

EVALUATION TECHNIQUES— FIXED SERVICE SYSTEMS TO POWER-LINE-CARRIER CIRCUITS

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ABSTRACT

Several methods for estimating the potential interference from systems in the Fixed Service to Power-Line-Carrier (PLC) circuits were developed. The Numerical Electromagnetic Code (NEC) computer program, originally developed by the Navy, was used to calculate the electric field intensity of the PLC radiated from a number of representative electric transmission lines. Measured field intensity data, obtained from five different geographical sites in the United States, were compared with the calculated results obtained using the NEC computer model and the agreement was found to be acceptable. In addition, the NEC program was used to estimate the coupling factor between the antennas of Ground Wave Emergency Network (GWEN), a system being developed by the U.S. Air Force, and a representative electric transmission line used for PLC applications in the United States. Interference threshold levels for PLC receivers were established from the test data, and corresponding field intensities near a transmission line that can produce those levels were calculated. Rules and regulations pertaining to the systems in the Fixed Service in the 150-190 kHz frequency range were reviewed and no regulatory problems were identified relative to the operation of PLC and systems in the Fixed Service in this frequency range.

Key Words

Compatibility Between PLC Systems and Radio Transmitters

GWEN System

Interference Analysis Model

Numerical Electromagnetic Code (NEC)

Power-Line-Carrier System

Radiated Field from Power Transmission Lines

Systems in the 150-190 kHz

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SECTION 1

INTRODUCTION

The National Telecommunications and Information Administration (NTIA) is responsible for managing the radio spectrum allocated to the U.S. Federal Government. Part of NTIA's responsibility is to: "establish policies concerning spectrum assignment, allocation and use, and provide the various Departments and agencies with guidance to assure that their conduct of telecommunications activities is consistent with these policies" (Department of Commerce, 1985). In support of these requirements, NTIA has undertaken a number of studies. The objectives of these studies are to: assess spectrum utilization, identify existing and/or potential compatibility problems between systems of various departments and agencies, provide recommendations for resolving any compatibility conflicts, and recommend changes to promote efficient use of the radio spectrum and to improve spectrum management procedures.

In carrying out its responsibility, NTIA has undertaken the task of investigating the potential interference to PLC systems from the Government radio communication facilities operating in the Fixed Service in the 150-190 kHz frequency range. A special working group was formed by the NTIA which consisted of representatives from a number of Government agencies and public utility organizations. It was the function of this working group to determine the criteria for compatibility between Government and PLC systems operating in the frequency range 150-190 kHz.

BACKGROUND

Power line carrier (PLC) systems have helped serve the communication needs of electric power utilities for over 60 years. The first application of a modulated carrier on a power line was made in 1921. By this time the use of multiplexed carrier systems for telephony and telegraphy on open-wire lines was already a highly developed technology.

Early PLC installations used 50-watt transmitters for distances up to about 140 km and 250 watts for longer distances. Frequencies employed were in the range from 50 to 150 kHz. Although modern PLC equipment operates with lower transmitter power, usually 10 watts or less; there are some transmitters which generate nearly 100 watts output power. Frequencies outside the 50 to 150 kHz range are now in use, and a large number of PLC systems operate between 150 and 190 kHz.

In the past, the need for regulatory status of PLC has been considered, but no action was taken because of administrative cost and the fact that compatibility between PLC and radio systems using the same frequencies as PLC transmitters has been acceptable. Recently, however, growing awareness of the probability of interference has prompted concern that certain frequency management practices may be necessary to maintain compatibility.

In September 1977, the U.S. Coast Guard (USCG) advised the Chairman of the Interdepartment Radio Advisory Committee (IRAC) (Document 19814/1.4.24) of certain problems associated with the "unregulated" nature of carrier systems, their "proliferation throughout frequency bands that include radionavigation, and their expansion geographically." The USCG expressed its concern with respect to the potential for interference to radionavigation by carrier systems and recommended that the IRAC, in coordination with Federal Communications Commission (FCC) consider certain actions to define a program in the national interest to resolve the conflicting trends in frequency usage. Ad Hoc Committee 162 was established in October 1977 and held its first meeting on January 19, 1978. Its final report was presented to the IRAC in April 1981.

Meanwhile, the Utilities Telecommunications Council (UTC), which is the telecommunication representative for the Nation's electric and gas utilities, was concerned over certain disadvantages in the regulatory classification of PLC and felt that the importance of PLC to the electric power utility industry was not properly understood or appreciated. In September 1980, the UTC filed a petition with the FCC (General Docket 82-9, RM-3747) seeking improved regulatory status for PLC. In January 1983, the FCC released its Report and Order providing amendments relative to PLC systems and their operation in Parts 2, 15, and 90 of the FCC Rules and Regulations.

Since January 1982, the Spectrum Planning Subcommittee (SPS) has considered early stage system reviews of Federal Emergency Management Administration's Low Frequency Mobile Warning System (LFMWS) and the Air Force's Ground Wave Emergency Network (GWEN), noting that the PLC systems operated by electric power utilities within the private sector, as well as the Federal Government, might be affected. It recommended that an Electromagnetic Compatibility (EMC) analyses of the proposed GWEN and PLC systems be performed.

NTIA recognized that PLC systems operate within the current FCC and NTIA regulations on a non-interference and unprotected basis with respect to allocated services in the 150-190 kHz frequency range. However, NTIA also recognized the importance of the PLC systems to the operation of the national electric power grid. As yet, the extent of the interaction and the criteria for compatibility between PLC and authorized radio systems, especially LFMWS and GWEN systems, are not known. NTIA established a Government-Industry working group to provide a technical base for assessing the potential interference to PLC circuits from systems in the Fixed Service (e.g., GWEN and LFMWS) and to determine the criteria for evaluation of this potential interference.

OBJECTIVES

The objectives of this effort were to:

1. Define criteria that may be used to obtain an approximation of potential interference from systems in the Fixed Service operating in the 150-190 kHz frequency range to PLC receivers
2. Identify and validate an analytical model and associated procedures that could be used to apply such criteria in an EMC analysis.

APPROACH

To accomplish the objectives of this effort, the following approach was taken.

1. An analytical model was identified as potentially useful in evaluating the electromagnetic coupling between systems in the Fixed Service in the 150-190 kHz frequency range and PLC systems. The model used in the analysis is called Numerical Electromagnetic Code (NEC) and takes into account the effects of the transmission line geometry and the losses due to finite ground conductivity. NEC is a computer model developed by the U.S. Navy and is generally used for calculating radiation from wire antennas. Six different locations in the United States were identified for the purpose of measuring field intensities near the power lines. The data obtained from five of the locations was compared with the theoretically calculated field intensities using the NEC.

2. The prototype version of the GWEN system in Pueblo, Colorado was used in a measurement to determine the power coupled into the PLC circuits located in Midway, Boone, and La Junta. The data was used to validate the coupling factor between the GWEN transmitter and these power line receivers. The measured coupling factors were compared with calculated values obtained by the NEC model. Field intensities were measured in the vicinity of the transmission lines and compared with signal levels coupled in the PLC circuit.

3. Interference threshold levels for several types of PLC receivers were determined by a series of tests. The GWEN-type signal was generated through a simulation process and used as an interferer in the tests. These results were used to determine acceptable signal-to-interference ratios (S/I) for PLC systems.

4. Analysis results were used to develop three procedures for assessing potential EMC problems to PLC from systems in the Fixed Service. Two of these techniques use the NEC model while the last one was derived using measured or calculated near field intensity data and the free-space propagation formula.

Potential interference from a proposed GWEN transmitter to a typical PLC system was analyzed as an illustration for the analysis procedures.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

GENERAL

The conclusions and recommendations are based on the results of an analysis conducted to determine the compatibility between the power line carrier (PLC) and Fixed Service systems operating in the 150-190 kHz frequency range. This analysis includes several field measurements performed at six different locations in the United States. The measured data was in acceptable agreement with the results obtained analytically using the NEC algorithm. In addition, the measurement results were used to determine field intensity levels that provide satisfactory PLC operation. The analysis may be applied to land based transmitters and receivers. Airborne radio transmitters were not considered during this investigation.

Five different functions performed by PLC receivers were considered in the analysis and an interference threshold for each receiver function was identified. These functions are: Transferred-Trip Relaying, CW Protective Relaying, Voice Transmission, Data Transmission, and Analog Telemetry. It is generally agreed that the first two functions named are of greater importance to electric utilities than the last three.

CONCLUSIONS

1. The measured data indicates that field intensities in the region under transmission lines conducting PLC signals from 1 to 10 watts in the 150-190 kHz frequency range vary from 80-110 dB above one microvolt per meter.

2. Analysis results, based on the measurements performed near the GWEN site in Pueblo, Colorado indicated that PLC systems on transmission lines can operate compatibly with in-band Fixed Service radio transmitters if the field intensities from these transmitters in the vicinity of transmission lines

remain below the levels indicated in Figure 47. These measurements represent the only available data to date for a prototype GWEN transmitter.

3. The analytical computer model developed during this task may be used to generate the field intensity contours near transmission lines due to transmitters in the Fixed Service operating in the 150-190 kHz frequency range.

4. The analytical computer model was found useful to predict the coupling factor between any specific segment of transmission line and the antenna of a terrestrial system.

5. The analysis results indicate the coupling factor between a transmission line and the antenna of a system in the Fixed Service is primarily a function of the geometry, the separation distance between the antenna and the transmission line, and the ground conductivity.

6. Measured data indicate that acceptable S/I and I/N criteria for compatible operation of PLC receivers are:

a) Transferred trip receivers maintain adequate dependability and security with signal-to-interference ratios of 10 dB or higher.

b) The sensitivity setting of CW protective relaying (pilot relay) receivers can be adjusted for satisfactory operation with signal-to-interference ratios equal to or greater than 13 dB.

c) A bit-error rate of 10^{-5} , which is generally acceptable by the industry for most inter-computer data transmission, can be achieved with signal-to-interference ratios equal to or greater than 10 dB.

d) FSK analog telemetry operates satisfactorily with signal-to-interference ratios equal to or greater than 5 dB.

e) The quality of single sideband telephone service remains acceptable for interference-to-noise ratio equal to zero dB. (The noise level

referred to here is equal to the level of adverse weather noise given by the curves in Figure 21.). This is equivalent to a signal-to-noise ratio of 25 dB or more.

7. The allocation rules and regulations applicable to systems in the 150-190 kHz frequency range were reviewed and no problems were identified relative to the operation of PLC systems.

RECOMMENDATIONS

The following are the Special Working Group and NTIA staff recommendations based on the technical findings contained in this report. Any action to implement these recommendations will be accomplished under separate correspondence by modifications of established rules, regulations, and procedures.

1. Computational procedures (a. coupling factor method, b. field intensity method, c. approximate method) described in this report and S/N and I/N ratios shown in the conclusions should be used in estimating potential interference from Fixed Service transmitters to PLC systems.

2. Government agencies using frequencies 150-190 kHz for Fixed Service transmitters should cooperate to minimize potential interference with electric power utilities using PLC to the extent practicable.

SECTION 3

ALLOCATIONS AND STANDARDS

GENERAL

The U.S. allocation table for the 150-190 kHz frequency range, along with all applicable footnotes, are described in this section. Rules and regulations pertaining to the operation of PLC and Fixed Service systems allocated in this frequency range are included in the discussion. Of particular interest are the frequency assignments in the 150-190 kHz frequency range granted to two recent systems under development by the Government (i.e., GWEN and LFMWS). A large majority of PLC receivers operate between 30-200 kHz, however, frequencies outside this range are also used by PLC circuits.

RULES AND REGULATIONS

The portions of the Federal Communications Commission Rules and Regulations (FCC Rules) containing policies relevant to this study include Part 2 that presents the National Table of Frequency Allocations, cited as 47CFR2.06, plus the equipment authorization procedures for all electronic products subject to the FCC Rules, cited as 47CFR2 subpart J; Part 15, cited as 47CFR15, which defines the constraints placed on the use and marketing of radio frequency (RF) devices put into operation without licenses; and Part 90 cited as 47CFR90.63.

The NTIA Manual of Regulations and Procedures for Federal Radio Frequency Management (NTIA Manual) contains policies established under the authority of the President. This document includes policies that have been developed by the NTIA under the delegation of authority provided by Executive Order 12046. A detailed tabular presentation of the allocated services for the Government and non-Government users is given in Chapter 4 of the Manual. These tables are comparable to those in Part 2 of the FCC Rules. Differences between the allocation tables in the NTIA Manual and the FCC Rules are largely a matter of format. Table 1 contains excerpts from the NTIA Manual (9 through 495 kHz) listing the primary and secondary services for both Government and

Non-Government users including those with allocations in the 150-190 kHz frequency bands. Table 1 also includes the complete text of all footnotes applicable to this analysis including footnote US294 which was added recently to cover the operation of power line carrier systems.

Note that the frequency range 150-190 kHz is allocated to Fixed and Maritime Mobile Services and 190-200 kHz is allocated to Aeronautical Radionavigation Service on a primary basis. Systems operating in the Fixed Service are germane to this study. Fixed Service is a radio-communication service between specified fixed points.

For regulation purposes, PLC equipment is classified the same as restricted radiation devices and is governed by the provisions set forth in Part 15 of the FCC Rules. The general conditions of operation discussed in Section 15.3 are applicable to restricted or incidental radiation devices including PLC systems. Section 15.4(t), added recently, provides a separate definition of PLC systems. Operation of these systems is governed by the provisions in Section 15.8. They are exempt from the operating requirement of Section 15.7. The following are pertinent excerpts from Part 15.

15.3 General Conditions of Operation

Persons operating restricted or incidental radiation devices (including Power Line Carrier Systems) shall not be deemed to have any vested or recognizable right to the continued use of any given frequency by virtue of prior registration or certification of equipment, or on the basis of prior notification of use pursuant to Section 90.63(g) of this chapter.

TABLE 1
EXCERPTS FROM THE U.S. TABLE OF ALLOCATIONS
IN THE FREQUENCY RANGE 9-495 kHz

| UNITED STATES | | | | |
|------------------|-------------------------------|--|--|--|
| Band MHz 1 | National Provisions 2 | Government Allocation 3 | Non-Government Allocation 4 | Remarks 5 |
| Below 9 | 444 445 | (Not Allocated) | (Not Allocated) | |
| 9-14 | US18 US294 | RADIONAVIGATION | RADIONAVIGATION | |
| 14-19.95 | US288 US294 | FIXED MARITIME MOBILE | Fixed | |
| 19.95-20.05 | US294 | STANDARD FREQUENCY AND TIME SIGNAL (20 kHz) | STANDARD FREQUENCY AND TIME SIGNAL (20 kHz) | FCC Rules and Regulations make no provisions for the licensing of standard frequency stations. |
| 20.05-59 | US288 US294 | FIXED MARITIME MOBILE | FIXED | |
| 59-61 | US294 | STANDARD FREQUENCY AND TIME SIGNAL (60 kHz) | STANDARD FREQUENCY AND TIME SIGNAL (60 kHz) | FCC Rules and Regulations make no provisions for the licensing of standard frequency stations. |
| 61-70 | US288 US294 | FIXED MARITIME MOBILE | FIXED | |
| 70-90 | US288 US294 | FIXED MARITIME MOBILE Radiolocation | FIXED Radiolocation | |
| 90-110 | US18 US104 US294 453 | RADIONAVIGATION | RADIONAVIGATION | |
| 110-130 | US294 454 | FIXED MARITIME MOBILE Radiolocation | FIXED MARITIME MOBILE Radiolocation | |
| 130-160 | US294 454 | FIXED MARITIME MOBILE | FIXED MARITIME MOBILE | |
| 160-190 | US294 459 | FIXED MARITIME MOBILE | FIXED | |
| 190-200 | US18 US226 US294 | AERONAUTICAL RADIONAVIGATION | AERONAUTICAL RADIONAVIGATION | |
| 200-275 | US18 US294 | AERONAUTICAL RADIONAVIGATION Aeronautical Mobile | AERONAUTICAL RADIONAVIGATION Aeronautical Mobile | |
| 275-285 | US18 US294 | AERONAUTICAL RADIONAVIGATION Aeronautical Mobile Maritime Radionavigation (Radiobeacons) | AERONAUTICAL RADIONAVIGATION Aeronautical Mobile Maritime Radionavigation (Radiobeacons) | |
| 285-325 | US18 US293 466 | MARITIME RADIONAVIGATION (Radiobeacons) Aeronautical Radionavigation (Radiobeacons) | MARITIME RADIONAVIGATION (Radiobeacons) Aeronautical Radionavigation (Radiobeacons) | |

TABLE 1 (continued)
 EXCERPTS FROM THE U.S. TABLE OF ALLOCATIONS
 IN THE FREQUENCY RANGE 9-495 kHz (CONTINUED)

| UNITED STATES | | | | |
|------------------|----------------------------------|--|--|--|
| Band kHz 1 | National Provisions 2 | Government Allocation 3 | Non-Government Allocation 4 | Remarks 5 |
| 325-335 | US18 US294 | AERONAUTICAL RADIONAVIGATION (Radiobeacons) Aeronautical Mobile Maritime Radionavigation (Radiobeacons) | AERONAUTICAL RADIONAVIGATION (Radiobeacons) Aeronautical Mobile Maritime Radionavigation (Radiobeacons) | |
| 335-405 | US18 US294 | AERONAUTICAL RADIONAVIGATION (Radiobeacons) Aeronautical Mobile | AERONAUTICAL RADIONAVIGATION (Radiobeacons) Aeronautical Mobile | |
| 405-415 | US18 US294 468 | RADIONAVIGATION Aeronautical Mobile | RADIONAVIGATION Aeronautical Mobile | |
| 415-435 | US294 470 | MARITIME MOBILE AERONAUTICAL RADIONAVIGATION | MARITIME MOBILE AERONAUTICAL RADIONAVIGATION | |
| 435-495 | US231 US294 470 471 | MARITIME MOBILE | MARITIME MOBILE | The frequency 480 kHz is available to low power Government Coast stations for the calibration of ship direction finders on the condition that harmful interference is not caused to the maritime mobile services. |

Footnotes relevant to this study are as follows:

US294 In the spectrum below 490 kHz electric utilities operate Power Line Carrier (PLC) systems on power transmission lines for communications important to the reliability and security of electric service to the public. These PLC systems operate under the provisions of Part 15 of the Federal Communication Commission's Rules

and Regulations or Chapter 7 of the National Telecommunication and Information Administration's Manual of Regulations and Procedures for Federal Radio Frequency Management, on an unprotected and noninterference basis with respect to authorized radio users. Notification of intent to place new or revised radio frequency uses in the bands below 490 kHz is to be made in accordance with the Rules and Regulations of the FCC and NTIA, users are urged to minimize potential interference to the degree practicable. This footnote does not provide any allocation status to PLC radio frequency uses.

454 Only classes A1A or F1B, A2C, F1C or F3C emissions are authorized for stations of the fixed service in the bands allocated to this service between 90 kHz and 160 kHz (148.5 kHz in Region 1) and for stations of the maritime mobile service in the bands allocated to this service between 110 kHz and 160 kHz (148.5 kHz in Region 1). Exceptionally, class J2B or J7B emissions are also authorized in the bands between 110 kHz and 160 kHz (148.5 in Region 1) for stations of the maritime mobile service.

459 In the Region 2 polar areas (north of 60° N and south of 60° S), which are subject to auroral disturbances, the aeronautical fixed service is the primary service in the band 160-190 kHz.

Operation of these devices is subject to the conditions that no harmful interference is caused and that interference must be accepted that may be caused by other incidental or restricted radiation devices, industrial, scientific or medical equipment, or from any authorized radio user.

15.4 General Definitions

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*

(d) Restricted Radiation Device

A device in which the generation of radio frequency energy is initially incorporated into the design and in which the radio frequency energy is conducted along wires or is radiated, exclusive of transmitters which require licensing under other parts of this chapter and exclusive of devices in which the radio frequency energy is used to produce physical, chemical or biological effects in materials and which are regulated under the provisions of Part 18 of this Chapter.

*
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*

(t) Power Line Carrier System

A carrier current system used by an electric power utility entity on transmission lines for protective relaying, telemetering, etc. for general supervision of the power system. The system operates by the transmission of radio frequency signals in the band from 10 kHz to 490 kHz by conduction over the electric power transmission lines of the system. The system does not include those electric lines which connect the

distribution substation to the customer or house wiring.

15.7 General Requirement for Restricted Radiation Devices

- (e) *
- *
- *

NOTE: Radio receivers, cable television systems, computing devices, TV interface devices, low-power communication devices, and power line carrier systems as used by electric utilities on power transmission lines are regulated elsewhere in this chapter and are not regulated by this section.

15.8 Operation of a Power Line Carrier System

a. A power utility operating Power Line Carrier systems shall submit the details of all existing systems plus any proposed new systems or changes to existing systems to an industry-operated entity as set forth in Section 90.63(g) of this chapter. No notification to the FCC is required.

b. The operating parameters of a Power Line Carrier System (particularly the frequency) shall be selected to achieve the highest practical degree of compatibility with authorized or licensed users of the radio spectrum. A Power Line Carrier System shall operate on an unprotected, noninterference basis in accordance with Section 15.3 of this Part. If harmful interference occurs, the electric power utility shall discontinue or adjust its Power Line Carrier operation, as required, to remedy the interference.

c. Power Line Carrier systems apparatus shall be operated with the minimum power possible to accomplish the desired purpose.

d. The best engineering principles shall be utilized in the generation of radio frequency currents by Power Line Carrier systems so as to guard against interference to authorized radio users, particularly on the fundamental and harmonic frequencies.

e. Power Line Carrier system apparatus shall conform to such engineering standards as may from time to time be promulgated by the Commission. In addition, such systems should adhere to industry approved standards designed to enhance the use of Power Line Carrier systems.

Modifications to part 90 referred to above is as follows:

90.63(g) Power Radio Service

*
*
*

The frequencies 10-490 kHz are used to operate electric utility Power Line Carrier (PLC) systems on power transmission lines for communications essential to the reliability and security of electric service to the public, in accordance with Part 15 of this chapter. Any electric utility fulfilling requirements in paragraph(a)(1) of this section may operate PLC systems and shall supply to a Federal Communications Commission/National Telecommunications and Information Administration recognized industry-operated entity,

information on all existing changes to existing, and proposed systems for inclusion in a data base. Such information shall include the frequency, power, location of transmitter(s), location of receivers and other technical and operational parameters, which would characterize the system's potential both to interfere with authorized radio users, and to receive harmful interference from these users. In an agreed upon format, the industry-operated entity shall inform the National Telecommunications and Information Administration and the Commission of these system characteristics prior to implementation of any proposed PLC system and shall provide monthly or periodic lists with supplements of PLC systems. The Federal Communications Commission and National Telecommunications and Information Administration will supply appropriate application and licensing information to the notification activity regarding authorized radio stations operating in the band. PLC systems in this band operate on a noninterference basis to radio systems assigned frequencies by the NTIA or licensed by the FCC and are not protected from interference due to these radio operations.

On January 27, 1983, the FCC released a "Report and Order" (Gen. Docket No. 82-9, RM-3747) that ammended Parts 2, 15, and 90 of the FCC Rules. Status of PLC was reiterated under "Discussion" in this docket, which reads as follows:

"....The Commission in its NPRM in this proceeding recognized the importance of PLC operation in monitoring and protecting the electrical transmission systems that supply energy to the nation's homes and businesses. The Commission also agreed that because of the nationwide functions performed by PLC systems, enhanced recognition of their importance is desirable and in the public interest. The Commission further stated that because PLC systems operate under the unlicensed

provisions of Part 15, our first concern is that any recognition of PLC systems not be interpreted as the promotion of PLC at the expense of other users. Based on several comments in the proceeding which incorrectly speak of coordination rather than notification and of maintaining existing status of PLC relative to other Part 15 users, the Commission seeks to dispel any misunderstanding concerning the intent of this proceeding. Accordingly, the Commission wants to reaffirm its position that this proceeding does not elevate the status of PLC in any way and that their operation in the band must be on an unprotected, non-interference basis to authorized users and at the same time on a co-equal basis to other unlicensed users operating under Part 15 provisions. Cooperation between parties to the extent practicable is expected, but in any event, the PLC users must realize that in the event conflicts on spectrum usage cannot be resolved on a cooperative basis, their operation on an unprotected, non-interference basis must adjust to meet the requirements of the authorized radio users."

The term "authorized users," in the paragraph above, refers to any system that has been granted spectrum support. According to the FCC's "Discussion" quoted above, the status of PLC remains the same and as such, any discussion at the Spectrum Planning Subcommittee (SPS) regarding the request for spectrum support for a system in any allocated radio service, the subject of the mutual interference between this system and PLC operations should not be considered as a requirement in granting the request. However, cooperation, to the extent practicable, between the allocated services and PLC systems to minimize mutual interference is recommended by the FCC and NTIA.

Footnote US294 provides recognition of electric power utility PLC systems in the bands below 490 kHz. (see Table 1). This footnote brings to the attention of licensed users in these bands the presence of PLC systems. In practice, it is not a bargaining ground between PLC and allocated systems. Restriction of PLC to certain segments of the frequency group was considered by the FCC, but was not adopted.

To facilitate cooperation between PLC and radio users, a data base identifying the locations of PLC receivers and transmitters and the frequencies they use is being established. A "notification activity" was created by PLC users to serve as a center for information exchange between authorized users and the PLC. Notification procedures are discussed in the FCC's docket (Gen. Docket No. 82-9). A memorandum of understanding (MOU) was prepared and is under review by the FCC, NTIA, Utilities Telecommunication Council (UTC), and North American Electric Reliability Council (NERC). This MOU may specify the procedures and relationships expected among the data base users. Participation in the notification activity by the PLC users is required by the terms specified in 47CFR 90.63(g). NERC was designated to serve as the industry-operated entity to oversee the notification process.

NTIA's policy concerning the usage of radio frequencies below 30 MHz is stated in 8.2.11 of the NTIA Manual. This policy limits the use of these frequencies, by the Executive Branch of the Government, departments, and agencies for domestic Fixed Service, to certain circumstances listed in 8.2.11. This policy was adopted to ensure that, in so far as practicable, sufficient high frequencies will be available for the operation of radio circuits essential to the national security. In practice, this policy together with cooperation, may prevent proliferation of Government radios and, hence, it may reduce the possibility for potential interference between PLC and radio users.

TECHNICAL STANDARDS

The 150-190 kHz bands are basically allocated for communication and navigation purposes in the United States and Possessions. Technical standards requirements and objectives stated in Chapter 5 of the NTIA Manual are applicable to the Government systems operating in this 150-190 kHz frequency range. This chapter contains Radio Frequency Spectrum Standards applicable to Federal radio stations and systems. A radio frequency spectrum standard is a principle, rule, or criterion that bounds the spectrum-related parameters, and characteristics, of a radio station or system for the purpose of managing the Radio Frequency Spectrum. Spurious emission levels and frequency tolerances of different transmitters are given in 5.2.3 of the NTIA Manual.

PLC systems are under Part 15 of the FCC Rules and subject to applicable provisions of Chapter 7 of the NTIA Manual. While none of these regulations specify a limit for the radiated field intensity of a carrier signal, PLC operation is on a noninterference basis.

One objective of the FCC and NTIA is to prevent the occurrence of harmful interference from PLC's to authorized radio services. Operating practices, application techniques, equipment constraints, and other technical considerations necessary to accomplish the noninterference objective for PLC are of lesser concern to the regulating bodies. The development of technical standards by the industry to cover these areas is, therefore, strongly supported.

Early application of a carrier signal on power transmission lines was regarded more an art than a science, primarily because the design of the transmission line itself was determined by power system needs and could be influenced very little, if any, by communication needs. Standards directly applicable to PLC systems were slow to develop. Knowledge and experiences were exchanged through meetings and published transactions of technical societies such as the American Institute of Electrical Engineers (AIEE) that later merged with the Institute of Radio Engineers (IRE) to form the Institute of Electrical and Electronics Engineers (IEEE).

A guide for the "Application and Treatment of Channels for Power-Line Carrier" was developed and published as a transactions paper by the Power System Communications Committee of the AIEE in 1954 (AIEE, 1954). More recently, this guide was superceeded by a revised and updated version published as an IEEE Standard, 1980.

A committee of the American National Standards Institute (ANSI) deals entirely with standards for equipment used in PLC applications. Separate standards cover coupling capacitors (ANSI, 1981), coupling capacitor voltage transformers (ANSI, 1976), line traps (ANSI, 1981), line tuners (ANSI, 1984), and presently in preparation, PLC transmitter-receiver equipment (ANSI, 1984).

Various international organizations, notably CIGRE (Conference International des Grand Reseaux Electriques a Haute Tension, i.e., International Conference on Large High Voltage Electric Systems) and IEC (International Electrotechnical Commission) are responsible for the

publication of technical literature describing practices in different countries and for the development of standards needed by the international technical community. Both CIGRE and IEC have published guides on PLC. CIGRE has put emphasis on application, while the IEC deals more with equipment and services.

A new IEEE Standard (in preparation, 1985) will deal with providing assistance to PLC users for the purpose of achieving electromagnetic compatibility (EMC) with authorized radio systems (IEEE Standards Project, 198x).

ASSIGNMENTS

There are 2713 assignments in the Government Master File (GMF) in the 9-495 kHz frequency range, of which only 30 are in the 150-190 kHz frequency range. The data from the GMF shown in Table 2 were extracted in March 1984. Assignments to GWEN and LFMWS systems which are in the experimental station class were not included in Table 2. Table 2 shows that the maximum radiated power for the systems in the 9-495 kHz frequency range is from 50 kW to 2 MW. High-power transmitters (megawatts or more) in this frequency range are used for shore-to-ship communication and, hence, their radiation regions are in the direction of the oceans and extend beyond the coastal waters of the United States. Generally, radio transmitters used by Government agencies for inland communication have power levels in the kilowatt range. Note that these relatively high-power transmitters are already in operation in this frequency range. A review of the GMF records for the last decade indicated that there has not been significant change in the number of assignments in the 150-190 kHz frequency range. However, there are now definite plans for the two major systems, GWEN and LFMWS, to become operational in the 150-190 kHz frequency range. Both GWEN and LFMWS are nationwide radio communication networks and their radiated power may provide a potential source of interference to PLC receivers that use the same frequencies.

Information obtained from the non-Government Master File (NGMF) indicates that there are 2035 licenses in the 9-495 kHz frequency range and 11 licenses in the 150-190 kHz frequency range (see Table 3). Note that the non-

Government equipment in the 150-190 kHz has significantly lower power than those given in Table 2 for the Government equipment.

Table 4 gives a frequency distribution of PLC in the 9-495 kHz frequency range. Note that there are 4280 PLC transmitters in the 150-190 kHz frequency range. The combination of both the relatively low-power transmitters and, the low number of Government radio assignments in the frequency range 150-190 kHz offers credibility to the statement that so far, the PLC operation has been reasonably interference free.

TABLE 2

EXCERPTS FROM THE GMF IN THE 9-495 KHZ BANDS

(DATA EXTRACTED IN MARCH 1984.)

| STATION CLASS | 9-495 kHz | | 150-190 kHz | |
|-----------------------|-----------------------|-------------------------------|-----------------------|-------------------------------|
| | NUMBER OF ASSIGNMENTS | MAXIMUM POWER PER GMF (WATTS) | NUMBER OF ASSIGNMENTS | MAXIMUM POWER PER GMF (WATTS) |
| FA, FAB, FX, FC | 1412 | 600k | 16 | 100k |
| MA, MO, MS | 161 | 200k | -- | -- |
| RLB, RG, RLN, RLM, LR | 1133 | 2M | 14 | 16k |
| STANDARD FREQUENCY | 7 | 50k | -- | -- |
| TOTAL | 2713 | | 30 | |

Note: A brief description of the abbreviations in Table 2 is as follows:

FA = Aeronautical Station; FAB = Aeronautical Broadcast Station; FX = Fixed Station; FC = Coast Station; MA = Aircraft Station; MO = Mobile Station; MS = Ship Station; RLB = Aeronautical Radiobeacon Station; RG = Radio Direction Finding Station; RLN = Loran Station; RLM = Marine Radiobeacon Station; LR = Radiolocation Land Station.

TABLE 3

EXCERPTS FROM THE NGMF IN THE 9-495 KHZ BANDS

(DATA EXTRACTED IN JUNE 1984)

| STATION CLASS | 9-495 kHz | | 150-190 kHz | |
|---------------------------------|--------------------|--------------------------------|-----------------------|--------------------------------|
| | NUMBER OF LICENSES | MAXIMUM POWER PER NGMF (WATTS) | NUMBER OF ASSIGNMENTS | MAXIMUM POWER PER NGMF (WATTS) |
| FA, FB, FBR, FC, FCL, FX FXO | 91 | 20M | 3 | 1.0 |
| MA, MLP, MLR, MO, MSG | 48 | 1.0k | 8 | 10 |
| RLA, RLB, RLT | 1894 | 1.2k | -- | -- |
| FREQUENCY STANDARD | 2 | -- | -- | -- |
| TOTAL | 2035 | -- | 11 | -- |

Note: A brief description of the abbreviations in Table 3 is as follows:
 FA = Aeronautical Enroute Station; FB = Base Station; FBR = Base (Remote Pickup) Station; FC = Public Coast Station; FCL = Limited Coast Station; FX = Fixed Station; FXO = Operational Fixed Station; MA = Aircraft Station; MLP = Low Power Auxiliary Station; MLR = Remote Pickup Mobile Station; MO = Mobile Station; MSG = Ship Station (Telemetry); RLA = Aeronautical Marker Beacon Station; RLB = Aeronautical Radiobeacon Station; RLT = Radionavigation Land Test Station

TABLE 4

DISTRIBUTION OF POWER LINE CARRIER IN THE 9-495 KHZ FREQUENCY RANGE
(BASED ON 1979 ESTIMATE.)

| FREQUENCY (kHz) | APPROXIMATE NUMBER OF TRANSMITTERS | FREQUENCY (kHz) | APPROXIMATE NUMBER OF TRANSMITTERS |
|--------------------|--|--------------------|--|
| 9-23 | 300 | 150-190 | 4480 |
| 23-60 | 2570 | 190-200 | 860 |
| 60-70 | 650 | 200-282 | 1760 |
| 70-90 | 2320 | 282-325 | 250 |
| 90-110 | 2110 | 325-405 | 150 |
| 110-130 | 2140 | 405-495 | 15 |
| 130-150 | 2010 | <hr/> TOTAL | <hr/> 19615 |

SECTION 4

SYSTEMS IN 150-190 kHz FREQUENCY BANDS

GOVERNMENT RADIO EQUIPMENT

The frequency bands in the 150-190 kHz frequency range are used by both the Government and non-Government services mentioned in Section 3. The functions of Government equipment in this frequency range vary from medium to long-range communication networks. Additional functions are ship-to-shore communication and ionospheric research. The systems designed for these functions operate at sea, on land, and in the air. The transmitter power levels used by these systems range from a few watts to 2 MW. The higher power transmitters are generally used by the Coast Guard, the Navy, and the Air Force. High power transmitters in the 9-495 kHz frequency range are for shore-to-ship transmission that necessitates the antenna mainbeam to be directed toward the oceans bordering the United States. Hence, the interactions between PLC circuits and these high-power systems have been minimal. The signal structures for the system in this frequency range include on-off Continuous Wave (CW) keying, AM and FM teletype with audio reception, and single sideband for audio transmission. The high-power Navy systems are located in Annapolis, MD; Norfolk, VA; and Charleston, SC.

In addition to the existing systems in the 150-190 kHz frequency range, two major communication systems are under development by the Air Force and the Federal Emergency Management Agency (FEMA). These systems, as mentioned before, are GWEN and LFMWS. They have received spectrum support and a detailed description of their characteristics is as follows:

Ground Wave Emergency Network (GWEN)

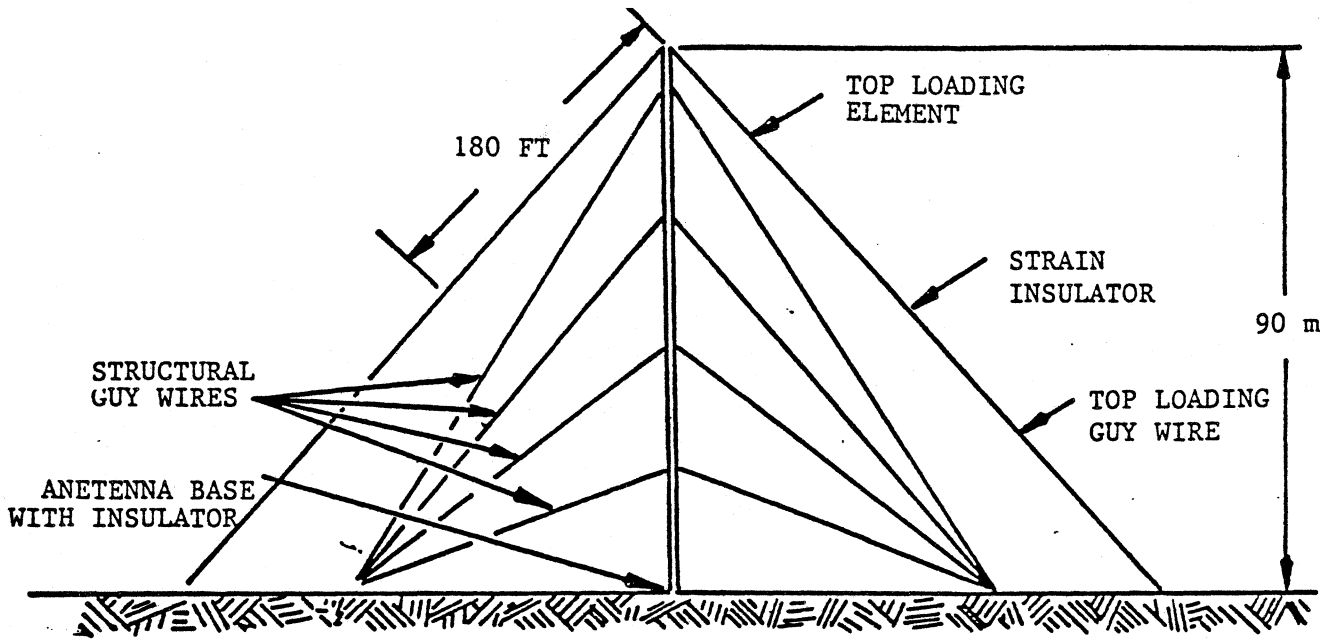
The GWEN system will provide the U.S. Air Force Strategic Air Command (SAC) with the ability to maintain critical long-range command, control, communications connectivity in the Continental United States (CONUS), despite atmospheric disturbances in the trans- and post-attack phases of a munitions laydown. Survivability for this system is provided primarily by a highly

redundant network of relay nodes, using unmanned and ground wave radio equipment. Three types of stations will be employed by the GWEN System: relay nodes, receive-only (R/O), and input-output (I/O) stations. The relay node stations can transmit and receive on low frequencies (LF) with selected relay nodes having UHF transmit and receive capabilities. Access communication equipment operating at UHF frequencies will be used at I/O stations to enable authorized users to inject messages into the LF system. Various user commands will be located within LF ground wave range of the relay nodes and will receive LF messages in R/O stations. The R/O stations will be located at bomber and dispersal bases, as well as at missile bases.

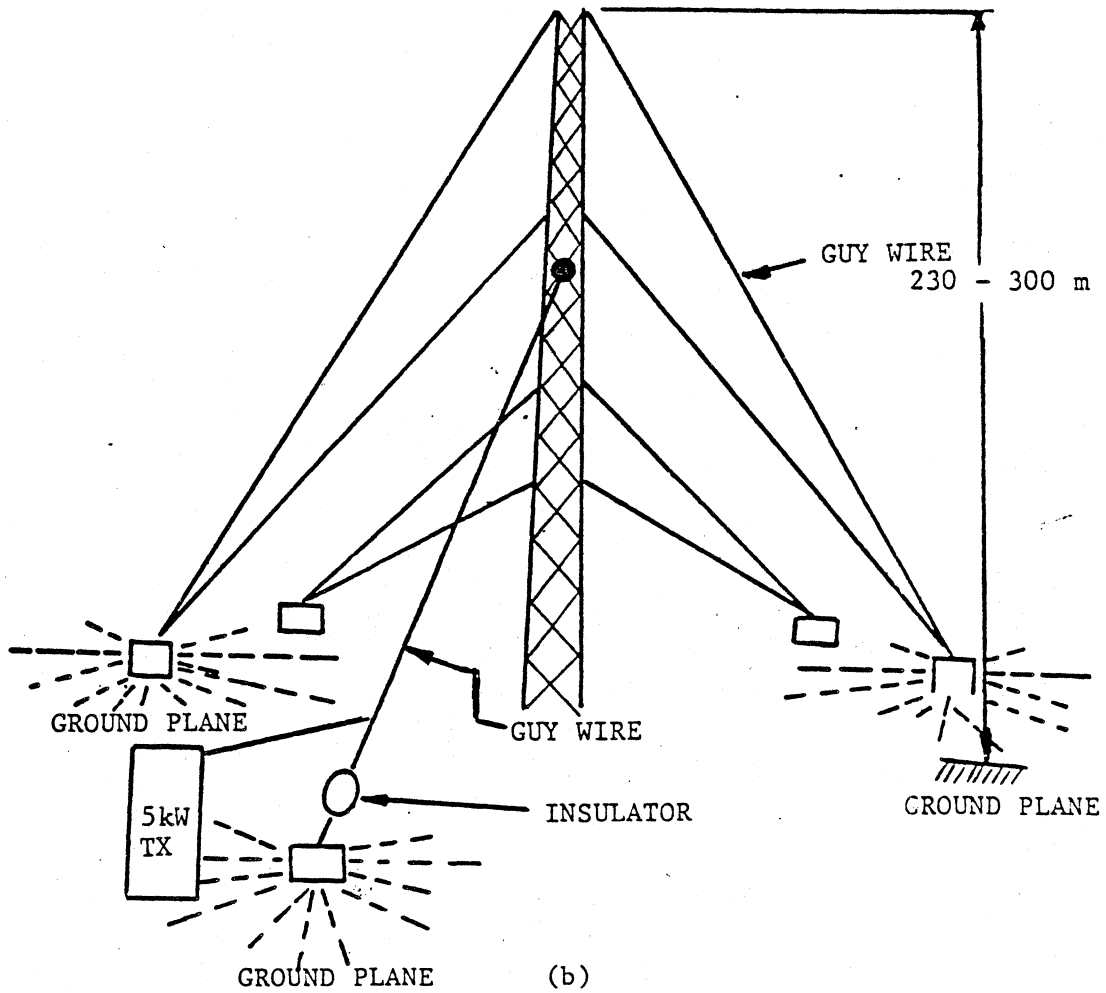
The GWEN System is being acquired in two phases, the Thin Line Connectivity Capability (TLCC) and the Final Operational Capability (FOC). The TLCC phase will include 57 relay nodes, 30 R/O receive only stations and 8 I/O stations. The TLCC was scheduled to be deployed in CY-84 and 85.

The FOC phase is scheduled for the CY-85 through the CY-88 time period. Additional fixed I/O and R/O terminals will be deployed, along with some mobile I/O and R/O terminals. The number of relay node terminals could increase.

The FOC configuration will provide survivability as well as increased system reliability. The low frequency band selected for GWEN is 150-175 kHz. The present channel plan starts at 150.250 kHz and has increments of 1,250 Hz. The modulation scheme is a special case of frequency shift keying, called "Continuous Phase FSK." The 3dB emission bandwidth is 712 Hz and the receiver 3 dB bandwidth is 1,250 Hz. The data rate is 1200 Hz. Several types of monopole antennas have been considered for use with GWEN transmitters. Two of the proposed types are shown in Figure 1. Figure 1a shows a top-loaded monopole which is placed over a ground screen approximately 150m in radius. The ground screen consists of a number of radial wires that pass through the antenna base separated from the ground by a large insulator. The antenna in Figure 1b is similar to that in Figure 1a, except that here the feed position is changed. The new feed structure permits a manual tuning capability that results in a better input impedance useful in matching the transmitter for maximum power transfer to the antenna. The GWEN system is now in Stage 4 review by the SPS of the Interdepartment Radio Advisory Committee (IRAC). Technical data for the GWEN System is listed below:



(a)



(b)

Figure 1. Proposed Antennas for GWEN System, (a) Monopole with Top Loading Element, (b) Matched Monopole with Guy Wires.

Transmitter

| | |
|----------------------|----------------|
| Frequency Range: | 150-175 kHz |
| Channeling: | 1.25 kHz |
| Emission: | 1K40FID |
| Emission Bandwidth: | 712 Hz (-3 dB) |
| Power: | 5 kw max |
| Spurious & Harmonics | -80 dBc |

Receiver

| | |
|---------------------|----------------------------|
| Bandwidth (3 dB) | 1,250 Hz (IF), 27 kHz (RF) |
| Sensitivity | -118 dBm, for 20 dB (C/N) |
| Spurious Rejection: | 80 dB |
| Image Rejection | 80 dB |

Antenna

| | |
|--------------|-------------------------|
| Transmitter: | Short Vertical monopole |
| Receiver: | Crossed Loops |

LOW FREQUENCY MOBILE WARNING SYSTEM (LFMWS)

FEMA is required to disseminate a warning of pending attack and subsequent information to thousands of state and local government points throughout the nation and to provide instructions to members of the Emergency Broadcasting System (EBS). Immediately following a nuclear attack, long-distance communications are expected to be disrupted as a result of damage to microwave-supported telephone circuits and high-frequency (HF) communication will be lost because of dispersion of the ionosphere. Therefore, FEMA is

developing the LFMWS to provide long-haul communications on frequencies not affected by the high-altitude nuclear detonation. The LFMWS is also known as the LF subsystem of the Direction, Control, Warning, and Communications System (DCWCS).

The proposed survivable LF system would use mobile units (MUs) with LF (160-190 kHz) high-power transmitters to disseminate the warning. To have suitable antenna facilities available for the LF signals, the concept calls for shared use of various fixed, commercial AM, FM, or TV antenna facilities. Twenty-seven transmit sites, each with an approximate 40 km radius, would be established with two MUs in each zone. One unit would be connected to a host broadcast facility tower and would be ready to transmit a warning without delay. The second unit would normally be enroute to or at another broadcast facility. The MUs would commute between facilities on an irregular schedule to preclude enemy prediction of the MU locations, thus complicating any effort to disable these units. The system would perform its function by having the active MUs receive a warning message from a National Warning Center and retransmit the warning throughout their transmit zone by LF.

The technical characteristics of the LFMWS are listed below.

Transmitter

| | |
|------------------------|-----------------------------------|
| Frequency Range: | 150-190 kHz |
| Channeling: | 3 kHz |
| Emission (USB or LSB): | 3K00J3 |
| Audio Characteristic: | 250-3000 Hz, + 1.5 dB variation |
| Emission bandwidth: | -3 dB 2.7 kHz Occupied 3.0 kHz |
| Intermodulation: | -35 dB below 2-tone test |
| Power: | 50 kw peak |
| Unwanted Sideband | -60 dB |
| Spurious Emission: | -60 dB |
| Harmonic Radiation: | -50 dB |

Receiver

| | |
|------------------------|--------------------------------|
| Audio Characteristics: | 250-3000 Hz, + 2 dB |
| IF Frequency: | 455 kHz |
| Sensitivity | .2 μ V for 10 dB (S + N)/N |
| AGC; Constant Audio: | 1 μ V to 1 V RF input |
| Spurious Rejection: | 35 dB |
| Image Rejection: | 70 dB |
| Intermodulation: | -35 dB |

Antenna

| | |
|--------------|-------------------|
| Transmitter: | Vertical Monopole |
| Receiver: | Undefined |

POWER LINE CARRIER (PLC) SYSTEM

In addition to licensed users in the 150-190 kHz frequency range, electric power utilities, under provisions of Part 15 of the FCC Rules, use frequencies below 490 kHz for operating PLC equipment. Approximately 18 percent of the PLC equipment in the U.S. belongs to utilities owned and operated by the Federal Government. Provisions pertaining to the operation of PLC systems by Government agencies are given in Chapter 7 of the NTIA Manual.

Electric power transmission lines provide an efficient medium for the propagation of PLC signals. Coupling capacitors capable of withstanding the high voltage are used to couple the signals to and from the line. Resonant circuits (i.e., line traps and line tuners) are used in conjunction with the coupling capacitors to maximize the efficiency of the path and to separate the signals by frequency. The PLC signal is frequently applied to a single transmission line conductor via ground return. This is called phase-to-ground coupling. Another commonly used method employs two conductors as a pair and is called phase-to-phase coupling.

Other media of transmission such as microwave radio and fiber optic cables are also widely used for power system communications. However, PLC on high-voltage transmission lines is important because of its reliability and other characteristics. PLC is a preferred medium for protective relaying applications - the most critical communications function involved in maintaining the integrity of the electric power network.

Modern electronic equipment being manufactured for PLC applications is all solid state, although there are many vacuum tube types still in service. These older models are gradually being phased out. Technical specifications governing the manufacture and performance of PLC apparatus are comparable to those for high quality radio equipment. For example, harmonics and other spurious outputs of a typical PLC transmitter are limited to a level of 50 to 60 dB below the fundamental output.

Protective relaying equipment uses either a CW or FSK signal. Most CW types are applied for transmission line protection and are normally quiescent, being keyed more frequently for test purposes than for actual use. Receiver response is simply a relay operation whenever an input signal higher than a preset operating threshold level is present. The output relay in some types of modern equipment is electronic rather than electromechanical. The application is called pilot relaying.

Occasionally, a pilot relay channel is equipped to serve as an emergency voice channel by the addition of an AM voice modulator. The transmitted bandwidth, with the modulator in use, is slightly less than 4 kHz; otherwise, its bandwidth is essentially zero (reported in the PLC data base as 100 Hz).

Receivers may come with either narrowband or wideband selectivity characteristics. The narrowband version is most common; however, if a voice modulator is to be used, or if higher speed is desired, the wideband is more appropriate. Figures 2 and 3 are sample response curves of each, illustrating the comparisons of older equipment with more modern designs.

FSK equipment is used for some versions of transmission line protection, but is more commonly used for direct transferred trip -- a scheme where a circuit breaker at a distant station must operate to isolate a local fault. The transmitted signal is not continuously keyed. Its standby state is a steady unmodulated (guard) signal that is shifted abruptly to accomplish

tripping. It is common practice to boost transmitter power by 10 dB when a trip signal is initiated. As with CW operation, the receiver output is simply one of two states; however, receiver circuits are much more complex than CW receivers. Much design attention is given to logic circuits and other methods of maximizing both security and dependability.

A typical selectivity curve for an FSK receiver with a plus and minus 100 Hz shift is shown in Figure 4. Wider shift ranges employed for higher-speed operation require correspondingly wider receiver passbands.

PLC protective relaying channels are usually designed for a minimum signal-to-noise ratio (S/N) of 13 dB based on noise as measured within the receiver passband. Most measurements of noise on PLC circuits are made using an instrument with 3 kHz selectivity. It is common practice to refer to S/N of a PLC channel in terms of 3 kHz noise rather than actual inband noise. For example, if a transferred trip receiver with a 400 Hz bandwidth has an inband S/N of 13 dB, its S/N based on measured 3 kHz noise, would be about 4 dB.

Equipment used for analog telemetering and data transmission sends an FSK signal in a conventional manner with a keying rate and bandwidth compatible with the speed of the information transmitted. Most manufacturers of FSK equipment supply different versions of the same general type equipment for protective relaying applications and for continuously keyed circuits. The recommended minimum S/N for telemetering and data circuits, based on inband noise, is 20 dB.

Although some older equipment uses double sideband AM and FM techniques, most PLC equipment for voice communication is single sideband (SSB) with a reduced carrier usually transmitted as a pilot for automatic regulation and frequency synchronization. In the United States, carrier frequencies for SSB equipment are assigned on 4 kHz multiples.

"Speech-plus-tone" operation is frequently applied to voice band channels. Separation filters confine the speech to the lower frequencies so that one or more narrowband frequency-shift keyed FSK audio tones can occupy the upper part of the audio spectrum at a spacing that ranges from 120 to 340 Hz. These tones may be used for slow speed analog telemetering, data, or control functions. A typical crossover frequency is 2200 Hz.

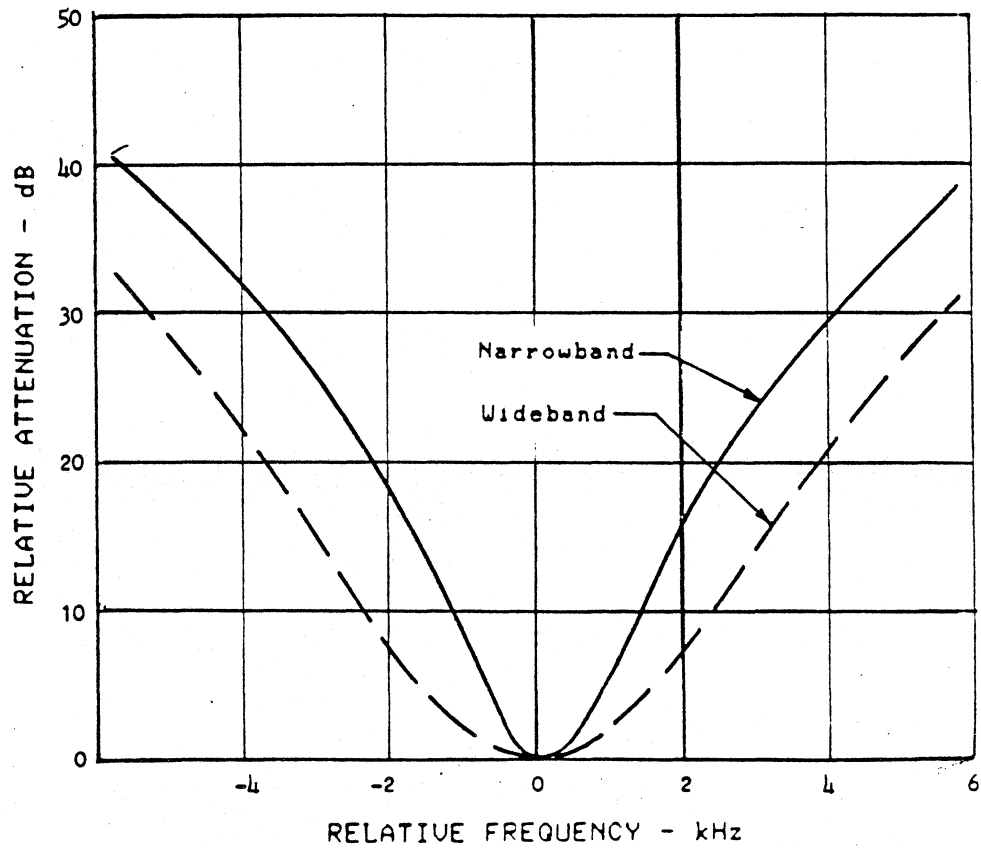


Figure 2. Frequency Response of Typical Earlier Models of Pilot Relay Receivers.

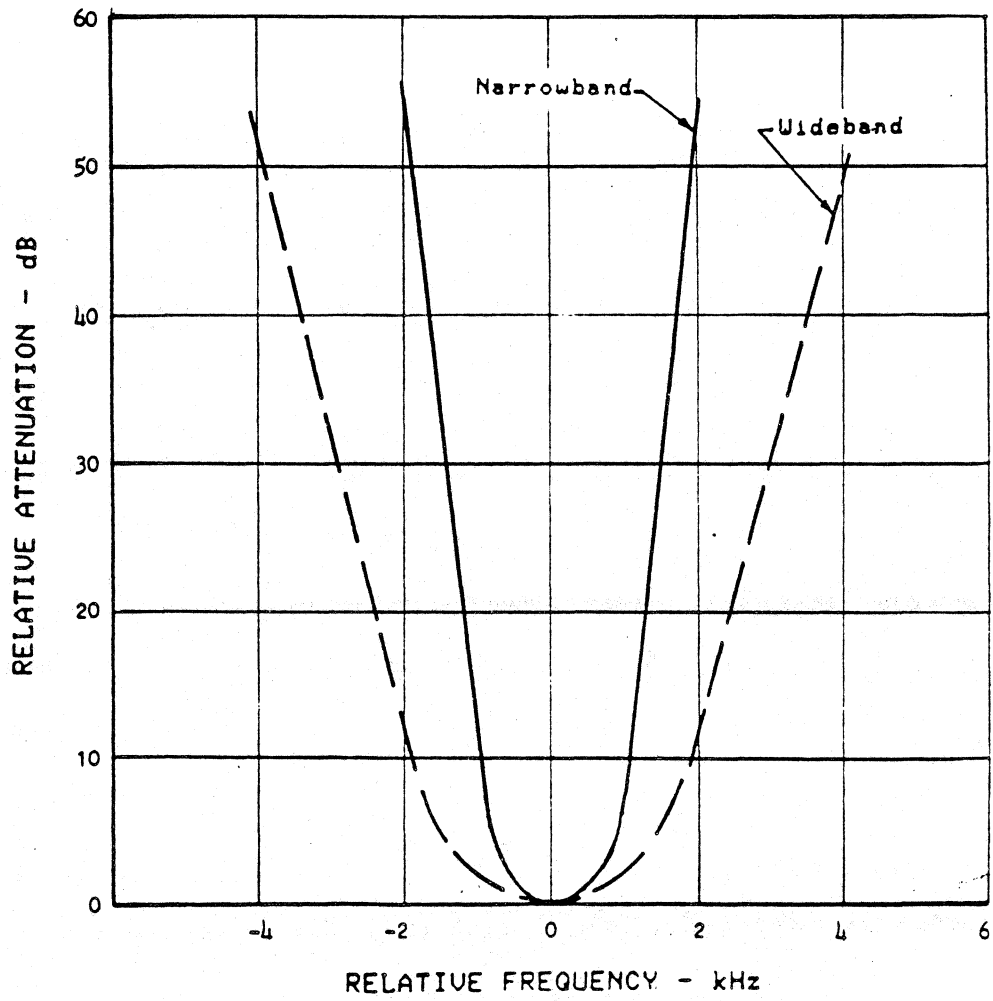


Figure 3. Frequency Response of Typical Modern Pilot Relay Receivers.

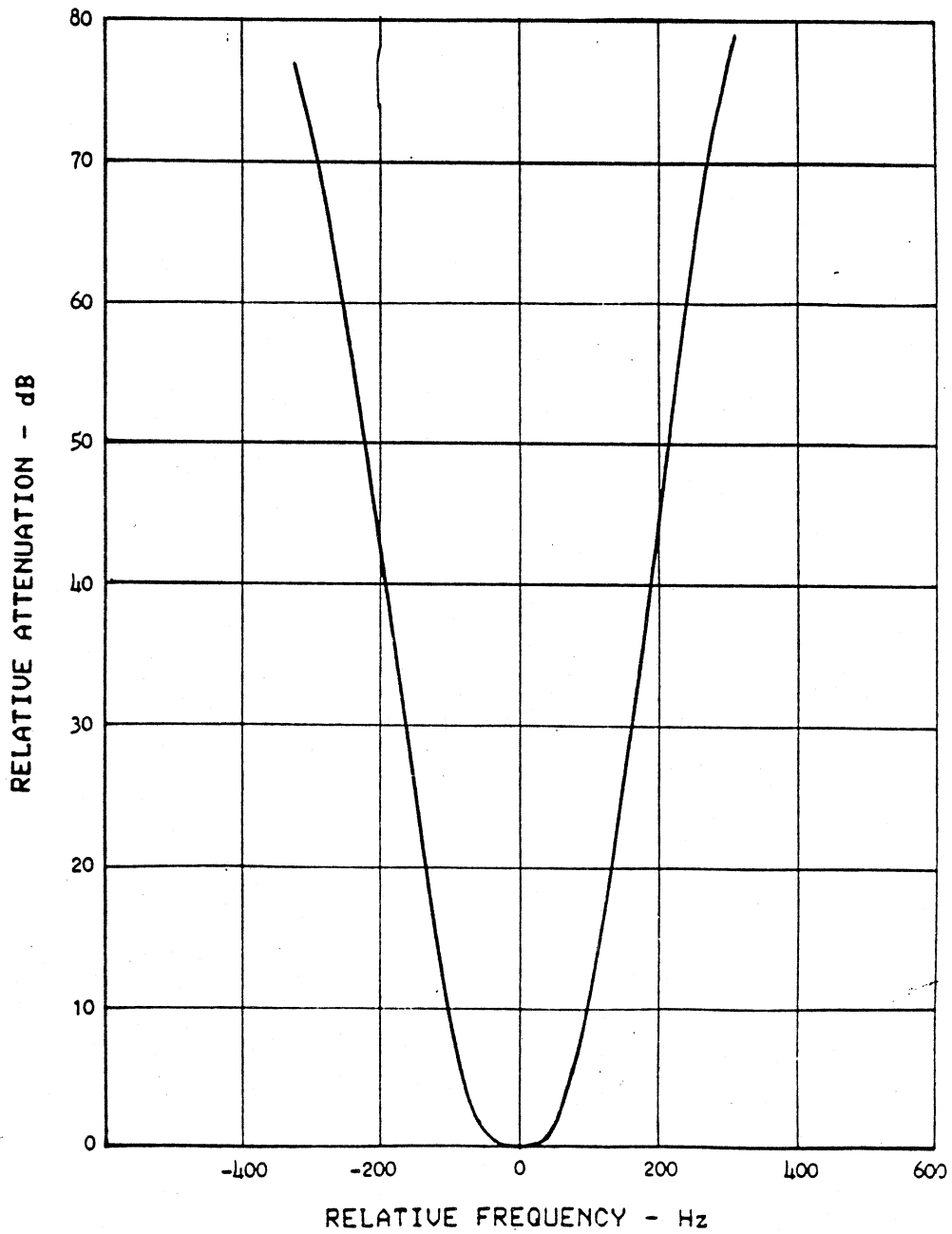


Figure 4. Frequency Response of Typical Transferred Trip Receivers.

PLC voice channels are usually designed for a minimum S/N of 25 dB. SSB receivers have excellent selectivity as illustrated in Figure 5, which shows a typical overall frequency response.

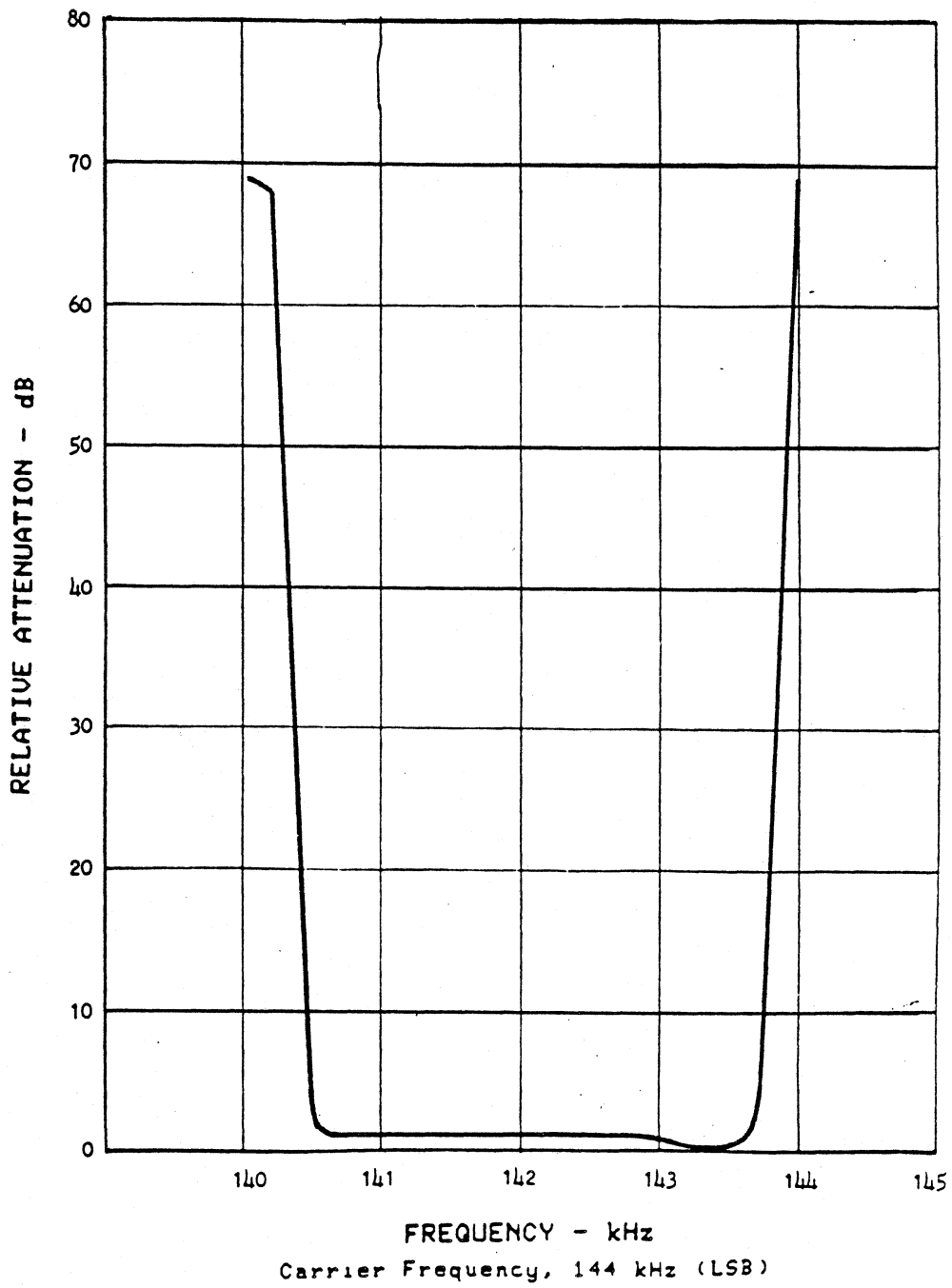


Figure 5. Frequency Response of a Typical Single-Channel SSB Receiver.

SECTION 5

ANALYSIS OF POTENTIAL INTERFERENCE TO PLC

PROBLEM DEFINITION

A problem definition is necessary before the discussion of analysis. Power line carrier is a low frequency communication system which makes use of high voltage electric power transmission lines as the medium for propagation of radio signals. These transmission lines are part of the high voltage lines used for the transmission of electric power in the United States. The PLC signals considered in this analysis operate in the 150-190 kHz frequency range. Fixed and Mobile Services allocated in this frequency range may induce undesired signals in transmission lines used by PLC systems. This problem is specially significant when nationwide radio networks such as GWEN or LFMWS are planned to operate in the frequency range used by PLC systems. The potential interference from systems in the Fixed Service has been treated in the analysis given here. Determination of the coupling factor for the radio signal and the interference threshold of PLC receivers constitute the major part of the analysis.

COUPLING FACTOR

The coupling of potential interference to PLC from Fixed Service radio networks in the 150-190 kHz is manageable using basic principles of frequency management techniques. Several methods for predicting the potential interference have been developed. A brief discussion of the coupling and a definition of coupling factor are useful in developing an insight for the problem treated in the analysis.

The electric field vector of a wave traveling along a perfectly conducting surface shown in Figure 6a is perpendicular to that surface. However, an electric power transmission line representing a wave antenna is not a perfect conductor. In addition, its radiation property is influenced by its proximity to the ground with finite conductivity and resistivity. The finite conductivity of the transmission line and the ground over which it is

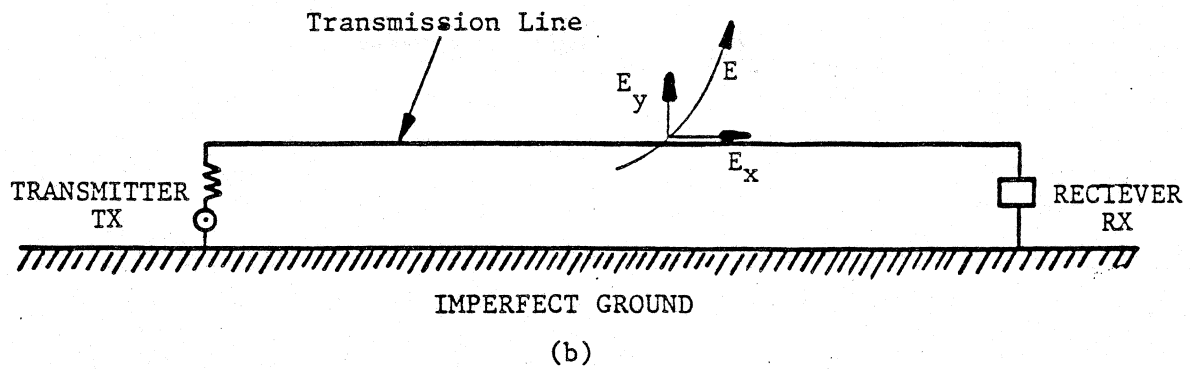
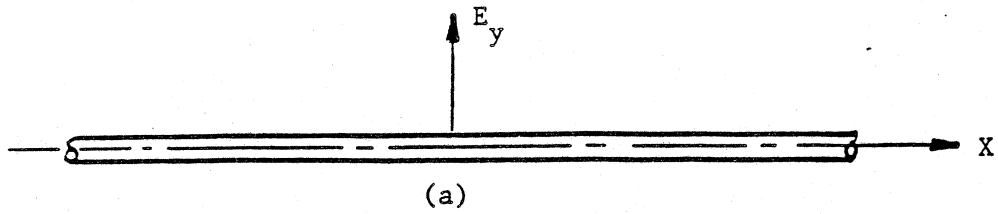


Figure 6. Transmission Line as a Wave Antenna. (a) Perfectly Conducting Transmission Line in Free Space. (b) Transmission Line Over Imperfect Ground.

located together with the geometry of the line produce a mechanism for an interfering signal to couple into the PLC.

In a transmission line, the electric field vector E, near the conductor surface, has a forward tilt as shown in Figure 6b. Note that at points very close to the conductor, the electric field E may be expressed by a vertical and horizontal components E_y and E_x , respectively. The magnitude of E_x is much smaller than E_y . However, the presence of E_x may explain the reason for a current induced in a horizontal transmission line by a vertically polarized radio signal. As we shall see later, transmission lines are not all perfectly horizontal nor are all the radio signal antennas entirely vertical. Therefore, the coupling between the power transmission lines and the radio antennas is further enhanced by partial copolarization of the radiated E field from these antennas in an operational environment. The vertical ground connection to the shielded wires, extensive hardware used for bonding and grounding, and the ground counterpoise wires used in some areas in the country add considerably to the complexity of the transmission lines as radiating antennas.

Despite the simplicity and wide usage, the term "antenna coupling" has been defined in different ways in the literature. Hence, a definition of coupling is needed here as a background for this analysis.

The term "antenna coupling" is defined here as the ratio of the power delivered (to a specific load connected to the receiving antenna) to the power input to the transmitting antenna. The common logarithm of this ratio multiplied by ten yields the "Coupling Factor" in decibels (dB) is as follows:

$$F_c = 10 \log \frac{P_{rw}}{P_{tw}} \text{ (dB)}$$

where

F_c = Coupling factor in dB

P_{rw} = Power delivered to the receiver in watts

P_{tw} = Power input to transmitter antenna in watts

The maximum coupling factor is calculated assuming matched impedances. However, the geometry and the orientation of the transmission lines which serve as receiving antennas, and the tower structures used by the radio transmitters, remain as variables in the computation of the coupling factor.

ANALYSIS METHODOLOGY

Overhead electric power transmission lines, used as a medium for propagation of carrier signal energy, also act as antennas for receiving radio signals in the 150-190 kHz frequency range. Since the transmission lines are linear circuits, the principle of reciprocity can be used to determine field intensity (FI) levels that correspond to an acceptable signal-to-interference plus noise ratio, S/(I+N) ratio. Determination of FI was carried out using the procedure outlined below.

Power transmission lines often have complex geometries and vary from three parallel conductors to more than 15 conductors. The NEC was found to be applicable to the analysis of radiation from these lines. Measured data obtained on field intensities from power lines for some typical geometries at six different locations in the United States were used to substantiate the results calculated using the NEC model.

The data taken with the field intensity meter were plotted. These data describe the relationship between the radiated field intensity from typical transmission line geometries with operating PLC systems and the transverse distance from the line for each configuration. The "coupling factor" for typical PLC systems was obtained using the NEC model in conjunction with the data given in these experimental curves. The calculated and/or measured data on the coupling factor was used in conjunction with the interference threshold data to calculate the FI criteria for power line carrier systems.

To determine an acceptable interference threshold for various types of PLC receivers, extensive bench tests were conducted at the Tennessee Valley Authority (TVA) facilities in Tennessee.

INTERFERENCE THRESHOLDS OF PLC RECEIVERS

A test plan was prepared for PLC bench tests to obtain data on interference thresholds for different types of PLC receivers. The following tests were performed in conformity with that plan in the Central Laboratories of the TVA near Chattanooga, Tennessee.

Each PLC receiver was set up to operate in a high-noise environment. Three isolated inputs were provided as shown in Figure 7. Carrier-frequency hybrids provided isolation to remove any possibility of intermodulation or other loading effects among the different inputs.

A commercial white noise generator was used as a noise source. Its level at the receiver was adjusted to approximate a value which might be expected on a 230 kV transmission line at 150 kHz during adverse weather. By referring to Figure 21, it can be seen that the midrange noise level for a power line of this voltage at 150 kHz is -20 dBm. The exact level used varied from test to test for convenience in adjusting the carrier receivers. Actual noise levels ranged from -22 dBm for the SSB voice tests to -16.5 dBm for the transferred trip dependability tests. Noise levels were measured using a selective level meter with a 3 kHz bandwidth and averaging response.

The PLC signal level into each receiver was adjusted to establish its operation with a minimum S/N where feasible. For example, to provide a minimum S/N of 25 dB for the SSB voice test, the carrier-frequency signal level at the receiver input was adjusted for +3 dBm (i.e., 25 dB above the noise level of -22 dBm).

Finally, a cochannel interfering signal provided the third input. Its level was increased until interference was first observed or measured, then it was further increased to the extent practicable to determine a bearable limit. To simulate the interfering signal, a radio frequency source was used, which closely resembled what the GWEN radio signal was expected to be. An FSK signal with a ± 500 Hz shift was keyed with random data at approximately 300 bps.

The frequency used for each test was determined solely on the basis of equipment availability. This was discussed by the special working group prior to the detailed planning of the tests. It was agreed that test frequencies need not fall within the 150-190 kHz range, since the selectivity of the receivers is not a function of operating frequencies.

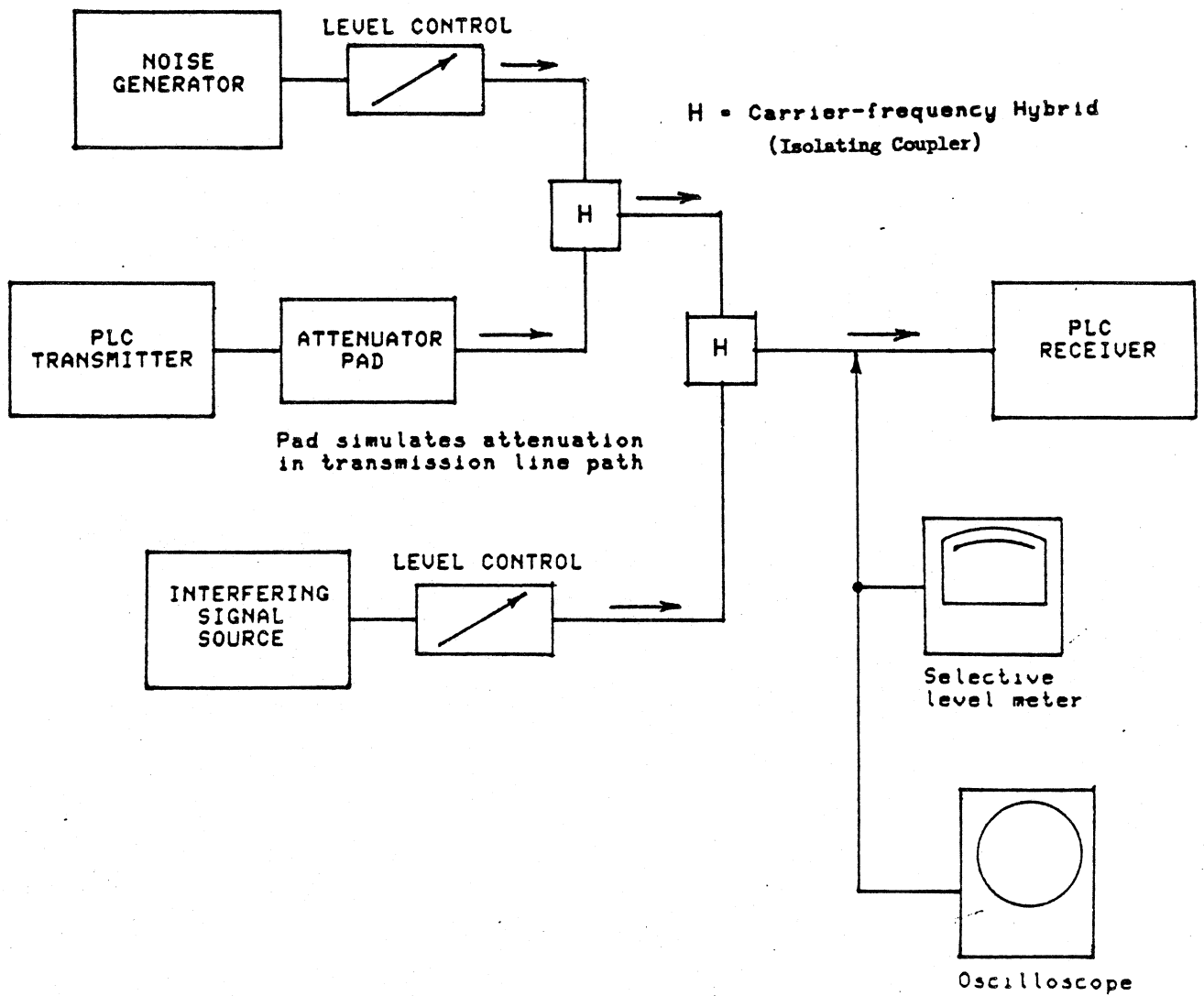


Figure 7. Schematic of the Set-Up for Measuring PLC Interference Threshold.

Some limitations on the threshold measurements are acknowledged. It would have been desirable to obtain more data than time and resources permitted. The PLC receivers used in the tests are believed to be typical; however, some variance should be expected in the field. The interfering signal used for the tests was a laboratory simulation of what the GWEN signal was believed to be. The nature of the LFMWS signal was not known. The data collected fell into logical patterns and within reasonable variances. Indicated conclusions are considered to be useful for this analysis.

PLC receivers used in each of the following functions were tested:

- Single Sideband (SSB) voice
- FSK transferred trip relaying
- FSK data Transmission
- FSK analog telemeter

Protective relaying equipment for keyed CW operation was not included in the tests. In normal service, this type of equipment is set for a given operating threshold, and the tolerable interference limit would be exactly equal to this same value.

Of these, correct operation of protective relaying receivers is most important to the operation of an electric utility. A false trip by a relay receiver may cause a regional blackout. Interference to SSB voice, FSK data and Telemetry may be detrimental to the operation of a utility organization; however, the impairment of such receivers due to noise or interference does not bring about an interruption of the utility service to consumers. The method for establishing interference thresholds varied for each type of PLC receiver. These methods are described below.

Single Sideband (SSB) Voice

This test arrangement was set up as a standard telephone circuit except that during the test it was used for one-way communication. This test was conducted at a frequency of 144 kHz (lower sideband). The interfering signal was adjusted to a center frequency of 1500 Hz in the derived voice band.

For all tests, the carrier-frequency signal level (test tone) at the receiver input was set at 3 dBm. The white noise level, representing adverse weather noise, was -22 dBm.

The SSB receiver audio output signal was connected to a divider circuit as shown in Figure 8 so that separate telephones could be provided for eight listeners. With a test tone transmitted at standard level, the receiver output was adjusted so that the level at each phone was approximately -5 dBm. The telephone receivers used in this test were not identical; however, each was a new set and was tested to verify a comfortable hearing level.

For this subjective test, eight listeners participated. The group consisted of the following:

- Office secretary
- Substation operator
- Power system dispatcher
- Wire chief test board operator
- Communication maintenance technician
- Design engineer
- Maintenance electrician
- Visitor

Several recorded voice messages were prepared for transmission over the PLC voice circuit. Each message used the same format (i.e., it contained an arbitrary test reference number, several statements and questions, and a series of six-digit numbers that the listeners were asked to write down). Parts of each message were relayed by both male and female voices.

This test was repeated several times under identical circumstances except for the level of the interfering signal. The average level of the transmitted voice was carefully maintained at the proper normal level. Participants were asked to judge the quality of the circuit after each test by answering a few multiple-choice questions.

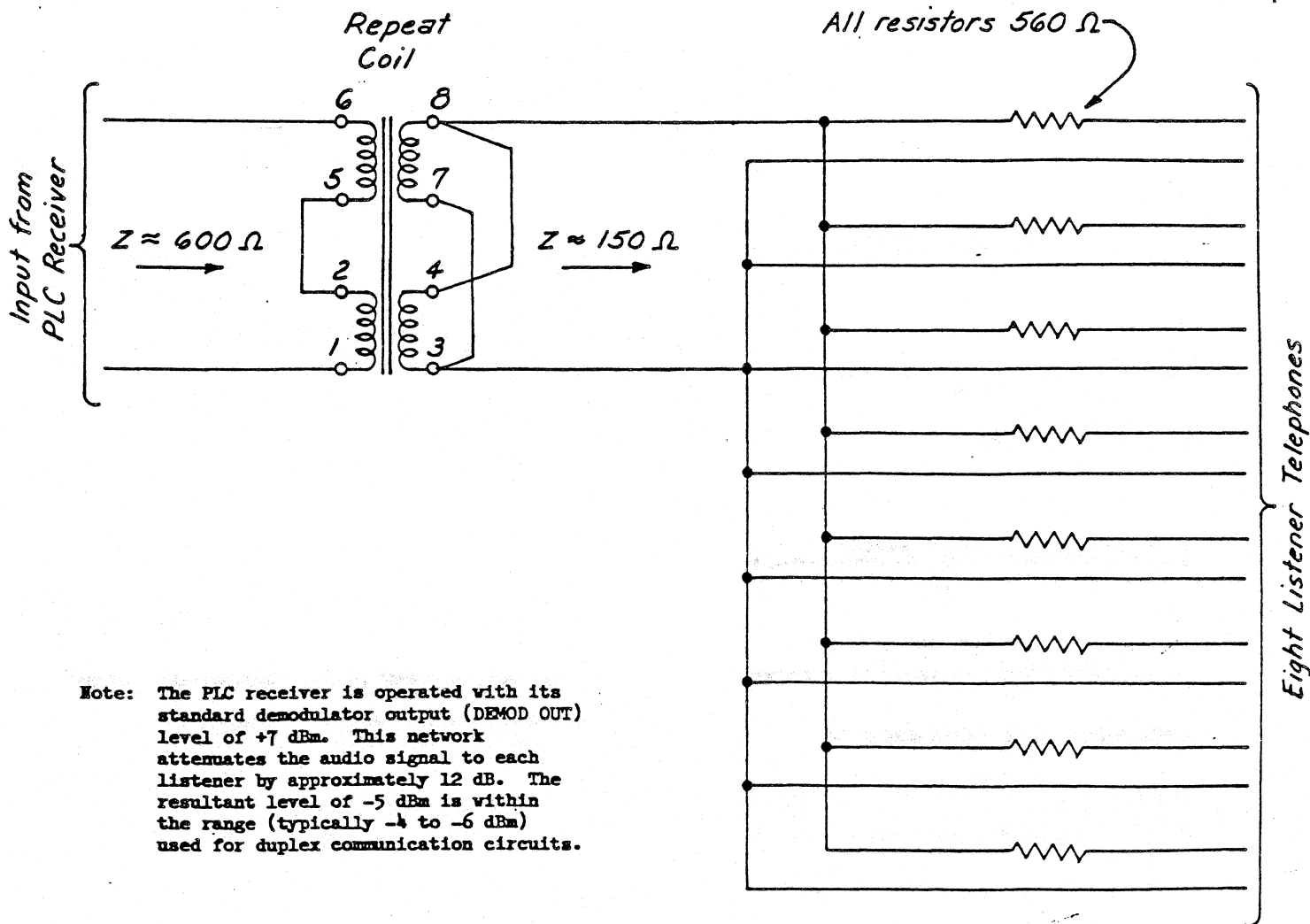


Figure 8. Circuit Permitting Use of Eight Listener Telephones For SSB Voice Test.

Two evaluations of intelligibility were attempted. Perceived intelligibility (the ease with which the listener felt he could understand the message) was taken as a judgement rating on the part of the listener. These results are shown in Figure 10. The second evaluation was an actual count of errors made in transcribing six-digit numbers. Plots of these errors are shown in Figure 12.

Figures 9, 10, and 11 show plots of listener ratings in the categories of background annoyance, intelligibility, and usage, respectively. In each of these figures, the numbers in circles represent listener votes on the indicated questionnaire choice. The heavy line plotted in each figure represents a weighted average of these votes.

Comparisons were made of the effect of interference with and without added white noise. Removal of background white noise with S/I ratios of 9 dB and 15 dB produced noticeable improvements in listener acceptance, particularly in perceived intelligibility. Compare figures 9b through 11b with Figure 9a, etc.

The high-level simulated GWEN signal alone did not cause as serious degradation in the quality of the voice transmission as the high-level white noise alone. Only one test was conducted with noise alone. This was at a S/N ratio of 9 dB. All listener votes (except one in the background category) were in the lowest position (not understandable).

The overall results indicated that in the presence of adverse weather noise, the quality of the voice circuit deteriorated when the interfering signal exceeded a level approximately 25 dB below the level of the desired signal. Temporary emergency operation would be possible with 5 to 10 dB higher levels of interference.

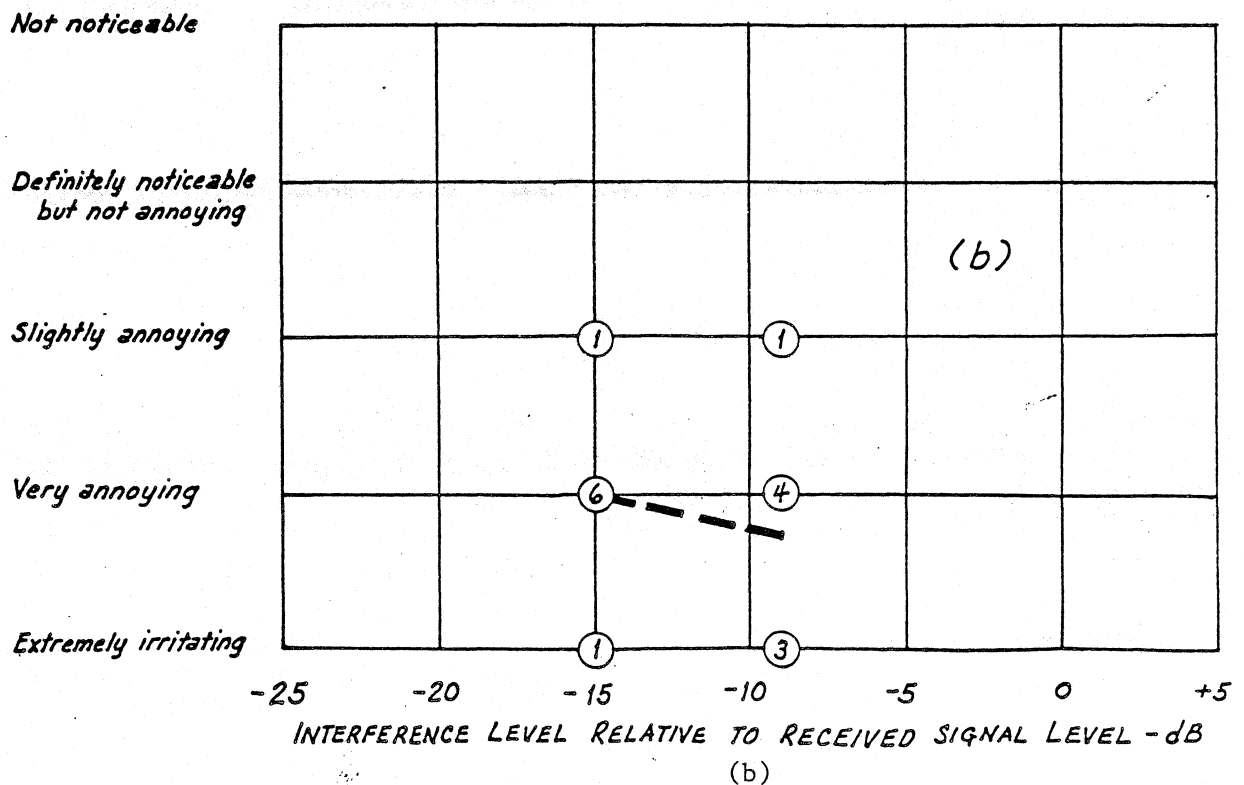
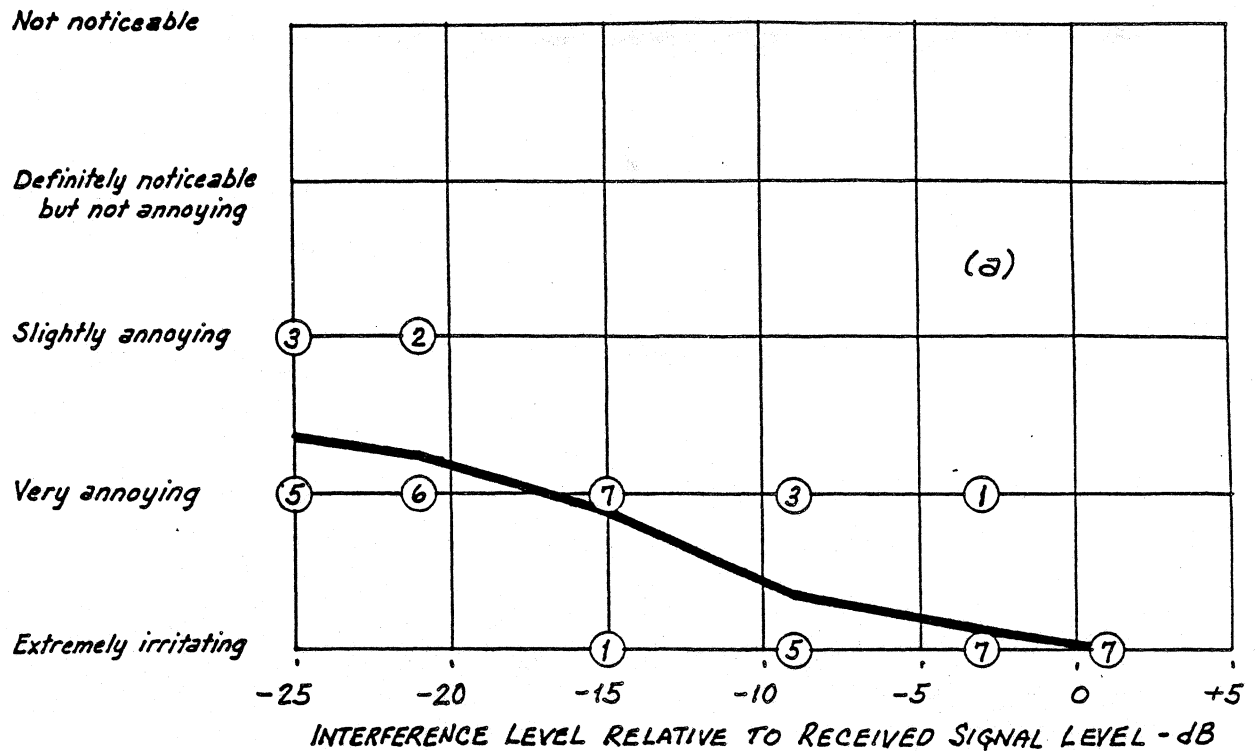


Figure 9. Plot of Judgement Ratings of Background Annoyance. (a) With White Noise Present 25 db Below the Receiver Signal Level and (b) With No White Noise. Numbers in Circles Represent Listener Votes for The Indicated Rating.

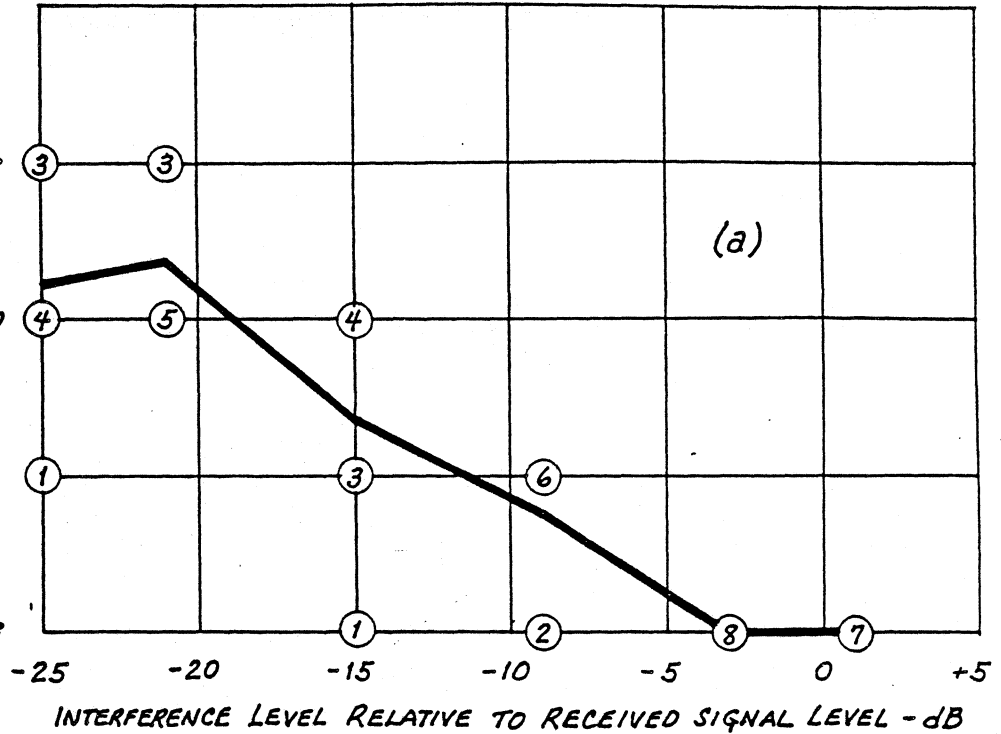
Excellent

Easily understandable

Understandable with slight difficulty

Understandable with great difficulty

Not understandable



Excellent

Easily understandable

Understandable with slight difficulty

Understandable with great difficulty

Not understandable

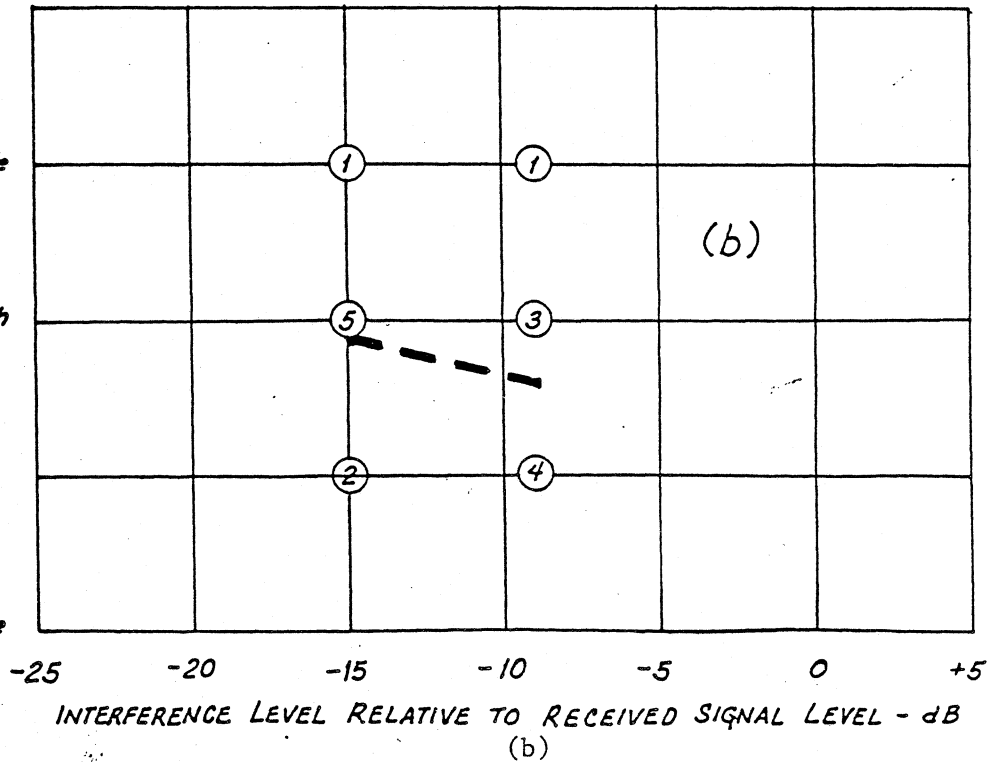


Figure 10. Plot of Judgement Ratings of Intelligibility. (a) With White Noise Present 25 db Below the Received Signal Level and (b) With No White Noise. Numbers in Circles Represent Listener Votes For the Indicated Rating.

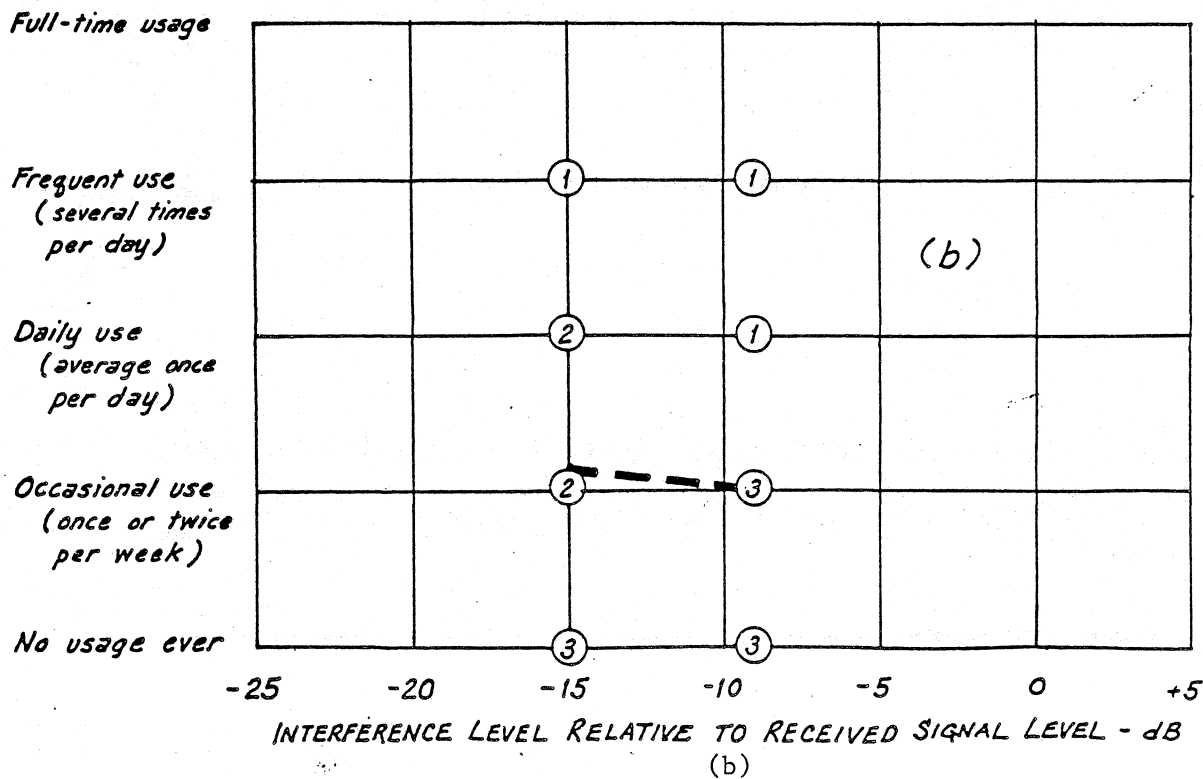
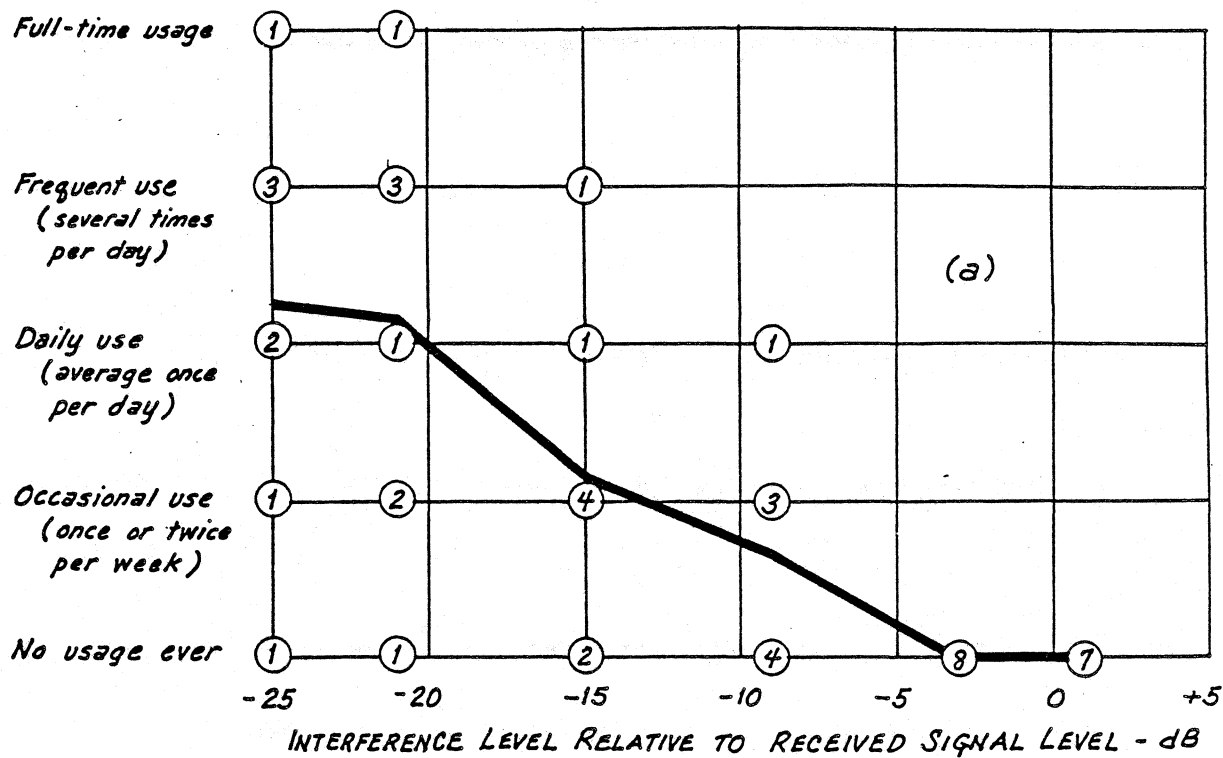


Figure 11. Plot of Judgment Ratings of Usage. (a) With White Noise Present 5 db Below the Received Signal Level and (b) With No White Noise. Numbers in Circles Represent Listener Votes For the Indicated Ratings.

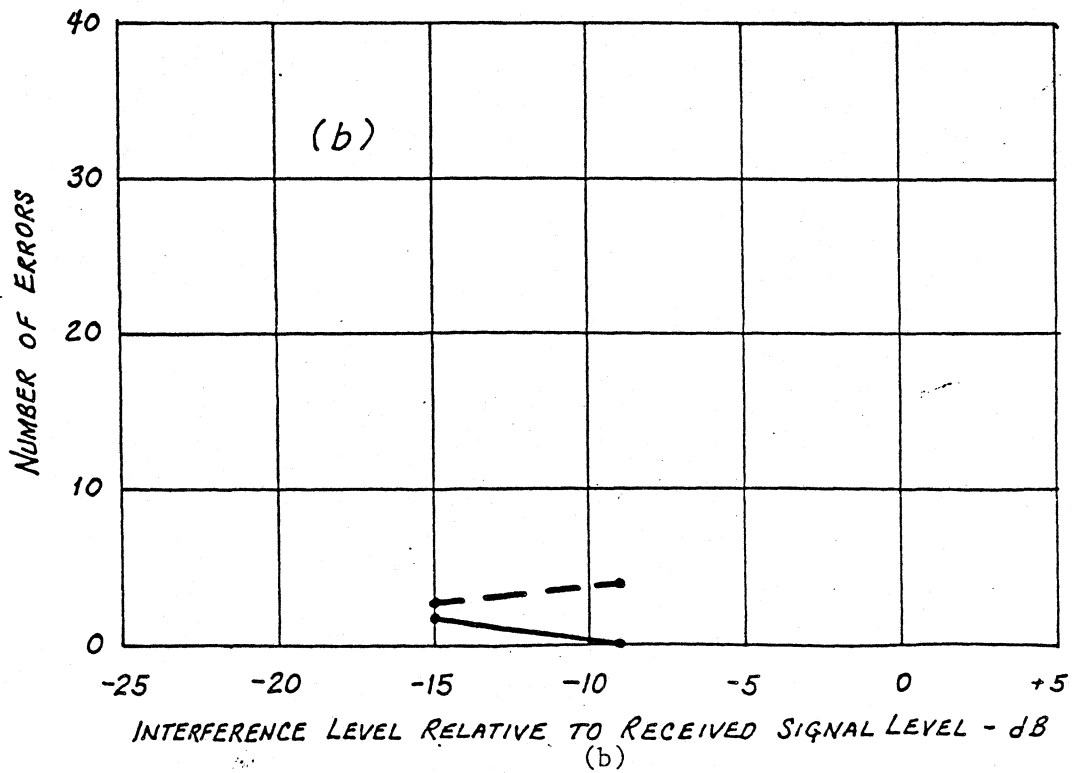
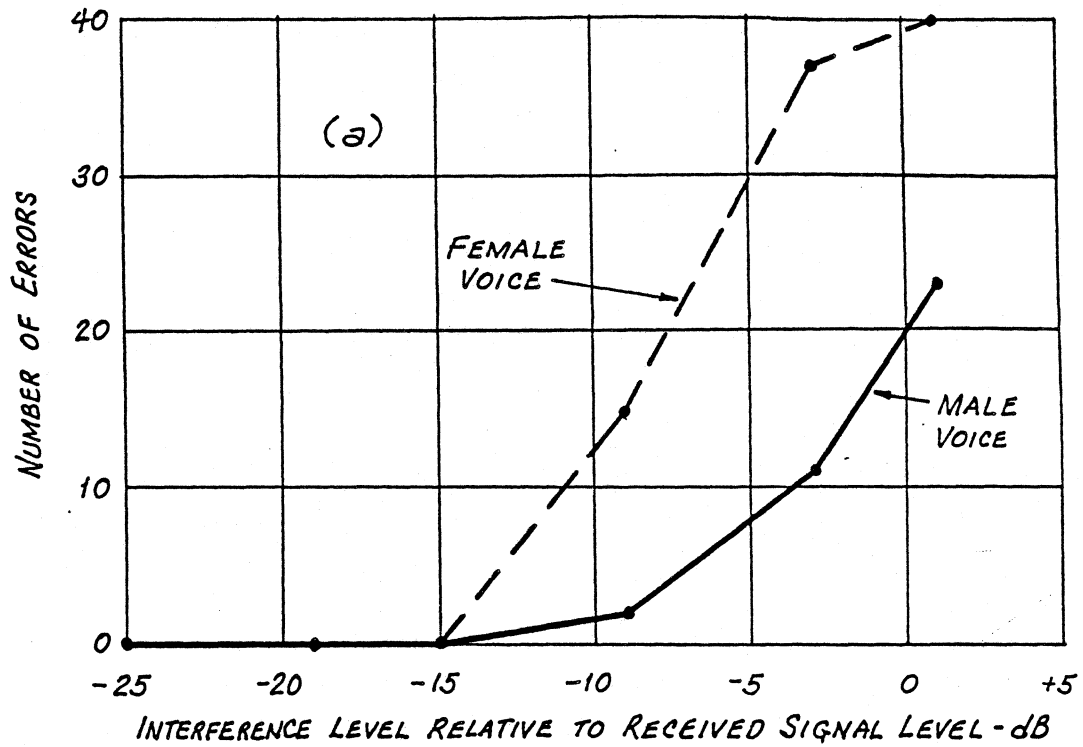


Figure 12. Plot of Errors Made in Transcribing Six-Digit Numbers During SSB Voice Test. (a) With White Noise Present 25 db Below the Received Signal Level and (b) With No White Noise.

Frequency Shift Keying (FSK) Transferred Trip Test

Within the electric power industry, a transferred trip relay function is evaluated on the basis of security and dependability. Security refers to the ability to resist false operation, while dependability refers to the degree of certainty that the circuit will operate correctly when triggered. The influence of a given interfering signal on security and dependability was tested separately. The carrier equipment used for these tests was FSK type operating at 65 kHz.

For evaluating an interference threshold with regard to security, the transferred trip circuit was operated on a continuous guard (standby) status. Several tests were made with the interfering signal set at successively higher levels. A detector circuit was arranged to identify if a false trip occurred. Each test lasted at least 15 minutes.

All the security tests were made with the frequency of the interfering signal offset downward from the PLC channel frequency by 600 Hz. This arrangement places most of the spectral energy of the interfering signal on the trip side of the receiver discriminator and causes one peak of the interference spectrum to coincide with the trip frequency. This was considered the worst case.

The guard signal level at the receiver input was maintained at -14 dBm. Both the noise level and the interfering signal level were varied over wide ranges.

It was difficult to establish a meaningful interference threshold that would produce a false trip with the desired received signal present because of the lockout features of the receiver under test. Lockout occurs upon loss of the desired received (guard) signal and also in the presence of a high-level interfering signal. However, the lockout logic circuit usually requires about 150 ms to be set. It was found that the abrupt addition of a high-level interfering signal could cause the receiver to trip falsely. With no white noise added, this occurred readily when the interfering signal was 5 dB higher than the received guard signal level, but would not occur when the interfering signal was equal to, or less than, the received signal.

Various combinations of high noise plus interference could cause the receiver's lockout status to operate in an intermittent manner. A false trip was produced during one unusual combination, i.e., interfering signal 2 dB below, and white noise 2-5 dB above the guard signal level.

One final and more significant condition was found to produce a false trip. With an interfering signal 8 dB or less below the guard signal level, (but no white noise included), a false trip occurred whenever the PLC signal was interrupted. With the interfering signal 9 dB or more below the guard level, this would not occur. White noise alone would not cause this condition except at one critical level (1 dB below guard level) where an intermittent lockout status was established upon signal failure. After several minutes in this state, a trip occurred. Upon signal failure with noise levels higher or lower than this value, receiver lockout occurred with no false trip.

For the dependability test, a circuit was set up to repeatedly key the transmitter from guard to trip at a rate of approximately one trip per second, with the trip signal being on for 450 ms and off for 550 ms. Necessary circuitry including detectors, timers, and counters were set up so that the total attempts, correct trips, delayed trips, and failures to trip could be counted separately for each level of interference. The total time required for a relay trip is generally accepted as a measure of circuit dependability, since interference of different types will cause various delays to the response of the receiver. Operate-time benchmarks were set up at 50 ms and 200 ms. Trips that took place within 50 ms or less were called correct trips; those occurring between 50 and 200 ms were termed delayed trips; and those occurring beyond 200 ms were called failures.

For these tests, the noise level at the input to the receiver was set at -16.5 dBm. The input guard signal level was adjusted to -12.5 dBm to establish a 4 dB SNR. Except as noted, these levels were maintained for all levels of the added interfering signal.

There are several operational adjustments that affect the performance of a PLC receiver. For example, intentional delay can be increased for added security. Repeat tests were made to verify that false conclusions were not being drawn based on a single arbitrary combination of variables. Figures 13, 14, and 15 portray three different sets of data taken with the original receiver (specimen 1). Figure 16 shows the results of similar tests on a

different type of equipment that became available just before the test setup was disassembled (specimen 2). No experimenting was done with this receiver's adjustments and its security was not tested.

While minor differences may be noted in the different tests, reasonable repeatability is evident. The effect of noise versus no noise and also the effect of off-setting the frequency of the interfering signal to its worst case value is evident from the graphs.

Transferred trip receivers were found to be capable of maintaining dependability even with fairly high interference levels. Through a wide range of conditions, observed thresholds ranged from about 6 dB below the normal received guard signal level (with worst-case frequency setting) to about 8 dB above the received guard signal level.

In a variety of security tests, the lowest level of interfering signal found to produce a false trip was 8 dB below the received guard signal level. The interference threshold for transferred trip receivers was established as 10 dB below the received guard level to provide a small margin.

FSK Data Transmission

For this test, apparatus was set up to transmit data at 300 bps from the transmitter to the receiver. The data test instrument that generated the pseudorandom bit stream was also used to monitor the received data, and a count of bit error rate (BER) was obtained for each level of interference. The PLC receiver operated at 65 kHz. Its shift range was ± 250 Hz.

For these tests, the noise level at the input of the receiver was -22 dBm. The carrier signal level was adjusted to -7 dBm to achieve a S/N ratio of 15 dB.

A preliminary "benchmark" was determined and counts of the BER were obtained with relatively short duration tests. Lower error rates, to have acceptable accuracy, need fairly long test periods. Overnight runs of 20 to 25 hours each were used to establish the three lowest points in Figure 17. Only slight differences were seen between the effects of white noise alone, interfering signal alone, or interfering signal added to a fixed background level of white noise.

Transferred-Trip Equipment - Specimen 1
 Center Frequency 65 kHz
 Received Signal Level -12.5 dBm
 Noise Level (3-kHz) -16.5 dBm
 SNR (w/o external interference) 4 dB

Interfering signal on
 channel frequency, 65 kHz

Note: T_{ac} is the total actual time
 from initiation of transmitter
 input to receiver TRIP output

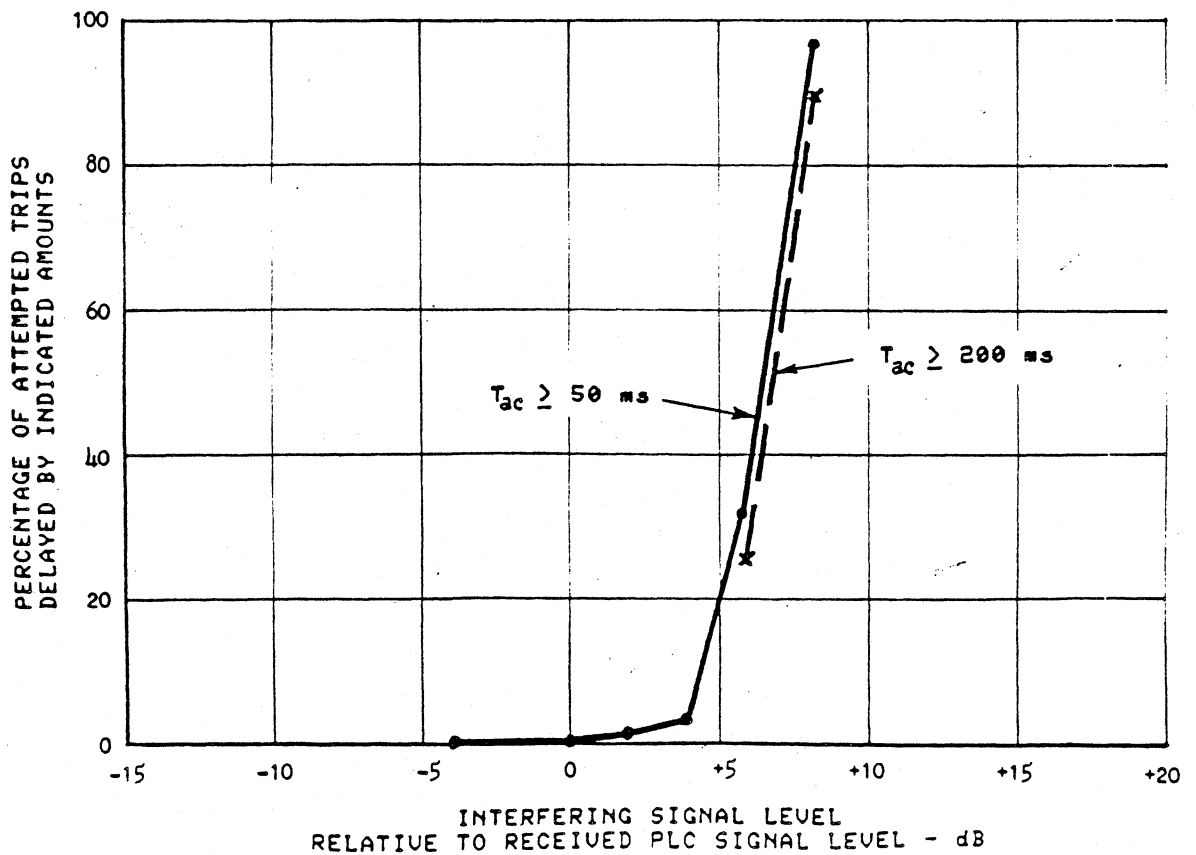


Figure 13. Dependability Test Data For Transferred Trip Equipment, Specimen 1.

Transferred-Trip Equipment - Specimen 1
 Center Frequency 65 kHz
 Received Signal Level -12.5 dBm
 Noise Level -22 dBm
 SNR 9.5 dB

Note: T_{ac} is the total actual time
 from initiation of transmitter
 input to receiver TRIP output

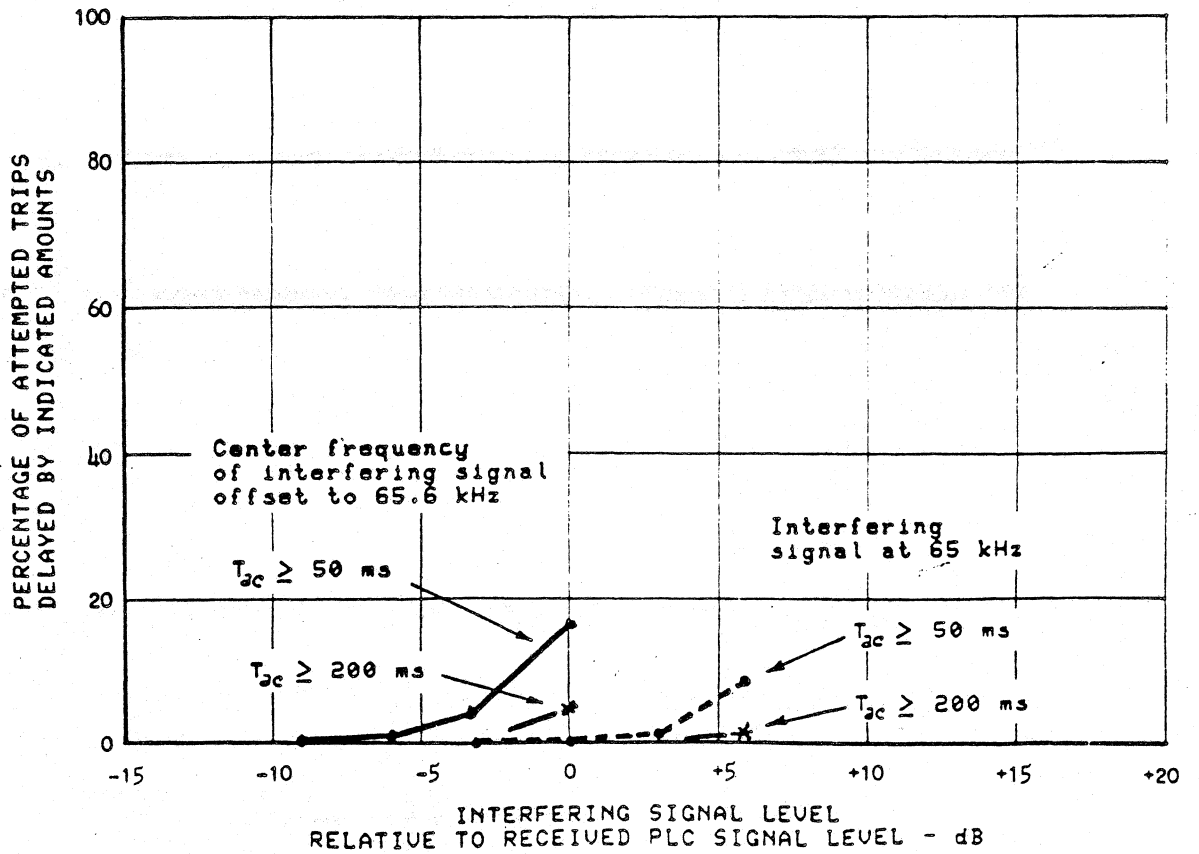


Figure 14. Dependability Test Data for Specimen 1.

Transferred-Trip Equipment - Specimen 1
 Center Frequency 65 kHz
 Received Signal Level -14 dBm
 Noise Level -18 dBm
 SNR 4 dB

Note: T_{ac} is the total actual time
 from initiation of transmitter
 input to receiver TRIP output

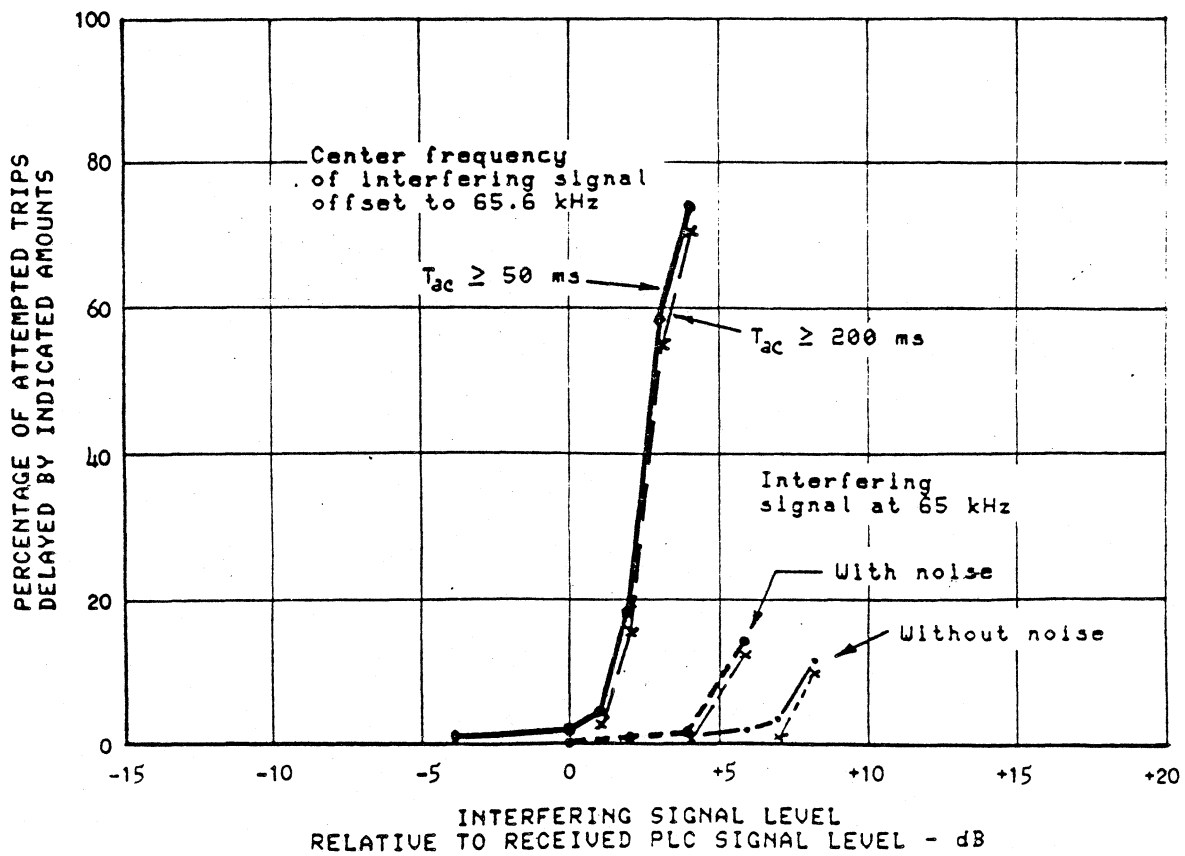


Figure 15. Dependability Test Data for Specimen 1.

Transferred-Trip Equipment - Specimen 2
 Center Frequency 90 kHz
 Received Signal Level -10 dBm
 Noise Level -14 dBm
 SNR 4 dB

Interfering signal frequency
 offset to 90.6 kHz

Note: T_{ac} is the total actual time
 from initiation of transmitter
 input to receiver TRIP output

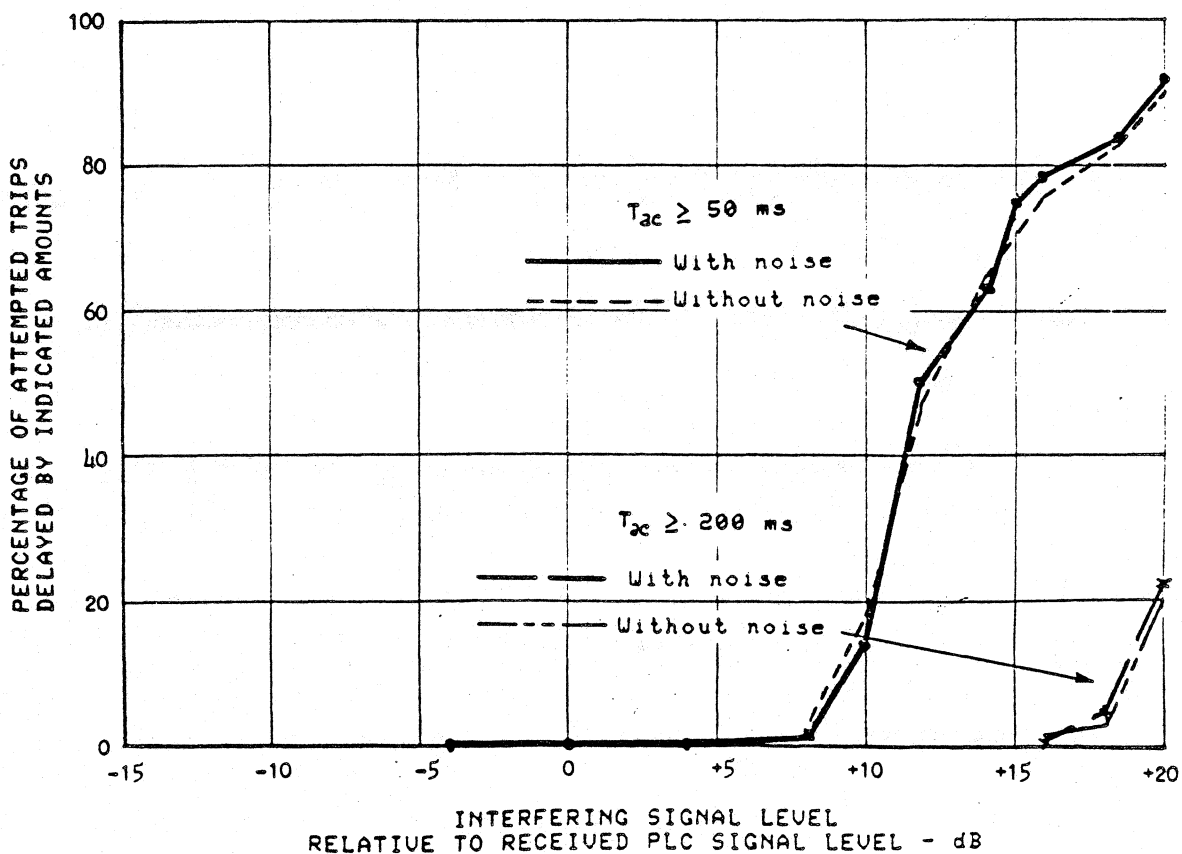


Figure 16. Dependability Test Data For Transferred Trip Equipment, Specimen 2.

Received carrier signal at -7 dBm

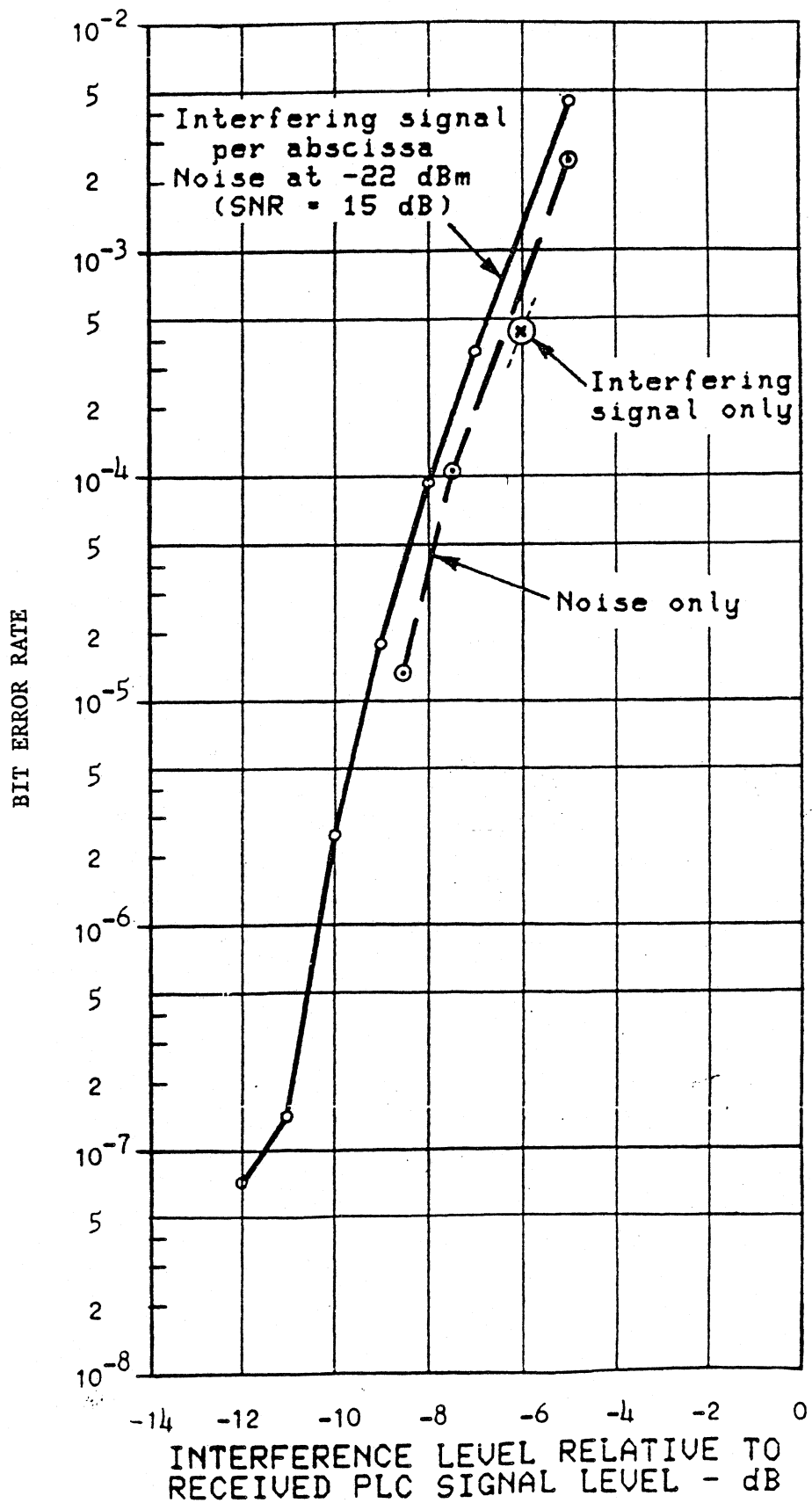


Figure 17. Bit Error Rate (BER) for Data Tests Made with FSK Receiver.

For most data channels interconnecting computer centers, the acceptable error rate is 10^{-5} . Counts of BER on the test channel indicated that the interfering signal had a measurable influence for levels as low as 12 dB or more below the desired signal level; however, the point at which the error rate became unacceptable was approximately 10 dB below the received signal level.

FSK Analog Telemeter

For this test, a signal representing a fixed telemetered quantity was used to key the PLC transmitter and a chart recorder was used to monitor the receiver output. Under normal operating conditions, the signal representing the fixed quantity should cause a straight line to appear on the receiver recorder. Tests were made with successively higher levels of the interfering signal. The presence of harmful interference was monitored by observing the spikes, or deviations, in the recorded chart. The PLC receiver used in the telemeter test was operated at 133 kHz.

For the telemeter tests for which both white noise and interfering signal were applied, the noise level was set at -22 dBm and the input signal level at -10.5 dBm. This corresponds to an S/N of 11.5 dB. The published minimum S/N for the narrowest telemeter channels, based on 3 kHz noise, is 5 dB and, for somewhat higher speeds, 10 dB. The bandwidth of the receiver used for these tests would not permit proper operation with an S/N of 5 dB. The white noise used was found to be more detrimental than the interfering signal at comparable levels. Tests with the higher S/N and tests with no noise at all were made to clearly evaluate the effect to the telemetry operation being measured.

Figures 18, 19, and 20 show a few segments of the recorded chart obtained during this test. The vertical trace through the center of the chart indicates what should be expected of a good received signal with no noise or interference. "Excursions" to the right are spikes indicating the influence of a disturbance. Excursions to the left were the result of manually keying

Received signal at -10.5 dBm
White noise(N) as shown
No added interfering signal

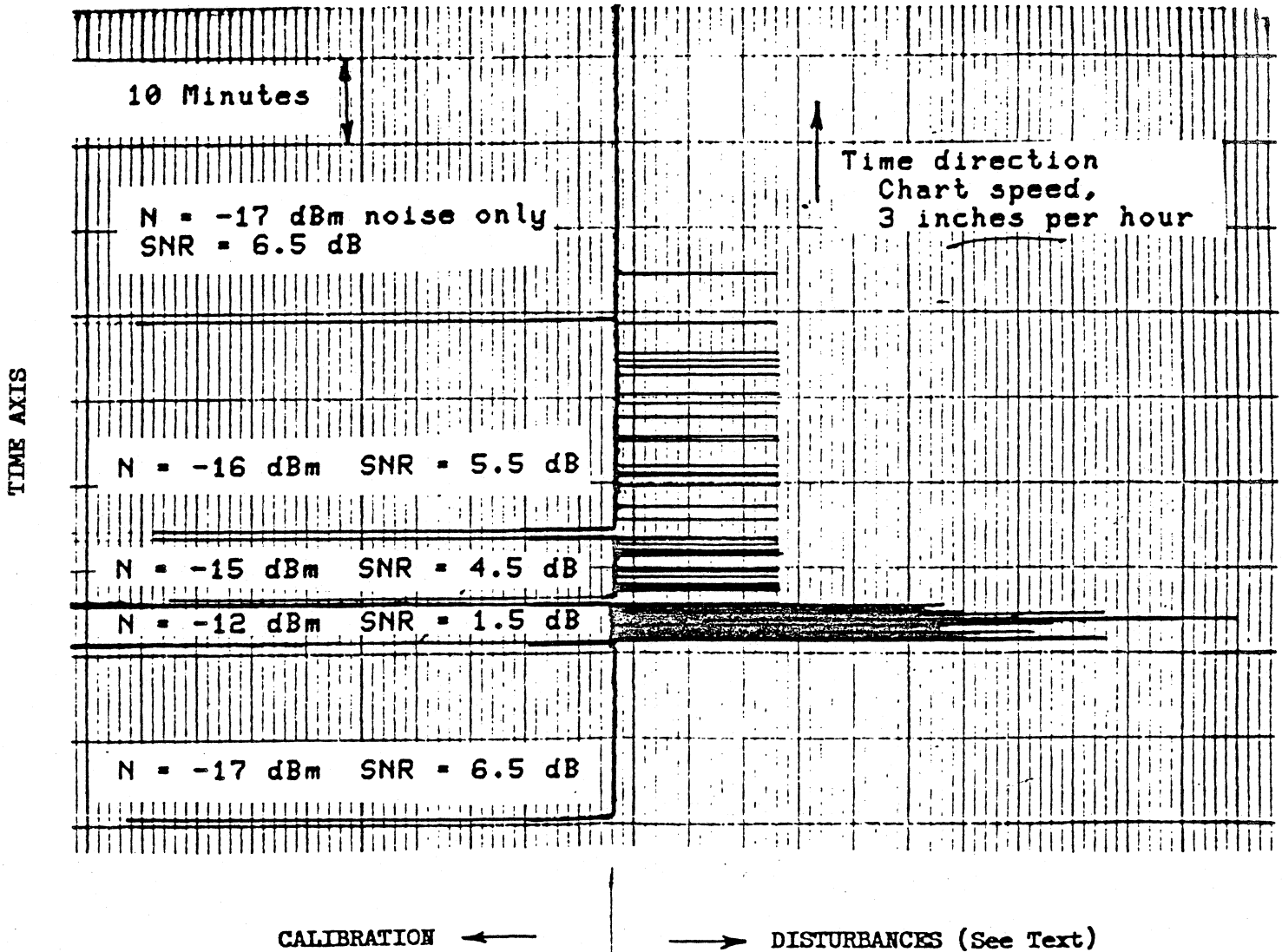


Figure 18. Recorder Chart for FSK Analog Telemeter Test with White Noise at Various Levels; No Interfering Signal.

Received signal at $-10.5 \text{ dBm} = 0 \text{ dB(Ref)}$
 Interfering signal level (ISL) as shown
 No background white noise

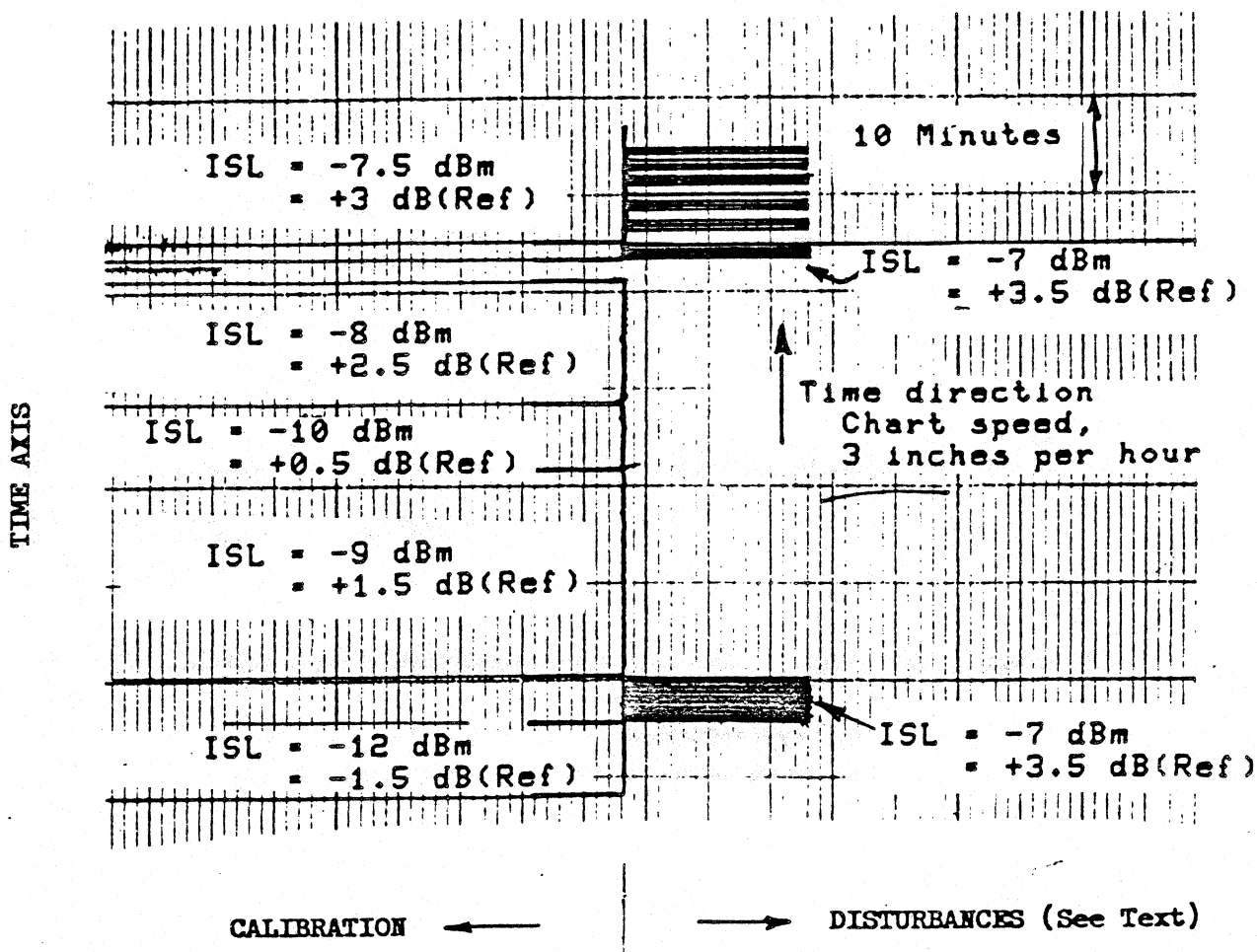


Figure 19. Recorder Chart for FSK Analog Telemeter Test with Interfering Signal at Various Levels; No White Noise.

Received signal at $-10.5 \text{ dBm} = 0 \text{ dB(Ref)}$
 Interfering signal level (ISL) as shown
 White noise level = $-22 \text{ dBm} = -11.5 \text{ dB(Ref)}$

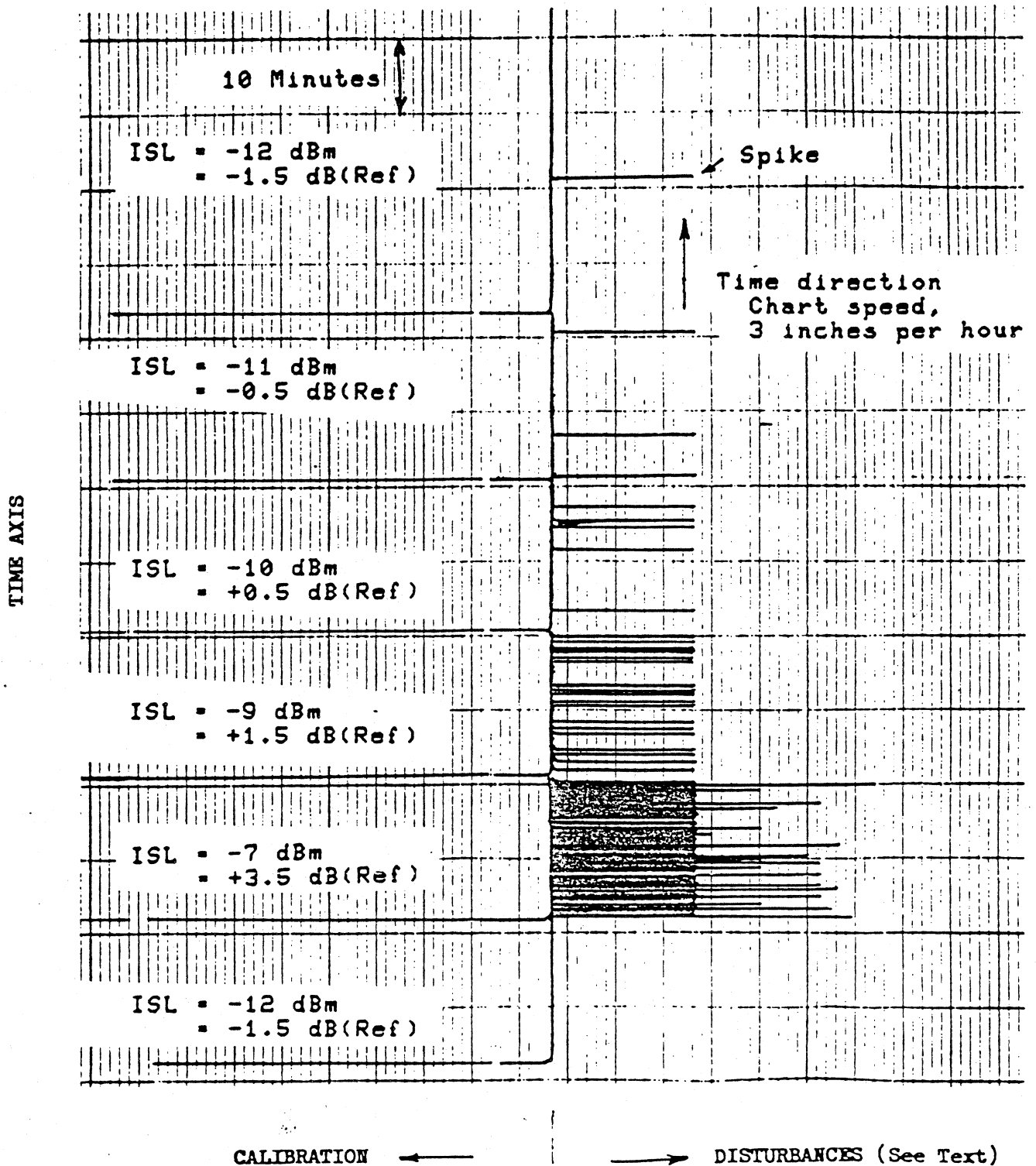


Figure 20. Recorder Chart for FSK Analog Telemeter Test With White Noise Fixed at 11.5 dB Below the Received Signal Level; Interfering Signal at Varying Levels.

the signal to establish a marker between different levels or types of interference. The severity of interference is indicated first by the repetition rate of the spikes and, beyond a certain limit, by the amplitude of the spikes.

Examination of the charts reveal the following apparent thresholds:

| <u>Disturbing Source</u> | <u>Minimum Level Seen to Cause Disturbance</u> |
|--|--|
| Noise only | 6.5 dB below received sign |
| Interfering signal only | 3 dB above received signal |
| Interfering signal (with noise 11.5 dB below received signal) | 1.5 dB below received signal |

During the relatively short periods of observation, the lowest level of interfering signal seen to produce disturbances was 1.5 dB below the received signal level. The threshold over longer periods would probably be lower. The accepted threshold of 5 dB below the received signal level provides a safe margin for the proper operation of FSK analog telemeter receivers.

CW Protective Relaying

CW Protective Relaying equipment for keyed CW operation was not included in the tests, however, some discussion of its operation and the applicable interference threshold is needed.

Sensitivity of a CW protective relaying (pilot relay) receiver is adjusted so that its operating threshold is below the normal received signal level by an amount called the operating margin. Some users set their receivers for an operating margin of 10 dB; however, most prefer higher margins, up to 15 dB, to allow for increased channel attenuation during adverse weather.

For a pilot relay channel operating in a high noise environment or with a low desired signal level, the operating margin must obviously be less than the actual S/N ratio to prevent noise from keying the receiver. The published recommendation for minimum S/N is 13 dB.

If it is assumed that a pilot relay channel is operating with a minimum S/N of 13 dB and a minimum operating margin of 10 dB, an interfering signal at a level within 13 dB of the normal received signal level could be additive with the noise and key the receiver. Therefore, the interference threshold for CW operation is a minimum of 13 dB below the received signal level.

Acceptable PLC Interference Threshold

Noise on electric power transmission lines has been measured extensively during various weather conditions. A plot of data based on such measurements is shown in Figure 21. The data in Figure 21 were extracted from the information received from General Electric Company (PLC Application Seminar) and are generally applicable in areas not subject to substantial line icing. It is estimated that in an average climate, actual noise levels do not exceed the adverse weather levels shown in Figure 21 more than 1 percent of the time or the fair weather levels shown more than 25 percent of the time.

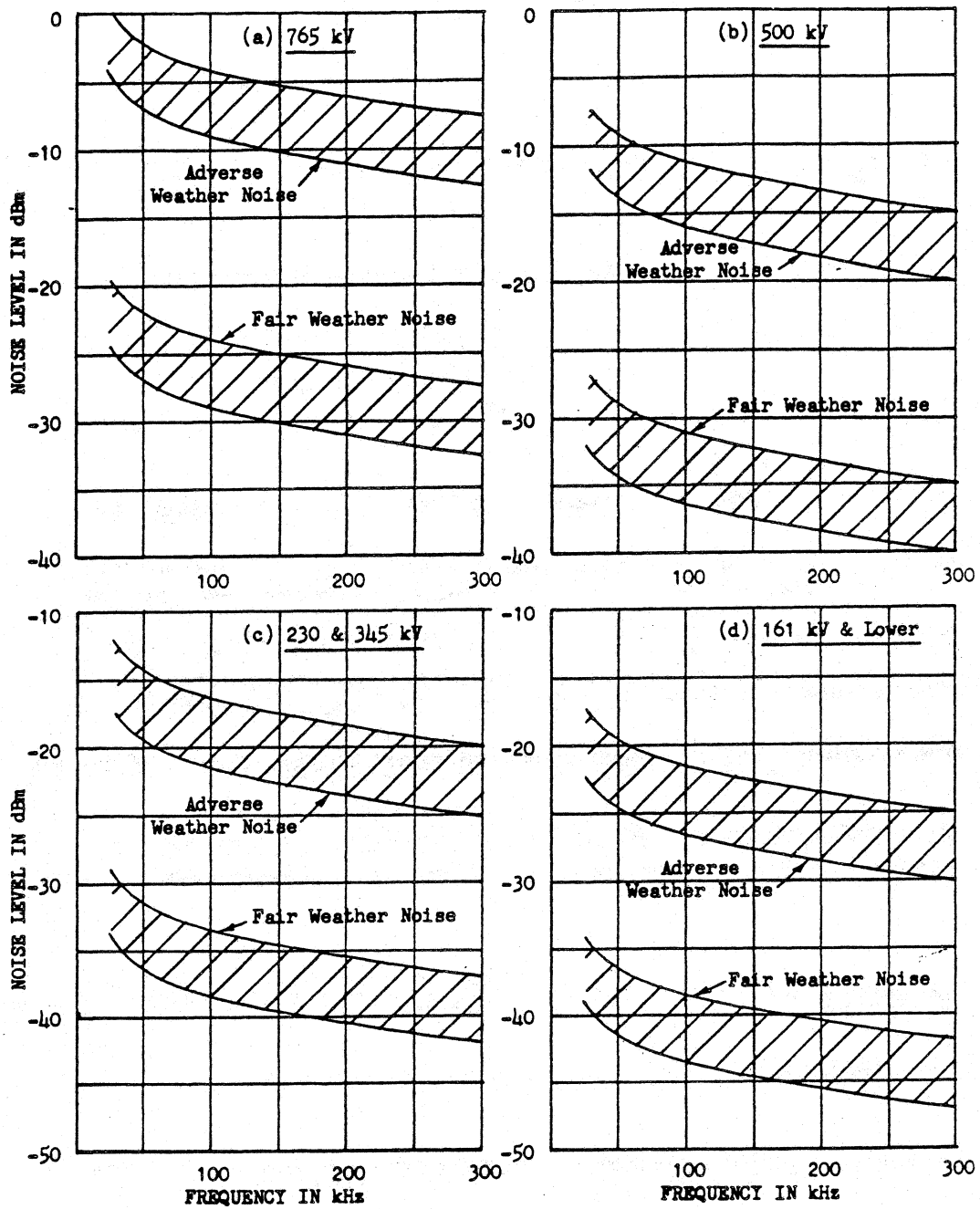


Figure 21. Long Term Noise Levels (Measured in 3 KHz Bandwidth) on a Transmission Line as a Function of Frequency and Line Voltage.

According to the data in Figure 21, the adverse weather noise level for any given frequency is 17 to 20 dB higher than the corresponding fair weather noise level. Statistically, adverse weather noise levels prevail approximately 5 percent of the time. PLC design criteria are set to achieve satisfactory operation through these higher noise periods. For example, for voice circuits, the design minimum S/N is approximately 25 dB and is established under adverse weather conditions. Therefore, PLC voice receivers generally operate with $S/N = 25 + 17 = 42$ dB for as much as 75 percent of the time.

An induced radio signal is perceived by a PLC system as a non-additive noise and may affect the operation of that system in a manner similar to that of an undesired PLC signal. Treating an interference signal as noise in a receiver would be too conservative, and the results will be restrictive for radio users.

For the tests made to determine interference threshold for PLC receivers, background noise was added to establish the operation of each receiver in its most vulnerable state, i.e., with minimum S/N.

For each type of receiver tested, the indicated interference threshold was very near the level of applied background noise with only minor exceptions. In the voice test, the definition of interference threshold was dependent upon subjective evaluations; therefore, acceptance of an exact value was difficult. During the transfer trip security tests, in one unusual situation, a false trip was produced by an interfering signal 4 dB lower than the maximum level of applied background noise.

In order to simplify the estimating techniques discussed in this report and effectively meet the objectives of the Working Group, it is considered feasible to assume that the interference threshold for any type of PLC receiver is equal to the mid-range adverse weather noise level for the appropriate line voltage as shown in Figure 21.

This approach will allow preliminary analyses to be made without detailed knowledge of individual PLC receiver characteristics and signal levels.

FIELD INTENSITY MEASUREMENT

Electric field intensity data reported here were obtained from measurements made at six different locations in the United States. The purpose of these measurements was to validate the results obtained using the analytical model and to determine a coupling factor. The data represents the radiated field intensity levels from typical transmission lines and include the effects of the ground losses at the measurement sites. An intensive effort was rendered by a number of the participating organizations in the collection of the data. Some of the atypical results found during these measurements may provide guidelines for the application of the analysis results given here. The six different agencies that took part in these measurements were:

Tennessee Valley Authority (TVA)
Nebraska Public Power District (NPPD)
Virginia Electric and Power Company (VEPCO)
Northeast Utilities Service Company (NUSCO)
Public Service Company of Colorado (PSCC)
Southern Colorado Power Company (SCPC)

The field intensity meters used by the different agencies were calibrated prior to performing the measurements and the calibration curves for different meters were compared in order to ensure accurate comparison of the measured results. The field intensities given here were measured on the ground in a direction transverse to the power transmission lines under test. No airborne measurements were carried out.

The data recorded in these tests included distance between the location of the field intensity meter and the transmission line and the readings observed on the dial indicator of the meter. The data also included a clear description of the geometry of the transmission line together with any accessories such as traps, capacitors, and towers that may have had an impact on the radiation from the transmission line. In addition, the PLC frequency and the location of each measurement site, if different from the PLC transmitter site, were identified. The transmission lines used in these tests

ranged from 161 kV to 500 kV and carrier frequencies were between 150 and 200 kHz. No field intensity measurement was conducted at lower frequencies; however, the analytical models discussed here could be used at frequencies of 30 kHz or lower to determine the coupling factor.

Most carrier signals operate in the phase-to-ground mode although there is also substantial usage of phase-to-phase coupling. A schematic of a typical transmission line with associated PLC operating in the phase-to-ground mode is shown in Figure 22. Although there are transmission lines and carrier equipment that operate with parameters different from the examples used for these tests, these parameters are typical of those employed by the majority of PLC users in the United States. Specific parameters of the PLC and power lines selected for the field intensity tests will be discussed separately for each individual test.

Tennessee Valley Authority (TVA)

Some of the data on field intensity obtained by the TVA was influenced by rough terrain and the presence of scatters and electric distribution lines in close proximity to the transmission lines being tested. These atypical effects in measurements are site dependent and require judgement based on observation of the site and examination of the data in order to assess the utility of the results. Despite these difficulties, a substantial quantity of good data was obtained. A comparison of the calculated results with the measured data for each site is given.

Field intensities were measured on three different power lines, all in Tennessee, extending between Murfreesboro and Gallatin, Clarksville and West Nashville, and Montgomery and Wilson. One longitudinal and two or more lateral profiles were measured on each line. Only the data for representative lateral profiles are given here. At most of the measuring sites, two readings were taken, one with the plane of the loop antenna vertical and parallel to the transmission line, and the other with the loop oriented for maximum field strength meter reading. Unless otherwise noted, data shown in the plots are

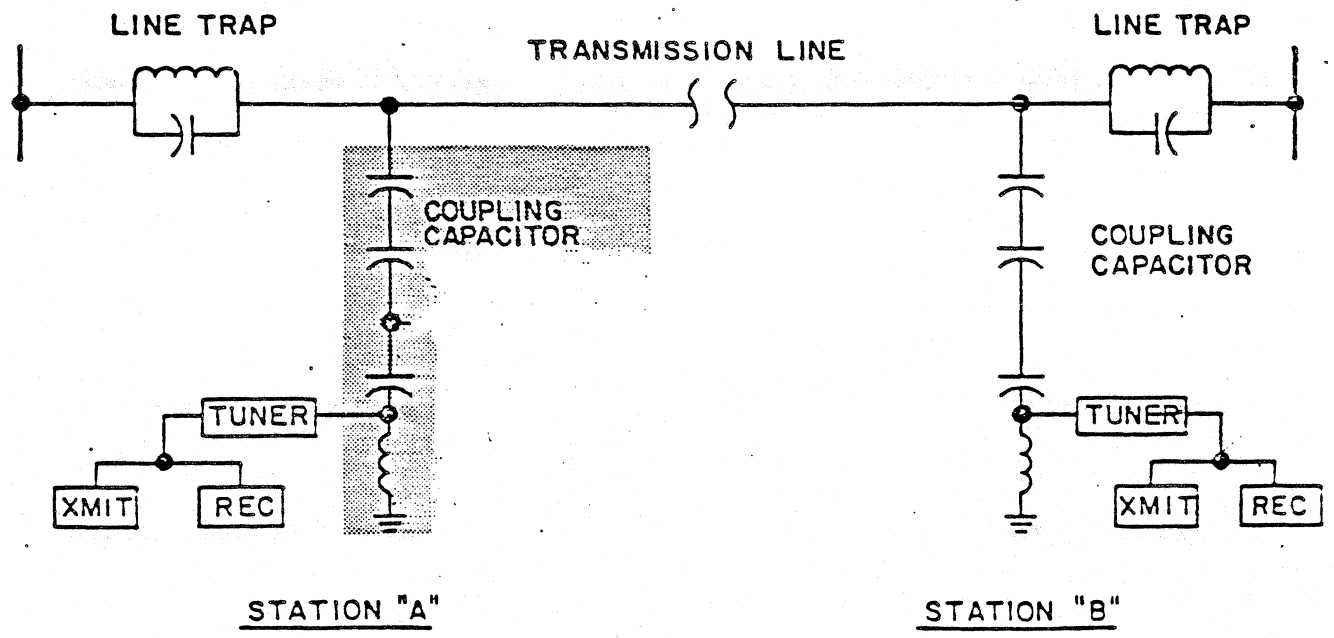


Figure 22. Schematic of a Power Line Carrier Connection.

the maximum readings. Descriptions of measurements and results for each transmission line are given in the following paragraphs.

Murfreesboro-Gallatin Line:

This 161 kV transmission line is one of a double-circuit pair for the first 6.5 km nearest to Murfreesboro substation. Beyond this, in the range where the most representative measurements were made, its configuration is single-circuit vertical as shown in Figure 23. The signal source for all measurements on this line was an existing 10-watt carrier transmitter located at Murfreesboro substation and operating at 172 kHz. The signal was coupled phase-to-ground on the center phase of the vertical array.

Data for the plot in Figure 24 was taken at a gravel road crossing approximately 27 km from the transmitter and about 21 km from the point where the double-circuit portion of the line separated into the two respective single-circuit lines. This location was identified as site A. Measurements were extended on the east side of the line to a distance of almost 5 km; however, distribution lines, service drops, and telephone cables were present at several points along the path. It is not felt that the data taken beyond what is shown in Figure 24 is representative of the transmission line itself. The plotted data near the line, particularly within the first 300 meters, is believed to be reasonably valid.

Additional measurements on this transmission line were performed at another location referred to as site C. This site was at a gravel road crossing about 35 km from the transmitter. The area to the west of the line is wooded with rolling hills. No visible distribution lines are present even out to 5 km distance. Figure 25 shows a plot of all the data taken west of the line. A prominent distribution line exists approximately 600 m east of the line. It crosses the transmission line diagonally at a point about 1500 m south of the profile path. Farther to the east, the path crosses U.S. Highway 231 and enters a State park area. Several distribution lines were noted along this route. Data measured on the east side of the line are not included.

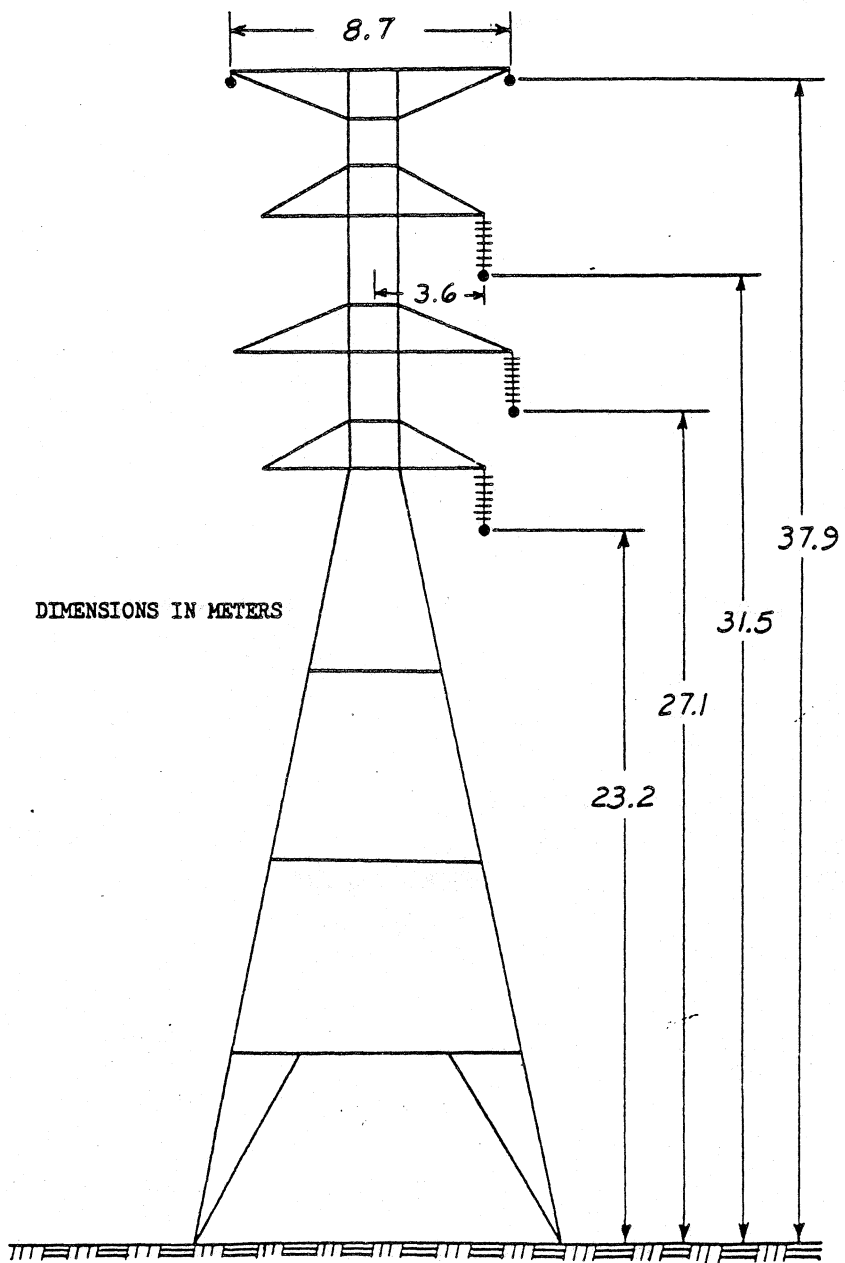


Figure 23. Configuration of a Typical Tower Used in The Murfreesboro-Gallatin 161-kV Transmission Line.

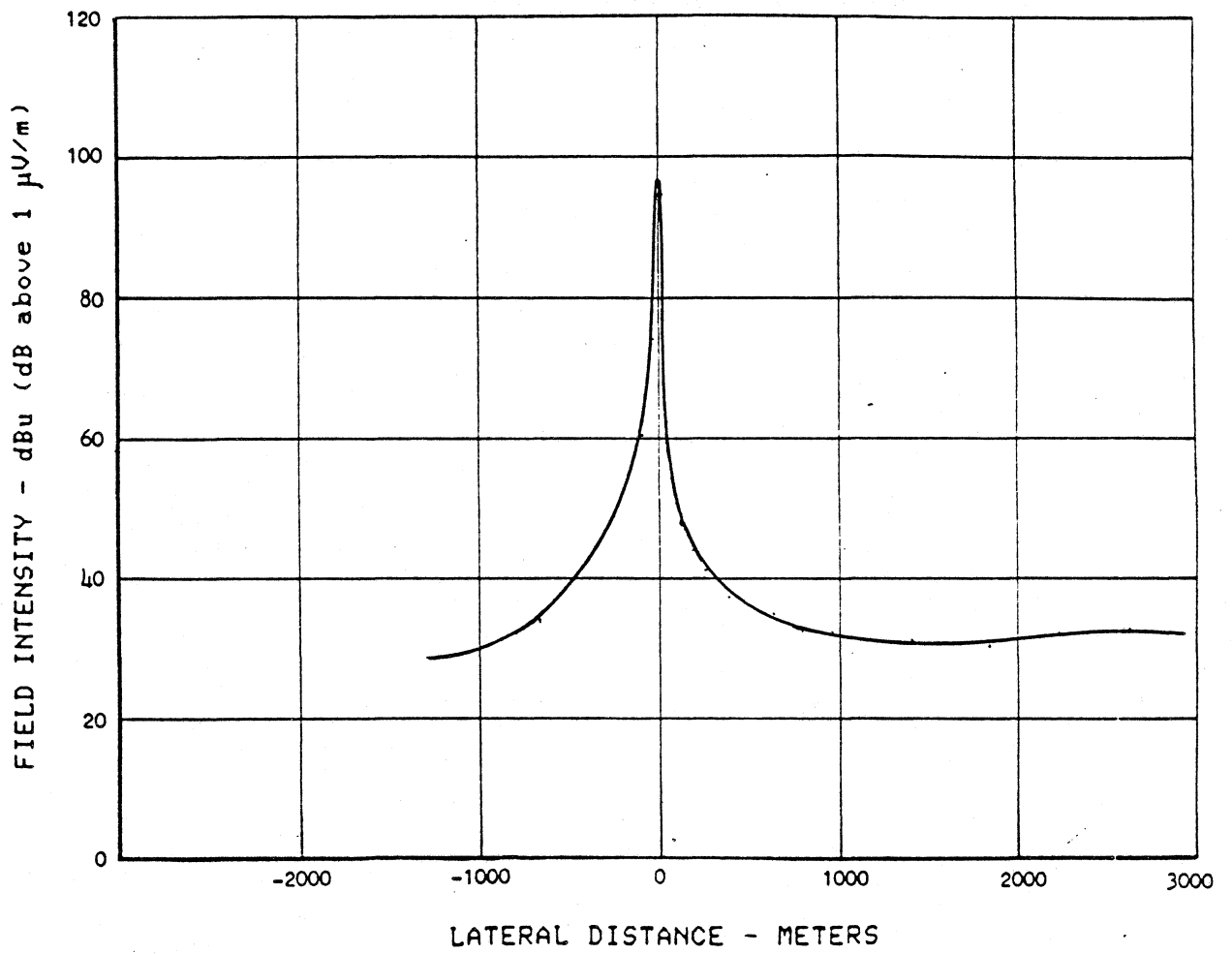


Figure 24. A Plot of Data Obtained for the Transmission Line Between Murfreesboro and Gallatin (Site A)

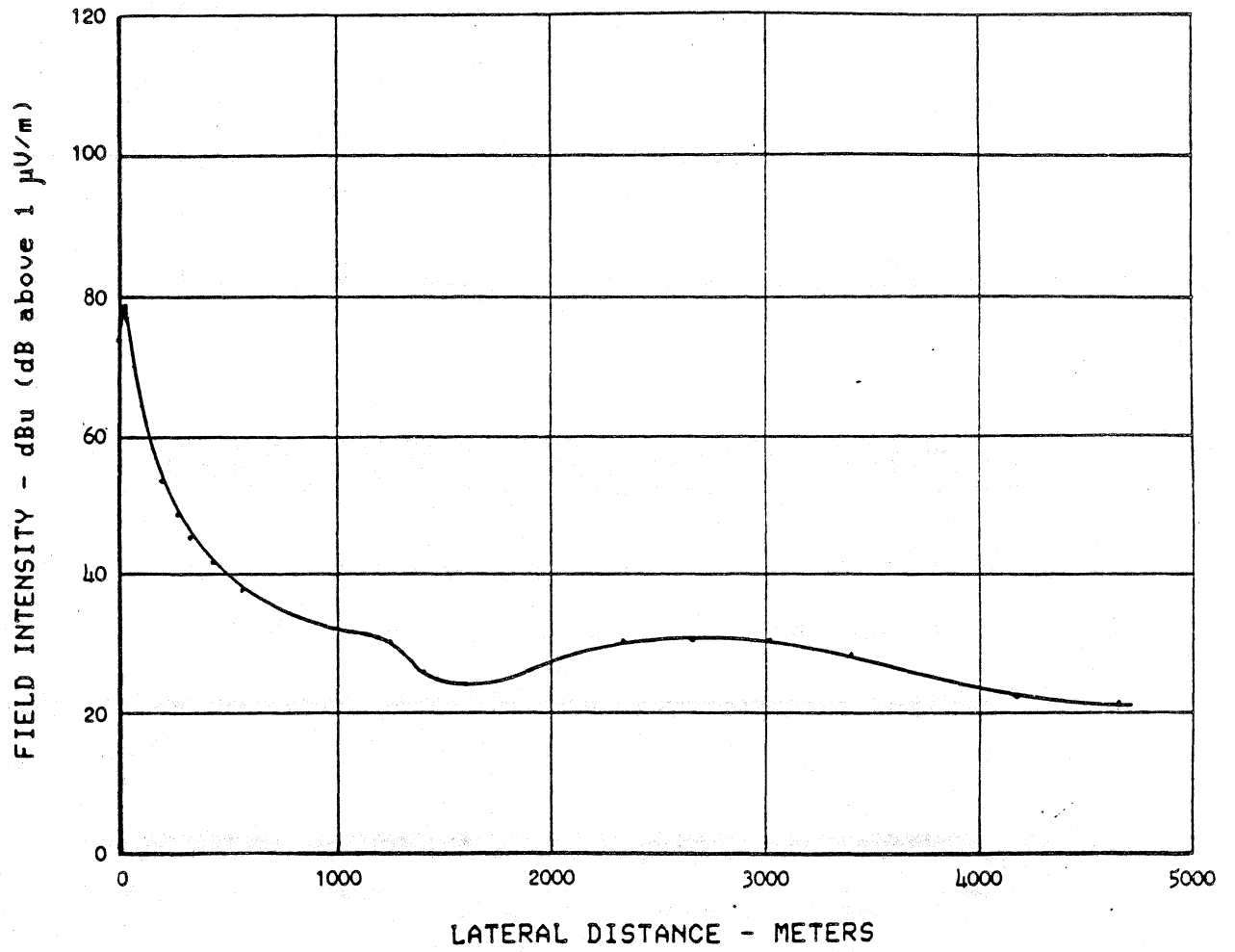


Figure 25. A Plot of Data Obtained for the Transmission Line Between Murfreesboro and Gallatin (Site C)

Figure 26 shows a comparison of the measured data taken at site A and C with the calculated results obtained using the NTIA's analytical model. A discussion of this model is given later in this section. The vertical axis shows the normalized field intensity. The normalization factors used were the values of maximum field intensity for each curve. This method of normalization has been used in all the comparison curves shown in this report. Note that the calculated results shown in Figure 26 are not in good agreement with the data obtained at either site A or C. The ground conductivity used in this calculation was 0.001 mhos/m. At distances beyond about 300 meters of the transmission line, the effect of the ground conductivity in the calculations of field intensity from the line is more pronounced. In the calculations, the ground was assumed to be homogeneous.

Clarksville-West Nashville Line:

This is a single-circuit, horizontal 161 kV transmission line with a configuration as shown in Figure 27. A 10 W signal at 183 kHz was coupled phase-to-phase at Clarksville substation. The most representative data taken for this line was measured in a large open area about 32 km from the transmitter at the Clarksville substation. The nearest distribution line was over 750 m away from the transmission line. Its path was almost parallel to the power line and there were no other secondary lines in the vicinity.

A short (120 m) profile was run in line with a steel tower; however, the main profile was run approximately 100 m toward midspan. Figure 28 shows a plot of the short profile and also the first 300 m of the main profile. The comparison of these two plots provides a good indication of the effect of a steel tower on the field pattern. This effect is quite predictable qualitatively, but not necessarily quantitatively. The main profile, shown in Figure 29, was extended to a lateral distance of approximately 1000 m. The field pattern near the isolated distribution line is clearly evident. The validity of the data taken 600 m or less from the transmission line is believed to be very good.

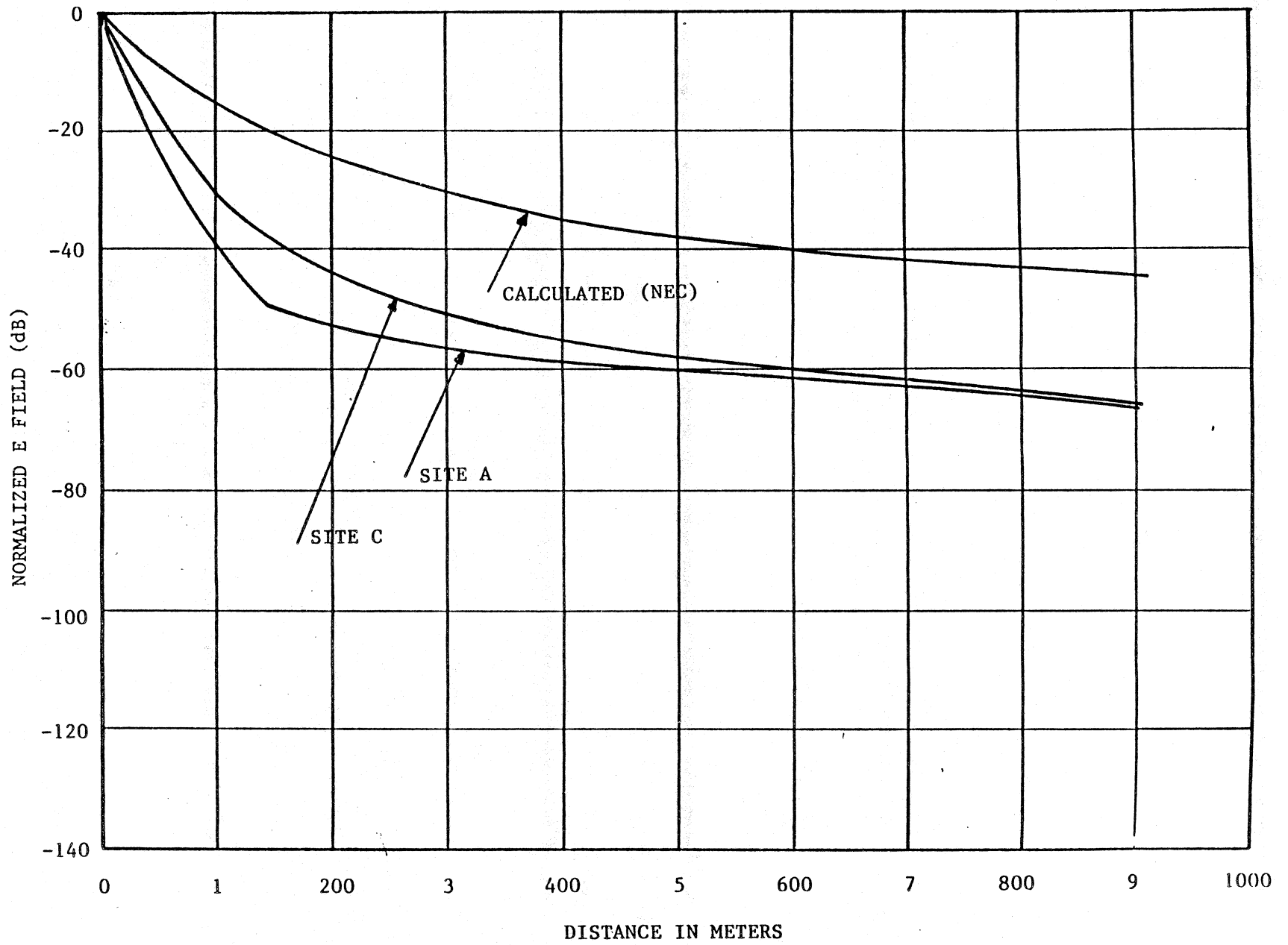


Figure 26. Comparison of Calculated Results with Measured Data at Sites A and C on the Transmission Line Between Murfreesboro and Gallatin.

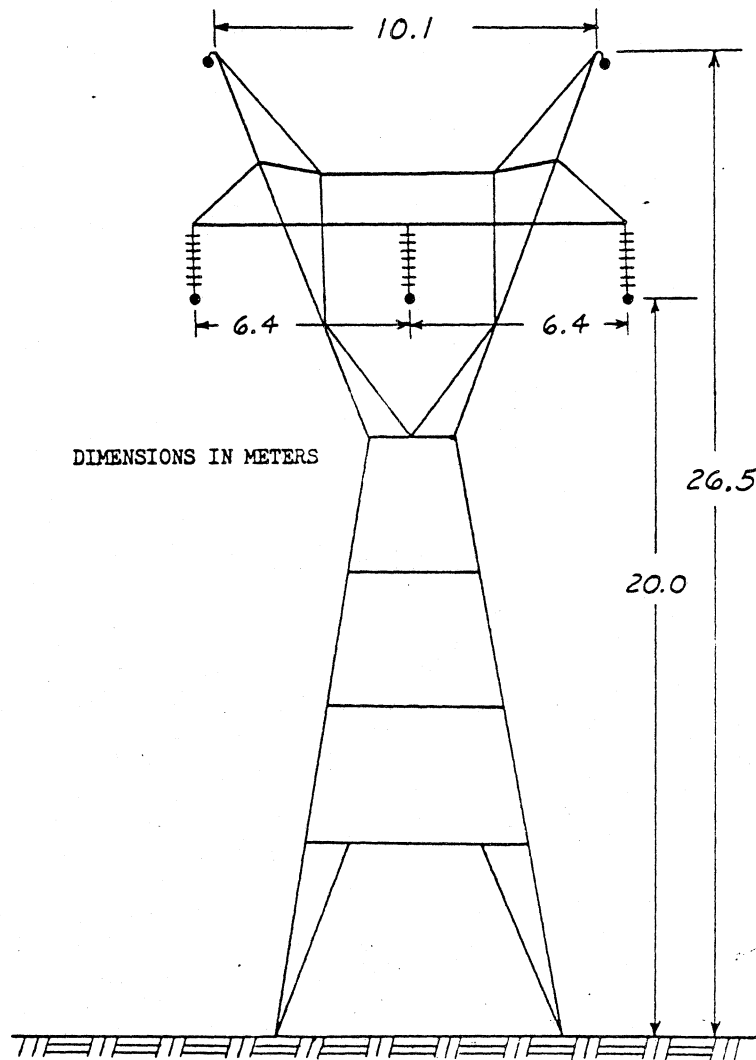


Figure 27. Configuration of a Typical Tower Used in the Clarksville-West Nashville 161-kV Transmission Line.

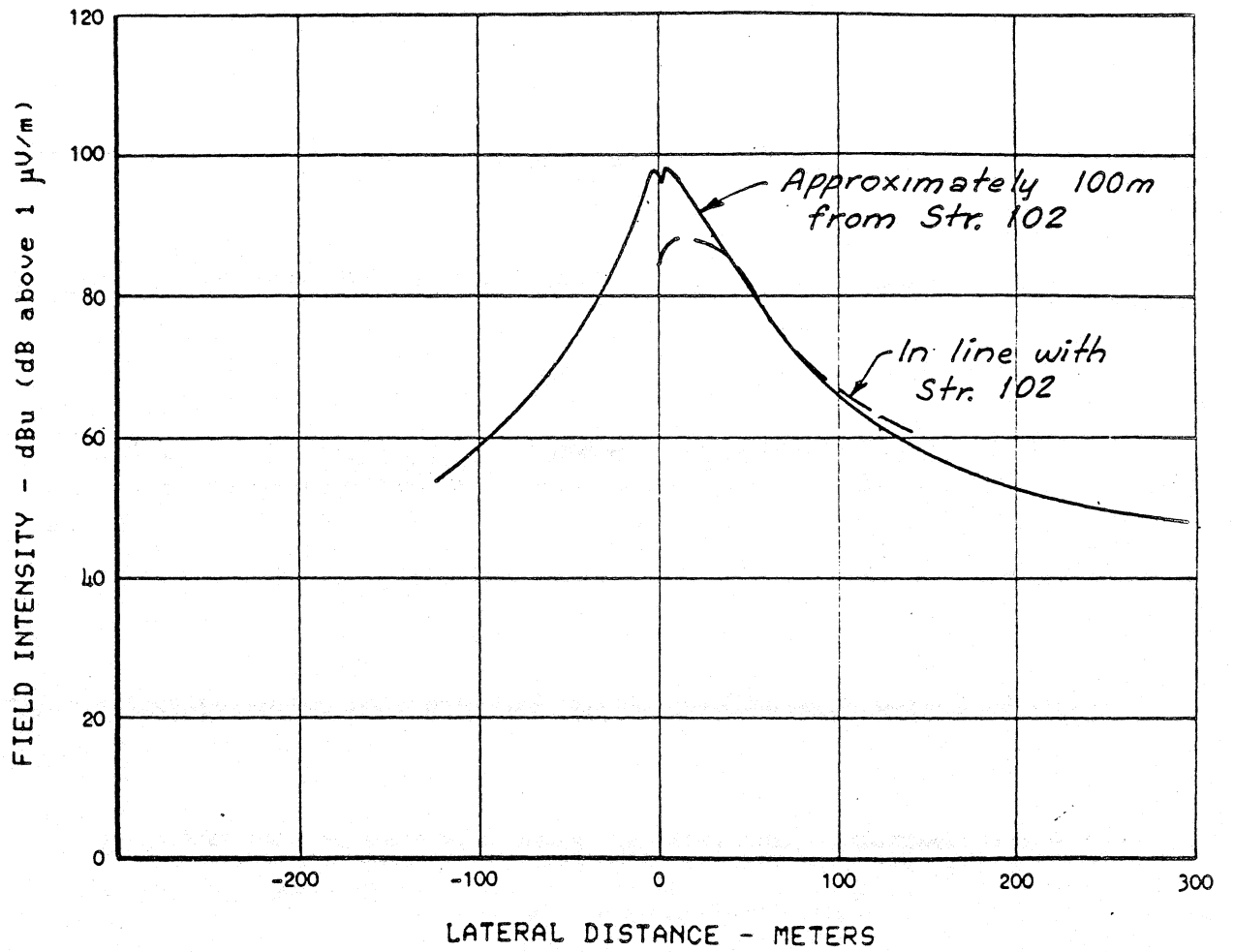


Figure 28. Measured Data At a Site Near Clarksville-West Nashville Transmission Line Showing Comparison of Field Intensity Near a Steel Structure With That Near Midspan.

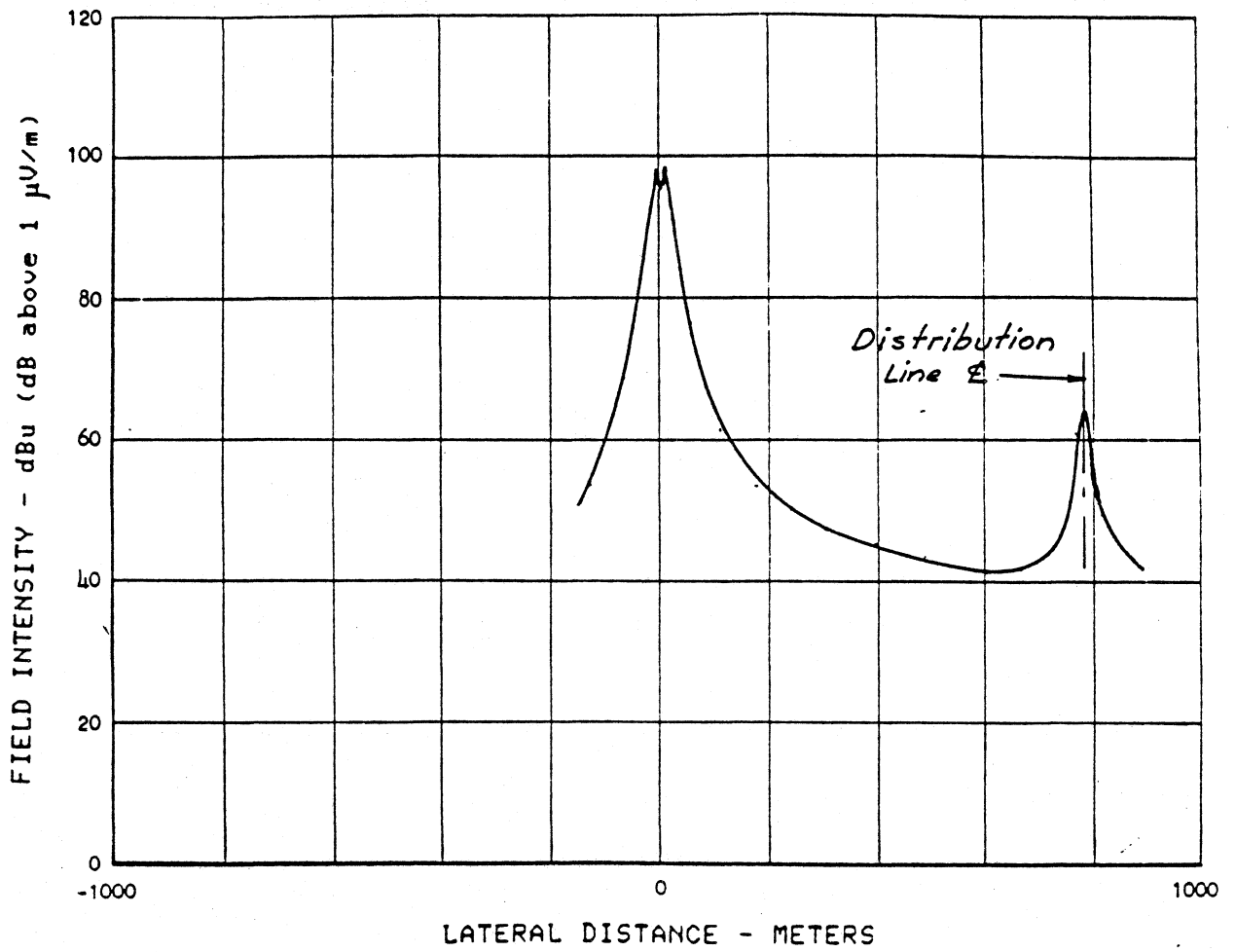


Figure 29. A Plot of Data Taken Near Clarksville-West Nashville Transmission Line.

A comparison of measured data obtained in this test with the calculated results is shown in Figure 30. It should be pointed out that the difference between the measured and calculated results grows larger at distances beyond 300 m. This phenomenon has been shown to be true in all the comparisons made in this analysis. This may be because all the variables, such as the inhomogeneity of the ground, were not included in the model.

Montgomery-Wilson Line:

This is a single-circuit, horizontally arranged, 500 kV transmission line with V-string configuration as shown in Figure 31. Because of rugged terrain and the presence of distribution lines at most points of access, the most favorable site for making measurements was judged to be along an interstate highway, crossing the transmission line almost perpendicularly. This was approximately 55 km from Montgomery substation where a 10 W signal at 183 kHz was coupled phase-to-phase on the north and center phase conductors. Because of heavy highway traffic, the loop antenna was not oriented for maximum readings except for a few isolated checks. Therefore, all plotted data for this site represents measurements with the antenna in a vertical position. Passing vehicles themselves had no significant effect. Measurements were made both north and south of the line along each direction of the freeway. Figure 32 shows a plot of these data. The distortions in the shape of the field patterns south of the line were believed to be due to the relatively steep slopes in the surrounding terrain. Measurements on the north side of the line appear to be in keeping with the more open and level ground. The dips in field intensity, one about 670 m and another one at 3200 m north of the line, occurred where the measurement path passed under a crossing overpass. Measurements north of the line were extended to a distance of over 4 km.

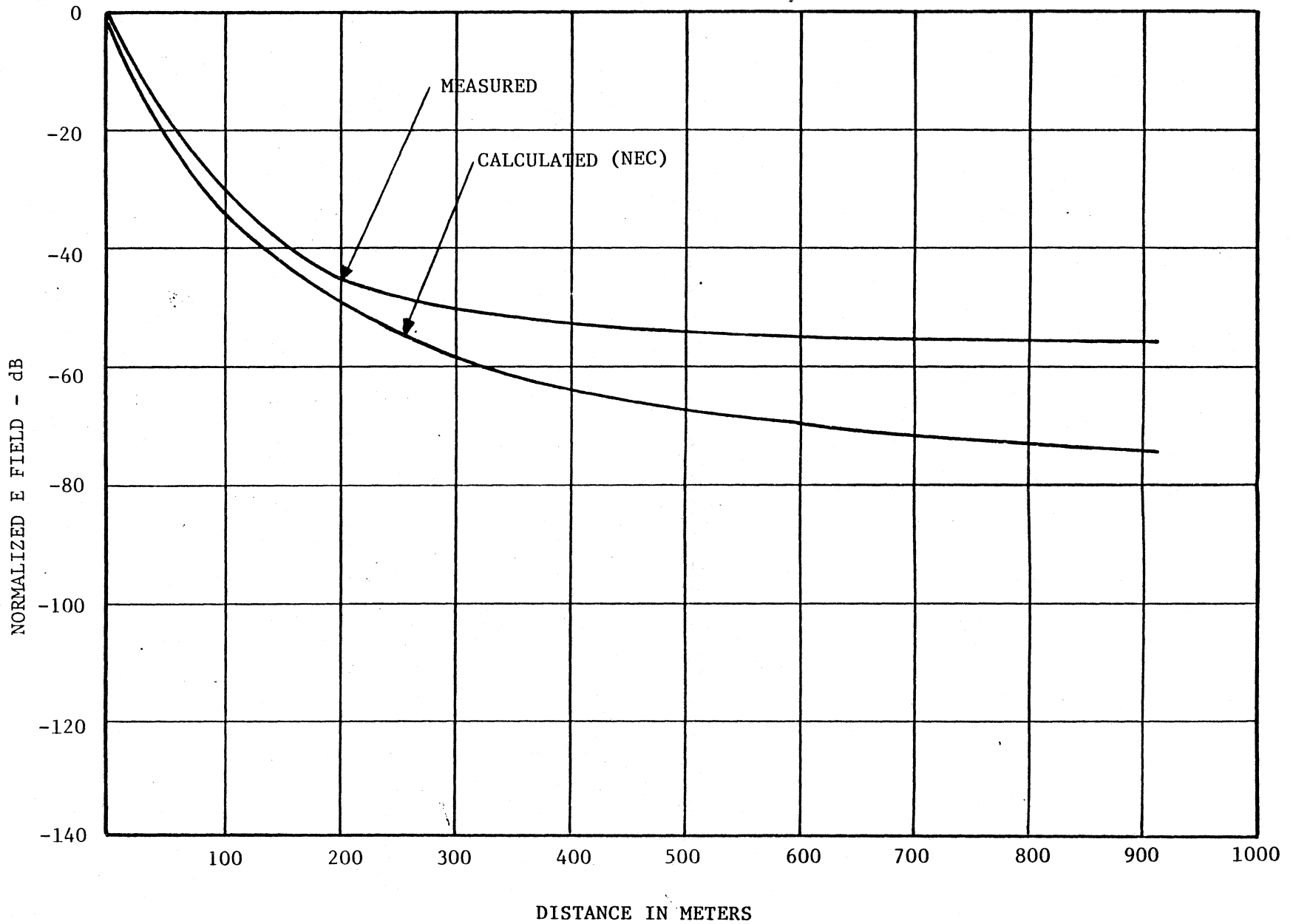


Figure 30. Comparison of calculated results with the data taken near Clarksville-West Nashville transmission line.

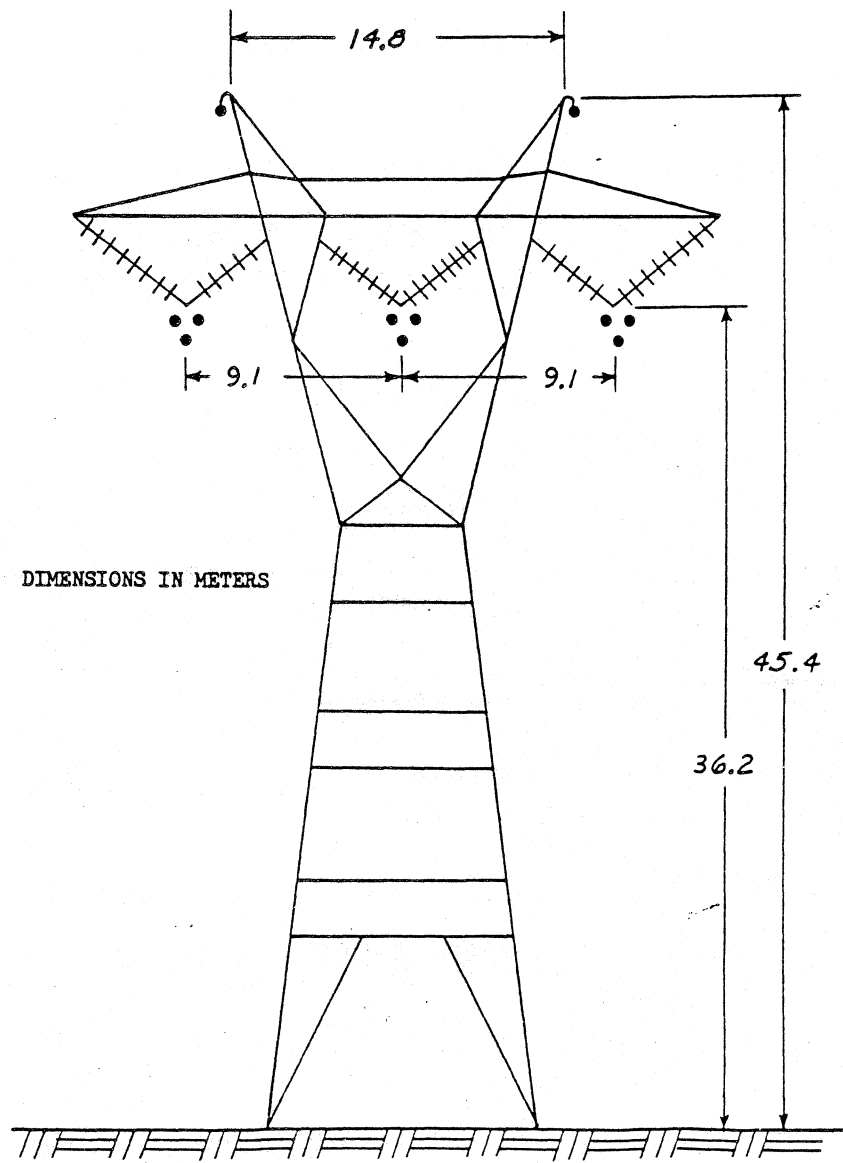


Figure 31. Configuration of a Typical Tower Used in the Montgomery-Wilson 500-kV Transmission Line.

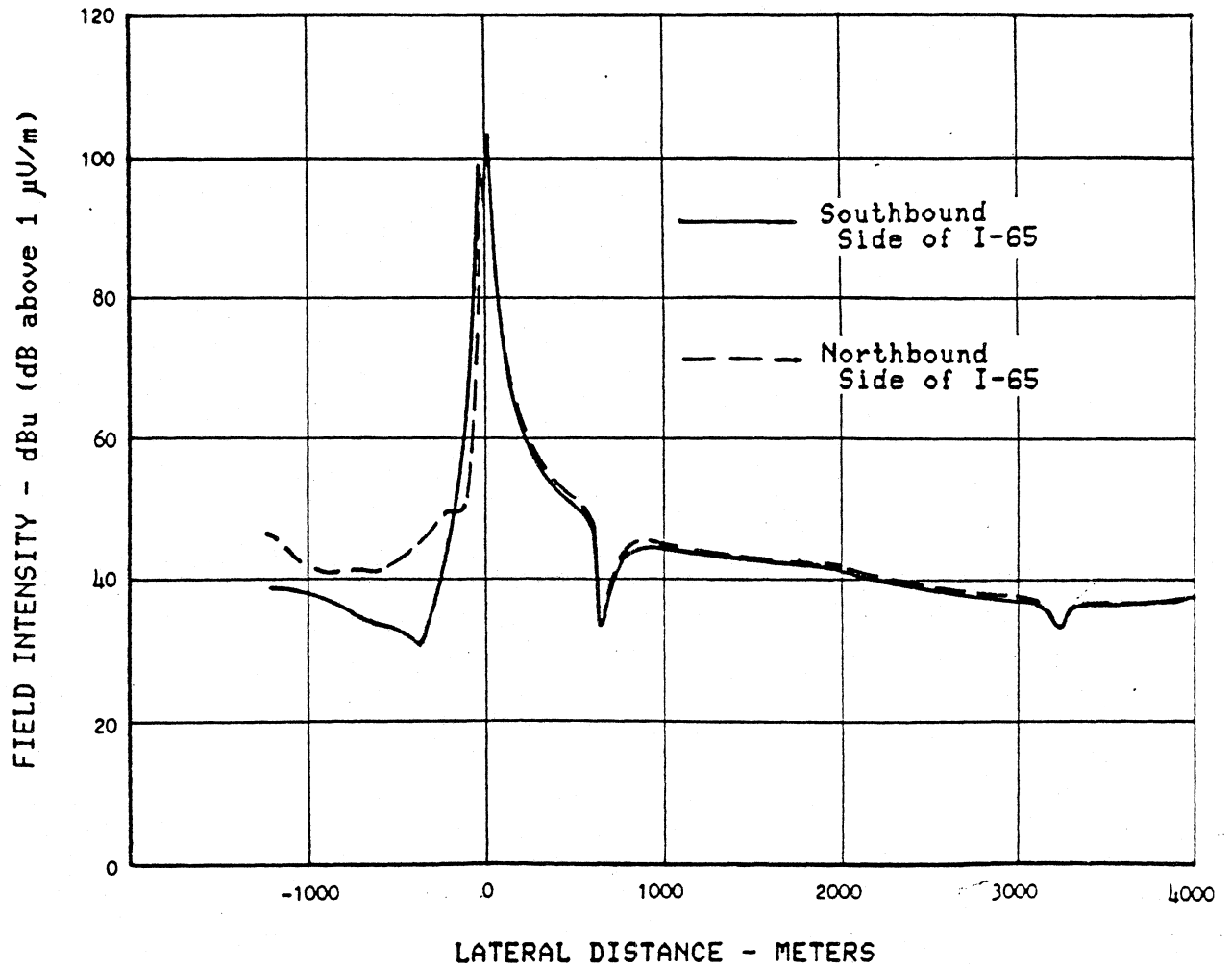


Figure 32. A Plot of Data Taken Near the Montgomery-Wilson Transmission Line Showing the Effects of Uneven Terrain South of the Line (Left) and Two Highway Overpasses North of the Line.

A comparison of the measured data shown in Figure 32 with the calculated results is illustrated in Figure 33. Note the change in the results as a function of ground conductivity. At distances beyond 300 m, the effect of the ground conductivity on the calculated field intensity clearly exhibits the surface wave-type properties of the ground at low frequencies used by the PLC transmitters.

Data on field intensity, measured by the TVA at various sites, clearly points out an important fact that such measurements are always influenced by the terrain and any sizable scatterer located in the vicinity of a power line. In addition, it was shown that the ground parameters have a noticeable effect on the field intensity measured near the ground for the transmission lines used by the PLC systems.

Nebraska Public Power District (NPPD)

Nebraska is relatively flat and compared to Virginia and Tennessee, has a smaller population density, and fewer highways. As such it is easy to find a suitable site for field intensity measurements in Nebraska. For brevity, only the measurement at site number 3 will be discussed here. The support structures for power lines in Nebraska are generally made of wood and the transmission lines are closer to ground. Figure 34 shows a typical tower carrying a three-wire transmission line designed by the NPPD. This transmission line operates at 230 kV and serves as a medium for transmission of a 173 kHz carrier system. The line used at the test site extends between the Kelly and Grand Island substations. A schematic diagram of this carrier system is shown in Figure 35. The site selected for measuring radiation field intensity from this system was nearly flat and free from reflecting structures such as farm buildings, silos, and farm sprinklers. Two measuring teams with two different measurement setups participated in this test. One team was from the Institute for Telecommunications Science (ITS) and the other team was from NPPD. The field intensity meters in this test were the Electromagnetic Interference Analyzer (Model EMC-25) and the Rhode and Schwartz Field Strength Meter (Model HFH) used by NPPD and ITS, respectively. Both meters were calibrated prior to measurements. The data shown in Figure 36 was taken on one side of the transmission line extending between Kelly and Grand Island.

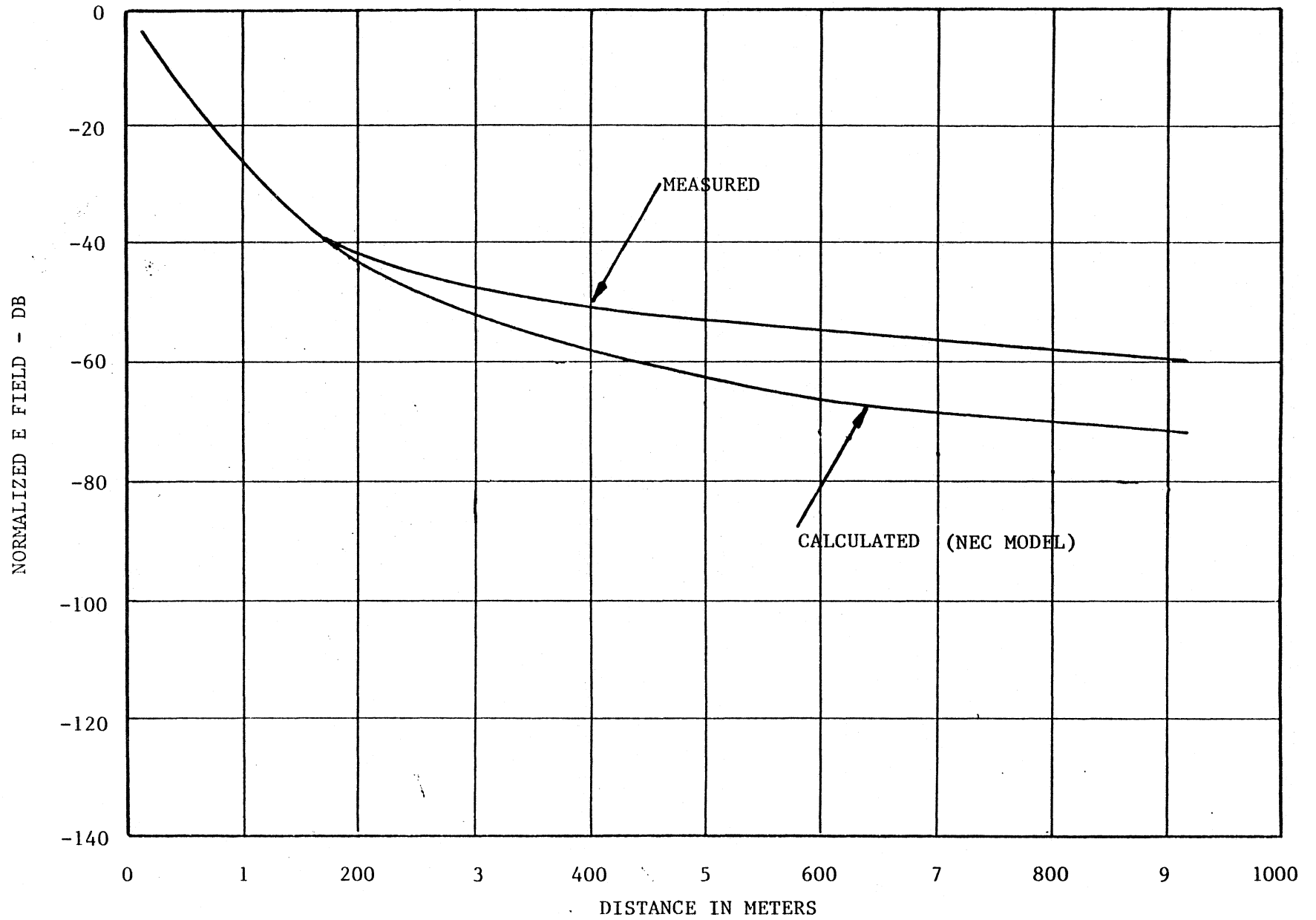


Figure 33. Comparison of Measured and Calculated Data for Montgomery-Wilson Transmission Line.

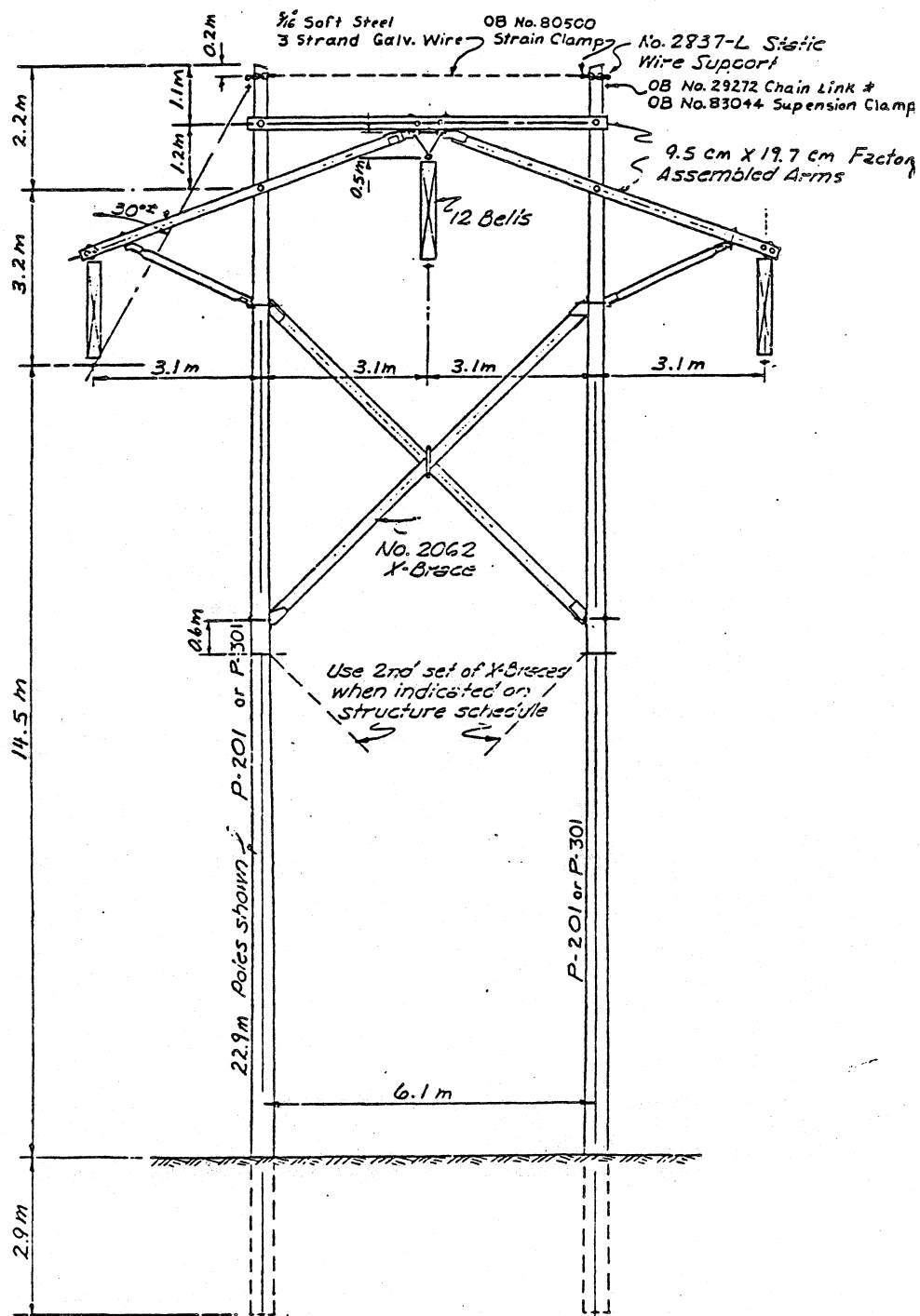
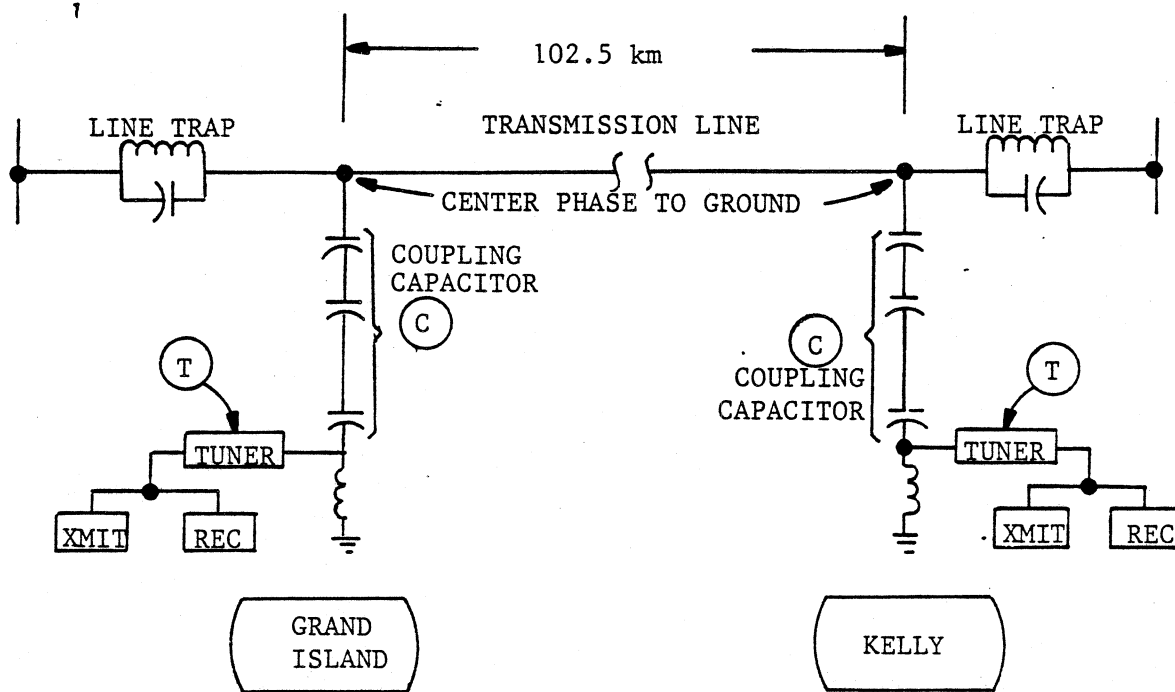


Figure 34. Typical Support Structure for Power Transmission Lines in Nebraska.



- (C) .0032 μ fd capacity with 0.88 db loss at 173 kHz.
- (T) Tuner has 0.7 db loss at 173 kHz.

Figure 35. A Diagram of PLC System designed by Nebraska Public Power District (NPPD).

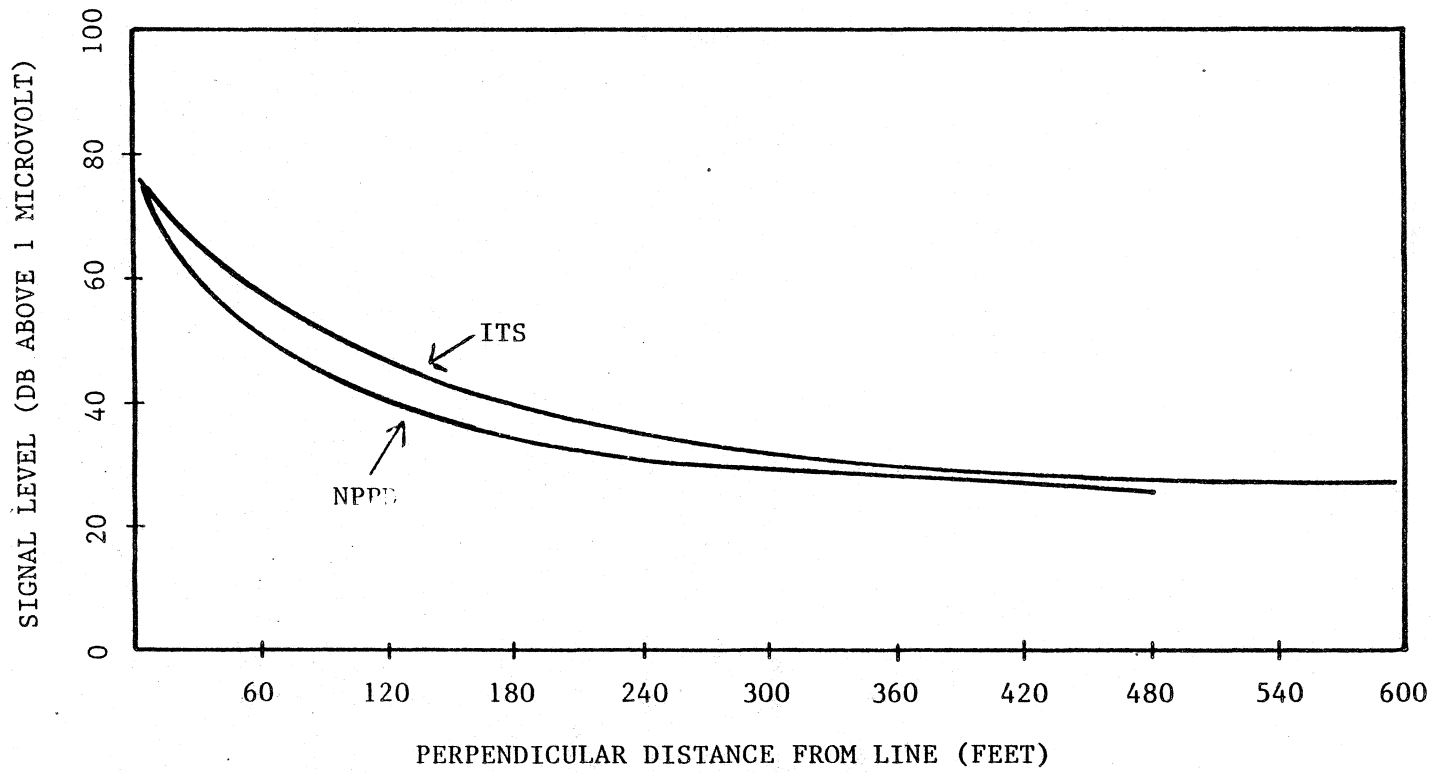


Figure 36. A Plot of Data Taken by ITS and NPPD at a Site Near the Kelly-Grand Island Transmission Line in Nebraska.

The data taken at this site was used to substantiate the results obtained using an analytical model. A comparison of the analytical results and the measured data obtained at this site is illustrated in Figure 37. Note the close agreement of the measured and calculated results as depicted in Figure 37.

Virginia Electric Power Company (Veeco)

Measurements conducted by Veeco represent field strength levels of a transmission line in a metropolitan area. The measurement site was a residential area with a distribution power line running parallel to the line carrying the carrier signal. In addition, telephone lines at the site contributed much to anomalous type data. As was pointed out earlier, these anomalies are site dependent and it was considered unnecessary to attempt any analytical explanations for them. A plot of data taken by Veeco at the above mentioned site is given in Figure 38.

Northeast Utilities Service Company (NUSCO)

Northeast utilities presented results of measurements taken at a site near the Bokum substation. Several measurement sites were selected by NUSCO for this measurement. For brevity, only the results for the site near Bokum substation will be presented here. Typical support structures used by NUSCO are shown in Figure 39. The supports, as shown in Figure 39, are made of wood and steel. The data presented in Figure 40 were obtained using a three-wire transmission line. Note that the plot in Figure 40 indicates a steady decrease in field strength as a function of the perpendicular distance travelled away from the transmission line. The equipment used in this test was the Singer Model NM-25T Receiver (S/N 0607-06209). The data shown in Figure 40 indicates higher field intensity levels than those reported by NPPD. The reason for this increase is the fact that the measurement site selected by NUSCO was only 1km away from the carrier transmitter site as compared with 26 km reported by NPPD. Considering the line losses,

NORMALIZED E FIELD - DB

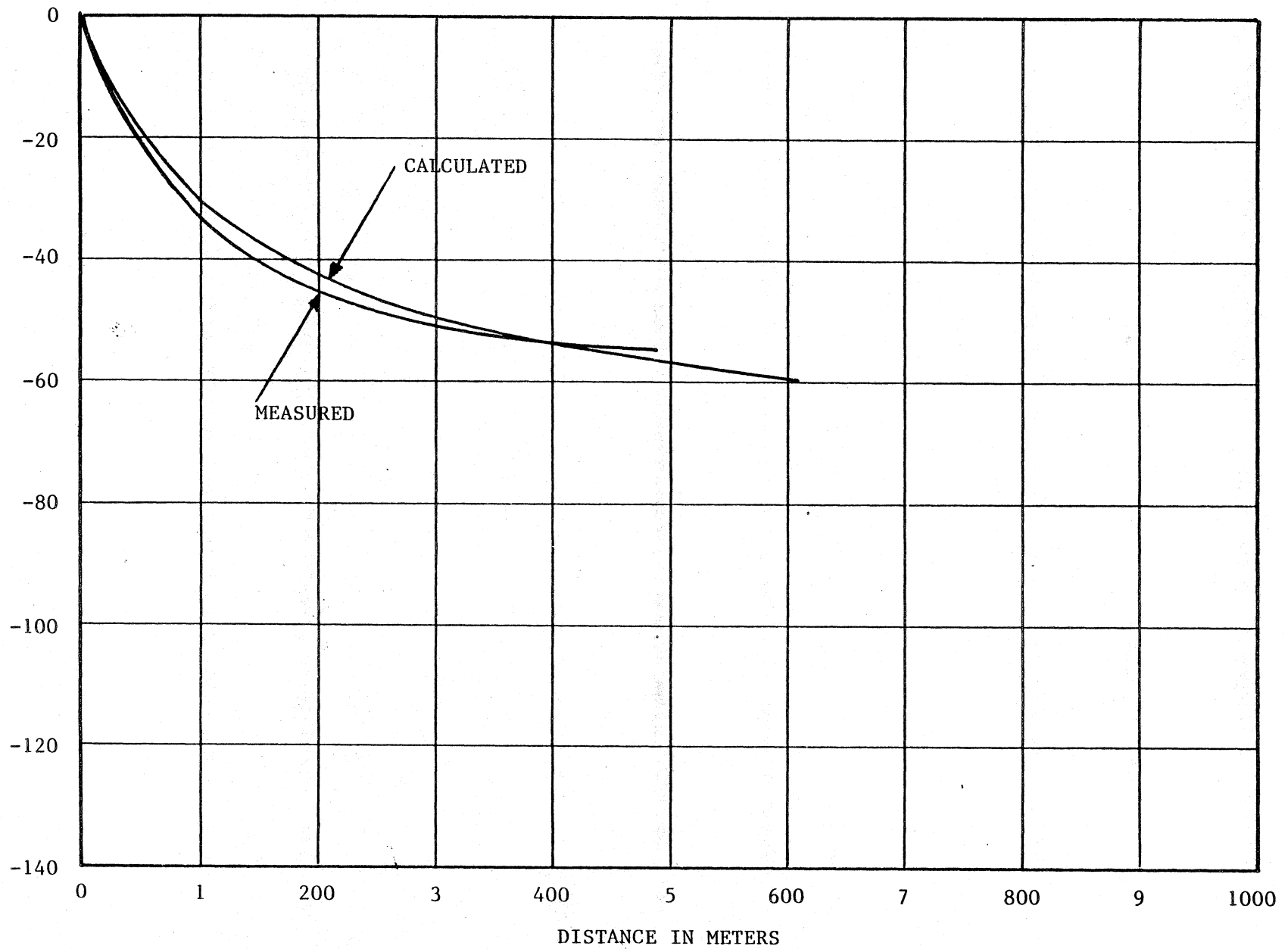


Figure 37. Comparison of the Data Measured in Nebraska (Kelly-Grand Island Transmission Line) with Calculated Results Obtained using NTIA's Computer Model.

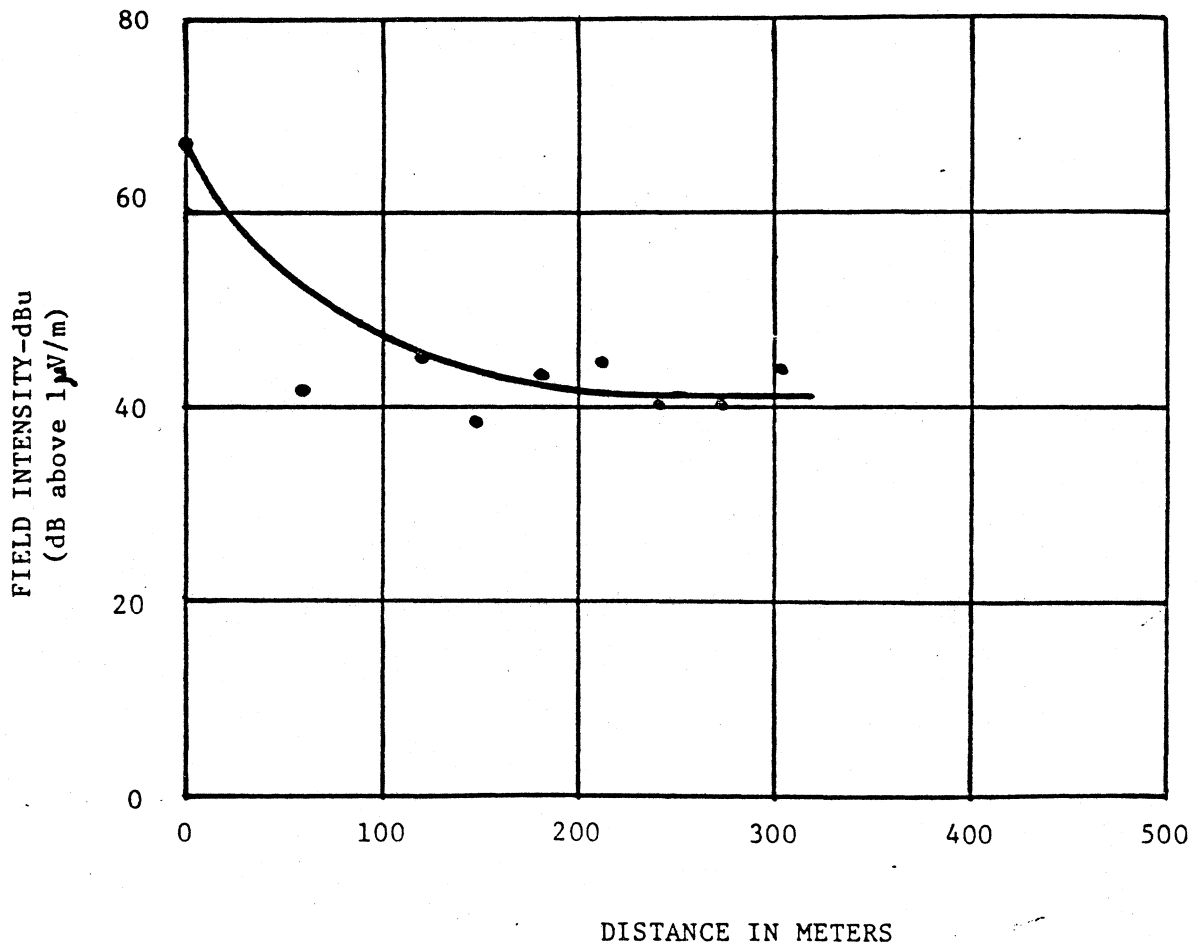


Figure 38. Data Taken by Vepco in a Location Close to Distribution and Telephone Lines.

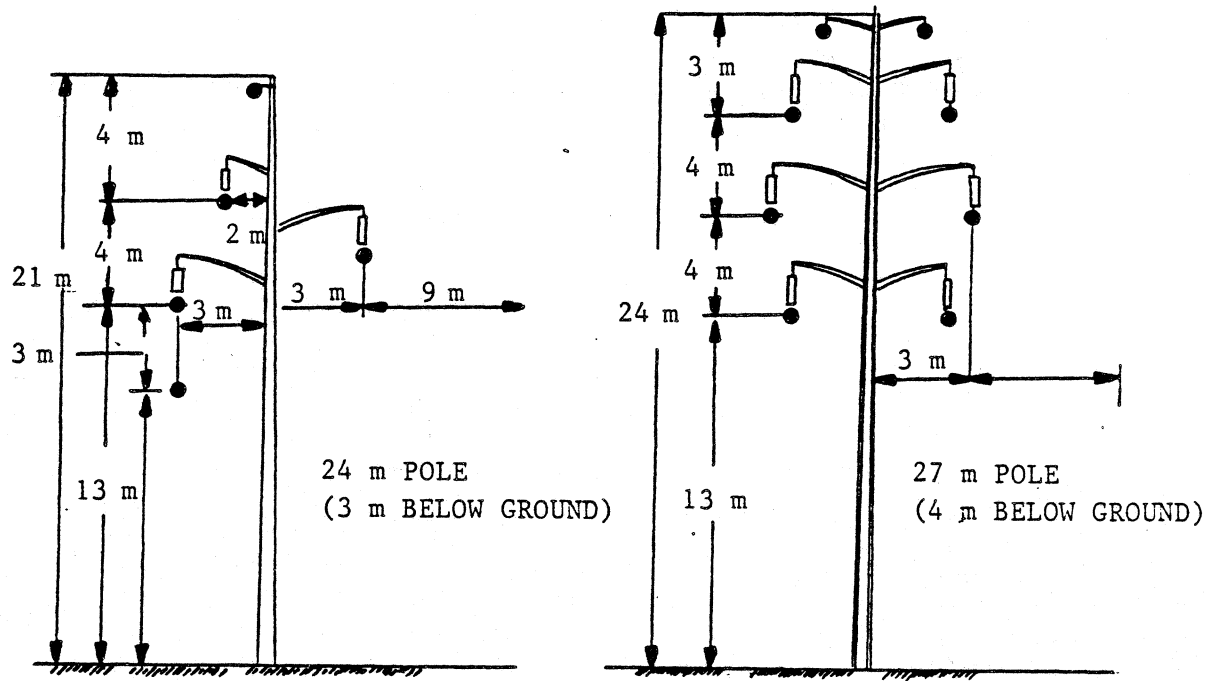


Figure 39. Typical Support Structures used by NUSCO for 115 kV Transmission Lines.

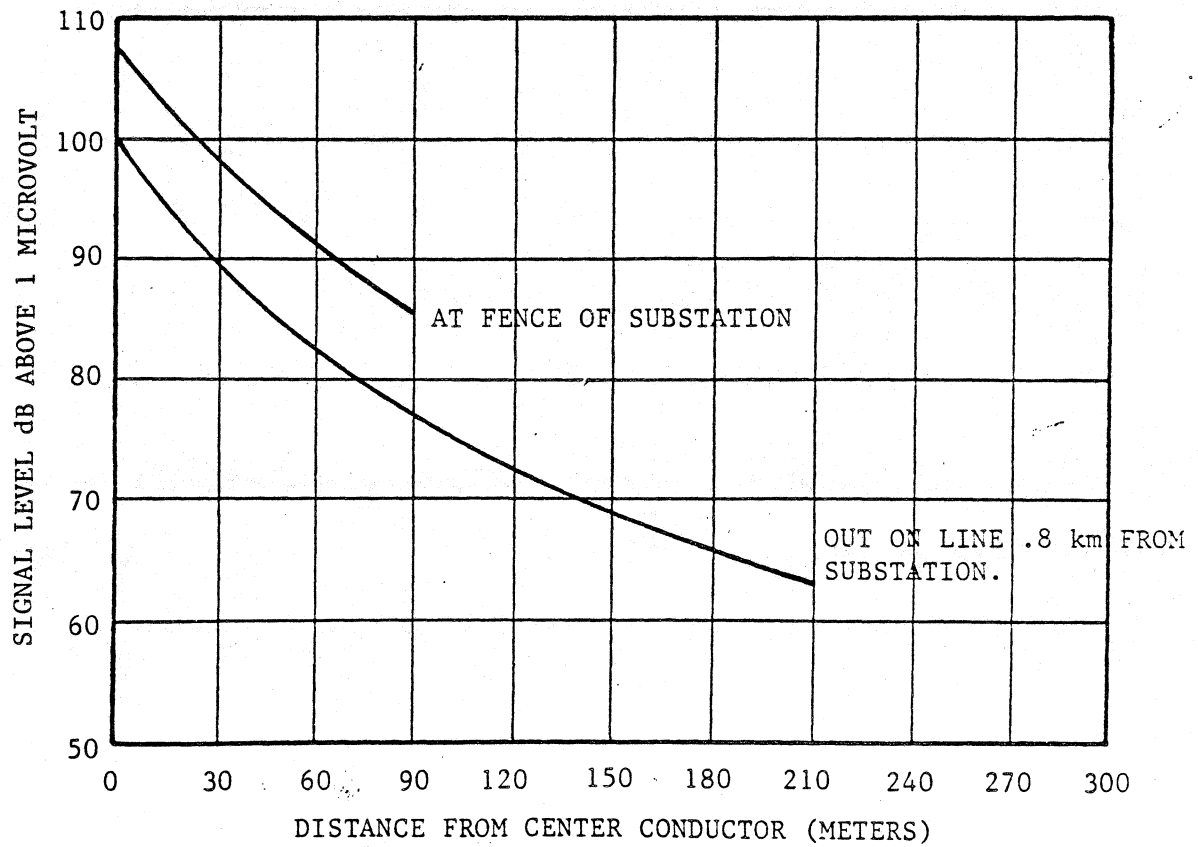


Figure 40. Electric Field Intensities Measured by NUSCO at a Site Near Bokum Substation.

calibration discrepancies for the two measurements, and the effects of scattering surfaces under a substation on open field measurements, one may infer that the results reported by NUSCO are similar to those obtained by NPPD.

Public Service Company of Colorado (PSCC)

The Institute for Telecommunications Sciences (ITS), in cooperation with PSCC, conducted field intensity measurements at a site near Denver, Colorado. The site where these measurements were taken is 16 km outside Denver near Smokey Hill. The transmission line used in the measurement is 230 kV and is supported by wooden towers. Three-wire transmission lines are most prevalent in the Denver area and the carrier system used in the measurement operated at 170 kHz. ITS used the Rhode and Schwartz Field Strength Meter for the measurement after it was calibrated by the National Bureau of Standards (NBS). The ground conductivity at the site was estimated to be 0.02 mhos/m and the relative permittivity of the ground was approximately 15.2. The measurement site was approximately 4 miles away from the carrier transmitter with a nominal output power of 8 watts. Several measurements near Smokey Hill were taken. The data plotted in Figure 41 represent the results of the measurement performed on county road 129. The site up to approximately 700 meters from the transmission line, was on smooth terrain. Rolling hills, which sometimes contribute to the scattering of the waves, were seen at distances beyond 700 meters. Note the distortion in the results at separation distances beyond 600 meters which may have been caused by the effects of the terrain.

Southern Colorado Power Company (SCPC)

The purpose of the measurements in the area served by the SCPC was to determine empirically the coupling factor between an existing GWEN antenna and nearby electric power transmission lines. In addition to the measurement of coupling factor and signal levels, field intensity levels produced by the existing GWEN signal near Boone substation were measured. A description of the measurement site is necessary.

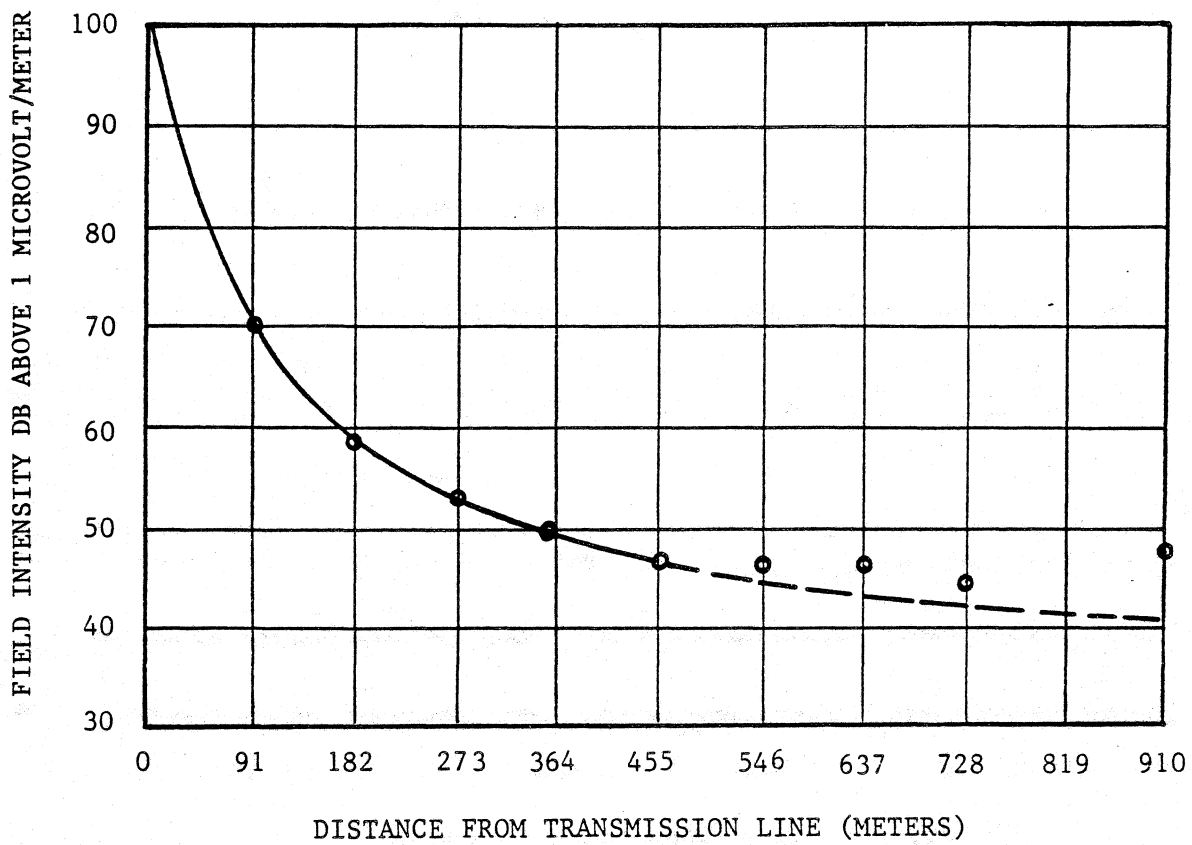


Figure 41. Field Strength Measurement Near Smokey Hill, Colorado.
The Data was Obtained by the ITS.

The GWEN antenna, a prototype version as shown in Figure 1(a), was located at Pueblo, Colorado. The nearby substations located at Midway, Boone, and La Junta were used to monitor the signal transmitted by the GWEN station. The radiated power of the GWEN antenna was 2000 watts, or 63 dBm. The GWEN transmitter was tuned to 170 kHz. The PLC circuit on the power lines provided telephone service using the lower sideband of a 172-kHz carrier. The pilot carrier signal was present on the lines at all times.

A schematic of the measurement setup and levels of the received signal from the GWEN transmitter and the PLC circuit are given in Figure 42. The geographical relationships are shown in Figure 43. Switches B2 and B4 were closed during the test. Switches B1 and B3 were open for some of the measurements and closed (normal) for others as stated in the text or in Figure 42. The matching transformers (MT) in the PLC coupling circuits were wideband and the insertion loss for these networks at 170 kHz was assumed to be negligible.

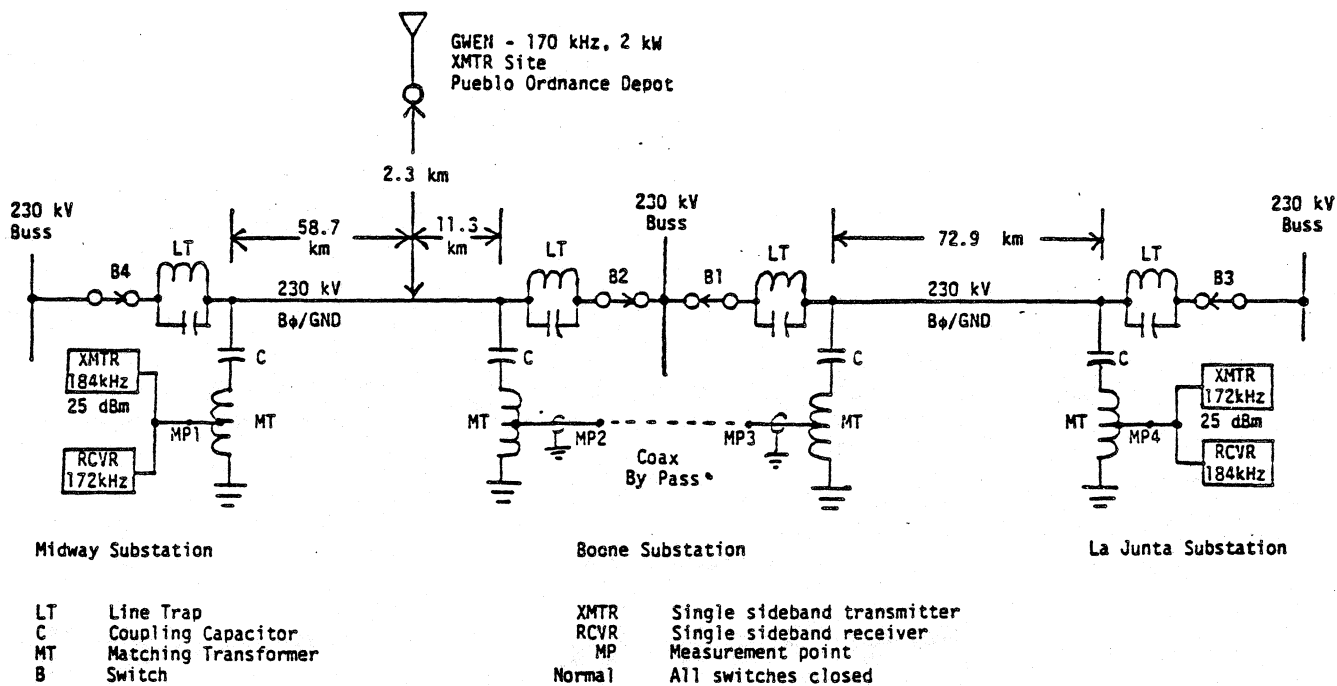
The measurements at 172 kHz showed PLC signal levels of 25 dBm at La Junta, 7.3 dBm at Boone, and -11 dBm at Midway. The indicated PLC line losses are therefore 17.7 dB from La Junta to Boone and 18.3 dB from Boone to Midway. These individual line segment losses are not proportional to their respective line lengths; however, this type of discrepancy is fairly common, particularly with phase-to-ground coupled signals.

It cannot always be assumed that PLC signal losses are uniform along a transmission line; however, it is useful to consider the loss between Boone and Midway in its two parts, one from Boone to the point on the transmission line nearest the GWEN transmitter and the other from this point to Midway. On the assumption that the losses are distributed approximately according to the length of each part of the line, the loss of the first part would be:

$$\frac{11.3 \text{ km}}{70 \text{ km}} \times 18.3 \text{ dB} = 3 \text{ dB}$$

and the loss for the other part would be 15.3 dB.

Various measurements were made of the field intensity (FI) of the GWEN signal at 170 kHz. Immediately adjacent to the transmission line at the point nearest to the GWEN transmitter, the FI was 103.2 dBu (dB above 1 microvolt



MEASURED POWER LEVELS

| MP1 | MP2 | MP3 | MP4 |
|------------------|--------------------|-------------------|---------------------|
| Normal | B1-open B3-open | B1-open B3-open | B1-open B3-open |
| By-pass in | By-pass open | By-pass open | By-pass open |
| 172 kHz, -11 dBm | 172 kHz, -19 dBm | 172 kHz, 7.3 dBm | 170 kHz, -16 dBm |
| 170 kHz, -16 dBm | 170 kHz, -6 dBm | 170 kHz, -17 dBm | B1-closed B3-closed |
| | | | By-pass open |
| | Normal | Normal | 170 kHz, -22 dBm |
| | By-pass open | By-pass open | |
| | 172 kHz, -19.7 dBm | 172 kHz, +7.3 dBm | |
| | 170 kHz, -5 dBm | 170 kHz, -25 dBm | |

Figure 42. Schematic of measurement set-up in southern Colorado used to measure coupling factors between GWEN and electric power line.

per meter). At a point very near Boone substation, the FI was 97 dBu. The 170-kHz signal received at Midway was -16 dBm. At Boone, the measured signal was -5 dBm with one switching condition and -6 dBm with another switching condition.

Considering the line loss of approximately 3 dB and the difference of more than 6 dB between the FI at the "nearest point" and that at Boone substation, it seems reasonable that the mechanism by which the measured 170-kHz signal arrived at Boone was via coupling which occurred primarily in the vicinity of the point nearest the GWEN antenna and hence propagated over the power line from there into Boone. This is in agreement with the methods generally proposed for analyzing potential interference situations. For example, calculation of coupling factor, which will be discussed in more detail later in the report, is based on the assumption that all significant coupling takes place within a few wavelengths of the closest point of exposure. Coupling which takes place beyond this range simply tends to lower the apparent propagation loss to the GWEN signal (along the transmission line) by a small amount.

Since a measurement of coupled power level could not be made on the high-voltage transmission line at the closest point of exposure, it was necessary to derive the GWEN signal level existing there by an indirect technique. To accomplish this, it was assumed that the signal coupled at that point was propagated in each direction (toward Midway and toward Boone) with an equal rate of attenuation.

Corresponding measurements of the 170-kHz signal received at Midway and at Boone (switches B1 and B3 closed) were -16 dBm and -5 dBm, respectively. The coupled signal (CS) can be evaluated from the relationship:

$$\frac{L_{P1}}{d_1} = \frac{L_{P2}}{d_2}$$

Where L_{P1} and L_{P2} are propagation losses and d_1 and d_2 are corresponding distances along the line.

Using the data described above,

$$L_{p1} = CS - (-16)$$

$$L_{p2} = CS - (-5)$$

$$d_1 = 58.7 \text{ km}$$

$$d_2 = 11.3 \text{ km}$$

Therefore:

$$CS = -2.4 \text{ dBm}$$

Similarly, using the other measurement at Boone, of -6 dBm, the indicated coupled signal is

$$CS = -3.6 \text{ dBm}$$

An average of these two values is -3 dBm. The empirical value of the coupling factor based on this average value can be evaluated by setting P_r equal to -3 dBm and remembering that P_t is 63 dBm in the following relationship:

$$\begin{aligned} F_c &= P_r - P_t & (1) \\ &= -3 - 63 = -66 \text{ dB} \end{aligned}$$

where

F_c = Coupling factor (dB)

P_r = Interference power received by PLC receiver (dBm)

P_t = Interference power transmitted (dBm)

The coupling factor for a separation distance of 2.3 Km, corresponding to the shortest distance between the GWEN antenna and the transmission line under test, was calculated to be -70 dB. The method of calculation will be discussed later. The empirical value of the coupling factor of -66 dB represents a variance of 4 dB from the computed value. Such variances are to be expected and must be considered in other similar assessments.

While the technique described above was found useful in rationalizing actual measurements on an existing site, it cannot be generally applied to estimate coupling factors at other sites where measurements are not available.

Some additional discussion of the data and conclusions drawn from the Colorado measurements is in order. It may be noted from Figure 43 that a sharp bend exists in the transmission line between Boone and Midway. In any general analysis of a potential interference situation, a bend such as this one can be very significant if it falls within or very near the segment of line to be used in computing the coupling factor. In this case, it would be necessary for the analytical model to include the bend and a few wavelengths of the line beyond in order to correctly assess the "wraparound" effect of the transmission line geometry. On the Boone-Midway line, the bend is far enough away from the vicinity of maximum coupling that its influence is considered negligible.

The data taken of the 170-kHz GWEN signal at La Junta substation were not used in the analysis because of the complexity of the PLC transmission network.

ANALYTICAL MODEL

Among the various analysis techniques, method of moment (matrix method) was found to be most appropriate for estimating radiation from the electric power transmission lines. This method uses no assumption for the current distribution on the lines. It does take into account the effects of the conductivity and permittivity of the ground over which the transmission lines are constructed. In addition, the effects of mutual coupling between transmission lines on the results are considered when the moment method is

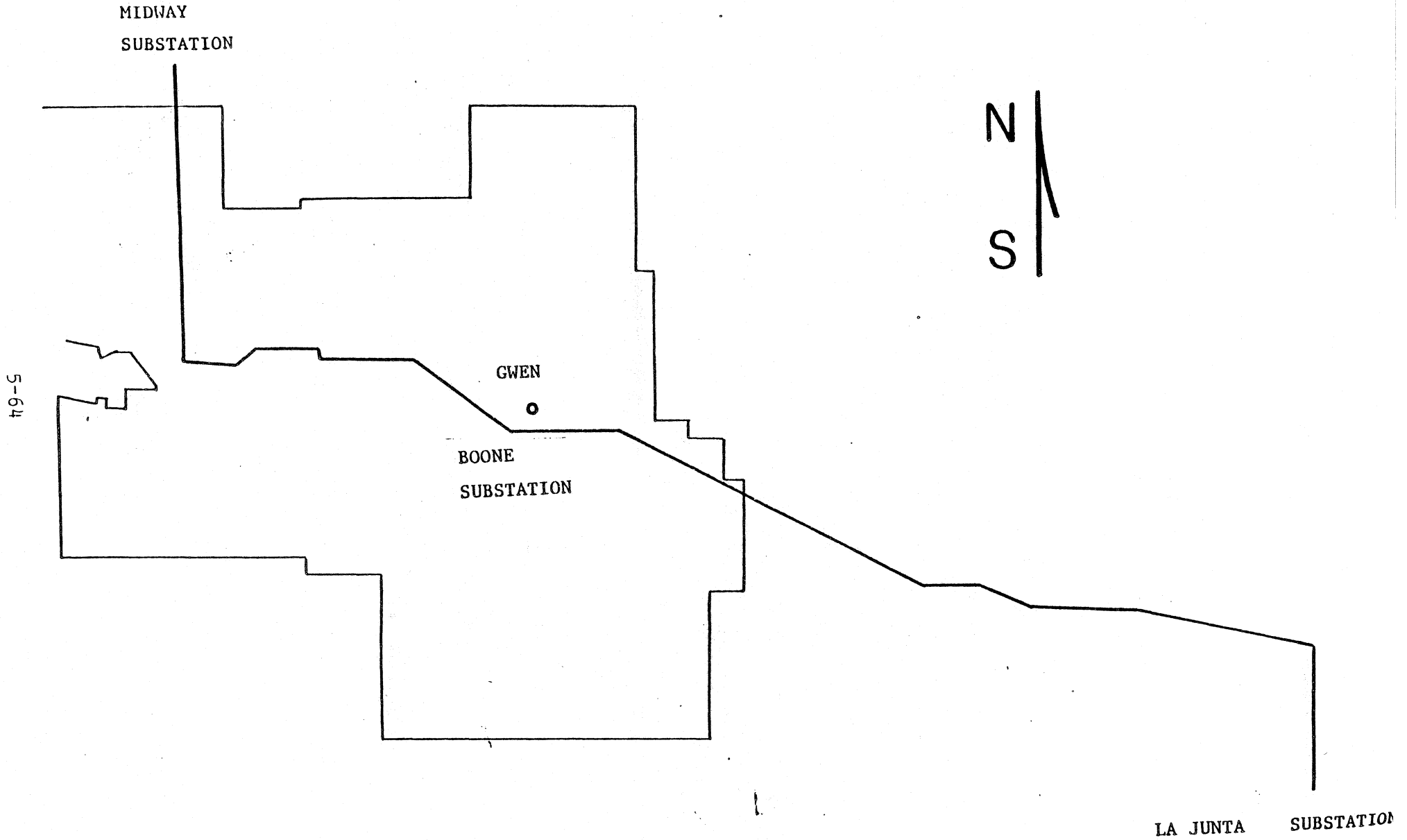


Figure 43. Geometry of Transmission Line Connecting La Junta, Boone, and Midway Substations Near Pueblo, Colorado.

employed. Simpler solutions can be developed when a convenient current distribution for the lines is assumed and the ground effects are ignored. However, these simpler solutions do not take into account the geometry of the lines. Therefore, the method of moment is the best technique for determining the radiation from the power line. The moment method is based on a unified principle for reducing functional relationships of a problem to matrix equations. Specific solutions may be obtained when boundary conditions are applied. Treatment of nearly all electromagnetic radiation problems by the moment method involves the inversion of matrices of large order. As such, the method is best suited for computation by electronic computers.

Application of the matrix method to a transmission line is as follows. The current on the line is described by a set of complex unknown vectors (i_1, i_2, \dots, i_n , assuming n segments in the line) associated with expansion functions that are represented by a pulse or triangular functions. As a result of this approximation of the current by a finite number of expansion functions, the basic integro-differential equation characterizing the problem is reduced to matrix Equation (1)

$$[V] = [Z] \times [I] \quad (2)$$

where V_i , an element of $[V]$, represents generalized voltage and Z_{ij} , an element of $[Z]$, is a generalized impedance function. Loading of a line may be taken into account by adding a diagonal load matrix to $[Z]$. The matrix method can be used directly for the calculation of near electric and magnetic field intensities of power lines. Equation 2 describes a set of simultaneous equations that can be solved using a coded algorithm for use on digital computers. The NEC is a computer coded algorithm developed by the U.S. Navy and is based on a matrix method for treating thin wire antennas such as an electric power transmission line. The NEC program is available on NTIA's computer and was used in this analysis.

Numerical Electromagnetic Code (NEC)

The NEC is a user-oriented code designed for the analysis of radiating or scattering wires and surfaces. The NEC program has a built in algorithm for calculating the elements of the impedance matrix given in Equation 1 from the geometry data prepared as an input by the user. The program is used to model a variety of structures, perfect or imperfect conductors, placed over a ground plane that may either be perfect or lossy. The excitation for the problem can be a voltage or current source. A plane wave with linear or elliptical polarization may also be modeled by the NEC program. The user's manual prepared by Burke (Burke and Poggio, 1981) gives a detailed description of the code and has easy-to-follow instructions for preparing the input data required. NEC-2, the most recent version of NEC, is the latest in a long line of modifications that have been made to the program in the last decade. There are a number of options available in the application of the NEC for the analysis of transmission lines. There are also some limitations that impede a rigorous solution of the problem. The advantages, as well as the disadvantages, of the NEC-2, as applied to the analysis of transmission lines, should be noted in the interpretation of the analysis results. A major disadvantage of the NEC-2 (or simply NEC) is the inability to take into account the effects of the terrain under, or in the vicinity of the power lines. The ground under the transmission line, as far as NEC is concerned, is always flat. A flat ground plane is applicable to locations where roughness of the ground (hills and valleys) presents no serious scattering problems and has no shadow regions. The nearby terrain often produces anomalies that make it difficult to achieve a good agreement between the calculated or measured data. Often, in a region where terrain roughness is serious, measurement may be the only method available for the determination of the field intensities near a power line. Another limitation of the NEC program, which is common in any type of numerical analysis, is that the choice of the size or matrix order is limited by the size of the memory available in the computer. This limitation determines the extent to which the detailed structure of an antenna can be modeled. Note that each segment of the transmission line is represented by an element of the impedance matrix in Equation 1. This element is complex and requires two locations in the memory storage of the computer. For example, if a transmission line is represented by 100 segments, the

impedance matrix is of the order 100, and 20,000 memory locations are required in order to store the matrix. The larger the matrix, the more Central Processing Unit (CPU) time is needed to carry out the computation. Note that the two major limitations discussed above for the analysis of the power lines are solely for the application of NEC in the analysis of these lines and should not be considered as general limitations to the matrix methods or even the NEC program. There are a large number of electromagnetic problems that may be solved rigorously using the NEC program.

The advantage of the NEC in considering the near or far field of a transmission line is its flexibility in taking into account the geometry of the line and the antenna, or antenna-like structures, in the vicinity of the line. Hence, one can readily model any bends or orientation of the line as well as its support structures. In addition, the NEC program takes into account the effects of the imperfect ground under the transmission line. The length of the segment discussed above is a function of wavelength. Usually, a segment can be as long as 0.1 wavelength. Therefore, the longer the wavelength, the larger the antenna size that can be analyzed using the NEC program. At low frequencies, such as those used by the PLC systems, the NEC program can handle large size transmission lines. This is advantageous and allows reasonable computation time (less than one hour).

Despite the limitations, NEC, is an appropriate computer model that may be used for predicting the electric and/or magnetic field intensities of a transmission line as an antenna.

The NEC model on the NTIA computer has a graphics capability. The graphics part of the program may be used in demand mode to provide a plot of geometry data cards. The user can exercise this option to obtain a plot of the antenna geometry which he has modeled by the data card and to verify that the data cards describe the intended geometry. The graphics capability may also be used to plot the calculated results produced by the program. The near field capability of the model can determine electric and magnetic field intensities for any given geometry at any location above the ground in front of the antenna. The contour plot capability of the model, which is presently available only on the NTIA version of the NEC, can produce contours of the near field for applications such as radiation hazard analyses.

DESCRIPTION OF NEC VALIDATION

Comparisons of the measured data with the calculated results for four different sites are shown in Figures 26, 30, 33, and 37. The results illustrated in Figures 33 and 37 show a reasonably good agreement between the measured and calculated field intensities. Factors and parameters effecting the field intensities produced by a power transmission line are discussed in the following paragraphs.

Generally, ground level radiation from an electric power line at distances beyond approximately 360 meters is effected more by the properties of the ground than the intricacies of the transmission line support structures. In the calculations of field intensities from the power lines the support structure had negligible effects and therefore, were not included in the input data for the computer calculations. Figure 44 shows a plot of the normalized electric field intensity measured at four different sites in the United States. The data in Figure 44 were extracted from the information presented in Figures 26, 37, 40, and 41. The differences between the data taken at different sites (shown in Figure 44) may be attributed to the geometry of the transmission line and different properties of the ground at different sites.

Bends and turns in the transmission lines effect the data for the field intensities. The transmission line in the Nebraska site was found to be free from bends and the measurement site had no electromagnetic obstacles or scatterers. The configuration described below was used in modeling a transmission line using the NEC computer program.

A three-wavelength-long transmission line illustrated in Figure 45 was considered to be sufficiently long for calculating field intensities. In addition, the lines were terminated with their characteristic impedance so that as far as the carrier signal was concerned, the line was a representation of an infinite line. Figure 45 shows a physical representation of a typical three-phase transmission line including the sag in the conductor height. Support structures are not included because their effect on the computer results have been found to be minimal. The excitation was applied at the

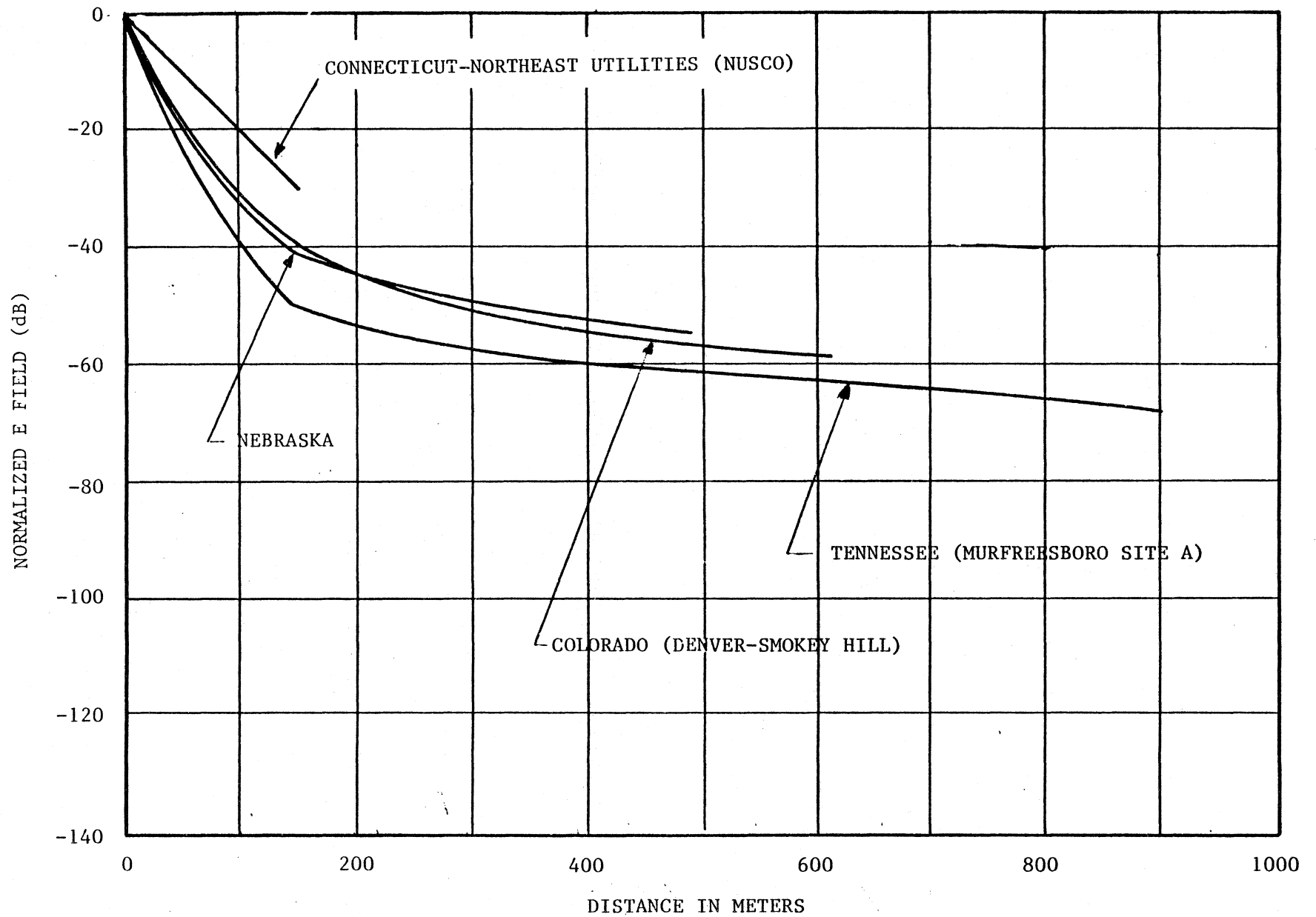


Figure 44. A Plot of Normalized Field Intensity Data Measured at Four different locations in the United States :

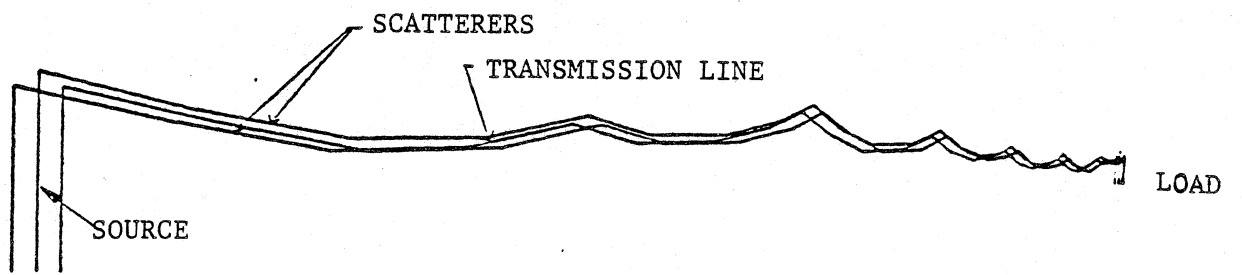


Figure 45. Triple wire transmission line without poles.

segment indicated. Both E & H field intensities at a level approximately 2 meters above the ground were calculated. The results of the calculation for electric field intensity at different sites were discussed earlier. The reasonable agreement between the calculated and measured data indicated that the model may be used in the calculation of the coupling factor between transmission lines and antennas for systems in the 150-190 kHz frequency range.

The general behavior of the electric and magnetic-field vectors at a near field point can be described by a vector, generally consisting of three orthogonal components. The relative magnitude of these components vary, and in some geometries, it is possible that one component almost completely dominates the others. For electric power transmission lines, the component of the field perpendicular to the axis of the transmission line is always several orders of magnitude greater than the component in the direction of the line.

COMPUTATION OF THE COUPLING FACTOR

As was discussed above, the coupling between any two antennas is a function of orientations and geometrical dimensions of the antennas. The NEC computer program was used to illustrate the use of this model in calculating the coupling factor between transmission lines and typical antennas for systems in the 150-190 kHz frequency range.

In the illustration given here, two antennas proposed for use by the GWEN system were used. A typical antenna shown in Figure 1(a) is proposed for use at six GWEN sites. The transmitter is connected to the antenna base and the radiation takes place mainly by the tower and the six wires attached to the top of the tower; extending approximately 55 meters at an angle of 45 degrees. The conductivity of the ground is enhanced by the radial wires placed under the tower. The geometry shown in Figure 1(a) was used to prepare the data input for the NEC computer model. The data for the three-wire power transmission line shown in Figure 45 was also used as input parameters in order to calculate the coupling factor between GWEN antenna in Figure 1(a) and the three-wire transmission lines. The separation distance between the GWEN antenna and the power transmission line was used as a variable ranging from

500 to 3,000 meters. The results of the calculations were plotted in Figure 46. Data obtained at Pueblo, Colorado are in good agreement with the calculated results shown in Figure 46. Similar calculations were performed for the GWEN antenna shown in Figure 1(b). The calculated data for this geometry was also plotted in Figure 46.

The data plotted in Figure 46 was for maximum coupling. Maximum coupling or maximum power transfer between the GWEN antenna and a power transmission line occurs when the source impedance and receiver load impedance are conjugate-matched to their respective antennas. A closed form solution for maximum coupling based on the relationship developed by Rubin (1969) was used in the calculation of the results shown in Figure 46. The equation for maximum coupling, C_{max} , is given by

$$C_{max} = [1 - (1 - L^2)^{1/2}] / L \quad (3)$$

where

$$L = |Y_{21} Y_{12}| / [2 R_e(Y_{11}) R_e(Y_{22}) - R_e(Y_{12} Y_{21})]$$

Y_{12}, Y_{21} = transfer admittance

Y_{11}, Y_{22} = self admittance

The coupling factors shown in Figure 46 include the effects of the ground, polarization, and the antenna gain. The results in Figure 46 were obtained for a receiver input impedance equal to 320 ohms which represents the characteristic impedance of the 230-kV line near the GWEN site in Pueblo, Colorado. By definition

$$F_c = P_r - P_t \text{ (dB)}$$

where P_r is the power in dBm at the input to the receiver and P_t is the power input to the transmitting antenna. For example, the GWEN antenna in Pueblo,

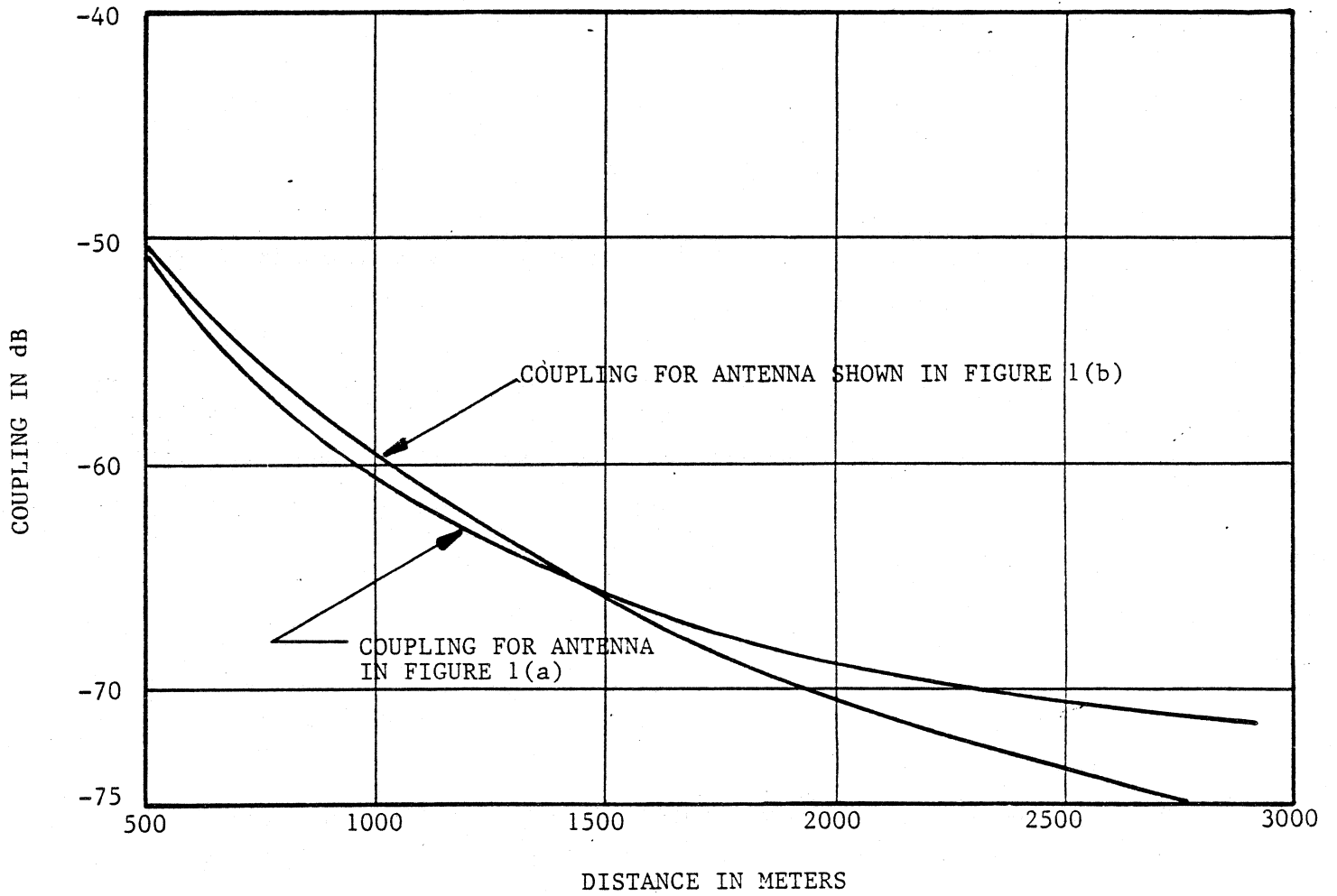


Figure 46. Coupling Factor Between Two Types of Proposed GWEN Antennas and PLC Transmission Line.

Colorado is located at 2.3 km from the transmission line. The coupling factor corresponding to 2.3 km is approximately -70 dB. Assuming the GWEN radiated power level to be 63 dBm (2,000 watts), the coupled power input to the PLC circuit will be -7 dBm. The measured data shown in Figure 42 indicated that the empirically determined received power at the point on the transmission line nearest the GWEN antenna at Pueblo was -3 dBm. This variance between calculated and measured signal levels is reasonable and supports the utility of the NEC computer model in the calculation of reactions between the PLC and radio transmitter antennas operating in the 150-190 kHz bands.

ANALYSIS PROCEDURE

In the preceding paragraphs, it was shown that the measured field intensity from the transmission lines were in reasonably good agreement with those calculated using the NTIA's analytical model. This agreement demonstrated by the analysis was found to be acceptable and the model was used to evaluate the coupling factor between a typical electric power transmission line and the antennas proposed for use by the GWEN System, a major system in the 150-190 kHz frequency band. The procedure discussed here is to show how any one of the three methods described below may be used to approximately assess the potential interference between a carrier receiver and a radio transmitter in the 150-190 kHz frequency range.

It should be realized that each of the methods to be described here does calculate the power coupled to the transmission line at the point on the line nearest the radio transmitter. Additional loss in the coupled power may exist if the PLC receiver is located at a significant distance away from the point of maximum coupling. In some typical cases this loss will be close to the propagation loss on the transmission line. Published data by the General Electric Company [DC PLC Application Seminar] are available for the computation of this loss.

1. Coupling Factor Method

The NTIA's analytical model (NEC) may be used to calculate the coupling

factor between a transmission line and a radio transmitter antenna. The computation of coupling factor between two types of GWEN antennas and a typical power line was carried out earlier and the results are shown in Figure 46. The level of an interfering signal coupled into a PLC channel on a typical power transmission line by a GWEN transmitter at a known separation distance from the line may be determined using the data in Figure 46 and the relationship:

$$P_r = P_t + F_c \quad (4)$$

where:

P_r = Interference power received by PLC receiver (dBm)

P_t = Interference power transmitted (dBm)

F_c = Coupling factor (dB)

Equation (4) may be applied in the opposite direction to determine the minimum safe separation distance for a given situation by setting P_r equal to the known receiver interference threshold.

The coupling factor in (4) is a function of separation distance as shown by the curves in Figure 46. As a numerical example, consider a 4000-watt GWEN transmitter with an antenna as in Figure 1(b) located a distance of one kilometer from a typical transmission line. The transmitter power of 4000 watts can be expressed as +66 dBm, and the coupling factor from Figure 46 is approximately -60 dB. Substituting these values in (4):

$$P_r = 66 - 60 = +6 \text{ dBm}$$

Assume a PLC receiver with an acceptable S/I of 15 dB. Neglecting line losses, the received PLC signal level must be +21 dBm or higher for satisfactory operation. If the actual received signal is, for example, only +10 dBm, the interference threshold would be -5 dBm. The computation using (4) may be reversed:

$$-5 = 66 + F_c$$

$$F_c = -71 \text{ dB}$$

From Figure 46 it is seen that satisfactory operation will be possible with a separation distance of two kilometers or greater.

2. Field Intensity Level Method

The field intensity level method is based on the assumption that the interfering signal level coupled into a PLC channel is a direct function of the field intensity (FI) which exists around the transmission line nearest the radio antenna. This method permits one to project the results of a known example to a wide range of applications. The only known example available at this time is based on the measurements near Pueblo, Colorado, which have already been discussed.

The maximum FI produced by the GWEN transmitter in the Colorado example measured at its closest distance from the transmission line near Boone substation was about 103 dBu. The interfering signal coupled into the transmission line at this point was approximately -3 dBm as derived from the measured data shown in Figure 42. Using these numbers as benchmarks, it is assumed that an interfering signal in any other situation may be computed in dBm by deducting 106 dB from FI in dBu. The FI may be obtained by measurement or by computation. The NEC computer program may be used to calculate the field intensity contours for any radio transmitter antenna near a power transmission line prior to or after the installation of the antenna.

Interference criteria for PLC receivers were discussed earlier. Specifically, it was stated that the midrange adverse weather noise levels shown in Figure 21 were acceptable as primarily values of interference threshold for any type of PLC receiver. The curves for field intensity limits shown in Figure 47 were computed by adding 106 dB to the midrange adverse

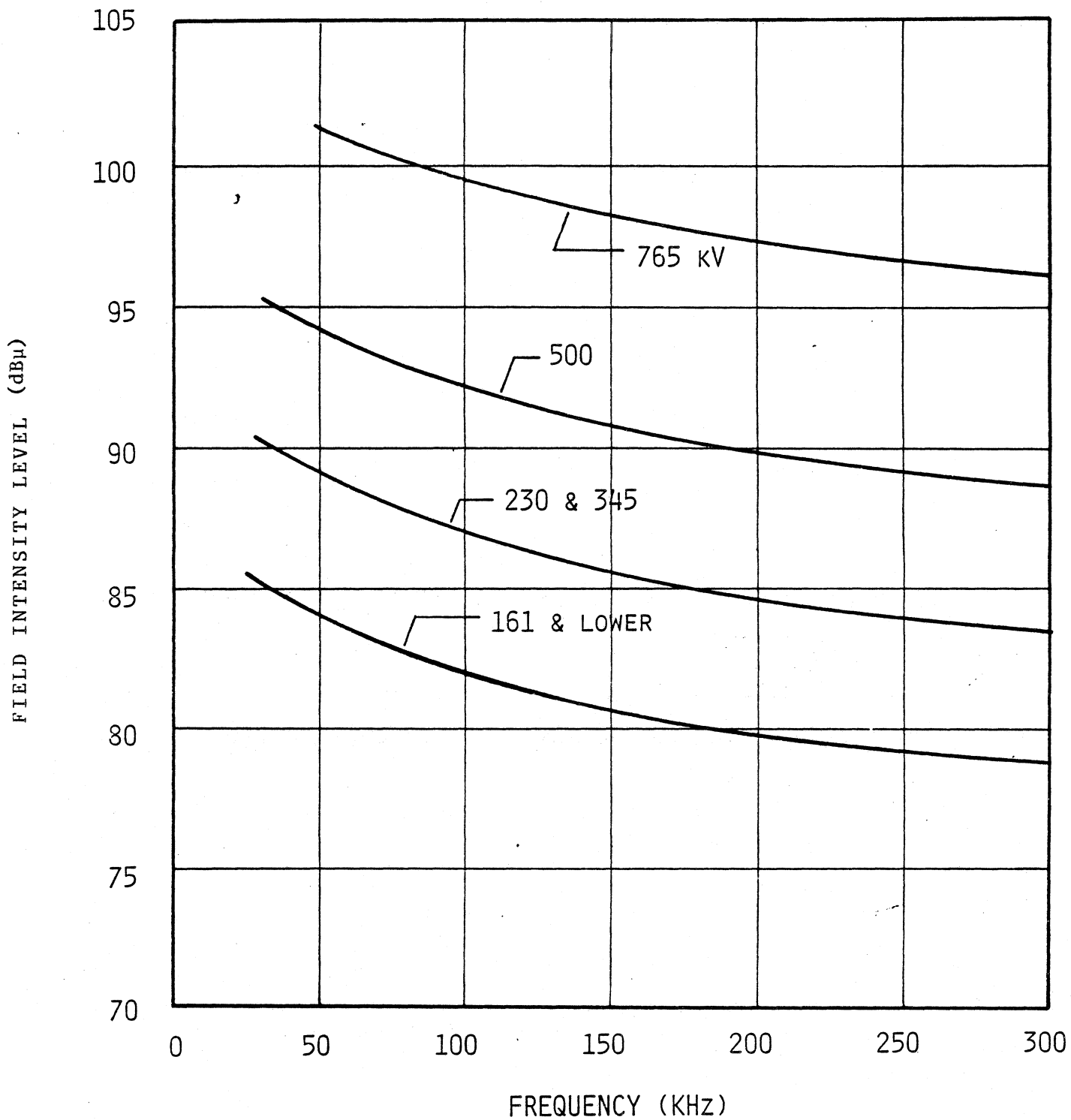


Figure 47. Field Intensity Levels From a Radio Transmitter Near a Transmission Line.

weather noise level as a function of frequency for each of the transmission line voltage classes shown in Figure 21.

On the assumption that the Boone-Midway power line may be considered representative, it can be stated that a PLC receiver connected to a similarly representative transmission line should perform properly if the FI surrounding that line from a radio transmitter does not exceed the levels shown in Figure 47.

3. Approximate Method

This method was prepared by ECAC (Groot, 198x) and is based on the assumption that at separation distances beyond 1000 meters, the field intensity from a power line decreases inversely with the distance. A brief description of the approximate method is as follows.

The separation distance between a radio transmitter and a power line carrier receiver may be calculated using the equation below (Skolnik, 1970).

$$L(d) = P_{\text{Rad}} + G_{\text{PLC}} - P_{\text{Th}} - \text{FDR} \quad (5)$$

where:

$$L(d) = \text{Free space propagation loss} = 20 \log d_c + 20 \log f - 27.5$$

d_c = separation distance, (meters)

f = Frequency of radio transmitter, (MHz)

P_{Rad} = Radiated power, (dBm)

G_{PLC} = Transmission line factor, (dBi)

P_{Th} = Interference threshold of PLC receiver from Figure 21, (dBm)

FDR = Frequency-dependent rejection, (dB)

Note that in Equation (5) interference-to-noise ratio was assumed to be equal to unity.

The frequency-dependent rejection (FDR) in (5) includes bandwidth and off-tune correction factors. For on-tune interference calculations and when the bandwidth of the interfering signal does not exceed the receiver selectivity, FDR becomes zero and (5) simplifies to the equation:

$$L(d) = P_{\text{Rad}} + G_{\text{PLC}} - P_{\text{Th}} \quad (6)$$

Equation (6) was derived using far-field relationships and, for best accuracy, should be used where the separation distance between a transmission line and a radio antenna is greater than a few wavelengths. However, a value for G_{PLC} can be determined empirically at separation distances smaller than a wavelength (e.g., 1000 meters) and can be used in (5) or (6) to obtain approximate data for general application.

Measured data given in Figures 25, 29, 33, and 37 indicate that the value of G_{PLC} varies from -40 to -50 dB. It was assumed that -44 dB is a realistic value for this parameter. Substituting -44 for G_{PLC} in (6), we obtain

$$L(d) = P_{\text{RAD}} - 44 - P_{\text{Th}}$$

A typical example will now be used to illustrate the principal. Assume a 161-kV transmission line carrying a 175-kHz PLC signal of undetermined level passing near an area where a 1000-watt radio transmitter is to be located. The radio transmitter frequency is also 175 kHz. It is desired to determine the separation distance beyond which the threshold will not be exceeded. From the data in Figure 21, the adverse weather noise level for the 161-kV line is approximately -25.5 dBm; therefore, P_{Th} is assigned this value. For a transmitter power of 1000 watts, P_{Rad} is 60 dBm.

$$L(d) = 60 - 44 + 25.5 = 41.5 \text{ dB}$$

$$41.5 = 20 \log d_c + 20 \log (0.175) - 27.5$$

$$20 \log d_c = 84.1 \text{ dB}$$

$$d_c = 16,032 \text{ m or } 16 \text{ km}$$

Like the previous techniques, this method can be applied in the opposite order to determine the interference level which might be expected if the separation distance is known. For instance, if the only feasible site for the new 1000-watt transmitter in the previous example had already been determined to be 11 kilometers from the transmission line, the procedure would be as follows:

$$L(d) = 20 \log 11,000 + 20 \log (0.175) - 27.5 = 38.2 \text{ dB}$$

$$38.2 = 60 - 44 - P_{TH}$$

$$P_{TH} = -22.2 \text{ dBm}$$

In this instance, additional study would be necessary to evaluate the actual risk of interference from the new transmitter. This study would include a consideration of the type of PLC service employed and a determination of the actual level of the received PLC signal on the 161-kV line.

By referring again to Figure 21, it can be seen that if the transmission line voltage were 230 kV or higher, the interference threshold would be clearly above the received signal level of -22.2 dBm.

When the radio transmitter operates at a different frequency from the PLC circuit, substantial reduction in interference may result from the frequency separation. Equation (5), which contains the frequency-dependent rejection term, FDR, should be used for "off-tune" calculations. Note that for any given problem situation, (5) may be rewritten as follows:

$$FDR + L(d) = \text{Constant} \tag{6}$$

The propagation loss, $L(d)$, is a function of distance separation. The frequency-dependent rejection, FDR, is a function of off-tuning. The solution to (6) may be presented graphically in a two-dimensional plot known as a

frequency-distance (FD) curve. A computer model implementing an algorithm based on (6) was used to calculate the frequency-distance curve shown in Figure 48. For this calculation, the PLC receiver was assumed to have a selectivity as shown in Figure 5. The radio transmitter emission data given in the report by Groot was used. The results of this computation are given in Figure 48. More extensive data and a description of the computer program used are given in a report to be published by Groot.

APPLICATION OF ANALYSIS TECHNIQUES

The three analysis procedures described in the preceding discussion will now be used to calculate the separation distance between a typical power transmission line and a radio transmitter using the GWEN antenna depicted in Figure 1(a). For this illustration, the transmitter power is assumed to be 2000 watts (+63 dB) at a frequency of 170 kHz. For simplicity, the losses in the matching network and the antennas are neglected. The ground constants are shown below:

Conductivity = 0.01 mhos/m

Relative Permittivity = 15.2

The transmission line is assumed to consist of three phase conductors with 161-kV line voltage. The PLC frequency is co-channel with the radio frequency at 170 kHz.

The separation distances to be calculated are based on the criteria of interference threshold levels discussed earlier in this report for the operation of PLC receivers. The interference threshold derived from Figure 21 is -25.5 or approximately 26 dBm.

1. Coupling Factor Method

For a transmitter power level (P_t) of 63 dBm and an interference threshold (P_r) of -26 dBm, Equation (3) may be written as

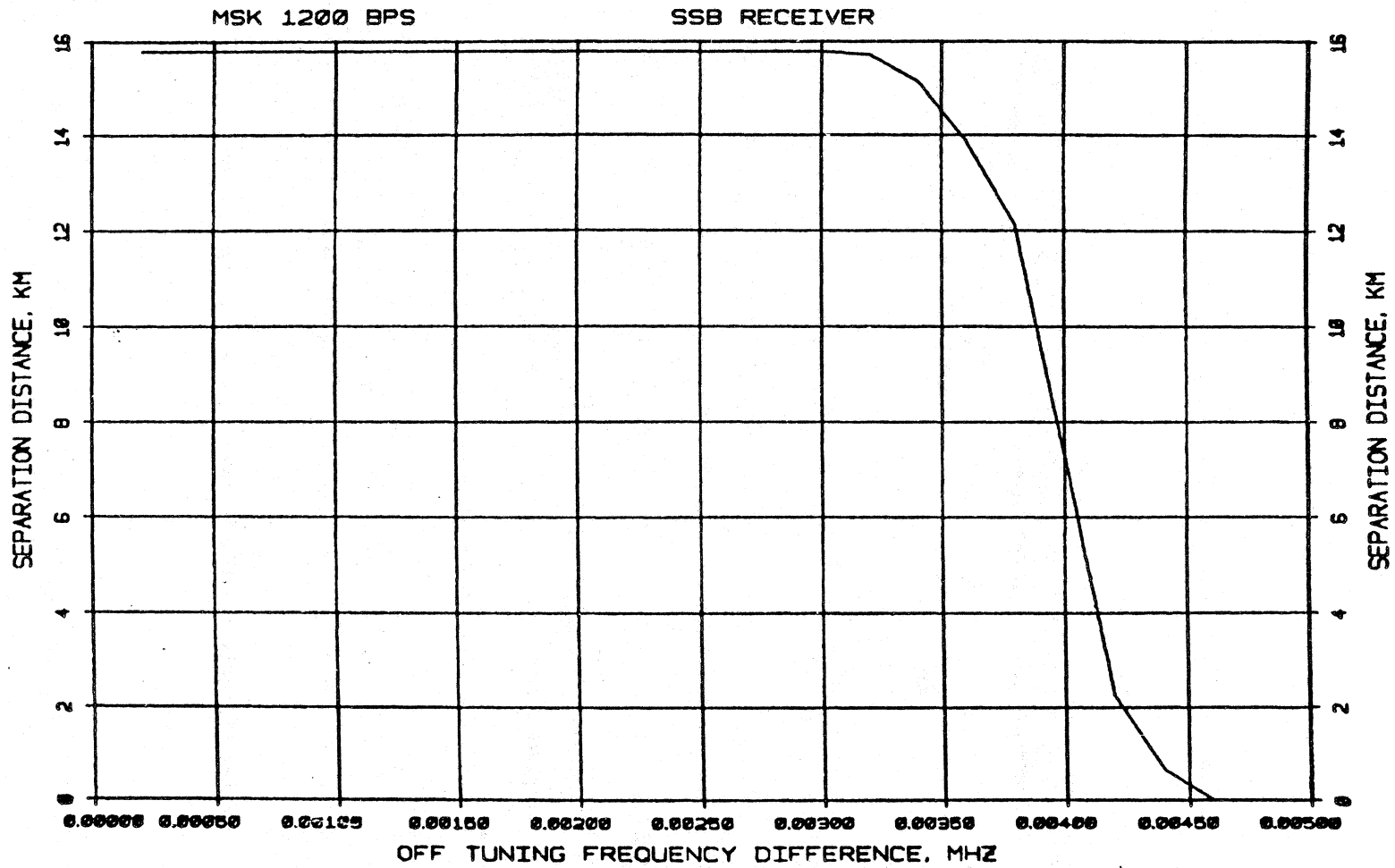


Figure 48. Frequency-Distance Curve for a PLC Receiver.
(Taken from a report to be published by Groot)

$$-26 = 63 + F_c$$

$$F_c = -89 \text{ dB}$$

This coupling factor is beyond the range plotted in Figure 46. It is possible to use the NEC program to extend the data in Figure 46 beyond its 3000-meter limit; however, for this example, it is easier to apply the same program in conjunction with the following equation:

$$L(d) = P_{\text{Rad}} + F_f - P_{\text{Th}} \quad (8)$$

where F_f is a factor representing field reduction versus distance calculated by the NEC program. This procedure depends upon the ability to determine the propagation loss at a known point within the range of Figure 46 and thus evaluate the factor F_f . This equation can then be applied at greater distances. The maximum distance appearing in Figure 46, 3000 meters, is selected as the "known point" for this procedure.

If the field intensities at two distances are known (or can be computed) and expressed in decibel units, the propagation loss between the two distances can be expressed as the difference between the field intensities.

$$L(d) = FI_1 - FI_2 \text{ (dB)} \quad (9)$$

Since the antenna base has an effective radius of approximately 100 meters

$$L(3000) = FI(100) - FI(3000)$$

where $L(3000)$ = Propagation Loss at 3000 m from the antenna

$FI(100)$ = Field Intensity at the antenna base

$FI(3000)$ = Field Intensity at 3000 m from the antenna

Using the NEC program, the appropriate values of field intensity were evaluated. The results obtained were:

$$FI(100) = 141.1 \text{ dBu}$$

$$FI(3000) = 101.6 \text{ dBu}$$

$$L(d) = 141.1 - 101 = 40.1 \text{ dB}$$

From Figure 46, the coupling factor at 3000 meters is -71.5 dB. Applying this to (4):

$$P_r = 63 - 71.5 = -8.5 \text{ dBm}$$

Equation (8) can now be applied with 40.1 dB as the value for $L(d)$ and -8.5 dBm as the value for P_{Th} .

$$40.1 = 63 + F_f + 8.5$$

Therefore,

$$F_f = -31.4 \text{ dB}$$

To compute the propagation loss at the final separation distance, the interference threshold of -26 dBm is now entered for P_{Th}

$$L(d) = 63 - 31.4 + 26 = 57.6 \text{ dB}$$

and applying Equation (9)

$$57.6 = 141.1 - FI(d)$$

$$FI(d) = 83.5 \text{ dBu}$$

Using the NEC program, the distance at which the electric field intensity is equal to 83.5 dBu was determined to be 21 km. Therefore,

according to this method, if the radio transmitter is separated from the transmission line by 21 km, the received power in the PLC channel will be -26 dBm.

2. Field Intensity Method

The transmission line voltage is 161 kV, and the PLC frequency is 170 kHz. The field intensity threshold corresponding to these parameters as illustrated in Figure 47 is 80.5 dBu. The NEC program was used to calculate the distance from the radio transmitter at which the field intensity produced by the transmitter antenna was about 80.5 dBu. It was found that this level may be produced at a distance of about 31 km from the base of the antenna.

3. Approximate Method

Equation (6) is applicable to the example used to illustrate this method. Substituting -26 dBm for P_{Th} and 63 dBm for P_{Rad} and assuming that G_{PLC} is -44 dBi, we have:

$$L(d) = 63 - 44 + 26 = 45 \text{ dB}$$

Free space loss formula used in the development of this method is:

$$L(d) = 20 \log d_c + 20 \log f - 27.5$$

$$45 = 20 \log d_c + 20 \log (.170) - 27.5$$

$$20 \log d_c = 87.9$$

$$d_c = 24800 \text{ m} \quad \text{or} \quad 24.8 \text{ km}$$

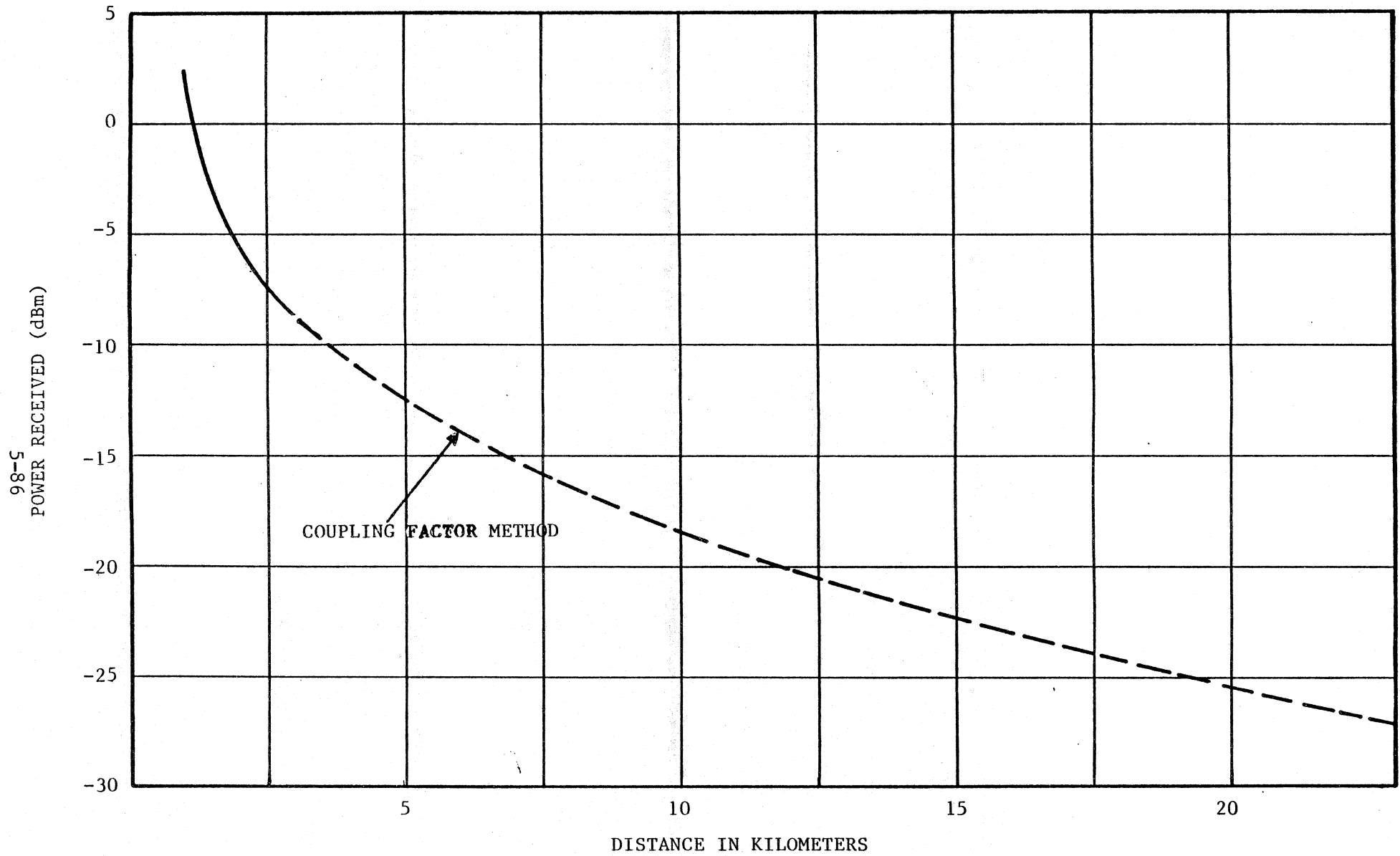


Figure 49. Power Received by a PLC Receiver from a GWEN Transmitter with radiated Power Equal to 2 KW.

REFERENCES

- AIEE Committee Report, "Guide to Application and Treatment of Channels for Power-Line Carrier," Power Apparatus and Systems, No.12, pp.417-436, June 1954.
- ANSI (American National Standards Institute, 1430 Broadway, New York, NY), Requirements for Power Line Coupling Capacitors- C93.1-1981.
- ANSI, Requirements for Line Traps, C93.3-1981.
- ANSI, Requirements for Power Line Coupling Capacitor Voltage Transformers, C93.2-1976.
- ANSI, Requirements for Power Line Carrier Line Tuning Equipment, C93.4-1984.
- ANSI, Requirements for Power Line Carrier Transmitter-Receiver Equipment, C93.5-19XX.
- CIGRE Committee Report, "Guide on Power Line Carrier," Study Committee 35, Working Group 04, Paris, 1979.
- Federal Communications Commission REPORT AND ORDER, G-3, FCC 83-84, 32748, Gen. Docket No.82-9, RM-3747, Adopted: January 24, 1983, Released: January 27, 1983.
- Guide for Power-Line Carrier Applications, IEEE Standard 643-1980.
- IEC Committee Report, "Manual for the Planning of (SSB) Power Line Carrier Systems," Technical Committee No. 57, 1979.
- NTIA (1985), Manual of Regulations and Procedures for Federal Radio Frequency Management National Telecommunications and Information Administration, Washington, D.C., (1983).
- Recommendations to PLC Users for Achieving Electromagnetic Compatibility with Authorized Radio Services, IEEE Standards Project P956, in Preparation, 1985.
- Rubin, D., The Linville Method of High Frequency Transistor Amplifier Design, Naval Weapons Center, Research Department, NWCCL TP 845, Corona Laboratories, Corona, California, March (1969).

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corresponding field intensities near a transmission line that can produce those levels were calculated. Rules and regulations pertaining to the systems in the Fixed Service in the 150-190 kHz frequency range were reviewed and no regulatory problems were identified relative to the operation of PLC and systems in the Fixed Service in this frequency range.