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Tactical Line-of-Sight Radio Propagation Reliability

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13. ABSTRACT *(Maximum 200 words)*
Recent deployment to Southwest Asia (SWA) of tactical Line-of-Sight (LOS) radio links, such as those used with Mobile Subscriber Equipment (MSE) and other Tri-Service Tactical Communications (TRI-TAC) systems, and user feedback indicating time-varying performance have raised the question of link reliability. The climate encountered in SWA (desert terrain in proximity to bodies of water) is known to be very difficult for LOS radio because it causes frequent and large reductions in received signal strength, referred to as time-varying fading. This report provides predictions of propagation performance for the systems fielded based on the latest technical literature and validates them with current information collected from system users. The conditions that cause time-variant fades on LOS paths are also addressed. Particular focus will be directed at the tactical environment and the unique challenge that exists to achieve highly reliable links with the limited antenna gains and terrain clearances present in the tactical world. This report also addresses future work that should be accomplished to ensure that LOS operators and planners have the latest data available to optimize the effectiveness of their current LOS capability.

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FOREWORD

The Mission of the LOS Propagation Reliability Working Group

- o Enhance Army Tactical Line-of-Sight (LOS) Radio performance.
- o Increase soldiers' capabilities to successfully deploy Tactical LOS Radio in difficult propagation environments.
- o Assist acquisition managers in fielding highly reliable transmission systems.

EXECUTIVE SUMMARY

This report will focus on Army Tactical Line-of Sight (LOS) Radio and the significant threat posed by the propagation environment to highly reliable communications. Anecdotal reports from LOS operators indicated that large performance-affecting variations in received signal strength on many of their radio links were a daily problem during recent Southwest Asia (SWA) operations. The climate in SWA is known to be difficult for LOS radio propagation because it causes large and frequent reductions in received signal strength, referred to as time-varying fading. The LOS Propagation Reliability Working Group was established to investigate the problem of degraded link reliability due to time-varying fading and other related propagation issues.

A key element of our effort is user feedback from the soldiers. Data corroborating the existence of significant link propagation problems and degraded link reliability were obtained during visits to the 35th Signal Brigade at Fort Bragg, North Carolina, and the 57th Signal Battalion at Fort Hood, Texas. Frequency management issues and the related radio frequency interference problems were identified. It was evident that the soldiers were not adequately trained with regard to either time-varying propagation or the fragility of digital transmission systems. This, in part, aggravated the link reliability problems encountered in SWA. Satisfactory reliability, however, was achieved on the overall radio network by employing extensive link level redundancies. Due to the success of the overall network, after-action reports often failed to mention single-link reliability problems. Such redundancies may not always be feasible in future applications such as the nonlinear battlefield of AirLand Operations (ALO). The users also identified a need for Mobile Subscriber Equipment (MSE) link reliabilities much greater than the current 90-percent design point. For single-thread links, a reliability approaching 100 percent was requested.

This report baselines the key Army LOS radio specifications and develops the maximum possible equipment fade margins as a prelude to assessing the environmental threat. The operating fade margin is defined as the difference in the average received signal power and that required for operation at a Bit Error Rate of 10^{-5}. Tactical frequency ranges investigated included the UHF bands of 220 to 400 MHz and 1350 to 1850 MHz and the SHF band of 4.4 to 5.0 GHz. The evaluation of Army LOS link engineering methods for MSE found that small and fixed fade margins of 4 to 6 dB (Bullington, 1957) are allocated for signal strength variations due to fading. We find this margin value too small in view of current LOS link engineering methodology, which includes parameters for climate, location, frequency, and path length.

A major contribution of our effort is the development of a multipath fading reliability model suitable for Army tactical LOS radio. This model accounts for frequency, path length, and climate, and provides fade margin requirements for any needed reliability. Application graphs and tables are derived and provided in this report. This model is primarily based on the extensive radio systems work done at AT&T Bell Laboratories in the last 20 years and on results reported in a recent paper (Olsen-Segal, 1991). We found, for example, that a radio operating at 1600 MHz on a 20-km path in a SWA climate would require an operating fade margin of 17 dB for 99.9-percent reliability (15 minutes/day of fading outage). At 40 km, the operating fade margin required would increase to 28 dB. Clearly, high reliability links require substantial fade margins.

The amount of fade margin available for allocation to other threats and equipment degradations is the difference in the ideal maximum fade margin, obtained when all the equipment is working at its baseline specification with the antennas completely unobstructed by hills or trees, and the required fade margin. A value of 0 dB for the available fade margin determines the maximum possible path length for a given reliability requirement. For 99.9-percent link reliability and a difficult propagation climate such as SWA, the maximum possible link path lengths range from 35 to 45 km for the radios considered. These results indicate that the radios have the capability to meet their application requirements, but only if the required fade margins are realized in practice. This capability may be diminished by such effects as misaligned antennas or reduced link clearance, which can easily cost 10 dB or more of margin. For example, a net 3 dB of degradation would reduce the maximum path lengths by about 5 km.

Our principal conclusion is that the environmental threat imposed by propagation may cause significant degradation in the reliability of Army Tactical LOS Radio Systems as presently engineered and operated. The propagation threat appears to be at least as serious as the interference noise threat since the latter can be equated to a loss in fade margin. We also conclude that setup and operation at a BER of 10^{-5} gives a false sense of security. This follows from the likelihood of fading, the fragility of digital transmission systems, and the inadequacy of the operators' training regarding fading.

Our main recommendations are that the link engineering tools and methodology be modified to provide predicted link reliabilities for proposed links using fade margins developed in this report, that a reliability requirement of 99.9 percent be adopted for single-thread and special services links, and that operating and planning personnel be trained regarding fading. We also recommend a continuing work program focused on other known propagation issues, including the occurrence and effects of ducting and the impact of Radio-Frequency (RF) interference on link fade margins. A principal issue for Tactical Radio is the increase in fading for reduced terrain clearances that are smaller than the free-space clearances assumed in the model utilized in this report.

ACKNOWLEDGMENTS

This work program was initiated by A. W. Madnick of the Office of the Project Manager (OPM), Mobile Subscriber Equipment. The continuing support of the PM MSE organization was essential to this work program. We appreciate the cooperation and contributions of the personnel of the 35th Signal Brigade at Fort Bragg and the 57th Signal Battalion at Fort Hood. The availability of a pre-publication release of the Olsen-Segal paper (1991) and discussions with R.L. Olsen were invaluable. The DCEC (1990) publication made available by D.R. Smith of the Defense Communications Engineering Center was helpful.

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1. INTRODUCTION

Recent deployment to Southwest Asia (SWA)* of tactical Line-of-Sight (LOS) radio links, such as those used with Mobile Subscriber Equipment (MSE) and other Tri-Service Tactical Communications (TRI-TAC) systems, and user feedback indicating time-varying performance have raised the question of link reliability. The climate encountered in SWA (desert terrain in proximity to bodies of water) is known to be very difficult for LOS radio because it causes frequent and large reductions in received signal strength, referred to as time-varying fading. This report provides predictions of propagation performance for the systems fielded based on the latest technical literature and validates them with current information collected from system users. The conditions that cause time-variant fades on LOS paths are also addressed. Particular focus will be directed at the tactical environment and the unique challenge that exists to achieve highly reliable links with the limited antenna gains and terrain clearances present in the tactical world. This report also addresses future work that should be accomplished to ensure that LOS operators and planners have the latest data available to optimize the effectiveness of their current LOS capability.

2. PROBLEM STATEMENT

LOS propagation reliability at UHF is affected by signal strength variations due to multipath transmission and/or bending of the beam emitted by the antenna due to abnormal variations of refractive index with height in the lower atmosphere.

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*A list of acronyms is provided as Appendix B.

At frequencies below about 8 GHz and on paths having adequate clearance, time-varying fading on LOS paths is generally of two main types: (1) atmospheric multipath, which occurs relatively rapidly and is caused by interference between two or more refracted rays arriving at the receiving antenna by different paths, and (2) reflection multipath, which occurs less rapidly and is due to interference between direct and ground-reflected rays (see Figure 2-1). The two types of multipath fading can be present at the same time. In general, the number of fades per unit time due to atmospheric multipath increases with path length.

In terms of occurrence on a single link, multipath propagation is the prevalent cause of degraded transmission reliability resulting from anomalous atmospheric structures. This is why multipath fading is considered in this report. Future work will include investigation of the effects of ducting, obstruction fading, and multipath fading on links where terrain clearance is small, and the integration of models for these effects with the current long-term transmission-loss model.

The evaluation of Army LOS link engineering methods for MSE showed that small fade margins of 4 to 6 dB are used to accommodate multipath fading. This fixed margin (Bullington, 1957) was to provide for a link reliability of 90 percent for average climatic conditions. We find this margin to be too small for difficult propagation environments and outdated in view of current LOS link engineering methodology, which includes parameters for climate, location, terrain, and path length. The minimum link availability of 90 percent is deemed low, especially for MSE SEN radio links, since they are single links with no alternate routing capability. Additionally, the Signal School has noted a requirement for high-reliability links for the Tactical Fire

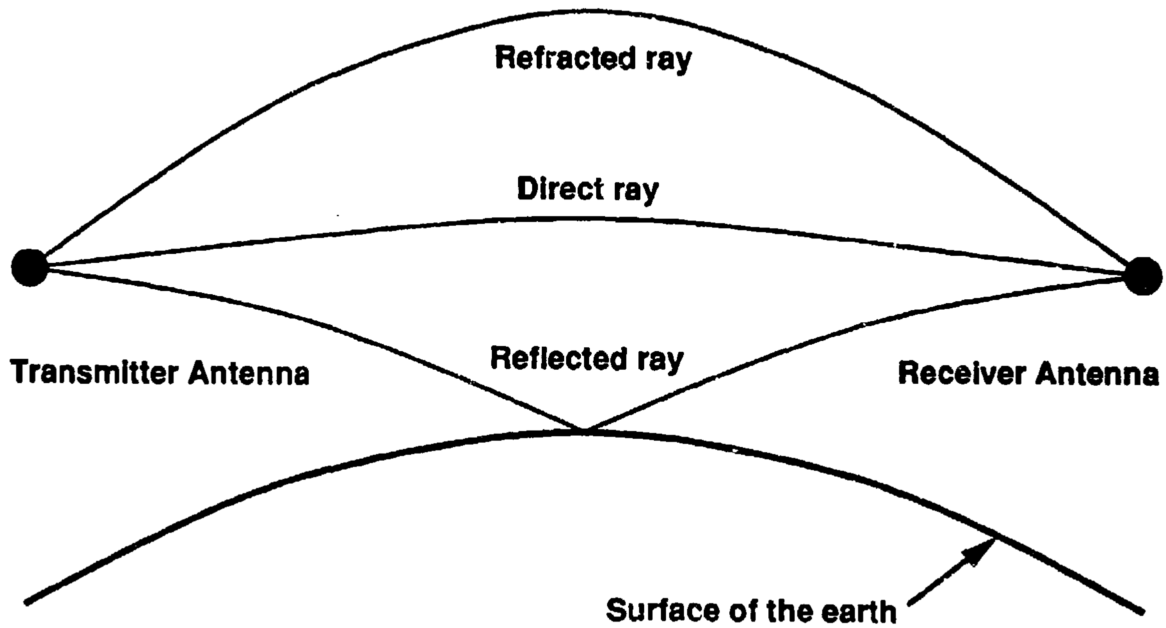


Figure 2-1. Multipath Fading: Destructive Interference of Multiple Rays

Direction System (TACFIRE) and other Battlefield Functional Area (BFA) data links based on field experience in SWA (Mims-Hamilton, 1991).

A major focus of this effort is to review currently available literature/data on fading and its relation to the current and proposed fielding of LOS radios and planning tools. Variables that affect the severity of fading, such as frequency, path length, atmospheric conditions, and terrain, will be investigated. Solutions to minimize the effects of fading will also be investigated and recommended. The tactical frequency ranges to be investigated include the UHF bands of 225 to 400 MHz and 1350 to 1850 MHz and the SHF band of 4.4 to 5.0 GHz.

3. TACTICAL LOS RADIO

3.1 APPLICATIONS

Army tactical LOS radio communications systems are used for two applications: (1) Corps and Division (down to Brigade level) and (2) Echelons Above Corps (EAC). Corps and Division requirements are satisfied with the MSE system; EAC uses the TRI-TAC system. A typical slice of the MSE system is shown in Figure 3-1. All internodal (Node Center [NC] or backbone and extension links to LENs and SENs) operate in the UHF frequency bands of 225 to 400 MHz and 1350 to 1850 MHz of the AN/GRC-226 Radio Set.

In EAC, internodal communication links operate in the 4.4-to-5.0 GHz frequency band of the AN/GRC-144 and its replacement, the AN/GRC-222. The extension links operate in the 1350-to-1850 MHz and 220-to-405 MHz frequency bands, which are provided by the AN/GRC-103 Radio Set.

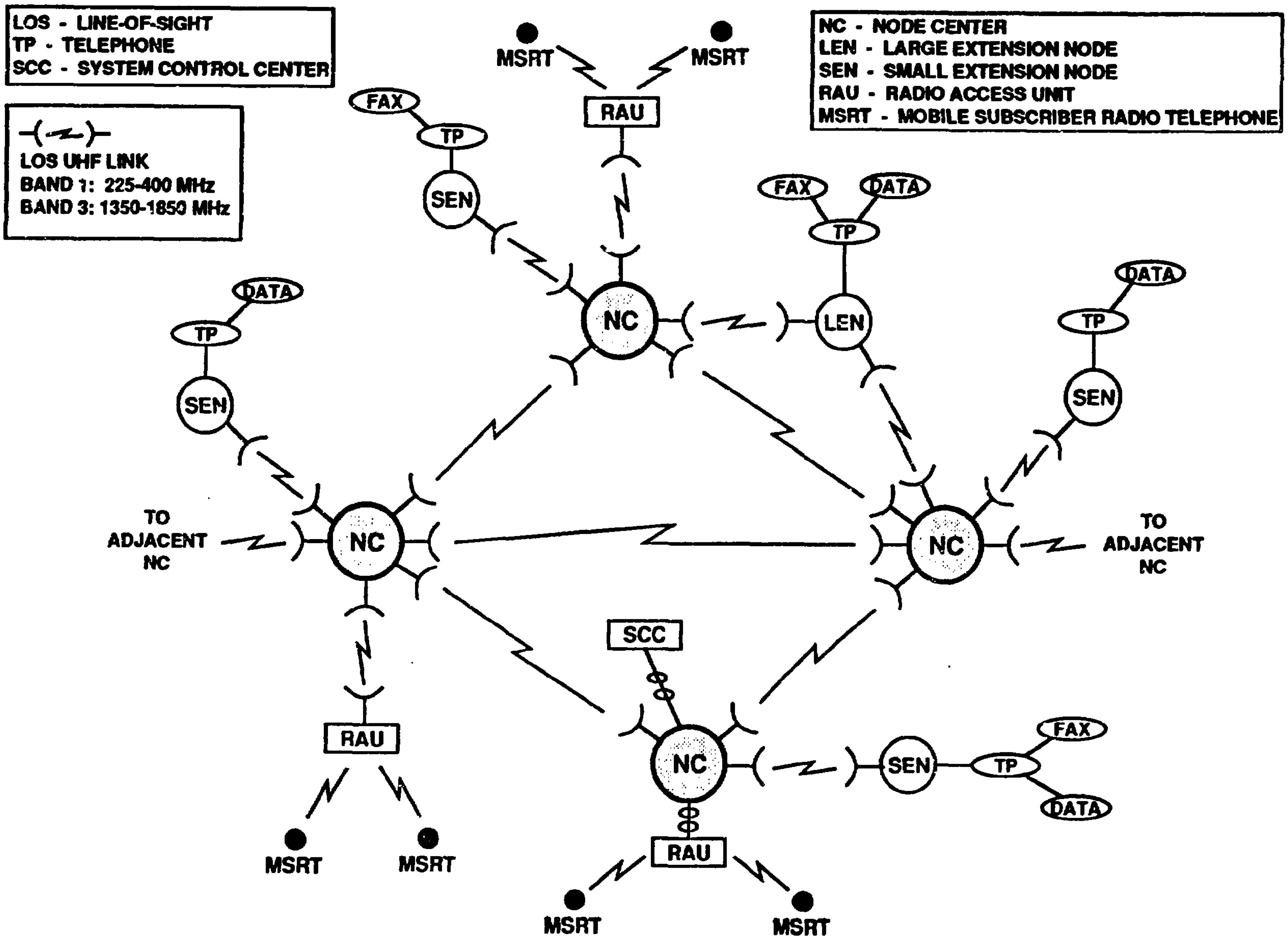


Figure 3-1. Typical Multichannel Communication System

3.2 DESCRIPTION

The following LOS radios are used in the Army for tactical communications:

a. Corps and Division areas

(1) AN/GRC-226: UHF radio used in the MSE AN/TRC-190(V) radio assemblages to provide the backbone and extension LOS multichannel communications links. The AN/GRC-226 is designed to provide a nominal 25-km link and operate in the 225-to-400 MHz and 1350-to-1850 MHz frequency bands. Technical characteristics are listed in Table 3-1.

(2) AN/GRC-103: UHF radio used in the Army Tactical Communications System (ATACS) AN/TRC-113, 145, 151, and 152 radio assemblages (to be replaced by MSE) to provide all backbone multichannel communication links. The AN/GRC-103 was designed to provide nominal 48-km links and operate in the 220-to-405 MHz (Band I) and 1350-to-1850 MHz (Band IV) frequency bands. Technical characteristics are listed in Table 3-1. Band IV of the AN/GRC-103 is also used in the TRI-TAC extension links (see below) to provide a nominal 48-km planning range.

b. EAC

(1) AN/GRC-144: SHF radio used in the TRI-TAC AN/TRC-138 radio assemblage to provide high-capacity LOS multichannel communication links for interconnection of nodes in EAC operating in the 4.4-to-5.0 GHz frequency band with a nominal

Table 3-1. Radio Parameters
(Revised June, 1992)

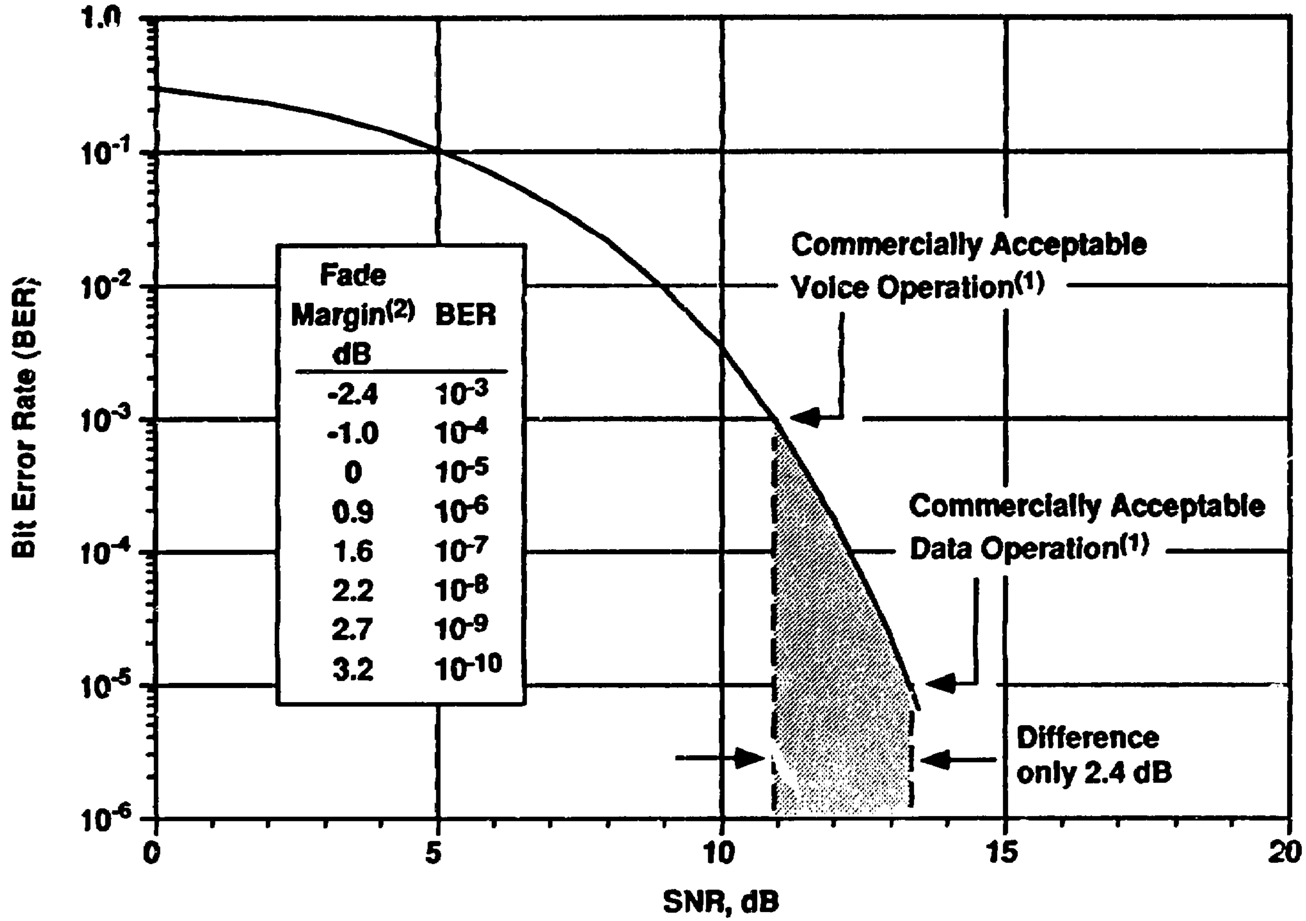
Radio	Frequency Ranges	Transmit Power	Minimum RSL (dBm) @ 10^{-5} BER	Bit Rate(s)	Antenna Type	Midband Antenna Gain (dBi) / 3 dB Beamwidth (Degrees)
AN/GRC-226 (V) 1	225-400 MHz	10 w (high) 1 w (low)	-93 @ -90 @	256, 512 1024 kb/s	Array with slot element	9 / 80°
(V) 2	1350-1850 MHz	5 w (high) 0.5 w (low)	-92 @ -89 @	256, 512 1024 kb/s	Truncated mesh parabola	20 / 13°
AN/GRC-103 (V) I	220-405 MHz	25 w	-93 @ -88 @	576 1152 kb/s	Corner reflector	11 / 65°
(V) IV	1350-1850 MHz	15 w	-93 @ -88 @	576 1152 kb/s	3-foot parabolic dish	19 / 13°
AN/GRC-222 (TRI-TAC, Internodal)	4.4-5.0 GHz	2.5 w	-88	1.024, 2.048, 4.096, 4.608 Mb/s	4 1/2-foot parabolic dish	33 / 1.5°
AN/GRC-144 (TRI-TAC, Internodal)	4.4-5.0 GHz	0.25 w	-93	1.024, 2.048, 4.096, 4.608 Mb/s	4 1/2-foot parabolic dish	33 / 1.5°

planning range of 40 km. Technical characteristics are listed in Table 3-1.

(2) AN/GRC-222: SHF Radio designed to replace the AN/GRC-144, which also operates in the 4.4-to-5.0 GHz frequency band. Technical characteristics are listed in Table 3-1.

The UHF radios listed above and the AN/GRC-144 utilize Non-Coherent Frequency Shift Keying (NC-FSK) type modulation. A theoretical Signal-to-Noise Ratio (SNR) versus Bit Error Rate (BER) curve describing NC-FSK is shown in Figure 3-2 with a corresponding table of values. As can be seen from the table, the difference in SNR values between BERs of 10^{-5} and 10^{-3} is 2.4 dB (a BER of 10^{-3} is assumed to be the largest BER acceptable for all digital service modes; a BER of 10^{-5} is assumed to be the minimum BER acceptable for data transmission). The AN/GRC-222 utilizes four-level coherent phase shift keying which has about 0.4 dB better performance than binary noncoherent FSK.

Figure 3-2 clearly illustrates the fragility of digital transmission systems. The SNR difference in dB between unacceptable performance for any service (BER of 10^{-3}) and acceptable performance for, say, data (BER of 10^{-5}) is only 2.4 dB. Time variations in received signal power due to fading can and will often exceed 2.4 dB, hence the recommendation for adequate operating fade margin. The latter is defined as the difference between the average received signal power and that for a BER of 10^{-5}. When a radio system is installed, it is important for the operators to realize that obtaining/maintaining a received signal strength that gives a BER between 10^{-5} and 10^{-10} is not sufficient to ensure satisfactory performance when the inevitable fading occurs.



Notes:
1. Commercially acceptable operation is assumed to be 10^{-3} BER for digital voice mode and 10^{-5} BER for data.
2. This fade margin is in dB relative to acceptable data operation level.

Figure 3-2. Theoretical Non-Coherent Frequency-Shift-Keying Radio Performance

3.3 LOS RADIO FADE MARGINS

Table 3-2 provides the maximum possible fade margins for a 40-km unobstructed link for the AN/GRC-226 operating in Bands I and III, and for the AN/GRC-222 and AN/GRC-144 Radio Sets. These margins were calculated from the radio parameters given in Table 3-1. Fade margin values are shown for the low-, mid-, and high-frequency values of each band. For example, for Band I these values are 225, 300, and 400 MHz; for Band III, 1350, 1600, and 1850 MHz; and for the SHF Band, 4400, 4750, and 5000 MHz. The calculation is based on free space loss given by note 5, and does not consider difficult propagation environments or inadequate Fresnel zone clearance. It should be noted that the nominal path length for which the AN/GRC-226 is intended is 25 km rather than 40 km. At 25 km, the AN/GRC-226 Band I and Band III fade margin will be 4 dB greater than the values shown for 40 km.

The maximum fade margins of Table 3-2 do not include the effects of radio interference of various kinds. When interference is present, the fade margin will be reduced in proportion to the equivalent noise increase caused by the interference. For example, a 30-dB reduction in SNR due to interference noise is equivalent to a 30-dB reduction in fade margin. Alternatively, a 30-dB fade has the same effect as a 30-dB noise-caused degradation. Thus intereference noise and fading are both threats to radio system reliability.

4. USER FEEDBACK AND USER NEEDS

4.1 BACKGROUND

Initial anecdotal reports from LOS operators indicated that LOS signal fading was a daily problem during recent SWA operations. This was supported by a lessons-learned report from PATRIOT task force 2/1 ADA. This report stated "Propagation problems were a daily problem through the entire deployment; however, it would

Table 3-2. LOS Radio Fade Margins for Ideal Free Space Transmission (Revised June, 1992)

Parameter	Radio Type			
	AN/GRC-226 (V)1	AN/GRC-226 (V)2	AN/GRC-144	AN/GRC-222
Band (MHz)	225-400	1350-1850	4400-5000	4400-5000
PTmax (dBW)	10.0	7.0	-6.0	4.0
Gant (dB,spec. value)	9.0	20.0	33.0	33.0
Acable (dB,Fmin)	1.7(1)	5.4(1)	10.5(2)	10.5(2)
Acable (dB,Favg)	2.1(1)	5.9(1)	10.5(2)	10.5(2)
Acable (dB,Fmax)	2.6(1)	6.4(1)	10.5(2)	10.5(2)
Rcvr Sens (dBW) (BER=10^{-5})	-123.0 (512 kb/s)	-122.0 (512 kb/s)	-123.0 (4.6Mb/s)	-118.0 (4.6Mb/s)
NF Increase (dB, Fmin)(3)	10.4	0.7	0.1	0.1
NF Increase (dB, Fmin)(3)	8.2	0.6	0.1	0.1
NF Increase (dB, Fmin)(3)	6.2	0.4	0.1	0.1
Aradio (dB,Fmin)(4)	137.2	157.5	161.9	166.9
Aradio (dB,Favg)(4)	138.6	156.6	161.9	166.9
Aradio (dB,Fmax)(4)	139.6	155.8	161.9	166.9
Pathloss (dB,40 km,Fmin)(5)	111.5	127.1	137.4	137.4
Pathloss (dB,40 km,Favg)(5)	114.0	128.6	137.9	137.9
Pathloss (dB,40 km,Fmax)(5)	116.5	129.8	138.5	138.5
Max Fade Margin(dB,Fmin)(6)	25.7	30.4	24.5	29.5
Max Fade Margin(dB,Favg)(6)	24.6	28.0	24.0	29.0
Max Fade Margin(dB,Fmax)(6)	23.1	26.0	23.4	28.4

Notes:
1. Cable length of 34 m.
2. Cable length of 49 m.
3. Due to environmental noise (ITT, 1986).
4. Aradio = PT+ 2 Gant - 2 Acable - Phold - NF Increase.
5. Pathloss = 32.46+20logF(MHz)+20logD(km).
6. Ideal Free Space Fade Margin (40 km) = Aradio - Pathloss (40 km).

affect only one or two systems at a time and only for approximately 15 to 30 minutes at a time, usually late at night or early in the morning." These reports, coupled with the knowledge that the environmental conditions of the Persian Gulf region of SWA are difficult for LOS radio propagation, called into question the adequacy of current Army LOS link engineering methods for that area. Of particular interest were the accommodations for time varying fading. The CECOM LOS Reliability Working Group was established to address this and other propagation-related issues, and site visits were conducted to obtain user feedback from both EAC units using TRI-TAC LOS equipment and a unit using MSE equipment.

4.2 SITE VISITS

Two site visits were conducted in order to obtain feedback on propagation effects from LOS operators with recent SWA experience. One visit was to Fort Bragg, North Carolina, to interview elements of the 35th Signal Brigade that used TRI-TAC LOS equipment to support EAC communication requirements. The second visit, to Fort Hood, Texas, was to the MSE-equipped 57th Signal Battalion, which was in proximity to, and under the operational control of, the EAC Brigade.

The TRI-TAC LOS radios discussed were the AN/GRC-103 UHF, AN/GRC-144 SHF, and AN/GRC-222 SHF radios; for MSE, the radios were the AN/GRC-226 UHF and AN/GRC-224 SHF radios. Note that the AN/GRC-222 information was based on experience in Germany.

Both visits confirmed the occurrence of LOS propagation problems in three related areas: (1) multipath fading, (2) RF interference, and (3) frequency management. For both the EAC and MSE units, we found that single-link LOS transmission reliability was significantly degraded for all frequency bands due to time-varying fading. Signal outages of varying duration and frequency occurred on many nights and sometimes in the daytime for both UHF and SHF links. A majority of the propagation problems experienced with the AN/GRC-226 occurred on path lengths that did not exceed the nominal design path length of 25 km.

However, the overall radio network achieved high reliability by using multiple links, redundantly connected, and operating on multiple frequencies. Due to the success of the overall network, after-action reports often failed to mention single-link propagation problems. In future applications, such redundancy may not be feasible and network performance could be degraded or even unsatisfactory. This is a particular concern for AirLand Operations (ALO).

Generally, fading and propagation anomalies experienced in the desert, foliage blockages experienced in the European environment, and easier equipment setup stimulated use of Band I over Band III. This resulted in many frequency management problems associated with the overpopulation of Band I radios.

Frequency management problems affected both EAC and MSE units. Blocks of frequencies assigned were inadequate because there was no flexibility when trouble occurred. Also, when MSE and TRI-TAC are used jointly, as they were in this case, close coordination of frequency allocation and use is required.

RF interference impaired performance in all bands but was overwhelming in UHF Band I due to the preference for Band I and the routine cositing of several systems within 50 to 100 meters. This was further exacerbated in the desert by use of Band I by Allied units with high antenna towers, high-power transmitters, and the extremely wide beamwidth (80 degrees) of our AN/GRC-226 Band I antennas.

Figure 4-1 provides a summary of problems for both EAC and MSE units as reflected in questionnaire feedback. These data were obtained during the team's on-site visits.

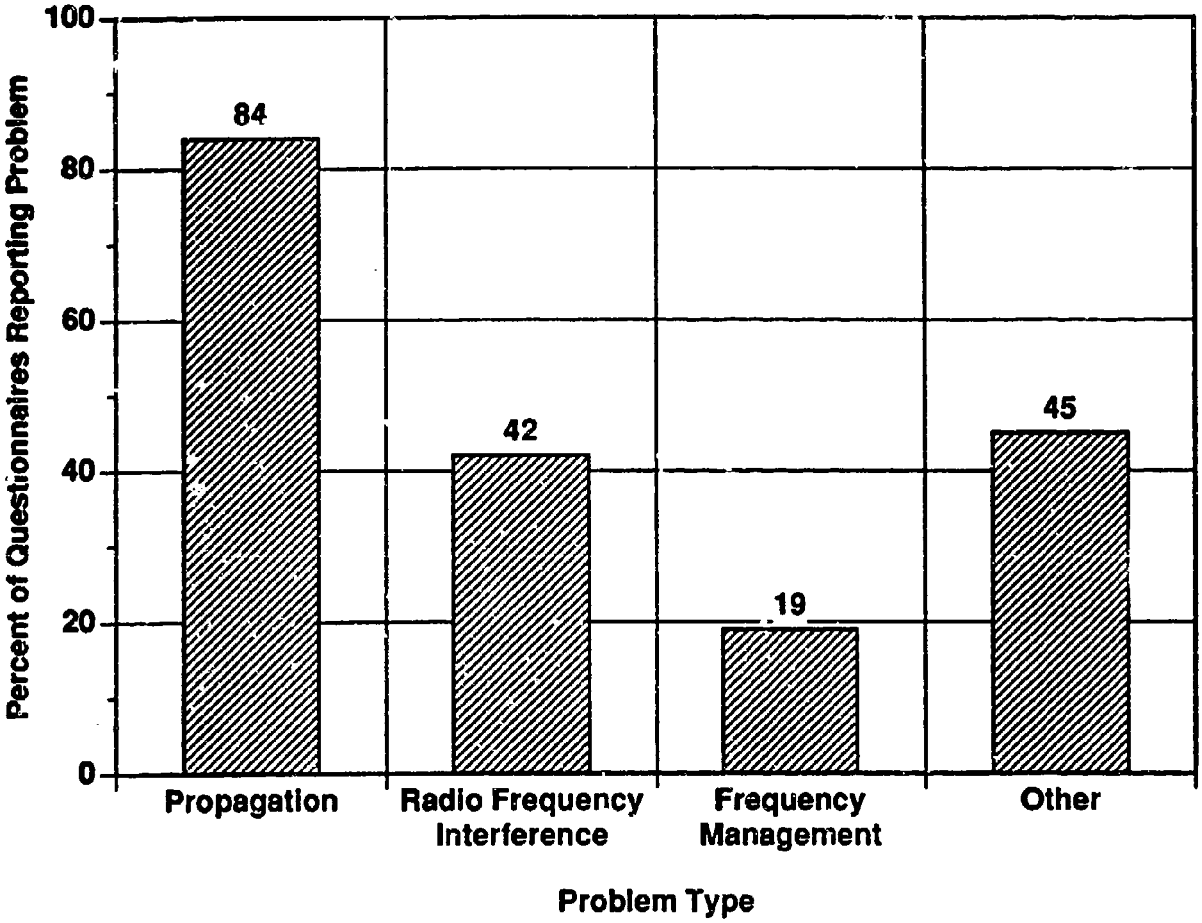


Figure 4-1. Radio Problems Identified from Fort Bragg and Fort Hood Visits

Also identified during the site visits were training, operational, and equipment issues. Operational and equipment issues are outside the scope of this report; training with respect to fading is not. Operators were trained, consistent with current tactical doctrine, to set up links with antennas as low as possible and with radios operating at the low-power setting to minimize signature. This arrangement significantly increases the link sensitivity to fading. As noted in Section 3.2, a fade as small as 2.4 dB can force a complete loss of digital throughput, as reportedly often occurred. One possible reaction to such an outage would be to switch to high power and then, if necessary, raise one or both antennas. This was not often done. Generally it was found that the operators had not been trained on any aspects of fading, including how and when it occurs, what happens when it occurs, and how to respond to its occurrence; hence, preventable or correctable outages may have been improperly diagnosed and uncorrected.

New operational requirements identified by the operators for UHF LOS include range extension to distances as great as 80 km (50 miles) to accommodate the large areas encountered in desert operations, a link reliability approaching 100 percent for single-link extensions, and quicker deployment of antenna assemblies. The latter was achieved in SWA by attaching antenna masts to vehicles to accommodate rapid moves.

5. PROPAGATION METHODOLOGY

5.1 BACKGROUND

The Army's current LOS design requirements are based to a considerable degree on requirements and experience in the European Theater. Propagation conditions in Germany are benign compared to those in the coastal areas of the Persian Gulf and in other warm and humid climates. Allowances for temporarily reduced received power caused by time-varying fading are based on knowledge of fading dating back over 30 years (Bullington, 1957).

A large body of new knowledge about LOS fading has been accumulated over the past 20 years, e.g., Vigants (1971, 1975, 1984) and DCEC (1990). Much of this knowledge has its origin in the research performed for the engineering of commercial LOS links in the United States, where in the 1980s at least two-thirds of long distance communications traffic was routed over long-haul LOS microwave radio. The initiation of this propagation research was related to more efficient use of the frequency spectrum when the Federal Communications Commission reduced the number of frequency-diversity protection channels from two to one in each frequency band. This required understanding of fading for a large variety of climatic conditions, including those causing severe fading in Florida. The resulting models of fading and its countermeasures (frequency diversity and space diversity) permitted commercial link engineering to meet increasing reliability requirements related to increasing amounts of data transmission in the network. Subsequent introduction of microwave digital radio technology resulted in further propagation research on the inband distortion of the frequency spectrum caused by multipath fading. The fading models developed from this research included meteorological variables. This permitted generation of an LOS propagation description for worldwide application when business opportunities arose related to providing microwave LOS communications to Saudi Arabia and developing countries.

The methods developed to engineer international commercial LOS links provide initial approaches for updating the engineering of tactical LOS links for worldwide deployment. However, additional fundamental work is needed to model aspects of tactical links that are different from those of commercial links, such as the reduction in terrain clearance.

The Army's transmission systems of interest are UHF and SHF digital radio utilizing LOS propagation through the atmosphere. The focus is the single link propagation reliability defined as the percentage of time that the received signal strength is above the receiver's 10^{-5} BER threshold. Commercial systems employing modern digital radio typically require link reliabilities of 99.99 percent or better. These systems have been designed and are engineered on a per-link basis to accommodate clear-air received signal decreases of 40 to 50 dB due to time-varying fading of the received signal. It is important to note that commercial systems are designed for fixed-plant operation with generally good clearances and high antenna gains while Army tactical LOS radios are rapidly deployed and moved in tactical operations where good sites and high-gain antennas are not the norm. The link engineering for the Army tactical digital radio systems does not adequately take time-varying fading into account and does not incorporate results from the large body of recent published work on this topic.

The received signal strength varies when clear-air atmospheric refractive effects cause multipath fading. The ability of a radio installation to withstand decreases in received signal strength is represented by its fade margin, i.e., the amount of power in dB that the average received signal strength exceeds the receiver threshold. This report addresses multipath fading on paths where a maximum or free-space fade margin, obtained for clearances greater than 0.6 of a Fresnel zone for an equivalent earth radius factor of 4/3, can be realized.

For lesser clearances, the fade margin will decrease and the impact of multipath fading will increase accordingly. The methodology (ECAC, 1986) for determining the average received power and the fade margin for obstructed paths will be addressed in future work of the LOS Propagation Reliability Working Group.

The objective of this task is to utilize and adapt the latest propagation methodology available in order to determine and specify the multipath fade margins required to provide a specified link propagation reliability as functions of the relevant environmental and operational radio parameters. A model for tactical LOS radio subject to clear-air, time-varying fading is developed in the following sections for a large range of climates, terrains, fade margins, and path lengths.

5.2 MULTIPATH FADING DESCRIPTION

The principal cause of atmospheric multipath fading on LOS paths with sufficient clearance is an interference (cancellation) phenomenon that usually occurs at night when the atmosphere is stratified. Air masses of different temperatures and humidities overlie each other without mixing. Because these strata cause radio waves to travel different paths, the receiver is subject to two or more replicas of the transmitted signal as illustrated in Figure 2-1. Figure 2-1 also illustrates reflective multipath fading which can also generate one or more additional replicas of the signal. The replicas, each with a different amplitude and phase, can and often do combine destructively to reduce the received signal strength by more then enough to cause unsatisfactory performance of the radio link. Typical durations of each event range from a few seconds (40-dB fade) to tens of seconds (20-dB fade). The number of events in a night can range from fewer than ten to more than a hundred. The multipath-fading phenomenon is complex, time-varying, nonstationary, and dependent on many physical quantities. Nonetheless it can be accommodated for by careful engineering of the radio links and by using high-quality radio systems.

In terms of occurrence, multipath propagation is the prevalent cause of degraded transmission reliability resulting from anomalous atmospheric structures. To discuss a classification of atmospheric structures, consider first a normal daytime atmosphere where the index of refraction decreases gradually as the height above ground increases. The index of refraction is measured in units, referred to as N-units, that describe the deviation of the index of refraction from unity, multiplied by 10^6. Thus, a representative, ground-level index of refraction value of 1.000320 becomes a refractivity of 320 when expressed in N-units. In the standard daytime atmosphere, the decrease in height is essentially linear in the first km above ground. The rate of decrease (the gradient) is -40 N-units per km, which corresponds to the standard equivalent earth radius factor of 4/3 used as a baseline for engineering LOS links.

A statistical description of refractivity gradients occurring in nature is obtained by measuring the difference in refractivity at points that are separated in height by 100 meters. The result is a probability distribution of the gradient, expressed as a percent of time during which it exceeds a particular value. Such a distribution is illustrated qualitatively in Figure 5-1, where the curve is broken up into straight-line segments corresponding to different atmospheric structures. The break points in the curve and the shape of the curve can change drastically with geophysical location.

The central portion of the curve around the gradient of -40 N-units/km represents linear gradients that affect terrain clearance and change the relative phases of ground-reflected rays. The multipath fading segment is centered on a -157 N-units/km value. The presence of such gradients creates multiple ray paths which can generate multipath fading. Experience indicates that gradients substantially more negative than -157 N-units/km are necessary to cause prolonged and severe reductions of received signal power related to ducting. This is indicated in Figure 5-1.

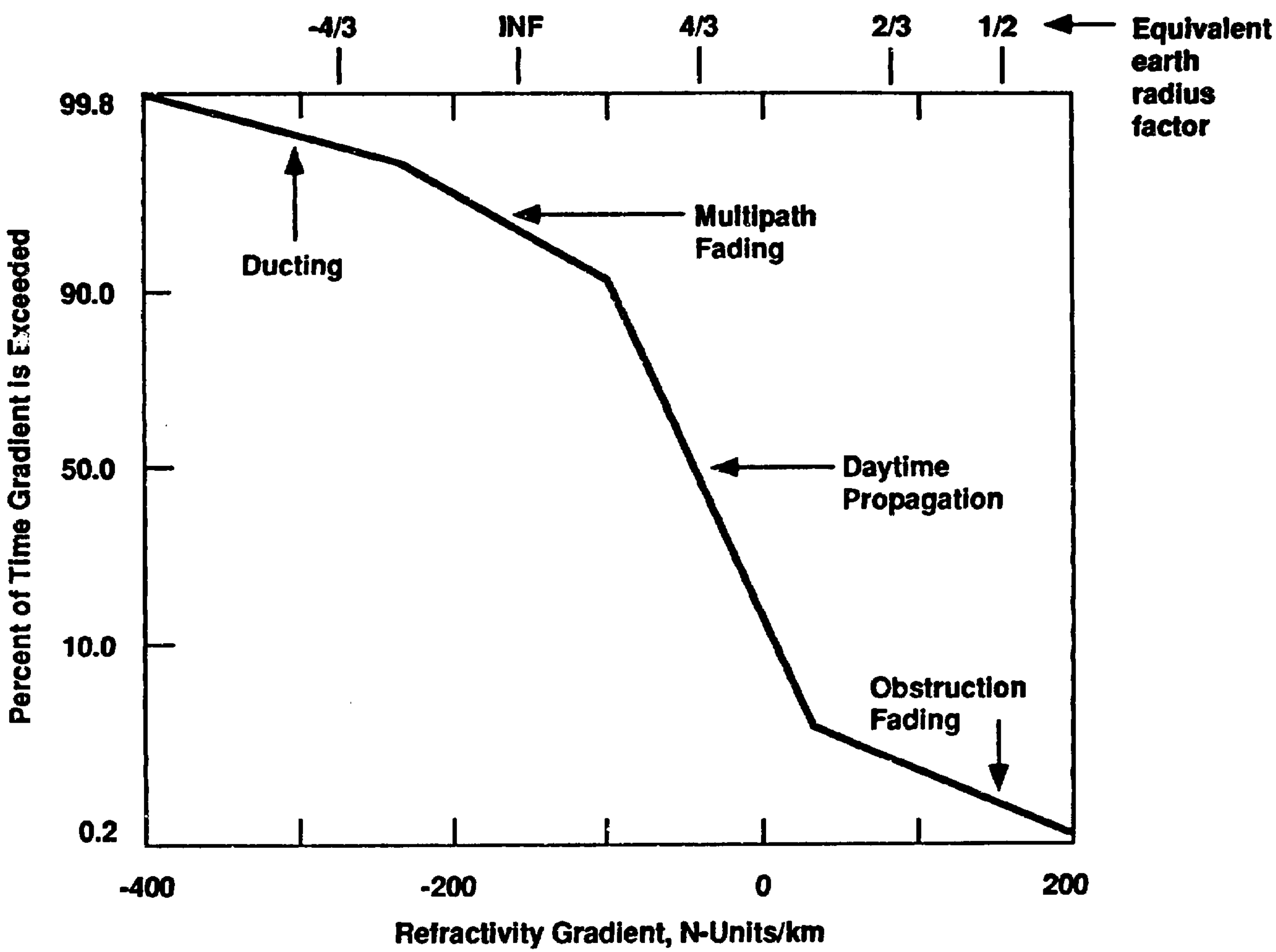


Figure 5-1. Refractivity Gradient Distribution (Illustrative Example)

Referring to the other end of the probability distribution, a positive gradient can also cause prolonged and severe reductions of received signal power. This is a result of a temporary blockage of the LOS path, referred to as obstruction fading.

Generically, the probability of the daytime propagation regime is the largest (note that the percent scale in Figure 5-1 is nonlinear, the so-called normal-probability scale). The probabilities of the ducting and obstruction fading regimes are relatively small, but can be significant in areas such as those near the Persian Gulf. The multipath fading regime has the largest probability among the anomalous propagation regimes, which is why it is addressed in this report.

Analytical models of multipath fading, formulated for the engineering of radio links, describe multipath fading in terms of the time during which the received signal power is smaller than a value of interest. The time is accumulated over all fades in a month, and it is usually expressed as a percentage of a month, denoted P. As an example, a value of the fading probability P of 0.1 percent corresponds to approximately 44 minutes per month.

Multipath fading models, being statistical in nature, include the effects of both atmospheric and reflective multipath fading. A separate issue is path engineering for ground reflection when, in the absence of atmospheric layers that produce multipath fading, a strong ground-reflected ray significantly reduces the received signal power. This can occur at any time of day. The issue of dominant ground-reflected rays will not be treated in this report.

The received signal level is described in terms of fade depth, denoted by A, expressed in positive dB relative to the signal power in the absence of fading. Thus, if the received signal power of interest is one percent of the power in absence of fading, then the value of A is 20 dB.

For deep fades, when A is 20 dB or larger, the fading probability P has a simple analytical form

$$P = 100\ R\ 10^{-A/10}\ ,\ A >= 20$$

where R is the multipath-fade-occurrence factor. As an example, if the fade occurrence factor is 0.1 and the fade depth is 20 dB, the probability of fading is 0.1 percent. This means that the received signal power is smaller than one percent of normal for a total of approximately 44 minutes in a month.

The above behavior of the probability P as a function of the fade depth A is a consequence of basic physics. This behavior always occurs when fading is caused by multiple interfering rays. The probability is usually plotted on a vertical logarithmic scale as a function of fade depth on a horizontal linear scale (see Figure 5-2). The probability becomes a straight line on such a plot. The slope of the line is decade of time (ratio of ten) per 10 dB of fade depth. This is referred to as the Rayleigh slope, after a theoretical probability function that describes the result of the interference of multiple rays. The Rayleigh probability function cannot be used to describe fade depths smaller than 20 dB (shallow fades). Such fades can contain a ray that is dominant, which requires a different mathematical model for their description.

The vertical position of the fading probability line in Figure 5-2 is determined by the fade-occurrence factor R, which is a function of climate, terrain features, radio frequency, and path distance. The functional form of R has been the subject of international propagation research for many years. A CONUS form for R (Barnett, 1972) is

$$R = 6\ C\ F\ D^3\ 10^{-7}$$

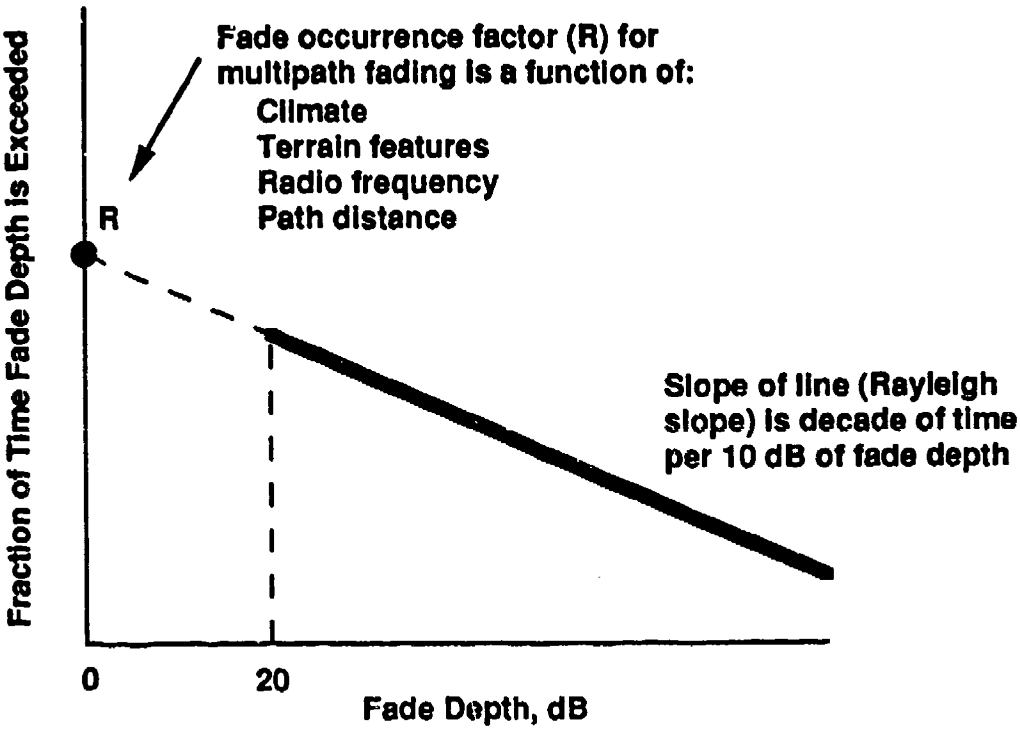


Figure 5-2. Statistical Description of Deep Multipath Fading

where D is the path length in km, and F is the radio frequency (greater than 2000 MHz) in GHz. Values for the climate and terrain factor C are obtained from maps that are frequently proprietary. A low-resolution qualitative propagation map for CONUS is shown in Figure 5-3. In terms of this map, for general planning purposes, C = 1 is recommended for areas of average propagation conditions.

For difficult CONUS climates and terrains (e.g., the U.S. gulf coast), C = 10 is recommended. The value of C = 10 is also recommended for like international climates and terrains, e.g., Saudi Arabia. For worst case conditions, C = 100 is recommended. This would be appropriate for cases of extreme heat and humidity such as the Red Sea or Persian Gulf coastal plain, or equatorial climates. For mountainous, dry, or northerly conditions, C = 0.25 is recommended. This would be appropriate for the Rocky Mountains, Canada, and sections of Germany.

Given the path length and frequency, selecting the climate and terrain factor, and using the above equations, the site-specific probability curve for the received power can be drawn (it will be a scaled version of Figure 5-2). The link reliability (outage) is determined by reading off the probability corresponding to the fade depth equal to the link fade margin.

The engineering of tactical LOS links requires extension of the methods described above to include fades shallower than 20 dB and radio frequencies smaller than 2000 MHz. This is described in the next section.

5.3 GENERAL MULTIPATH FADING MODEL FOR RECEIVED POWER

A general multipath fading model for received signal power is needed for link engineering at frequencies above 200 MHz, path lengths from 10 to 100 km, fade depths from 0 dB to 40 dB, and for a wide range of climates and terrains. The pioneering work in

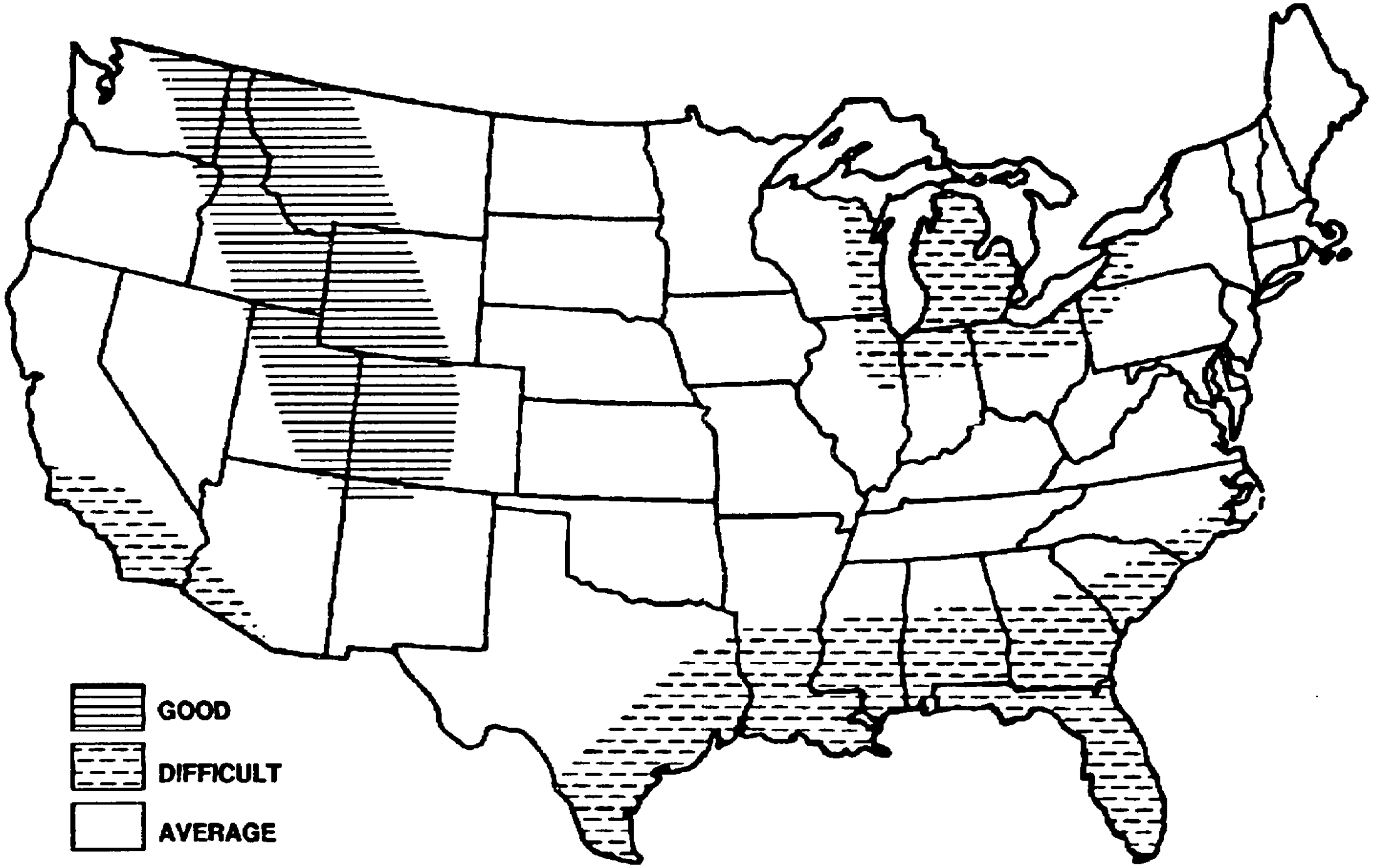


Figure 5-3. Geographic Variability of Propagation Conditions (Qualitative Example)

this area was done by K. Bullington (Bullington, 1957). His results have been utilized for engineering worldwide, including many Army systems. His work used large-scale averages for the operating parameters. For example, path length dependence was not explicitly specified and no allowance was made for climatic variability. Bullington's work, however, paved the way for follow-on work at AT&T Bell Laboratories and elsewhere that addressed more of the specifics as illustrated in the previous section. This latter work--published throughout the 1970s and 1980s--also addressed amplitude and phase dispersion, fading countermeasures (frequency and space diversity,, and rain attenuation, none of which will be addressed in this report.

A very recent Canadian paper (Olsen-Segal, 1991) provides the needed methodology for fading estimates in the shallow fade depth region between 0 dB and 20 dB and for frequencies down to 100 MHz. The Olsen-Segal work is adapted and used to meet the goals of this report.

The Olsen-Segal result for P in the deep-fade region (A> = 25 dB) for Canada is (in percent)

$$P = 10^{(G/10-5.7)} D^{3.6} F^{0.89} (1+|ep|)^{-1.4} 10^{(-A/10)}$$

where parameters not previously defined are

G = climatic factor in dB

ep = path inclination in mrad

A relationship between G and the previously used climate factor C will be established in subsequent paragraphs. The path inclination angle, ep, is the arctangent of a ratio where the numerator is the difference of the heights of the transmitting and receiving antennas, and the denominator is the path length.

The exponents of the parameters differ from those in the previously stated fade occurrence factor R for CONUS. In general, such exponents and additional parameters in the fade occurrence factor are obtained empirically from experimental data. Coordination of the values of the exponents is an ongoing standards effort at the International Radio Consultative Committee (CCIR, 1990). We will use the Olsen-Segal exponents in this work.

The Olsen-Segal deep-fade region empirical results were developed from various experimental databases for path lengths from 7.5 to 95 km, and frequencies from 2 to 37 GHz. These authors suggest that the model provides satisfactory results up to 180-km path length and down to 100 MHz (depending on path length). The model will be used here for frequencies down to 200 MHz and path lengths from 10 to 100 km. Also, the path inclination effect will be assumed to be negligible, i.e., ep will be set equal to zero.

The new Olsen-Segal result is a probability function Ps for shallow fade depths (0 to 25 dB) in percent,

$$Ps = 100\ (1 - \exp(-10^{(-qA/20)}))$$

where the functional form of the shape factor q has been determined from experimental data. The values of the coefficients in q are determined from the deep-fade probability P, which is assumed to be known.

The Olsen-Segal work provides two important capabilities regarding the modeling of multipath fading on tactical LOS links. First, the shape factor q permits description of shallow fades. Second, the observation that available fading modeling techniques apply at frequencies down to 100 MHz permits extension of such techniques to tactical links. Given these capabilities, the LOS

Propagation Reliability Working Group has incorporated geoclimatic factors into the model to describe a worldwide range of multipath fading conditions and their impact on tactical LOS links.

The model for the probability of fading is composed of the shallow-fade probability Ps and the deep-fade probability P. In this work, Ps describes the fading probability when A<25 dB, and P describes this probability when A>25 dB. Ps and P have the same value when A = 25 dB. The Olsen-Segal approach also allows use of 35 dB as the value separating the regions for the use of Ps and P. The 35-dB value imposes more constraints on the fading model than the 25-dB value and is therefore not used in this work.

The shape factor q in Ps is an empirically derived function that replicates experimentally observed shapes of shallow fading and merges Ps smoothly into P at the transition point at A = 25 dB. The expression for the shape factor q is

$$q = 2 + KA\ (qt + RA)$$

where KA and RA are empirically obtained functions of A

$$KA = 10^{-0.016A}\ (1 + 0.3\ 10^{-A/20})$$

$$RA = 4.3\ (10^{-A/20} + A/800)$$

The parameter qt is constant for a particular Ps curve. Its value is

$$qt = (\ (r - 2)\ /\ K25) - R25$$

where K25 and R25 are the respective values of KA and RA at A = 25 dB. The parameter r (which is distinct from the fade occurrence factor R) is calculated from the deep-fade probability

$$r = -0.8 \log(-\ln(1-P25/100))$$

where ln denotes the natural logarithm and P25 is the value of P at A = 25 dB.

The shallow-fade probability Ps and the shape factor q describe shallow fading associated with atmospheric structures that cause multipath fading. The method is valid for such description when qt >= -2. For qt < -2, the shallow fading is too large to be accommodated by this model. Such enhanced shallow fading can occur when multipath propagation is superimposed on depressed levels of received signal caused by ducting or temporary increase in terrain blockage due to the presence of a layer of moist air over a ground-based layer of dry air.

The final step in the adaptation of the Olsen-Segal model for worldwide use is to establish the linkage between the average deep fading in Canada and in CONUS. This can be done by calculating the fade depths for both Canada and CONUS at an identical probability in the deep-fade region using the same set of parameter values. The values selected are D = 40 km, P = 0.1 percent, and F = 4 GHz since these represent those for which there are most extensive experimental data. This calculation yields a Canadian climate factor of G = 5.8 dB corresponding to the average CONUS fading value of C = 1. Since G = 0 dB is the Canadian average, this result indicates that the average worst month fading in Canada is one quarter that of CONUS, as is expected for the colder Canadian climate.

The fading model needed is now complete. To use it, values for the parameters of path length (D), frequency (F), and climate (G) need to be selected. At this time, it is recommended that

G = 0 dB for mountainous, dry, or northerly climates, e.g., Canada or Germany

G = 5.8 dB for average climates, CONUS

G = 15.8 dB for difficult climates, CONUS or International

G = 25.8 dB for very difficult International climates

A future work item is to provide more detailed contours of G for International climates.

6. RESULTS

6.1 FADE MARGINS

The multipath fading model developed in Section 5 has been utilized to calculate link reliability as a function of fade margin (0 to 40 dB) for selected values of link path length (10 to 80 km) for frequencies of 300 MHz, 1600 MHz, and 4750 MHz. The latter are selected as representative of the 225-to-400 MHz, 1350-to-1850 MHz, and 4400-to-5000 MHz frequency bands, respectively. For each of the three frequencies, three values of the climate factor have been selected to span the climate range of application: average CONUS (5.8 dB), difficult CONUS or International (15.8 dB), and very difficult International (25.8 dB). Alternatively, the link fade margin has been calculated as a function of link path length for selected values of link reliability (90, 99, 99.9, and 99.99 percent). Typical results of the calculations are given in Table 6-1 for 300 MHz, Table 6-2 for 1600 MHz, and Table 6-3 for 4750 MHz. Table 6-4 summarizes the results for a difficult propagation climate and path lengths of 20 km, 40 km, and 60 km.

A complete set of graphs is provided in Appendix A as reference information. Figures A-1A to A-9A display probability (reliability) results versus required fade margin for a fixed-path length. Figures A-1B to A-9B display required fade margin versus link

Table 6-1. Fade Margins Required for Multipath Fading (300 MHz)

Reliability, Percent	Required Fade Margin in dB Relative to Free Space at 300 MHz — Path Distance, kilometers: 10	20	30	40	50	60	70	80
	Average CONUS Propagation Climate							
90	1.3	1.6	1.8	2.0	2.3	2.6	2.8	3.1
99	3.1	3.9	4.7	5.6	6.6	7.7	9.1	10.6
99.9	5.3	7.3	9.5	12.0	14.7	17.5	20.1	22.4
99.99	8.6	12.7	17.3	21.6	25.3	28.2	30.6	32.7
	Difficult Propagation Climate (International or CONUS)							
90	1.5	2.0	2.5	3.0	3.5	4.2	5.1	6.4
99	3.8	5.4	7.4	10.0	13.3	16.7	19.7	22.3
99.9	7.1	11.4	16.6	21.4	25.3	28.2	30.6	32.7
99.99	12.2	20.7	27.4	31.9	35.3	38.2	40.6	42.7
	Very Difficult Propagation Climate (International)							
90	1.9	2.9	3.9	5.8	9.7	15.0	na	na
99	5.2	9.4	15.6	21.2	25.3	28.2	na	na
99.9	10.9	20.5	27.4	31.9	35.3	38.2	na	na
99.99	19.9	31.0	37.4	41.9	45.3	48.2	na	na

Note: na indicates excessive fading.

Table 6-2. Fade Margins Required for Multipath Fading (1600 MHz)

Reliability, Percent	Required Fade Margin in dB Relative to Free Space at 1600 MHz							
	Path Distance, kilometers							
	10	20	30	40	50	60	70	80
	Average CONUS Propagation Climate							
90	1.4	1.8	2.2	2.6	3.0	3.4	3.9	4.5
99	3.5	4.7	6.1	7.8	9.9	12.5	15.3	17.9
99.9	6.3	9.5	13.4	17.6	21.4	24.6	27.1	29.2
99.99	10.6	17.4	23.7	28.3	31.8	34.7	37.1	39.2
	Difficult Propagation Climate (International or CONUS)							
90	1.8	2.5	3.3	4.2	5.7	8.6	12.9	16.7
99	4.6	7.4	11.7	16.8	21.2	24.6	27.1	29.2
99.9	9.2	16.7	23.7	28.3	31.8	34.7	37.1	39.2
99.99	16.7	27.5	33.8	38.3	41.8	44.7	47.1	49.2
	Very Difficult Propagation Climate (International)							
90	2.4	4.0	7.5	15.3	na	na	na	na
99	7.1	15.8	23.6	28.3	na	na	na	na
99.9	15.9	27.5	33.8	38.3	na	na	na	na
99.99	26.6	37.5	43.8	48.3	na	na	na	na

Note: na indicates excessive fading.

Table 6-3. Fade Margins Required for Multipath Fading (4750 MHz)

Reliability, Percent	Required Fade Margin in dB Relative to Free Space at 4750 MHz							
	Path Distance, kilometers							
	10	20	30	40	50	60	70	80
	Average CONUS Propagation Climate							
90	1.6	2.0	2.6	3.1	3.7	4.4	5.5	7.0
99	3.8	5.6	7.7	10.5	14.0	17.5	20.5	23.1
99.9	7.3	11.8	17.3	22.2	26.0	28.9	31.3	33.4
99.99	12.7	21.4	28.0	32.5	36.0	38.9	41.3	43.4
	Difficult Propagation Climate (International or CONUS)							
90	2.0	3.0	4.1	6.2	10.9	16.3	na	na
99	5.4	9.8	16.5	22.1	26.0	28.9	na	na
99.9	11.3	21.3	28.0	32.5	36.0	38.9	na	na
99.99	20.6	31.7	38.0	42.5	46.0	48.9	na	na
	Very Difficult Propagation Climate (International)							
90	2.9	5.7	14.7	na	na	na	na	na
99	9.3	21.0	28.0	na	na	na	na	na
99.9	20.3	31.7	38.0	na	na	na	na	na
99.99	30.9	41.7	48.0	na	na	na	na	na

Note: na indicates excessive fading.

Table 6-4. Fade Margins Required for Multipath Fading (Difficult Climate)

Reliability, Percent	Required Fade Margin in dB Relative to Free Space for Difficult Climate								
	Path Distance, kilometers								
	20			40			60		
	Frequency (MHz)			Frequency (MHz)			Frequency (MHz)		
	300	1600	4750	300	1600	4750	300	1600	4750
90	2.0	2.5	3.0	3.0	4.2	6.2	4.2	8.6	16.3
99	5.0	7.4	9.8	10.0	16.8	22.1	16.7	24.6	28.9
99.9	11.4	16.7	21.3	21.4	28.3	32.5	28.2	34.7	38.9
99.99	20.7	27.5	31.7	31.9	38.3	42.5	38.2	44.7	48.9

path length for a fixed reliability. Each set of curves is equivalent to the other. Both are included since applications usually begin with either a given distance or a given desired reliability. The curves labeled Ideal Maximum Fade Margin on Figures A-1B to A-9B are derived from the maximum fade margin given in Table 3-2. They will be discussed further in Section 6.2.

These results satisfy the objective of this work, which was to provide the means for specifying the link-fade-margin requirement as a function of link reliability and establishing the trade-offs with the physical link parameters.

As expected, the required fade margins vary from a few dB up to 40+ dB. For example, Table 6-4 specifies for 40 km and 1600 MHz, and a difficult propagation climate, a fade margin requirement of 4.2 dB for 90-percent link reliability (144 minutes/day of multipath fading outage) increasing to 38.3 dB for 99.99-percent reliability (0.144 minutes/day of multipath fading outage). Clearly, high-reliability links require substantial fade margins.

Some simple rules of thumb for the fade region beyond, say, 15 dB can provide useful mnemonics:

- A decade of fade probability corresponds to 10 dB of fade margin.

- For a constant reliability, doubling the link distance requires an additional 10.8 dB of fade margin.

- For a constant reliability, doubling the frequency corresponds to 2.7 dB of fade margin. Increasing the frequency from 300 to 1600 MHz requires an additional 6.5 dB of fade margin. And increasing the frequency from 1600 to 4750 MHz requires an additional 4.2 dB of fade margin.

- For a constant fade margin, doubling the link distance increases the fade probability by a factor of 12.

- For a constant fade margin, doubling the frequency increases the fade probability by a factor of 1.85. Increasing the frequency from 300 MHz to 1600 MHz increases the fade probability by a factor of 4.4. And increasing the frequency from 1600 MHz to 4750 MHz increases the fade probability by a factor of 2.6.

6.2 MAXIMUM LINK PATH LENGTHS AND AVAILABLE FADE MARGIN

The ideal maximum fade margins developed in Section 3.3 and listed in Table 3-2 are obtained when all the equipment is working at its baseline specification (see Table 3-1). They are given for a 40-km path but can easily be converted to other lengths by using the equation given in footnote 5 of Table 3-2. This has been done as plotted on Figures A-1B to A-9B. The other curves on these figures are the required fade margins for a fixed reliability. Therefore the dB difference between the ideal maximum fade-margin curve and the required fade-margin curve is the fade margin available for allocation to other threats and equipment degradations. For example, referring to Figure A-2B, the available fade margin for 30 km and 99.9-percent reliability is about 11 dB. The path length corresponding to an available fade margin of 0 dB is the maximum possible path length. From Figure A-2B and for 99.9-percent reliability, the maximum possible path length is 45 km. This procedure has been repeated for other frequencies and propagation climates with the maximum path results summarized in Table 6-5. For example, a link reliability objective of 99.9 percent (1.44 minutes/day outage) will limit the maximum possible path lengths in a difficult propagation climate (CONUS or international) to 45 km at 300 MHZ, 40 km at 1600 MHz, and 35 km at 4750 MHz. Another representation of available fade margin for a difficult climate and a 99.9-percent reliability is displayed on Figure 6-1. The crossover point at 0

Table 6-5. LOS Radio Maximum Path Lengths for Optimum Conditions and Free Space Path Loss

Reliability, Percent	Maximum Path Length, kilometers[1, 2] Average Climate	Difficult Climate	Very Difficult Climate
	300 MHz Fade Margin at 40 km = 24.5 dB, AN/GRC-226 (V)1		
99.0	100	70	45
99.9	70	45	30
99.99	45	30	20
	1600 MHz Fade Margin at 40 km = 28 dB, AN/GRC-226 (V)2		
99.0	95	60	40
99.9	60	40	26
99.99	40	26	18
	4750 MHz Fade Margin at 40 km = 28.9 dB, AN/GRC-222		
99.0	80	52	35
99.9	52	35	23
99.99	35	23	16

Notes:

1. Assuming ample antenna clearance and radio operating at equipment specification values.
2. Maximum path length for a fixed frequency would decrease 4% for every dB of margin degradation due to hardware degradation, antenna misalignment, reduced maintenance, etc.

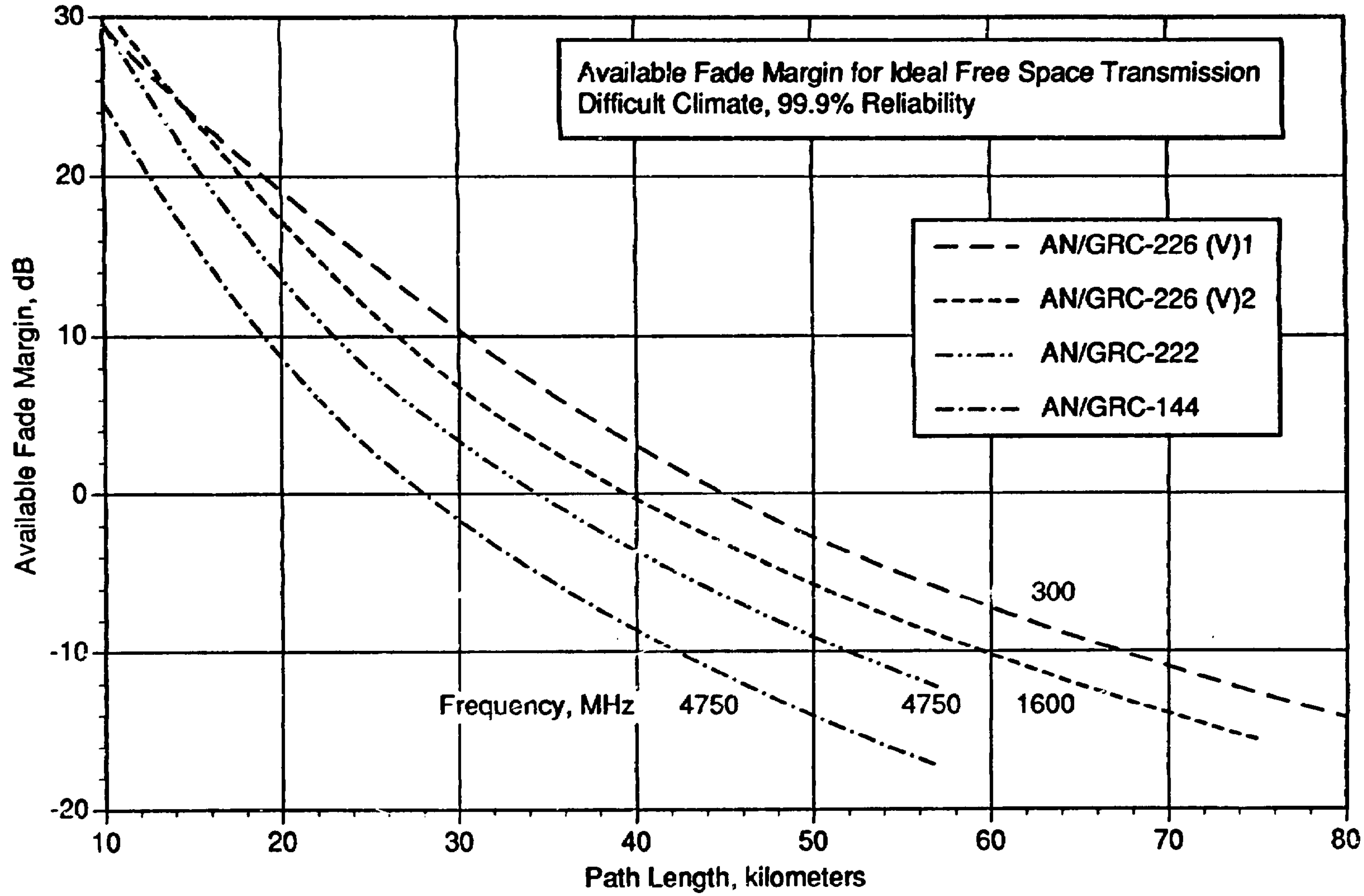


Figure 6-1. Ideal Available Fade Margin (99.9% Reliability, Difficult Climate)

dB is again the maximum possible path length. Path lengths longer than this cannot provide 99.9-percent reliability in difficult climates.

The maximum path length results indicate that the radio has the capability to meet its baseline requirements if and only if the required fade margins are realized in field applications. To reiterate, the maximum possible path lengths assume adequate antenna clearance (ideal free space transmission), on-beam antenna alignment, radio equipment operating at its specification values, and negligible radio frequency interference. All this is unlikely. Misaligned antennas or those with reduced clearance can easily cost 10 dB or more of margin. The values of available fade margin derivable from Figures A-1B to A-9B are the budget available for such use if necessary. For example a net 3-dB degradation would reduce the maximum path lengths by about 12 percent or roughly 5 km for the previous Table 6-4 example. As an aside, note that every 1-dB change in fade margin changes the maximum link path lengths for a fixed frequency by about 4 percent. This relationship follows from the 3.6 power relationship of fade depth with distance combined with the second power relationship of fade margin with distance. Thus the change in fade margin varies with the log of the 5.6 power of distance.

7. CONCLUSIONS

Our principal conclusion is that time-varying reduction in received signal strength (fading) causes significant degradations in the reliability of Army Tactical LOS Radio Systems. Based on our analysis and a review of the literature, we find that fade margin recommendations used in current engineering methods are much too small, especially for difficult propagation environments. We have developed new fade margin recommendations, which accommodate time-varying multipath fading and could be incorporated into LOS engineering methods. These improvements provide a means for engineering critical links requiring enhanced reliabilities. Greater link reliability is recommended for single-thread links and links serving BFAs with critical data requirements. We also conclude, based on user feedback, that the radio system operators have not been trained on any aspects of fading, including how and when it occurs, what happens when it occurs, and how to respond to its occurrence.

A listing of our main conclusions follows:

- Time variations in received signal strength due to fading cause Army Tactical LOS Radio Systems to have degraded reliability as confirmed by user feedback.

- The need for realizing adequate fade margins is not recognized by current tactical doctrine.

- Current fade margin requirements are too small for difficult propagation environments; current link engineering methods do not adequately consider fading.

- Fading exposes and increases the effects of any deficiencies in the equipment, its operation, or the link engineering.

- Setup and operation at a BER of 10^{-5} gives a false sense of security.

- The fragility of digital transmission when operating at system-measurable BERs is not recognized.

- There is a projected need for 99.9-percent link reliability for single-thread and BFA data applications.

- Propagation issues cause preferential use of Band I over Band III. This results in many frequency management problems associated with the overpopulation of Band I radios.

- Radio system operators require increased training with respect to fading.

8. RECOMMENDATIONS

We recommend that:

- The fade margins used to engineer MSE links be changed to accommodate time-varying multipath fading depending on path length and climate.

- Link engineering tools be modified so that the network planner may predict link reliabilities for proposed links.

- Reliability requirements of 99.9 percent be adopted for single-thread and BFA data links.

- MSE and other operating personnel be trained regarding fading.

- The capability be added to measure the actual received signal strength when high reliability is required.

- The methods, models, and tools from this effort be incorporated into FURIES, the Network Planning Tool, and the Integrated System Control (ISYSCON).

We also recommend that additional work be done to:

- o Analyze and model the effects of reduced clearance resulting from lowering the antennas as is commonly done in tactical operational environments.
- o Investigate and model combined effects of power fading (Longley-Rice, TIREM) and multipath fading.
- o Analyze and model the occurrence and effects of ducting.
- o Evaluate the impact of RF interference on link fade margins.
- o Determine the reliability impact of significantly increasing the path lengths, i.e., range extension.
- o Determine link reliability requirements for Army Tactical LOS Radio Systems.
- o Develop fading countermeasure strategies and models enabling improved reliability and increased path length.
- o Generate a plan for an experimental fading measurement program spanning all LOS radios used by the Army.

9. FUTURE WORK

9.1 NEAR TERM

The evaluation of current methods for predicting average receiver signal power is essential for establishment of accurate planning tools to assist network managers. Longley-Rice and TIREM models are currently accepted as the standards for this purpose. Both are currently used by commercial and military LOS designers. However, tactical LOS application of these models is an area of concern, since these models do not include all factors related to reduced clearances required for tactical LOS operations. Also, the parameters used for these models are somewhat different than those used for time-variant-fading models such as Olsen-Segal. These functions must be incorporated into the path loss baseline predictions of Longley-Rice and TIREM. A technical report (ESSA, 1970) identified some of the results of low clearance performance. Specifically, the report focused on increased variability of path loss when LOS sites with reduced clearances were tested. Our efforts will be focused on obtaining a better understanding of the factors that influence the models and enhancing the current models in order to reduce this variability for tactical LOS applications.

As a part of this effort, the group will investigate the time-variant atmospheric fading effects for reduced-clearance applications. This will include the necessary tailoring of the Olsen-Segal model in order to predict the effects of low clearance in applications where clearances are smaller than 0.6 of a Fresnel zone. The group will also investigate the occurrence and effects of ducting.

The group will develop a plan for link performance and propagation measurements relevant to the application of Army LOS radios in the tactical environment. This effort is needed to obtain data to evaluate reduced-clearance operation and to further improve LOS network planning tools. The group will develop a user's guide of actions and procedures to assist in identification of propagation threats and countermeasures for each situation. The guide will also include suggestions for LOS planners to assist them in planning LOS links with adequate margins to reduce the threat and to deal with adjustment of the network where propagation variability impacts LOS performance.

9.2 LONG TERM

The following projected goals follow from the above near-term efforts and are subject to change based on information received from customers and acquisition managers:

- o Execute measurement plan.
- o Develop geoclimatic propagation charts for regions of interest.
- o Provide countermeasure strategies and model.
- o Further improve predictive performance models.
- o Develop next-generation LOS models for soldier's use.

10. REFERENCES

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APPENDIX A

GRAPHS OF PROBABILITY OF FADING AND REQUIRED FADE MARGINS

APPENDIX A

This appendix contains pairs of graphs describing the probability of fading and the corresponding required fade margins for particular values of propagation reliability. Figures A-1A to A-9A display probability (reliability) results versus required fade margin for a fixed-path length. Figures A-1B to A-9B display required fade margin versus link path length for a fixed reliability. Each set of curves is equivalent to the other. Both are included since applications usually begin with either a given distance or a given desired reliability. The curves labeled Ideal Maximum Fade Margin on Figures A-1B to A-9B are derived from the maximum fade margin given in Table 3-2.

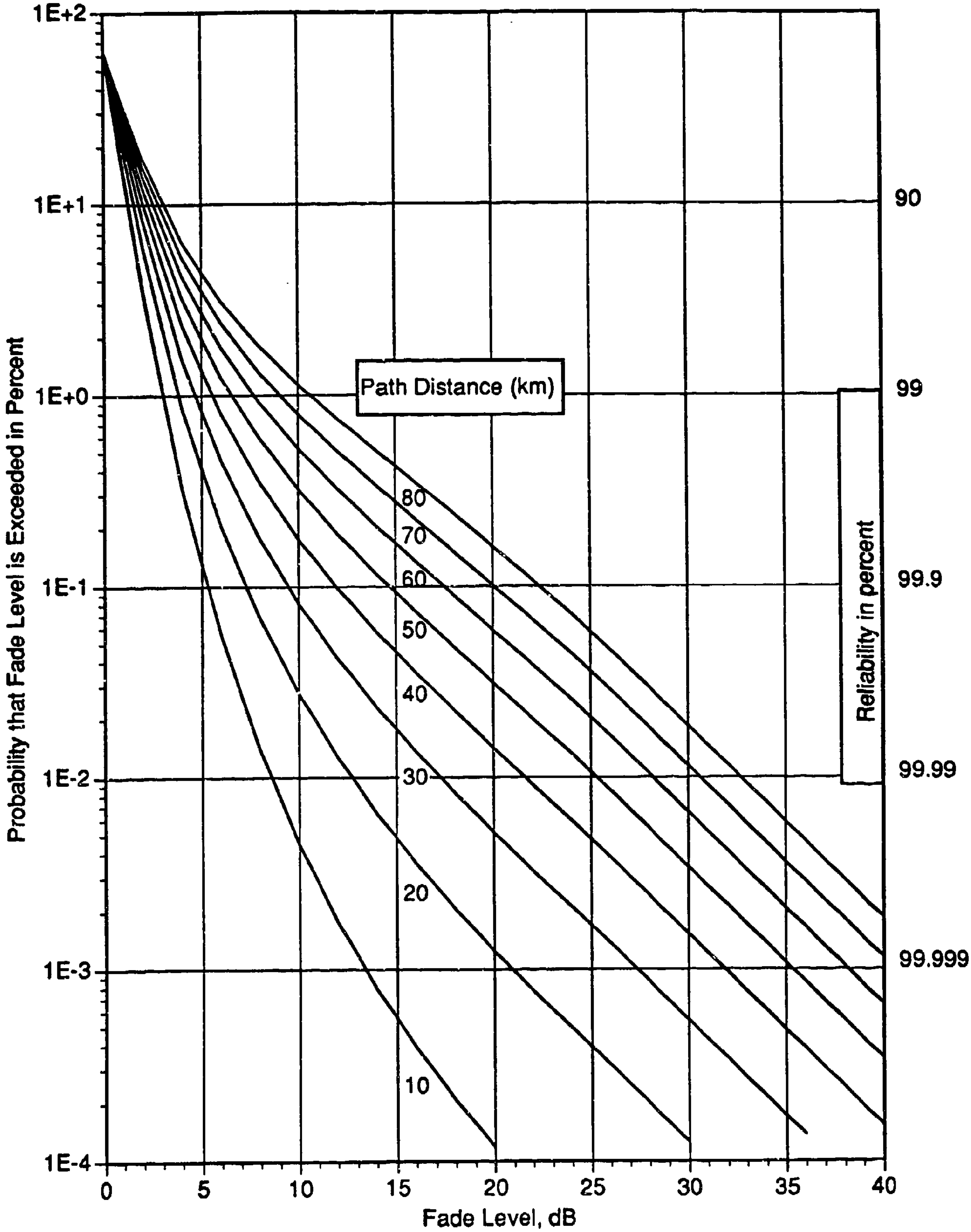

Figure A-1A. Probability of Fading (300 MHz, Average Climate)

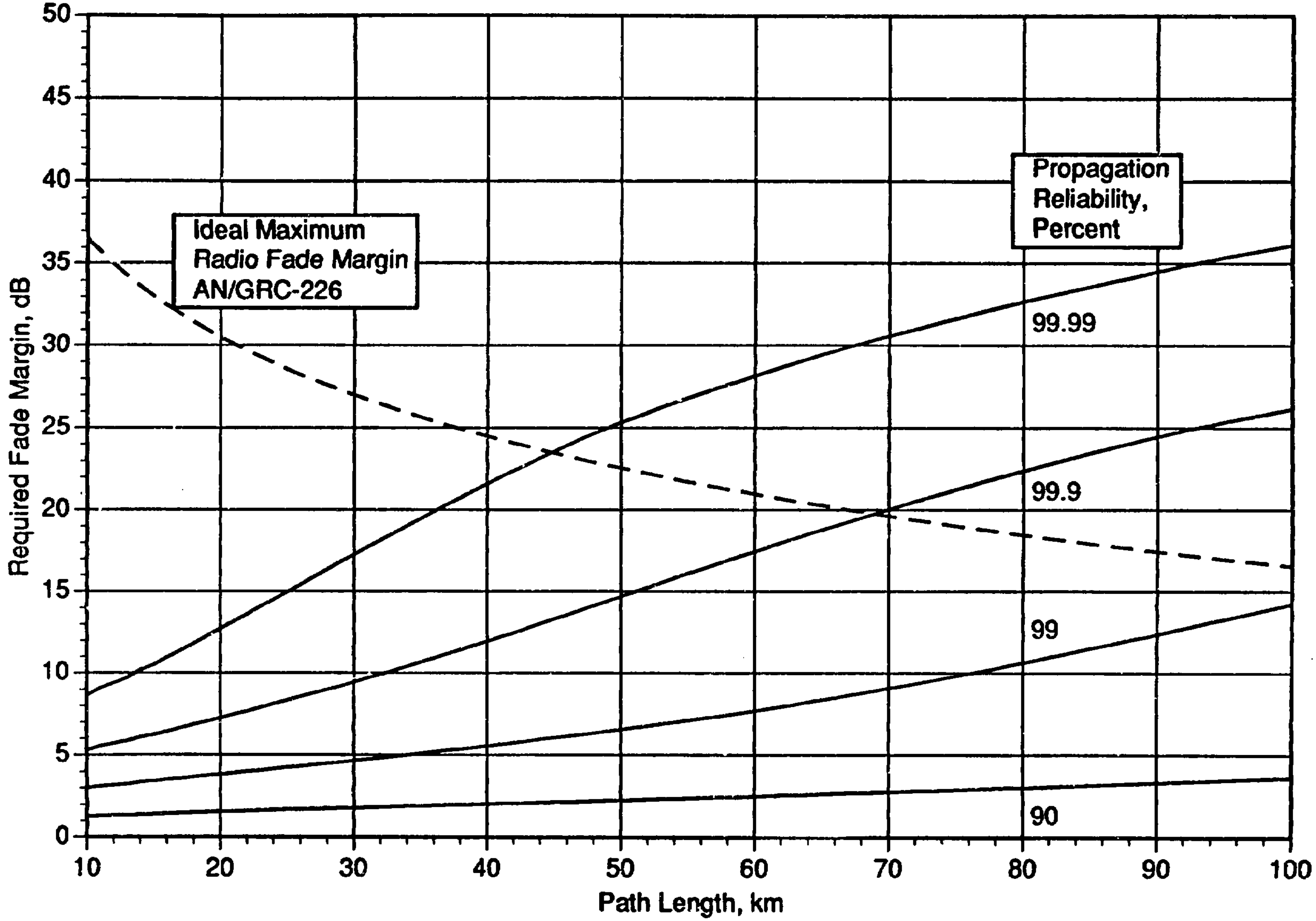

Figure A-1B. Required Fade Margin (300 MHz, Average Climate)

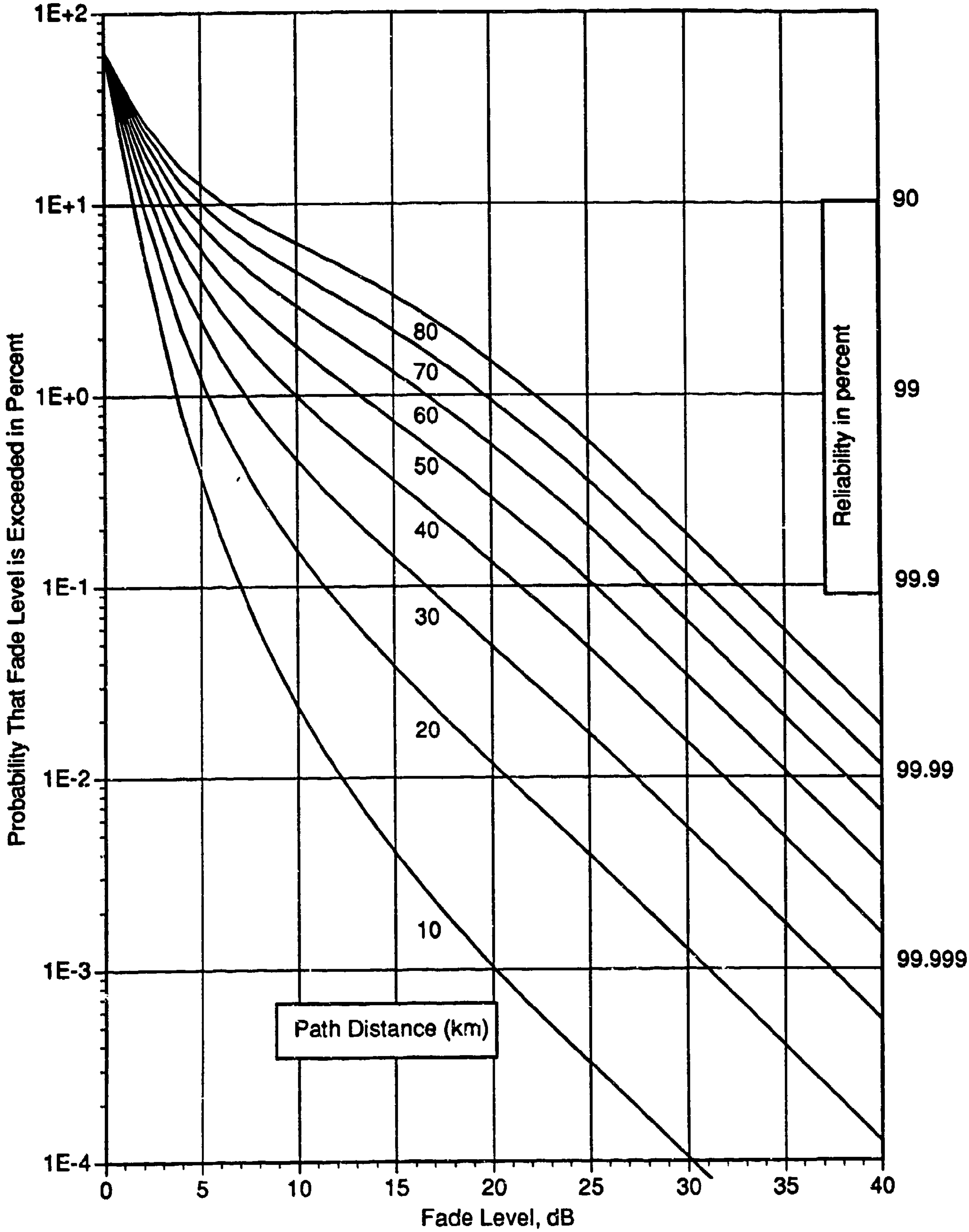

Figure A-2A. Probability of Fading (300 MHz, Difficult Climate)

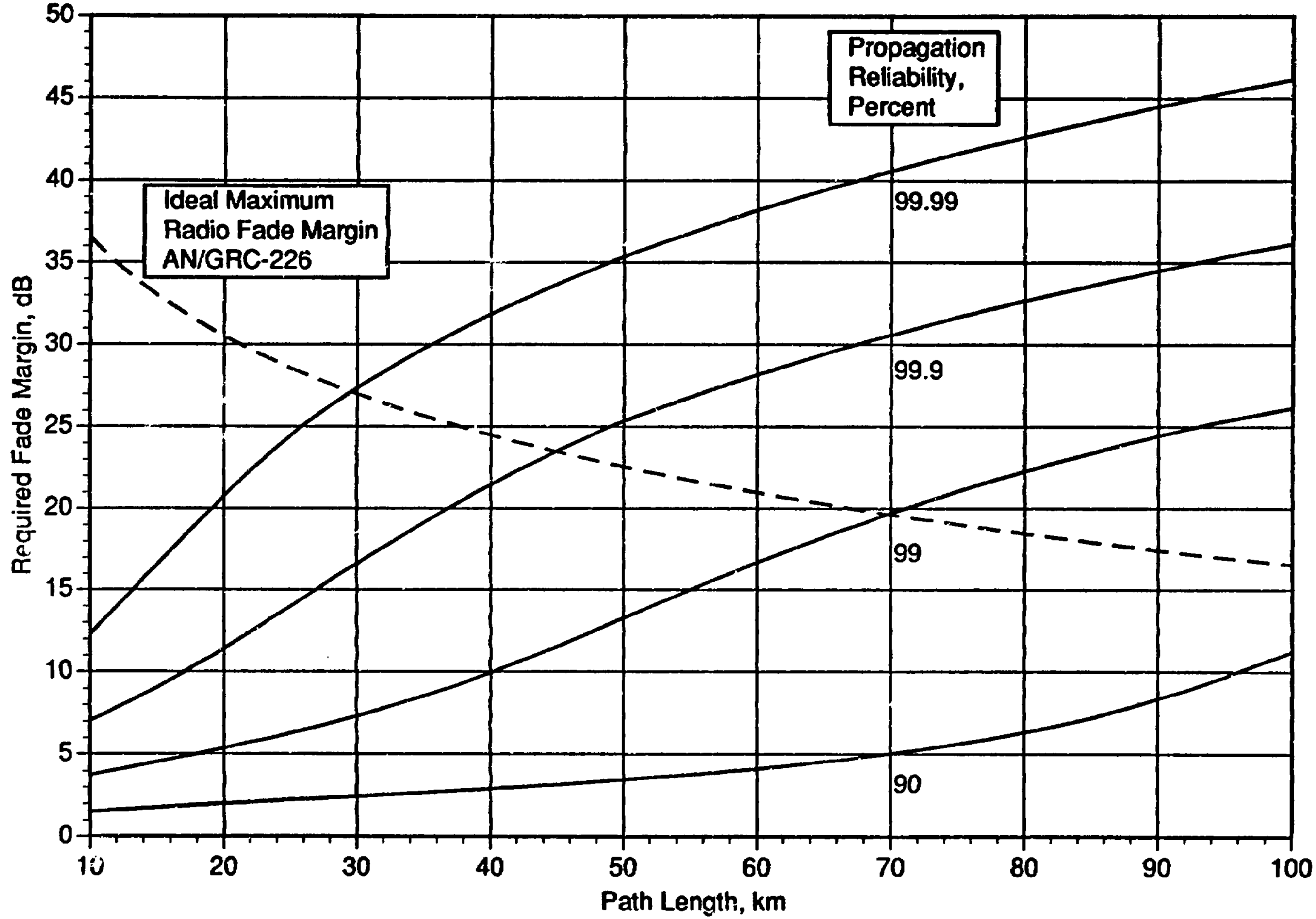

Figure A-2B. Required Fade Margin (300 MHz, Difficult Climate)

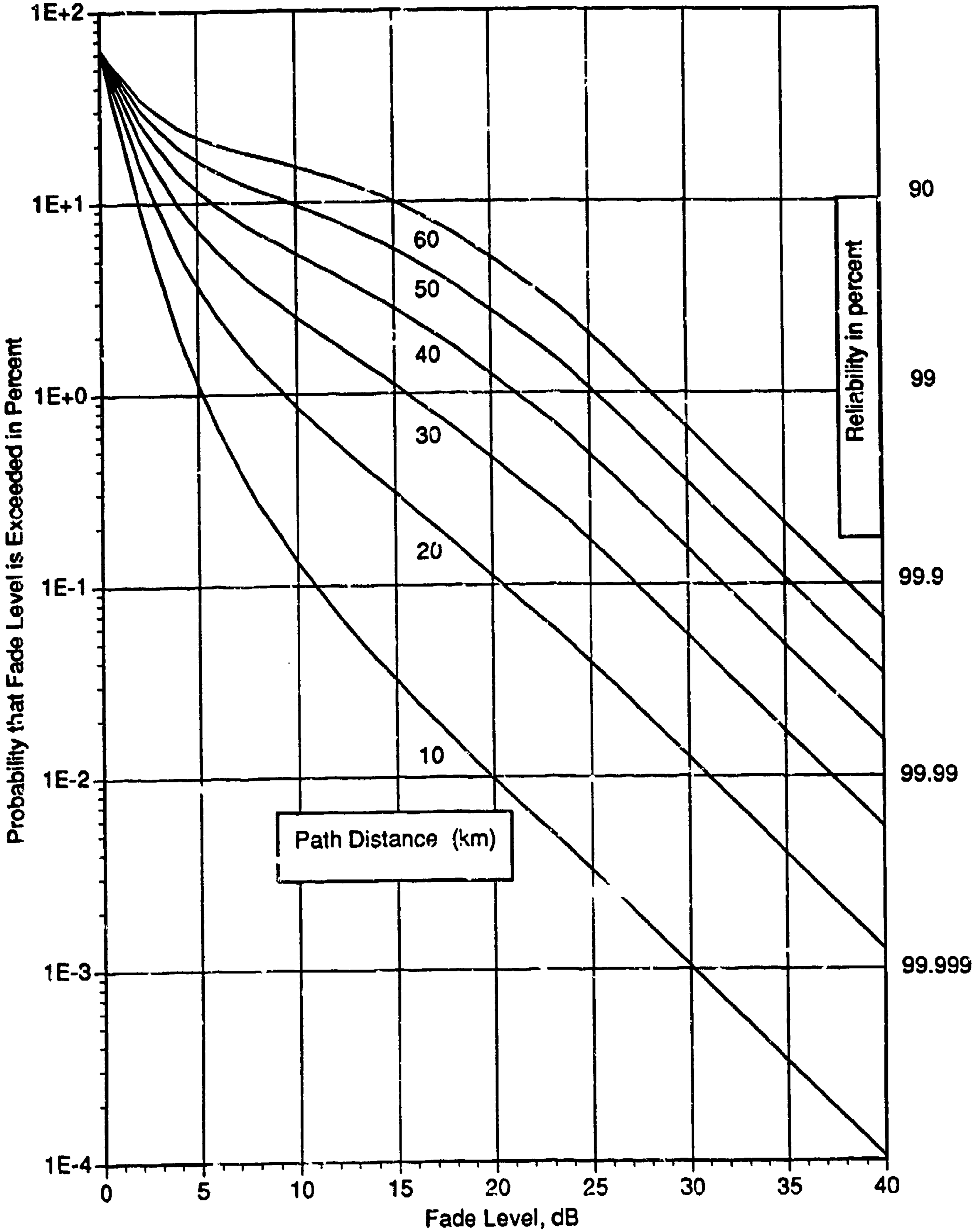

Figure A-3A. Probability of Fading (300 MHz, Very Difficult Climate)

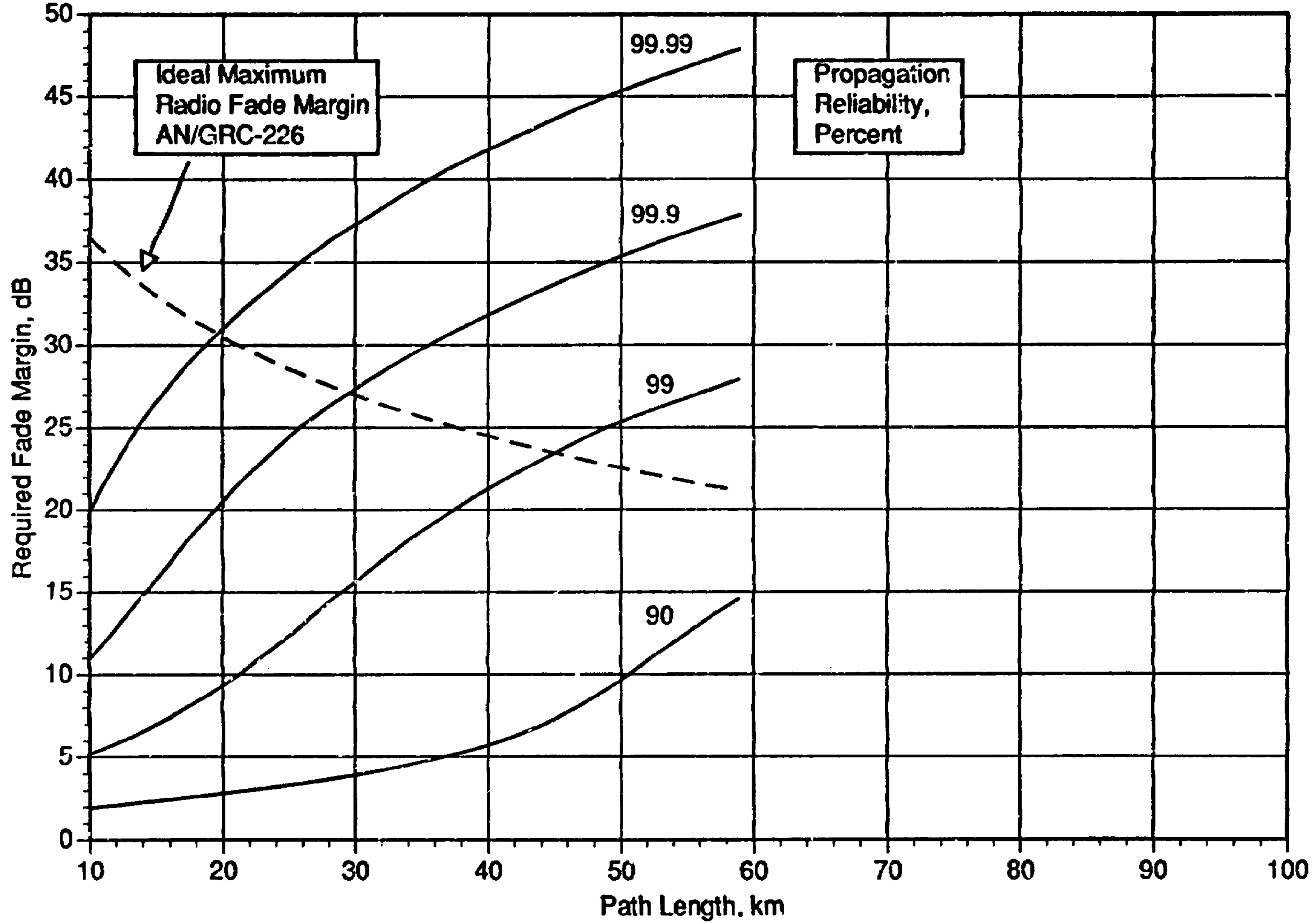

Figure A-3B. Required Fade Margin (300 MHz, Very Difficult Climate)

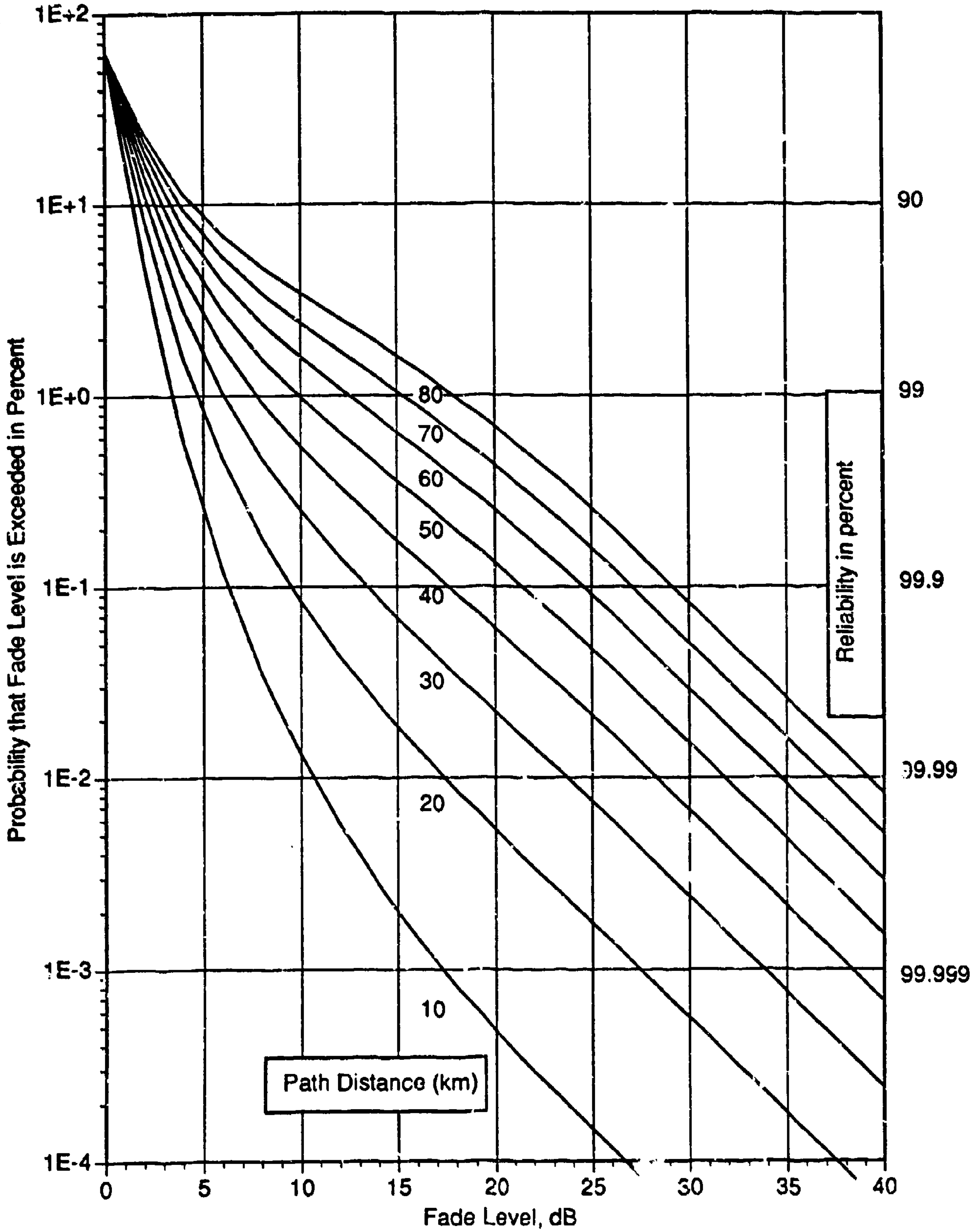

Figure A-4A. Probability of Fading (1600 MHz, Average Climate)

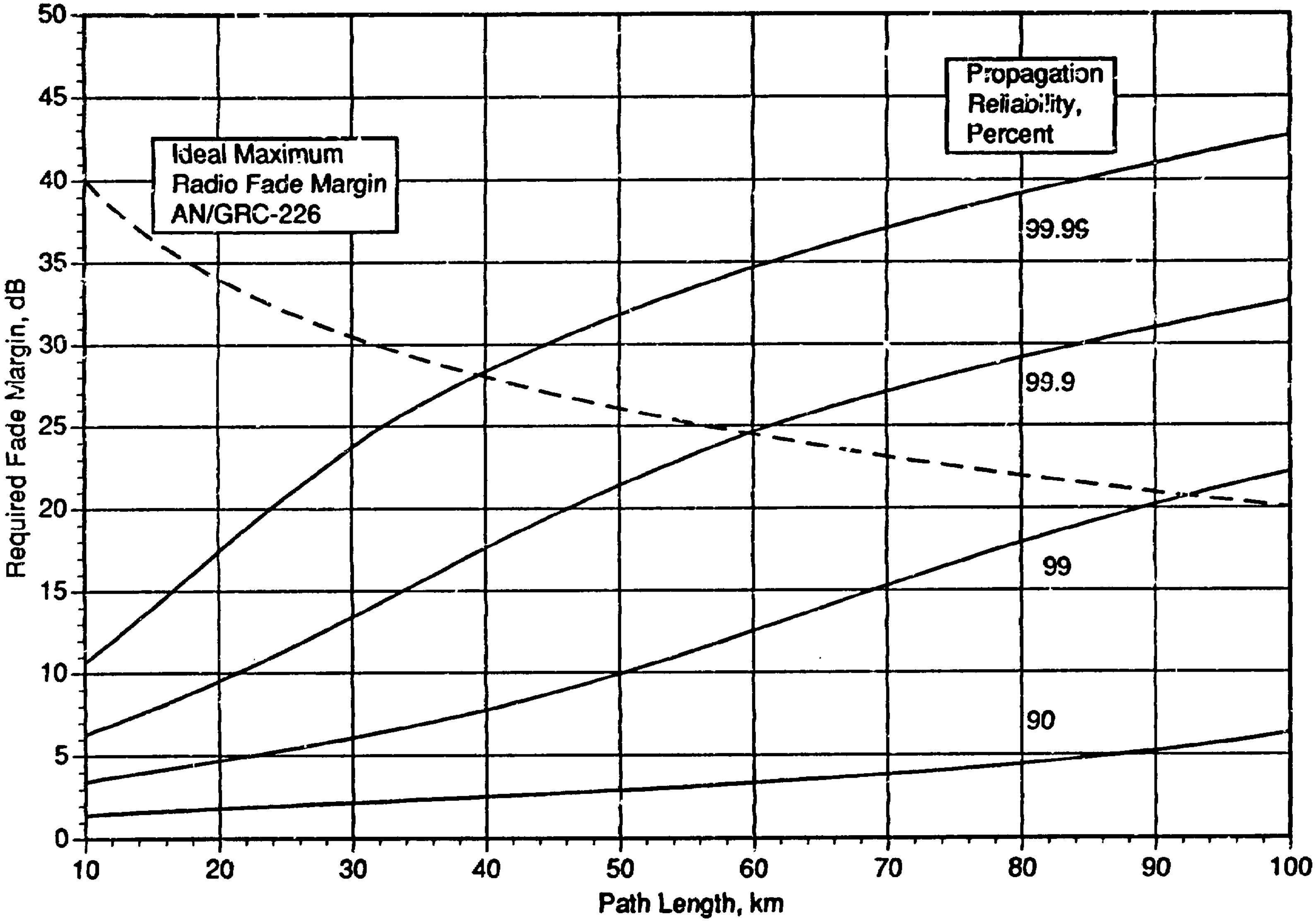

Figure A-4B. Required Fade Margin (1600 MHz, Average Climate)

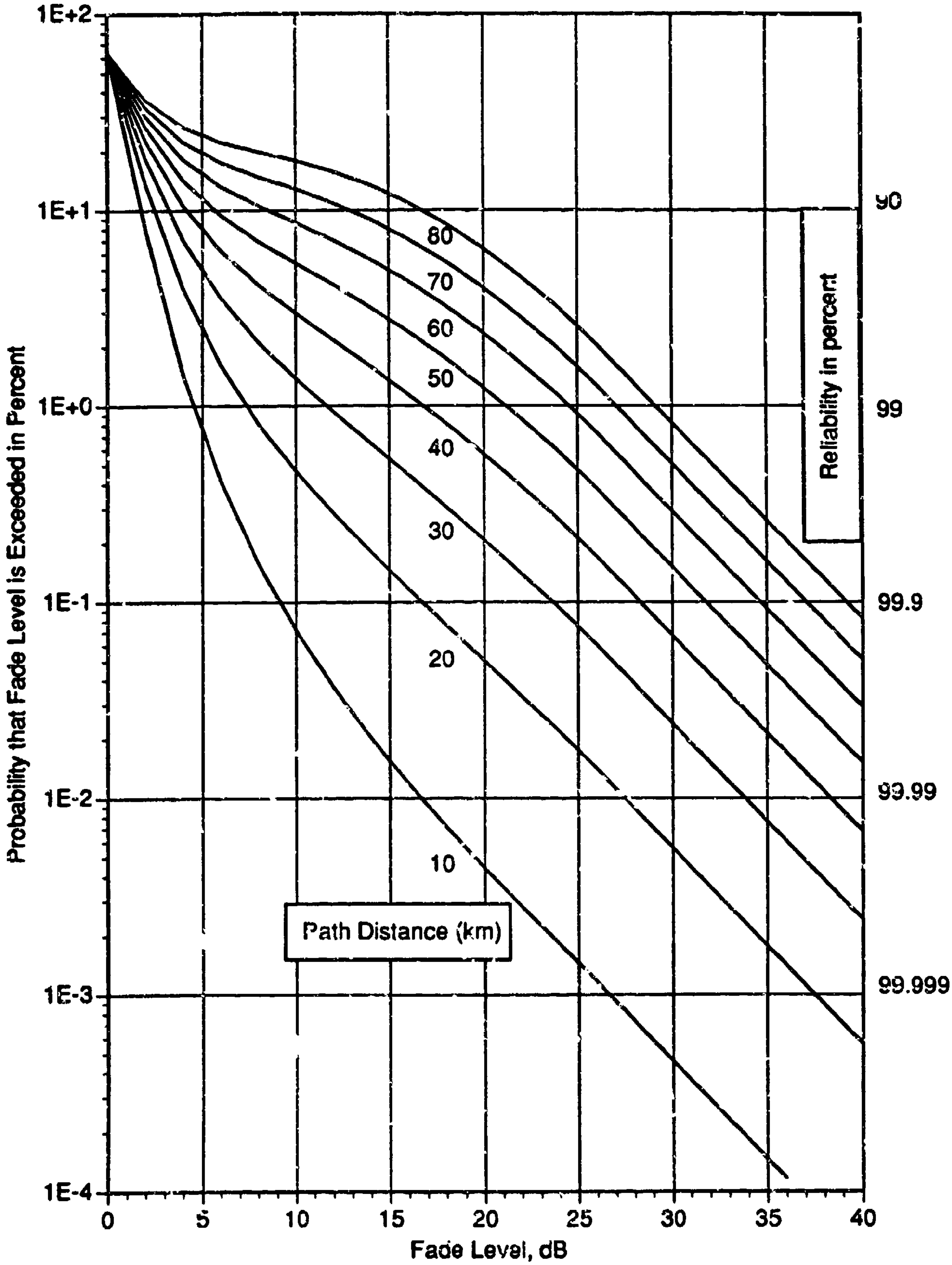

Figure A-5A. Probability of Fading (1600 MHz, Difficult Climate)

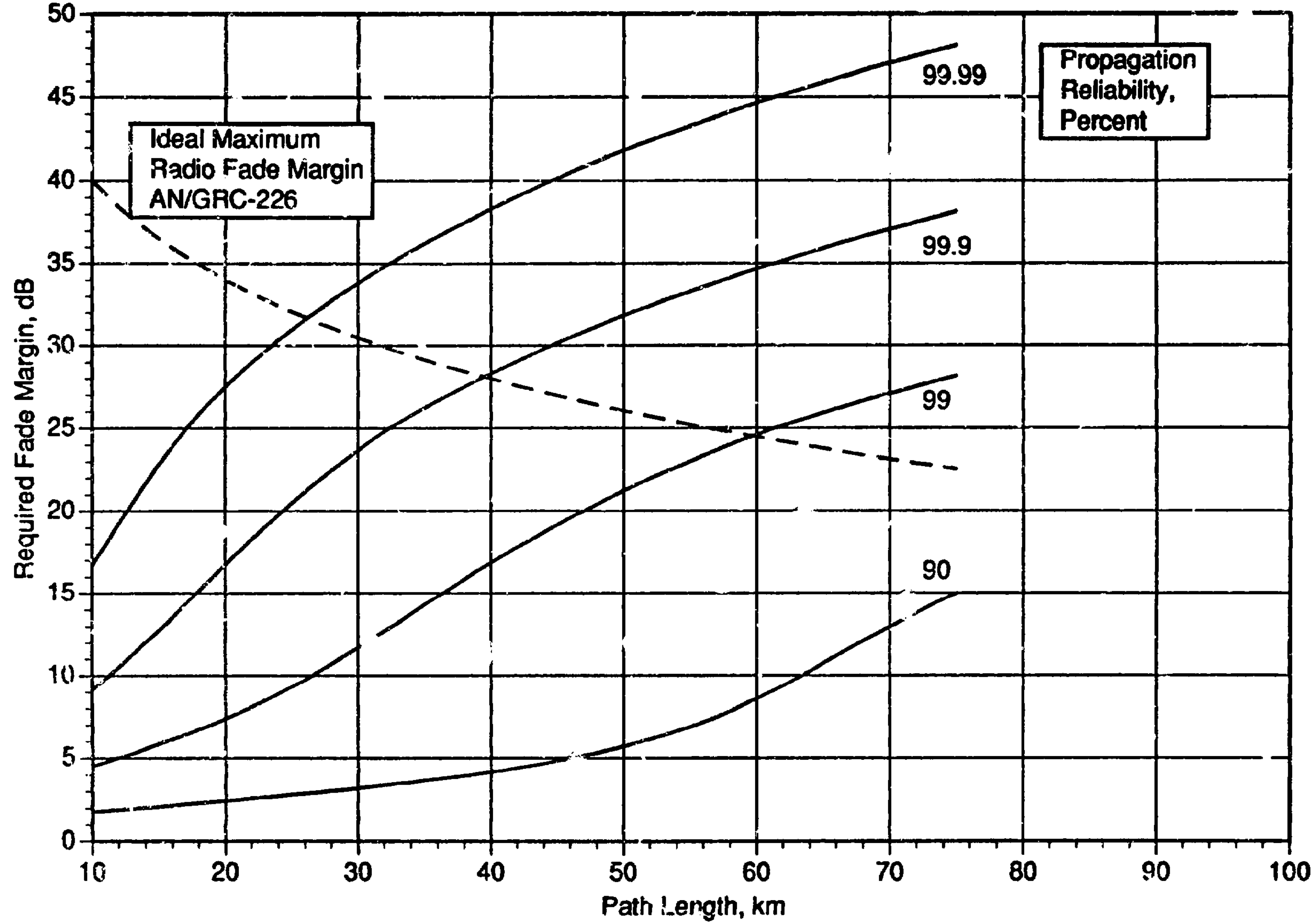

Figure A-5B. Required Fade Margin (1600 MHz, Difficult Climate)

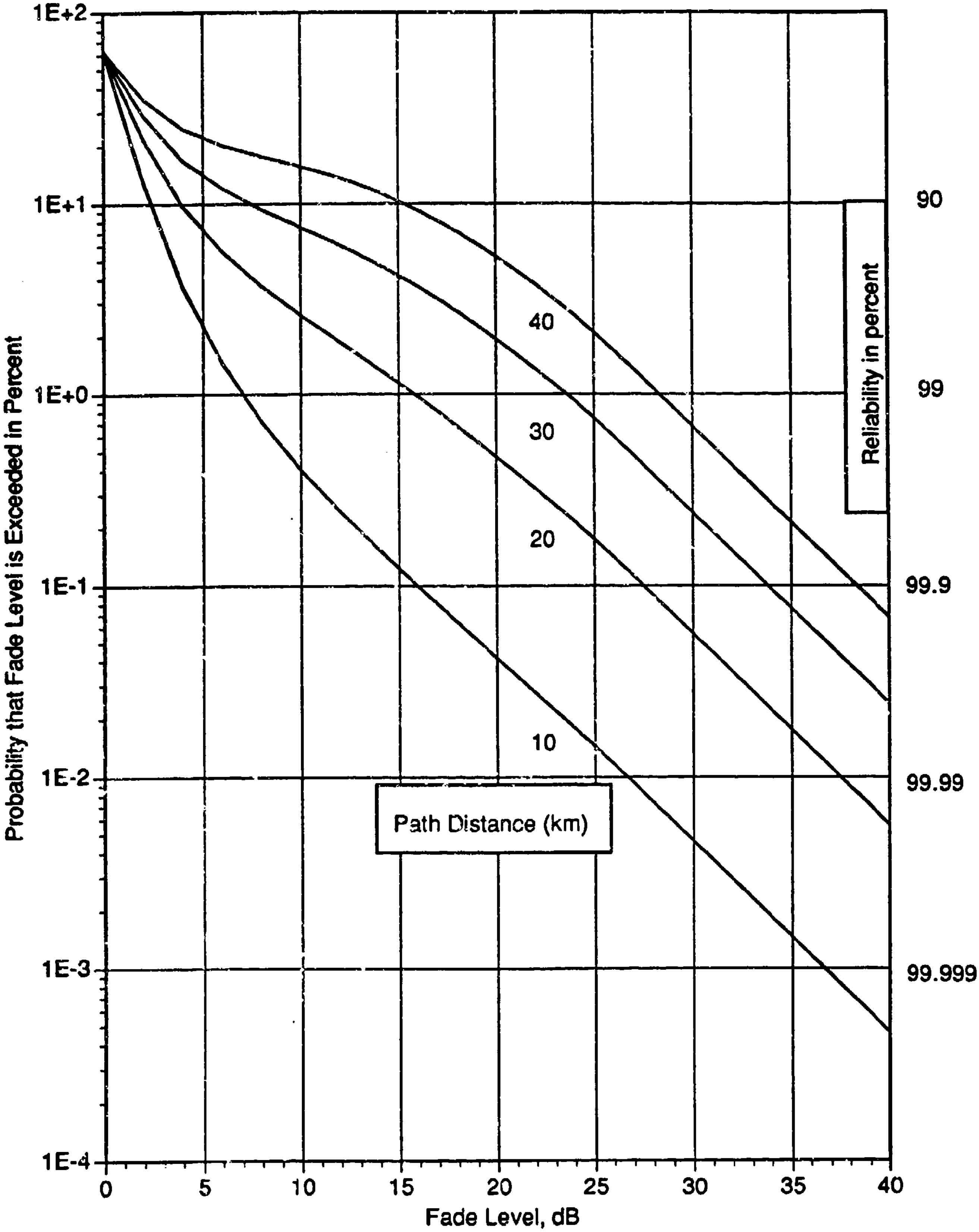

Figure A-6A. Probability of Fading (1600 MHz, Very Difficult Climate)

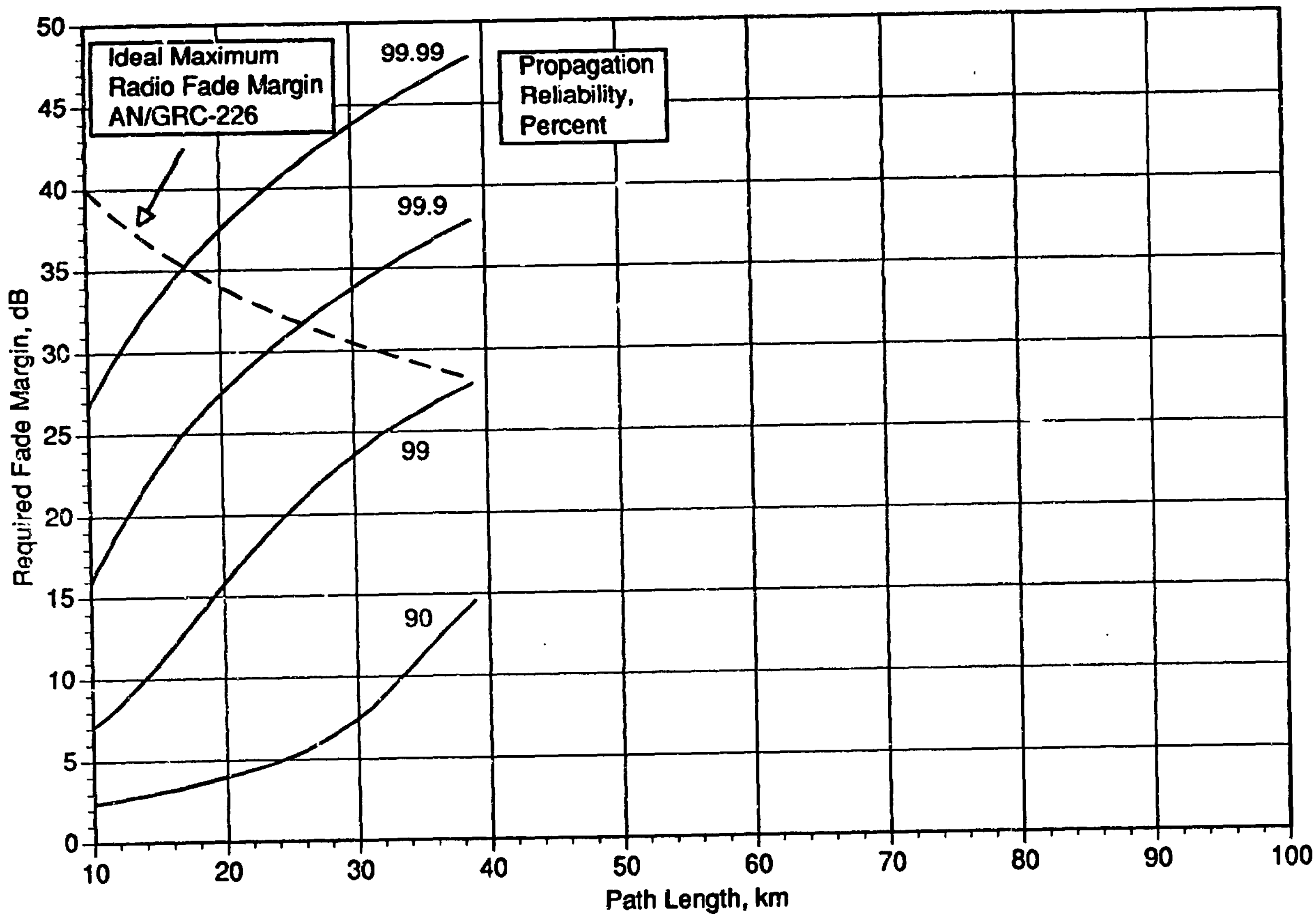

Figure A-6B. Required Fade Margin (1600 MHz, Very Difficult Climate)

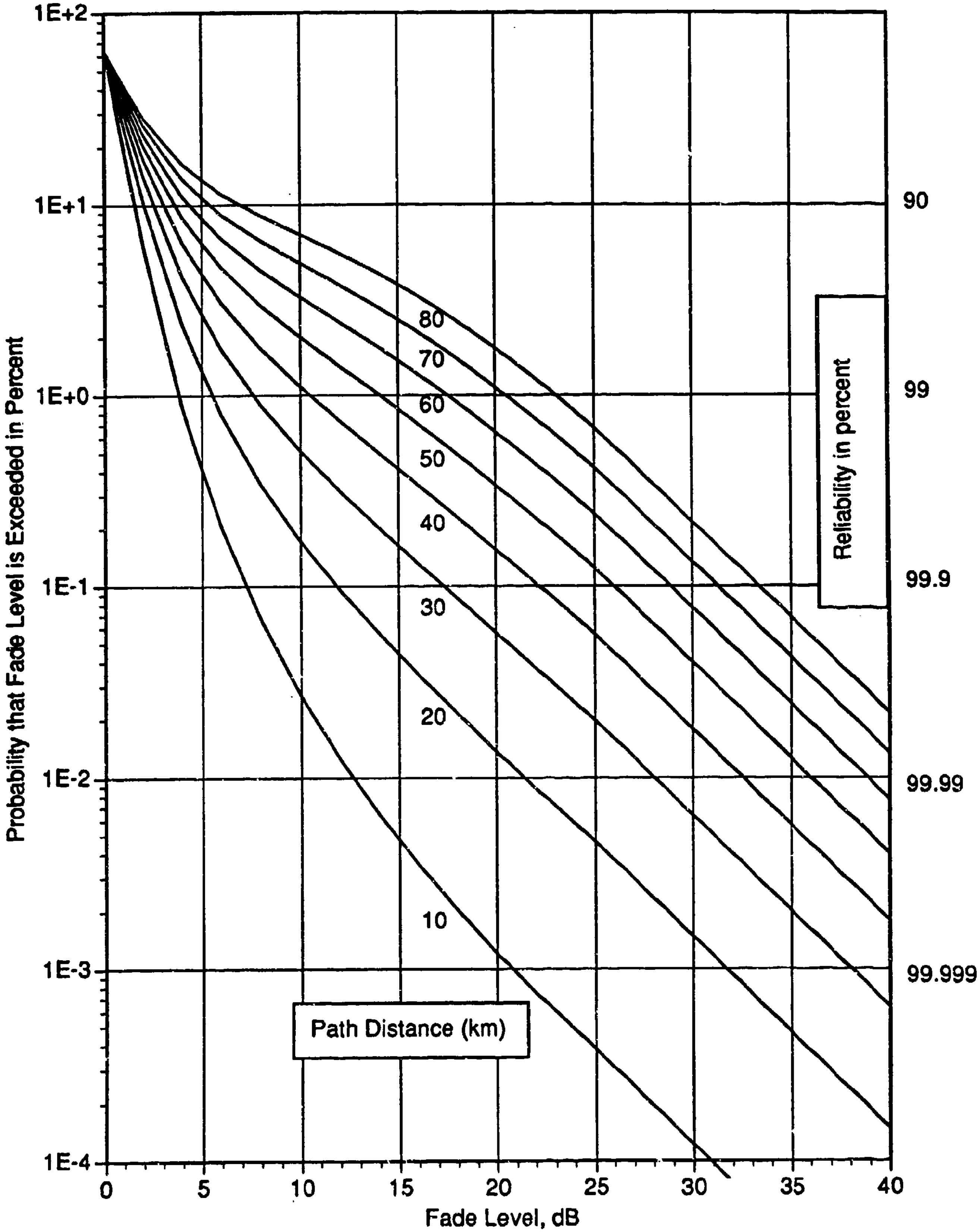

Figure A-7A. Probability of Fading (4750 MHz, Average Climate)

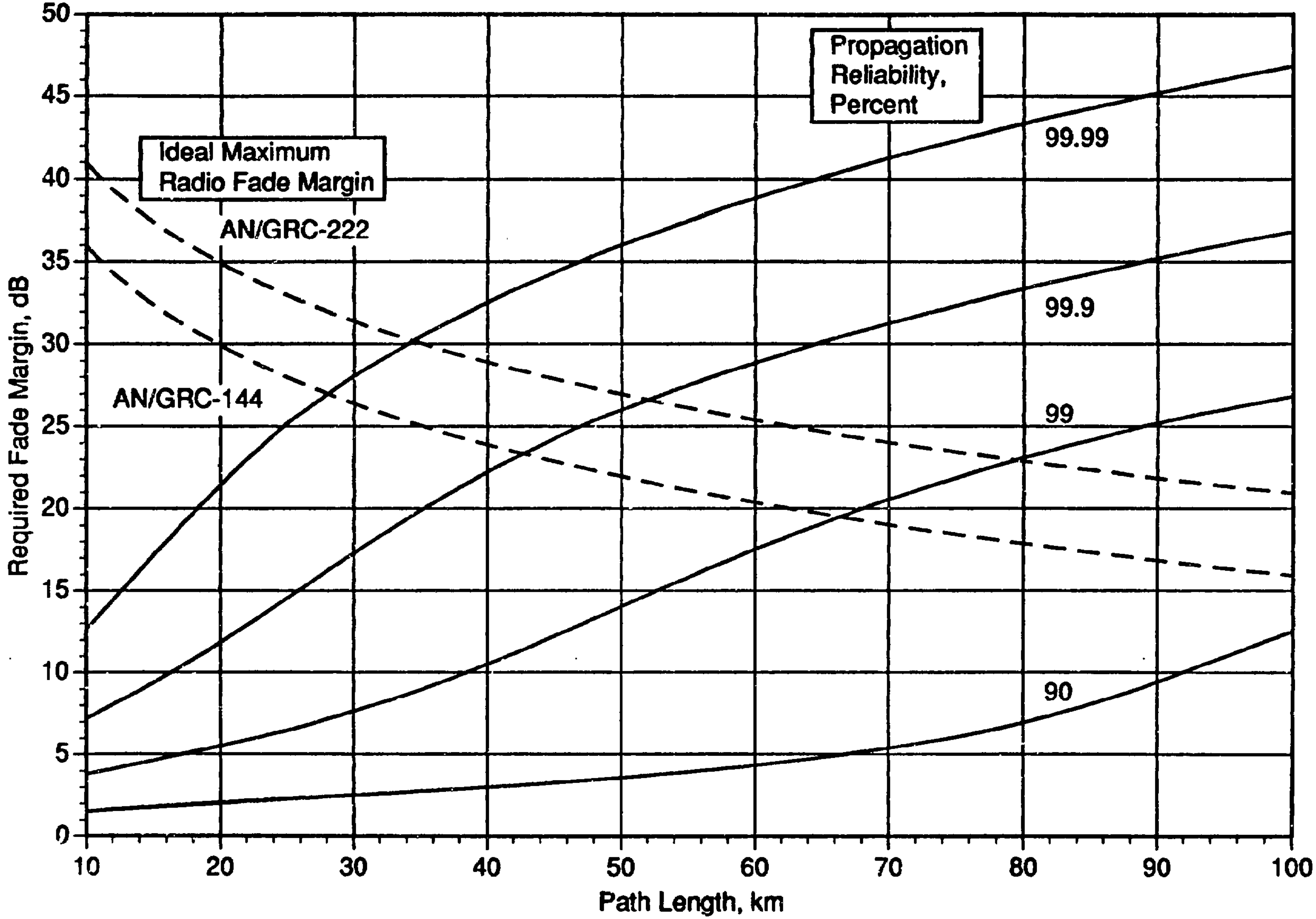

Figure A-7B. Required Fade Margin (4750 MHz, Average Climate)

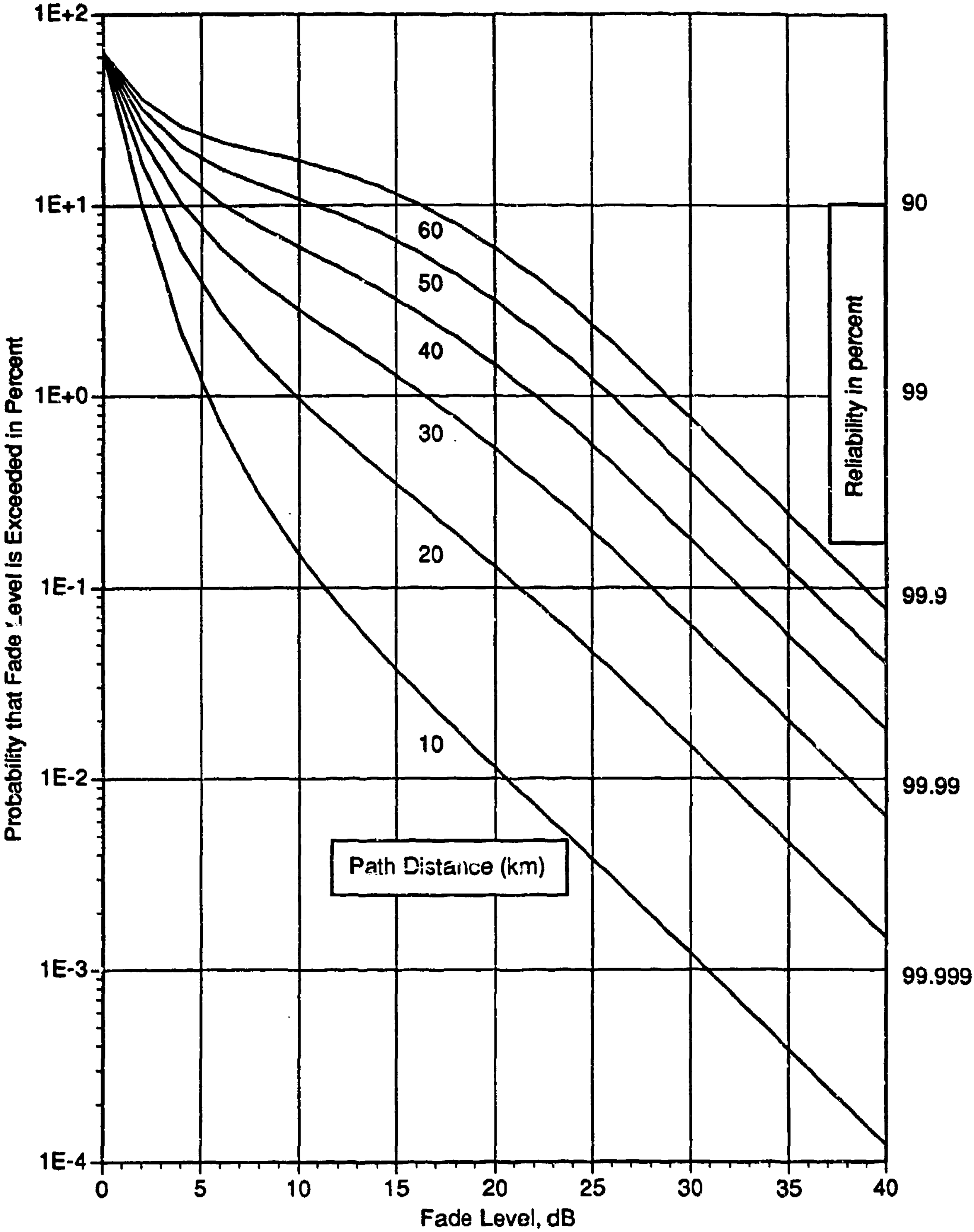

Figure A-8A. Probability of Fading (4750 MHz, Difficult Climate)

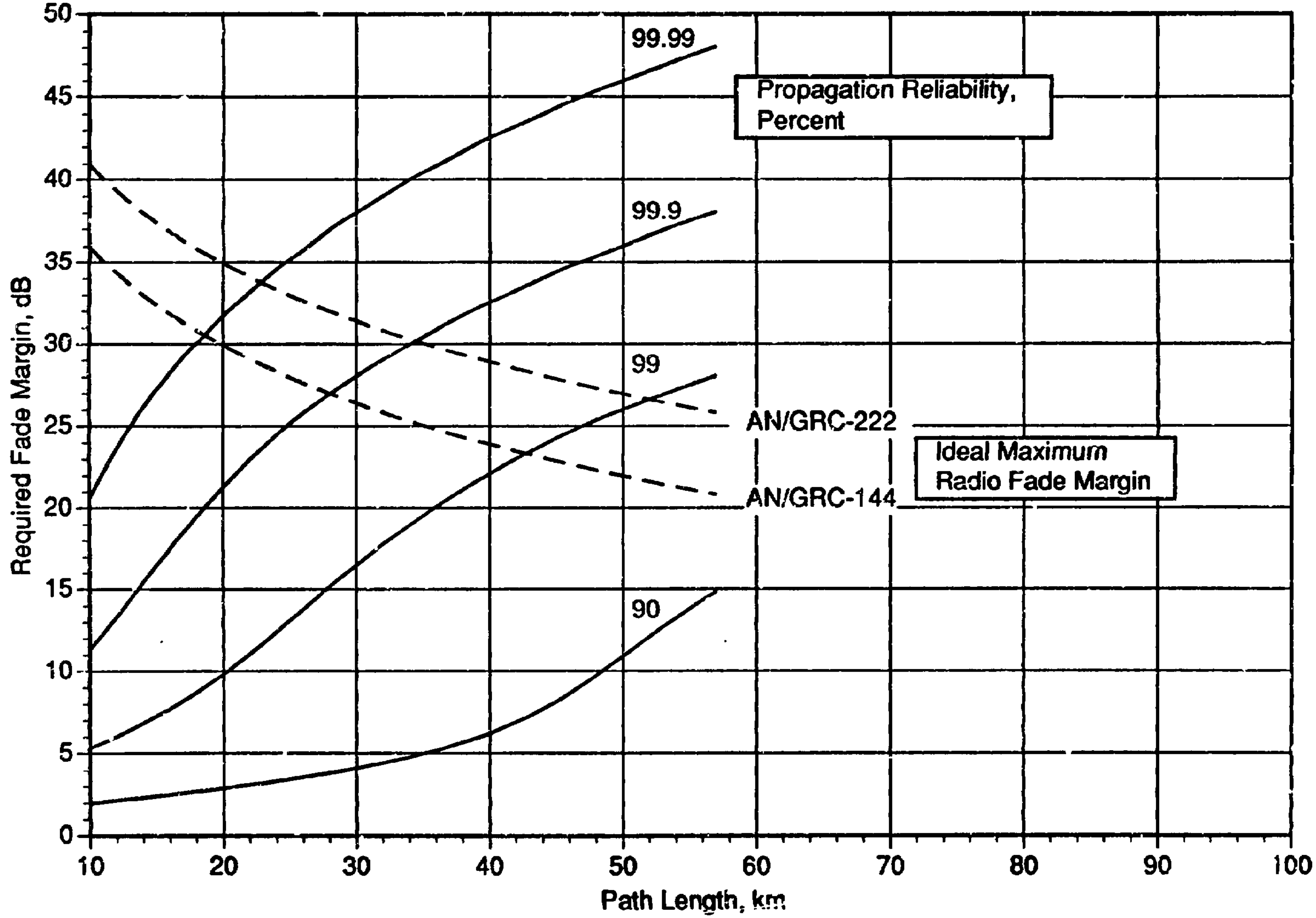

Figure A-8B. Required Fade Margin (4750 MHz, Difficult Climate)

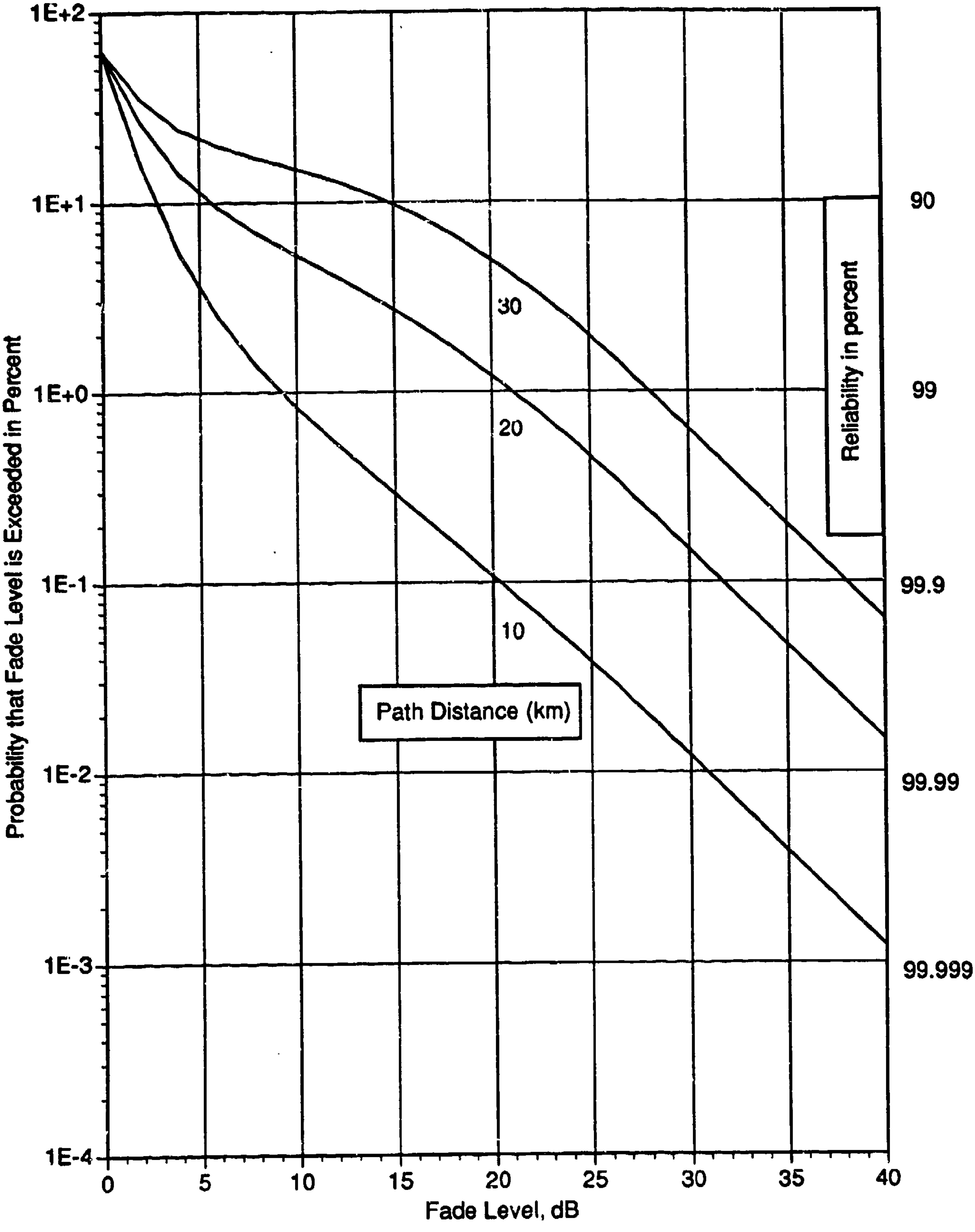

Figure A-9A. Probability of Fading (4750 MHz, Very Difficult Climate)

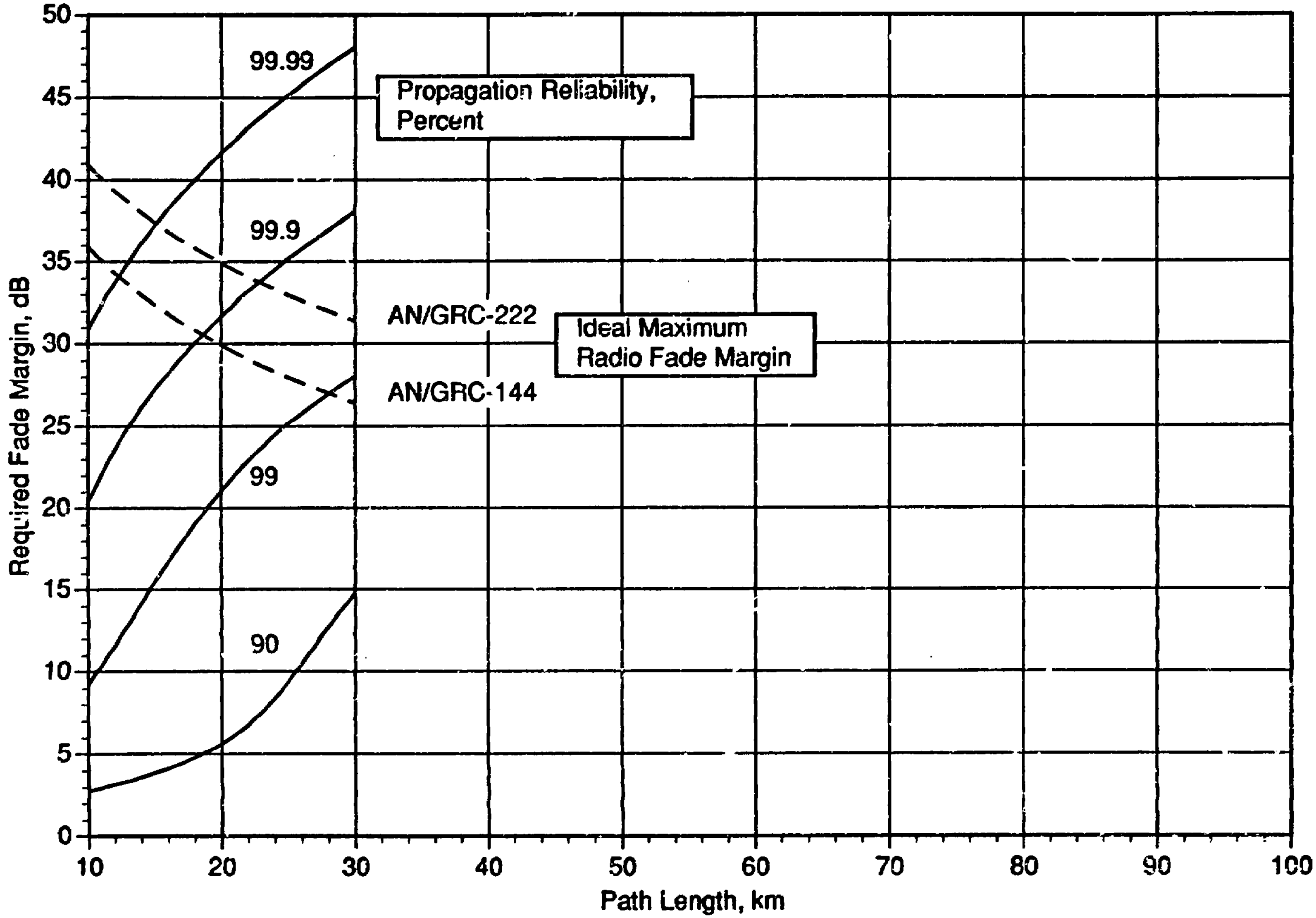

Figure A-9B. Required Fade Margin (4750 MHz, Very Difficult Climate)

APPENDIX B

LIST OF ACRONYMS

LIST OF ACRONYMS

ALO	AirLand Operations
ATACS	Army Tactical Communications System
BER	Bit Error Rate
BFA	Battlefield Functional Area
CCIR	International Radio Consultative Committee
CECOM	Communications-Electronics Command
CONUS	Continental United States
DCEC	Defense Communications Engineering Center
EAC	Echelons Above Corps
FSK	Frequency Shift Keying
FURIES	Frequency Utilization Resource Integration and Engineering System
ISYSCON	Integrated System Control
LEN	Large Extension Node
LOS	Line-of-Sight
MSE	Mobile Subscriber Equipment
NC	Node Center
NC-FSK	Non-Coherent Frequency Shift Keying

OPM	Office of the Project Manager
PM	Project Manager
RAU	Radio Access Unit
RF	Radio Frequency
RSL	Received Signal Level
SEN	Small Extension Node
SHF	Super High Frequency
SNR	Signal-to-Noise Ratio
SWA	Southwest Asia
TACFIRE	Tactical Fire Direction System
TIREM	Terrain-Integrated Rough Earth Model
TRI-TAC	Tri-Service Tactical Communications
UHF	Ultra High Frequency