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COMMUNICATIONS/ELECTRONICS RECEIVER PERFORMANCE  
DEGRADATION HANDBOOK (SECOND EDITION)

Frank Kravitz, et al

IIT Research Institute

Prepared for:

Electromagnetic Compatibility Analysis Center  
Office of Telecommunications

August 1975

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**COMMUNICATIONS/ELECTRONICS RECEIVER  
PERFORMANCE DEGRADATION HANDBOOK  
(SECOND EDITION)**

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This revised Receiver Performance Degradation Handbook provides refer- ence curves for determining receiver performance as a function of input signal-to-interference ratio. The performance degradation curves were obtained using both measured data and simulation models. The desired-signal modulation types considered are A1, A2, A3, A3J, ASC, A7J, A9B, F1, F3, F9 and P9. The interference modulation types are A1, A3, A3J, ASC, A9B, F1, F3, F9, P9 and noise. This version supersedes ESD-TR-73-014, published in June 1973.		

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EXECUTIVE SUMMARY

The Department of Defense Electromagnetic Compatibility Analysis Center (ECAC) and the Office of Telecommunications (OT), U.S. Department of Commerce have jointly sponsored the development of a receiver performance degradation handbook. The handbook provides reference curves for determining receiver performance as a function of input signal-to-interference ratio. The desired-signal modulation types considered are A1, A2, A3, A3J, A5C, A7J, A9B, F1, F3, F9 and P9. The interference-signal modulation types are A1, A3, A3J, A5C, A9B, F1, F3, F9, P0 and noise. The performance degradation curves were generated using both simulation models and measured data.

In addition to the degradation curves the handbook contains a description of the procedures used to obtain the curves and a discussion of the techniques needed to use the degradation curves. Descriptions of the different types of performance degradation, receiver technical characteristics, and signal characteristics are included.

## PREFACE

The Electromagnetic Compatibility Analysis Center (ECAC) is a Department of Defense facility, established to provide advice and assistance on electromagnetic compatibility matters to the Secretary of Defense, the Joint Chiefs of Staff, the military departments and other DoD components. The Center, located at North Severn, Annapolis, Maryland 21402, is under executive control of the Office of the Secretary of Defense, Director of Telecommunications and Command and Control Systems and the Chairman, Joint Chiefs of Staff, or their designees, who jointly provide policy guidance, assign projects, and establish priorities. ECAC functions under the direction of the Secretary of the Air Force and the management and technical direction of the Center are provided by military and civil service personnel. The technical operations function is provided through an Air Force sponsored contract with the IIT Research Institute (IITRI).

This report was prepared as part of AF Project 649E under Contract F-19628-76-C-0017 by the staff of the IIT Research Institute at the Department of Defense Electromagnetic Compatibility Analysis Center.

To the extent possible, all abbreviations and symbols used in this report are taken from American Standard Y10.19 (1967) "Units Used in Electrical Science and Electrical Engineering" issued by the United States of America Standards Institute.

Frank Kravitz, Emory Harrison, Dan Craig and Michael Lemke, of ECAC and Robert Mayher of the Office of Telecommunications (formerly of ECAC) were primarily responsible for the analysis work that preceded the report, and for preparation of the report itself.

Most of the measurements upon which the analysis work was based were provided by the U.S. Army Electronics Proving Ground, Fort Huachuca, Arizona.

The Receiver Waveform Simulation Model, developed by Robert Meyers, formerly of ECAC, and the Digital Receiver Analysis Program, developed by Dr. Leonard Farber of ECAC, were the primary analytical tools used for the generation of the performance curves in this handbook.

Users of this report are invited to submit comments which would be useful in revising or adding to this material to the Director, ECAC, North Severn, Annapolis, Maryland 21402, Attention ACV.

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REFERENCES

## GLOSSARY

$\alpha$	=	The probability of false alarm
AGC	=	Automatic gain control
AI	=	Articulation Index
AM	=	Amplitude Modulation
AS	=	Articulation Score
A1	=	Telegraphy without the use of a modulating audio frequency
A2	=	Telegraphy with on-off keying of a modulating audio frequency or audio frequencies
A3	=	Amplitude modulation Telephony Double sideband full carrier
A3J	=	Single sideband telephony, suppressed carrier
A5C	=	Television video vestigial sideband
A7J	=	Multichannel voice-frequency telegraphy single sideband suppressed carrier
A9B	=	Amplitude modulated composite transmission four independent voice channels full carrier
B	=	IF bandwidth (kHz) used for a degradation curve
$B_s$	=	Desired-signal bandwidth (Hz)
$\beta$	=	The probability of false dismissal
BAUD	=	One bit per second in a train of binary signals
$BW_{BB}$	=	3-dB baseband bandwidth (Hz)
$BW_{IF}$	=	3-dB IF bandwidth (Hz)
$BW_I$	=	3-dB bandwidth of the interference spectrum (Hz)
CORODIM	=	Correlation of the recognition of degradation with intelligibility measurements
$D_{PK}$	=	Maximum frequency deviation
$\Delta f$	=	Off-tuned frequency difference between the carrier or reference carriers of the desired and undesired signals
$\bar{e}^2$	=	Mean square error
$F_S$	=	Frequency Shift for FSK Systems
FDM	=	Frequency Division Multiplex
FM	=	Frequency Modulation
FSK	=	Frequency-Shift Keying
F1	=	Telegraphy by frequency-shift keying without the use of a modulating audio frequency, one of two frequencies being emitted at any instant
F3	=	Frequency modulated telephony
F9	=	Composite transmission in which the main carrier is frequency modulated
GEL	=	General Electronics Laboratory

## GLOSSARY (Continued)

- $i$  = Input average interference power (watts)  
 $I$  = Interference signal power (dBm)  
 $\hat{I}$  = Peak interference power (dBm)  
 IND. DSB-SC = Independent double sideband, suppressed carrier  
 $(\hat{I}/N)$  = Ratio of peak interference power to mean noise power (dB)  
 $(\hat{I}/N)_I$  = Peak interference power-to-mean noise power ratio (dB) at the receiver input  
 ISB = Independent Sideband  
 $l$  = Lower performance threshold (dB)  
 $m$  = Transmitted message  
 $\hat{m}$  = Received message  
 $m_I$  = Interference signal modulation index  
 $m_s$  = Desired signal modulation index  
 MIT = Minimum Interference Threshold (dB)  
 $N$  = White Gaussian noise  
 $n_i$  = Input average noise power (watts)  
 $N_i$  = Noise power within the  $i$ th frequency band (dBm)  
 $N_o$  = Mean noise power (dBm)  
 $P_c$  = Probability of error  
 PAM = Pulse Amplitude Modulation  
 PB = Phonetically balanced  
 PCI = Pattern Correspondence Index  
 PCM = Pulse code modulation  
 PG = Processing gain (dB)  
 PRF = Pulse repetition frequency (pps)  
 PSI/COMP = Automated AI calculator  
 PSK = Phase-shift keying  
 PW = Pulse width at  $\frac{1}{2}$  voltage points, ( $\mu$ s)  
 $PW_I$  = Pulse width of the interfering pulse ( $\mu$ s)  
 $P_n(X)$  = Output probability density function with signal, noise and interference present  
 PO = Pulsed carrier modulation  
 P9 = Main carrier modulated in frequency or phase by a series of pulses which in turn are modulated by composite signals  
 $Q_n(X)$  = Output probability density  
 $R_I(\Delta f)$  = IF rejection (dB) at the off-tuned frequency  $\Delta f$   
 RMS = Root mean square

## GLOSSARY (Continued)

RWS	=	Receiver Waveform Simulation
$s$	=	Input average desired-signal power (watts)
$S$	=	Desired-signal power (dBm)
$S_i$	=	Voice power within the $i$ th voice frequency band (dBm)
SCIM	=	Speech Communications Index Meter
$S(\Delta f)$	=	Relative attenuation of the spectral density (dB) at the off-tuned frequency $\Delta f$
$(S/I)$	=	The mean signal-to-mean interference power ratio (dB)
$(S/\hat{I})$	=	The mean signal-to-peak interference power ratio (dB)
$(S/I)_I$	=	The mean signal-to-mean interference power ratio (dB) at the receiver input
$(S/\hat{I})_I$	=	The mean signal-to-peak interference power ratio (dB) at the receiver input
$(S/I)_{I,M}$	=	Receiver input signal-to-interference ratio (dB) modified for the effects of off-tuning the interference out of the audio passband
$(S/\hat{I})_{I,PRF}$	=	The PRF-corrected receiver input mean signal-to-peak interference power ratio (dB)
$(S/\hat{I})_{I,PW}$	=	The pulse-width-corrected receiver input mean signal-to-peak interference power ratio (dB)
$(S/I)_O$	=	The mean signal-to-mean interference power ratio at the receiver output (dB)
$(S/N)$	=	The mean signal-to-mean noise power ratio (dB)
$(S/N)_I$	=	The mean signal-to-mean noise power ratio (dB) at the receiver input
$(S/N)_{I,B}$	=	The input S/N ratio (dB) for the system with IF 3-dB bandwidth of $B$
$(S/N)_O$	=	The mean signal-to-mean noise power ratio (dB) at the receiver output
SSB	=	Single Sideband
SSB-SC	=	Single Sideband, suppressed carrier
$T_s$	=	Duration of desired signal (seconds)
$U$	=	Upper performance threshold (dB)
VFT	=	Voice Frequency Telegraphy
VIAS	=	Voice Intelligibility Analysis Set

## SECTION 1

## INTRODUCTION

BACKGROUND

The Electromagnetic Compatibility Analysis Center (ECAC) is engaged in a continuing study of the performance of receiving systems in the presence of various desired and undesired signals. This investigation is part of the Center's effort to formulate methods of electromagnetic compatibility analysis. Parts of this performance evaluation effort have been previously reported.<sup>1,2,3,4,5</sup> Because of a parallel interest in documenting receiver performance criteria, the Office of Telecommunications, U.S. Department of Commerce, jointly sponsored the development of a degradation handbook.<sup>6,7</sup>

Criteria are required by EMC engineers so they can predict when interference is expected to degrade performance in communications/electronics systems. Such criteria can be presented as degradation thresholds. In order to obtain these thresholds, one must know how receiver output performance varies as a function of receiver input signal-to-interference ratio. A requirement exists for a handbook containing performance degradation curves, and the associated thresholds, to aid the project engineer in analyzing the desired and undesired modulation signals most commonly encountered in interference problems. A long term objective is to prepare performance

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<sup>1</sup>Mayher, R., *Introduction to the Analysis of Interference to the Performance of Communications Systems*, ESD-TR-65-1, ECAC, Annapolis, MD, May 1965.

<sup>2</sup>Mayher, R. and Serafin, R., *Interference Effects in Matched Filter Receivers*, ESD-TR-66-7, ECAC, Annapolis, MD, August 1966.

<sup>3</sup>Hatch, W., Hinkle, R. and Mayher, R., *Analysis of Pulsed Interference to Amplitude Modulated Receivers*, Volumes I and II, ESD-TR-70-207, ECAC, Annapolis, MD, December 1970.

<sup>4</sup>Meyers, R., *A Receiver Waveform Simulation (RWS) Model*, ESD-TR-71-099, ECAC, Annapolis, MD, August 1971.

<sup>5</sup>Kravitz, F., *Communications/Electronics Receiver Performance Handbook*, ESD-TR-73-014, ECAC, Annapolis, MD, June 1973.

<sup>6</sup>Office of Telecommunications, U.S. Department of Commerce letter of April 10, 1972, Subject: Addendum to OT Support Plan.

<sup>7</sup>National Bureau of Standards, Purchase Order Number 4-44198, December 4, 1973.

degradation data for all desired-to-interference modulation categories described by an X in TABLE 1.

### OBJECTIVES

The objective of the Degradation Handbook is to provide the EMC analyst with a readily usable set of reference curves for evaluating receiver performance degradation for the cases indicated in TABLE 1.

### APPROACH

The digital error probability model (Reference 1) the Receiver Waveform Simulation (RWS) model (Reference 4) and the Digital Receiver Analysis Program (DIRAP)<sup>8</sup> were used in conjunction with appropriate measured data<sup>9,10,11,12,13</sup> to formulate the relationship between output performance degradation and the input signal-to-interference power ratio.

For most modulation categories, the relationship between output degradation and input signal-to-interference ratio was prepared for:

1. Two specific input signal-to-noise ratios, a low signal-to-noise ratio representing reception at the receiver sensitivity level, and a high signal-to-noise ratio representing good quality reception. In both cases, the signal-to-noise ratio was maintained

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<sup>8</sup>Farber, L., *Time Domain Simulation of Digital Receivers*, ECAC-TN-74-30, ECAC, Annapolis, MD, December 1974.

<sup>9</sup>Thompson, A., *The Application of the Voice Interference Analysis System to the Prediction of Voice Intelligibility*, Part 1, Bell Report No. A 70009-280, November 1967.

<sup>10</sup>Measurement Data Packet for Degradation of Pulse-Code Modulated (PCM) Digital Communications Systems, USAEPG-FR-559, Fort Huachuca, Arizona, October 1970.

<sup>11</sup>Performance Degradation Data of Digital Systems Under Controlled Interference Conditions, Vol. 1, Special Investigation Report No. 610, USAEPG, Fort Huachuca, Arizona, April 1967.

<sup>12</sup>Fine, H., *A Further Analysis of TASO Panel 6 Data on Signal-to-Interference Ratios and Their Application to Description of Television Service*, T.R.R. Report No. 5.1.2, FCC, Washington, DC, April 1, 1960.

<sup>13</sup>Conklin, W., *Analysis of Pulsed Interference to Television Receivers*, ESD-TR-74-079, ECAC, Annapolis, MD, June 1974.

TABLE 1  
DESIRED/INTERFERENCE MODULATION CASES COVERED IN THE PERFORMANCE DEGRADATION HANDBOOK

Desired	Undesired													
	Modulation Description	A1	A2	A5	A5J	A5C	A9B	F1	F3	F9	P0	Noise		
A1	CW Telegraphy	(X)		(X)	(X)		X	X	X	X	X	(X)		
A2	2-Tone Telegraphy	(X)	X	(X)			(X)	(X)	X	X	X	(X)		
A3	Voice	(X)		(X)			(X)	(X)	(X)	(X)	(X)	(X)		
A3J	SSB-SC Voice	(X)		(X)			(X)	(X)	(X)	(X)	(X)	(X)		
A5C	TV Video	(X)				(X)	X	X	X	X	(X)	(X)		
A7J	Multichannel VFT SSB-SC	(X)		(X)			(X)	X	X	X	(X)	(X)		
A9B	4 ISB Voice Channels			(X)			(X)	(X)	(X)	(X)	(X)	(X)		
F1	FSK Telegraphy (2 Frequencies)	(X)		(X)			(X)	X	(X)	X	(X)	(X)		
F3	Voice (no de-emphasis)	(X)		(X)			(X)	(X)	(X)	(X)	(X)	(X)		
F3	Voice (with de-emphasis)	X					(X)	(X)	(X)	(X)	X	(X)		
F9	FDM (12 voice channels)	(X)		(X)			(X)	(X)	(X)	(X)	(X)	(X)		
F9	Wideband Telemetry	(X)		(X)			(X)	(X)	(X)	(X)	(X)	(X)		
F9	PCM	(X)		(X)			X	(X)	(X)	(X)	(X)	(X)		
F9	PSK	(X)		(X)			X	(X)	(X)	(X)	X	(X)		
P0	Pulse	X					X	X	X	X	X	X		
P9	Spread Spectrum			(X)			X	X	X	X	(X)	(X)		

Note:

X Indicates cases to be covered by long term objective.

(X) Cases completed and covered herein.

constant and independent of the interference signal level as the interference signal level was varied throughout the span of each performance degradation curve.

2. Three cases of relative tuning between the desired and undesired signal:

a. Cochannel on-tune (interfering carrier frequency approximately coincides with desired signal carrier)

b. Cochannel off-tuned (interfering carrier tuned within the information 3 dB-bandwidth of the receiver)

c. Adjacent signal (interfering carrier off-tuned between the frequencies of the 3 dB and the 80 dB IF rejection levels of the receiver).

3. Two specific performance thresholds for each performance degradation curve (an upper and a lower performance threshold). These thresholds indicate the points on the curve where the interference levels reach values sufficient to degrade receiver performance by specified amounts. The threshold levels, and the specific terminology used to describe receiver performance above and below the thresholds, differ from case to case depending upon the type of desired and/or interference signal.

#### SYNOPSIS

The techniques used to obtain and apply the performance degradation curves are discussed in the Analysis Section, which contains the following:

1. The Discussion subsection contains a discussion of the logic used in transferring desired and interference signals through the receiver components.

2. The Procedure subsection explains the basis for the equipment characteristics chosen and contains the procedure used to obtain the degradation curves.

3. The Application subsection discusses the techniques needed to use the degradation curves, including their possible extension to parameters which were not analyzed.

The appendixes of the handbook contain the information needed to predict performance degradation for the specified desired-to-interference signal cases. In APPENDIX A the different types of performance degradation considered are described. Included are discussions and definitions of articulation score (AS), articulation index (AI), minimum interference threshold (MIT), error probability ( $P_e$ ), mean square error  $\overline{\epsilon^2}$  and TASO TV score.

APPENDIX B contains the equipment characteristics for the receivers analyzed, and descriptions of the desired and interference signals considered. APPENDIX C contains a brief description of a sample degradation curve, and the degradation curves for the desired-to-interference signal cases analyzed.

## SECTION 2

## ANALYSIS

DISCUSSION

The starting point for the performance degradation analysis of a receiver is to define the decision mechanism. This definition involves deriving and/or measuring the intelligibility of the output information as a function of the output desired signal-to-undesired signal (signal-to-interference) power ratio. The formulation of receiver performance degradation begins at the decision mechanism and works backward through the receiving system elements toward the input of the receiver.

For analog systems, the derivation of receiver performance degradation can be viewed as a three-step operation, shown symbolically in Figure 1. The first step derives the output information intelligibility as a function of output signal-to-interference power ratio. The second step derives the power transfer functions of various receiver stages. These transfer functions show the relationship between the input and output signal-to-interference ratios. The third step combines the previous two steps and transforms the output information intelligibility to a function of the input signal-to-interference ratio.

Receiver performance degradation can be determined at three locations in the signal path, as shown in Figure 2. The first location occurs at the IF output, which is also the input to the demodulator or second detector. Determining the degradation relative to desired and interference signal levels at the second detector input is useful for basic theoretical considerations. The problem at the second detector becomes that of operating on the desired and undesired signals by nonlinear and linear transfer functions of the second detector, low pass filter and receiver decision mechanism. The degradation solution at this point remains independent of RF and IF filter characteristics. On the other hand, differences from one receiver to another in the RF and IF filter characteristics modify the transfer of interference power through the receiver to the IF output, and so the interference power must be calculated for each separate case. When the RF and IF transfer characteristics are included, the detector input degradation characteristics can be reflected back to the receiver input point, and the complete receiver input degradation curves are obtained.

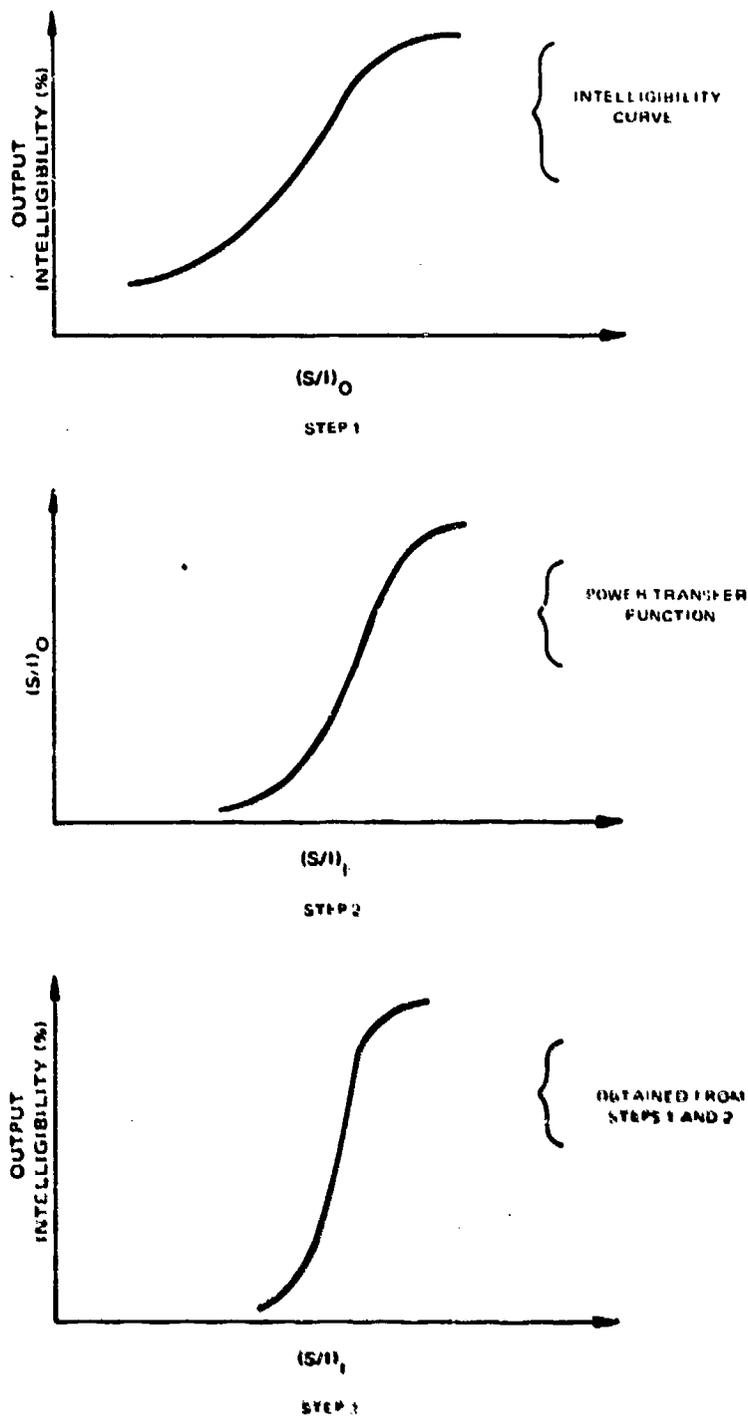


Figure 1. Synthesized performance degradation procedure.

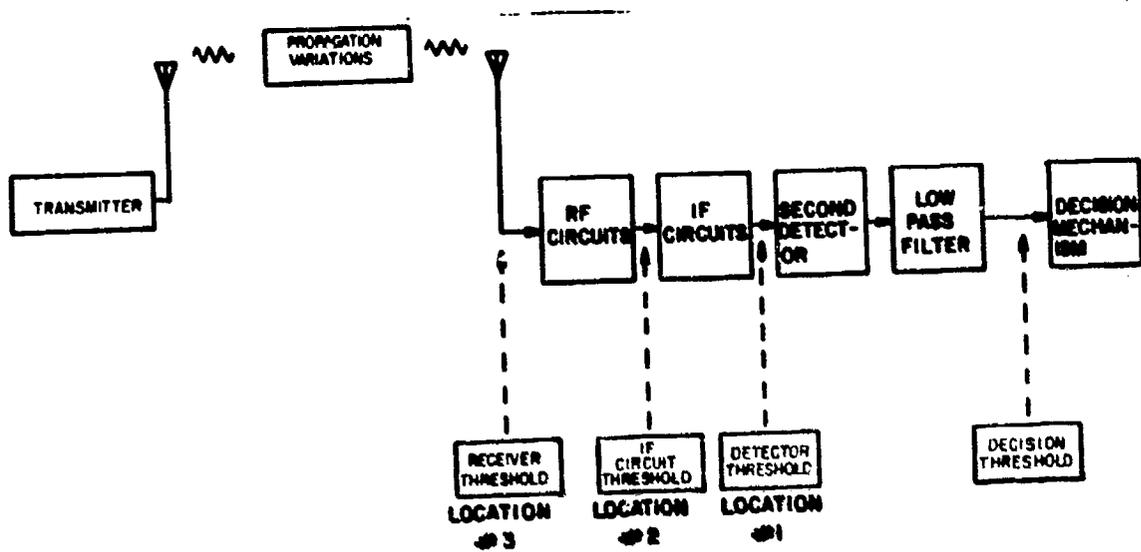


Figure 2. Various receiver degradation analysis locations.

The second location is at the input to the IF amplifier. Performance degradation specified for this location includes the effects of the IF filter, second detector and decision mechanism. The solution of a problem at this location is usually the same as the solution at the receiver input when RF nonlinearities are not significant. This is true because the filtering effect of the cascade of RF and IF amplifiers is approximately equal to the overall effect of the IF amplifiers taken alone. Receiver degradation models at this location are convenient to analyze and use in interference prediction.

The third location is at the input to the receiver. Performance analysis at this location can be complicated if cross modulation, intermodulation, spurious response and saturation problems are considered. These problems typically involve nonlinear effects, including the effects of high power interfering signals at frequencies outside the IF bandpass region. Such nonlinear analysis is outside the scope of this handbook.

The degradation curves contained in APPENDIX C were obtained for the second and third locations discussed above. The Receiver Waveform Simulation (RWS) model (Reference 4) and the Digital Receiver Analysis Program (DIRAP) (Reference 8) use the second location, the IF input, when analyzing performance degradation. Most of the measured data was taken at the third location, the receiver input. The agreement between the measured data and the outputs of the RWS and DIRAP models indicates that the two locations, IF input and receiver input, give identical results for a restricted range of interference frequencies and power levels.

The second location, the IF input, is the same as the third location, the receiver input, if the RF amplifiers have no effect, which will be true when the interference is tuned between the frequencies that are at approximately the 80 dB rejection level of the IF amplifiers. Within these limits, the degradation at the receiver input location is relatively easy to analyze, to validate with measurements, and to use in interference prediction problems. The performance degradation solution at this point becomes essentially the same as the IF input solution. The curves in APPENDIX C provide performance degradation as a function of input signal-to-interference ratio  $(S/I)_I$ , even though the analysis was performed at the input to the IF in some cases. The generalized receiver model used is shown in Figure 3.

This Degradation Handbook does not attempt to provide performance degradation measures for interference tuned outside the frequencies of the 80 dB rejection level of the IF filter. The solution of this

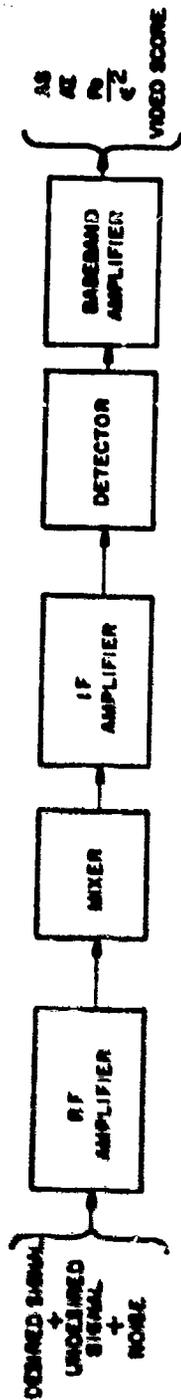


Figure 3. Components modeled to obtain performance degradation.

type of problem however, can be obtained by performing a separate RF nonlinear analysis to determine the structure and rejection level of the translated (or shifted) interfering signal as it would appear at the IF Input. It is then practical to use the appropriate modulation case in the handbook with the interference level modified by the effective rejection level.

The usual input for solving a problem using the Degradation Handbook will be discrete values of signal and interference power. The performance degradation resulting from the discrete, or deterministic, signal-to-interference ratio will also be a discrete (or single) value. However, for some interference prediction problems, the input signal-to-interference ratio is described in statistical terms. There are two methods of using the handbook curves for "probabilistic" input signal-to-interference ratios  $(S/N)_I$ .

The first approach is to use a "conditional" signal-to-interference ratio to obtain a single value of performance degradation. A single S/I value is selected from the input S/I distribution to obtain a single performance degradation value. An example of this type of description is, "the S/I value which will result in an articulation index (AI) of 0.68 or high 99% of the time". This performance degradation value must be carefully labeled with the appropriate conditional probability obtained from the input S/I probability distribution.

The second method of using a probabilistic input S/I with the handbook curves is to combine the entire S/I probability density function with the performance degradation curve. This procedure obtains the performance probability density function (probability of occurrence of a specific performance degradation).

#### PROCEDURE

The purpose of the Degradation Handbook is to present the EMC analyst with a readily usable set of reference curves for evaluating receiver performance degradation. The performance degradation curves were developed from a combination of measured data, theoretical analysis, and the outputs from RWS, DIRAP and the digital error probability models. These curves describe the degradation of the receiver output information in terms of a degradation measure (i.e., bit error probability for digital systems, articulation score (AS) and articulation index\* (AI) for voice systems, mean square error for analog systems, etc.) as a function of the input desired signal-to-interference power ratio. The relative power levels of the desired

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\*A discussion of AS and AI is provided in APPENDIX A.

and interference signals are those occurring at the receiver input.

The equipment characteristics and signal parameters used to develop the degradation curves were those most representative of each modulation type. For some modulation types, the signal and receiver parameters vary greatly from equipment to equipment; therefore, only the representative set of parameters was picked. The parameters were chosen after a search to determine the most representative under operational conditions. This procedure was necessary because the large number of possible combinations of receiver and signal parameters does not permit them all to be represented by individual curves. The most commonly occurring receiver parameters and modulation parameters for each category of desired signal and interference modulation are presented in APPENDIX B.

The equipment parameters chosen may not represent the parameters for a particular problem. If one has a problem involving parameters which differ from those used in the generation of the degradation curves, a separate analysis may be required to obtain accurate performance degradation. Some variations in the parameters can be accounted for by applying equations to modify the degradation curves. In particular, modifications can be made to the degradation curves to account for different IF bandwidths, pulsed interference characteristics, and in some instances different wideband (F9 or P0) interference characteristics. The possible modifications are discussed later in more detail.

#### APPLICATION

In order to use the handbook it is necessary to calculate the receiver input signal-to-interference ratio. The ratio is then used with the appropriate Degradation Handbook curve (for cochannel interference) to obtain the level of performance at the output of the victim receiving system. The adjacent signal interference must be modified to represent the effect of the IF filter on the interference and the effect of the audio filter on the combination of the desired and undesired signals. In some instances, the degradation curves must be modified to account for parameters different from the parameters used to obtain the curves.

In most cases, degradation curves are provided for two input signal-to-noise  $[(S/N)_i]$  ratios, two degradation thresholds and three frequency separations (i.e., off-tunings) between the desired and interference signals for most cases.

The two input signal-to-noise ratios are for the cases of an output signal-to-noise ratio representing good quality (25 dB for a voice system) and a minimum usable output (10 dB for a voice system)\*. These two cases bracket the range of possible usable output signal-to-noise ratios encountered in most receivers.

The curves in APPENDIX C reflect degradation measures appropriate to the type of system involved (see APPENDIX A). For voice systems, a continuous range of AS and AI scores is used (AS applies only to the curves for high S/N ratios). For digital systems, the criterion is bit-error probability,  $P_e$ . Mean square error,  $\overline{e^2}$ , is used for analog or continuous modulation systems. For TV systems, Television Allocation Study Organization (TASO) scoring grades were used.

In general, two performance thresholds are presented. The first threshold delineates the separation between acceptable and marginal performance; the second threshold delineates the boundary between marginal and unacceptable performance. Performance thresholds for various combinations of desired and interfering signals are listed in TABLE 2. Pulsed and digital interference affect voice system performance differently than do CW and analog interference; therefore, the thresholds in terms of AI are different. These given for pulsed or digital interference are operator-annoyance thresholds rather than performance thresholds, per se.

The thresholds for a voice modulated desired signal with analog interference are based on articulation score criteria and are defined in terms of the more easily obtained AI values. The thresholds for pulsed interference to voice modulation signals are defined in terms of Minimum Interference Threshold (MIT) and an AI of 0.7. Rectangular pulsed interference does not appreciably lower voice intelligibility in terms of articulation score (AS) independent of the value of AI. Therefore, the AI threshold value of 0.3 is not meaningful in terms of actual system performance and will not be used as an interference threshold for pulsed interference cases. The first threshold for pulsed interference will be the MIT. The MIT denotes the boundary between a region in which there is no perceptible interference and a region in which there is perceptible interference but no degradation of intelligibility.

The MIT is a threshold of perceptibility and not a measure of system performance as is AI or AS. However, for a given signal level, it does denote the point where interference is first detected

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\*The 10 dB (S/N) ratio also corresponds to a realistic definition of sensitivity.

TABLE 2  
INTERFERENCE THRESHOLDS FOR VARIOUS DESIRED AND INTERFERENCE COMBINATIONS

	CW or Analog Interference		Pulse or Digital Interference	
	First	Second	First	Second
Voice Modulated Desired Signal	AI = 0.7 <sup>a</sup>	AI = 0.3 <sup>a</sup>	MIT <sup>b</sup>	AI = 0.7 <sup>b</sup>
Digital Desired Signal <sup>c</sup>	$P_e = 10^{-4}$	$P_e = 10^{-2}$	$P_e = 10^{-4}$	$P_e = 10^{-2}$
Analog Modulated Desired Signal	$\overline{\epsilon^2} = 10^{-4}$	$\overline{\epsilon^2} = 10^{-2}$	$\overline{\epsilon^2} = 10^{-4}$	$\overline{\epsilon^2} = 10^{-2}$
Television-Video Desired Signal <sup>d</sup>	TASO Score 1.5	TASO Score 3.5	TASO Score 1.5	TASO Score 3.5

<sup>a</sup>From a Bell Aerosystems Company study of voice communications scoring procedures, done for USAEPG, Ft. Huachuca, Arizona.

<sup>b</sup>From Reference 3.

<sup>c</sup>These upper ( $10^{-4}$ ) and lower ( $10^{-2}$ ) bit error probability values are consistent with the digital interference threshold criteria used by CCIR.

<sup>d</sup>From Reference 13.

and will be referred to as the upper threshold for pulsed interference to voice modulated systems. The MIT is mainly significant as a threshold when the desired signal strength is sufficient for an AI score greater than 0.7 with no interference present. If this condition is not satisfied the MIT, since it is actually the threshold of perceptibility, will be below the second performance threshold and thus the MIT would be ambiguous as a performance threshold. The region between MIT and an AI of 0.7 is used to denote tolerable interference. The pulsed signal is present in the audio output; however, acceptable communications can still be maintained if the operator annoyance or fatigue factor, caused by the detected pulse in the audio output, is considered to be of secondary importance. The degradation curves in APPENDIX C are divided into performance regions by the threshold criteria discussed here. For voice desired signals, the thresholds, and the labels for the regions defined by the thresholds, are different from the cases of analog interference and digital interference. The thresholds for digital desired signals are based on average interference power criteria and the same thresholds can be used for pulsed and analog interference.

Performance degradation was investigated for three cases of frequency separation between the desired and interfering signals; a cochannel on-tune case, a cochannel off-tuned case and an adjacent signal case. These cases bracket the range of possible interference tuning involved in most interference problems.

A summary of the performance degradation thresholds presented in this handbook is given in TABLES 3 and 4 and the complete degradation curves are contained in APPENDIX C. TABLES 3 and 4 show the input signal-to-interference values representing the first and second performance thresholds. TABLE 3 gives the cochannel performance thresholds for the cochannel on-tune case (i.e., when the frequency difference between the desired and interference carriers is approximately zero). TABLE 4 gives the cochannel performance thresholds for the cochannel off-tuned case (i.e., when the frequency difference between the desired and interference carriers produces a beat frequency in the baseband of the desired modulating signal). Both tables contain information for two signal-to-noise ratios which would normally (in the absence of interference) represent a high (good quality) input signal level and a low (sensitivity) signal level. The adjacent signal cases (interference tuned between the frequencies of the 3 dB and 80 dB rejection levels of the IF skirt) are not included in the table because these performance thresholds vary with the frequency difference between the desired signal and the interference.

TABLE 3  
 (S/I)<sub>I</sub> THRESHOLD VALUES (dB) FOR COCHANNEL ON-TUNE INTERFERENCE (Af = 0)  
 AS A FUNCTION OF SIGNAL-TO-NOISE RATIO

Desired (S/N) <sub>I</sub> (dB)	Interference (S/N) <sub>I</sub> (dB)		A1 <sup>a</sup>		A2		A3		A3J		ASC		AUB		F1 <sup>b</sup>		F3		F9		Pop <sup>c</sup>		Noise-Like		
	1 <sup>st</sup>	2 <sup>nd</sup>	1 <sup>st</sup>	2 <sup>nd</sup>	1 <sup>st</sup>	2 <sup>nd</sup>	1 <sup>st</sup>	2 <sup>nd</sup>	1 <sup>st</sup>	2 <sup>nd</sup>	1 <sup>st</sup>	2 <sup>nd</sup>	1 <sup>st</sup>	2 <sup>nd</sup>	1 <sup>st</sup>	2 <sup>nd</sup>	1 <sup>st</sup>	2 <sup>nd</sup>	1 <sup>st</sup>	2 <sup>nd</sup>	1 <sup>st</sup>	2 <sup>nd</sup>	1 <sup>st</sup>	2 <sup>nd</sup>	
A1	16	NA	6	12	5	14	+5																	17	15
A2	18	NA	4	4	NA	NA	NA	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	9	6
A3	35	25	30 <sup>b</sup>	4	NA	1 <sup>c</sup>	1 <sup>c</sup>	1 <sup>c</sup>	1 <sup>c</sup>	10															
A3J	25	25	10 <sup>b</sup>	-14	-14	-28	2	-12																	4
ASC	10	10	NA	-6	NA	-28	NA	-12																	10
	c		42	28																					31
A7J	26	NA	8	8																					14
A8J	15	NA	10	NA	10	NA	10																		14
AUB	30	2J		8	3																				6
	20	10		NA	3																				6
F1	18	NA	0	0	NA	NA	NA	NA	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	6
F3	22	25	20 <sup>b</sup>	4	0	8	0																		6
DE-EMPHASIS	6	10	NA	NA	NA	G	NA	2																	2
DE-EMPHASIS	22	42																							0
F9	25	25	20 <sup>b</sup>	3	4	0																			2
FCM	10	10	NA	10	NA	1																			2
F9 (FCM-F9)			1	4	5																				7
F9 (PST)	9	NA	NA	5	15	2																			4
F9 (PST)	7	NA	NA	5	NA	2																			4
F9 (PST)	35	NA	27	18	3	13	1																		5
F9 (PST)	25	NA	NA	7	NA	3	NA	1																	5
F9 (PST)	6	NA																							4
F9 (PST)	5	NA																							4

<sup>a</sup> Above the pulsed interference cases, the threshold values are in terms of (S/I)<sub>I</sub>.  
<sup>b</sup> These values are interference thresholds, not performance thresholds. (See page 24.)  
<sup>c</sup> High signal-to-noise ratio; exact level of strong signal not available.  
<sup>d</sup> F9 interference in this case is F9(FCM-F9).  
<sup>e</sup> F9 interference in this case is F9(PST).



The degradation curves included in the report are in many cases applicable to more than one off-tuning category. For example, the degradation for P0 or F9 interference does not change as the interference is off-tuned. As a result, only one degradation curve is provided for these cases. The figure number of the proper curve to use for each situation (desired signal, interference,  $\Delta f$ ) is given in TABLE 5. In addition to the figure number of the curve, the equation describing any modification of the curve for adjacent signal cases is included. The adjacent signal case is defined as interference between the frequencies of the 3 dB and 80 dB rejection level of the IF selectivity curve.

Because TABLE 5 is important in selecting the proper degradation curve, a brief description is included here. For each combination of desired and interference modulation, three conditions of interference off-tuning with respect to the desired-signal carrier frequency are listed. For each tuning condition, the figure number of the appropriate curve in APPENDIX C is given. In some adjacent signal conditions the curve given by the figure number must be modified by an equation. For these cases, the equation number precedes the figure number.

In some cases, a single figure number is given because the curve for the cochannel on-tune condition is also applicable to the cochannel off-tune and/or adjacent signal conditions. In the case of white noise interference, one figure number is listed because tuning differences do not matter for broadband noise. Cases that have not been analyzed are indicated by an X.

The RF desired-to-interfering signal ratio is the difference in level between the desired radio-frequency signal and the undesired radio-frequency signal in decibels, measured under defined operational conditions at the radio-frequency input of the receiver.

Various measures such as mean power, peak power, peak-envelope-power, and carrier power have been used as a measure of the power of desired signals or interfering signals. The measure of power used in the handbook for the desired emissions is, in all cases, the mean power. The measure of power used for the interfering signal is: mean power for analog or continuous (non pulsed) interference and peak power for pulsed interference. The peak power, as used in the handbook and by various radar manufacturers, is equivalent to the peak-envelope-power as specified by CCIR. Since it may be desirable to express the power of the desired and interfering signals in one of the forms mentioned above, conversion factors were obtained which can be used to relate the mean power or peak power used in

TABLE 5

FIGURE NUMBER OF DEGRADATION CURVE FOR EACH DESIRED SIGNAL TO INTERFERENCE CASE

Desired	Interference		A1	A3	A3J	ASC	A90	F1	F3	F9	P0	Noise
	Cochannel	Adjacent Channel										
A1	On Tune		C-2	C-4	C-5							C-7
	Off Tune		C-3									
	Adjacent Channel		1/C-2	2/C-4	2/C-5							
A2	On Tune		C-8	C-9			C-10		C-11			C-12
	Off Tune											
	Adjacent Channel		1/C-8	2/C-9			2/C-10		1/C-11			
A3	On Tune		C-13	C-17	C-19		C-21	C-23	C-25	C-26	C-27	C-29
	Off Tune		C-14	C-18	C-20		C-22	C-24			C-28	
	Adjacent Channel		1/C-13	2/C-17	4/C-19		2/C-21	1/C-23	1/C-25	1/C-26	1/C-27	
A3J	On Tune		C-30	C-34	C-36		C-38	C-40	C-42	C-43	C-44	C-45
	Off Tune		C-31	C-35	C-37		C-39	C-41				
	Adjacent Channel		1/C-30		1/C-36		C-38	1/C-40			1/C-44	
ASC	On Tune		C-46			C-48					C-51	C-53
	Off Tune		C-47			C-48					C-52	
	Adjacent Channel		C-47			C-49 or 50					C-52	
A7J	On Tune		C-54	C-55			C-56		C-57		C-58	C-59
	Off Tune											
	Adjacent Channel		1/C-54	1/C-55			1/C-56		1/C-57		1/C-58	
A90	On Tune			C-60			C-62	C-64		C-66	C-67	C-68
	Off Tune			C-61			C-63	C-65				
	Adjacent Channel			2/C-60			2/C-62	1/C-64			1/C-67	
F1	On Tune		C-69	C-70			C-71		C-72		C-73	C-74
	Off Tune											
	Adjacent Channel		1/C-69	1/C-70			1/C-71		1/C-72		1/C-73	
F3 No De- Emphasis	On Tune		C-75	C-76	C-78		C-79	C-80	C-82	C-83	C-84	C-85
	Off Tune			C-77			C-81					
	Adjacent Channel		3/C-75	3/C-76	3/C-78		3/C-79	1/C-80	1/C-82		1/C-84	
F3 De- Emphasis	On Tune						C-86	C-87	C-88	C-89		C-90
	Off Tune											
	Adjacent Channel						3/C-86	1/C-87	1/C-88			
F9 (PDM)	On Tune		C-91	C-95			C-99	C-103	C-107	C-112	C-115	C-119
	Off Tune		C-92	C-96			C-100	C-104	C-108	C-113	C-116	
	Adjacent Channel		3/C-91	3/C-95			3/C-99	3/C-103	3/C-107	3/C-112	3/C-115	
F9 (PCM-PQ)	On Tune		C-120	C-121					C-122	C-123	C-124	C-125
	Off Tune											
	Adjacent Channel		3/C-120	3/C-121					3/C-122	3/C-123	1/C-124	
F9 (PSE)	On Tune		C-126	C-127					C-128	C-129		C-132
	Off Tune								C-130			
	Adjacent Channel		1/C-126	1/C-127					1/C-128	1/C-129		
F9 (Telemetry)	On Tune		C-133	C-135	C-137		C-139	C-141	C-143	C-145	C-147	C-149
	Off Tune		C-134	C-136	C-138		C-140	C-142	C-144	C-146	C-148	
	Adjacent Channel		3/C-133	3/C-135	3/C-137		3/C-139	3/C-141	3/C-143	3/C-145	1/C-147	
F9	On Tune			C-150-152					C-153-154	C-155-156	C-159-161	C-162 to 164
	Off Tune											
	Adjacent Channel			1/C-150 to 152					1/C-153 to 154	1/C-155 to 156	1/C-159 to 161	

the handbook to the previously mentioned powers. The conversion factors given in TABLE 6 were obtained from CCIR Recommendation 326-1<sup>14</sup> for the modulation parameters used in the Handbook.

The cochannel interference degradation curves may be used directly in an analysis to obtain performance degradation as a function of  $(S/I)_I$ . However, the adjacent-signal interference case usually requires several more steps in order to obtain the degree of performance degradation. It will not be necessary to describe each desired-to-interference case because the cases can be divided into several distinct categories. That is, desired signals can be placed into categories of very narrowband (A1 and F1), narrowband (A2, A3, A3J, A7J, A9B, F3 voice), and wideband (F9 and P9). Interference signals can be placed into categories of narrowband (A1, A3, A3J, A9B, F1, F3) and wideband (F9, P0, Noise).

#### Very Narrowband Desired Signals

Other modulation types are wide compared to the narrow filters used for digital desired signals (A1 and F1). In addition, the narrow IF bandwidth (less than 1 kHz) and its associated sharp selectivity remove the cochannel off-tune and adjacent signal cases from consideration. The only important criterion for the very narrowband (A1 and F1) digital desired signal cases is the interference power within the receiver IF pass band. To determine this, one must know the interference spectral density. Knowing the spectral density, one can calculate the interference power in the IF pass band when the interfering signal is at the adjacent signal frequency, relative to the power in the IF pass band for on-tune interference. The cochannel on-tune performance degradation curve can then be used by subtracting the attenuation of the interference from the signal-to-interference ratio at each degradation value.

$$(S/I)_{I,N} = (S/I)_I + S(\Delta f), BW_I > BW_{IF} \quad (1)$$

where

$(S/I)_{I,N}$  = Receiver input signal-to-interference ratio (dB), modified for the effects of off-tuning the interference out of the base band

$(S/I)_I$  = Receiver input signal-to-interference ratio (dB) given in the handbook

<sup>14</sup>CCIR (1970) Power of Radio Transmitters Recommendation 326-1, CCIR Green Book 1 pp 18-35, ITU.

TABLE 6

THE RELATIONSHIP BETWEEN MEAN POWER, CARRIER POWER  
AND PEAK ENVELOPE POWER OF RADIO TRANSMITTERS

Modulation	Ratio of Mean Power to Peak Envelope Power (dB)	Ratio of Mean Power to Carrier Power (dB)
A1	-3	-3
A2	-5.1	.9
A3	-5.8	.2
A3J	-10	NA
A5C	NA	-2.2 <sup>a</sup>
A7J	-6	NA
A9B	-5.8	.2
F1	0	0
F3	0	0
F9	0	0
P0	d <sup>b</sup>	d <sup>b</sup>

Note:

<sup>a</sup>For all black modulation.

<sup>b</sup>For pulse emissions, it is assumed that the pulses are rectangular and that the peak envelope power is unity. The duty cycle  $d$  is the ratio of pulse duration to pulse repetition period, in dB.

$S(\Delta f)$  = Relative attenuation of the interference signal spectral density (dB) for the off-tuned frequency,  $\Delta f$

$BW_I$  = 3 dB bandwidth of the interference spectrum.

### Narrowband Desired Signals

The next category of desired signals to be discussed is narrowband voice signals. For wideband interference to narrowband voice desired signals, the interference spectral density is constant over the emission bandwidth of the interfering signal. Therefore, the interference rejected by the IF selectivity is also constant over the emission bandwidth, and the cochannel on-tune degradation curve is applicable for all three regions. For the case of narrowband interference to narrowband voice desired signals, separate curves are required for cochannel, on-tune and off-tuned interference because the differences in performance degradation are significant (greater than 3 dB). The adjacent-signal interference cases give results which are a function of the rejection of the IF filter at the off-tuned frequency and the frequency components which lie within the audio pass band of the receiver. For the A3-to-A3 adjacent-signal case Equation 2, derived from Equation 4-1 of Reference 1, is used. (For other applications of Equation 2 see TABLE 5.)

$$(S/I)_{I,M} = \frac{1}{2} (S/I)_I - R_{IF}(\Delta f) \quad (2)$$

where

$(S/I)_{I,M}$  = Receiver input signal-to-interference ratio (dB), modified for the effects of off-tuning the interference out of the audio pass band, and reflected back to the receiver input

$(S/I)_I$  = Receiver input signal-to-interference ratio (dB) given in the handbook

$R_{IF}(\Delta f)$  = IF rejection (dB) at the off-tuned frequency,  $\Delta f$  (limited to rejection levels between 3 dB and 80 dB).

The case of an A3 receiver with A3 interference will be used as an example to illustrate the calculation of the adjacent-signal performance degradation. As can be seen in TABLE 5, the same curve applies to the cochannel on-tune and the adjacent-signal degradation cases. However, in the adjacent signal case the curve must be modified

to account for the effects of off-tuning the interference beyond the 3 dB bandwidth of the IF filter. This modification is accomplished using the equation referenced in TABLE 5 (Equation 2).

If the  $R_{IF}(\Delta f) = 60$  dB and the  $(S/I)_I = 6$  dB for a 0.7 AI, the value of  $(S/I)_{I,M} = -57$  dB for a 0.7 AI threshold. This means that interference off-tuned from the desired signal to a frequency where it is 60 dB down on the IF selectivity curve will require an  $(S/I)_{I,M} = -57$  dB for a 0.7 AI threshold.

Analysis of some of the other narrowband systems, interfered with by narrowband interference, will require a more simplified version of Equation 2:

$$(S/I)_{I,M} = (S/I)_I - R_{IF}(\Delta f) \quad (3)$$

where

$(S/I)_{I,M}$  = Receiver input signal-to-interference ratio (dB), modified for the effects of off-tuning the interference out of the audio pass band

$(S/I)_I$  = Receiver input signal-to-interference ratio (dB) given in the handbook

$R_{IF}(\Delta f)$  = IF rejection (dB) at the off-tuned frequency,  $\Delta f$  (limited to rejection levels between 3 dB and 80 dB).

A special case is the A3 receiver with A3J interference. The adjacent signal interference case has the form:

$$(S/I)_{I,M} = \frac{[(S/I)_I - 10]}{2} + R_{IF}(\Delta f) \quad (4)$$

where

$(S/I)_{I,M}$  = Receiver input signal-to-interference ratio (dB), modified for the effects of off-tuning the interference out of the audio pass band

$(S/I)_I$  = Receiver input signal-to-interference ratio (dB) given in the handbook (10 dB is subtracted to account for the fact that A3J interference has 10 dB more power in the sidebands than the A3 desired signal)

$$R_{IF}(\Delta f) = \text{IF rejection (dB) at the off-tuned frequency, } \Delta f \text{ (limited to rejection levels between 3 dB and 80 dB)}$$

In the case of a narrowband voice receiver analysis, radar and digital-data adjacent-signal interference that is outside the IF pass band follows the fall-off of the interfering spectrum. This occurs because the interference spectrum is approximately constant across the receiver IF bandwidth (Reference 3). In addition, the IF rejection at the tuned frequency of the interference will exceed the spectral fall-off in the IF pass band. The degradation effect is primarily caused by the power of the interference in the IF pass band, and the degradation follows the spectral fall-off.

The on-tune and off-tuned cochannel A3J receiver cases are similar to the A3 receiver cases. However, the adjacent-signal cases that are outside the IF bandwidth of the A3J receiver have not been calculated since the IF fall-off rate of the receivers examined was extremely steep and would not require an adjacent-signal degradation evaluation.

The A3 receiver used in the analysis had an IF 3-dB bandwidth of 8 kHz. Some A3 receivers have a bandwidth wider than 8 kHz and these receivers, with some modification of the input parameters, can be analyzed using the same performance degradation curves. The input desired signal-to-noise ratio,  $(S/N)_I$ , must be determined for an equivalent 8-kHz bandwidth.

In general, if the  $(S/N)_{I,BW}$  is given for a receiver 3-dB bandwidth wider than B kHz (the bandwidth used to generate the curve), the equivalent  $(S/N)_I$  for a system having a bandwidth of B kHz would become:

$$(S/N)_I = (S/N)_{I,BW} + 10 \log \frac{BW_{IF}}{B} \text{ for } BW_{IF} > B \text{ kHz} \quad (5)$$

where

$(S/N)_I$  = Input S/N (dB) for a system with an IF 3-dB bandwidth of B kHz

$(S/N)_{I,BW}$  = Input S/N (dB) for a system with IF 3-dB bandwidth of BW

$BW_{IF}$  = IF bandwidth (kHz) of receiver being analyzed

B = IF bandwidth (kHz) used for degradation curve (for the A3 receiver curves, B = 8 kHz)

The  $(S/N)_I$  calculated from Equation 5 is used to determine the appropriate degradation curve for A3 receivers. The curve may be used without modification for narrowband interference (A1, A3, A3J, A9B, F1).

For wideband interference (F3, F9), to AM systems the  $(S/I)_I$  must be changed by:

$$(S/I)_I = (S/I)_{I,BW} + 10 \log \frac{BW_{IF}}{B} \quad \text{for } BW_{IF} > B \text{ kHz} \quad (6)$$

where

$(S/I)_{I,BW}$  = Input signal-to-interference ratio (dB) for systems with IF 3-dB bandwidth of BW

$(S/I)_I$  = Input signal-to-interference ratio (dB)

$BW_{IF}$  = IF bandwidth (kHz) of receiver being analyzed

B = IF bandwidth (kHz) used for degradation curve.

For pulsed interference (A1 and P0) to AM systems the input signal-to-peak-interference  $(S/\hat{I})_{I,BW}$  must be modified:

$$(S/\hat{I})_I = (S/\hat{I})_{I,BW} + 20 \log \frac{BW_{IF}}{B} \quad \text{for } BW > B \text{ kHz} \quad (7)$$

where

$(S/\hat{I})_I$  = Receiver input signal-to-peak-interference ratio (dB)

$(S/\hat{I})_{I,BW}$  = Input  $S/\hat{I}$  (dB) for a system with IF 3-dB bandwidth BW

$BW_{IF}$  = IF bandwidth (kHz) of receiver being analyzed

B = IF bandwidth (kHz) used for degradation curve.

The above modifications to the degradation curves can also be made for A2, A3J, and A9B receivers using the appropriate 3-dB IF bandwidth ( $BW_{IF}$ ) of the desired receiver and the IF bandwidth (B) used for the degradation curve.

The pulse interference curves that are given in the handbook were calculated for pulse widths (PW) and pulse repetition rates (PRF) that are representative of this category. In order to modify these results to account for different PW's and PRF's, it is necessary to correct the input signal-to-peak-interference ratio  $[(S/\hat{I})_I]$  scale by the duty cycle and, in addition, to limit or restrict these corrections where applicable. In particular, for changes in PW, it is required that:

$$\begin{aligned} (S/\hat{I})_{I_{PW}} &= (S/\hat{I})_I + 20 \log \frac{PW_I}{5}, \text{ for } PW_I < \frac{10^3}{BW} \\ &= (S/\hat{I})_I + 10 \log \frac{PW_I}{5} + 14, \text{ for } PW_I > \frac{10^3}{BW} \end{aligned} \quad (8)$$

where

$(S/\hat{I})_{I_{PW}}$  = Receiver input signal-to-peak-interference ratio (dB), corrected for change in pulse width

$PW_I$  = Pulse width of the interfering pulse in  $\mu s$

$BW_{IF}$  = IF bandwidth (kHz).

For changes in PRF

$$(S/\hat{I})_{I_{PRF}} = (S/\hat{I})_I + 10 \log \frac{PRF}{300}, \text{ for } PRF < 1000 \text{ pps} \quad (9)$$

where

$(S/\hat{I})_{I_{PRF}}$  = Receiver input signal-to-peak-interference ratio (dB), corrected for changes in PRF

PRF = The pulse repetition frequency in pulses per second.

#### Wideband Desired Signals

The last category of desired signal is wideband (F9 and P9) signals. For narrowband interference tuned outside the IF 3 dB bandwidth, Equation 3 would apply. For wideband interference a determination must be made as to which has greater significance, the IF filter or the spectral density fall-off. The smaller value of the two would then be used as the final term in Equation 1 or 3, as applicable. Equations 8 and 9 apply to both narrowband and wideband systems.

Example

As an example, let us examine the case of a single-sideband receiver (A3J) subjected to interference from a radar (PO). The assumed desired-signal and receiver parameters are:

1.  $BW_{IF}$  = 2.7 kHz (ten double-tuned stages).
2.  $BW_{BB}$  = 0.3-3 kHz (six low- and six high-pass stages).
3. Noise Figure = 10 dB.

The assumed interference parameters are:

1. Pulse width = 5  $\mu$ s.
2. Pulse repetition frequency = 200 pps.
3. Peak interference power at the receiver is -70 dBm.

For this particular example, the interference (PO) is wideband and the interference power is constant across all tuning conditions considered in the analysis. That is, the approximate 150-kHz bandwidth of the interference means the degradation will be constant out to 65 kHz of off-tuning. This is much wider than the frequency of the 80-dB point on the IF selectivity curve.

The first parameter to determine is the IF output noise power in the receiver:

$$\begin{aligned} N_o &= 10 \log KT_o + 10 \log BW_{IF} \text{ (Hz)} + \text{Noise Figure (dB)} \\ &= -174 + 34 + 10 \\ &= -130 \text{ dBm} \end{aligned}$$

where

$N_o$  = Receiver noise power, in dBm

$K$  = Boltzmann's constant

$T_o$  = Absolute temperature, in °K (290°K in this case).

The  $I/N$  at the receiver input is

$$(I/N)_I = -70 \text{ dBm} - (-130 \text{ dBm})$$

$$(I/N)_I = 60 \text{ dB}$$

The desired-signal power will first be assumed to be high so that  $(S/N)_I = 25$  dB.

$$\begin{aligned}(S/\hat{I})_I &= (S/N)_I - (\hat{I}/N)_I \\ &= 25-60 \\ (S/\hat{I})_I &= -35 \text{ dB}\end{aligned}$$

From the degradation curve for  $(S/N)_I = 25$  dB (Figure C-44) it is found that  $AI = 0.76$  for an  $(S/\hat{I})_I = -35$  dB. This value is just above the minimum performance level for pulsed interference ( $AI = 0.7$ ).

If the desired-signal power is low so that  $(S/N)_I = 10$  dB, then

$$\begin{aligned}(S/\hat{I})_I &= 10-60 \\ (S/\hat{I})_I &= -50 \text{ dB}\end{aligned}$$

For the value of  $(S/\hat{I})_I = -50$  dB, using the  $(S/N)_I = 10$  dB curve in Figure C-44, the  $AI = 0.36$ . This is unacceptable performance for a voice system with pulsed interference. If the  $(S/\hat{I})_I$  were increased to  $-30$  dB (See Figure C-44) the  $AI$  would be  $0.7$  for the low-signal curve [ $(S/N)_I = 10$  dB]. The 20-dB reduction in interference could be accomplished by off-tuning the A3J receiver approximately  $0.65$  MHz from the radar tuned frequency (assuming 20 dB/decade spectral fall-off for the pulsed emission).

As a result of this simplified analysis one could say that the receiver could operate with performance above the minimum ( $AI = 0.7$ ) for a high signal level. Under low-signal-level conditions the receiver could maintain a minimum performance level except when tuned closer than  $0.65$  MHz to the interfering radar carrier.

## APPENDIX A

## DEGRADATION MEASURES

GENERAL

The following is a discussion of how the baseband output (desired and undesired signals) is measured to evaluate performance degradation of voice and digital systems. Reference 15 contains a general discussion of this topic.

The "complete" mathematical modeling of a system's performance is the end objective of a prediction analysis. However, there is no single complete mathematical operation for analyzing all types of system performance and the best that can be accomplished is to use the measures that are most appropriate to a particular system (i.e., mean-square measures, probability measures, etc.). The basic difficulty is to determine what exact type of evaluation should be associated with interference degradation. Although considerable research has been conducted on performance degradation evaluation, the desired outputs for receiving systems still reduce to a few basic types. In particular, for voice systems, Articulation Score (the percent of words correctly received) is still used as the main intelligibility standard. For Digital systems, the probability of detection and probability of false alarm are desired. For analog signals, the mean-square error (or the RMS error) is usually desired.

The following discussion will examine the performance measures of articulation score, articulation index, CORODIM and minimum interference thresholds for voice systems. Performance degradation of digital systems will be examined in terms of error probabilities. Analog system performance is described by the mean-square measures.

ARTICULATION SCORE

The basic measure of the intelligibility of a voice system is in terms of the percentage of words correctly understood over a channel perturbed by interference. This intelligibility indication has been designated as an articulation score (AS) and its measurement is usually conducted with specific types of words or syllables

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<sup>15</sup>Hawthorne, G. Jr., Jones, W. Jr., Robinette, S. Jr., Smith, V. Jr., Warren, W. Jr., and Wright, W. Final Report - Volume I Performance of Communications Systems in the Presence of Interference, RADG-TR-59-133A.

as well as specific system parameters. In an attempt to define the main voice parameters that are involved, experiments have been conducted by varying (at audio frequencies) the word content, bandwidth, audio S/N, and the type of talkers and listeners that are involved. Through these experiments, articulation scores have been obtained as functions of the above variables and, as one would expect, the scores increased with increasing bandwidth, number of syllables in the words, speaker-listener familiarity, and audio (S/N).

If the receiving system is subjected to a range of distortion or masking conditions, the AS may then be determined as a function of the interfering condition. Figure A-1 presents typical AS curves for different phonetically balanced (PB) word groupings in which the interference was white Gaussian noise of various bandwidths.<sup>16</sup> White Gaussian noise, which contains a continuous uniform spectrum, is one of the most effective maskers of speech and is often used in speech intelligibility studies as a standard or reference interference.

The articulation testing procedure is not simple nor has it always been standardized. Because it deals with the performance of human beings, the tests can yield variable results in individual cases when proper statistical safeguards are not taken. It is generally necessary to use a number of listeners in order to obtain statistically meaningful results. Proper conduct of the test is tedious and time consuming. The situation is aggravated by the necessity for training the listeners to an efficiency level where the improvement resulting from repeated exposure to most word lists no longer occurs. The test procedures, the material used, and the techniques employed to measure the average power of the desired and undesired signals vary among investigators.

In spite of such shortcomings, the tests provide the most valid objective method available for evaluating the intelligibility of speech communications components or systems. When the AS tests are carefully organized, the scores are repeatable 68% of the time within a 2-dB data spread (Reference 9).

The AS test was used as the basic standard of intelligibility for this study. However, since this method cannot be mechanized, it is advantageous to use other techniques that allow machine computation. A number of these techniques will be subsequently discussed.

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<sup>16</sup>Robertson, D., *A Comparison of the Procedures and Results of Intelligibility Tests for a Number of Interference Conditions*, ECAC Technical Memorandum No. X003-10, April 1962.

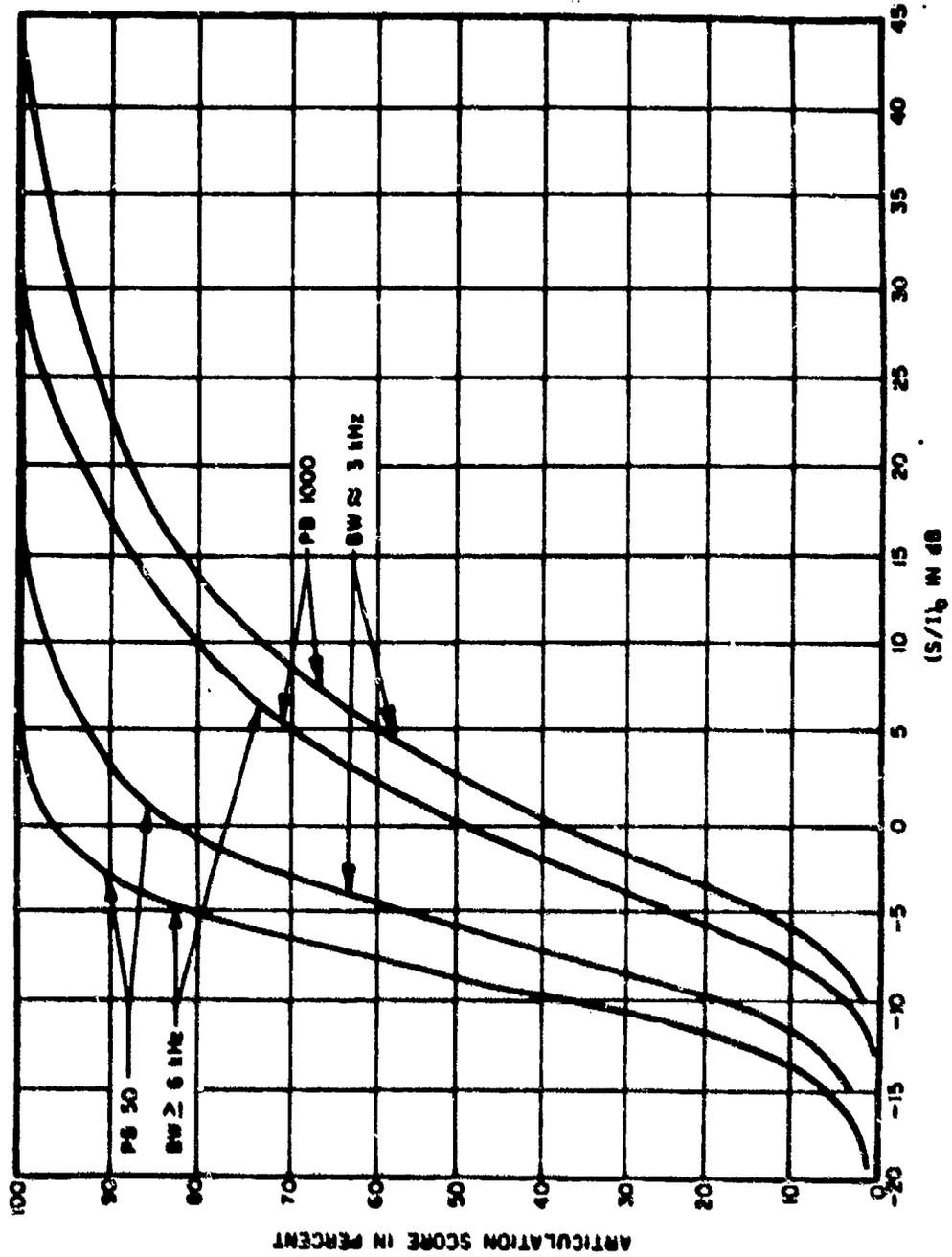


Figure A-1. Articulation score versus noise interference.

ARTICULATION INDEX

The best predictor of voice intelligibility for a channel interfered with by noise and/or interference is the percent of words which are correctly perceived by a group of trained listeners (the articulation score testing procedure), but the previous discussion delineates the difficulties of making AS tests. In order to be able to circumvent these difficulties, the Articulation Index AI procedure was developed and validated for white noise interference. In order to validate the AI procedure for different types of receivers interfered with by various types of undesired signals calibration curves relating AI to simultaneously measured AS scores were examined. References 9 and 17 discuss this problem and show the possible variation of AI versus AS with the AI measured by means of Voice Intelligibility Analysis Set VIAS procedure for non-pulsed interfering signals. Reference 3 discusses the same problem for pulsed signals interfering with AM receivers. These reports indicate that, for the continuous modulation and pulsed interference cases, the relationship between AS and AI was not constant.

For the CW interference case, the reports show that the range of variation in the AS scores for the typical AI criteria of 0.7 and 0.3 are 8% and 26% respectively. The AI criterion of 0.7, therefore, results in a reasonably constant standard in terms of AS intelligibility scores. The AI criterion of 0.3, however, can result in values of AS between 11% and 37% (Reference 9) for the cases of AM, FM and SSB modulation with the same types of interference. Therefore, the type of modulation and interference would have to be specified in order to determine a lower acceptability threshold more accurately. The AI of 0.3 has been used as a lower criterion by different investigators.<sup>18</sup> In order to be consistent with these past investigations the AI of 0.3 is used in this handbook as a lower threshold. In addition, most AI values are related herein to AS scores so that individual users can determine, for a particular problem or fixed AI criterion, if a change in the AI criterion of 0.3 is required.

For the pulsed interference cases, the AS score is approximately independent of AI score (Reference 3, Figure 6-6) because of the large amount of redundancy in a voice signal and the low duty cycle of the pulsed interference. AS scores typically vary between about

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<sup>17</sup>Thompson, A., *Articulation Index as a Predictor of Communication Link Performance in a RFI Environment*, 1966 IEEE Region Six Conference Record, Tuscon, Arizona, April 1966.

<sup>18</sup>Chandler, D. S., Chambers, R. W., *The Probability Scoring Model for Scoring Voice Communications Reception*, USAEPG-IR-268, August 1966.

98% and 95% for AI scores from 0.7 to 0.3, respectively. Because of the large variation in AI scores for a relatively small change in AS scores, an AI value of 0.7 was chosen to describe the lower threshold for pulsed interference. The upper threshold, MIT, is not a performance threshold, but indicates the level at which the interference is just perceptible.

Several approaches provide a measure of the effects of undesired signals on speech communications systems by calculation and/or instrumentation of a criterion measure in each of a number of bands in the speech frequency spectrum. The articulation index (AI) approach is relatively well-known. Others are the formant intelligibility and pattern correspondence index (PCI) approaches.

All of these methods operate on the short-term power spectrum to obtain a performance measure of speech. Basically, the procedures stem from the original work of French and Steinburg that led to the concept of articulation index (AI).<sup>19</sup> That effort, essentially, determined that one can divide the speech spectrum into N unequal contiguous bands which contribute equally to intelligibility (in terms of AS). The method ideally assumes there are negligible effects on intelligibility due to the speech sounds from one band masking, or in some way affecting, sound components of another band. Effects of noise and other factors (interference, distortion) prevent these bands from making their full contribution to intelligibility. The intensity of speech varies according to the band. For these and other reasons, a weighting factor must be included for each band in recognition of the fact that some bands do not make the maximum possible contribution to speech intelligibility. The weighting factors vary for each band according to the ratio of the speech energy (in that band) to the hearing threshold. When the speech energy level in the band is 30 dB or more above the threshold level, it contributes its maximum value and hence has a unit weighting factor. When the speech energy level is between 0 and 30 dB above the threshold, the band's contribution is proportional to its energy level, in dB. When the energy level is below the threshold there is no contribution to intelligibility and the weighting factor vanishes. These weighting factors are additive and the sum can be used with empirical curves to determine the corresponding articulation score.

The French and Steinburg method is, however, still fairly complex and simpler methods have been developed. Another procedure, the tonal method, asserts that the intelligibility of speech depends, not

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<sup>19</sup>French, N., Steinburg, J., *Factors Governing the Intelligibility of Speech Sounds*, Journal of the Acoustical Society of America, Vol. 19, pp. 90-119.

on the absolute magnitude of speech and undesired signal intensities, but rather on the amount by which the speech exceeds the auditory threshold level for a particular type of noise. This perception level is determined in each of 20 equally contributing bands covering 100 Hz to 10,000 Hz for standardized speech and for particular undesired signals. The tonal method, "formant intelligibility"<sup>20</sup> has the property of additivity such that the overall intelligibility is the sum of the contributions from each band.

The formant intelligibility process is readily automated by feeding pure tones from an artificial voice source, one at a time, to each of the *i* channels. Listeners then measure the excess noise in each band by attenuating the standard test signal until it is barely audible. The formant intelligibility can then be related to syllabic intelligibility by empirically obtained curves. The importance of this method is that it eliminates most of the variabilities associated with the transmission process and eliminates the AS scoring procedure. It does not, however, eliminate the listener as the end subjective evaluator.

Other methods have been developed which measure the effects of the undesired signals without subjective listener evaluation. Two of these have led to the development of testing machines by General Electronics Labs (GEL), based upon the assumption that speech intelligibility resides principally in the short-term spectrum.

One machine measures a number called the pattern correspondence index (PCI).<sup>21</sup> This number is an index of the correlation between a speech spectrum without interference and the same speech pattern with interference. The PCI is actually obtained by taking the average spectral difference between recorded sentences without interference and the transmitted sentences with interference. The PCI, theoretically, has a monotonic relationship to articulation score and should be calibrated for white-noise interference. It is postulated that the curve for white noise is universally applicable as a function of signal-to-noise ratio, independent of the type of interference. If AS-versus-noise curves are available for the particular undesired signal case being investigated, a direct translation between PCI and AS can be made. This machine uses an

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<sup>20</sup>Tkachenko, A., *Tonal Method For Determining the Intelligibility of Speech Transmitted by Communications Channels*, Soviet Physics-Acoustics, Vol. 1, No. 2 (January - June 1955).

<sup>21</sup>Licklider, J. C. R., Bisberg, A., and Schwarzlander, H., *An Electronic Device to Measure the Intelligibility of Speech*, 1959 Proceedings of The National Electronic Conference, No. 15, 1959.

autocorrelation measure of the desired signal and the corrupted output. Therefore, except for possible mechanical deficiencies, this approach is adequate or inadequate depending on the effectiveness of the autocorrelation measure for the particular interference being considered.

The other machine, produced by GEL to measure voice intelligibility mechanically, is called the Voice Intelligibility Analysis Set (VIAS).<sup>15,22</sup> This device also operates on the principle, previously described, of dividing the spectrum into a number of unequal contiguous bandwidths (14) and measuring the desired-to-undesired signal ratio relative to the hearing threshold. The width of each band is selected such that all bands contribute equally to intelligibility. The sum of the contributions from each band is then averaged over all 14 bands to produce the composite AI. The 14 VIAS frequency bands are shown in Figure A-2 and the calculation of AI is depicted graphically in Figure A-3. In order to perform this basic calculation, a synthetic desired-speech signal, which consists of a triangle-modulation 950 cycle tone, is transmitted over the test channel and is then measured by the recording portion of the device, in order to determine representative speech levels in the 14 bands. The average power (over a 17-second period) of the undesired signal,  $N_i$ , in the 14 bands is then measured and

from knowledge of the average desired signal in that band, the desired-to-undesired signal ratio is computed. The articulation index is then computed by summing the contribution from each of the 14 bands. VIAS incorporates empirically derived correction factors to account for the upward spread of masking. This is the phenomenon in which interference at a low frequency masks a higher frequency portion of the voice spectrum. A correction must also be inserted manually for the receiver's frequency characteristics, which are determined by measurement of the system. Reference 9 discusses this correction factor in detail. The important difference between the AI machines and the tonal method is the simplification to one test signal and the elimination of the subjective evaluation. The VIAS method implies that interfering effects are independent and, consequently, additive. This last statement is especially critical since the use of a number based on this technique, even for the simplest use (i.e., that of system comparison and not performance measurement), requires validation for situations in which the noise is not additive.

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<sup>22</sup>Fitts, R., *Electronic Evaluation of Voice Communications Systems*, RADC-TUR-63-355, August 1963.

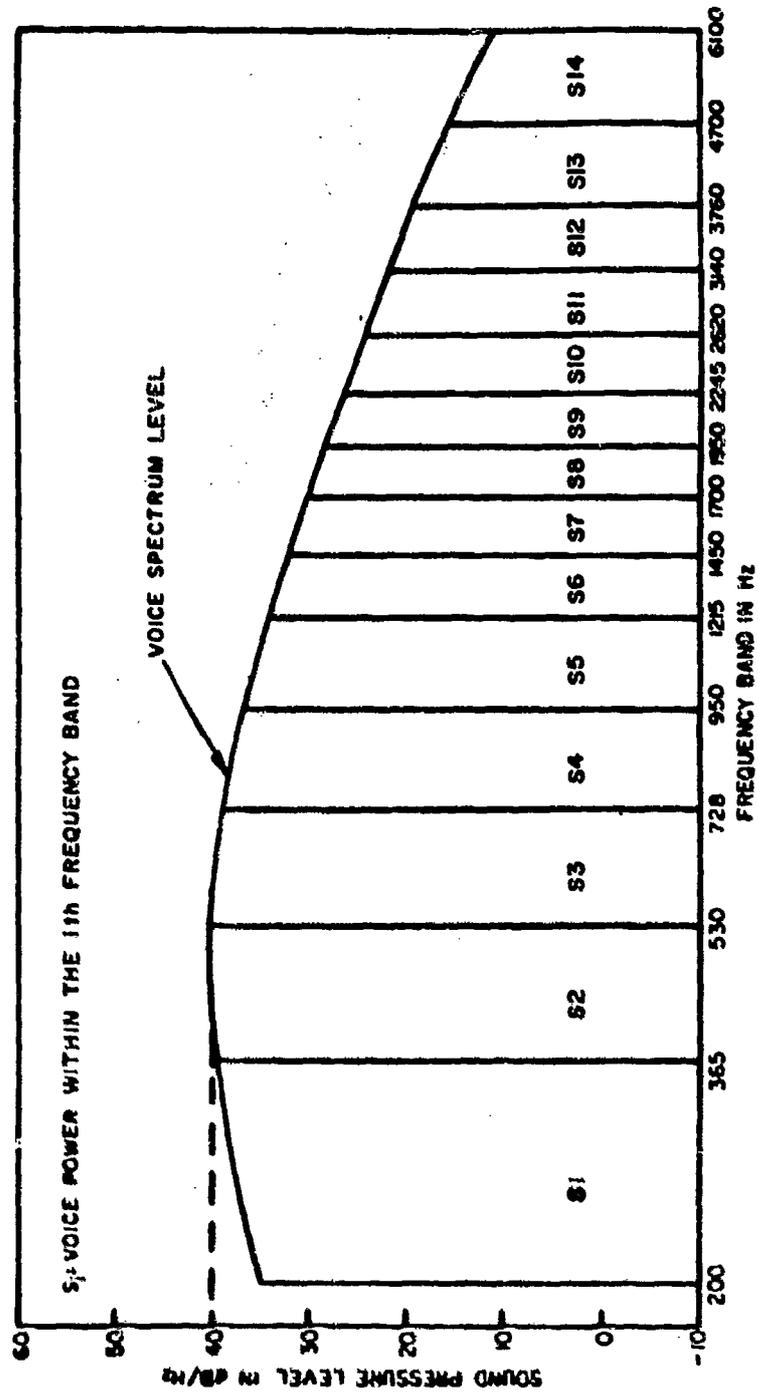
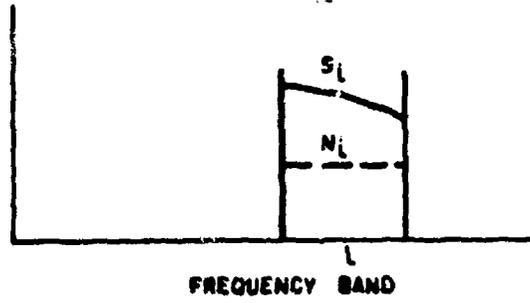
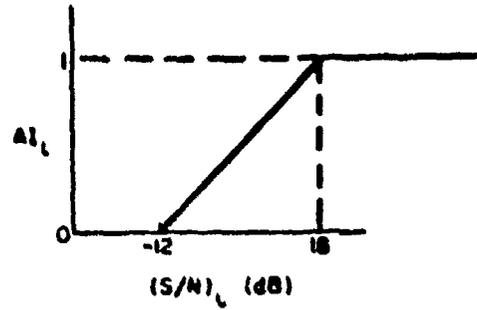


Figure A-2. Long term speech spectrum and associated AI bands.



$$AI = \frac{\sum_{l=1}^{10} (AI)_l}{10}$$



$$(S/N)_l = 10 \log_{10} \frac{S_L}{N_L}$$

Figure A-3. Theoretical calculation of AI score.

Another device that automatically calculates the AI, in a slightly different manner, is the Speech Communications Index Meter (SCIM) produced by Bolt, Beranek and Newman, Inc.<sup>23</sup> The basic difference between this device and VIAS is the manner in which the synthetic voice signal is generated. In the SCIM machine, a noise spectrum is transmitted that has been frequency-filtered or shaped to correspond to the average voice spectrum. This signal is then filtered into nine frequency bands and used to compute the desired-to-undesired signal ratios. Ideally, therefore, this system has an advantage over VIAS in that the actual synthetic signal power in band N is used rather than an extrapolation of that signal. The SCIM machine also takes into account the upward spread of the masking effect.

A version of the automated AI calculator is the PSI/COMP machine. The performance of this machine should be very similar to the SCIM machine, since it employs the same basic signal processing.

Degradation measurements involving a large number parameter variations (PW, PRF, etc.) were desired for this investigation. Because of the time required to run AS tests with all these parameter variations, it was desired to use an automated measure. The VIAS AI scoring machine was chosen for these measurements because preliminary investigation had shown that the PSI/COMP machine (and probably SCIM, since they are very similar) did not appear to respond correctly to pulsed interference.

If hand calculations of AI scores are desired, the American National Standard 20-band Method of calculating AI<sup>24</sup> can be used. The use of this procedure for noise interference results in AI scores similar to the VIAS 14-band method previously described. However, in order to calculate AI scores for interference cases, the baseband output spectrum is required for both methods. The interference spectrum can only be obtained from the output of a receiver being measured, or simulated (i.e., the RWS model, Reference 4). It was, therefore, necessary to simulate the VIAS 14-band AI scoring procedure in order to compare VIAS AI values with the measurements of AI (and simultaneously measured AS) scores.

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<sup>23</sup>Hudson, C., Limburg, W., Loss of System Effectiveness due to Electromagnetic Interference, Tenth Tri-Source Conference on Electromagnetic Compatibility, Chicago, Illinois, November 1964.

<sup>24</sup>American National Standard Method for the Calculation of the Articulation Index, ANSI S3.5-1969, January 16, 1969.

Another concept, called CORODIM (Correlation of the Recognition of Degradation with Intelligibility Measurements), has also been developed.<sup>25</sup> This technique is similar to the previous methods in that the baseband power spectrum is again used as a basic measure. It differs from other automatic intelligibility measuring techniques in that it transmits a test signal composed of speech-like sounds representative of phonemic consonants. The degradation manifests itself as an "effective noise spectrum" which is measured and matched to one of a library of reference noise spectra. For each reference spectrum, data are stored relating phonemic recognition probability to speech-to-noise ratio. Thus, by means of the spectrum-matching operation and a measurement of signal-to-noise ratio, each component sound of the test signal is assigned a probability of recognition. These values are weighted by phonemic probability of occurrence factors, summed and normalized to obtain a score representative of word intelligibility based on either initial or final consonant recognition. CORODIM evaluates scores for both the initial and final consonants and takes their product for the overall word intelligibility score.

The scores obtainable for CORODIM are directly comparable to listener panels according to Philco, the developer. If sufficient audio spectra have been pretested, the AS results from CORODIM should also be valid for most (but not necessarily all) interfering signals. This technique, therefore, has an important theoretical advantage over all previous automated scoring techniques.

CORODIM was not used in this investigation. It has been discussed because of its potential use in future voice degradation problems. In particular, it should be apparent that it is only necessary to couple the CORODIM process with the simulated receiver output to obtain simulated AS scores.

#### MINIMUM INTERFERENCE THRESHOLDS

For the audio case being considered, the minimum interference threshold is the level at which the interference is first heard. Since this level is obtained through a subjective evaluation there is an inherent variability due to the human observer and also one due to the manner in which the threshold is defined to the observer. In particular, the threshold level can be determined by decreasing or increasing the interference level relative to a fixed desired

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<sup>25</sup>Strehmeyer, G., Richards, J., and Schultz, J., *Voice Quality Determination Study*, RADC-TR-67-319, August 1967.

level. In the first case the test begins with very noticeable interference and stops when the interference is just perceptible. In the second case the interference is increased until the subject records that the interference is first heard. The first method is more repeatable than the second, although care must be taken to insure that the level recorded is indeed the last level that can be heard. This is easily implemented by allowing the subject to adjust the interference level above and below the threshold level to definitely determine that the interference was or was not heard.

The test can also be made without the presence of a desired signal. This type of test would be used for high fidelity, TV, or stereo systems where the presence of interference during the time the desired signal intelligence is absent may be unacceptable. A lower threshold interference level would be required for this case than if the desired signal were present, since the desired signal aids in masking the presence of the interference.

The validity of this type of measurement is shown in Reference 21. Two separate listening crews were used to determine the threshold of perceptibility (minimum interference threshold) for speech masked by noise. One crew contained three experienced listeners and the other contained eight inexperienced listeners. The signal (speech)-to-noise ratio (S/N) was then adjusted by each listener until he obtained the threshold of perceptibility. The maximum variation in the S/N ratio required by individual listeners was 3 dB. The average difference in S/N between the two crews was less than 1 dB.

#### ERROR PROBABILITIES

The evaluation of digital performance measures basically consists of computing error probabilities. In a general sense this consists of evaluating the categories of false acceptance and false dismissal. In the simplest type of detection problem (single alternative decision), false acceptance is equal to the probability of error of commission while that of probability of error of omission is equal to the quantity one minus the probability of detection. These can be considered by simply examining the probability densities for noise alone and for signal and noise at the receiver output (see Figure A-4). In this figure  $Q_n(x)$  refers to output noise distribution density while  $P_n(x)$  is the output distribution density when signal, noise and interference are present. The error of commission probability  $\alpha$  is the area of  $Q_n(x)$  above the decision

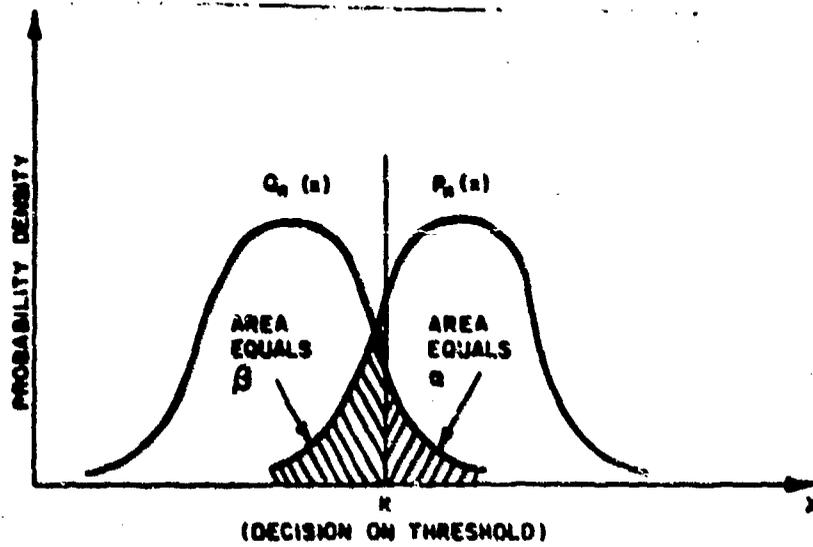


Figure A-4. System probability density with decision regions.

threshold  $K$ . The area of  $P_n(x)$  above the threshold  $K$  is the probability of detection. One minus this value or the area of  $P_n(x)$  below the threshold  $K$  is the error of omission probability  $\beta$ . These quantities can be stated mathematically as:

$$\alpha = \int_K^{\infty} Q_n(x) dx$$

$$\beta = \int_{-\infty}^K P_n(x) dx$$

Both  $P_n(x)$  and  $Q_n(x)$  are output probability densities obtained by operating on the input probability densities with the receiver system structure. If, as an example, the receiver has an envelope detection-threshold type of structure the envelope of the input probability density distribution must be obtained in order to obtain  $P_n(x)$  or  $Q_n(x)$  before the false-acceptance or false-dismissal probabilities can be calculated. This operation is, in general, nonlinear.

The calculation of  $Q_n(x)$  and  $P_n(x)$  for specific a priori interference and noise assumptions generally involves untractable analysis problems. However, the modeling of the receiver structure and the simulation process readily allow error probability evaluation. In particular, it is basically only necessary to count the number of undesired responses above a desired threshold ( $K$ ) in the simulated receiver time-amplitude output response to obtain false alarm probabilities. It is, of course, also necessary to properly randomize the input variables to obtain the desired output density function for these calculations. The false dismissal probabilities can also be obtained in a similar manner.

#### MEAN SQUARE ERROR

In digital or discrete communication systems it is meaningful to measure the system performance in terms of the probability of error. However, in the case of an analog or continuous modulation system the transmitted and received messages are in general different because of small interference or noise perturbations. The probability of error would be unity in most situations and is a useless indicator of the performance of an analog system.

The classical approach is to assume that fidelity of waveform reproduction is the communication objective of an analog system. The criterion of goodness for an analog communication system disturbed by white Gaussian noise has become the mean square error between the input and output waveform. For the single random variable communication system of Figure A-5, the mean square error is defined by the equation:<sup>26</sup>

$$\overline{\epsilon^2} \triangleq E[(m-\hat{m})^2] = \overline{(m-\hat{m})^2}$$

where

$E[ \quad ]$  = expected value

$\overline{\epsilon^2}$  = mean square error

$m$  = transmitted message

$\hat{m}$  = received message.

The theoretical approach to determining the mean error was implemented using modifications to the RWS model (Reference 4). The input signal to the model was a tone with peak amplitude one in the bandpass of the telemetry channel. This tone represented a telemetry message varying in a sinusoidal manner. The interference and noise were combined with the desired signal within the receiver model. The output, consisting of a combination of signal, interference and noise, was subtracted from the input signal after the output was compensated for the amplitude change and time shift added by the receiver. The difference between the messages received and transmitted messages was squared and averaged over 8192 time samples. The message waveforms involved are normalized to a modulation amplitude range of  $\pm 1$ .

#### TELEVISION SCORING PROCEDURE

The degradation of the television video information was measured using the TASO subjective scoring method (Reference 12). In essence, observers were asked to rate picture quality on a scale of one to six as shown in TABLE A-1.

<sup>26</sup>Kozencraft, J. M., Jacobs, I. M., *Principles of Communication Engineering*, John Wiley and Sons, New York, New York, January 1967.

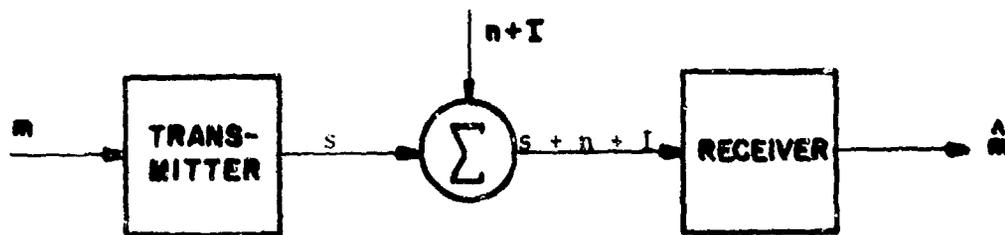


Figure A-5. Single random variable communication system.

The TV degradation curves in APPENDIX C are plots of TASO score versus  $(S/I)_I$ . The curves indicate the minimum  $(S/I)_I$  level necessary for 50% of the sampled population to grade the picture quality at a particular TASO score or better.

TABLE A-1

TASO SCORING GRADES<sup>a</sup>

Grade Number	Name	Description
1	Excellent	The picture is of extremely high quality, as good as you could desire.
2	Fine	The picture is of high quality providing enjoyable viewing. Interference is perceptible.
3	Passible	The picture is of acceptable quality, interference is not objectionable.
4	Marginal	The picture is poor in quality and you wish you could improve it. Interference is somewhat objectionable.
5	Inferior	The picture is very poor but you could watch it. Definitely objectionable interference is present.
6	Unusable	The picture is so bad that you could not watch it.

<sup>a</sup>Taken from Reference 13.

## APPENDIX B

DESIRED AND INTERFERENCE MODULATION DESCRIPTION  
AND RECEIVER CHARACTERISTICSGENERAL

The performance degradation curves included in the Degradation Handbook are grouped by desired-to-interference modulation categories. The desired modulation types consist of A1, A2, A3, A3J, A5C, A7J, A9B, F1, F3, F9, P9, and the interference modulation types consist of A1, A3, A3J, A5C, A9B, F1, F3, F9, P0, and Noise. This section of the report contains a description of the signal and receiver parameters needed for the analysis. These parameters are representative of those contained in MIL-STD-188C, CCIR reports, IEEE standards and the ITU Radio Regulations. Each desired-signal category consists of a description of the modulation type and the receiver for that type of modulation. The desired-signal and receiver parameters used to generate the degradation curves are listed in the specifications. The interference-signal description is included in the Interference-Signal Specification subsection when the interference-signal description is not the same as the desired-signal description. The parameters of the interference signals are listed under the Interference-Signal Specifications.

A1 (DIGITAL) RECEIVER AND SIGNAL DESCRIPTION

A1 modulation is described as telegraphy without the use of a modulating audio frequency, i.e., by on-off keying of the carrier. In the absence of measured data the DIRAP model (Reference 8) was used to generate the degradation curves for the A1 receiver.

The A1 modulation described in this handbook is simulated by randomly transmitting a continuous wave carrier with a fifty-percent duty cycle. This allows each binary state equal probability.

Figure B-1 shows the block diagram of a typical A1 receiver that is analyzed to solve cochannel interference problems. IF filtering, detection, and a decision mechanism are considered.

Desired-Signal and Receiver Specifications

The following are the desired-signal and receiver specifications used in the analysis:

1. Modulation rate: 75 bauds.
2. IF filter: Butterworth, 100-Hz bandpass, 5 poles.

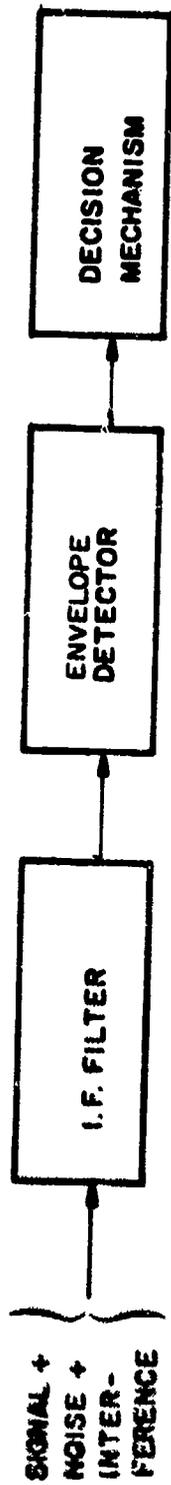


Figure B-1. AI receiver analysis structure.

## A2 (DIGITAL) RECEIVER AND SIGNAL DESCRIPTION

A2 modulation is described by standard codes for modulation types<sup>27</sup> as "Telegraphy by the on-off keying of an amplitude-modulating audio frequency or audio frequencies, or by the on-off keying of the modulated emission (special case: an unkeyed emission amplitude modulated)".

The A2 modulation described in this handbook is simulated by amplitude-modulating a continuous-wave carrier 100% with two tone frequencies (2100 and 2900 Hz). This approximates the condition where each modulating tone is on 50% of the time (i.e., each binary state is equally probable).

Figure B-2 shows the block diagram of the analysis structure of a typical A2 receiver for solving cochannel interference problems. The IF adjacent-channel interference case is eliminated for narrow-band interference signals by the sharp filter characteristics. The wideband IF adjacent-interference-signal case is discussed in SECTION 3. The analysis considers audio filtering, discriminator baseband filtering, and bit error probability degradation criteria. The bit error probability is obtained by calculating the output (S/I) power ratio at the low-pass filter using the method described in Reference 4. The binary probability of error is then calculated using Equation (7-77) from Reference 28. This equation pertains to the probability of detection of binary signals in white Gaussian noise. However, the interference present at the discrimination output, while noise-like, does not have white Gaussian noise statistics. A comparison between the available measured data and the model results indicate that the difference is negligible for the range of the degradation curves. The model was, therefore, extended to cases where measured data was not available.

### Desired-Signal and Receiver Specifications

The following are the desired-signal and receiver parameters used in the A2 analysis:

1. Modulation rate 100 Bauds.
2. Baseband filter 100 Hz.
3. Modulation index 100%.
4. Baseband frequency shift  $\pm 425$  Hz.
5. IF bandwidth 8 kHz.

<sup>27</sup>ITU Radio Regulations, General Secretariat of the International Telecommunication Union, Geneva, 1968.

<sup>28</sup>Schwartz, *Information Transmission, Modulation and Noise*, 1959, page 384.

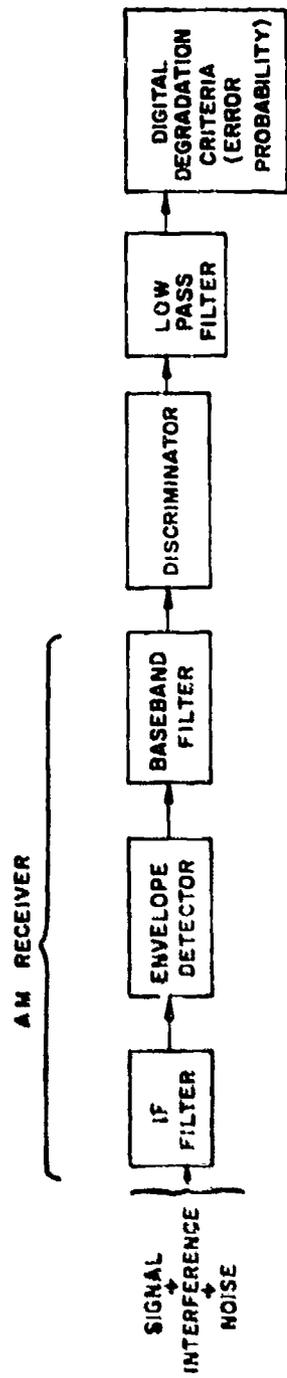


Figure B-2. A2 receiver analysis structure.

A3 (AM) VOICE RECEIVER AND DESIRED SIGNAL DESCRIPTIONS

The A3 modulation category describes the transmission of voice information by amplitude-modulating a continuous wave carrier. Reference 28 describes A3 modulation as "Double-Sideband Telephony". A voice signal modulates a carrier at a peak modulation level of 100%. This corresponds to an rms modulation level of approximately 30%. The voice baseband of commercial or military equipments is specified as extending from 0.3 to 3.5 kHz.

The typical block diagram of the receiver analysis structure for solving cochannel and adjacent-signal interference problems is shown in Figure B-3. IF filtering, nonlinear envelope detection, baseband filtering, nonlinear AGC desensitization, and either articulation index (AI) or articulation scoring (AS) degradation criteria are considered. The structure shown is used for the analysis of interfering signals that are off-tuned as far as the 80-dB IF rejection level.

Desired Signal and Receiver Specifications

The following are the specifications of desired signal and receiver parameters used in the analysis:

1. Audio bandwidth of 0.3 to 3.5 kHz (six low-and six high-pass stages).
2. IF bandwidth of 8 kHz (five double-tuned stages).
3. Modulation index of 30% ( $m_s = 0.3$ ).
4. Harvard phonetically balanced (PB) 1,000-word vocabulary used in articulation scoring (AS) criteria (fatigue factors and hard clipping are not considered).

A3J (SINGLE SIDEBAND) VOICE RECEIVER AND DESIRED SIGNAL DESCRIPTIONS

The A3J modulation category describes the transmission of voice information by amplitude modulation with suppression of the continuous wave carrier and lower sideband. The voice baseband bandwidth of commercial or military equipments is specified as extending from 0.3 to 3.0 kHz.

The block diagram of the typical receiver analysis structure for solving cochannel problems is shown in Figure B-4. The IF adjacent signal interference case is eliminated for narrowband interference signals by sharp IF filter characteristics. The wideband IF adjacent signal interference case is discussed in SECTION 3. IF filtering, ideal product detection, audio filtering, and either articulation index (AI) or articulation scoring (AS) degradation criteria are considered. The reference carrier in the A3J system is located 1650

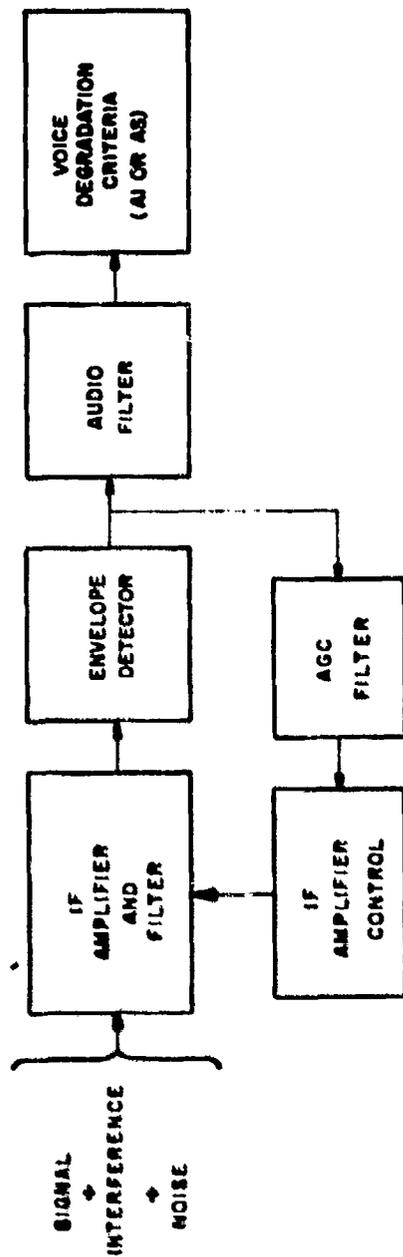


Figure B-3. A3 receiver analysis structure.



Figure B-4. ASJ receiver analysis structure.

Hz below the center of the IF filter. Therefore, frequencies obtained from frequency management systems where the carrier is assumed to be in the center of the IF filter must be reduced by 1650 Hz when using the A3J curves.

#### Desired Signal and Receiver Specifications

The following are the specifications of desired signal and receiver parameters used in the analysis:

1. Audio bandwidth of 0.3 to 3.0 kHz (six low-and six high-pass stages).
2. IF bandwidth of 2.7 kHz (ten double-tuned stages).
3. Harvard phonetically balanced (PB) 1,000-word vocabulary used in articulation scoring (AS) criteria (fatigue factors and hard clipping are not considered).
4. Upper sideband is used.

#### A5C (TELEVISION) VIDEO RECEIVER AND DESIRED SIGNAL DESCRIPTION

A5C modulation is the transmission of an amplitude modulated carrier with one full sideband and one vestigial sideband for the purpose of encoding video information for television systems.

The analysis of the degradation to an A5C signal by various types of interference is based on measured data (References 12 and 13).

Figure B-5 depicts the block diagram of a typical U.S. monochrome television receiver.

#### Desired Signal and Receiver Specifications

The following are the specifications of the desired-signal and receiver parameters used in the analysis:

1. Frame rate: 30 frames/second.
2. Horizontal sweep frequency: 15,750 Hz.
3. Video Bandwidth: 4.0 MHz.

#### A7J (TELEGRAPHY) RECEIVER AND DESIRED SIGNAL DESCRIPTION

A7J modulation is multichannel, voice-frequency telegraphy with a single-sideband suppressed carrier transmitted signal. The transmitted single sideband is divided into six channels, and within each channel one of two frequencies exists at any given time denoting either a mark or a space.

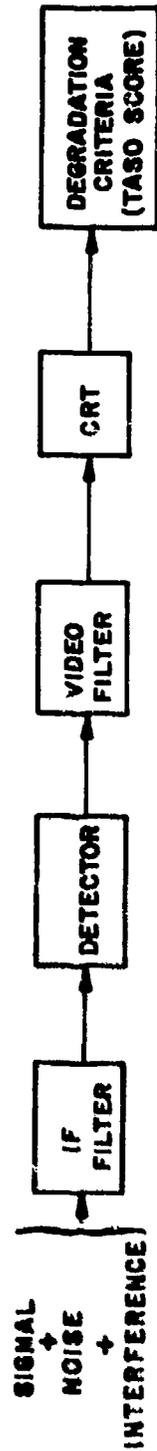


Figure B-5. A5C receiver analysis structure.

The block diagram of a typical receiver structure is shown in Figure B-6. In the analysis, IF filtering, product detection, baseband filtering and bit error probability degradation criteria are considered. The bit error probability is obtained by calculating the output S/I power ratio at the output of the baseband filter using the method described in Reference 4. The binary probability of error is then calculated using Equation (7-77) of Reference 28. This equation pertains to the probability of detection of binary signals in white Gaussian noise. However, the interference present at the discrimination output, while noise-like, does not have white Gaussian noise statistics. A comparison between the available measured data and the model results indicate that the difference is negligible for the range of the degradation curves. The model was, therefore, extended to cases where measured data was not available.

#### Desired Signal and Receiver Specifications

The following are the specifications of the desired signal and receiver parameters used in the analysis:

1. Bit rate: 100 bits/second/channel.
2. IF bandwidth: 6.3 kHz (10 double-tuned stages).
3. Channel bandwidth: 1050 Hz.
4. Base band filter: 100 Hz.
5. Frequency shift:  $\pm 425$  Hz.
6. 6 channels.

#### A9B (VOICE) RECEIVER AND DESIRED SIGNAL DESCRIPTIONS

A9B describes a broad category of amplitude modulation. Technical manuals for equipments with A9B modulation were searched for descriptions of the modulations used. The most representative type of A9B modulation is a four-channel voice-composite transmission.

This type is described as four independent voice channels single-sideband modulated so as to be spaced one adjacent to the other symmetrically around a continuous wave carrier. At the receiver the IF filter eliminates the two sidebands above the carrier of the two below. The two remaining channels are then envelope-detected about the carrier frequency. The upper sideband is removed by a low pass filter if the lower channel is desired. If the upper channel is desired a product detector shifts it to baseband.

The block diagram of the receiver analysis structure for solving cochannel problems is shown in Figure B-7. The IF adjacent-signal-interference case is excluded for narrowband interference signals because the sharp IF filter characteristics eliminate the possibility of this condition occurring. The wideband IF adjacent signal interference case is discussed in SECTION 3.

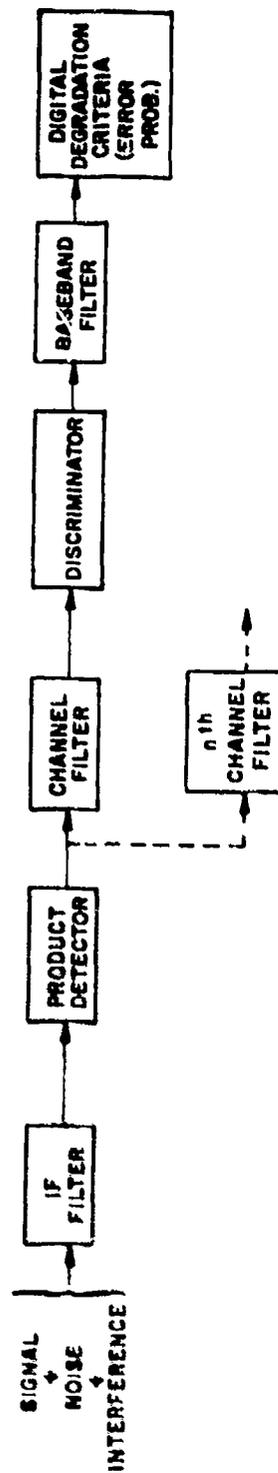


Figure B-6. A7J receiver analysis structure.

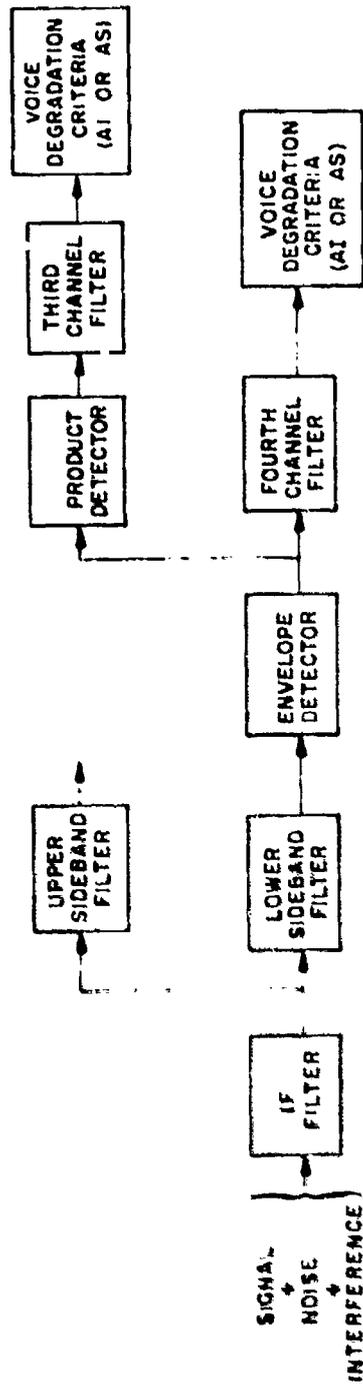


Figure B-7. A9B receiver analysis structure.

Desired Signal and Receiver Specifications

The following are the specifications of desired signal and receiver parameters used in the analysis:

1. Audio bandwidth of 0.3 to 3.5 kHz (six low-and six high-pass stages).
2. IF bandwidth of 16 kHz (ten double-tuned stages).
3. Harvard phonetically balanced (PB) 1,000 word vocabulary used in articulation scoring (AS) criteria (fatigue factors and hard clipping are not considered).
4. Modulation index 30%.

F1 (FREQUENCY SHIFT KEY, FSK) DIGITAL RECEIVER AND SIGNAL DESCRIPTIONS

The standard code for modulation types (Reference 28) describes the F1 category as "telegraphy by frequency shift keying without the use of a modulating audio frequency, one of two frequencies being emitted at any instant". Binary frequency shift key modulation is a continuous wave carrier which shifts from one frequency to another, each channel frequency representing a mark or space of binary coded information. The reference carrier for the F1 system is defined to be at center of the two frequencies.

The FSK modulation is simulated by a continuous wave carrier frequency modulated by a tone frequency. The peak-to-peak frequency deviation of the carrier approximates the channel separation of the FSK signal. The tone modulating signal approximates a 50% duty cycle rectangular pulse train (i.e., a binary signal where a mark or space is equally probable).

Figure B-8 shows the block diagram of a typical low-speed F1 receiver analysis structure for solving cochannel interference problems. The IF adjacent signal interference case is eliminated for narrowband interference signals by the sharp IF filter characteristics. The wideband IF adjacent signal case is discussed in SECTION 3. IF filtering, ideal limiting, discriminator detection, baseband filtering and a bit error probability degradation criteria are considered in the analysis. The bit error probability is obtained by calculating the output S/I power ratio at the low pass filter using the method described in Reference 4. The binary probability of error is then calculated using Equation (7-77) of Reference 28. This equation pertains to the probability of detection of binary signals in white Gaussian noise. However, the interference present at the discriminator output, while noise-like, does not have white Gaussian noise statistics. A comparison between the available measured data and the model results indicate that the difference is negligible for the range of the degradation curves. The model was, therefore, extended to cases where measured data was not available.

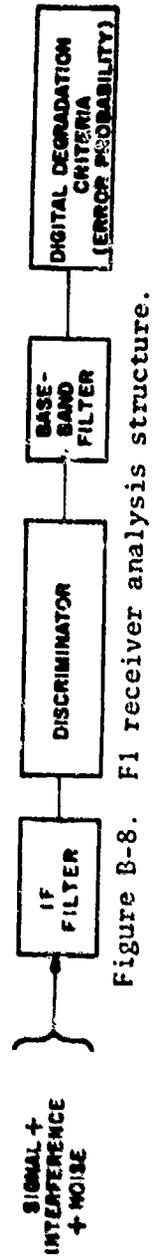


Figure B-8. F1 receiver analysis structure.

Desired Signal and Receiver Specifications

The following are the desired signal and receiver parameters used in the F1 analysis:

1. Bit rate 100 bauds.
2. Frequency shift  $\pm 425$  Hz.
3. IF bandwidth 1050 Hz.
4. Baseband filter 100 Hz.

F3 (FM) VOICE RECEIVER AND DESIRED SIGNAL DESCRIPTIONS

The F3 modulation category describes the transmission of voice information by frequency-modulating a continuous wave carrier. A voice signal deviates the carrier to 5 kHz on the peaks. The 5-kHz peak deviation times 60% modulation times 0.707 (peak-to-rms conversion) corresponds to an rms deviation of 2.1 kHz. The voice baseband bandwidth of narrowband commercial and military equipments is specified as extending from 0.3 to 3.5 kHz.

The block diagram of the typical FM receiver analysis structure for solving cochannel and adjacent signal interference problems is shown in Figure B-9. IF filtering, ideal limiting, discriminator detection, baseband filtering and either articulation index or articulation scoring degradation criteria are considered. The structure shown in this diagram is used in the analysis of interfering signals that are off-tuned to approximately the 80-dB IF rejection level.

Desired Signal and Receiver Specifications

The following are the desired signal and receiver parameters used in the F3 (no de-emphasis) analysis:

1. Audio bandwidth 0.3 to 3.5 kHz (six high-and six low-pass stages).
2. IF bandwidth of 16 kHz (four double-tuned stages).
3. Peak frequency deviation of 5 kHz.
4. RMS frequency deviation of 2.1 kHz.
5. 60% modulation.
6. Harvard phonetically balanced (PB) 1,000-word vocabulary used in articulation scoring (AS) criteria (fatigue factors or hard clipping are not considered).

F3 (FM) VOICE RECEIVER (WITH DE-EMPHASIS) AND DESIRED SIGNAL DESCRIPTION

F3 is the transmission of voice information by frequency modulating a continuous wave carrier. A voice signal deviates the carrier to 5 kHz on the peaks. The 5-kHz peak deviation times 60% modulation times 0.707

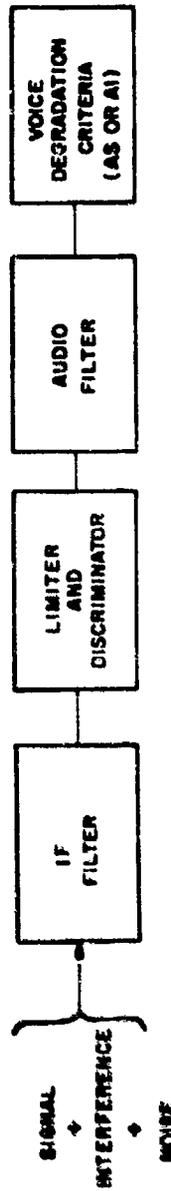


Figure B-9. F3 receiver analysis structure.

(peak-to-rms conversion) corresponds to a rms deviation of 2.1 kHz. The voice baseband bandwidth of narrowband commercial equipments is specified as extending from 0.3 to 3.5 kHz.

The block diagram of the typical FM receiver (with de-emphasis) analysis structure for solving cochannel and adjacent signal interference problems is shown in Figure B-10. IF filtering, ideal limiting, discriminator detection, de-emphasis filtering, baseband filtering and either articulation index or articulation scoring degradation criteria are considered. The structure shown in this diagram is used in the analysis of interfering signals that are off-tuned to approximately the 80-dB IF rejection level.

#### Desired Signal and Receiver Specifications

The following are the desired signal and receiver parameters used in the F3 (de-emphasis) analysis:

1. Audio bandwidth 0.3 to 3.5 kHz (six high-and six low-pass stages).
2. IF bandwidth of 16 kHz (four double-tuned stages).
3. Peak frequency deviation of 5 kHz.
4. RMS frequency deviation of 2.1 kHz.
5. 60% modulation.
6. De-emphasis filter - single stage low pass filter with 250 Hz break point.
7. Harvard phonetically balanced (PB) 1,000-word vocabulary used in articulation scoring (AS) criteria (fatigue factors or hard clipping is not considered).

#### F9 (WIDEBAND FM MULTIPLEX) RECEIVER AND DESIRED SIGNAL DESCRIPTIONS

One of the most prevalent types of F9 is frequency-division-multiplex (FDM) transmission using 12 voice channels to frequency-modulate a continuous wave carrier. The 12-channel baseband signal is simulated as a white-noise modulated baseband. The desired channel is represented by a single audio frequency of rms level equal to the rms level of a noise-loaded channel. The baseband signal is pre-emphasized and frequency-modulates a continuous wave carrier which is deviated 50 kHz on the peaks (35.3 kHz rms). The bandwidth of a single voice channel is specified as extending from 0.3 to 3.5 kHz. Both low and high baseband frequency channels are used in the analysis.

The block diagram of the typical F9 receiver analysis structure for solving cochannel and adjacent signal interference problems is shown in Figure B-11. The cochannel interference condition implies the interference signal is tuned within the low or high desired channel.

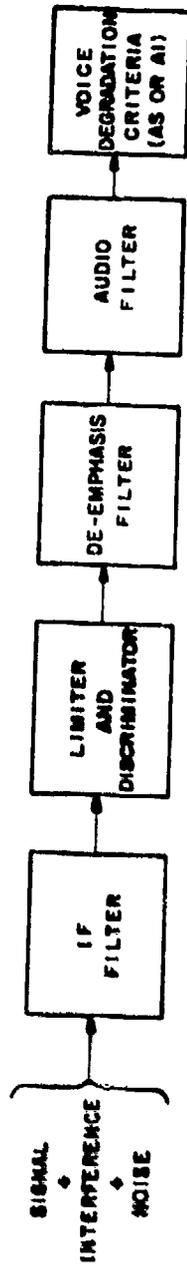


Figure B-10. F-3 receiver (with de-emphasis) analysis structure.

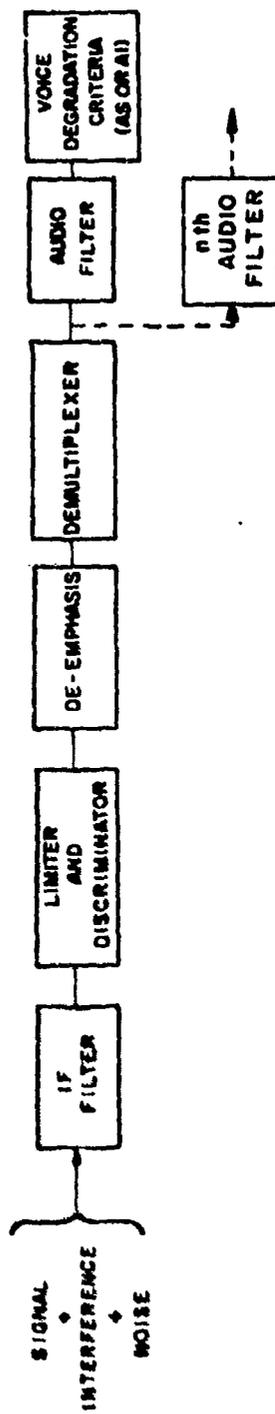


Figure B-11. F9 (FDM) receiver analysis structure.

The cochannel interference condition implies the interference signal is tuned within the low or high desired channel. IF filtering, ideal limiting, discriminator detection, de-emphasis, de-multiplexing, baseband filtering and either articulation index or articulation scoring degradation criteria are considered.

#### Desired Signal and Receiver Specifications

The following are the desired signal and receiver parameters used in the F9 desired signal analysis:

1. Baseband: 12 channels of 4-kHz white noise.
2. Desired channel occupied by only 600 Hz tone with rms power of one noise-loaded channel.
  - Low Channel - 4-8 kHz
  - High Channel - 44-48 kHz
3. Audio bandwidth 0.3 to 3.5 kHz (six high-and six low-pass stages).
4. Single-stage pre-emphasis filter with breakpoint frequency 3 kHz.
5. Total peak deviation of 50 kHz.
6. Total RMS deviation of 35.3 kHz.
7. Peak-to-mean power ratio of 13 dB.
8. IF bandwidth of 200 kHz (eight double-tuned stages).
9. De-emphasis: single stage with 3-kHz breakpoint frequency.
10. Harvard phonetically balanced (PB) 1,000-word vocabulary used in AS criteria (fatigue factors and hard clipping are not considered).

#### F9 (PCM-FM) RECEIVER AND DESIRED SIGNAL DESCRIPTION

In this type of modulation a signal is sampled at discrete intervals, and several pulses are then used as a code group to describe the quantized amplitude of a single sample. The signal is then pulse-code modulated (PCM) and used to frequency-modulate an RF carrier.

The system analyzed consists of 12 voice channels, each with a baseband of 0.3 to 3.5 kHz. Each channel is sampled at an 8-kHz rate and coded into six bits. The samples from the 12 channels are sequentially combined, resulting in a total system bit rate of 576 kilobits per second.

A block diagram of a typical PCM-FM system for interference analysis is shown in Figure B-12. RF filtering, IF filtering, limiting, discriminator detection, time division de-multiplex, digital to analog conversion and baseband filtering are considered in the analysis. The

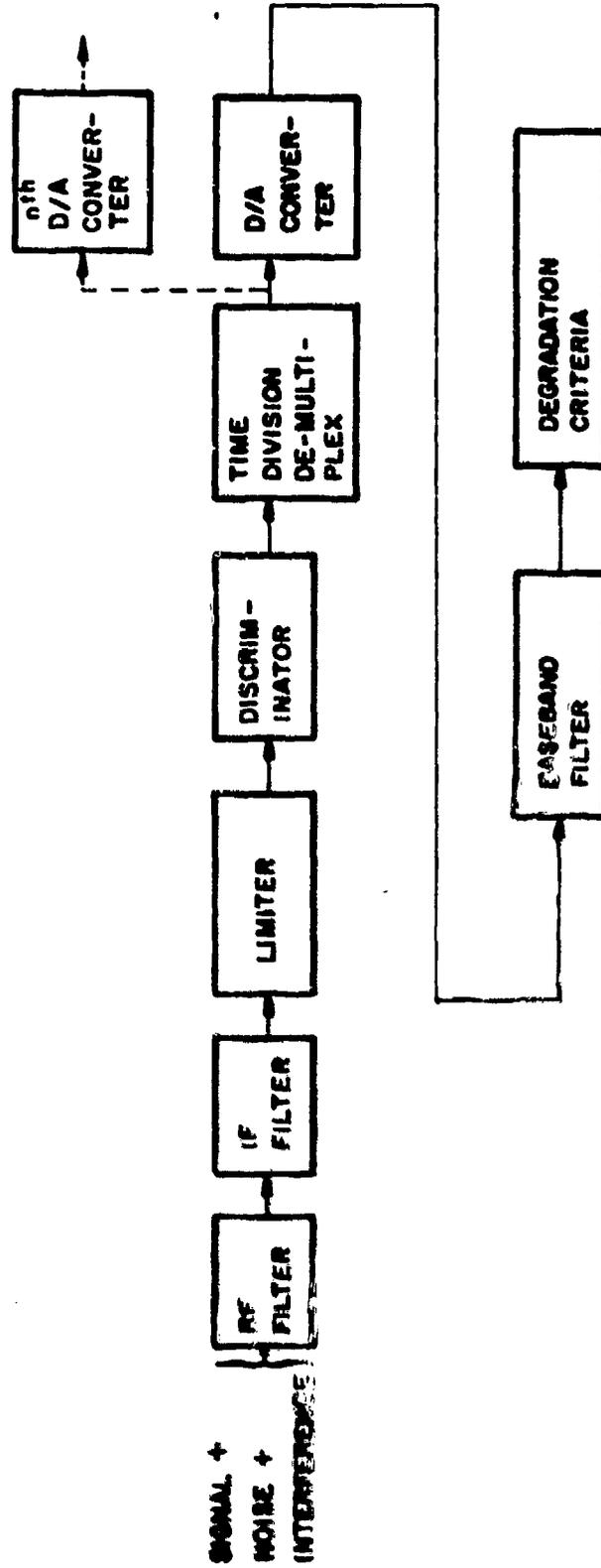


Figure B-12. PCM-FM receiver analysis structure.

degradation criteria, given in terms of Articulation Index, and bit error probability, were obtained from measurements (Reference 10).

#### Desired Signal and Receiver Specifications

The following are the desired-signal and receiver parameters used in the F9 (PCM/FM) modulation considered in this analysis:

1. Channels: 12 time division multiplex (TDM).
2. Bit rate: 576 kilobits per second.
3. IF Bandwidth: 3.5 MHz.
4. Channel sampling rate: 8 kHz.
5. Bits per sample = 6.
6. Baseband bandwidth: 0.3 to 3.5 kHz.

#### F9 (COHERENT PSK) RECEIVER AND DESIRED SIGNAL DESCRIPTION

In this type of modulation, digital information is transmitted by using a relative phase shift in a carrier of constant amplitude and constant angular frequency. In coherent detection, a phase reference is provided in the receiver, permitting the receiver to be phase-synchronized with the transmitter.

A block diagram of a typical coherent PSK receiver structure for interference analysis is shown in Figure B-13. IF filtering, discriminator detection, a constant phase reference, and a decision mechanism providing a degradation criterion of bit error probability are considered. In the absence of measured data, the DIRAP model (Reference 8) was used to simulate the PSK receiver.

#### Desired-Signal and Receiver Specifications

The following are the desired-signal and receiver parameters used in the F9 (PSK) analysis:

1. Bit rate: 600 bits per second of binary data.
2. IF filter: 2400-Hz bandpass (five poles).
3. Phase shift: between 0° and 180°.

#### F9 (TELEMETRY) RECEIVER AND DESIRED SIGNAL DESCRIPTION

F9 (telemetry) modulation considered in this analysis is of the frequency-division multiplex type; that is, it consists of a radio frequency carrier frequency modulated by a group of subcarriers, each of a different frequency. The subcarriers are frequency modulated in a manner determined by the intelligence to be transmitted. The

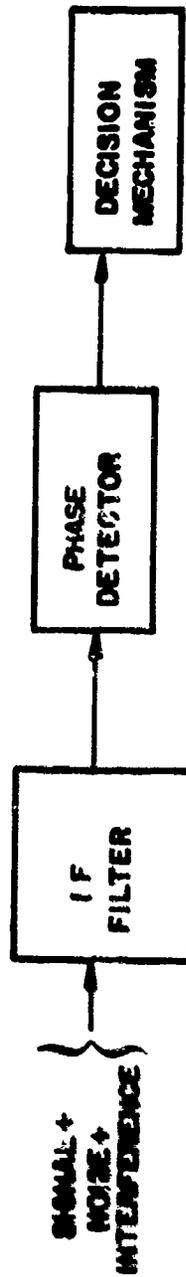


Figure B-13. F9 (coherent PSK) receiver analysis structure.

model chosen for this analysis conforms to the standards established by the Inter-Range Instrumentation Group (IRIG).<sup>29</sup> Information consisting of a 1000-Hz tone was transmitted on subcarrier band E as defined by the IRIG.

A block diagram of a typical F9 (telemetry) receiver analysis structure, used for this analysis, is shown in Figure B-14. IF filtering, a discriminator, channel selection filters, a second discriminator, baseband filter and a mean square error degradation criterion are considered.

#### Desired Signal and Receiver Specifications

The following are the desired signal and receiver parameters used in this F9 (telemetry) analysis.

1. IF bandwidth: 800 kHz.
2. Peak Carrier Deviation: 200 kHz.
3. Channel bandwidth: 70 kHz to 78 kHz.
4. Baseband filter bandwidth: 0.5-1.5 kHz.

#### P9 (SPREAD SPECTRUM) RECEIVER AND DESIRED SIGNAL DESCRIPTION

P9 (Spread Spectrum) modulation involves frequency hopping or the pseudo-random phase modulation of an RF carrier for the prevention of jamming or interference and minimizing the possibility of the detection of the spread spectrum signal by undesired receivers. In this analysis, the modulation of the signal is pseudorandom phase modulation.

A block diagram of the spread-spectrum receiver model is presented in Figure B-15. It is general in that either matched filter or active correlation detection, followed by a threshold detector, can be assumed.

The value of probability error per bit at the output of the simple threshold detector shown in Figure B-15 can be calculated as a function of  $(S/N)_i$  and  $(S/I)_i$  ratios, using equations B-1 and B-2 (Reference 2).

Case 1 ( $BW_i \leq B_s$ ):

$$P_e = \frac{1}{2} \operatorname{erfc} \left( \frac{1}{2} \sqrt{\frac{B_s T_s}{\delta \frac{i}{s} + \frac{n_i}{s}}} \right) \quad (\text{B-1})$$

<sup>29</sup>Foster, LeRoy, "Telemetry Systems", John Wiley and Sons, New York, 1965.

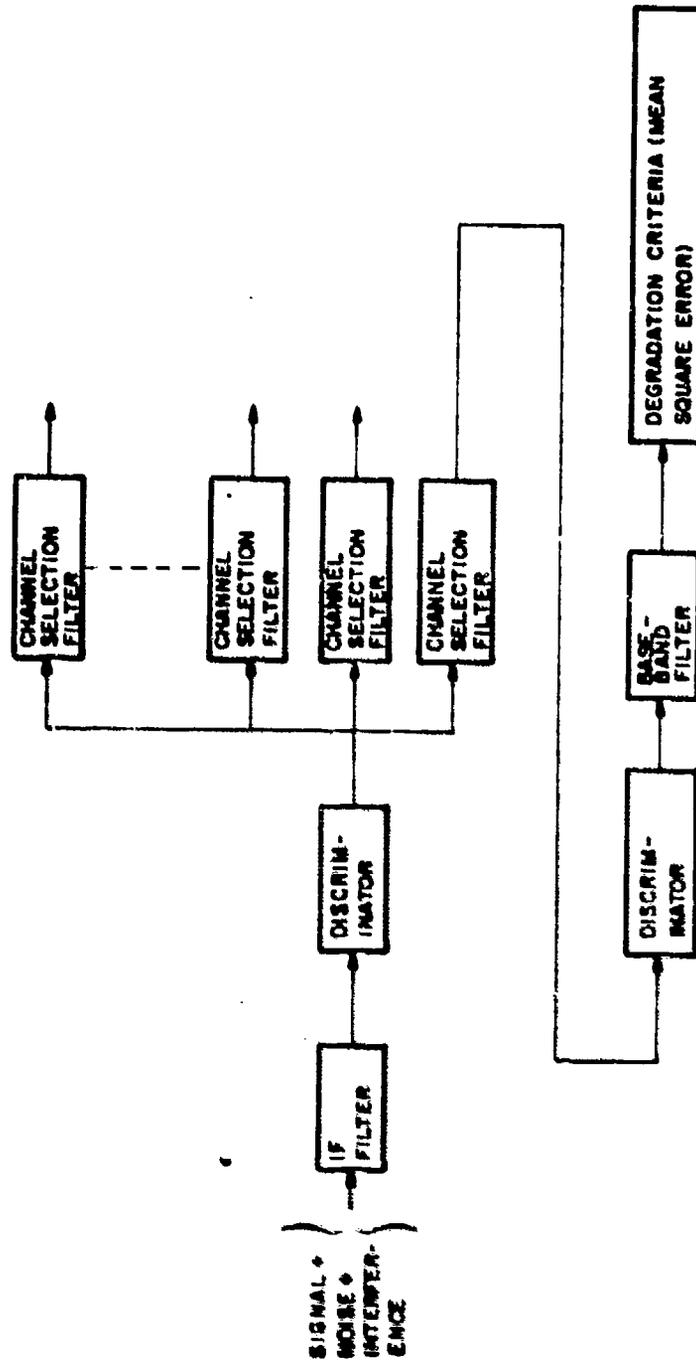
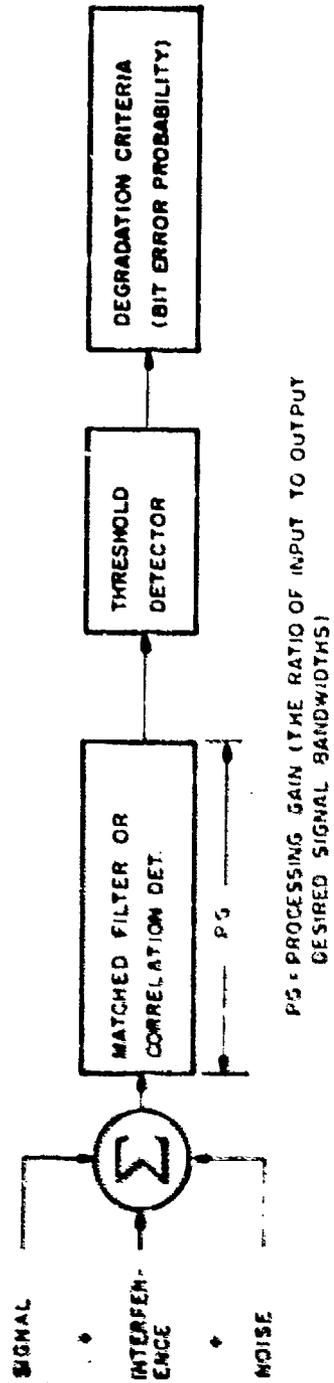


Figure B-14. F9 (Telemetry) receiver analysis structure.



PG = PROCESSING GAIN (THE RATIO OF INPUT TO OUTPUT  
DESIRED SIGNAL BANDWIDTHS)

Figure B-15. P<sub>9</sub> (spread spectrum) receiver analysis structure.

Case 2 ( $BW_I > B_S$ ).

$$P_e = \frac{1}{2} \operatorname{erfc} \left( \frac{1}{2} \sqrt{\frac{B_S BW_I T_S}{\lambda \frac{B_S i}{s} + \frac{BW_I n_i}{s}}} \right) \quad (\text{B-2})$$

where

 $P_e$  = Probability of error per bit $BW_I$  = Interference-signal bandwidth (Hz) $B_S$  = Desired-signal bandwidth (Hz) $T_S$  = Duration of desired signal (seconds) $i$  = Input average interference power (watts) $n_i$  = Input average noise power (watts) $s$  = Input average desired-signal power (watts)

$$\delta = \frac{\sin^2 (\Delta f / 2B_S)}{(\Delta f / 2B_S)^2}$$

$$\lambda = \frac{\sin^2 (\Delta f / 2BW_I)}{(\Delta f / 2BW_I)^2}$$

 $\Delta f$  = Frequency difference (Hz) $\operatorname{erfc}$  = Complimentary error function.

When the correlator is followed by an ideal bi-phase PSK detector, the error probability for a high correlator output signal-to-noise ratio is given by the same expression without the factor of  $\frac{1}{2}$  inside the "erfc". Therefore, the curves given in this handbook can also be used for the PSK case by decreasing the  $(S/N)_I$  and  $(S/I)_I$  values by 6 dB.

#### Desired Signal and Receiver Specifications

The following are the desired signal and receiver parameters used in the PS (Spread Spectrum) analysis:

1. Modulation rate: 100 bits/second.
2. Several processing gains and spread spectrum bandwidths were analyzed; they are:

PG	Spread-Spectrum Bandwidth
10 dB	1.0 kHz
20 dB	10.0 kHz
40 dB	1.0 MHz

#### A1 (DIGITAL) INTERFERENCE SIGNAL DESCRIPTION

A1 modulation, according to the standard codes for modulation types (Reference 28), is "telegraphy without the use of a modulating audio frequency (by on-off keying)". A1 modulation is simulated by an on-off keyed (pulsed modulated) continuous wave carrier. All of the A1 interference signal parameters used in measurements are not listed in the specifications:

1. Pulse width 10 ms.
2. Bit rate 100 bauds.
3. Peak interference power ( $\hat{i}$ ) used to specify A1.

#### A3 (AM) INTERFERENCE SIGNAL DESCRIPTION

The following are the interference specifications or parameters used in the A3 analysis:

1. Voice bandwidth from 0.3 to 3.5 kHz.
2. Modulation index of 50% ( $m_1 = 0.3$ ).
3. Single voice-babble modulation used in AS scoring.
4. Voice-shaped noise used in AI scoring.

#### A3J (SSB) INTERFERENCE SIGNAL DESCRIPTION

The following are the interference specifications of parameters used in the A3J analysis. The reference carrier in the A3J system is located 1650 Hz below the center of the IF filter. Therefore, frequencies obtained from frequency management systems where the carrier is assumed in the center of the IF filter must be reduced by 1650 Hz when using the A3J curves.

1. Voice bandwidth from 0.3 to 3.0 kHz.
2. Single voice-babble modulation used in AS scoring.
3. Voice-shaped noise used in AI scoring.

A9B INTERFERENCE SIGNAL DESCRIPTION

The A9B interference consists of a four channel (voice) composite signal, amplitude modulating a continuous wave carrier. A9B interference is simulated as 6 kHz of band-limited white noise, amplitude modulating a continuous wave carrier.

The following are the interference specifications or parameters used in the A9B analysis:

1. Voice bandwidth from 0.3 to 3.0 kHz.
2. Modulated RF bandwidth of 12 kHz.
3. Total modulation index of 30% ( $m_I = 0.3$ ).
4. Single voice-babble modulation used in AS scoring.
5. Band-limited (6 kHz) white noise used in AI scoring.

F1 INTERFERENCE SIGNAL DESCRIPTION

F1 Interference is simulated by a continuous wave carrier shifting between two frequencies with continuous phase between frequency transitions. Each carrier frequency is emitted 50% of the signal duration.

1. Modulation rate of 50 bauds.
2. Channel separation of 400 Hz.
3. Rectangular pulses.
4. Reference carrier assumed at the center of the two frequencies.

F3 (FM) INTERFERENCE SIGNAL DESCRIPTIONS

The following are the interference specifications used in the F3 analysis:

1. Voice bandwidth of 0.3 to 3.5 kHz.
2. RMS frequency deviation of 2.1 kHz.
3. Single voice-babble modulation used in AS scoring.
4. Voice-shaped noise modulation used in AI scoring.
5. Peak frequency deviation of 5 kHz.

F9 (FDM) INTERFERENCE SIGNAL DESCRIPTION

The following are the interference specifications used in the F9 analysis, except for the PSK and PCM-FM cases:

1. Baseband of 48 kHz white noise.
2. No pre-emphasis.
3. Total RMS frequency deviation of 35.3 kHz.
4. Total Peak frequency deviation of 50 kHz.
5. Peak-to-mean power ratio of 13 dB.
6. Single voice babble modulation used in AS scoring.

#### F9 (PCM-FM) Interference Signal Description

This type of interference is used only with F9 (PCM-FM) desired signal:

1. 12-channel TDM.
2. Bit rate 576 kB/s.

#### F9 (PSK) INTERFERENCE SIGNAL DESCRIPTION

This type of interference is used only with F9 (PSK) desired signal:

1. Bit rate: 607 bits per second.
2. Marks and spaces sent randomly with 180° phase shifts.

#### P0 (PULSE) INTERFERENCE SIGNAL DESCRIPTION

P0 modulation is described by standard codes for modulation types (Reference 16) as "a pulsed carrier without any modulation intended to carry information (e.g., radar)". The P0 interference is a continuous wave carrier modulated by a rectangular periodic pulse train.

1. Pulse width 5  $\mu$ s.
2. Pulse repetition rate 300 pulses/second.
3. Peak interference power ( $\hat{I}$ ) used to specify P0.

## APPENDIX C

## PERFORMANCE DEGRADATION CURVES

PERFORMANCE DEGRADATION CURVES (FIGURES C-1 THROUGH C-164)

This portion of the Degradation Handbook (APPENDIX C) contains the results of the analysis described in the main body of the report. The relationship between performance degradation and input signal-to-interference power ratio are given in the form of receiver performance degradation curves. In most cases, two desired signal-to-noise ratios (a high and a low signal level) and three relative values of interference off-tuning (cochannel on-tone, cochannel off-tuned and adjacent signal) were considered for each desired-signal-to-interference category.

For example, the performance degradation for an AM receiver with cochannel, on-tuned, AM interference is shown in Figure C-1. The two curves in the figure represent a high signal level representing good performance,  $(S/N)_I = 35$  dB, and a low signal level representing performance at the sensitivity level,  $(S/N)_I = 20$  dB, in the absence of an interference signal. The abscissa scale of the curve is the input signal-to-interference ratio,  $(S/I)_I$ , in dB. The ordinate scale indicates the performance degradation measure; in this case, the articulation score (AS) and the articulation index (AI). The AS scale is only applicable for the high signal-to-noise ratio (S/N) curve because the available measured data was limited to this S/N value. The minimum interference threshold, MIT, is the  $(S/I)_I$  value which causes a just-perceptible interference effect. The MIT value is noted on each degradation curve for a voice-modulated desired signal. The marginal performance region of each A3-to-A3 curve is the region between the 0.7 AI and the 0.3 AI values. It is a region of usable but degraded performance. For  $(S/I)_I$  values that lie above the partially degraded region, no interference effect is noticeable because the interfering signal is masked by normal system noise. For  $(S/I)_I$  values that lie below the marginal performance region (below the 0.3 AI point), communications are not satisfactory because the receiver performance degradation process has become almost complete.

The curves for digital system performance should be used carefully. The slope of the curves in the region between acceptable and unacceptable performance is very steep in all cases. The

variations among individual receivers may be greater than the spread of  $(S/I)_I$  values encompassed by the curves.

TABLE 5, which indicates the number of the degradation curve for each desired signal-to-interference case, has been repeated for convenience in this appendix as TABLE C-1.

TABLE C-1

FIGURE NUMBER OF DEGRADATION CURVE FOR EACH DESIRED-SIGNAL-TO-INTERFERENCE CASE

Desired	Interference		A1	A3	A3J	A5C	A9B	F1	F3	F9	P0	No. of
	Channel	On Tune Off Tune										
A1	Adjacent Channel	On Tune	C-2	C-4	C-5							C-7
		Off Tune	C-3									
A2	Adjacent Channel	On Tune	1/C-2	2/C-4	2/C-5							
		Off Tune										
A2	Adjacent Channel	On Tune	C-8	C-9			C-10		C-11			C-12
		Off Tune										
A2	Adjacent Channel	On Tune	1/C-8	2/C-9			2/C-10		1/C-11			
		Off Tune										
A3	Adjacent Channel	On Tune	C-13	C-17	C-19		C-21	C-23	C-25	C-26	C-27	C-29
		Off Tune	C-14	C-18	C-20		C-22	C-24			C-28	
A3	Adjacent Channel	On Tune	1/C-13	2/C-17	4/C-19		2/C-21	1/C-23	1/C-25	1/C-26	1/C-27	
		Off Tune										
A3J	Adjacent Channel	On Tune	C-30	C-34	C-36		C-38	C-40	C-42	C-43	C-44	C-45
		Off Tune	C-31	C-35	C-37		C-39	C-41				
A3J	Adjacent Channel	On Tune	1/C-30		1/C-36		C-38	1/C-40				1/C-44
		Off Tune										
A5C	Adjacent Channel	On Tune	C-46			C-48					C-51	C-53
		Off Tune	C-47			C-48					C-52	
A5C	Adjacent Channel	On Tune	C-47			C-48					C-52	
		Off Tune										
A71	Adjacent Channel	On Tune	C-54	C-55			C-56		C-57		C-58	C-59
		Off Tune										
A71	Adjacent Channel	On Tune	1/C-54	1/C-55			1/C-56		1/C-57		1/C-58	
		Off Tune										
A9B	Adjacent Channel	On Tune		C-60			C-62	C-64		C-66	C-67	C-68
		Off Tune		C-61			C-63	C-65				
A9B	Adjacent Channel	On Tune		2/C-60			2/C-62	1/C-64			1/C-67	
		Off Tune										
F1	Adjacent Channel	On Tune	C-69	C-70			C-71		C-72		C-73	C-74
		Off Tune										
F1	Adjacent Channel	On Tune	1/C-69	1/C-70			1/C-71		1/C-72		1/C-73	
		Off Tune										
F3 No De- Emphasis	Adjacent Channel	On Tune	C-75	C-76	C-78		C-79	C-80	C-82	C-83	C-84	C-85
		Off Tune						C-81				
F3 De- Emphasis	Adjacent Channel	On Tune	1/C-75	3/C-76	3/C-78		1/C-79	1/C-80	1/C-82		1/C-84	
		Off Tune										
F9 (FM)	Adjacent Channel	On Tune	C-91	C-95			C-99	C-103	C-107	C-112	C-115	C-119
		Off Tune	C-92	C-96			C-100	C-104	C-108	C-113	C-116	
F9 (FM-FM)	Adjacent Channel	On Tune	3/C-91	3/C-95			3/C-99	3/C-103	3/C-107	3/C-112	1/C-115	
		Off Tune										
F9 (FM)	Adjacent Channel	On Tune	C-120	C-121					C-122	C-123	C-124	C-125
		Off Tune										
F9 (FM)	Adjacent Channel	On Tune	3/C-120	3/C-121					3/C-122	3/C-123	1/C-124	
		Off Tune										
F9 (FM)	Adjacent Channel	On Tune	C-126	C-127					C-128	C-129		C-132
		Off Tune								C-130		
F9 (FM)	Adjacent Channel	On Tune	1/C-126	1/C-127					1/C-128	1/C-130		
		Off Tune										
F9 ( telemetry)	Adjacent Channel	On Tune	C-133	C-135	C-137		C-139	C-141	C-143	C-145	C-147	C-149
		Off Tune	C-134	C-136	C-138		C-140	C-142	C-144	C-146	C-148	
F9 ( telemetry)	Adjacent Channel	On Tune	3/C-133	3/C-135	3/C-137		3/C-139	3/C-141	3/C-143	3/C-145	1/C-147	
		Off Tune										
P0	Adjacent Channel	On Tune		C-152					C-153-155	C-156-158	C-159-161	C-162 to 164
		Off Tune										
P0	Adjacent Channel	On Tune		1/C-152					1/C-153 to 155	1/C-156 to 158	1/C-159 to 161	
		Off Tune										

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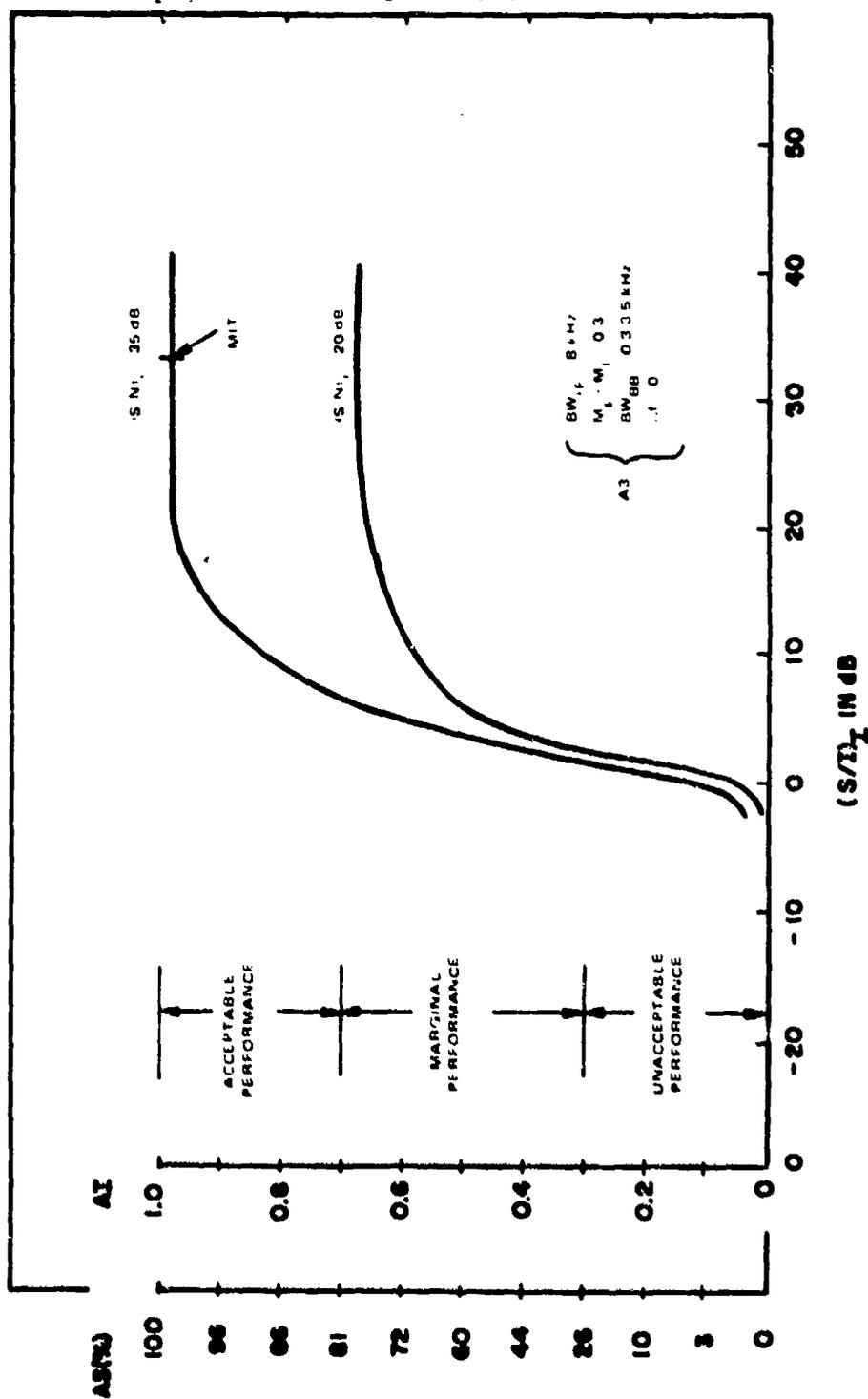


Figure C-1. Sample performance degradation curve for A3 receiver with A3 interference ( $\Delta f = 0$ ).

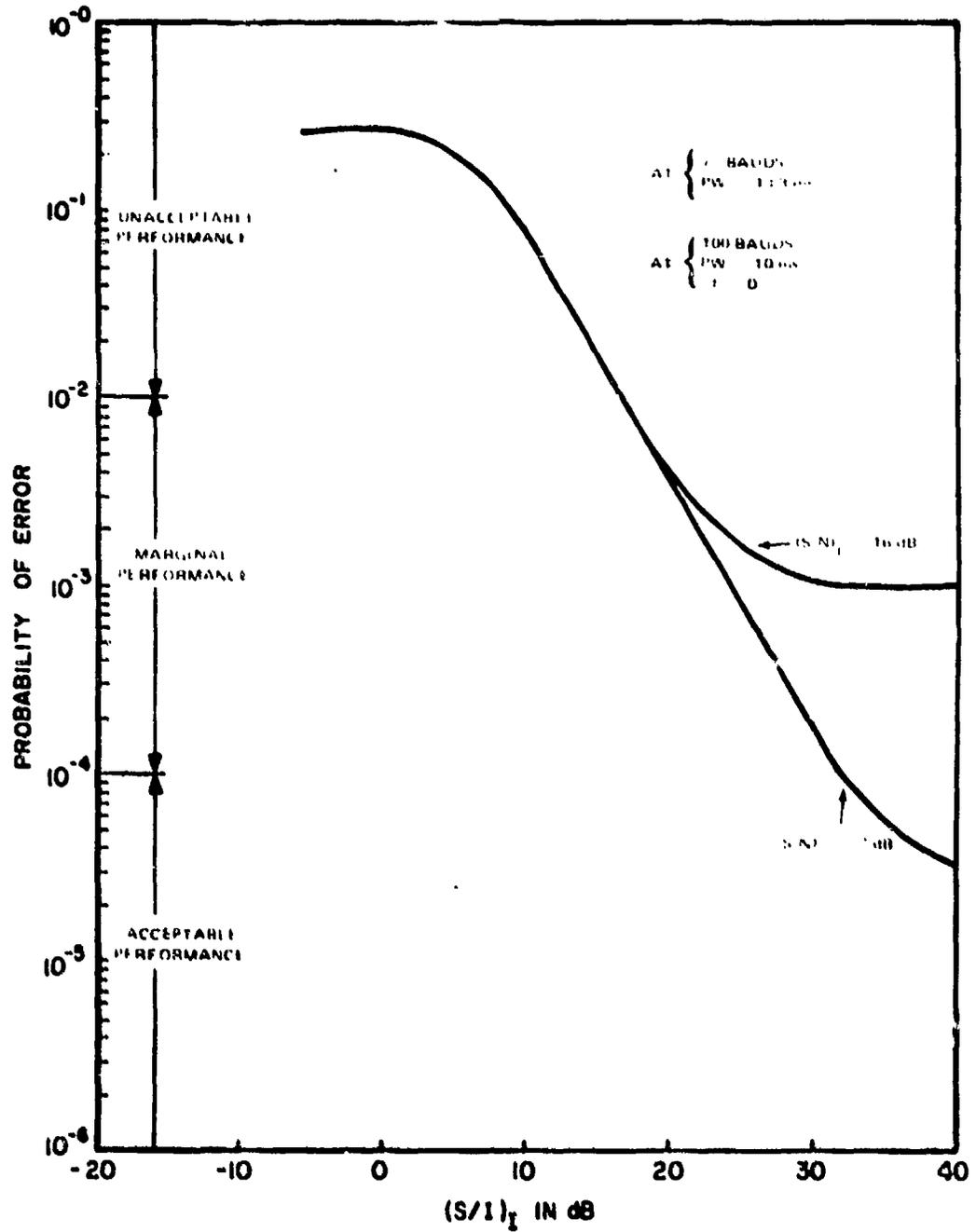


Figure C-2. Performance degradation curve for A1 receiver with A1 interference,  $\Delta f = 0$  Hz.

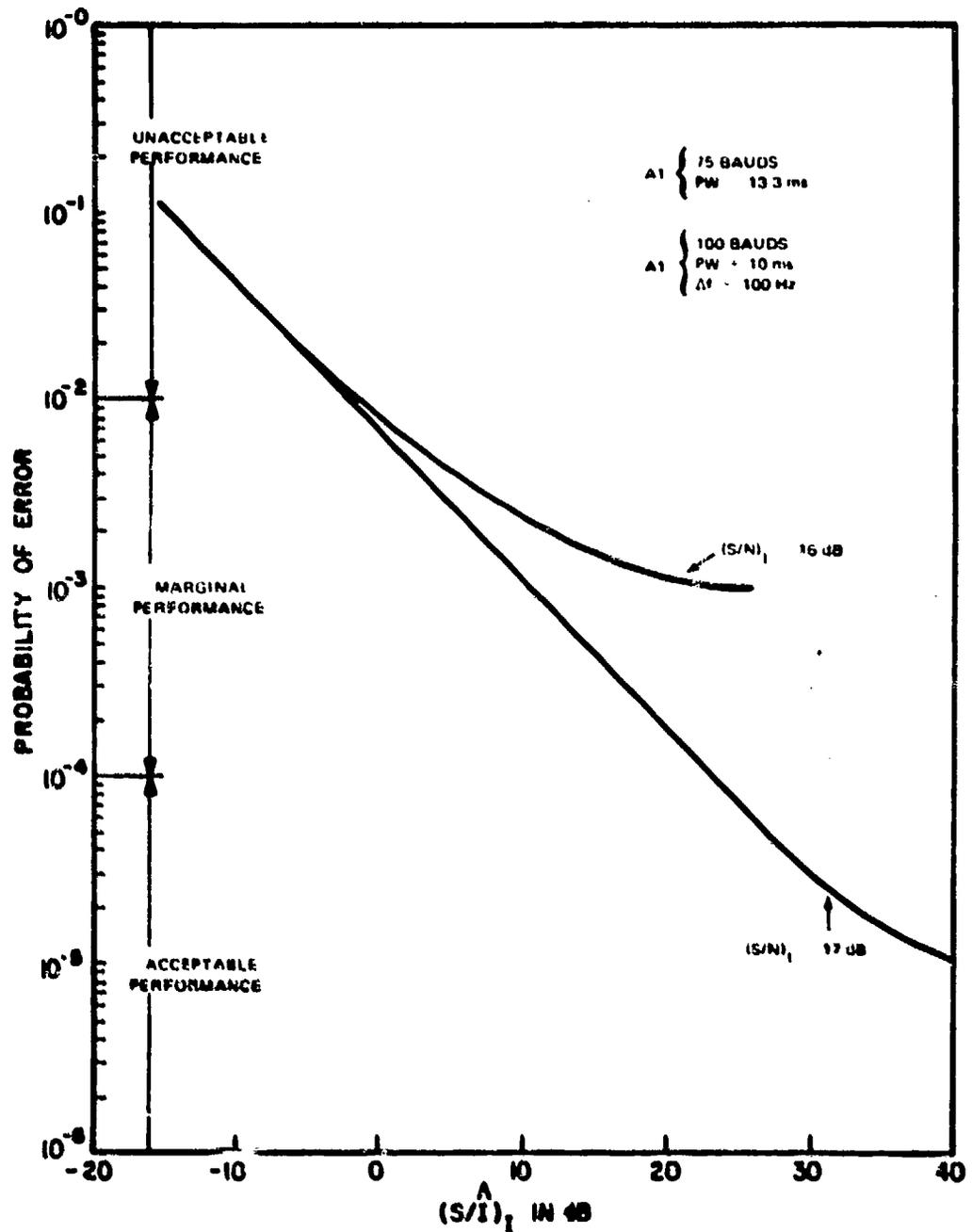


Figure C-3. Performance degradation curve for A1 receiver with A1 interference,  $\Delta f = 100 \text{ Hz}$ .

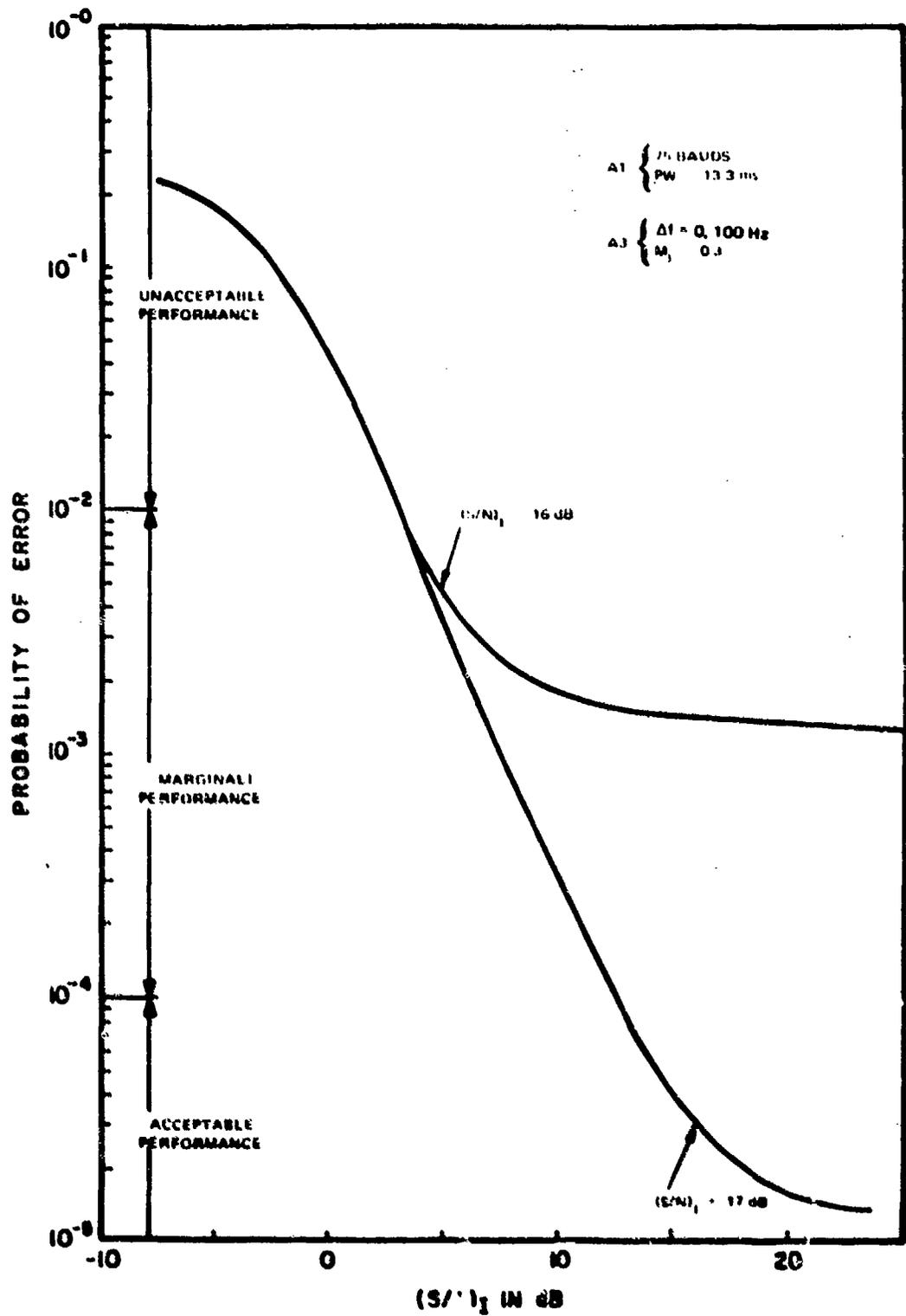


Figure C-4. Performance degradation curve for A1 receiver with A3 interference.

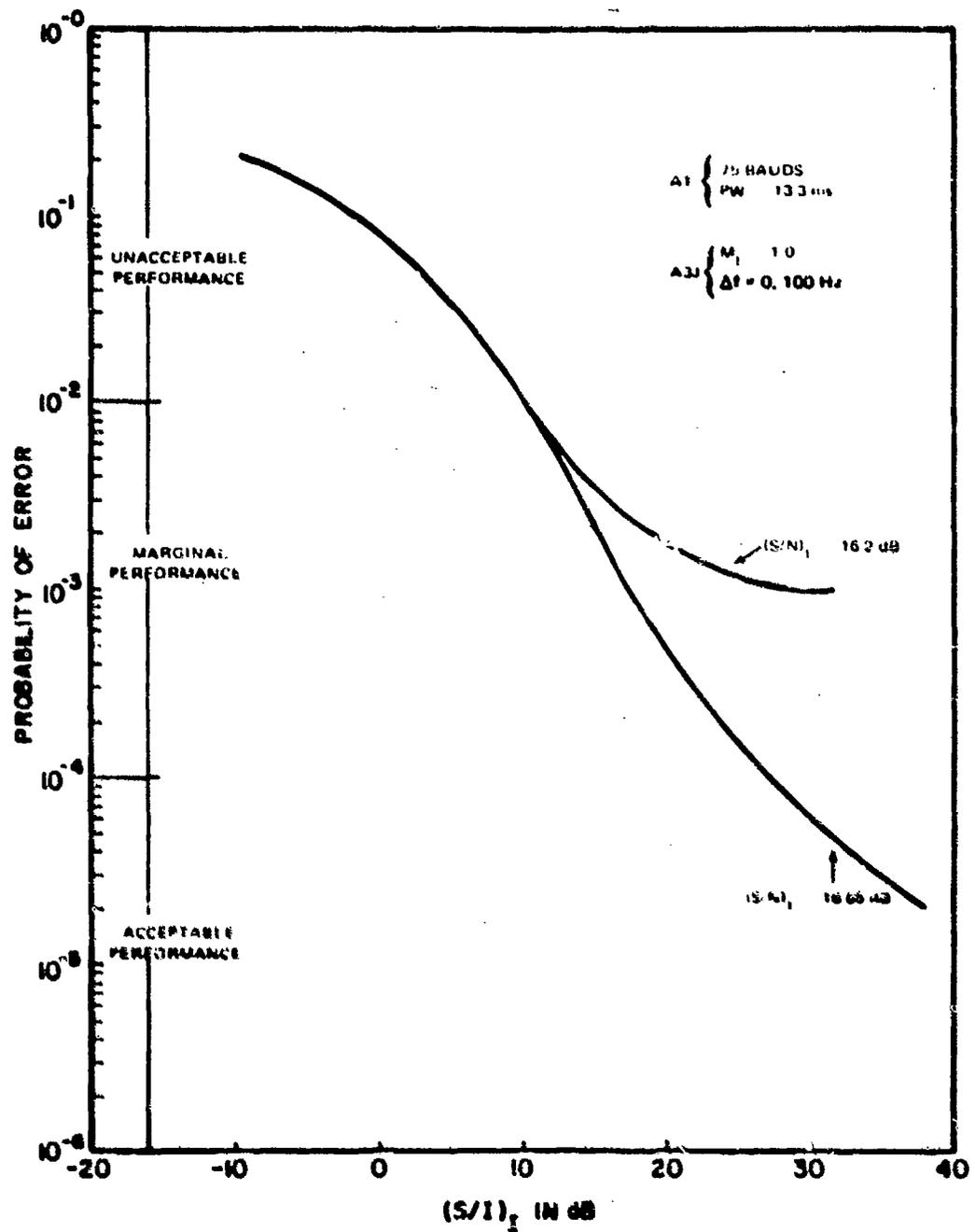


Figure C-5. Performance degradation curve for an AI receiver with ASJ interference.

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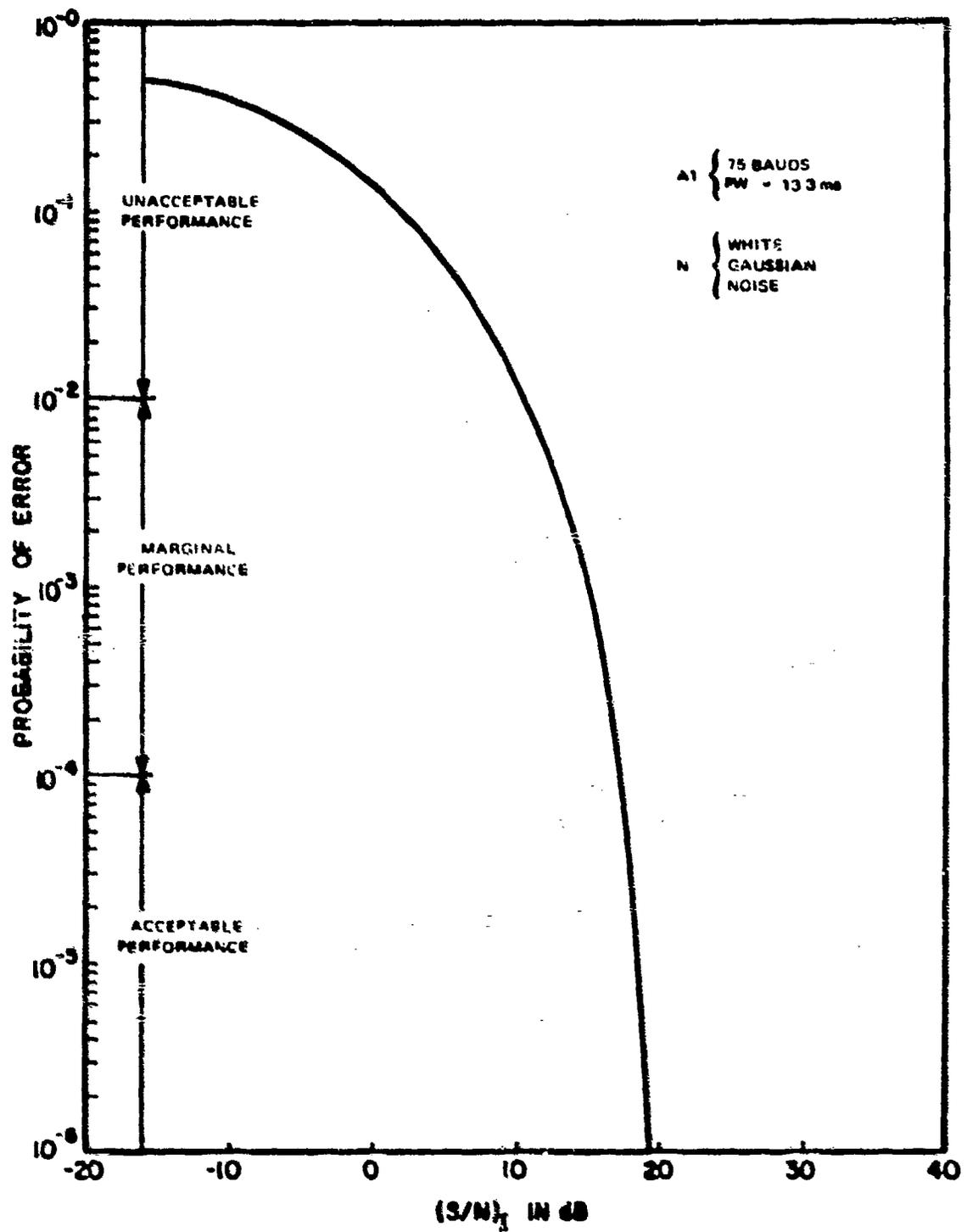


Figure C-7. Performance degradation curve for AI receiver with noise interference.

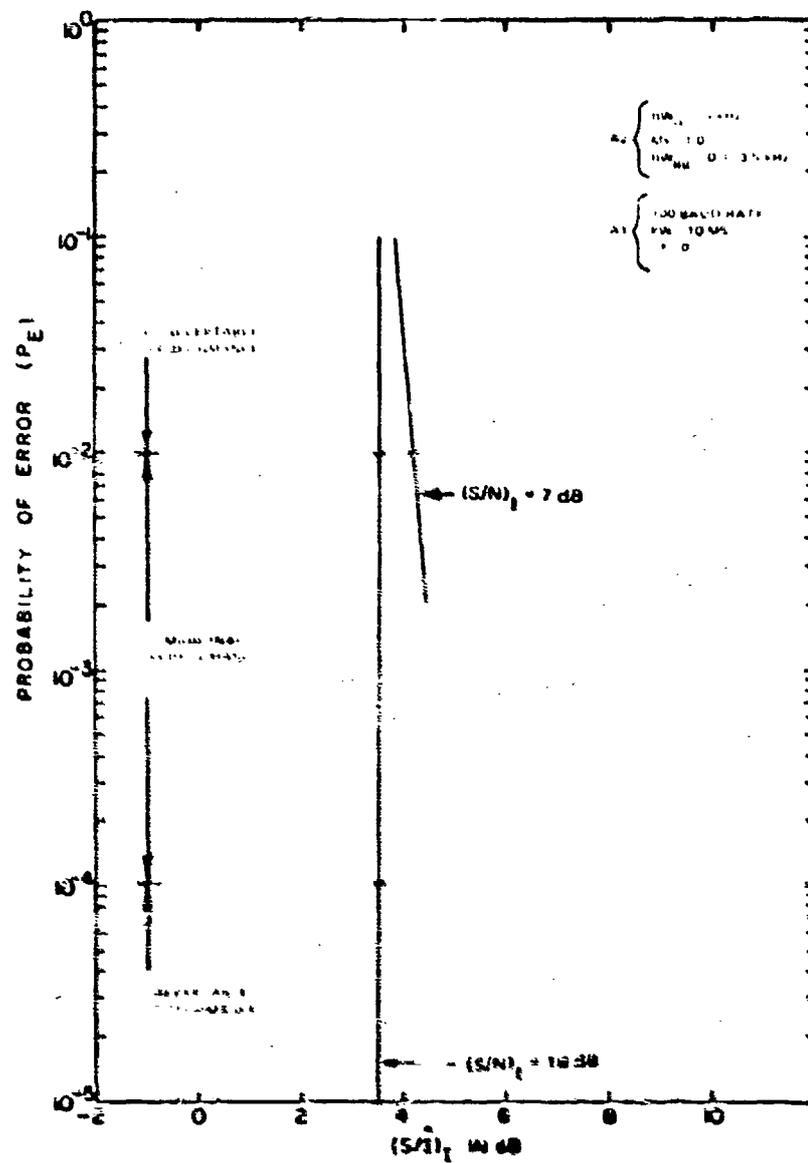


Figure C-8. Performance degradation curve for A2 receiver with A1 interference.



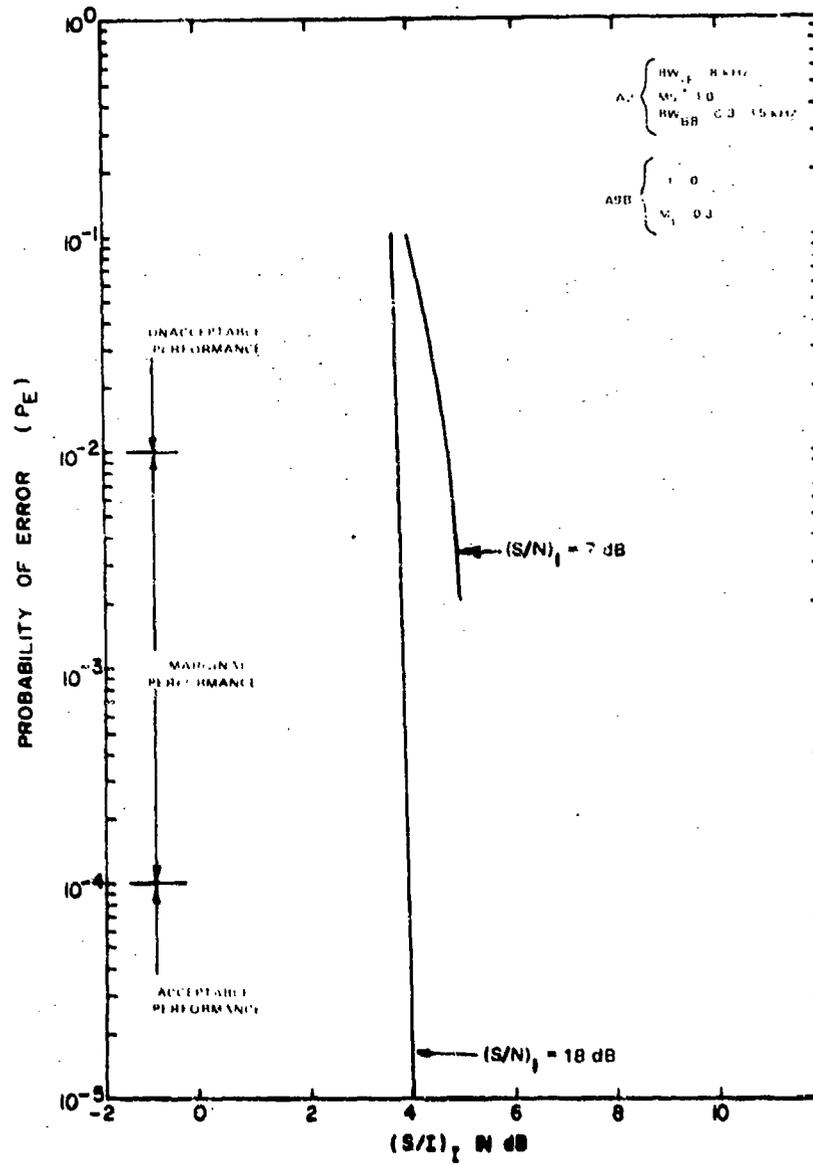


Figure C-10. Performance degradation curve for A2 receiver with A9B interference.

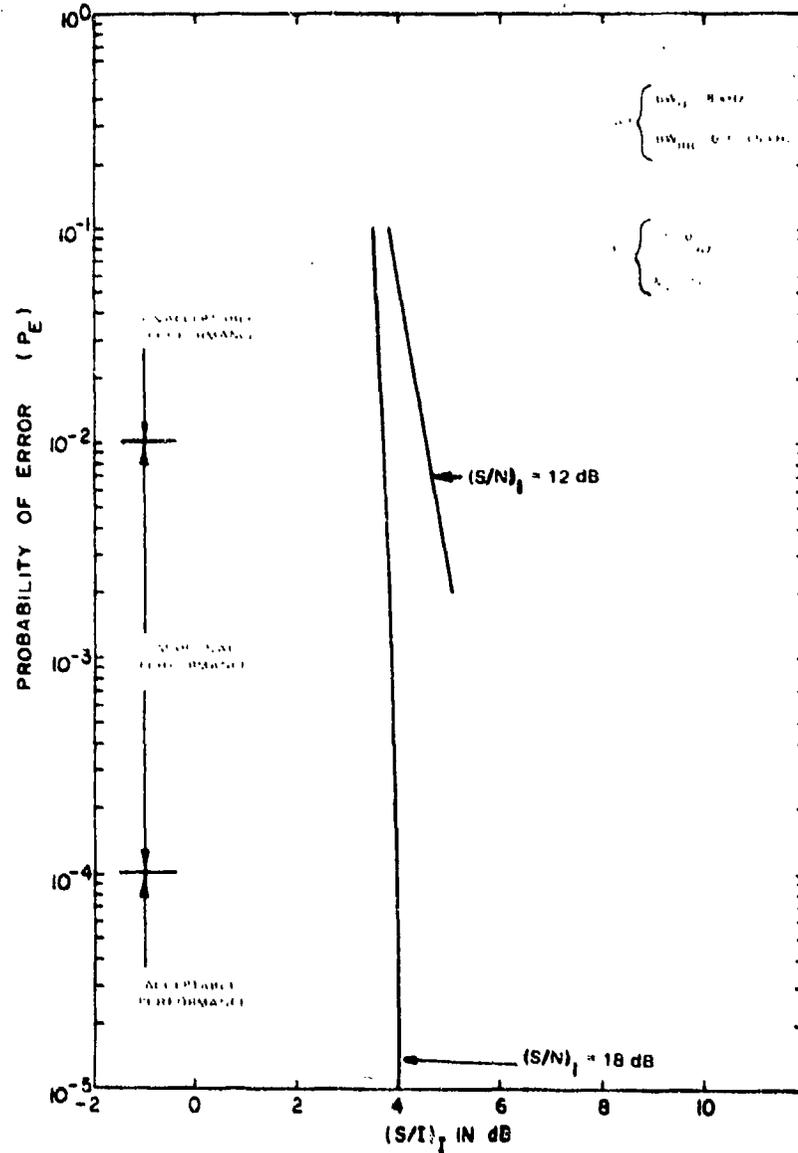


Figure C-11. Performance degradation curve for A2 receiver with F3 interference.

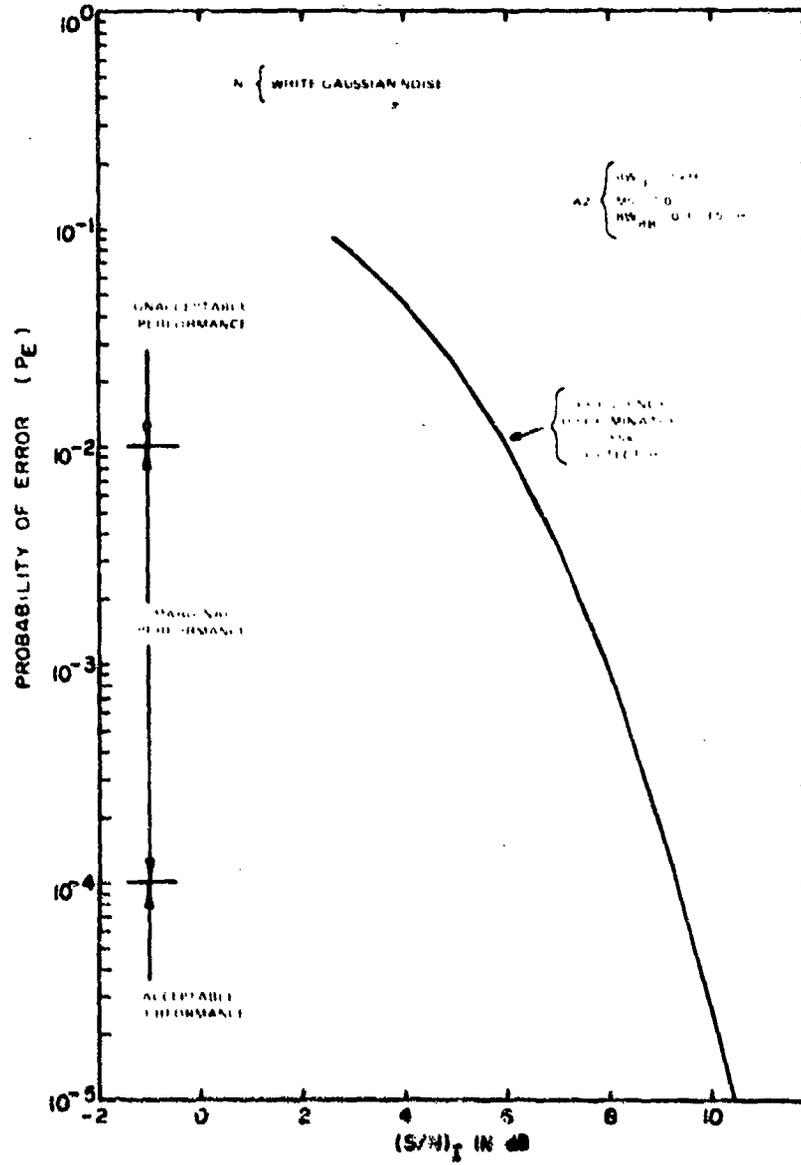


Figure C-12. Performance degradation curve for A2 receiver with Noise.

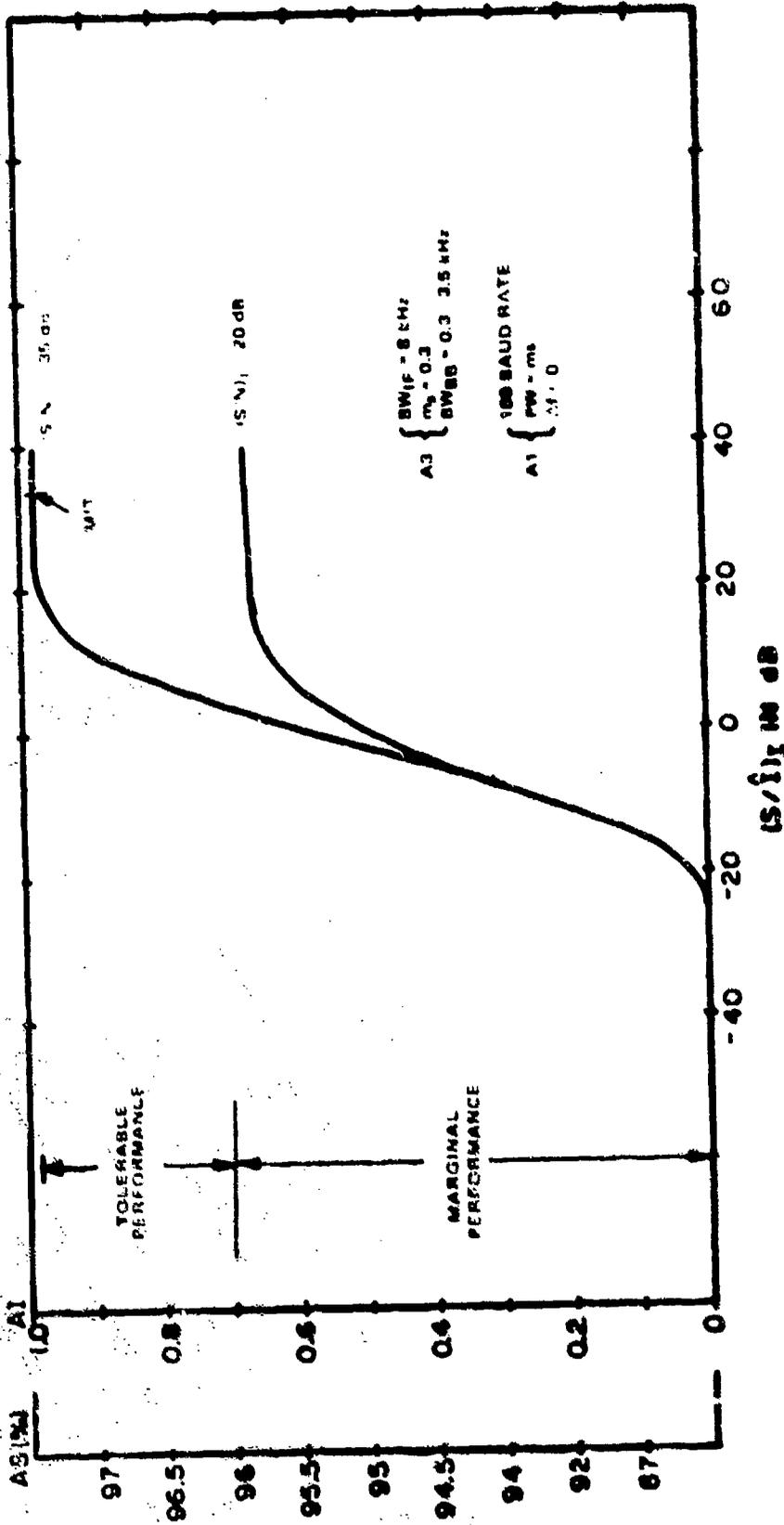


Figure C-13. Performance degradation curve for A3 receiver with A1 interference (100 baud rate, Δf = 0).

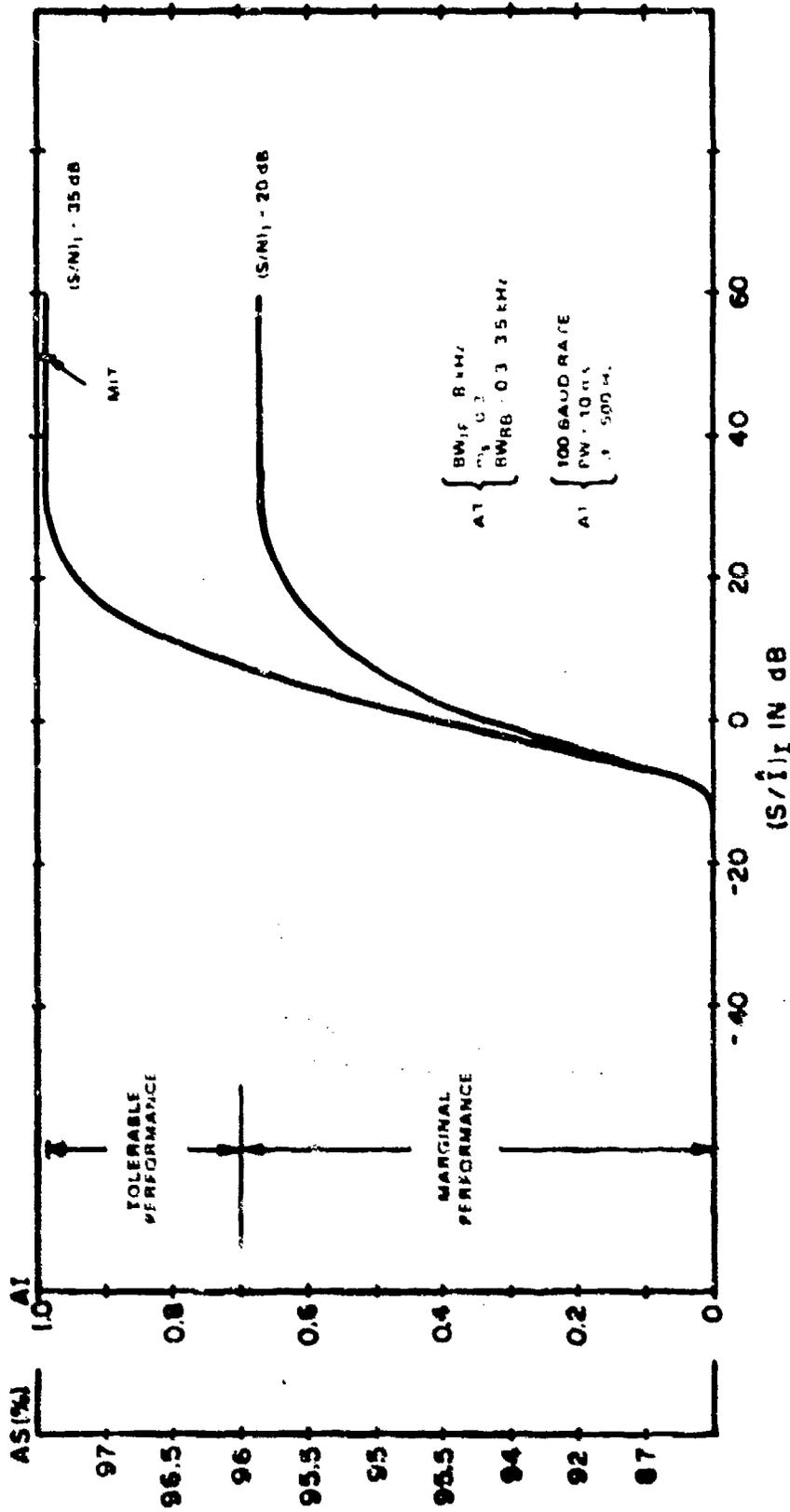


Figure C-14. Performance degradation curve for A3 receiver with AI interference (100 baud rate,  $f = 500$  Hz).

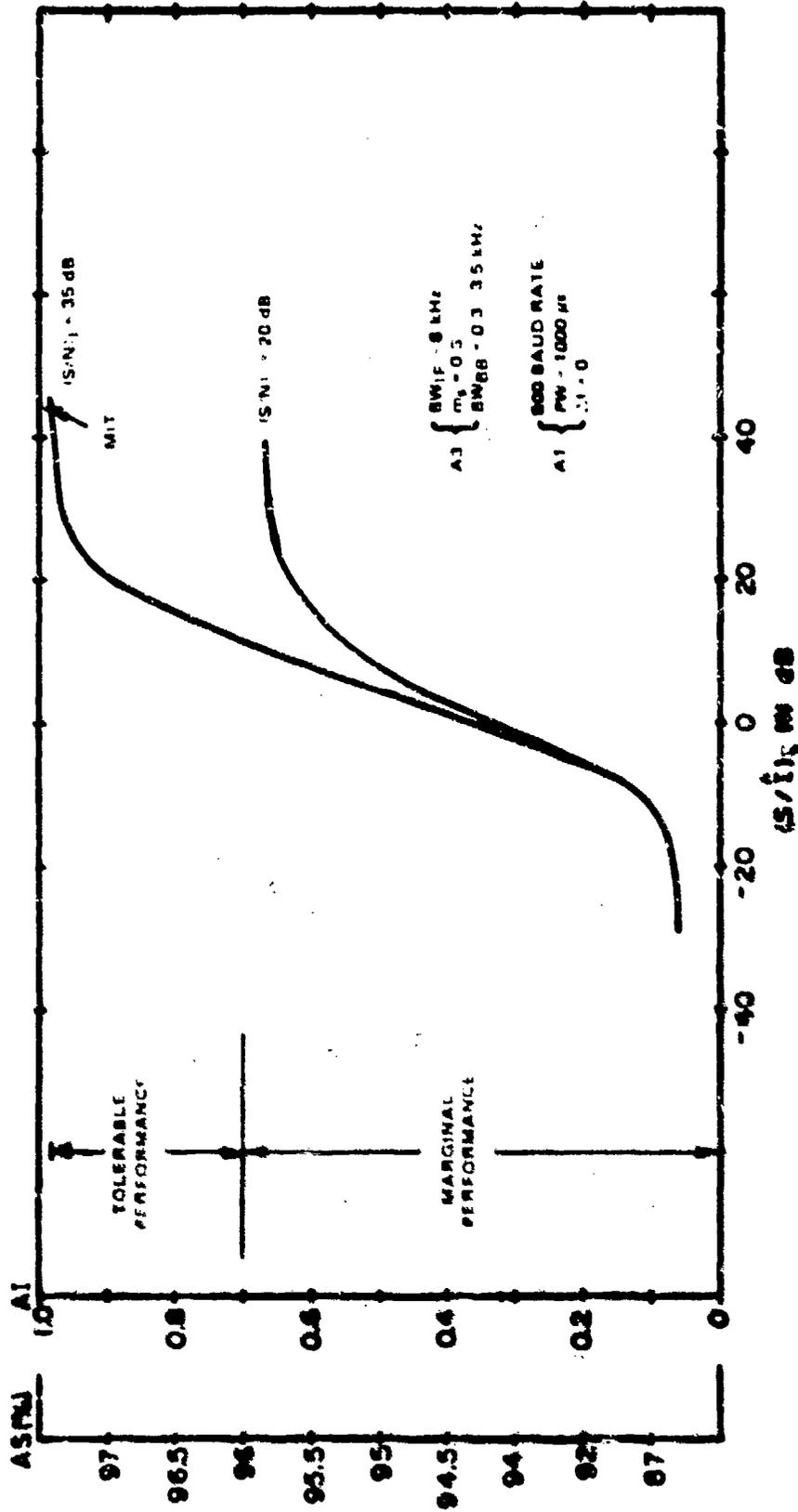


Figure C-15. Performance degradation curve for A3 receiver with A1 interference (800 baud rate,  $\Delta f = 0$ ).

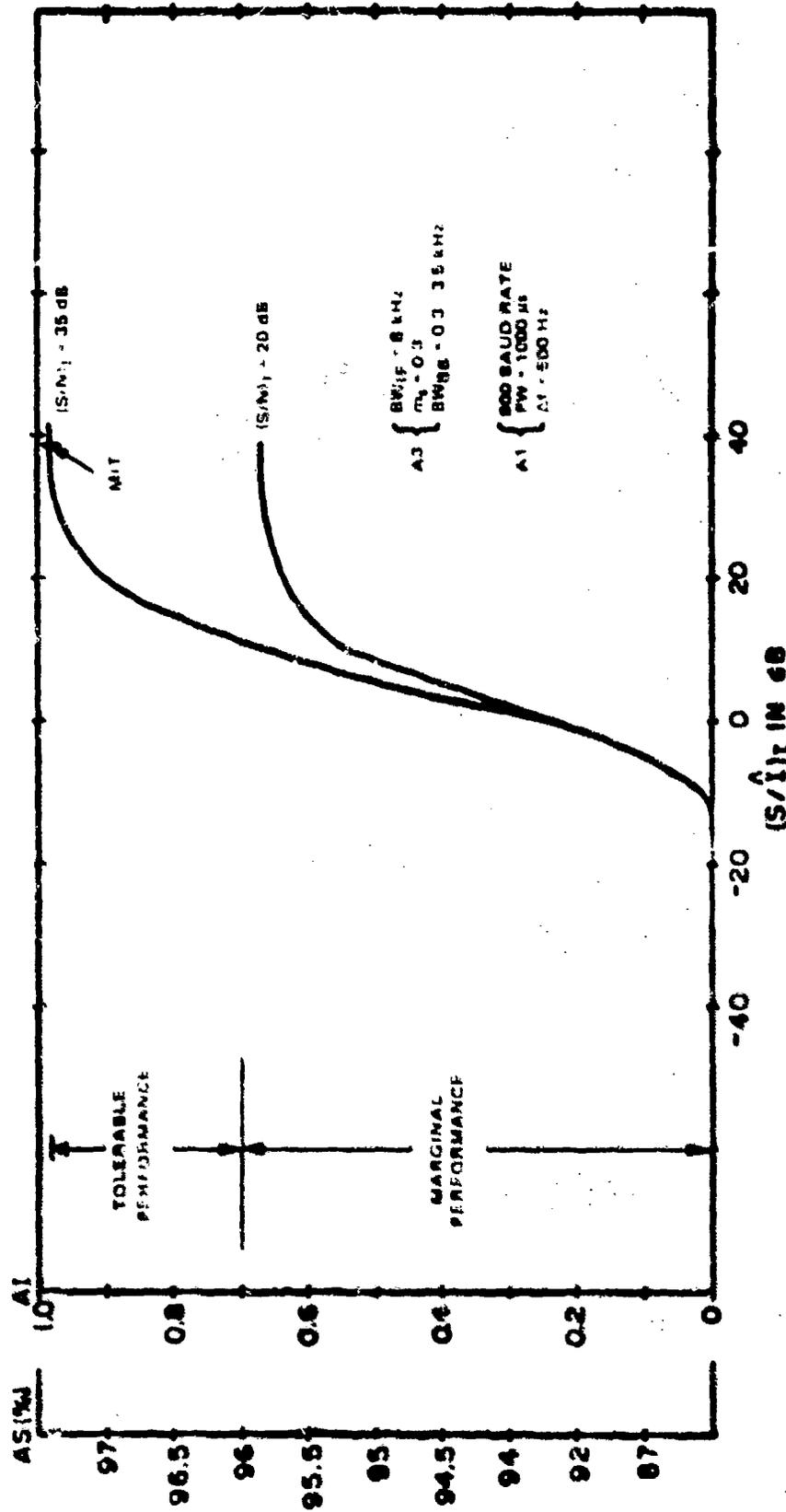


Figure C-16. Performance degradation curve for A3 receiver with A1 interference (800 baud rate, Δf = 500 Hz).

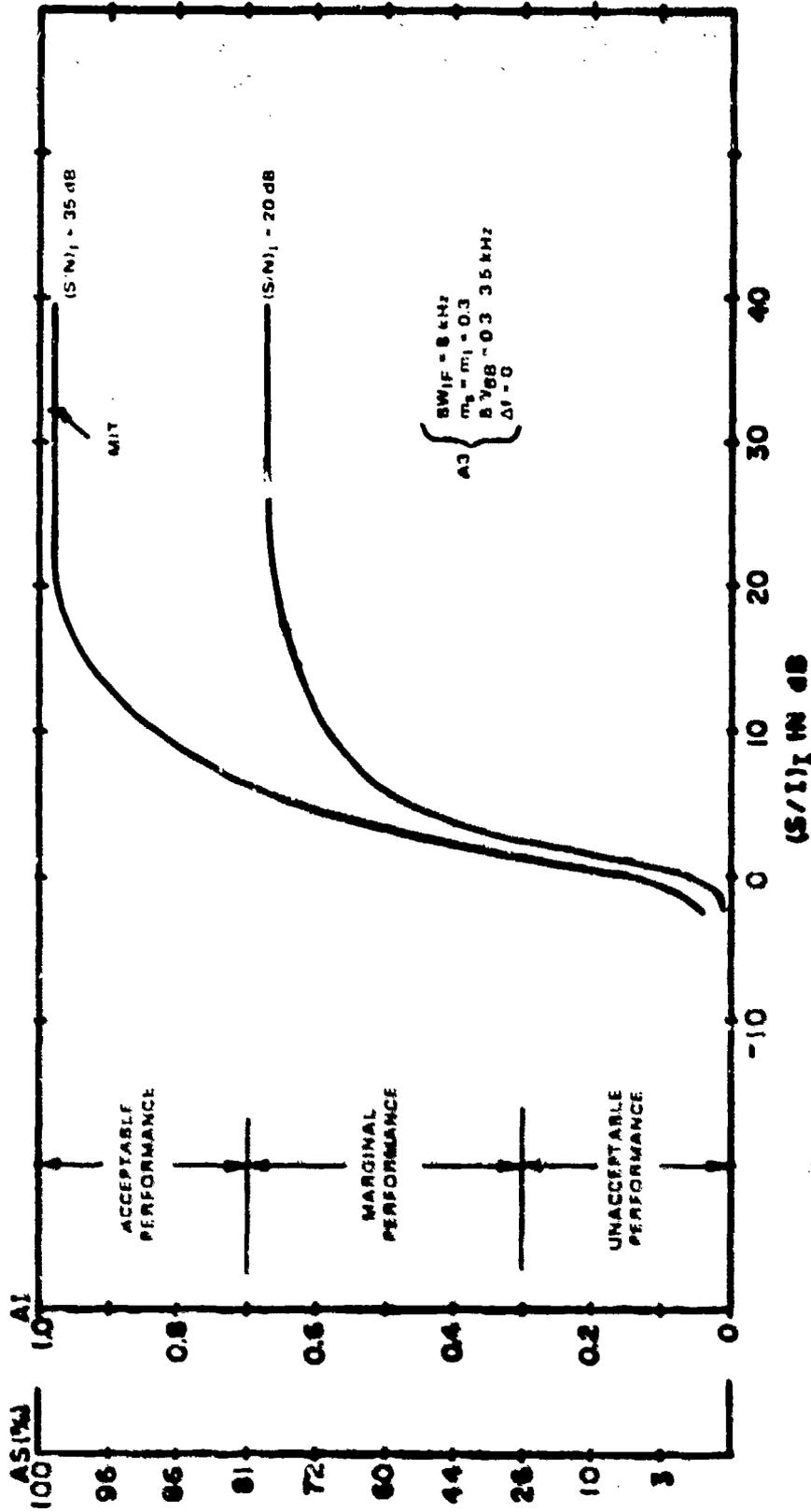


Figure C-17. Performance degradation curve for A3 receiver with A3 interference (Af = 0).

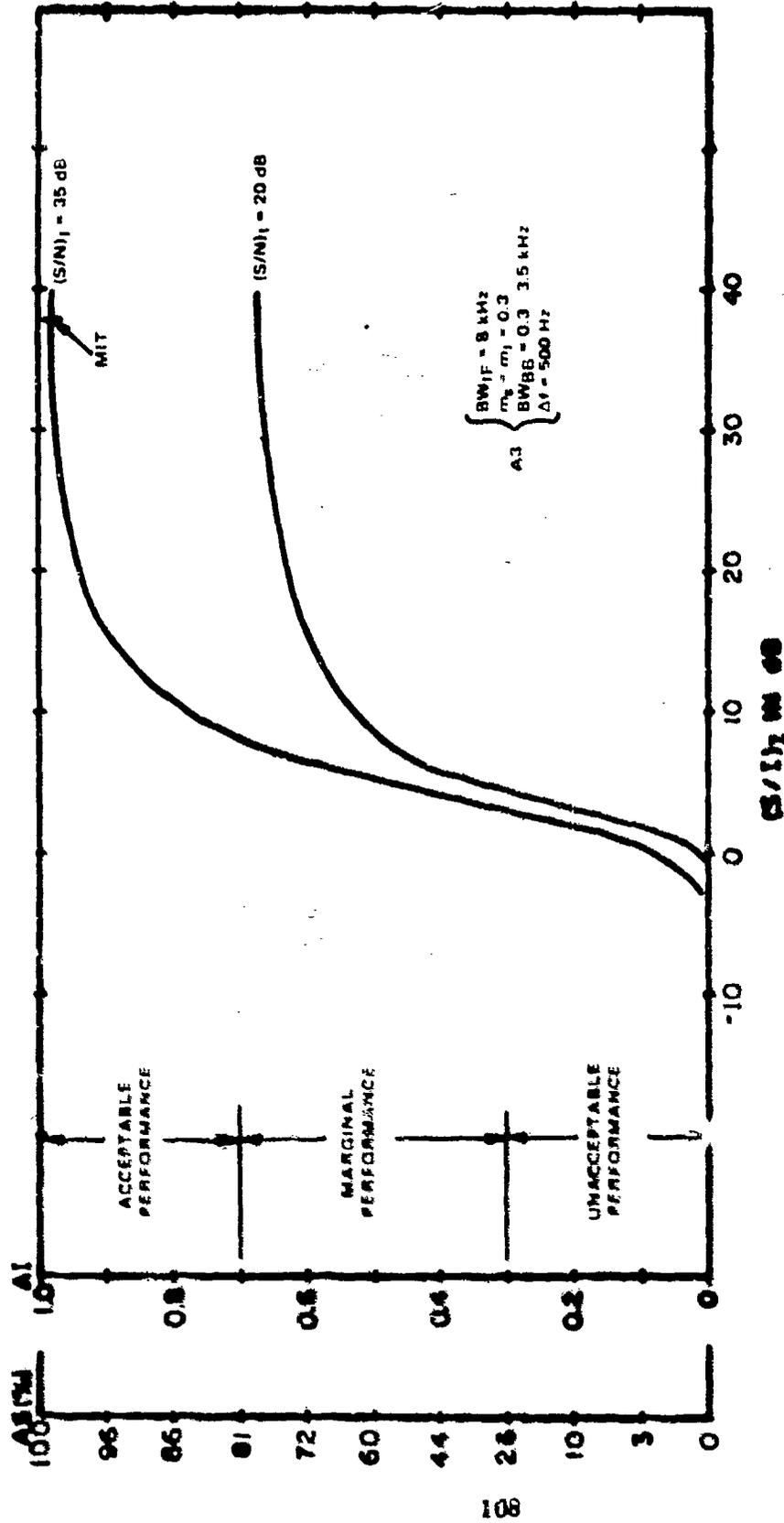


Figure C-18. Performance degradation curve for A3 receiver with A3 interference ( $\Delta f = 500 \text{ Hz}$ ).

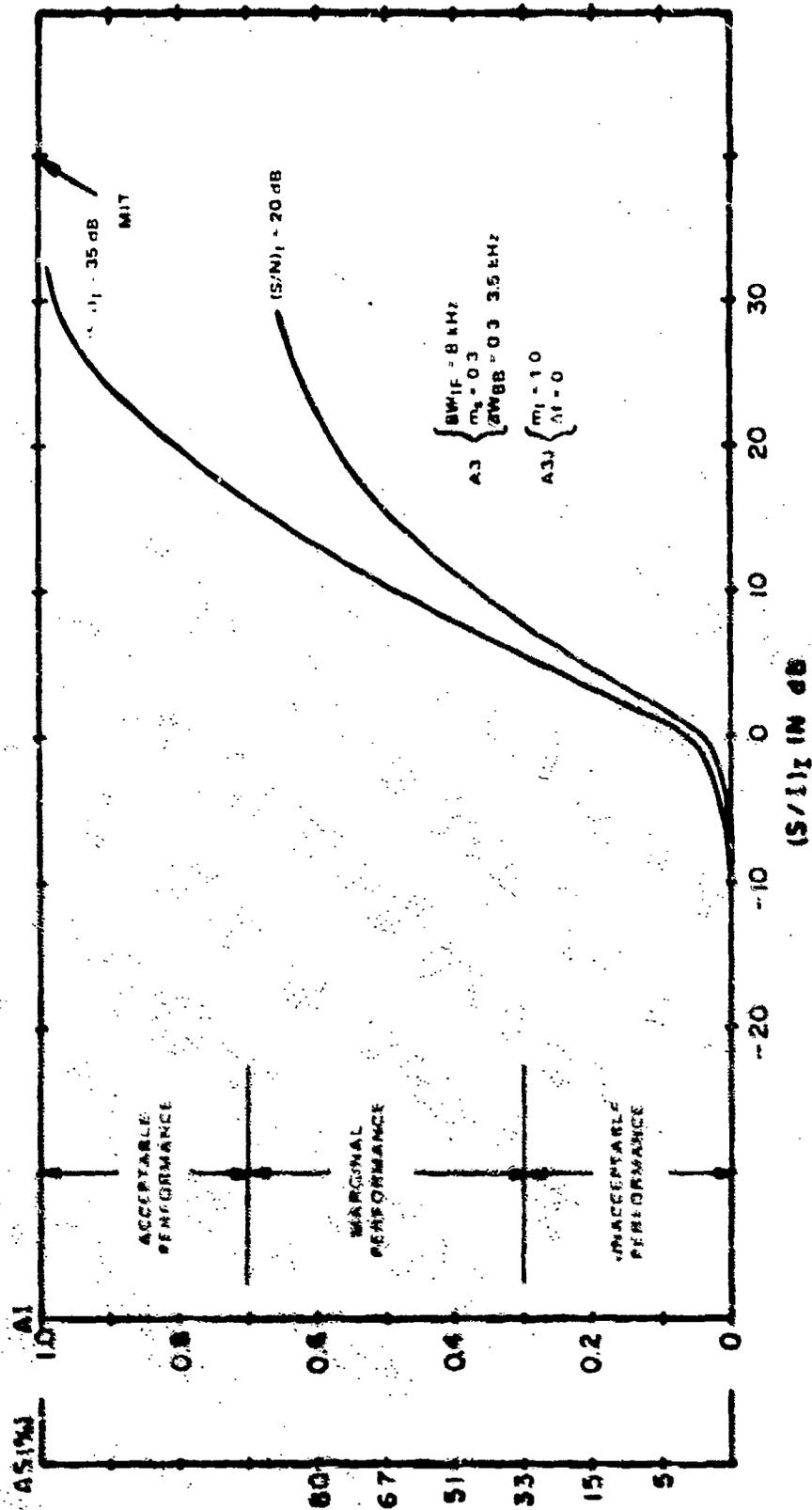


Figure C-19. Performance degradation curve for A3 receiver with A3J interference ( $\Delta f = 0$  Hz).

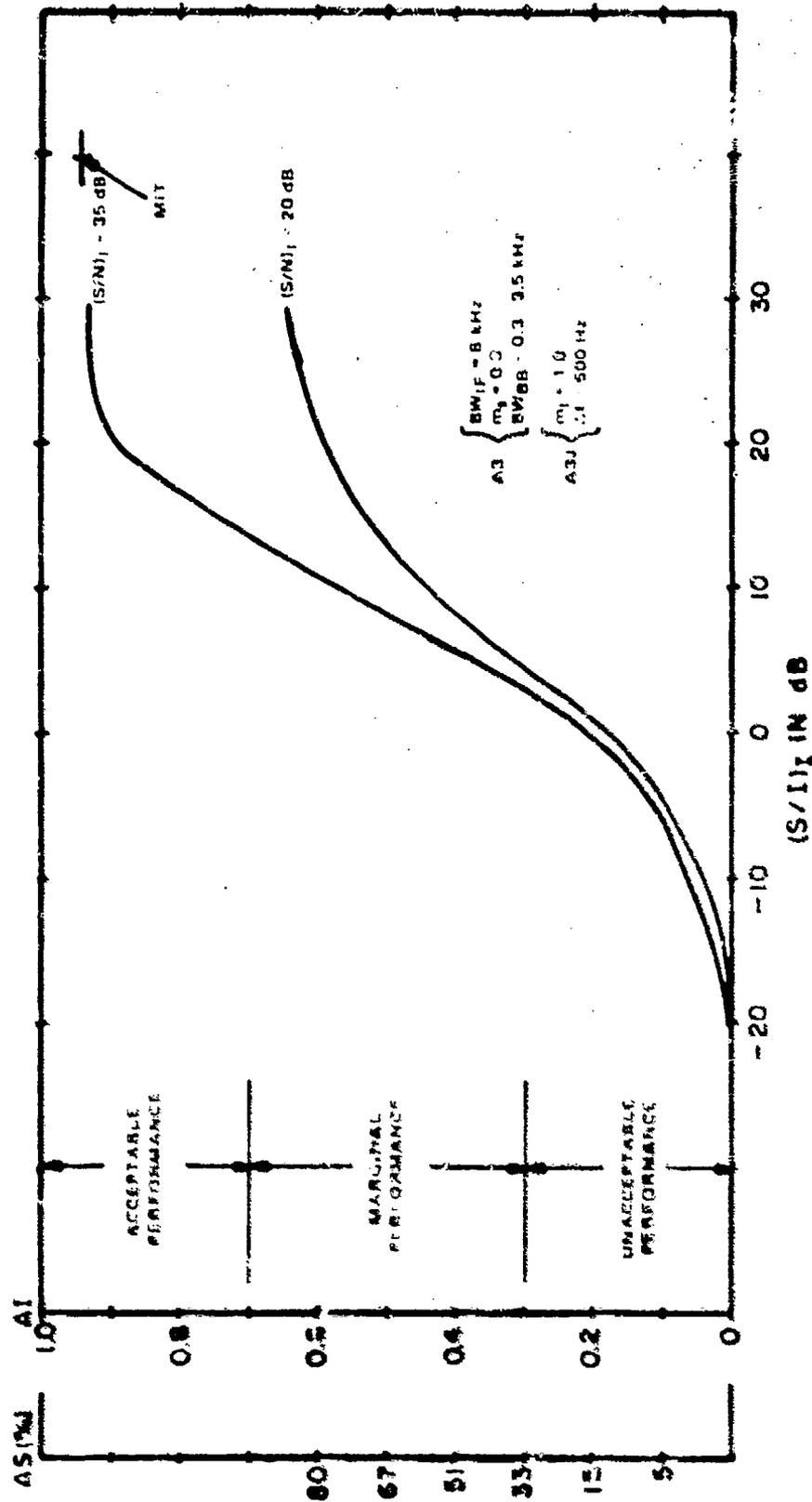


Figure C-10. Performance degradation curve for A3 receiver with A3J interference ( $\Delta f = 500$  Hz).

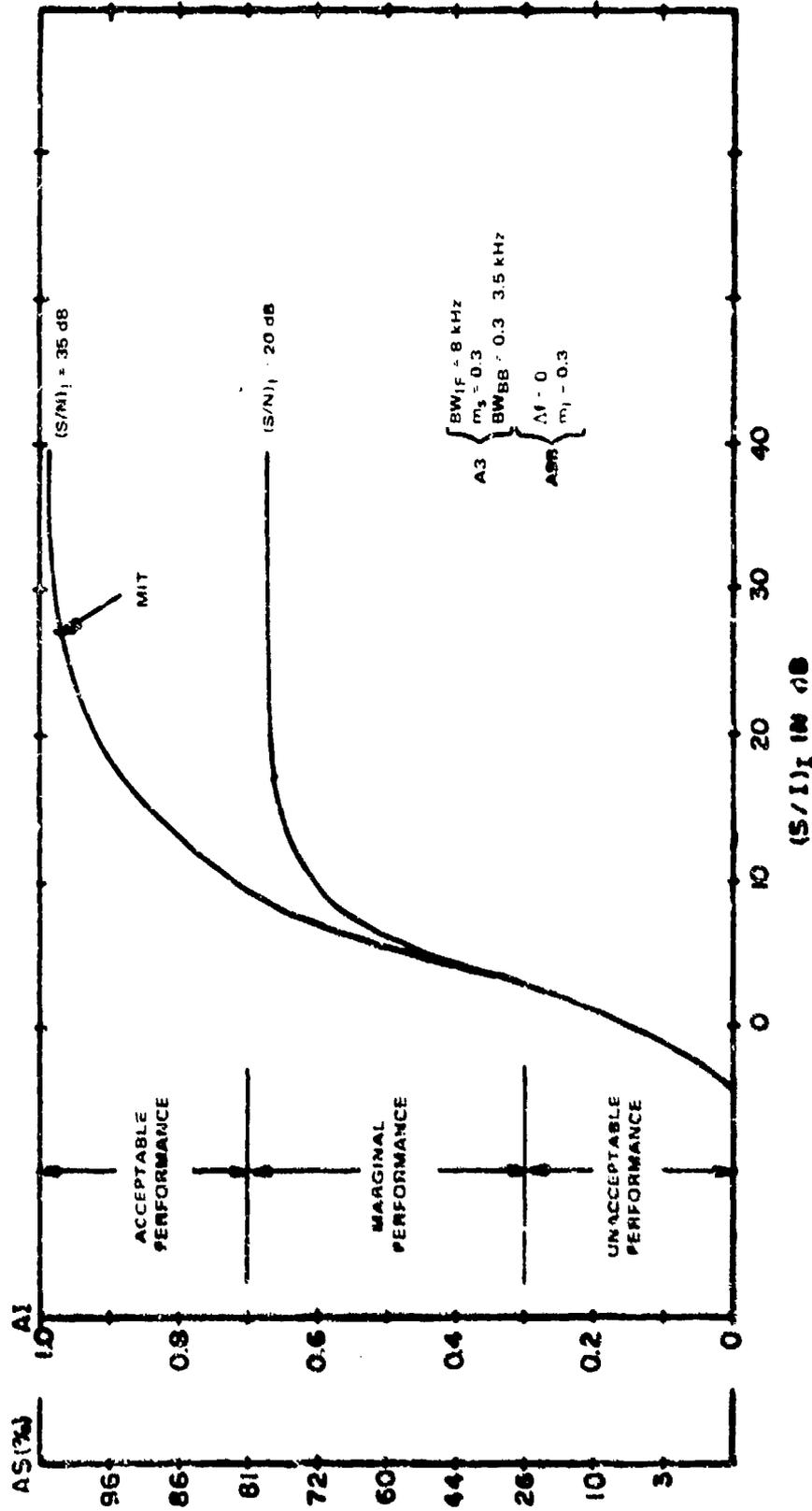


Figure C-21. Performance degradation curve for A3 receiver with A9B interference ( $\Delta f = 0 \text{ Hz}$ ).

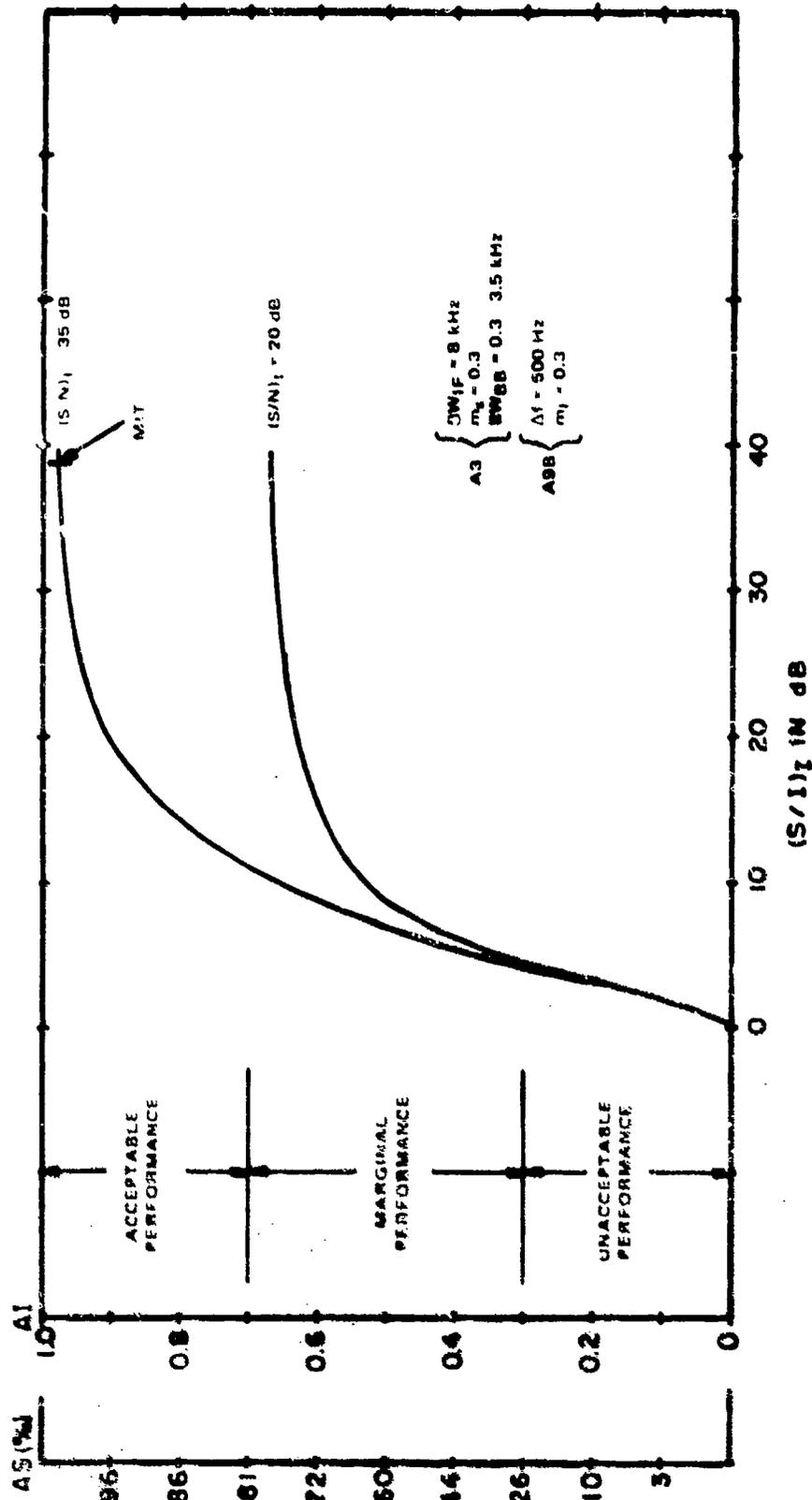


Figure C-22. Performance degradation curve for A3 receiver with A9B interference ( $\Delta f = 500 \text{ Hz}$ ).

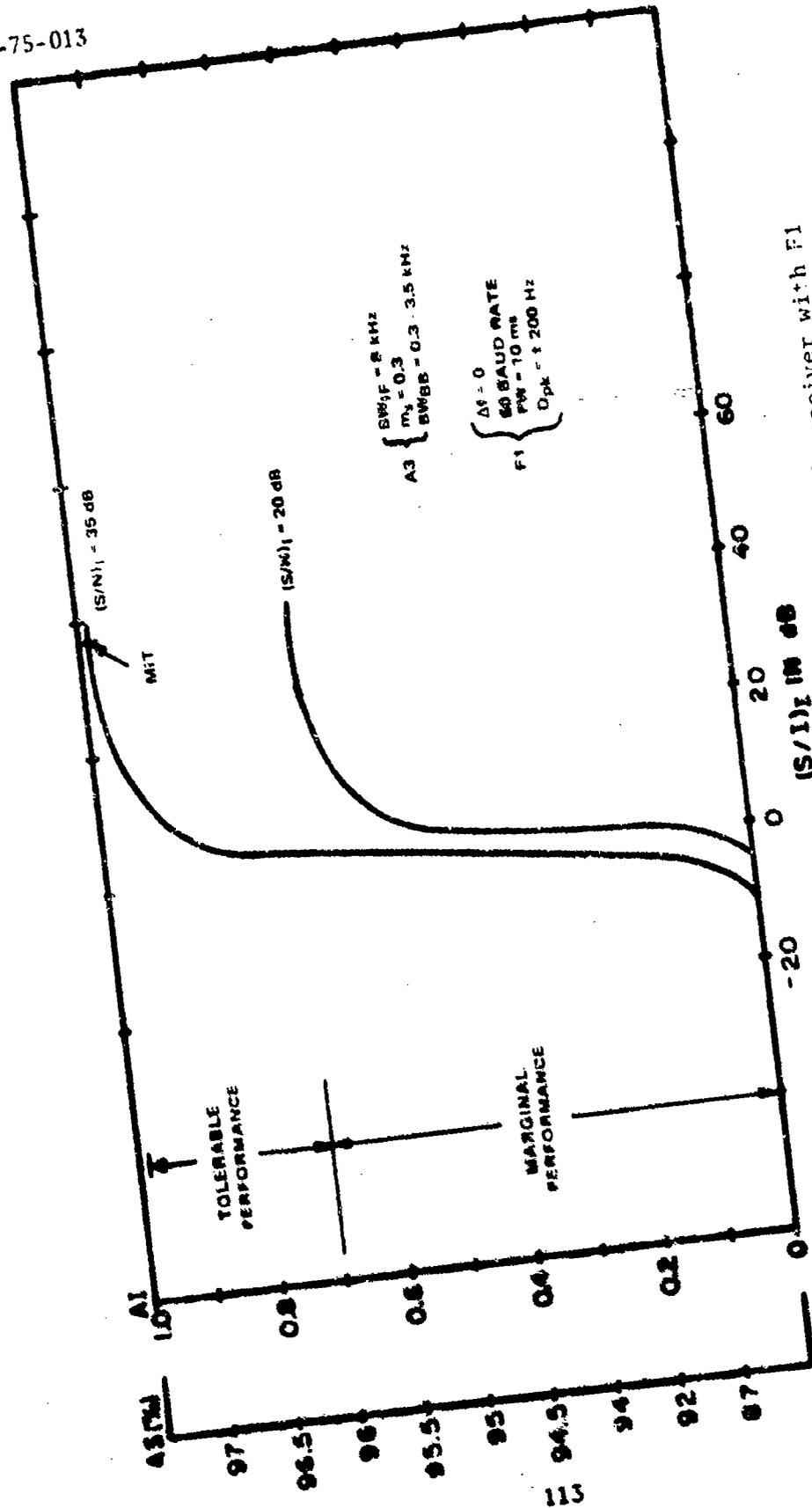


Figure C-23. Performance degradation curve for A3 receiver with F1 interference ( $\Delta f = 0 \text{ Hz}$ ).

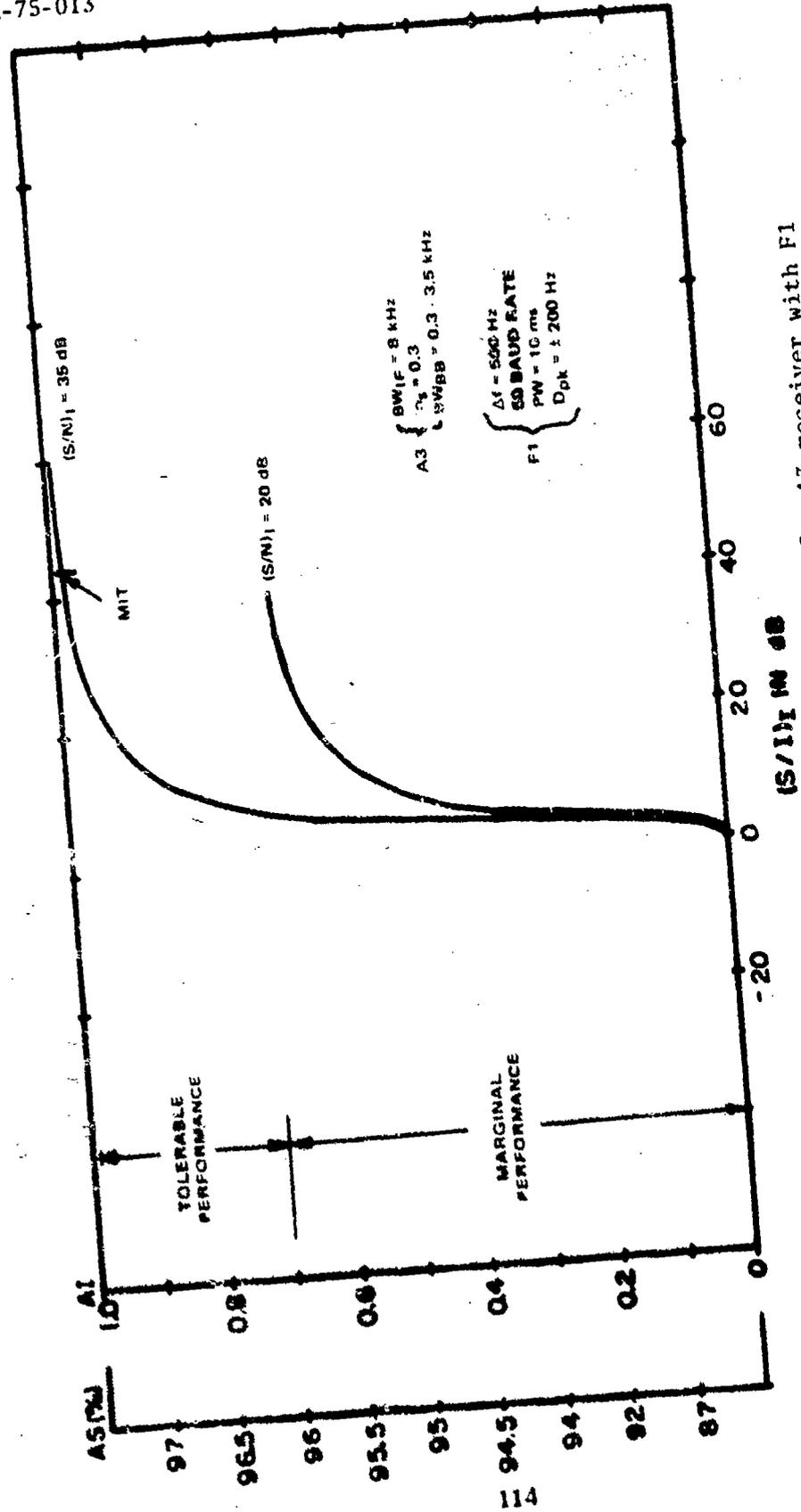


Figure C-24. Performance degradation curve for A3 receiver with F1 interference (Δf = 500 Hz).

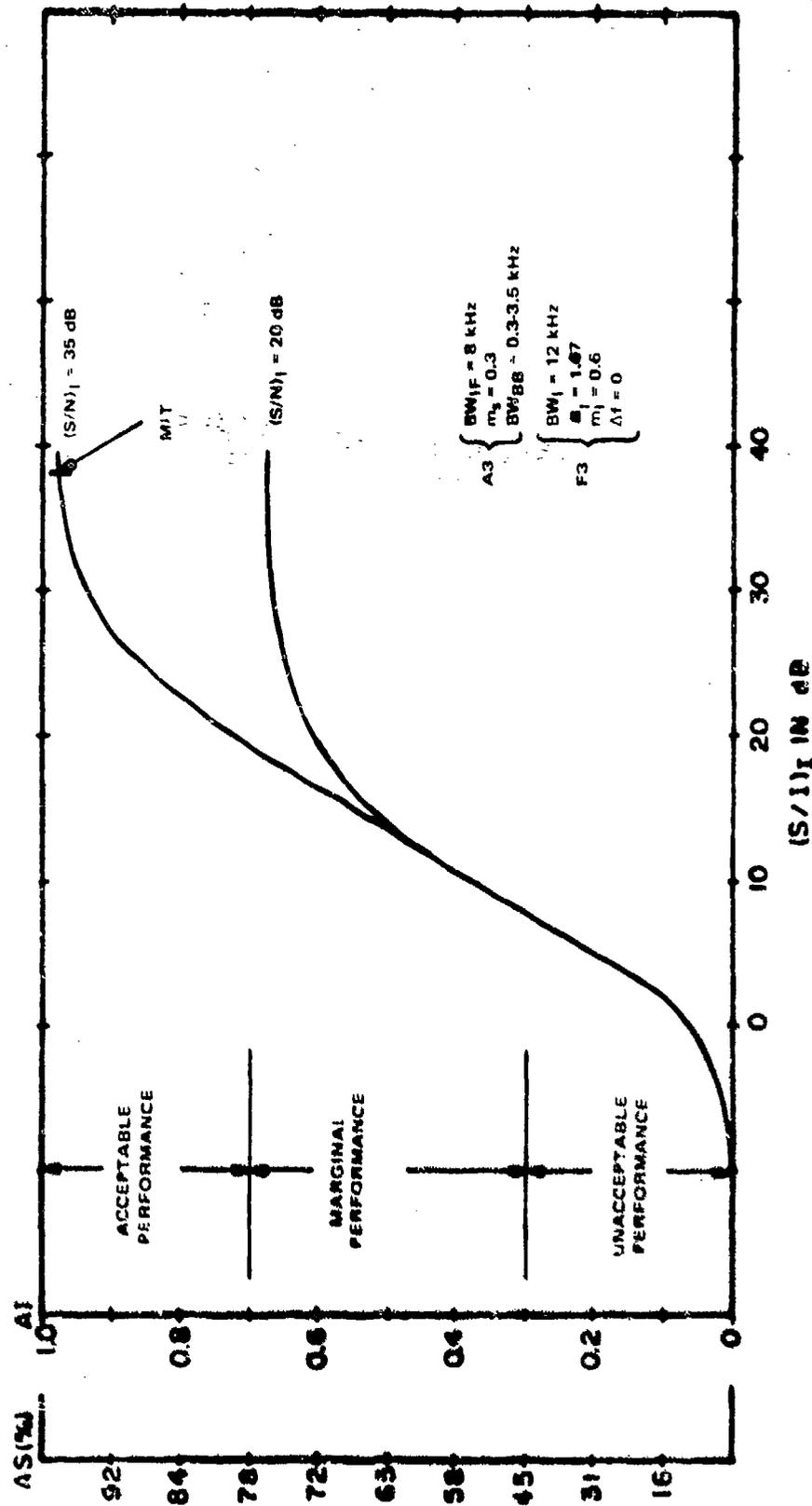


Figure C-25. Performance degradation curve for A3 receiver with F3 interference.

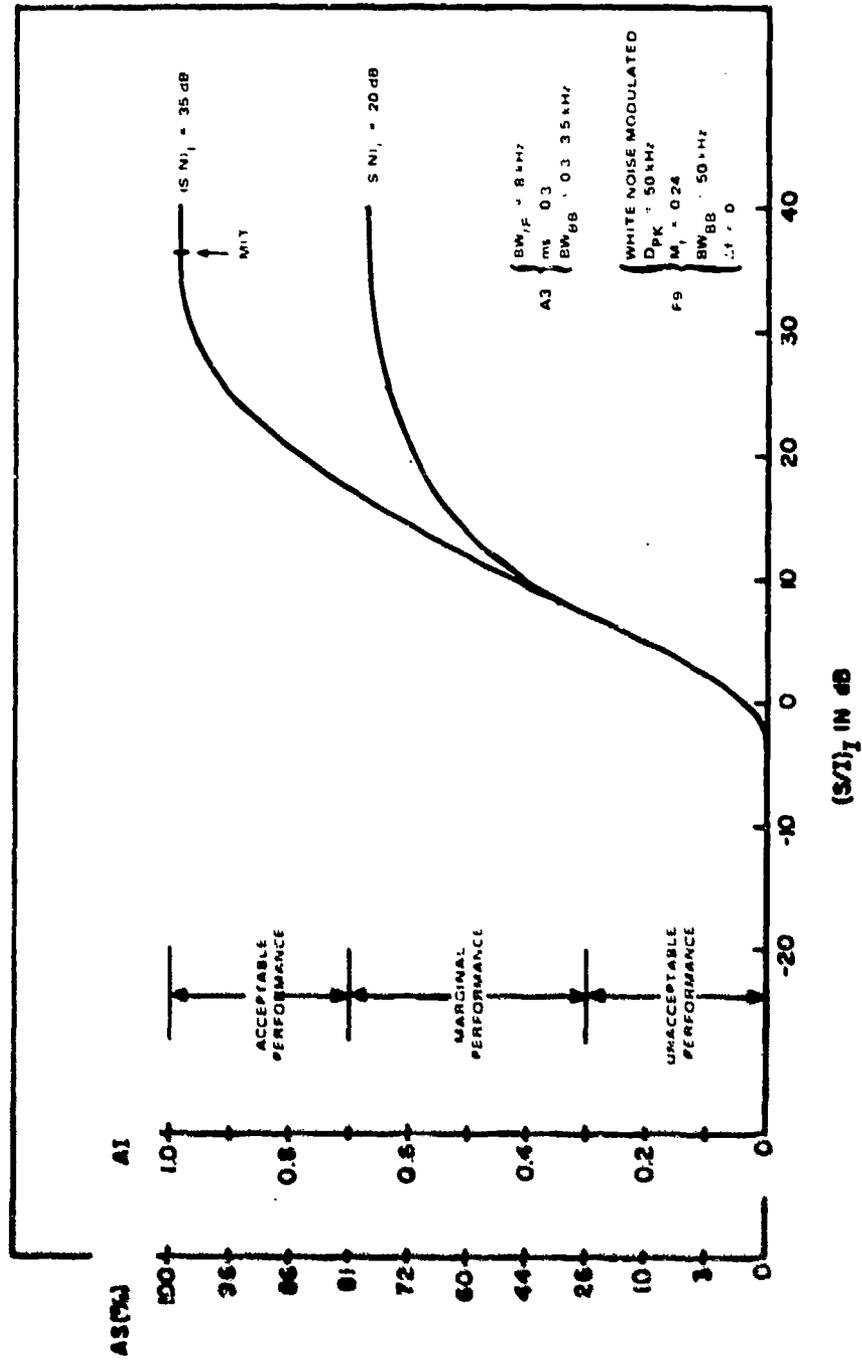


Figure C-26. Performance degradation curve for A3 receiver with F9 interference.

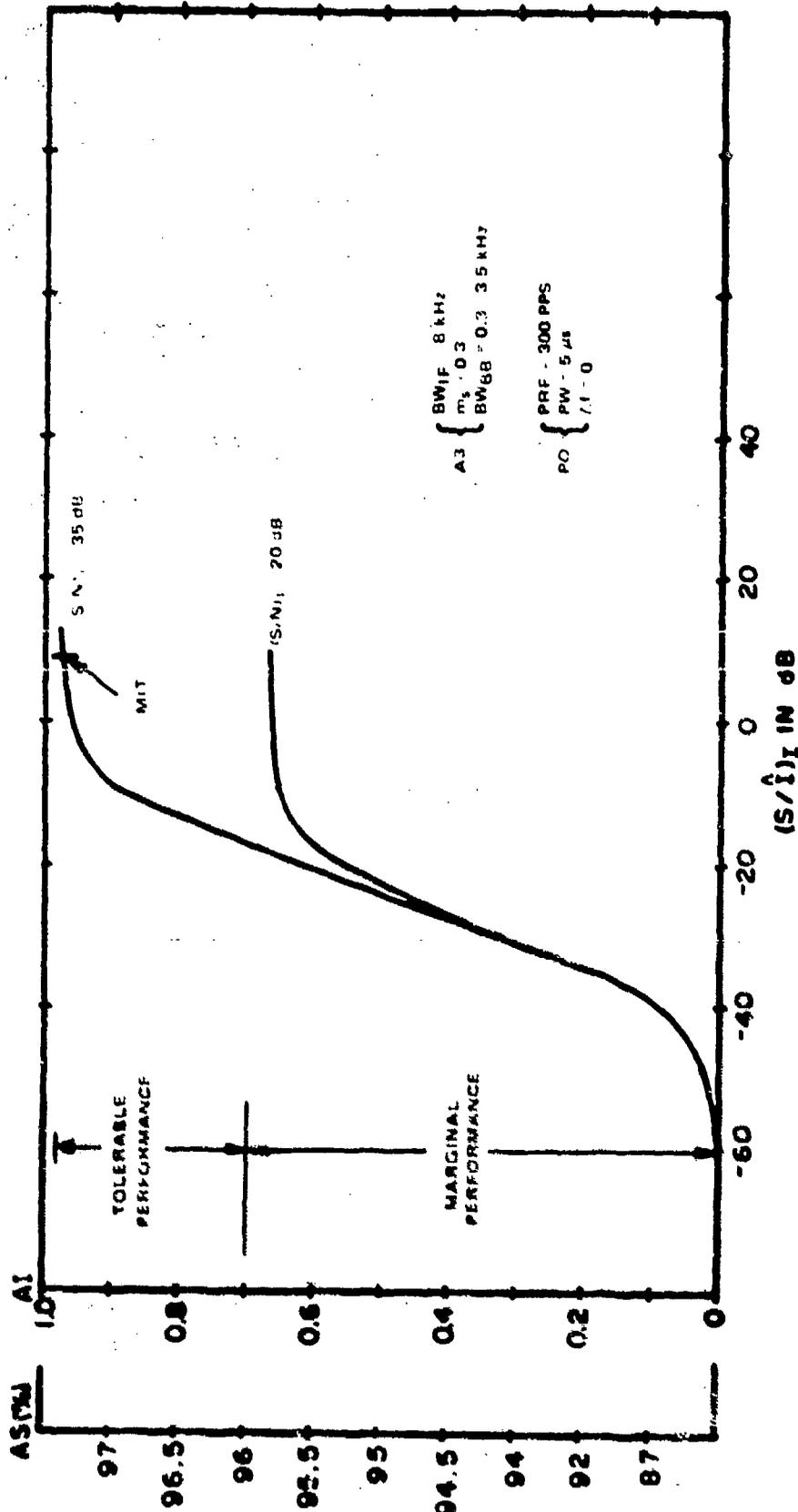


Figure C-27. Performance degradation curve for A3 receiver with PO interference ( $A_f = 0$  Hz).

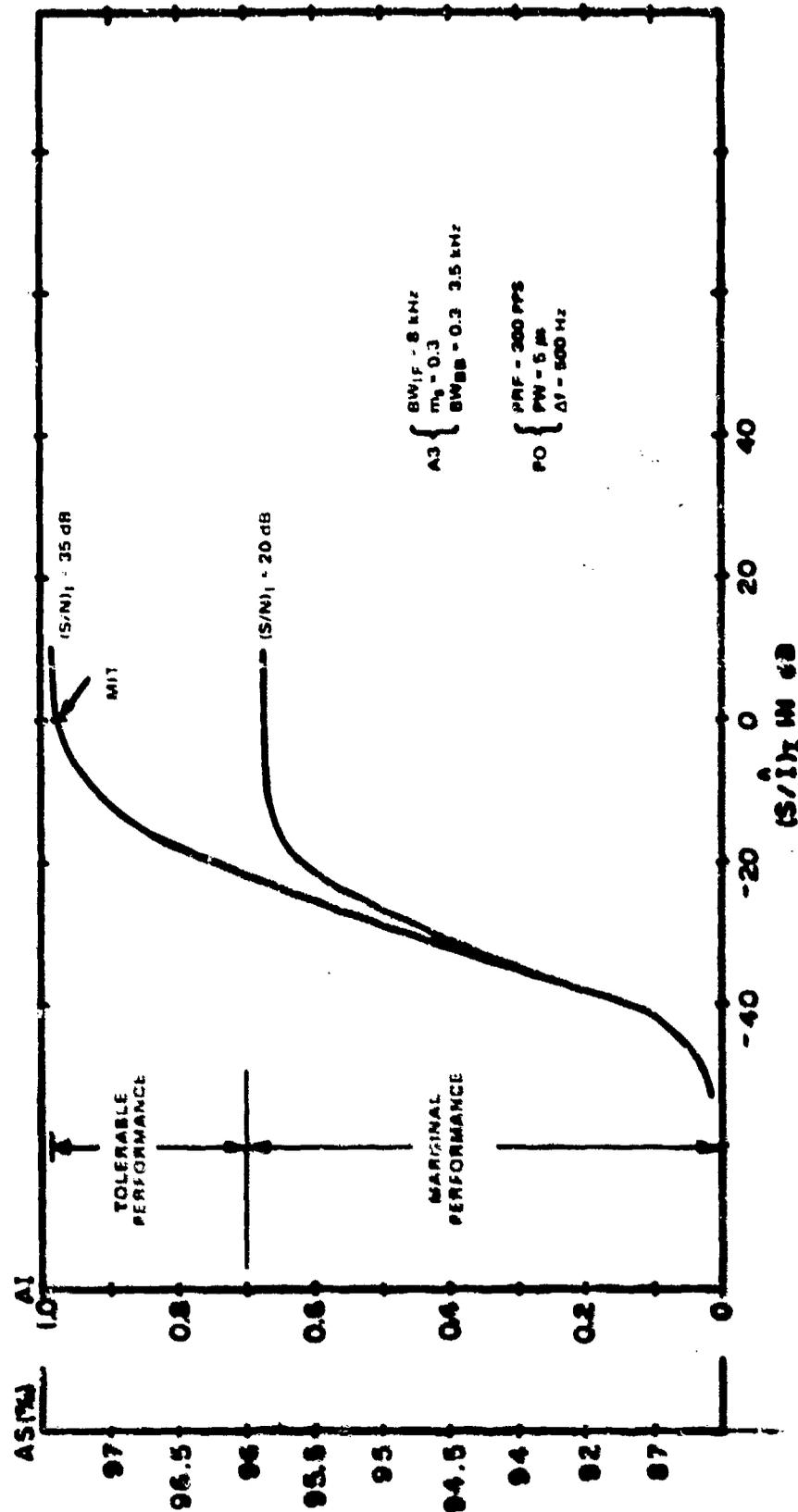


Figure C-28. Performance degradation curve for A3 receiver with PO interference ( $\Delta f = 500$  Hz).

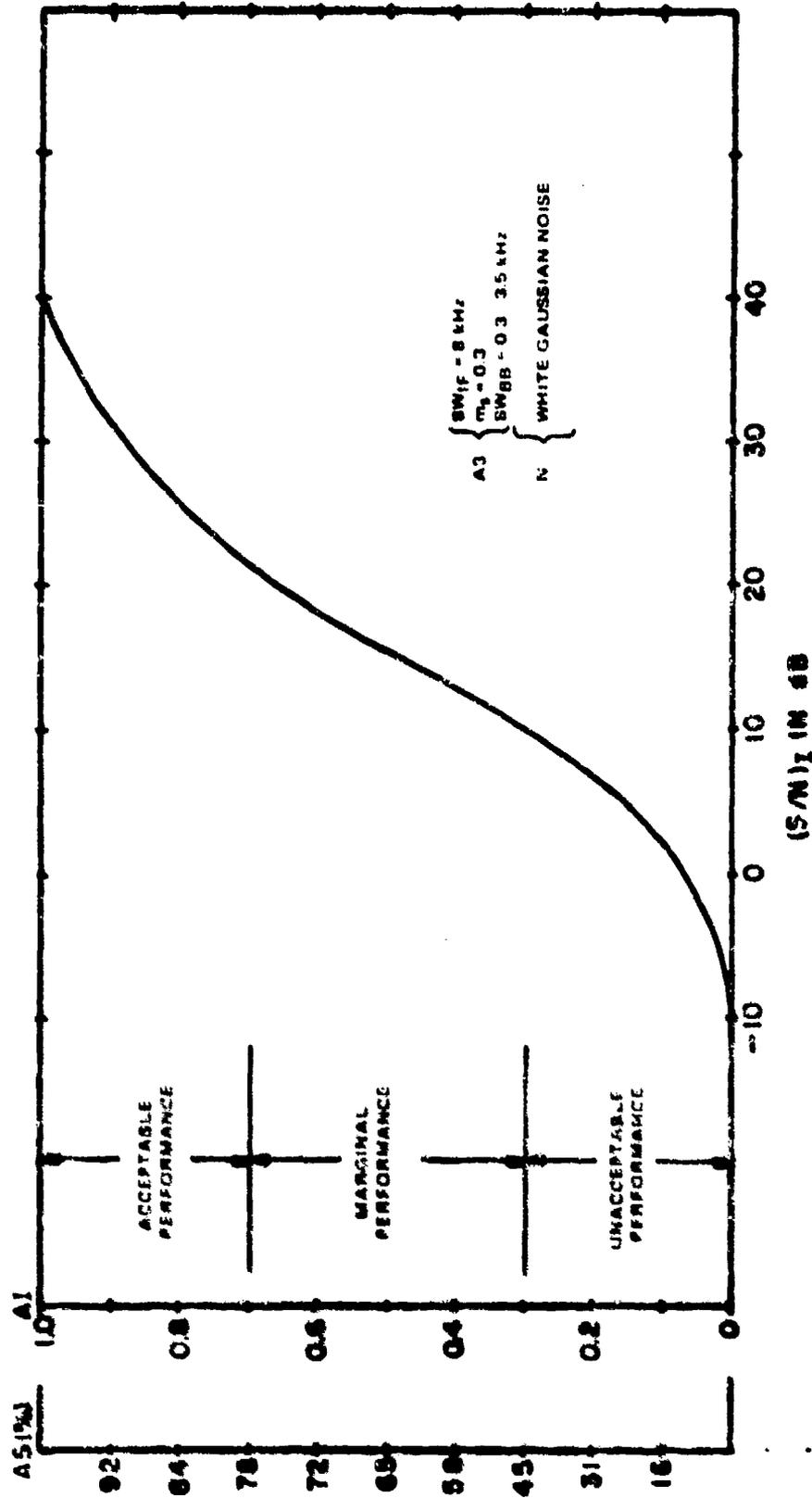


Figure C-20. Performance degradation curve for A3 receiver with noise.

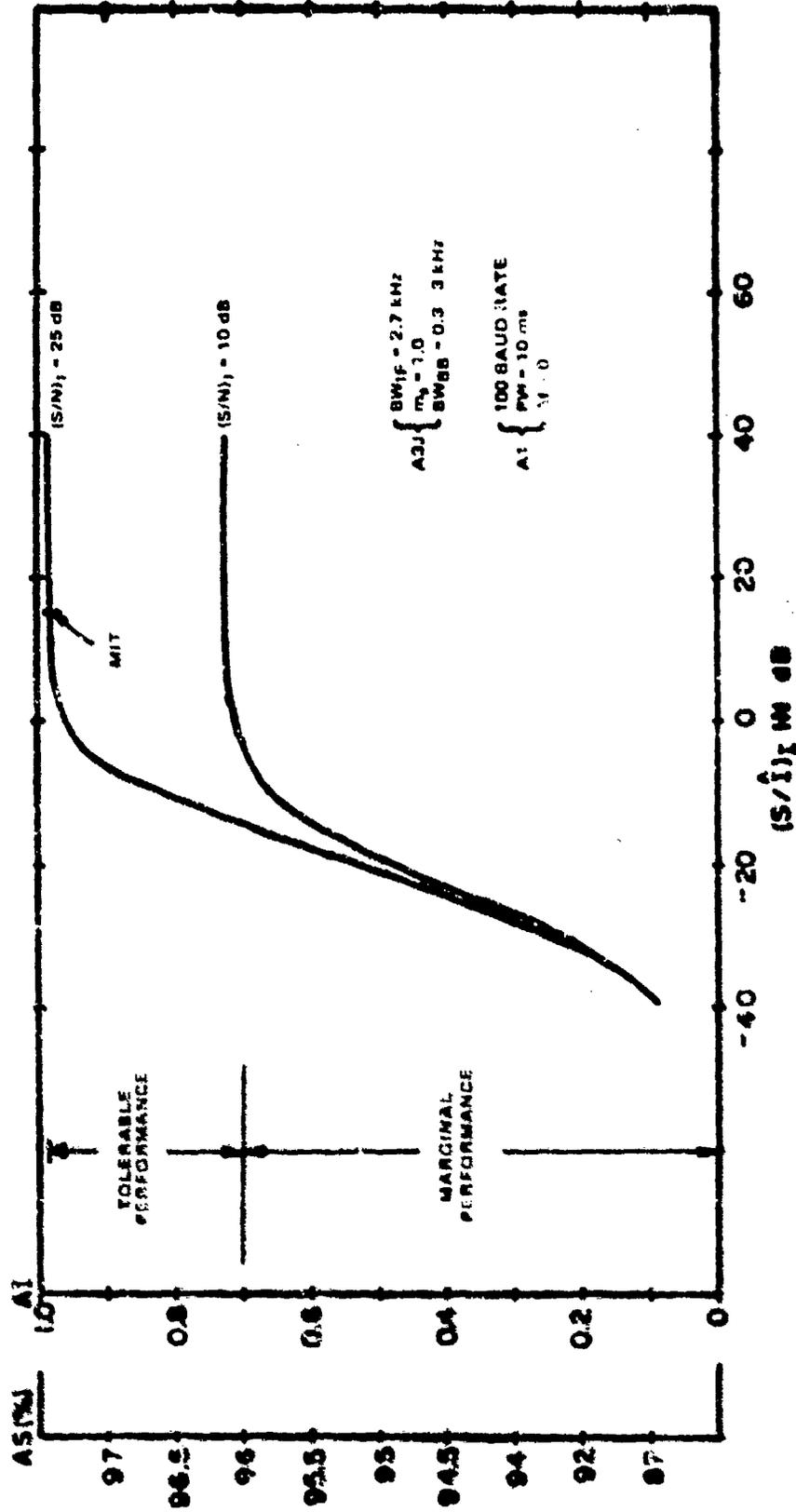


Figure C-30. Performance degradation curve for A3J receiver with A1 interference (100 baud rate; Δf = 0 Hz).

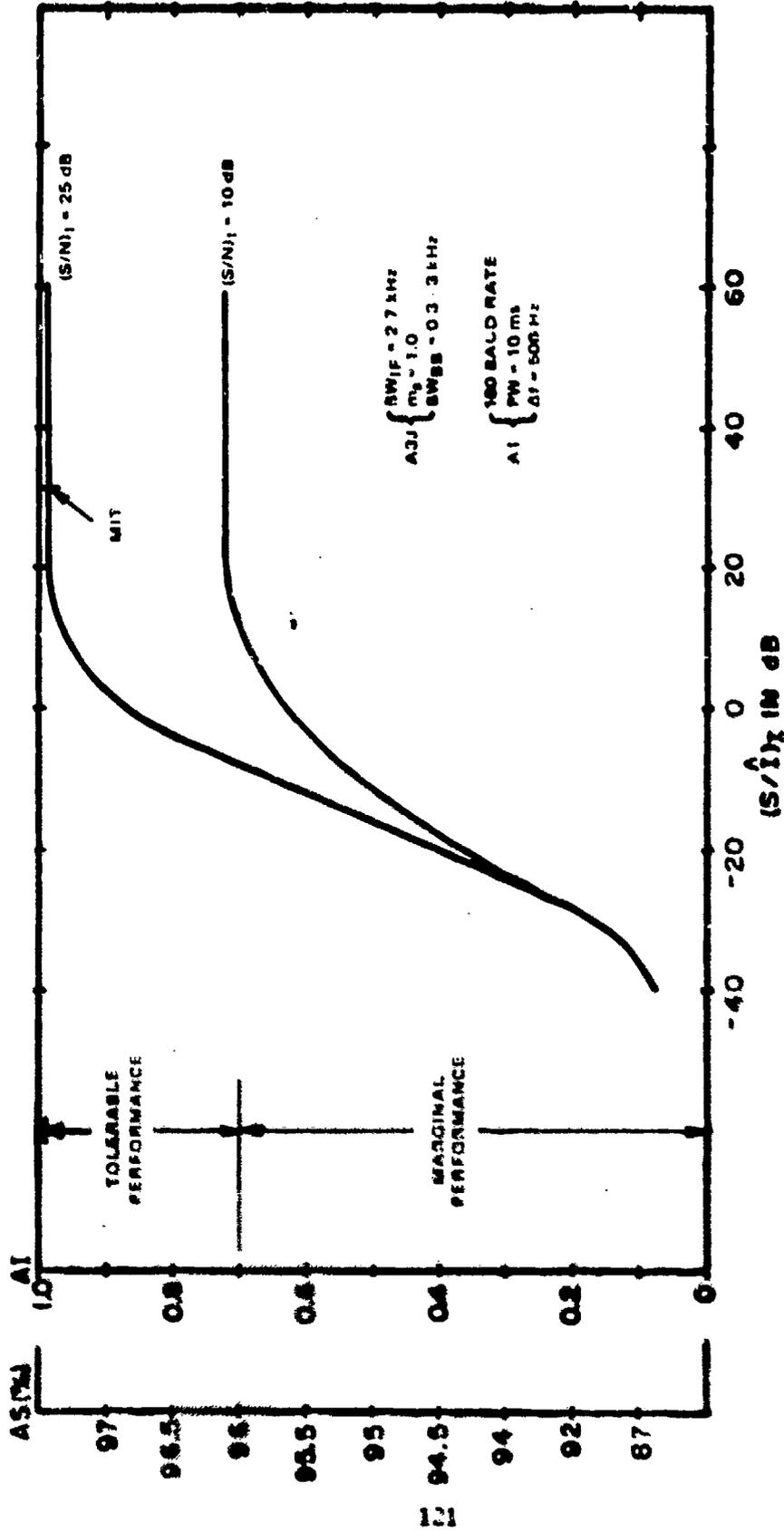


Figure C-31. Performance degradation curve for ASJ receiver with AI interference (100 baud rate, Δf = 500 Hz).

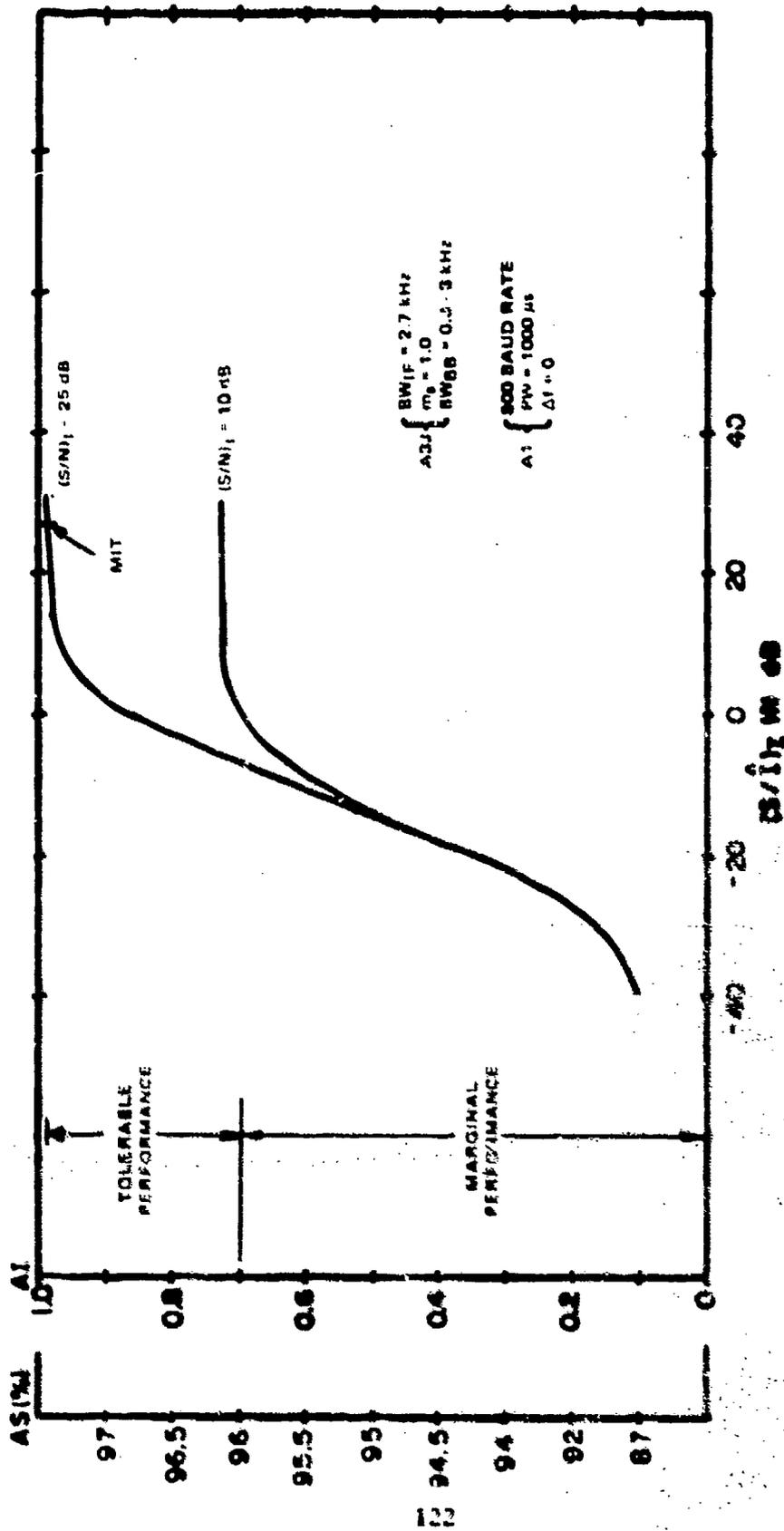


Figure C-32. Performance degradation curve for A3J receiver with AI interference (800 baud rate, Δf = 0 Hz).

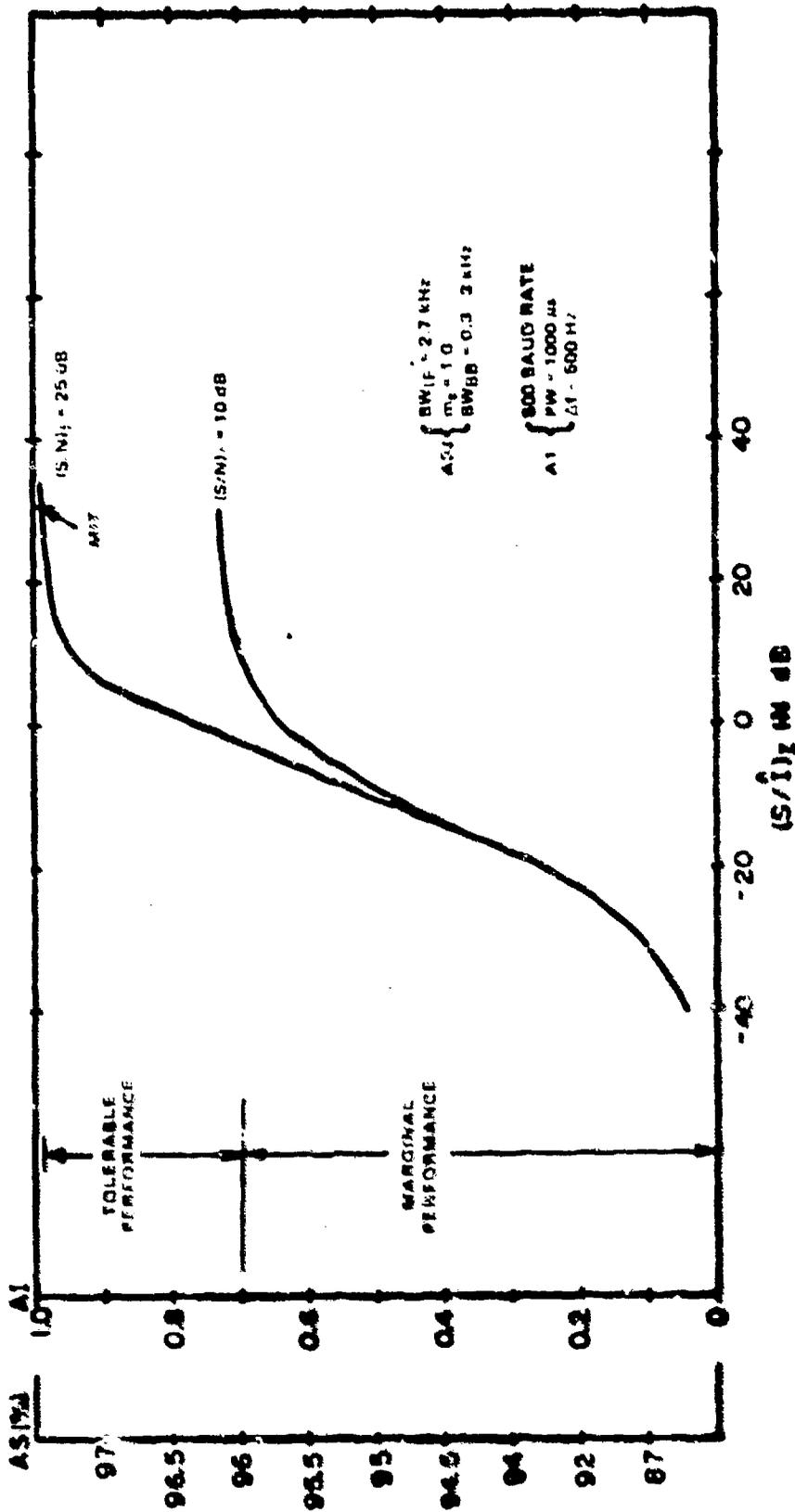


Figure C-31. Performance degradation curve for A3J receiver with A1 interference (800 baud rate,  $\Delta f = 500$  Hz).

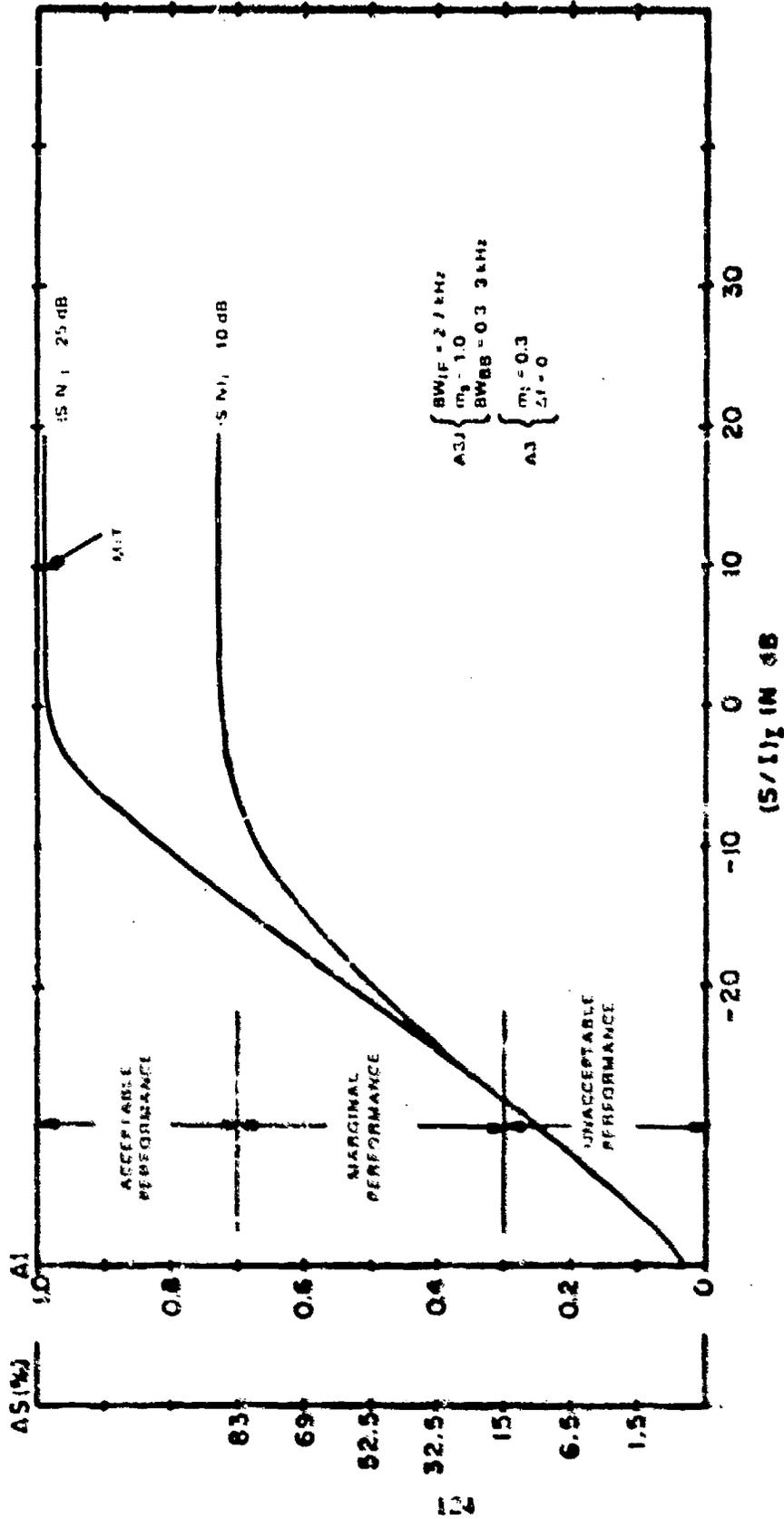


Figure C-34. Performance degradation curve for A3J receiver with A3 interference ( $\Delta f = 0 \text{ Hz}$ ).

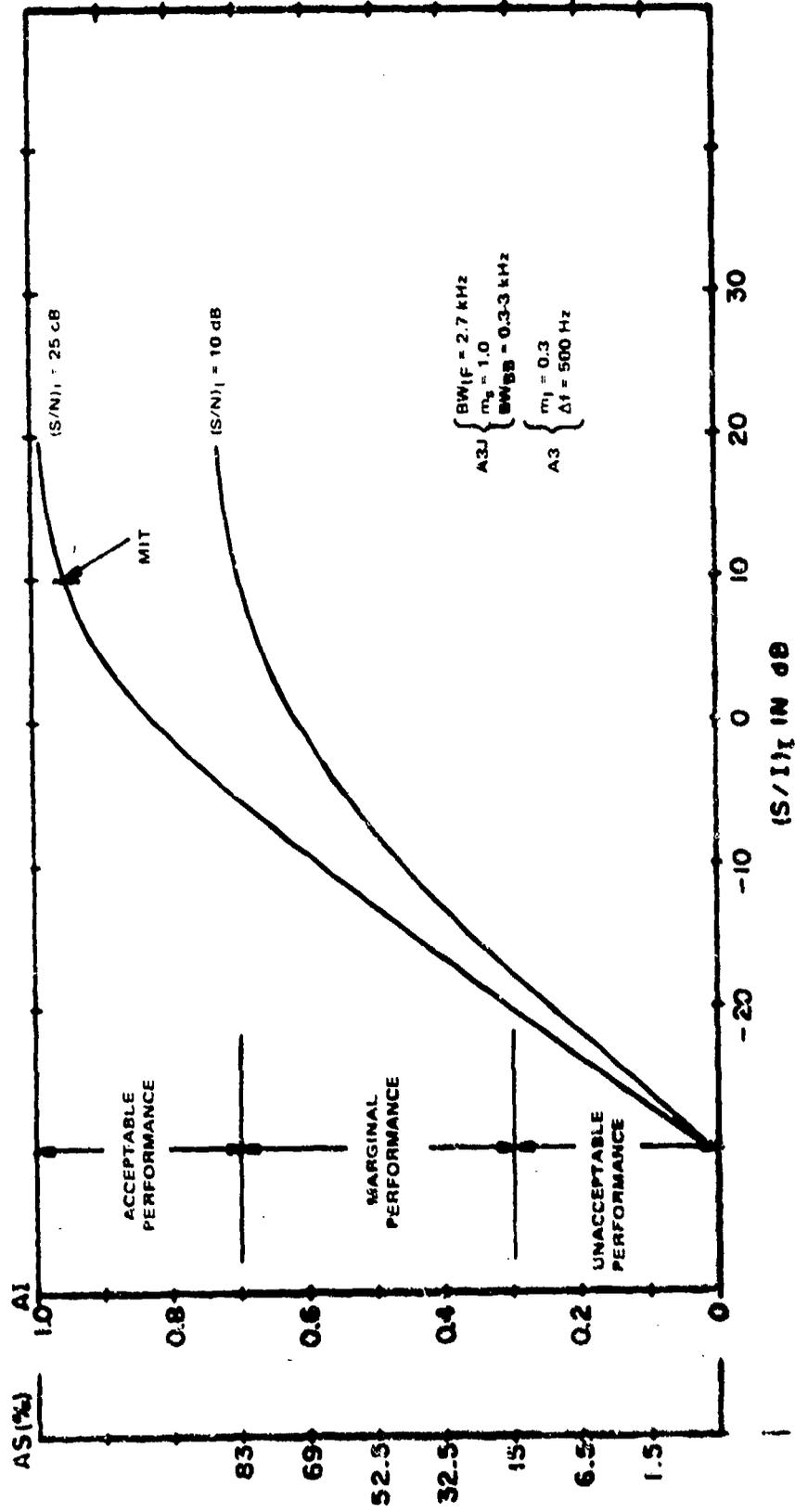


Figure C-35. Performance degradation curve for A3J receiver with A3 interference ( $\Delta f = 500 \text{ Hz}$ ).

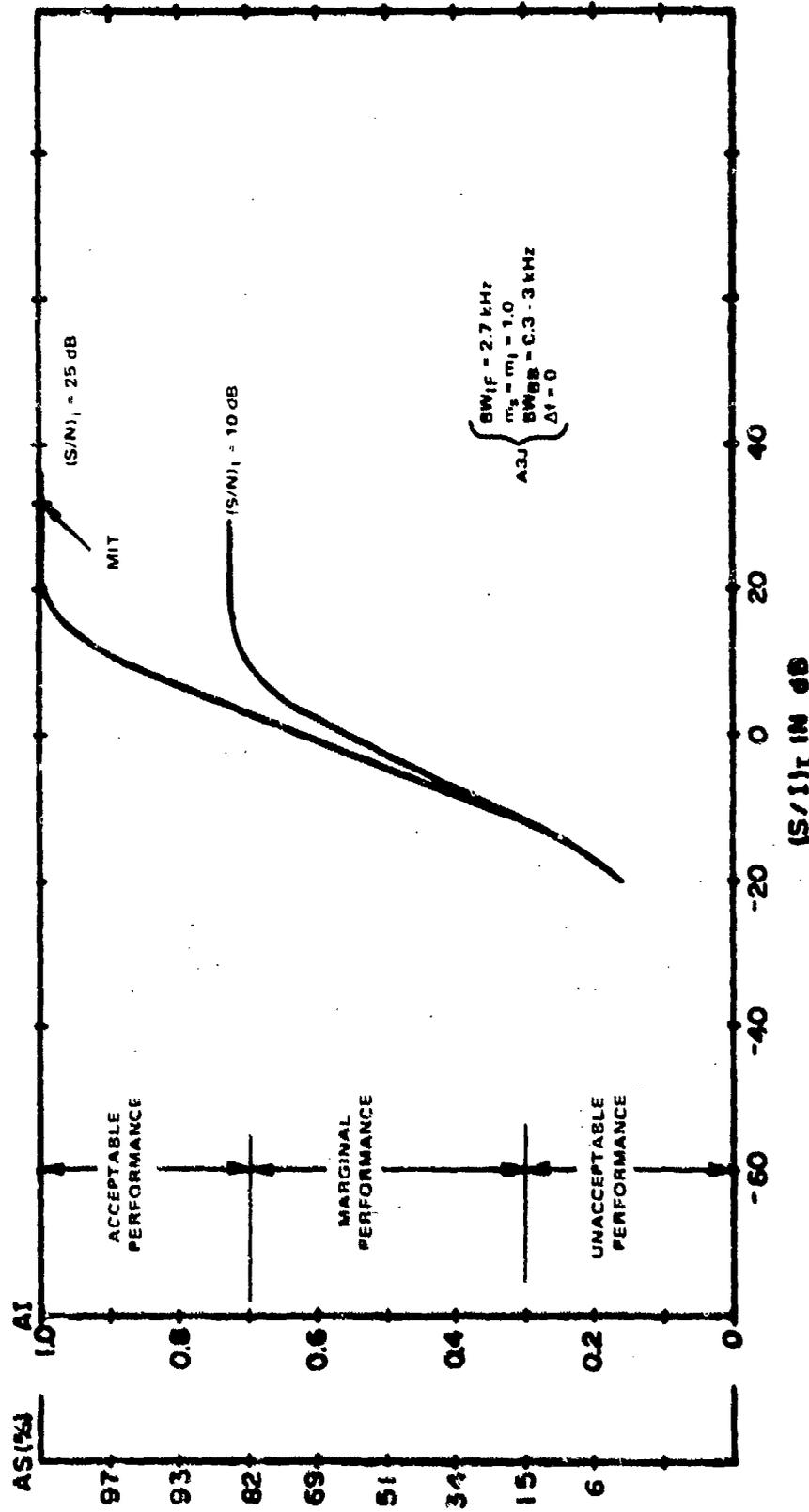


Figure C-36. Performance degradation curve for A3J receiver with A3J interference ( $\Delta f = 0$  Hz).

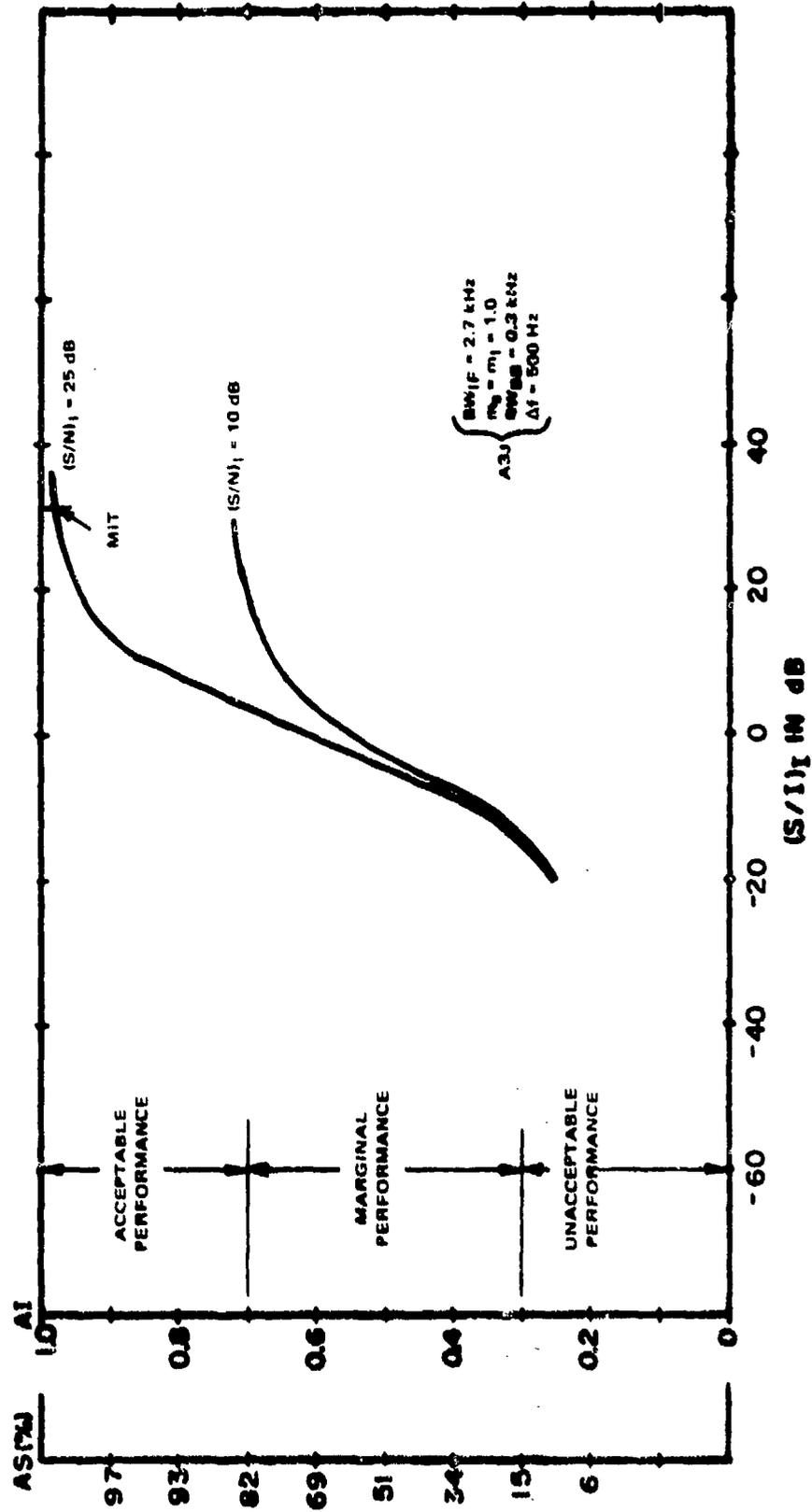


Figure C-37. Performance degradation curve for A3J receiver with A3J interference ( $\Delta f = 500$  Hz).

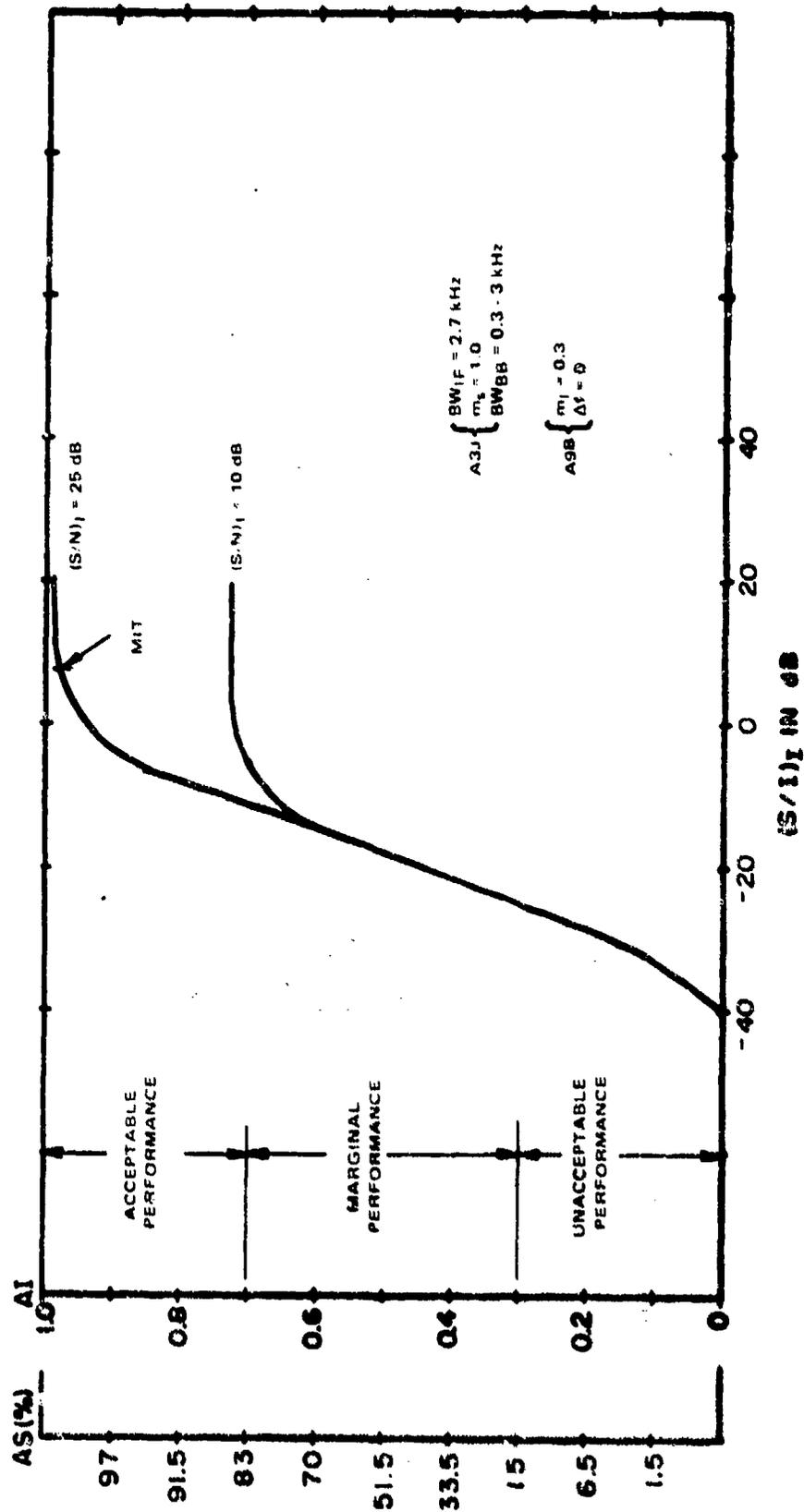


Figure C-38. Performance degradation curve for A3J receiver with A9B interference ( $\Delta f = 0 \text{ Hz}$ ).

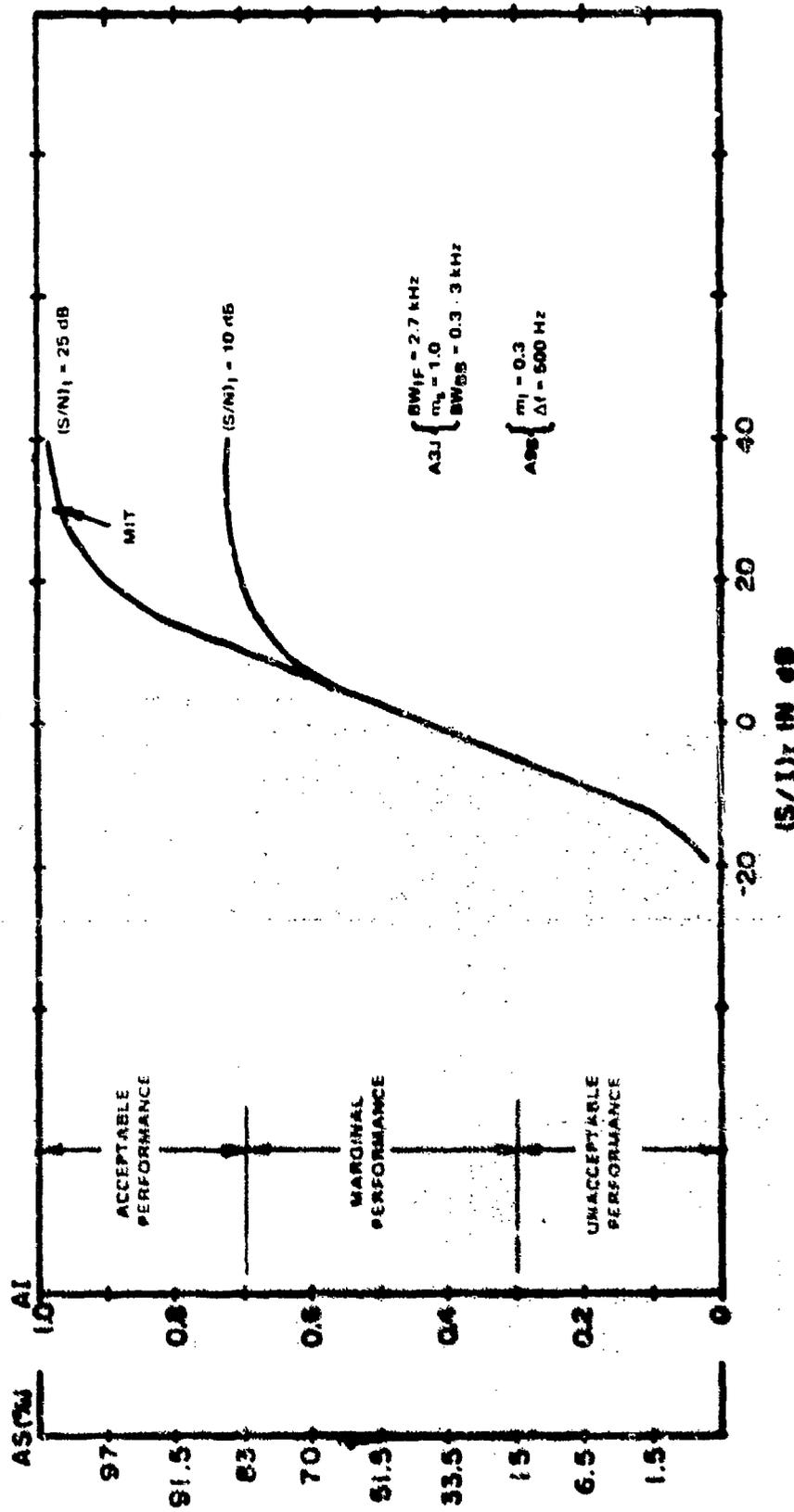


Figure C-39. Performance degradation curve A3J receiver with A9B interference ( $\Delta f = 500$  Hz).

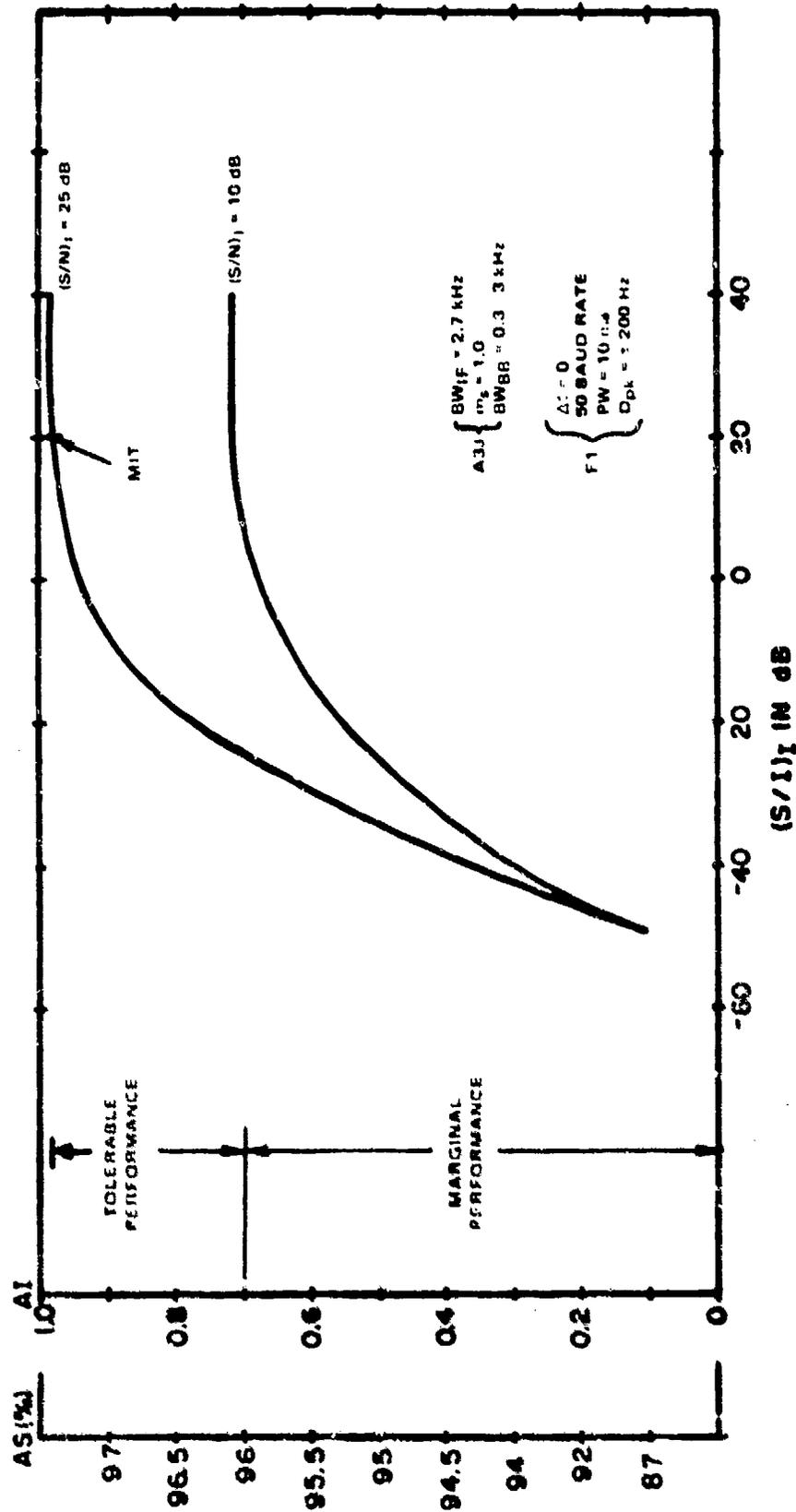


Figure C-40. Performance degradation curve for A3J receiver with F1 interference ( $\Delta f = 0$  Hz).

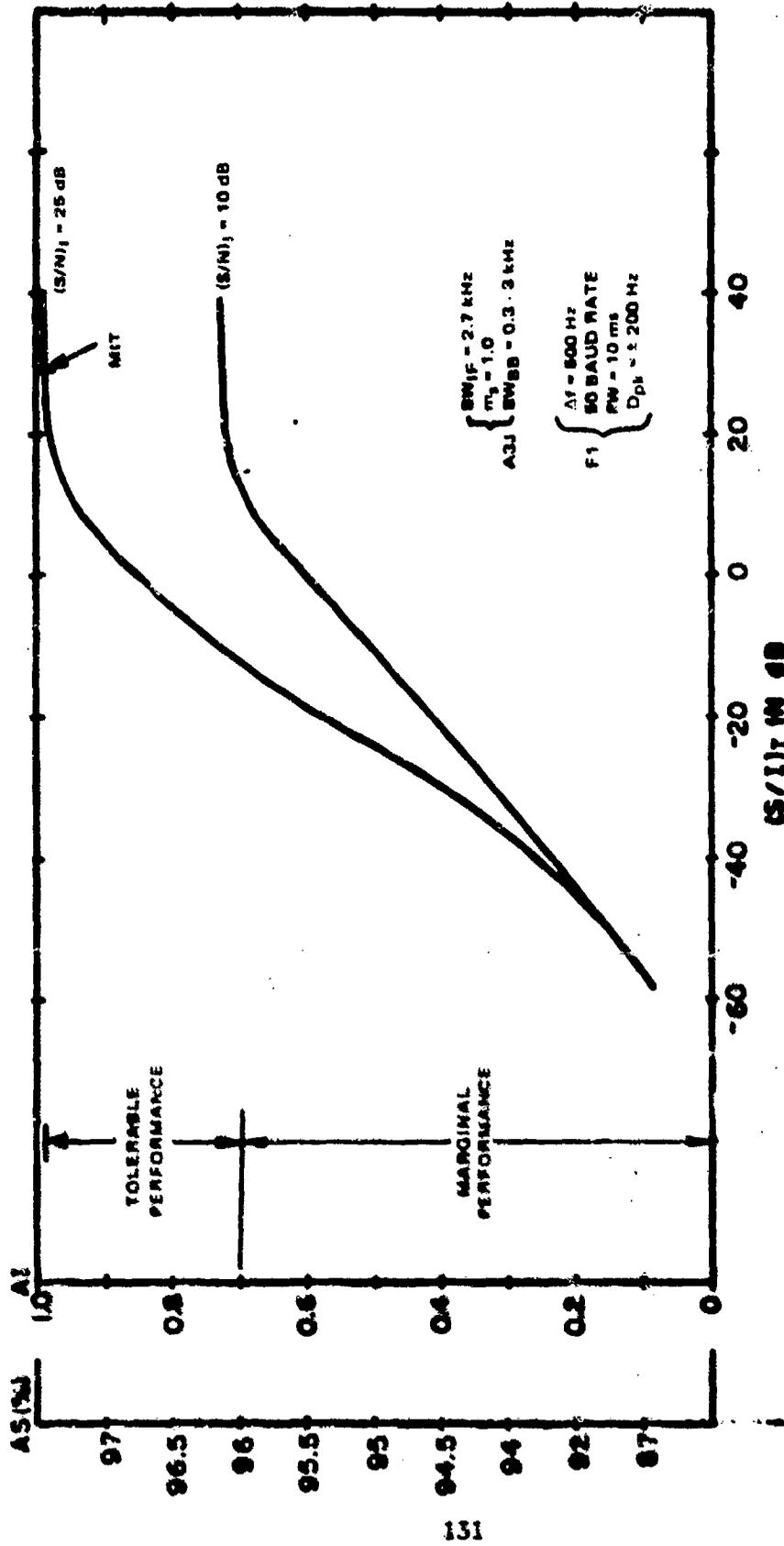


Figure C-41. Performance degradation curve for A3J receiver with F1 interference (Δf = 500 Hz).

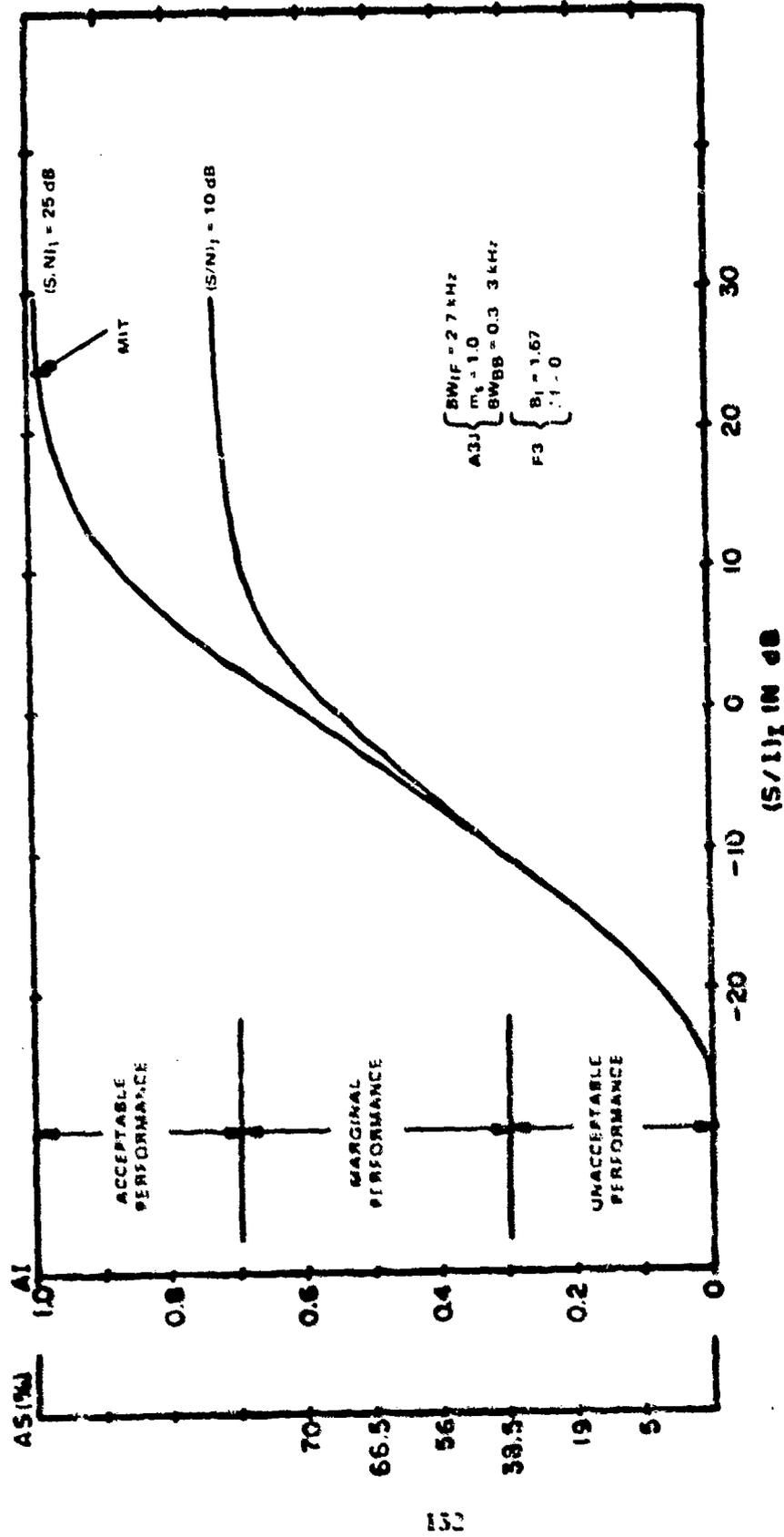


Figure C-42. Performance degradation curve for A3J receiver with F3 interference.

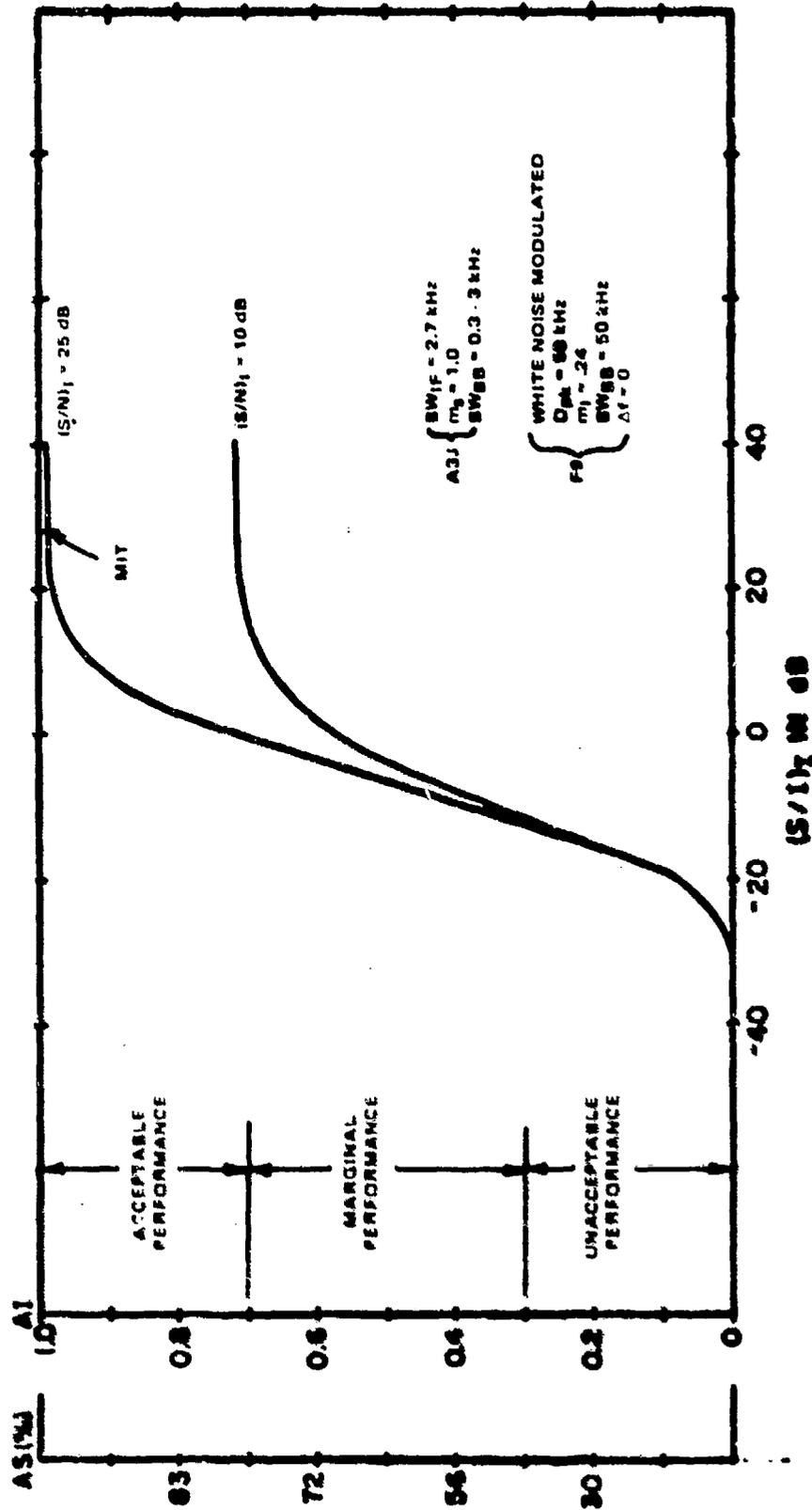


Figure C-43. Performance degradation curve for A3J receiver with F9 interference.

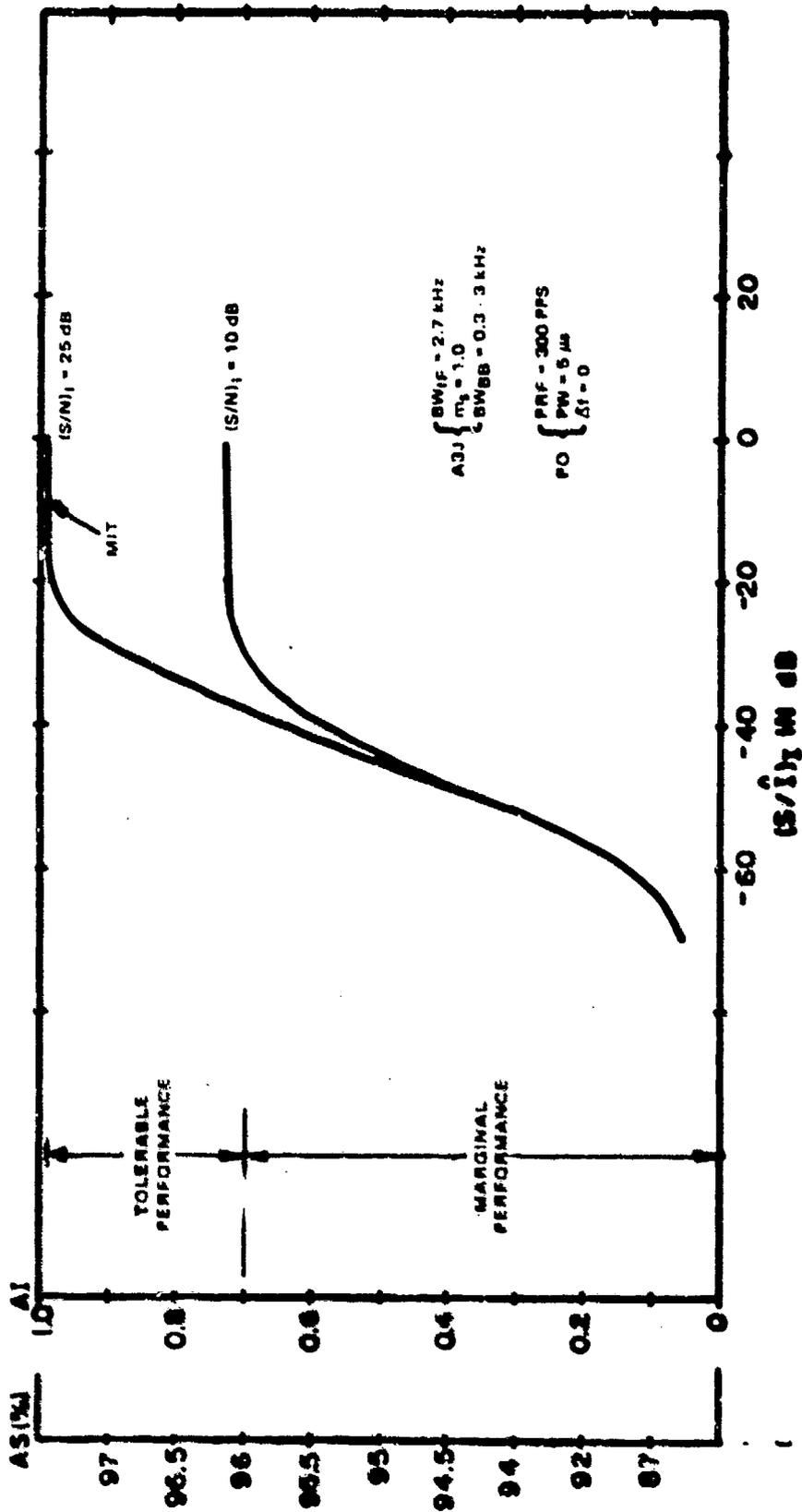


Figure C-44. Performance degradation curve for A3J receiver with P0 interference.

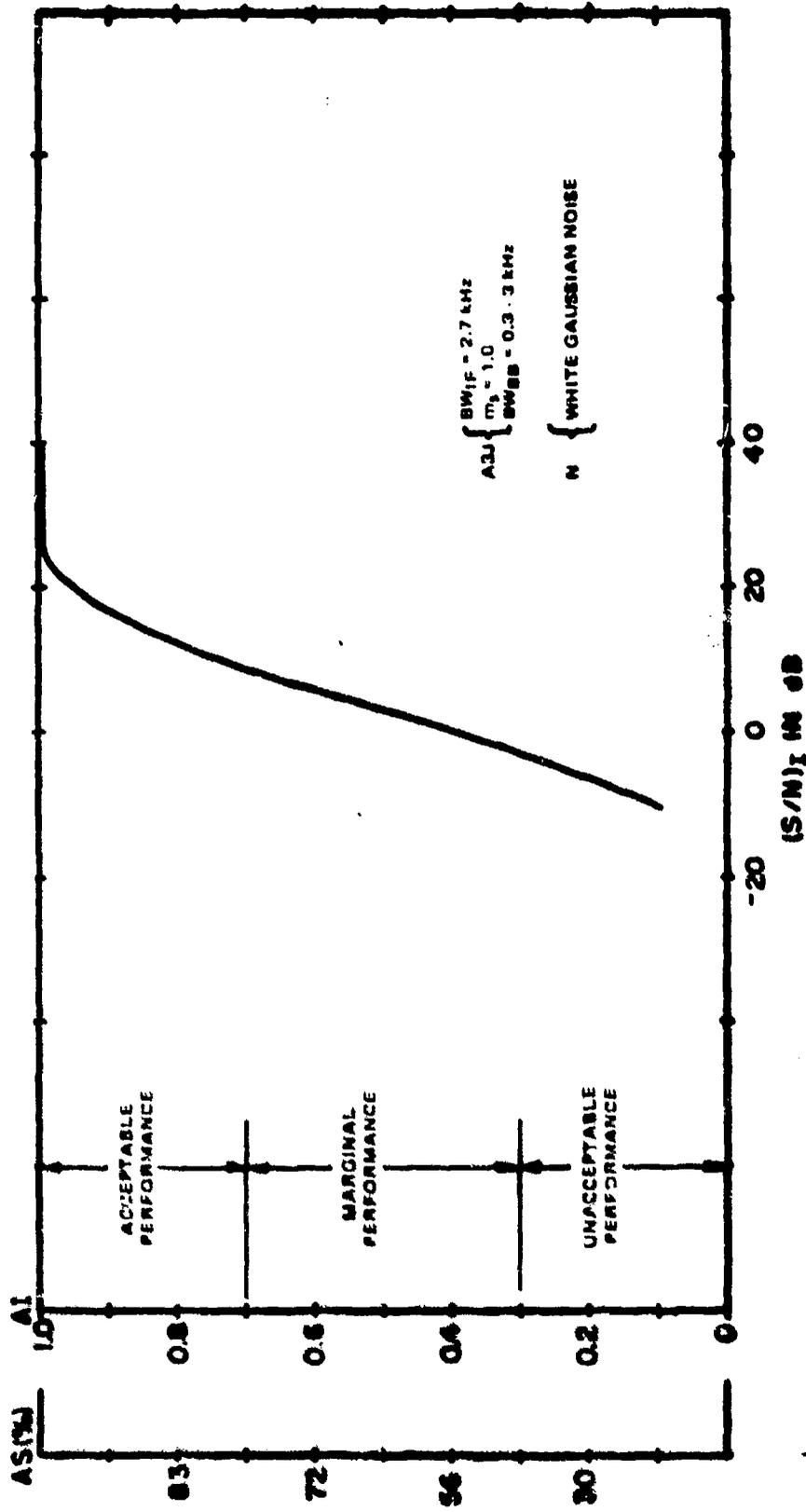


Figure C-45. Performance degradation curve for A3J receiver with noise.

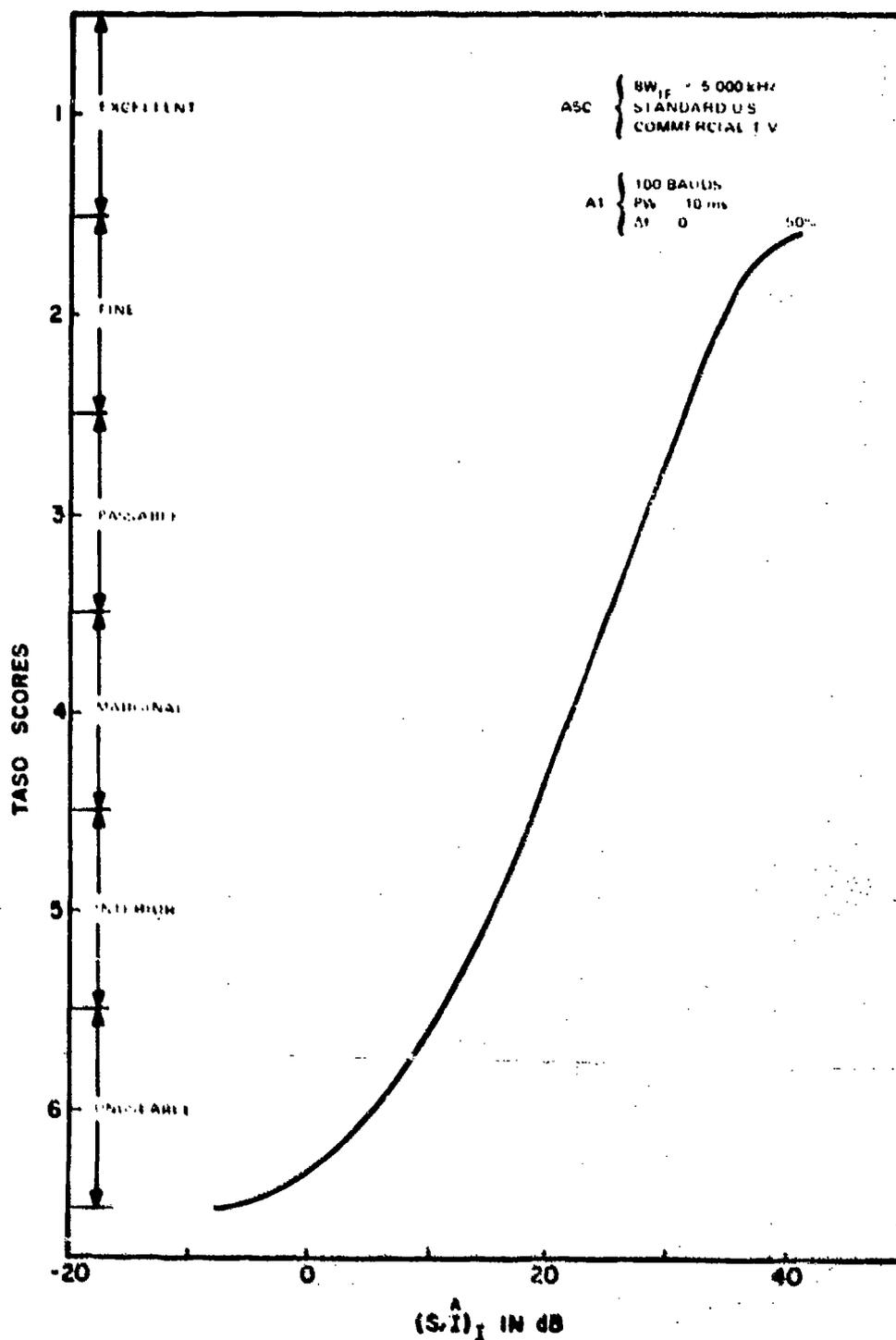


Figure C-46. Performance degradation curve for ASC receiver with AI interference ( $\Delta f = 0$  MHz).

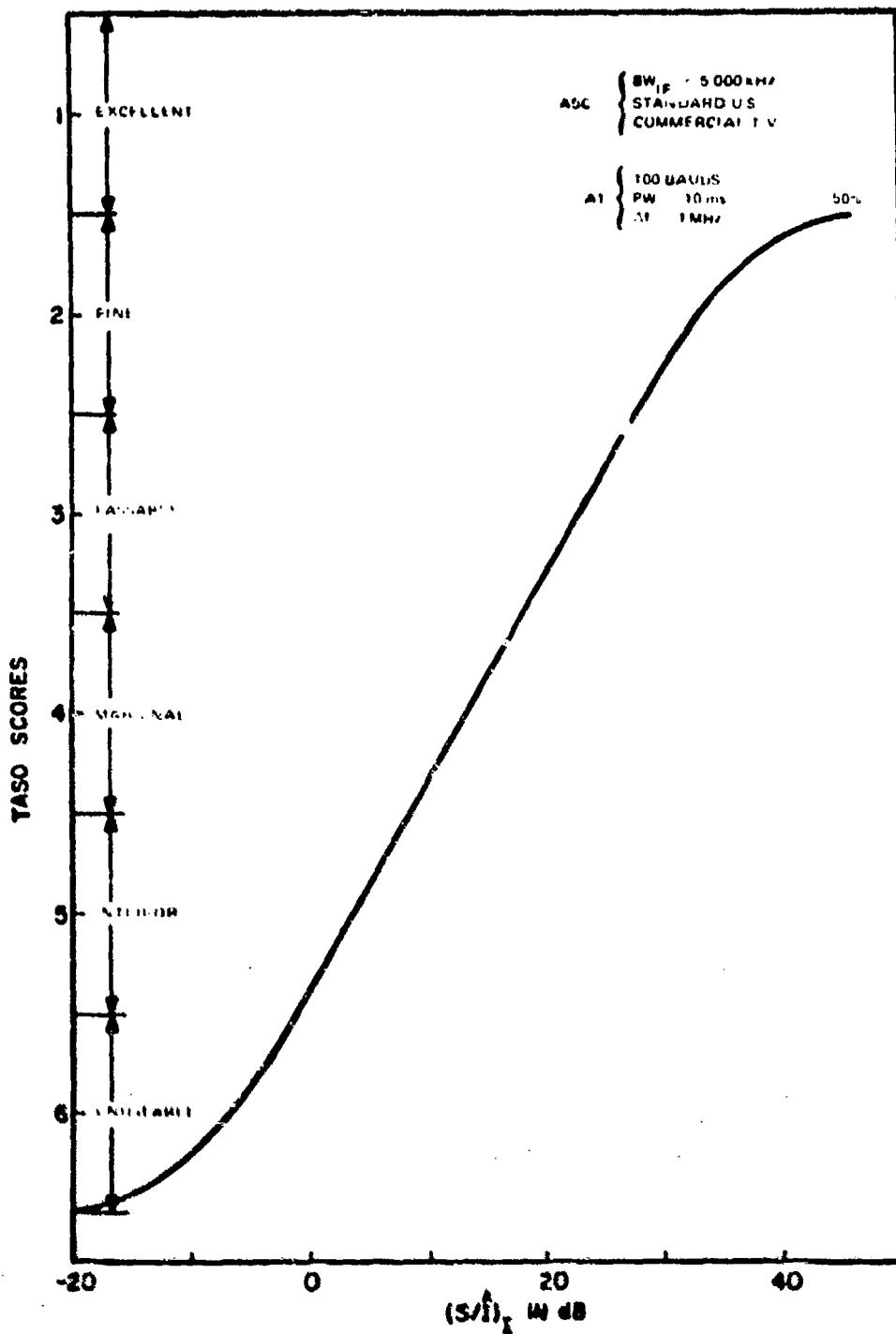


Figure C-47. Performance degradation curve for ASC receiver with A1 interference ( $\Delta f = 1$  MHz).

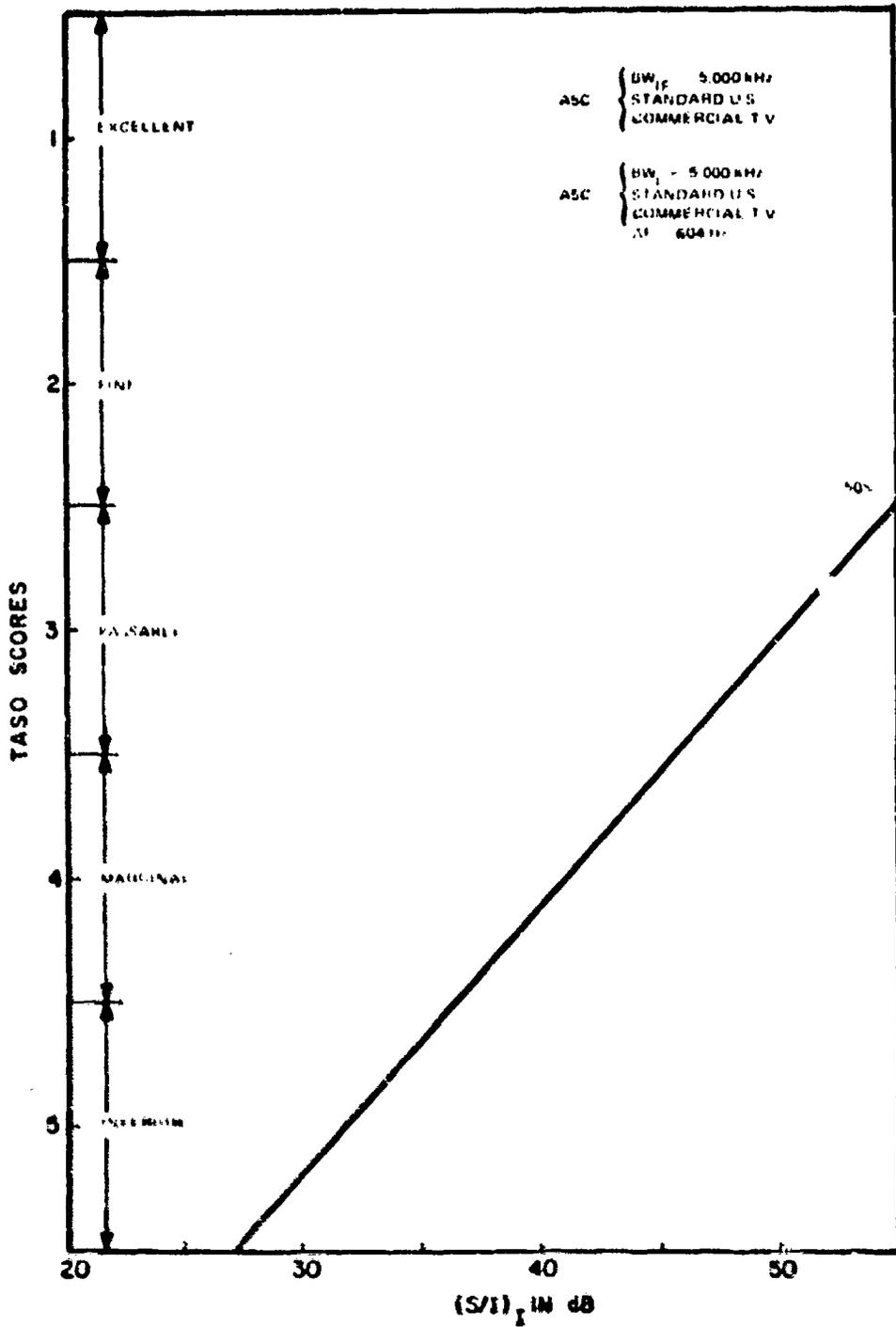


Figure C-48. Performance degradation curve for an ASC curve with ASC interference ( $AF = 604 \text{ Hz}$ ).

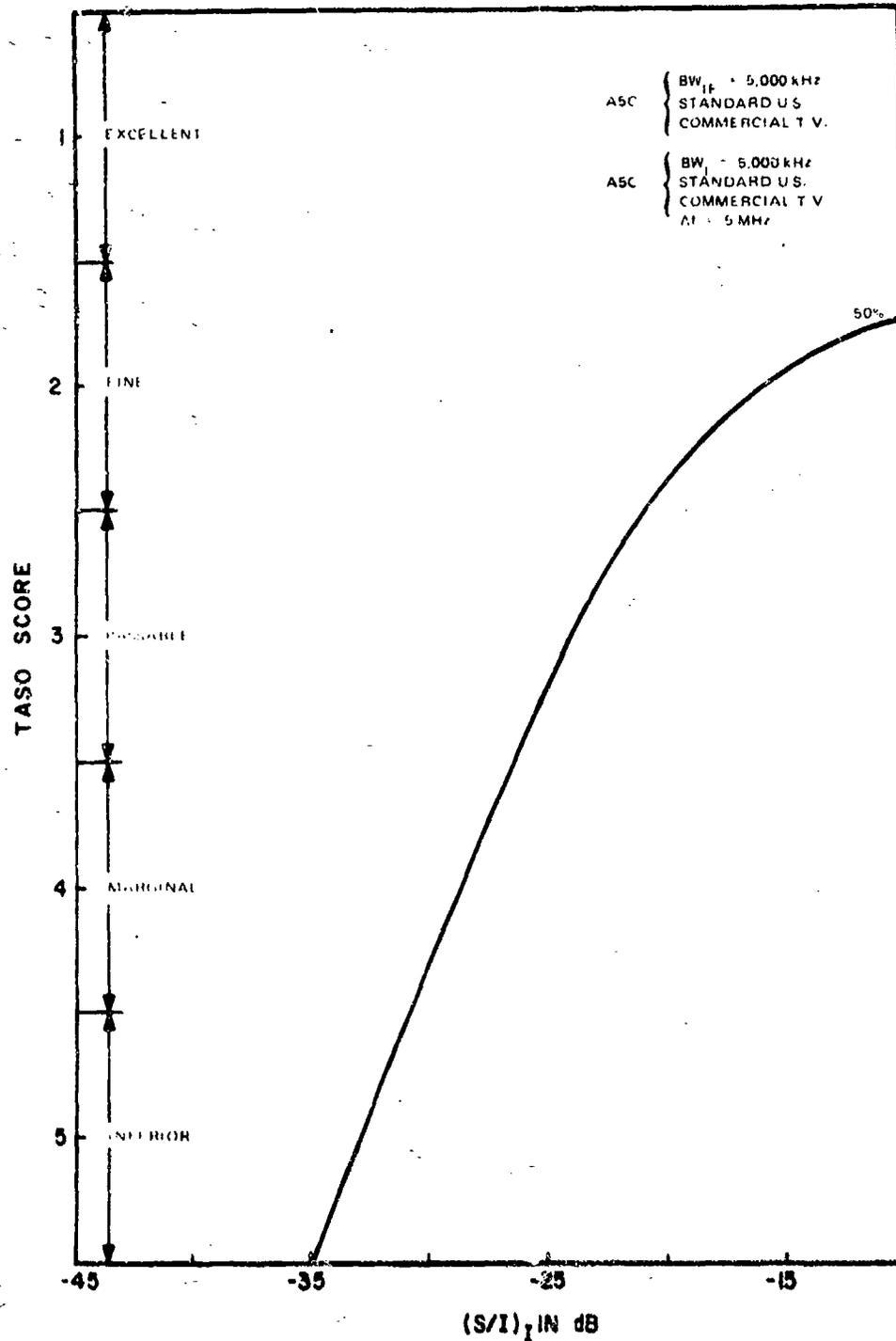


Figure C-49. Performance degradation curve for an ASC receiver with ASC interference ( $\Delta f = +5$  MHz, upper adjacent channel).

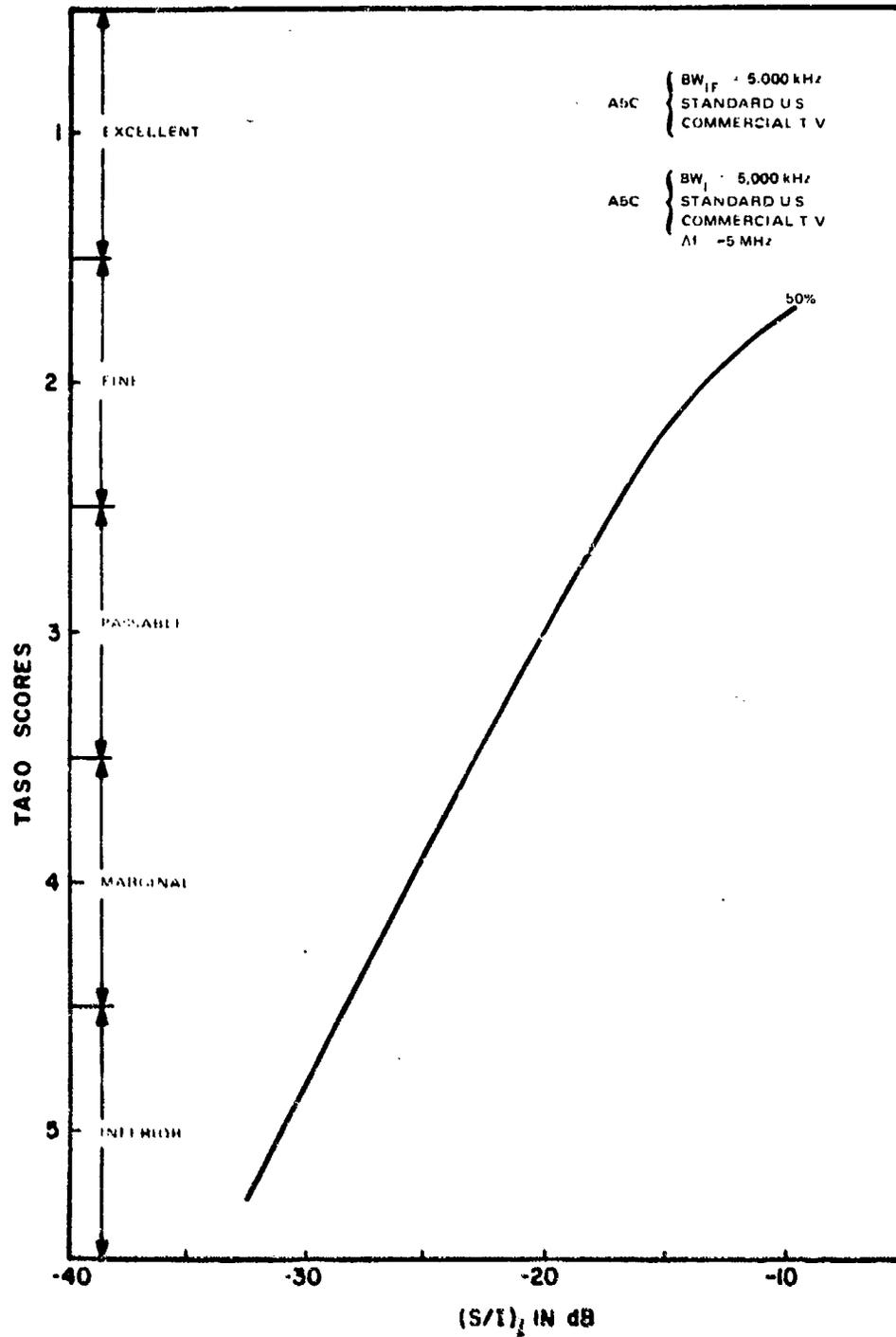


Figure C-50. Performance degradation curve for an A5C receiver with A5C interference ( $\Delta f = -5 \text{ MHz}$ , lower adjacent channel).

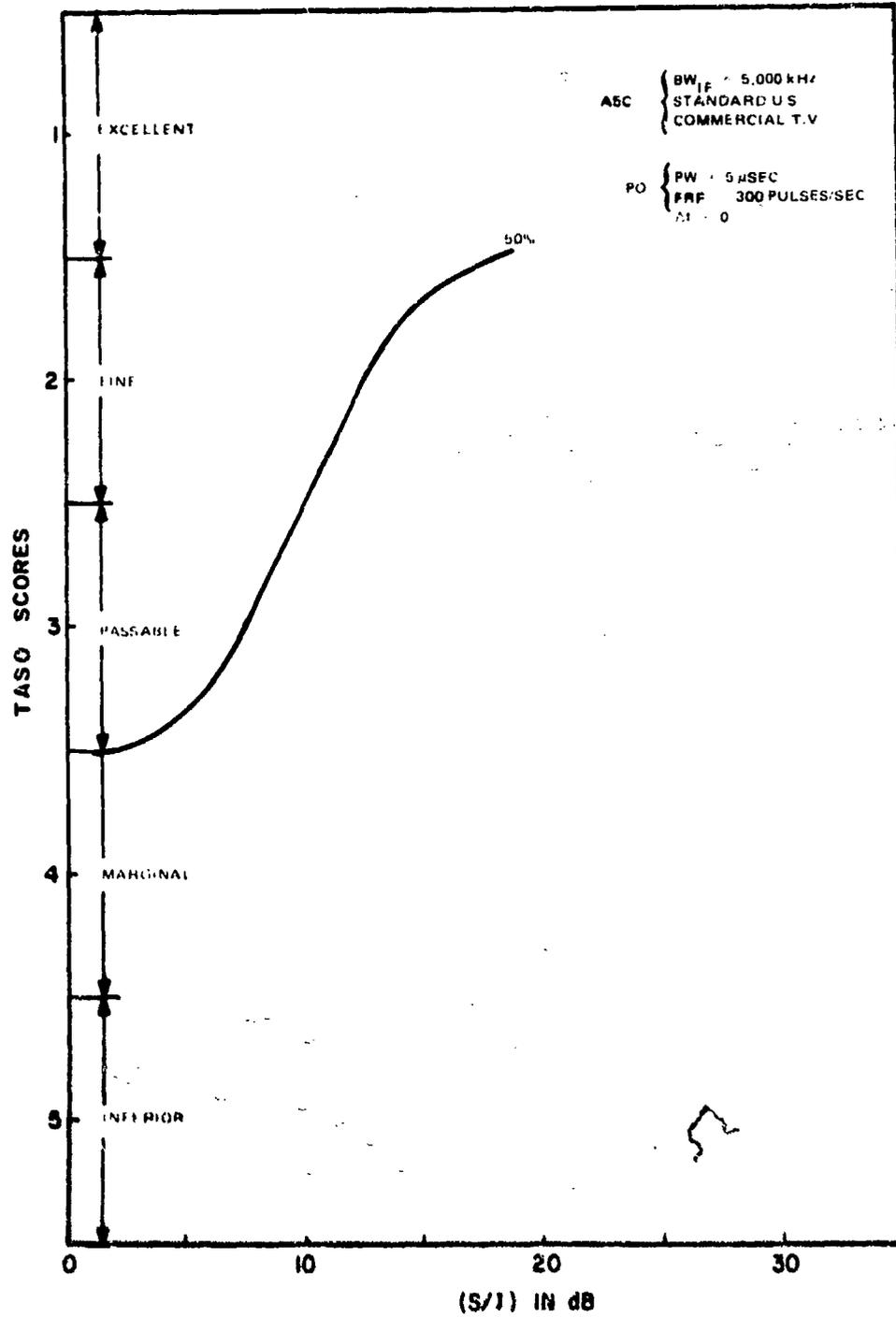


Figure C-51. Performance degradation curve for an ASC receiver with PO interference ( $\Delta f = 0$ ).

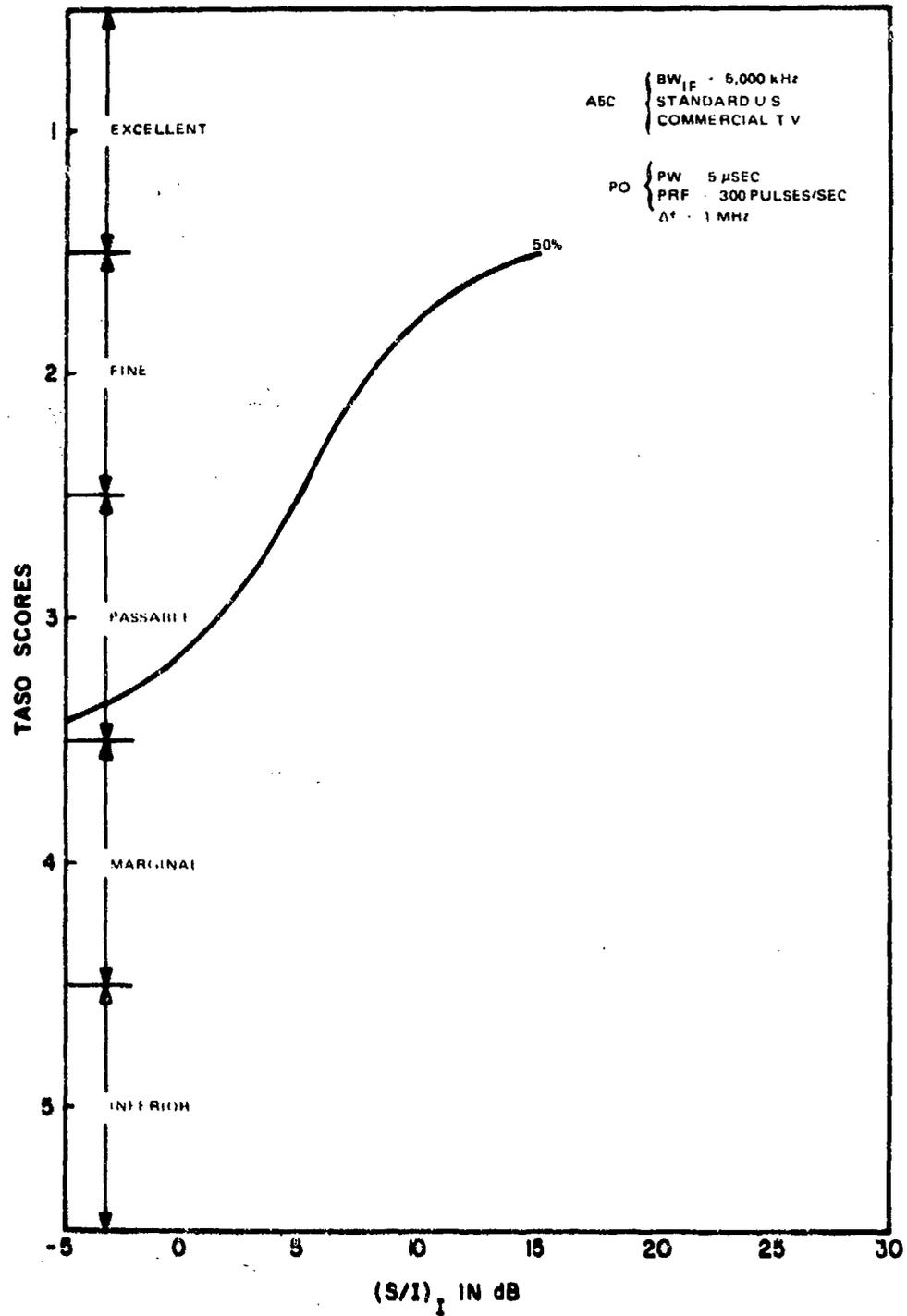


Figure C-52. Performance degradation curve for an ASC receiver with PO interference ( $\Delta f = 1$  MHz).

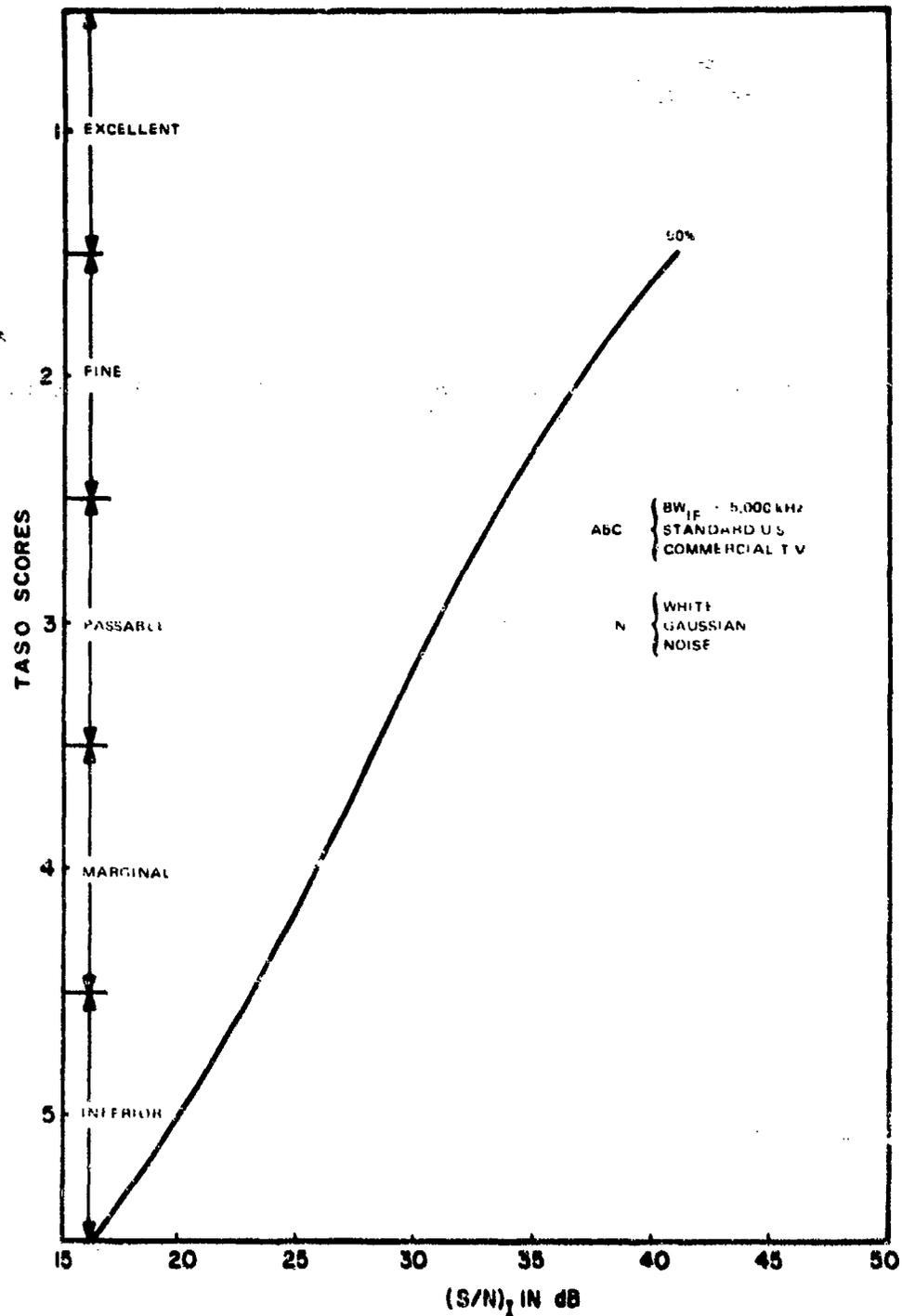


Figure C-53. Performance degradation curve for A5C receiver with noise interference.

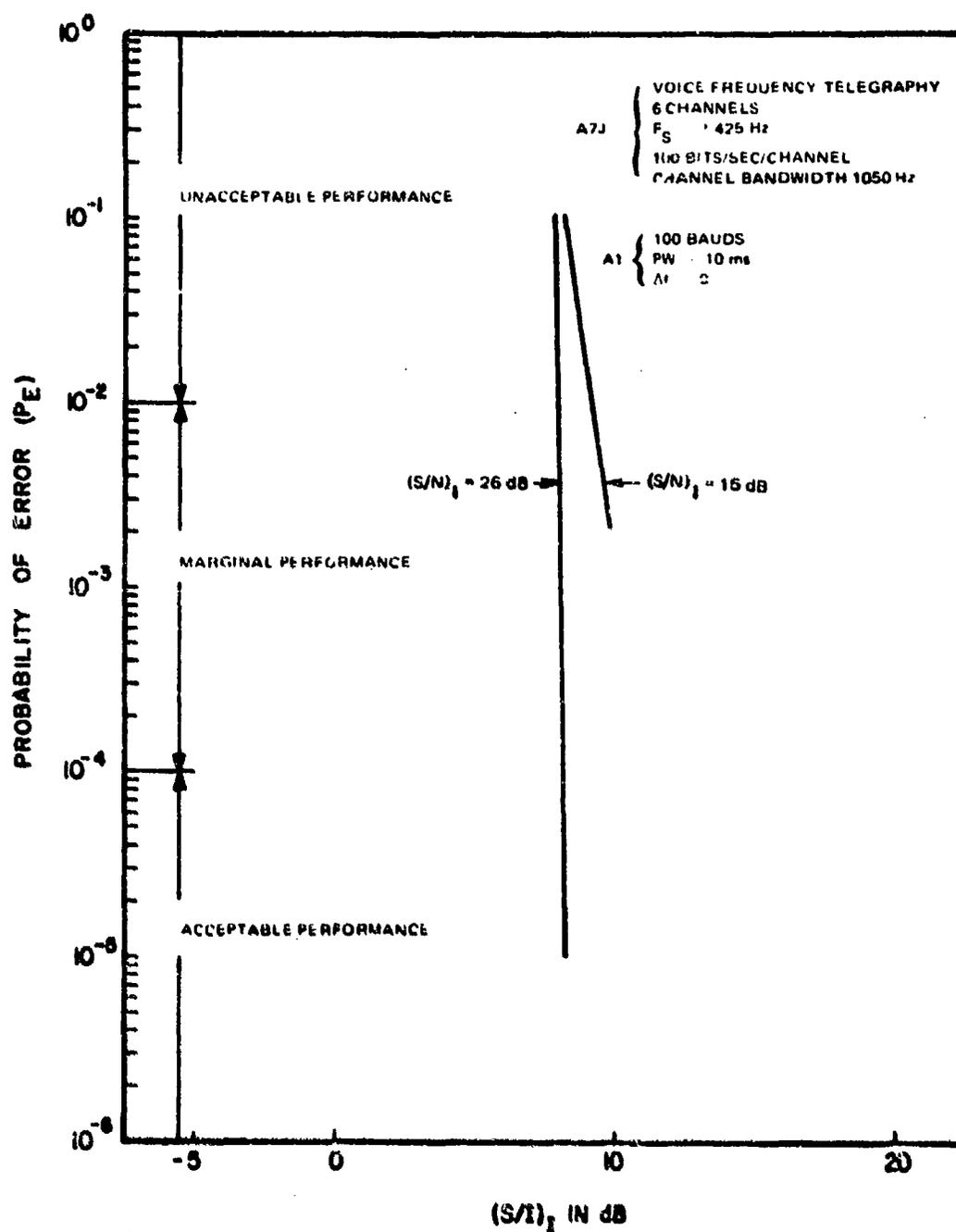


Figure C-54. Performance degradation curve for an A7J receiver with A1 interference.

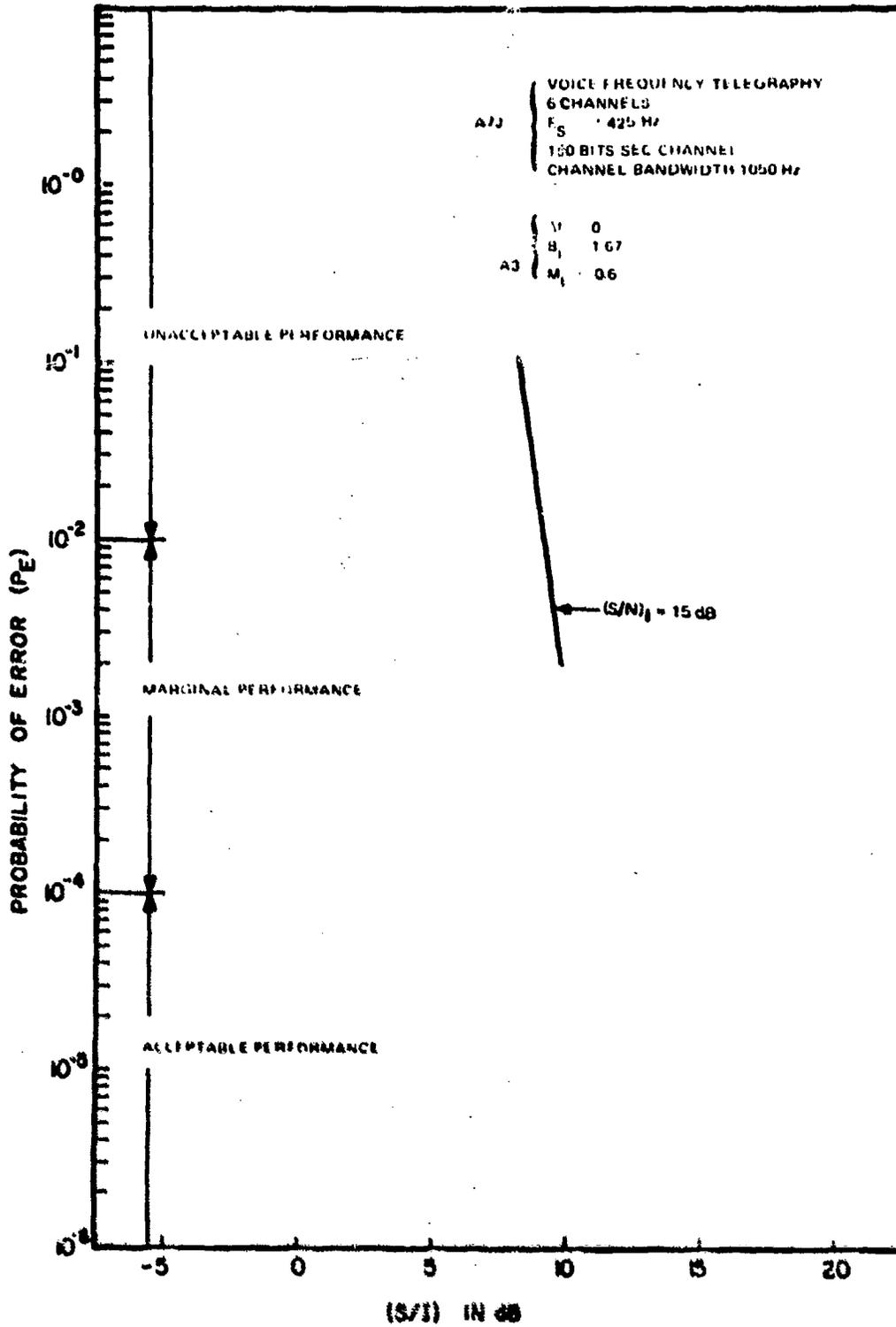


Figure C-58. Performance degradation curve for an A7J receiver with A3 interference.

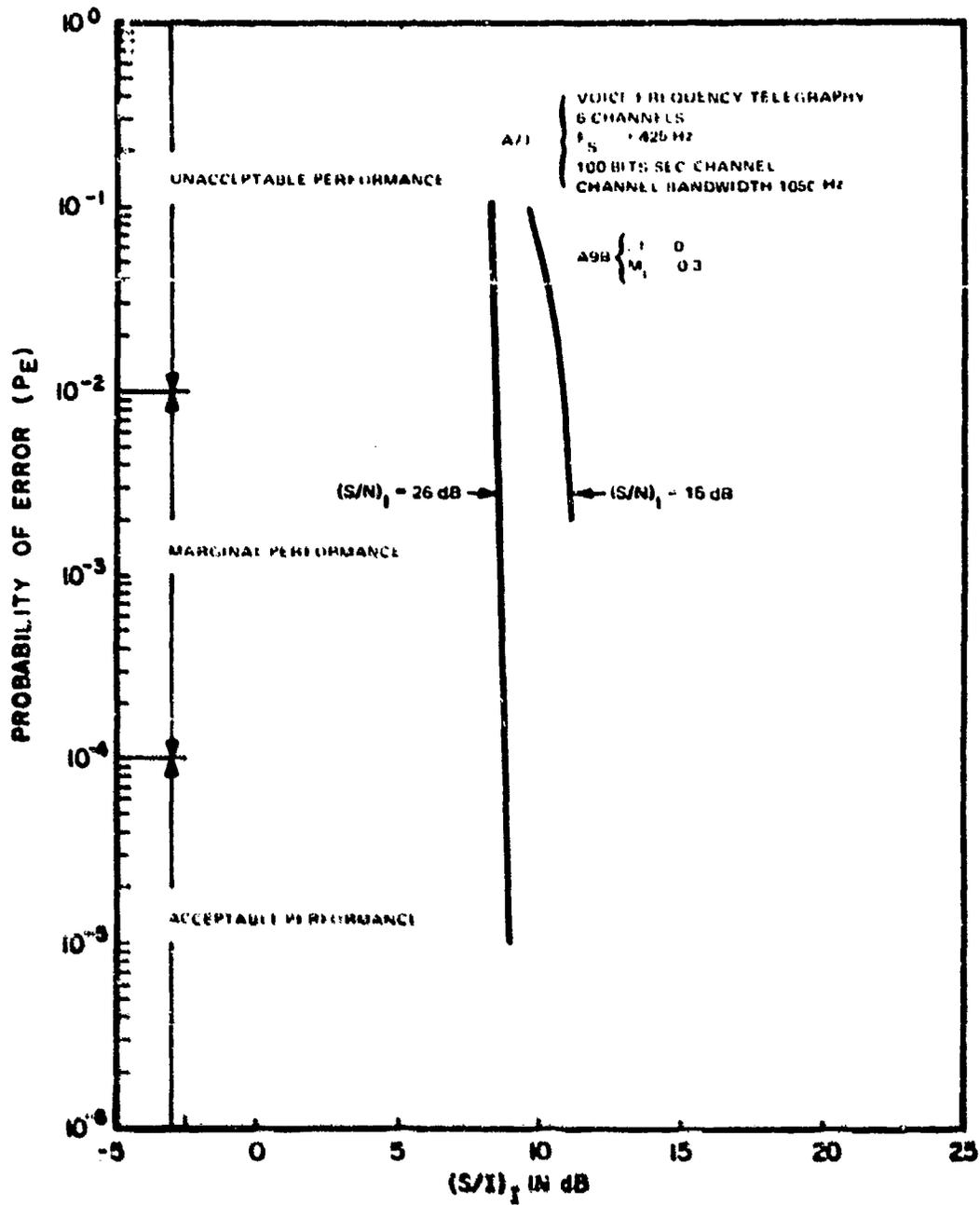


Figure C-56. Performance degradation curve for an A7J receiver with A9B interference.

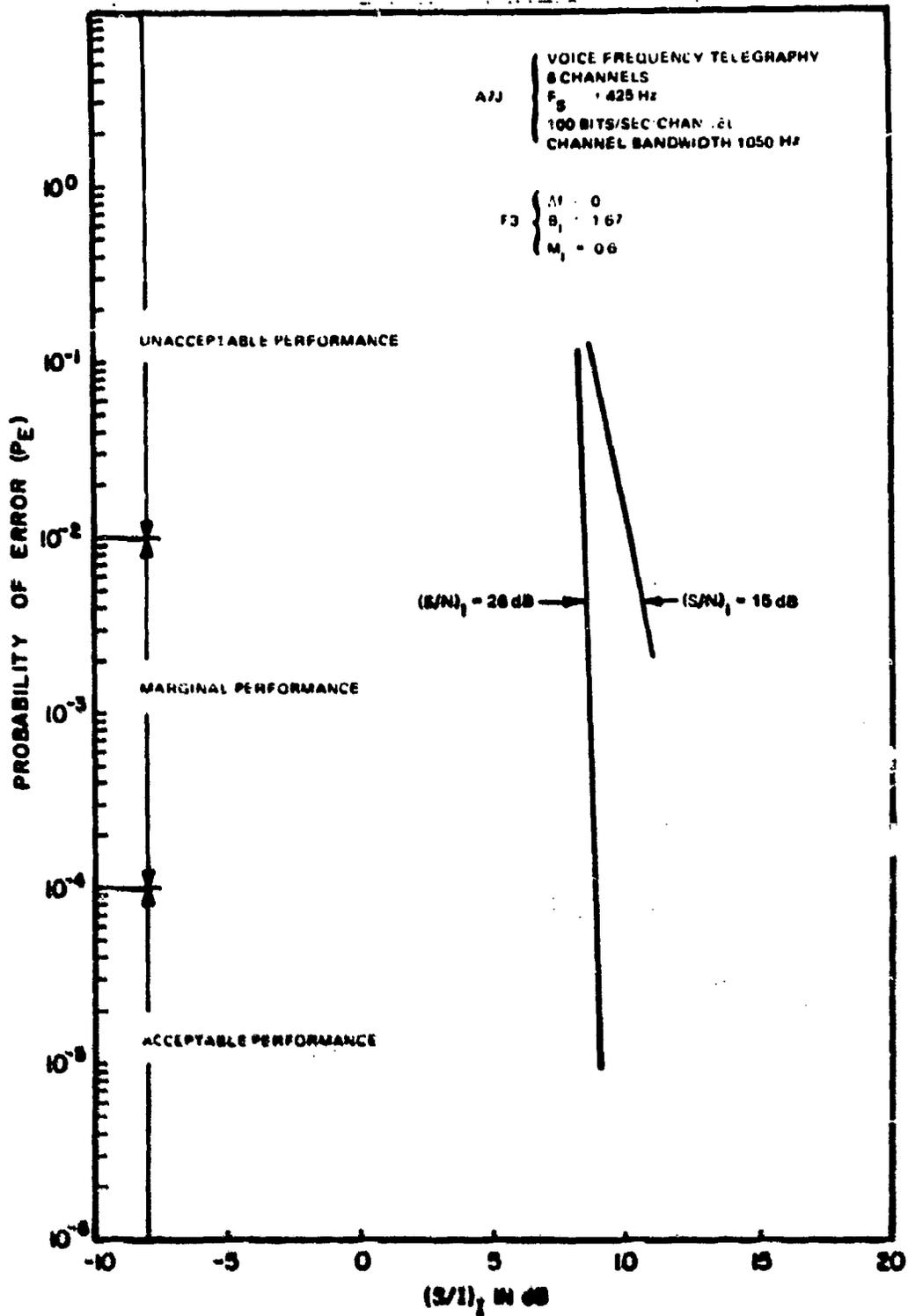


Figure C-57. Performance degradation curve for an A7J receiver with FS interference.

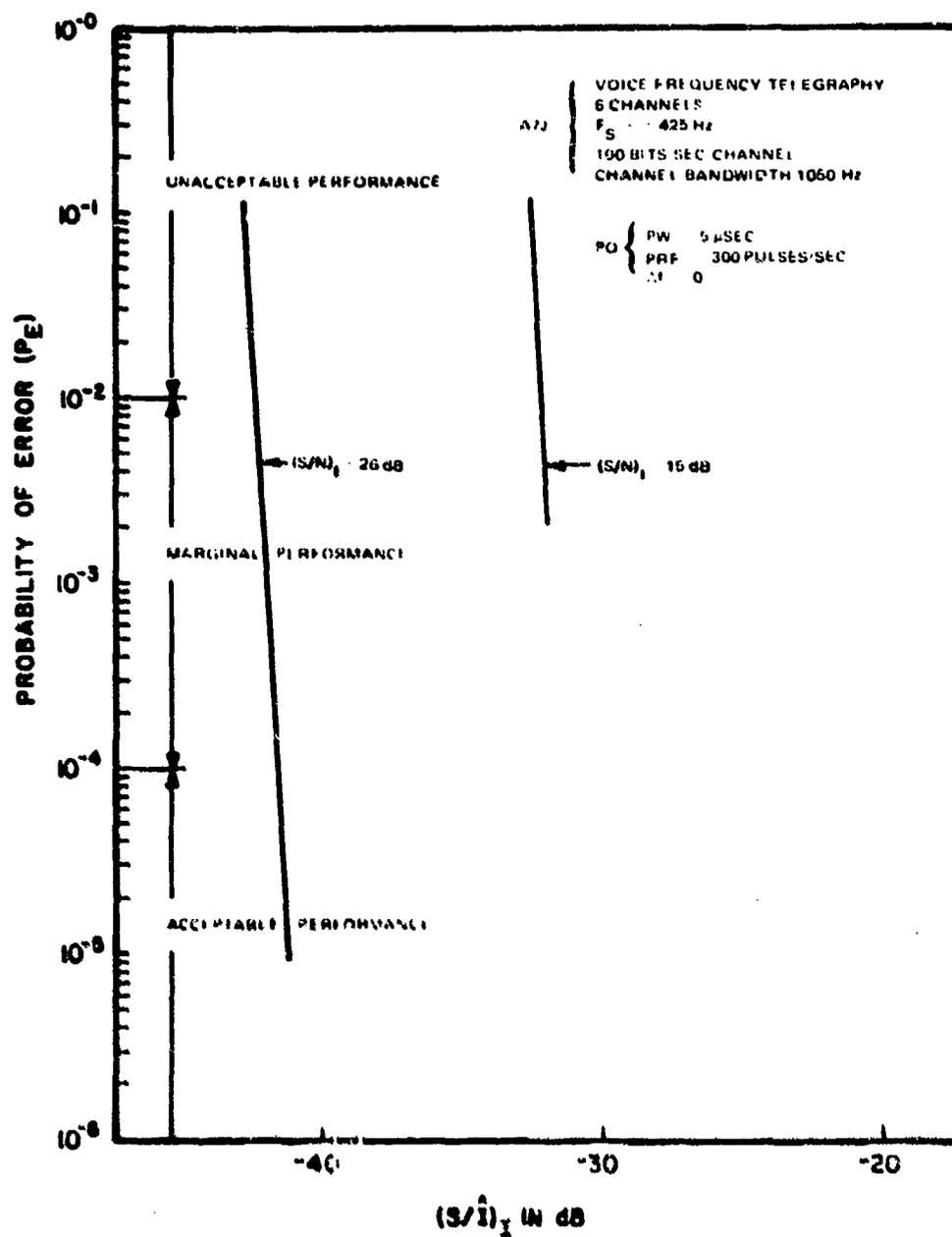


Figure C-58. Performance degradation curve for an A7J receiver with PO interference.

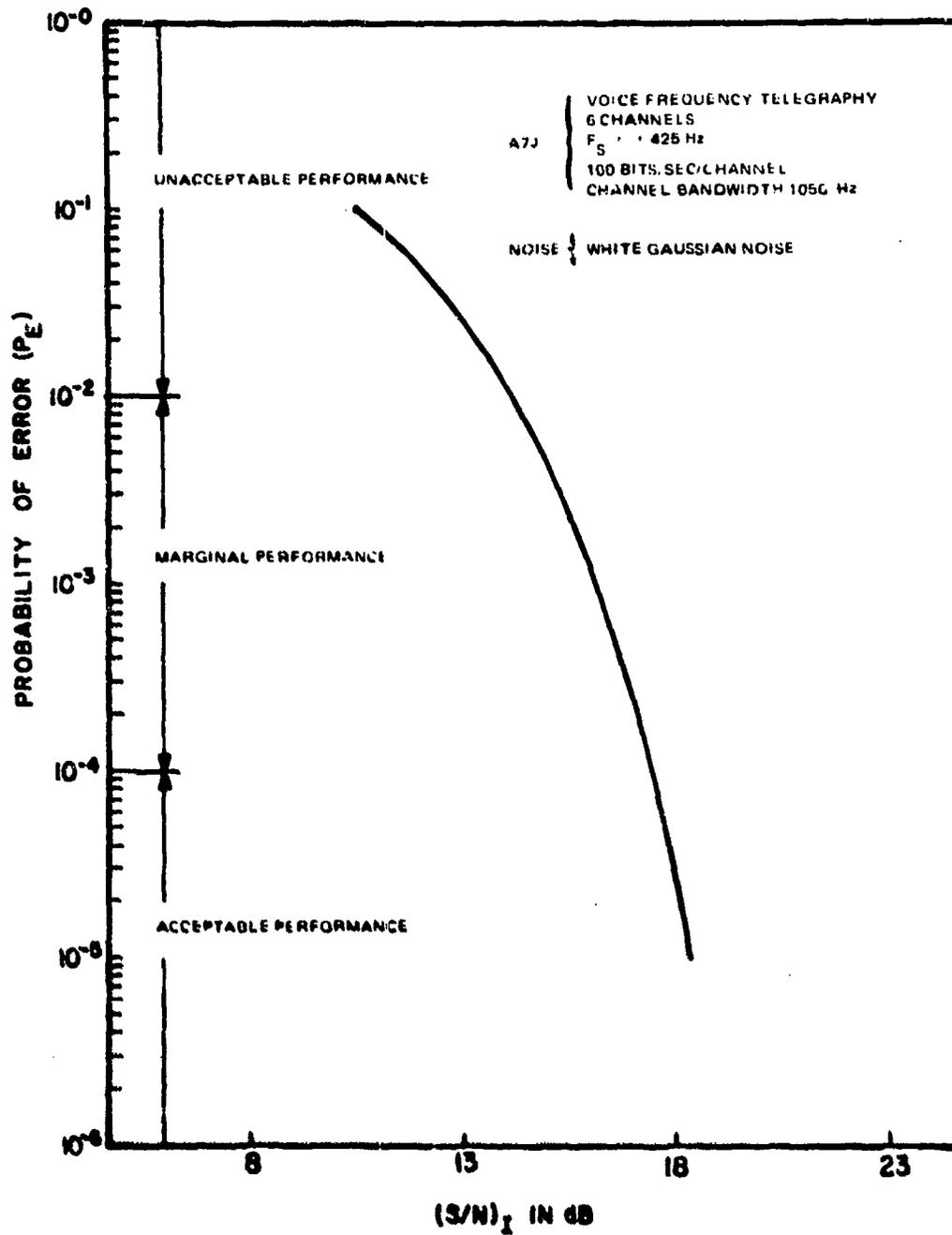


Figure C-59. Performance degradation curve for an A7J receiver with noise interference.

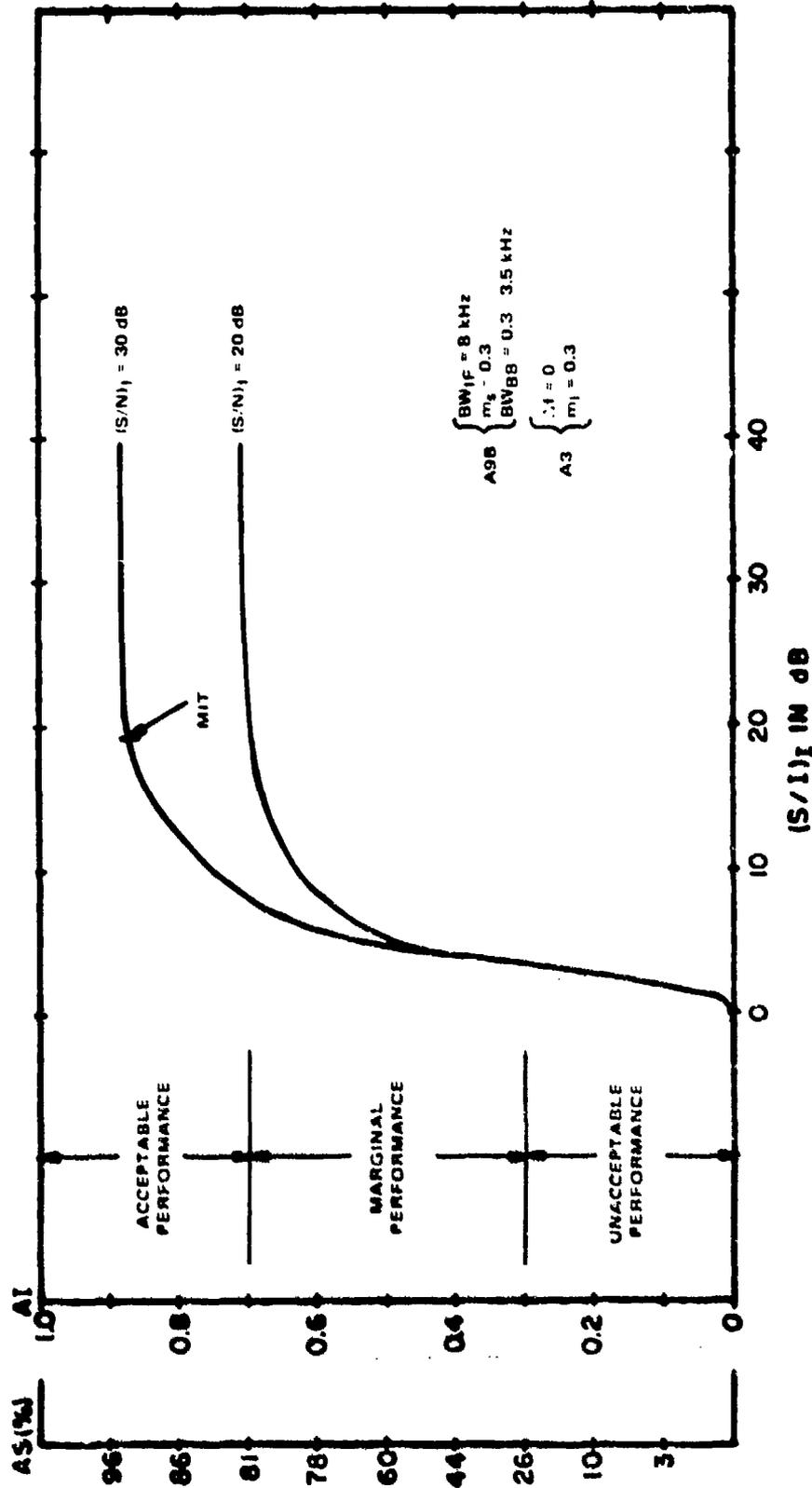


Figure C-60. Performance degradation curve for A9B receiver with A3 interference ( $\Delta f = 0 \text{ Hz}$ ).

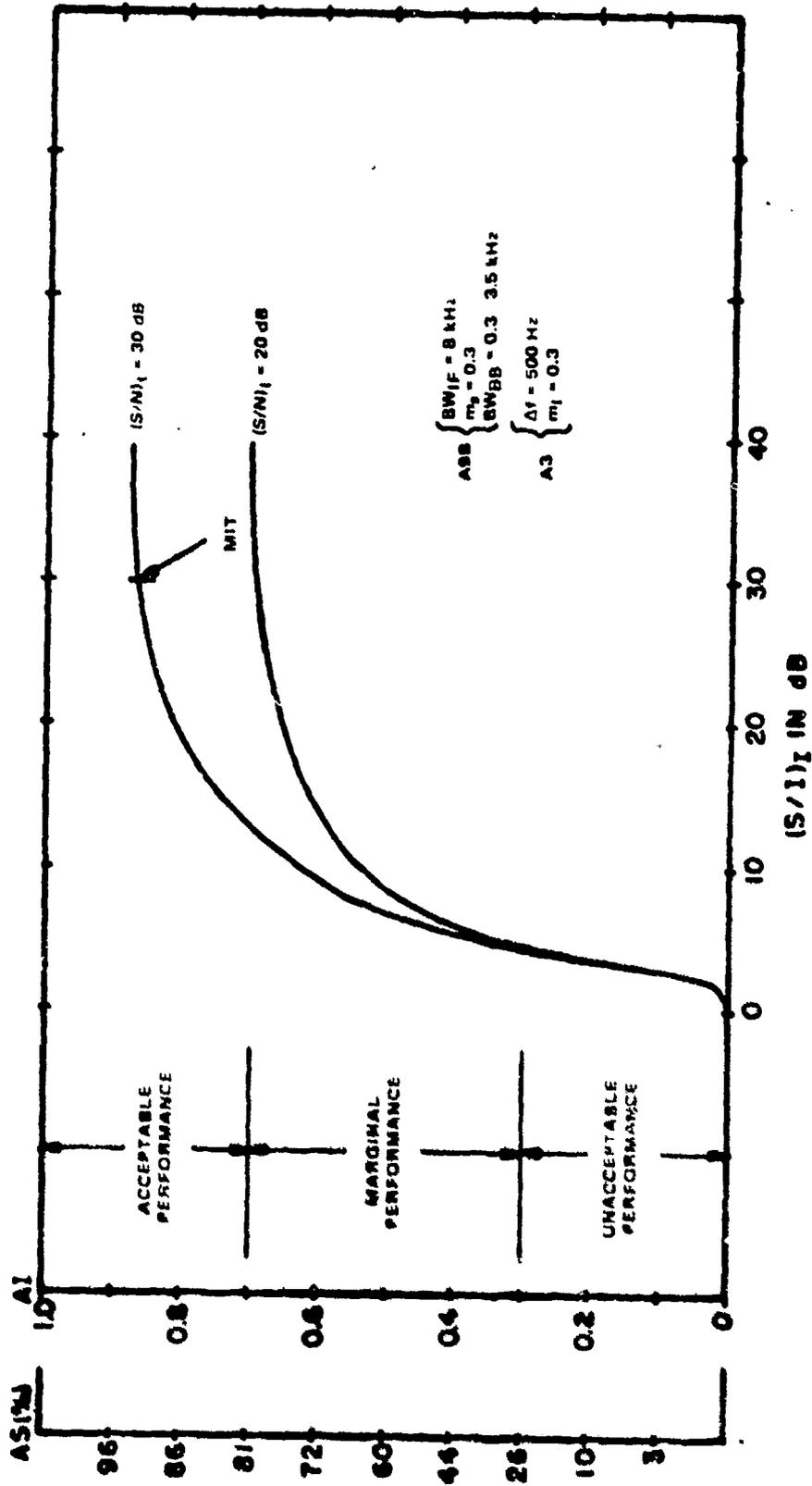


Figure C-61. Performance degradation curve for A9B receiver with A3 interference (Δf = 500 Hz).

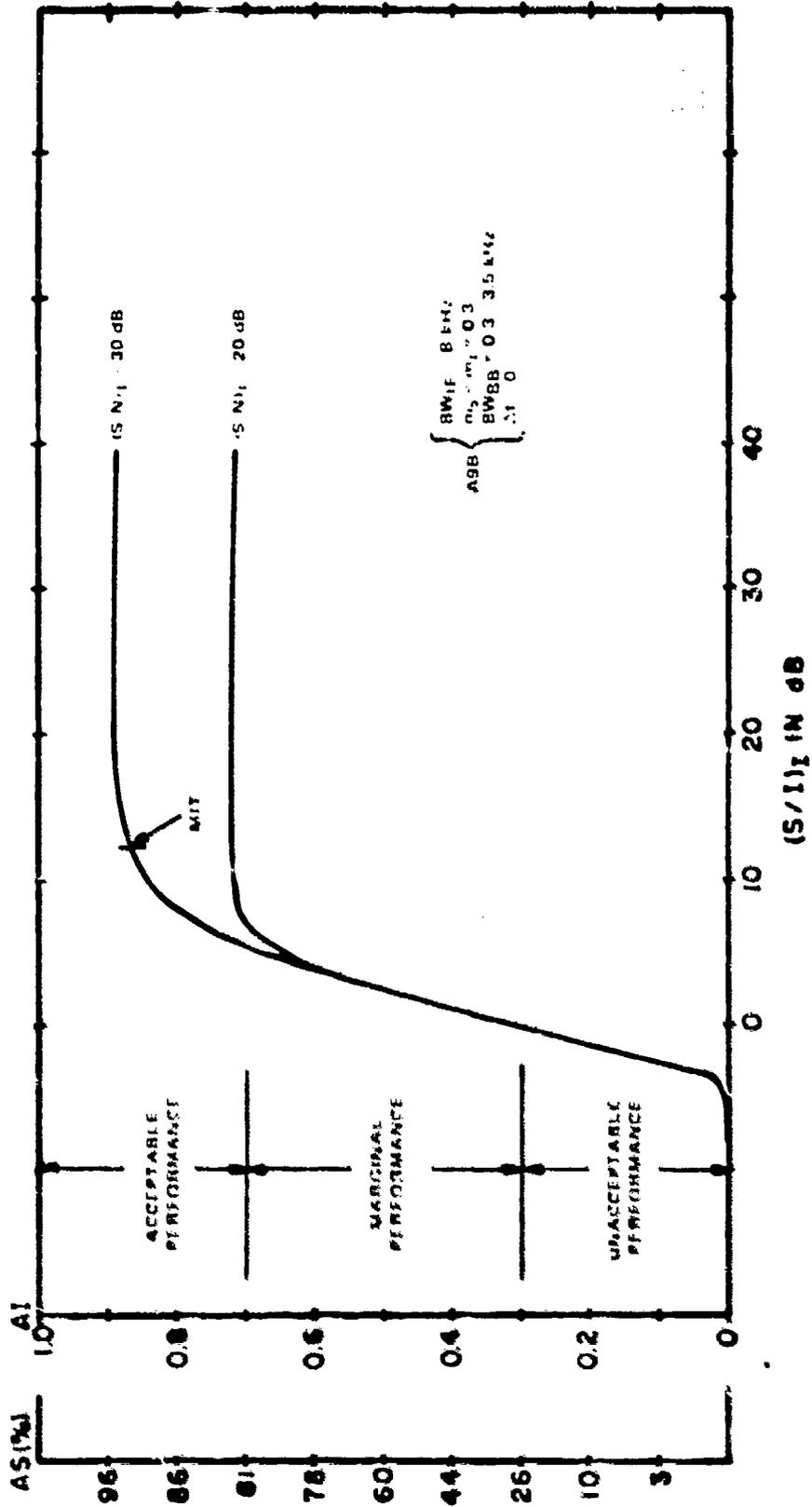


Figure C-62. Performance degradation curve for A9B receiver with A9B interference ( $\Delta f = 0 \text{ Hz}$ ).

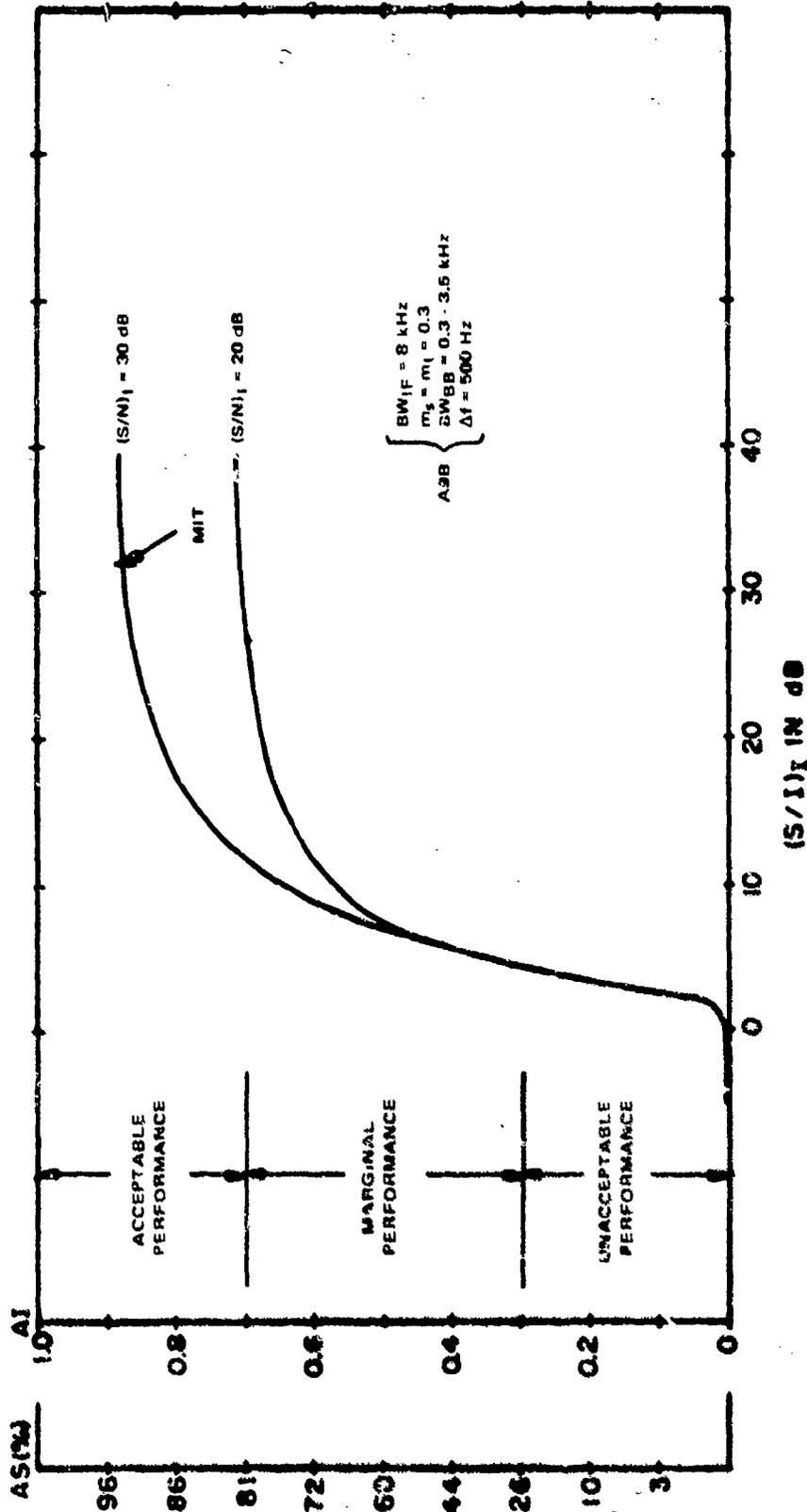


Figure C-63. Performance degradation curve for A9B receiver with A9B interference ( $\Delta f = 500 \text{ Hz}$ ).

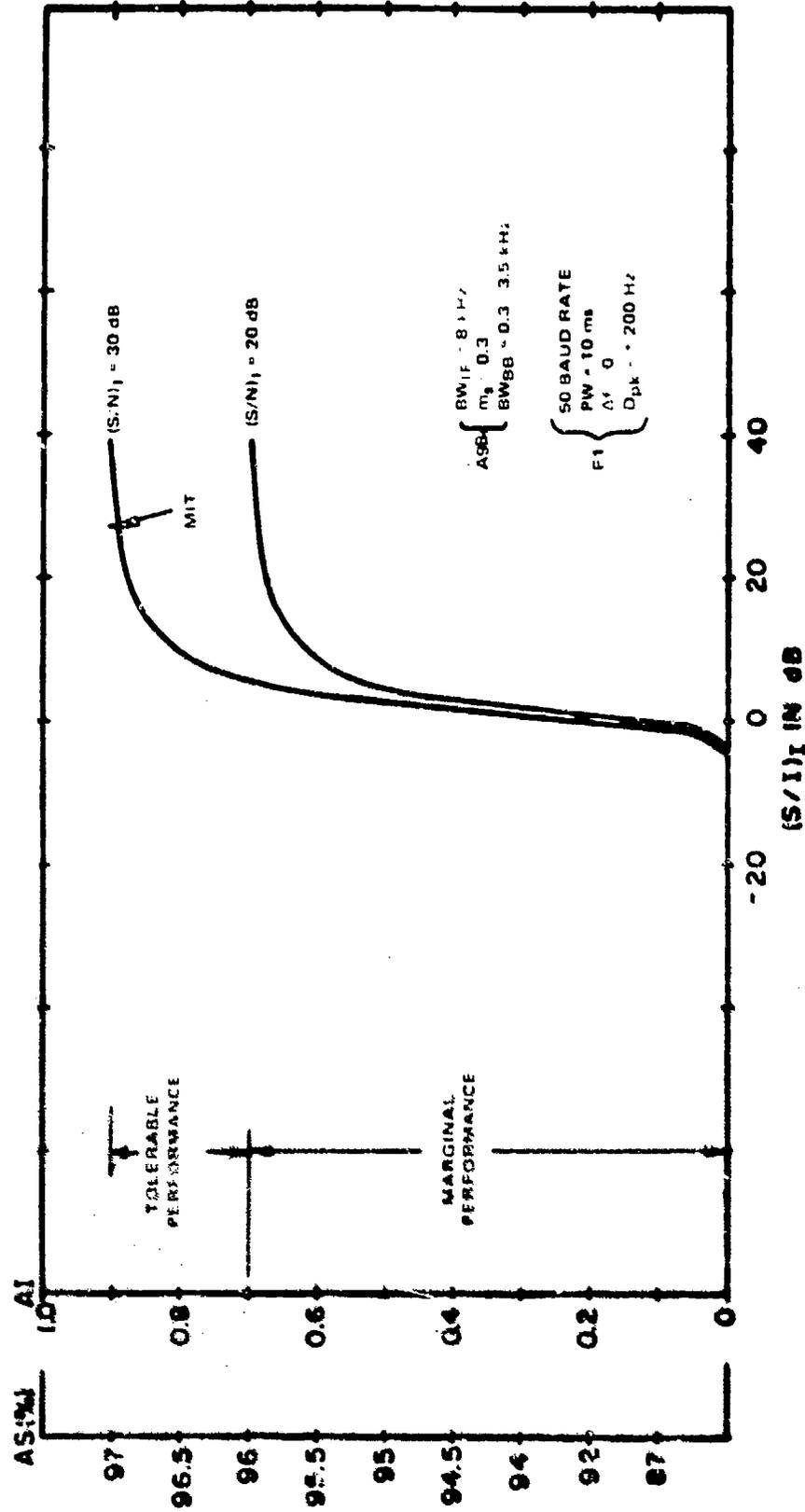


Figure C-64. Performance degradation curve for A9B receiver with F1 interference ( $\Delta f = 0$  Hz).

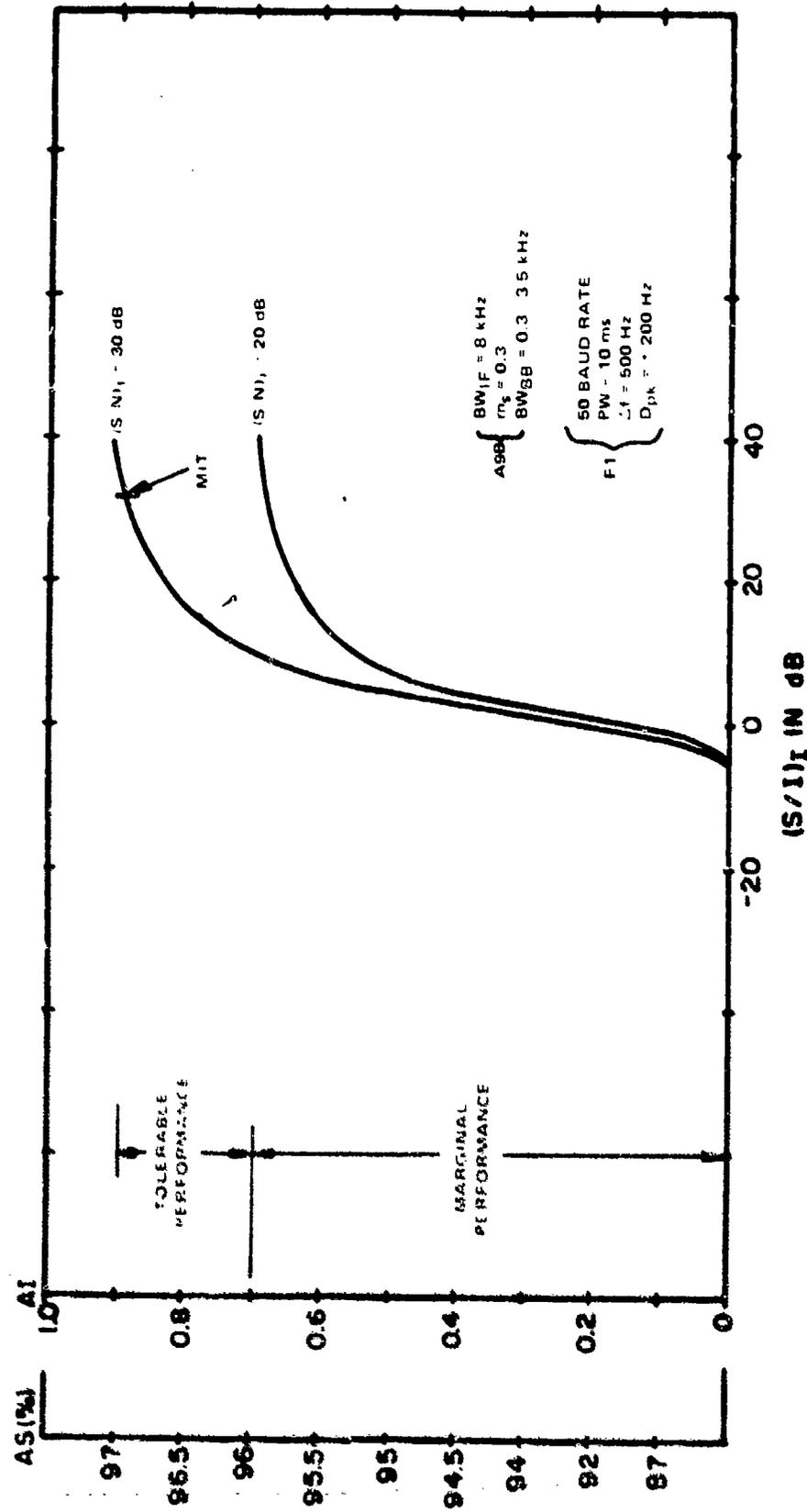


Figure C-65. Performance degradation curve for A9B receiver with F1 interference ( $\Delta f = 500$  Hz).

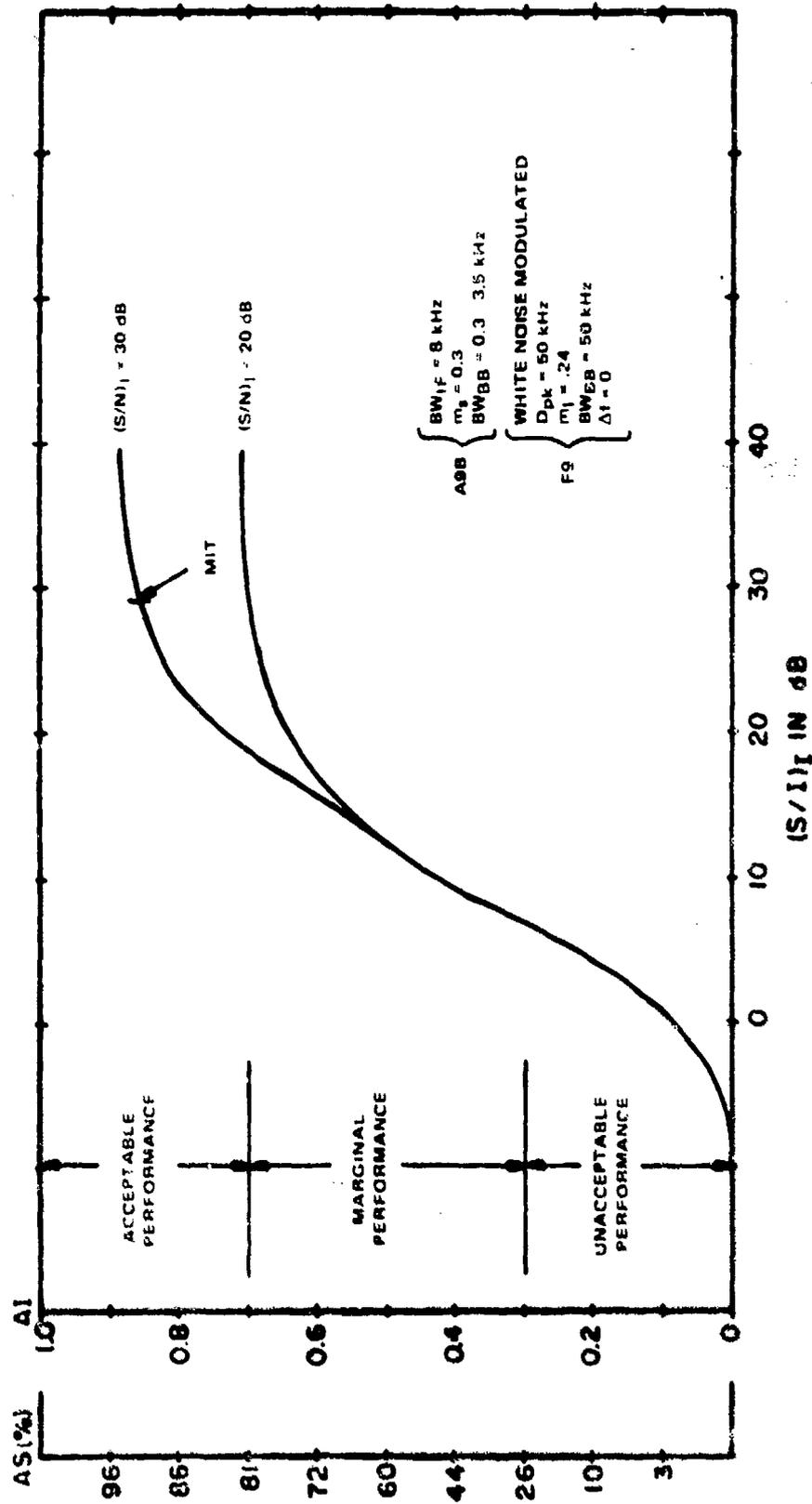


Figure C-66. Performance degradation curve for A9B receiver with F9 interference.

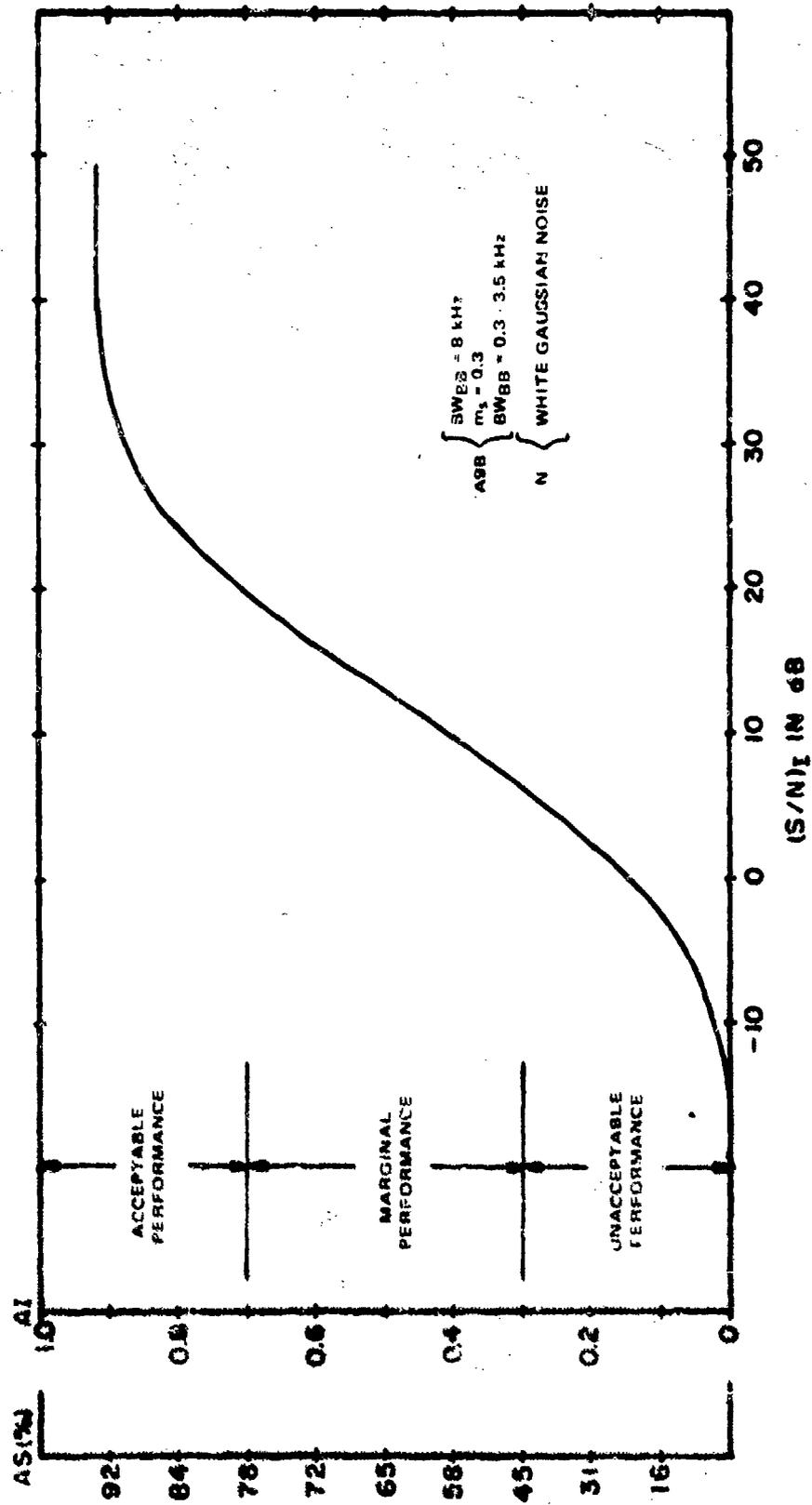


Figure C-67. Performance degradation curve for A9B receiver noise.

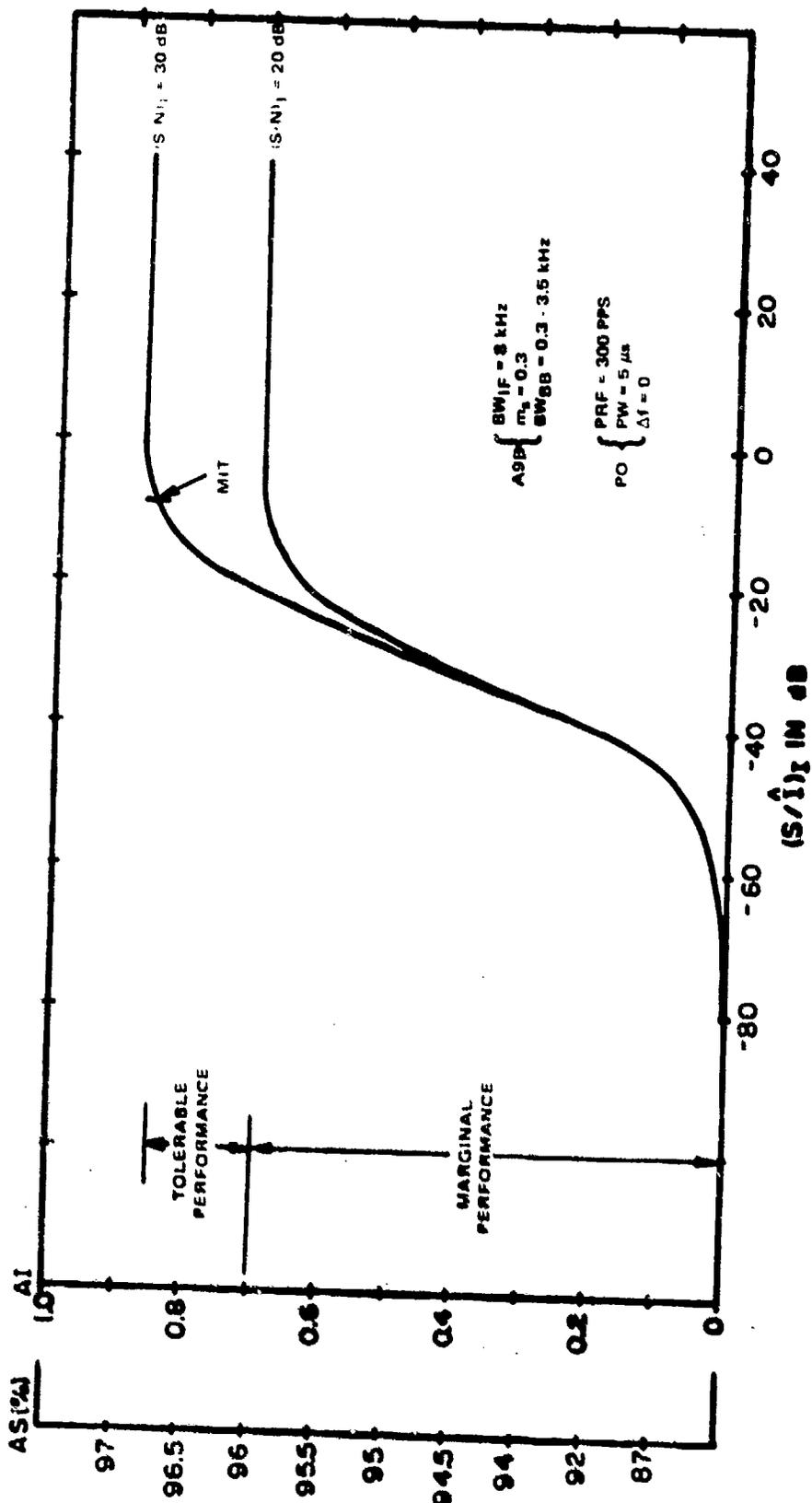


Figure C-68. Performance degradation curve for A9B receiver with PO interference.

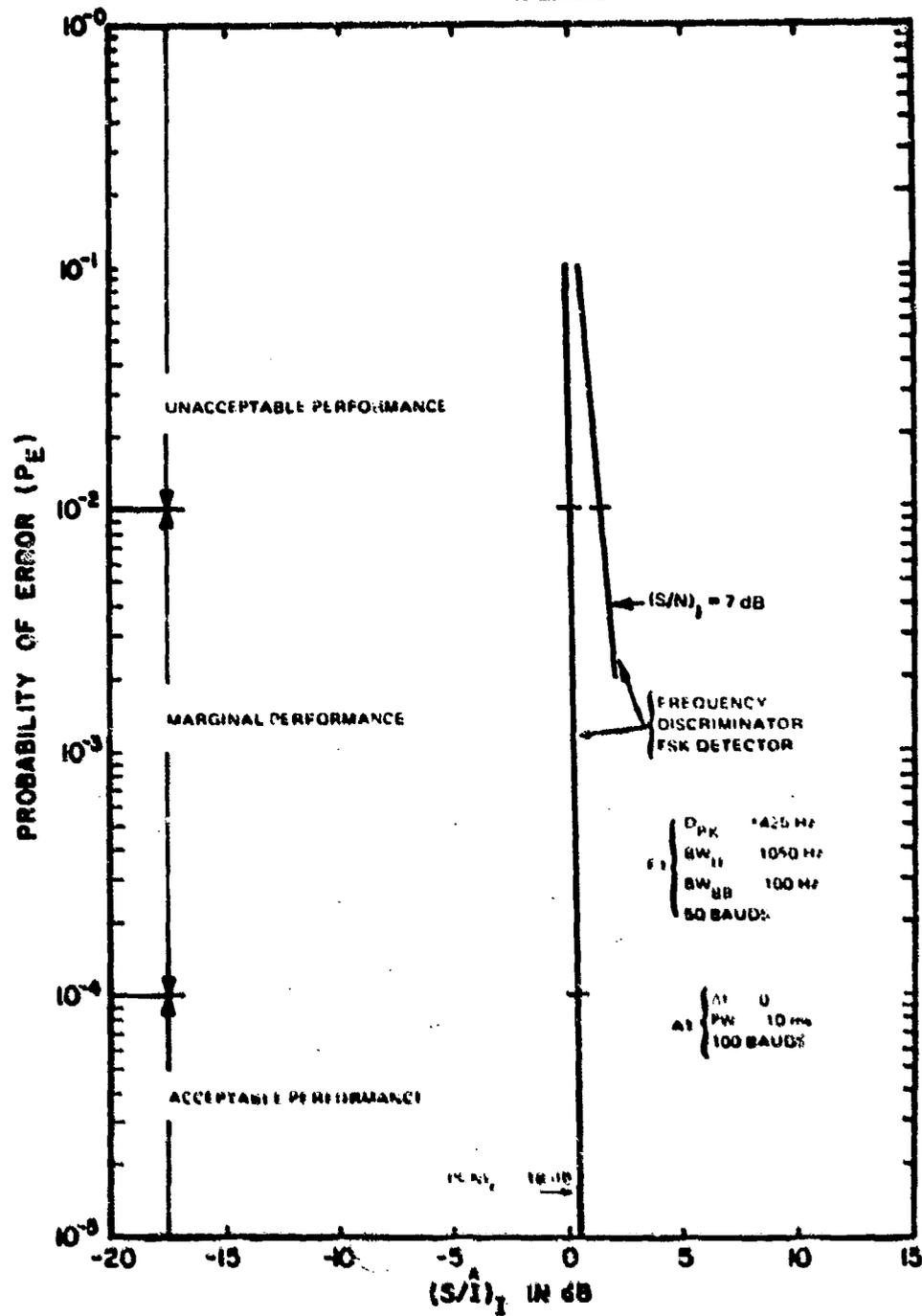


Figure C-69. Performance degradation curve for FI receiver with AI interference.

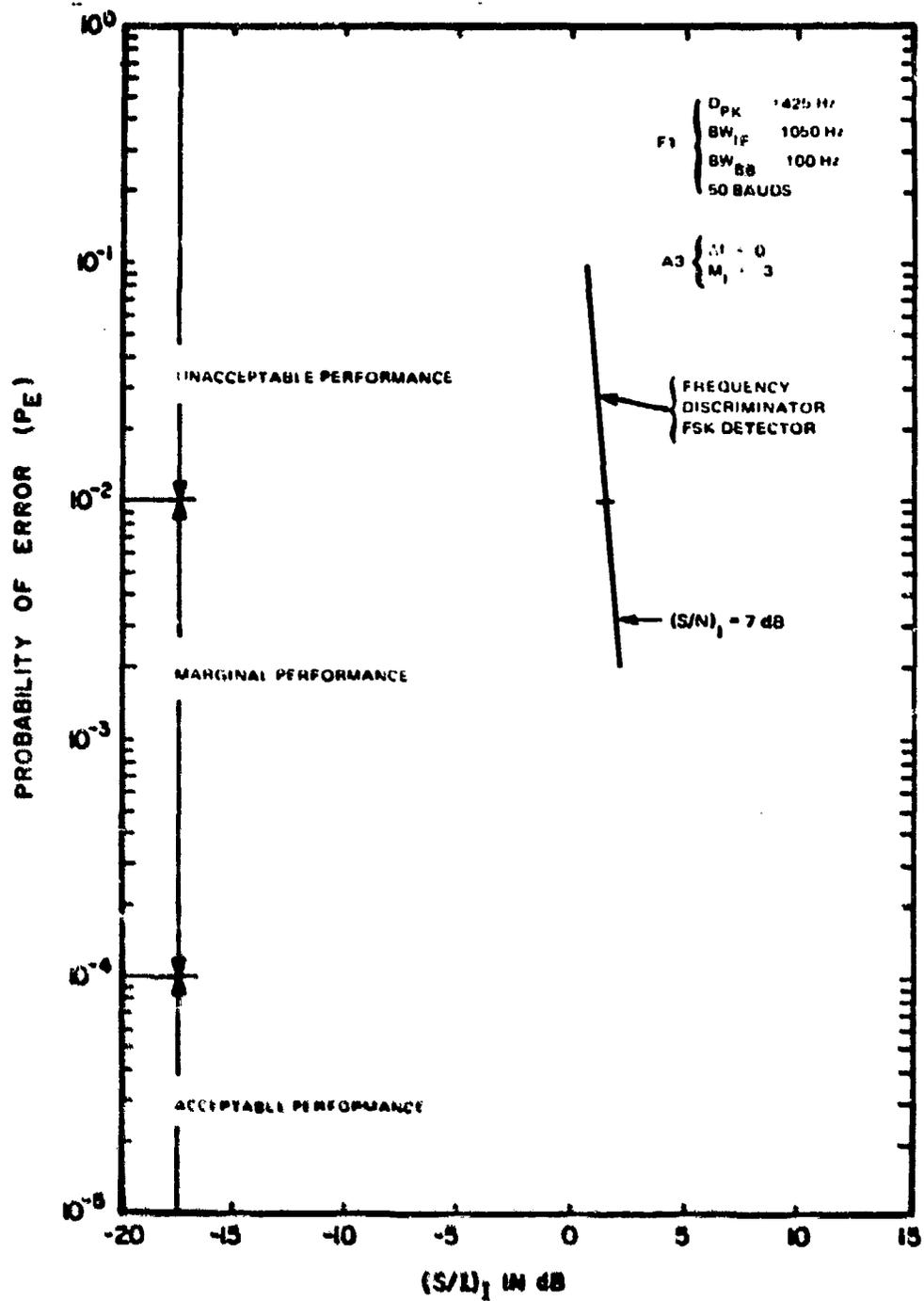


Figure C-70. Performance degradation curve for F1 receiver with A3 interference.

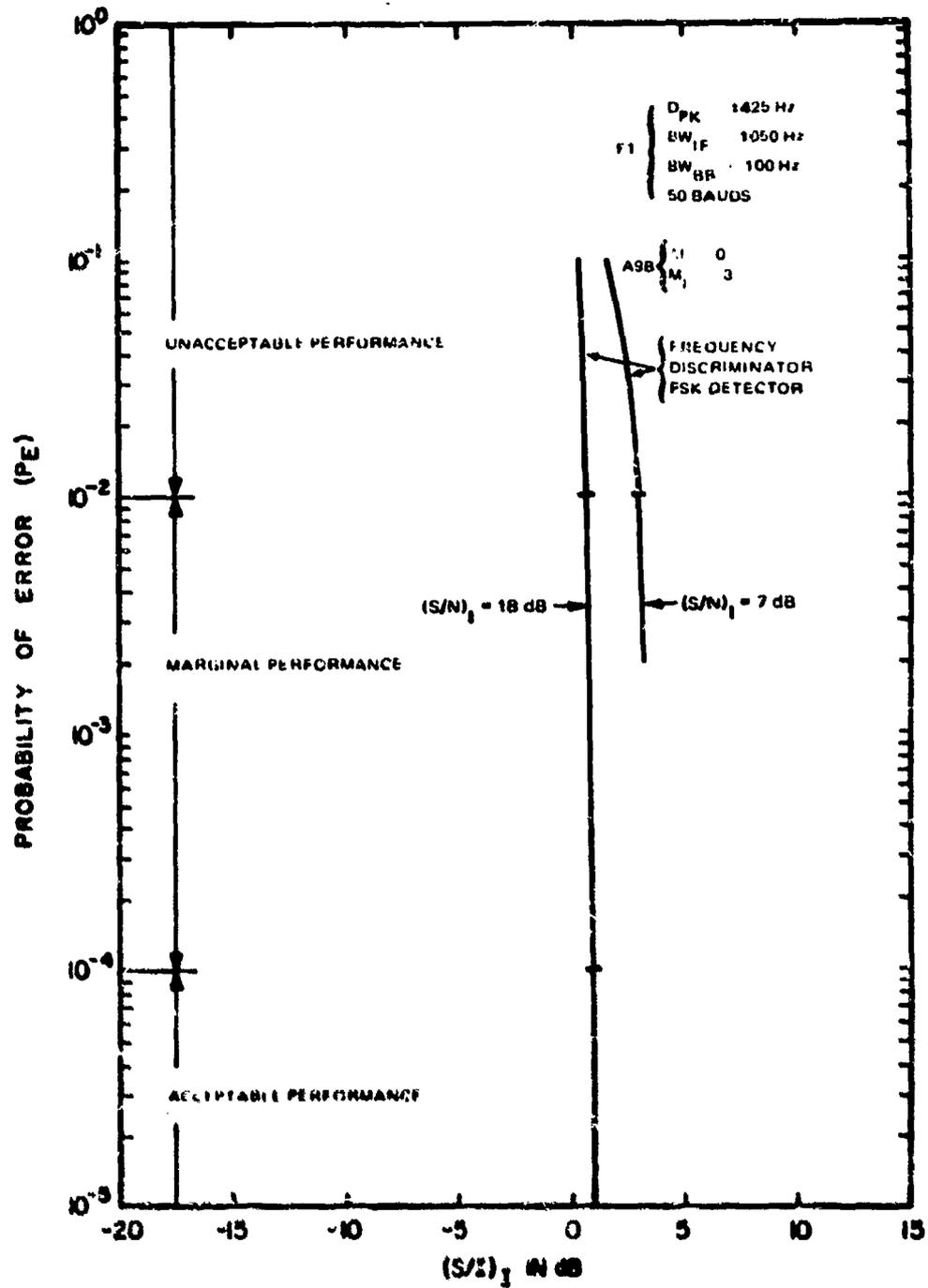


Figure C-71. Performance degradation curve for F1 receiver with A9B interference.

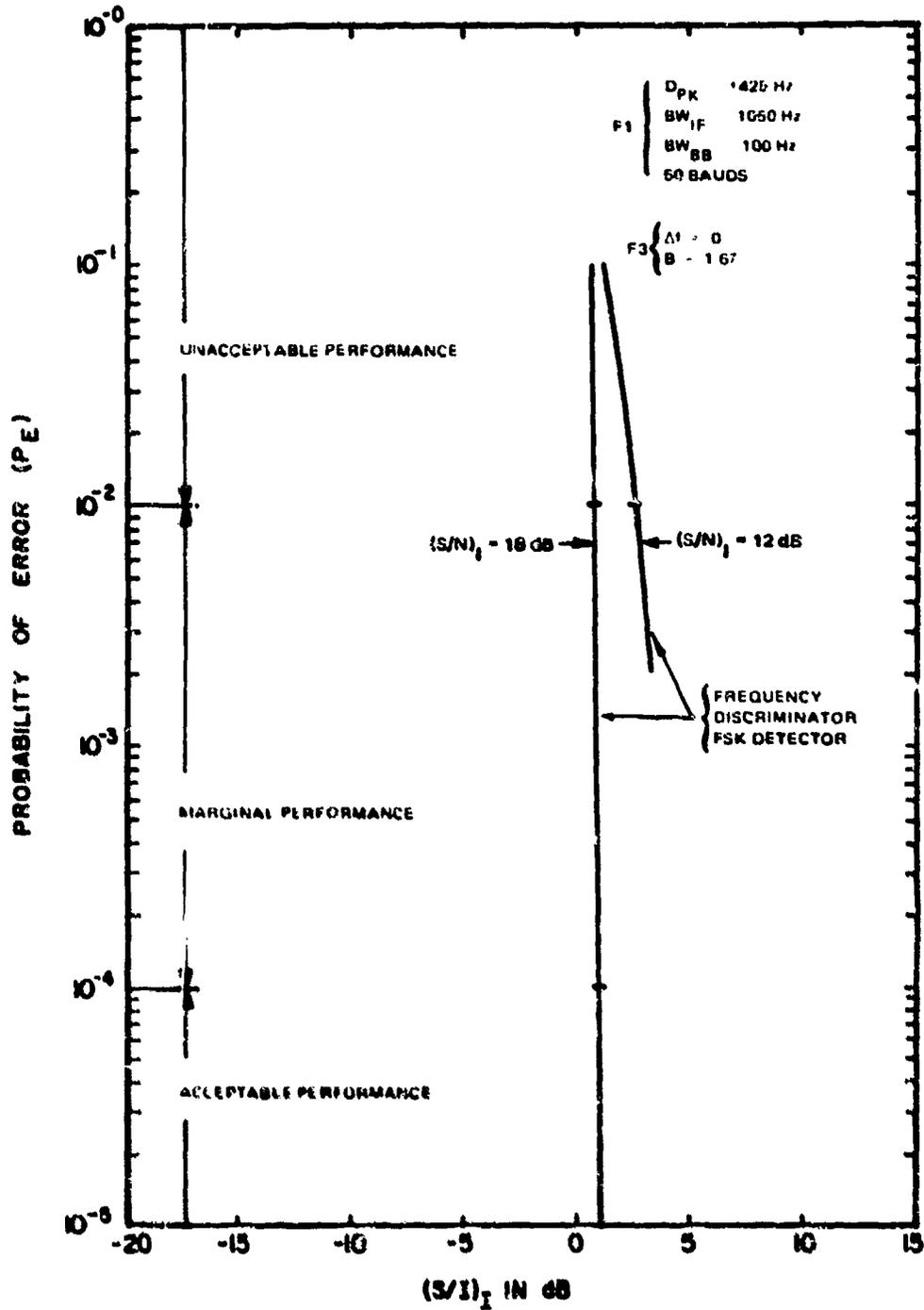


Figure C-72. Performance degradation curve for F1 receiver with F3 interference.

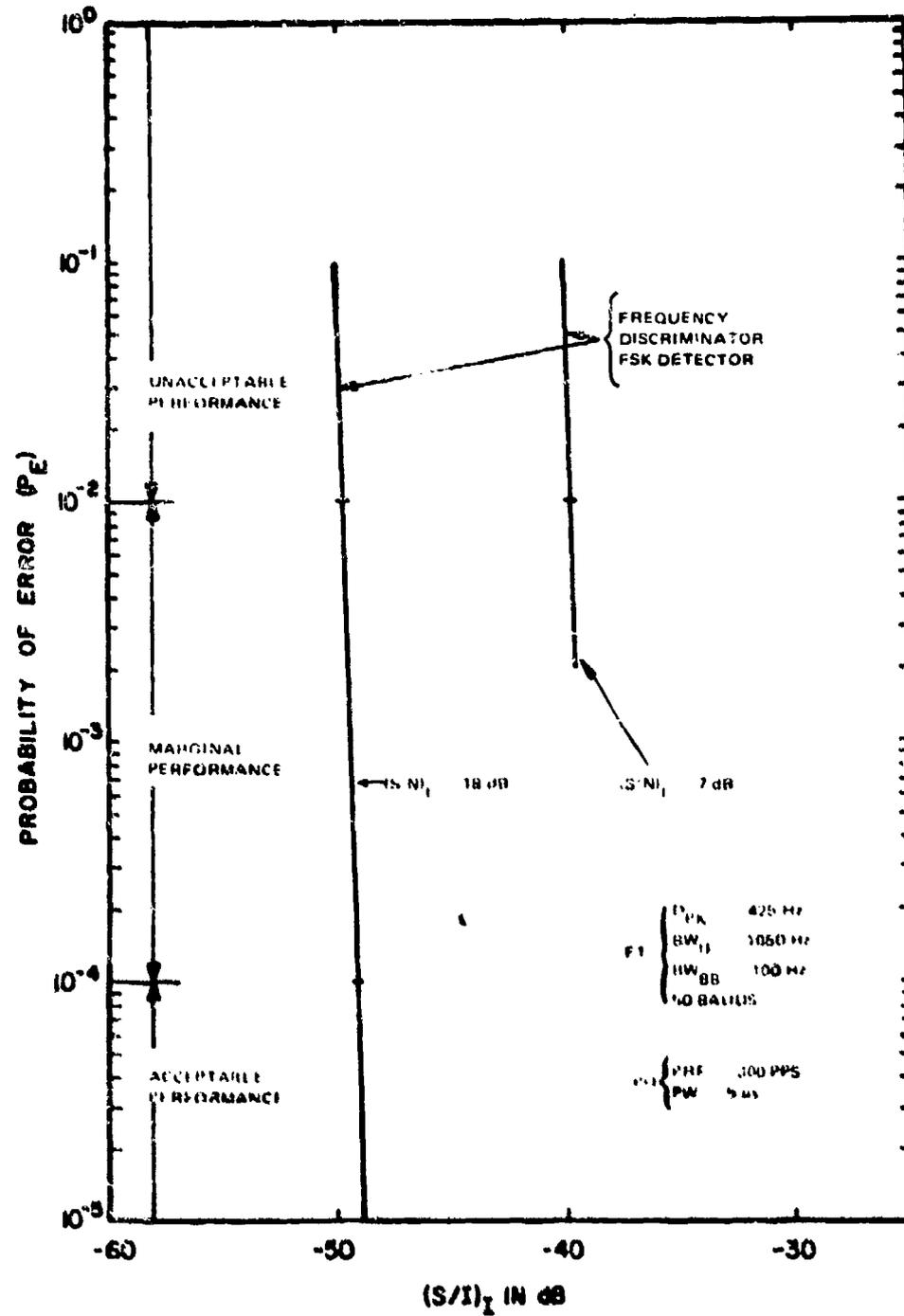


Figure C-75. Performance degradation curve for F1 receiver with PO interference.

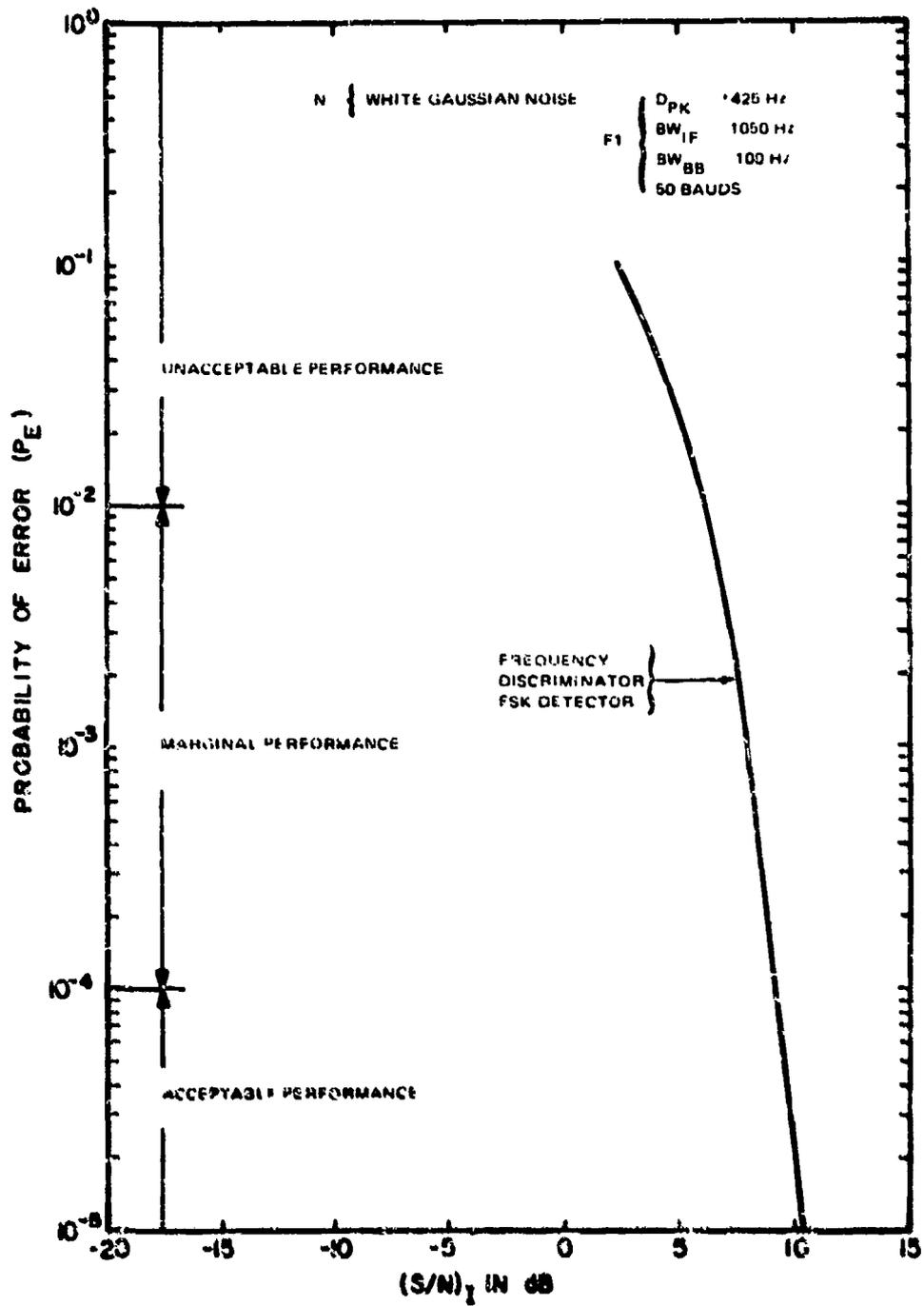


Figure C-74. Performance degradation curve for F1 receiver with noise.

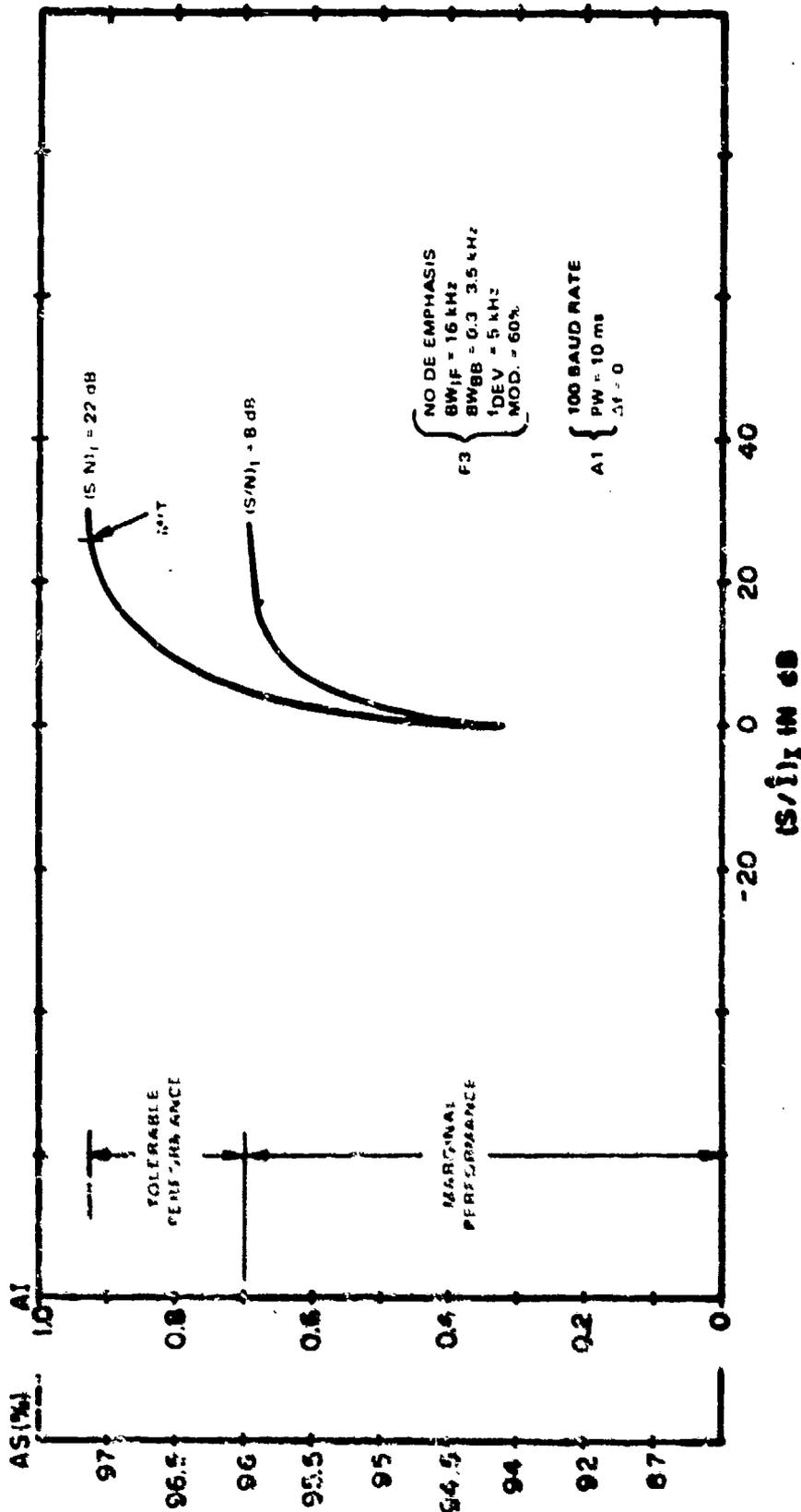


Figure C-75. Performance degradation curve for F3 receiver with A1 interference.

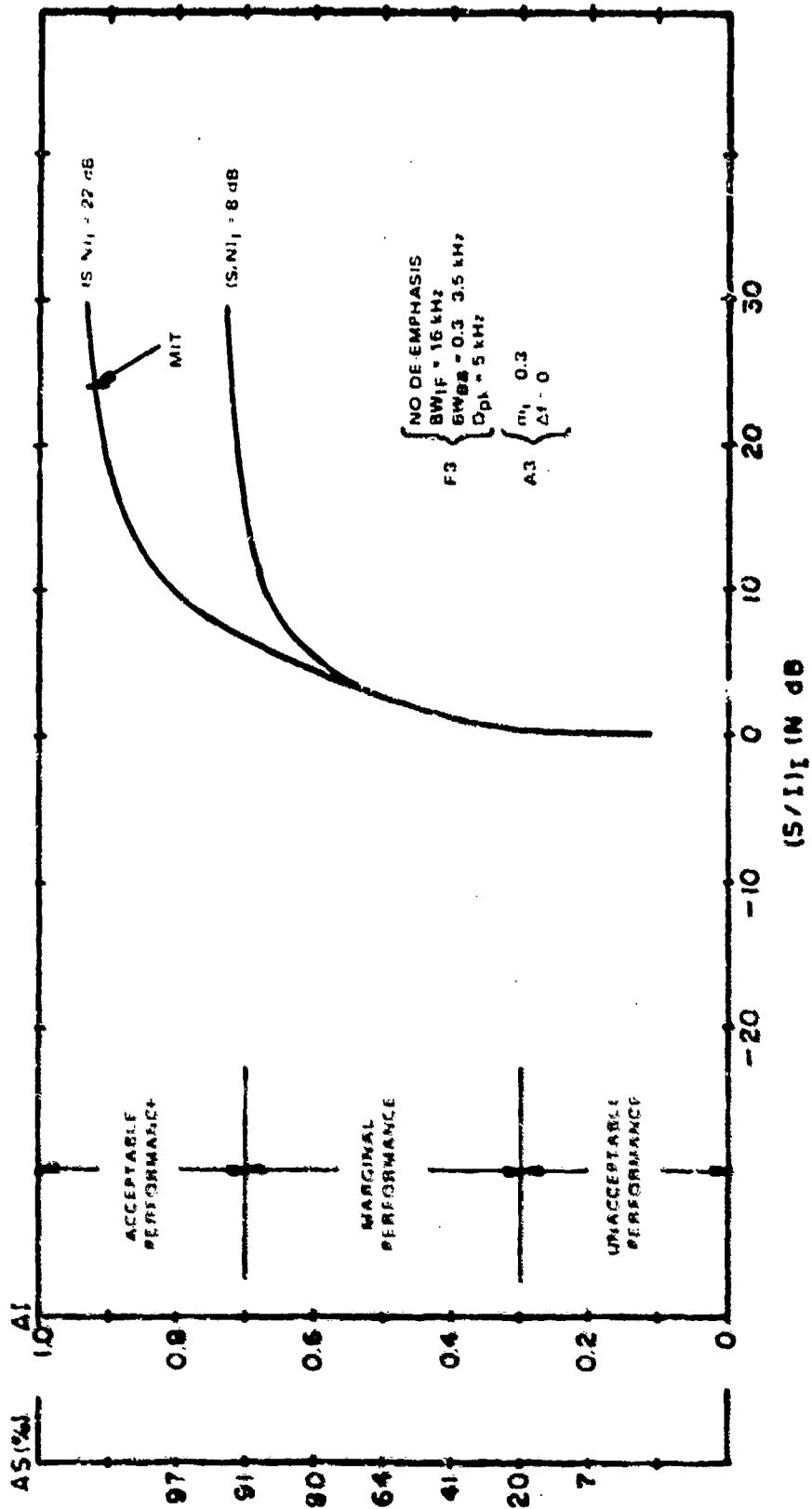


Figure C-76. Performance degradation curve for F3 receiver with A3 interference ( $\Delta f = 0$  Hz).

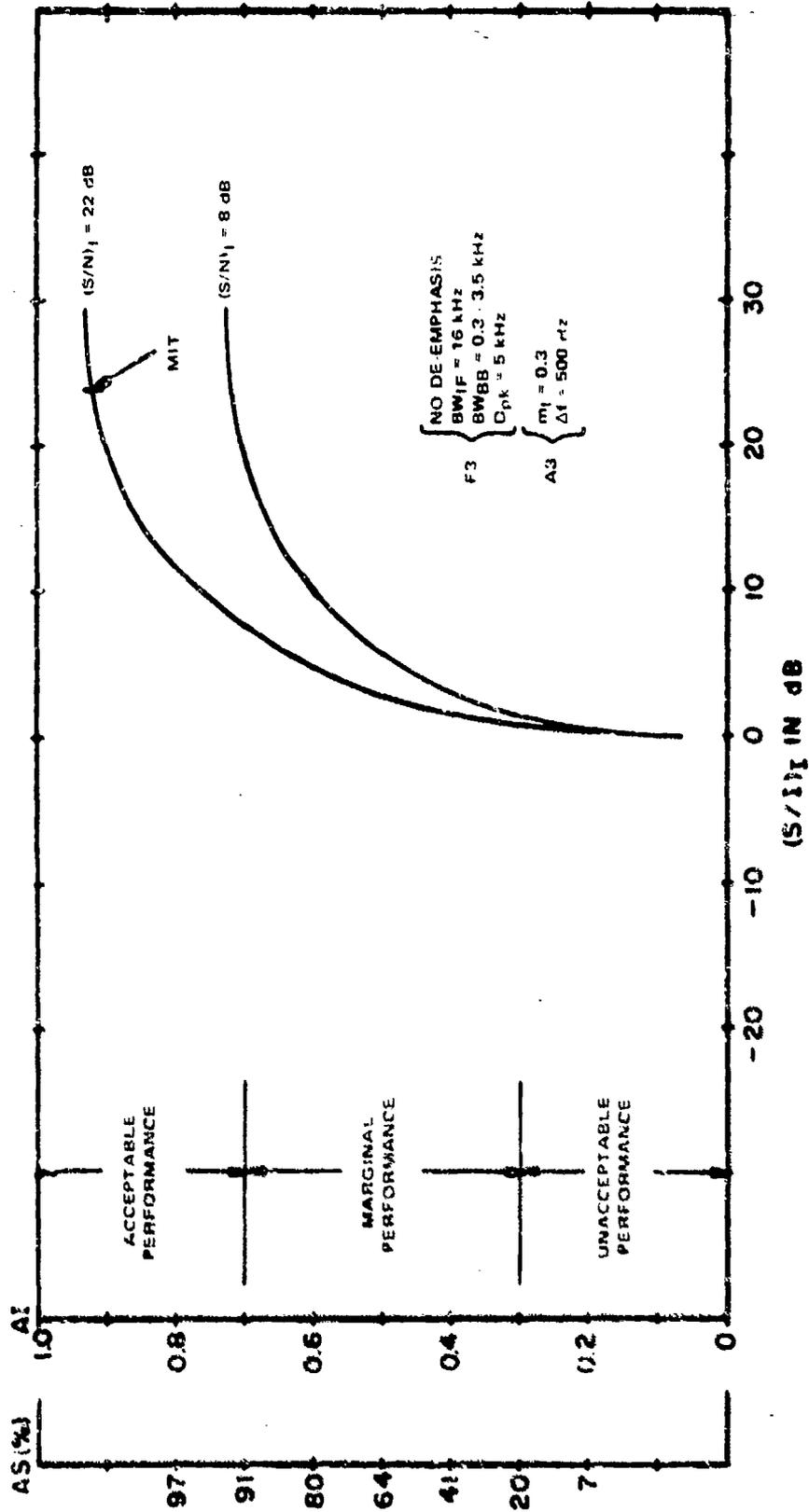


Figure C-77. Performance degradation curve for F3 receiver with A3 interference ( $\Delta f = 500$  Hz).

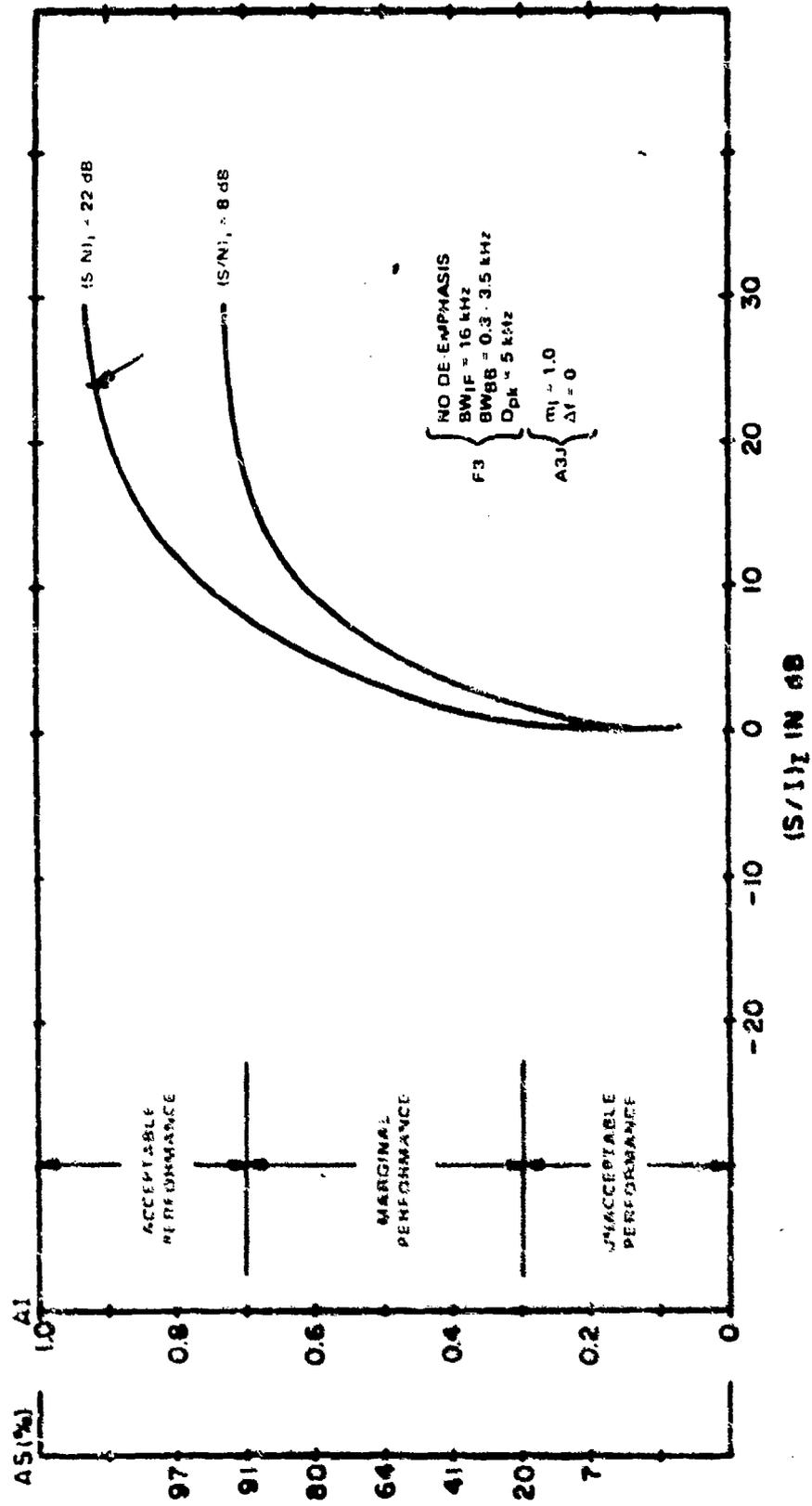


Figure C-78. Performance degradation curve for F3 receiver with A3J interference.

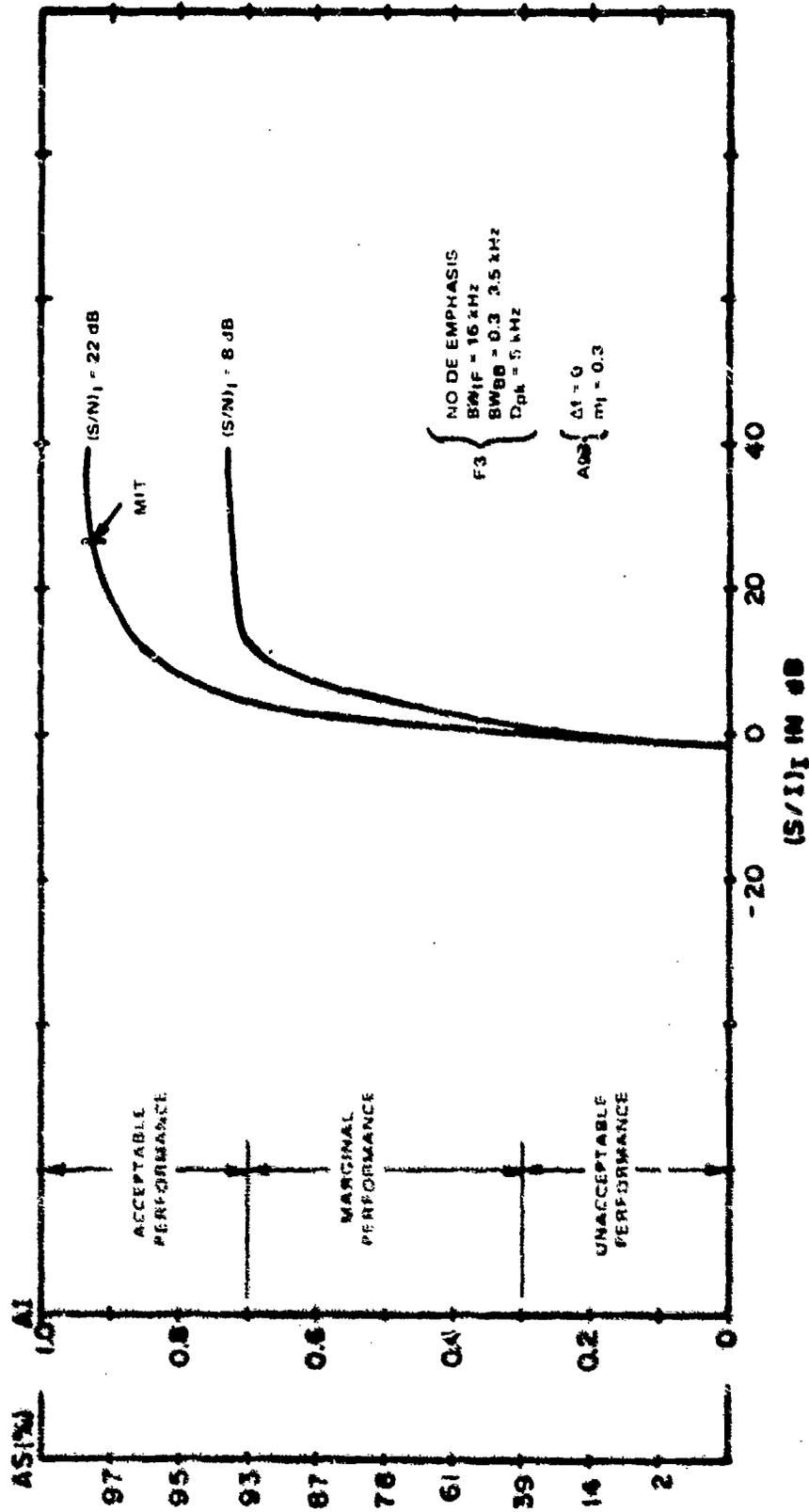


Figure C-79. Performance degradation curve for F3 receiver with A9B interference.

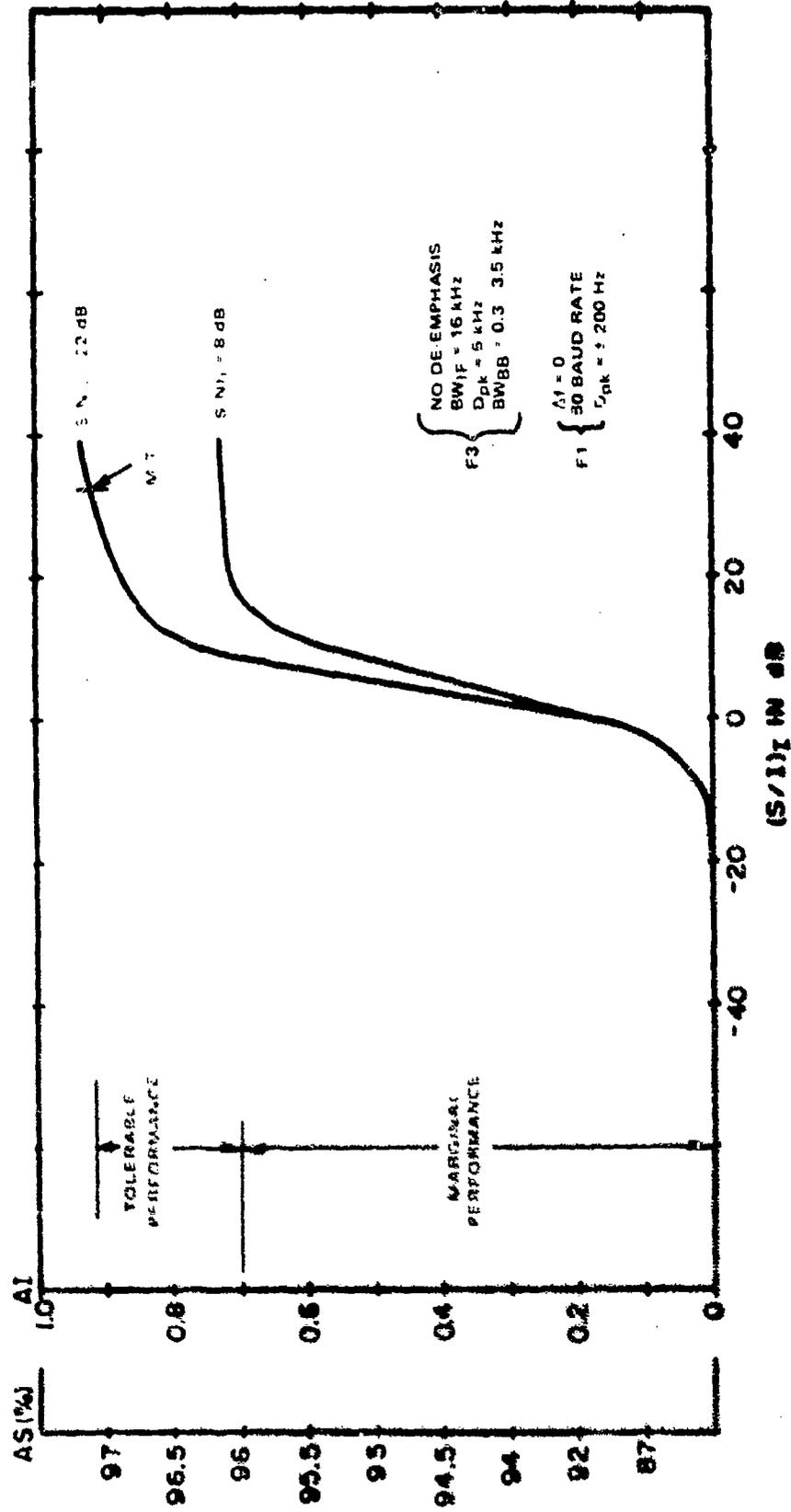


Figure C-80. Performance degradation curve for F3 receiver with F1 interference ( $\Delta f = 0$  Hz).

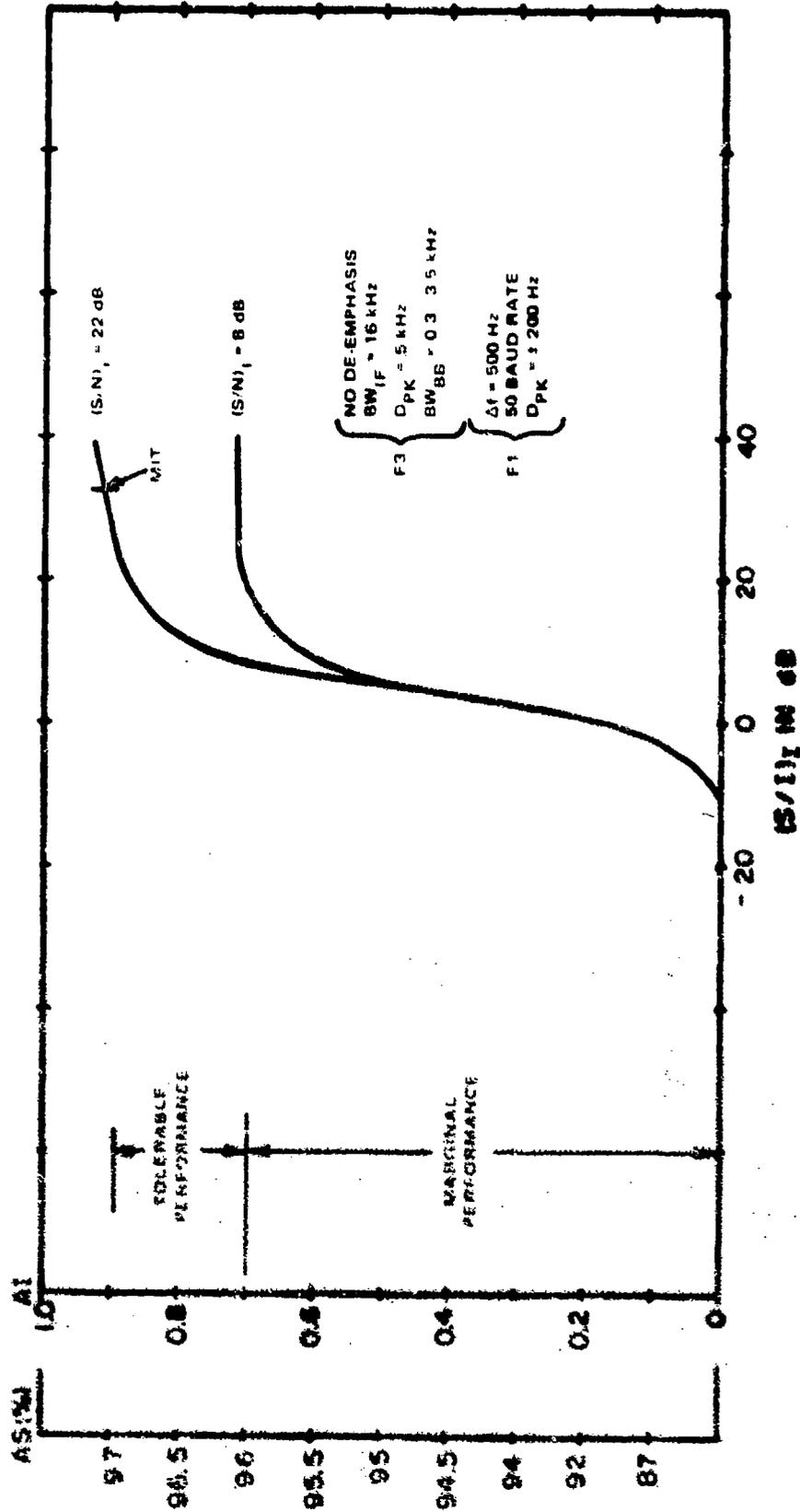


Figure C-81. Performance degradation curve for F3 receiver with F1 interference ( $\Delta f = 500$  Hz).

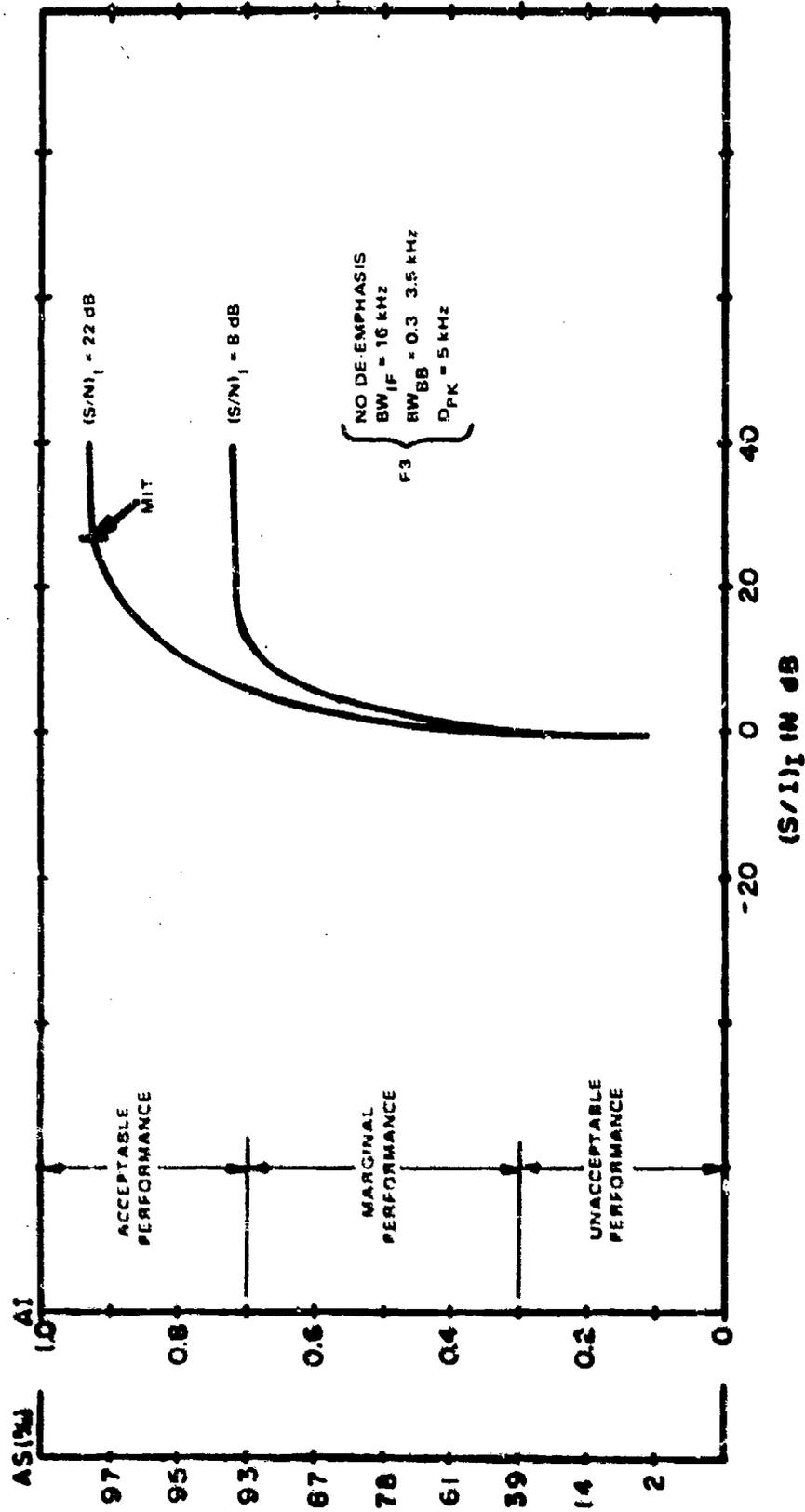


Figure C-82. Performance degradation curve for F3 receiver with F3 interference.

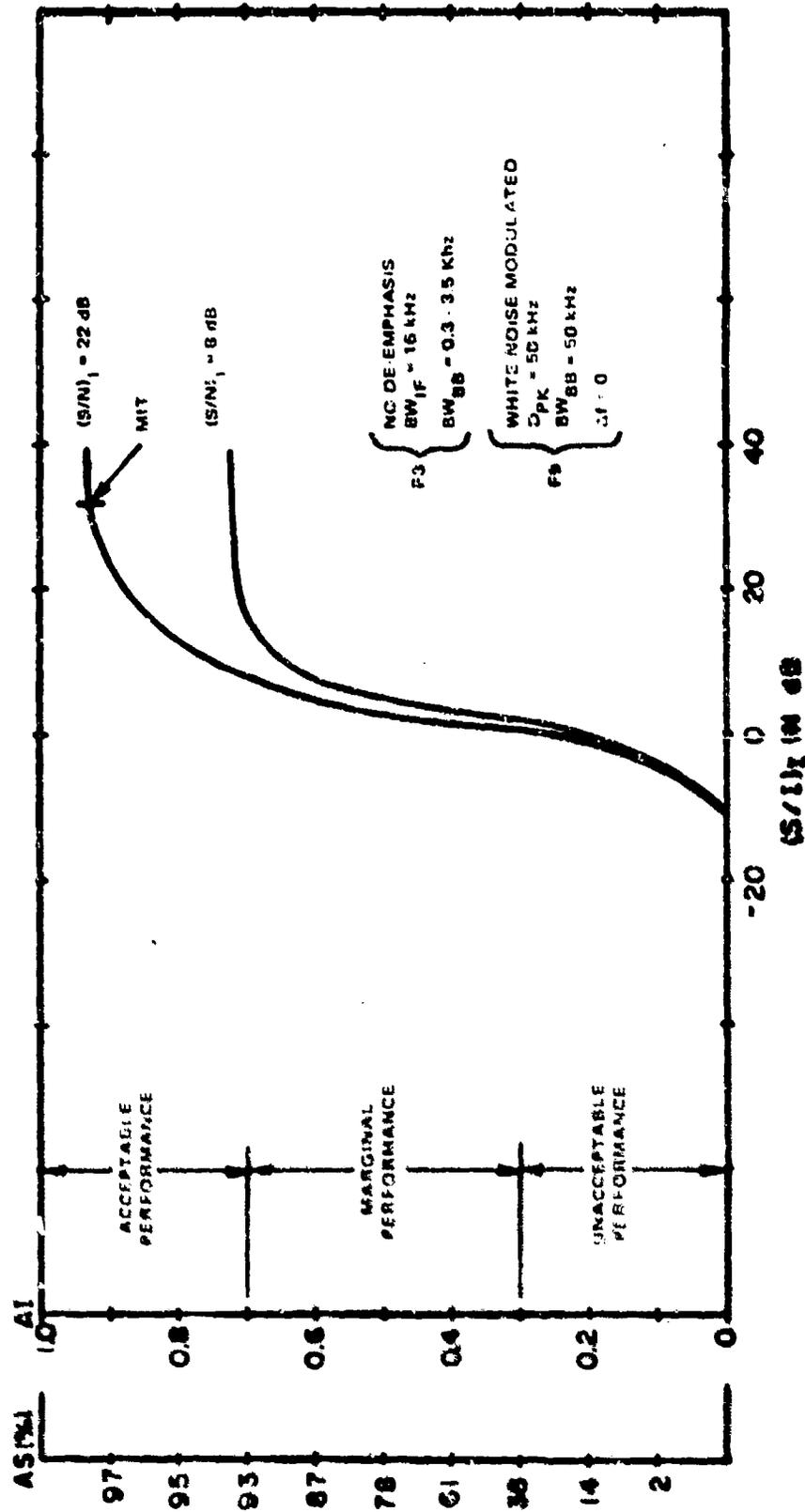


Figure C-83. Performance degradation curve for F3 receiver with F9 interference.

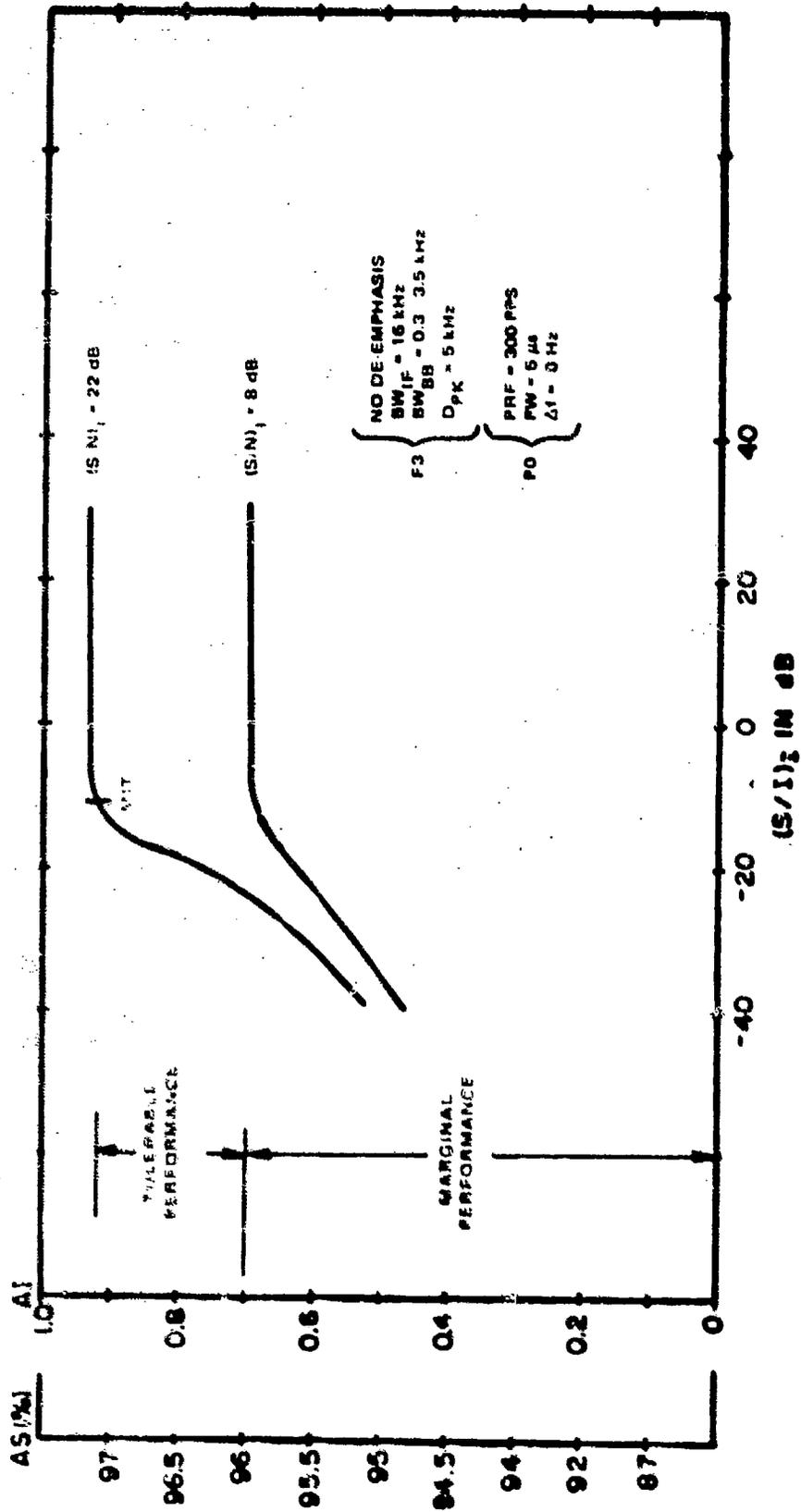


Figure C-84. Performance degradation curve for F3 receiver with P0 interference.

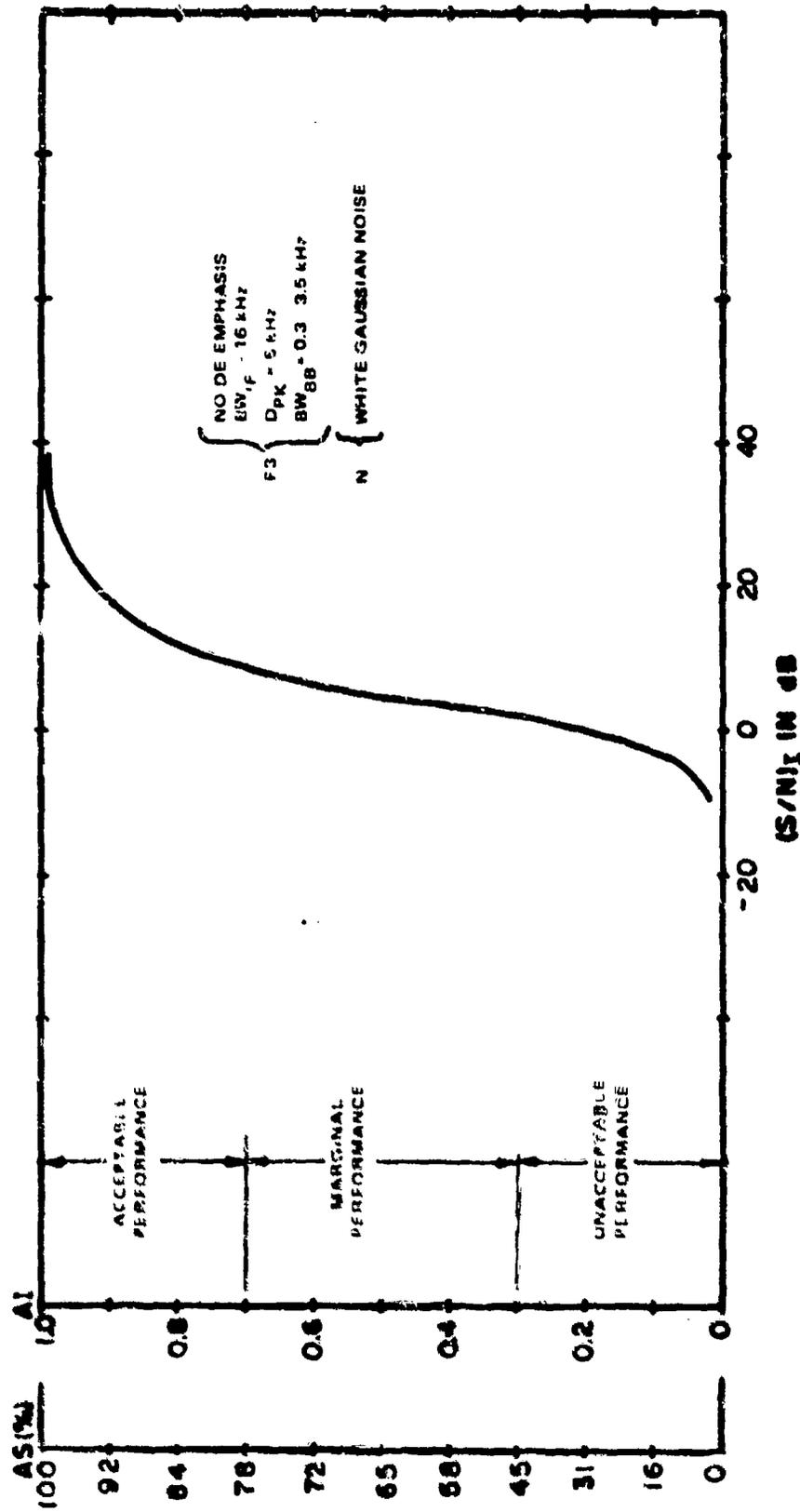


Figure C-85. Performance degradation curve for F3 receiver with noise.

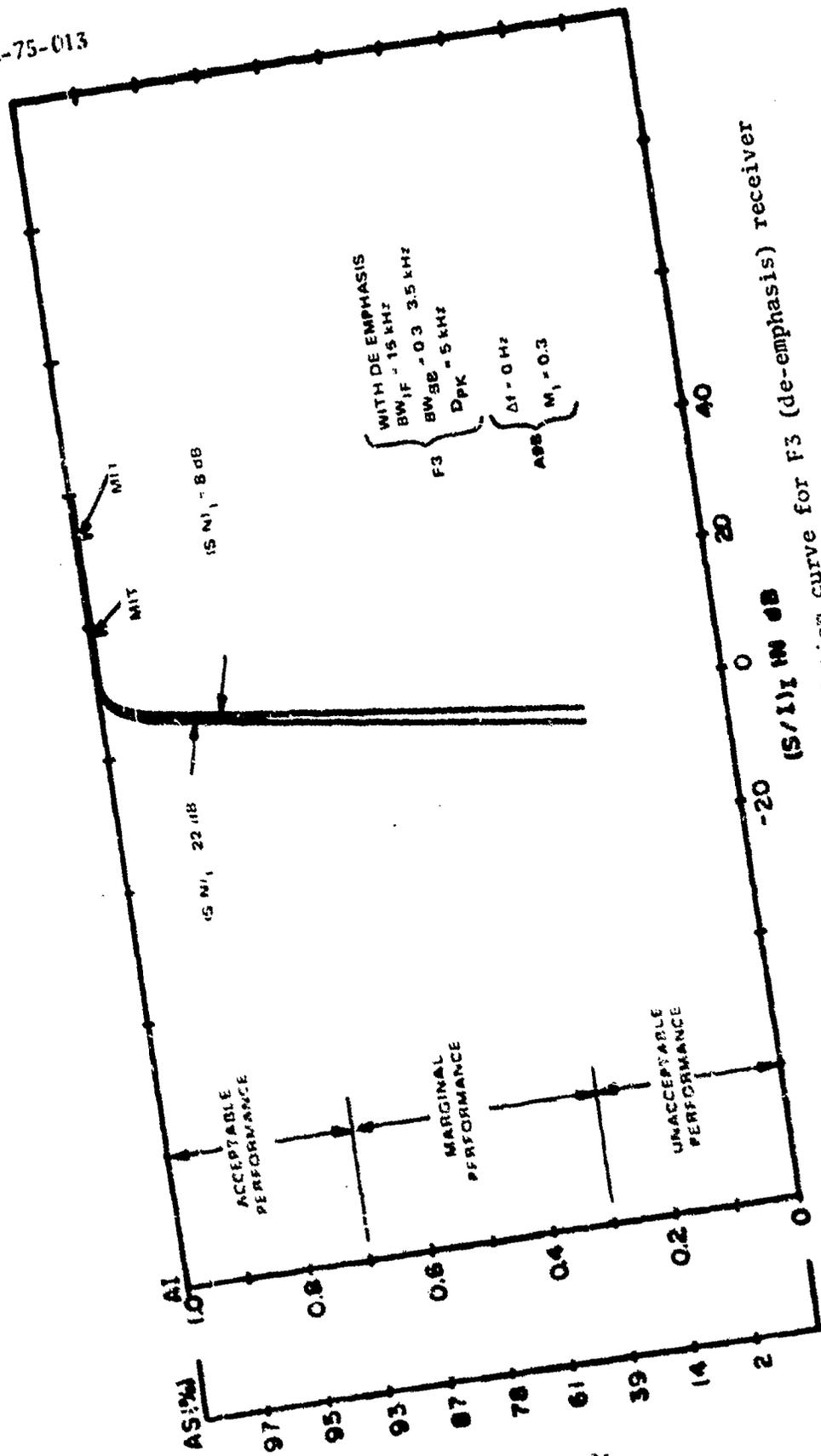


Figure C-86. Performance degradation curve for F3 (de-emphasis) receiver with AGB interference.

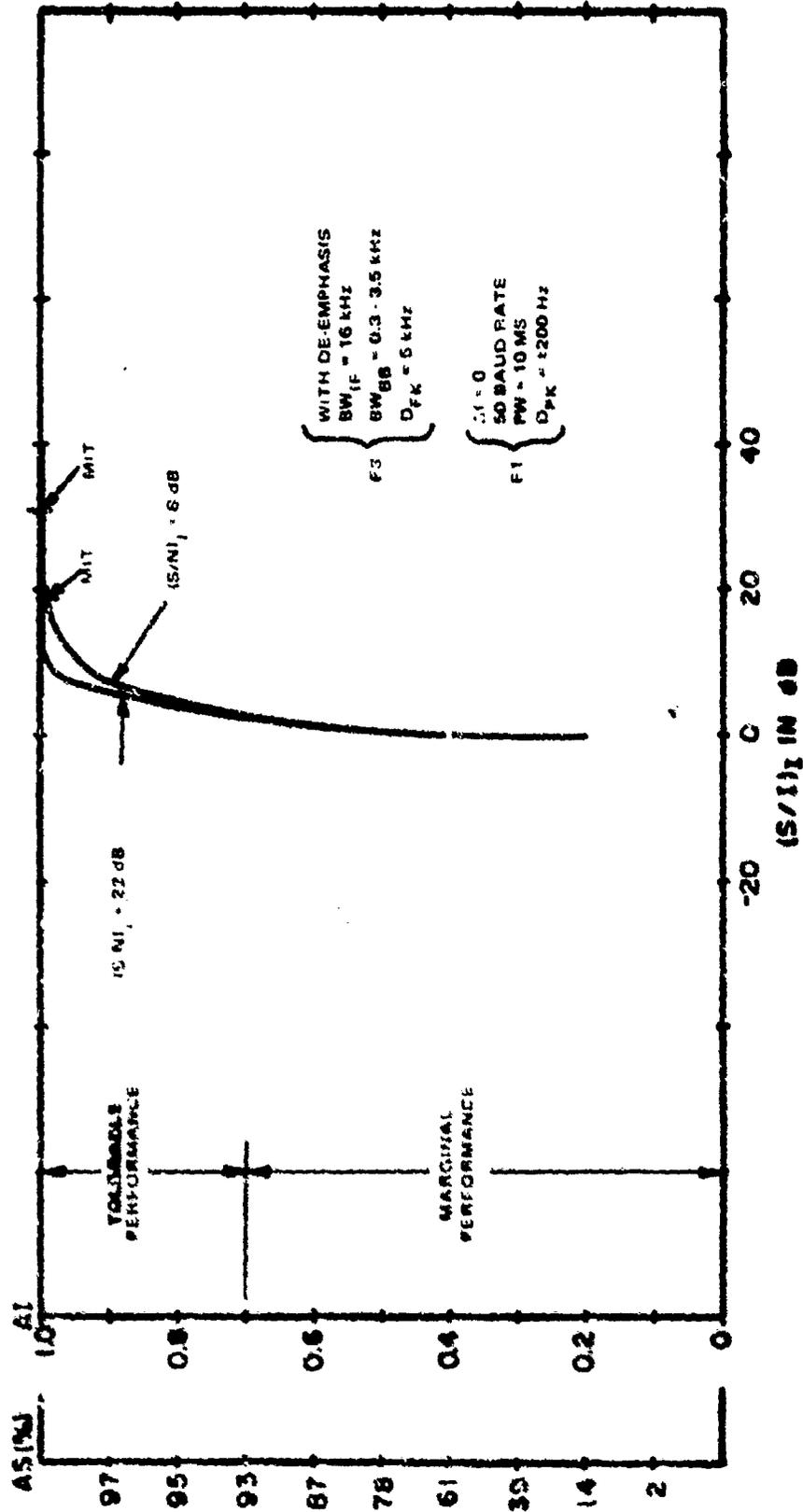


Figure C-87. Performance degradation curve for F3 (de-emphasis) receiver with F1 interference.

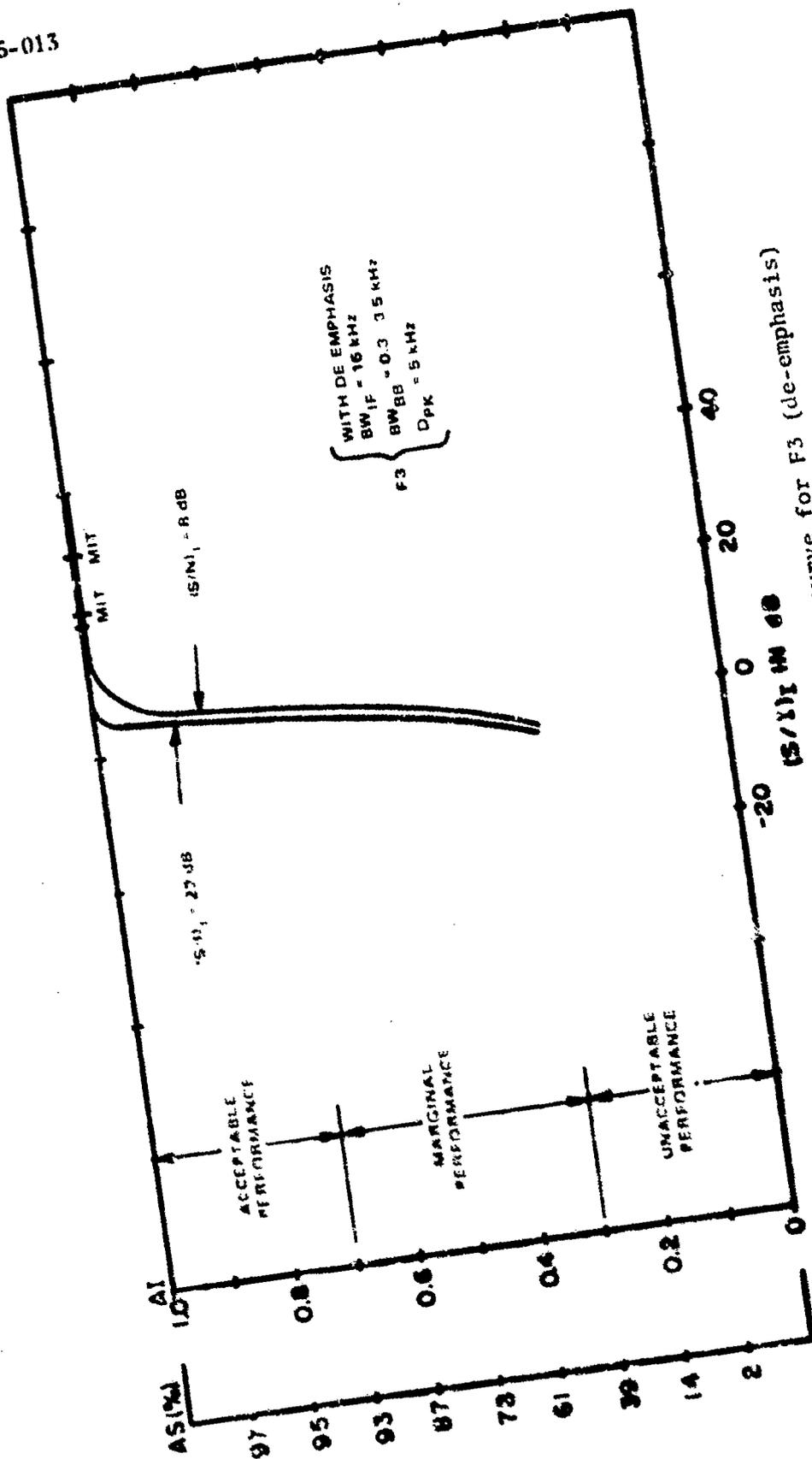


Figure C-88. Performance degradation curve for F3 (de-emphasis) receiver with F3 interference.

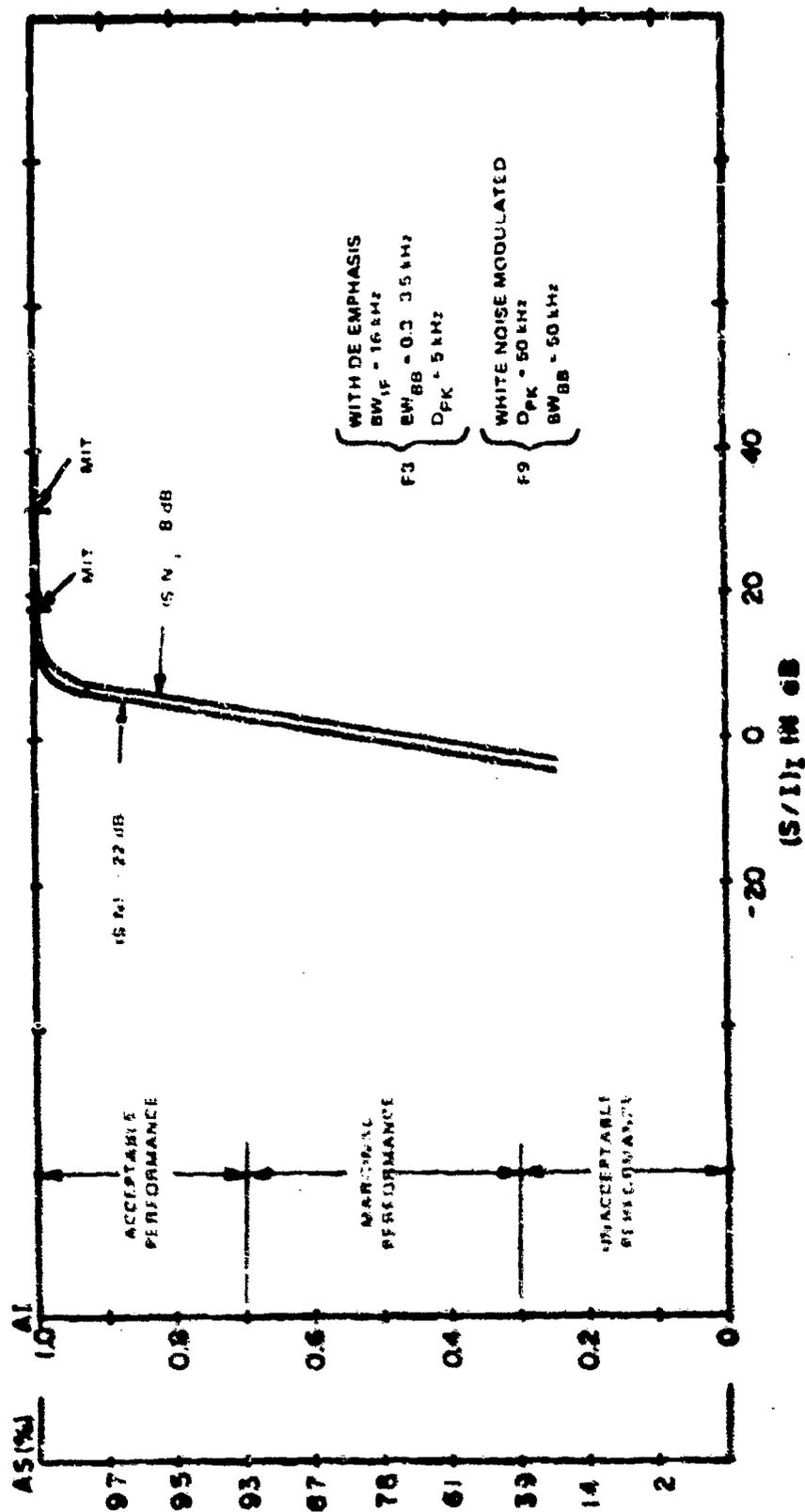


Figure C-89. Performance degradation curve for F3 (de-emphasis) receiver with F9 interference.

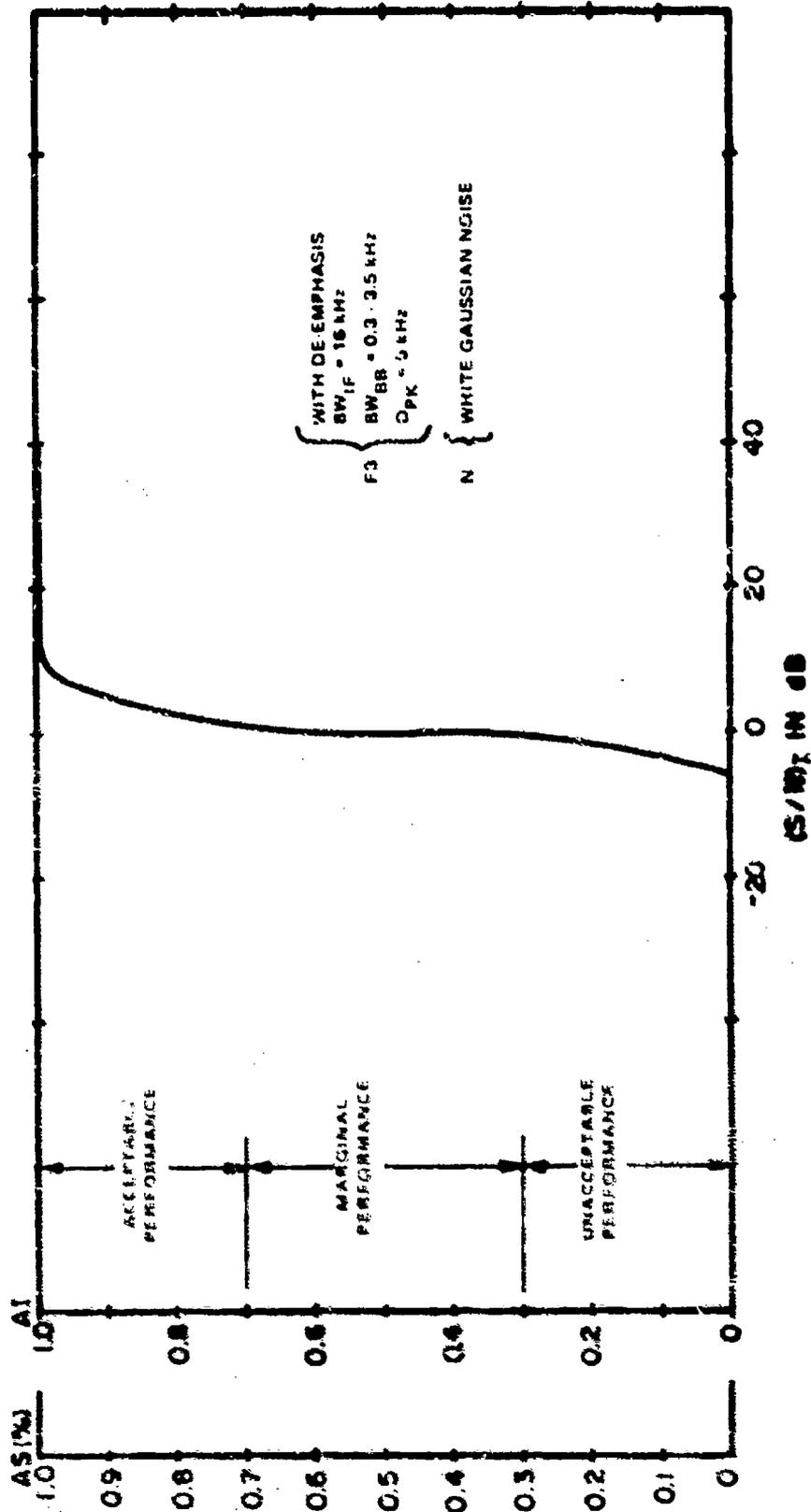


Figure C-90. Performance degradation curve for F3 (de-emphasis) receiver with noise.

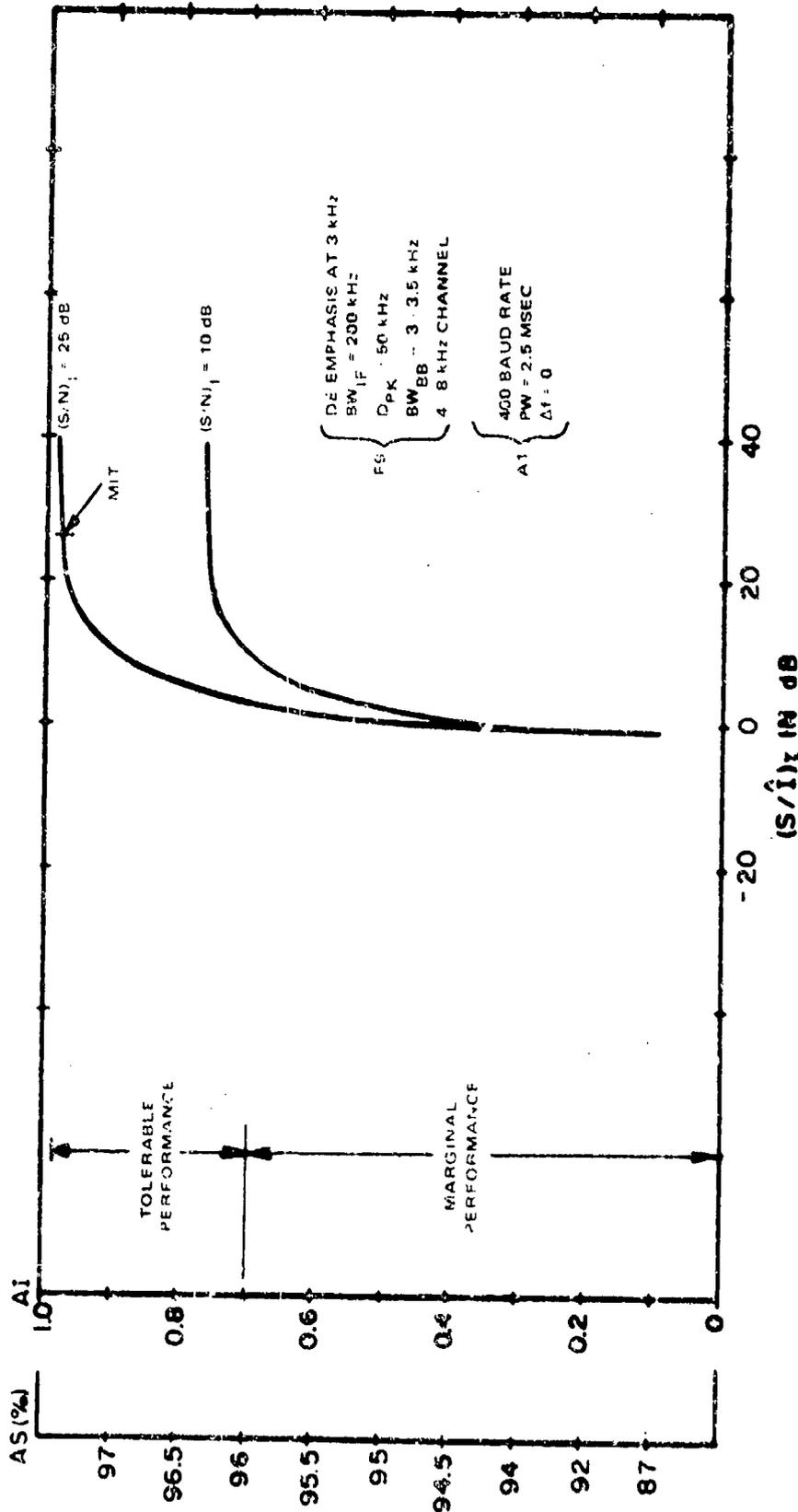


Figure C-91. Performance degradation curve for F9 receiver with AI interference (4-8 kHz lower channel, 400 baud rate, Δf = 0 Hz).

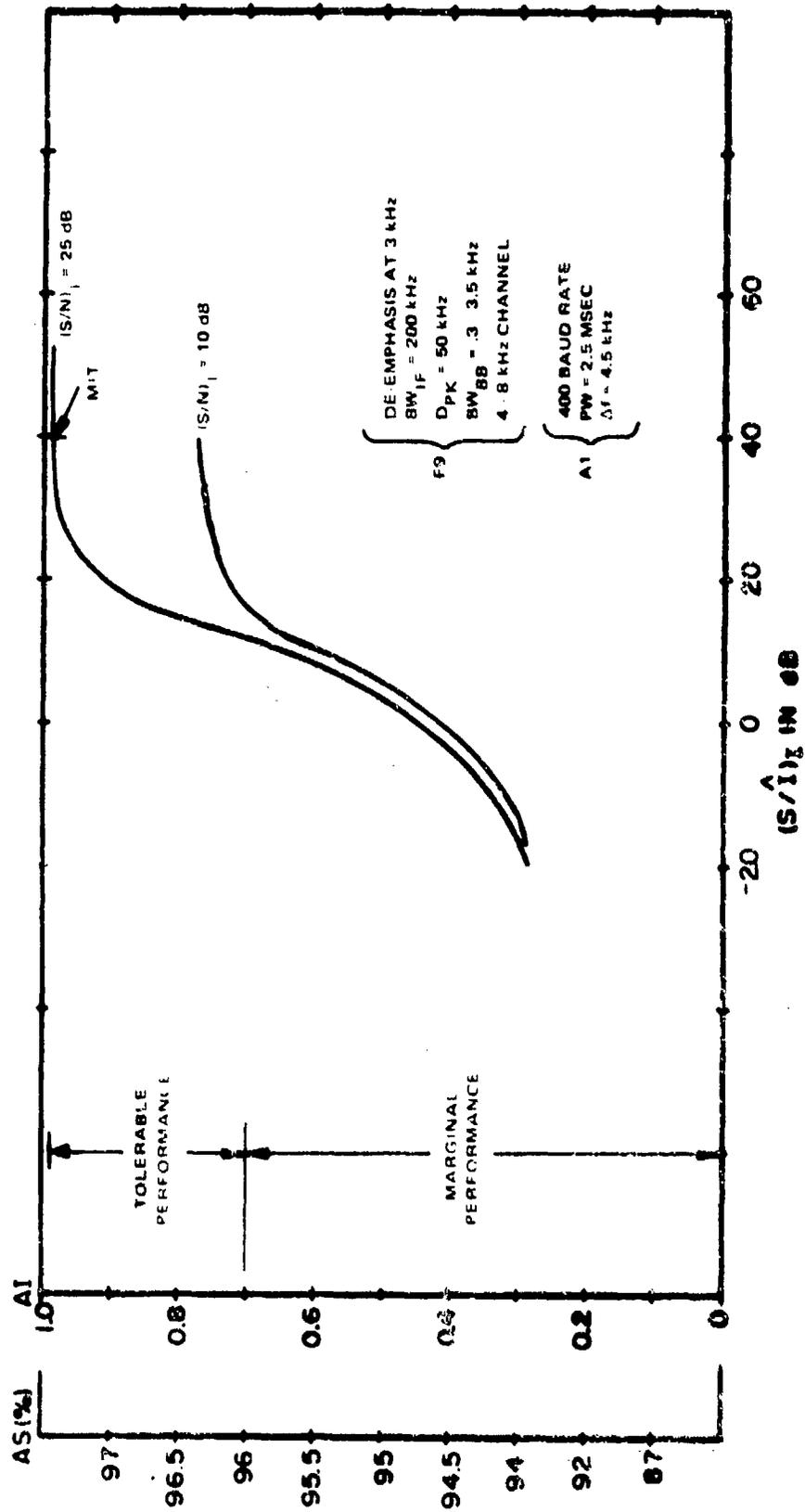


Figure C-92. Performance degradation curve for F9 receiver with A1 interference (4-8 kHz lower channel, 400 baud rate, Δf = 4.5 kHz).

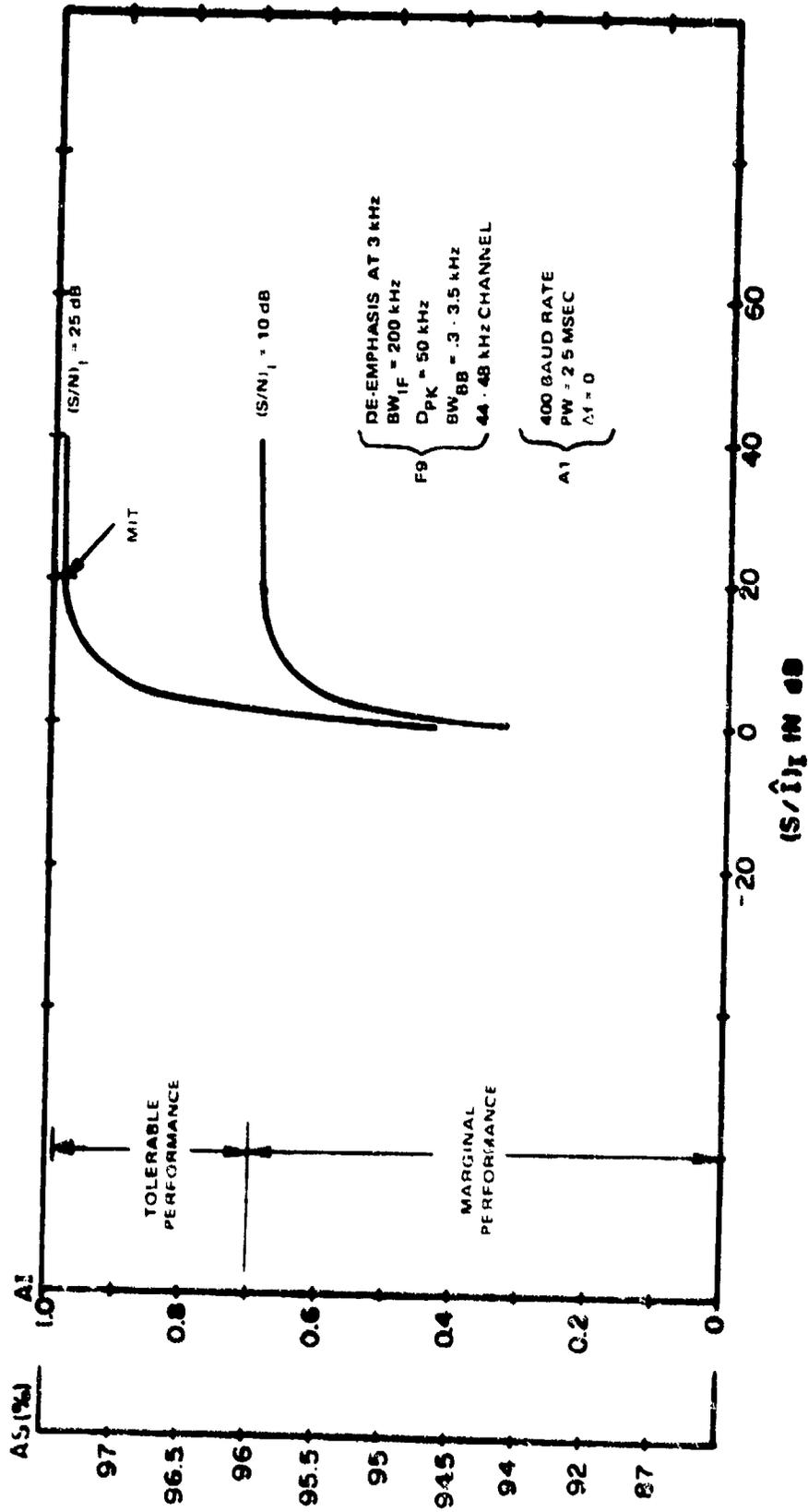


Figure C-93. Performance degradation curve for F9 receiver with A1 interference (44-48 kHz upper channel, 400 baud rate, Δf = 0 Hz).

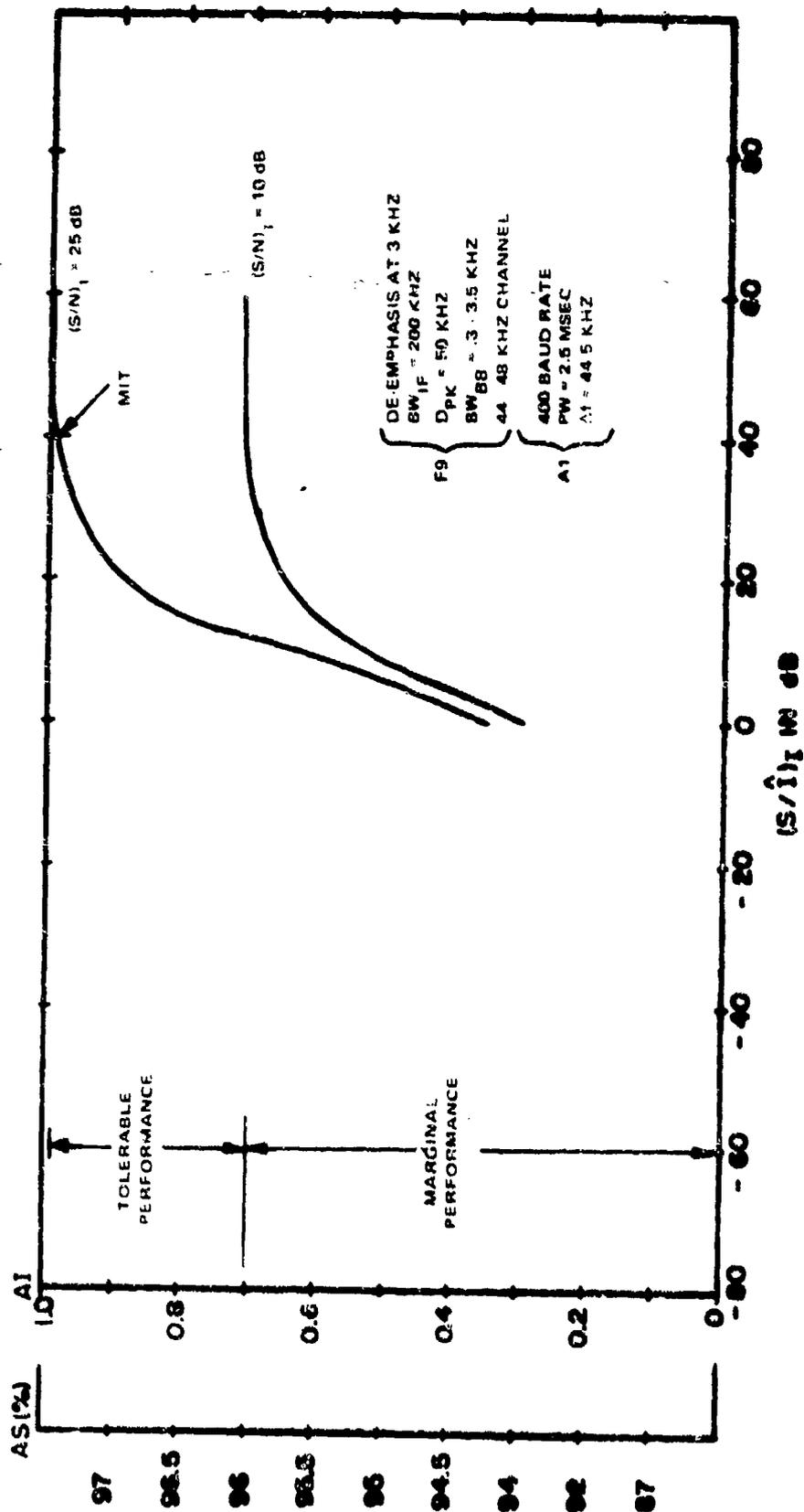


Figure C-94. Performance degradation curve for F9 receiver with A1 interference (44-48 kHz upper channel 400 baud rate, Δf = 44.5 kHz).

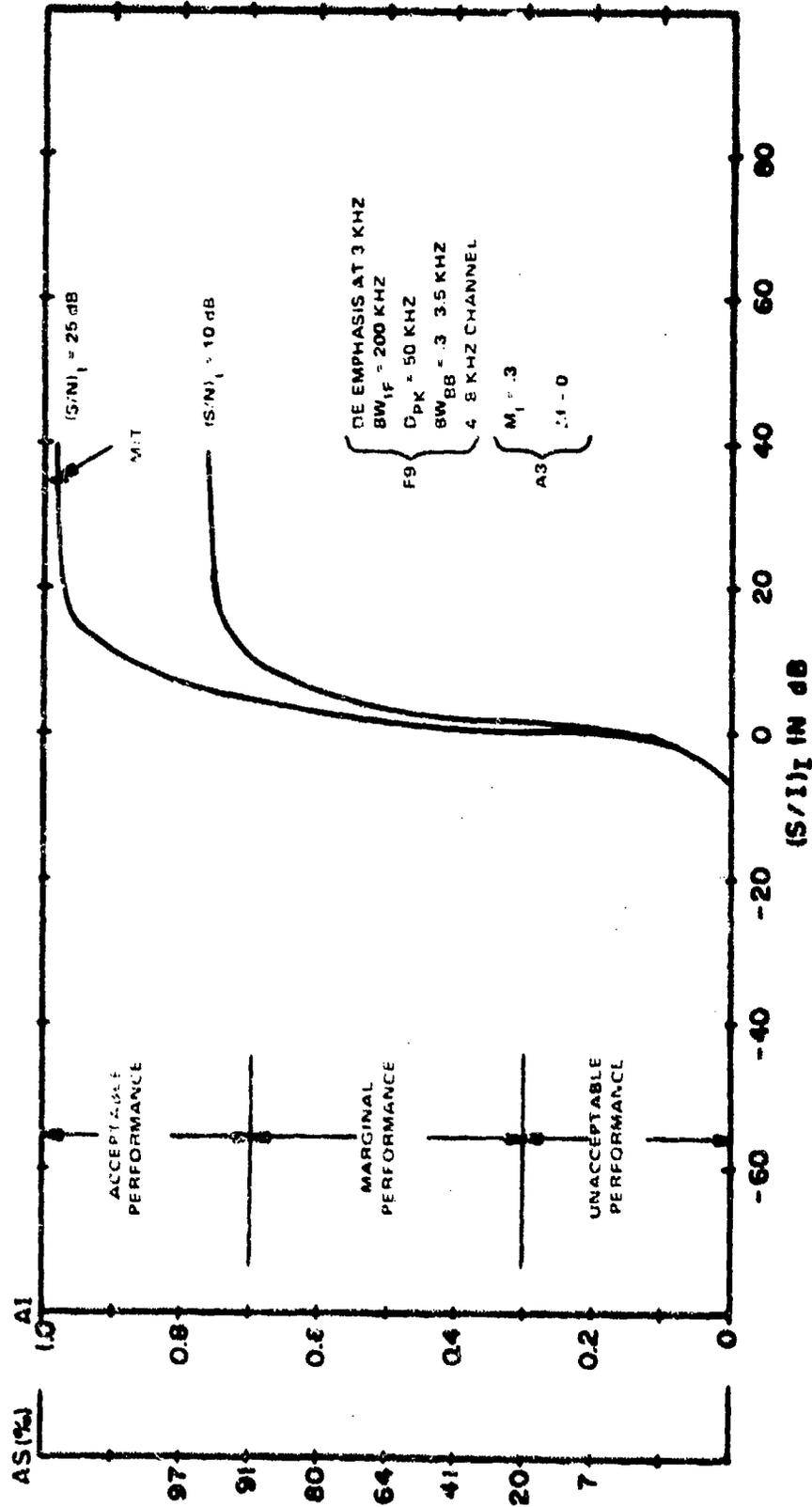


Figure C-95. Performance degradation curve for F9 receiver with A3 interference (4-8 kHz lower channel, Δf = 0 Hz).

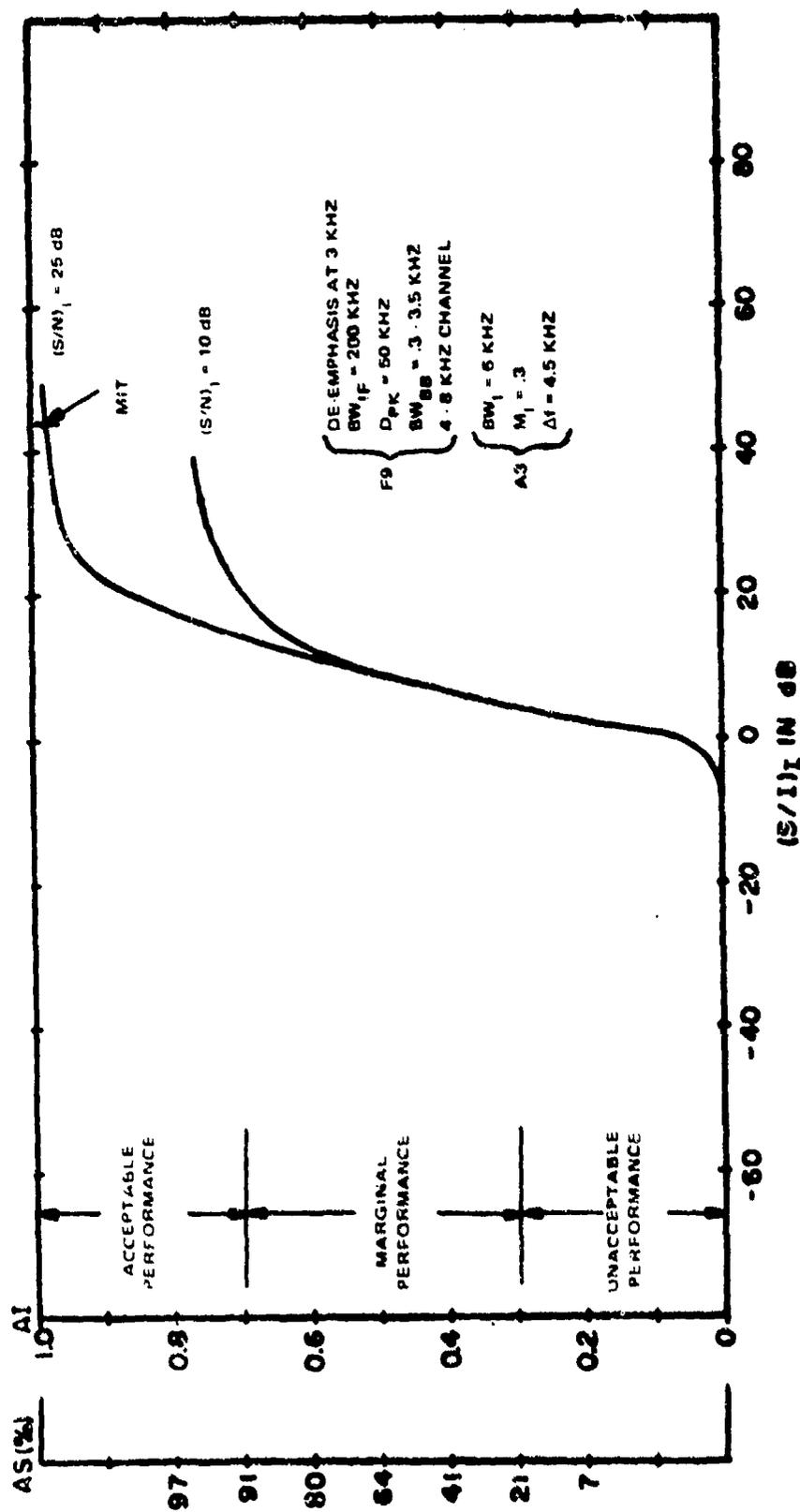


Figure C-96. Performance degradation curve for F9 receiver with A3 interference (4-8 kHz lower channel, Δf = 4.5 kHz).

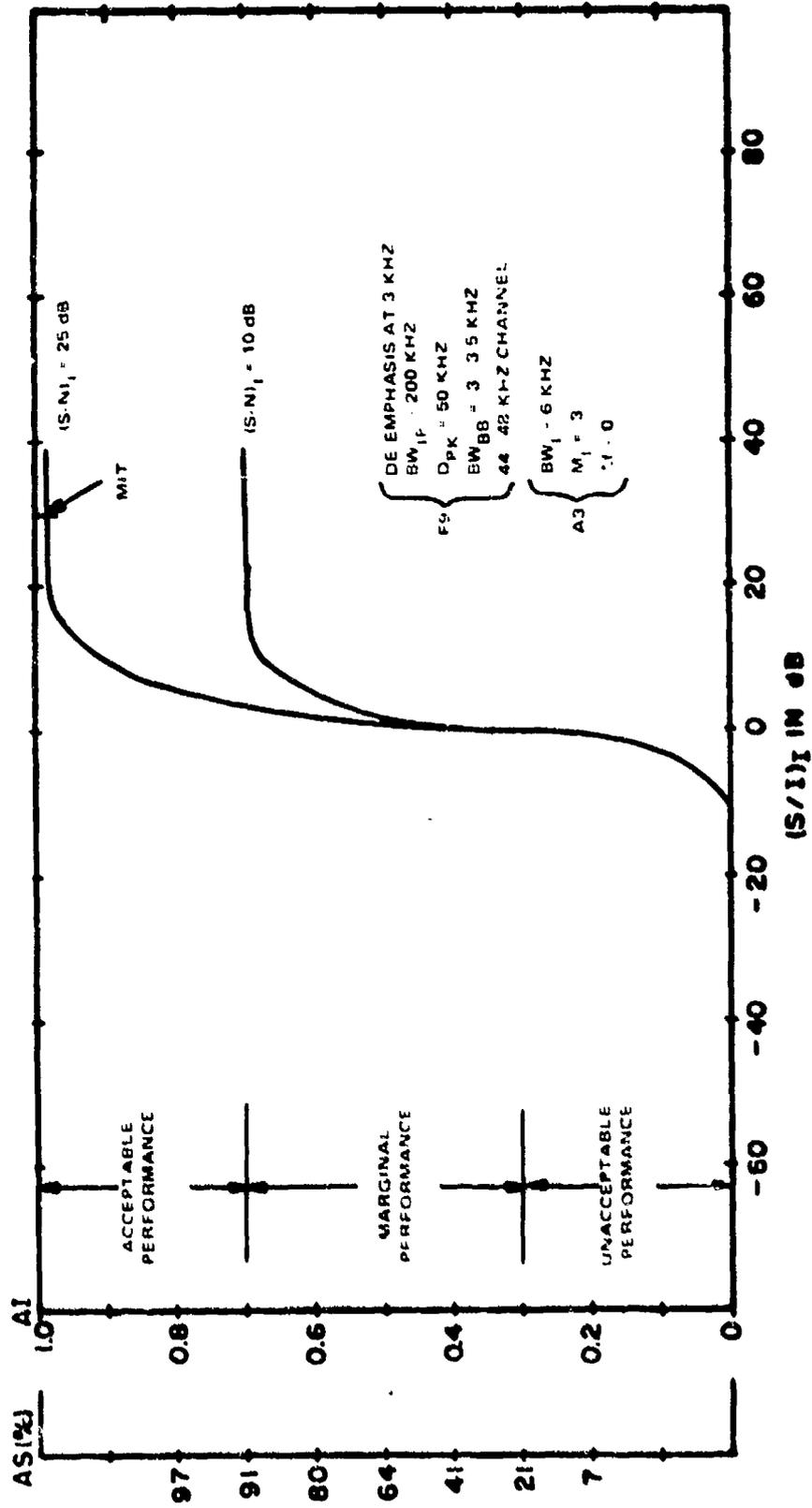


Figure C-97. Performance degradation curve for F9 receiver with A3 interference (44-48 kHz upper channel,  $\Delta f = 0$  Hz).

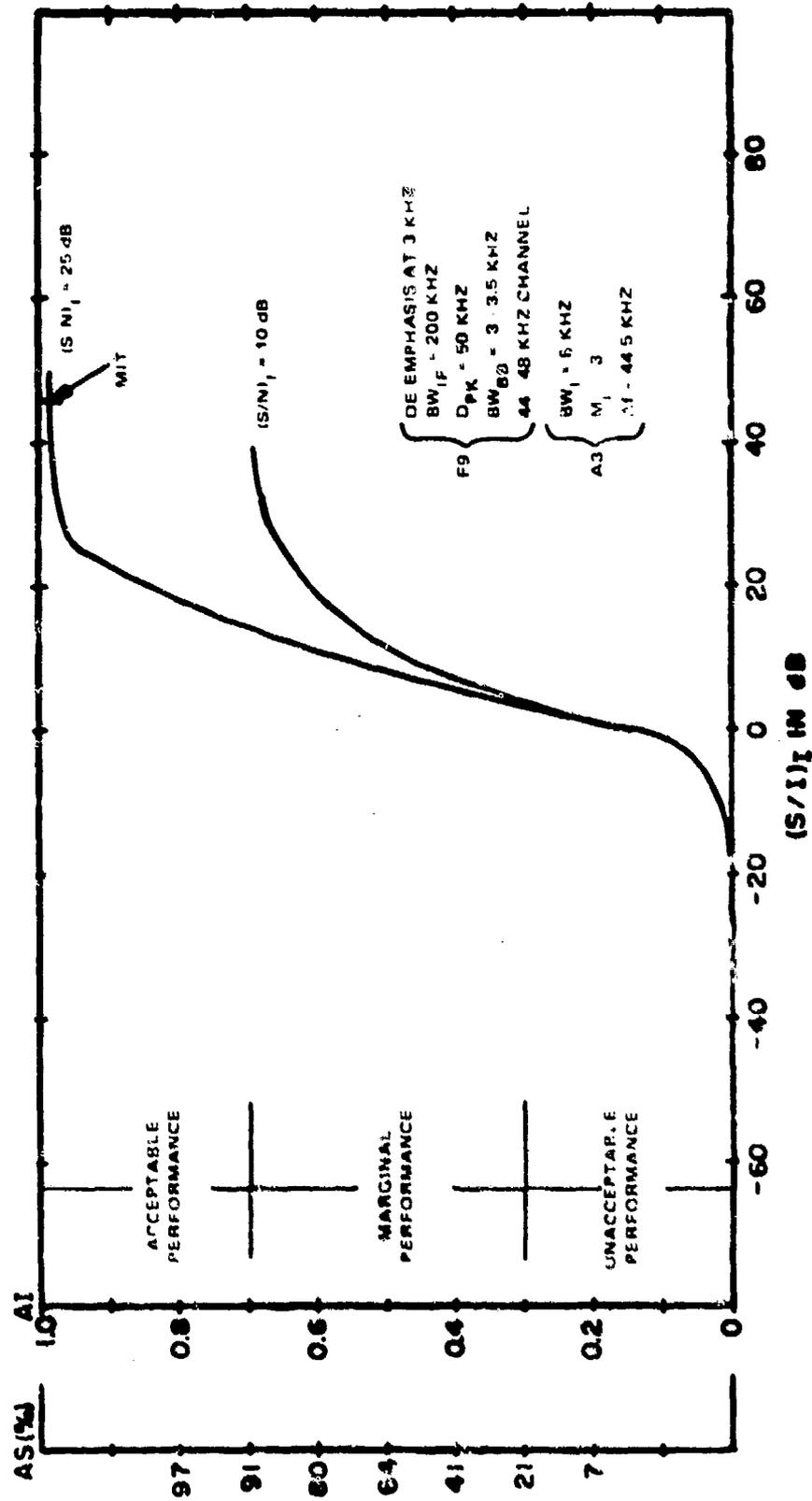


Figure C-98. Performance degradation curve for F9 receiver with A3 interference (44-48 kHz upper channel, Δf = 44.5 kHz).

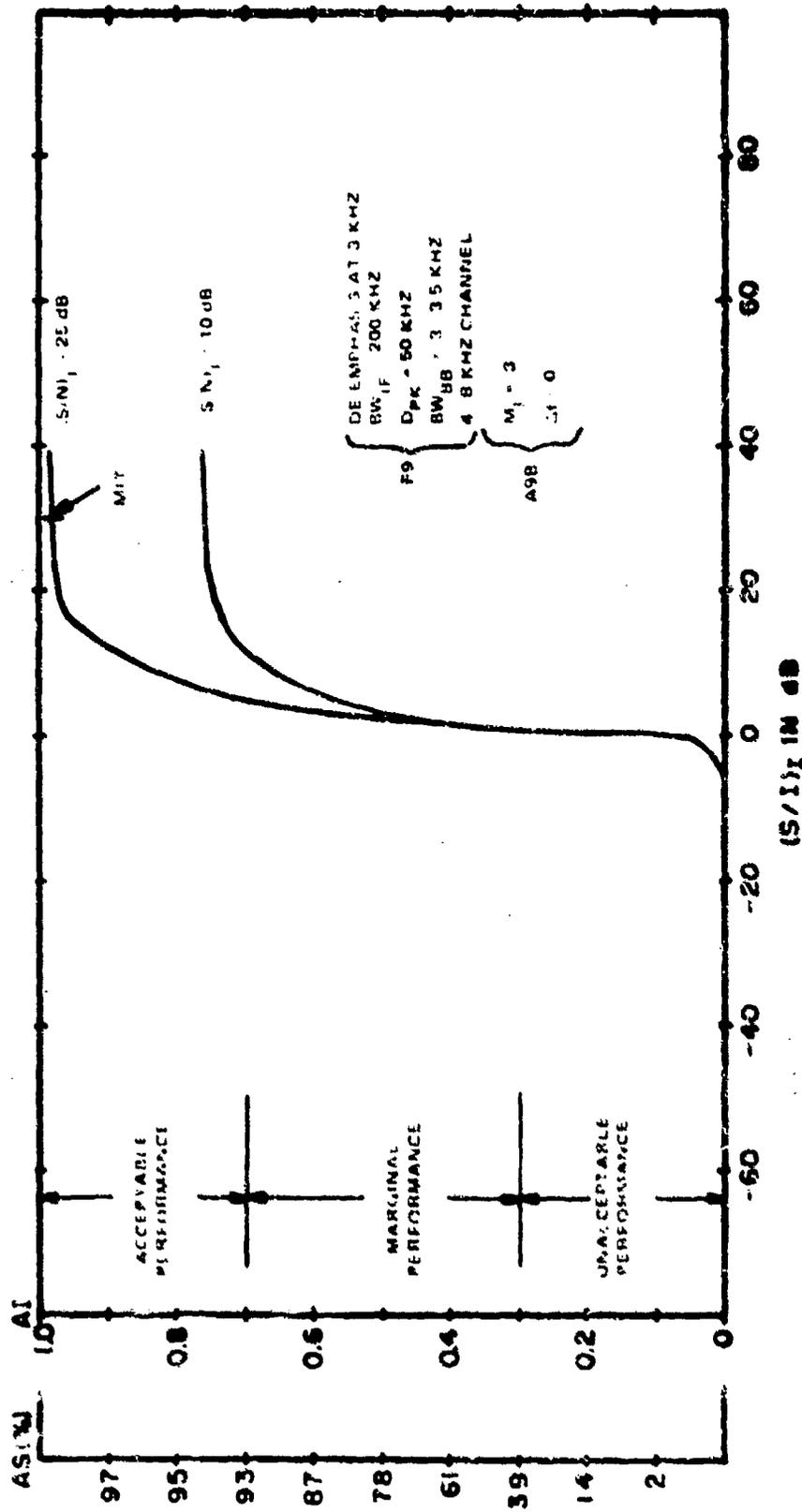


Figure C-99. Performance degradation curve for F9 receiver with A9B interference (4-8 kHz lower channel,  $\Delta f = 0$  kHz).

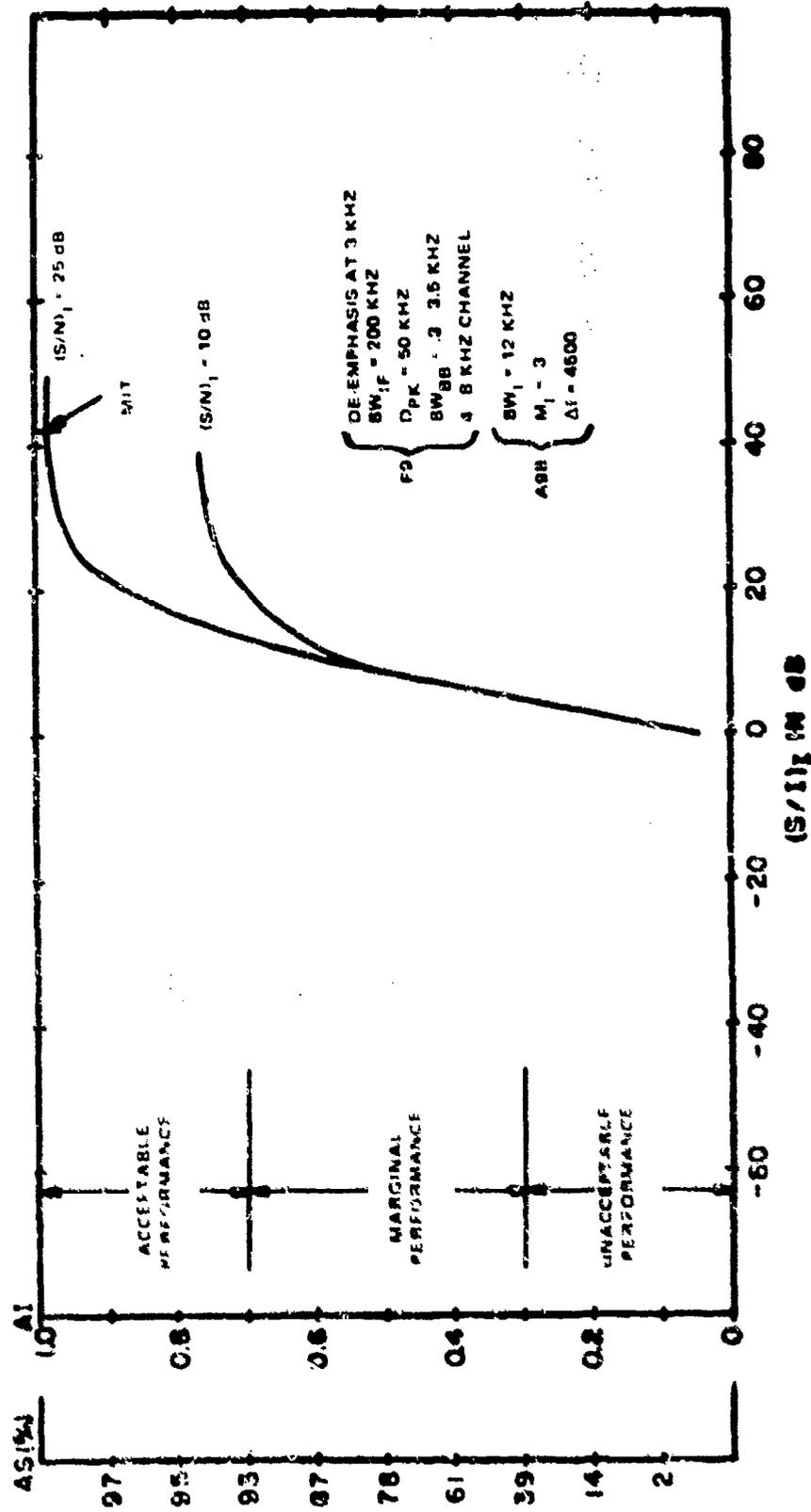


Figure C-100. Performance degradation curve for F9 receiver with A9B interference (4-8 kHz lower channel, Δf = 4.5 kHz).

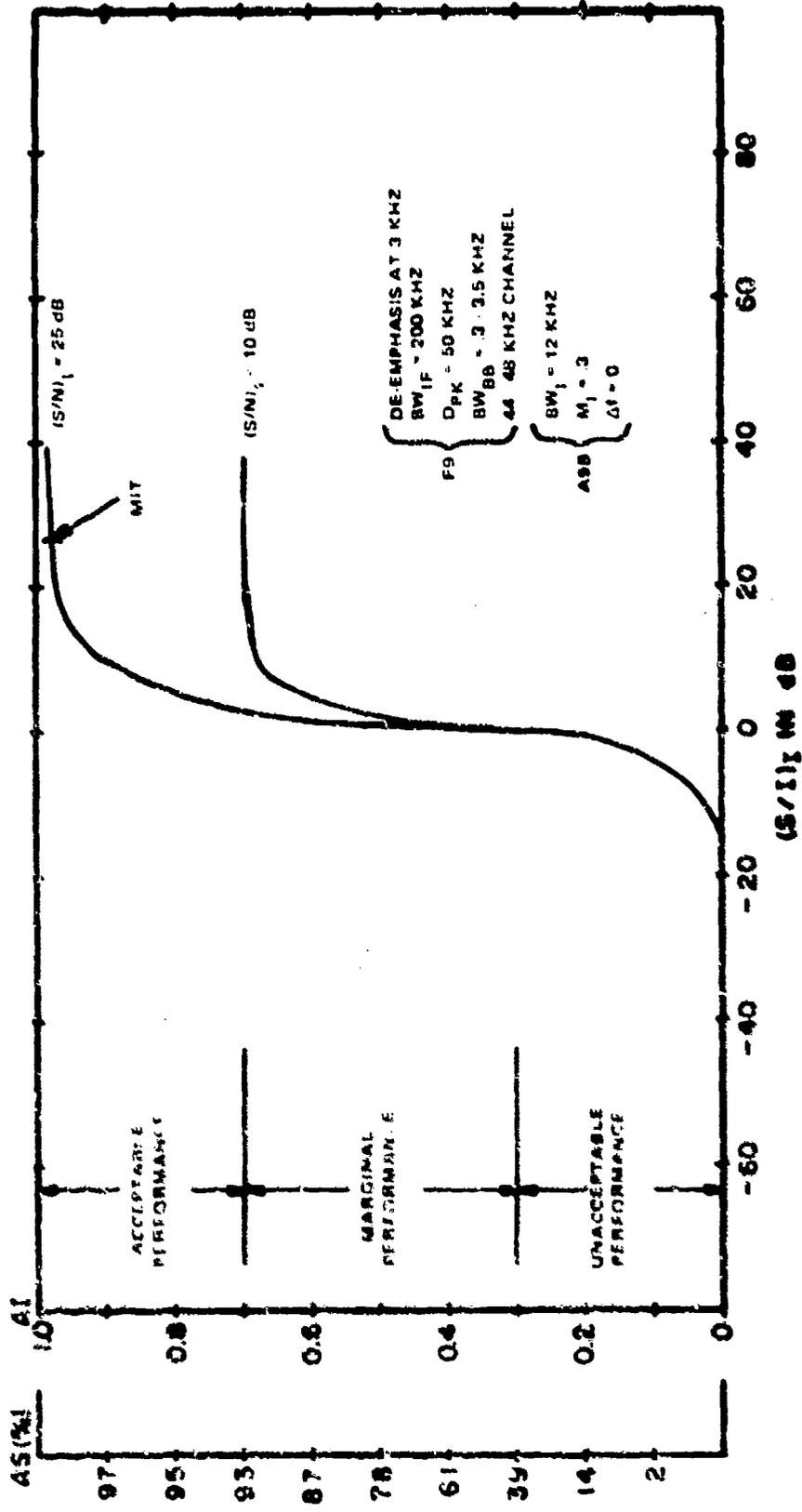


Figure C-101. Performance degradation curve for F9 receiver with A9B interference (44-48 kHz upper channel Δf = 0 Hz).

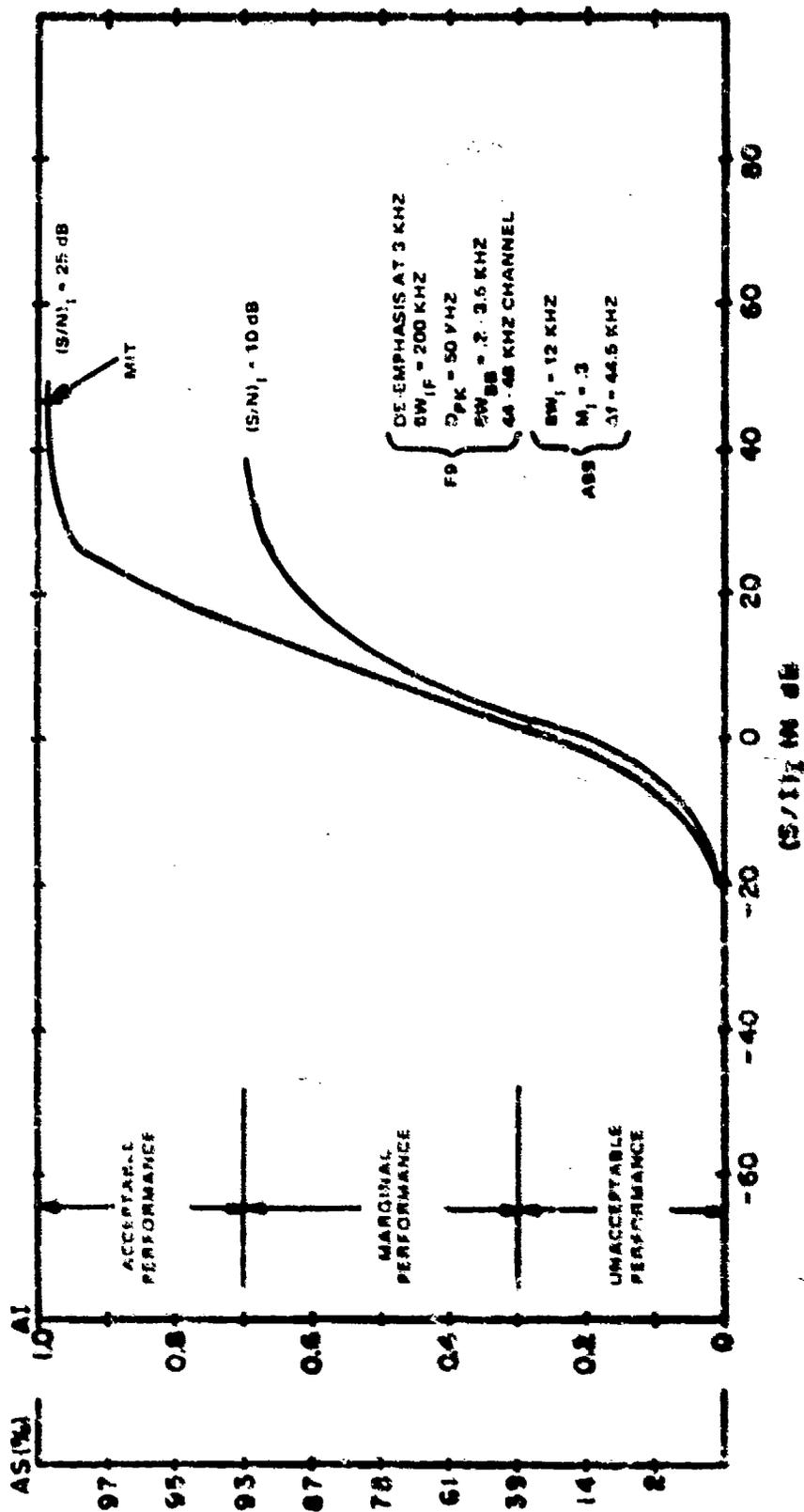


Figure C-102. Performance degradation curve for F9 receiver with A9B interference (44-48 kHz upper channel, Δf = 44.5 kHz).

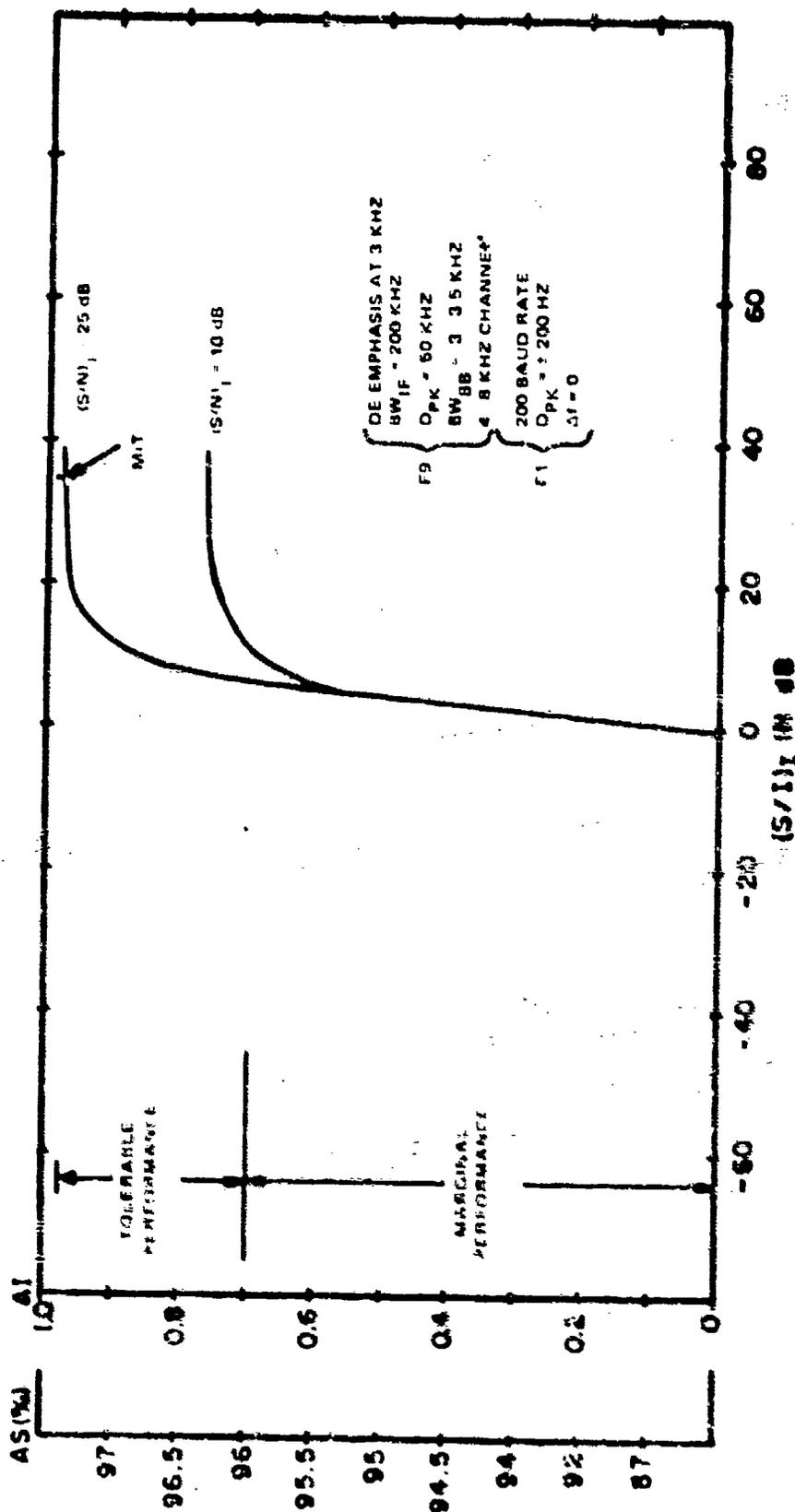


Figure 4-103. Performance degradation curve for F9 receiver with F1 interference (4-8 kHz lower channel), Δf = 0 Hz).

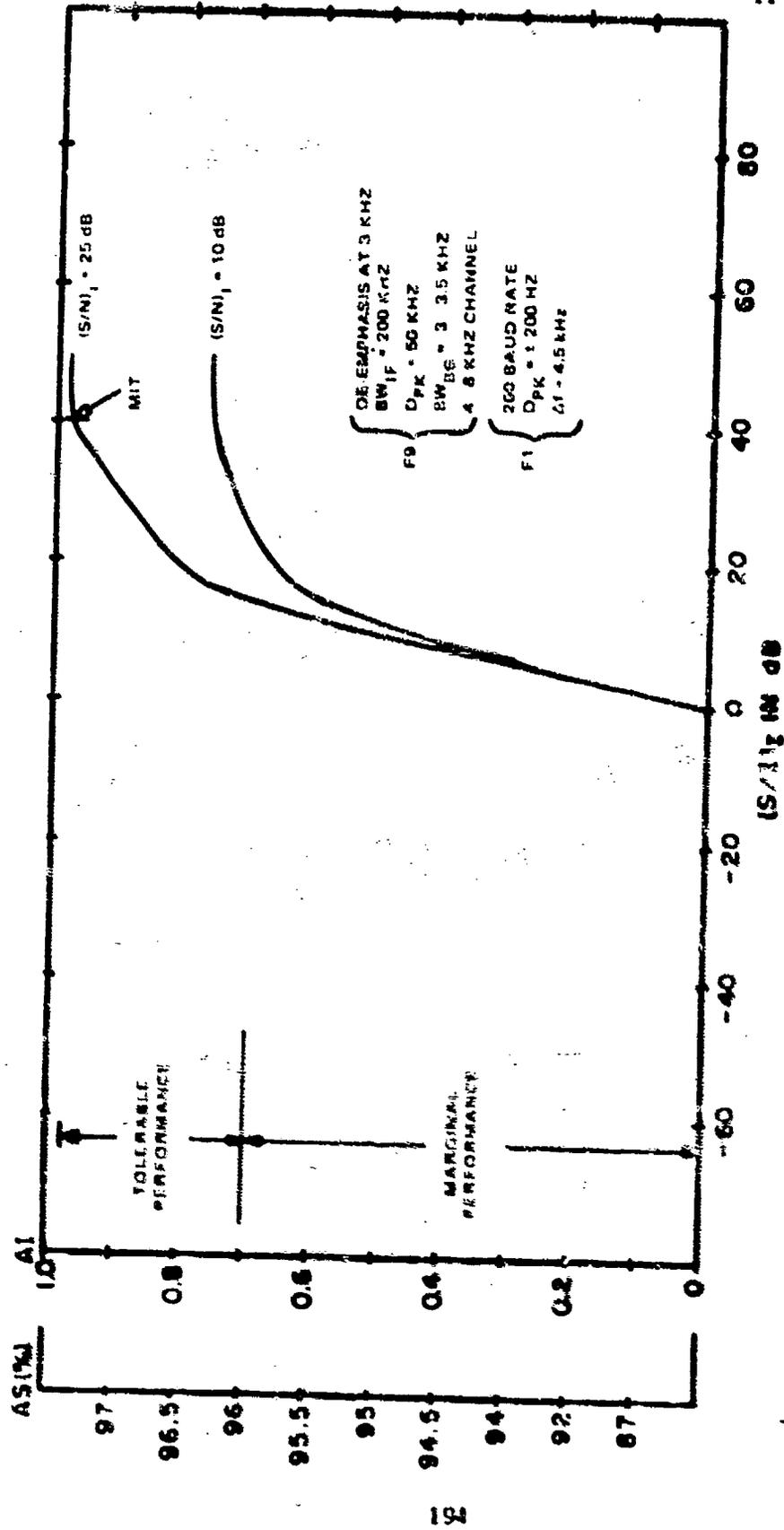


Figure C-101. Performance degradation curve for F9 receiver with F1 interference (4-8 kHz lower channel, Δf = 4.5 kHz).



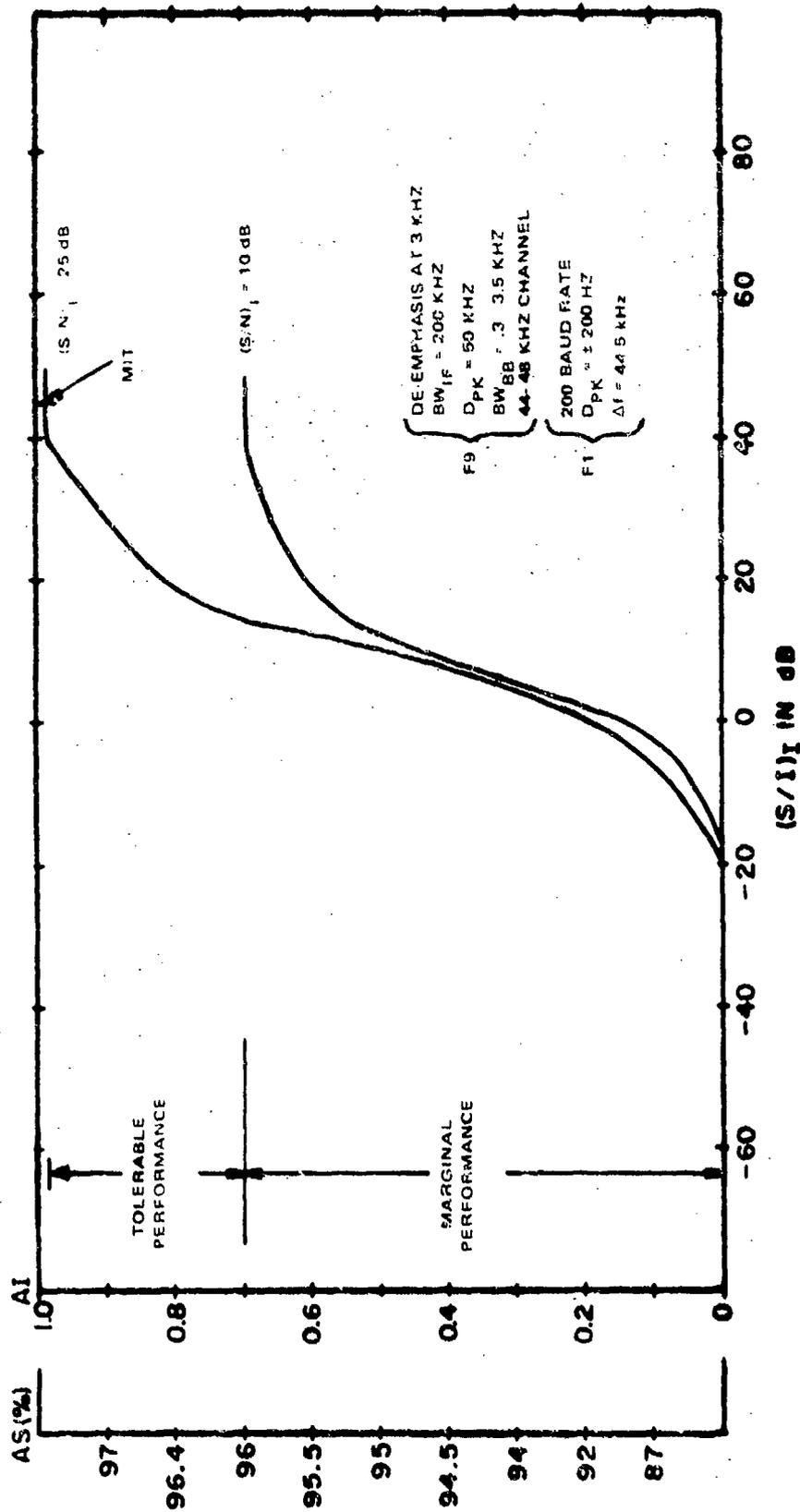


Figure C-106. Performance degradation curve for F9 receiver with F1 interference (44-48 kHz upper channel, Δf = 44.5 kHz).

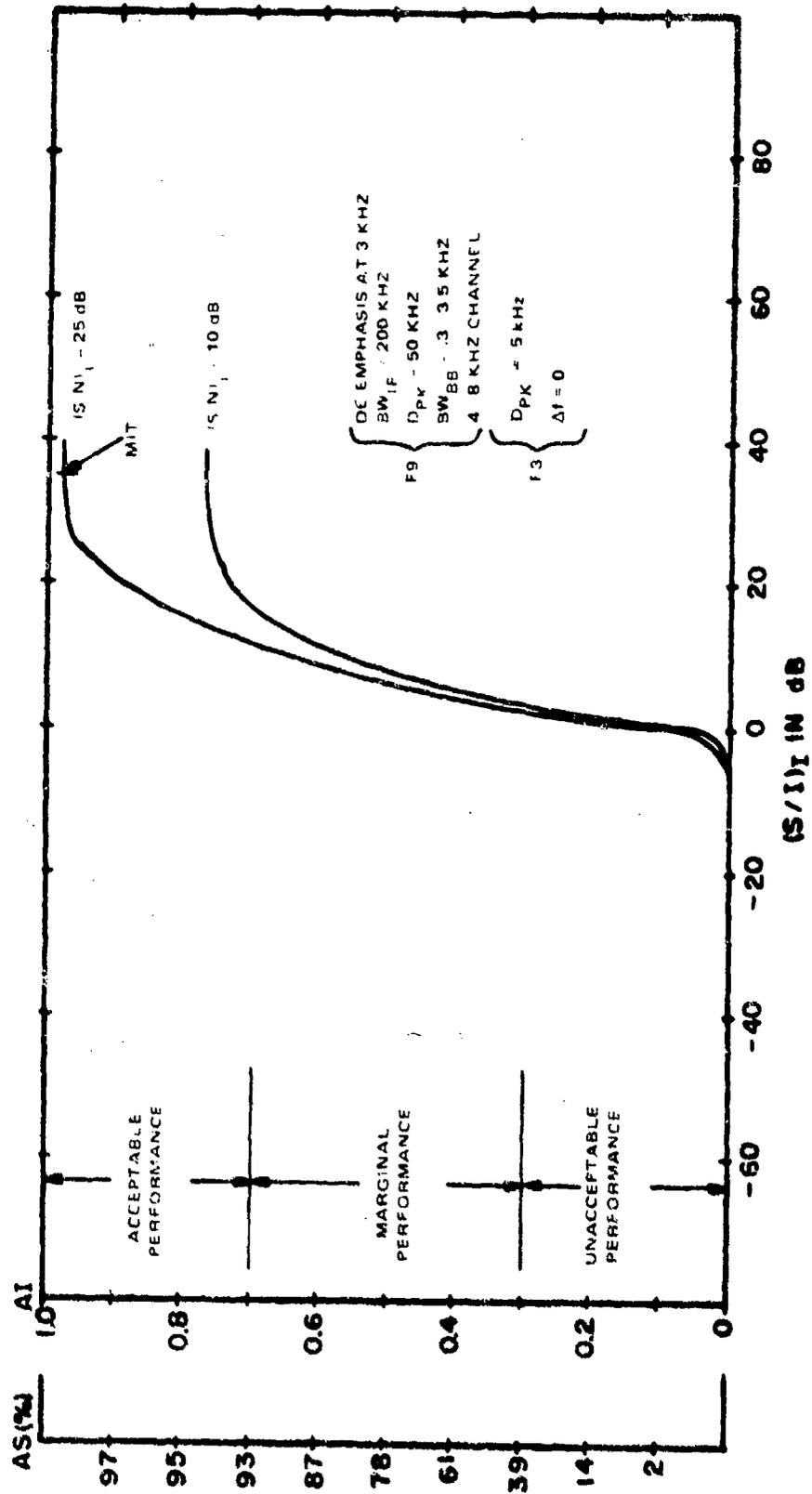


Figure C-107. Performance degradation curve for F9 receiver with F3 interference (44-48 kHz upper channel, Δf = 0 kHz).

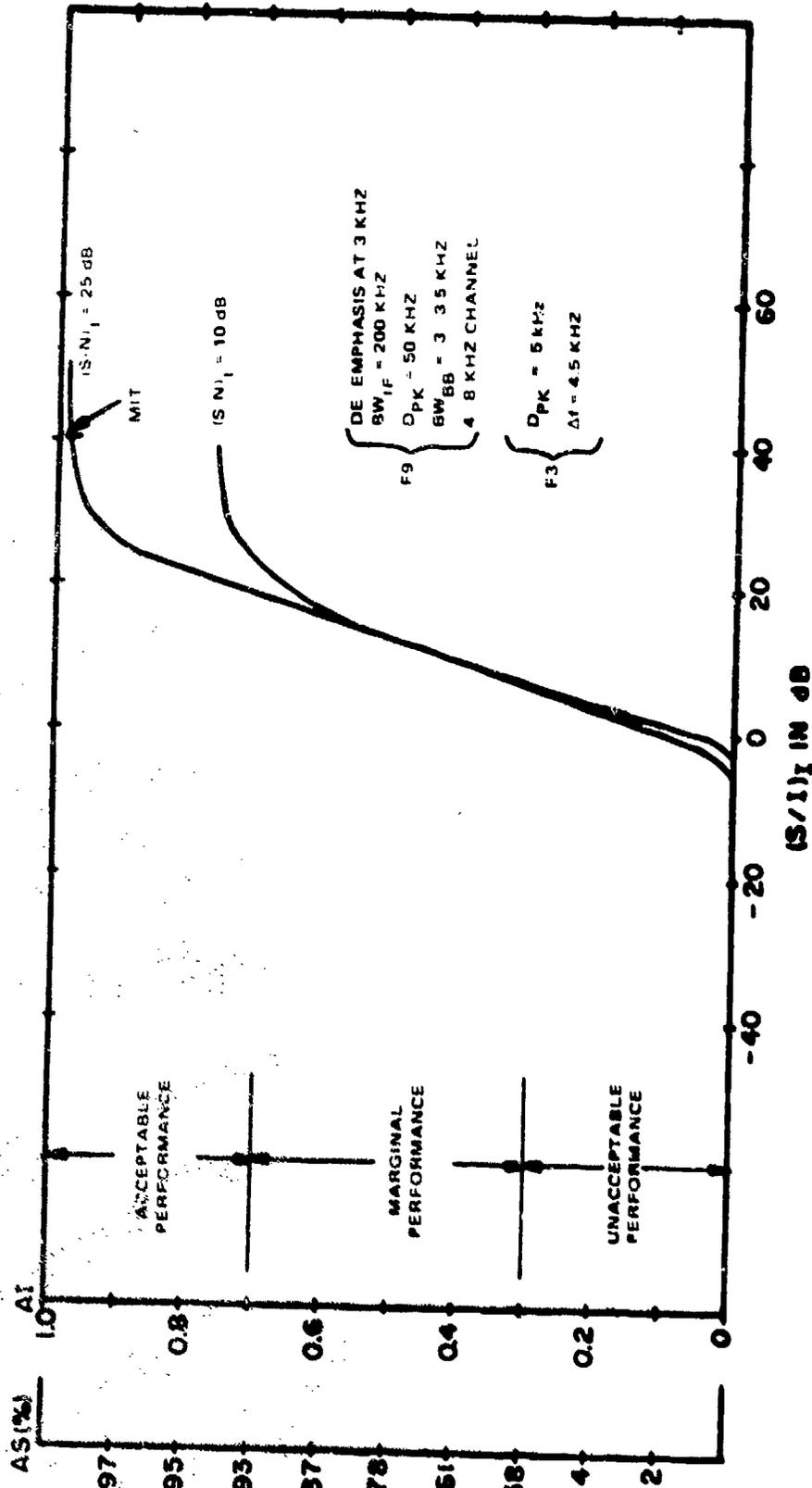


Figure C-108. Performance degradation curve for F9 receiver with F3 interference (4-8 kHz lower channel,  $\Delta f = 4.5 \text{ kHz}$ ).

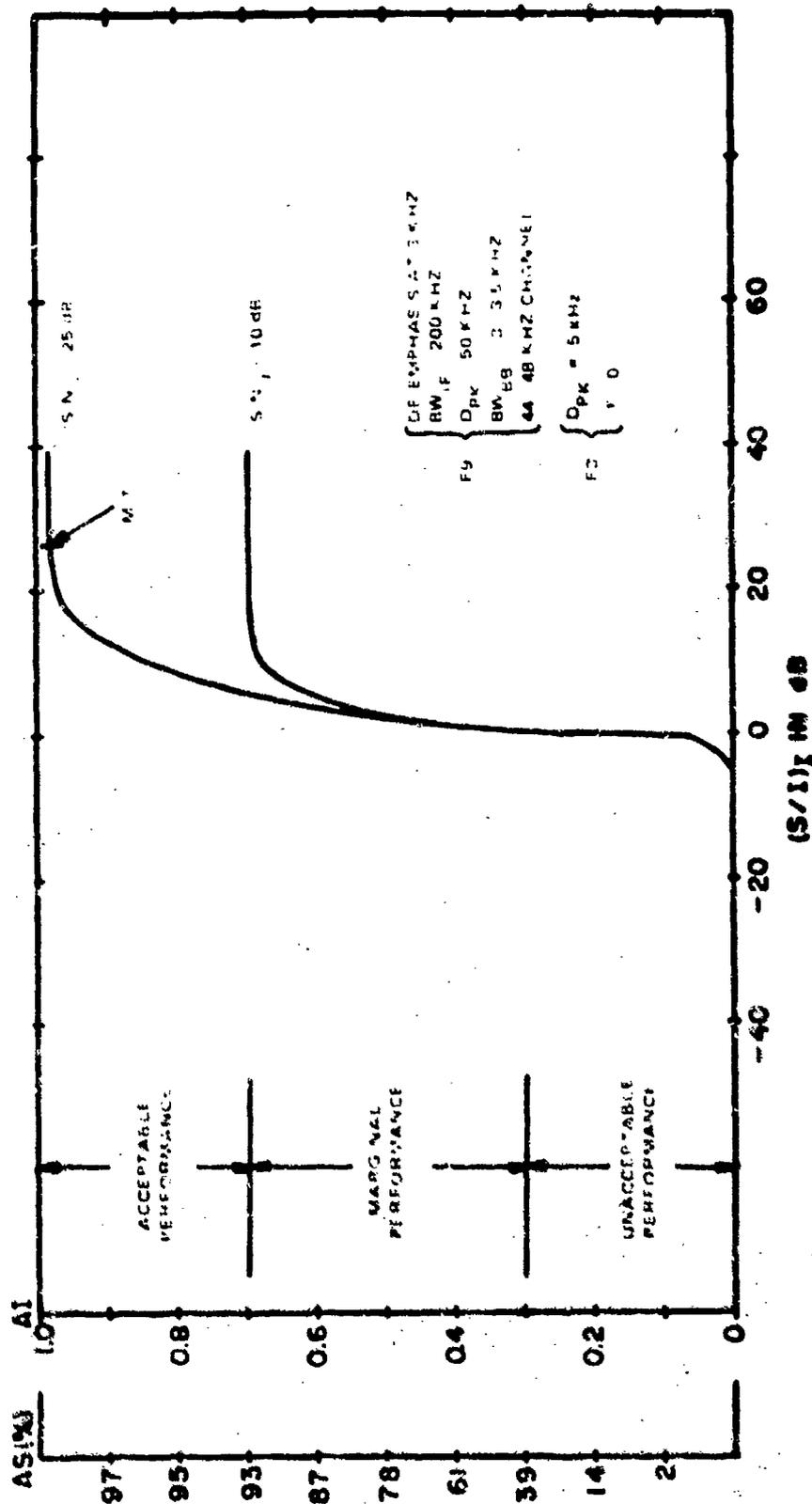


Figure C-109. Performance degradation curve for F9 receiver with F3 interference (44-48 kHz upper channel,  $\Delta f = 0$  kHz).

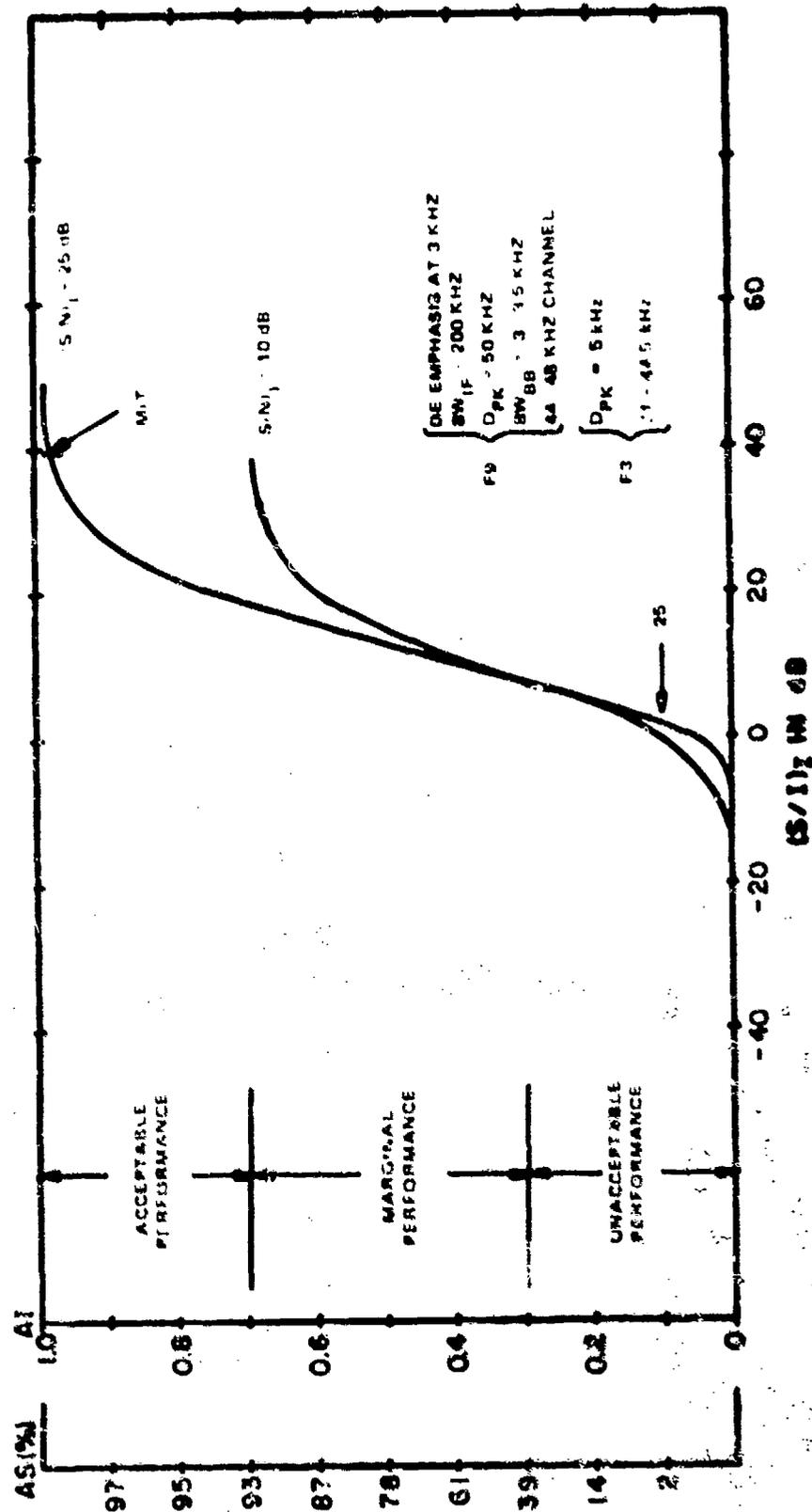


Figure C-1111. Performance degradation curve for F9 receiver with 1.5 kHz interference (44-48 kHz upper channel,  $f_f = 44.5 \text{ kHz}$ ).

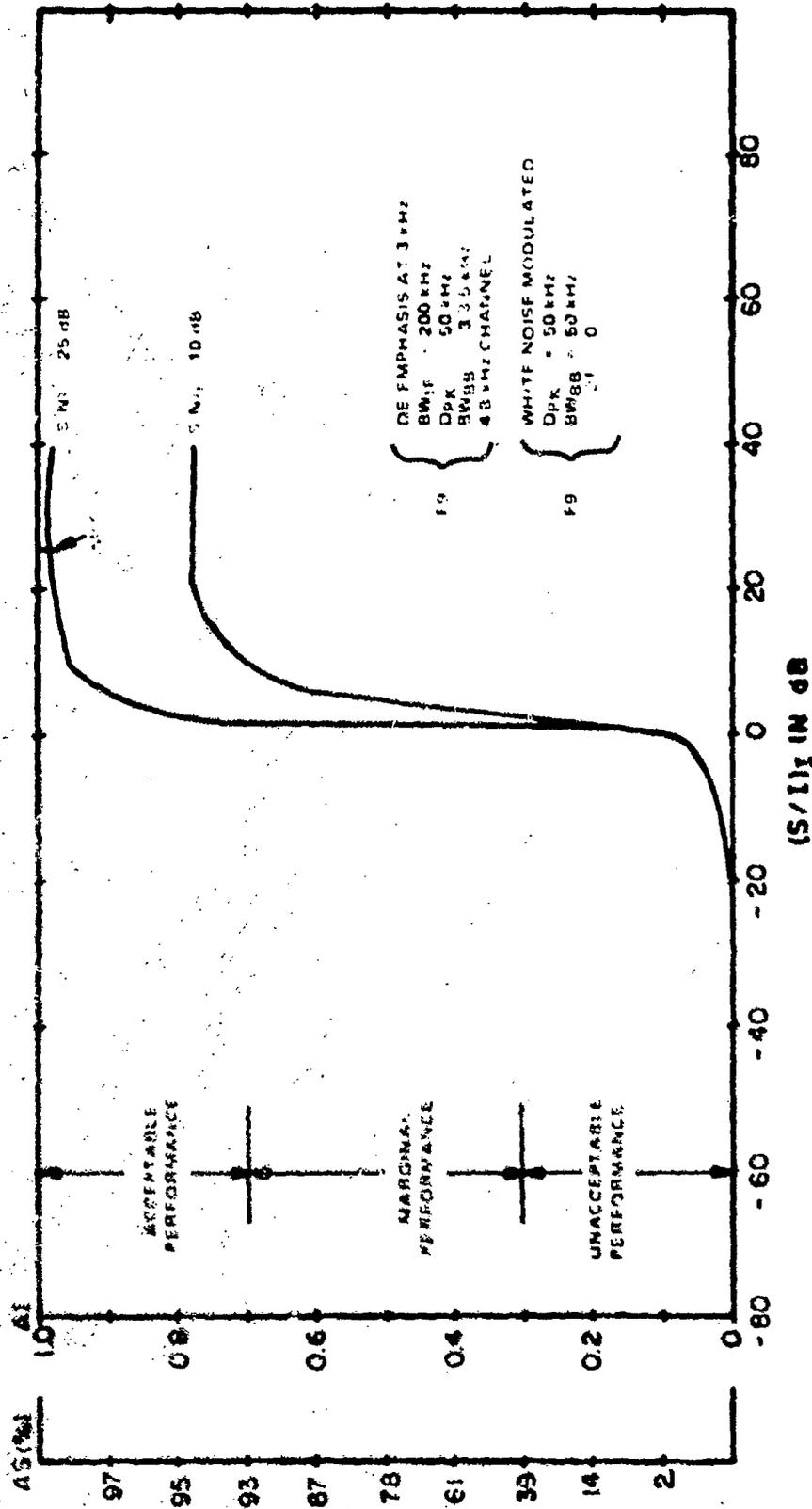


Figure C-111. Performance degradation curve for F9 receiver with F9 interference (4-8 kHz lower channel, Af = 0 Hz).

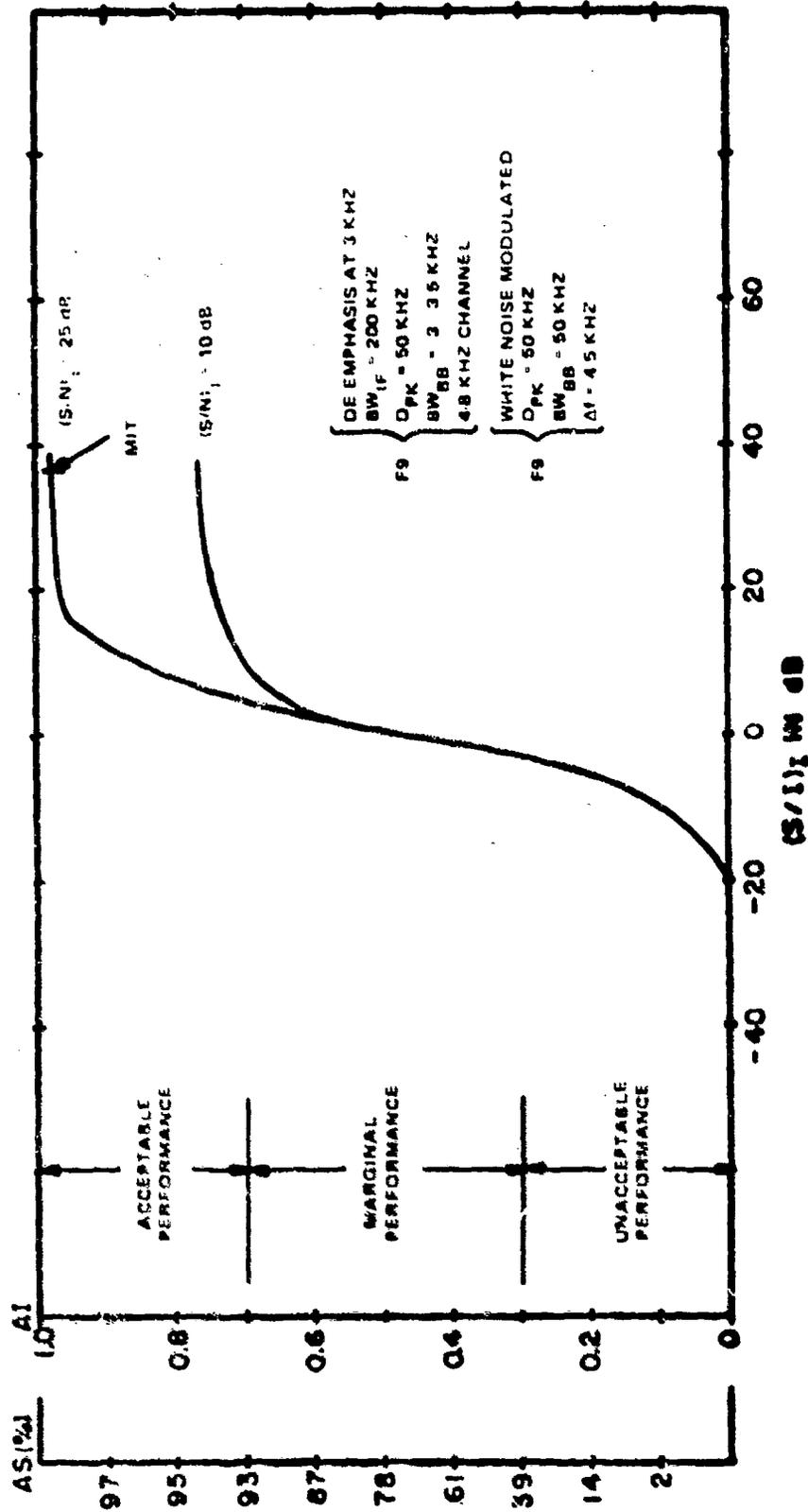


Figure C-112. Performance degradation curve for F9 receiver with F9 interference (4-8 kHz lower channel, Δf = 4.5 kHz).

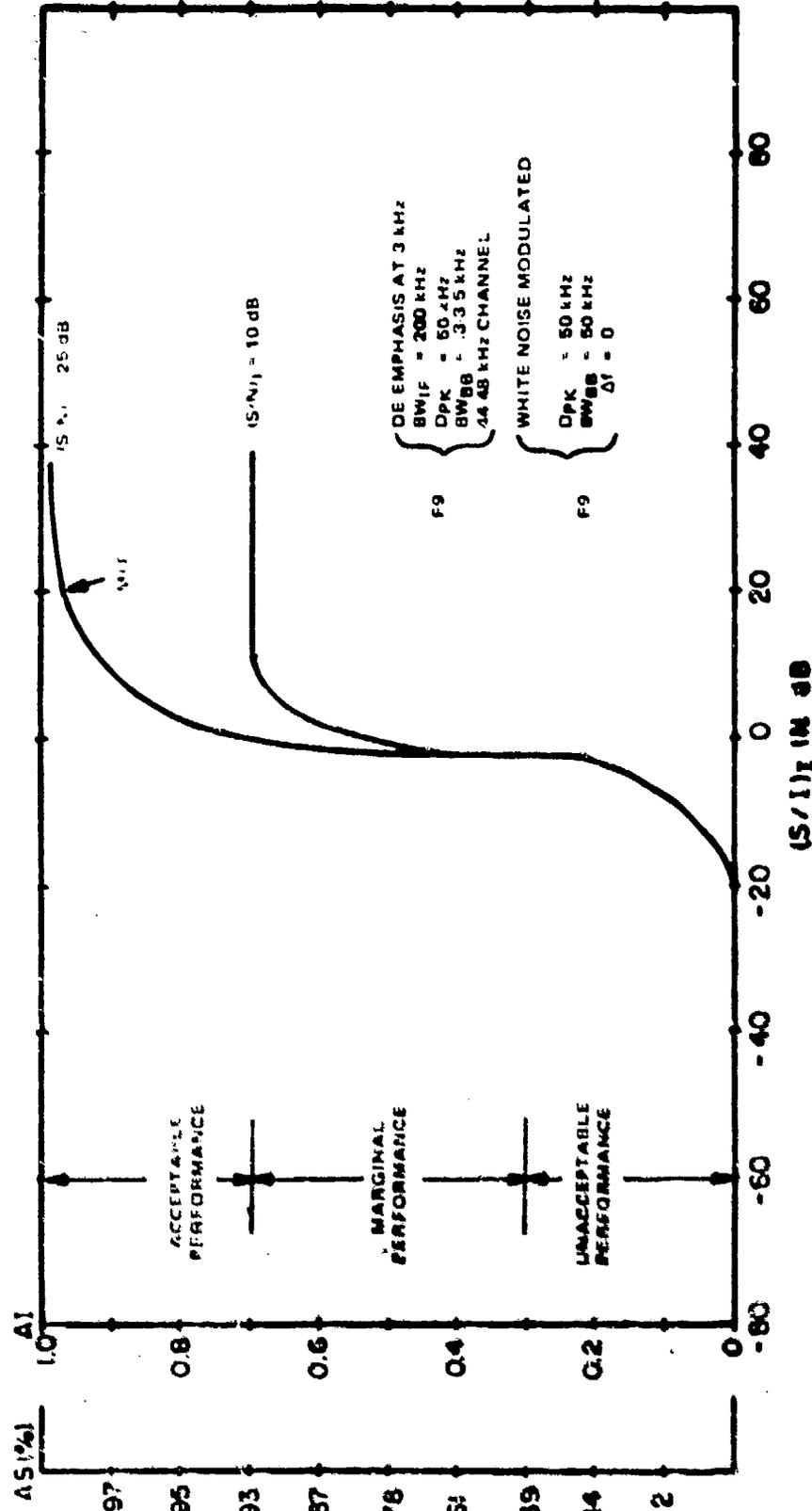


Figure C-113. Performance degradation curve for F9 receiver with F9 interference (44-48 kHz upper channel, Δf = 0 Hz).

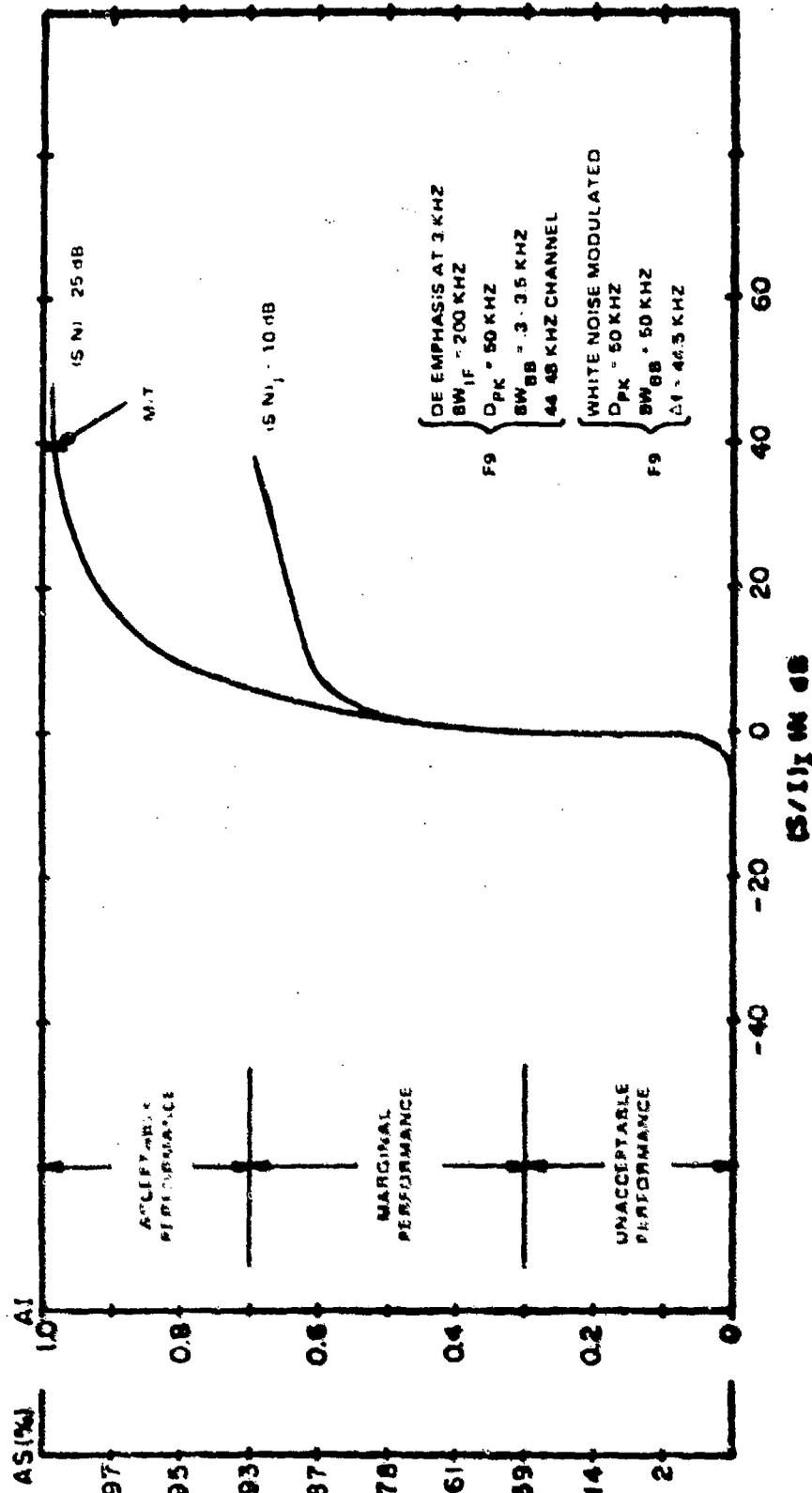


Figure C-114. Performance degradation curve for F9 receiver with F9 interference (44-48 kHz upper channel, Δf = 44.5 kHz).

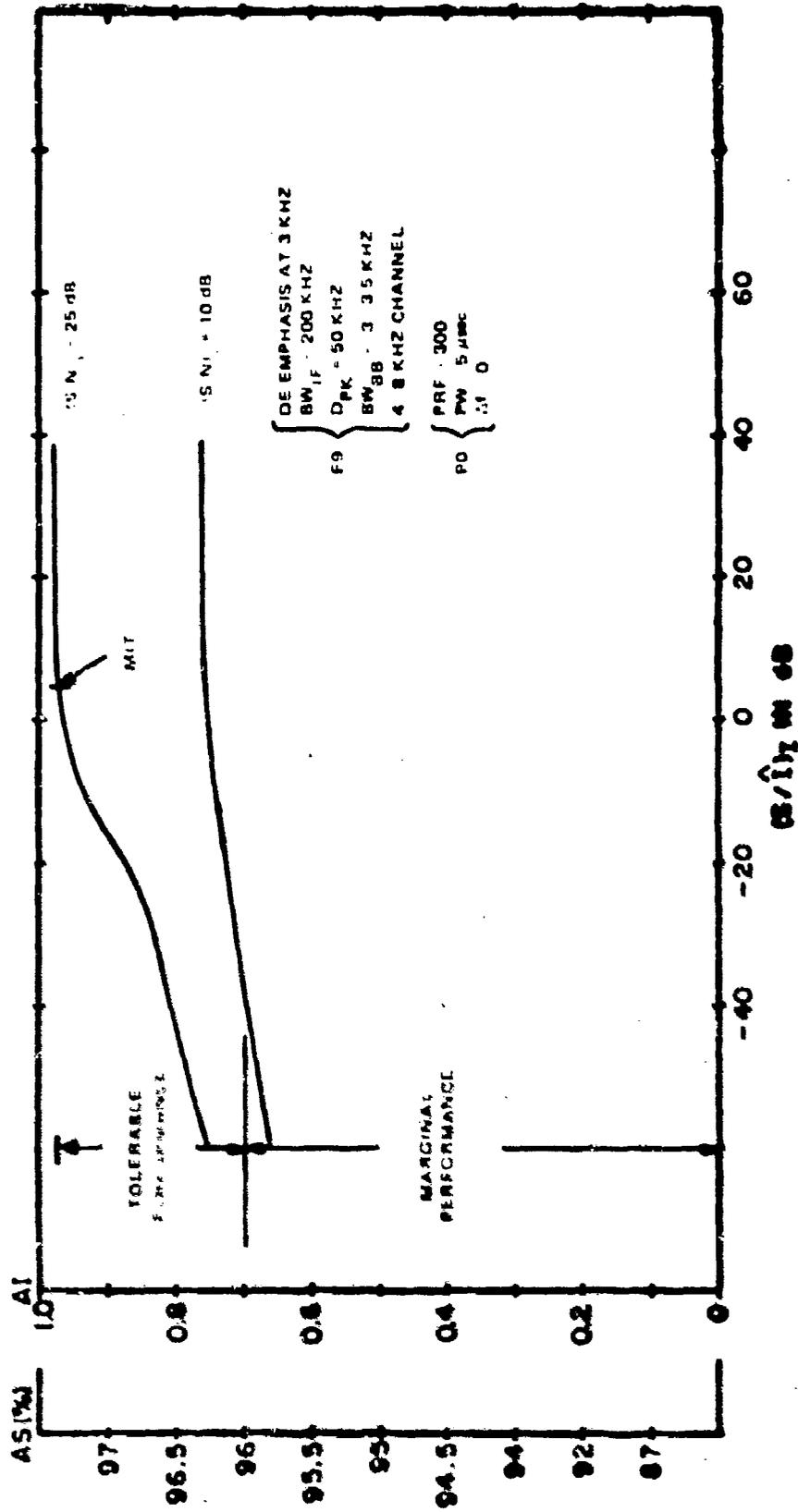


Figure C-115. Performance degradation curve for F9 receiver with PO interference (1-8 kHz lower channel, Af = 0 Hz).

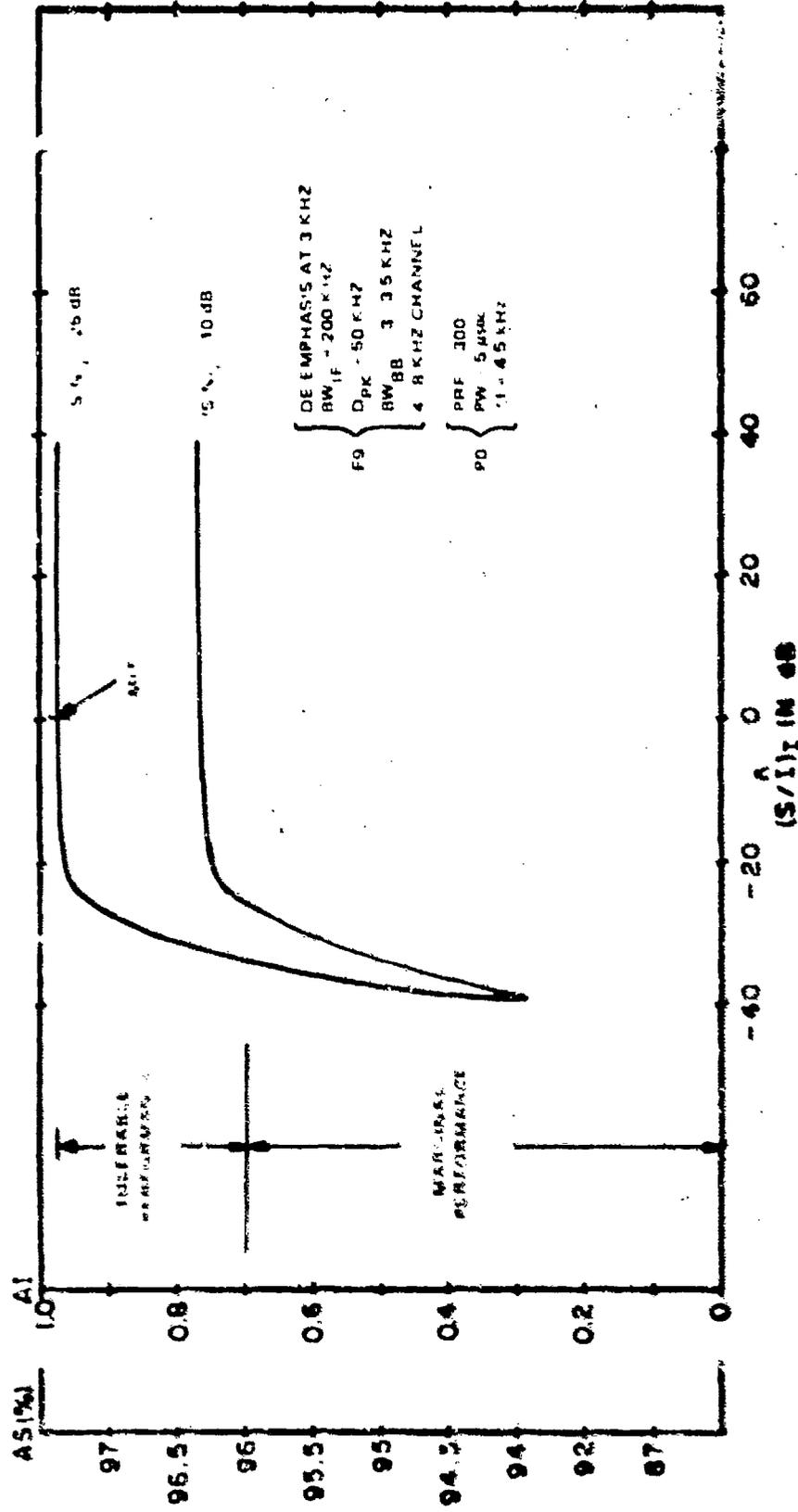


Figure C.116. Performance degradation curve for F9 receiver with P0 interference (4-8 kHz lower channel, Δf = 4.5 kHz).

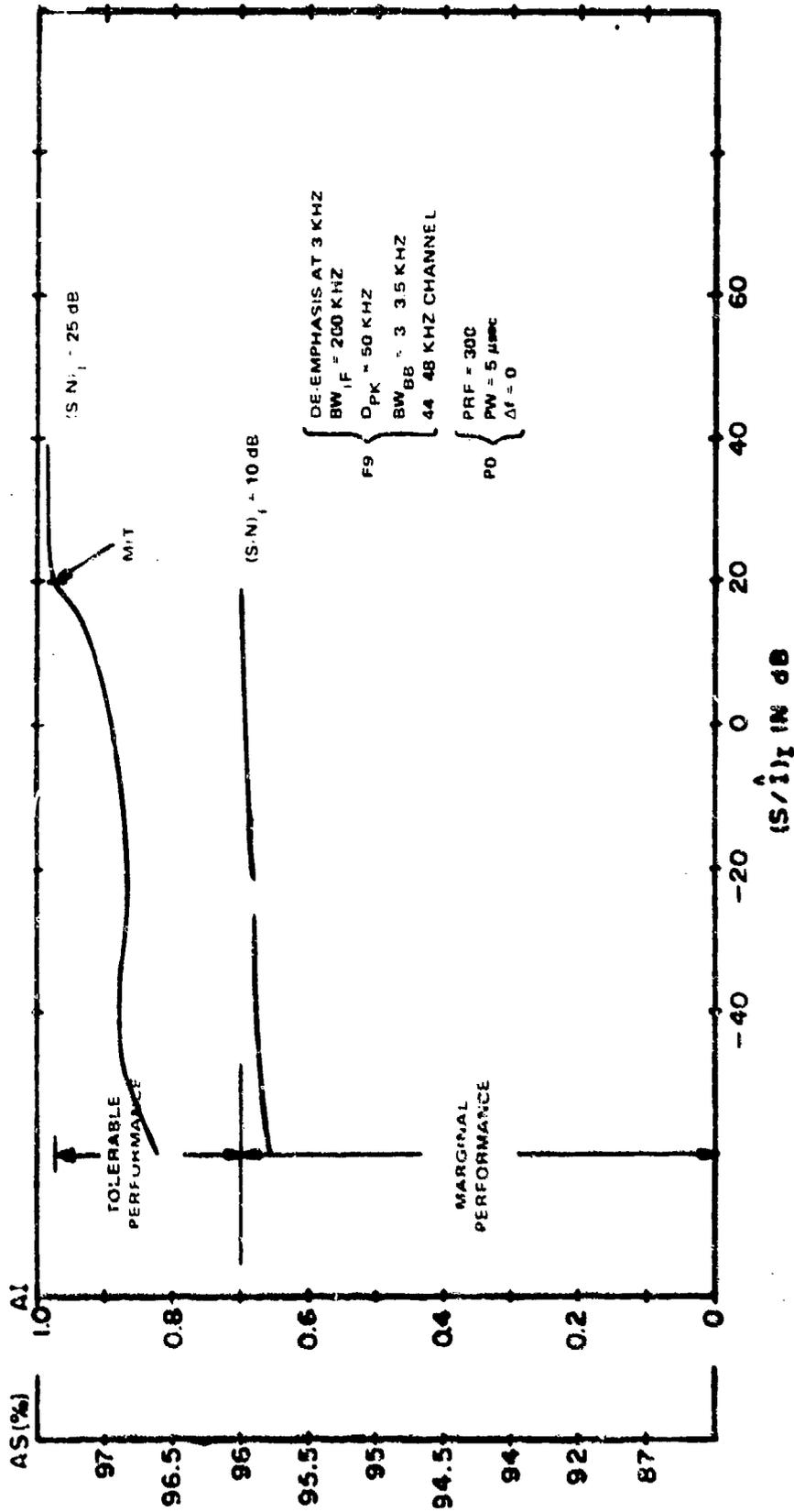


Figure C-117. Performance degradation curve for F9 receiver with PO interference (44-48 kHz upper channel, Δf = 0 Hz).

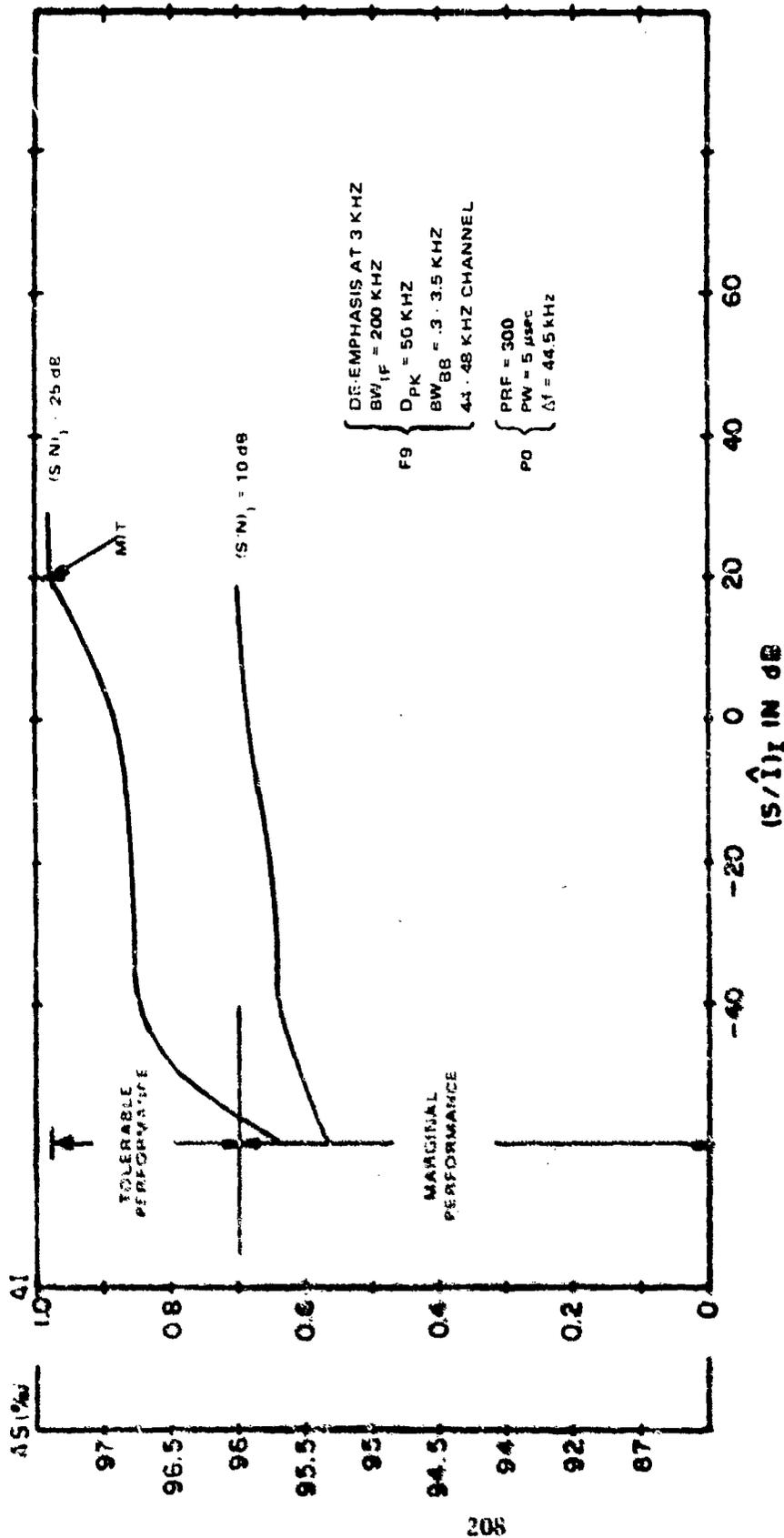


Figure C-118. Performance degradation curve for F9 receiver with P0 interference (44-48 kHz upper channel, Δf = 44.5 kHz).

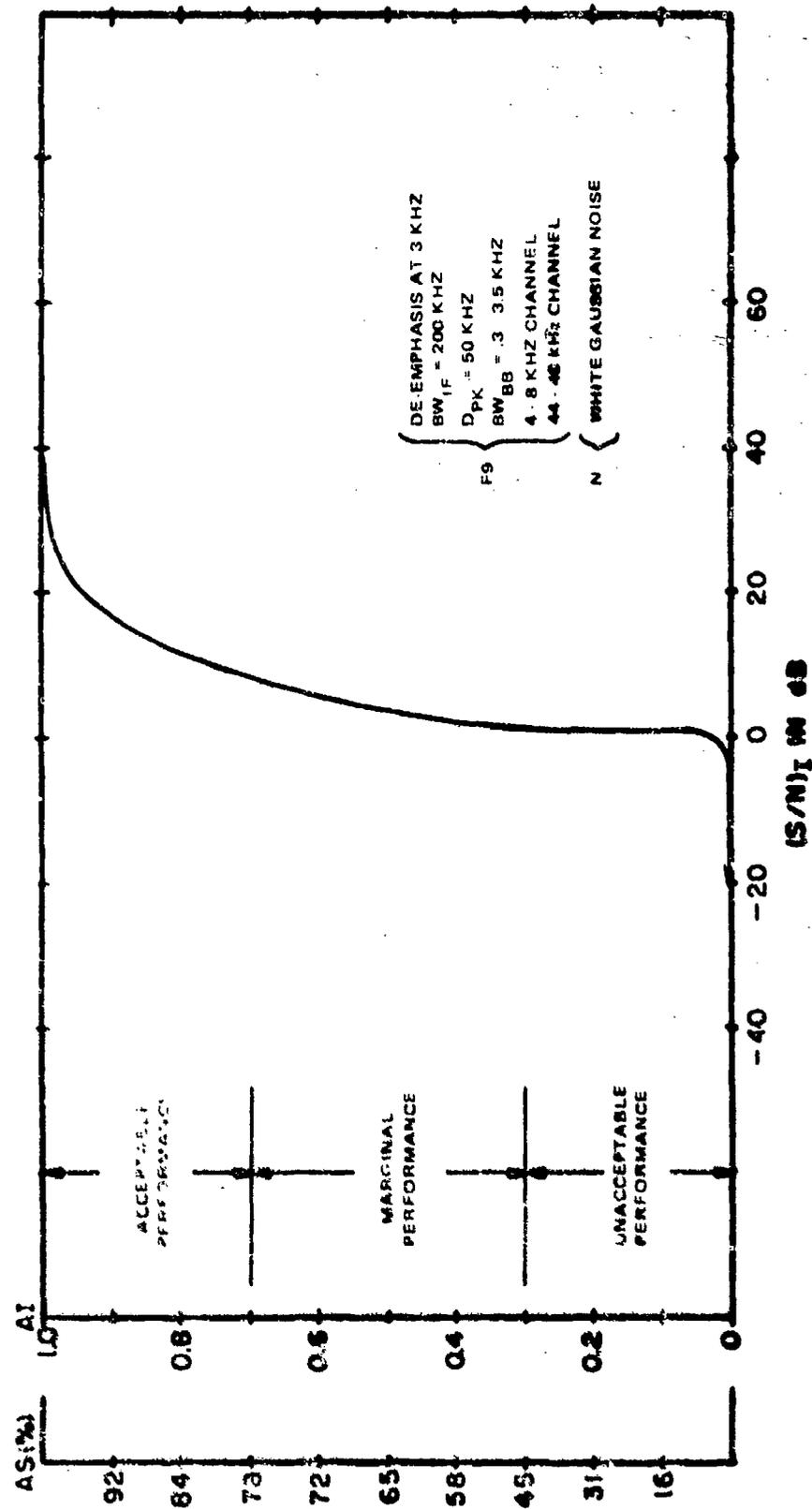


Figure C-119. Performance degradation curve for F9 receiver with noise.

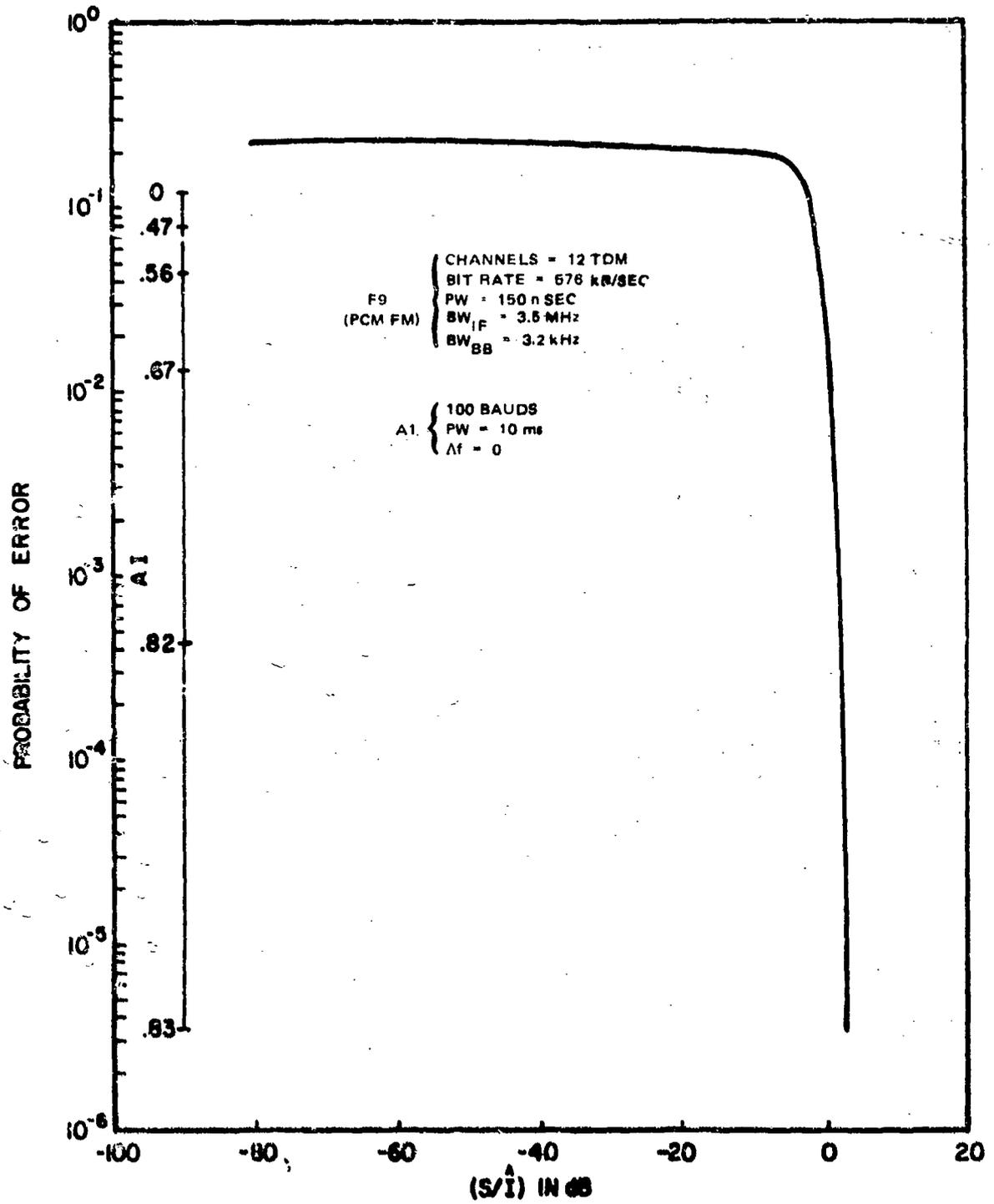


Figure C-120. Performance degradation curve for an F9 (PCM-FM) receiver with A1 interference.

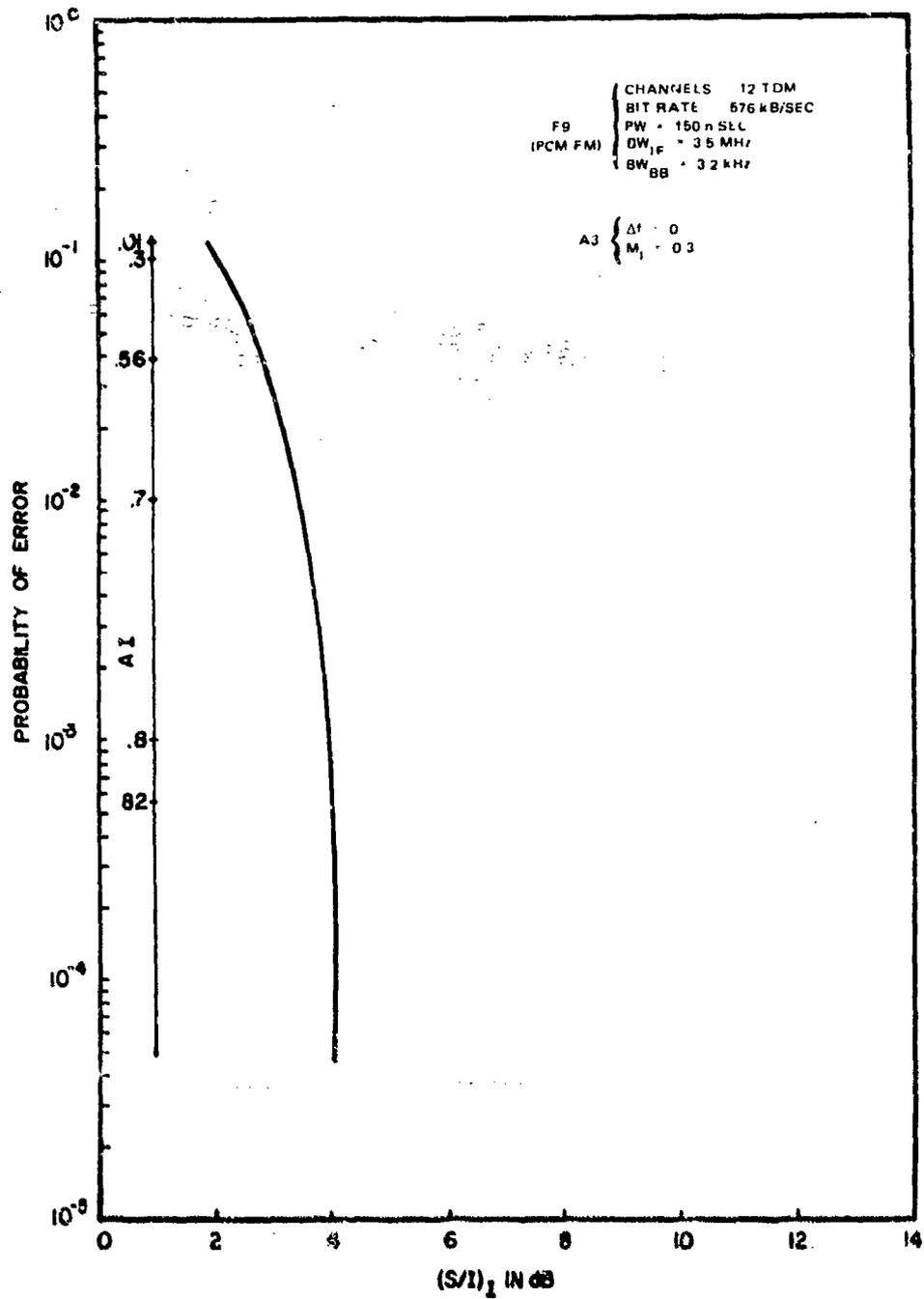


Figure C-121. Performance degradation curve for an F9 (PCM-FM) receiver with A3 interference.

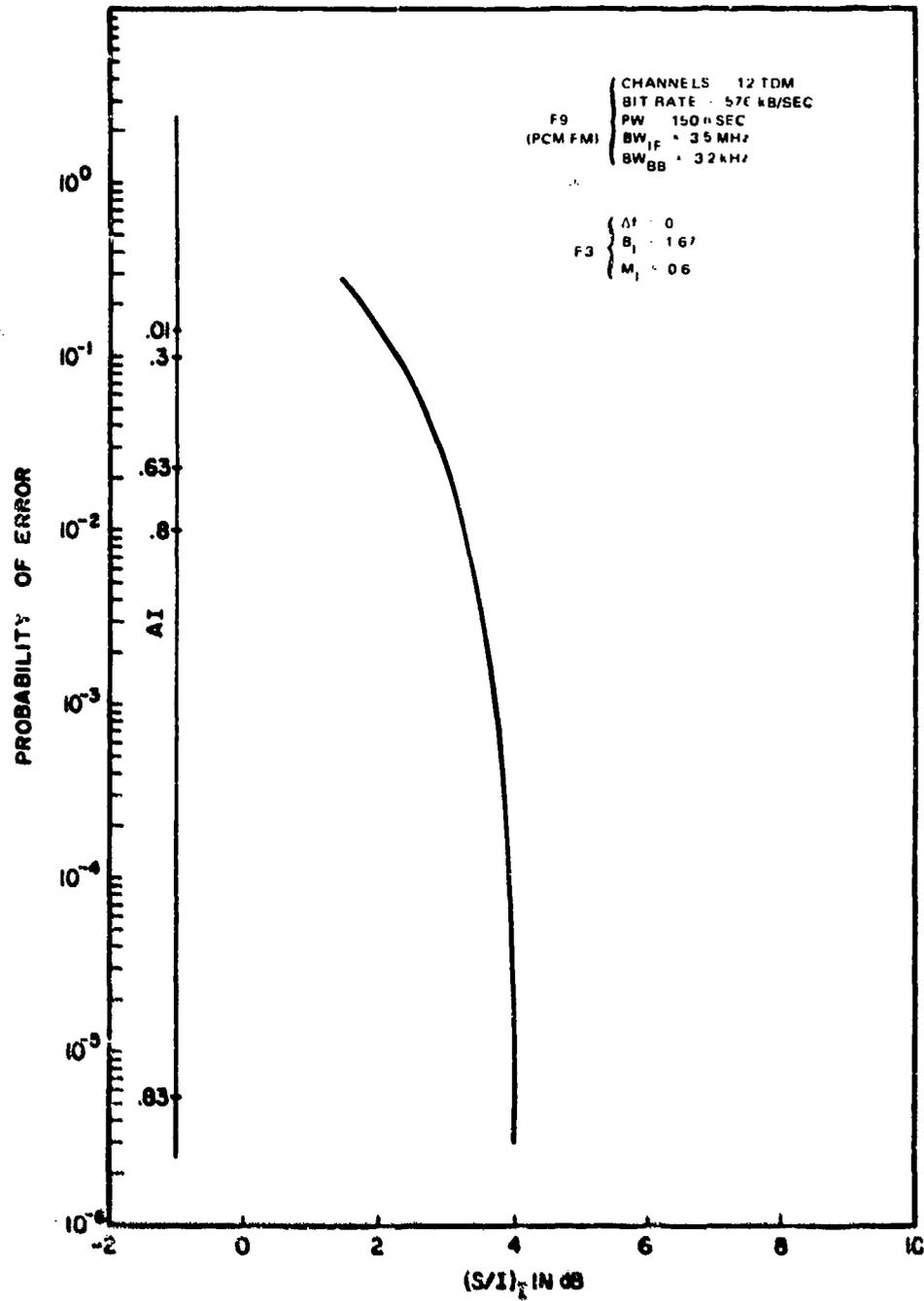


Figure C-122. Performance degradation curve for an F9 (PCM-FM) receiver with F3 interference.

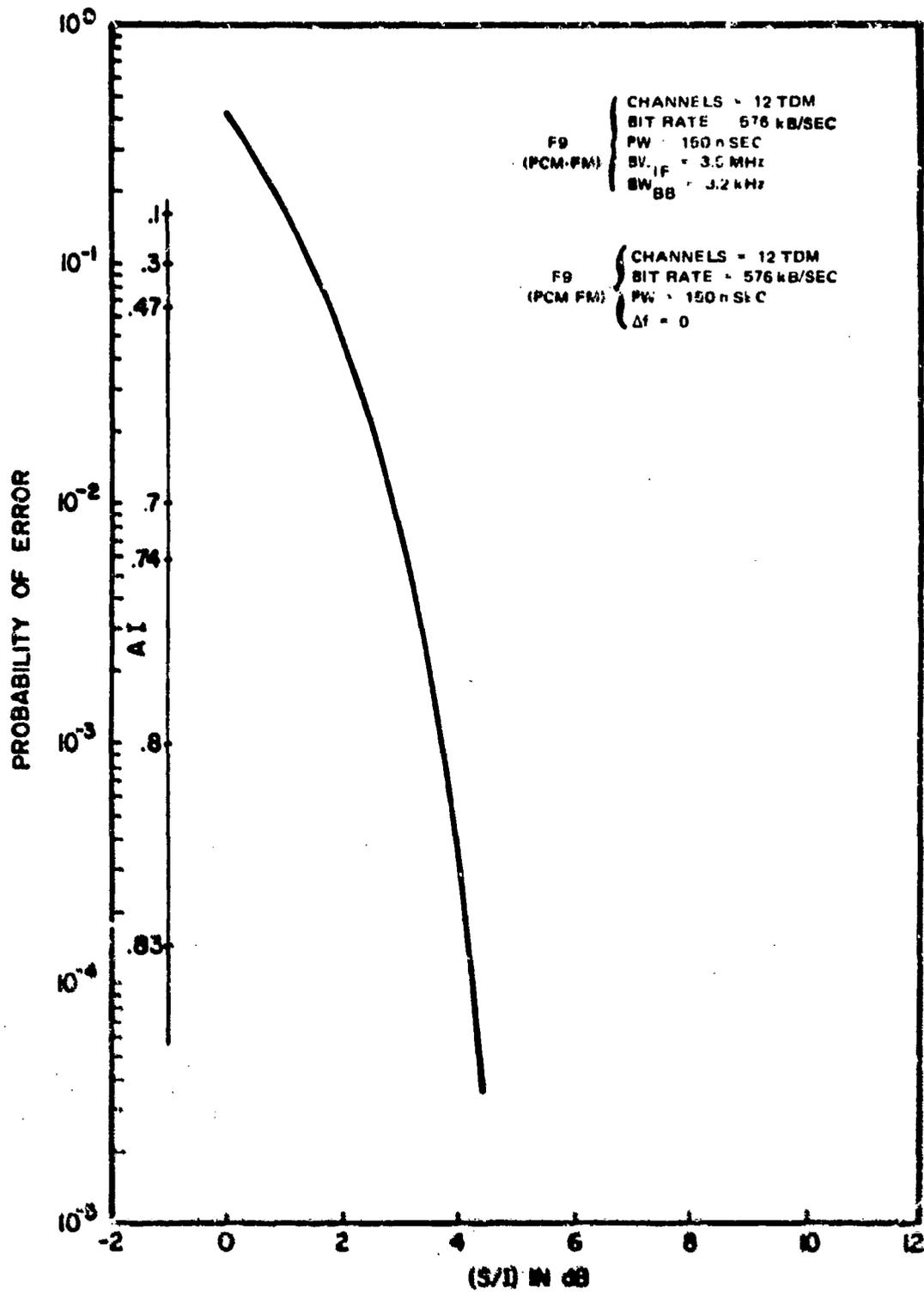


Figure C-125. Performance degradation curve for an F9 (PCM-FM) receiver with F9 interference.

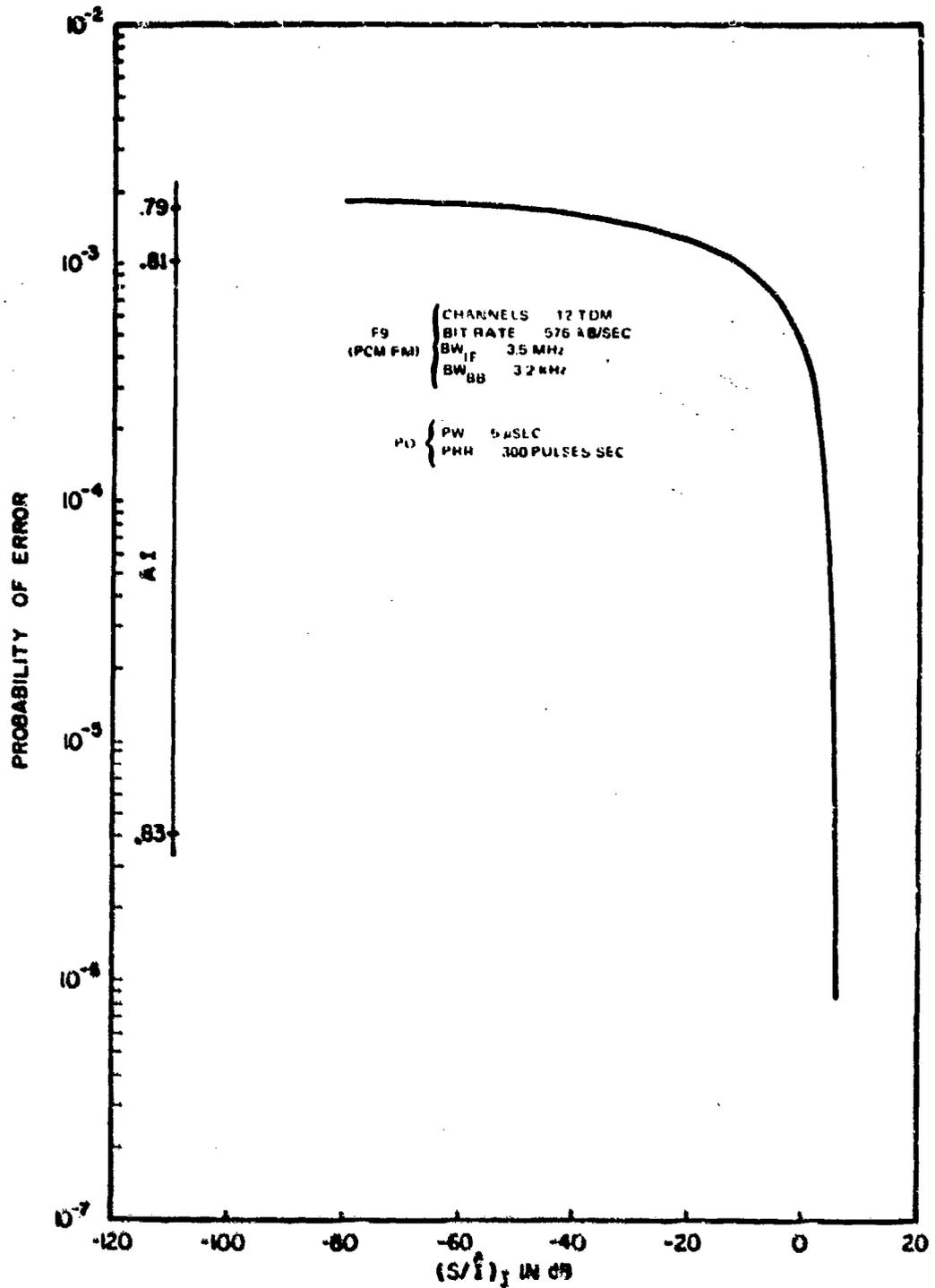


Figure C-124. Performance degradation curve for an F9 (PCM-FM) receiver with P0 interference.

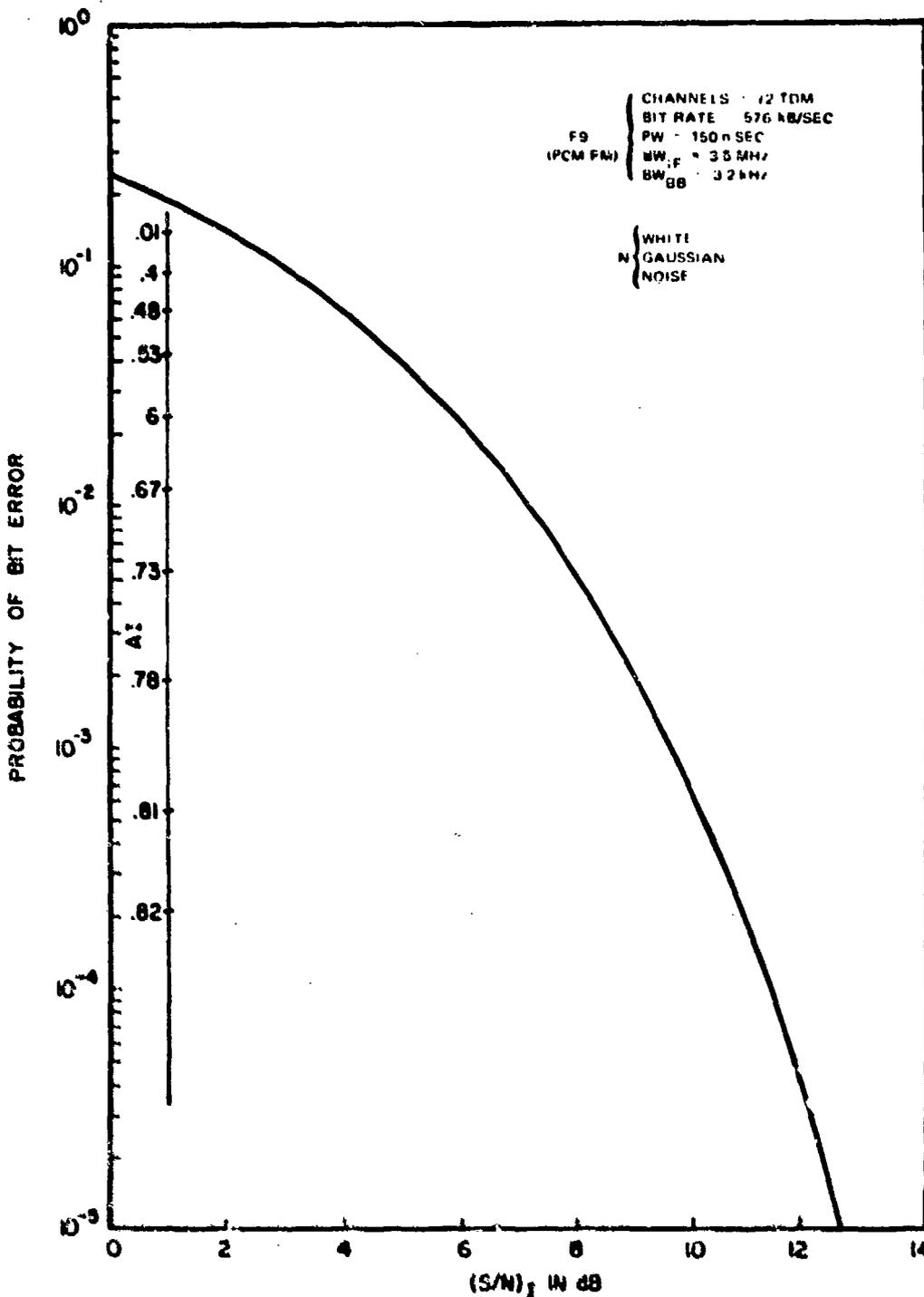


Figure C-135. Performance degradation curve for an F9 (PCM-FM) with noise interference.

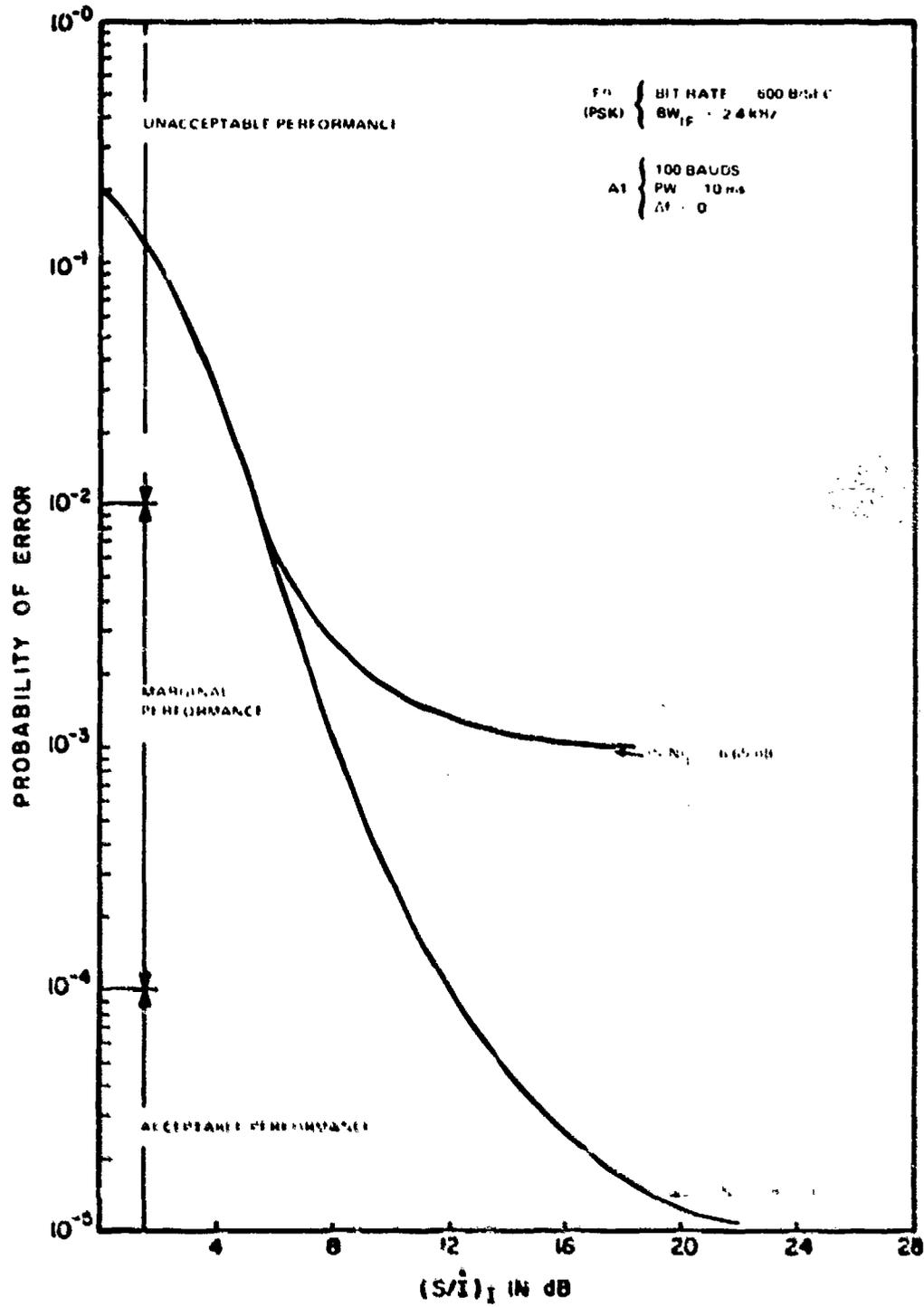


Figure C-126. Performance degradation curve for an F9 (PSK) receiver with A1 interference.

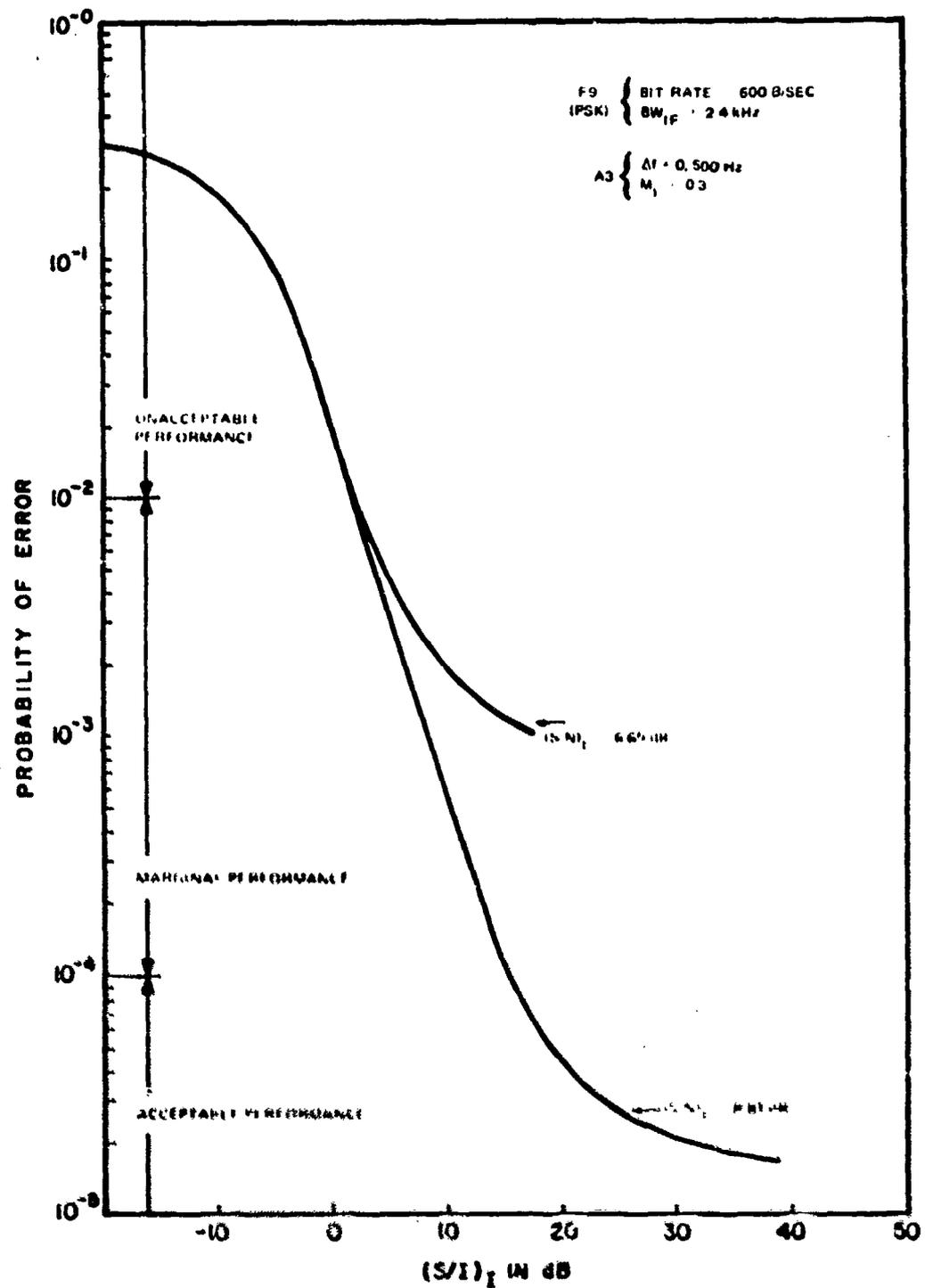


Figure C-127. Performance degradation curve for an F9 (PSK) receiver with A3 interference.

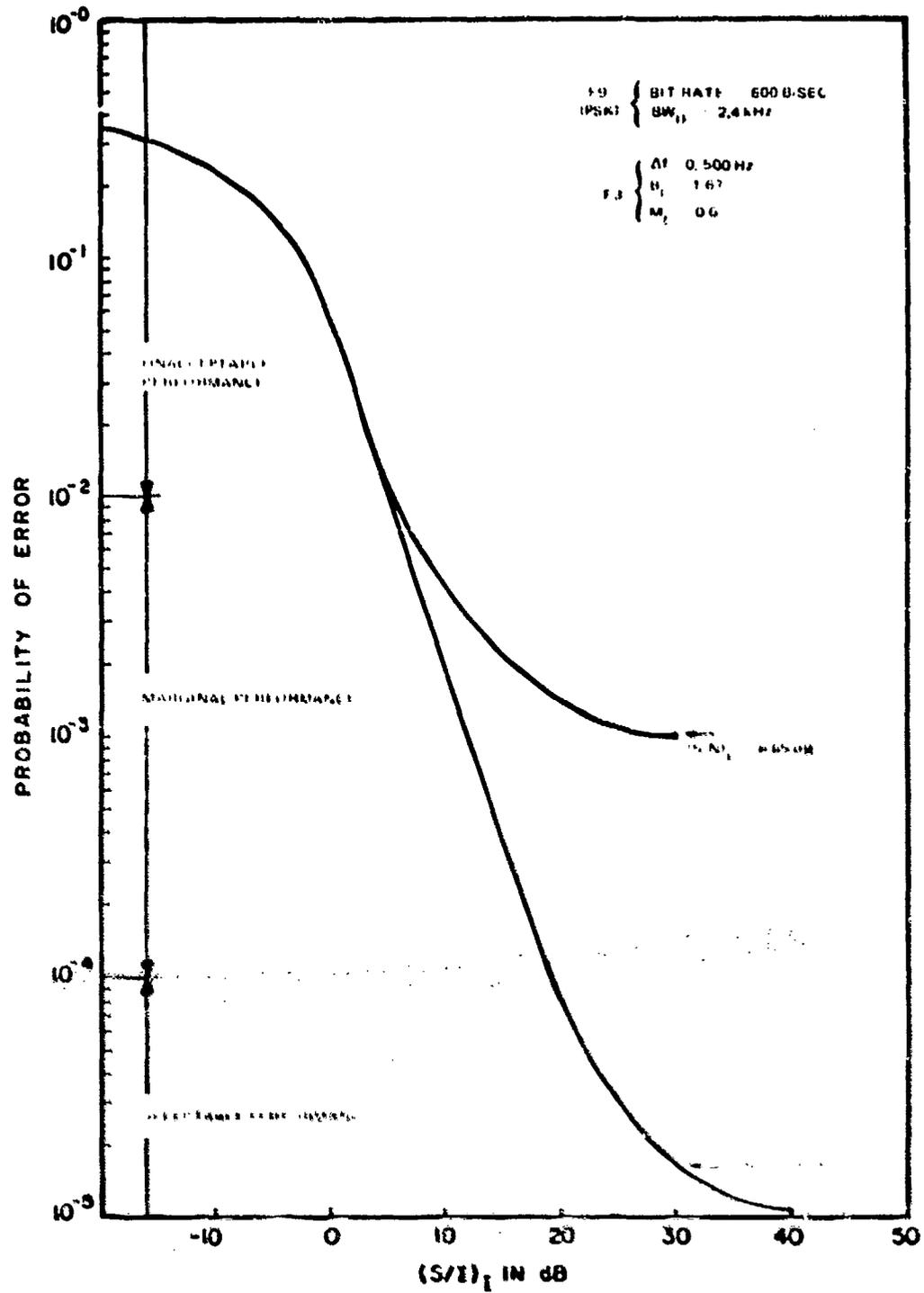


Figure C-128. Performance degradation curve for an F9 (PSK) receiver with F5 interference.

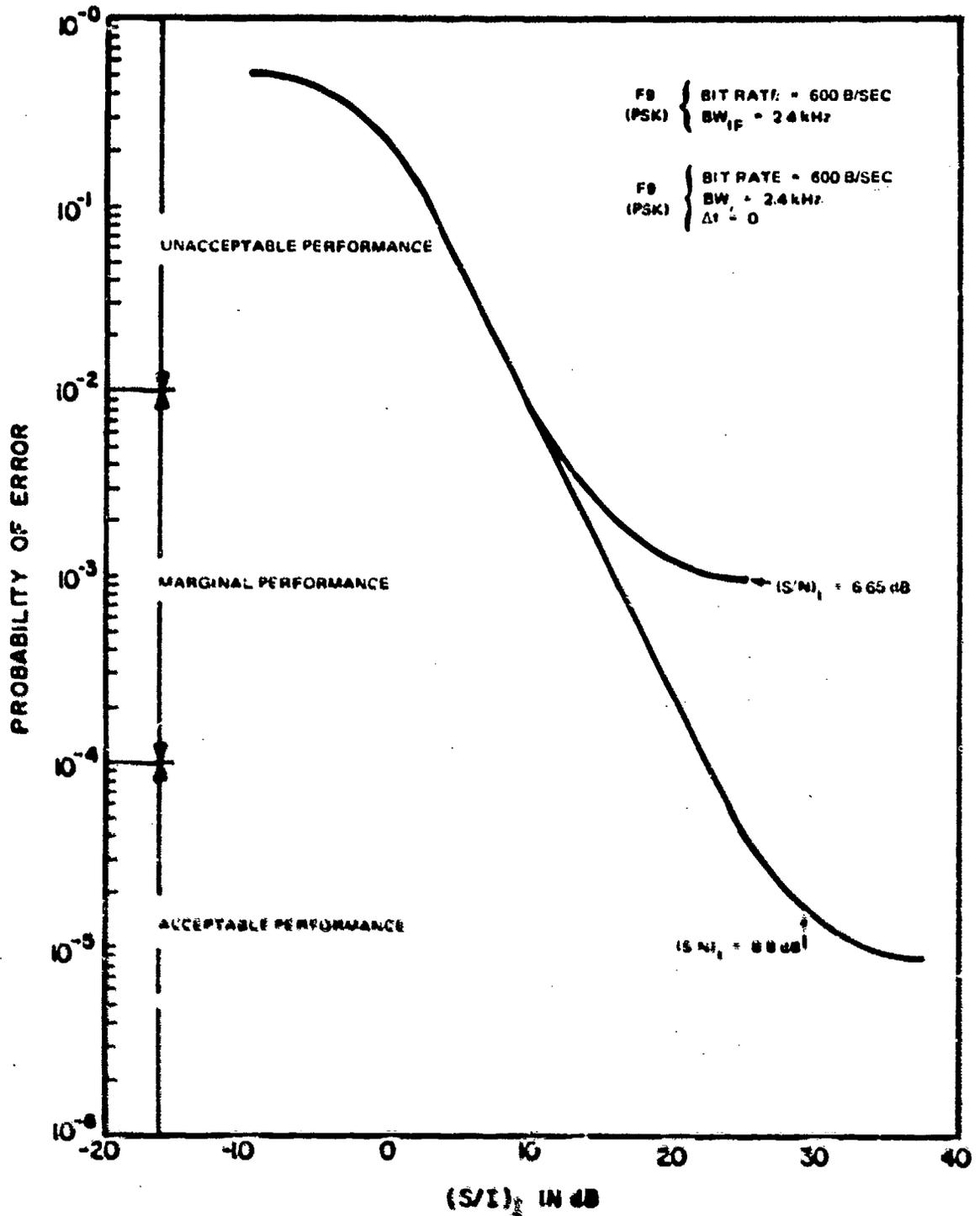


Figure C-129. Performance degradation curve for an F9 (PSK) receiver with F9 (PSK) interference (Δf = 0 Hz).

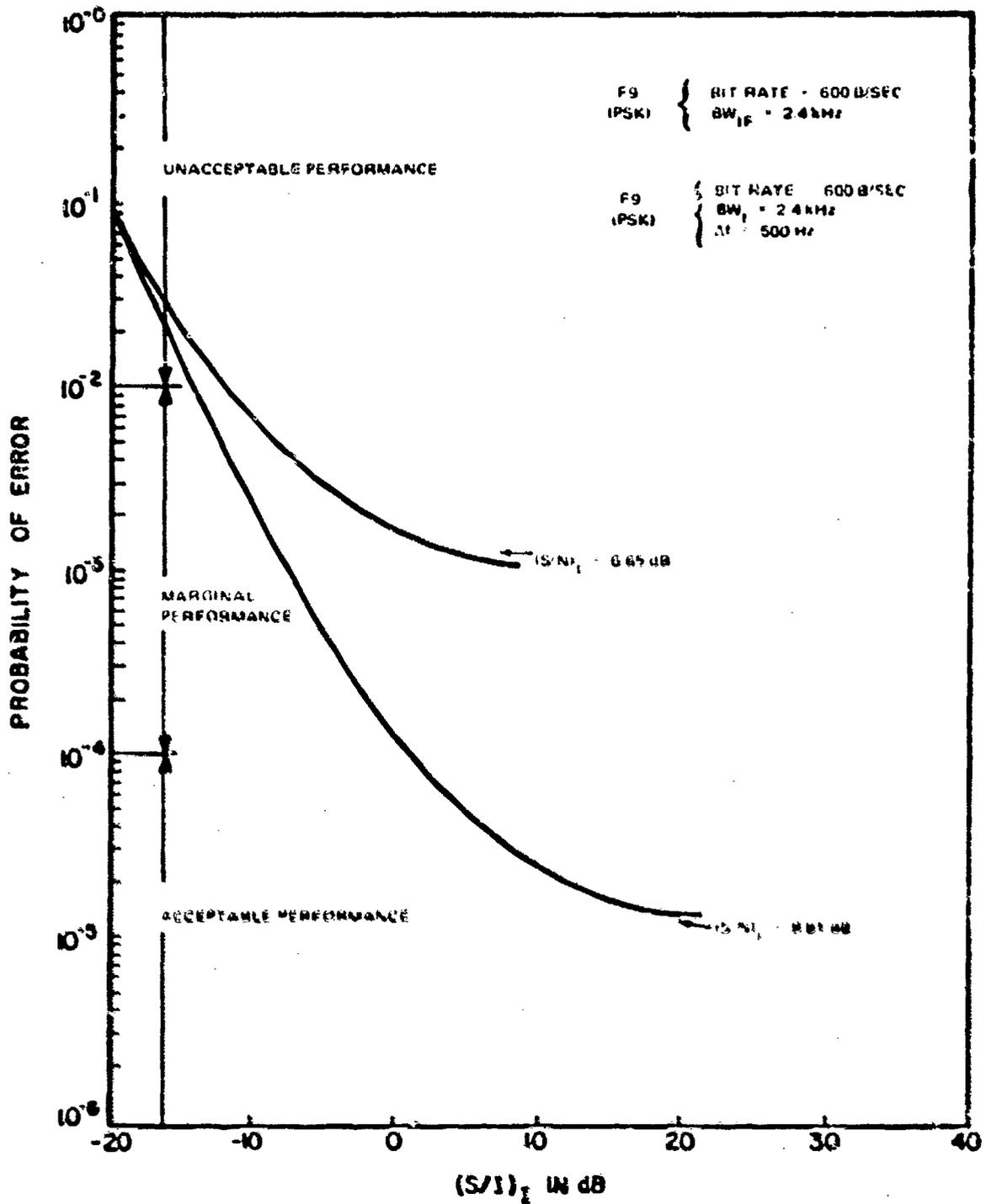


Figure C-130. Performance degradation curve for an F9 (PSK) receiver with F9 (PSK) interference ( $\Delta f = 500$  Hz).

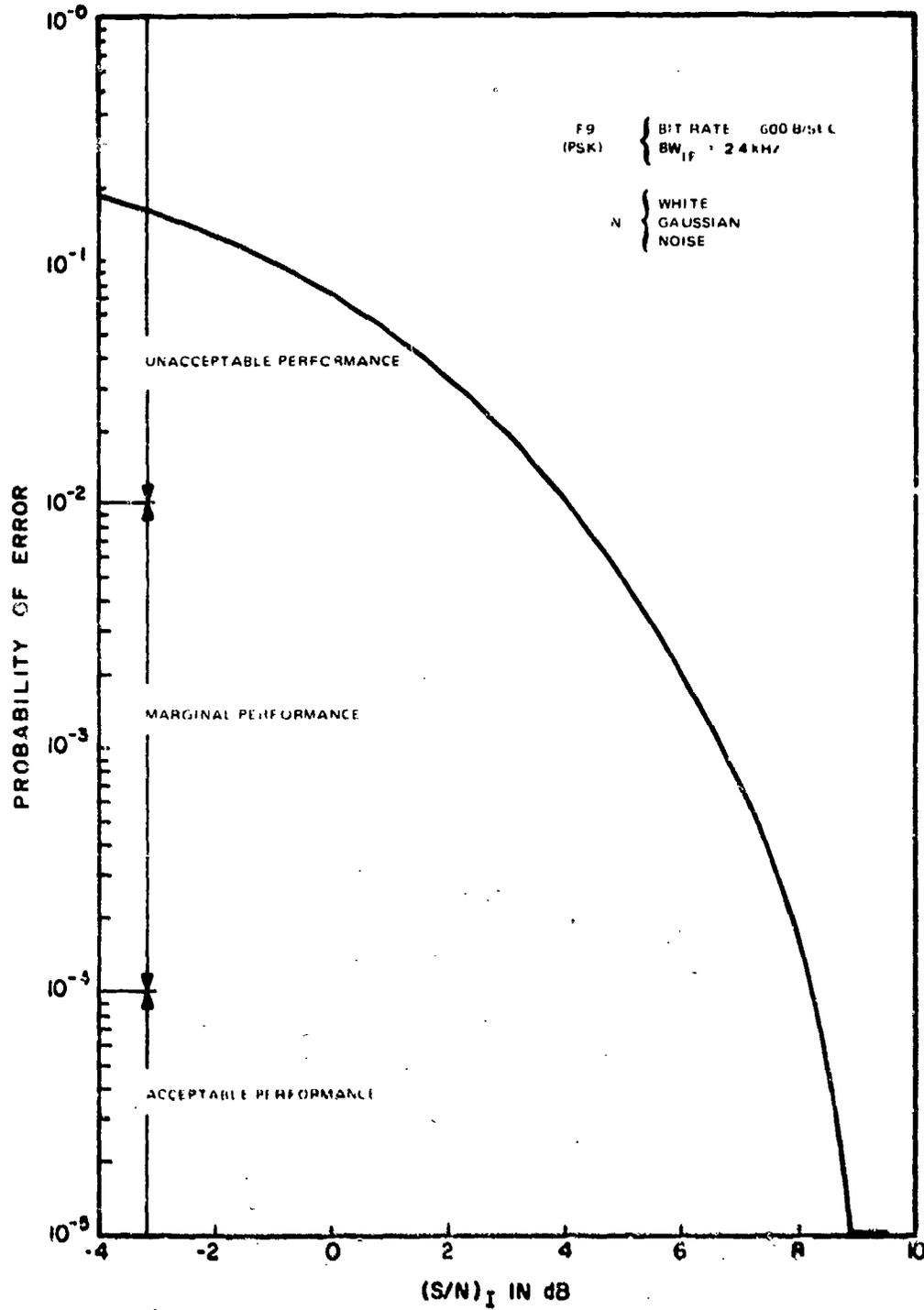


Figure C-132. Performance degradation curve for an F9 (PSK) receiver with noise interference.

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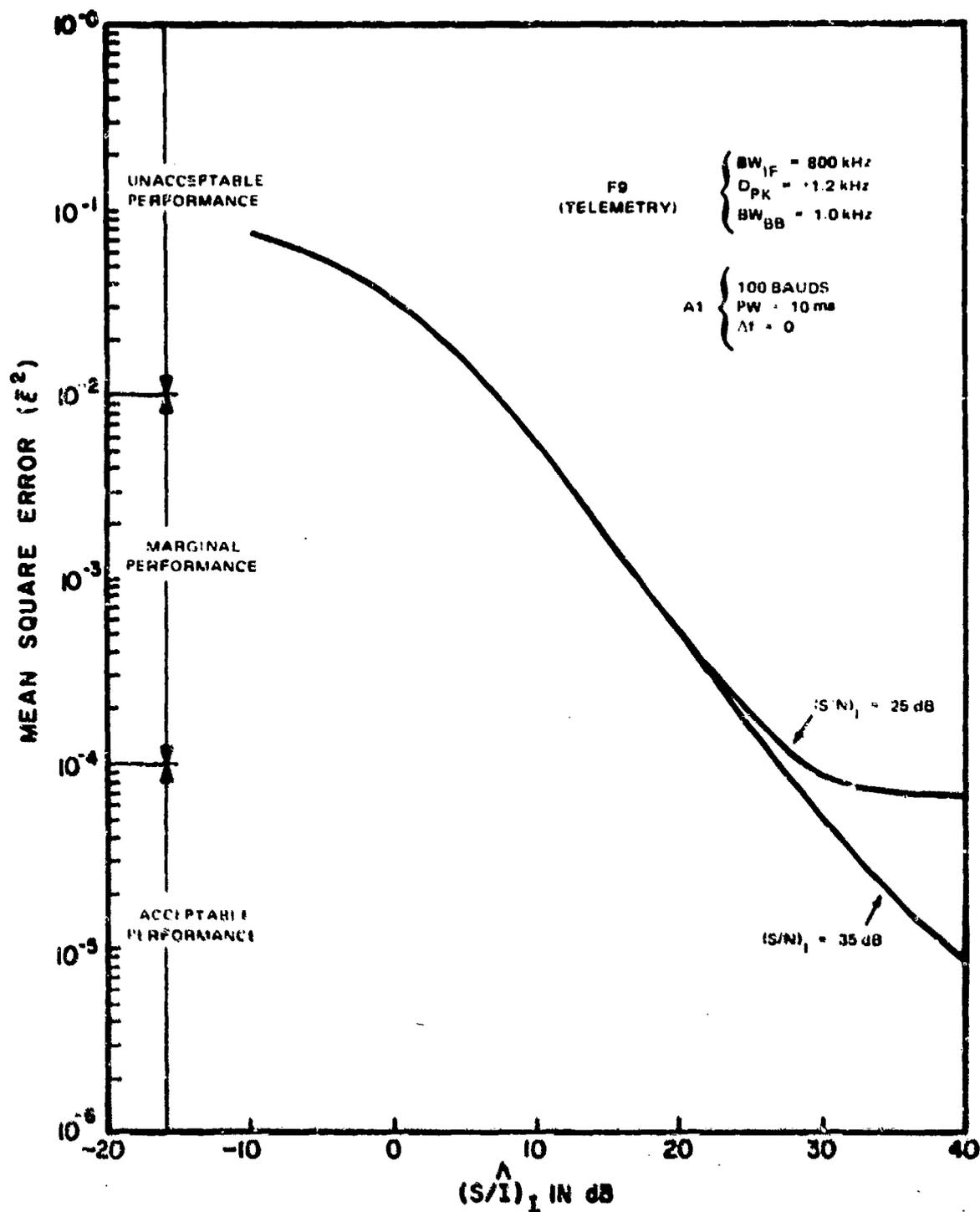


Figure C-13. Performance degradation curve for an F9 (telemetry) receiver with A1 interference.

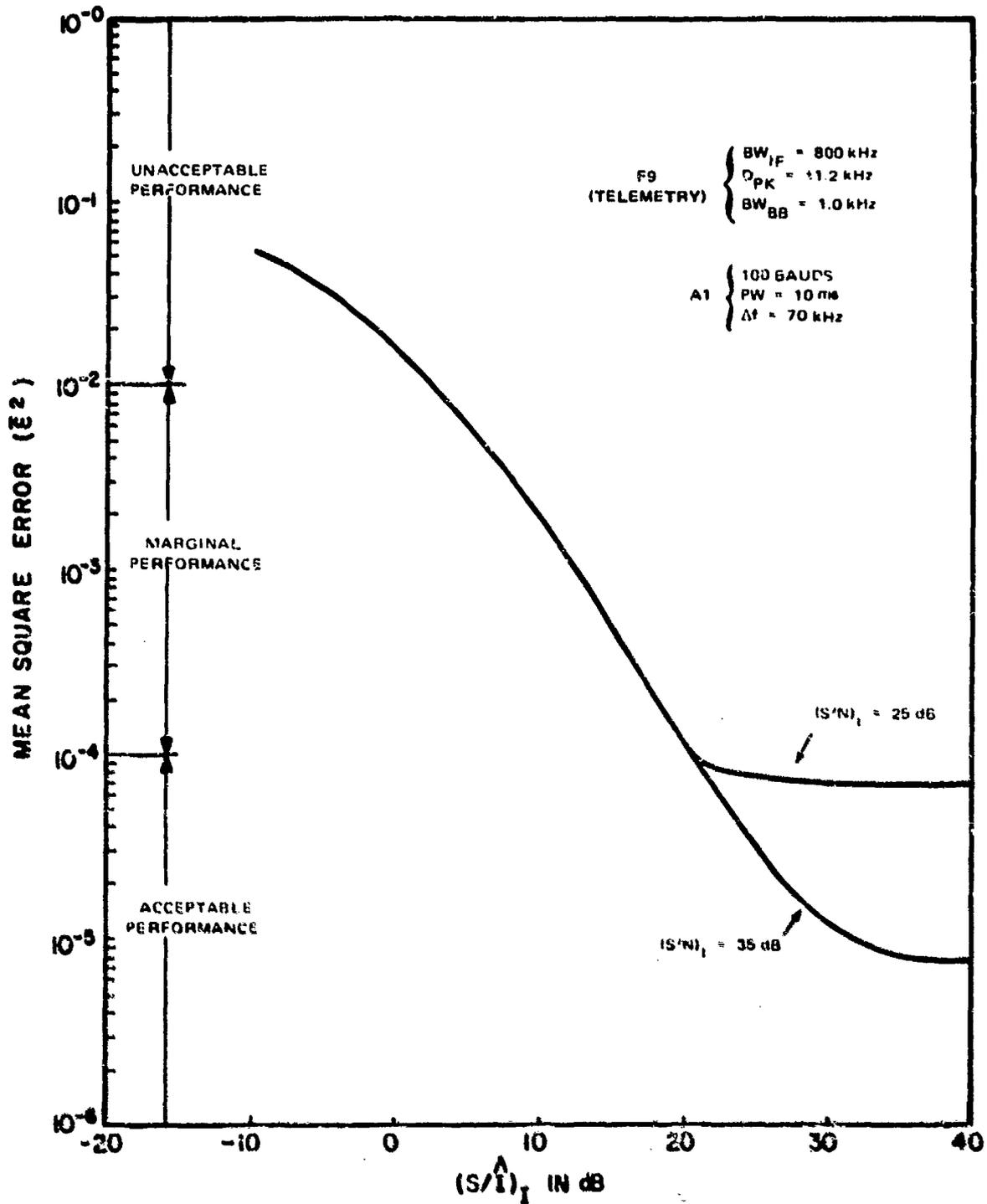


Figure C-134. Performance degradation curve for an F9 (telemetry) receiver with A1 interference ( $\Delta f = 70 \text{ kHz}$ ).

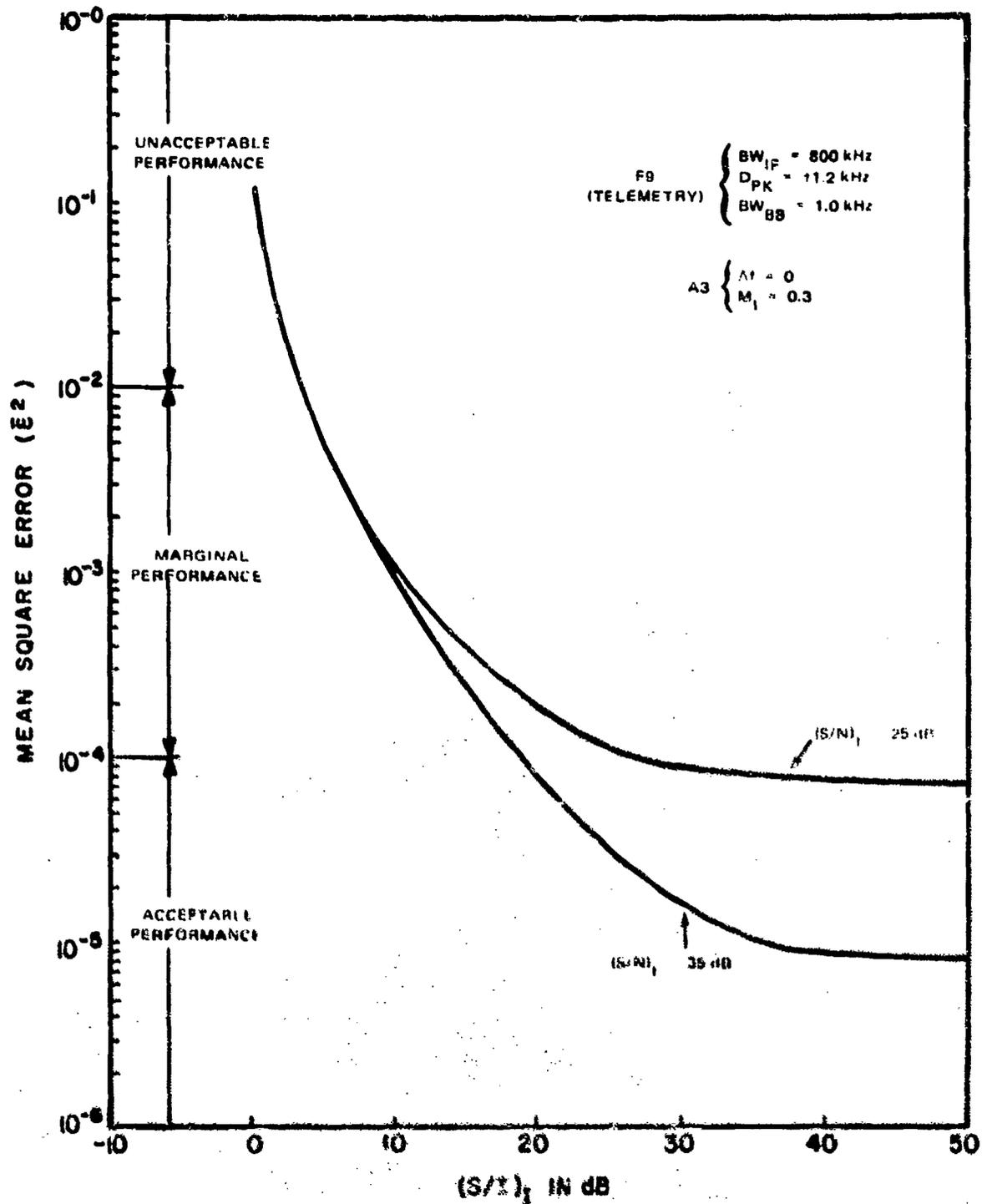


Figure C-135. Performance degradation curve for an F9 (telemetry) receiver with A3 interference.

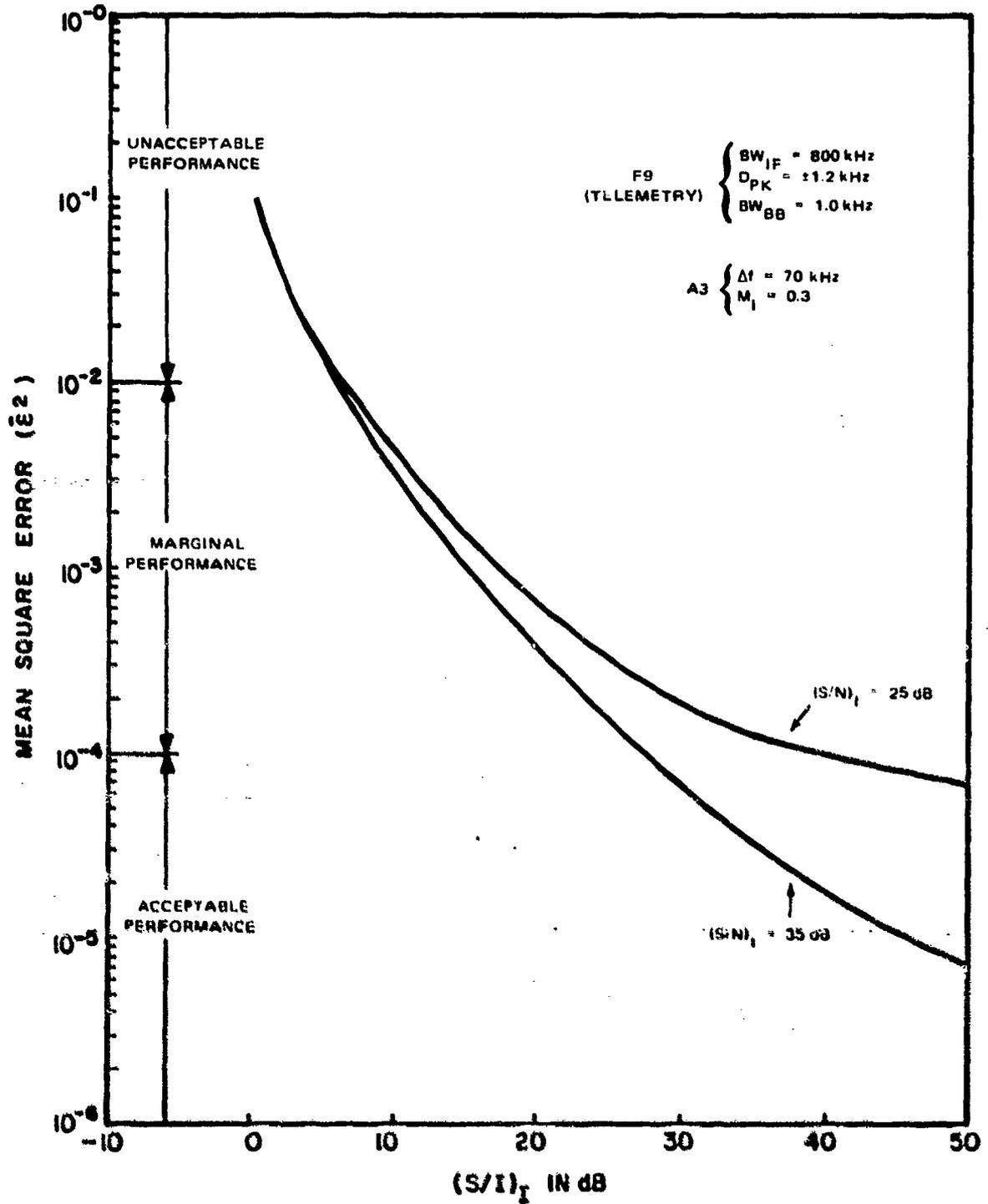


Figure C-136. Performance degradation curve for an F9 (telemetry) receiver with A3 ( $\Delta f = 70$  kHz) interference.

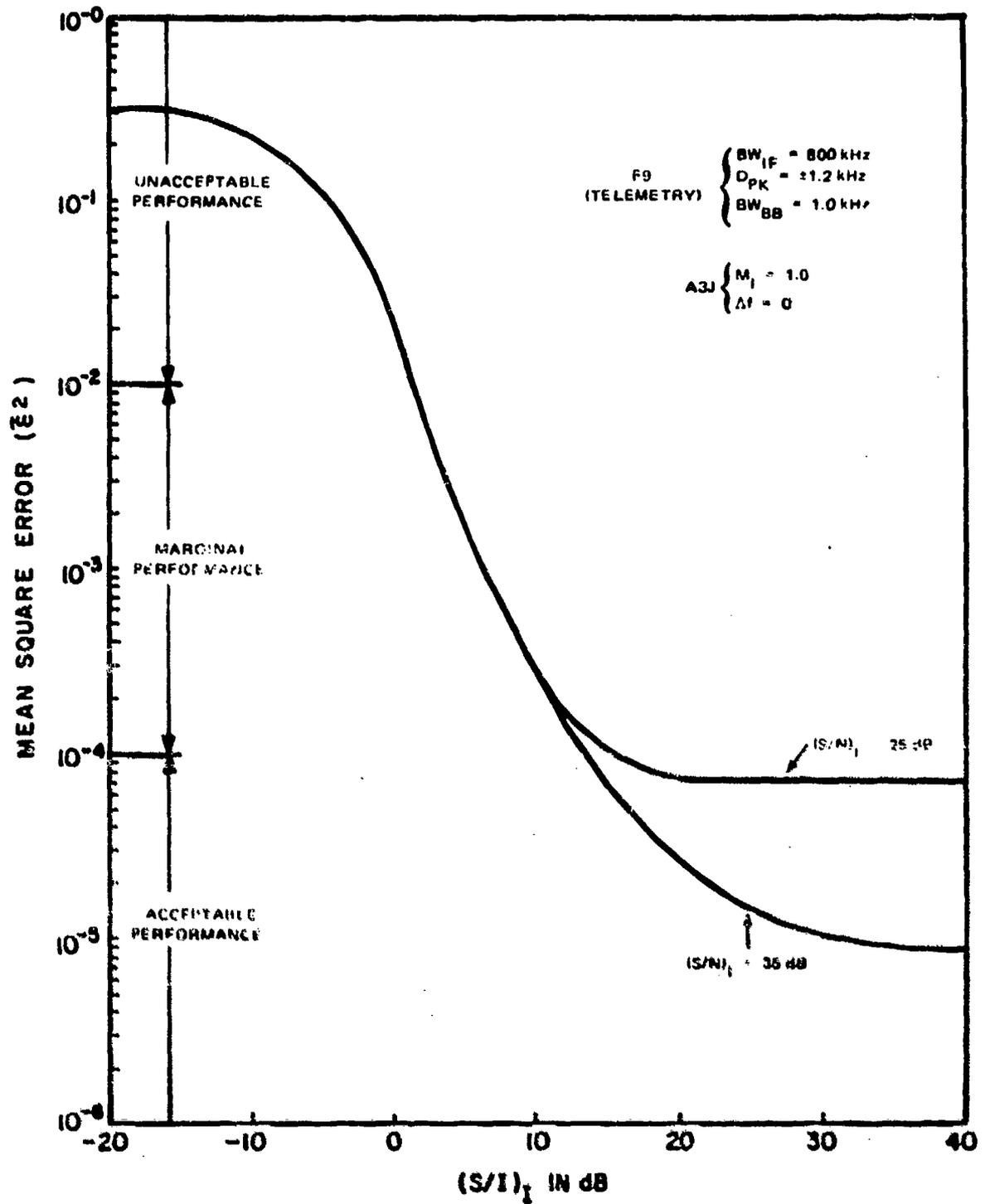


Figure C-157. Performance degradation curve for an F9 (telemetry) receiver with A3J interference.

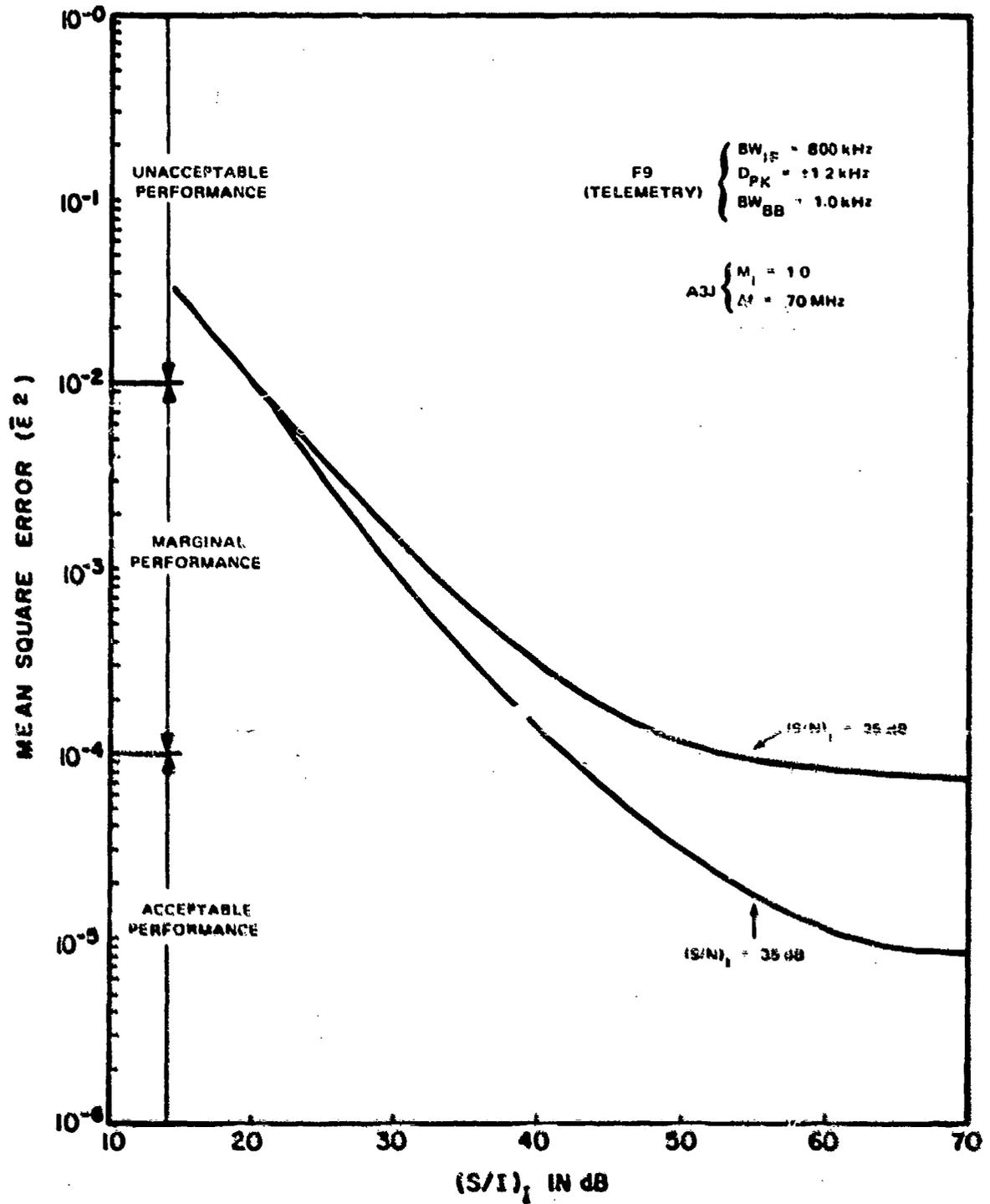


Figure C-138. Performance degradation curve for an F9 (telemetry) receiver with A3J ( $\Delta f = 70 \text{ MHz}$ ) interference.

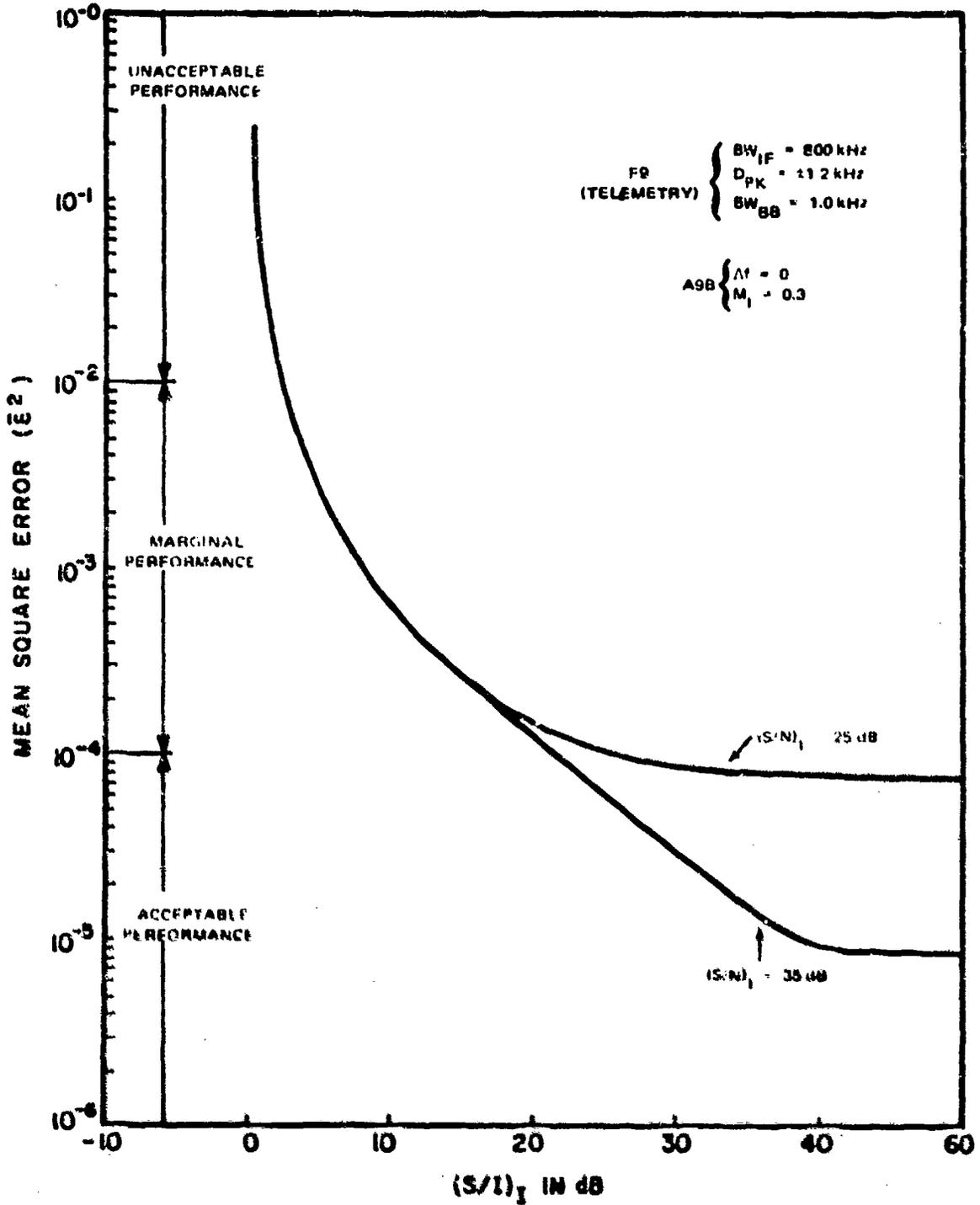


Figure C-139. Performance degradation curve for an F9 (telemetry) receiver with A9B interference.

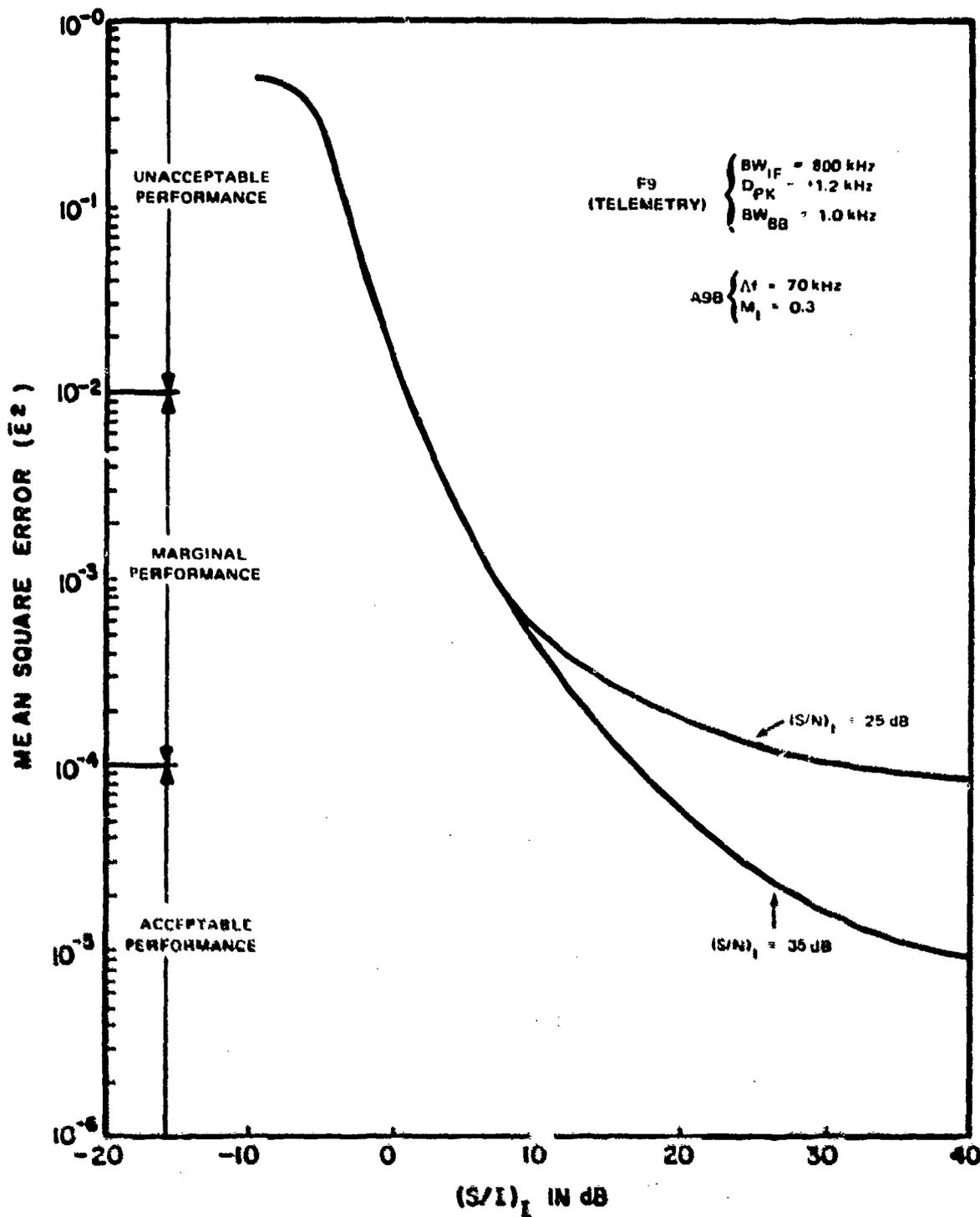


Figure C-140. Performance degradation curve for an F9 (telemetry) receiver with A9B ( $\Delta f = 70 \text{ MHz}$ ) interference.

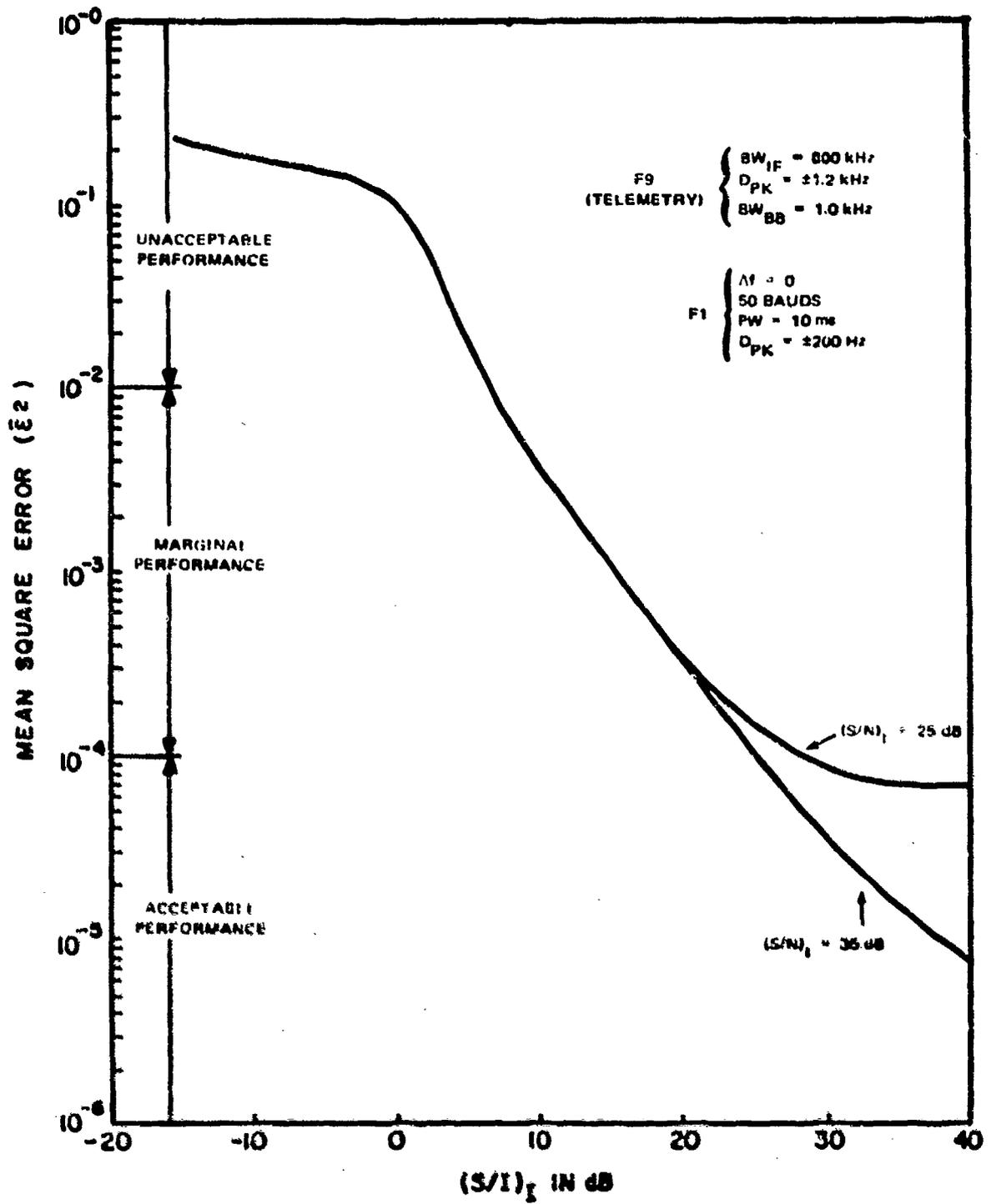


Figure C-141. Performance degradation curve for an F9 (telemetry) receiver with F1 interference.

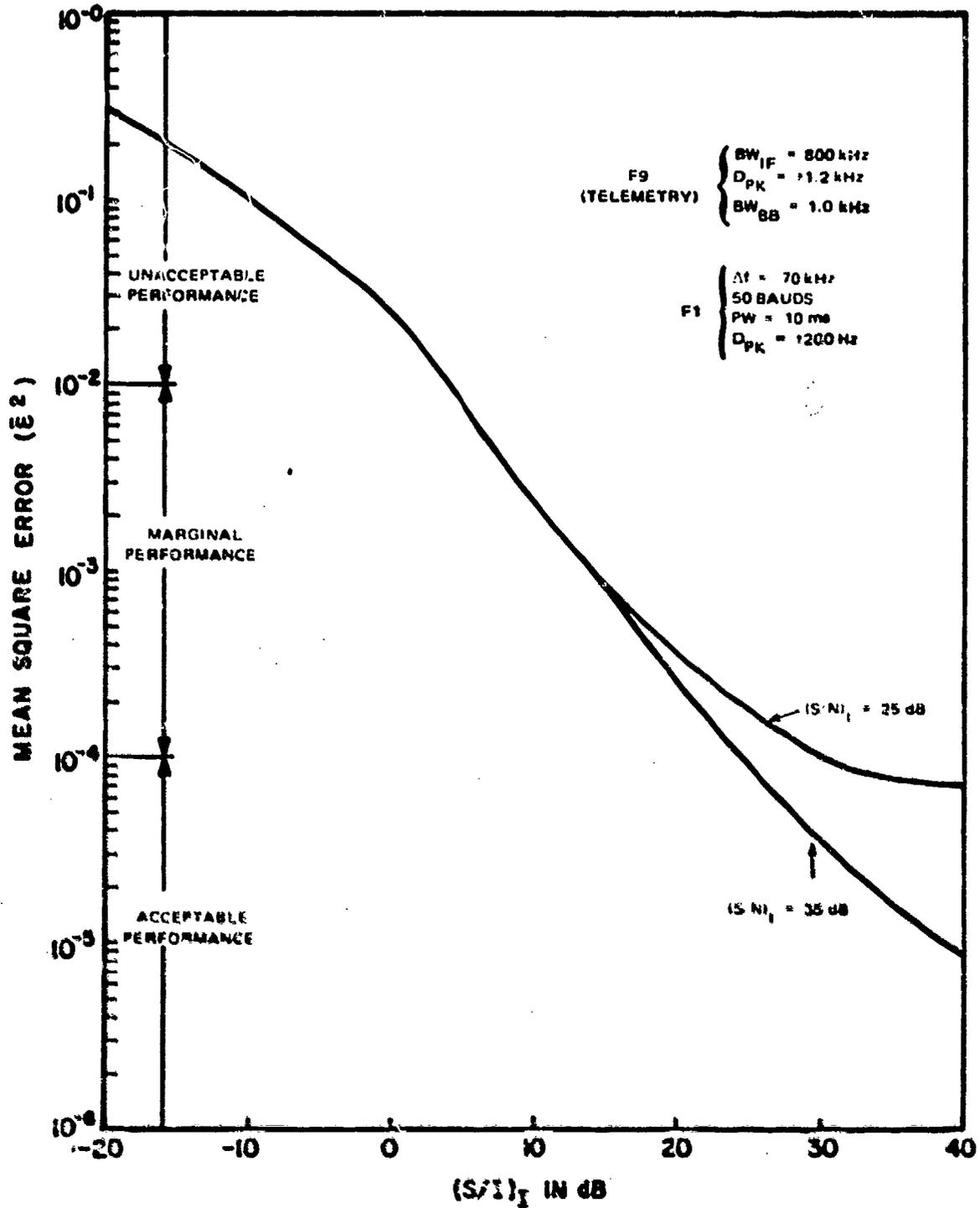


Figure C-142. Performance degradation curve for an F9 (telemetry) receiver with F1 ( $\Delta f = 70 \text{ kHz}$ ) interference.

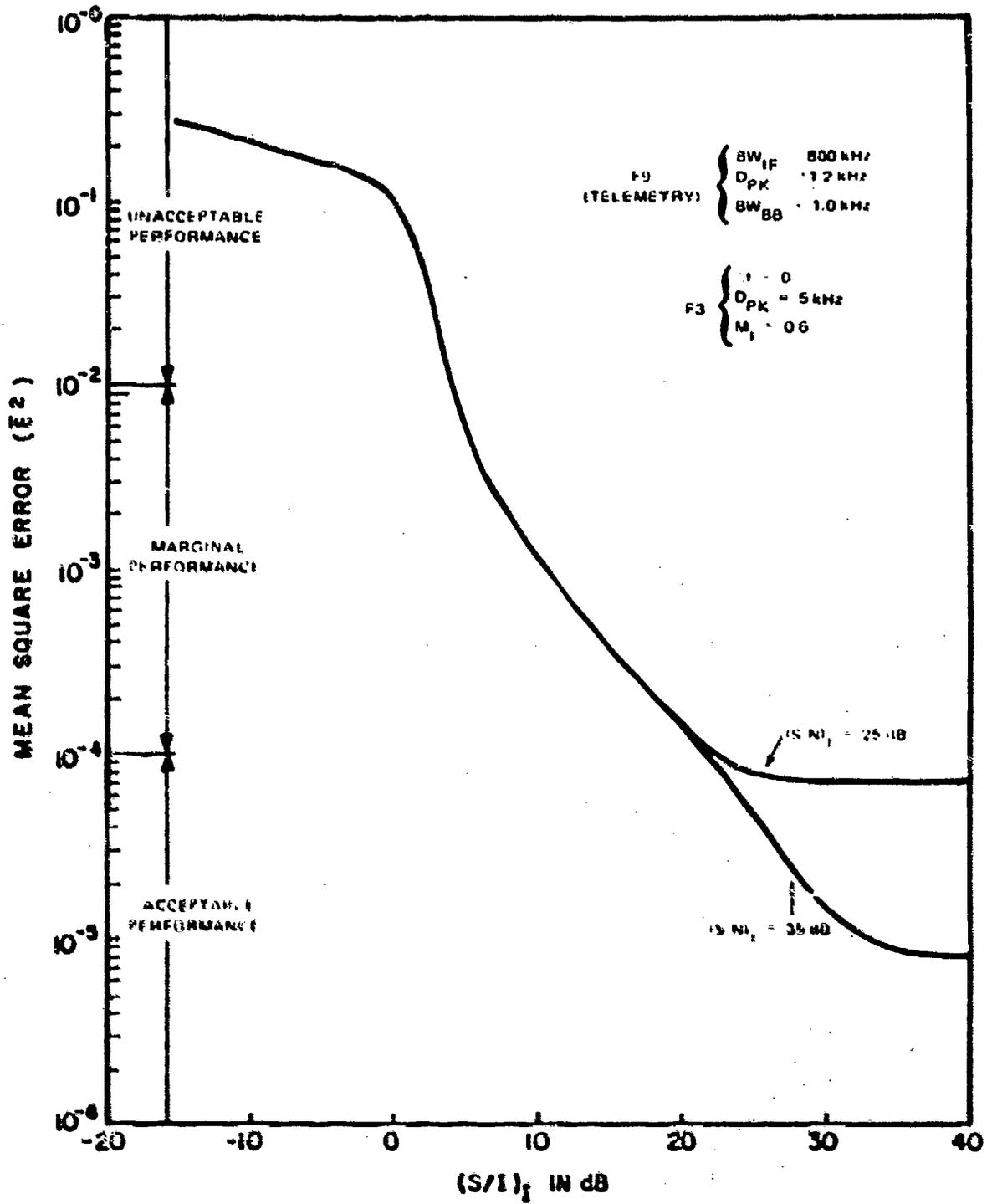


Figure C-143. Performance degradation curve for an F9 (telemetry) receiver with F3 interference.

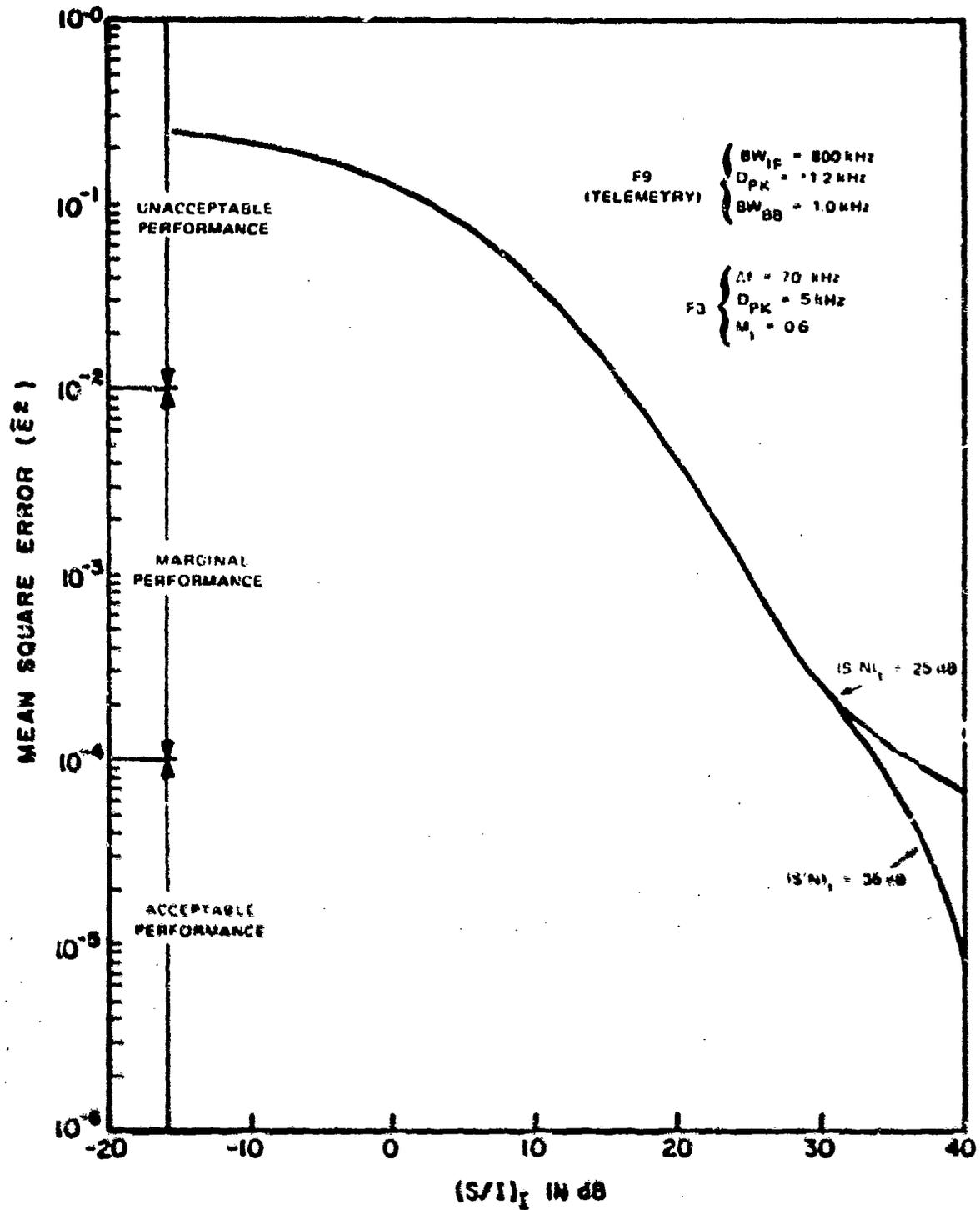


Figure C-144. Performance degradation curve for an F9 (telemetry) receiver with F3 ( $\Delta f = 70$  kHz) interference.

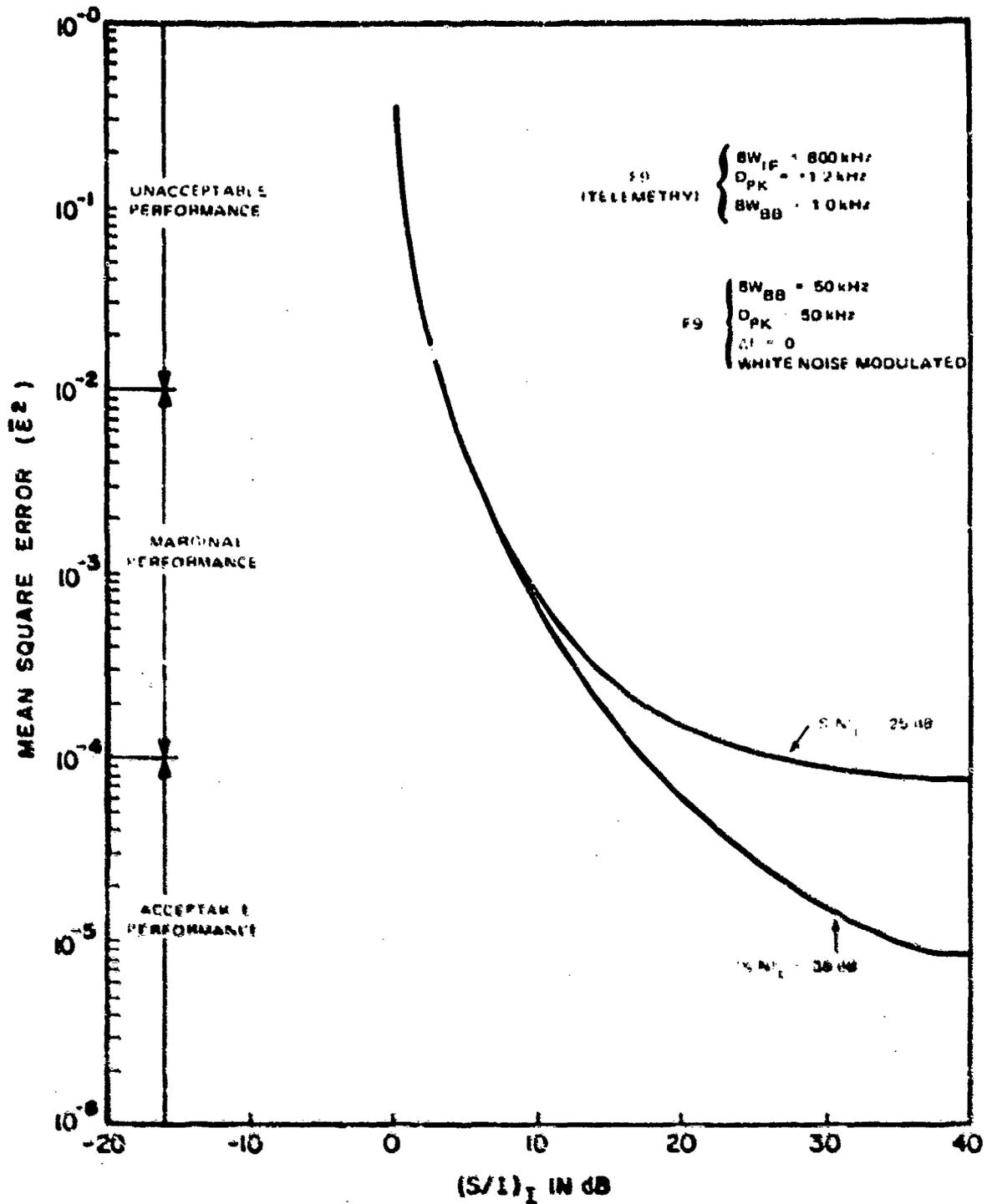


Figure C-145. Performance degradation curve for an F9 (telemetry) receiver with F9 ( $\Delta f = 0$ ) interference.

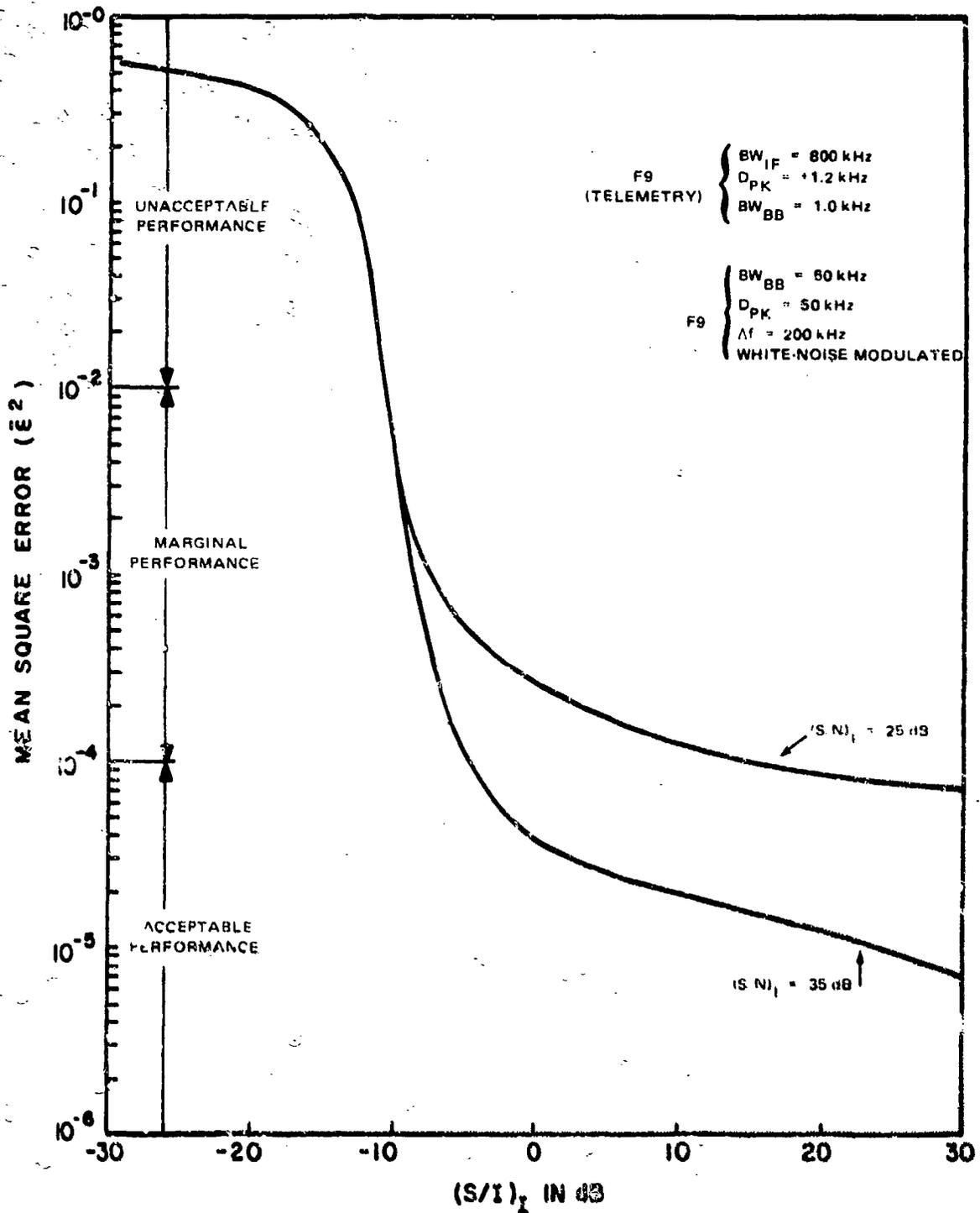


Figure C-146. Performance degradation curve for an F9 (telemetry) receiver with F9 ( $\Delta f = 200 \text{ kHz}$ ) interference.

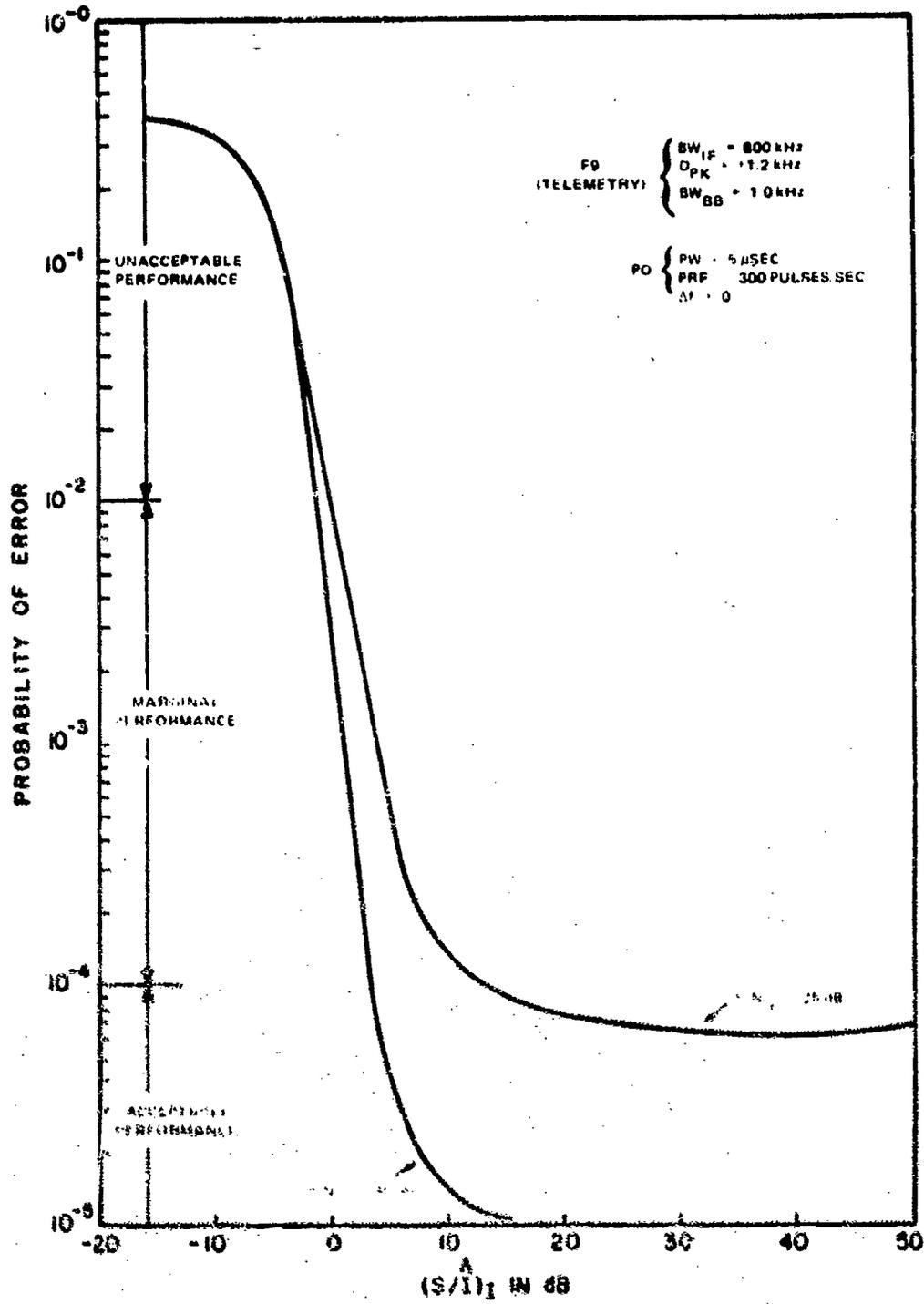


Figure C-147. Performance degradation curve for an F9 (telemetry) receiver with PO ( $\Delta f = 0$ ) interference.

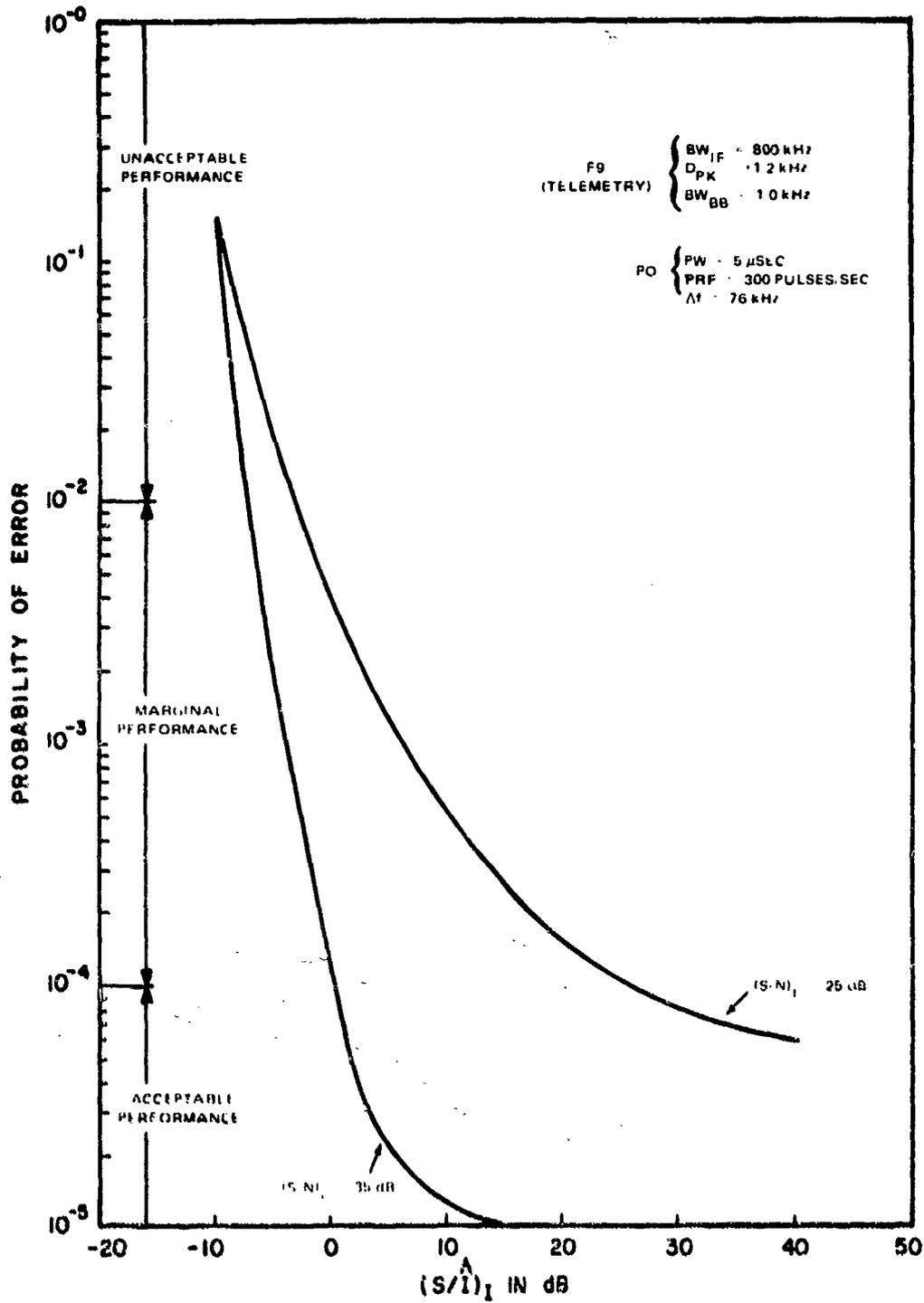


Figure C-148. Performance degradation curve for an F9 (telemetry) receiver with PO ( $\Delta f = 76$  kHz) interference.

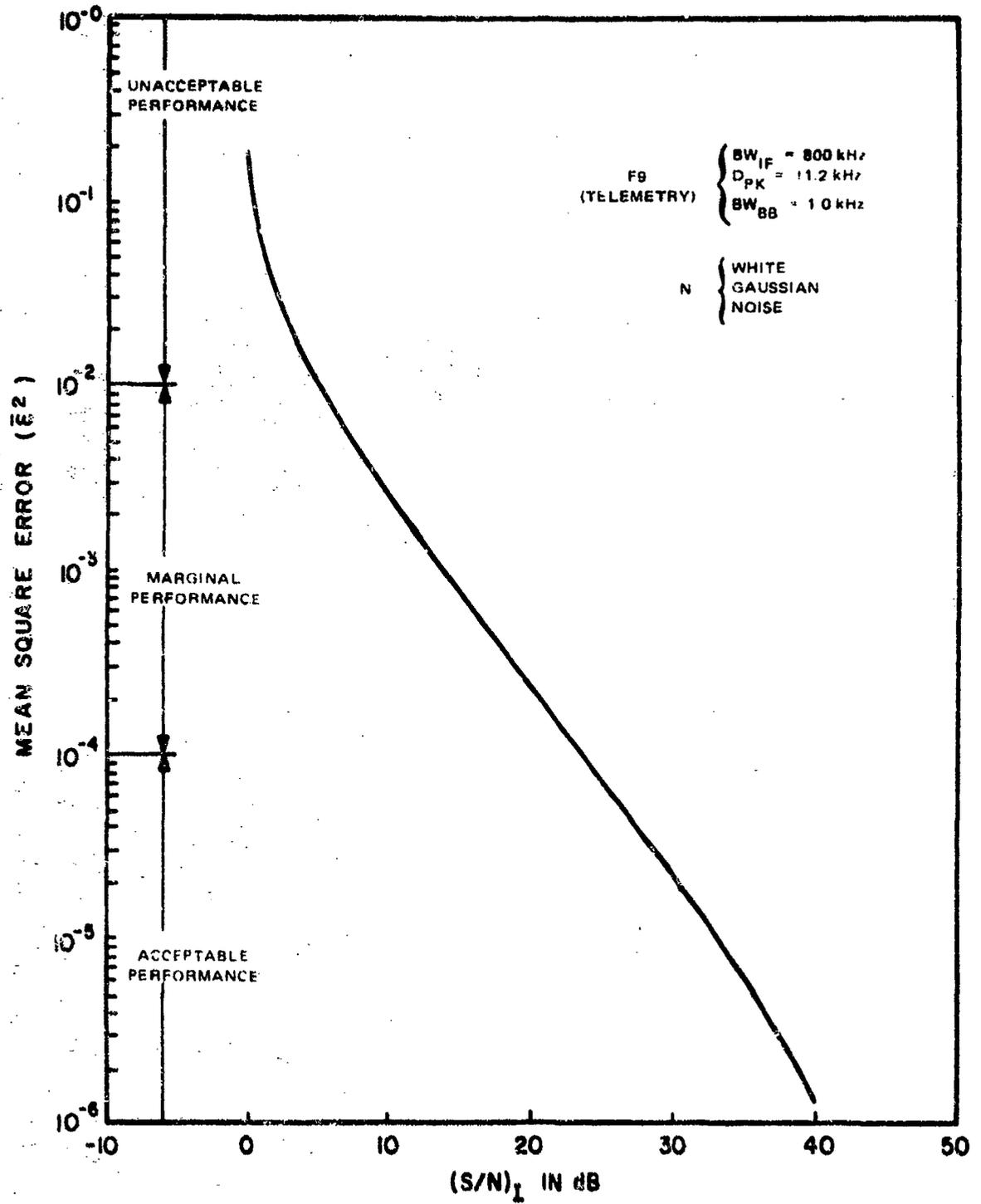


Figure C-149. Performance degradation curve for an F9 (telemetry) receiver with noise interference.

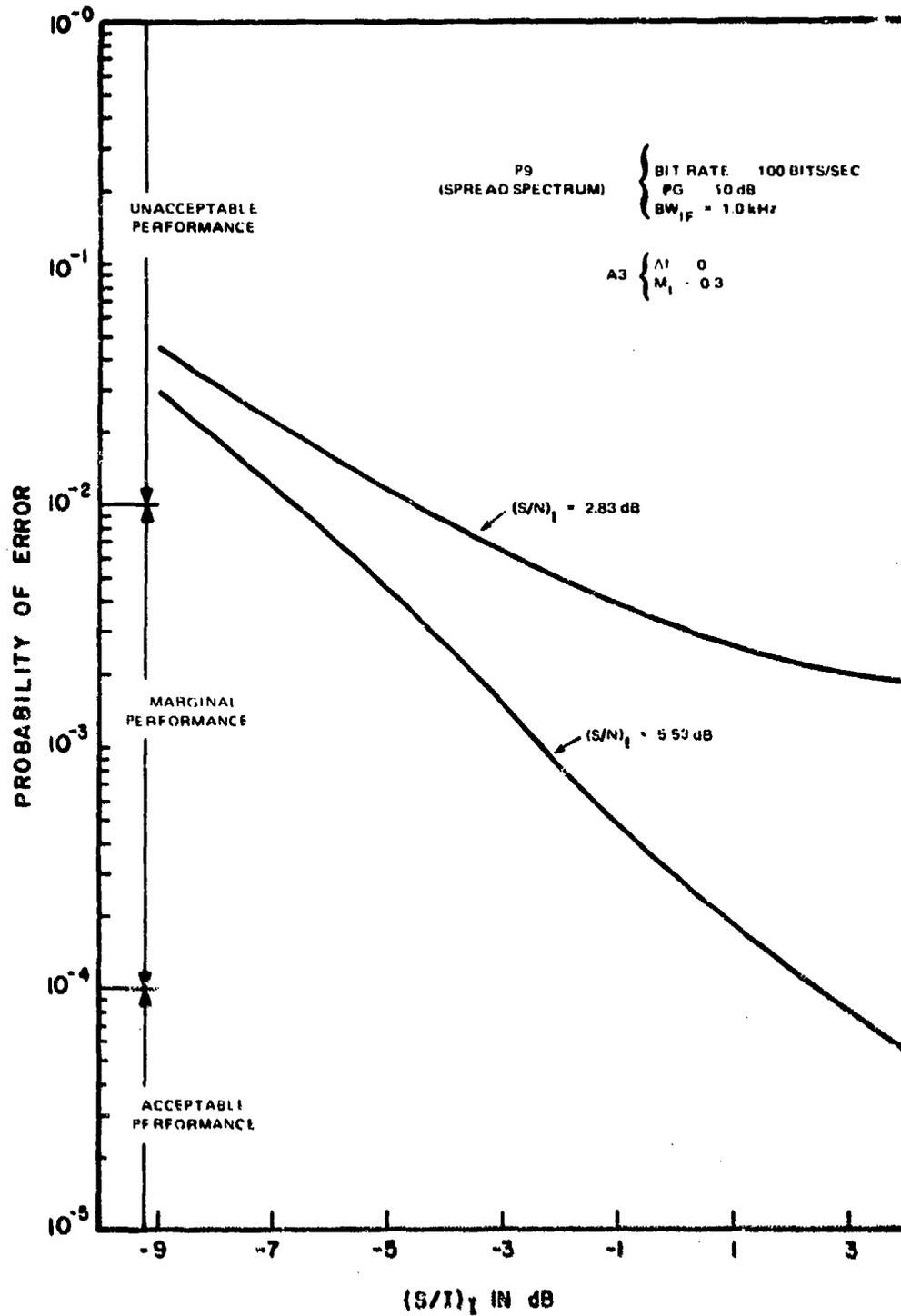


Figure C-150. Performance degradation curve for an P9 (spread spectrum) receiver with A3 interference. Receiver processing gain = 10 dB.

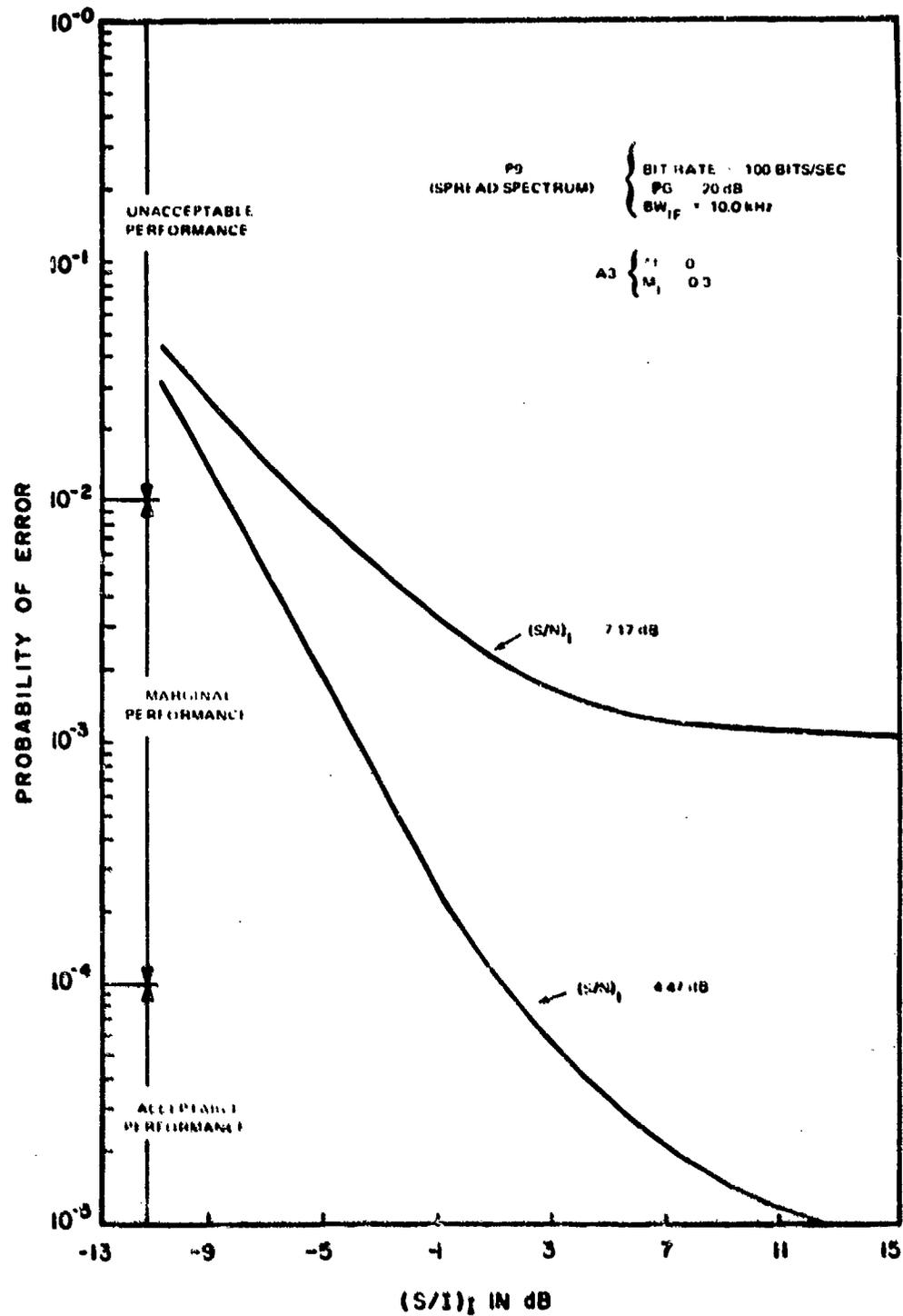


Figure C-151. Performance degradation curve for an P9 (spread spectrum) receiver with A3 interference. Receiver processing gain = 20 dB.

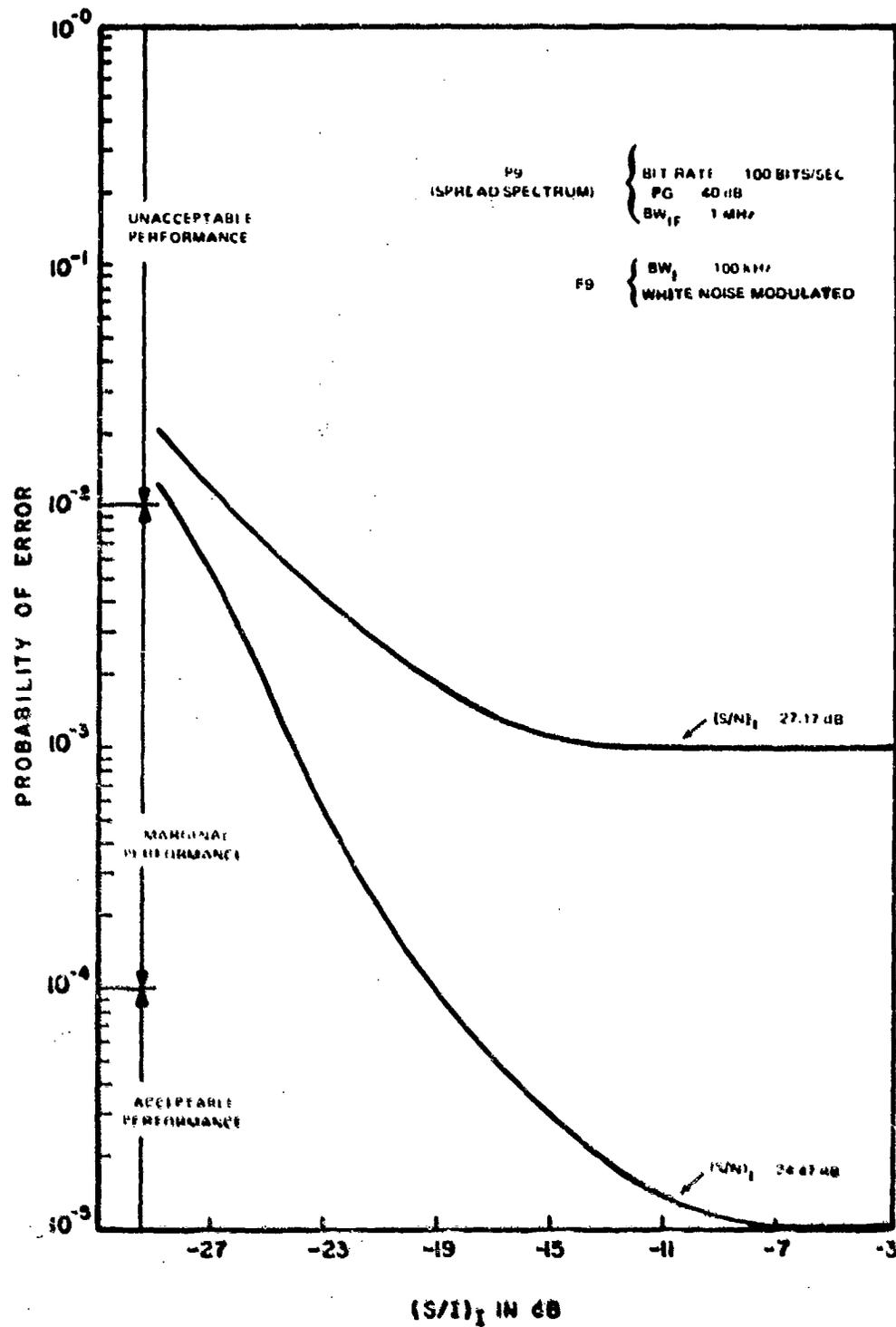


Figure C-152. Performance degradation curve for a P9 (spread spectrum) receiver with A3 interference. Receiver processing gain = 40 dB.

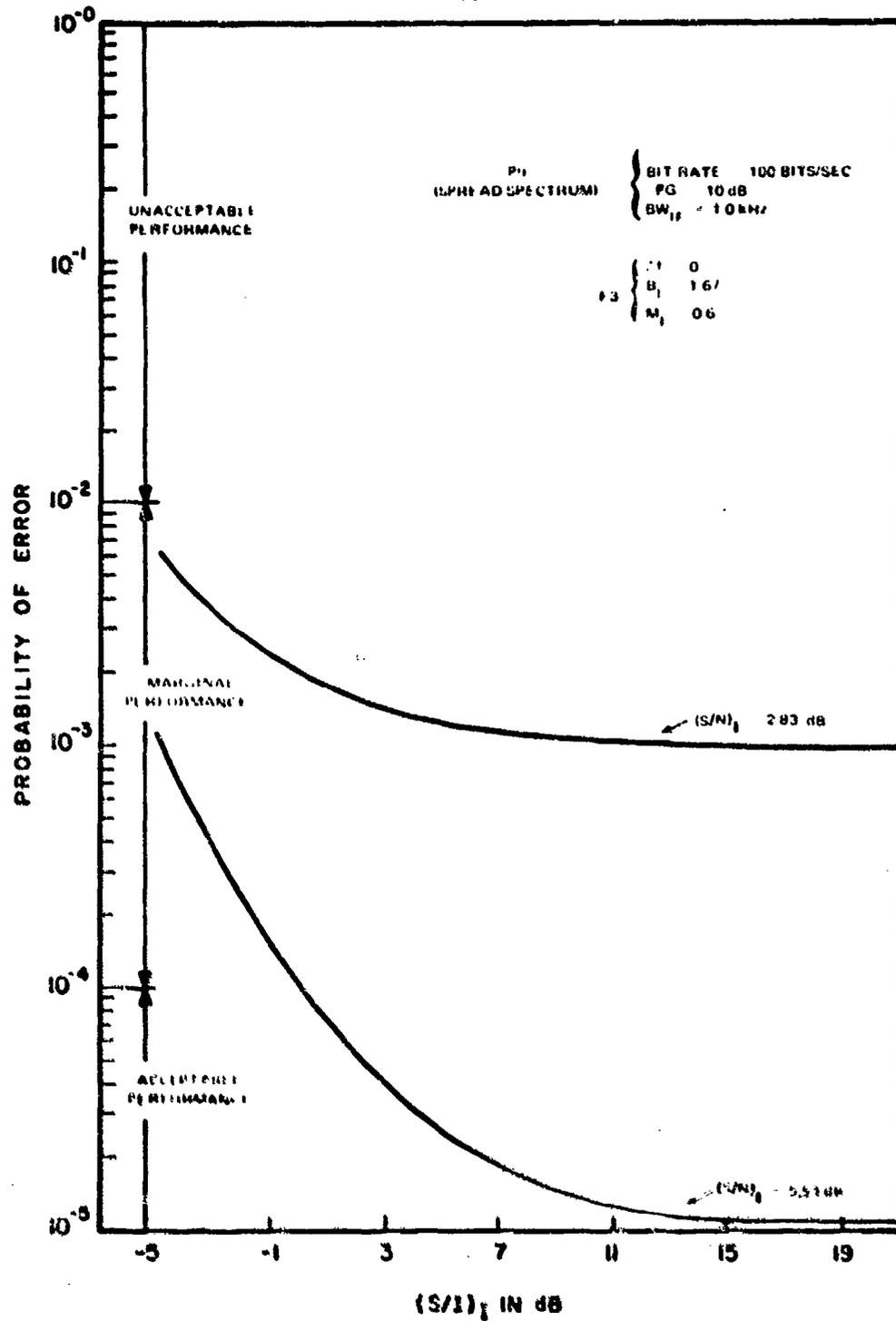


Figure C-153. Performance degradation curve for a F9 (spread spectrum) receiver with F3 interference. Receiver processing gain = 10 dB.

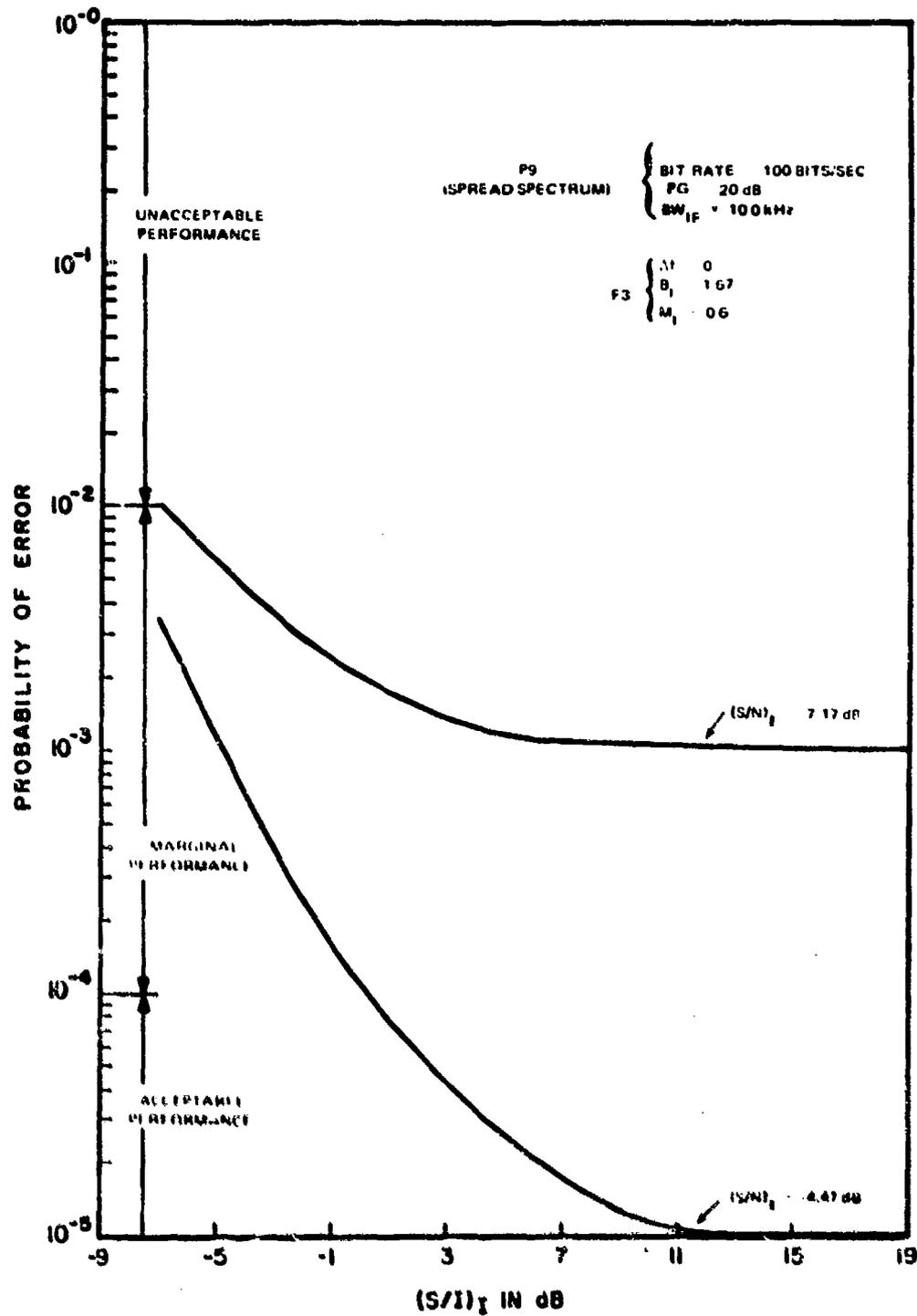


Figure C-154. Performance degradation curve for a P9 (spread spectrum) receiver with F3 interference. Receiver processing gain = 20 dB.

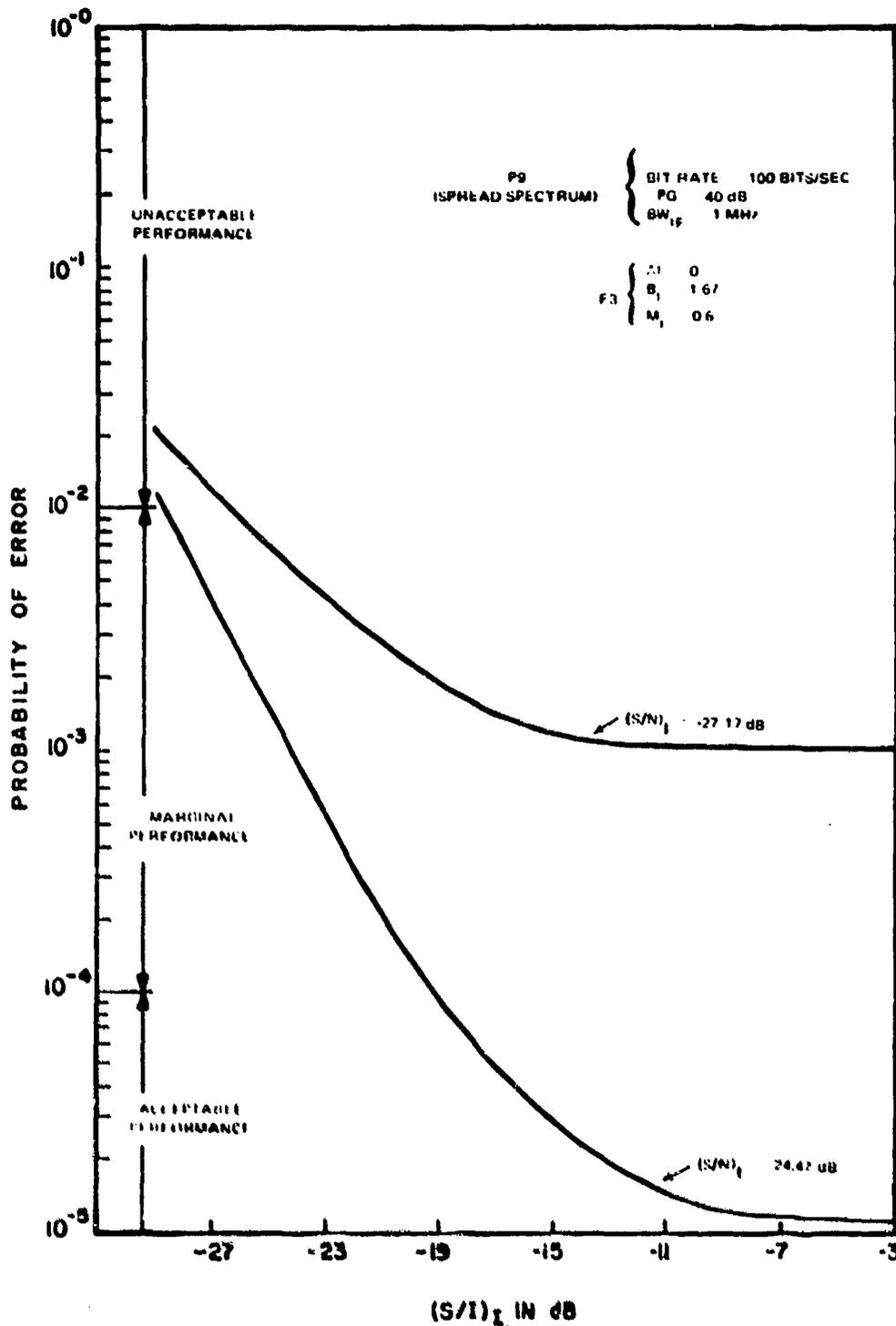


Figure C-155. Performance degradation curve for a P9 (spread spectrum) receiver with F3 interference. Receiver processing gain = 40 dB.

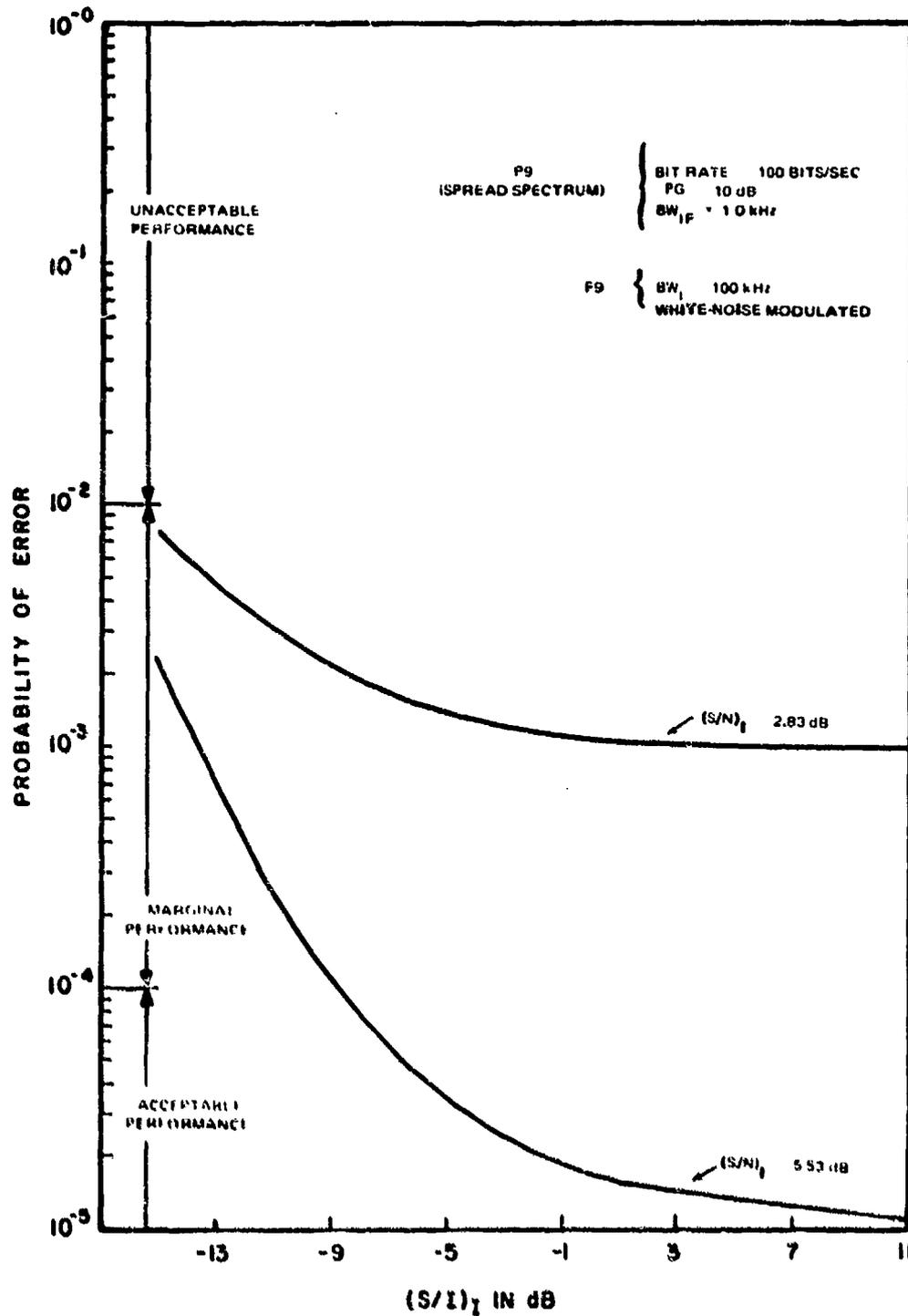


Figure C-156. Performance degradation curve for a P9 (spread spectrum) receiver with F9 interference. Receiver processing gain = 10 dB.

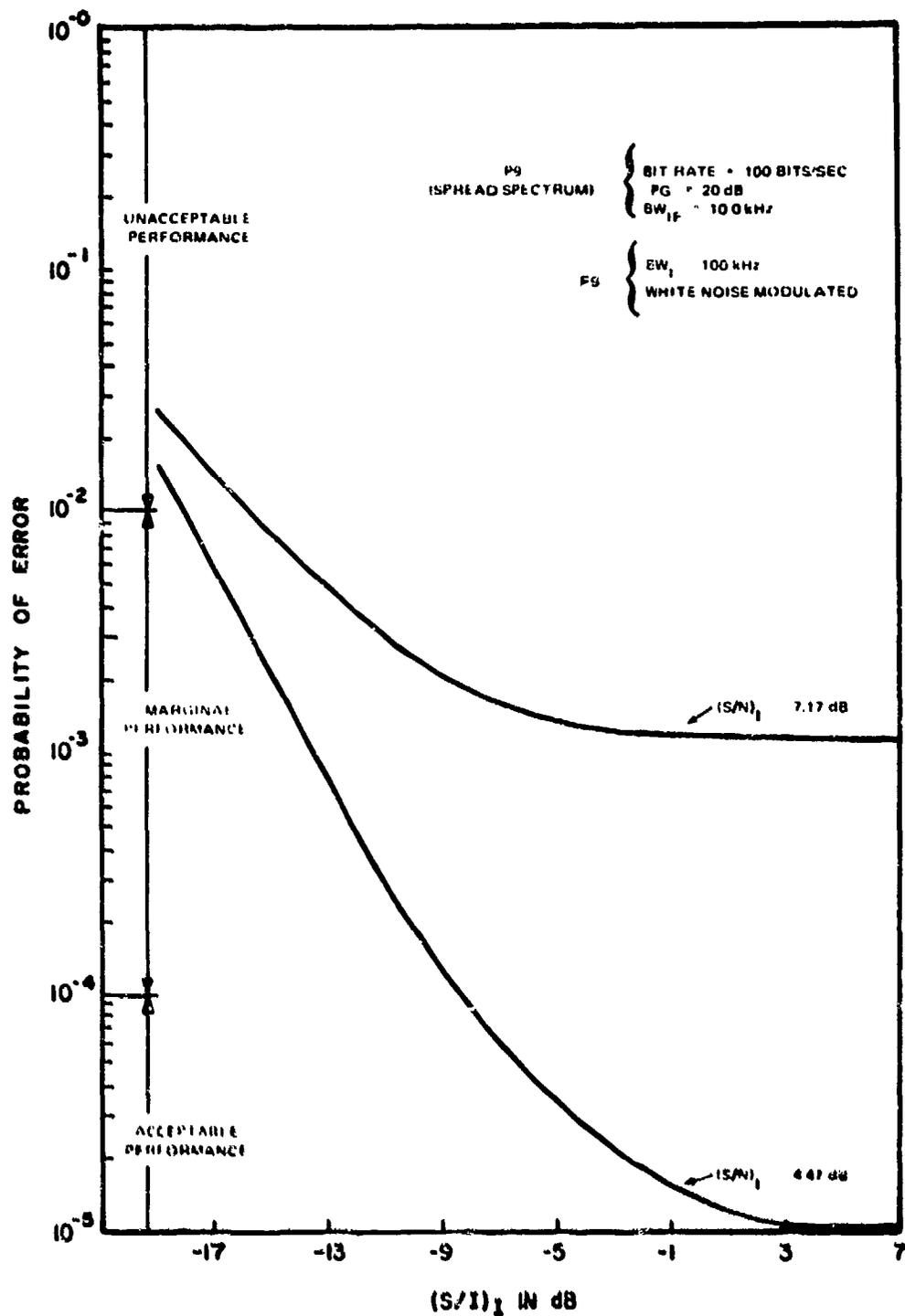


Figure C-157. Performance degradation curve for an P9 (spread spectrum) receiver with F9 interference. Receiver processing gain = 20 dB.

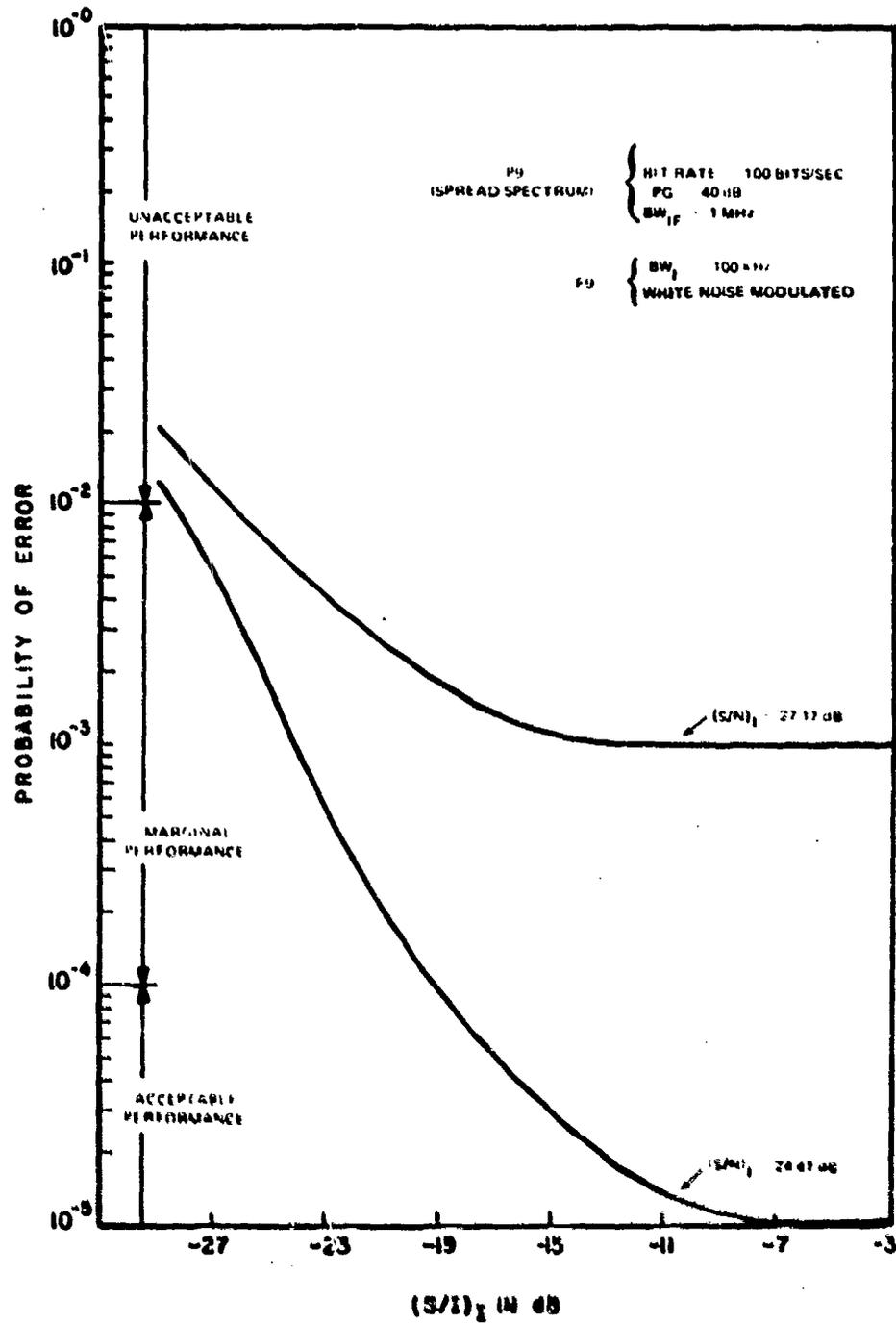


Figure C-158. Performance degradation curve for a P9 (spread spectrum) receiver with F9 interference. Receiver processing gain = 40 dB.

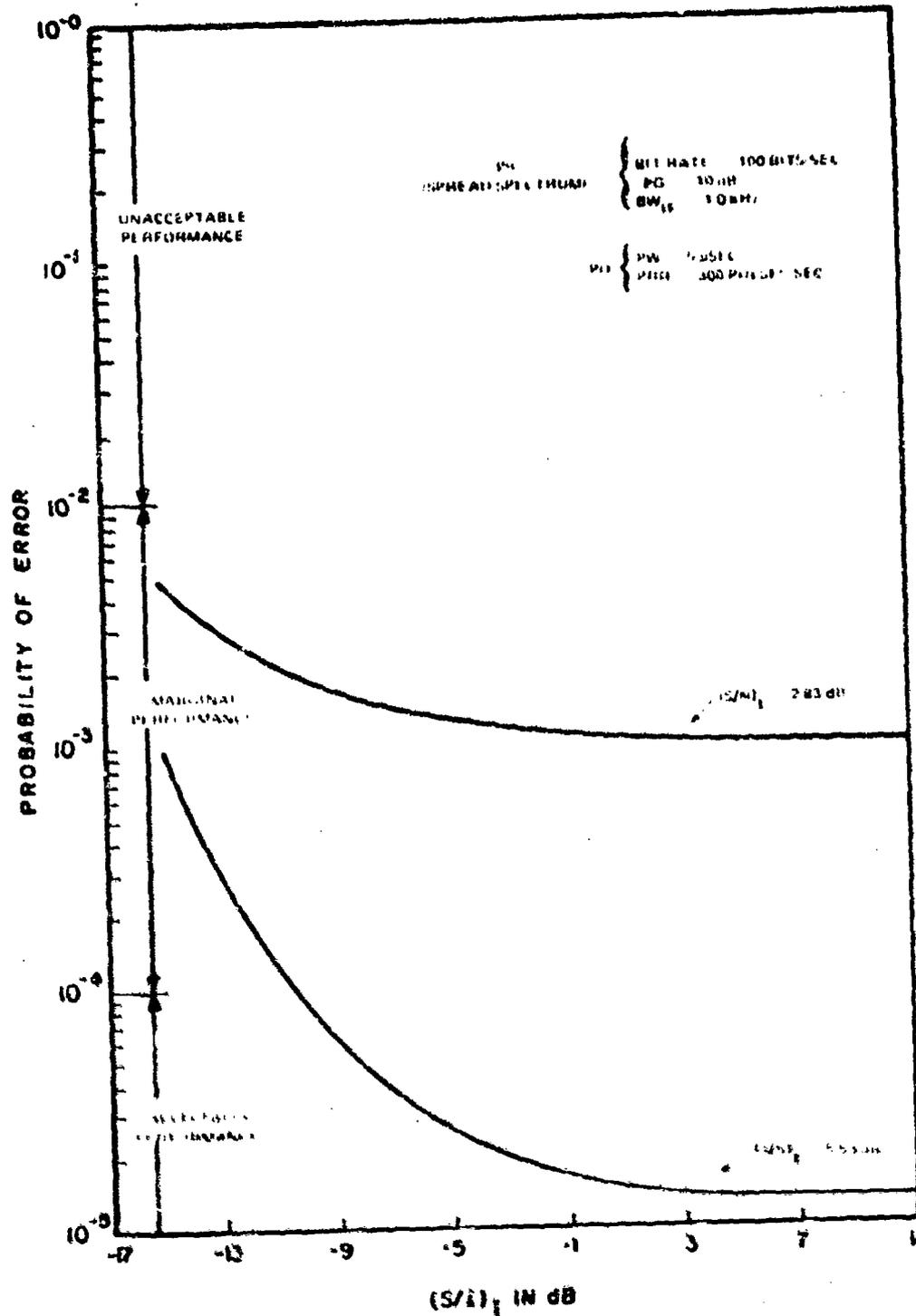


Figure C-159. Performance degradation curve for a P0 (spread spectrum) receiver with P0 interference. Receiver processing gain = 10 dB.

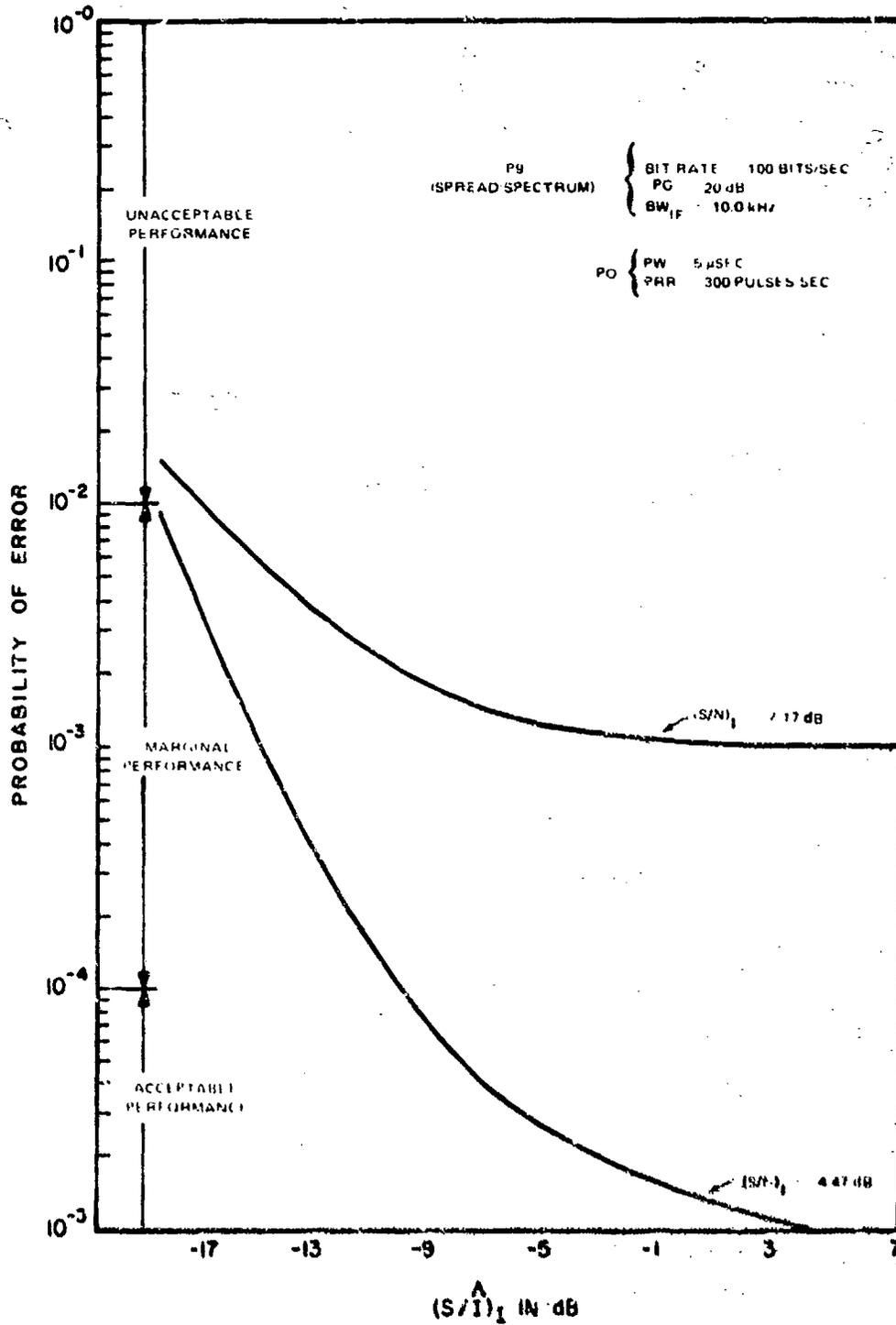


Figure C-160. Performance degradation curve for a P9 (spread spectrum) receiver with P0 interference. Receiver processing gain = 20 dB.

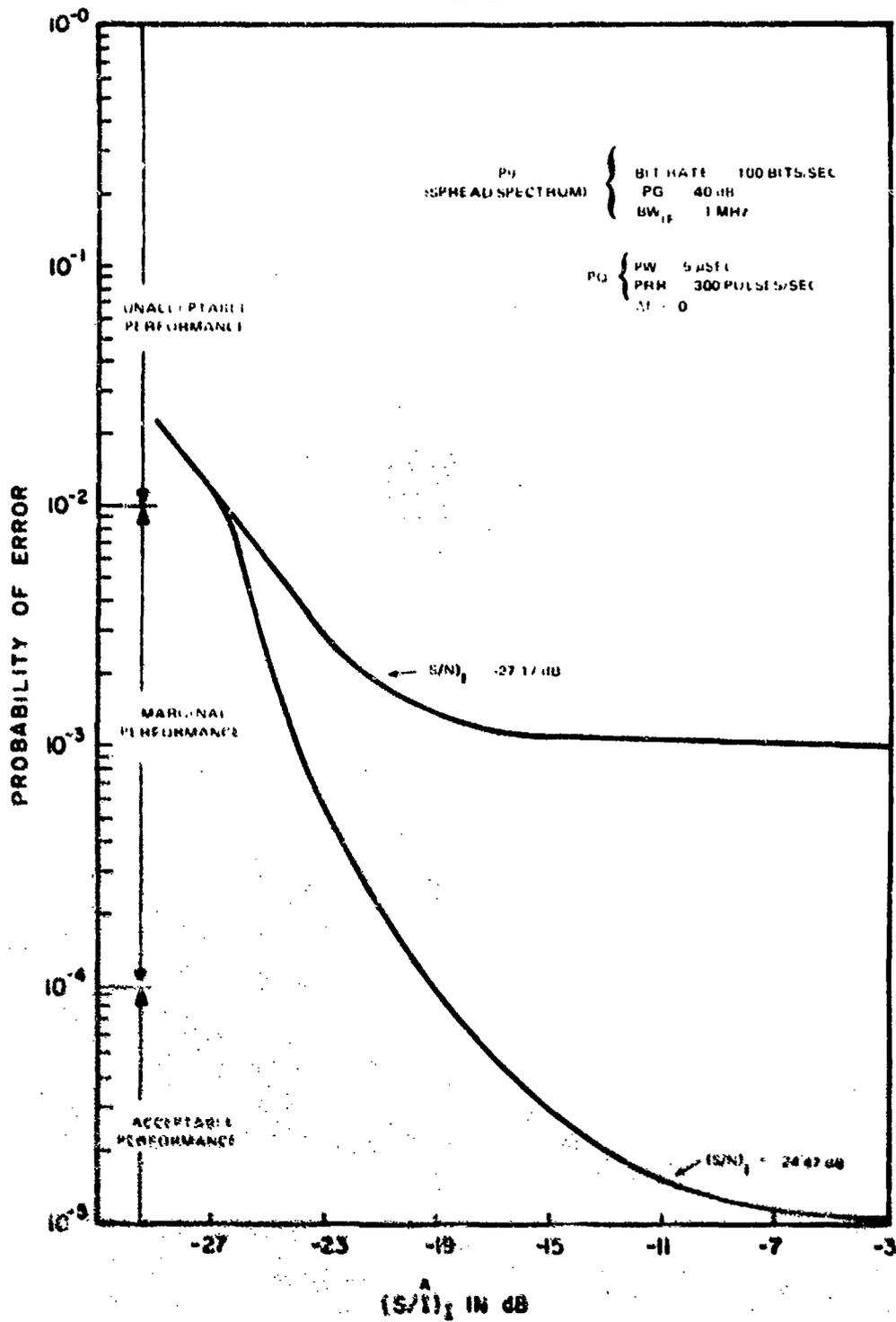


Figure C-161. Performance degradation curve for a P9 (spread spectrum) receiver with P0 interference. Receiver processing gain = 40 dB.

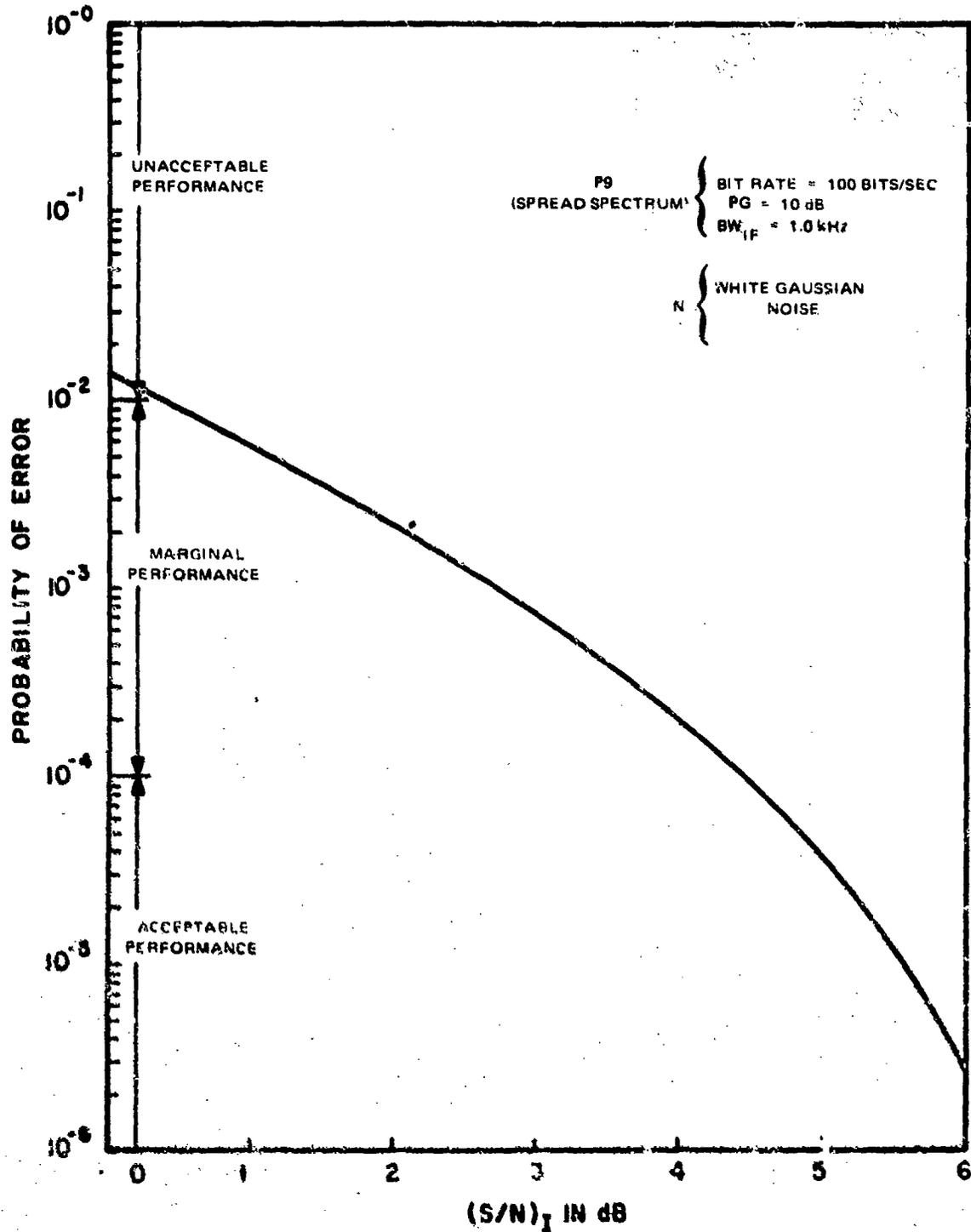


Figure C-162. Performance degradation curve for a P9 (spread spectrum) receiver with noise interference. Receiver processing gain = 10 dB.

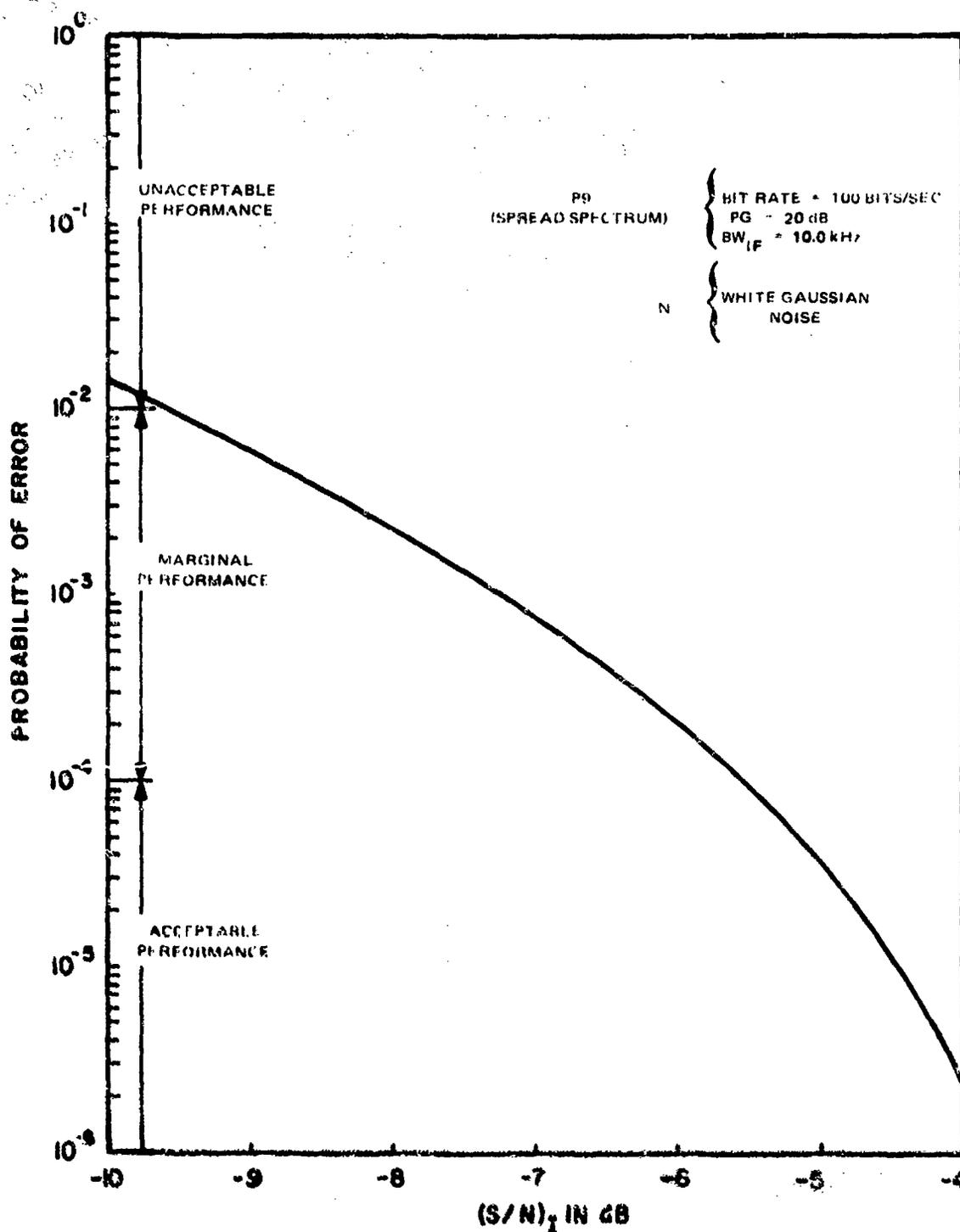


Figure C-163. Performance degradation curve for a P9 (spread spectrum) receiver with noise interference. Receiver processing gain = 20 dB.

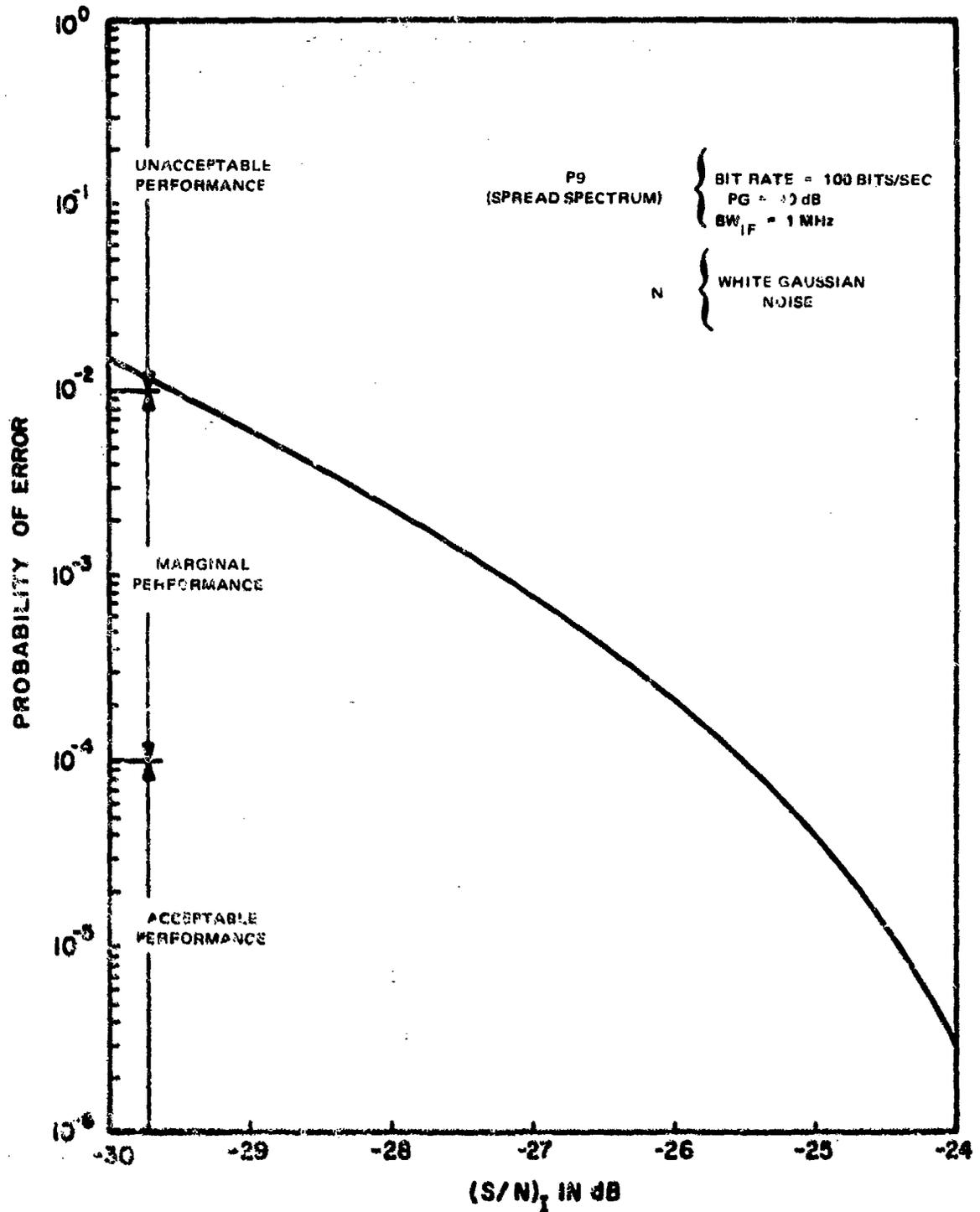


Figure C-104. Performance degradation curve for a P9 (spread spectrum) receiver with noise interference. Receiver processing gain = 40 dB.

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