Project Title: Vulnerability/Compatibility of PLRS/JTIDS Hybrids: An Engineering Assessment

Project No: A-2781

Project Director: R.W. Moss

Sponsor: U.S. Army Signal Center

Agreement Period: From 9/25/80 Until 6/25/81

Type Agreement: Delivery Order No. 0002 under BOA DABT11-79-G-0020

Amount: $69,930

Reports Required: Interim, Progress; Final

Sponsor Contact Person(s):

Technical Matters

Mr. Marland M. Ferguson; GS-13
254-56-8464
U.S. Army Signal Center and Fort Gordon
ATTN: ATZHCD-CS
Fort Gordon, GA 30905
(404) 791-3782/6548

Contractual Matters (thru OCA)

Mr. Tom Bryant
ONR RR
206 O'Keefe Building
Georgia Institute of Technology
Atlanta, GA 30332

Defense Priority Rating: N/A

Assigned to: ETL/CSG

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Project Code (GTRI)
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GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION

Date: 7/27/81

Project Title: Vulnerability/Compatibility of PLRS/JTIDS Hybrid: An Engineering Assessment

Project No: A-2781

Project Director: R. W. Moss

Sponsor: US Army Signal Center

Effective Termination Date: 6/25/81

Clearance of Accounting Charges: 6/25/81 (perf.) 7/10/81 (rpts.)

Grant/Contract Closeout Actions Remaining:

- [x] Final Invoice
- Final Fiscal Report
- [x] Final Report of Inventions
- Govt. Property Inventory & Related Certificate
- Classified Material Certificate
- Other

Assigned to: ECSL/CSD

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Other: ____________________________
February 9, 1981

Mr. Marland M. Ferguson
U.S. Army Signal Center and Fort Gordon
ATTN: ATZHCD-CS
Fort Gordon, Georgia 30905

Attention: Mr. Marland M. Ferguson, ATZHCD-CS

Reference: Contract No. BOA DABT11-79-C-0020,
Delivery Order No. 0002
"Vulnerability/Compatibility Assessment
of PLRS/JTIDS Hybrid"
Georgia Tech Project A-2781

Subject: Interim Report and
Monthly Progress Report No. 1

Gentlemen:

During this reporting period, Task 0002 was initiated and work has commenced on the engineering assessment of the Vulnerability/Compatibility of the PLRS/JTIDS Hybrid.

Initial efforts have been placed on developing the work plan for the task and obtaining the data necessary to carry out the assessment. Attachment I to this progress report constitutes the Interim Report work plan. As noted in the work, two of the tasks have been essentially completed. These two tasks involve collection of appropriate documents and literature dealing with PLRS/JTIDS in particular and vulnerability/compatibility in general. Substantial reference data has been found dealing with propagation considerations and the conceptual aspects of PLRS/JTIDS. These data include the PJH Definition and Evaluation Report by Hughes Aircraft Company (18 September 1980).

Since little material has been found regarding technical specifications for the PJH, additional information if available would be useful in the assessment. We are particularly interested in specific descriptions of the modulation waveforms and performance of the systems in a multipath environment.
During discussions with the COTR, it has been indicated that Task 0003 (related task under the above referenced BOA) dealing with MSE is more timely. Thus, initial efforts on both tasks are being placed on RF propagation and networking considerations. This approach permits the similar RF propagation results to be applied to both MSE and PJH systems.

During the next reporting interval, effort will continue in accordance with the work plan.

Sincerely,

R. W. Moss, Chief
Communications Systems Division

RWM:ame
ASSESSMENT OF PLRS/JTIDS HYBRID PHYSICAL INTERFACE AND CONNECTIVITY IN THE INTACS ARCHITECTURE

INTERIM REPORT (WORK PLAN)

Prepared For

U.S. ARMY SIGNAL CENTER
FORT GORDON, GEORGIA

CONTRACT DABT11-79-G-0020 (TASK 0002)

Prepared By

COMMUNICATIONS SYSTEMS DIVISION
ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA

January 1980
1. Objectives and Scope

Task 0002 of Contract DABT11-79-G-0020 is concerned with formulation of an assessment methodology for the PLRS/JTIDS Hybrid communications system. The primary objective is to provide a document which will facilitate the straightforward assessment of the system performance under a variety of operational conditions which include terrain variations, changes in system parameters, and the use of electronic countermeasures (ECM).

The purpose of this document is to outline a detailed work plan and provide an approximate schedule of major tasks to be performed during performance of the contract. While careful deliberation has been given to choosing the tasks and estimating the effort required by each, it is to be recognized that this work plan is subject to some variation during the contract performance in order to provide the most efficient effort.

2. Work Plan

This effort has been organized into ten major tasks to be performed in a more or less connective manner. These tasks are briefly described below:

**TASK 1:** Conduct a literature search to uncover relevant sources of information with respect to this assignment. This task is to be carried out by both manual research and computer keyword search techniques and will include both open literature and Government documents. (Most of this task has been done but additional specialized data is being sought.)

**TASK 2:** Collect the useful portions of the literature in a centralized source for ready reference. (Data collected has been assembled for ready reference.)

**TASK 3:** Summarize the electrical characteristics for both the PLRS and JTIDS systems. This is to include block diagrams, electrical operating parameters, code characteristics, etc. for each system.
TASK 4: Perform a link budget analysis for each system under line-of-sight, clear channel operating conditions to establish a base line for system performance.

TASK 5: Formulate methodology for evaluating link degradation resulting from factors not included in the baseline analysis such as terrain, higher noise level, antenna gain, etc.

TASK 6: Based on the baseline link analysis and operating characteristics of the systems (modulation waveforms, spectrum shape, etc.), determine the potential sources of performance degradation and rank order them in terms of relative significance.

TASK 7: Formulate methodology for evaluating link degradation resulting from interference sources mentioned above.

TASK 8: Assess the network performance in terms of overall error rate and system vulnerability.

TASK 9: Formulate overall assessment methodology based on analysis performed in previous tasks.


3. Work Schedule

Figure 1 is a schedule of the primary tasks to be performed, indicating approximate completion time for each. Due to the interrelated nature of the tasks, considerable overlap between them is anticipated. Moreover, as work proceeds, it is likely that some changes in the effort will be dictated by interim findings. Thus, the schedule is subject to some variation during the performance of the contract.
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1. LITERATURE SEARCH

2. COLLECT AND ORGANIZE LITERATURE

3. SUMMARIZE ELECTRICAL CHARACTERISTICS

4. BASE LINE LINK ANALYSIS

5. LINK DEGRADATION ANALYSIS

6. IDENTIFY INTERFERENCE SOURCES

7. ECM ANALYSIS

8. NETWORK ANALYSIS

9. ASSESSMENT METHODOLOGY

10. DOCUMENTATION

Figure 1. Work Schedule
4. Data Base Requirements

In order to perform the stated tasks, it will be necessary to obtain essential information about the RLRS/JTIDSA system. This information falls into three basic categories: (1) information about PLRS, (2) information about JTIDS, and (3) information about the hybrid interface. For convenience the required information is tabulated in Table 1.

TABLE 1

I. PLRS System
   A. Block diagram of electric subsystems
   B. Electrical specifications
   C. Detailed description of system
   D. Status report on current state of development
   E. Known operational and/or performance characteristics

II. JTIDS System
   A. Block diagram of electric subsystems
   B. Electrical specifications
   C. Detailed description of system
   D. Status report on current state of development
   E. Known operational and/or performance characteristics

III. PLRS/JTIDS Hybrid
   A. Typical network configuration
   B. Developmental status
5. Final Report Outline

Attached as Table 2 is a copy of the preliminary final report outline for this project. Although thought to be reasonably accurate at this time, some variation is anticipated as more is learned about the nature of the problem.

6. Progress Report

Since initiation of the project, we have essentially completed Tasks 1 and 2 per the work plan as outlined above.

Three computer assisted literature searches have been conducted in order to uncover sources of information in the literature on PLRS/JTIDS and similar systems. Two of these were directed toward open engineering literature and one toward government documents. A total of over 400 sources were found. In addition, considerable time has been spent manually searching for relevant information sources. Considerable information has been uncovered by both methods.

The sources found by the aforementioned searches has been reviewed and the relevant portion thereof collected in a central file for further study. Although a considerable amount of useful literature has been found, we are still lacking in detailed information about detailed technical specifications for the systems to be analyzed. We are continuing our efforts in this area. (Two Hughes reports were recently received.)
TABLE 2

PRELIMINARY FINAL REPORT OUTLINE
PLRS/JTIDS HYBRID ASSESSMENT

1. Introduction

2. Basis System Concepts
   2.1 RF Transmission
   2.2 Introduction to Spread Spectrum
   2.3 Networks
   2.4 Interface
   2.5 Performance Parameters

3. The RF Link
   3.1 Performance Equations
   3.2 Propagation Factors
      3.2.1 Loss
      3.2.2 Effect of Multipath
   3.3 Noise (SNR)
      3.3.1 Sources of Noise
      3.3.2 Computing the RF SNR
   3.4 Error Rate
      3.4.1 SS Processing Gain
      3.4.2 Coding for Error Detection/Correction
      3.4.3 Detection Threshold Effects
      3.4.4 Computing Bit-Error-Rate (BER)
   3.5 Evaluation of Link Performance

4. Jamming and Interference
   4.1 Performance Equations
   4.2 The Jammer Link
   4.3 Jammer Mismatch
   4.4 Other types of Interference
   4.5 Stressed Performance
   4.6 Performance Evaluation

5. Networks
   5.1 Computing Cascaded BER
   5.2 Timing/Synchronization
   5.3 Network Protocol
   5.4 Performance Parameters
   5.5 Network Jamming/Interference
   5.6 Survivability

6. Assessment Methodology
February 11, 1981

U.S. Army Signal Center, Fort Gordon
ATTN: ATZHCD-CS (Mr. Marland M. Ferguson)
Fort Gordon, Georgia 30905

Attention: Mr. Marland M. Ferguson, ATZHCD-CS

Reference: Contract No. BOA DABT11-79-C-0020
Delivery Order No. 0002
PLRS/JTIDS Hybrid
Georgia Tech Project A-2781

Subject: Monthly Progress Report No. 2
and Performance and Cost Report

Gentlemen:

During this reporting period, principal emphasis has been placed on analysis of RF propagation characteristics. The purpose is to allow the user to accurately predict the usable communication range for a variety of communication configurations. The approach which has been selected is based on the use of a standarized worksheet, thereby leading to considerable simplification of the otherwise complex equations. Other features include the use of graphic techniques for intermediate computations and the provision of "typical" performance and environmental data in tabular form. At the present time the RF analysis is approximately 50% complete.

The RF assessment makes considerable use of a set of propagation curves which will ultimately form an appendix of the report. A mathematical formulation of propagation has been completed and will be used to generate these curves. This formulation is based on physical phenomenon as well as a statistical model of the variability of the physical conditions on which the model is based.
The literature search is complete; however, there are still a number of system parameters and characteristics which remain unspecifed. As a result, we are trying to formulate our assessment in as general a manner as possible in order to ensure its suitability for the widest variety of system possibilities.

A summary status of contract expenditures as of 1 January is attached.

Sincerely,

R. W. Moss, Chief
Communication Systems Division

Attachment

RWM:ame
PERFORMANCE AND COST REPORT

For the period 25 September 1980
through 31 December 1980

Contract BOA DABT11-79-G-0020 (Task 0002)

Cumulative Total Cost to Date: $18,405.65

Estimate to Complete: $51,524.35

Estimated Effort Expended: 4 Man-months
During this reporting period, most of the effort has been continued on development of a framework and methodology for defining RF connectivity for the PLRS/JTIDS hybrid. Since the hybrid uses a "nodeless" TDMA architecture, the RF connectivity will play a central role in the performance of ground-based terminals.

A meeting with the COTR (Mr. Mike Ferguson) was held at Georgia Tech on 15 January 1981. Progress was reviewed on the PJH vulnerability task and the work sheets being developed were described.

Initial efforts are being made to develop assessment procedures for PJH jamming situations. Since many specific jamming threats may exist, the approach being taken is to generically describe the jamming effectiveness. This generic framework will treat the jamming power as an equivalent white Gaussian noise process with equal power. Although not totally accurate, this approach allows vulnerability to be treated in a general sense.
During the next interval these planned efforts will continue with a shift of emphasis to the vulnerability effects.

Sincerely,

R. W. Moss, Chief
Communication Systems Division

Attachment

RWM:ame
PERFORMANCE AND COST REPORT

For the period 1 January 1981
through 31 January 1981

Contract BOA DABT11-79-G-0020 (Task 0002)

Cumulative Total Cost to Date: $23,472.45

Estimate to Complete: $46,457.55

Estimated Effort Expended: 5 Man-months
The effort on this BOA task during this reporting period has been placed on (1) completion of the unstressed (no jamming) RF connectivity; (2) development of the RF connectivity worksheet for jamming analysis; and (3) determination of systems most likely to produce vulnerability or incompatibility.

RF connectivity equations along with related worksheets and charts have been completed for the unjammed situations. This development provides the analytical framework for assessing PLRS/JTIDS RF connectivity under a variety of terrain conditions. A similar development is underway for analysis of performance under jamming conditions.

The survey of vulnerability and compatibility is proceeding by reference to both classified and unclassified sources. The classified information will be provided as an annex to the report. Sources for the survey include international frequency band assignments, and foreign systems operating within or near the proposed PJH bands.
During the next reporting interval, these activities will continue and initial draft report material will be prepared.

Sincerely,

R. W. Moss, Chief
Communication Systems Division

Approved:

F. L. Cain, /Director ECSL

Attachment

RWM:scy
PERFORMANCE AND COST REPORT

For the period 1 February 1981
through 28 February 1981

Contract BOA DABT11-79-G-0020 (Task 0002)

Cumulative Total Cost to Date: $28,617.91

Estimate to Complete: $41,312.09

Estimated Effort Expended: 6.1 Man-months
U.S. Army Signal Center, Fort Gordon
ATTN: ATZHCD-CS (Mr. Marland M. Ferguson)
Fort Gordon, Georgia 30905

Attention: Mr. Marland M. Ferguson, ATZHCD-CS

Reference: Contract No. BOA DABT11-79-G-0020
Delivery Order No. 0002
PLRS/JTIDS Hybrid
Georgia Tech Project A-2781

Subject: Monthly Progress Report No. 5
(For the Period 26 March through 26 April 1981)
and Performance and Cost Report

Gentlemen:

During this period, emphasis on this BOA task has been in the areas of (1) completion of the RF connectivity for jamming analysis, (2) computation of typical coverage ranges, and additional survey of sources likely to produce interference or jamming.

Several typical parameter values have been selected and are being used to compute typical coverage areas for both PLRS and JTIDS applications. Initial results indicate some very limited ranges for low antenna heights and rough terrain. Results are now being computed for PJH links stressed by jamming.

Several possible sources of interference and jamming have been identified from the survey. The classified information will be transmitted as an annex to the draft report.
Attention has now shifted to preparation of the draft report and during the next interval most of the effort will be devoted to this task. Task progress was reviewed with Mr. Fergson, COTR, during a visit to Georgia Tech on 10 April 1981.

Sincerely,

R. W. Moss, Chief
Communication Systems Division

Approved:

F. L. Cain, Director ECSL

Attachment
RWM:ame
PERFORMANCE AND COST REPORT

For the period 1 March 1981 through 31 March 1981

Contract BOA DABT11-79-G-0020 (Task 0002)

Cumulative Total Cost to Date: $32,091.17

Estimate to Complete: $37,838.73

Estimated Effort Expended: 7 Man-months
May 28, 1981

U.S. Army Signal Center, Fort Gordon
ATTN: ATZHCD-CS (Mr. Marland M. Ferguson)
Fort Gordon, Georgia 30905

Attention: Mr. Marland M. Ferguson, ATZHCD-CS

Reference: Contract No. BOA DABT11-79-G-0020
Delivery Order No. 0002
PLRS/JTIDS Hybrid
Georgia Tech Project A-2781

Subject: Monthly Progress Report No. 6
(for the Period 26 April through 26 May 1981)
and Performance and Cost Report

Gentlemen:

During this reporting period, intensive effort has been applied toward completion of the technical effort and preparation of a draft report. The draft report is now about 90% complete and will soon be submitted for approval. Additional technical material was prepared for the report including evaluation of typical PLRS/JTIDS hybrid links.

During June while the draft technical report is being reviewed, activities will include additional review and editing of the draft report and verification of some of the engineering results.

Sincerely,

R. W. Moss, Chief
Communication Systems Division

Approved:

F. L. Cain, Director ECSL

Attachment
RWM:ame
PERFORMANCE AND COST REPORT

For the period 1 April 1981 through 31 May 1981*

Contract BOA DABT11-79-G-0020 (Task 0002)

Cumulative Total Cost to Date: $57,000.00

Estimate to Complete: $12,930.00

Estimated Effort Expended: 12.5 Man-months

* Effort for the month of May has been estimated and included to bring the cost data up to date.
U.S. Army Signal Center, Fort Gordon  
ATTN: ATZHCD-CS (Mr. Marland M. Ferguson)  
Fort Gordon, Georgia 30905

Attention: Mr. Marland M. Ferguson, ATZHCD-CS

Reference: Contract No. BOA DABT11-79-G-0020  
Delivery Order No. 0002  
PLRS/JTIDS Hybrid  
Georgia Tech Project A-2781

Subject: Monthly Progress Report No. 7  
(for the Period 26 May through 26 June 1981)  
and Performance and Cost Report

Gentlemen:

During this reporting period, the draft final report was submitted for approval. Government comments concerning the report were reviewed at a meeting held at Fort Gordon between the COTR and Georgia Tech personnel. The report has been reviewed and approved and changes requested have been incorporated in the report.

During the time the draft report was being reviewed, additional activities included review and editing of the report material and verification of some of the engineering results. The final report has now been submitted and all contract requirements are now complete.

Sincerely

R. W. Moss, Chief  
Communication Systems Division

Approved:

F. L. Cain, Director ECSL

Attachment  
RWM:ame
PERFORMANCE AND COST REPORT

For the period 1 June 1981 through 30 June 1981*

Contract BOA DABT11-79-G-0020 (Task 0002)

Cumulative Total Cost to Date: $69,930.00

Estimate to Complete: $0.00

Estimated Effort Expended: 15 Man-months

* Effort for the month of June has been estimated and included to bring the cost data up to date.
ASSESSMENT OF PLRS/JTIDS HYBRID
PHYSICAL INTERFACE AND
CONNECTIVITY

By
R.W. Moss, Project Director
J.O. Battle
H.H. Jenkins
W.W. Butler
J.A. Aaron
B.J. Wilson

Prepared For
U.S. ARMY SIGNAL CENTER
Fort Gordon, Georgia 30905

Contract DABT11-79-G-0020(TASK 0002)
June 1981

GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station
Electronics And Computer Systems
Laboratory
Atlanta, Georgia 30332
ASSESSMENT OF PLRS/JTIDS HYBRID
PHYSICAL INTERFACE AND CONNECTIVITY

By

R.W. Moss, J.O. Battle, H.H. Jenkins,
W.W. Butler, J.A. Aaron, and B.J. Wilson

Contract DABT11-79-G-00120 (TASK 0002)
Georgia Tech Project A-2781

June 1981

Prepared for

U.S. Army Signal Center
Fort Gordon, Georgia 30905

Communications Systems Division
Electronics and Computer Systems Laboratory
Georgia Institute of Technology
Atlanta, Georgia 30332
FOREWORD

This report was prepared by the Communications Systems Division of the Electronics and Computer Systems Laboratory of the Georgia Institute of Technology. The work described was performed under the overall supervision of Mr. F.L. Cain, Director of the Electronics and Computer Systems Laboratory and under the general supervision of Mr. R.W. Moss, Chief of the Communications Systems Division. Mr. Moss also directed the project.

Within the U.S. Army Signal Center, the assistance of Mr. Mike Ferguson, COTR, and LTC James Mullen is acknowledged. The report preparation efforts of Mrs. Ann Evans are appreciated.
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1. INTRODUCTION

1.1 Background

The Integrated Tactical Communications Systems (INTACS) plan specifies a data distribution capability on the future battlefield to satisfy data communications requirements. Future applications are numerous and include intelligence data, command and control, fire control, and data transmission between computer processors. Potential candidates for data distribution include packet radio, the Joint Tactical Information Distribution System (JTIDS), the Position Location Reporting System (PLRS), and a combination of PLRS and JTIDS referred to as the PLRS/JTIDS Hybrid (PJH). The PJH system is a primary candidate and is the subject of this report.

In order to meet the requirements of data distribution, it is imperative that the hybrid perform under a wide range of propagation, deployment, and network conditions. It is equally important that proposed PJH configurations be evaluated for acceptable performance under stressed conditions. This report deals with an assessment of PLRS/JTIDS performance under such conditions.

1.2 Scope and Objectives

The scope of work represented by this report encompasses an engineering assessment of RF connectivity, and vulnerability to potential sources of interference or jamming for PLRS/JTIDS ground-to-ground links. The assessment deals with proposed RF bands which include anticipated frequency allocations for PLRS and JTIDS (0.3 to 2 GHz). The assessment is stated in terms of an analytical framework which will provide the information and procedures required for later detailed analysis by the users of this report.

The general objective of the assessment is to provide an analytical and computational framework that will permit detailed performance
analysis by the Signal Center. Specific objectives included characterization of potential PLRS/JTIDS radio channels in terms of propagation factors and noise, assessment of sources that have potential for intentional or unintentional degradation of PJH performance, and development of an analytical framework for performance evaluation.

It is to be emphasized that the scope of this assessment was not exhaustive and available time and funds did not permit all possible sources of applicable data to be reviewed or abstracted. In some instances, related work is being done by other DOD agencies or DOD contractors. Most notable of these is the PJH work by Hughes Aircraft under Contract DAAB07-78-C-3331 (Report dated 18 September 1980). Some of these results may contain additional useful information.

1.3 Approach

The overall approach to the assessment included the following activities:

- Survey of classified and unclassified literature to determine emitters (specific or generic) which may degrade PJH performance.

- Determination of major performance parameters which influence the PJH network connectivity.

- Development of an assessment methodology which would permit statistical characterization of PJH links in terms of propagation loss, noise levels, terrain types, jamming level, etc.

- Application of the analytical assessment methodology to specific typical cases.
Since it is intended that the assessment methodology be useful for a variety of yet undefined situations, considerable emphasis was placed on developing the results in the form of work sheets and supporting data. This format allows considerable parametric flexibility for future analysis of specific cases.

Including this introductory chapter, this report is organized into seven chapters. Basic PJH concepts are briefly described in Chapter 2, followed by the survey of jamming or interference sources in Chapter 3. Analytical procedures for network connectivity are described in Chapter 4, followed by analysis of typical cases in Chapter 5. Several appendices contain detailed work sheets and data for detailed link analysis under stressed and unstressed conditions.

The classified information pertaining to possible sources of interference or jamming is being submitted as a classified annex to this report. All other information is contained in this document.
2. SUMMARY OF PJH CONCEPTS

2.1 PLRS (Position Location Reporting System)

The Position Locating Reporting System (PLRS) is a network designed for the Army and Marine Corps to provide position information, navigation data, and secure data transfers for a variety of users. The system consists of two major components: a Master Unit (MU) and multiple User Units (UU). The MU consists of (1) a Command Response Unit (CRU) which provides the RF signal processing and system timing, (2) an AN/UYK-20 network control processor, (3) an AN/UYK-7 which does position computations, and (4) an AN/UYK-20 display processor. All of this equipment is housed in the standard S-280 shelter which can be transported by either a 2-1/2 ton truck or by helicopter. The complete MU housed in an S-280 shelter weighs 6,300 pounds and has a volume of 620 cubic feet.

The UU's basic package is designed as a manpack unit and has adapters which permit its installation on various platforms. The major modules in the UU are (1) an RF/IF signal processor, (2) an encoding/decoding network for encrypted messages, (3) a timing network, and (4) a control panel processor. The manpack version of the UU weighs less than 23 pounds, has a volume of 500 cubic inches, and has a battery capacity of 24 hours.

The radio link associated with PLRS operates in the 420 to 450 MHz range (UHF) and employs spread spectrum modulation. In this case, the frequency spreading is achieved by a combination of pseudorandom noise (PRN) coding and frequency hopping (FH). A time-division multiple access (TDMA) protocol composed of epochs, frames, and timeslots is used in the PLRS network. The epoch, which is 64 seconds in duration, is the minimum time period for performing all network functions in the fully deployed system. There are 256 frames per epoch and each frame consists of 128 time slots. The time slot, which is the basic transmission interval, is
1.95 milliseconds in length, and consists of an 800 microsecond data burst of 94 bits preceded and followed by guard times. The time slot is the minimum transmission period assigned to an active user in an epoch.

The position of an individual user is determined by PLRS through multilateration. In particular, since each user is assigned a specific transmission time, the distance between the point of reception can be determined through the signal's time of arrival (TOA). In general, the site of the MU and two UUs are surveyed into position. These three receiving sites then provide three independent range measurements which are sufficient to determine the location of the other user units. The AN/UYK-7 in the MU uses the observed ranges to compute position, and the computed position is reported in either Universal Transverse Mercator (UTM) or Universal Polar Stereographic Coordinates. In field tests at Camp Pendleton, the manpack unit exhibited an (X,Y) accuracy of 7 meters for line-of-sight (LOS) conditions and 13-26 meters for non-LOS conditions.

2.2 JTIDS (Joint Tactical Information Distribution System)

A new architecture has been defined for military communications: The Joint Tactical Information Distribution System (JTIDS). This system has been designed to serve the communication, navigation, and identification (CNI) needs of the four services in the 1980's. JTIDS accomplishes its objectives through the use of a node-less, time-division, multiple-access (TDMA) configuration. The basic JTIDS signal is a spread spectrum signal generated through a combination of pseudorandom noise coding (PRN) and frequency hopping. The details of this system are provided below.

The key to the JTIDS concept is time division multiplexing, and time division multiplexing is a simple recognition that it is not necessary to transmit continuous analog signals on a continuous basis to achieve an accurate transfer of information. In short, data from several different sources are combined and transmitted as one composite signal. Most commonly the process of combining data sets actually amounts to interleaving the various data pulses.
In JTIDS, one complete communications cycle is called an epoch and is 12.8 minutes in duration. The epoch consists of 64 frames of 12 seconds each, and each frame consists of 1536 slots of 7.8 msec each. The time slot is the basic transmission interval for JTIDS, and the time slot consists of a synchronization burst, an identification segment, the data to be transmitted, and a guard period.

The synchronization burst is typically a pseudorandom noise (PRN) code which is used to synchronize the receiver to the incoming transmission. Additionally, the burst serves to add a degree of security to the transmission process since decoding the transmission without knowledge of the PRN code is virtually impossible.

The identification segment allows the receiver to automatically determine if the received transmission is of interest, and the guard period is simply a quiet period which allows the transmission to propagate to its intended recipient(s) before the next transmission begins. This is to minimize interference.

As noted earlier, JTIDS provides some navigational information in addition to its communications functions. In particular, the current version of JTIDS provides a two-coordinate system using standard geodesic latitudes and longitudes or a relative rectilinear grid tangent to the earth's surface. The former coordinate scheme requires one member of the JTIDS net to serve as a position reference, and it is required that the position of the reference be known with high precision. In the latter system, any net member may serve as the reference, but all locations are strictly relative and are tied to the position reference. It has been estimated that the JTIDS positioning system is capable of determining location with a precision of 9 meters. It should be stressed that the positioning feature of the JTIDS system is restricted in coverage to the basic communications coverage area. JTIDS has been designed to provide communications up to a maximum 300 nmi range.

Implementation of the phase one JTIDS hardware and software is well underway, and utilization of advanced technologies is allowing
significant reductions in the size and weight of the JTIDS package. For example, the JTIDS package currently being developed for use on fighter aircraft occupies about 1.25 cubic feet. The major system component which is receiving intensive scrutiny is the modulator/demodulator unit, and at present two different technologies appear to hold equal promise for size, weight, power consumption reductions: surface acoustic wave (SAW) filters and charge coupled devices (CCDs). Application of these technologies in addition to the use of large scale integration (LSI) offer the hope of future reductions in size and weight.

2.3 PJH (PLRS/JTIDS Hybrid)

As a outgrowth of the JTIDS and PLRS development and in recognition of growing needs for a data distribution capability for the future INTACS, a hybrid concept has emerged based on the features of PLRS and JTIDS. The hybrid system is expected to consist of standard elements of both systems as well as special interface units and modified components.

The primary equipment elements of PJH are expected to include: (1) the enhanced PLRS user unit (EPUU); (2) JTIDS terminal; (3) net control unit (NCU); (4) A PLRS/JTIDS interface terminal; and (5) a net control master unit (NCMU). Capabilities expected to be provided by PJH include digital data communications, unit identification and location, navigation, and automatic repeating of location and status to central locations. PJH is intended primarily as a divisional asset and would be a cornerstone system for data distribution and automatic status tracking. An operational deployment would include roughly 1000 EPUU's and 70 JTIDS terminals within a division.

2.4 Technical Features of PJH

Because the hybrid is an outgrowth of both PLRS and JTIDS, the communication technology employed shares great similarity with both PLRS and JTIDS. Specifically the PJH concept retains the broadcast TDMA,
nodeless structure and includes spread spectrum modulation for ECCM and security advantages.

The principal technical feature of PJH is the fact that a broadcast TDMA mode of operation is used. From an operational point of view, this means that no communications switching is used (although message relay via intermediate terminals is a standard feature) with the result that connectivity between users is basically established by RF propagation factors and receipt of an adequate signal-to-noise ratio.

Thus, an assessment of connectivity for PJH basically involves a determination of link budget details including propagation loss, signal level, noise level, and jamming level. Key performance parameters include the maximum communications range under adverse conditions, the received signal-to-noise ratio (SNR), the bit-error-rate (BER), and the reduction in SNR due to jamming.
3. POTENTIAL JAMMING AND INTERFERENCE SOURCES

3.1 Introduction

One point of concern for PJH is the potential for serious interference or jamming when the system is deployed in a central European environment. As is well-known, any communication system, no matter how well designed, can be degraded in performance by either deliberate jamming or unintentional interference.

Because of this potential, a brief survey was made of potential sources which may produce vulnerability or incompatibility. This survey was not exhaustive and is intended primarily to give insight into possible sources of other RF system which could possibly reduce RF connectivity of the PLRS/JTIDS Hybrid. Georgia Tech believes that Hughes Aircraft Company and possibly E-Systems have investigated jamming of JTIDS. It is suggested the reader pursue this possibility if more detailed information is desired.

3.2 Survey of Specific Systems

A survey of potential jamming and interference sources has been conducted using classified sources. This survey included "friendly" emissions, possible ECM (jamming) sources, and intercept/DF threats. The results of this survey are classified and have been submitted as an annex to this report.

An unclassified survey was also made of frequency band allocations which coincide with PLRS and JTIDS. The purpose of this survey was to assess possible sources of non-military emissions which could degrade hybrid performance. The results are described below.
3.3 PLRS/JTIDS Frequency Band Assessment

A limited assessment of the JTIDS/PLRS frequency bands was conducted to determine the spectrum utilization for each band. A comprehensive data file with additional detailed information is available from various sources. These additional sources are:

1. Government Master Files — maintained by the Interdepartment Radio Advisory Committee (IRAC). This file contains (military and non-military) information representing transmitter assignments and receiver locations throughout the United States, Alaska, Hawaii, and other U.S. possessions.

2. Federal Communications Commission (FCC) and the American Telephone and Telegraph (AT&T) Files — maintained by the Electromagnetic Compatibility Analysis Center (ECAC). These files represent the non-government sector of the United States environment.

3. International Frequency List — maintained by the International Frequency Registration Board of the International Telecommunications Union (ITU-IFL). These files contain frequency assignments reported in Europe and other nations worldwide.

4. NATO Master Radio Frequency List (MRFL) — maintained at ECAC based on tapes received from NATO. These files contain information on spectrum utilization by NATO forces in Europe.

5. Frequency Resource Records System (FRRS) — this file system was developed and is maintained at ECAC as an aid to the frequency management process within the U.S. military. This file contains information on frequency management activities under the commander-in-chief of each overseas unified command.
Table 3-1 summarizes these environments and source files which are available from ECAC for additional information.

During the World Administrative Radio Conference (WARC) held in December 1979, no new modifications or allocations were proposed or made to the JTIDS frequency band (960-1215). However, in the PLRS frequency band a minor modification was made to the frequency range 435 MHz - 438 MHz to allow greater flexibility in amateur satellite experimentation.

PLRS Frequency Assessment (420-450 MHz)

The frequency band 420-450 MHz is divided into three separate bands on the international level (Region One). In accordance with the International Table of Frequency Allocation, the frequency range 420-430 MHz is assigned to fixed mobile (except aeronautical mobile) and radiolocation operation; the frequency range 430-440 MHz is assigned to amateur and radiolocation; and the frequency range 440-450 MHz is assigned to fixed mobile (except aeronautical mobile) and radiolocation. These frequency assignments are allocated to Region One, which includes the Central European area.

Within the United States the above frequency bands are allocated for government use of radiolocation systems and are allocated on a non-government basis for amateur radio services.

Footnote (G55) to the allocation tables states "The authority to operate a joint-use radar (Air Defense/Air Traffic Control) in the band 216-225, 420-450, 1215-1300, and 2300-2500 MHz may be issued to the agency responsible for the technical operation and maintenance of that radar. In spite of this dual usage, such radars shall be authorized in the radiolocation service. Present and future requirements for air defense need shall take precedence over any secondary usage for air traffic control purposes." However, the presently available information does not indicate that any of these systems are operational within the 420-450 MHz range in Central Europe.
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In a study conducted for ECAC* by the IIT Research Institute during April, May, and June 1972, an airborne-platform was used to make European RF measurements in the 100-500 MHz band. The frequency range 420-450 MHz band was found to be a relatively uncongested band in which 93 percent of all signals recorded were low power, <-99 dBm.

In the frequency range 420-430 MHz only moderate use of the spectrum was found. The frequency range 430-440 MHz indicated relatively low power signals distributed uniformly across the band. The frequency range 440-450 indicated fairly uniform distribution of low power signals.

Although these data are not current, they do suggest the lack of long term use of this portion of the spectrum by high power sources.

JTIDS Frequency Assessment (960-1215 MHz)

The frequency band 960-1215 MHz is reserved on a worldwide basis for the use and development of airborne electronic aids to air navigation and any directly associated ground-based/activities. Within the United States and possessions, this FAA administered band contains a mixture of government and non-government aeronautical radionavigation system which provide safety-of-life services, e.g. Distance Measuring Equipment (DME). In a previous study**, it was found that approximately 7,000 frequency assignments were allocated on a worldwide basic in this frequency range.

---


The frequency record data indicate that the majority of these assignments are for the Aeronautical Radiolocations services. Examples of these emitters are listed below:

- TACAN (Tactical Air Navigation)
- Amateur transmitters
- Homing beacons
- ATCRBS (Air Traffic Control Radar Beacons)
- ILS (Instrument Landing Systems)
- Tactical navigational system
- DME (Distance Measuring Equipment)

Further assessment of the use of these emitters indicates that the power output ranges from less than 10 watts to a maximum of 10 kW with the majority of these emitters being in the low power class.

It should be noted that the above emitters will have antenna coverage over a wide area, with the exception of the ILS which is very localized. Since most of these systems use low power and directional antennas for air-to-ground and ground-to-air coverage, they should not be a major factor within the JTIDS/PLRS frequency bands for ground based equipment. However, because of the "dished-up" antenna patterns, there is a probability of interference to airborne platforms within the JTIDS/PLRS frequency band within the United States and Central Europe.

It may be concluded from this survey that some potential sources of interference do exist for either PLRS or JTIDS frequency bands. However, no major salient source of interference appears likely (beyond those already considered when the proposed PLRS/JTIDS bands were selected). It is probable that interference, if encountered, will consist of the combined effects of many low-powered sources from random locations.

One additional potential source of interference which cannot be neglected is the relatively high level of man-made noise in Central
Europe. Due to the relatively high population density and degree of industrialization, a higher than average noise level can be expected from such sources as power line noise, electrical switches, motors, ignition noise, etc. In fact, it is probable that received noise will limit system performance more so than intrinsic receiver thermal noise.
4. PLRS/JTIDS LINK BUDGET ANALYSIS

4.1 Unstressed RF Connectivity (No Jamming)

Appendix A and Appendix B describe a detailed procedure, along with work sheets and supporting data, for analyzing unjammed RF links connecting PLRS and JTIDS terminals. The principal result of this detailed analysis produces the maximum range that will be achieved with a specified value and reliability for SNR. This result corresponds to the following probability statement:

\[
P(SNR > SNR_0 | R) = \text{link reliability},
\]

where \( R \) is the computed maximum range and \( SNR_0 \) is the required signal-to-noise ratio. Thus, for example, a 97.5% reliability means that there is a 97.5% probability that an adequate signal-to-noise ratio will be exceeded at the range determined.

Therefore, in assessing the performance of proposed PLRS/JTIDS links, the first step is to determine the maximum range that can be supported, given a required value of receiver SNR. This step is accomplished by making use of the detailed work sheet and related data presented in Appendix A. The work sheet and the result derived accounts for the following factors:

- Propagation loss for classes of terrain including plains, hills, mountains, and urban environments.

- Received noise levels including low, medium, and high noise.

- Soil conductivity effects on propagation including poor, good, and excellent classes of soil (worldwide conductivity charts are also included).
• Receiver parameters including frequency, noise figure, bandwidth, and antenna height and gain.

• Transmitter parameters including frequency, power output, and antenna height and gain.

Also included in the procedure are statistical measures such as propagation loss variability and noise variability.

It should be emphasized that the RF coverage computation is based on a statistical approach for area coverage. That is, the predicted range is that which would be expected if many actual ranges were measured and averaged for the stated terrain class. Under a given set of circumstances for a specific path, the actual measured range may be more or less than the predicted range. This type of area statistical coverage was chosen in lieu of point-to-point prediction because of the highly mobile nature of PLRS and JTIDS.

Since both PLRS and JTIDS are TDMA systems with no communications switching, there will be no contention between multiple users as in the case of conventional multichannel systems. Consequently, the "grade of service" for the Hybrid is established by the link reliability as stated above.

4.2 Stressed RF Connectivity (Links with Jamming)

Appendix C and Appendix D describe a procedure for analyzing the effects of jamming on PLRS/JTIDS links. The procedure includes a detailed work sheet and supporting data in Appendix C. The primary result of the procedure produces the probability of link denial. This result corresponds to the probability statement:

\[
\text{Probability of link denial} = P(\text{SNR} < \text{SNR}_o | \text{link configurations}),
\]
where SNR\textsubscript{o} is the minimum value of signal-to-noise ratio required for link operation. The probability is conditioned on a specified PJH link distance and the distance between a PJH receiving terminal and the jammer. For example, suppose a 10 km PJH link exists with a SNR of 20 dB. For a specific jammer-receiver distance and selection of parameters, a typical result might be probability of link denial of 10\%. This result would mean that there is a 10\% probability that the SNR would fall below an acceptable level due to jamming or interference.

Several points should be noted with regard to the analysis of stressed (jammed) links. First, the "noise" factor includes not only intrinsic receiver noise and atmospheric noise, it also includes interference and jamming. Second, the analytical procedure is somewhat less flexible since two specific links (transmitter-receiver, jammer-receiver) must be assumed before the analysis can begin. Third, the procedure makes use of an acceptable but nonetheless rough approximation that jamming and interference sources may be treated as equivalent additive Gaussian noise. This latter assumption is necessary in order to develop a generalized result applicable to generic assessment.

Assessment of jamming and interference effects on PLRS/JTIDS links proceeds by postulating or otherwise establishing specific parameters for jamming or interference sources (see Chapter 3). The work sheet is then exercised and the probability of link denial is determined. As before, the stressed RF connectivity work sheet includes selection of a range of terrain classes, noise levels, soil conditions, and technical parameters. The results are based on statistical area analysis for RF coverage as in the unstressed case.

4.3 Link Budget SNR Criteria

In order to use the work sheets, described above, several parameters must be specified (see Figures A-2 and C-2). These parameters include technical parameters of the receiver, transmitter, and jammer; antenna parameters; terrain conditions; and required values of signal-to-noise
ratio. Various tables and curves are provided for selection of these parameters. In addition, a detailed supplemental procedure is set forth in this section for determining an accurate value for signal-to-noise ratio. This supplemental procedure for SNR determination can be bypassed if required values of SNR are known or can be otherwise estimated. If SNR requirements are unknown, it is recommended that the material in this section be used to develop accurate SNR requirements.

In designing or evaluating the performance of PLRS or JTIDS links, it is necessary to include sufficient margin to account for all sources of potential degradation. For propagation loss, this margin has been included via the path reliability factor and the various factors related to terrain and noise dependencies. An additional important determination is the value of required SNR to produce an acceptable error rate.

In order to determine the maximum reliable range and the likelihood of jamming or interference, a value of SNR must be stated. Various factors which contribute to determination of an adequate SNR are as follows:

- Acceptable bit error rate for data.
- Extent of error correction due to coding.
- Modulation type.
- Detection method used by receiver.
- Additional bit errors produced by equipment imperfections (mismatched filters, intersymbol interference, decision circuits, synchronization errors, etc.).

To aid in this determination, Appendix E contains a collection of BER curves versus SNR. These curves include parametric values for variation of the above factors including non-ideal decision circuits, detection
methods, and modulation type. This appendix also contains suggested values which pertain to PLRS and JTIDS.

To illustrate how these curves are applied, consider a JTIDS implementation based on use of 4-phase Minimum Shift Keying (MSK) with phase-locked-loop fourth power carrier extraction. Suppose it is desired to achieve a bit error rate of less than $10^{-5}$. Following guidance in Appendix E, the curves in Figures E-33 through E-35 are found to be applicable. If the reasonable assumptions are now made that the phase-locked-loop SNR is high (100 or larger), and that all remaining parameters are small (2 or less), we can estimate using Figure E-34 that the required output SNR must be about 11 dB or larger. If a pilot carrier detection mode is used, we can similarly use Figure E-31 to estimate a required output SNR of about the same value of 11 dB. In both figures, it is also apparent that reduced loop SNR and larger values of circuit phase error will require larger values of SNR to achieve the desired error rate.

With regard to use of the curves in Appendix E, it should be noted that the curves relate to output SNR. For spread spectrum systems such as PLRS and JTIDS, the input SNR will typically be smaller by the amount of the processing gain. It is also to be noted that the curves may not be exact for specific implementations of PLRS or JTIDS; however, the curves should provide reasonable estimates for required values of output SNR for PLRS/JTIDS.

In addition to the degrading factors parametrically described in Appendix E, there are other sources of BER degradation including intersymbol interference (ISI), limiter SNR degradation, and mismatched filters.

As a guide to the total combined effects of these various factors which produce bit errors, Tables 4-1 through 4-5 contain estimates of the equivalent SNR loss for various PSK modulation types. The net values at the bottom of the tables show the total equivalent SNR loss. These values must be added to the "ideal" (best case) SNR values. Table 4-6
### Table 4-1

**SNR IMPLEMENTATION BUDGET**

**MODULATION:** COHERENT PSK  
**DEMODULATION:** NOISY M'TH POWER LOOP

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$m = 2$</th>
<th>$m = 4$</th>
<th>$m = 8$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase Error (net)</td>
<td>$4.8^\circ$</td>
<td>$5.0^\circ$</td>
<td>$5.8^\circ$</td>
</tr>
<tr>
<td>Modulator</td>
<td>$2.9^\circ$</td>
<td>$1.7^\circ$</td>
<td>$2.3^\circ$</td>
</tr>
<tr>
<td>Transmitter RF</td>
<td>$1.2^\circ$</td>
<td>$0.6^\circ$</td>
<td>$0.6^\circ$</td>
</tr>
<tr>
<td>Transponder</td>
<td>$1.7^\circ$</td>
<td>$1.7^\circ$</td>
<td>$1.7^\circ$</td>
</tr>
<tr>
<td>Receiver RF</td>
<td>$1.2^\circ$</td>
<td>$0.6^\circ$</td>
<td>$0.6^\circ$</td>
</tr>
<tr>
<td>Demodulator</td>
<td>$2.9^\circ$</td>
<td>$2.0^\circ$</td>
<td>$2.0^\circ$</td>
</tr>
<tr>
<td>Synchronization</td>
<td>$0^\circ$</td>
<td>$2.0^\circ$</td>
<td>$2.0^\circ$</td>
</tr>
<tr>
<td>Decision Threshold</td>
<td>$1.7^\circ$</td>
<td>$1.7^\circ$</td>
<td>$1.7^\circ$</td>
</tr>
<tr>
<td>Limiter</td>
<td>$0.5$ dB</td>
<td>$0.5$ dB</td>
<td>$0.5$ dB</td>
</tr>
<tr>
<td>ISI</td>
<td>$1.0$ dB</td>
<td>$1.0$ dB</td>
<td>$1.0$ dB</td>
</tr>
<tr>
<td>PLL SNR</td>
<td>$10$ dB</td>
<td>$10$ dB</td>
<td>$10$ dB</td>
</tr>
<tr>
<td>Mismatch Filter</td>
<td>$1.0$ dB</td>
<td>$1.0$ dB</td>
<td>$1.0$ dB</td>
</tr>
</tbody>
</table>

**NET IMPLEMENTATION**

| LOSS                       | $2.8$ dB | $4.1$ dB | $6.0$ dB |

*Equivalent loss in energy per bit-to-noise (SNR) ratio.
### Table 4-2

**SNR Implementation Budget**

*Modulation: Coherent PSK*

*Demodulation: Pilot Carrier Loop*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$m = 2$</th>
<th>$m = 4$</th>
<th>$m = 8$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase Error (net)</td>
<td>$4.8^\circ$ 0.1 dB</td>
<td>$5.0^\circ$ 0.8 dB</td>
<td>$5.8^\circ$ 2.2 dB</td>
</tr>
<tr>
<td>Modulator</td>
<td>$2.9^\circ$ 0.0 dB</td>
<td>$1.7^\circ$ 0.2 dB</td>
<td>$2.3^\circ$ 0.7 dB</td>
</tr>
<tr>
<td>Transmitter RF</td>
<td>$1.2^\circ$ 0.0 dB</td>
<td>$0.6^\circ$ 0.1 dB</td>
<td>$0.6^\circ$ 0.1 dB</td>
</tr>
<tr>
<td>Transponder</td>
<td>$1.7^\circ$ 0.0 dB</td>
<td>$1.7^\circ$ 0.2 dB</td>
<td>$1.7^\circ$ 0.5 dB</td>
</tr>
<tr>
<td>Receiver RF</td>
<td>$1.2^\circ$ 0.0 dB</td>
<td>$0.6^\circ$ 0.1 dB</td>
<td>$0.6^\circ$ 0.1 dB</td>
</tr>
<tr>
<td>Demodulator</td>
<td>$2.9^\circ$ 0.0 dB</td>
<td>$1.7^\circ$ 0.2 dB</td>
<td>$2.3^\circ$ 0.7 dB</td>
</tr>
<tr>
<td>Synchronization</td>
<td>$0^\circ$ 0.0 dB</td>
<td>$2.0^\circ$ 0.2 dB</td>
<td>$2.0^\circ$ 0.7 dB</td>
</tr>
<tr>
<td>Decision Threshold</td>
<td>$1.7^\circ$ 0.0 dB</td>
<td>$1.7^\circ$ 0.3 dB</td>
<td>$1.7^\circ$ 0.8 dB</td>
</tr>
<tr>
<td>Limiter</td>
<td>SNR 0.5 dB</td>
<td>SNR 0.5 dB</td>
<td>SNR 0.5 dB</td>
</tr>
<tr>
<td>ISI</td>
<td>2BT 1.0 dB</td>
<td>2BT 1.0 dB</td>
<td>2BT 1.0 dB</td>
</tr>
<tr>
<td>PLL SNR</td>
<td>20 dB 0.2 dB</td>
<td>30 dB 0.5 dB</td>
<td>30 dB 0.5 dB</td>
</tr>
<tr>
<td>Mismatch Filter</td>
<td>------ 1.0 dB</td>
<td>------ 1.0 dB</td>
<td>------ 1.0 dB</td>
</tr>
</tbody>
</table>

**Net Implementation Loss**

- $m = 2$: 2.8 dB
- $m = 4$: 4.1 dB
- $m = 8$: 6.0 dB

*Equivalent loss in energy per bit-to-noise (SNR) ratio.*
### TABLE 4-3

**SNR IMPLEMENTATION BUDGET**

**MODULATION: COHERENT PSK**  
**DEMODULATION: DIFFERENTIAL DETECTION**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$m = 2$</th>
<th>$m = 4$</th>
<th>$m = 8$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase Error (net)</td>
<td>$6.9^\circ$</td>
<td>$8.3^\circ$</td>
<td>$8.85^\circ$</td>
</tr>
<tr>
<td>Modulator</td>
<td>$2.9^\circ$</td>
<td>$1.7^\circ$</td>
<td>$2.3^\circ$</td>
</tr>
<tr>
<td>Transmitter RF</td>
<td>$1.2^\circ$</td>
<td>$0.6^\circ$</td>
<td>$0.6^\circ$</td>
</tr>
<tr>
<td>Transponder</td>
<td>$1.7^\circ$</td>
<td>$1.7^\circ$</td>
<td>$1.7^\circ$</td>
</tr>
<tr>
<td>Receiver RF</td>
<td>$1.2^\circ$</td>
<td>$0.6^\circ$</td>
<td>$0.6^\circ$</td>
</tr>
<tr>
<td>Demodulator</td>
<td>$5.8^\circ$</td>
<td>$5.8^\circ$</td>
<td>$5.8^\circ$</td>
</tr>
<tr>
<td>Synchronization</td>
<td>$0^\circ$</td>
<td>$2.0^\circ$</td>
<td>$2.0^\circ$</td>
</tr>
<tr>
<td>Decision Threshold</td>
<td>$1.7^\circ$</td>
<td>$1.7^\circ$</td>
<td>$1.7^\circ$</td>
</tr>
<tr>
<td>Limiter</td>
<td>SNR 0.5 dB</td>
<td>SNR 0.5 dB</td>
<td>SNR 0.5 dB</td>
</tr>
<tr>
<td>ISI</td>
<td>2BT 1.0 dB</td>
<td>2BT 1.0 dB</td>
<td>2BT 1.0 dB</td>
</tr>
<tr>
<td>PLL SNR</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>Mismatch Filter</td>
<td>----- 1.0 dB</td>
<td>----- 1.0 dB</td>
<td>----- 1.0 dB</td>
</tr>
</tbody>
</table>

**NET IMPLEMENTATION**

<table>
<thead>
<tr>
<th>Loss</th>
<th>$m = 2$</th>
<th>$m = 4$</th>
<th>$m = 8$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.9 dB</td>
<td>4.1 dB</td>
<td>7.8 dB</td>
</tr>
</tbody>
</table>

*Equivalent loss in energy per bit-to-noise (SNR) ratio.*
Table 4-4
SNR IMPLEMENTATION BUDGET

MODULATION: COHERENT OFFSET QPSK
DEMODULATION: NOISY M'TH POWER LOOP

<table>
<thead>
<tr>
<th>Parameter</th>
<th>E/N₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase Error (net)</td>
<td>5.0°</td>
</tr>
<tr>
<td>Modulator</td>
<td>1.7°</td>
</tr>
<tr>
<td>Transmitter RF</td>
<td>0.6°</td>
</tr>
<tr>
<td>Transponder</td>
<td>1.7°</td>
</tr>
<tr>
<td>Receiver RF</td>
<td>0.6°</td>
</tr>
<tr>
<td>Demodulator</td>
<td>1.7°</td>
</tr>
<tr>
<td>Synchronization</td>
<td>2.0°</td>
</tr>
<tr>
<td>Decision Threshold</td>
<td>1.7°</td>
</tr>
<tr>
<td>Limiter</td>
<td>SNR</td>
</tr>
<tr>
<td>ISI</td>
<td>2BT</td>
</tr>
<tr>
<td>PLL SNR</td>
<td>10 dB</td>
</tr>
<tr>
<td>Mismatch Filter</td>
<td>-----</td>
</tr>
</tbody>
</table>

NET IMPLEMENTATION LOSS 3.5 dB

*Equivalent loss in energy per bit-to-noise (SNR) ratio.
Table 4-5

SNR IMPLEMENTATION BUDGET

MODULATION: COHERENT OFFSET QPSK
DEMODULATION: PILOT CARRIER LOOP

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$m = 4$</th>
<th>$E/N_0^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase Error (net)</td>
<td>5.0°</td>
<td>0.6 dB</td>
</tr>
<tr>
<td>Modulator</td>
<td>1.7°</td>
<td>0.1 dB</td>
</tr>
<tr>
<td>Transmitter RF</td>
<td>0.6°</td>
<td>0.0 dB</td>
</tr>
<tr>
<td>Transponder</td>
<td>1.7°</td>
<td>0.1 dB</td>
</tr>
<tr>
<td>Receiver RF</td>
<td>0.6°</td>
<td>0.0 dB</td>
</tr>
<tr>
<td>Demodulator</td>
<td>1.7°</td>
<td>0.1 dB</td>
</tr>
<tr>
<td>Synchronization</td>
<td>2.0°</td>
<td>0.1 dB</td>
</tr>
<tr>
<td>Decision Threshold</td>
<td>1.7°</td>
<td>0.2 dB</td>
</tr>
<tr>
<td>Limiter</td>
<td>SNR</td>
<td>0.5 dB</td>
</tr>
<tr>
<td>ISI</td>
<td>2BT</td>
<td>1.0 dB</td>
</tr>
<tr>
<td>PLL SNR</td>
<td>30 dB</td>
<td>0.2 dB</td>
</tr>
<tr>
<td>Mismatch Filter</td>
<td>-------</td>
<td>1.0 dB</td>
</tr>
</tbody>
</table>

NET IMPLEMENTATION LOSS  3.5 dB

*Equivalent loss in energy per bit-to-noise (SNR) ratio.*
### TABLE 4-6

SNR PERFORMANCE COMPARISONS FOR VARIOUS MODULATION TYPES

<table>
<thead>
<tr>
<th>Modulation Type</th>
<th>m = 2 (Ideal)</th>
<th>m = 2 (Probable)</th>
<th>m = 4 (Ideal)</th>
<th>m = 4 (Probable)</th>
<th>m = 8 (Ideal)</th>
<th>m = 8 (Probable)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coherent PSK</td>
<td>9.6</td>
<td>12.4</td>
<td>9.6</td>
<td>13.7</td>
<td>12.9</td>
<td>18.9</td>
</tr>
<tr>
<td>m'th power loop</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coherent PSK</td>
<td>9.6</td>
<td>12.4</td>
<td>9.6</td>
<td>13.7</td>
<td>18.9</td>
<td>18.9</td>
</tr>
<tr>
<td>pilot carrier loop</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Differential PSK</td>
<td>10.3</td>
<td>13.2</td>
<td>11.9</td>
<td>16.0</td>
<td>15.5</td>
<td>23.3</td>
</tr>
<tr>
<td>Offset QPSK</td>
<td>-----</td>
<td>-----</td>
<td>9.6</td>
<td>13.1</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>m'th power loop</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Offset QPSK</td>
<td>-----</td>
<td>-----</td>
<td>9.6</td>
<td>13.1</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>pilot carrier loop</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
shows a comparison of the various modulation and detection modes and indicates a "probable" value of output SNR to achieve an error rate of $10^{-5}$. (Tables 4-1 through 4-6 were abstracted from a previous Georgia Tech Report: "Sensitivity Analysis of Link Transmissions Study," Volume II, prepared for Electronic Systems Division, Hanscom AFB, September 1975.)

Unless detailed design information is available, it is recommended that the data in Tables 4-1 through 4-5 be used as follows: (1) Select the modulation and demodulation type. For PJH, the results in Table 4-5 are most applicable. (2) Select the net implementation loss value of 3.5 dB. This value is the estimated amount by which an ideal value of SNR must be increased to account for various non-ideal performance characteristics of PJH receivers.

The error rate curves in Appendix E and the results in Tables 4-1 through 4-6 give a relationship between baseband BER and output SNR. The BER quantity produced does not include any additional reduction in bit error rate due to coding or error correction. Typically, error corrections are accomplished by using some of the basic data bits as "overhead" for parity checks, forward error connection (FEC), etc. For instance, it is understood that both PLRS and JTIDS will use some form of FEC to improve performance. In these cases, the required SNR is still established by the basic output BER but the decrease in information bit error rate (bits left after overhead bits subtracted) is achieved by reducing the information bit rate.

In the case where more sophisticated coding techniques are applied such as "soft decision" detection, and convolutional coding, some improvement in output BER can be achieved by both information data rate reduction and decreased probability of bit error. For example, a typical net improvement in required SNR would be about 3-4 dB for rate one-half, constraint length seven, convolutional coding/decoding.
4.4 Work Sheet for SNR Determination

As an aid for determining the required value of SNR for PLRS/JTIDS links, a work sheet for this purpose was prepared and is shown in Table 4-7. Unless a value for output SNR (not input SNR for spread spectrum systems) is separately specified or given, this work sheet should be used to estimate a value for the required output SNR. The worksheet assumes that the uncorrected (baseband) error rate is stated as a requirement.

The work sheet is self explanatory and gives suggested typical values where appropriate. The user is cautioned to be aware that the result produced should be treated as an approximation only. Much more accurate results can be established provided that design and implementation details are known.

As one final comment, the reader is again reminded that the work sheet gives the output SNR (after correlation) for a spread spectrum system such as PLRS or JTIDS. If desired, the input (RF) SNR can be estimated by subtracting the processing gain (dB) from the output SNR (dB).
Table 4-7
WORK SHEET FOR ESTIMATING REQUIRED SNR
(PSK MODULATION, BIPHASE OR QUADRI PHASE)

1. Select Modulation/Detection Type
   Biphase (m = 2): __________
   or Quadriphase (m = 4): __________

   Select Detection Type:
   Ideal Coherent Detection: __________
   Differential Coherent Detection: __________
   Noisy Coherent Detection: __________
   M'th Power PLL: __________
   Pilot Carrier PLL: __________
   Offset QPSK: __________

2. Data available for various system imperfections (decision thresholds, static phase errors, intersymbol interference, PLL parameters, etc.)?
   Yes _____: Tabulate and go to Step 3.
   No _____: Estimate SNR implementation loss from Tables 4-1 through 4-6 and go to Step 4.

3. Locate appropriate curves in Appendix E using data from Steps 1 and 2. Determine estimate for SNR:
   Required BER*: ______
   Value of SNR: ______dB

   Go to Step 5
   (*Use uncorrected error rate)
4. Locate appropriate curves in Appendix E using data from Step 1. In all cases use the curve which produces the smallest value of SNR (ideal case) for the required BER.

   Required BER*: 
   
   (a) Value of SNR: _____ dB
   (b) SNR implementation loss from Step 2: _____ dB
   (c) Required SNR: _____ dB
      (add a + b)

Go to Step 5
(*Use uncorrected error rate)

5. Apply correction factor for BER improvement due to encoding/decoding such as convolutional (viterbi) coding and soft decision detection. (See text: If applicable, this factor is typically equivalent to a reduction of required SNR by 2 to 6 dB with a typical value of 3 dB. Otherwise enter 0 dB.)

   Equivalent SNR improvement: _____ dB

6. Apply correction factor for equivalent SNR reduction due to multipath. This quantity may be highly variable and can range from 0 dB for LOS channels to greater than 10 dB for severely fading channels. For well designed spread spectrum systems, a typical value of 3 dB is recommended (see text).

   Multipath SNR reduction: _____ dB

7. Determine net required SNR by adding result from Step 3 or Step 4 to result from Step 6 and subtracting result of Step 5 from sum.

   Net Required SNR: _____ dB
   (Step 3 or Step 4 plus Step 6 less Step 5)

Use this value of SNR as an input to the RF propagation work sheets in Appendix A and Appendix C.
5. ANALYSIS OF PLRS/JTIDS LINKS

5.1 Introduction

As a part of this assessment of PJH connectivity, several specific typical cases were selected for evaluation. The purpose of this analysis is twofold - to illustrate application of the link connectivity procedure, and to document expected performance of typical PJH nets.

These specific cases were analyzed using the procedures documented in Chapter 4. In addition, however, a computer evaluation program was also used to assess area coverage effectiveness for typical PJH terminals. The computer model was previously developed by Georgia Tech in conjunction with analysis of FM combat net radio. Parameters of the model were adjusted to enable application to spread spectrum PJH links. Although the computer model is structured somewhat differently from the work sheet procedure described in Appendix A, it produced reasonable results and permitted a larger variety of cases to be examined.

5.2 PJH RF Coverage

For the analysis of PJH RF coverage neglecting possible jamming considerations, a determination of the maximum possible link range (given certain specifications) was chosen as the most effective and practical approach. The RF model developed in Appendix A, along with its accompanying work sheet, was used for this purpose.

The specifications assumed for JTIDS and PLRS are given in Tables 5-1 and 5-2, respectively. Different combinations of the values of certain parameters, such as transmitter power and antenna gain, were evaluated. These are expressed through the different links given in Table 5-3. The RF ranges for each link vs. type of terrain were calculated, and are displayed in Table 5-4.

Several trends become noticeable from a study of these tables. It was found that, in general, the PLRS link ranges were somewhat greater...
**TABLE 5-1**

**EXAMPLE JTIDS SPECIFICATIONS**

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUES (S)</th>
<th>UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>POWER</td>
<td>100, 200</td>
<td>WATTS</td>
</tr>
<tr>
<td>ANTENNA GAIN</td>
<td>4, 6</td>
<td>dBi</td>
</tr>
<tr>
<td>ANTENNA HEIGHT</td>
<td>2, 10</td>
<td>METERS</td>
</tr>
<tr>
<td>FEED SYSTEM LOSS</td>
<td>2</td>
<td>dB</td>
</tr>
<tr>
<td>RECEIVER NOISE FIGURE</td>
<td>4</td>
<td>dB</td>
</tr>
<tr>
<td>ENVIRONMENT</td>
<td>RESIDENTIAL (MEDIUM NOISE)</td>
<td>NONE</td>
</tr>
<tr>
<td>TERRAIN</td>
<td>URBAN, MOUNTAINS, HILLS, PLAINS</td>
<td>NONE</td>
</tr>
<tr>
<td>SOIL</td>
<td>GOOD</td>
<td>NONE</td>
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<tr>
<td>FREQUENCY</td>
<td>1200</td>
<td>MHz</td>
</tr>
<tr>
<td>POLARIZATION</td>
<td>VERTICAL</td>
<td>NONE</td>
</tr>
<tr>
<td>NOISE BANDWIDTH</td>
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<td>KHz</td>
</tr>
<tr>
<td>LINK RELIABILITY</td>
<td>95</td>
<td>%</td>
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<tr>
<td>BIT RATE</td>
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<td>KILOBITS/SEC</td>
</tr>
<tr>
<td>CHIP RATE</td>
<td>5.0</td>
<td>MEGABITS/SEC</td>
</tr>
<tr>
<td>REQUIRED SNR</td>
<td>10</td>
<td>dB</td>
</tr>
<tr>
<td>PARAMETER</td>
<td>VALUES (S)</td>
<td>UNITS</td>
</tr>
<tr>
<td>------------------------</td>
<td>------------</td>
<td>---------</td>
</tr>
<tr>
<td>POWER</td>
<td>100</td>
<td>WATTS</td>
</tr>
<tr>
<td>ANTENNA GAIN</td>
<td>4, 6</td>
<td>dBi</td>
</tr>
<tr>
<td>ANTENNA HEIGHT</td>
<td>2, 10</td>
<td>METERS</td>
</tr>
<tr>
<td>FEED SYSTEM LOSS</td>
<td>2</td>
<td>dB</td>
</tr>
<tr>
<td>RECEIVER NOISE FIGURE</td>
<td>4</td>
<td>dB</td>
</tr>
<tr>
<td>ENVIRONMENT</td>
<td>RESIDENTIAL (MEDIUM NOISE)</td>
<td>NONE</td>
</tr>
<tr>
<td>TERRAIN</td>
<td>URBAN, MOUNTAINS, HILLS, PLAINS</td>
<td>NONE</td>
</tr>
<tr>
<td>SOIL</td>
<td>GOOD</td>
<td>NONE</td>
</tr>
<tr>
<td>FREQUENCY</td>
<td>450</td>
<td>MHz</td>
</tr>
<tr>
<td>POLARIZATION</td>
<td>VERTICAL</td>
<td>NONE</td>
</tr>
<tr>
<td>NOISE BANDWIDTH</td>
<td>10000</td>
<td>KHz</td>
</tr>
<tr>
<td>LINK RELIABILITY</td>
<td>90</td>
<td>%</td>
</tr>
<tr>
<td>BIT RATE</td>
<td>19.2</td>
<td>KILOBITS/SEC</td>
</tr>
<tr>
<td>CHIP RATE</td>
<td>5.0</td>
<td>MEGABITS/SEC</td>
</tr>
<tr>
<td>REQUIRED SNR</td>
<td>10</td>
<td>dB</td>
</tr>
<tr>
<td>LINK</td>
<td>POWER (WATTS)</td>
<td>ANTENNA GAIN (dBi)</td>
</tr>
<tr>
<td>------------</td>
<td>---------------</td>
<td>--------------------</td>
</tr>
<tr>
<td>J1 (JTIDS)</td>
<td>100 100</td>
<td>4 4</td>
</tr>
<tr>
<td>J2</td>
<td>100 200</td>
<td>4 4</td>
</tr>
<tr>
<td>J3</td>
<td>100 200</td>
<td>4 6</td>
</tr>
<tr>
<td>J4</td>
<td>200 200</td>
<td>4 4</td>
</tr>
<tr>
<td>J5</td>
<td>200 200</td>
<td>4 4</td>
</tr>
<tr>
<td>J6</td>
<td>200 200</td>
<td>6 6</td>
</tr>
<tr>
<td>P1 (PLRS)</td>
<td>100 100</td>
<td>4 4</td>
</tr>
<tr>
<td>P2</td>
<td>100 100</td>
<td>4 6</td>
</tr>
<tr>
<td>P3</td>
<td>100 100</td>
<td>6 6</td>
</tr>
</tbody>
</table>
### TABLE 5-4

**COMPUTED PJH RF COVERAGE RADIUS (KM)**

<table>
<thead>
<tr>
<th>LINK</th>
<th>URBAN</th>
<th>MOUNTAINS</th>
<th>HILLS</th>
<th>PLAINS</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1</td>
<td>0.19</td>
<td>0.84</td>
<td>2.5</td>
<td>5.3</td>
</tr>
<tr>
<td>J2</td>
<td>0.19</td>
<td>0.84</td>
<td>2.5</td>
<td>5.3</td>
</tr>
<tr>
<td>J3</td>
<td>0.54</td>
<td>2.3</td>
<td>6</td>
<td>13</td>
</tr>
<tr>
<td>J4</td>
<td>0.25</td>
<td>1.1</td>
<td>3</td>
<td>6.2</td>
</tr>
<tr>
<td>J5</td>
<td>0.63</td>
<td>2.5</td>
<td>8</td>
<td>16</td>
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<tr>
<td>J6</td>
<td>1.9</td>
<td>6.3</td>
<td>18</td>
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</tr>
<tr>
<td>P1</td>
<td>0.63</td>
<td>2.1</td>
<td>5.5</td>
<td>12</td>
</tr>
<tr>
<td>P2</td>
<td>1.7</td>
<td>5.5</td>
<td>15</td>
<td>30</td>
</tr>
<tr>
<td>P3</td>
<td>4.1</td>
<td>13</td>
<td>35</td>
<td>71</td>
</tr>
</tbody>
</table>
than those of JTIDS. This is due mainly to the higher operating frequencies and assumed higher reliability requirements of JTIDS. More prominent were the effects of transmitter power and antenna type. An increase in power or antenna height (with its associated increase in gain) tends to increase the RF range. Even more obvious is the effect of terrain type on range. The maximum range for a given link is minimal in the case of urban areas, and increases for each subsequent change of terrain through mountainous areas, hills, and plains.

Of course, certain apparent exceptions to these general rules are possible. For instance, as transmitter power for station B is increased from link J1 to link J2, the range remains unimproved due to the limiting effect of the weaker transmitter (A). Also, since these example results are intended primarily as a comparative guide, specific calculations for cases which have not been treated here may be advisable. In this regard, the RF analysis procedure described earlier should prove useful since it was designed with this possibility in mind.

5.3 PJH Link Reliability with Jamming

For the analysis of RF coverage under the influence of jamming of interference, it was decided to determine the probability that certain typical PJH links would be jammed (signal links denied) due to the effects of generic jamming sources. The stressed RF communications system model of Appendix C, along with its accompanying work sheet, was used to provide these results.

Tables 5-5 and 5-6 give the communication system specifications used as inputs to the model. Specific combinations of these parameters, and thus specific links, were considered. These are designated in Table 5-7. The typical jammers used are described in Table 5-8. Note that JTIDS and PLRS are again treated separately due to the difference in operating frequency.

The procedure first determines the unstressed (without jamming) link reliability. These percentages are converted to percentage of link
TABLE 5-5

JTIDS SPECIFICATIONS ASSUMED FOR JAMMING ANALYSIS

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUES (S)</th>
<th>UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>POWER</td>
<td>100, 200</td>
<td>WATTS</td>
</tr>
<tr>
<td>ANTENNA GAIN</td>
<td>4, 6</td>
<td>dBi</td>
</tr>
<tr>
<td>ANTENNA HEIGHT</td>
<td>2, 10</td>
<td>METERS</td>
</tr>
<tr>
<td>FEED SYSTEM LOSS</td>
<td>2</td>
<td>dB</td>
</tr>
<tr>
<td>ADDITIONAL SYSTEM LOSS</td>
<td>1</td>
<td>dB</td>
</tr>
<tr>
<td>RECEIVER NOISE FIGURE</td>
<td>4</td>
<td>dB</td>
</tr>
<tr>
<td>ENVIRONMENT</td>
<td>SUBURBAN (MEDIUM NOISE)</td>
<td>NONE</td>
</tr>
<tr>
<td>TERRAIN</td>
<td>HILLS</td>
<td>NONE</td>
</tr>
<tr>
<td>SOIL</td>
<td>GOOD</td>
<td>NONE</td>
</tr>
<tr>
<td>FREQUENCY</td>
<td>1200</td>
<td>MHz</td>
</tr>
<tr>
<td>ANTENNA POLARIZATION</td>
<td>VERTICAL</td>
<td>NONE</td>
</tr>
<tr>
<td>NOISE BANDWIDTH</td>
<td>10000</td>
<td>KHz</td>
</tr>
<tr>
<td>BIT RATE</td>
<td>57.5</td>
<td>KILOBITS/SEC</td>
</tr>
<tr>
<td>CHIP RATE</td>
<td>5.0</td>
<td>MEGABITS/SEC</td>
</tr>
<tr>
<td>REQUIRED SNR</td>
<td>10</td>
<td>dB</td>
</tr>
<tr>
<td>PARAMETER</td>
<td>VALUES (S)</td>
<td>UNITS</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>------------</td>
<td>------------</td>
</tr>
<tr>
<td>POWER</td>
<td>100</td>
<td>WATTS</td>
</tr>
<tr>
<td>ANTENNA GAIN</td>
<td>4, 6</td>
<td>dBi</td>
</tr>
<tr>
<td>ANTENNA HEIGHT</td>
<td>2, 10</td>
<td>METERS</td>
</tr>
<tr>
<td>FEED SYSTEM LOSS</td>
<td>2</td>
<td>dB</td>
</tr>
<tr>
<td>ADDITIONAL SYSTEM LOSS</td>
<td>1</td>
<td>dB</td>
</tr>
<tr>
<td>RECEIVER NOISE FIGURE</td>
<td>4</td>
<td>dB</td>
</tr>
<tr>
<td>ENVIRONMENT</td>
<td>SUBURBAN (MEDIUM NOISE)</td>
<td>NONE</td>
</tr>
<tr>
<td>TERRAIN</td>
<td>HILLS</td>
<td>NONE</td>
</tr>
<tr>
<td>SOIL</td>
<td>GOOD</td>
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<tr>
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<td>450</td>
<td>MHz</td>
</tr>
<tr>
<td>ANTENNA POLARIZATION</td>
<td>VERTICAL</td>
<td>NONE</td>
</tr>
<tr>
<td>NOISE BANDWIDTH</td>
<td>10000</td>
<td>KHz</td>
</tr>
<tr>
<td>BIT RATE</td>
<td>19.2</td>
<td>KILOBITS/SEC</td>
</tr>
<tr>
<td>CHIP RATE</td>
<td>5.0</td>
<td>MEGABITS/SEC</td>
</tr>
<tr>
<td>REQUIRED SNR</td>
<td>10</td>
<td>dB</td>
</tr>
</tbody>
</table>
### TABLE 5-7

**PJH EXAMPLE LINKS FOR ANALYSIS OF JAMMING**

<table>
<thead>
<tr>
<th>LINK</th>
<th>T POWER (WATTS)</th>
<th>T</th>
<th>R</th>
<th>I</th>
<th>R</th>
<th>LINK DISTANCE (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J_a (JTIDS)</td>
<td>100</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>J_b</td>
<td>200</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>J_c</td>
<td>200</td>
<td>6</td>
<td>6</td>
<td>10</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>J_d</td>
<td>200</td>
<td>6</td>
<td>6</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>J_e</td>
<td>200</td>
<td>6</td>
<td>6</td>
<td>10</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>J_f</td>
<td>200</td>
<td>6</td>
<td>6</td>
<td>10</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>J_g</td>
<td>200</td>
<td>6</td>
<td>6</td>
<td>10</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>P_a (PLRS)</td>
<td>100</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>P_b</td>
<td>100</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>P_c</td>
<td>100</td>
<td>6</td>
<td>6</td>
<td>10</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>P_d</td>
<td>100</td>
<td>6</td>
<td>6</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>P_e</td>
<td>100</td>
<td>6</td>
<td>6</td>
<td>10</td>
<td>10</td>
<td>20</td>
</tr>
</tbody>
</table>

**NOTE:**

"T" = "TRANSMITTER"  
"R" = "RECEIVER"
TABLE 5-8

ASSUMED JAMMER PARAMETERS

<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>J POWER (WATTS)</th>
<th>ANTENNA GAIN (dBi)</th>
<th>ANTENNA HEIGHT (METERS)</th>
<th>J-R DISTANCE (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JTIDS</td>
<td>10,000, 1000, 200</td>
<td>6</td>
<td>10</td>
<td>10, 20, 30</td>
</tr>
<tr>
<td>PLRS</td>
<td>1000, 500, 100</td>
<td>6</td>
<td>10</td>
<td>5, 10, 20</td>
</tr>
</tbody>
</table>

NOTE: "J" = "JAMMER"

"R" = "RECEIVER"
denial by subtracting from one hundred. The first column of Table 5-9 gives the unstressed link denial probability for each example signal link. Each link was then considered with various jamming situations, and the resulting probabilities of link denial are also given in Table 5-9. Note that the signal link was not changed.

It is apparent from the final results that the probability that a given link will be jammed decreases as the jammer power decreases and/or as the distance of the jammer from the signal receiver increases. Since this is dependent upon the specific signal link under consideration, a general idea of the effects of various jamming situations on the PJH system may be obtained from the results in Table 5-9.

Specific cases of further interest can be examined in detail by making use of the procedure described in Appendix C.

5.4 Area Coverage Analysis of PJH Links

To gain further insight into PJH link performance, an area coverage analysis was performed using a computer evaluation model. The system parameters used as input to the computer model are identical to those used for the RF model with jamming (see Tables 5-5 and 5-6), except that a required SNR (or signal-to-jam-plus-noise ratio (SJNR) if jamming is considered) of 13 dB was used. This link reliability requirement is therefore slightly more stringent. The situations considered (with and without jamming) are listed in Tables 5-10 and 5-11 for JTIDS and PLRS, respectively. Also, listed are the figures in Appendix F in which the results for each example are given. No jammer antenna specifications are listed because, as in the case of the RF model, an invariant height of 10 meters and gain of 6 dBi are used throughout.

The computer model results are in the form of plots consisting of a grid covering the geographical area being considered. Kilometer scales are provided, and the positions of the transmitter and jammer are denoted by a circle and a square, respectively. For ease of identification, the numeral "1" is printed close to both symbols.
### TABLE 5-9

**LINK RELIABILITY WITH JAMMING CONSIDERED**

#### PROBABILITY OF JTIDS LINK DENIAL (%)

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<thead>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
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<td>10</td>
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<td>1</td>
<td>0.001</td>
<td>0.001</td>
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<tr>
<td>10</td>
<td>40</td>
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<td>20</td>
<td>10</td>
</tr>
<tr>
<td>20</td>
<td>75</td>
<td>55</td>
<td>30</td>
<td>15</td>
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<tr>
<td>30</td>
<td>90</td>
<td>75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>98</td>
<td>93</td>
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<td></td>
</tr>
</tbody>
</table>

#### (2) PROBABILITY Of DENIAL (%)

<table>
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<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
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<td>0</td>
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<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>0</td>
<td>6</td>
<td>10</td>
<td>6</td>
<td>10</td>
<td>6</td>
<td>10</td>
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<tr>
<td>0</td>
<td>10</td>
<td>75</td>
<td>10</td>
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<tr>
<td>0</td>
<td>75</td>
<td>98</td>
<td>89</td>
<td>85</td>
<td>75</td>
<td>89</td>
<td>85</td>
</tr>
</tbody>
</table>

*"JP" is "JAMMER POWER (WATTS)"

"JR" is "DISTANCE FROM JAMMER TO RECEIVER (KM)"

---

5-12
TABLE 5-10

JTIDS COMPUTER MODEL SIMULATIONS

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>T-POWER (WATTS)</th>
<th>T AND R ANTELLA HEIGHT (M.)/GAIN (dBi)</th>
<th>ACTUAL J-POWER (WATTS)</th>
<th>T-J DISTANCE (KM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F-1</td>
<td>100</td>
<td>2/4</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>F-2</td>
<td>100</td>
<td>2/4</td>
<td>10000</td>
<td>10</td>
</tr>
<tr>
<td>F-3</td>
<td>100</td>
<td>2/4</td>
<td>600</td>
<td>10</td>
</tr>
<tr>
<td>F-4</td>
<td>100</td>
<td>2/4</td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>F-5</td>
<td>100</td>
<td>2/4</td>
<td>10000</td>
<td>30</td>
</tr>
<tr>
<td>F-6</td>
<td>200</td>
<td>2/4</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>F-7</td>
<td>200</td>
<td>2/4</td>
<td>10000</td>
<td>10</td>
</tr>
<tr>
<td>F-8</td>
<td>200</td>
<td>2/4</td>
<td>600</td>
<td>10</td>
</tr>
<tr>
<td>F-9</td>
<td>200</td>
<td>2/4</td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>F-10</td>
<td>200</td>
<td>2/4</td>
<td>10000</td>
<td>30</td>
</tr>
<tr>
<td>F-11</td>
<td>200</td>
<td>10/6</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>F-12</td>
<td>200</td>
<td>10/6</td>
<td>10000</td>
<td>10</td>
</tr>
<tr>
<td>F-13</td>
<td>200</td>
<td>10/6</td>
<td>600</td>
<td>10</td>
</tr>
<tr>
<td>F-14</td>
<td>200</td>
<td>10/6</td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>F-15</td>
<td>200</td>
<td>10/6</td>
<td>10000</td>
<td>30</td>
</tr>
<tr>
<td>F-16</td>
<td>200</td>
<td>10/6</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>F-17</td>
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<td>10/6</td>
<td>50</td>
<td>1</td>
</tr>
</tbody>
</table>

NOTE: "T" IS "TRANSMITTER"
"R" IS "RECEIVER"
"J" IS "JAMMER" OR "INTERFERENCE"
## TABLE 5-11

PLRS COMPUTER MODEL SIMULATIONS

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>T-POWER (WATTS)</th>
<th>T AND R ANTENA HEIGHT(M.)/GAIN (dBi)</th>
<th>ACTUAL J-POWER (WATTS)</th>
<th>T-J DISTANCE (KM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F-18</td>
<td>100</td>
<td>2/4</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>F-19</td>
<td>100</td>
<td>2/4</td>
<td>1000</td>
<td>5</td>
</tr>
<tr>
<td>F-20</td>
<td>100</td>
<td>2/4</td>
<td>250</td>
<td>5</td>
</tr>
<tr>
<td>F-21</td>
<td>100</td>
<td>2/4</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>F-22</td>
<td>100</td>
<td>2/4</td>
<td>1000</td>
<td>20</td>
</tr>
<tr>
<td>F-23</td>
<td>100</td>
<td>10/6</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>F-24</td>
<td>100</td>
<td>10/6</td>
<td>1000</td>
<td>5</td>
</tr>
<tr>
<td>F-25</td>
<td>100</td>
<td>10/6</td>
<td>250</td>
<td>5</td>
</tr>
<tr>
<td>F-26</td>
<td>100</td>
<td>10/6</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>F-27</td>
<td>100</td>
<td>10/6</td>
<td>1000</td>
<td>20</td>
</tr>
<tr>
<td>F-28</td>
<td>100</td>
<td>10/6</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>F-29</td>
<td>100</td>
<td>10/6</td>
<td>50</td>
<td>1</td>
</tr>
</tbody>
</table>

**NOTE:**  "T" IS "TRANSMITTER"
"R" IS "RECEIVER"  
"J" IS "JAMMER" OR "INTERFERENCE"
A receiver with specifications identical to those of the transmitter is assumed to exist at each grid point, which is denoted by a cross. A diamond is superimposed upon each cross, the size of which gives the probability that the SNR (or SJNR if jamming is considered) will exceed 13 dB at that particular receiver. A diamond which is exactly equal in size to the cross represents a probability of 50 percent. Likewise, a diamond of 1/2 size represents 25 percent. Therefore, the greater the size of that diamond relative to the cross (up to twice the size), the greater the probability for the signal link from the given transmitter to that particular receiver.

Each plot is labeled according to the situation which it describes. From left to right the label consists of the system under consideration, the transmitter power (watts), the antenna height (meters) of the transmitter and each receiver, the terrain, the jammer power (watts), the distance of the jammer from the transmitter (km), and whether or not jamming is considered. Note that if jamming is not considered, then the actual jammer power used is zero watts. The two examples following should clarify this.

**Example 1:**
JTIDS T200 ANT2 HILLS J10K DIU N

This label specified JTIDS, a transmitter power of 200 watts, transmitter and receiver antennas of 2 meters height (4 dBi gain implied), hilly terrain, a jammer power of 10 kilowatts, a distance between the jammer and transmitter of 10 km, and the fact that jamming was not considered.

**Example 2:**
PLRS T100 A10 HILLS J50 D1 J

Here the label specified PLRS, a transmitter power of 100 watts, transmitter and receiver antennas of 10 meters height (6 dBi gain implied), hilly terrain, a jammer power of 50 watts, a distance between the jammer and transmitter of 1 km, and the fact that jamming effects were considered.
Figures F-1 through F-15 and F-18 through F-24 display various types and magnitudes of jamming situations for JTIDS and PLRS. Notice that the quality of each signal link improves (the diamonds get larger) as the distance from the jammer to the receiver increases or as the jammer power decreases. Also, the coverage pattern is asymmetrical with regard to the geographical area since receivers on the jammer side of the transceiver are affected more than others.

Figures F-17 and F-29 display situations of interference. That is, the jammer powers are so low (fifty watts) and the area under consideration so small that interference rather than jamming is simulated. The result of this is that the RF coverage is quite good except in the immediate area of the interference source, at which a "hole" in the coverage pattern is located. Note that this "hole," however, covers a relatively small area.
APPENDIX A

WORK SHEET FOR ANALYSIS
OF UNJAMMED RF LINKS
APPENDIX A

In order to provide a uniform method of assessing communication system link performance for a wide variety of system implementations and operational parameters, an RF link analysis procedure was developed. The model procedure includes a universal work sheet and a number of graphical computational aids. Its use will be discussed in this section.

Figure A-1 is a block diagram of the general communication system link for which the model has been formulated. The system consists of a transceiver and an antenna at each end of an electromagnetic channel. Provision has been made for inclusion of the effects of environmental noise, path attenuation, spread spectrum processing, and transmission system losses. The model computes median range and corrects for the required reliability by the use of a link margin parameter. Effects of both path loss variability and noise variability are taken into account.

In order to facilitate use of the model, the computational process has been organized around a work sheet, see Figure A-2. In this way, the calculations are organized in a uniform, logical manner, thereby reducing confusion and minimizing opportunities for error. The use of shading further reduces confusion in the application of the work sheet. Individual steps are numbered and the data are arranged into two columns, corresponding to the respective ends of the communication link. Scales on the graphical computational aids are annotated with the line number for which the data is to be taken or into which it must be placed. Detailed instructions for work sheet use are summarized in the following paragraphs.

The power, operating frequency, antenna gain, and feed system loss are first entered into lines 1 through 4 of the work sheet. (Note: the feed system loss is the total loss between the transceiver and the antenna, usually consisting of transmission line loss, which can be estimated from Figure A-3, plus connector loss, losses in switches and
couplers, etc. The latter factor can usually be safely estimated at 3 or 4 decibels (if it is unknown). The indicated subtraction is then performed, column by column, to find the effective antenna gain for each station. Figure A-4 is then used to compute the corresponding effective radiated power for each station.

Figures A-5 and A-6 are now used to estimate the excess environmental noise and its standard deviation, entering the values obtained into lines 8 and 7 of the work sheet respectively. The noise figure of each of the receivers is entered into line 9 of the work sheet and the indicated subtraction performed to find the noise ratio (line 10). If the receiver noise figure is unknown, Figure A-7 may be used for estimation purposes. Also, Figure A-8 may be used to convert noise temperature into noise figure.

Using Figure A-9, the noise standard deviation reduction factor is computed from the noise ratio. This factor is then multiplied by the standard deviation of the environmental noise in order to compute the effective noise standard deviation. Figure A-10 is then used to compute the overall SNR standard deviation for each system. Given this value, and the required link reliability, Figure A-11 is used to compute the required link margin, which is entered into the appropriate columns of line 15 of the work sheet.

The equivalent noise bandwidth of each receiver is entered into line 16. In general, this is approximately equal to the half-power bandwidth. For systems for which the bandwidth is unknown, it may be approximate by the rules of thumb given in Table A-1.

In all cases, it is preferable to use the actual receiver specifications, where available. Next, Figures A-12 and A-13 are used to compute the total excess noise and total system noise for the systems, the results being entered into the proper columns of lines 17 and 18 of the work sheet. (Note: the negative sign is omitted when entering the amount of total system noise.)
The required output SNR is now entered into line 19. This is the minimum signal-to-noise ratio at which the receiver will do an acceptable job of demodulating the signal into usable information. Figures A-14 and A-15 may be used as general guidelines where quick estimates are desired. Alternatively, this number may be available from the equipment specifications. As a general rule, values of around 10 to 15 dB have been found to provide the system specifications where available, or Figure A-16 otherwise.

Now, the shaded columns of lines 5, 6, 18, and 20 are added together and entered into the shaded column of line 21. Likewise, the unshaded portions of the same lines are entered into the unshaded column of line 21. A similar procedure is used to obtain entries for the shaded and unshaded columns of line 22. Each column of line 22 is now subtracted from the corresponding column of line 21 and entered into the corresponding column of line 23. The minimum of the two entries of column 23 is selected as the maximum allowable path loss, and entered into line 24 of the work sheet. This figure indicates the maximum amount of propagation loss that can be tolerated while still maintaining the required level of system performance. This figure may be used with standard propagation curves to obtain the maximum system range.

In the absence of detailed propagation information, the following procedure may be used with good results. It has been checked with other, more sophisticated propagation models (including the Longley-Rice model) over the range of interest with very good results. First, the height of each antenna is entered into the appropriate column of line 25. The soil type at each location and the antenna polarization are entered into the next lines (26 and 27 respectively). Next, the minimum effective antenna height at each location is computed using Figure A-17. The larger of line 25 or line 26 is the effective antenna height at each station, and is entered into the appropriate column of line 29. The two effective antenna heights are multiplied to obtain the antenna height product which is entered into line 30.
The maximum free-space range is now computed, using Figure A-18, and entered into line 31. This is the range which could be obtained in the absence of all obstacles, including the earth. Figure A-19 is now used to compute the maximum multipath-limited range by first drawing a line connecting the frequency and the antenna height product, and then drawing a second line connecting the maximum allowable attenuation with the point of intersection of the first line with the scale without divisions. The resulting range is entered into line 32. The minimum of line 31 and line 32 is entered into line 33 as the maximum two-way system range.

The use of the model is best illustrated by the use of an example. Consider a mobile to base communication system whose electrical and operational characteristics are summarized in Table A-2. Figure A-20 is a complete work sheet for this system. Figures A-21 through A-33 illustrate the corresponding numerical calculations for the example.
Figure A-1. Block diagram of communication system link.
### System Description

<table>
<thead>
<tr>
<th>Station</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 TRANSMITTER POWER</td>
<td>WATT</td>
</tr>
<tr>
<td>2 FREQUENCY</td>
<td>HZ</td>
</tr>
<tr>
<td>3 ANTENNA GAIN</td>
<td>dBi</td>
</tr>
<tr>
<td>4 FEED SYSTEM LOSS</td>
<td>dB</td>
</tr>
<tr>
<td>5 EFFECTIVE ANTENNA GAIN (LINE 3 MINUS LINE 4)</td>
<td>dBi</td>
</tr>
<tr>
<td>6 EFFECTIVE RADIATED POWER</td>
<td>dBm</td>
</tr>
<tr>
<td>7 STANDARD DEVIATION OF ENVIRONMENTAL NOISE</td>
<td>dB</td>
</tr>
<tr>
<td>8 EXCESS ENVIRONMENTAL NOISE</td>
<td>dB/KT</td>
</tr>
<tr>
<td>9 NOISE FIGURE</td>
<td>dB</td>
</tr>
<tr>
<td>10 NOISE RATIO (LINE 8 MINUS LINE 9)</td>
<td>dB</td>
</tr>
<tr>
<td>11 STANDARD DEVIATION REDUCTION FACTOR</td>
<td>-</td>
</tr>
<tr>
<td>12 EFFECTIVE NOISE STANDARD DEVIATION (MULTIPLY LINES 7 AND 11)</td>
<td>dB</td>
</tr>
<tr>
<td>13 SNR STANDARD DEVIATION</td>
<td>dB</td>
</tr>
<tr>
<td>14 REQUIRED LINK RELIABILITY</td>
<td>%</td>
</tr>
<tr>
<td>15 REQUIRED LINK MARGIN</td>
<td>dB</td>
</tr>
<tr>
<td>16 NOISE BANDWIDTH</td>
<td>KHz</td>
</tr>
<tr>
<td>17 TOTAL EXCESS NOISE</td>
<td>dB/KT</td>
</tr>
<tr>
<td>18 SYSTEM NOISE POWER (OMIT MINUS SIGN)</td>
<td>dBm</td>
</tr>
<tr>
<td>19 REQUIRED SNR</td>
<td>dB</td>
</tr>
<tr>
<td>20 PROCESSING GAIN</td>
<td>dB</td>
</tr>
<tr>
<td>21 ADD SIMILARLY SHADEd COLUMNS OF LINES 5, 6, 18, AND 20</td>
<td>dB</td>
</tr>
<tr>
<td>22 ADD SIMILARLY SHADEd COLUMNS OF LINES 15 AND 19</td>
<td>dB</td>
</tr>
<tr>
<td>23 SUBTRACT LINE 22 FROM LINE 21</td>
<td>dB</td>
</tr>
<tr>
<td>24 MINIMUM OF ENTRIES ON LINE 23</td>
<td>dB</td>
</tr>
<tr>
<td>25 ANTENNA HEIGHT</td>
<td>M</td>
</tr>
<tr>
<td>26 SOIL TYPE</td>
<td>-</td>
</tr>
<tr>
<td>27 POLARIZATION</td>
<td>-</td>
</tr>
<tr>
<td>28 MINIMUM EFFECTIVE ANTENNA HEIGHT</td>
<td>M</td>
</tr>
<tr>
<td>29 EFFECTIVE ANTENNA HEIGHT (GREATER OF LINES 25 AND 28)</td>
<td>M</td>
</tr>
<tr>
<td>30 ANTENNA HEIGHT PRODUCT (MULTIPLY COLUMNS OF LINE 29)</td>
<td>-</td>
</tr>
<tr>
<td>31 MAXIMUM FREE-SPACE RANGE</td>
<td>K</td>
</tr>
<tr>
<td>32 MAXIMUM MULTIPATH-LIMITED RANGE</td>
<td>K</td>
</tr>
<tr>
<td>33 MAXIMUM RANGE (MINIMUM OF LINES 31 AND 32)</td>
<td>Km</td>
</tr>
</tbody>
</table>

**Figure A-2.** The communication system range worksheet.
Figure A-3. Typical feedline loss characteristics.
Figure A-4. Effective radiated power nomogram.
Figure A-5. Standard deviation of environmental noise.
Figure A-6. Excess environmental noise.
Figure A-7. Typical noise figures.
Figure A-8. Noise figure vs. noise temperature.
Figure A-9. Noise standard deviation reduction factor.
Figure A-10. Overall SNR standard deviation.
Figure A-11. Link margin nomogram.
### TABLE A-1

**APPROXIMATE NOISE BANDWIDTH**

<table>
<thead>
<tr>
<th>TYPE MODULATION</th>
<th>NOISE BANDWIDTH</th>
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</thead>
<tbody>
<tr>
<td>DIGITAL</td>
<td>2 X (DATA RATE)</td>
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<tr>
<td>SPREAD-SPECTRUM</td>
<td>2 X (CHIP RATE)</td>
</tr>
<tr>
<td>SSB</td>
<td>d kHz</td>
</tr>
<tr>
<td>NARROWBAND FM</td>
<td>15 kHz</td>
</tr>
<tr>
<td>WIDEBAND FM</td>
<td>2 X (MAX DEVIATION)</td>
</tr>
<tr>
<td>AM</td>
<td>6 kHz</td>
</tr>
</tbody>
</table>

A-16
Figure A-12. Total excess noise nomogram.
Figure A-13. Total system noise power computation.
Figure A-14. Required SNR for speech systems.
Figure A-15. Required SNR for data systems.
Figure A-16. Processing gain nomogram.
Figure A-17. Minimum effective antenna height.
Figure A-18. Free space range nomogram.
Figure A-19. Multipath limited range nomogram.
## TABLE A-2

SPECIFICATIONS FOR MOBILE TO BASE EXAMPLE

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>MOBILE</th>
<th>BASE</th>
<th>UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>POWER</td>
<td>25</td>
<td>150</td>
<td>WATTS</td>
</tr>
<tr>
<td>ANTENNA GAIN</td>
<td>4</td>
<td>8</td>
<td>dB</td>
</tr>
<tr>
<td>ANTENNA HEIGHT</td>
<td>1</td>
<td>25</td>
<td>METERS</td>
</tr>
<tr>
<td>FEED SYSTEM LOSS</td>
<td>1</td>
<td>4</td>
<td>dB</td>
</tr>
<tr>
<td>RECEIVER NOISE FIGURE</td>
<td>8</td>
<td>4</td>
<td>dB</td>
</tr>
<tr>
<td>ENVIRONMENT</td>
<td>RURAL</td>
<td>RURAL</td>
<td>(LOW NOISE) (LOW NOISE)</td>
</tr>
<tr>
<td>TERRAIN</td>
<td>HILLS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOIL</td>
<td>GOOD</td>
<td>POOR</td>
<td></td>
</tr>
<tr>
<td>FREQUENCY</td>
<td>300</td>
<td></td>
<td>MHz</td>
</tr>
<tr>
<td>POLARIZATION</td>
<td>VERTICAL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NOISE BANDWIDTH</td>
<td>30</td>
<td>30</td>
<td>KHz</td>
</tr>
<tr>
<td>REQUIRED RELIABILITY</td>
<td>95%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BIT RATE</td>
<td>16</td>
<td></td>
<td>KILOBITS/SEC</td>
</tr>
<tr>
<td>CHIP RATE</td>
<td>16</td>
<td></td>
<td>KILOBITS/SEC</td>
</tr>
</tbody>
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A-25
GEORGIA INSTITUTE OF TECHNOLOGY
COMMUNICATION SYSTEM RANGE WORKSHEET

SYSTEM DESCRIPTION Mobile to Base Communications Example

<table>
<thead>
<tr>
<th>STATION</th>
<th>UNITS</th>
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</thead>
<tbody>
<tr>
<td>1 TRANSMITTER POWER</td>
<td>25 150</td>
</tr>
<tr>
<td>2 FREQUENCY</td>
<td>300</td>
</tr>
<tr>
<td>3 ANTENNA GAIN</td>
<td>4.0 8.0</td>
</tr>
<tr>
<td>4 FEED SYSTEM LOSS</td>
<td>1.0 4.0</td>
</tr>
<tr>
<td>5 EFFECTIVE ANTENNA GAIN (LINE 3 MINUS LINE 4)</td>
<td>3.0 4.0</td>
</tr>
<tr>
<td>6 EFFECTIVE RADIATED POWER</td>
<td>46.5 55.5</td>
</tr>
<tr>
<td>7 STANDARD DEVIATION OF ENVIRONMENTAL NOISE</td>
<td>2.1 2.1</td>
</tr>
<tr>
<td>8 EXCESS ENVIRONMENTAL NOISE</td>
<td>0.0 0.0</td>
</tr>
<tr>
<td>9 NOISE FIGURE</td>
<td>8.0 4.0</td>
</tr>
<tr>
<td>10 NOISE RATIO (LINE 8 MINUS LINE 9)</td>
<td>-8.0 -4.0</td>
</tr>
<tr>
<td>11 STANDARD DEVIATION REDUCTION FACTOR</td>
<td>.13 .29</td>
</tr>
<tr>
<td>12 EFFECTIVE NOISE STANDARD DEVIATION (MULTIPLY LINES 7 AND 11)</td>
<td>.3 .6</td>
</tr>
<tr>
<td>13 SNR STANDARD DEVIATION</td>
<td>6.0 6.0</td>
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<tr>
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<td>97.5</td>
</tr>
<tr>
<td>15 REQUIRED LINK MARGIN</td>
<td>11.5 14.5</td>
</tr>
<tr>
<td>16 NOISE BANDWIDTH</td>
<td>30 30</td>
</tr>
<tr>
<td>17 TOTAL EXCESS NOISE</td>
<td>8.4 4.1</td>
</tr>
<tr>
<td>18 SYSTEM NOISE POWER (OMIT MINUS SIGN)</td>
<td>121.0 125.0</td>
</tr>
<tr>
<td>19 REQUIRED SNR</td>
<td>11.5 11.5</td>
</tr>
<tr>
<td>20 PROCESSING GAIN</td>
<td>0.0 0.0</td>
</tr>
<tr>
<td>21 ADD SIMILARLY SHADED COLUMNS OF LINES 5, 6, 16, AND 20</td>
<td>179.5 183.5</td>
</tr>
<tr>
<td>22 ADD SIMILARLY SHADED COLUMNS OF LINES 15 AND 19</td>
<td>23.0 23.0</td>
</tr>
<tr>
<td>23 SUBTRACT LINE 22 FROM LINE 21</td>
<td>156.5 160.5</td>
</tr>
<tr>
<td>24 MINIMUM OF ENTRIES ON LINE 23</td>
<td>156.5</td>
</tr>
<tr>
<td>25 ANTENNA HEIGHT</td>
<td>1 25</td>
</tr>
<tr>
<td>26 SOIL TYPE</td>
<td>GOOD POOR</td>
</tr>
<tr>
<td>27 POLARIZATION</td>
<td>VERTICAL</td>
</tr>
<tr>
<td>28 MINIMUM EFFECTIVE ANTENNA HEIGHT</td>
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</tr>
<tr>
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<td>1.0 25</td>
</tr>
<tr>
<td>30 ANTENNA HEIGHT PRODUCT (MULTIPLY COLUMNS OF LINE 29)</td>
<td>2.5</td>
</tr>
<tr>
<td>31 MAXIMUM FREE-SPACE RANGE</td>
<td>6000</td>
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<tr>
<td>32 MAXIMUM MULTIPATH-LIMITED RANGE</td>
<td>15</td>
</tr>
<tr>
<td>33 MAXIMUM RANGE (MINIMUM OF LINES 31 AND 32)</td>
<td>15</td>
</tr>
</tbody>
</table>

Figure A-20. Worksheet for mobile to base example.
Figure A-21. Example calculation of ERP for Station A.
Figure A-22. Example determination of the standard deviation of environmental noise.
Figure A-23. Example determination of the excess environmental noise.
Figure A-24. Example determination of the noise standard deviation reduction factor for Station A.
Figure A-25. Example determination of the SNR standard deviation.
Figure A-26. Example calculation of the required link margin.
Figure A-27. Example calculation of the total excess noise for Station A.
Figure A-28. Example determination of the total system noise for Station A.
Figure A-29. Example determination of the required SNR.
Figure A-30. Example calculation of the processing gain.
Figure A-31. Example determination of the minimum effective antenna height for Station A.
Figure A-32. Example calculation of the maximum free space range.
Figure A-33. Example calculation of the multipath range.
APPENDIX B

EQUATIONS FOR THE RF MODEL
APPENDIX B

The principle of the RF link model is as follows: First, the electrical parameters of the system are used to compute the maximum permissible propagation loss which will allow some specific level of communication quality to be supported in each direction through the link. Based on known environmental variability statistics, an additional safety margin is included to assure a specified degree of link reliability. The minimum value is selected as the maximum permissible propagation loss, since two-way communication is required. A propagation model is then used to predict the maximum range which will comply with this loss constraint. The basic mathematical formulation of the model will be summarized in the following paragraphs. In order to avoid confusion, ratios expressed in dB will be indicated by parenthesis with the subscript "dB", e.g. \( (G)_{dB} \), \( (L)_{dB} \). The variable inside the parenthesis is assumed to be expressed as a ratio. Thus,

\[
(G)_{dB} = 10 \log_{10} G \tag{1}
\]

\[
(L)_{dB} = 10 \log_{10} L \tag{2}
\]

The same nomenclature is used to express power in dBm, e.g.:

\[
(P)_{dBm} = 30 + 10 \log_{10} P \tag{3}
\]

The effective antenna gain is simply the antenna gain, relative to isotropic, corrected for losses in the feed systems, i.e.

\[
(G_{EFF})_{dBi} = (G)_{dBi} - (L)_{dB} \tag{4}
\]

Antenna gains are sometimes given in decibels relative to a dipole, abbreviated dBi. Since a dipole has a gain of 2.4 dBi, the gain in dBi may be found by simply adding 2.4 dB to the gain in dBi,

\[
(G)_{dBi} = (G)_{dBd} + (2.4)_{dB} \tag{5}
\]
Effective radiated power is calculated by:

\[
(\text{ERP})_{\text{dBm}} = (P)_{\text{dBm}} + (G_{\text{EFF}})_{\text{dBi}}
\]  

\[
(\text{ERP})_{\text{dBm}} = 30 + 10 \log_{10} P_{\text{watts}} + (G_{\text{EFF}})_{\text{dBi}}
\]  

As an aid to following the equation development, a superscript notation is followed where the superscript denotes the applicable end of the communications link, i.e.,

\[
A \Rightarrow \text{signifies receiver end}
\]

and

\[
B \Rightarrow \text{signifies transmitter end.}
\]

The basic link equations for the communication system are:

\[
A_{\text{max}} = \min \left\{ \frac{(P)^B(G)^A(G_{\text{PROC}})^A}{(L)^A(L)^B(M)^A(SNR)^A(P_N)^A}, \frac{(P)^A(G)^B(G_{\text{PROC}})^B}{(L)^B(L)^A(M)^B(SNR)^B(P_N)^B} \right\}
\]

where $A_{\text{max}}$ is the maximum link loss which can be tolerated within required performance constraints. The factors $G_{\text{PROC}}$, $\text{SNR}$, $P_N$, and $M$ are the processing gain, required signal-to-noise ratio, receiver noise power, and required link margin, and will be discussed later. Converting Equation (8) to decibels and substituting Equations (4) and (6), Equation (8) can be written:
\[
(A_{\text{max}})'_d B = \min \left\{ \begin{align*}
(G_{\text{EFF}})'_d B + (\text{ERP})'_d Bm + (G_{\text{PROC}})'_d B - (M)'_d B - (\text{SNR})'_d B - (P_N)'_d B \\
(G_{\text{EFF}})'_d B + (\text{ERP})'_d Bm + (G_{\text{PROC}})'_d B - (M)'_d B - (\text{SNR})'_d B - (P_N)'_d B
\end{align*} \right\}
\]

For the work sheet, this equation is broken up into two factors in order to simplify computations as follows:

\[
(A_{\text{max}})'_d B = \min \left\{ \begin{align*}
(X)'_A - (Y)'_A \\
(X)'_B - (Y)'_B
\end{align*} \right\}
\]

\[
(X)'_A = (G_{\text{EFF}})'_d B + (\text{ERP})'_d Bm + (-P_N)'_d Bm + (G_{\text{PROC}})'_d B
\]

\[
(X)'_B = (G_{\text{EFF}})'_d B + (\text{ERP})'_d Bm + (-P_N)'_d Bm + (G_{\text{PROC}})'_d B
\]

\[
(Y)'_A = (M)'_d B + (\text{SNR})'_d B
\]

\[
(Y)'_B = (M)'_d B + (\text{SNR})'_d B
\]

The processing gain is the effective improvement in signal-to-noise ratio which is afforded by spread-spectrum processing. It is ordinarily taken to be the ratio of CHIP rate to BIT rate in decibels, i.e.:

\[
(G_{\text{PROC}})'_d B = 10 \log_{10} \left[ \frac{\text{CHIP RATE (CHIPS/SEC)}}{\text{BIT RATE (BITS/SEC)}} \right]
\]
Alternatively, it can be computed in terms of RF and baseband bandwidths, viz:

$$\left( C_{\text{PROC}} \right)_{\text{dB}} = 10 \log_{10} \left( \frac{\text{RF Bandwidth (Hz)}}{\text{Baseband Bandwidth (Hz)}} \right) \quad (16)$$

The required signal-to-noise ratio is simply the IF signal-to-noise ratio required to assure some specific level of system performance. The relationships between SNR and bit-error-rate for a number of common digital modulation formats are plotted in the model in Figure A-15. The equations used to obtain these plots were:

$$\left( P_e \right)_{\text{ON-OFF KEYING}} = \frac{1}{2} \text{erfc} \left( \frac{1}{2} \sqrt{\text{SNR}} \right) \quad (17)$$

$$\left( P_e \right)_{\text{INC ASK}} = \frac{1}{2} e^{-\text{SNR}/2} \left[ 1 + \frac{1}{\sqrt{2\pi(\text{SNR})}} \right] \quad (18)$$

$$\left( P_e \right)_{\text{INC FSK}} = \frac{1}{2} e^{-\text{SNR}/2} \quad (19)$$

$$\left( P_e \right)_{\text{COH FSK}} = \frac{1}{2} \text{erfc} \left( \sqrt{\frac{1}{2}(\text{SNR})} \right) \quad (20)$$

$$\left( P_e \right)_{\text{DPSK}} = \frac{1}{2} e^{-\text{SNR}} \quad (21)$$

$$\left( P_e \right)_{\text{PSK}} = \frac{1}{2} \text{erfc} \sqrt{2\text{SNR}} \quad (22)$$

Figure A-14 provides a method of relating word articulation score (or percent of correctly understood words) for several common types of speech modulation. The curve for single sideband was taken from data found in Akima [1]. The data for the narrowband FM curve was taken from Crosby [3]. The data for CVSD was found in Jayant [2].
\[ P_N^A = K \left[ T_R + T_M G_A + T_E (1 - G_A) \right] B_N \] (23)

where:
- \( K \) = Boltzmann's constant = \( 1.38 \times 10^{-23} \) Joules/°K
- \( T_R \) = Receiver effective noise temperature-°K
- \( T_M \) = Noise temperature seen by antenna main beam-°K
- \( T_E \) = Noise temperature of environment
- \( G_A \) = Antenna gain
- \( B_N \) = Noise bandwidth (Hz) (24)

For our purposes we will assume \( T_M = T_E \), then:

\[ P_N^A = K \left[ T_R + T_E \right] B_N \] (25)

The quantities \( T_R \) and \( T_E \) are usually defined in terms of a receiver noise figures, \( F \), and the excess environmental noise factor, \( E \), and are related by:

\[
F = 1 + \frac{T_R}{T_o}
\] (26)

\[
E = \frac{T_E}{T_o}
\] (27)

where \( T_o \) is the reference temperature in °K.

Thus, in terms of these parameters,

\[ P_N^A = K T_o B_N \left( F^A + E^A - 1 \right) \] (28)

The reference temperature is usually taken to be 300 °K, hence:

\[ P_N^A = 4 \times 10^{-21} B_N \left( F^A + E^A - 1 \right) \] (29)
The noise power in dBm, then is given by:

\[
(P_N)_A \text{dBm} = -174 + 10 \log_{10} B_N(\text{Hz}) + 10 \log_{10} \left[ 10^{0.1(F)_A \text{dB}} + 10^{0.1(E)_A \text{dB}} - 1 \right] \tag{30}
\]

\[
(P_N)_B \text{dBm} = -174 + 10 \log_{10} B_N(\text{Hz}) + 10 \log_{10} \left[ 10^{0.1(F)_B \text{dB}} + 10^{0.1(E)_B \text{dB}} - 1 \right] \tag{31}
\]

The noise bandwidth, \( B_N \), is given by:

\[
B_N = \frac{1}{\left| H(f_0) \right|^2} \int_0^\infty H(f)^2 df \tag{32}
\]

where: \( H(f) \) = receiver frequency-response function

\( f_0 \) = center frequency of receiver (Hz)

For most receivers, this is approximately equal to the half-power or 3 dB bandwidth.

All the computations so far have been in terms of median values. By definition, this implies a link reliability of 50%. The link margin is the number of extra decibels of SNR required to ensure a given link reliability other than 50%.

In order to simplify the calculations, the assumption is made that the decibel values of the path attenuations and the noise are both normally distributed random variables which can be described by a mean value and a standard deviation. Since these variables are statistically independent, the overall standard deviation of their effect on the system is given by:
(σ)_{dB}^A = \sqrt{[(σ_{NOISE})_{dB}^A]^2 + [(σ_{ATT})_{dB}^A]^2} \tag{33}

where:  
(σ)_{dB}^A = \text{standard deviation of B to A channel performance in decibels}

(σ_{NOISE})_{dB}^A = \text{standard deviation of noise level in dB at A}

(σ_{ATT})_{dB}^A = \text{standard deviation of path attenuation in dB.}

likewise:

(σ)_{dB}^B = \sqrt{[(σ_{NOISE})_{dB}^B]^2 + [(σ_{ATT})_{dB}^B]^2} \tag{34}

Now, the factor (σ_{ATT})_{dB}^A is plotted in Figure A-5. The factor, (σ_{NOISE})_{dB}^B, is computed from the excess environmental noise standard deviation.

The total noise power, P_N, is the sum of the receiver noise, P_R, and the environmental noise, P_E.

\[ P_N = P_E + P_R \tag{35} \]

or, in decibels:

\[ (P_N)_{dB} = 10 \log_{10} \left[ 10^{0.1(P_E)_{dB}} + 10^{0.1(P_R)_{dB}} \right] \tag{36} \]

Now, we can compute the partials of (P_N)_{dB} with respect to (P_E)_{dB} as:

\[ \frac{\partial (P_N)_{dB}}{\partial (P_E)_{dB}} = \frac{10^{0.1(P_E)_{dB}}}{10^{0.1(P_E)_{dB}} + 10^{0.1(P_R)_{dB}}} \tag{37} \]
We can approximate,

\[
\sigma_N^2 = \sigma_E^2 \frac{\sigma_P}{\sigma_E} + \sigma_R^2 \frac{\sigma_P}{\sigma_R} \quad (39)
\]

Since the receiver noise is assumed to be constant,

\[
\sigma_R^2 = 0, \quad (40)
\]

Then,

\[
\sigma_N^2 = \sigma_E^2 K_s \quad (41)
\]

where:

\[
K_s = \frac{10^{0.1(P_E)}}{10^{0.1(P_E)} + 10^{0.1(P_R)}} \quad \text{NOISE STANDARD DEVIATION REDUCTION FACTOR}
\]

Since we have assumed a Gaussian distribution, we can now write:

\[
p(x_o) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{1}{2} \left( \frac{x_o - \mu}{\sigma} \right)^2} \quad (42)
\]

where:

\[
x_o = \text{instantaneous signal-to-noise ratio in dB}
\mu = \text{mean signal-to-noise ratio in dB}
\]

Hence:

\[
P(x > x_o) = \frac{1}{\sigma \sqrt{2\pi}} \int_{x_o}^{\infty} e^{-\frac{1}{2} \left( \frac{\delta - \mu}{\sigma} \right)^2} d\delta \quad (43)
\]
Solving, we find:

\[ P(x > x_0) = \frac{1}{2} \pm \frac{1}{2} \left[ 1 - e^{-\frac{2}{\pi} \left( \frac{x_0 - \mu}{\sigma} \right)^2} \right]^{1/2}; x_0 < \mu \] (44)

Rearranging the terms and solving for \( x_0 - \mu \),

\[ x_0 - \mu = \pm \sigma \sqrt{-\frac{\pi}{2} \ln \left\{ 1 - \left[ 2p(x > x_0) - 1 \right]^2 \right\}} \] (45)

We now define \( m = x_0 - \mu \) to be the link margin in decibels. The nomogram of Figure 2-11 allows easy computation of the final equation:

\[ (m)_{dB} = \pm (\sigma)_{dB} \sqrt{-\frac{\pi}{2} \ln \left\{ 1 - (2p - 1)^2 \right\}} \text{ for } p \geq \frac{1}{2} \] (46)

where:
- \( p \) = link reliability
- \((M)_{dB}\) = link margin in dB

The propagation equations used in the model assume either free space propagation or first-lobe multipath. Since the model is intended for relatively short range systems, the inclusion of other propagation modes has been found to be unnecessary. Comparison with more extensive models, e.g. Longely-Rice, has shown very good correspondence.

The free space loss is found by computing the energy intercepted by a receiving aperture at a distance \( R \) from an isotropic transmitting antenna
\[ P_R = \left\{ \frac{P_T}{4\pi R^2} \right\} \times \left\{ \frac{\lambda^2}{4\pi} \right\} \quad (47) \]

where: \( P_T \) = transmitter output power

\( R_R \) = received power

Thus, the path attenuation, \( A \), is:

\[ A_{FS} = \frac{P_T}{P_R} = \left\{ \frac{4\pi R}{\lambda} \right\}^2 \quad (48) \]

where: \( \lambda \) = wavelength in meters

\( C \) = speed of light = \( 3 \times 10^8 \) (m/s)

\( f \) = frequency in Hz

Thus, for free space paths, the maximum range is

\[ R_{max, FS} = \frac{C \sqrt{A_{max, FS}}}{4\pi f} \quad (49) \]

Converting to decibels, megahertz, and kilometers, this becomes:

\[ R_{max, FS} = \left\{ \frac{3 \times 10^8}{4000\pi} \right\} \left\{ \frac{1}{f_{MHz}} \right\} 10^{0.05(A_{max, FS}) dB} \quad (50) \]
Next, consider the case of a single reflected signal over plane earth. We define the pattern propagation factor as:

\[
F_P = \frac{PR \text{ (including reflected ray)}}{PR \text{ (neglecting reflected ray)}}
\] (51)

The total loss is given by:

\[
A = \frac{A_{FS}}{F_P}
\] (52)

\[
F_P = \left[ 1 + Pe^{-j\phi} + (1-P)(R)e^{j\phi} \right]^2
\] (53)

where: \(P = \text{ground reflection coefficient} \)

\(-1\text{ for horizontal} \)

\(+1\text{ for vertical} \)

\(c(R) = \text{ground wave attenuation factor}\)

\(\phi = (2\pi/\lambda) \text{ (path length difference) in radians}\).

Ignoring the ground wave terms, we can write:

\[
F_P = \left[ 1 - e^{-j\phi} \right]^2 = 2(1 - \cos \phi)
\] (54)

The direct and indirect path lengths for plane earth are given by,

\[
l_I = \sqrt{R^2 + (h_A + h_B)^2} = R \left\{ 1 + \frac{(h_A + h_B)^2}{R^2} \right\}^{1/2}
\] (55)

\[
l_d = \sqrt{R^2 + (h_A - h_B)^2} = R \left\{ 1 + \frac{(h_A - h_B)^2}{R^2} \right\}^{1/2}
\] (56)
Using a Maclaurin series for \((x + 1)^{1/2}\), we can write:

\[
(x + 1)^{1/2} = 1 + x/2 - x^2/8 + x^3/48 - \ldots \quad : (57)
\]

Hence:

\[
\ell_1 = R \left\{ 1 + \frac{h_A^2 + h_B^2 + 2h_A h_B}{2R^2} \right\} \quad : (58)
\]

\[
\ell_d = R \left\{ 1 + \frac{h_A^2 + h_B^2 - 2h_A h_B}{2R^2} \right\} \quad : (59)
\]

Then:

\[
\ell_1 - \ell_d = R \left\{ \frac{2h_A h_B}{2R^2} \right\} \quad : (60)
\]

Therefore:

\[
\phi = \frac{4\pi h_T h_R}{\lambda R} \quad : (61)
\]

Substituting into Equation (54), we find

\[
F_P = \left\{ \frac{4\pi h_T h_R}{\lambda R} \right\}^2 \quad : (62)
\]

Hence:

\[
A_{MP} = \frac{A_{FS}}{F_P} = \left\{ \frac{R^2}{h_T h_R} \right\}^2 \quad : (63)
\]
As noted by Elgi [4], this equation seems to be in considerable error at higher frequencies, yielding a loss which is too low. The correction suggested by Elgi is to include a \((f_{\text{MHz}}/40)^2\) term in Equation (63), i.e.:

\[
A_{\text{MP}} = \left\{ \frac{R^2}{h_{\text{T}}h_{\text{R}}} \right\} \left\{ \frac{f_{\text{MHz}}}{40} \right\}^2
\]  \hspace{1cm} (64)

The resulting equation for multipath range is:

\[
R_{\text{max, MP}} = \left\{ 6.32 \times 10 (0.025(A_{\text{max, MP}}\, \text{dB} - 3) \right\} \sqrt[3]{\frac{h_{\text{T}}h_{\text{R}}}{f_{\text{MHz}}}}
\]  \hspace{1cm} (65)

This Equation (65) gives good results for all cases except extremely low antennas. Bullington [5] has shown that these cases can be accounted for by using an effective antenna height. This factor is computed as follows:

\[
h_0 = \lambda \frac{1}{2\pi Z} \quad \text{(minimum effective antenna height)}
\]  \hspace{1cm} (66)

The value of \(Z\) is given by:

\[
Z = \begin{cases} 
\frac{1}{\varepsilon_0} \sqrt{\frac{\varepsilon_0}{\varepsilon_0 - 1}} ; \text{vertical} \\
\sqrt{\frac{\varepsilon_0}{\varepsilon_0 - 1}} ; \text{horizontal}
\end{cases}
\]  \hspace{1cm} (67)

where \(\varepsilon_0\) is the soil dielectric constant (complex) and is given by

\[
\varepsilon_0 = \varepsilon - j \sigma 60\varepsilon_0
\]  \hspace{1cm} (68)

where \(\varepsilon\) = soil relative dielectric constant

\(\sigma\) = soil conductivity in mhos per meter.
REFERENCES


APPENDIX C

WORK SHEET FOR ANALYSIS
OF JAMMED RF LINKS
In order to reduce the probability that successful communication can be carried out on an RF link, jammers are often used to increase the effective noise present in the receiving system. Figure C-1 depicts this situation. Here the transmitter, A, is attempting to send information to the receiver, B, by means of an RF communication link which is $R_t$ kilometers in length. The jammer, on the other hand, is attempting to "jam" the communication by radiating a noiselike signal toward the receiver via another link whose length is $R_j$. Since the directions of the two sources are not, in general, the same, then the gain of the receiving antenna for them is not necessarily the same. The effect of the jamming signal is to increase the level of the noise present in the receiver, thereby reducing the probability of communication or increasing the probability that the link will be "jammed."

In order to determine the effectiveness of the jamming system, or conversely, the effectiveness of the receiving system in avoiding this interference from the jamming station, a number of numerical calculations must be performed. In order to simplify these calculations, the work sheet shown in Figure C-2 and a number of graphical calculation aids have been developed. The example of Figure C-3 should prove useful in explaining the use of the work sheet and its associated graphical nomograms. Appendix D provides the theoretical background for the model.

The use of the work sheet is straightforward. Each item in the work sheet is identified by a line number. In addition, many of the lines are broken into two or three columns, indicated by lower case letters. Following the line number is a short statement of the meaning of the data to be entered into the line. The next column is a brief statement of instructions for carrying out the operations necessary to complete the line. The instructions are one of three types: (1) "ENTER," indicating that data is to be entered from direct knowledge of the system and/or operational parameters, (2) simple arithmetic instructions, e.g. (11a) -
Figure C-1. Typical jamming situation for RF links.
### Table C-1

<table>
<thead>
<tr>
<th>Instruction</th>
<th>TRANS a</th>
<th>REC b</th>
<th>JAM c</th>
<th>Units</th>
</tr>
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<tbody>
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<td></td>
<td></td>
<td>dB/KT</td>
</tr>
<tr>
<td>Receiver Noise Figure</td>
<td>ENTER</td>
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<td></td>
<td>dB</td>
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<td>Noise Ratio</td>
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<td></td>
<td>B/KT</td>
</tr>
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<td>Receiver Noise Bandwidth</td>
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<td>KHZ</td>
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<td>dB</td>
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<td>Equivalent Rec Input Noise</td>
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<td></td>
<td>dBm</td>
</tr>
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<td>Environmental Noise Variability</td>
<td>Table C-1</td>
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<td></td>
<td>dB</td>
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<td>Total Noise Variability</td>
<td>Figure C-5</td>
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<td>dB</td>
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<td>Output Power</td>
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<td>WATT</td>
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<td>Antenna Gain</td>
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<td>dBm</td>
</tr>
<tr>
<td>Effective Radiated Power</td>
<td>Figure C-6</td>
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<td>dBm</td>
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<td>Antenna Height</td>
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<td>m</td>
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<tr>
<td>Soil Conductivity</td>
<td>Figure C-7-C-12</td>
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<td></td>
<td>S/m</td>
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<tr>
<td>Min Effective Ant Height</td>
<td>Figure C-13</td>
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<td>m</td>
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<tr>
<td>Effective Antenna Height</td>
<td>Max (12), (14)</td>
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<td></td>
<td>m</td>
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<th>Units</th>
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<td>Range</td>
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<td>Free Space Loss</td>
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<tr>
<td>Multipath Region Loss</td>
<td>Figure C-15</td>
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<td>dB</td>
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<td>Total Path Loss</td>
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<td>Path Loss Variability</td>
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<td>dB</td>
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<td>Rec Ant Gain on Trans</td>
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<td>dBm</td>
</tr>
<tr>
<td>Rec Ant Gain on Jammer</td>
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<td>dBm</td>
</tr>
<tr>
<td>Received Signal Power</td>
<td>(11a)-(5b)-(20a)+(22a)</td>
<td>(24a)-(6b)</td>
<td>dBm</td>
</tr>
<tr>
<td>Median Signal-to-Noise Ratio</td>
<td>(26a)-(6b)</td>
<td></td>
<td>dB</td>
</tr>
<tr>
<td>Received Jammer Power</td>
<td>(11c)-(5b)-(20b)+(23b)</td>
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<td>dBm</td>
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<tr>
<td>Median Jammer-to-Noise Ratio</td>
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### Other Instructions

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<td>Required Baseband SNR</td>
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<td>Unstressed Link Margin</td>
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<tr>
<td>Unstressed Link Variability</td>
<td>Figure C-17</td>
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<tr>
<td>Unstressed Link Reliability</td>
<td>Figure C-18</td>
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<tr>
<td>Jammer Mismatch</td>
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<tr>
<td>Jamming Margin</td>
<td>Figure C-19</td>
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<tr>
<td>Stressed Link Margin</td>
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<tr>
<td>Stressed Link Variability</td>
<td>Figure C-20</td>
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<tr>
<td>Probability of Link Denial</td>
<td>Figure C-21</td>
</tr>
</tbody>
</table>

Figure C-2. Work sheet for evaluating jammed RF links.
(5b) - (20a) - (22a), meaning to enter a numerical quantity equal to the algebraic sum of the quantities indicated with the proper operations (addition and subtraction) performed, and (3) figure or table numbers which may be used, in conjunction with data already entered, to determine the value to be entered into the space in question. The following notes are intended to help clarify the meaning of the quantities which must be entered into the work sheet.

**EXCESS ENVIRONMENTAL NOISE:** This is the ratio of the power spectral density of the environmental noise to the power spectral density which would be observed from a resistor whose temperature is 300 degrees Kelvin and is specified in decibels.

**RECEIVER NOISE FIGURE:** Noise figure is simply a way of specifying the sensitivity of the receiver. It is related to the equivalent noise temperature by the following equation:

\[
(F)_{dB} = 10 \log_{10} \left[ 1 + \frac{T_R}{300} \right]
\]

where:  
- \( T_R \) = equivalent receiver noise temperature in °K  
- \((F)_{dB}\) = receiver noise figure in dB

**RECEIVER NOISE BANDWIDTH:** Ordinarily numerically equal to the half-power bandwidth, the noise bandwidth is defined by the following equation:

\[
B_N = \frac{1}{|H(f_o)|^2} \int_{f_o}^{\infty} |H(f)|^2 df \sim 3 \text{ dB bandwidth}
\]

- \( H(f) \) = receiver frequency response function (complex ratio)  
- \( f_o \) = receiver center frequency (Hz)  
- \( B_N \) = noise bandwidth in Hz

C-4
RF LOSSES: This factor is included to take into account the electrical losses in the transmission system which connects the transmitter/receiver/jammer to the appropriate antenna system. It is equal to the sum of all losses including coaxial cable, switches, connectors, etc. and usually has a value of around one or two decibels.

OUTPUT POWER: This is the total output power of the jammer or transmitter which appears at the input to the coaxial transmission system.

ANTENNA GAIN: The gain of an antenna is a measure of its ability to concentrate power in a particular direction. It is usually specified in terms of an antenna which has no directivity, called an isotropic antenna, and is given in dBi, or dB's relative to isotropic. For antennas specified relative to a dipole, in units of dBi, it is simply necessary to add 2.4 dB in order to determine the gain in dBi to enter into the work sheet.

ANTENNA HEIGHT: Height of the respective antenna in meters above average terrain.

RANGE: Distance between transmitting/jamming antenna and receiving antenna in kilometers, see Figure C-1.

RECEIVING ANTENNA GAIN ON TRANSMITTER: This is the gain of the receiving antenna in the direction of the transmitting station in dBi.

RECEIVING ANTENNA GAIN ON JAMMER: This is the gain of the receiving antenna in the direction of the jamming station.

REQUIRED BASEBAND SNR: This is the processed signal-to-noise ratio required by the system in order to support the required communication quality. For example, a bit error rate of 0.0001 using on-off keying might require a baseband SNR of 14 dB; that is, any lesser
signal-to-noise ratio would result in a higher bit-error-rate than the desired goal.

**PROCESSING GAIN:** The processing gain is the ratio of the RF-to-baseband bandwidth in decibels, i.e:

\[
\text{(Processing Gain)}_{\text{dB}} = 10 \log_{10} \left( \frac{\text{BW}_{\text{RF}}}{\text{BW}_{\text{BASEBAND}}} \right)
\]

Figure C-16 may be used to compute the processing gain or it may be found in system specifications.

**SYSTEM LOSS:** This factor is included to account for the reduction in processing efficiency due to imperfect signal processing and is given in dB.

**JAMMER MISMATCH:** In most cases, the jammer mismatch will be zero dB. However, if some portion of the jammer's energy falls outside the passband of the receiver, then this factor must account for the jammer loss of power, in dB.

The output from the work sheet consists of two numbers: the unstressed link reliability and the probability of link denial. The first of these is simply the probability that, in the absence of jamming, the system is capable of supporting the link as specified. The second is the probability that the link will be denied by the specified jamming situation.
### Table C-1

<table>
<thead>
<tr>
<th>1</th>
<th>Excess Environmental Noise</th>
<th>Table C-1</th>
<th>a. Trans</th>
<th>b. Rec</th>
<th>c. Jammer</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Receiver Noise Figure</td>
<td>Enter</td>
<td>0</td>
<td>4</td>
<td>dB</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Noise Ratio</td>
<td>(1)-(2)</td>
<td>-4</td>
<td>dB/KT</td>
<td>dB/KT</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Receiver Noise Bandwidth</td>
<td>Enter</td>
<td>10 K</td>
<td></td>
<td>KHz</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>RF Losses</td>
<td>Enter</td>
<td>2</td>
<td>2</td>
<td>dB</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Equivalent Rec Input Noise</td>
<td>Figure C-4</td>
<td>-98</td>
<td>dB</td>
<td>dB</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Environmental Noise Var.</td>
<td>Table C-1</td>
<td>8</td>
<td></td>
<td>dB</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Total Noise Variability</td>
<td>Figure C-5</td>
<td>2</td>
<td></td>
<td>dB</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Output Power</td>
<td>Enter</td>
<td>200</td>
<td></td>
<td>10K Watt</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Antenna Gain</td>
<td>Enter</td>
<td>6</td>
<td>15</td>
<td>dB</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Effective Radiated Power</td>
<td>Figure C-6</td>
<td>57</td>
<td>84</td>
<td>dBm</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Antenna Height</td>
<td>Enter</td>
<td>10</td>
<td></td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Soil Conductivity</td>
<td>Fig. C-7-C-12</td>
<td>.01</td>
<td>.01</td>
<td>s/m</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Min Effective Ant Height</td>
<td>Figure C-13</td>
<td>.3</td>
<td>.3</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Effective Antenna Height</td>
<td>Max (12),(14) 10</td>
<td></td>
<td></td>
<td>m</td>
<td></td>
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### Table C-2

<table>
<thead>
<tr>
<th>16</th>
<th>Antenna Height Product</th>
<th>(15b)x(15c)</th>
<th>100</th>
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<th>m²</th>
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<tbody>
<tr>
<td>17</td>
<td>Range</td>
<td>Enter</td>
<td>10</td>
<td></td>
<td>Km</td>
<td></td>
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<tr>
<td>18</td>
<td>Free Space Loss</td>
<td>Figure C-14</td>
<td>115</td>
<td>115</td>
<td>dB</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Multipath Region Loss</td>
<td>Figure C-15</td>
<td>148</td>
<td>148</td>
<td>dB</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Total Path Loss</td>
<td>Max (12),(14) 148</td>
<td></td>
<td></td>
<td>dB</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Path Loss Variability</td>
<td>Table C-2</td>
<td>8</td>
<td>8</td>
<td>dB</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Rec Ant Gain on Trans</td>
<td>Enter</td>
<td>6</td>
<td></td>
<td>dBi</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Rec Ant Gain on Jammer</td>
<td>Enter</td>
<td>6</td>
<td></td>
<td>dBi</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Received Signal Power</td>
<td>(11a)-(5b)-(20a)+(22a) -87</td>
<td></td>
<td></td>
<td>dBm</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Median Signal-to-Noise Ratio</td>
<td>(24a)-(6b) -11</td>
<td></td>
<td></td>
<td>dB</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>Received Jammer Power</td>
<td>(11c)-(5b)-(20b)+(23b) -66</td>
<td></td>
<td></td>
<td>dBm</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Median Jammer-to-Noise Ratio</td>
<td>(26b)-(6b) 32</td>
<td></td>
<td></td>
<td>dB</td>
<td></td>
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### Table C-3

<table>
<thead>
<tr>
<th>28</th>
<th>Processing Gain</th>
<th>Figure C-16</th>
<th>19.4</th>
<th></th>
<th>dB</th>
<th></th>
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<tr>
<td>29</td>
<td>System Loss</td>
<td>Enter</td>
<td>1</td>
<td></td>
<td>dB</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>Required Baseband SNR</td>
<td>Enter</td>
<td>10</td>
<td></td>
<td>dB</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>Unstressed Link Margin</td>
<td>(25)+(28)-(29)-(30) 19.4</td>
<td></td>
<td></td>
<td>dB</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>Unstressed Link Variability</td>
<td>Figure C-17</td>
<td>5.7</td>
<td></td>
<td>dB</td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>Unstressed Link Reliability</td>
<td>Figure C-18</td>
<td>99.97</td>
<td></td>
<td>z</td>
<td></td>
</tr>
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</table>

### Table C-4

<table>
<thead>
<tr>
<th>34</th>
<th>Jammer Mismatch</th>
<th>Enter</th>
<th>0</th>
<th></th>
<th>dB</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>Jamming Margin</td>
<td>Figure C-19</td>
<td>32</td>
<td></td>
<td>dB</td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>Stressed Link Margin</td>
<td>(31)-(35) -12.6</td>
<td></td>
<td></td>
<td>dB</td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>Stressed Link Variability</td>
<td>Figure C-20</td>
<td>11.5</td>
<td></td>
<td>dB</td>
<td></td>
</tr>
<tr>
<td>38</td>
<td>Probability of Link Denial</td>
<td>Figure C-21</td>
<td>86</td>
<td></td>
<td>z</td>
<td></td>
</tr>
</tbody>
</table>

Figure C-3. Example work sheet.
<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>SYSTEM</th>
<th>BUSINESS OR (HIGH NOISE)</th>
<th>RESIDENTIAL OR (LOW NOISE)</th>
<th>RURAL (LOW NOISE)</th>
<th>UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXCESS ENVIRONMENTAL NOISE</td>
<td>PLRS</td>
<td>+23</td>
<td>+9</td>
<td>-7</td>
<td>dB/KT</td>
</tr>
<tr>
<td></td>
<td>JTIDS</td>
<td>+14</td>
<td>0</td>
<td>-17</td>
<td></td>
</tr>
<tr>
<td>ENVIRONMENTAL NOISE VARIABILITY</td>
<td>PLRS</td>
<td>7</td>
<td>8</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>JTIDS</td>
<td>7</td>
<td>8</td>
<td>3</td>
<td>dB</td>
</tr>
</tbody>
</table>
Figure C-4. Equivalent receiver input noise nomogram.
Figure C-5. Total noise variability nomogram.
Figure C-6. Effective radiated power nomogram.
Figure C-7. Soil Conductivity-South America.
Figure C-8. Soil Conductivity-Austrailia.
Figure C-9. Soil Conductivity—Europe.
Figure C-10. Soil Conductivity—North America.
Figure C-11. Soil Conductivity - Asia.
Figure C-12. Soil Conductivity-Africa.
Figure C-13. Soil conductivity (millimhos/meter) vs. effective antenna height (vertical polarization).
Figure C-14. Free space loss nomogram.
Figure C-15. Multipath region loss nomogram.
## TABLE C-2

**PATH LOSS VARIABILITY**

<table>
<thead>
<tr>
<th>ENVIRONMENT</th>
<th>PATH LOSS VARIABILITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLAINS</td>
<td>6dB</td>
</tr>
<tr>
<td>HILLS</td>
<td>8dB</td>
</tr>
<tr>
<td>MOUNTAINS</td>
<td>10dB</td>
</tr>
<tr>
<td>URBAN</td>
<td>20dB</td>
</tr>
</tbody>
</table>
Figure C-16. Processing gain nomogram.
Figure C-17. Unstressed link variability nomogram.
Figure C-18. Unstressed link reliability nomogram.
Figure C-19. Jamming margin monogram.
Figure C-20. Stressed link variability nomogram.
Figure C-21. Probability of link denial nomogram.
APPENDIX D

MATHEMATICAL DEVELOPMENT
FOR ANALYSIS OF JAMMED RF LINKS
APPENDIX D

The following appendix summarizes the equations used in the stressed RF communication system model. In all cases, the following convention will be used with regard to decibel and non-decibel (ratio) values: decibel values will be indicated by the use of parentheses, e.g. (G) or (G)_{dB}. The use of the subscript "dB" will be optional. Non-decibel values will be indicated by the absence of parenthesis.

Thus: \( (G) = (G)_{dB} = 10 \log_{10}[G] \).

Moreover, the same convention will be applied to power expressed in dBm, or decibels with respect to one milliamp, e.g. \( (P)_{dBm} = 10 \log_{10}[P] + 30 \). The use of the subscript dB will indicate antenna gains with respect to a theoretical isotropic radiator. Likewise, dBd may be used to indicate antenna gains with respect to a dipole, thus: \( (G)_{dBi} = (G)_{dBd} + (2.4) \).

The following expressions are used to evaluate the total equivalent noise referenced to the receiver input:

\[
(P_n)_{dBm} = (-174) + 10 \log_{10}[n] + 10 \log_{10}[10^{0.1(F)} + 10^{0.1(E)} - 1] - (L_R)
\]

(D-1)

\[
(P_n)_{dBm} = (-174) + 10 \log_{10}[n] + 10 \log_{10}[10^{-0.1(F)} + 10^{0.1(E)}] - (L_R)
\]

(D-2)

where: \( (P_n) \) = total noise referenced to receiver input in dBm

\( (L_R) \) = receiver RF losses in dB
\[ B_n = \text{equivalent receiver noise bandwidth in Hz} \]

\( (F) = \text{receiver noise figure in } \text{dB relative to } 290^\circ \text{K} \)

\( (E) = \text{excess environmental noise in } \text{dB relative to } KT \)

The nomogram in Figure C-4 may be used to conveniently evaluate Equation (D-2) which provides a good approximation for Equation (D-1) over the range of interest.

The decibel value of the noise power spectral density, and hence the decibel value of the total receiver noise power, is assumed, for the purpose of this model, to be a Gaussian distributed random variable. Moreover, it is assumed to consist of two components: the internal receiver noise, whose power is assumed to be a constant, and the external, or environmental noise, the decibel value of whose power is assumed to be Gaussian distributed. Thus, the distribution of the dB value of the total received noise may be expressed in terms of the receiver noise figure, the excess noise mean power level, and the standard deviation of same, as:

\[
(\sigma_N)_{dB} = \frac{10^{0.1(E)}}{10^{0.1(E)} + 10^{0.1(F)}}
\]

\[ (D-3) \]

where:

\( (\sigma_N)_{dB} \) = standard deviation of total noise power in dB

\( (\sigma_E)_{dB} \) = standard deviation of environmental noise in dB

\( (E) \) = excess environmental noise in dB/KT

\( (F) \) = receiver noise figure in dB
For a derivation of Equation (D-3), see Appendix B. The nomogram in Figure C-5 may be used to evaluate Equation (D-3).

The effective radiated power for both the jammer and the transmitter are found by evaluating Equation (D-4):

\[
(ERP)_{\text{dBm}} = 10 \log_{10} [P] + (G_T)_{\text{dBi}} - (L_T)_{\text{dB}} - (L_I)_{\text{dB}} + (30)_{\text{dB}}
\]  

(D-4)

where: 
- \( (ERP) \) = effective radiated power in dBm
- \( P \) = transmitter or jammer output power in watts
- \( (G_T)_{\text{dBi}} \) = transmitter or jammer antenna gain in dBi
- \( (L_T)_{\text{dB}} \) = transmitter or jammer RF losses in dB

Figure C-6 is a nomogram which can be used to evaluate this expression.

The path attenuation for both the jammer and the transmitter is calculated by evaluating the following expression:

\[
(L_p)_{\text{dB}} = \max \left\{ \begin{array}{ll}
20 \log_{10}[R] + 20 \log_{10}[f_{mc}] + 32.4 \\
88 + 40 \log_{10}[R] + 20 \log_{10}[f_{mc}] - 20 \log_{10}[h] + C
\end{array} \right.
\]  

(D-5)

where:
- \( (A)_{\text{dB}} = 10 \log_{10} \left[ \frac{\text{POWER SUPPLIED TO ISOTROPIC TRANSMITTING ANTENNA}}{\text{POWER RECEIVED BY ISOTROPIC ANTENNA AT RANGE R}} \right] \)
\[(L_P)_{dB} = \text{PATH LOSS in dB}\]

\[R = \text{range in km}\]
\[f_{mc} = \text{frequency in MHz}\]
\[H = \text{antenna height product in m}^2\]
\[C = \text{terrain correction factor}\]

\[

\begin{align*}
C &= \begin{cases} 
0 & \text{..................hills} \\
-10 & \text{...............plains} \\
+15 & \text{..............mountains} \\
+20 & \text{..............urban}
\end{cases}
\end{align*}

\]

The antenna height product, \(H\), is the product of the effective heights of the transmitting (either jammer or transmitter) antenna and the receiving antenna. For heights of several wavelengths or more, the effective height is numerically equal to the actual antenna height in meters. For very low antennas, the effective height is bounded by a minimum value which depends on the frequency, and soil conditions. Details of the method of determining the value of the minimum height are given in Appendix B, and are summarized by Equations (D-6) through (D-8).

\[
\begin{align*}
h_{\min} &= \lambda \left| \frac{1}{2 \pi z} \right| \\
z &= \begin{cases} 
\frac{1}{\varepsilon_0 \sqrt{\varepsilon_0 - 1}} & \text{; vertical polarization} \\
\sqrt{\varepsilon_0 - 1} & \text{; horizontal polarization}
\end{cases} \\
\varepsilon_0 &= \varepsilon - j 60 \sigma \lambda \\
h &= \max \left\{ h, h_{\min} \right\} \\
H &= h_T h_R
\end{align*}
\]
where:
\[ \lambda = \text{wavelength in meters} \]
\[ \varepsilon = \text{relative dielectric constant of soil} \]
\[ \sigma = \text{soil conductivity in mhos per meter} \]
\[ h_{\text{min}} = \text{minimum effective antenna height in meters} \]
\[ h = \text{actual antenna height in meters} \]
\[ h' = \text{effective antenna height in meters} \]
\[ h_R' = \text{effective height of receiving antenna in meters} \]
\[ H = \text{antenna height product in square meters} \]

Next, the received signal power is calculated using Equation (D-11), and this value is used to compute the received signal-to-noise ratio using Equation (D-12).

\[
(P_R)^T_{\text{dBm}} = (\text{ERP})^T_{\text{dBm}} + (G_R)^T_{\text{dBi}} - (L_R)^T_{\text{dB}} - (L_p)^T_{\text{dB}} \tag{D-11}
\]

\[
(SNR)^T_{\text{dB}} = (P_R)^T_{\text{dBm}} - (P_N)^T_{\text{dBm}} \tag{D-12}
\]

where:
\[(P_R)^T_{\text{dBm}} = \text{received signal power in dBm} \]
\[(\text{ERP})^T_{\text{dBm}} = \text{transmitter effective radiated power in dBm} \]
\[(G_R)^T_{\text{dBi}} = \text{gain of receiving antenna in direction of transmitter in dBi} \]
\[(L_R)^T_{\text{dB}} = \text{RF losses in receiving system in dB} \]
\[(L_p)^T_{\text{dB}} = \text{path loss between transmitter and receiver in dB} \]
\[(P_N)_{dBm} = \text{equivalent received noise power in dBm}\]

\[(SNR)_{db} = \text{received signal-to-noise ratio (in absence of jamming) in dB}\]

In a similar manner, the receiver jammer power and the jammer-to-noise ratio are calculated using Equations (D-13) and (D-14).

\[(P_R)_{dBm}^J = (ERP)_{dBm}^J + (G_R)_{dBi} - (L_R)_{dB} - (L_P)_{dB}^J\]  \hspace{1cm} (D-13)

\[(JNR)_{dB} = (P_R)_{dBm}^J - (P_N)_{dBm}\]  \hspace{1cm} (D-14)

where:

\[(P_R)_{dBm}^J = \text{received jammer power in dBm}\]

\[(ERP)_{dBm}^J = \text{jammer effective radiated power in dBm}\]

\[(G_R)_{dBi} = \text{gain of receiving antenna indirection of jammer in dBi}\]

\[(JNR)_{dB} = \text{jammer-to-noise ratio in dB}\]

\[(L_P)_{dB}^J = \text{path loss between jammer and receiver in dB}\]

The unstressed link margin is now calculated using Equation (D-15). The unstressed link margin is the amount of excess signal-to-noise ratio above the required amount which will result from a median value of link loss and noise power. The unstressed SNR variability (standard deviation) is found by combining the path loss variability with the noise variability, see Equation (D-16).

\[(M_u)_{dB} = (SNR)_{dB} + (C_P)_{dB} - (L_s)_{dB} - (S_R)_{dB}\]  \hspace{1cm} (D-15)
\[
(M_u)_{\text{dB}} = \text{unstressed link margin in dB}
\]

\[
(G_p)_{\text{dB}} = \text{processing gain in dB}
\]

\[
(L_s)_{\text{dB}} = \text{system (processing) loss in dB}
\]

\[
(S_R)_{\text{dB}} = \text{required signal-to-noise ratio in dB}
\]

\[
(\sigma_u)_{\text{dB}} = \text{standard deviation of unstressed link SNR in dB}
\]

\[
(\sigma_T)_{\text{dB}} = \text{standard deviation of transmitter-receiver link loss in dB}
\]

The probability of achieving link connectivity can now be calculated using Equation (D-17).

\[
P_u = \frac{1}{(\sigma_u)\sqrt{2\pi}} \int_{-(M_u)}^{+\infty} \exp \left\{ -\frac{1}{2} \left[ \frac{\zeta - (M_u)}{(\sigma_u)} \right]^2 \right\} d\zeta
\]

where: 

\[
P_u = \text{probability of connectivity for single link}
\]

\[
\zeta = \text{dummy variable of integration}
\]

The number thus obtained is the probability of being able to establish a single communication link without jamming (unstressed).

In order to compute the effect of stress (jamming) on the link, a jamming margin is first calculated. The jamming margin is the effective
increase in receiver noise due to the presence of the jamming signal. The jamming margin is computed from Equation (D-18) below. The nomogram of Figure C-19 may be used to simplify the calculation.

\[
(M_J)_{dB} = 10 \log_{10} \left[ 10^{0.1 \left\{ (JNR) - (MM) \right\} + 1} \right] \quad (D-18)
\]

where: \( (M_J)_{dB} \) = jammer margin in dB

\( (JNR) \) = jammer-to-noise ratio in dB

\( (MM) \) = jammer mismatch in dB

The jamming margin is then simply subtracted from the unstressed link margin in order to find the stressed link margin, see Equation (D-19) below.

\[
(M_s)_{dB} = (M_u)_{dB} - (M_J)_{dB} \quad (D-19)
\]

where: \( (M_s)_{dB} \) = stressed link margin in dB

Equation (D-20) is now used to compute the stressed link variability. Using Equation (D-21), the probability of the link being jammed may now be computed. The nomograms of Figures C-20 and C-21 may be used to simplify these calculations.

\[
\sigma_s^2_{dB} = \sqrt{\sigma_j^2_{dB} + \sigma_T^2_{dB}} \quad (D-20)
\]

\[
P_J = \frac{1}{(\sigma_s)^2 \sqrt{2 \pi}} \int_{-(M_s)}^{+\infty} \exp \left\{ -\frac{1}{2} \left[ \frac{\xi - (M_s)}{(\sigma_s)} \right]^2 \right\} d\xi \quad (D-21)
\]
where: \((\sigma_j)_{dB} = \text{jammer-receiver link loss variability in dB}\)

\((\sigma_s)_{dB} = \text{stressed link variability in dB}\)

\(P_J = \text{probability of link denial}\)
APPENDIX E

BIT-ERROR-RATE (BER) CURVES
FOR PHASE SHIFT KEYED MODULATION
APPENDIX E

BIT-ERROR-RATE (BER) CURVES
FOR PHASE SHIFT KEYED MODULATION

This appendix contains a collection of curves of bit-error-rate (BER) versus signal-to-noise ratio (SNR) for phase-shift-keyed (PSK) modulation. These curves have been abstracted and adapted from a previous Georgia Tech Report ("Sensitivity Analysis of Link Transmissions Study," Volumes I and II, prepared for Electronic Systems Division, Hanscom AFB, December 1974).

The BER curves are parametric and allow estimation of the error rate for given values of signal-to-noise ratios and other pertinent parameters. The parameters are defined as follows:

- **SNR**: Signal-to-noise ratio (dB) [also defined as $E_b/N_0$ or normalized SNR when measured in a bandwidth equal to the bit rate, where $E_b$ is the energy per bit and $N_0$ is the noise power spectral density.] For a spread spectrum TDMA system, the value of SNR corresponds to the output SNR.

- **BER**: Bit error rate.

- **m**: An integer indicating the number of phase states for a PSK system ($m = 2$ indicates biphase and $m = 4$ indicates quadriphase).

- **γ**: Decision threshold half-width (degrees). Typically used to represent non-ideal detector performance.

- **∆**: Static phase error (degrees). Also reflects non-ideal detection due to phase errors.
α Phase locked loop (PLL) parameter proportional to loop signal-to-noise ratio. (PLL is typically used for carrier and clock synchronization.)

β Phase locked loop parameter proportional to loop frequency offset.

Ideal An ideal PSK demodulation mode where carrier synchronization is assumed to be perfect.

Coherent Detection

Differential A PSK detection mode where a previous symbol state provides the phase reference for the next phase state.

Coherent Detection

Noisy PSK detection with some form of non-ideal carrier synchronization (usual case). Curves shown include two cases:

(1) Use of a pilot carrier PLL for reference extraction and
(2) An \(m\)'th power PLL for harmonic synchronization.

Coherent Detection

Offset QPSK A 4-phase \((m = 4)\) form of PSK where one binary stream is delayed by half a symbol period relative to the other binary stream. (Closely related to the "minimum shift keying" form of QPSK planned for JTIDS.)

Figures E-1 and E-2 further explain the definitions of decision threshold widths and static phase errors. The particular example shown corresponds to quadriphase (4 phase PSK).

In order to apply these curves to PLRS or JTIDS for system performance assessment, it is suggested that the following typical ranges of parameters be followed:

\[ m = 2 \text{ or } 4 \] (typically \(m = 4\) for PLRS or JTIDS)
Figure E-1. Finite Width Decision Thresholds.

Figure E-2. Static Phase Error.
$0 \, \text{dB} \leq \text{SNR} \leq 30 \, \text{dB}$  
(Output SNR after processing gain)

$0 \leq \Delta \leq 4$ (degrees)

$0 \leq \gamma \leq 4$ (degrees)

$10 \leq \alpha \leq 1000$

$0 \leq \beta \leq 4$

With regard to labeling of the curves, the convention is followed of listing the parameter sets from top to bottom in the same order that the curves appear. In some cases, the individual curves (on a family) are very close together or coincide and may not be resolvable.
IDEAL COHERENT DETECTION
Figure E-3. Probability of Bit Error vs $E_b/N_0$ for Various Values of $\gamma$ and $\Delta$ (degrees), $m = 2$; Ideal Coherent Detection.
Figure E-4. Probability of Bit Error vs. $E_b/N_0$ for Various Values of $\gamma$ and $\Delta$ (degrees), $m = 4$; Ideal Coherent Detection.
Figure E-5. Probability of Bit Error vs. $E_b/N_o$ for Large Variations of $\gamma$ and $\Delta$ (degrees), $m = 2$; Ideal Coherent Detection.
Figure E-6. Probability of Bit Error vs. $E_b/N_0$ for Large Variations of $\gamma$ and $\Delta$ (degrees), $m = 4$; Ideal Coherent Detection.
DIFFERENTIAL COHERENT DETECTION
Figure E-7. Probability of Bit Error vs. $E_b/N_0$ for Various Values of $\gamma$ and $\Delta$ (degrees), $m = 2$; Differential Detection.
Figure E-8. Probability of Bit Error vs. $E_b/N_0$ for Various Values of $\gamma$ and $\Delta$ (degrees), $m = 4$; Differential Detection.
Figure E-9. Probability of Bit Error vs $E_b/N_0$ for Large Variations of $\gamma$ and $\Delta$ (degrees), $m = 2$; Differential Detection.
Figure E-10. Probability of Bit Error vs. $E_b/N_0$ for Large Variations of $\gamma$ and $\Delta$ (degrees), $m = 4$; Differential Detection.
NOISY COHERENT DETECTION
Figure E-11. Probability of Bit Error vs. $E_b/N_0$ for $m = 2, 4, 8$; $m'$th Power PLL with $\alpha = 10, \beta = 0$. 
Figure E-12. Probability of Bit Error vs. $E_b/N_0$ for $m = 2, 4, 8$; $m$'th Power PLL with $\alpha = 10, \beta = 1$. 
Figure E-13. Probability of Bit Error vs. $E_b/N_o$ for $m$'th Power PLL Detection, $m = 2$, with Variations in $\alpha$ and $\beta$. 

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Figure E-13. Probability of Bit Error vs. $E_b/N_o$ for $m$'th Power PLL Detection, $m = 2$, with Variations in $\alpha$ and $\beta$. 

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E-18
Figure E-14. Probability of Bit Error vs. $E_b/N_0$ for Two Values of $\gamma$, $m = 2$; $m$'th Power PLL with $\alpha = 10$, $\beta = 0$. 
Figure E-15. Probability of Bit Error vs. $E_b/N_0$ for Two Values of $\gamma$, $m = 2$; $m$'th Power PLL with $\alpha = 10$, $\beta = 1$. 
Figure E-16. Probability of Bit Error vs. $E_b/N_0$ for $m$'th Power PLL Detection, $m = 4$, with Variations in $\alpha$ and $\beta$. 

E-21
Figure E-17. Probability of Bit Error vs. $\frac{E_b}{N_0}$ for Two Values of $\gamma$, $m = 4$; $m'$th Power PLL with $\alpha = 10$, $\beta = 0$. 
Figure E-18. Probability of Bit Error vs. $E_b/N_0$ for Two Values of $\gamma$, $m = 4$; $m$'th Power PLL with $a = 10$, $\beta = 1$. 
Figure E-19. Probability of Bit Error vs. $E_b/N_0$ for Various Values of $\gamma$ and $\Delta$ (degrees), $m = 4$; $m$'th Power PLL with $\alpha = 10$, $\beta = 0$. 
Figure E-20. Probability of Bit Error vs. $E_b/N_0$ for Various Values of $\gamma$ and $\Delta$ (degrees), $m = 4$; $m$'th Power PLL with $\alpha = 10$, $\beta = 2$. 
Figure E-21. Probability of Bit Error vs. $E_b/N_o$ for Two Values of $\gamma$, $m = 4$; $m$'th Power PLL with $a = 10$, $\beta = 1$. 

$\gamma = 2$

$\gamma = 0$

$m = 8$

$a = 10$

$\beta = 1$

$\Delta = 0$
Figure E-22. Probability of Bit Error vs. $E_b/N_0$ for Pilot Carrier PLL Detection, $m = 2, \alpha = 10$, with Variations in $\beta$. 
Figure E-23. Probability of Bit Error vs. $E_b/N_o$ for Pilot Carrier PLL Detection, $m = 2$, with Variations in $\alpha$ and $\beta$. 

E-28
Figure E-24. Probability of Bit Error vs. $E_b/N_0$ for Pilot Carrier PLL Detection, $m = 4$, with Variations in $\alpha$ and $\beta$. 
OFFSET QPSK
Figure E-25. Probability of Bit Error vs. $E_b/N_0$ for BPSK, Conventional QPSK, and Offset QPSK for Pilot Carrier PLL Detection with $a = 100$, $b = 0$, and $\Delta = 0$. 

E-31
Figure E-26. Probability of Bit Error vs. $E_b/N_0$ for BPSK, Conventional QPSK, and Offset QPSK for Pilot Carrier PLL Detection with $\alpha = 50$, $\beta = 0$, and $\Delta = 0$. 
Figure E-27. Probability of Bit Error vs. $E_b/N_0$ for BPSK, Conventional QPSK, and Offset QPSK for Pilot Carrier PLL Detection with $\alpha = 20$, $\beta = 0$, and $\Delta = 0$. 
Figure E-28. Probability of Bit Error vs. $E_b/N_0$ for BPSK, Conventional QPSK, and Offset QPSK for Pilot Carrier PLL Detection with $\alpha = 10$, $\beta = 0$, and $\Delta = 0$. 
Figure E-29. Probability of Bit Error vs. $E_b/N_0$ for BPSK, Conventional QPSK, and Offset QPSK for Pilot Carrier PLL Detection with $\alpha = 5$, $\beta = 0$, and $\Delta = 0$. 
Figure E-30. Probability of Bit Error vs. $E_b/N_0$ for Offset QPSK with Pilot Carrier PLL Detection for Various Values of $\alpha$ and $\beta$, $\Delta = 0$. 
Figure E-31. Probability of Bit Error vs. $E_b/N_0$ for Offset QPSK with Pilot Carrier PLL Detection for Various Values of $\alpha$ and $\beta$, $\Delta = 4^\circ$. 
Figure E-32. Probability of Bit Error vs. $E_b/N_0$ for Offset QPSK with Pilot Carrier PLL Detection for Various Values of $\alpha$ and $\beta$, $\Delta = 8^\circ$. 

E-38
Figure E-33. Probability of Bit Error vs. $E_b/N_0$ for Offset QPSK with $M$'th Order PLL Detection for Various Values of $\alpha$ and $\beta$, $\Delta = 0^\circ$. 

E-39
Figure E-34. Probability of Bit Error vs. Eb/N₀ for Offset QPSK with M'th Order PLL Detection for Various Values of α and β, Δ = 4°.
Figure E-35. Probability of Bit Error vs. $E_b/N_0$ for Offset QPSK with $M$'th Order PLL Detection for Various Values of $\alpha$ and $\beta$, $\Delta = 8^\circ$. 
The following plots were generated using the computer model discussed in the text for area coverage analysis. Each plot's label identifies the situation, jammed or unjammed, which is shown by that particular plot. See Section 5.4 for a detailed description.
Figure F-1. GEOGRAPHICAL REGION (KILOMETERS)
JTIDS T100 ANT2 HILLS J10K D10 N
Figure F-2. GEOGRAPHICAL REGION (KILOMETERS)

JTIDS T100 ANT2 HILLS J10K D10 J
Figure F-3. GEOGRAPHICAL REGION (KILOMETERS
JTIDS T100 ANT2 HILLS J600 D10 J
Figure F-4. GEOGRAPHICAL REGION (KILOMETERS)
JTIDS T100 ANT2 HILLS J10k D30 N
Figure F-5. GEOGRAPHICAL REGION (KILOMETERS)

JTIDS T100 ART2 HILLS J10K D30 J
Figure F-7. GEOGRAPHICAL REGION (KILOMETERS)
JTIDS T200 ANT2 HILLS J10K D10 J
Figure F-8. GEOGRAPHICAL REGION (KILOMETERS)
JTIDS T200 ANT2 HILLS J600 D10 J
Figure F-9. GEOGRAPHICAL REGION (KILOMETERS)
JTIDS T200 ANT2 HILLS J10K D50 N
Figure F-10. GEOGRAPHICAL REGION (KILOMETERS)

ITIDS T200 ANT2 HILLS J10K D30 J
Figure F-11. GEOGRAPHICAL REGION (KILOMETERS)
JTIDS T200 A10 HILLS J10K D10 N
Figure F-12. GEOGRAPHICAL REGION (KILOMETERS)

JTIDS T200 A10 HILLS J10K D10 J
Figure F-13. GEOGRAPHICAL REGION (KILOMETERS)

JTIDS T200 A10 HILLS J600 D10 J
Figure F-14. GEOGRAPHICAL REGION (KILOMETERS)

JTIDS T200 A10 HILLS J10K D30 N
Figure F-15. GEOGRAPHICAL REGION (KILOMETERS)

JTIDS T200 A10 HILLS J10K D30 J
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Figure F-16. GEOGRAPHICAL REGION (KILOMETERS)
JTIDS T200 A10 HILLS J50 D1 N
Figure F-17. GEOGRAPHICAL REGION (KILOMETERS)

JTD S T200 A10 HILLS J50 D1 J
Figure F-18. GEOGRAPHICAL REGION (KILOMETERS)
PLRS T100 ANT2 HILLS J1000 DS N
Figure F-19. GEOGRAPHICAL REGION (KILOMETERS)
PLRS T100 ANT2 HILLS J1000 DS J
Figure F-20. GEOGRAPHICAL REGION (KILOMETERS)
PLRS T100 ANT2 HILLS J250 DS J
Figure F-21. GEOGRAPHICAL REGION (KILOMETERS)
PLRS T100 ANT2 HILLS J1000 D20 N
Figure F-22. GEOGRAPHICAL REGION (KILOMETERS)
PLRS T100 ANT2 HILLS J1000 D20 J
Figure F-23. GEOGRAPHICAL REGION ( KILOMETERS )
PLRS T100 A10 HILLS J1000 D5 N
Figure F-24. GEOGRAPHICAL REGION (KILOMETERS)

PLRS T100 A10 HILLS J1000 D5 J
Figure F-25. GEOGRAPHICAL REGION (K I L O M E T E R S )

PLRS T100 A10 HILLS J250 DS J
Figure F-26. GEOGRAPHICAL REGION (KILOMETERS)
PLRS T100 A10 HILLS J1000 D20 N
Figure F-27. GEOGRAPHICAL REGION (KILOMETERS)

PLRS T100 A10 HILLS J1000 D20
Figure F-28. GEOGRAPHICAL REGION (KILOMETERS)
PLRS T100 A10 HILLS J50 D1 N
Figure F-29. GEOGRAPHICAL REGION (KILOMETERS)

PLRS T100 A10 HILLS J50 D1 J