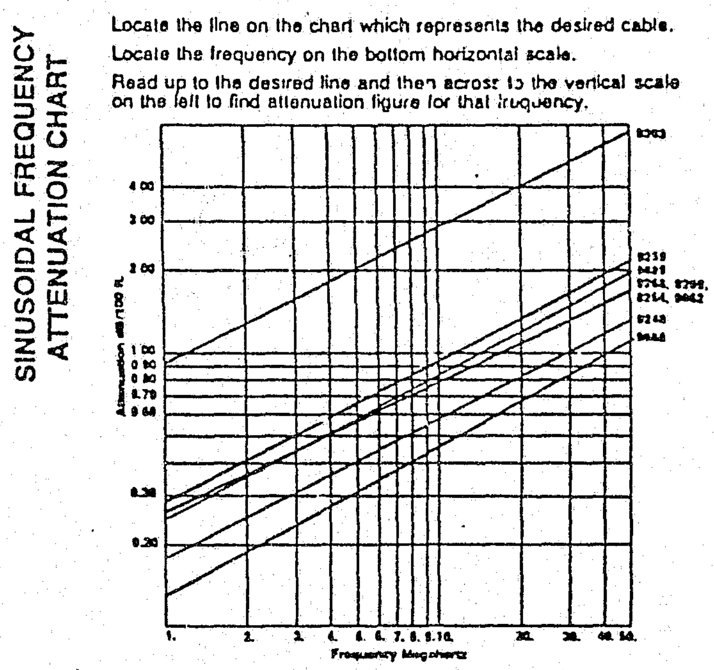


Figure 3.8 Typical Manufacturers' Guidelines for Broadband Coaxial Cable Transmission

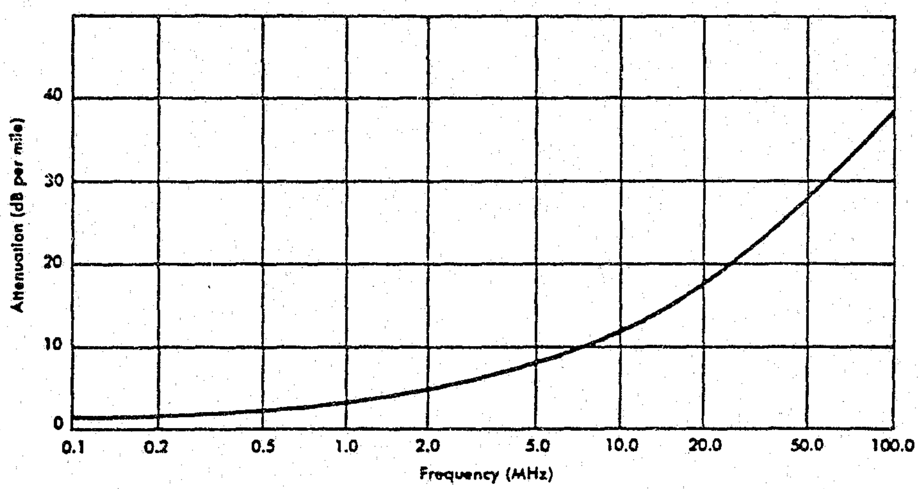


Figure 3.9 Attenuation Rate Versus Frequency for Ø.375 in. dia., 75 Ohm Broadband Coaxial Cable

is often used as a reference attenuation rate for Ø.375 in. dia. broadband coaxial cables. Exact repeater spacing for a broadband system depends upon the bandwidth of the signal to be transmitted. The higher the bandwidth, the closer the repeater spacing. Basic repeaters are usually spaced every 6 to 8 miles. In addition to basic repeaters, regulating repeaters are required after every 6th or 7th basic repeater. In addition, equalizers are required after about every 3Ø basic repeaters (Freeman 1985, p. 261). Additional design considerations for broadband coaxial cable systems can be found in Dunbar 1986.

3.4.3 Power Line Carrier

Power line carrier systems allow two-way data communications to take place over the power distribution lines. The major advantage of these systems is that they do not require the installation of a separate data communications link. The disadvantages of power line carrier systems are the limited data rates and the requirement to incorporate additional equipment into the power distribution system. Commercially available power line carrier units are limited to data rates of around 3ØØ bps (Field Demonstrations of Communication Systems for Distributed Automation vols. 2 and 3, Mak and Reed 1982, and Mak and Moore 1984). The low data rate will limit the use of a power line carrier systems to when only the display data is communicated to the base station (see Chapter 4). The major pieces of additional equipment that need to be integrated throughout the power distribution systems are: capacitor blocking units, line coupling units, line tuning units, signal repeaters and transformer bypass units.

There are two types of power line carrier units. The first type directly modulates the voltage or current of the 6Ø Hz power signal. Since power distribution cables are tuned to 6Ø Hz, attenuation is minimal. However, any disruption in power will also cause a loss in communication between the sensors and the remote base station. In the second type of power line carrier system, the sensor data would be modulated by a high frequency carrier and then coupled to the power distribution lines. The carrier frequency can be fixed or variable (Field Demonstrations of Communication Systems for Distributed Automation vols. 2 and 3). Carrier frequencies above 2ØØ KHz are restricted by the FCC to avoid potential interference with aircraft navigational frequencies (Hamsher 1967, Chapter 14).

It is difficult to predetermine the exact attenuation per unit length of a power line carrier channel. Consistent predicting methods have not been formulated and considerable variation in attenuation can be found among completed systems (Hamsher 1967, Chapter 14). Attenuation of the data signal depends on the carrier frequency and the size of the power distribution cables. For a carrier frequency of 5Ø KHz it is possible to achieve less than Ø.1 db of attenuation per mile (Hamsher 1967 p. 14-13). Losses due to line couplers and by pass units range from Ø.5 to 2 db depending upon the carrier frequency. For overhead power distribution cables, an additional 1Ø db margin in signal to noise ratio should be allowed to compensate for the effects of temperature variations (Hamsher 1967, p. 14-14). The performance of various commercially available power line carrier systems has varied. One unit has demonstrated a 99.88 percent success rate at a data rate of 60 bps over 47 miles of a 13.8 KV power distribution system (Mak and Reed 1982).

3.4.4 Fiber Optic

Optical fiber is the probably the most rapidly changing technology of all the candidate transmission media. Lightwave components that are state of the art today, will be replaced by newer, more sophisticated components within six months to a year. Current trends in fiber optic technology are: attenuation loss of fiber optic cable (Kapron 1985), couplers, taps, splices and splitters (Nelson et al. 1983, Baker 1985 pp. 253-270, and Williams 1984) will decrease, higher bandwidth fiber optic cables (Kapron 1985) will be developed, and more efficient transmitters and more sensitive receivers (Kapron 1985) will be realized. Also, several new developments in fiber optic technology such as wave division multiplexing and bidirectional communications (Keiser 1983, pp. 220-225, Liz and Metcalf 1982 and Palais 1984, pp. 195-199), heterodyne and homodyne receivers, (Midwinter 1985, Basch and Brown 1985) and minimum dispersion shift fibers (Lynch 1985) which will become common place within the next decade. Most importantly, the price of optical fiber cable and ardware will continue to decrease from the results of mass production and increased competition among manufacturers. The influence of decreasing prices and new developments makes it difficult to compare fiber optic systems with some of the more established technologies like coaxial cable.

This short summary of fiber optic systems will not attempt to discuss the technical aspects or operating characteristics of fiber optic cable and its associated components. Instead, a brief discussion of the advantages and disadvantages of optical fiber transmission systems will be presented and, where applicable, the impact of projected future developments will be discussed.

There are many reasons for using fiber optics as a transmission medium. Fiber optic cable has the largest potential bandwidth of all the candidate transmission media. With improved receivers and transmitters, bit rates up to 10 Gbps will be achievable (Henry 1985). New low loss materials should bring the attenuation rate of fiber optic cable down to as low as 0.01 db per kilometer in the 3 to 5 micrometer wavelengths (Kapron 1985). For a long line sensor system, fiber optic cable would require fewer intermediate repeaters and fewer components to maintain. The small size and light weight of fiber optic cable reduces the installation costs. Since glass and polymer compounds are natural electrical insulators, fiber optic cable provides excellent immunity to electromagnetic interference without the use of additional shielding or conduit. Fiber optic cable is more secure than the other cable media because it is extremely difficult to tap without detection. In addition, the cost of fiber optic cable will continue to decrease while the reliability and projected life span continues to increase (Senior 1985, pp. 7-9).

The main disadvantage of using fiber optic cable as a transmission media is that passive optical taps have not yet been perfected. As discussed earlier, fiber optic cable could only be used in a bus topology configuration. A total of 50 optical taps, one every two miles, would be required for a 100 mile sensor system.

There are two types of optical taps: active and passive. Active taps convert optical signals to an electrical signals and electrical signals to optical signals. Passive taps are strictly optical and use no electrical components. Active taps are more expensive than passive taps and are also more difficult to maintain.

The loss due to each passive tap depends upon the power splitting ratio (Palais 1984, p. 183-186) and the additional excess loss due to the tap design. For a fiber optic system, the difference between the transmitter power and receiver sensitivity depends upon a variety of factors (Chipman 1982) but is typically in the range of 35 db. Commercially available passive taps have splitting power losses of around 1.5 db and excess power losses of about 1 db; for a total loss of 2.5 db per tap. Excess losses as low as 0.11 db (Baker 1985, p. 257) and .2 to .3 db (Nelson et al. 1983) have been reported for experimental passive taps. Even with taps that have low excess attenuation losses, cross talk between the input and output ports of the tap will limit the number of taps which can be connected in series (Baker 1985, p. 256). At 2.5 db per tap, only about 10 taps, taking into account losses due to splices, couplers and a 5 db system margin, would be allowed before an optical regenerative repeater would be necessary. The cost of two way regenerative repeaters varies from around 100 to 200 dollars for low bit rates to as much as 5,000 dollars for high bit rates (Gowar 1984, p. 497). The cost would be higher for environmental proof repeaters.

3.4.5 Low, Medium and High Frequency Radio

The low, medium and high frequency radio band systems range from 30 kilohertz to 30 megahertz (Figure 3.10). Propagation in these frequency bands is principally by ground wave and by reflection from the ionosphere (Reference Data for Radio Engineers 1975, Chapter 28). The advantage of using these frequency bands is that long distance communication, more than 100 miles, can easily be achieved by using just a few watts of effective radiated power. Properly designed high frequency radio links permit communication up to 4000 miles at 90 percent reliability (Freeman 1981, Chapter 4).

The disadvantage of using these frequencies is that intelligent transmitters and receivers must be used in order to combat the affects of fading. Fading is caused by interference of the ground waves and sky waves and by daily, seasonally and sporadic changes in the ionosphere (Freeman 1981, Chapter 4 and Reference Data for Radio Engineers 1975, Chapter 28). At any particular time, the current frequency in use may not be usable within the next hour. Transmitters and receivers must be

NAME	BAND	EXAMPLE
Low Fequency (LF)	30-300 KHz	Navigation
Medium Frequency (MF)	300-3000 KHz	AM Radio
High Frequency (HF)	3-30 MHz	Shortwave Radio
Very-High Frequency (VHF)	30-300 MHz	FM Radio
Ultra-High Frequency (UHF)	300-3000 MHz	Terrestrial Microwave
Super-High Frequency (SHF)	3-30 GHZ	Satellite

Figure 3.10 Common Radio Bands

able to change frequencies as often as necessary depending upon which frequencies demonstrate good propagation characteristics. Under certain conditions, frequencies in these bands propagate on a world wide basis and it can be difficult to find a clear channel regardless of international regulatory laws. The use of diversity techniques; time, frequency, space, polarization or angle of arrival, would be essential in order to achieve reliable communications. An experimental, transcontinental high frequency communications system, using frequency shift keying modulation at a baud rate of 75 symbols per second, achieved the following results: Ø.1 watts of transmitted power, 55 percent reliable, 1 watt, 85 percent reliable and with 1Ø watts of transmitted power, 9Ø percent reliability (McRae 1985). However, 9Ø percent reliable communications was achieved with just Ø.1 watts of power using an error control coding technique called automatic request for repeat.

These frequency bands are most suitable for low bit rate communications because of the affects of channel fading. Highly reliable communications, above 95 percent, can only be achieved through the use of diversity and error control coding. Both of these methods would increase the cost of the sensor transmitters and base station receiver.

3.4.6 Very-High and Ultra-High Frequency Band Radio

The very-high and ultra-high frequency band radios range from 3Ø megahertz to 3 gigahertz (Figure 3.1Ø). The ionosphere is basically transparent to frequencies above 30 megahertz so propagation at these frequency bands is almost line of sight. Slightly greater than line of sight communications can be achieved because the refractive index of the atmosphere decreases with height causing a bending of the electromagnetic waves. To compensate for this refraction, the radius of the earth is modified so the relative curvature between the earth and the propagating waves remains the same. This new radius of the earth, denoted as K, is the ratio of the effective earth radius to the true earth radius. A typical value for K under normal atmospheric conditions is 1.33. Figure 3.11 (Freeman 1981, p. 179) is a nomograph giving the maximum line of sight communications distance when K = 1.33 and the height, in feet, of the transmitting and receiving antennas are known. From this nomograph, it is evident that in order to achieve large propagation distances with small transmitting antennas, the receiver antennas must be located on mountain tops. For example, in order to achieve a communications distance of 50 miles with a transmitting antenna height of 10 feet, the receiving antenna height would have to be approximately 1150 feet.

The maximum propagation distance also depends upon the receiver sensitivity. Common VHF and UHF receivers have sensitivity ranges around -150 to -160 db. Realistic free space attenuation loss varies significantly depending upon the frequency, type of terrain and transmitter antenna height. Figure 3.12 (Tobagi et al. 1984, p. 27) shows the effects of path attenuation versus range over various

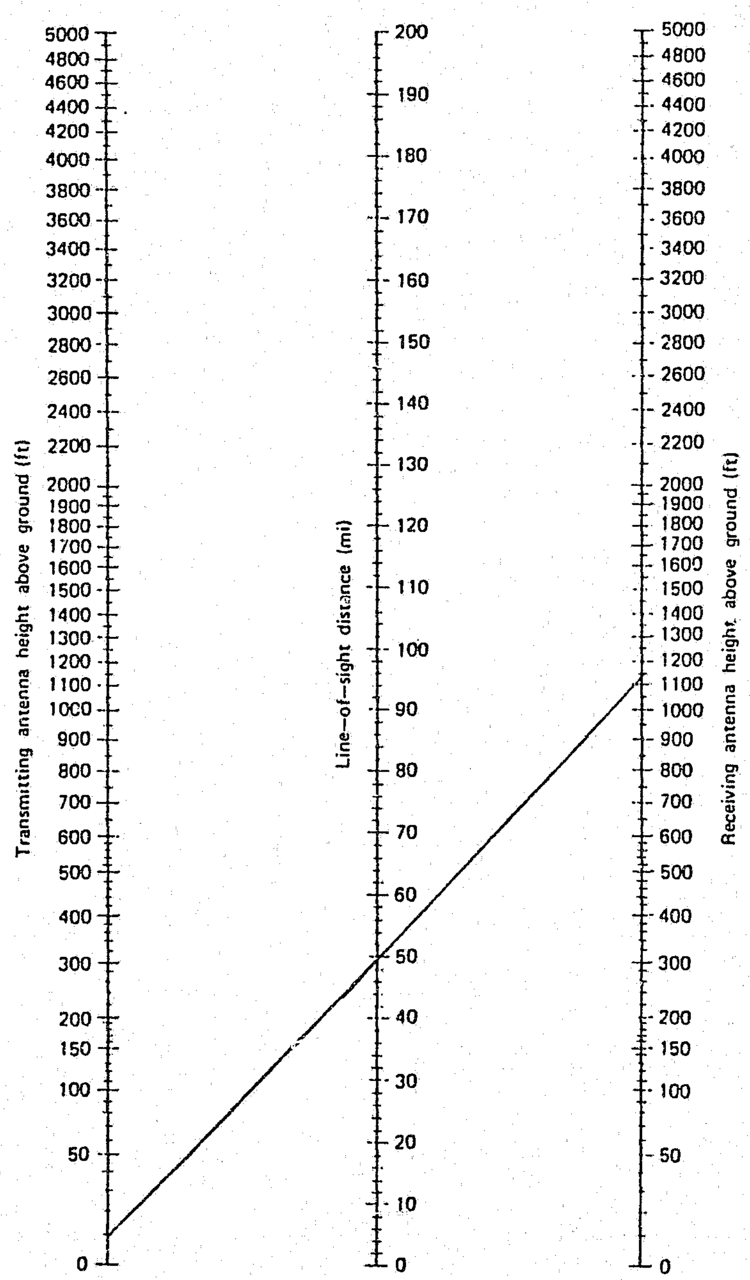


Figure 3.11 Line of Sight Propagation Distances for a Smooth Spherical Earth with K = 1.33

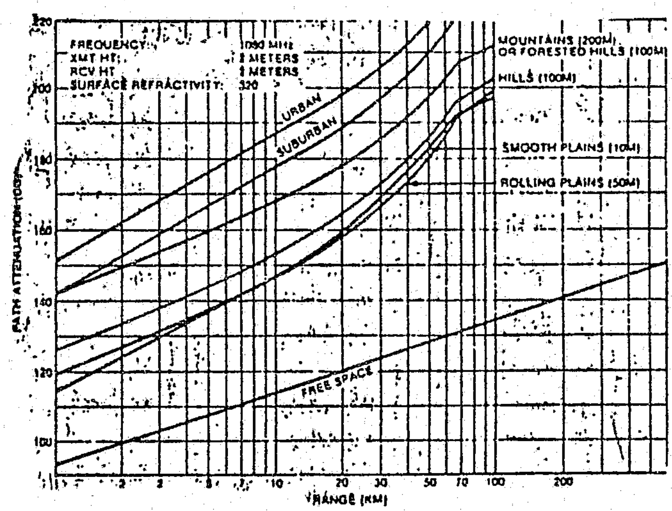


Figure 3.12 Effects of Path Attenuation Versus Range over Various Terrains for a Fixed Frequency and Fixed Antenna Heights

terrains for a fixed frequency and fixed antenna heights. A VHF or UHF communications link would have to be designed around the parameters of frequency, receiver sensitivity, antenna heights and type of terrain.

High-frequency and ultra-high frequency radio system suffer from the effects of multipath interference. Multiple path interference can be overcome by the use of diversity, coding or spread spectrum techniques. Implementation of these techniques would add additional cost to the sensor and base station receivers and transmitters.

Experimental results using very-high frequency and ultra-high frequency band radio communications has varied. One system for data collection operating in the 900 MHz range recommended that in order to obtain a minimum path loss of 150 db, repeaters needed to be spaced every 2.5 to 4.0 kilometers (Smalling and Poteat 1983 and Field Demonstrations of Communication Systems for Distributed Automation vol. 4). Another system was successful in achieving low error rates from 3 to 30 kilometers using 20 single channel per carrier channels in the 154 MHz range and bit rates up to 60 bits per second. However, the output power of the transmitters ranged from 2 to 10 watts (Holbrow and Owen 1985 and Martinez 1981).

3.4.7 Microwave Radio

Microwave communications is primarily used for high bandwidth applications. Microwave bandwidth allocations range from 0.8 to 100 megahertz (Figure 3.13, Stallings 1985, p. 56). Basically, microwaves propagate at close to line of sight with typical repeater spacings

Band Name	Range (GHz)	Maximum Channel Bandwidth (MHz)	Necessary Spectral Efficiency (bits/Hz)	Type of Service
2 GHz	1.71 – 1.85	—		Federal government
2 GHz	1.85 – 1.99	8		Private; local government
2 GHz	2.11 – 2.13	3.5	2	Common carrier (shared)
2 GHz	2.13 – 2.15	0.8/1.6		Private; local government
2 GHz	2.15 – 2.16	10		Private; multipoint
2 GHz	2.16 – 2.18	3.5	2	Common carrier
2 GHz	2.18 – 2.20	0.8/1.6		Private; local government
2 GHz	2.20 – 2.29	—		Federal government
2 GHz	2.45 – 2.50	0.8		Private: local government (shared)
4 GHz	3.70 – 4.20	20	4.5	Common carrier: satellite
6 GHz	5.925– 6.425	30	3	Common carrier; satellite
6 GHz	6.525– 6.875	5/10		Private: shared
7–8 GHz	7.125– 8.40	—		Federal government
10 GHz	10.550–10.680	25		Private
11 GHz	10.7 –11.7	50	2.25	Common carrier
12 GHz	12.2 –12.7	10/20		Private; local government
13 GHz	13.2 –13.25	25		Common carrier; private
14 GHz	14.4 –15.25	—		Federal government
18 GHz	17.7 –19.7	220		Common carrier; shared
18 GHz	18.36 –19.04	50/100		Private; local government
22 GHz	21.2 –23.6	50/100		Private; common carrier
31 GHz	31.0 –31.2	50/100		Private; common carrier
38 GHz	36.0 –38.6	—		Federal government
40 GHz	38.6 –40.0	50		Private; common carrier
	Above 40.0	—		Developmental

Figure 3.13 Principal Microwave Bands Authorized for Fixed Telecommunications in the United States

every 2Ø to 3Ø miles. Anomalies in the atmosphere can cause either an increase or decrease in the line of sight propagation distance (Transmission Systems for Communications 1982, Chapter 23). To insure adequate obstruction clearance, over level terrain, during less than line of sight propagation times, tower heights are often at least 1ØØ to 15Ø feet high. The free space loss of microwaves decreases as the square of the distance which is equivalent to about 6 db for every doubling of the distance between repeaters. The exact attenuation loss is difficult to predict because of fading caused by disturbances in the atmosphere and multipath propagation. Attenuation of microwave frequencies above 1Ø GHz is increasingly affected by rainfall. Fading losses can be overcome by the use of diversity techniques. The main disadvantage of use microwave radio would be the installation costs of constructing a tower and antenna system at each two mile sensor segment and the construction costs of building the necessary remote repeater stations. FCC approval would have to be obtained for the use of any part of the microwave frequency spectrum. Microwave radio would only be cost effective if large amounts of data needed to be communicated to the base station.

3.4.8 Satellite

The major advantage satellite communications systems have over the other transmission media is their inherent suitability for point-to-multipoint communications. A sensor located anywhere within the satellites footprint could communicate directly to the base station.

Individual sensors could be relocated to meet changing monitoring requirements provided that they remained within the satellites footprint. Additional sensors could easily be added to the system as long as transponder bandwidth was available. For widely dispersed and changing communications requirements, satellite systems offer greater flexibility then point-to-point radio systems and all of the cable transmission media.

A typical satellite system would consist of a large antenna, with appropriate multiplexing and demultiplexing equipment, located at the base station and smaller antennas with transceiver logic located at each sensor site.

In order to keep the cost of the additional transceiver logic and storage logic at each sensor site to a minimum, one of the best multiple-access modulation techniques to use would be preassigned single channel per carrier frequency division multiple access (SCPC-FDMA). This access scheme would allow each sensor to have its own unique, dedicated channel to communicate to the base station at random.

An alternative to SCPC-FDMA would be to use anyone of the numerous random access or reservation protocols (Tobagi et al. 1984). A typical protocol, similar to token passing, each sensor would transmit on the same uplink frequency and receive on the same downlink frequency. The base station would interrogate each sensor successively. Upon interrogation by the base station, sensors would transmit any intrusion data stored in memory. Such an access protocol would be feasible only if the display data was being sent to the base station. It will be shown in the next chapter that the other distributed processing schemes would require each sensor to have a dedicated channel to the base station.

Commercial satellite transponder bandwidths are usually 36, 54 or 72 MHz although special purpose satellites have been built with a variety of transponder bandwidths. Depending upon the bandwidth needed for each sensor, one or more transponders would be required. Commercial satellites have anywhere from one to 24 transponders. If transponder bandwidth was limited, access protocols such as carrier sensed multiple access or slotted Aloha, which would allow every sensor to communicate to the base station over the same uplink frequency, could be used at the expense of more complicated electronics at each sensor site.

It would be desirable to keep the sensor site antenna size as small as possible. This can be accomplished by either using higher frequencies, in the Ku band of 10.9 to 18 GHz, or by employing larger antennas in space. Higher frequencies suffer from greater attenuation in adverse weather conditions which must be offset by higher transmitted power, more elaborate coding techniques or diversity. Also, the cost of transceiver logic increases as the up/down link transmission frequency increases.

Small ground antennas; 12" nonsteered drooping dipole or 30 by 30 centimeter microstrip, and low power requirements; 5 watts, are possible in the frequency ranges of the upper L-band; 1.5 to 1.6 GHz, or in the 800 to 809 MHz range, but require larger antennas in space.

There are basically two options for establishing a satellite communications system. One option would be to construct and launch a satellite for exclusive use by INS. Such a system would cost in the millions of dollars (Vaisnys 1980 and Bergen 1981). Approval for the use of the appropriate frequency spectrum would have to be obtained from the International Frequency Regulation Board (IFRB) sense the Federal Communications Commission (FCC) only has jurisdiction on frequency allocation inside the United States borders. Part of the satellites footprint would most likely lie outside the U.S. border. It is very doubtful that a portion of the international frequency spectrum could be obtained for use solely by the INS. A more likely case would be to lease the appropriate transponder space from a commercial satellite. Such satellites, with large space antennas, allowing for the use of small earth antennas, have not yet been built. These types of satellites are not expected to be built or launched until 1987 or later (Hills 1985). The cost of leasing transponder bandwidth, if available, is unknown, but is expected to be more expensive then most of the other transmission media.

CHAPTER 4

PRELIMINARY EVALUATION OF CANDIDATE SYSTEMS

4.1 Introduction

More than one hundred and twenty unique candidate systems can be derived by taking combinations of the three variables of the communications problem. Three different topologies, five different processing distributions and eight different transmission media are under consideration; forming a total of 120 possible candidate systems. Additional systems can be formed by using tree topologies and two different communications medium.

A candidate system is derived by picking one choice from each communications group. For example, one possible candidate system would use a bus topology, have each sensor send the unsummed digital data to the base station and use fiber optic cable as a transmission medium. Some candidate systems are obviously not feasible. If a star topology was chosen, the only practical transmission media would be nonline of sight radio and satellite radio. It would be impractical to bury one of the cable transmission media from the base station to each sensor and systems using line of sight radio would require intermediate relay stations.

It is not efficient to list every possible candidate system and then try to judge each system separately for its technical feasibility and practicality. Instead, for the preliminary evaluation, all systems will be judged simultaneously from the criteria of bandwidth and timing and control. The required bandwidth depends upon the degree of distributed processing. Bandwidth calculations are given in section 4.2. All of the signal processing stages of the GUIDAR receiver operate from common timing and control circuitry. The effect that this centralized timing and control has on separating any of the signal processing stages will be discussed in section 4.3.

It is reasonable to begin the evaluation of the candidate systems by considering the different distribution of processing arrangements since one of the major tasks of this study is to determine if it is technically practical to remotely locate any portion of the GUIDAR receiver. On one extreme, only the transmitter would be located at each two mile segment. On the other extreme, a complete GUIDAR system would be located at each two mile segment. First, the bandwidth will be calculated for each major processing stage. Once the bandwidth is known, a compatible transmission media can be chosen. Low bandwidth requirements would probably use transmission media such as twisted wire pair, power line carrier and single channel per carrier broadband coaxial cable and radio systems. High bandwidths would require using base or broadband coaxial cable, fiber optic cable, microwave radio or satellite radio systems. In some cases, it might be advantageous to use a large bandwidth communications medium for a low bandwidth requirement. For example, a single mode fiber optic cable can have a bandwidth exceeding 1 GHz but it also has such properties as low attenuation rate, immunity to electromagnetic interference, light weight and flexibility (see section 3.4.4) that might make it a desirable communications medium for certain low bandwidth applications.

Once a transmission medium is chosen to accommodate the required bandwidth, a suitable topology can be selected.

The list of the surviving candidate systems can be further reduced (Chapter 5) by examining such criteria as the current technology of the transmission media and components, the vulnerability to intentional sabotage and the installation requirements.

4.2 Bandwidth Calculations

As mentioned in section 3.3, there are five places in the GUIDAR receiver where the signal processing components could be separated to create a distributed processing system. In this section, the approximate bandwidth needed to transmit each of these signals to the base station or some intermediate node will be calculated and discussed. The results of these calculations will help to determine if it is practical to remotely locate any of the signal processing components.

4.2.1 Received Signal

The receive signal is the signal located at the input port of the GUIDAR receiver (Figure 3.2). This signal is obtained directly from the receive cable, prior to any signal processing and still contains the original 57, 63 or 69 MHz carrier frequency.

In practice, the bandwidth of a rectangular pulse can be approximated by the inverse of the pulse width in time. The recommended pulse width setting is 450 nanoseconds. This yields a bandwidth of 2.22 MHz. The total bandwidth required per sensor would be the sum of 2.22 MHz and the original carrier frequency. Using 63 MHz as an example for the carrier frequency, the total bandwidth required per sensor would be 65.22 MHz. Since over 40,000 pulses are processed every second, each sensor would be required to have its own dedicated channel. Fifty sensors would require a total bandwidth of 3.261 GHz.

The 65.22 MHz bandwidth requirement per sensor limits the transmission media to fiber optic cable, microwave radio or satellite radio. As mentioned earlier, for a 100 mile system, it would be impractical to bury a separate fiber optic cable to each sensor from the base station. Satellite and microwave radio would require the installation of large antennas at each sensor site. Such antenna systems would be vulnerable to intentional sabotage and potential weather damage. Also, it is very doubtful that FCC approval could be obtained for the use of 3.261 GHz of the microwave or satellite frequency spectrum.

4.2.2 Received Signal Envelope

The received signal envelope contains the same information as the received signal except the carrier frequency has been removed. This signal is obtained directly after the coherent demodulator (Figure 3.2). This signal is represented by signal S1 in Figure 2.1.

At this point, a carrier frequency could be added to the envelope or the envelope could be digitized prior to transmission. If a carrier frequency of 60 MHz, for example, was added to the envelope, the bandwidth required for each sensor would be 4.44 MHz for double sideband transmission or 2.22 MHz for single sideband transmission. The implementation of single sideband would require the addition of a filter in the transmitter to filter out either the upper or lower sideband. Coaxial cable in addition to fiber optics, microwave radio and satellite radio have the necessary bandwidth to transmit the received signal envelope. Digitizing the signal would increase the bandwidth.

If the signal was sampled at the Nyquist rate of 4.44 Mbps and quantized to 8 levels, the total bit rate would be 35.52 Mbps. If this bit rate was transmitted digitally, using baseband signaling (NRZ, Biphase, Delay etc.), each sensor would require between 17.76 (Delay) and 52.28 (Biphase) MHz of bandwidth (Stallings 1985, p. 72). Using Nyquist pulses, the required bandwidth would be about 23.68 MHz. If the signal was transmitted in an analog format, using QPSK, each sensor would require about 26.64 MHz of bandwidth. An error correcting coding algorithm could be added to the digitized signal for more reliable transmission but this process would increase the bandwidth.

The digitized bandwidth is much larger than the original envelope bandwidth and no extra bits for error correcting coding have been added and the minimum sampling rate and quantization level were assumed. Ideally, the signal envelope should be sampled higher then the Nyquist rate and more quantization levels would be necessary to detect small changes in the signal envelope. The conclusions are the same as the first case.

4.2.3 Unsummed Digital Data

At this point, the received signal envelope has been divided electronically into 60 cells and quantized into 8 bits. This sampling and quantization process takes place sequentially in a time of 17.1 us for 60 cells (see single cycle breakdown, section 2.2.1).

If this data was relayed to the base station, the data transfer rate would have to take place within 17.1 us. A longer data transfer time would slow down the single target detection cycle time of 99.8 ms. A slower target detection cycle time would increase the probability of missed detection.

The data rate of the unsummed digital data is: 8 bits X 60 cells in 17.1 us or 480 bits in 17.1 us. This is equivalent to a data rate of 28.07 Mbps. For digital transmission, without any error correcting code bits, each sensor would require a bandwidth between 14.035 and 42.105 MHz. For analog transmission, QPSK, each sensor would need a bandwidth of about 21.052 MHz. Each sensor would require its own dedicated channel because of the high pulse repetition rate. The conclusions are the same as the previous two cases.

4.2.4 Preprocessor Output

The preprocessor output consists of sixty, sixteen bit data words, each word representing the sum of 2048 eight bit quantized cells of either the inphase or quadrature phase component of the received signal. Each sixteen bit word is transferred in parallel from the preprocessor RAM to the processor RAM for intrusion detection computation. The total read cycle time for all 60 cells is one millisecond (see section 2.2.3). If this data was transferred to the base station or some intermediate node, the data transfer rate could be no more than 1 ms because the single target detection cycle time can not be slowed down.

The data rate of the preprocessor output would be 16 bits X 60 cells in 1 ms, or 960 bits in 1 ms. This is equivalent to a data transfer rate of 960,000 bits per second. For digital transmission, the required bandwidth would be at least 480,000 Hz and for analog transmission the bandwidth would be about 720,000 Hz. The conclusions are the same as the previous cases.

4.2.5 Display Data

The display data consists of only the essential bits needed to identify the location and type of intruder. The display data would be relayed to the base station only after an intrusion has occurred. In most areas covered by a long line sensor system, it would probably not be necessary to identify the intruders location to the nearest one cell or 33 meters. Intrusion detection to the nearest 100 meters would be practical. The maximum number of bits needed for the display data would be:

Identification for fifty systems	=	6 bits
Response Number (400-32,766)	=	15 bits
32 Zones + Equipment Status Codes	=	6 bits
Total	=	27 bits

Rounding off to the nearest power of two, 32 bits would be sufficient to identify each two mile system, the zone number of the intruder, the response number of the intruder, equipment status codes and additional bits for an error correcting code or for future expansion.

Since the display data rate is very low, and not continuous, most of the transmission media or topologies could be used to relay this data to the base station. Baseband coaxial cable and microwave radio are strictly used for high data rate communications. Transmission media such as fiber optic cable, satellite radio and broadband coaxial cable are usually used for high data rate communications but they can be adapted for low bit rate communications.

A variety of two way, low bit rate , real time data communications systems have been built and tested. Radio systems include: a fixed sending and receiving UHF system built by Westinghouse Electric Corporation (Field Demonstrations of Communication Systems for Distributed Automation vol. 4 and Smalling 1983) and a fixed frequency AM forward link with a VHF single channel per carrier return link, built by McGraw-Edison Company (Holbrow 1985 and Martinez 1981).

Power line carrier systems for two way, low bit rate communications have been built by; Brown Boveri Compuguard Corporation (Field Demonstrations of Communication Systems for Distributed Automation vol. 2), Westinghouse Electric Corporation (Field Demonstrations for Communications Systems for Distributed Automation vol. 4) and Emmerson Electronics Corporation (Mak and Reed 1982 and Mak and Moore 1984).

Two way data communications between the sensors and the base station may not be necessary but would be desirable. Two way communications would enable the base station to interrogate each sensor to verify data, check the operating status of the equipment and to adjust cell thresholds.

4.3 Timing and Control

Each major signal processing component of the GUIDAR receiver operates from centralized timing and control circuitry (see Figure 2.2 and Figure 3.2). All timing is derived from a single 24.5 MHz oscillator. The oscillator provides timing for: the inphase/quadrature phase switch in the receiver demodulator; the dither, sample and hold and A/D converter in the digitizer; the adder and dynamic RAM in the preprocessor and the TMS 9900 microprocessor in the processor module. The TMS microprocessor acts as a controller for the receiver demodulator, the digitizer and the preprocessor. The TMS 9900 microprocessor also provides system malfunction alarms to the operator and performs component self testing (Harman and Mackay 1976). If any part of the GUIDAR receiver circuitry was remotely located, a local oscillator and additional control circuitry would have to be added to each section.

It is important for each of the signal processing steps to be executed within their specific time allotment. Any slow down in the target detection cycle will decrease the probability of detection. It is highly unlikely that such precise synchronization could be maintained between each sensor site and an intermediate node or the base station. The cost for the design and manufacture of the additional timing and control circuitry would surely offset any savings gained by separating the components of the GUIDAR receiver.

4.4 Summary and Conclusions

After considering both the bandwidth requirements and the timing and synchronization requirements, the most logical place to divide the GUIDAR receiver would be after all signal processing has been completed. Only the display data would be sent to the base station.

There are two major advantages of sending only the display data to the base station. First, the bandwidth needed for each sensor would be minimal and, second, each sensor would not require a dedicated channel to communicate to the base station since the display data is generated only after an intrusion has occurred. It is assumed that a short delay between the the actual time of an intrusion and when the display data arrives at the base station would be acceptable. Storage logic for the display data would be added to each sensor transceiver. When a sensor is interrogated by the base station or when the communications channel is clear, the stored intrusion data would be relayed to the base station. Even if a delay in receiving the intrusion data was not acceptable, the bandwidth required per sensor would be small enough that each sensor could possibly have its own dedicated channel to communicate to the base station.

Since only the display data will be sent to the remote base station, some of the transmission media can be eliminated immediately. Microwave radio and baseband coaxial cable are strictly used for high data rate communications. Although satellite, fiber optic cable and broadband coaxial cable are mostly used for high data rate communications, they are occasionally used for low data rate communications. All of the transmission media except baseband coaxial cable and microwave radio will be evaluated in Chapter 5.

CHAPTER 5

FINAL EVALUATION OF CANDIDATE SYSTEMS

5.1 Introduction

In Chapter 4, the candidate systems were evaluated from the criteria of bandwidth and timing and control. The conclusion was that it is only feasible to send the display data to the base station. Two candidate transmission media, microwave radio and baseband coaxial cable, were determined to be impractical. In this chapter, the remaining candidate systems will be reevaluated. The evaluation criteria are current technology, vulnerability, and installation requirements.

5.2 Current Technology

Low bit rate, single channel per carrier satellite communications, enabling the use of small earth station antennas, is technically feasible, but current FCC regulations have restricted its development. The FCC has not specifically allocated any portion of the electromagnetic spectrum for remote data collection. The alternative would be to lease transponder bandwidth, which has been allocated for commercial use, from private industry. The FCC has allocated bandwidth in the 800 to 896 MHz range (Newman 1986) and is proposing additional bandwidth allocation in the L Band frequency range for mobile satellite communications. Proposed satellites for mobile communications would have space antennas large enough to enable multiple spot beams, frequency reuse and small earth station antennas. Twelve commercial companies have submitted applications to the FCC to provide this service (Hills 1985). The FCC is expected to award the contract to only one applicant. This will not occur until 1987 or later. The cost of leasing transponder space, if available, can not be determined at this time. For these reasons, the use of satellite as a transmission media is impractical at the present time and in the near future.

5.3 Vulnerability

The vulnerability of having an exposed antenna at each two mile sensor segment is a subjective idea. Clearly, an unguarded antenna could be subjected to deliberate sabotage. If an antenna was damaged, the entire two mile sensor section would be inoperative. The cost of replacement and repair would be inconvenient and expensive. All radio systems can be subjected to intentional jamming and propagation characteristics are affected by adverse weather conditions such as heavy rains and lightning. In addition to vulnerability, all radio systems must be approved by the Federal Communications Commission. The approval process, if bandwidth is available in the proposed area of the frequency spectrum, can take several years. For these reasons, all radio transmission media are considered to be impractical for this project.

5.4 Installation Requirements

The surviving candidate transmission media are twisted wire pair, broadband coaxial cable, fiber optic cable and power line carrier. Installation requirements for each of these transmission media are relatively the same. Twisted wire pair and fiber optic cable are lighter in weight than broadband coaxial cable and, in terms of weight only, would cost less per kilometer to install. Fiber optic cable is more expensive, in dollars per kilometer, than both twisted wire pair and broadband coaxial cable. Also, fiber optic cable is more difficult and expensive to splice than twisted wire pair and coaxial cable. A power line carrier system would be integrated into the power distribution system. A power line carrier system would probably be the least expensive system to install since it could be installed simultaneously with the power distribution system. Each of the transmission media could be buried in the same trench as the power distribution system, provided they are separated by about one foot of soil. To avoid electromagnetic interference, both the communications cables and power distribution cables must be separated from the leaky coaxial cable trenches.

5.5 Summary and Conclusions

In Chapter 4, it was shown necessary to send only the display data to the base station. In this chapter, all of the candidate transmission media listed in Figure 3.10, except twisted pair wire, broadband coaxial cable, fiber optic cable and power line carrier, have been eliminated. All of the remaining transmission media would be employed in a bus topology. A simple access protocol, such as carrier sensed multiple access or token passing, could be used to relay the display data to the base station. The main advantage of each of these systems is that they can all be completely buried underground. While the SENTRAX system has not been specifically addressed in this chapter, the issues and conclusions are identical to those for the GUIDAR system.

CHAPTER 6

DETAILED EVALUATION OF REMAINING SYSTEMS

6.1 Introduction

The remaining long line sensor systems would all use a bus topology, send only the display data to the base station and use one of the following transmission media: twisted wire pair, broadband coaxial cable, power line carrier or fiber optic cable. In this chapter, the advantages, disadvantages and approximate costs for each system will be outlined. The cost data has been derived from several different sources and serves only as a guideline for comparing the relative cost of one system against another. The estimated cost of the required power distribution system and the installation cost are will be given in Chapter 7. An additional study would be necessary to determine the most efficient power distribution system and the possibilities of using alternative power sources such as batteries and photovoltaic cells. Installation costs would depend primarily upon the amount of soil excavation needed to install the sensors, power distribution system and communications cable. The leaky coaxial cables must be installed in a trench separate from the power distribution cables and the communications cables. The cost estimate for installing the experimental sensor system, excluding power and communications equipment, has been estimated at 2,272 dollars for 3,200 meters

(Frankel et al. 1984). A costs comparison per mile and per kilometer for the GUIDAR and SENTRAX systems will be given in Chapter 7.

6.2 Twisted Wire Pair

The advantages are:

--- low cost

--- easy to tap

--- light weight/inexpensive installation cost

--- hardware is inexpensive and readily available

--- low attenuation rate for loaded cables

The disadvantages are:

--- narrow bandwidth

--- subject to electromagnetic interference and crosstalk unless shielded

Cost data: (Major Components Only)

Item	Cost
Cable (3 pair, 19 AWG, loaded, direct burial) \$0.25 per foot	\$132,000 (100 miles)
Transceivers \$100.00 each	\$5,000 (50)
Amplifiers (two way, voice frequency) \$100.00 each	\$1,000 (10)
Equalizers \$15 each	\$60 (4)
Taps \$10 each	\$500 (50)

Base Station Control	$10,000
Total:	$148,560

6.3 Broadband Coaxial Cable

The advantages are:

--- Large bandwidth can be subdivided into dedicated sensor channels

--- Off-the-shelf CATV Equipment readily available

--- Inherent immunity to noise

--- Easy to tap

The disadvantages are:

--- Difficult to expand once initial system is installed

--- High attenuation rate (4 db per mile at 1 MHz)

Cost Data: (Major Components Only)

Item	Cost
Cable (0.375 in, 75 ohm, direct burial) $0.50 per foot	$264,000 (100 miles)
Transceivers $500 each	$25,000 (50)
Amplifiers (two way broadband) $400 each	$4,800 (12)
Equalizers (broadband) $20 each	$200 (10)
Equalizers (Envelope/Amplitude Delay) $1000 each	$2,000 (2)
Taps $20 each	$1,000 (50)

Base Station Control	$10,000
Total:	$307,000

6.4 Power Line Carrier

The advantages are:

--- easy to expand

--- potential installation savings

--- integrated with power distribution system/easier to maintain

The disadvantages are:

--- subject to electromagnetic interference

--- special protective equipment required at each transceiver

--- narrow bandwidth

--- high power required to maintain good signal to noise ratio

Cost Data: (Major Components Only)

Item	Cost
Signal Coupling Unit $850 each	$42,500 (50)
Isolators $650 each	$32,500 (50)
Amplifiers (two way) $3,000 each	$150,000 (50)
Transceivers $250 each	$12,500 (50)
Base Station Control	$10,000
Total:	$247,500

6.5 Fiber Optic Cable

The advantages are:

--- excess bandwidth available for expansion

--- small size and weight/inexpensive installation costs

--- immunity to electromagnetic interference

--- signal security

--- low attenuation

--- fewer electrical components/less maintenance

--- decreasing costs of cable and hardware

The disadvantages are:

--- difficult to tap/splice

--- high cost per splice

--- passive taps have a large attenuation loss

Cost Data: (Major Components Only)

Item	Cost
Cable (multimode, direct burial) \$1.50 per meter	\$250,000 (100 miles)
Transceivers (half duplex) \$150 each	\$7,500 (50)
Regenerative Repeaters \$500 each	\$2,500 (5)
Passive Taps \$100 each	\$5,000 (50)
Connectors \$25 each	\$2,500 (100)

Base Station Control		$15,000
	Total:	$282,500

6.6 Summary

Transmission Medium	Cost	
	mile	kilometer
Twisted Wire Pair	$1,486	$921
Broadband Coaxial Cable	$3,070	$1,903
Power Line Carrier	$2,475	$1,534
Fiber Optic Cable	$2,825	$1,751

In terms of cost per mile, twisted wire pair is the least expensive communications medium and broadband coaxial cable is the most expensive communications medium. A communications medium should not be selected on the basis of cost alone. Other factors, such as expandability, ease of maintenance and reliability of components, should be weighed equally with the cost data before selecting a specific transmission medium. An average cost of $2,500 per mile for a transmission medium will be used as an estimate for computing the total long line sensor system cost per mile.

CHAPTER 7

SUMMARY AND CONCLUSIONS

Chapter 1 discussed the general operating characteristics of two commercially available intrusion detection sensors called GUIDAR and SENTRAX. The GUIDAR and SENTRAX systems differ in that the GUIDAR system is a pulse type sensor and the SENTRAX system is a continuous wave sensor. THe GUIDAR sensor has a total length of 2 miles and the SENTRAX system has a total length of 3 miles.

The possibility of installing a combination of pulse type and continuous wave type sensors over a 100 mile border segment was briefly mentioned in Chapter 1. As shown in Figure 7.1, the SENTRAX system, as currently implemented, is more expensive than the GUIDAR system in terms of cost per mile. On the basis of cost alone, it would be more economical to install only the GUIDAR system over the entire 100 miles. An approximate cost of 50,000 per mile for the GUIDAR system will be used in computing the total long line sensor system cost.

The main disadvantage of installing the GUIDAR system over the entire 100 miles would be the cost penalty of paying for a sensor which provides very fine range resolution in areas where coarse resolution would be sufficient. It is possible that some areas along a 100 mile section of border would not require the 33 and one third meter cell resolution of the GUIDAR system.

GUIDAR SYSTEM (Prices as of 9/85)

One processor unit*	43,308
One extension package	15,000
Two line amplifier units	12,632
Transducer Cables	54,080
Total (3.2 Kilometers) (2 miles)	125,020
Cost per mile	62,510
Cost per kilometer	39,069

SENTRAX SYSTEM (Prices as of 9/84)

One control module	7,707
Sensor cable sets (32)	60,032
Tranceiver Modules (16)	120,624
RF decouplers (32)	10,592
Total (4.8 kilometers) (3 miles)	198,955
Cost per mile	66,318
Cost per kilometer	41,449

*with display

Figure 7.1 Cost Comparison of GUIDAR and SENTRAX Systems

The primary advantage of using the GUIDAR system is that the smaller detection cell resolution provides a greater chance that the intrusion response for each cell will be within the suggested 3 to 1 ratio (Frankel et al. 1984). A 3 to 1 ratio will allow the GUIDAR system to distinguish small animals and other types of false alarms from actual human intrusions. The problem with having large detection cells is that the intrusion response ratio would most likely be greater than 3 to 1. For large detection cells, it might be possible to smooth out the intrusion response to within the 3 to 1 ratio by burying the leaky coaxial cables in a uniform soil (see part I of this study). In areas where the soil is nonuniform, smaller detection cells of 17 meters or even 8 meters might be necessary to keep the intrusion response ratio within the recommended range.

The resolution of the SENTRAX system is equal to the distance between transceivers. The maximum spacing between transceivers is 300 meters. This limit is due to the fact that both data and power distribution takes place over the leaky coaxial cables. If the data and power distribution were transmitted separately from the leaky cables, it might be possible to extend the distance between transceiver elements up to one half or one mile, however, line amplifiers would probably be necessary to maintain a sufficient signal to noise ratio. A continuous wave sensor with large detection cells would be the most efficient way to cover areas of the border where only coarse resolution is needed. It is estimated that the cost per mile of additional line amplifier units would be less than the cost of the required number of transceiver modules and separate data and power distribution links and, therefore, the total cost per mile of the SENTRAX long line sensor system could be reduced. As mentioned before, large detection cells could only be used if the intrusion detection response was maintained within the suggested 3 to 1 ratio.

Another possibility for a 100 mile long sensor system would be to use a newer version of the GUIDAR system which has variable cell lengths (Clarke and Sims 1984). In areas where coarse or fine resolution was needed, the cell lengths could be adjusted accordingly provided that the intrusion response ratio remained within the recommended limits.

Fifty of the two mile GUIDAR systems or about thirty three of the three mile SENTRAX systems would be necessary to cover one hundred miles. It is doubtful that either of these systems could be extended beyond their present length. Longer sensor systems would have longer detection times, would require a higher pulse transmission power, more line amplifier units and would lose some signal to noise ratio due to the additional noise accumulation with increasing length. The combination of these factors would lead to either a higher false alarm rates, a decrease in the probability of detection or both.

Chapter 2 discussed the detailed operation of the GUIDAR and SENTRAX systems. Also discussed in Chapter 2 were the power requirements, operating temperature range and possible system improvements for each sensor. Power distribution for a 100 mile long sensor system is not a trivial problem. Another study would be necessary to determine the most effective power distribution system. Some of the sensor components, such as the GUIDAR receiver/transmitter and the SENTRAX control module are normally located indoors and would have to be weatherized or put in an environmentally controlled container before installation. The cost of weatherizing these components is not known.

Chapter 3 discussed the three variables of the long line sensor communications problem. The three variables are topology, distribution of processing and type of transmission media. The advantages and disadvantages of each type of topology and transmission media were explained.

The preliminary evaluation of the candidate long line sensor systems was discussed in Chapter 4. The candidate long line sensor systems were derived by taking combinations of the three variables of the communications problem. Since one of the major tasks of this study was to determine if it is feasible to remotely locate any part of the GUIDAR system, the problem of distribution of processing was addressed first. The criteria used to evaluate the degree of distributed processing were bandwidth and timing and control. It was determined, because of the large bandwidths and centralized timing and control, that the only logical place to separate the GUIDAR system was after all signal processing had been completed. Only the appropriate display data would be sent to the base station. The two advantages of sending only the display data to the base station are the low bandwidth requirement and the fact that the display data would not have to be sent instantaneously to the base station. A short time delay between an intrusion and when the base station is notified would probably be acceptable. Therefore, each sensor would not require a dedicated communications channel to the base station. Once it was determined to send only the display data to the base station, baseband coaxial cable and microwave radio were eliminated from the list of candidate transmission media because they are not practical for low bit rate transmissions.

In Chapter 5, each of the remaining candidate systems were evaluated using the criteria of technology, vulnerability and installation requirements. It was decided to eliminate all radio transmission systems because of the vulnerability of exposed antennas to intentional sabotage, the fact that all radio systems can be subjected to jamming and the difficulty in obtaining approval from the FCC for the use of the appropriate frequency spectrum. The surviving candidate systems were twisted wire pair, broadband coaxial cable, fiber optic cable and power line carrier. The main advantage of each of these systems is that they can be completely buried underground. Each system would be installed in a bus topology configuration and an access protocol, such as carrier sensed multiple access or token passing, would be used to relay the display data to the base station.

Chapter 6 lists the advantages, disadvantages and the approximate costs of the major system components for the four remaining long line systems. Broadband coaxial cable is the most expensive but has the advantage of well proven, readily available technology. Twisted wire pair is the least expensive but the limited bandwidth would make future expansion difficult. Fiber optic cable has the largest bandwidth and projected decreasing component costs, but the rapidly changing technology might make some of the system components installed now obsolete within a few years. A power line carrier system would save on installation costs but would require special expertise for maintenance and installation and has limited bandwidth available for future expansion.

Other, long term factors which need to be considered are expandability, reliability, maintainability and security. The selected transmission media should have additional bandwidth available for expansion. The border patrols projected requirements for other types of sensors, remote communications, and power should all be integrated into this long line sensor project. The reliability of each component of the selected long line sensor system is important in determining future maintenance and replacement costs. Reliable components cost more initially but require less maintenance and replacement in the future. Analyzing the performance of previous sensor projects might give some insight into the reliability and vulnerability of this type of long line sensor system could be estimated. The survivability of the system to natural hazards, such as lightning and flash flooding, should also be studied. In order to keep the false alarm rate to a minimum, both the GUIDAR and SENTRAX systems would have to be equipped with the capability of adjusting the different cell thresholds automatically. As the moisture content and temperature of the soil changed over the 100 miles, the cell thresholds of each sensor would be adjusted continually so the same probability of detection could be maintained. Another option would be to design the system so the base station operator could adjust the cell thresholds remotely. To implement an automatic or remote cell threshold adjustment system would require additional hardware and redesign of the GUIDAR and SENTRAX systems.

The total system cost can be estimated as follows:

MAJOR ITEM	COST PER MILE
Communications Equipment (average)	$2,500
GUIDAR System	$50,000
Transformers ($200 each) (18 KV step down to 120 volts at 3 amps)	$100
Equipment Bunkers ($500 each) (GUIDAR and Communications Equipment)	$250
Equipment Bunkers ($200 each) (Transformer)	$100
Additional Power Distribution Equipment (Circuit Breakers, Receptacles, etc.)	$50
Power Distribution Cable (18 KV, 2 phase, direct burial coaxial cable at 2 amps)	$4,000
Installation (flat terrain, easily excavated soil, using a trench digger and backfilling trenches with the same soil)	$2,500
Total	$59,500

The major expense of a long line sensor system is the cost of the GUIDAR equipment. A single GUIDAR system, 2 miles in length, costs about $125,000. It is estimated that a slightly modified GUIDAR system which, does not include the LED display, is weatherized and is purchased in large quantities, would cost no more than $100,000. It is possible that a lower system cost could be achieved with mass production.

It is estimated that each sensor and additional communications equipment would require 3 amps at 120 volts, or 360 watts of power. A 100 mile system, using 50 sensors, would require 18 kilowatts of power. The cost of the power distribution system is estimated by assuming that all of the power is distributed from one end of the 100 mile sensor system. Transformers and additional equipment would be required at every 2 mile segment. Possibly, the optimal power distribution system might consist of a specially designed power cable which could also be used for communications. Instead of using off-the-shelf power line carrier cable and equipment, this system would be specifically designed for the power requirements and data rates of a 100 mile long sensor.

The estimated installation cost per mile assumes that the GUIDAR, communications and power distribution equipment are installed over level ground and in soil which is easily excavated. The actual terrain and type of soil across the southern international border varies considerably. In addition, part I of this study determined that better performance can be maintained if the leaky coaxial cables are buried in a homogeneous soil. Also, the power distribution cables should be installed in conduit to provide additional long term cable protection and safety against accidental electrocution. With these factors taken into consideration, the installation cost per mile might increase five or ten fold and become comparable to the cost per mile of the GUIDAR equipment.

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