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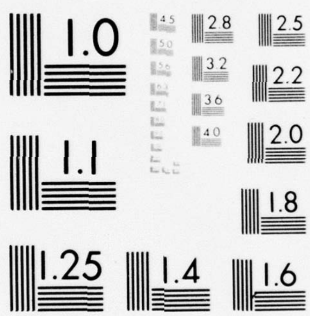

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DCA DIGITAL SYSTEMS EVALUATION - PHASE I
Microwave Digital Data Transmission

Frederick D. Schmandt

Approved for public release; distribution unlimited.

ROME AIR DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
GRIFFISS AIR FORCE BASE, NEW YORK 13441

PREFACE

The author is indebted to Mr. Brian M. Hendrickson for the overall direction of the project and many helpful discussions, to Messrs. Edward C. Miceli and William B. Desnoes who gathered much of the data, to Captain Steven S. Russell and Lieutenant David L. Wortley who aided in the test setup and analysis of the PCM and ATDM equipments and to the engineers at Aeroneutronics-Ford who provided a great deal of assistance in matters pertaining to the radios and modems.

This report has been reviewed by the Office of Information, RADC, and is releasable to the National Technical Information Service (NTIS). At NTIS it will be releasable to the general public, including foreign nations.

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Chief, Telecommunications Branch
Communications & Control Division

APPROVED:

FRED I. DIAMOND
Technical Director
Communications & Control Division

FOR THE COMMANDER:

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This report presents an in-depth experimental analysis of the transmission of high-quality digital traffic using an FDM type microwave radio system. After describing the equipments and test facility, the area is investigated from the point of the microwave modem's modulator to its demodulator. This establishes the basic capabilities and limitations entailed in the passing of digital traffic in the FDM radio system environment. Then performance parameters are obtained for typical digital systems configurations to be expected

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within the terrestrial DCS. A comparison of results evidences any degradation caused by the digital equipments. The overall emphasis is on determining what can be done with existing equipments and forming a foundation for overcoming existing technological deficiences rather than on developing optimized systems.

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SECTION 1

INTRODUCTION

1.0 General Overview

In support of the evolution of the Defense Communications System (DCS) towards a system based entirely on digital transmission techniques, various Department of Defense (DOD) agencies have been tasked with the development of advanced digital communications equipments. These include Pulse Code Modulation Devices (USA: TD968), Asynchronous Time Division Multiplexers (USAF: AN/GSC-24) and Group Data Modems (USAF: AN/USC-26). Prior to the introduction of these equipments into the terrestrial DCS, the Defense Communication Agency (DCA) desired that their tandemed performance be evaluated in non-operational digital network configurations. The Rome Air Development Center (RADC) was tasked with this system testing. The test phase reported herein is identified as Phase I. Phase II concerns cross-polarization operation and will be dealt with in subsequent reports.

The intent of the evaluation is to ascertain the expected performance of the equipments for envisioned DCS system configurations, to identify potentially troublesome interface problems, to establish overall system tolerance limits and where possible come up with recommendations for overcoming or minimizing problem areas.

Large inventories of equipment exist at terminals throughout the DCS. Because of costs involved and time required to modify or replace existing equipments, optimal configurations cannot always be obtained. New equipments are often interfaced with previously installed and perhaps much less sophisticated equipments. Present transmission requirements are predominantly voice band in nature and are accommodated in the DCS LOS transmission system with conventional FDM/FM technology. Conversion from this technology to PCM/TDM/FM or PCM/TDM/PM technology, in which all voice band information is converted to a digital form before transmission, represents a fundamental change in the method of transmission and introduces a number of system design considerations and alternatives [1].

This report presents an in-depth experimental analysis of the transmission of high quality digital traffic using an FDM type microwave radio system. After describing the equipments and test facility, the area is investigated from the point of the microwave modem's modulator to its demodulator. This establishes the basic capabilities and limitations entailed in the passing of digital traffic in the FDM radio system environment. Then performance parameters are obtained for typical digital system configurations to be expected within the terrestrial DCS. A comparison of results evidences any degradations caused by the new equipments. The overall emphasis is on determining what can be done with existing equipments and forming a foundation for overcoming existing technological deficiencies rather than on developing optimized systems.

Since a great deal of additional work relevant to digital communication over the line-of-sight (LOS) microwave media has occurred during the testing and documentation period it is worthwhile to indicate the present status of such communications. This is done in the summary (Section 7.3).

SECTION 2

PHASE I EQUIPMENTS AND TEST FACILITY

2.0 Introduction

The characteristics of the TD968 and AN/GSC-24 are covered in detail in Phase I interim reports [2-4] and the AN/USC-26 is described in references 5 and 6. Thus, these equipments while an integral part of the test program are not specifically described in this report.

The RADC digital microwave test facility which was established and the two types of microwave modems which were procured to carry out the Phase I testing are covered in detail in references 7 through 11. However, it is worthwhile to summarize the general characteristics and capabilities of the facility and associated equipments because of their interplay with the tests described in this report.

2.1 RADC Digital Microwave Test Facility

The RADC digital microwave test facility during the Phase I testing consisted of three sites interconnected by microwave radio. Their relative locations are shown in Figure 2.1. The equipment at the Verona Test Annex was subsequently moved to the Ava Annex to obtain a longer path for present and future test programs.

The test bed includes four modified Philco Ford Model LC-8D Radio Sets with eight cross-polarized, 6-foot diameter antennas in dual space diversity operation. In addition, a simulator assembly, which provides the capability to vary certain critical microwave radio parameters to analyze their effects on high speed data, was implemented for use in conjunction with the radio set at Griffiss AFB.

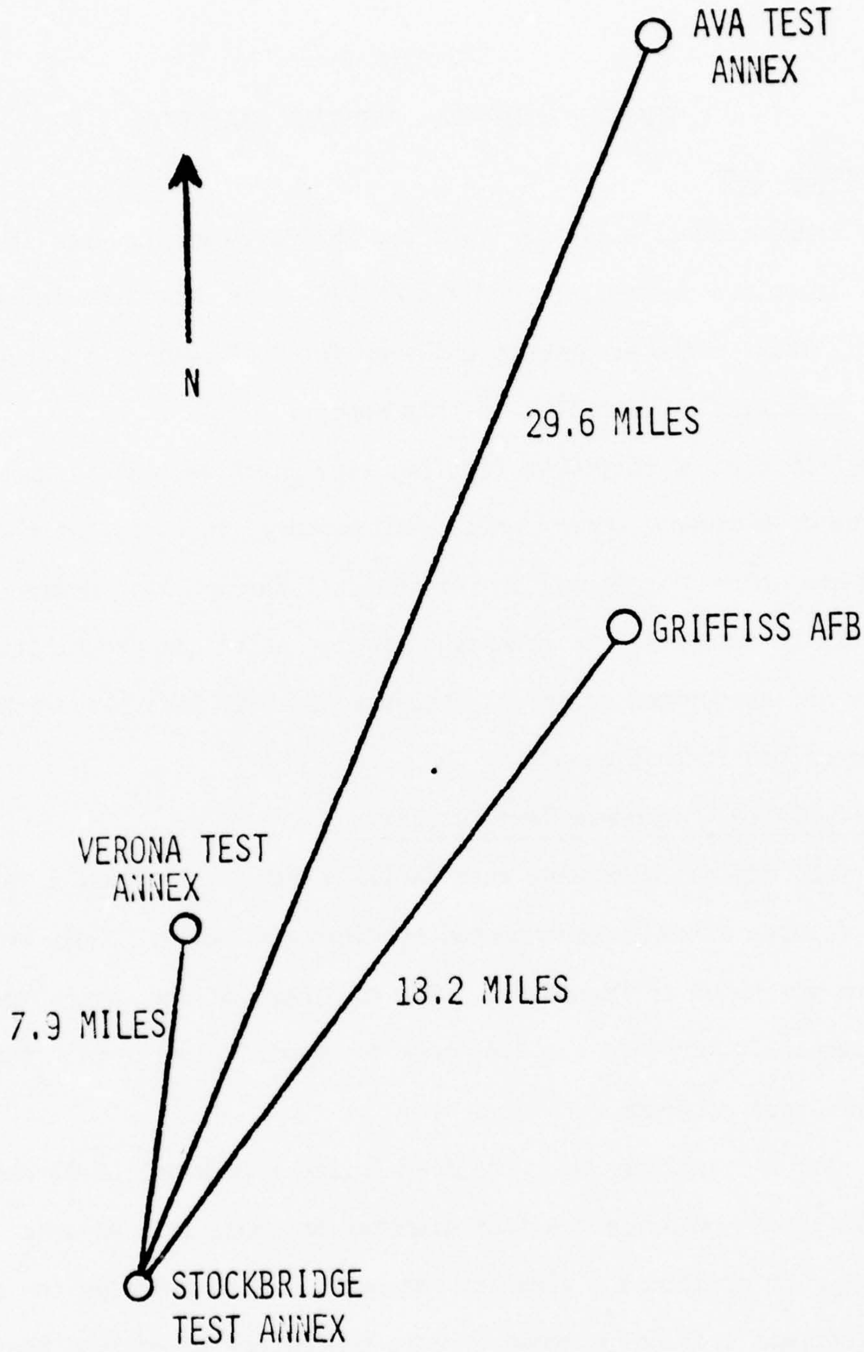


FIGURE 2.1: MICROWAVE SYSTEM MAP

The general characteristics of the radio set when used for conventional FDM traffic and the ranges of parameter control possible with the simulator assembly are listed in Tables 2.1 and 2.2, respectively. Detailed characteristics for the LC-8D are given in the T.O. manuals.

The radio sets at Stockbridge and Verona can be configured either as IF heterodyne repeaters or for baseband digital dropping. The two radio sets at Stockbridge may be arranged as dual space diversity IF heterodyne repeaters with hot standby or may be configured to permit either simultaneous transmission to Verona and Griffiss or as a loop back to Griffiss. The radio set at Verona could be configured either as a terminal or to provide a loop back through the Stockbridge repeater. The radio and associated simulator at Griffiss has the capability to originate and terminate traffic as well as to vary certain transmission path parameters so as to simulate microwave multiple hop effects. The simulator also contains a translator which provides an RF loop back testing capability: either RF transmitter output can be translated in frequency and looped back to either RF receiver. Such a capability provides a very stable media for modem performance evaluations. Additionally, it significantly simplified the test setup for determining the effects of various interfering signals as will be described in subsequent sections of the report.

The RADC microwave test bed provides a facility to qualify new equipments for potential DCS applications, to provide parameters for future development, to yield information needed to develop standards and to provide performance and equipment specifications required for acquisition of new equipment. Aspects of each are entailed in the Phase I results.

TABLE 2.1: LC-8D Radio Characteristics

Item	Characteristics
Radio Frequency	7.125 to 8.400 GHz
Transmitter Frequency Stability	± 0.0005% (does not include IF component)
Receiver Frequency Stability	± 150 kHz
Repeater Frequency Stability	± 34 kHz
RMS Per Channel Deviation	Adjustable up to 200 kHz RMS
Transmitter Output Power Rating	5.0 W (+37 dBm) (min at output flange)
Hot Standby Switching Time	10 μs
Receiver Noise Figure	12.0 dB maximum
Receiver AGC Dynamic Range	55 dB
Baseband Frequencies:	
Multiplex	20 to 2540 kHz, ± 0.5 dB
Orderwire	300 to 4000 Hz, ± 1.0 dB
Supervisory	4000 to 12000 Hz, ± 1.0 dB
Pilot Tone Frequency	3.2 MHz
Receive/Transmit Separation	100 MHz (nominal)
Intermediate Frequency:	
Center Frequency	70 MHz
Output Frequency Stability	± 68 kHz
Input/Output Level	+1 dBm ± 0.5 dB (0.3V)
Input/Output Impedance	75 ohms

TABLE 2.1: LC-8D Radio Characteristics (Continued)

Item	Characteristics
Output 2nd Harmonic Rejection	Equal or greater than 40 dB (deviator output)
Baseband Levels:	
Multiplex Input	-48 dBm to -15 dBm
Multiplex Output	-35 dBm to -14 dBm
Supervisory input, terminal	-35 dBm to -10 dBm
Supervisory input, repeater	-40 dBm to -30 dBm
Supervisory Output	-35 dBm to -14 dBm
Input and Output Impedances:	
Baseband	75 ohms, unbalanced
Supervisory	75 ohms, unbalanced
Ambient Operating Conditions:	
Temperature	32° to 122°F (0° to 50°C)
Altitude	15,000 ft (max)
Relative humidity	95% (max)

TABLE 2.2: Simulator Characteristics

Item	Characteristics
Primary Power Requirements	120 VAC Single-phase, approximately 1200 watts
(Simulator and Radio Set LC-8D):	
Simulation of Path Losses:	80 dB
Variations of Transmitter Power:	20:1
Simulation of IF Amplitude Response:	0 to ± 7 dB in 1 dB steps
Simulation of Group Delay Characteristics:	Parabolic: 0 to 31 nsec in 1 nsec steps
	Linear: 0 to 31 nsec in 1 nsec steps
Variation of Demodulator Linearity:	0 to ± 8% adjustable
Simulation of Phase Jitter:	> 10 degrees
Baseband Bandwidth Capability:	20 Hz to 10 MHz
Bands Supplied:	(1) 60 kHz to 2.8 MHz
	(2) 20 Hz to 4.5 MHz
	(3) 20 Hz to 10 MHz

2.2 Microwave Modems

The LC-8D radio set may be interfaced at either baseband or at the 70 MHz IF. As will be evidenced by a comparison of test results there are bit error rate performance advantages to an IF interface. However, certain radios within the DCS, the FRC-80, FRC-109 and FRC-155 through FRC-162, may only be interfaced at baseband. Furthermore, the results to be presented will show that bandwidth considerations may favor a baseband interface. While performance-wise it may be advisable to use an IF interface, practical reasons may preclude this possibility. To effectively evaluate the transmission of digital traffic within the DCS FDM microwave environment both heterodyne radios (70 MHz IF interface) and remodulating radios (baseband interface) need be considered. Of course, this entails two different types of modems.

The intent of Phase I was to determine performance using essentially off-the-shelf equipments. A competitive bid modem procurement was initiated to purchase conventional modems of each type. However, in order to test the anticipated system configurations it was necessary that the modems have a variable transmission rate capability. This feature precluded the direct purchase of off-the-shelf equipments. A contract was awarded to Philco Ford to construct two modems of each type to satisfy the test requirements. General descriptions of the modem type and characteristics follow. They are the microwave modems which were used throughout the Phase I tests.

2.2.1 Quaternary Baseband Modem

The baseband interface capability was satisfied by the procurement of two quaternary baseband modems. Each modem is designed to permit the transmission and reception of digital traffic at rates from 1.536 Mbps to 12.950 Mbps in 1 Kbps increments. This granularity is considered sufficiently fine to permit operation at any standard or nonstandard data rate within the specified data rate range. Table 2.3 lists the modem's characteristics. A detailed description of the modem and its theory of operation may be found in reference 10 or 11.

The modem is basically an AM modulator and demodulator which generates and receives a baseband four-level 1 volt peak-to-peak signal. When interfaced with FDM type microwave radios (Figure 2.2), the AM modulator produces quaternary frequency shift keyed modulation of the carrier signal.

2.2.2 Quadra-Phase Shift Keyed (QPSK) Modems

The IF interface capability (Figure 2.3) was satisfied by the procurement of two differentially encoded QPSK modems. The rate capabilities are identical to those of the baseband modems. Table 2.4 lists the modem's capabilities. A detailed description and theory of operation of this modem may also be found in reference 10 or 11.

2.3 Summary

The microwave test facility was established with the intent of obtaining as much flexibility in system testing as possible. While the facility was established during the Phase I program, it was established with subsequent tests in mind. It provides the means for investigating the requirements and limitations of an FDM type microwave radio system to convey high quality digital traffic and provides the vehicle for analyzing the relevant constraints and limitations of digital equipment. Its flexibility is evidenced by the tests performed during this program.

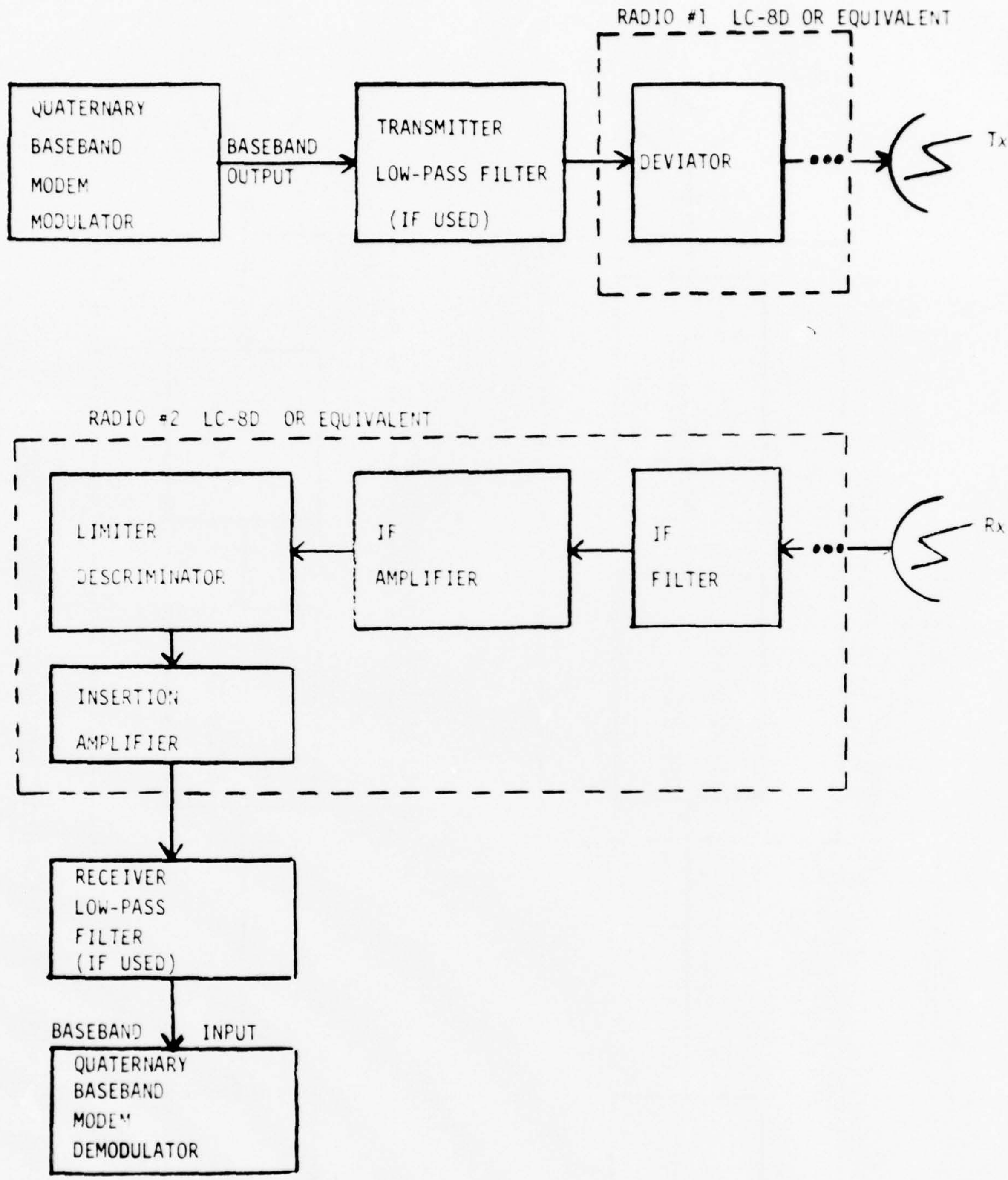


FIGURE 2.2: NORMAL CONNECTION OF QUATERNARY BASEBAND MODEM TO MICROWAVE RADIOS

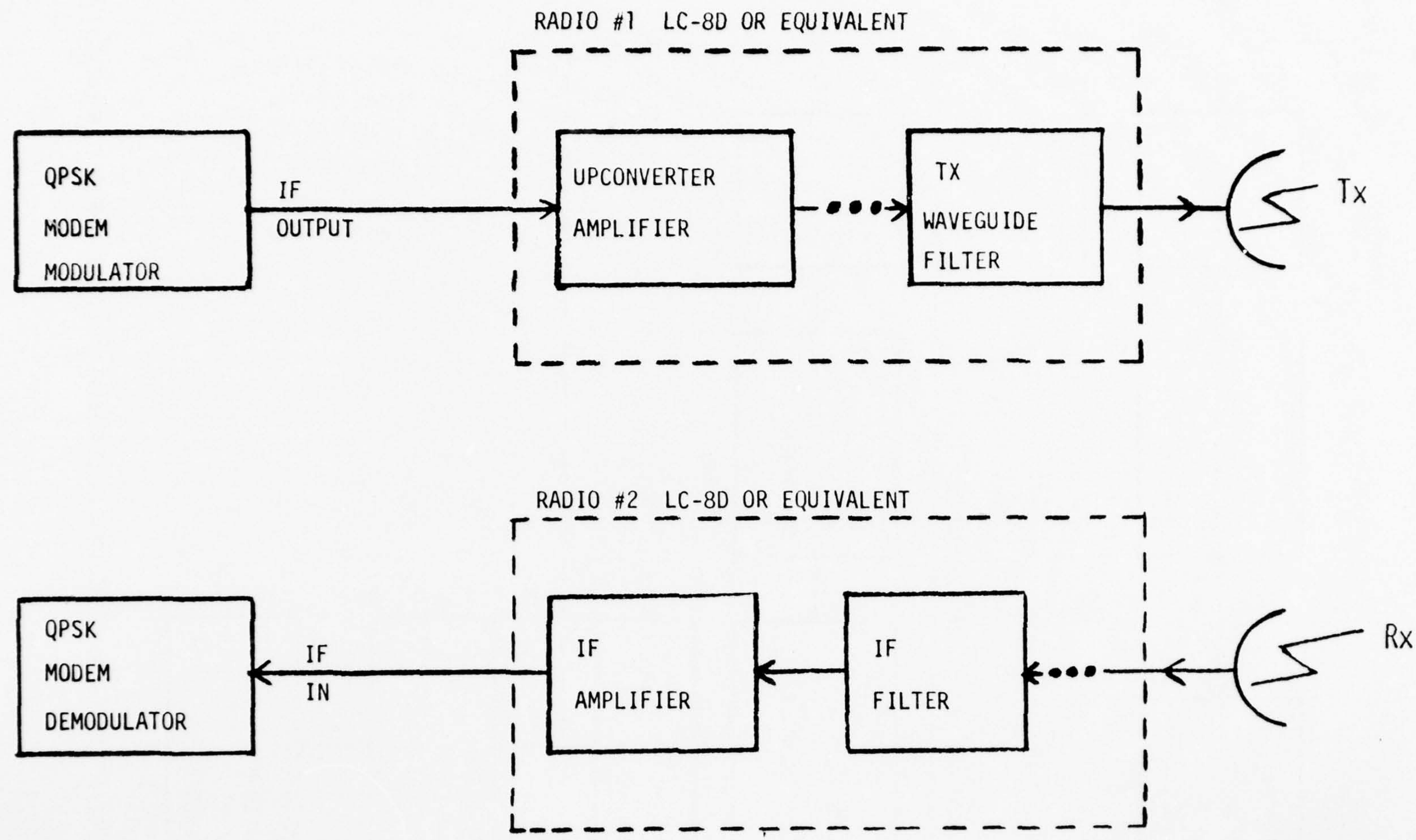


FIGURE 2.3: NORMAL CONNECTION OF QPSK MODEM TO MICROWAVE RADIOS

TABLE 2.3: Technical Characteristics of Quaternary Baseband Modem

Transmitter Section	
Data Input	
Rate:	1.536 Mbps to 12.950 Mbps in 1 Kbps step
Format:	Serial NRZ-L
Input Level:	1 to 5 Volt peak-to-peak
Input Connector:	BNC
Impedance:	75 ohms
Waveform:	Square Wave, rise and fall time 10% maximum of bit length
Internal Test Generator:	10 stage PRSG
Alarm:	Input data activity
Transmitter Clock	
Rate:	Same as bit rate (variable in 1 Kbps steps from 1.536 Mbps to 12.95 Mbps)
External Clock Input Level:	2 to 5 Volts peak-to-peak sineware or square wave
Internal Clock Output Level:	2 Volts peak-to-peak minimum
Impedance:	75 ohms
Clock Phase Adjustment:	One bit period minimum
Alarms:	Synthesizer Phase Lock, Timing (clock and data correctly phased)
Clock Accuracy and Stability:	$\pm$ 10 ppm
Rate Control:	5 digit thumbwheel switch

TABLE 2.3: Technical Characteristics of Quaternary Baseband Modem (Cont'd)

Baseband Modulator	
Type Modulation:	Four level amplitude; four level FSK when interfaced with microwave radio
Output Level:	1 Volt peak-to-peak (0 to -1 volt)
Type Code:	Gray Code
Output Impedance:	75 ohms
Receiver Section	
Baseband Demodulator	
Type Modulation:	Four level amplitude
Input Level:	1 Volt peak-to-peak. Accepts normal and inverted data
Input Impedance:	75 ohms
Alarm:	Quaternary Input Activity
Receiver Clock	
Rate:	1.536 to 12.950 Mbps in 1 Kbps steps.
Clock Phase Adjustment:	One bit period minimum
Errors Output:	Bit error output to frequency counter when operated as internal bit error rate tester
Data Output	
Rate:	1.536 to 12.950 Mbps in 1 Kbps step
Data Output Level:	2 Volts peak-to-peak (minimum) NRZ-L
Output Impedance:	75 ohms

TABLE 2.3: Technical Characteristics of Quaternary Baseband Modem (Cont'd)

Clock Output Level:	2 Volts peak-to-peak (minimum) NRZ-L
Output Impedance:	75 ohms
Waveform:	Square wave, rise and fall time 10% maximum of bit length
Alarm:	Data Output Activity
<u>General</u>	
Prime Power:	115 VAC $\pm$ 10%, 60 Hz, $\pm$ 5%, 290 watts maximum
Operating Temperature Range:	10° to 40° C
Size:	8-3/4" High x 19" Wide x 19" Deep
Weight:	55 pounds maximum
Input and Output Connectors:	BNC

TABLE 2.4: Technical Characteristics of QPSK Modem

Transmitter Section

Data Input

Rate:	1.536 Mbps to 12.950 Mbps in 1 Kbps step
Format:	Serial NRZ-L
Input Level:	1 to 5 Volt peak-to-peak
Input Connector:	BNC
Impedance:	75 ohms
Waveform:	Square Wave, rise and fall time 10% maximum of bit length
Internal Test Generator:	10 stage PRSG
Alarm:	Input data activity

Transmitter Clock

Rate:	Same as bit rate (variable in 1 Kbps) steps from 1.536 Mbps to 12.95 Mbps)
External Clock Input Level:	2 to 5 Volts peak-to-peak sinewave or square wave
Internal Clock Output Level:	2 Volts peak-to-peak minimum
Impedance:	75 ohms
Clock Phase Adjustment:	One bit period minimum
Alarms:	Synthesizer Phase Lock, Timing (clock and data correctly phased)
Clock Accuracy and Stability:	$\pm$ 10 ppm
Rate Control:	5 digit thumbwheel switch

TABLE 2.4: Technical Characteristics of QPSK Modem (Continued)

QPSK Modulator

Output Frequency:	70 MHz
Output Frequency Accuracy:	$\pm$ 7 kHz
Type Modulation:	70 MHz quadriphase shift keyed (differentially encoded)
Output Level:	+1 dBm (adjustable)
Output Impedance:	75 ohms
Output Return Loss/VSWR:	20 dB/1.22:1
Harmonic Content:	20 dB below carrier

Receiver

QPSK Demodulator

Input Signal:	70 MHz QPSK
Signal Level:	+1 dBm $\pm$ .5 dB (adjustable over $\pm$ 3 dB)
Input Impedance:	75 ohms
Input Return Loss/VSWR:	20 dB/1.22:1
Acquisition Range:	$\pm$ 500 kHz
Acquisition Time:	Less than 100 milliseconds
Demodulation:	Coherent
Alarms:	Carrier acquisition input level

TABLE 2.4: Technical Characteristics of QPSK Modem (Continued)

Receiver Clock	
Rate:	1.536 to 12.950 Mbps in 1 Kbps steps
Clock Phase Adjustment:	One bit period minimum
Errors Output:	Bit error output to frequency counter when operated as internal bit error rate tester
Data Output	
Rate:	1.536 to 12.950 Mbps in 1 Kbps step
Date Output Level:	2 Volts peak-to-peak (minimum) NRZ-L
Output Impedance:	75 ohms
Clock Output Level:	2 Volts peak-to-peak (minimum) NRZ-L
Output Impedance:	75 ohms
Waveform:	Square wave, rise and fall time 10% maximum of bit length
Alarm:	Data Output Activity
General	
Prime Power:	115 VAC $\pm$ 10%, 60 Hz, $\pm$5%, 290 watts maximum
Operating Temperature Range:	10° to 40°C
Size:	8-3/4" High x 19" wide x 19" Deep
Weight:	55 pounds maximum
Input and Output Connectors:	BNC

SECTION 3

TRANSMITTED BANDWIDTH OCCUPANCY

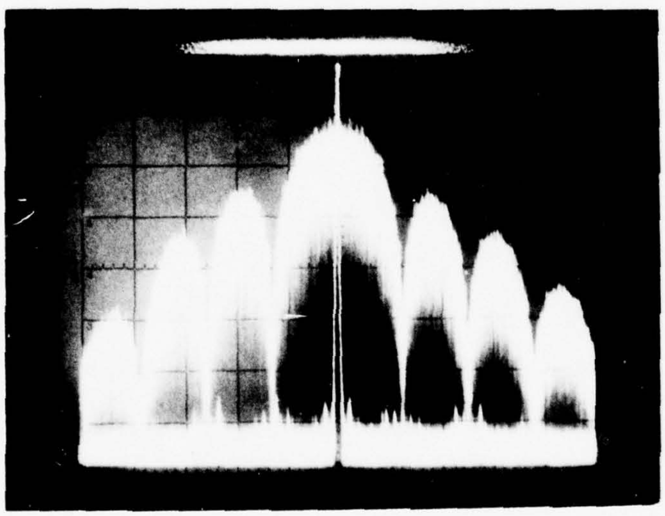
3.0 Introduction

Conversion of the DCS LOS microwave trunking system from FDM/FM to PCM/TDM technology represents a fundamental change in transmission methods. The existing DCS is a 4 KHz analog voice channel network: The switched voice networks utilize analog space-division switching; the switched digital networks utilize quasi-analog transmission techniques (voice channel modems) over the FDM/FM transmission system. Either all the analog networks must be converted to digital networks simultaneously with conversion of the trunking system, or the converted trunking system must continue to present a transparent voice channel interface to the analog networks. Since there are over 500 microwave links designed for and operated upon, FDM technology the first alternative is not economically feasible. The second requires PCM analog-to-digital conversion. Using 2 samples/Hz and 8 bits/sample, 64 Kbps are required per 4 KHz voice channel. This equates to 12.8 Mbps for 200 multiplexed channels. At this rate and a typical maximum RF bandwidth (99%) allocation of 14 MHz a bit packing density of approximately 1 bps/Hz is required.

This section addresses spectral occupancy for the two modem types. Since the highest bit rate imposes the most stringent bandwidth requirements, a rate of 12.8 Mbps, the highest rate of interest under Phase I, is used throughout the section. The results presented here are meaningful only in reference to performance results: It is useless to control bandwidth if in so doing performance is severely degraded. In Sections 4 and 5 experimental results are given which show the effects the various spectral truncation methods presented have on performance.

3.1 QPSK Spectrum

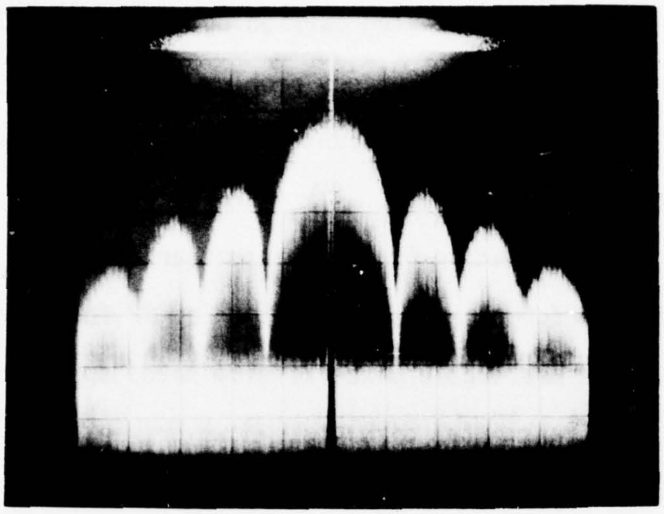
Spectral occupancy, as observed in Figure 3.1, is a severe problem with QPSK modulation because the QPSK modulator spectrum has a sin(x)/x characteristic with the sidelobes possessing substantial amounts of energy. A double exposure with a 70 MHz unmodulated carrier is used to show the center frequency location.



12.8 Mbps
Vertical: 10 dB/div
Horizontal: 5 MHz/div

FIGURE 3.1: QPSK Modulator IF Spectrum

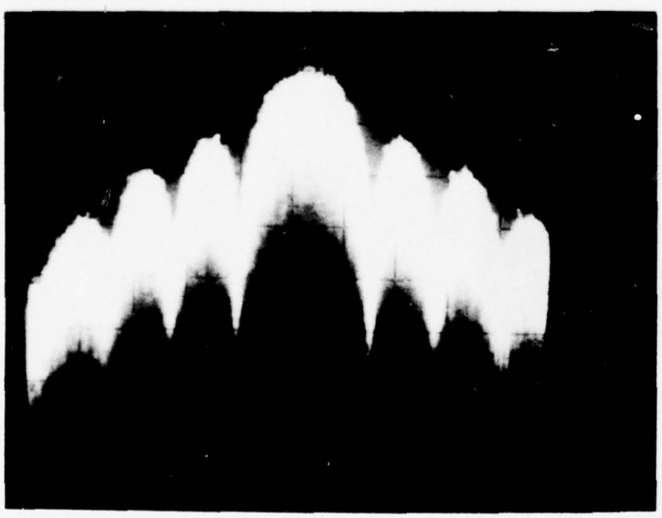
Figure 3.2, a photograph taken of the spectrum at the output of the TWT, shows the spectrum sidelobes are slightly higher after the upconversion and amplification stages and the spectrum shape is otherwise essentially unchanged. The normal RF filter in the LC-8D is a 5 section Butterworth



12.8 Mbps
Vertical: 10 dB/div
Horizontal: 5 MHz/div

FIGURE 3.2: QPSK RF Spectrum at TWT Output

type, with nominal 3 dB bandwidth of 52 MHz. With such a wide bandwidth the spectral shape following RF filtering, Figure 3.3, is little different



12.8 Mbps
Vertical: 10 dB/div
Horizontal: 5 MHz/div

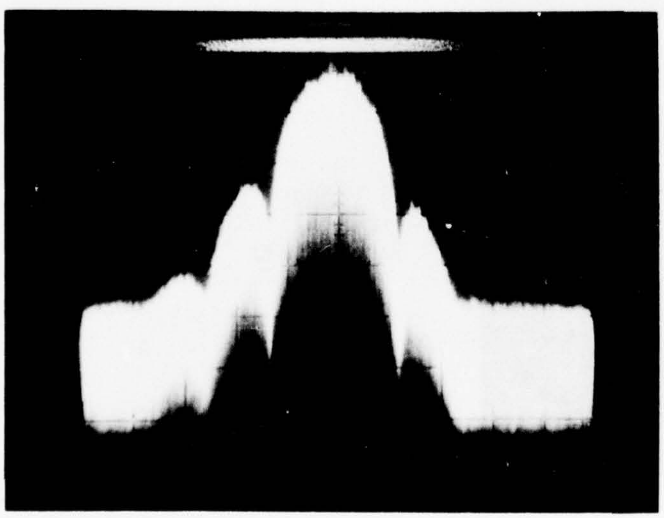
FIGURE 3.3: QPSK RF Spectrum following RF Filter

from the input. Consequently, the normal filtering carried out in the LC-8D radio does nothing to alleviate the spectral occupancy problem associated with QPSK operation. The sidelobes must be significantly attenuated to permit operation within normal frequency allocations.

Attenuation or signal spectrum truncation in the transmitter can be accomplished at either IF or RF. Performance-wise truncation at RF following the power amplifier would seem to be preferable since it eliminates spurious signals generated in the preceding transmitter circuits. However, both types of filters were addressed.

3.1.1 RF Filtering

A special RF filter (10.6 MHz 3 dB bandwidth) for transmission of 12.8 Mbps QPSK at 1 bps/Hz of RF (99%) bandwidth was designed and constructed to replace the radio's normal 52 MHz RF filter. This filter is also a 5 section Butterworth type. Figure 3.4 shows the resultant RF transmit spectrum.



12.8 Mbps
Vertical: 10 dB/div
Horizontal: 5 MHz/div

FIGURE 3.4: QPSK RF Spectrum following Special RF Filter

Spectral occupancy calculations, using numerical integration, yielded a 99% bandwidth of 11.45 MHz. This equates to a bit packing density of 1.12 bps/Hz. The experimental test performance results given in Section 4 will show comparable and acceptable bit error rate performance for the normal and special RF filters. Thus, RF filtering is a viable method of controlling the transmit spectrum. QPSK modems can be used with existing analog microwave radios to obtain satisfactory operation at bit packing densities of 1 bps/Hz provided the RF transmit filter is replaced by a narrower one such as the 10.6 MHz special filter used to obtain the experimental results of this report.

3.1.2 IF Filtering

IF filtering of QPSK signals results in spreading due to upconverter and TWT induced nonlinearities. Nonetheless, if the spreading is not too severe, IF filtering may be a viable technique for spectral truncation. IF filters readily available for testing were a special 7.7 MHz (3 dB) bandwidth 2 section Butterworth filter which had been designed for use as a receive filter in conjunction with the special RF transmit filter and the radio's normal 10 MHz, 15 MHz and 25 MHz receive filters.

The 25 MHz filter is clearly too wide for any meaningful spectral truncation and was dismissed from consideration. The various other IF filters were inserted between the QPSK modulator and the upconverter of transmitter B which contained the normal 52 MHz RF filter. To compensate for losses in the filters and obtain a correct radio input level of +1 dBm a variable attenuator and a HP 461A amplifier were inserted prior to the upconverter. RF transmit spectral plots obtained by use of an X-Y plotter and spectrum analyzer are shown in Figure 3.5 through 3.9. (Figure 3.5 has conditions

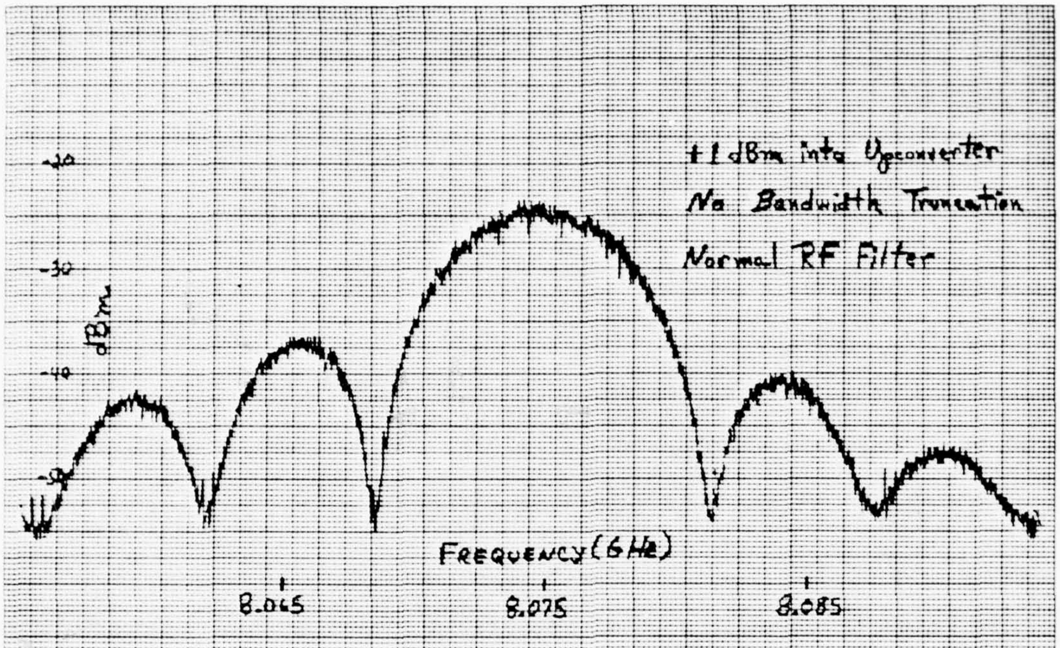


Figure 3.5: QPSK RF Spectrum following Normal RF Filter

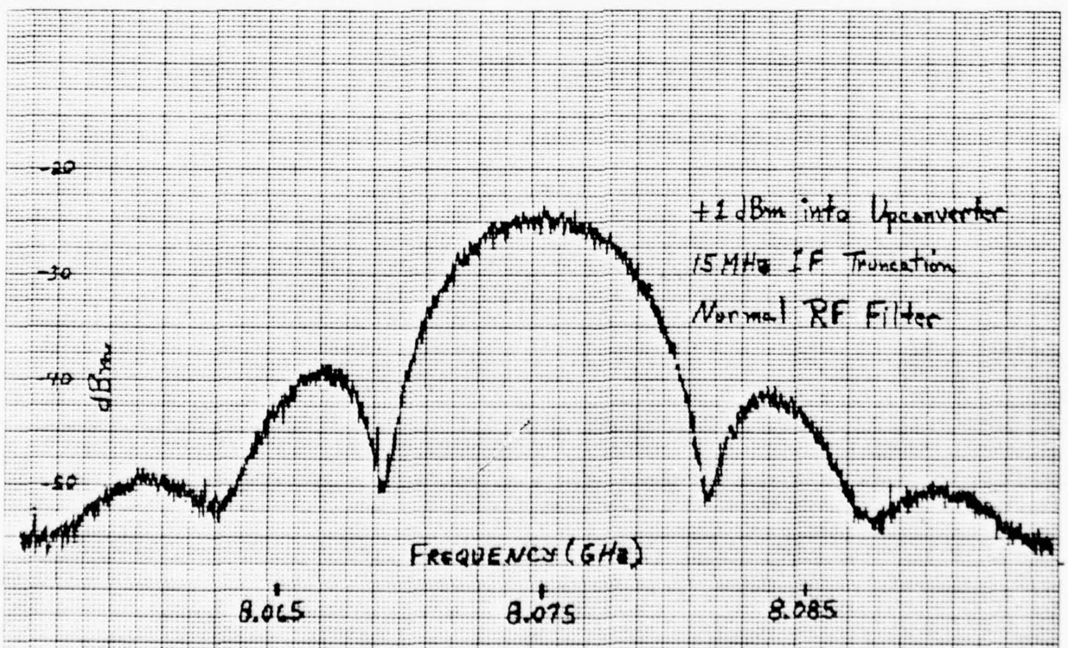


Figure 3.6: QPSK RF Spectrum with 15 MHz IF Bandwidth Truncation

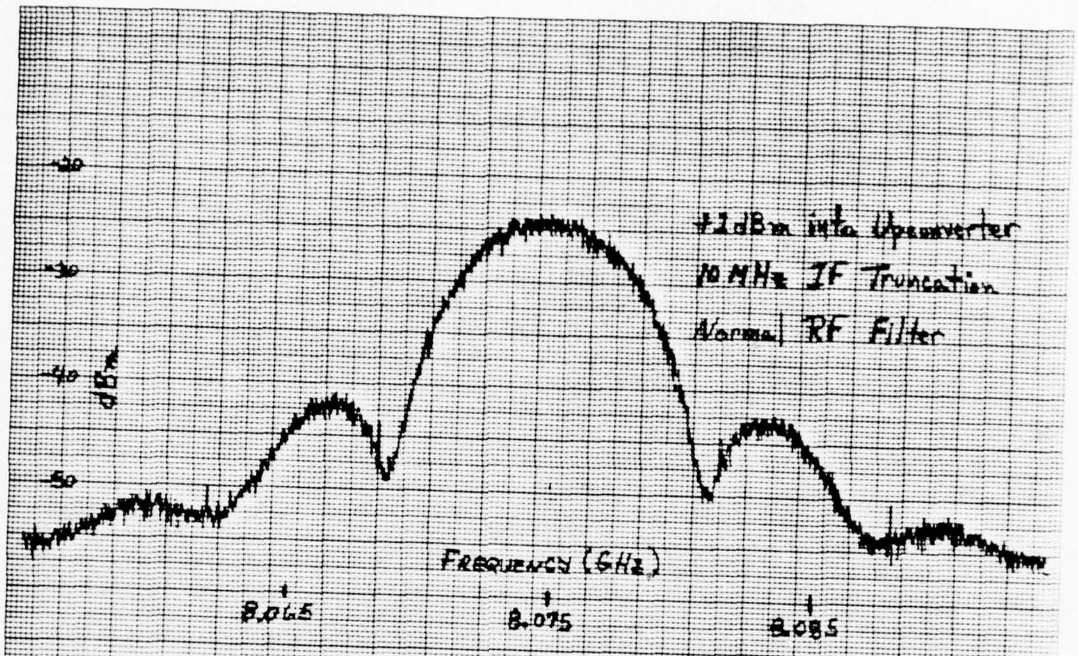


Figure 3.7: QPSK RF Spectrum with 10MHz IF Bandwidth Truncation

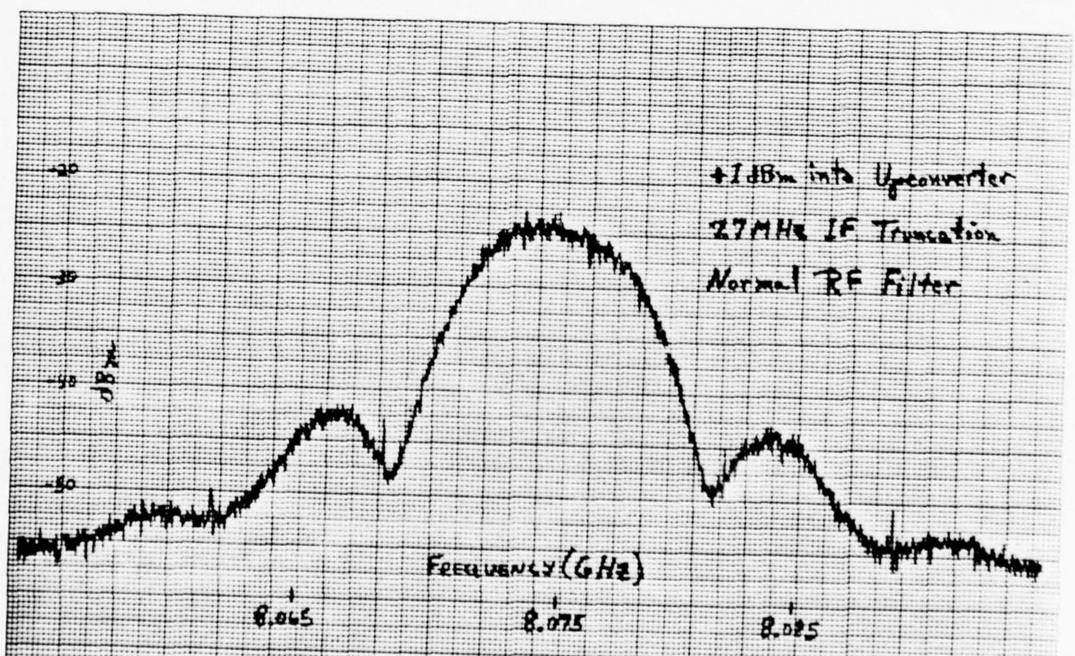


Figure 3.8: QPSK RF Spectrum with 7.7MHz IF Bandwidth Truncation

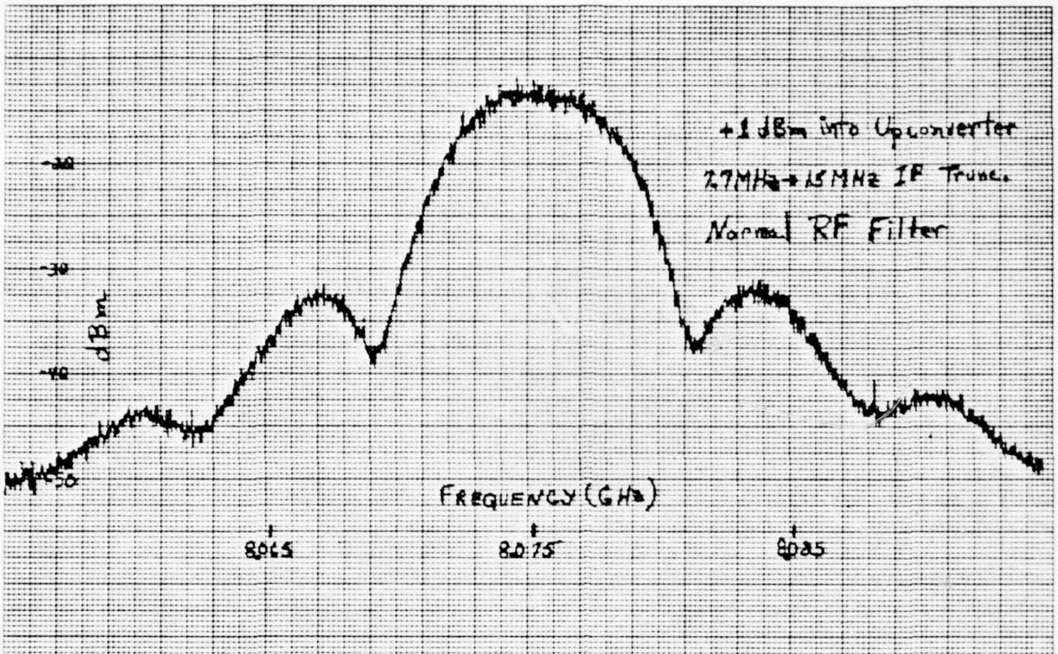


Figure 3.9: QPSK RF Spectrum with 7.7MHz into 15MHz IF Bandwidth Truncation

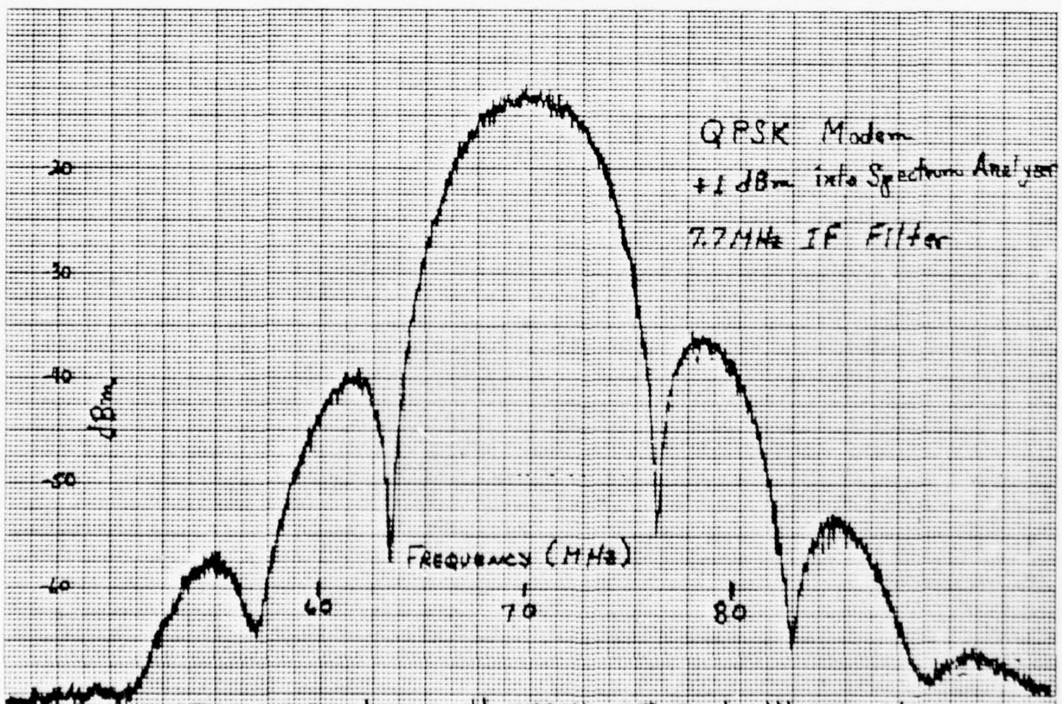


Figure 3.10: QPSK IF Spectrum with 7.7MHz IF Bandwidth Truncation

identical to those of Figure 3.3. It is presented to ease direct comparison with subsequent X-Y plots.) An indication of the success of these attempts at bandwidth truncation can be obtained by comparing these figures with Figure 3.4, the photograph obtained when the special RF filter was used. The first sidelobes with RF filtering are suppressed significantly more than with any of the IF truncation attempts. Clearly, since the occupancy with the special RF filter is 1.12 bps/Hz the IF filtering yields less than the desired 1 bps/Hz. Furthermore, performance results in Section 4 will show performance with IF filtering is poorer than that obtained with RF truncation.

A comparison of Figure 3.10, the OPSK IF spectrum at the output of the 7.7MHz truncation filter, and Figure 3.8 shows the nature of the IF truncation problem. The filter has significantly reduced the IF spectral occupancy; however, by the time the signal reaches the RF output port, the upconverter and TWT stages have caused much of the reduction to be lost due to non-linearity induced spreading.

Figure 3.11 shows the input/output characteristics of the 7.7 MHz filter. Some sharpness could be obtained in the skirts which would result in an improvement in bandwidth occupancy. However, such improvement would be minimal. To narrow the IF filter bandwidth any more is not advisable from a performance standpoint.

One additional method was used to control bandwidth with IF filtering. The level into the upconverter was reduced from +1 dBm to -7 dBm with the 7.7 MHz and 15 MHz filter tandem. The resultant spectrum, Figure 3.12, is quite similar to the one obtained with RF truncation and so the spectral occupancy should be acceptable. Operation with the reduced input level

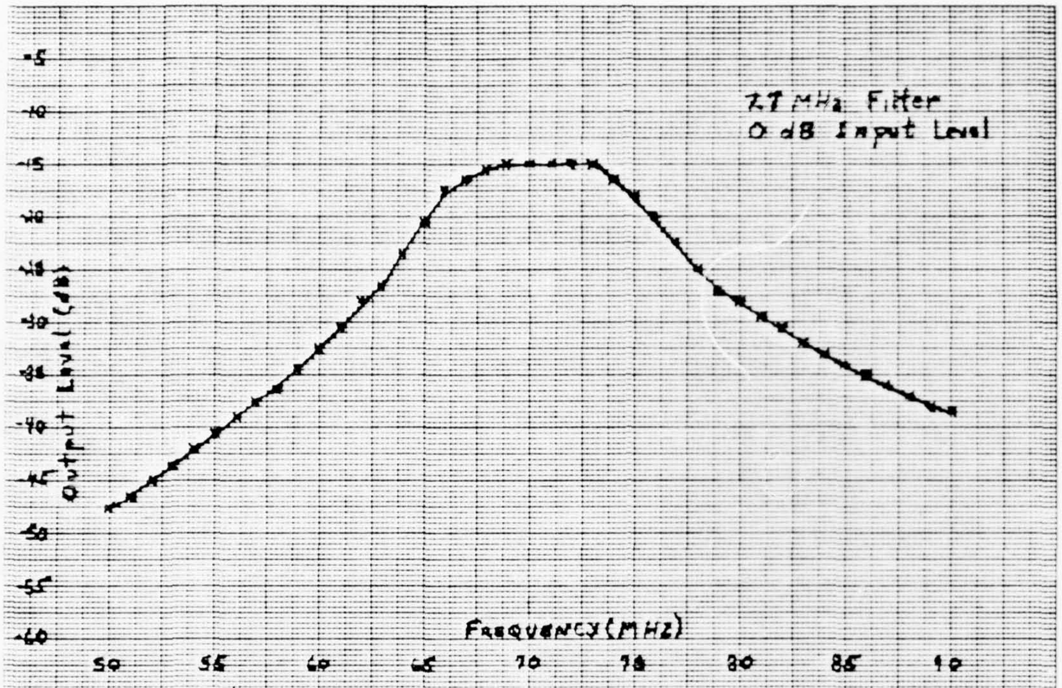


Figure 3.11: I/O Characteristic of 7.7 MHZ Filter

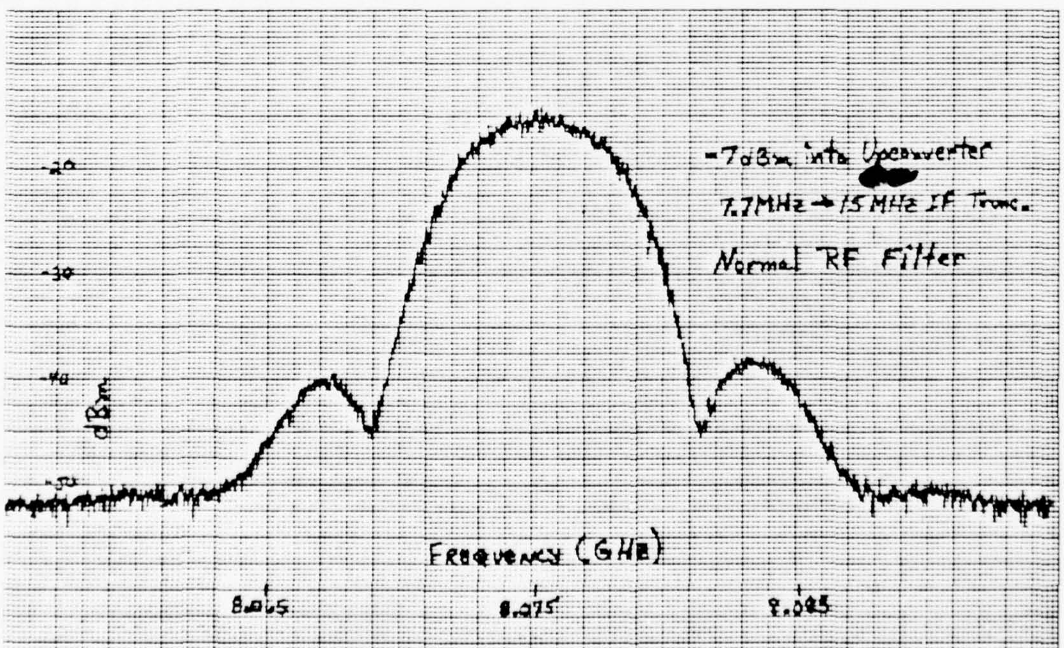


Figure 3.12: QPSK RF Spectrum with 7.7MHz into 15MHz IF Bandwidth Truncation (-7 dBm Radio Input)

amounts to a reduction in power causing the TWT to operate in its linear portion, thereby eliminating the spreading. Unfortunately, such operation is not generally acceptable because it limits the fade margin of the link.

The above results show that IF filtering is not a viable method of controlling the transmit RF spectrum for QPSK except in the rare cases where there is an extremely large fade margin.

3.2 Quaternary Baseband Spectrum

One of the prime considerations in obtaining desired performance is cost. As such a minimum amount of change in existing microwave radios is desired during the evolution toward all digital transmission. Phase I was concerned with obtaining the most cost effective method of obtaining satisfactory performance at 1 bps/Hz of occupied bandwidth.

Various combinations of low pass filtering and signal attenuation to control deviation and thereby control spectral occupancy were investigated for the quaternary baseband modem. These approaches entail no changes in the radio per se and consequently have a significant cost advantage over an RF or IF filtering approach. The experimental results given below along with the results presented in Section 5, where quaternary baseband performance is presented, verify modem signal attenuation to control bandwidth is a very effective method of controlling bandwidth without severely degrading performance.

The radio was adjusted for a peak-to-peak deviation of 10 MHz/volt. By attenuating the modem output the deviation can be adjusted. For example, an attenuation by 6 dB yields a peak-to-peak deviation of 5 MHz/volt as opposed to a 10 MHz/volt deviation when 0 dB attenuation is used. Figure

3.13 through 3.15 show the RF spectrum when the modem output is attenuated by 0 dB, 4 dB and 12 dB, respectively, prior to the radio baseband input.

Table 3.1 lists the 99% bandwidth calculated for various amounts of attenuation, where the bandwidth was obtained by numerical integration as indicated in [9]. It can be seen that varying deviation by signal attenuation represents a very economical method of controlling bandwidth.

Table 3.1: Transmitted Spectral Occupancy

Att (dB)	99% Bandwidth (MHz)	Bps/Hz
0	16.46	.78
1	14.70	.87
2	14.12	.91
3	13.12	.98
4	12.38	1.03
5	11.41	1.12
6	10.37	1.23
11	6.80	1.88
12	6.28	2.04

A commonly used approximation to occupancy is given by Carson's rule:

$$B = N + (n-1)\ \Delta f \tag{3.1}$$

where N = sample rate

n = number of levels

Δf = frequency separation

For the quaternary baseband system operating at 12.8 Mbps Carson's rule becomes:

$$B\ (\text{MHz}) = 6.4 + 3\Delta f \tag{3.2}$$

Table 3.2 is computed using (3.2) for a radio with deviation set at 10 MHz/volt.

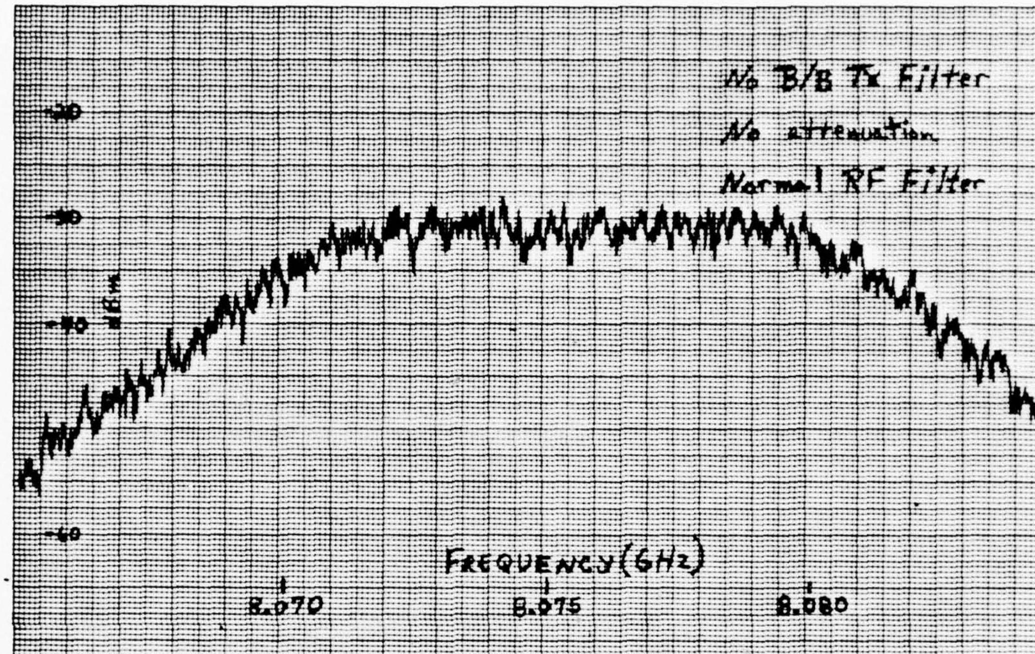


Figure 3.13: Quaternary Baseband Modem with 0dB Signal Attenuation - RF Transmit Spectrum

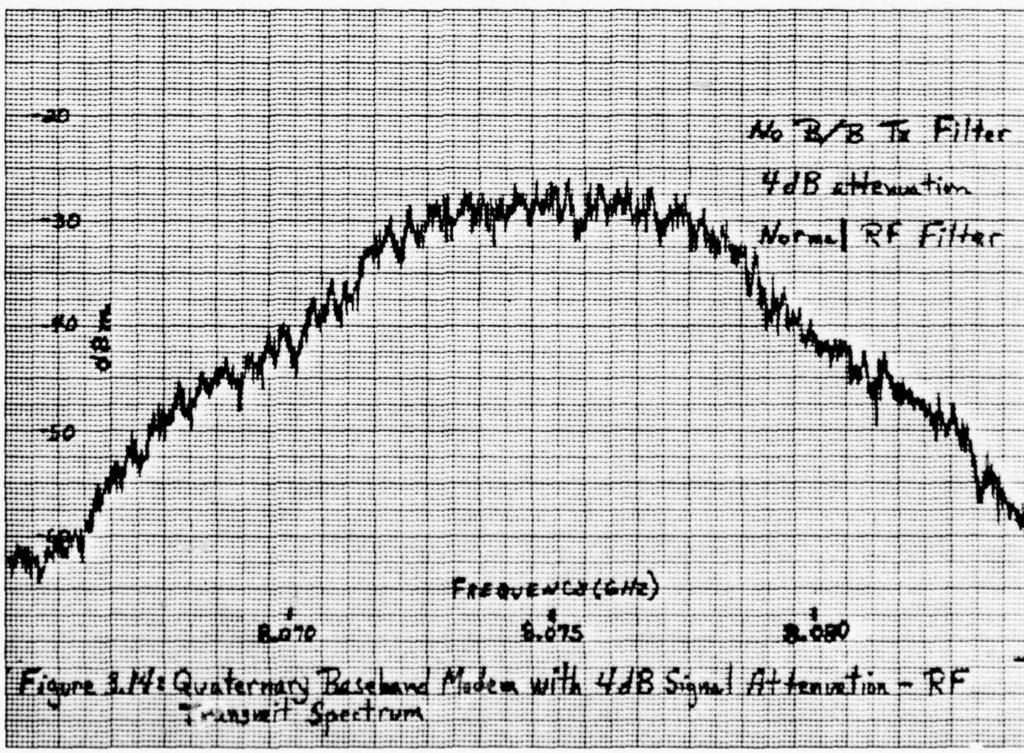


Figure 3.14: Quaternary Baseband Modem with 4dB Signal Attenuation - RF Transmit Spectrum

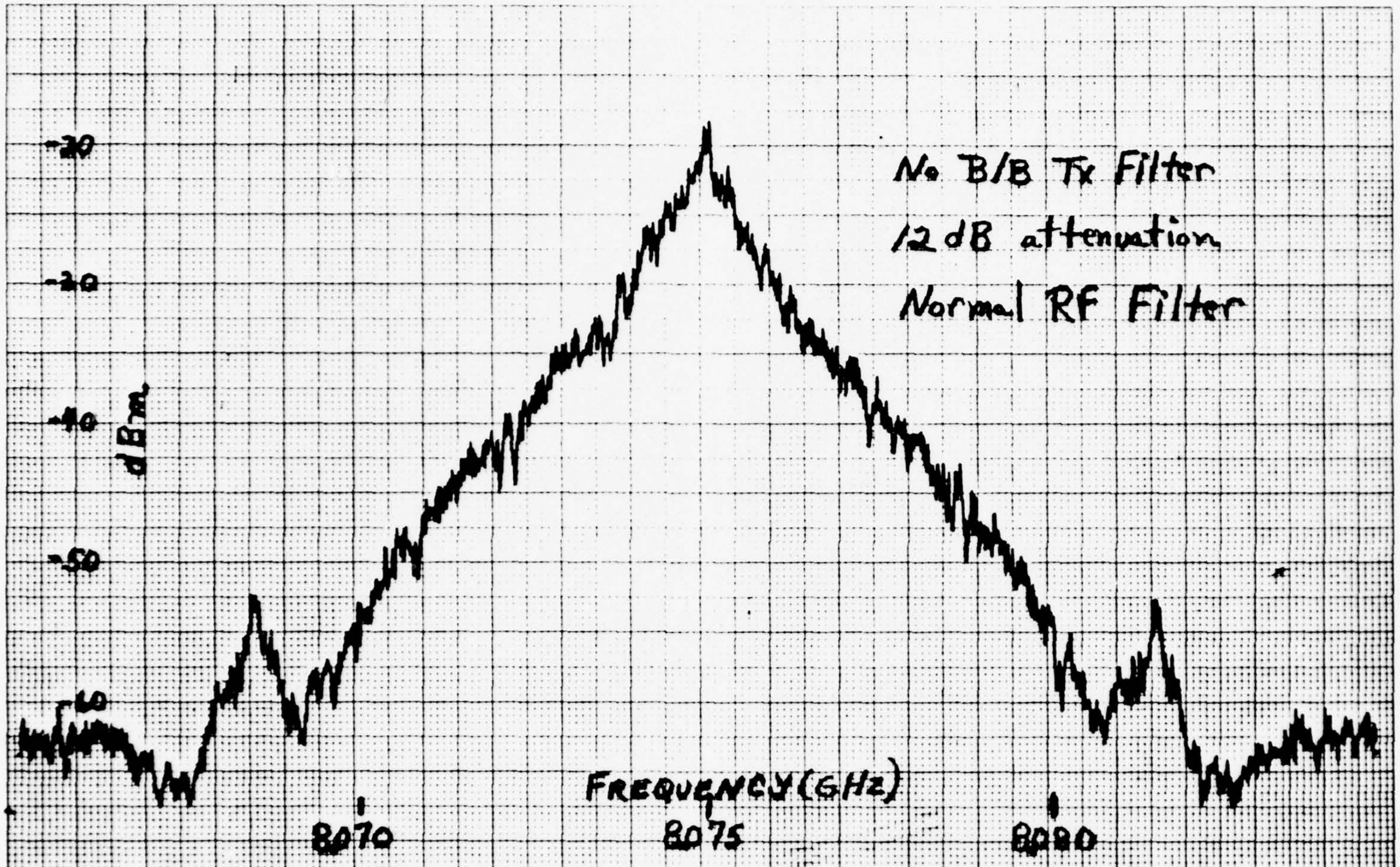


Figure 3.15: Quaternary Baseband Modem with 12dB Signal Attenuation - RF Transmit Spectrum

Table 3.2: Spectral Occupancy (Carson's Rule)

Att	$3\Delta f$ (MHz)	B	BPS/Hz
0	10.0	16.40	.78
1	8.91	15.31	.84
2	7.94	14.34	.89
3	7.08	13.48	.95
4	6.31	12.71	1.01
5	5.62	12.02	1.06
6	5.00	11.40	1.12
7	4.47	10.87	1.18
8	3.98	10.38	1.23
9	3.55	9.95	1.29
10	3.16	9.56	1.34
11	2.82	9.22	1.39
12	2.50	8.90	1.44

Comparing the measured values in Table 3.1 with Table 3.2 shows excellent agreement at the high deviation values but a rather poor approximation to the values calculated for the 11 and 12 dB settings. These results are shown graphically in Figure 3.16. It seems reasonable to use Carson's rule to establish deviation settings for operation up to packing densities of at least 1 bps/Hz. Some additional data presented in Section 5 further substantiates this conclusion.

Bandwidth measurements were also made with various premodulation low pass filters. Spectral plots using three different transmit low pass filters, 3.2 MHz, 4.5 MHz and 5.82 MHz, and various signal attenuation levels were obtained. Figure 3.17, the plot for the 4.5 MHz low pass filter with 4 dB attenuation, when compared to Figure 3.14 shows some additional truncation due to the filter. The 99% bandwidth was calculated to be 10.61 MHz yielding a 1.21 bps/Hz packing density. Consideration of all plots obtained lead to the conclusion that spectral occupancy is

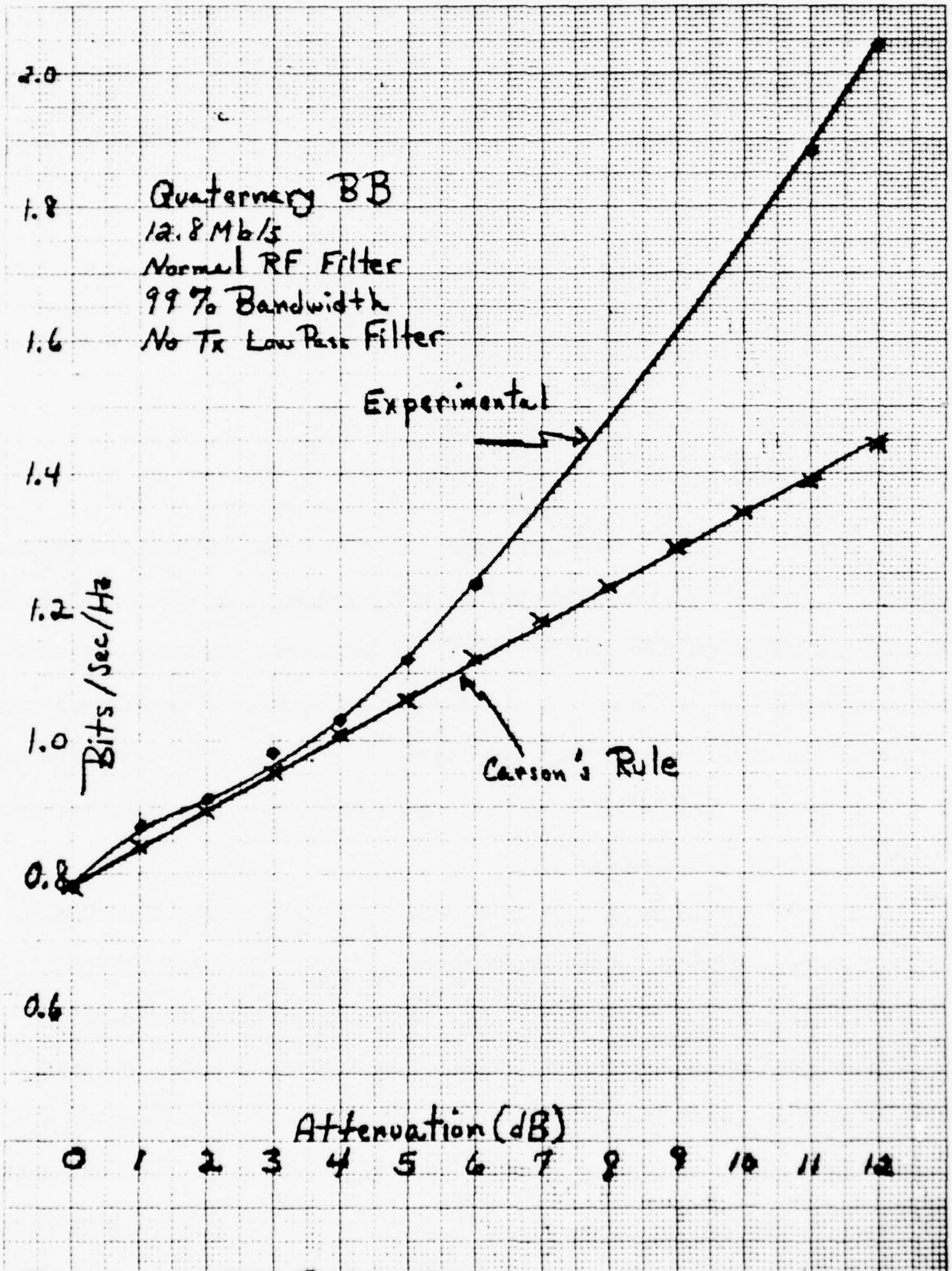


Figure 3.16: Bit Packing Density vs Modem Signal Attenuation

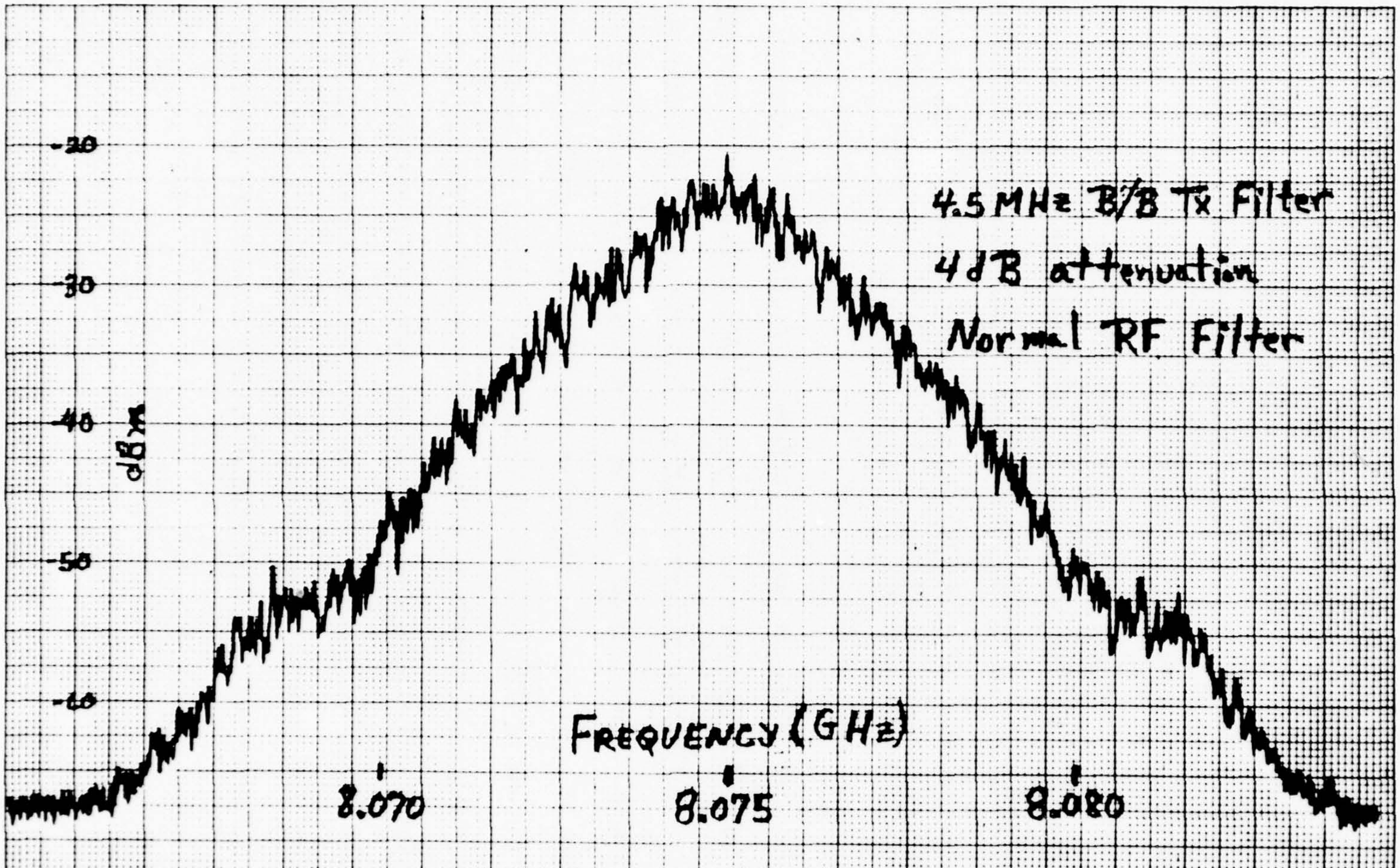


Figure 3.17: Quaternary Baseband Modem with 4 dB Signal Attenuation and 4.5 MHz B/B Filter – RF Transmit Spectrum

primarily determined by the peak-to-peak deviation and the influence of the premodulation low pass filter is secondary. Low pass filtering although not significant from the bandwidth standpoint might be important in limiting the baseband spectrum prior to the deviator, thereby affecting modem performance. This possibility is considered in Section 5.

Because of its immediate availability spectral plots were also obtained using the special (10.6 MHz 3dB bandwidth) RF filter with the low pass filters and various attenuator settings. This caused a small amount of additional data packing. However, RF filtering is unnecessary and costly and, therefore, was not investigated any further.

3.3 Conclusions

The modulation technique has a significant influence on how spectral truncation to permit operation at 1 bit/sec/Hz (99% bandwidth) at 12.8 Mbps is obtained over FDM type microwave radios. For QPSK modems IF filtering is inadequate unless a large enough fade margin exists to allow operation at reduced power so as to reduce upconverter and TWT induced nonlinearity effects. Generally, the use of QPSK modems will require RF filtering for bandwidth control. For the quaternary baseband modem attenuation of the signal to control deviation represents a very economical method of controlling the RF transmit bandwidth. In this case some transmit low pass filtering, while not necessary from the transmitted bandwidth occupancy standpoint, may be inserted to improve performance. Such filtering does have a secondary effect on occupancy.

SECTION 4

QPSK MODEM PERFORMANCE

4.0 Introduction

In Section 3 it was concluded that RF filtering is required with QPSK modulation to control the transmitted RF 99% bandwidth occupancy. The conclusion was drawn almost entirely from the occupancy standpoint with only references to performance results to be presented. This section addresses the experimental performance results for the QPSK modem in detail. It contains:

(1) a theoretical performance curve,

(2) performance results with and without special RF filter bandwidth truncation,

(3) performance results with IF filter bandwidth truncation,

(4) misalignment and distortion effects, and

(5) interfering signal effects.

4.1 Theoretical Performance

To provide a guideline for evaluating the experimental results an approximation to the theoretical BER performance for the QPSK modem under ideal conditions is provided in Figure 4.1. The curve is taken from Bennett and Davey [12] Figure 10-12 curve 3(b) except for a translation in error rate by the multiple 3 to compensate for the fact that the internal test mode contains a scrambler.

Equation (4.1) gives the relation between the carrier-to-noise in the IF bandwidth, $(C/N)_{IF}$, and the carrier-to-noise in the bit rate bandwidth, that is E_b/N_o.

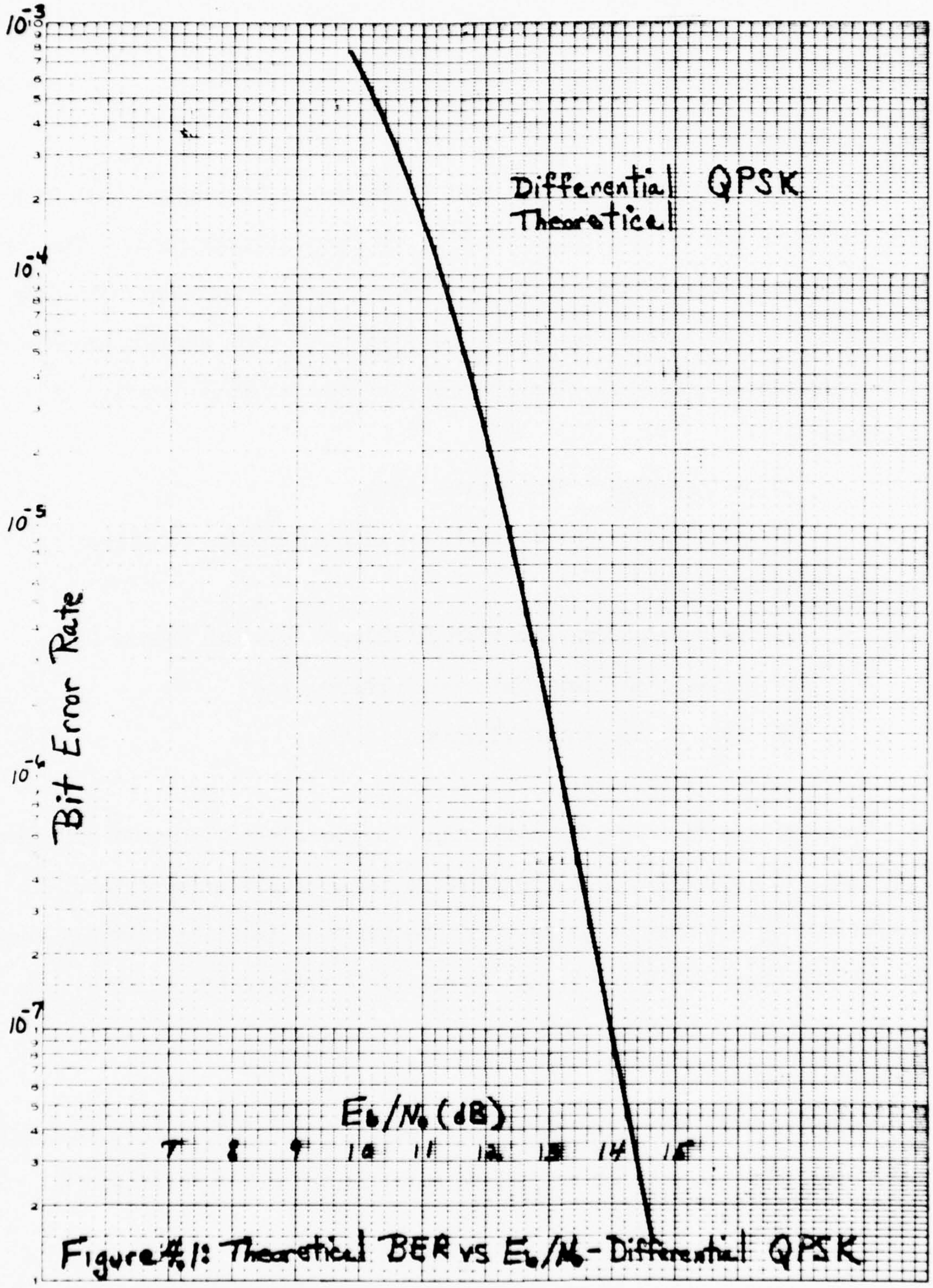


Figure #1: Theoretical BER vs E_b/N_o - Differential QPSK

$$E_b/N_o = (C/N)_{IF}\ B_{IF}/R \tag{4.1}$$

where

B_{IF} = IF bandwidth

R = bit rate

Two bit rates are addressed in detail in this report, 12.8 Mbps and 6.528 Mbps. Expression (4.1) for the 15 MHz IF bandwidth yields:

$$E_b/N_o = (C/N)_{15MHz} + 0.7 \text{ for } 12.8 \text{ Mbps} \tag{4.2a}$$

and

$$E_b/N_o = (C/N)_{15MHz} + 3.6 \text{ for } 6.528 \text{ Mbps} \tag{4.2b}$$

The relation between $(C/N)_{IF}$ and the received signal level, RSL, is given by

$$RSL = -114 + 10 \log_{10} B_{IF(MHz)} + NF + (C/N)_{IF} \tag{4.3}$$

where NF denotes the radio receiver's noise figure. The RSL values were calibrated relative to the 15 MHz IF filter. Therefore, equation (4.3) becomes

$$RSL = -102.2 + NF + (C/N)_{IF} \tag{4.4}$$

The LC-8D radio located at Griffiss AFB has noise figures of 11.0 and 9.8 dB on channels A and B, respectively. Consequently, equations (4.2) and (4.4) yield the following relationships:

$$RSL_A = E_b/N_o - 91.9 \text{ for } 12.8 \text{ Mbps} \tag{4.5a}$$

$$RSL_B = E_b/N_o - 93.1 \text{ for } 12.8 \text{ Mbps} \tag{4.5b}$$

$$RSL_A = E_b/N_o - 94.8 \text{ for } 6.528 \text{ Mbps} \tag{4.5c}$$

$$RSL_B = E_b/N_o - 96.0 \text{ for } 6.528 \text{ Mbps} \tag{4.5d}$$

Therefore, it is an easy matter to convert from the RSL measurements used during the testing to E_b/N_o, a parameter which is independent of the receiver's noise figure. This is done in all the figures to ease comparisons.

4.2 RF Transmit Filtering vs IF Receive Filtering

Throughout the remainder of the report the normal RF filter denotes the nominal 52 MHz (3 dB) bandwidth LC-8D RF filter and the special filter denotes the 10.6 MHz (3 dB) bandwidth RF filter designed and constructed for operation at 1 bit/sec/Hz at the 12.8 Mbps rate.

Some slight degradation was expected in the special transmit filter due to delay distortion introduced as a result of its narrower bandwidth. A 7.7 MHz filter equalized with 16/25 nsec/MHz^2 of parabolic equalization was designed and constructed to yield a raised cosine spectrum response at the input of the QPSK demodulator when used with the QPSK modulator signal and the special RF filter. The IF filter was initially expected to improve the BER results by virtue of the raised cosine spectrum. Later analyses indicated that, because of the demodulator integrate and dump circuitry, such a spectrum is not necessary. Theoretically, performance of the integrate and dump circuitry closely approximates a matched filter implementation [13]. Thus, the receiver IF filter is not required for spectrum shaping but only for noise bandwidth truncation.

The simulator was used in conjunction with the radio set at Griffiss to obtain a very stable media for comparative testing of the various filter combinations. The 7.7 MHz filter and the radio's normal 15 MHz IF filter were used with the two RF filters in obtaining bit error rate (BER) performance curves. The results are graphed in Figure 4.2. The curves show similar performance for the two RF filters when the 15 MHz IF filter is used; when the 7.7 MHz filter is used there is a 2 dB relative difference. For the normal RF filter the narrower IF filter causes a 3 dB loss relative to the

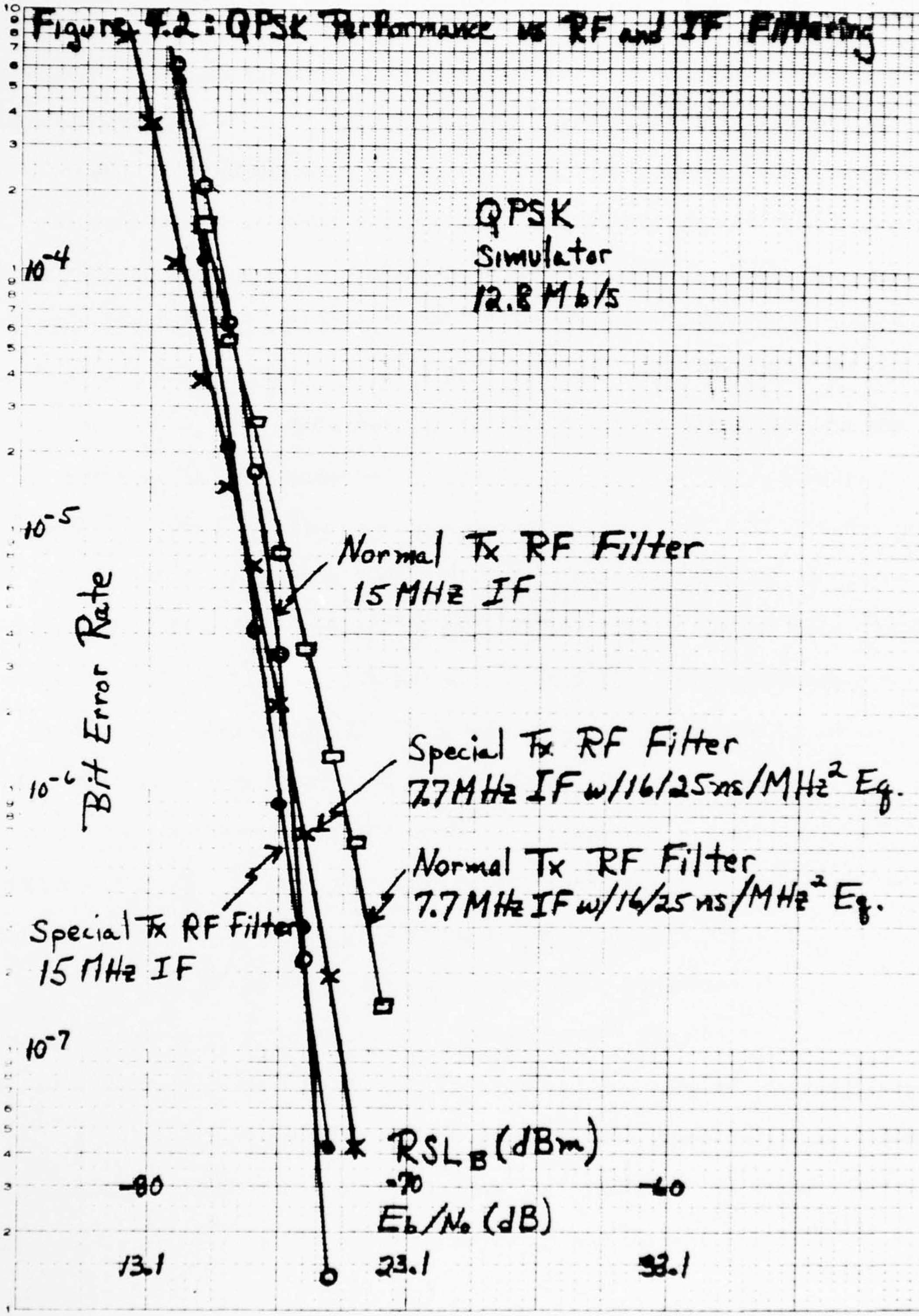


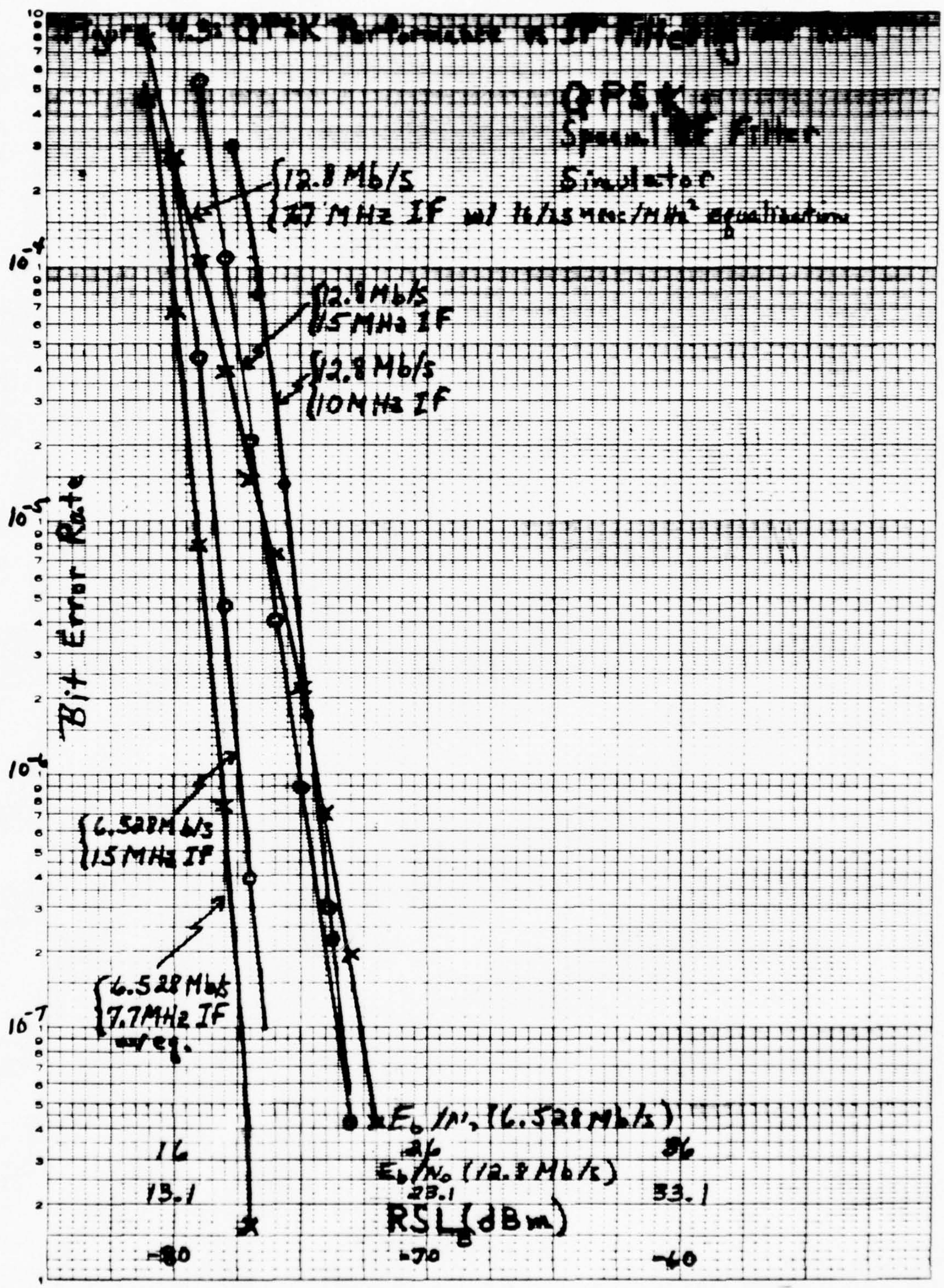
Figure 4.2: QPSK Performance vs RF and IF Filtering

15 MHz filter. With the special RF filter the loss is only 1 dB. These results illustrate the interrelation between bandwidths and performance.

At the poorer signal levels, where the noise is quite high relative to the signal, the narrower IF filter yields the best performance. However, as conditions improve the curves cross and the wider IF filter becomes better. At the 12.8 Mbps rate, as seen in Section 3, a significant amount of energy is contained outside the 7.7 MHz bandwidth, particularly when the normal RF filter is used. The BER results verify that the 7.7 MHz bandwidth is too narrow; signal truncation at IF is excessive.

Figures 4.3 and 4.4 further illustrate the effects of IF receiver filtering. At the 12.8 Mbps rate performance of the radio's 10 MHz IF filter is inferior to the others at the poorer RSL's but comparable to the 15 MHz filter under better conditions. At the 10^{-7} point, the 10 MHz and 15 MHz filters are both about a dB better than the 7.7 MHz filter. In line with the philosophy of minimizing changes, the 15 MHz IF filter being a standard filter, was used in most of the subsequent QPSK tests at the 12.8 Mbps rate.

The main lobe has a bandwidth equal to the bit rate and each (single sided) sidelobe has bandwidth equal to 1/2 the bit rate. Thus, for a fixed radio configuration the occupied bandwidth will decrease as the modem transmission rate is decreased. With the rate of 6.528 Mbps, a rate of importance since it was used in the system tests, the spectrum occupies considerably less bandwidth than the spectrum for the 12.8 Mbps rate. At the higher rate the special RF filter being 10.6 MHz wide at the 3 dB points truncates in the main lobe which is 12.8 MHz wide, whereas at the 6.528 Mbps rate more than half the signal energy in the first sidelobes is passed. Thus, quite different


QPSK
Simulator
12.8 Mb/s
12.8 Mb/s
15 MHz IF
12.8 Mb/s
10 MHz IF
6.528 Mb/s
15 MHz IF
6.528 Mb/s
7.7 MHz IF
w/ eq.
Bit Error Rate
E_b/N_o (6.528 Mb/s)
16
26
36
E_b/N_o (12.8 Mb/s)
13.1
23.1
33.1
RSL (dBm)
-80
-70
-60

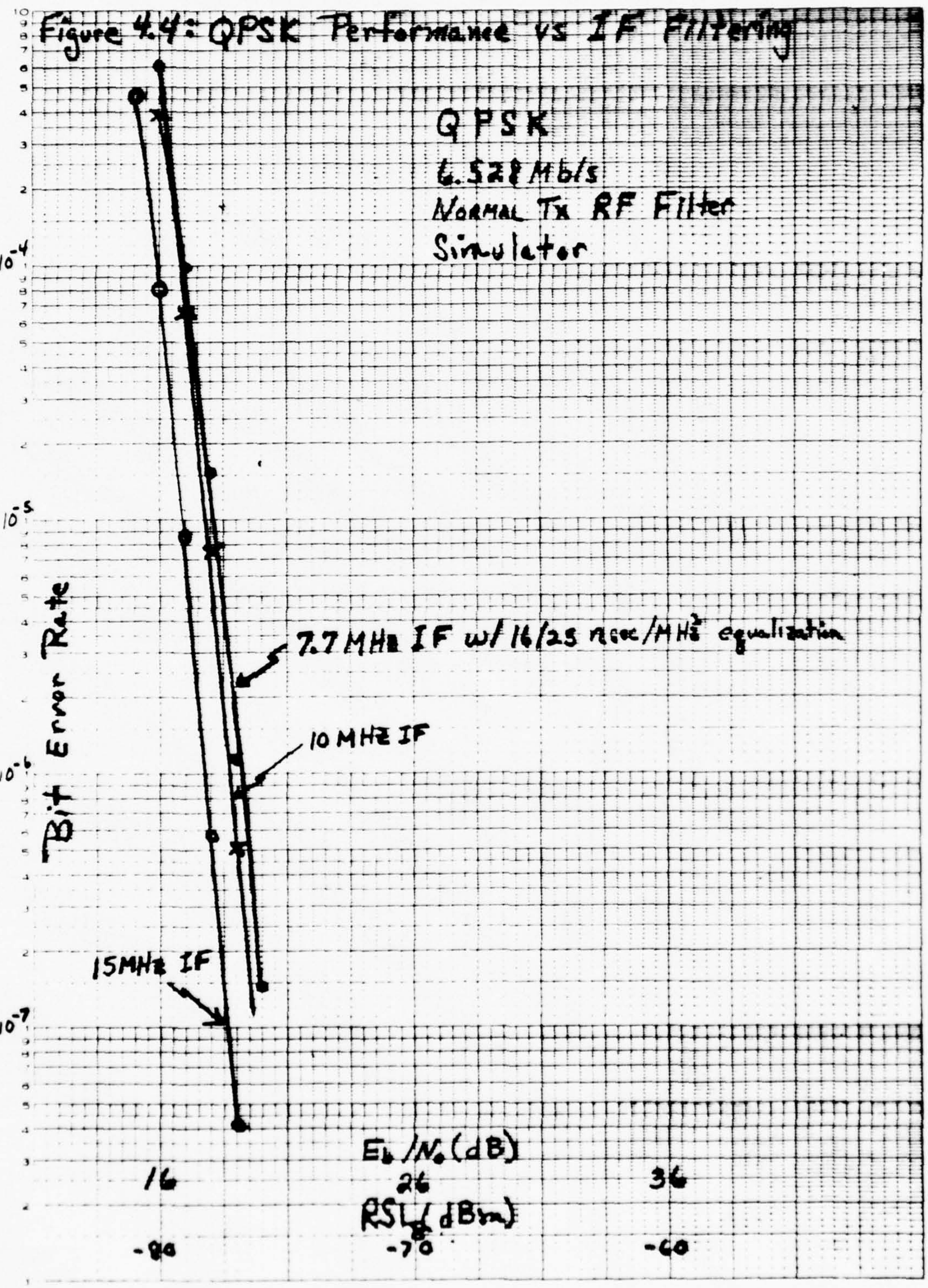


Figure 4.4: QPSK Performance vs IF Filtering
QPSK
6.528 Mb/s
NORMAL Tx RF Filter
Simulator
7.7 MHz IF w/ 16/25 nsec/MHz² equalization
10 MHz IF
15 MHz IF
Bit Error Rate
10^{-4}
10^{-5}
10^{-6}
10^{-7}
E_b/N_o (dB)
16
26
36
RSL (dBm)
-80
-70
-60

IF filter bandwidth results can be expected. At the lower rate, Figure 4.3 shows the 7.7 MHz filter outperforms the 15 MHz filter by about 1 dB. This is just the reverse of the results at the 12.8 Mbps rate. However, as seen in Figure 4.4, when the normal RF filter is used at the 6.528 Mbps rate the 15 MHz filter again outperforms the 7.7 MHz filter.

Overall the above shows performance is a function of the signal's spectral shape, which for QPSK is mainly determined by the rate and the RF transmit filter, and the IF receiver filter bandwidth. Too wide an IF filter allows an excess of pre-detection noise. Narrowing the IF filter reduces such noise but also causes some signal truncation and may introduce delay distortion. IF filter bandwidth selection must consider all these effects. The empirical results contained in the figures show the best IF filter selections among those tested for the various conditions.

4.3 IF Transmit Filtering

Figure 4.5 gives the BER performance obtained when IF transmit filtering was used to control spectral occupancy. In each case the level into the upconverter was +1 dBm. To enable direct comparison the curve for the special RF filter with 15 MHz receive IF filter is reproduced from Figure 4.2. The results leave no doubt that RF filtering is the proper method to control the bandwidth: performance is better and as seen in Section 3, IF transmit filtering yields less than the desired 1 bps/Hz packing density. The possible exception is the case where there is a very high fade margin which would permit operation with IF filtering at reduced power.

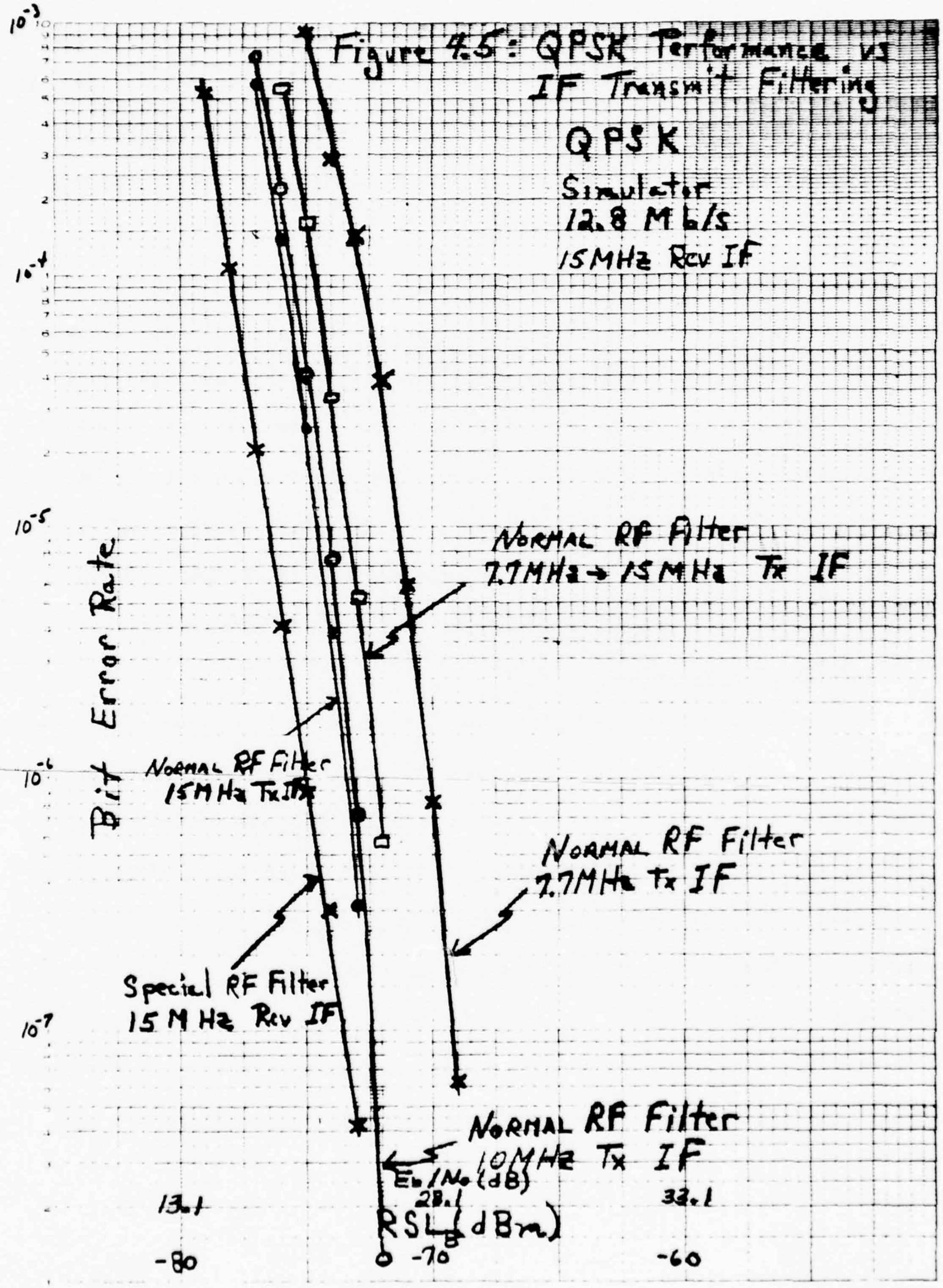


Figure 4.5: QPSK Performance vs IF Transmit Filtering
QPSK
Simulator
12.8 Mb/s
15MHz Rcv IF
Bit Error Rate
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
NORMAL RF Filter
7.7MHz → 15MHz Tx IF
NORMAL RF Filter
15MHz Tx IF
NORMAL RF Filter
7.7MHz Tx IF
Special RF Filter
15 MHz Rcv IF
NORMAL RF Filter
10MHz Tx IF
Eb/No (dB)
13.1
28.1
33.1
RSL (dBm)
-80
-70
-60

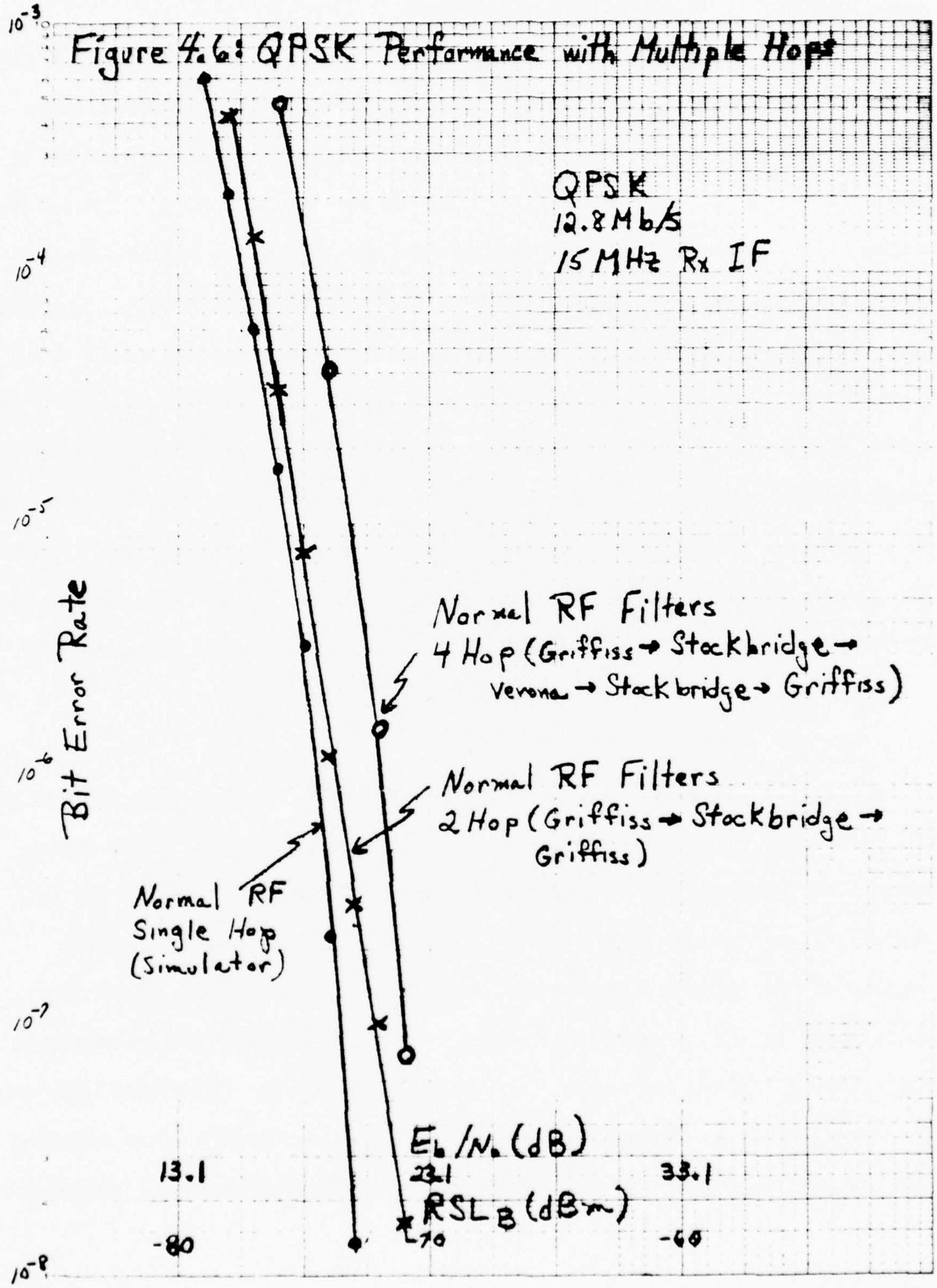
4.4 Theoretical vs Actual BER Performance

Normally one would expect to approach within 3 dB of theoretical in an optimized QPSK system. At the 12.8 Mbps rate the theoretical curve shows an E_b/N_o of 14 dB is required to achieve a BER = 10^{-7}. The achieved 10^{-7} BER's were at E_b/N_o's of 19.6 dB and 18.7 dB for the 12.8 Mbps and 6.528 Mbps, respectively. The 0.9 dB worse performance when using the higher rate is most likely caused by a higher degree of intersymbol interference. The ideal curve assumes no intersymbol interference. Under such a case, at the 6.528 Mbps rate performance is 4.7 dB worse than theoretical and 1.7 dB worse than normally expected from an optimized system. The most probable sources of this performance degradation are the 70 MHz carrier recovery and the integrate and dump demodulator circuitry. As indicated in Section 6.4 later modifications and alignments reduced the difference between the actual and theoretical performances to about 3.2 dB or within about 0.2 dB of what can reasonably be expected.

4.5 Multiple Radio Hops

Figure 4.6 along with Figure 15 of reference [9] indicate the effects of multiple hops. The normal RF filters were used in the multiple hop tests because only two of the special filters were constructed. The use of the special filter on some of the radios would be of little overall benefit because of the spreading due to the upconversion and TWT processes which would occur in the other radios. Because the BER performance is comparable for either RF filter the results in the multiple hop configurations when using the normal RF filters should closely approximate the results to be expected when all radios contain RF truncation filters. The difference in performance

Figure 4.6: QPSK Performance with Multiple Hops



with the number of hops can be associated with increased carrier recovery degradation resulting from frequency instabilities associated with the local oscillators of the radios, and with accumulative degradation of the repeatered signal-to-noise ratio. The results demonstrate that performance degradations for multi-hop repeater operation without regeneration are not excessive. It is generally not considered good practice to regenerate by amplification since noise accumulates. However, if modems are scarce or costs are critical some IF repeatering may be used for short hops where a digital orderwire is not used. Of course, such operation while technologically feasible would be recommended only in rare cases because it does result in a loss in fade margin.

4.6 Signal Impairments

To this point performance has been obtained under rather ideal conditions. The measurements were made with the simulator adjusted to exhibit essentially transparent transmission characteristics. Any distortion components introduced by the presence of the simulator in the transmission path were for all intents and purposes negligibly small. The remainder of Section 4 will consider the effect of various types of signal impairments on performance. Since it has been concluded that for QPSK operation at 12.8 Mb/s the special RF transmit filter should be used in conjunction with the 15 MHz IF filter such an arrangement will be used in most of the signal impairment tests.

To minimize measurement errors a performance curve under minimum distortion conditions was run immediately prior to some of the curves for distorted conditions. A comparison of this data shows only slight differences in the minimal distortion measurements, well within the accuracy expected. The consistency of the results obtained at different times also tends to substantiate the credibility of the measurement techniques.

4.6.1 Amplitude Distortion

The amplitude response distortion impairment capability of the simulator assembly entails the altering of the essentially flat response characteristic provided by the LC-8D radio equipment to a response which varies linearily as a function of frequency over the band of interest. The slope of the amplitude variation which can be positive or negative is adjustable from 0.1 dB/MHz to 0.7 dB/MHz. Figure 4.7 shows the amount of performance degradation for positive and negative amplitude distortions of 0.6 dB/MHz. No degradation is evident from the negative distortion value whereas about 2 dB is lost when positive amplitude distortion is used. Due to the symmetry of the signal, the error performance degradation due to an amplitude distortion of positive slope was expected to be the same as that achieved with a negative slope.

Figures 4.8 and 4.9 show the amplitude response at the 15 MHz IF filter output for the simulated QPSK single hop operation using, respectively, the normal and special RF transmit filters. The normal filter does yield a symmetric and relatively flat characteristic. The special filter, however, is not as symmetrical and has an amplitude distortion larger than that introduced by the simulator. Thus, it is not surprising that some difference is observed with the positive and negative slopes. Since the only difference between Figures 4.8 and 4.9 is the RF filter the lack of flatness is attributable directly to the RF filter. Inspection of Figure 3.4, the transmit spectrum using the special filter shows the asymmetry which causes the amplitude distortion.

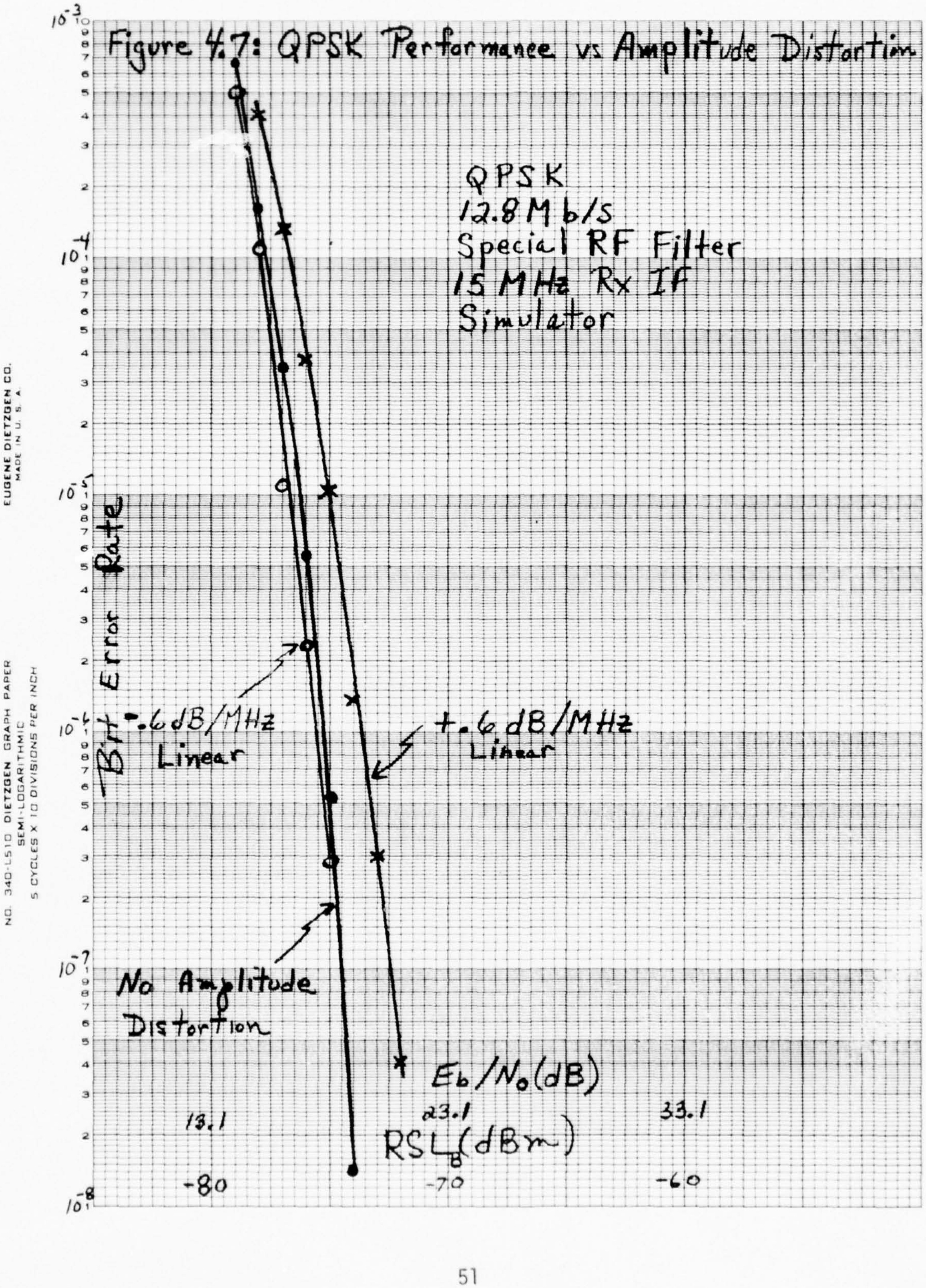
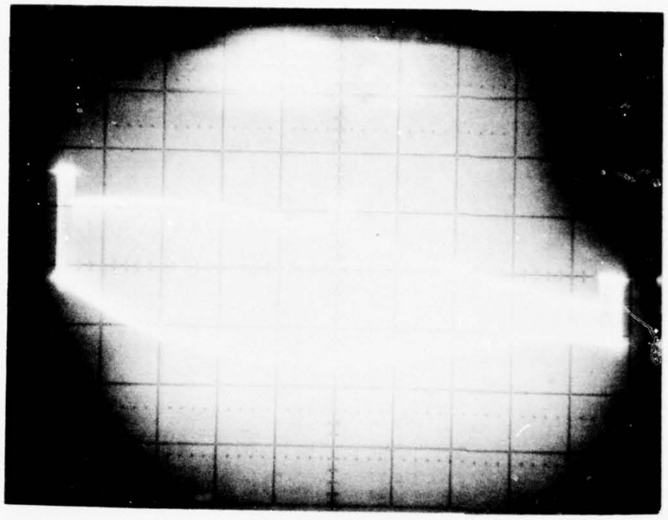
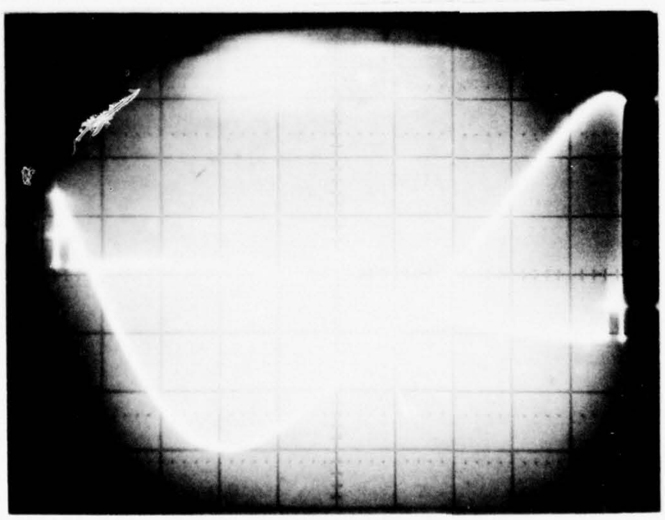


Figure 4.7: QPSK Performance vs Amplitude Distortion
QPSK
12.8 Mb/s
Special RF Filter
15 MHz Rx IF
Simulator
Bit Error Rate
-.6 dB/MHz
Linear
+.6 dB/MHz
Linear
No Amplitude
Distortion
Eb/No(dB)
13.1
23.1
33.1
RSL(dBm)
-80
-70
-60
EUGENE DIETZGEN CO.
MADE IN U. S. A.
NO. 340-L510 DIETZGEN GRAPH PAPER
SEMI-LOGARITHMIC
5 CYCLES X 10 DIVISIONS PER INCH



Calibration
Markers ± 5 MHz
Amplitude 1 dB/cm
Delay 5 nsec/cm

FIGURE 4.8: QPSK Amplitude Response - Normal RF Filter



Calibration
Markers ± 5 MHz
Amplitude 1 dB/cm
Delay 5 nsec/cm

FIGURE 4.9: QPSK Amplitude Response - Special RF Filter

Because of the lack of a flat amplitude characteristic the no distortion case indicated in Figure 4.7 is not truly a minimal distortion case, and the distortions are not of the actual values given. Nonetheless, based upon the results shown in Figure 4.2 little improvement in BER performance can be expected by adjusting the RF filter for more symmetry. Considering the performance obtained for the very large amount of amplitude distortion, it is concluded that distortions of this type will have minimal effect on performance. As a point of reference for the relative magnitude of distortion, 600 channel FDM radios are generally aligned for an amplitude distortion of 0.5 dB/10 MHz.

4.6.2 Linear Group Delay Distortion

The LC-8D radio equipment is usually aligned to provide a total group delay of less than 1 nanosecond over a 10 MHz bandwidth. Bit error rate obtained for various amounts of linear group delay distortion are given in Figure 4.10. The no impairment condition can be taken from Figure 4.7 as all the distortion curves were run consecutively. It is evident that linear group delay distortion of the magnitude provided has minimal effect on the error rate performance.

4.6.3 Parabolic Group Delay Distortion

The group delay characteristic of a typical 600 channel FDM radio, such as the LC-8D, is aligned to deviate by less than one percent of some nominal value over a 10 MHz band. Figure 4.11 gives the performance for two different values of parabolic group delay distortions. Again using the no distortion case shown in Figure 4.7 minimal performance degradation is observed.

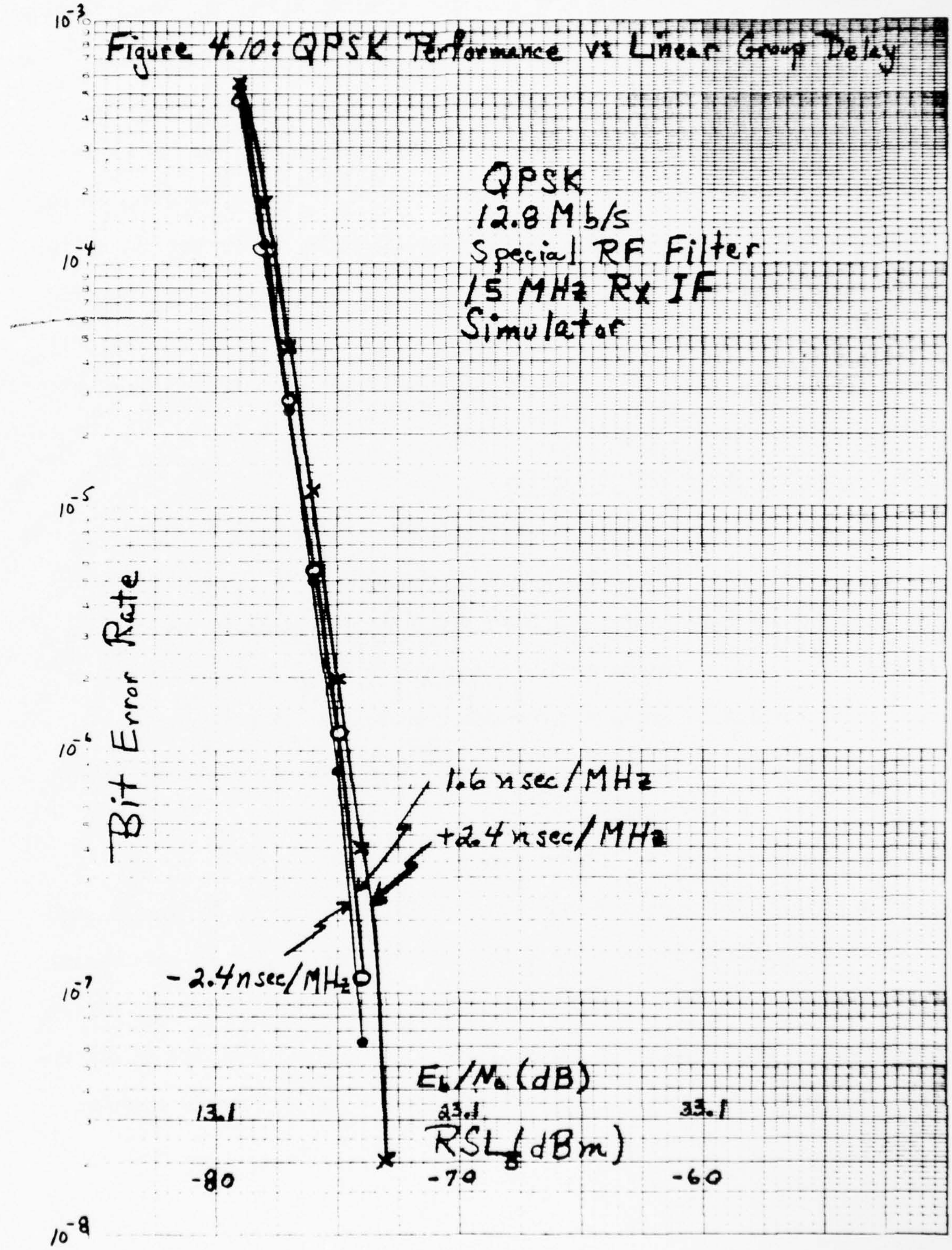


Figure 4.10: QPSK Performance vs Linear Group Delay
QPSK
12.8 Mb/s
Special RF Filter
15 MHz Rx IF
Simulator
Bit Error Rate
10-3
10-4
10-5
10-6
10-7
10-8
1.6 nsec/MHz
+2.4 nsec/MHz
-2.4 nsec/MHz
Eb/No (dB)
13.1
23.1
33.1
RSL (dBm)
-80
-70
-60

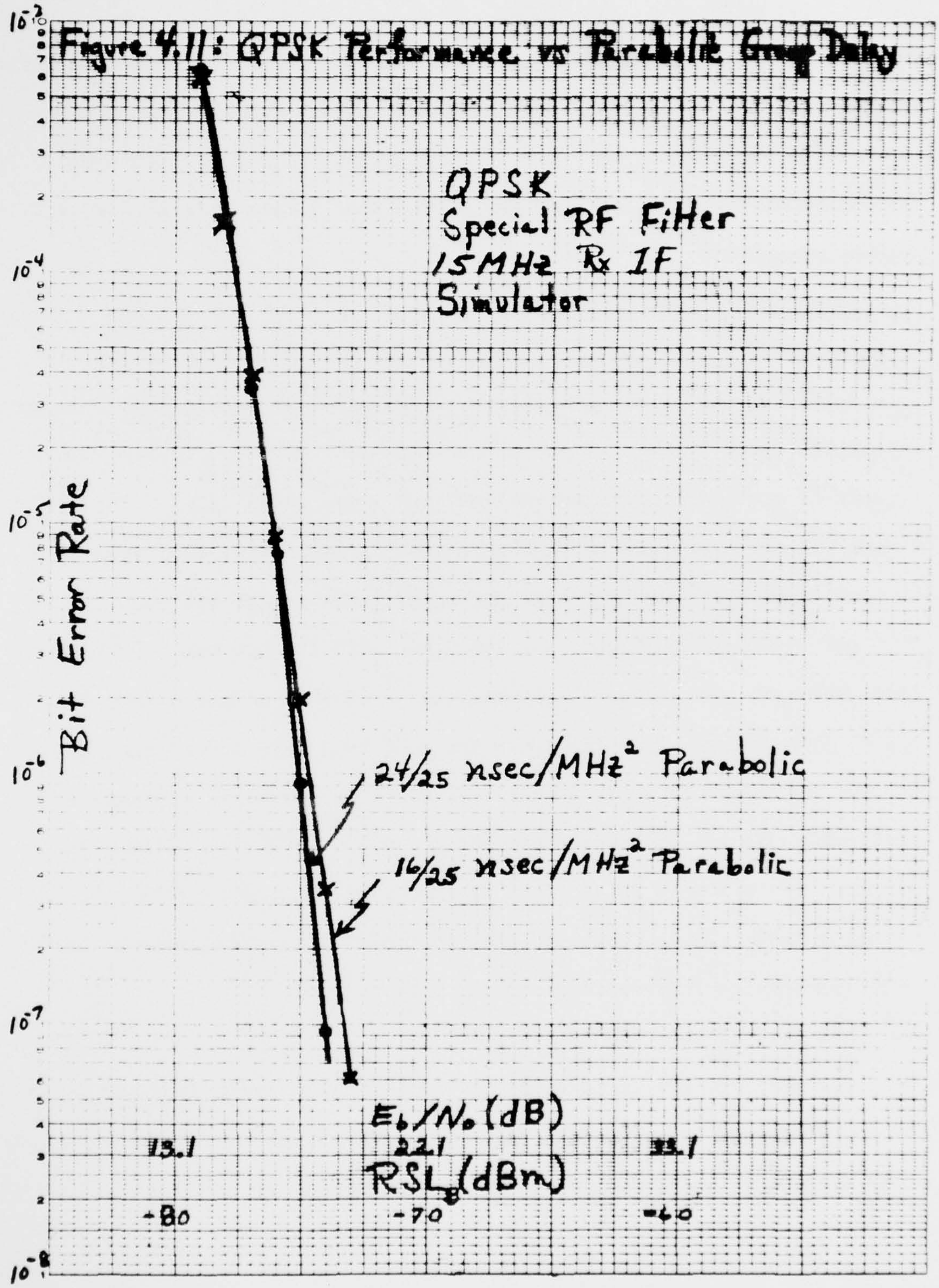


Figure 4.11: QPSK Performance vs Parabolic Group Delay
QPSK
Special RF Filter
15MHz Rx IF
Simulator
Bit Error Rate
24/25 nsec/MHz² Parabolic
16/25 nsec/MHz² Parabolic
Eb/No (dB)
13.1
22.1
33.1
RSL (dBm)
-80
-70
-60
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸

4.6.4 Summary of Distortion Tests

Distortions of magnitude larger than might reasonably be expected under normal operating conditions were introduced. Even under such conditions performance degradation was at most 2 dB and generally less than a dB. Consequently, no operational difficulties should be encountered due to such signal impairments.

4.7 Clock Rate Offset Effects

The variable rate feature of the modems allows operation at any rate from 1.536 Mbps to 12.950 Mbps with an external clock and in Kbps increments within the range if the internal clock circuitry is used. To test the effects of a clock rate offset on performance the clock rate of one of the modems was set at one value and the modem data and timing were used as an external source to feed the other modem which was set at the nominal 12.8 Mbps rate. Figure 4.12 gives the results. With 10 Kbps rate offset no degradation in performance is observable. A 30 Kbps offset causes about 0.5 dB degradation. From the curve for a 50 Kbps rate offset one might believe that there is an irreducible error rate. However, no errors were observed during an 180 sec measurement at an RSL = -70 dBm. Thus, the degradation for the 50 Kbps offset is concluded to be about 4 dB at a 10^{-7} bit error rate. It is concluded that the modem can compensate with little or no degradation for reasonable clock rate offsets.

4.8 Frequency Offset Effects

The translator frequency into the simulator was varied from the normal 315 MHz frequency in order to ascertain the effect of any frequency offsets which may occur in the radios. These results are given in Figure 4.13.

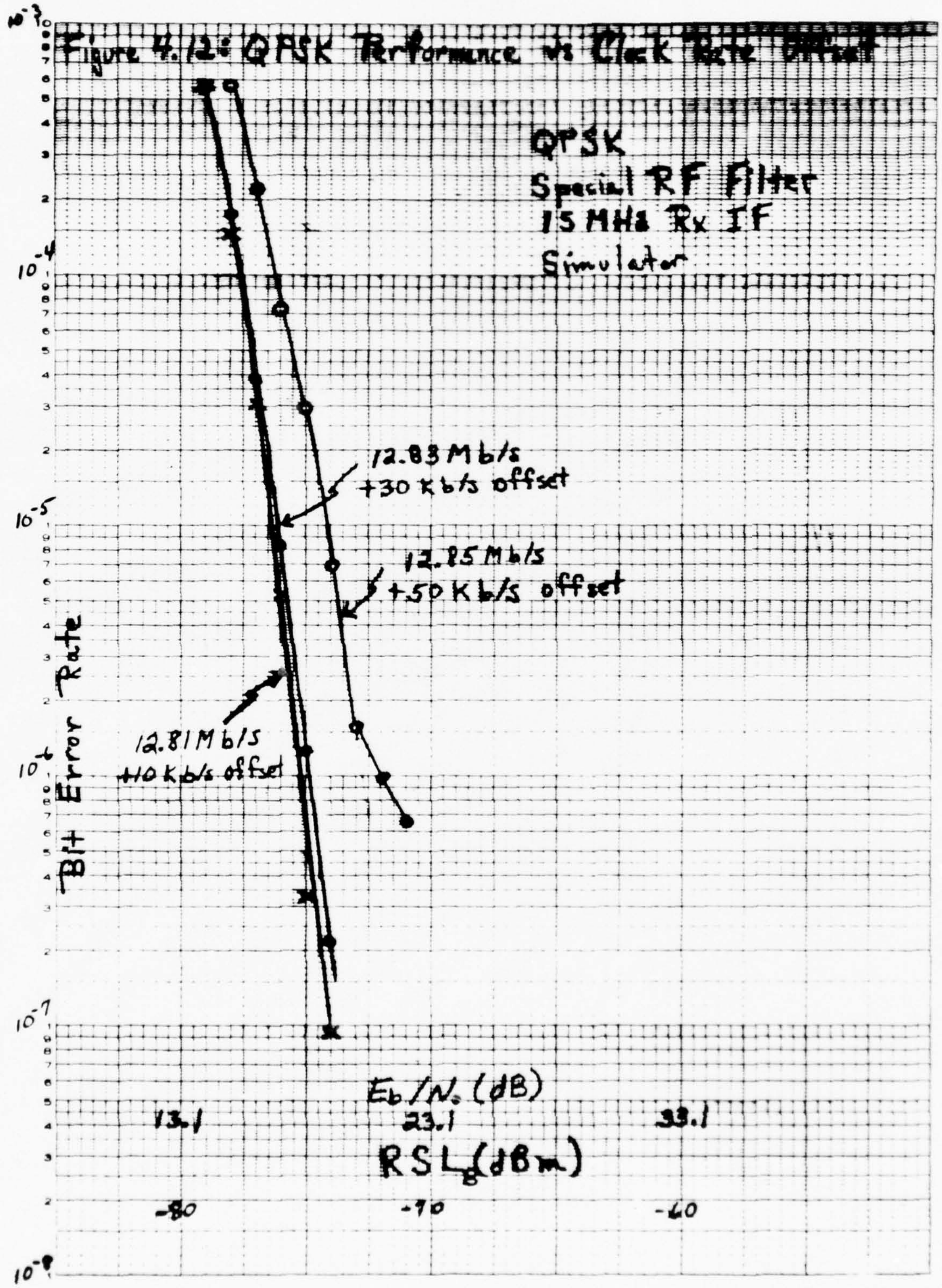


Figure 4.12: QPSK Performance vs Clock Rate Offset
QPSK
Special RF Filter
15 MHz Rx IF
Simulator
12.83 Mb/s
+30 Kb/s offset
12.85 Mb/s
+50 Kb/s offset
12.81 Mb/s
+10 Kb/s offset
Bit Error Rate
Eb/No (dB)
13.1
23.1
33.1
RSL (dBm)
-80
-70
-60

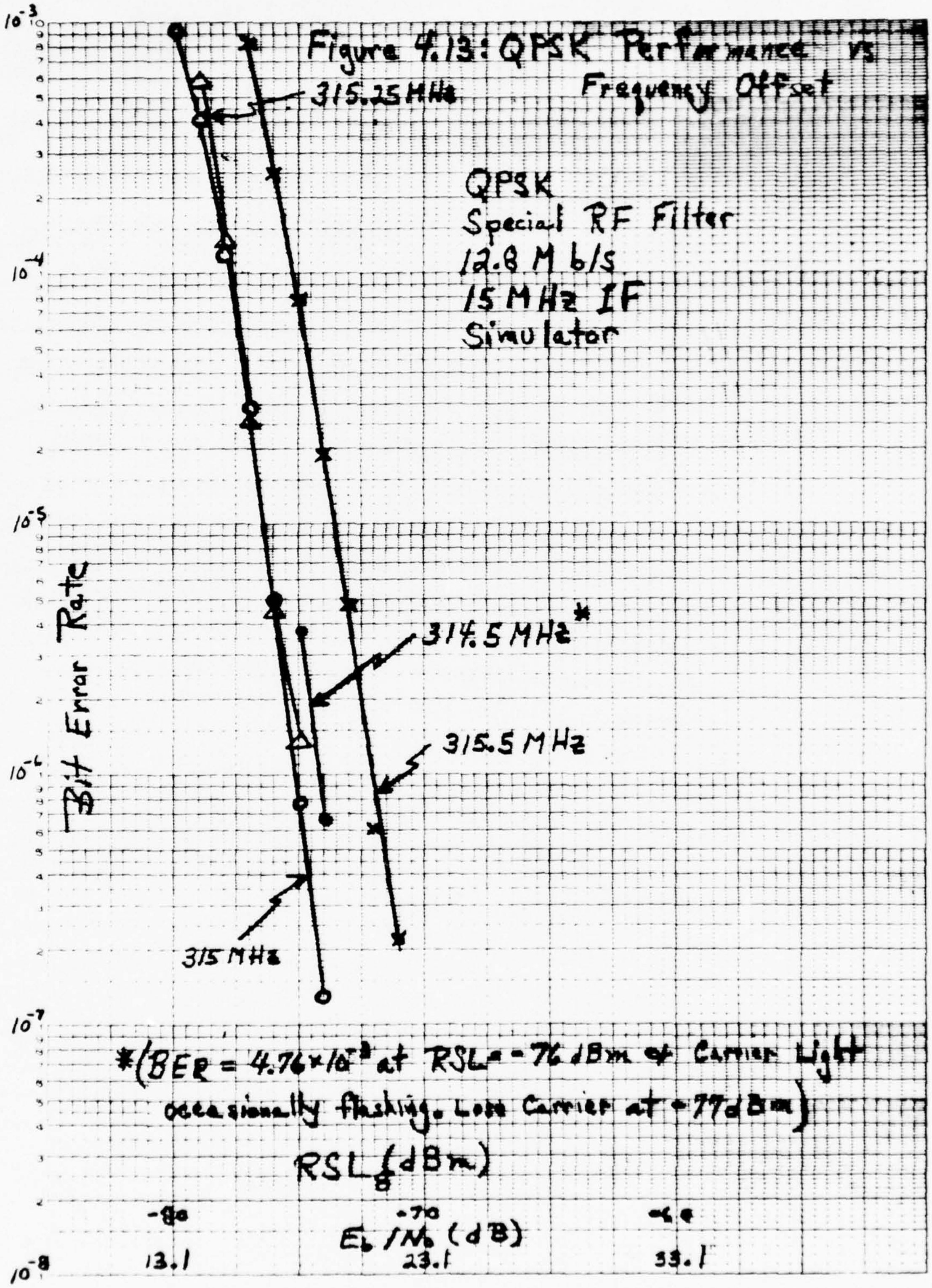


Figure 4.13: QPSK Performance vs Frequency Offset

With an offset of 0.25 MHz negligible degradation is observed. The performance loss at a -0.5 MHz offset is about 1 dB at the points where carrier tracking problems do not occur. About 3.2 dB loss occurs with a +0.5 MHz offset. Because of carrier recovery and tracking problems at frequency offsets of 0.5 MHz or greater quite large degradations may be expected. However, whenever frequency alignments are kept within reasonable tolerances no problems should occur.

4.9 Simulated 8 Hop System

While the individual impairments considered thus far yield minimal performance degradations their combined effects could conceivably cause some problems. To check on this possibility an 8 hop system using the following assumptions was simulated.

	Per Hop	Total
Time Delay (linear)	.5 nsec	4 nsec
Time Delay (parabolic)	1 nsec	8 nsec
Amplitude Tilt	3/4 dB/10 MHz	6 dB/10 MHz
Frequency Offset	50 kHz	400 kHz

This is not a truly valid 8 hop simulation because no bandwidth truncation was simulated nor were the effects discussed under Section 4.5. However, the results, which are shown in Figure 4.14, do verify that the combined distortion effects inserted present no operational problems.

The frequency offset was varied with the RSL at -70 dBm, an error free operating point under normal conditions. The QPSK modem would lose sync when the offset was greater than +500 kHz or less than -1.0 MHz.

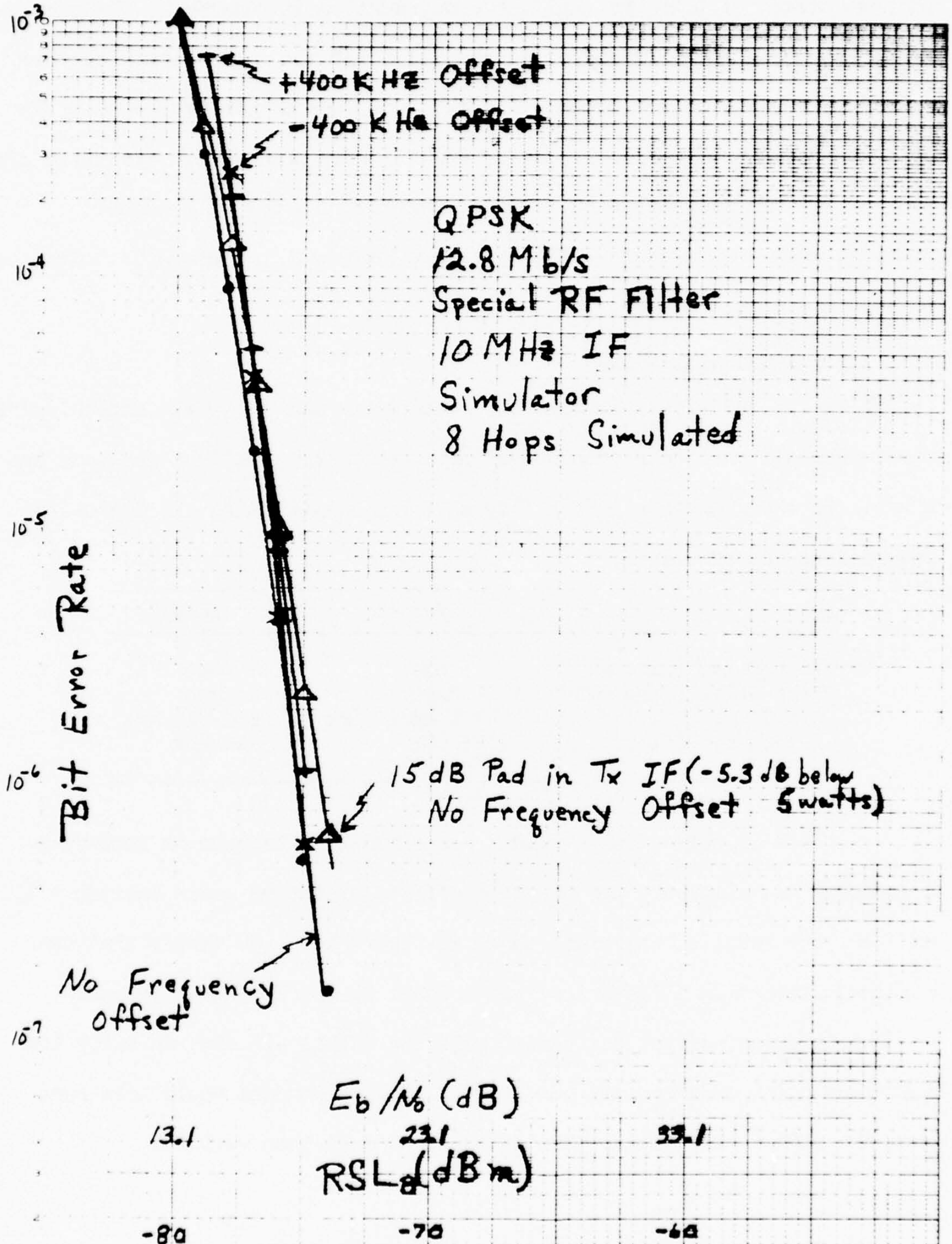


Figure 4.14 QPSK Performance - Simulated 8 Hop System

A 15 dB pad was inserted prior to the IF input to ascertain the effects of operation at a reduced power. About a 1 dB performance loss in RSL was observed. This should not be interpreted to mean operation over a link is feasible under this condition. The modem will operate under the reduced power condition but the link's fade margin will be reduced. The results indicate that digital traffic can be passed over media with an immunity to channel transmission impairment conditions which would severely degrade analog traffic.

4.10 Interfering Signal

Thus far, the signal impairments considered would be caused by the basic link equipments. The remainder of this section will address interference from other signal sources. The measurements were obtained by use of the following test configuration. By disconnecting the radio's wave guide switches both transmitters become active. Channel A is configured in the usual manner except the RF output of the simulator assembly is fed through a directional coupler prior to being fed into the receiver. The output of transmitter B is fed into a microwave translation unit and translated with a 315 MHz local oscillator frequency to the proper RF receiver frequency. The RF output is used as the other input to the directional coupler. By varying the transmitter power via the transmit power attenuators on one of the channels interfering signals of various amplitude can be simulated. The translation frequency can be varied to simulate signals at given frequency offsets.

4.10.1 Two QPSK Signals at the Same Frequency

Using the setup described in the preceding paragraph error performance curves were obtained for two QPSK signals of different amplitudes, operating at the same frequency. Figure 4.15 gives the results. For a relative interfering signal level of -10 dB, severe degradation and an irreducible error rate occurs. Reducing the signal to a relative -16 dB causes only about 1.5 dB degradation from the no interference case. At -20 dB the performance degradation is less than a dB. The results for a -30 dB relative signal are almost identical to the non-interference case.

Because of the requirement for frequency allocations the above type of conditions would not be expected to occur from someone else operating in the vicinity. However, the conditions are identical to those encountered in cross-polarization operation. If a cross-polarization isolation of at least 16 dB is obtained less than 2 dB will be lost in performance. These results, along with various results published on cross-polarization discrimination, indicated that cross-polarized QPSK operation is possible with minimal degradation on most microwave links. Its feasibility is determined solely by the amount of discrimination attainable.

4.10.2 Two QPSK Signals at Different Frequencies

Figure 4.16 shows the performance obtained when two QPSK signals of equal amplitude but different frequencies were combined. At a frequency offset of $\pm$ 6.4 MHz the demodulator would not lock up. With an offset of $\pm$ 9.5 MHz an irreducible error rate of 1.1×10^{-7} was obtained. At -12.8 MHz frequency offset only about a 0.5 dB performance degradation occurred. At +12.8 MHz the degradation was about 1.2 dB. Operationally, any interfering signal would be at a frequency offset larger than that simulated and should be of no consequence.

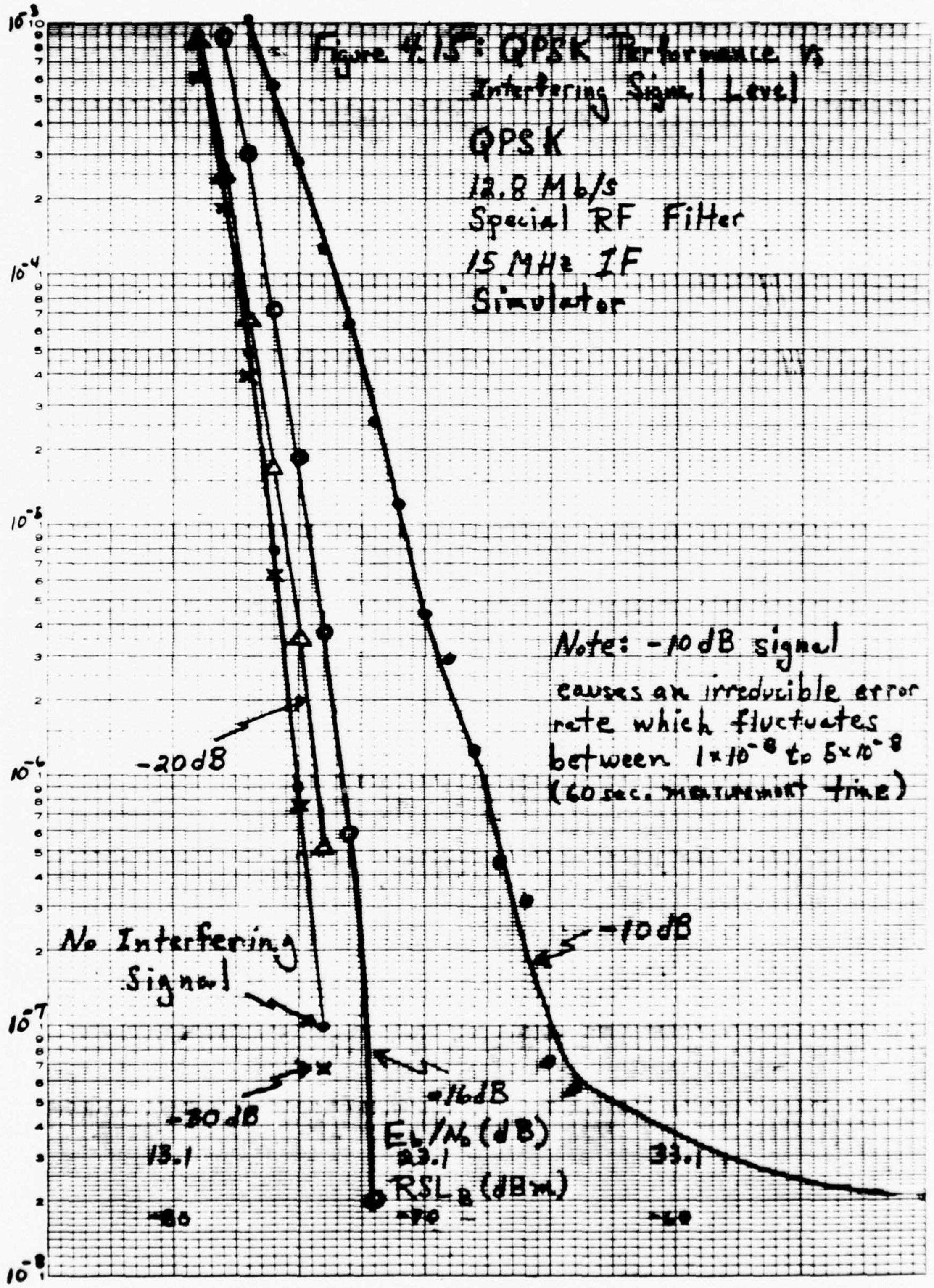


Figure 4.15: QPSK Performance vs Interfering Signal Level

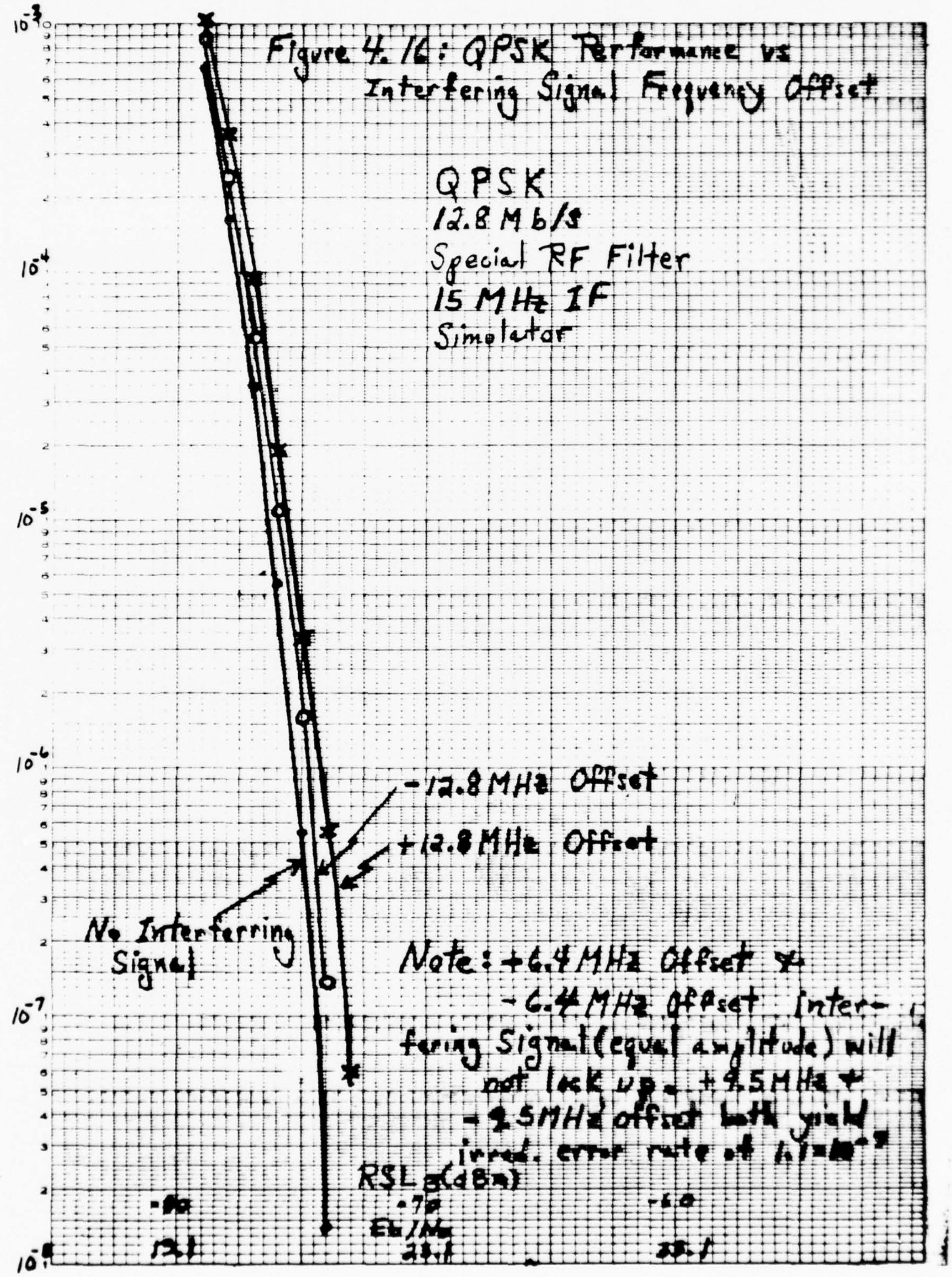


Figure 4.16: QPSK Performance vs Interfering Signal Frequency Offset

4.10.3 FDM Signals

Since analog and digital traffic might logically be expected in adjacent frequency allocations the effects of one upon the other were investigated.

A 300 channel equal amplitude FDM signal was transmitted on channel B which contained the normal RF transmit filter. The QPSK signal was transmitted using the special RF filter. Figure 4.17 shows the results obtained for the QPSK modem for various amounts of FDM signal frequency offset. Comparison of performance for the interfering FDM signal with Figure 4.16 shows that the modem operates equally well regardless of whether analog or digital traffic is in adjacent channels.

Having seen that digital operation is not adversely affected by FDM traffic in adjacent frequency bands, the converse is considered. Is the FDM traffic degraded by the digital signal? The quality of an FDM signal is measured as Noise Power Ratio (NPR) which can be related to the signal to noise ratio in a voice channel. Figures 4.18a, b and c show the results of NPR measurements at 3 different baseband frequencies when an interfering QPSK signal of equal amplitude but offset by a given frequency is present. The NPR is severely degraded if the interfering signal is offset 12.8 MHz. (Recall the degradation in the digital signal at such an offset was only about 1 dB.) At larger offsets the degradation is much less severe but still more significant than for the digital case. It is concluded that digital traffic enjoys a much greater immunity to interference than analog traffic but that operational frequency separations will be sufficient to permit effect transmission of both analog and digital traffic on adjacent channels.

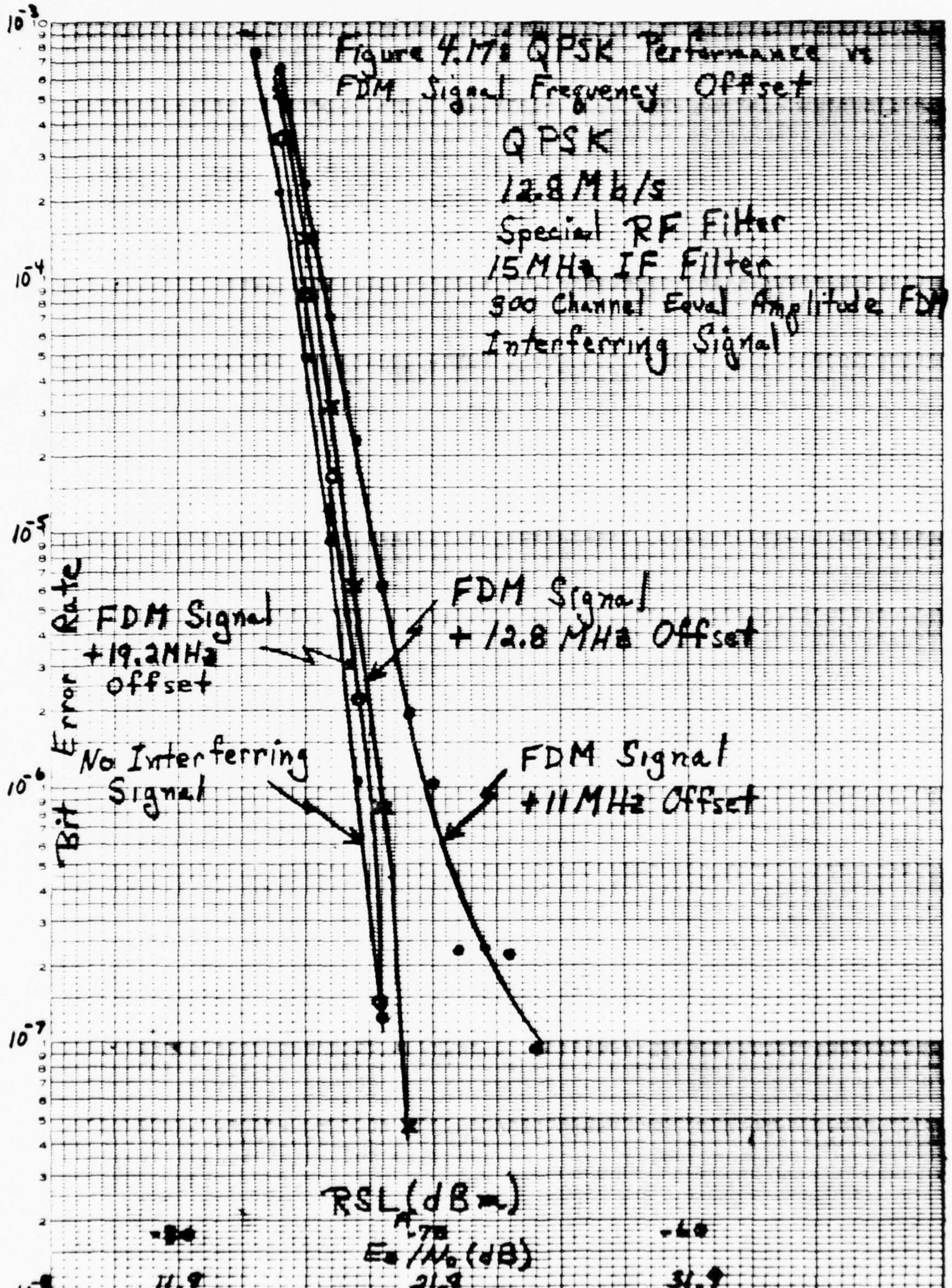


Figure 4.17: QPSK Performance vs FDM Signal Frequency Offset
QPSK
12.8 Mb/s
Special RF Filter
15 MHz IF Filter
900 Channel Equal Amplitude FDM Interferring Signal
FDM Signal +19.2 MHz offset
FDM Signal +12.8 MHz Offset
No Interferring Signal
FDM Signal +11 MHz Offset
Bit Error Rate
RSL (dBm)
Eb/No (dB)
11.9
21.9
31.9
-60

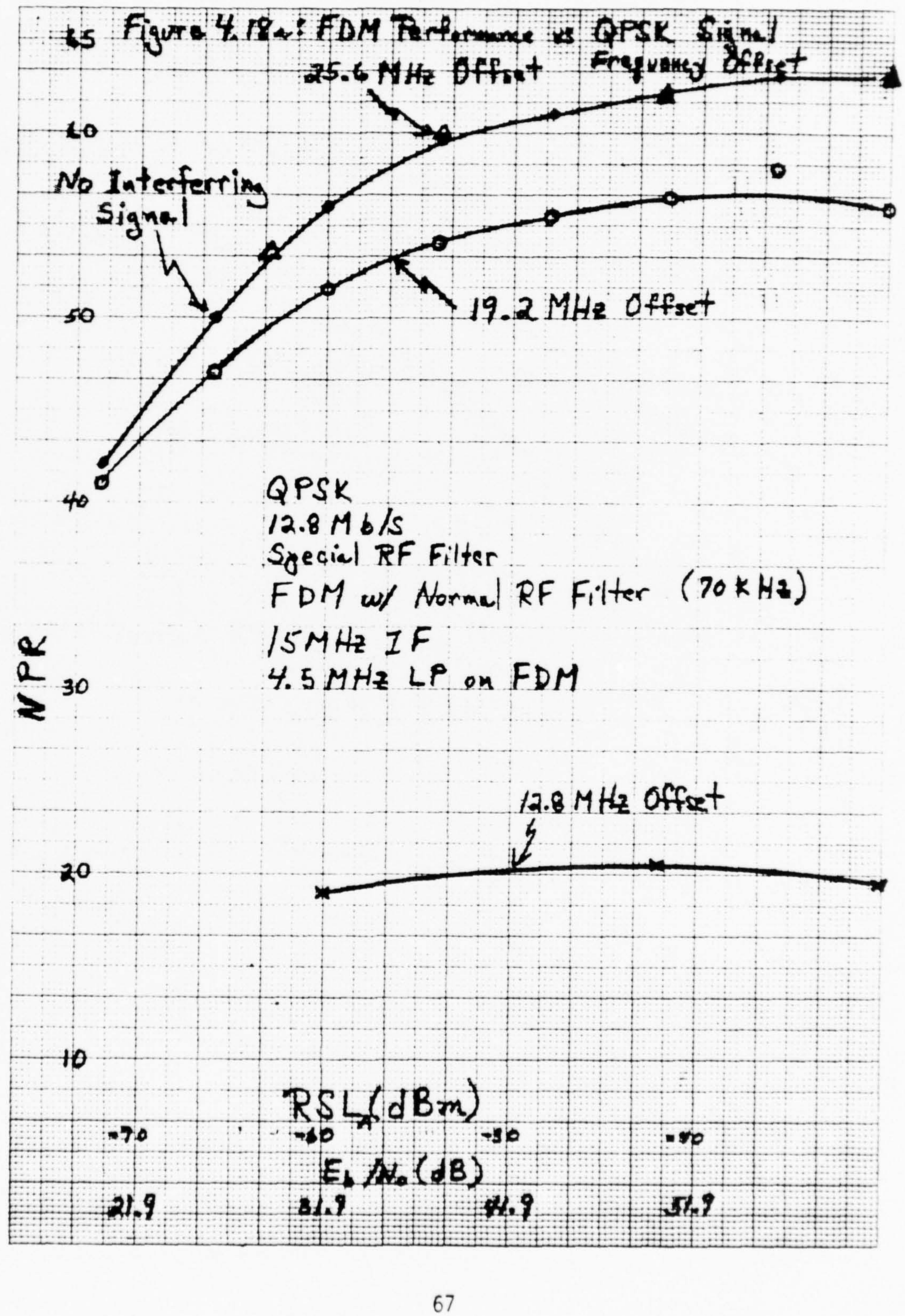


Figure 4.18a: FDM Performance vs QPSK Signal Frequency Offset
25.6 MHz Offset
No Interferring Signal
19.2 MHz Offset
QPSK
12.8 Mb/s
Special RF Filter
FDM w/ Normal RF Filter (70 kHz)
15 MHz IF
4.5 MHz LP on FDM
12.8 MHz Offset
NPR
RSL (dBm)
-70
-60
-50
-40
E_b/N_o (dB)
21.9
31.9
41.9
51.9
45
40
50
40
30
20
10

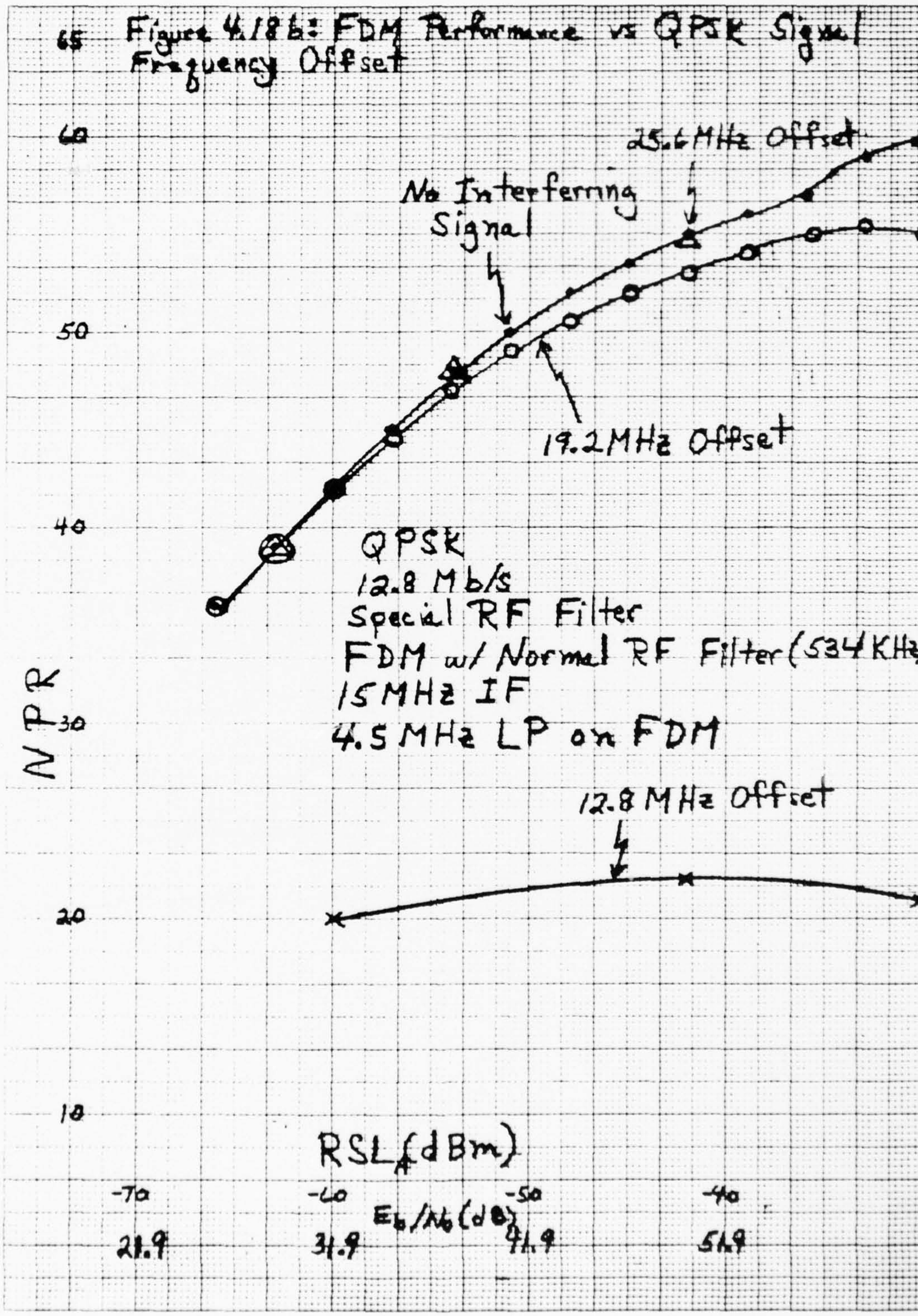


Figure 4.18b: FDM Performance vs QPSK Signal Frequency Offset
65
60
50
40
30
20
10
25.6 MHz Offset
No Interferring Signal
19.2 MHz Offset
QPSK
12.8 Mb/s
Special RF Filter
FDM w/ Normal RF Filter (534 KHz)
15 MHz IF
4.5 MHz LP on FDM
12.8 MHz Offset
NPR
RSL (dBm)
-70
-60
-50
-40
Eb/No (dB)
21.9
31.9
41.9
51.9

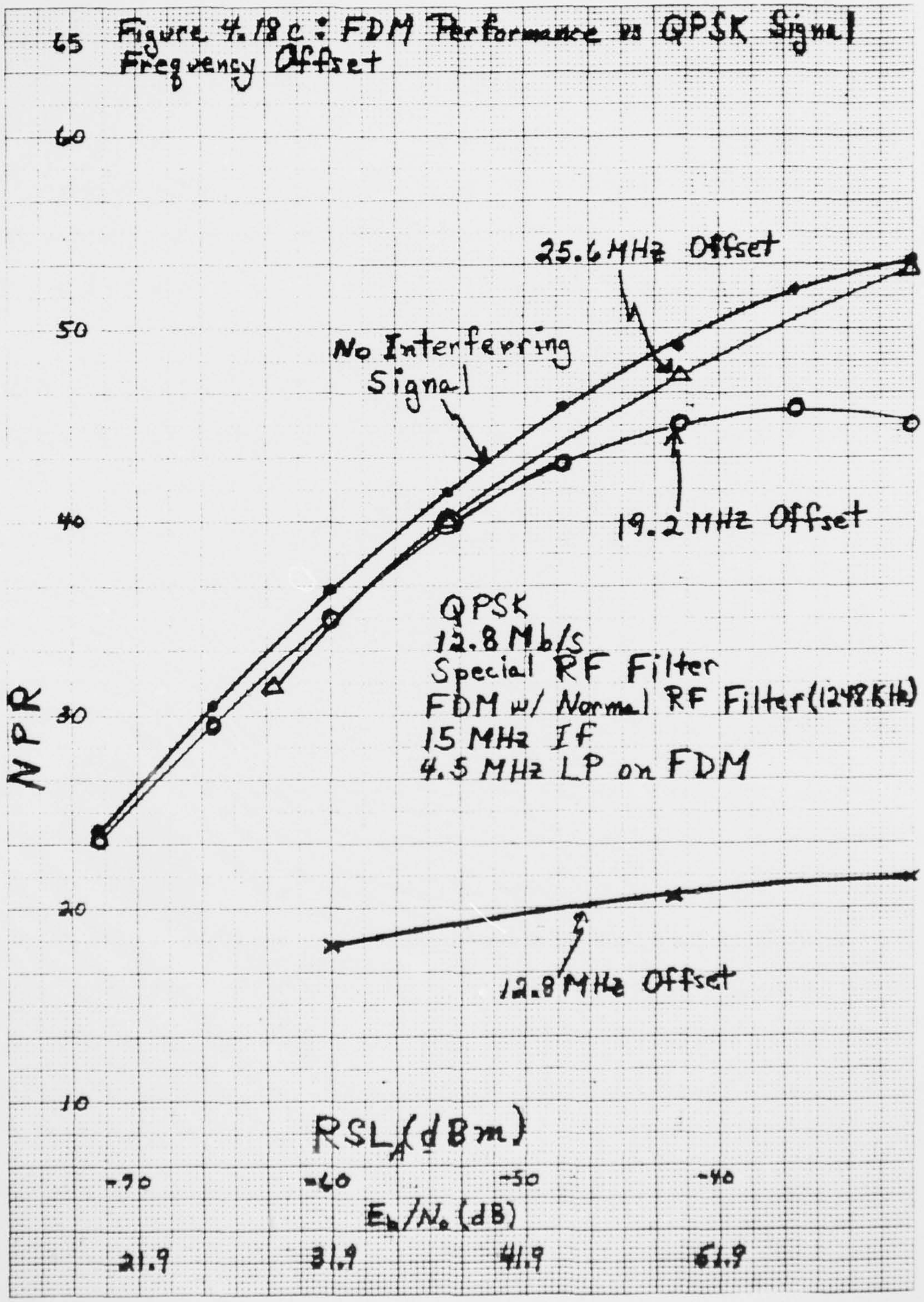


Figure 4.18c : FDM Performance vs QPSK Signal Frequency Offset
65
60
50
40
30
20
10
NPR
25.6 MHz Offset
No Interfering Signal
19.2 MHz Offset
QPSK
12.8 Mb/s
Special RF Filter
FDM w/ Normal RF Filter (1248 KHz)
15 MHz IF
4.5 MHz LP on FDM
12.8 MHz Offset
RSL (dBm)
-70
-60
-50
-40
E_b/N_o (dB)
21.9
31.9
41.9
51.9

SECTION 5

QUATERNARY BASEBAND MODEM PERFORMANCE

5.0 Introduction

This section has the same general structure as the preceding one. First, theoretical performance results are given, performance is ascertained under minimal impairment conditions and finally the effects of various kinds of signal impairments are considered.

With the QPSK system operating at a fixed clock rate, packing density is dictated almost entirely by the RF filter; a different density requires a relatively expensive RF filter change. For the QPSK system once the RF filter was fixed, attention was immediately focused upon the IF receive filter effects. With the baseband system all that is needed to change the signal's transmitted bandwidth occupancy is an attenuator for varying deviation: Table 3.1 or Figure 3.16 illustrate this fact. The intent is to obtain high quality digital traffic over existing FDM microwave equipments with a minimum of modification to the radio. This dictates, provided performance is acceptable, that attenuation rather than RF filtering be used to control bandwidth. The results will show such performance is attainable. Consequently, all the tests of the quaternary baseband modem were conducted with the radio's normal 52 MHz RF transmit filter. Even though the 1 bps/Hz density is of particular interest under Phase I, higher densities were addressed because of their potential requirements in future systems. To assess the attainable performance the effects of transmit and receive low pass filtering, as well as IF filter effects, need to be evaluated. Hence, the baseband modem performance assessment required an evaluation of many more possible combinations than the QPSK modem.

5.1 Theoretical Performance

The baseband system's theoretical performance is approximated by [14]:

$$Pe = \frac{1}{(2\pi\rho)^{1/2}} \quad \frac{\cot\left(\frac{\pi}{2}\cdot\frac{\Delta f}{N}\right)}{\left[\cos\left(\pi\cdot\frac{\Delta f}{N}\right)\right]^{1/2}} \exp\left[-2\rho \sin^2\left(\frac{\pi}{2}\cdot\frac{\Delta f}{N}\right)\right] \tag{5.1}$$

$$\frac{\Delta f}{N} < 1/2$$

where:

ρ = carrier-to-noise ratio

Δf = frequency separation

N = symboling rate

The relationship between ρ the carrier-to-noise in the IF bandwidth, and E_b/N_o which is equal to the carrier-to-noise in the bit rate bandwidth is given by:

$$\rho = \frac{2N}{B}(E_b/N_o) \tag{5.2}$$

where B is the occupied bandwidth. Combining (5.1) and (5.2) yields:

$$Pe = \left[\frac{B}{4\pi N(E_b/N_o)}\right]^{1/2} \frac{\cot\left(\frac{\pi}{2}\cdot\frac{\Delta f}{N}\right)}{\left[\cos\left(\pi\cdot\frac{\Delta f}{N}\right)\right]^{1/2}} \exp\left[-\left(\frac{4N}{B}\right)(E_b/N_o)\sin^2\left(\frac{\pi}{2}\cdot\frac{\Delta f}{N}\right)\right] \tag{5.3}$$

The experimental data (Table 3.1) yielded bandwidths of 12.38 MHz and 6.28 MHz for 4 dB and 12 dB attenuation, respectively. From Figure 3.16, an attenuation of 8 dB results in 1.47 bps/Hz. Dividing this number into the 12.8 Mbps rate yields a bandwidth of 8.71 MHz. Using these numbers for B, Table 5.1 was constructed and the results plotted in Figure 5.1.

Also shown is the theoretical performance for the 6.528 Mbps rate for 10 dB attenuation; these conditions were used during much of the system tests.

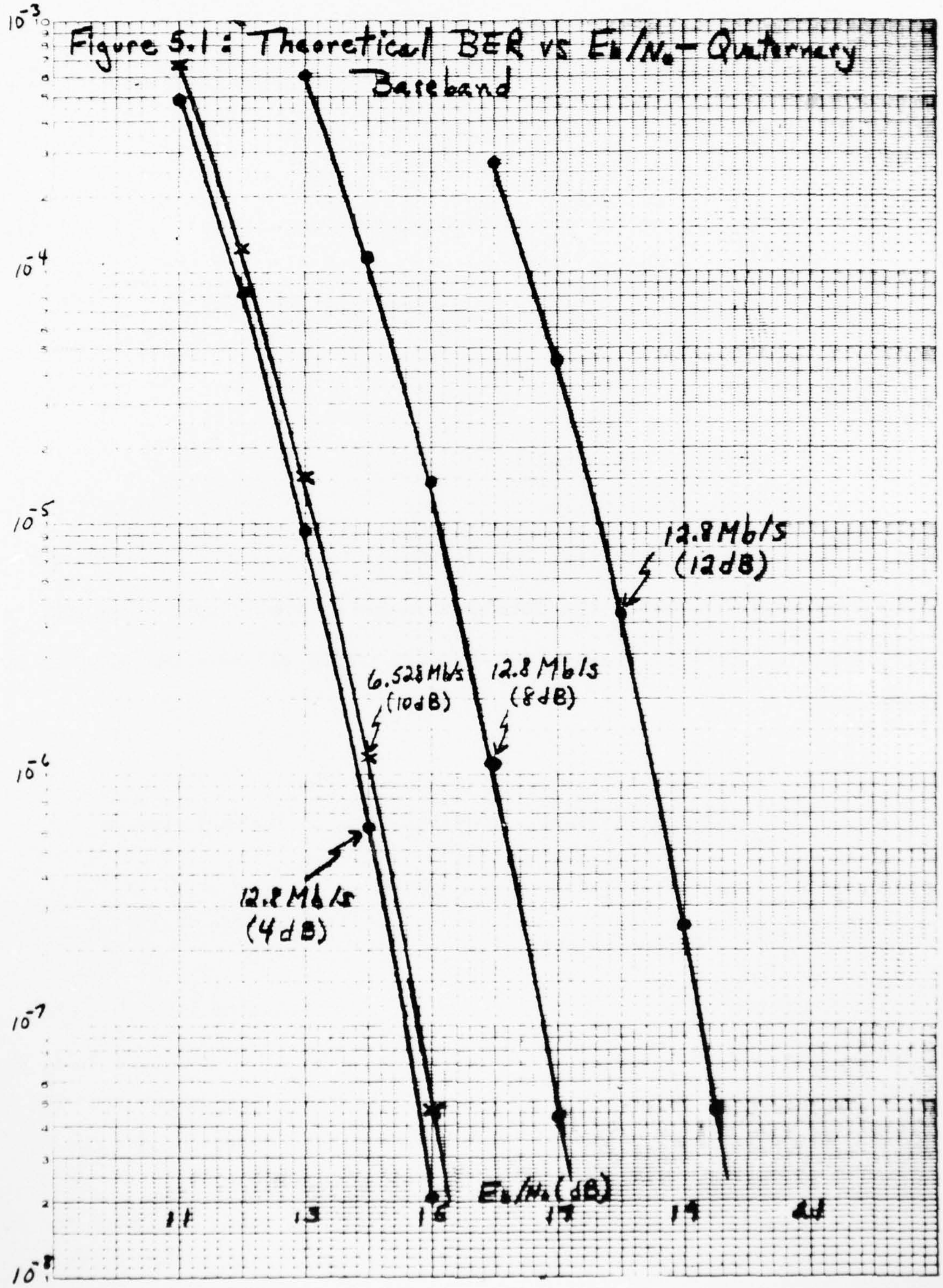


Figure 5.1: Theoretical BER vs E_b/N_o – Quaternary Baseband
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
12.8 Mb/s (12dB)
6.528 Mb/s (10dB)
12.8 Mb/s (8dB)
12.8 Mb/s (4dB)
E_b/N_o (dB)
11
13
15
17
19

Numerical integration of spectral plots at the 6.528 Mbps rate showed 98.9% of the energy was contained in 6.528 MHz when 9 dB attenuation was used, whereas 99.4% was obtained with 10 dB. Thus, experimentally 10 dB attenuation was determined to be the proper value to obtain 1 bps/Hz. The actual B was calculated to be 6.43 MHz which gives a 1.02 bps/Hz density. Carson's rule results in a value of 9.7 dB required for 1 bps/Hz. Again, the excellent approximation at the 1 bps/Hz occupancy, thereby, substantiates the validity of the rule for densities up to 1 bps/Hz.

Table 5.1: Quaternary Baseband Theoretical Performance

	12.8 Mbps			6.528 Mbps
E_b/N_o (dB)	4 dB	8 dB	12 dB	10 dB
8	1.60×10^{-2}	6.52×10^{-2}	1.94×10^{-1}	1.91×10^{-2}
9	6.26×10^{-3}	3.56×10^{-2}	1.31×10^{-1}	7.77×10^{-3}
10	1.98×10^{-3}	1.71×10^{-2}	8.28×10^{-2}	2.59×10^{-3}
11	4.79×10^{-4}	6.99×10^{-3}	4.77×10^{-2}	6.68×10^{-4}
12	8.26×10^{-5}	2.34×10^{-3}	2.46×10^{-2}	1.25×10^{-4}
13	9.31×10^{-6}	6.06×10^{-4}	1.10×10^{-2}	1.57×10^{-5}
14	6.14×10^{-7}	1.14×10^{-4}	4.11×10^{-3}	1.18×10^{-6}
15	2.07×10^{-8}	1.44×10^{-5}	1.23×10^{-3}	4.67×10^{-8}
16	2.98×10^{-10}	1.09×10^{-6}	2.76×10^{-4}	8.26×10^{-10}
17	----------	4.39×10^{-8}	4.34×10^{-5}	----------
18	----------	7.89×10^{-10}	4.37×10^{-6}	----------
19	----------	----------	2.49×10^{-7}	----------
20	----------	----------	7.00×10^{-9}	----------
21	----------	----------	8.01×10^{-11}	----------

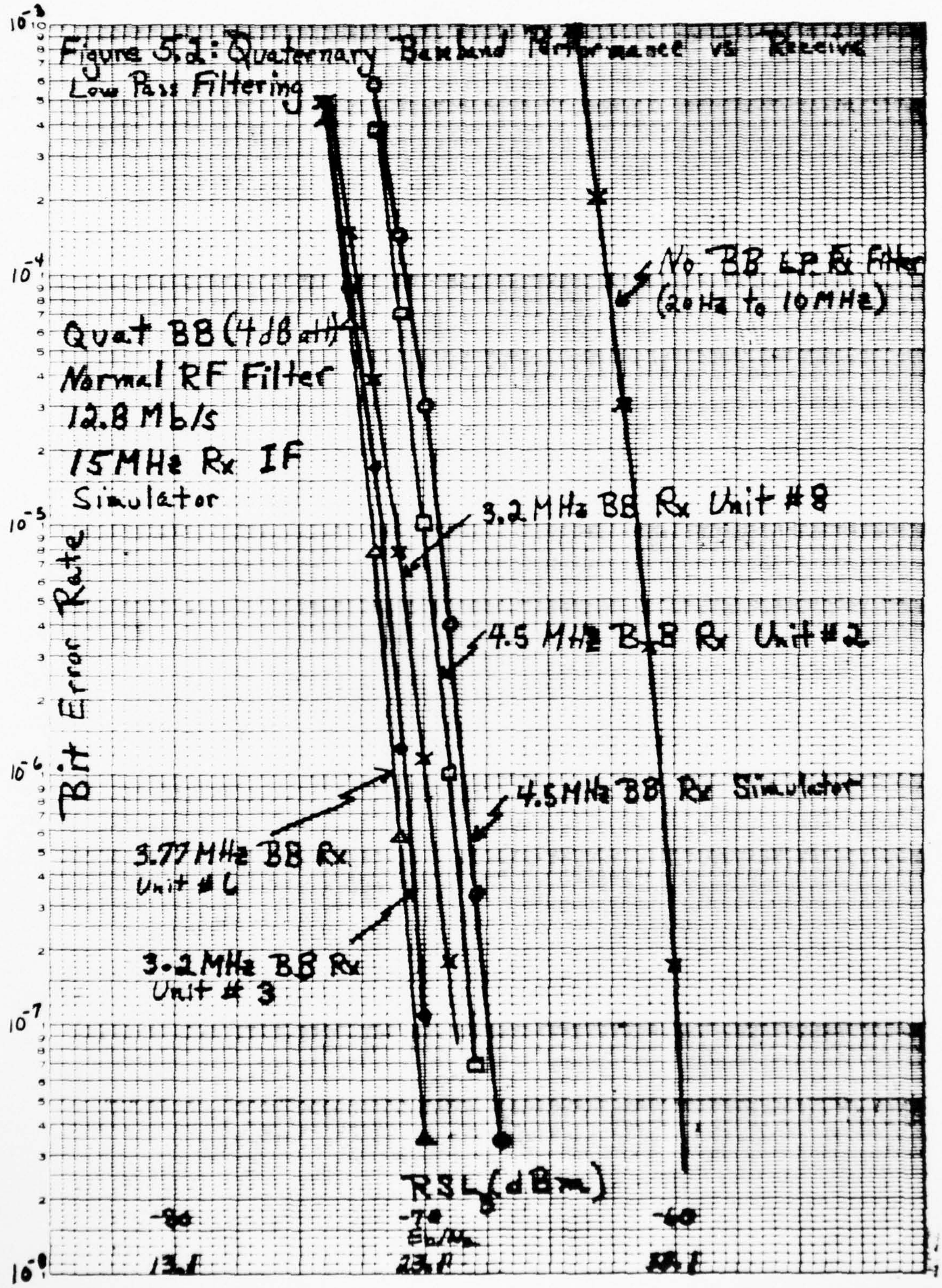
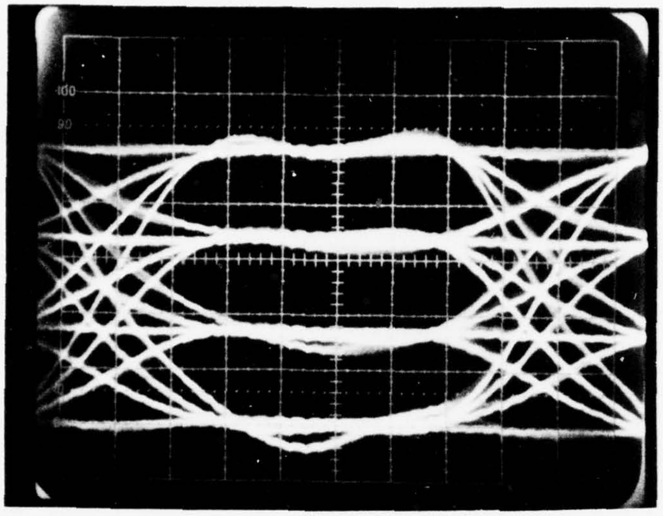


Figure 5.2: Quaternary Baseband Performance vs Receive Low Pass Filtering
Quat BB (4dB att)
Normal RF Filter
12.8 Mb/s
15MHz Rx IF
Simulator
No BB LP Rx Filter (20Hz to 10MHz)
3.2 MHz BB Rx Unit #8
4.5 MHz BB Rx Unit #2
4.5 MHz BB Rx Simulator
3.77 MHz BB Rx Unit #6
3.2 MHz BB Rx Unit #3
Bit Error Rate
RSL (dBm)
-80
-70
-60
E_b/N_o

5.2 Receive Low Pass Filtering

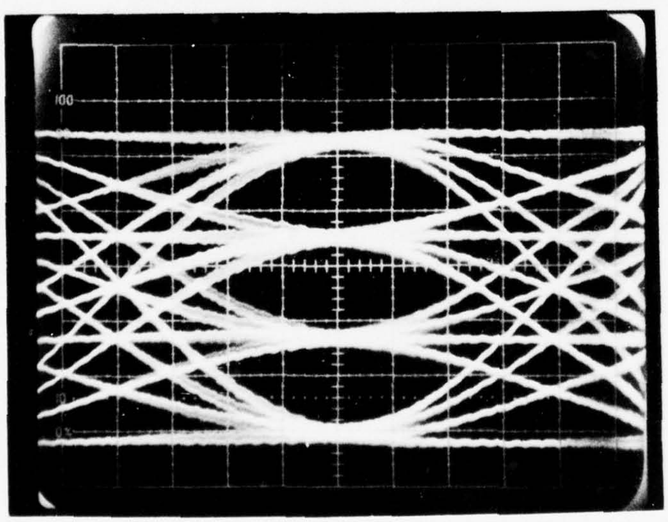
Initially 15 MHz was selected as the receiver's IF filter and performance with various baseband receive low pass filters was measured. The selection was based upon the fact that the filter is standard for the radio and closely approximates the signal's bandwidth. In addition to the baseband filters available on the simulator assembly other baseband filters were designed and constructed. In certain cases, filter pairs were constructed for testing with both transmit and receive low pass filtering. The units built were numbered for distinguishability purposes only. Figure 5.2 shows the effects on bit error rate performance of baseband low pass receive filters. The difference between the best performance obtained and no baseband filter is about 10 dB which certainly indicates that some such filtering is required. Performance varied over a range of 3 dB for the filters tested. Baseband low pass filtering should be used. To minimize changes, and thereby expense, the radio's normal 4.5 MHz filter can be used at the expense of about 3 dB in the link's fade margin over what is attainable with a more judicious choice of baseband filtering. However, considering the inexpensiveness of baseband filtering and the ease of interchange of filters, it is probably not advisable to sacrifice the 3 dB.

Figures 5.3a and 5.3b, respectively, are photos of the received eye patterns with no low pass filter and with the 3.2 MHz Bessel low pass filter unit number 3 when the 15 MHz IF filter was used. The horizontal opening indicates the range of correct sampling time, whereas the vertical dimension indicates the minimum margin against noise when sampling [12]. Therefore, with proper alignment the vertical opening at the eye's center is indicative



15 MHz IF
Receive Filter

Figure 5.3a: Received Eye Pattern - No Low Pass Filter



15 MHz IF
Receive Filter

Figure 5.3b: Received Eye Pattern - 3.2 MHz Low Pass Filter

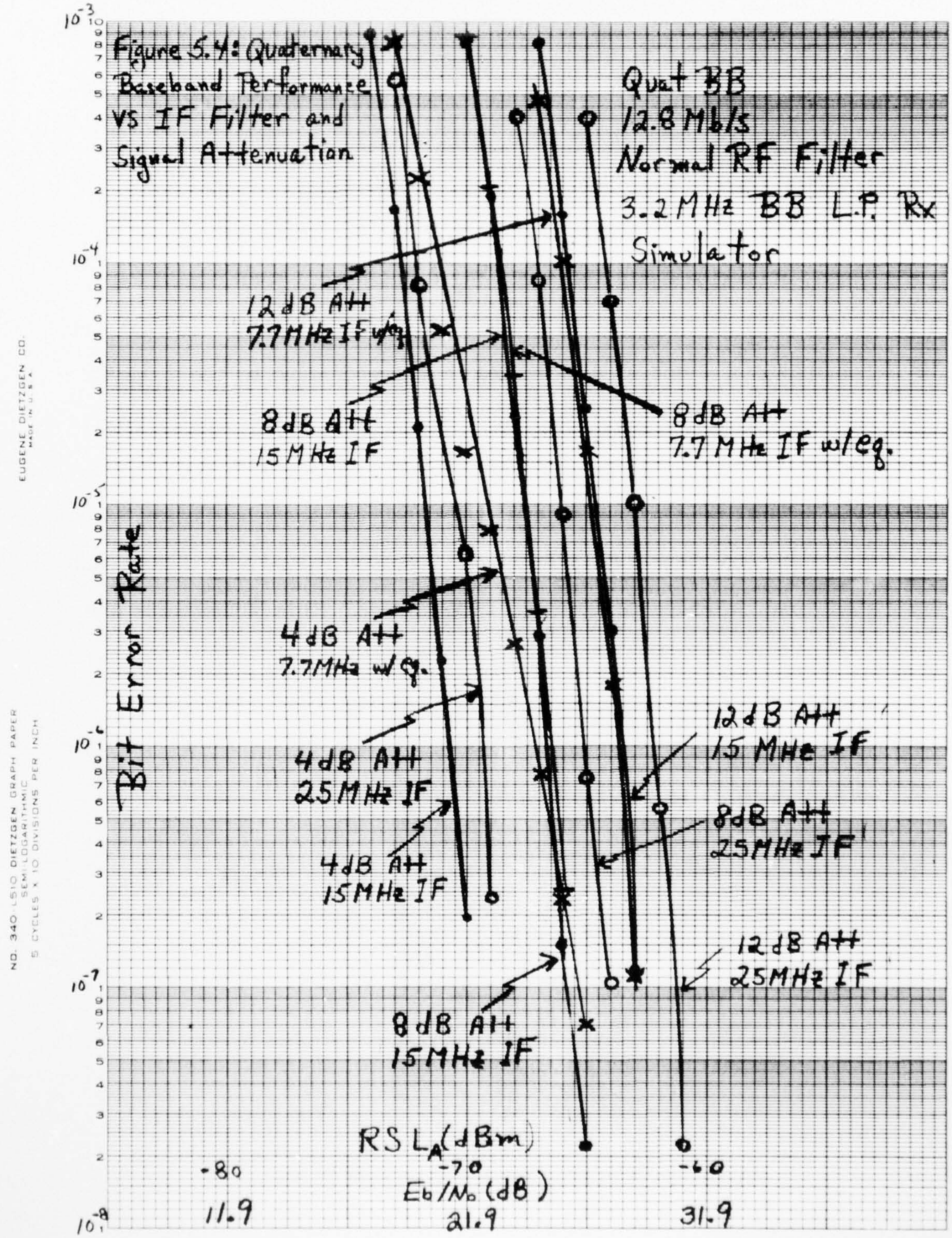
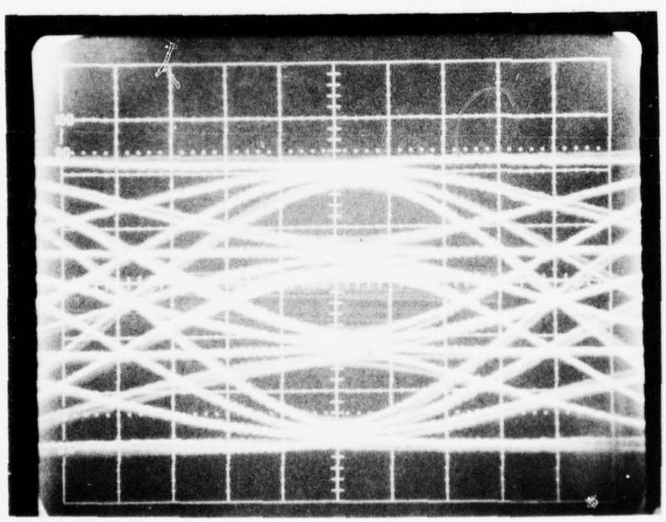


Figure 5.4: Quaternary Baseband Performance vs IF Filter and Signal Attenuation

of performance. Error rate tends to decrease rapidly as a function of closure. The relative opening of Figures 5.3a and b reflect the cause of degradation when no baseband low pass receive filter is used.

5.3 IF Filter Effects with Various Signal Attenuations

After determining that low pass filtering has a significant effect on performance, attention was given to IF filter effects. Performance was obtained not only at the 1 bps/Hz point of 4 dB signal attenuation but also for attenuations of 8 and 12 dB, the latter corresponding to the 2 bps/Hz point and the former estimated to be nearly 1.5 bps/Hz (1.47 bps/Hz from Figure 3.16). The results appear in Figure 5.4. At 1 bps/Hz the 15 MHz filter yields a clear superiority over the other two tested. Figure 5.5, the eye pattern for the 7.7 MHz IF filter, when contrasted with Figure 5.3b shows significant closure due to signal truncation. This illustrates the



7.7 MHz IF
Receive Filter

Figure 5.5: Received Eye Pattern- 3.2 MHz Low Pass Filter

cause of the 4 to 5 dB degradation of the 7.7 MHz filter relative to the 15 MHz filter. At the 1 bps/Hz packing density, 99% of the signal energy is contained in 12.8 MHz. Therefore, the 25 MHz filter is significantly wider than required. As such its performance can be expected to be inferior to the 15 MHz filter as it is by about 1 dB.

At 8 dB signal attenuation the difference between the 15 MHz and 7.7 MHz IF filters, which was observed at 1 bps/Hz, is no longer evidenced; performance of the two filters is nearly equal. This is because the 99% bandwidth of the signal is now 8.71 Hz rather than 12.38 MHz (actual measured value): the signal truncation with the 7.7 MHz filter is much less severe. The 25 MHz filter causes about 2 dB degradation.

At 2 bps/Hz performance differences among the IF filters are just about the same as the differences observed with the 8 dB signal attenuation.

It can be concluded that since in the worst case above at least 99% of the signal energy is within 12.38 MHz the 25 MHz filter is much too wide and will cause some degradation relative to the 15 MHz filter. The signal truncation caused at 1 bps/Hz by the 7.7 MHz filter becomes less significant as the packing density is increased. At 1.5 bps/Hz and 2.0 bps/Hz there is little to choose between the 7.7 MHz and 15 MHz filters.

The eye pattern pictures were taken at RSL's of about -20 dBm to show basic problems associated with certain IF and baseband low pass filters. They show

(1) signal truncation from too narrow an IF filter causes significant eye closure even in the presence of a very strong signal (Figure 5.5), and

(2) a failure to use receiver low pass filtering allows unusable energy to pass into the demodulator decision circuitry, thereby causing closure (Figures 5.3a and b).

Since the vertical opening indicates the minimum margin against noise smaller openings indicate more susceptibility to noise or fades. However, other factors need to be considered in filter selection. For example, at high RSL's a wide filter may be preferred so as to pass usable sidelobe energy. As the RSL is lowered the noise will reach a point where it starts to exceed the sidelobe energy. At such a point a narrower filter would be desirable. To actually assess relative performance via eye patterns, such patterns need to be considered at various RSL values.

5.4 Premodulation Low Pass Filters

In an attempt to assess the effects of premodulation as well as postmodulation filtering two different baseband filter pairs were selected for evaluation. Test results are shown in Figure 5.6. As seen by comparing Figures 5.2 and 5.6, the 3.77 MHz receive filter's performance is degraded by about 1.5 dB and the 3.2 MHz receive filter's performance is degraded by about 0.5 dB. However, it was previously seen (Section 3.2) that premodulation low pass filtering has an effect on bandwidth. The 5.82 MHz transmit filter has a minimal effect on bandwidth, the spectral plot is almost identical to that obtained without any transmit low pass filtering. Consequently, the packing density remains 1.0^{+} bps/Hz. When using the 3.2 MHz transmit filter a rather significant RF spectral occupancy change occurs. Calculations yield a bit packing density of 1.2 bps/Hz for this case. Thus, the apparent 0.5 dB degradation does not really exist since performance comparisons should be

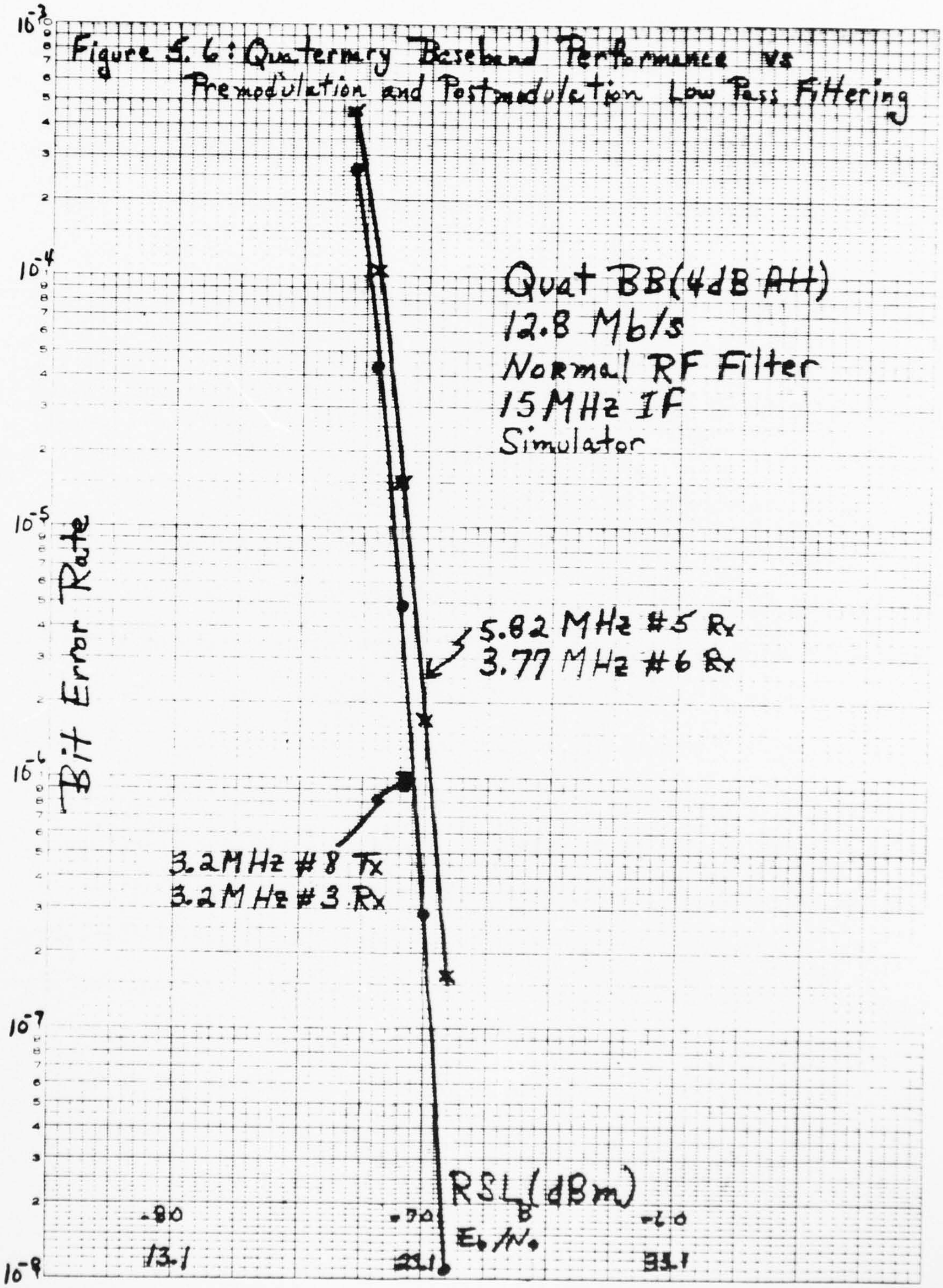


Figure 5.6: Quaternary Baseband Performance vs Premodulation and Postmodulation Low Pass Filtering
Quat BB (4dB AH)
12.8 Mb/s
Normal RF Filter
15 MHz IF
Simulator
5.82 MHz #5 Rx
3.77 MHz #6 Rx
3.2 MHz #8 Tx
3.2 MHz #3 Rx
Bit Error Rate
RSL (dBm)
E_b/N_o
-80
-70
-60
13.1
23.1
33.1
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}

made at equivalent bit packing density. A comparison of spectral plots shows only 1 dB signal attenuation is required with the 3.2 MHz transmit filter to obtain 1 bps/Hz operation. The data in Figure 5.4 and subsequent figures indicates that changing from 4 dB to 1 dB attenuation will more than compensate for the apparent 0.5 dB loss.

Premodulation low pass filtering, when properly carried out, will improve performance somewhat. However, the gains are rather small. When costs are considered transmit low pass filtering probably would not be used in most cases.

5.5 Signal Attenuation, IF and Baseband Filtering

This subsection is concerned with performance assessments of the various combinations of parameters shown in Figure 5.7. When baseband low pass receive filtering was used the 15 MHz IF filter outperformed the 10 MHz filter by about 0.7 dB at 1 bps/Hz and performance was equivalent at 2 bps/Hz. The penalty suffered in going from a density of 1 bps/Hz to 2 bps/Hz is approximately 6 dB. The large difference in performance evidenced when no low pass receive filter is used again points out the necessity of such filtering. The penalty for omitting it is severe regardless of the packing density.

It is pointed out that both occupancies are obtained for the 12.8 Mbps rate. That is, for the 2 bps/Hz density 12.8 Mbps are being sent over a 99% bandwidth of 6.4 MHz. This explains why the 10 MHz filter outperforms the 15 MHz filter so significantly at 2 bps/Hz when no low pass filter is used. With the receive low pass filter, the low pass filters effects dominate and equivalent performance is obtained.

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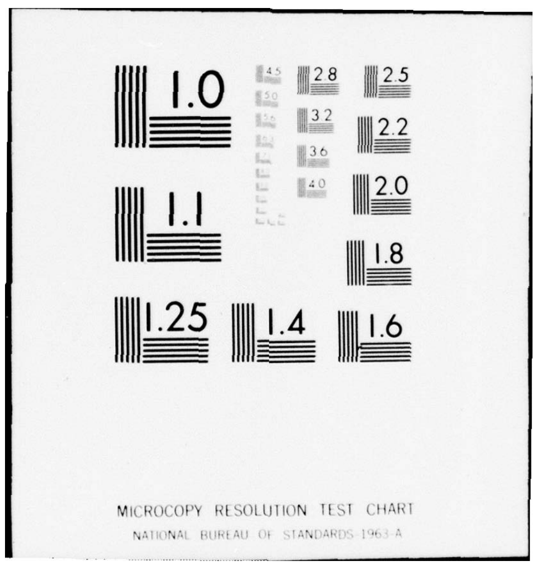
1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
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4.0
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

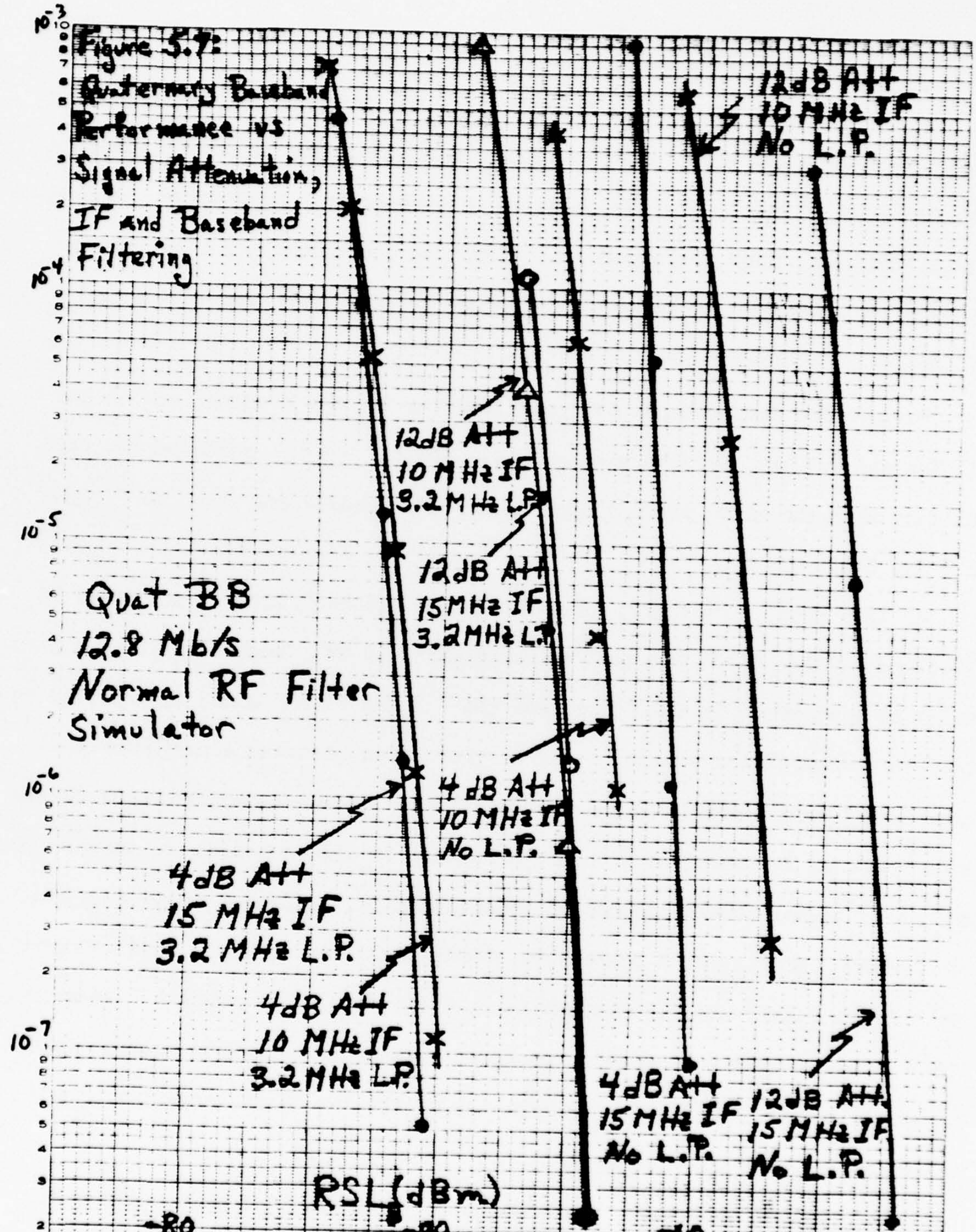


Figure 5.7: Quaternary Baseband Performance vs Signal Attenuation, IF and Baseband Filtering
Quat BB
12.8 Mb/s
Normal RF Filter Simulator
12dB Att 10 MHz IF No L.P.
12dB Att 10 MHz IF 3.2 MHz L.P.
12dB Att 15 MHz IF 3.2 MHz L.P.
4 dB Att 10 MHz IF No L.P.
4dB Att 15 MHz IF 3.2 MHz L.P.
4dB Att 10 MHz IF 3.2 MHz L.P.
4dB Att 15 MHz IF No L.P.
12dB Att 15 MHz IF No L.P.
RSL (dBm)
-80
-90
Eb/No (dB)
13.1
23.1
33.1
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}

5.6 Operation at 6.528 Mbps

Much of the system configuration testing was performed at the microwave modem rate of 6.528 Mbps. As seen (Section 5.1) 10 dB attenuation yields a density of 1.02 bps/Hz. An attenuation of 4 dB at this rate yields an estimated bandwidth (Carson's rule) of 9.56 MHz or equivalently a bit packing density of 0.68 bps/Hz. This condition was briefly addressed to further ascertain IF filter effects.

Performance measurements were made for the various combinations of the 15 MHz and 7.7 MHz IF filters and the 3.2 MHz and 4.5 MHz baseband low pass filters with the above packing densities. The results are shown in Figures 5.8 and 5.9.

At 12.8 Mbps, 4 dB signal attenuation the 99% bandwidth is contained in 12.38 MHz (Table 3.1), whereas at 6.528 Mbps, 10 dB attenuation gives a bandwidth of 6.43 MHz. In the first case the 7.7 MHz filter would be expected to perform a significant amount of signal truncation, causing a performance degradation with respect to the 15 MHz filter. At the lower rate most of the signal energy is contained within the 7.7 MHz (3 dB) bandwidth and so a minimal amount of signal truncation occurs. Consequently, it is not surprising that at a packing density of 1 bps/Hz the 15 MHz IF filter is about 4 dB better than the 7.7 MHz filter at 12.8 Mbps while at 6.528 Mbps it is about 1.7 dB worse. The 6.528 Mbps rate with 4 dB attenuation occupies a bandwidth between these two cases and so the relative performance of the two IF filters similarly should lie between them as it does.

Under optimal conditions performance for 1 bps/Hz at the two different rates should be equivalent as evidenced from a consideration of equation 5.3.

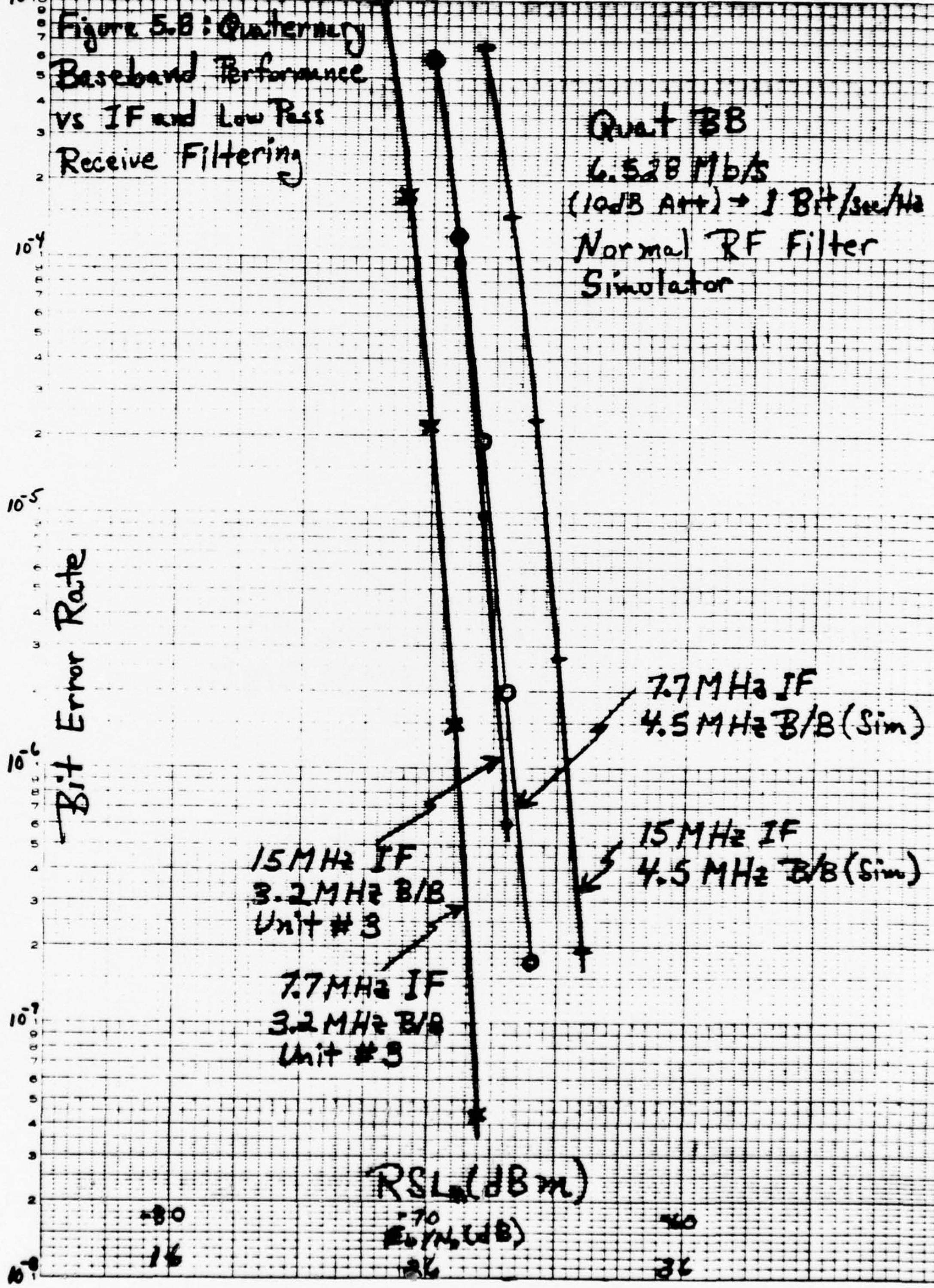


Figure 5.8: Quaternary Baseband Performance vs IF and Low Pass Receive Filtering
Quat BB
6.528 Mb/s
(10dB Att) → 1 Bit/sec/Hz
Normal RF Filter Simulator
7.7 MHz IF
4.5 MHz B/B (Sim)
15 MHz IF
4.5 MHz B/B (Sim)
15 MHz IF
3.2 MHz B/B
Unit # 3
7.7 MHz IF
3.2 MHz B/B
Unit # 3
Bit Error Rate
RSL (dBm)
-80
-70
-60
Eb/No (dB)
16
26
36
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8

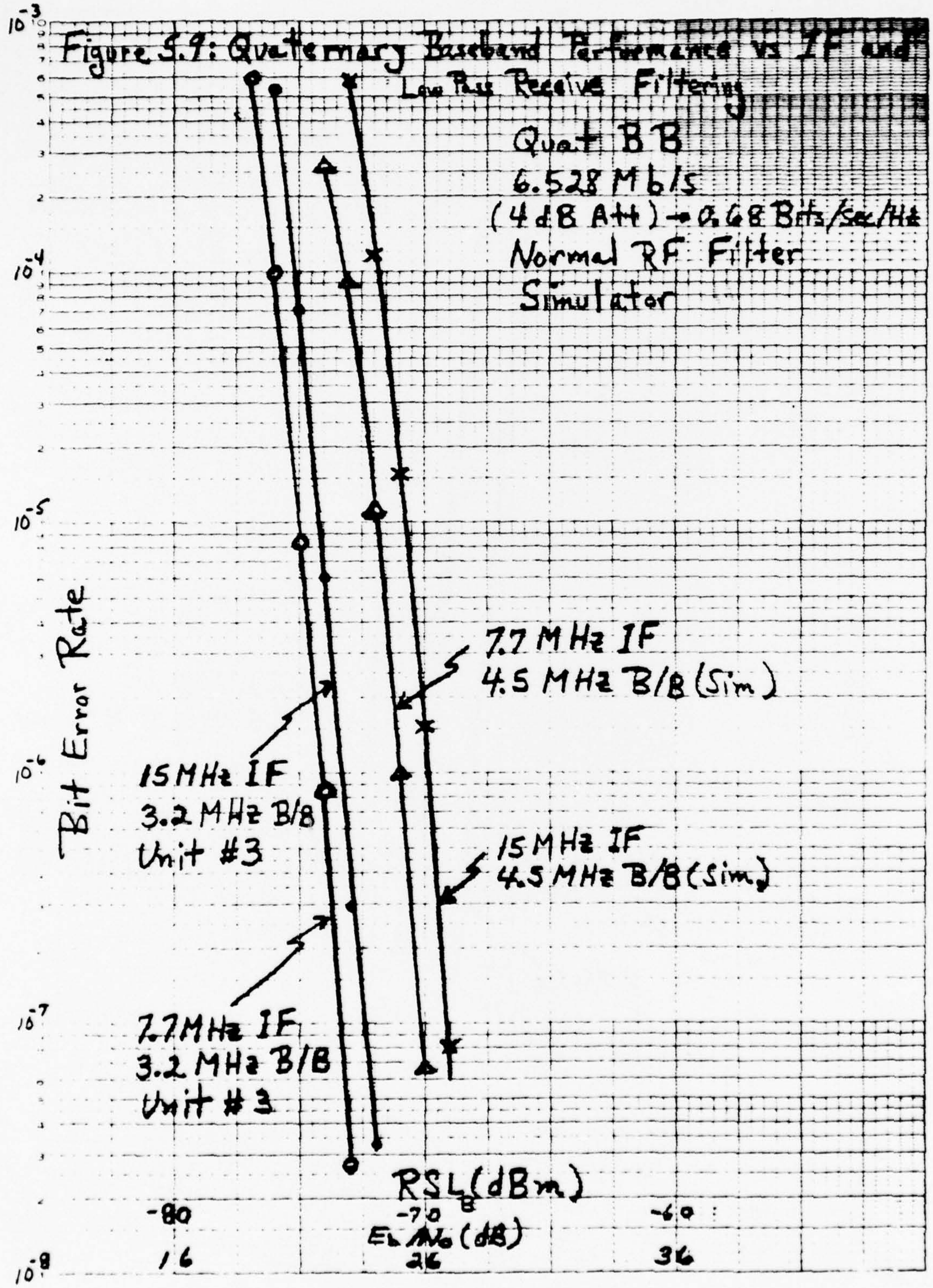


Figure 5.9: Quaternary Baseband Performance vs IF and Low Pass Receive Filtering
Quat BB
6.528 Mb/s
(4 dB Att) → 0.68 Bits/Sec/Hz
Normal RF Filter
Simulator
7.7 MHz IF
4.5 MHz B/B (Sim)
15 MHz IF
3.2 MHz B/B
Unit #3
15 MHz IF
4.5 MHz B/B (Sim)
7.7 MHz IF
3.2 MHz B/B
Unit #3
Bit Error Rate
RSL (dBm)
-80
-70
-60
Eb/No (dB)
16
26
36

Since the occupancies are slightly different about 0.5 dB difference would be expected as seen in Figure 5.1. The measurements show about a 3.2 dB difference. Low pass filtering has already been shown to significantly affect performance. The 3.2 MHz low pass filter was designed for use at the 12.8 Mbps rate. Lowering the rate to 6.528 Mbps dictates the use of a narrower filter. The performance loss at the lower rate should be recoverable with a more judicious choice of a low pass filter.

5.7 Performance vs Packing Density

Figure 5.10 illustrates the relation between performance and bandwidth. The figure shows the measured E_b/N_o required to obtain a bit error rate of $1x10^{-7}$ at 12.8 Mbps for the 10 MHz and 15 MHz IF filter and 3.2 MHz receiver low pass filter for the various packing densities. The points were taken for various data obtained throughout Phase I testing. The penalty for halving the bandwidth from 1 bps/Hz operation to 2 bps/Hz operation is 6.5 dB for the 15 MHz filter and 5.5 dB for the 10 MHz filter.

The observable fact that the error rate decreases as the bit packing decreases or equivalently as the deviation increases is not surprising. Frequency modulation is characterized by a signal-to-noise enhancement factor which is proportional to the magnitude of the modulation index: the enhancement is obtained in exchange for increased bandwidth.

5.8 Theoretical vs Experimental Data

Table 5.2 contains a comparison of theoretical and empirical performance at the 10^{-7} bit error rate point. The theoretical E_b/N_o is taken from Figure 5.1 but at the $3.33x10^{-8}$ point to adjust for the 3 to 1 increase in the error rate due to the scrambler within the modem. The empirical E_b/N_o is the best value obtained for the data taken.

Figure 5.10: Quaternary Baseband Performance vs Packing Density

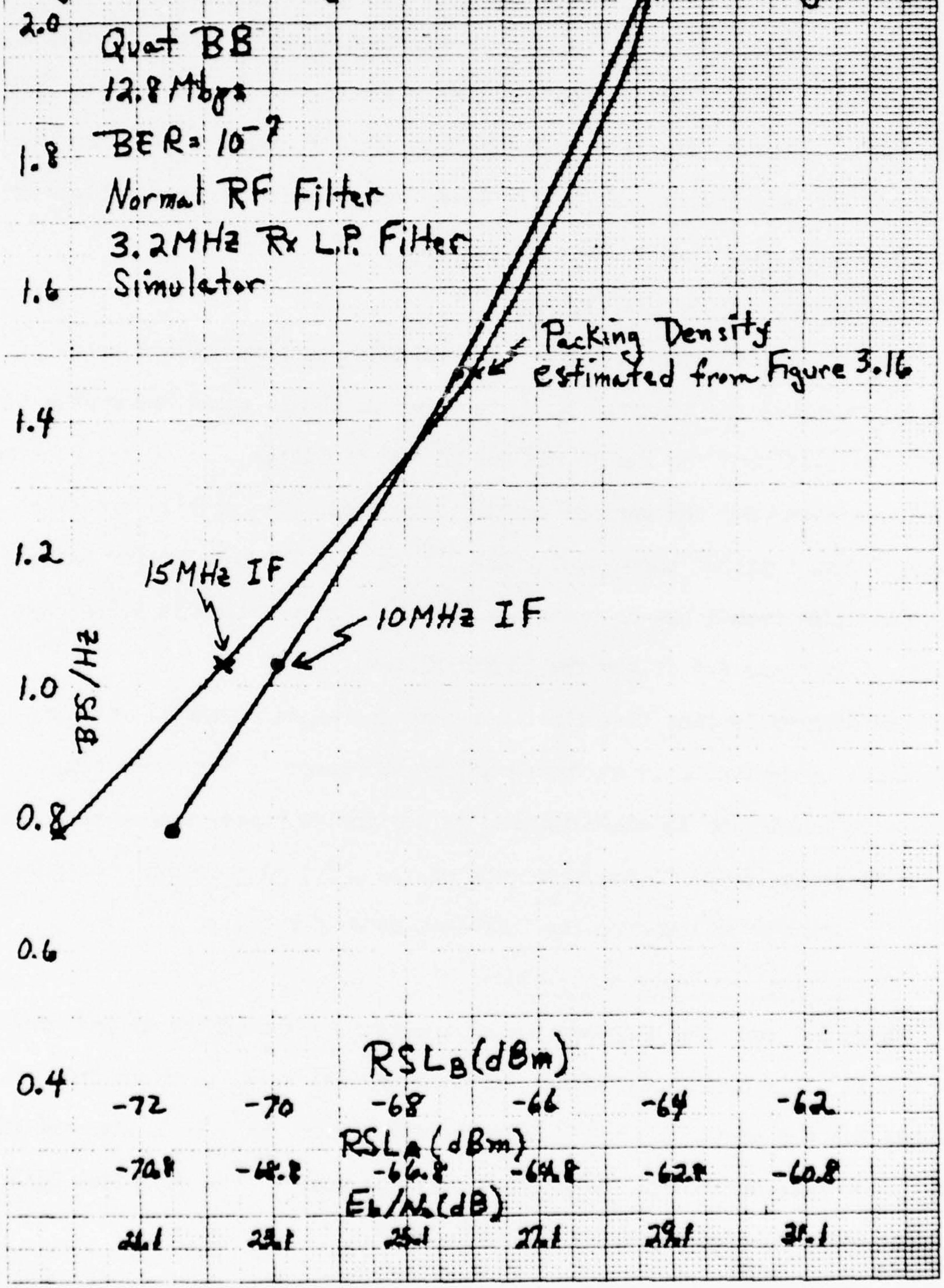


TABLE 5.2: Theoretical vs Empirical E_b/N_o for BER = 10^{-7}

RATE	21.8 Mb/s			6.52 Mb/s
Attenuation	4 dB	8 dB	12 dB	10 dB
Theoretical	14.9	17.1	19.6	15.1
Empirical	22.4	26.0	28.7	27.7
Difference	7.5	8.9	9.1	12.6

The signal-to-noise enhancement with increasing bandwidth mentioned in the previous subsection is observable in both the theoretical and experimental data. The theoretical curves are obtained under idealized assumptions. They are predicted on the employment of ideal filters compatible with the deviation and data rate. Actual performance approaching within 3 dB of theoretical is normally expected for a well designed modem. A small amount of the 7.5 dB difference at the 12.8 Mbps rate with an occupancy of 1 bps/Hz should be recoverable by premodulation low pass filtering. A postmodulation low pass filter whose response takes into account prior filtering should permit a further reduction in the difference. Finally, the IF receive filtering was selected from the choices available not from optimization considerations. With ideal filter conditions throughout the difference could perhaps be reduced to about 5 dB a quite reasonable practical figure but one which can be improved upon. Filter conditions were more optimal for the 12.8 Mbps case than the others, accounting for the smaller difference in the theoretical and actual performance. In the 6.528 Mbps case the baseband filter used is almost twice as wide as should be used for the data rate.

5.9 Multiple Radio Hops

Figure 5.11 indicates how performance degrades as a function of IF repeaters. The degradation evidenced is more severe than that measured for QPSK operation (Figure 5.6). During the contractor's in-plant testing a change in slope of the performance curves as the number of hops was increased past 4 was observed [7]. If the degradation was caused exclusively by receiver thermal noise it would be a uniform function of the number of hops. The fact that it was not and the slope changed suggests another source of noise as interference. A likely candidate is a deterioration of the transmitted signal to noise characteristic due to the lack of regeneration at the heterodyning type relays employed in the multiple hop configurations. If indeed this is the cause, performance should degrade even more rapidly as the number of hops increase. Such a noise component would become an integral part of the transmitted waveform and as such could not be compensated for by increasing the received level.

Figures 5.12 and 5.13 further identify the tradeoffs among multiple hop links which use regeneration and those which use repeaters. The system was configured either for normal 4 hop IF repeater operation, Figure 5.12, or for 4 hops with baseband regeneration on the Stockbridge to Verona path, Figure

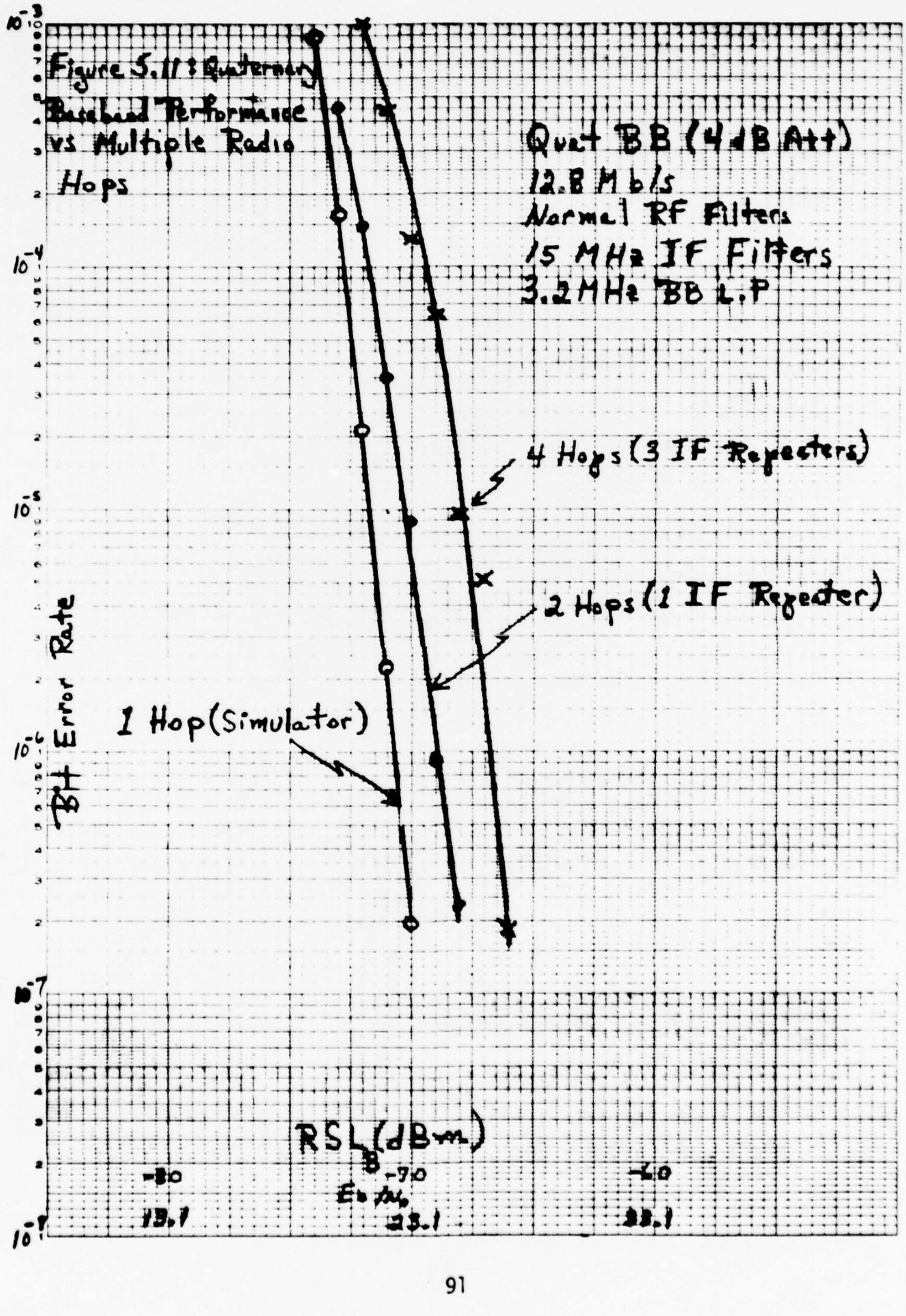


Figure 5.11: Quaternary Baseband Performance vs Multiple Radio Hops
Quat BB (4 dB Att)
12.8 Mb/s
Normal RF Filters
15 MHz IF Filters
3.2 MHz BB L.P
4 Hops (3 IF Repeaters)
2 Hops (1 IF Repeater)
1 Hop (Simulator)
Bit Error Rate
RSL (dBm)
-80
-70
-60
13.1
23.1
33.1

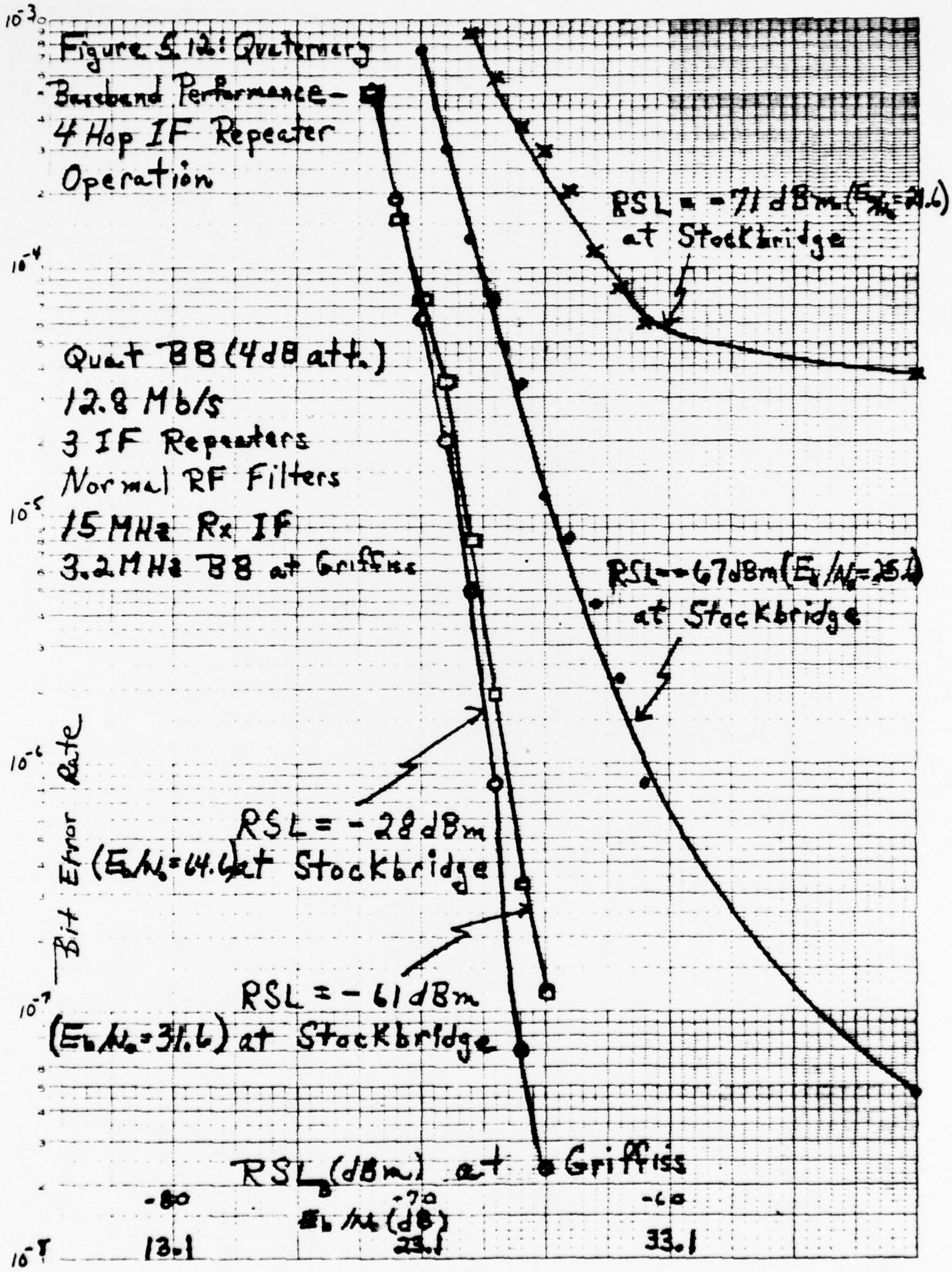


Figure 5.12: Quaternary Baseband Performance - 4 Hop IF Repeater Operation
Quat BB (4dB att.)
12.8 Mb/s
3 IF Repeaters
Normal RF Filters
15 MHz Rx IF
3.2 MHz BB at Griffiss
RSL = -71 dBm at Stockbridge
RSL = -67 dBm at Stockbridge
RSL = -28 dBm at Stockbridge
RSL = -61 dBm (E_b/N_0 = 31.6) at Stockbridge
Bit Error Rate
RSL (dBm) at Griffiss
-80
-70
-60
E_b/N_0 (dB)
13.1
23.1
33.1

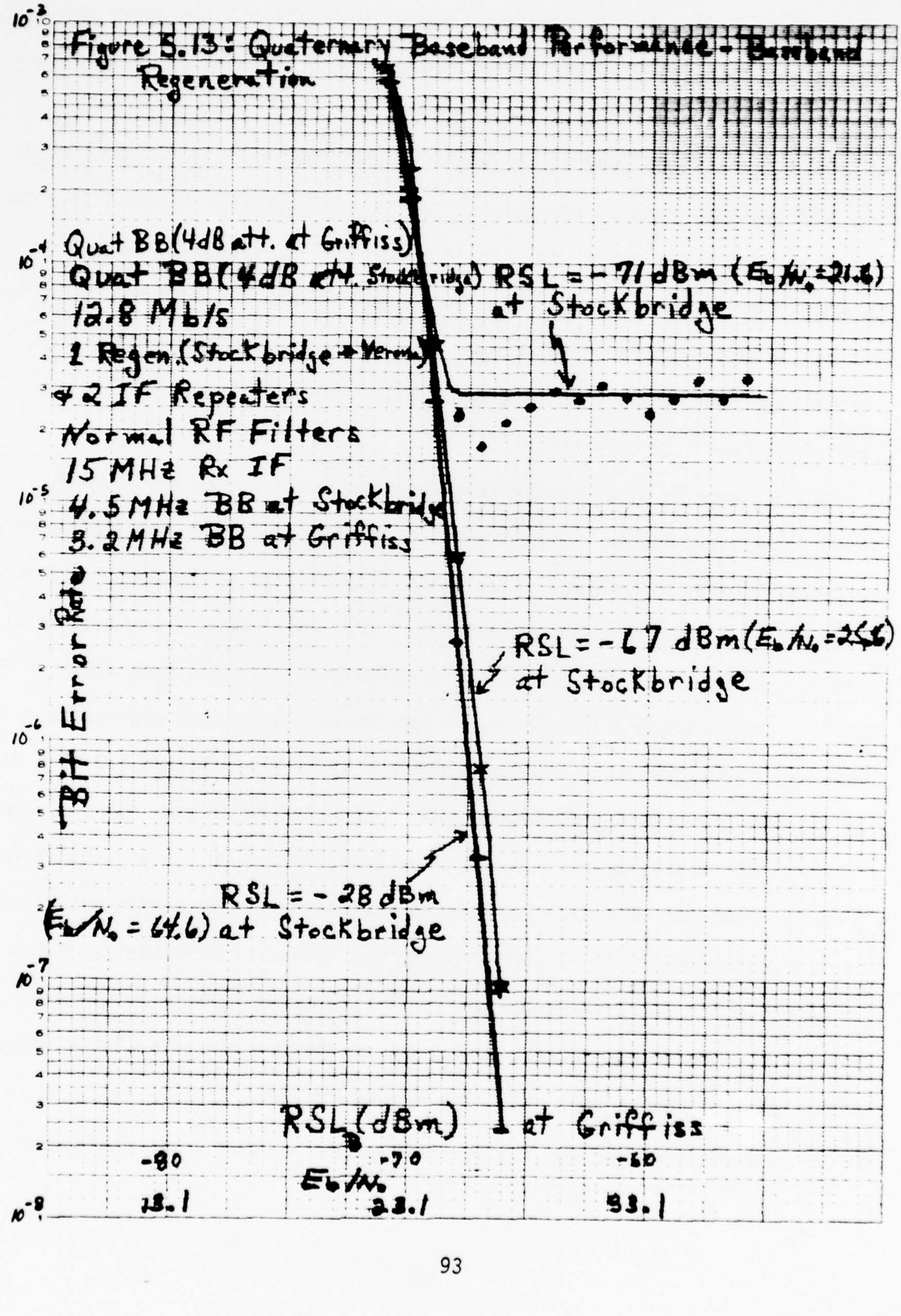


Figure 5.13: Quaternary Baseband Performance - Baseband Regeneration
Quat BB(4dB att. at Griffiss)
Quat BB(4dB att. Stockbridge)
12.8 Mb/s
1 Regen.(Stockbridge + Verona)
+ 2 IF Repeaters
Normal RF Filters
15 MHz Rx IF
4.5 MHz BB at Stockbridge
3.2 MHz BB at Griffiss
RSL = -71 dBm (E_b/N_o=21.6) at Stockbridge
RSL = -67 dBm (E_b/N_o=25.6) at Stockbridge
RSL = -28 dBm (E_b/N_o = 64.6) at Stockbridge
Bit Error Rate
RSL (dBm) at Griffiss
-80
-70
-60
E_b/N_o
13.1
23.1
33.1

5.13. In each case the data was originated at Griffiss. The power being transmitted from Griffiss was attenuated by use of the simulator assembly to obtain the levels shown in the figures.

The RSL = -28 dBm curves correspond to the full power case. As such in the 3 IF repeater case it corresponds to the 4 hop case of Figure 5.11. In the case where regeneration is used, the Griffiss to Stockbridge hop should be error free at an RSL = -28 dBm. Consequently, the curve is analogous to a 3 hop (2 IF repeaters) case because the error-free bit stream is being regenerated. Thus, the results should fall between the two and four hop cases in Figure 5.11 as they do.

As the power is attenuated errors start to occur on the Griffiss to Stockbridge hop. Figure 5.2 gave performance curves for two 4.5 MHz baseband low pass filters. Although a different 4.5 MHz filter and 15 MHz IF filter were used at Stockbridge the error rate at that point when the signal is demodulated should be comparable to the error rate obtained from Figure 5.2. The RSL (Stockbridge) = -71 dBm curve for the case involving regeneration shows an irreducible error rate of about 3×10^{-5}. From Figure 5.2 this value was obtained at an E_b/N_o = 22.6 dB. Using the 10.5 dB Stockbridge radio noise figure an RSL = -71 dBm corresponds to an E_b/N_o = 21.6 dB. A 1 dB difference is easily accounted for when one considers different filters were used, calibrations were made at two different sites and different demodulators* were used.

At the point of regeneration any errors which had already occurred are regenerated. Under good signal conditions no further errors would be expected. In this case the error rate will remain constant until the RSL at Griffiss is

*Modem checkout verified the two baseband modems yielded performance within about 0.5 dB when identical conditions were tested.

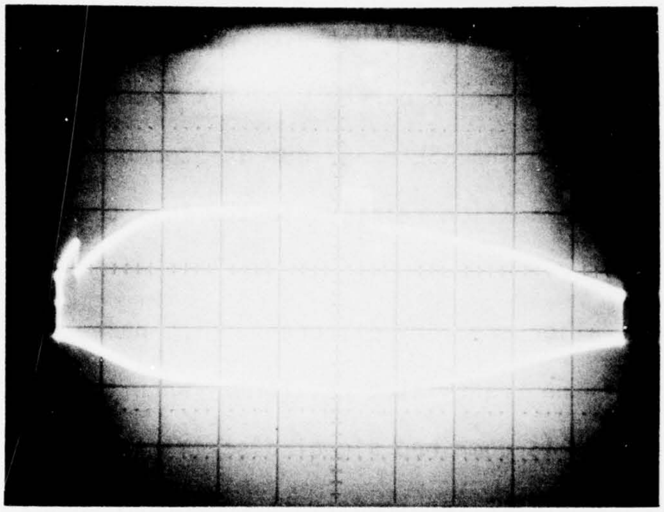
reduced to the point where new errors begin to occur. As has been stated above the last 3 hops are identically the 2 IF repeater case. When the error rate becomes high enough the significance of the original irreducible (regenerated) error rate decreases and all the curves in Figure 5.13 tend to overlap. The results show the not surprising fact that even when starting with poor signal conditions baseband regeneration can be used for the effective transfer of high speed digital data. The RSL = -67 dBm at Stockbridge only caused about 0.5 dB performance degradation relative to the full power RSL = -28 dBm conditions.

The results without regeneration are very different. The noise inherent in a reduced RSL becomes part of the transmitted waveform. When the additional degradation of the subsequent hops is combined signal discrimination becomes even more difficult. The overall effect can be seen by comparing the two cases for an RSL = -67 dBm at Stockbridge. Instead of having 0.5 dB degradation as in the case of regeneration, the degradation for a BER = 1×10^{-7} is about 12.3 dB. Under poorer channel conditions at Griffiss the relative degradation although less is still significant.

The above results indicate multi-hop repeater operation is less attractive for the baseband modem than the QPSK modem. Under the conditions indicated in Section 4.5 such operations might be considered but generally IF repeater operation should be avoided. The cost savings resulting from the elimination of a modem would result in a performance (fade margin) loss.

5.10 Signal Impairments

Thus far, the results in this section were obtained for minimal impairment conditions. Having observed (Section 4.6.1) that the special RF filter caused a lack of flatness in the amplitude characteristic for the QPSK modem, the linearity response for the quaternary baseband modem with the normal RF filter and 15 MHz IF filter was considered. Figure 5.14 shows the response. It is



Calibration

Markers = ± 5 MHz
Differential Gain = 1%/cm
Delay = 5 n sec/cm

FIGURE 5.14: Linearity Response for Quaternary Baseband Modem

essentially flat and so the conditions do correspond to minimal impairment conditions.

Figures 5.15 and 5.16 show the effects of various transmission path distortions under 2 bps/Hz operation. Based upon the point of reference values for 600 channel FDM radios given under the distortion test discussions of Section 4 the distortions simulated are larger than might reasonably be expected under normal operating conditions. Even under these severe distortion conditions, the worst case of degradation at 2 bps/Hz is seen to be less than 1.0 dB. Therefore, such signal impairments should be of little or no consequence.

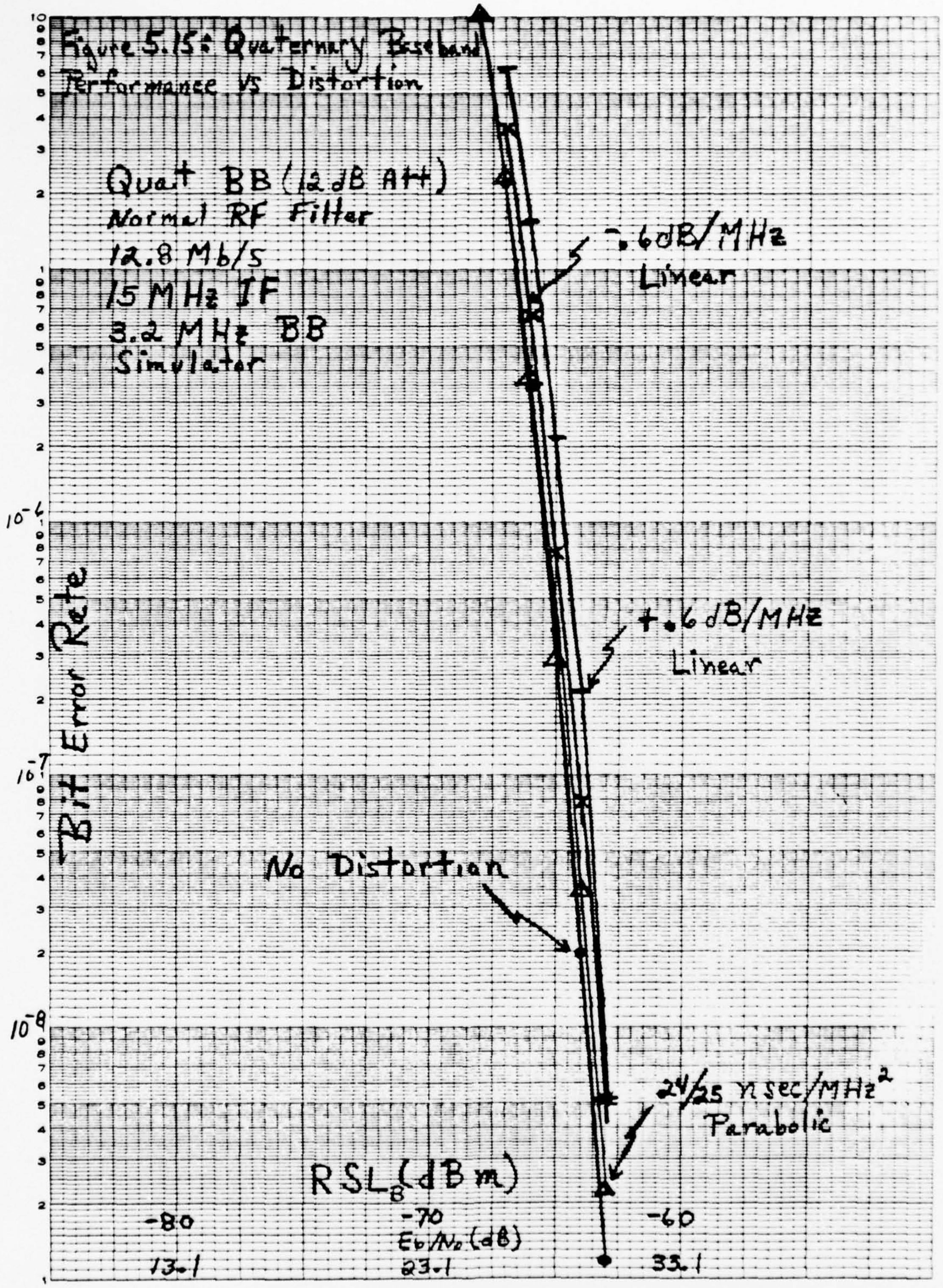


Figure 5.15: Quaternary Baseband Performance vs Distortion
Quat BB (12 dB Att)
Normal RF Filter
12.8 Mb/s
15 MHz IF
3.2 MHz BB
Simulator
-.6 dB/MHz Linear
+.6 dB/MHz Linear
No Distortion
24/25 n sec/MHz²
Parabolic
Bit Error Rate
RSL (dBm)
-80
-70
-60
Eb/No (dB)
13.1
23.1
33.1
10⁻⁶
10⁻⁷
10⁻⁸

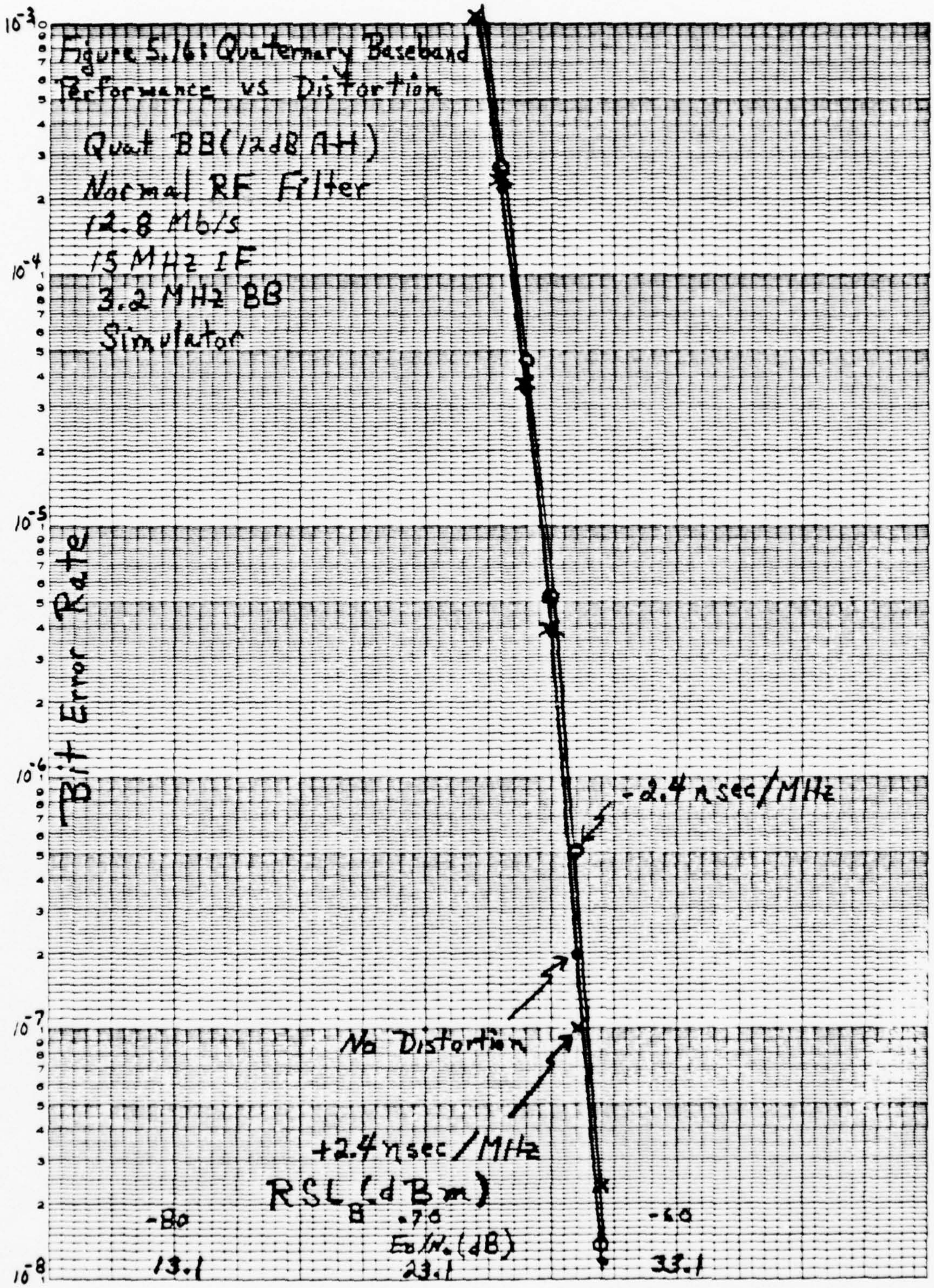


Figure 5.16: Quaternary Baseband Performance vs Distortion
Quat BB (12dB AH)
Normal RF Filter
12.8 Mb/s
15 MHz IF
3.2 MHz BB
Simulator
Bit Error Rate
-2.4 nsec/MHz
No Distortion
+2.4 nsec/MHz
RSL (dBm)
-80
-70
-60
Eb/No (dB)
13.1
23.1
33.1

When such distortions were simulated under 1 bps/Hz operation (see reference 7), the degradations were more severe. At 1 bps/Hz 99% of the energy is contained within a bandwidth of 12.8 MHz; the value for 2 bps/Hz is 6.4 MHz. Thus, the overall magnitude of the distortions simulated, from one end of the signal occupancy to the other, is larger for the wider bandwidth case, approximately twice as large for linear distortion. Considering the magnitude of the distortions simulated, transmission impairments of this type should present no operation problems at either of the bit packing densities.

5.11 External Clock Filter

In order to test the effects of clock jitter a HP 8660B Synthesized Signal Generator with an HP 86632A AM-FM plug-in modulation section was used as an external clock with various amounts of FM deviation. Test results are given in Figure 5.17. A peak-to-peak jitter of 2 KHz had no effect on performance. A relatively small amount of degradation resulted when the amount of jitter was increased to 4 KHz. Performance quickly falls off if jitter is increased any further. A clock jitter exceeding 4 KHz would not be expected and up to this point performance is minimally affected; clock jitter should be of little consequence operationally.

5.12 Frequency Offset Effects

The translation frequency into the simulator was varied from the normal 315 MHz for the 4 dB (1 bps/Hz) and 12 dB (2 bps/Hz) signal attenuation cases. The results are shown in Figures 5.18 and 5.19. The amount of degradation is comparable for the two cases. Up to 2 MHz offset causes at most 2.0 dB degradation. The QPSK modem, Figure 4.13, had carrier tracking problems for an offset as small as -0.5 MHz and had a degradation of 3.2 dB for a +0.5 MHz

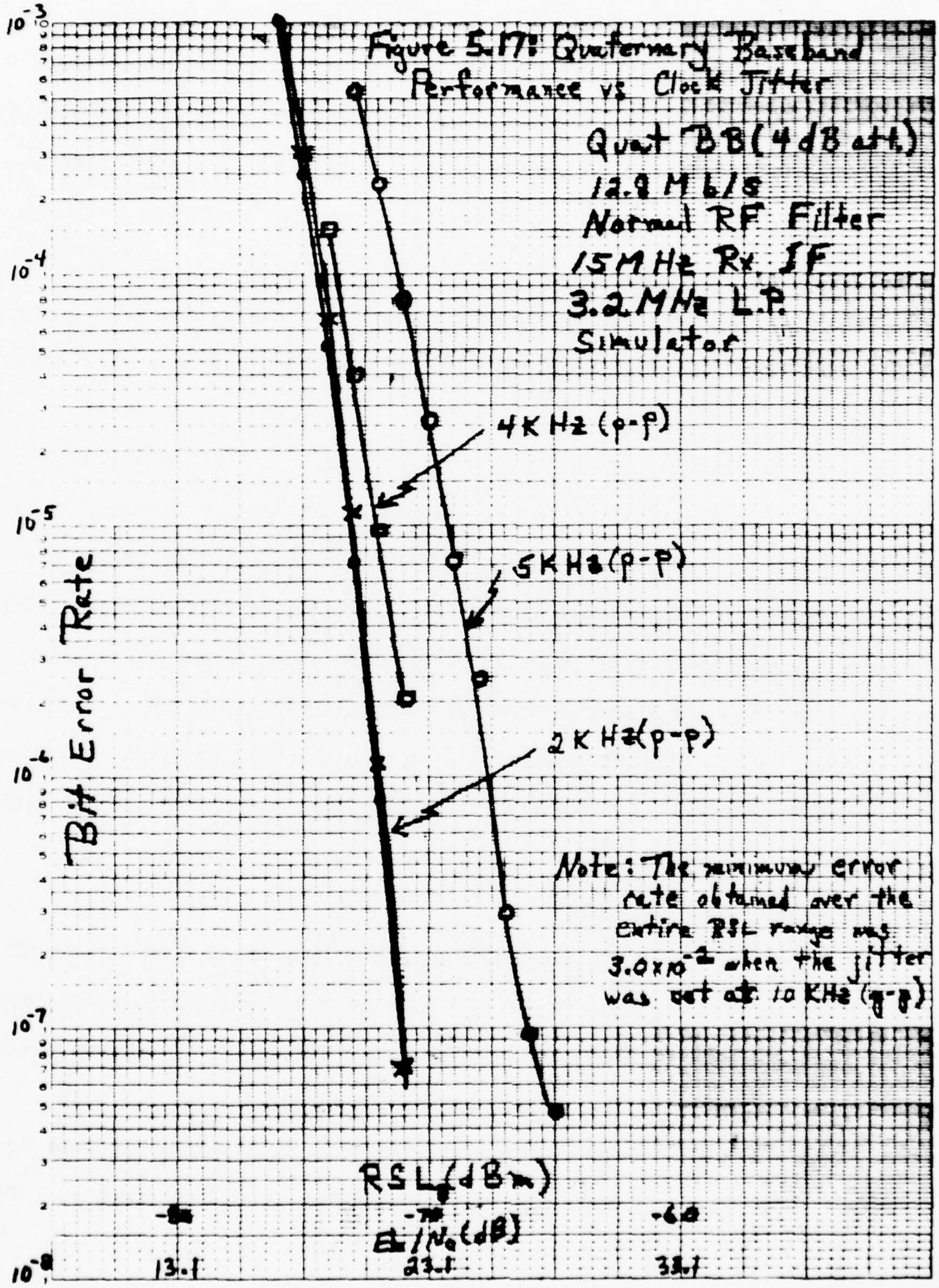


Figure 5.17: Quaternary Baseband
Performance vs Clock Jitter
Quat BB (4 dB att.)
12.9 Mb/s
Normal RF Filter
15 MHz Rx. IF
3.2 MHz L.P.
Simulator
4 KHz (p-p)
5 KHz (p-p)
2 KHz (p-p)
Note: The minimum error rate obtained over the entire RSL range was 3.0×10⁻² when the jitter was set at 10 KHz (p-p)
Bit Error Rate
RSL (dBm)
-70
-60
Eb/No (dB)
13.1
23.1
33.1
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸

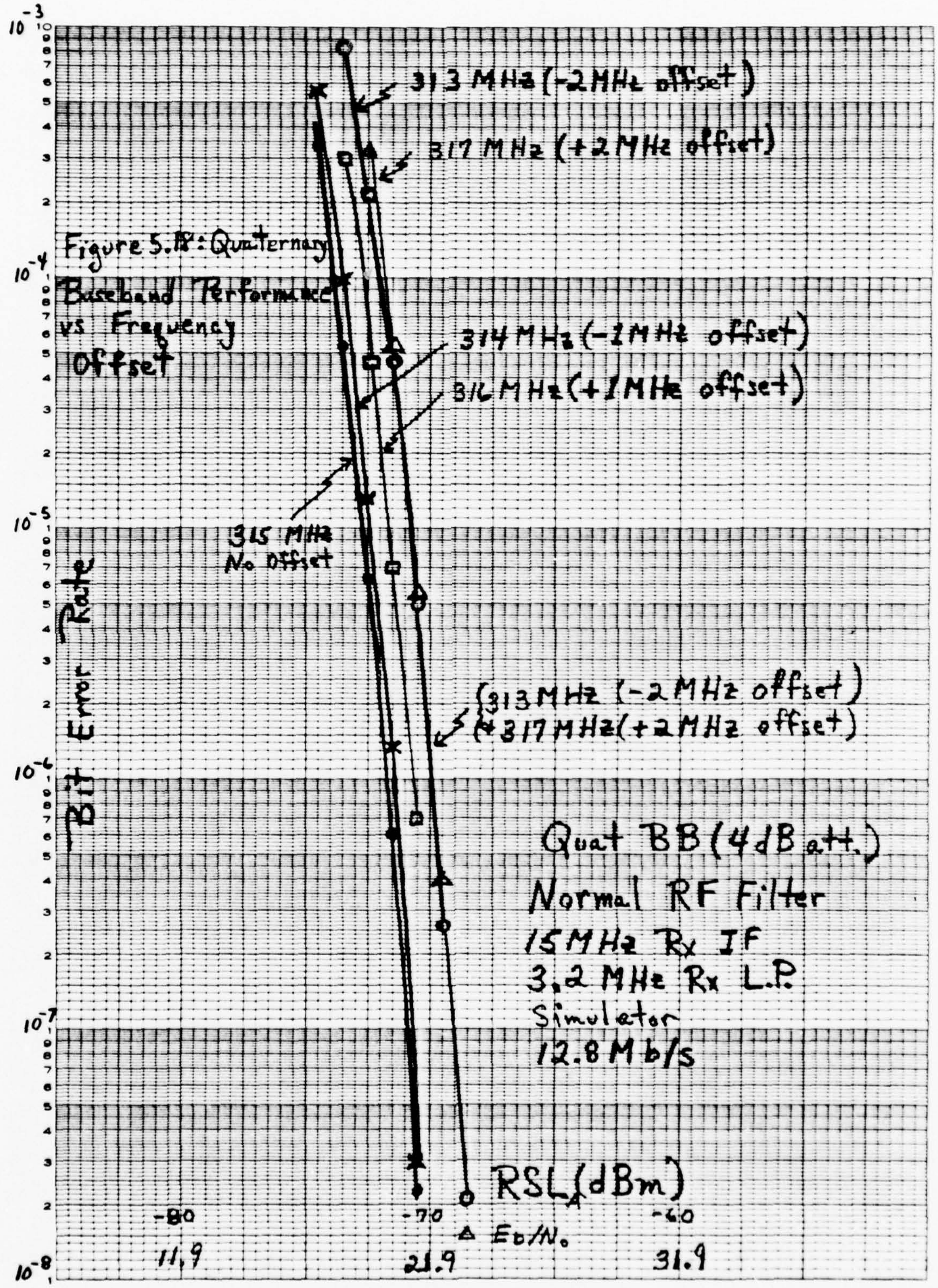


Figure 5.18: Quaternary Baseband Performance vs Frequency Offset
313 MHz (-2MHz offset)
317 MHz (+2MHz offset)
314 MHz (-1MHz offset)
316 MHz (+1MHz offset)
315 MHz No Offset
(313 MHz (-2MHz offset)
(317 MHz (+2MHz offset)
Quat BB (4dB att.)
Normal RF Filter
15 MHz Rx IF
3.2 MHz Rx L.P.
Simulator
12.8 Mb/s
Bit Error Rate
RSL (dBm)
E_b/N_o
-80
-70
-60
11.9
21.9
31.9
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}

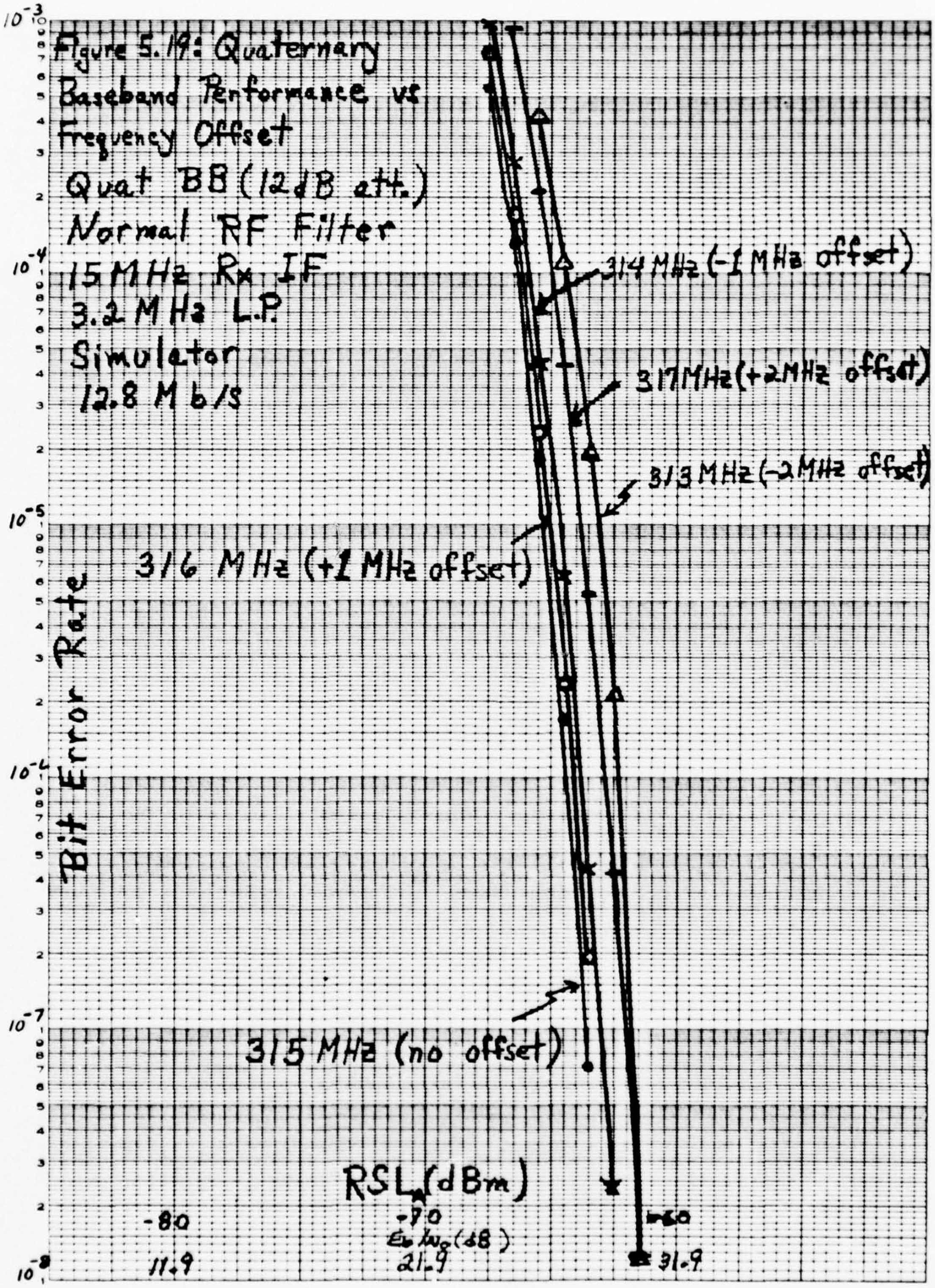


Figure 5.19: Quaternary Baseband Performance vs Frequency Offset
Quat BB (12dB att.)
Normal RF Filter
15 MHz Rx IF
3.2 MHz L.P.
Simulator
12.8 Mb/s
314 MHz (-1 MHz offset)
317 MHz (+2 MHz offset)
313 MHz (-2 MHz offset)
316 MHz (+1 MHz offset)
315 MHz (no offset)
Bit Error Rate
RSL (dBm)
-80
11.9
-70
Eb/No (dB)
21.9
-60
31.9
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8

offset. Obviously, the baseband modem is much less sensitive to frequency offset. Nonetheless, offsets of 0.5 MHz or greater should be rare occurring only when radio equipment oscillator problems are present. As long as frequency alignments are kept within tolerances little degradation should occur for either modem type.

5.13 Interfering Signals

The same basic configuration that was described in Section 4.10 was used to simulate various interference conditions. The results are described in the ensuing paragraphs.

5.13.1 Two Quaternary Baseband Signals at the Same Frequency

Figure 5.20 shows how performance varies as a function of an interfering baseband signal on the same frequency but at a different level. As mentioned (Section 4) this condition is analogous to cross-polarization operation. An irreducible error rate of about 1×10^{-3} occurs when the interfering signal is 13 dB down. For a cross-polarization isolation of 16 dB about 6.7 dB degradation occurs at the 1×10^{-7} point. The degradation then quickly drops off as the interfering signal level is lowered. The results, when compared to the QPSK results under similar test conditions (Figure 4.15), show a much higher susceptibility to interference. Nonetheless, cross-polarization operation still represents a viable technique for doubling data rates on many microwave links. Its applicability to specific links can be determined from the experimental data provided cross-polarization discrimination data is available.

5.13.2 Two Quaternary Baseband Signals at Different Frequencies

Figures 5.21 and 5.22 show the effect an equal amplitude signal offset in frequency has on performance in the 1 and 2 bps/Hz cases. The signals had

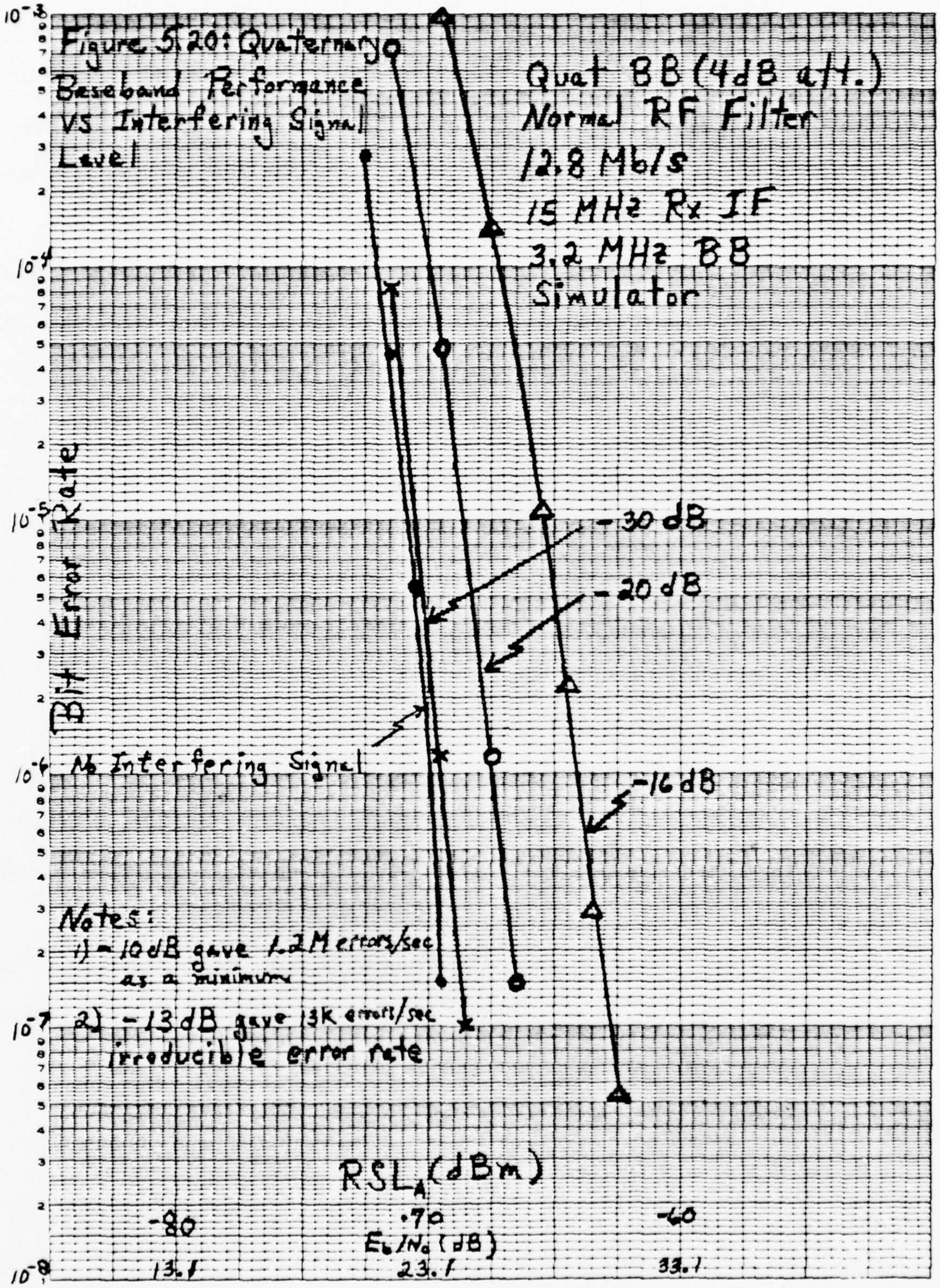


Figure 5.20: Quaternary Baseband Performance VS Interfering Signal Level
Quat BB (4dB att.)
Normal RF Filter
12.8 Mb/s
15 MHz Rx IF
3.2 MHz BB
Simulator
-30 dB
-20 dB
-16 dB
No Interfering Signal
Notes:
1) -10dB gave 1.2M errors/sec as a minimum
2) -13dB gave 13K errors/sec irreducible error rate
Bit Error Rate
RSL$_A$ (dBm)
-80
-70
-60
E_b/N_o (dB)
13.1
23.1
33.1
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}

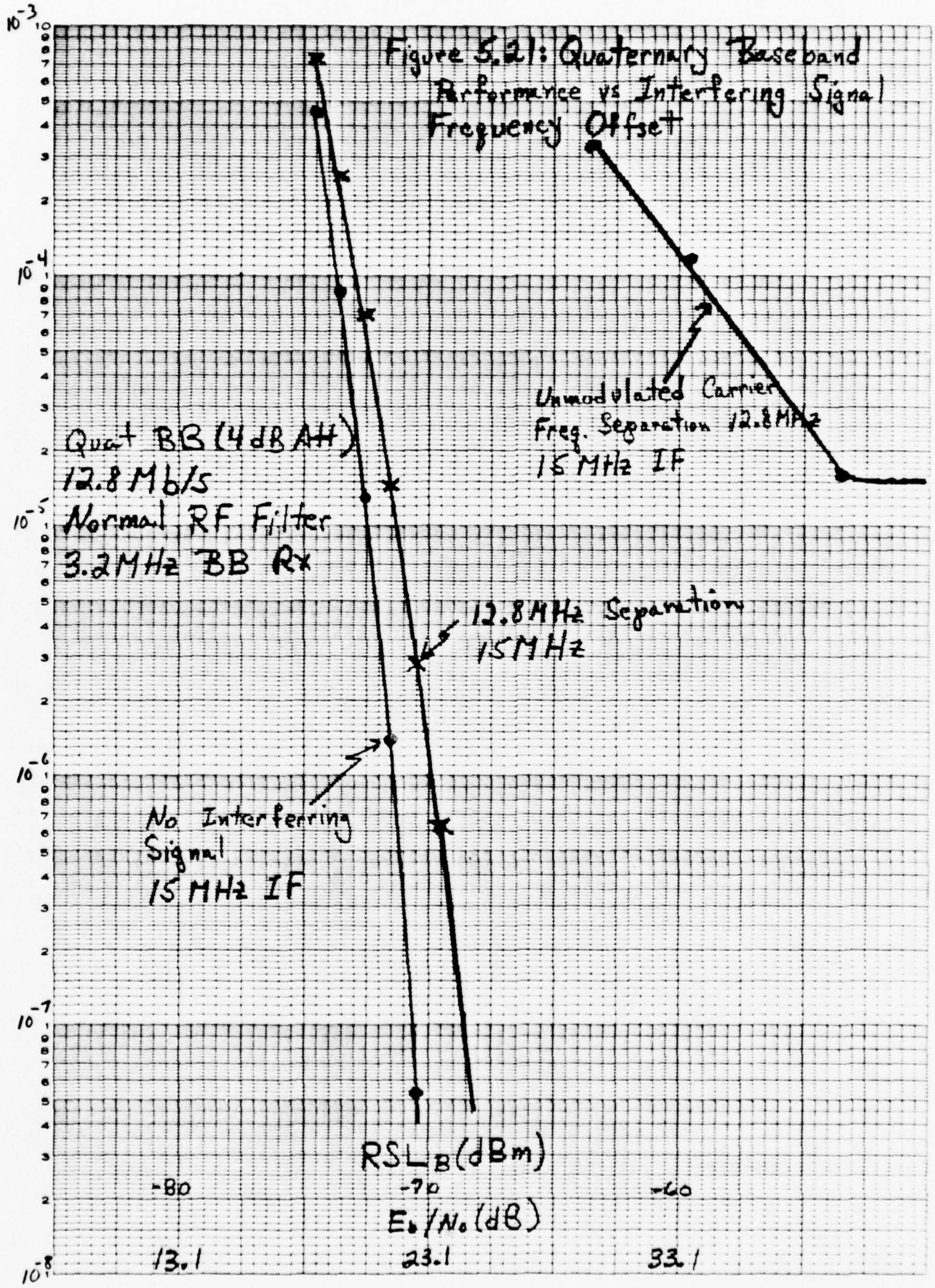


Figure 5.21: Quaternary Baseband Performance vs Interfering Signal Frequency Offset
Quat BB (4dB AH)
12.8 Mb/S
Normal RF Filter
3.2MHz BB Rx
Unmodulated Carrier
Freq. Separation 12.8MHz
15 MHz IF
12.8MHz Separation
15MHz
No Interferring Signal
15 MHz IF
RSL_B (dBm)
-80
-70
-60
Eb/No (dB)
13.1
23.1
33.1
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8

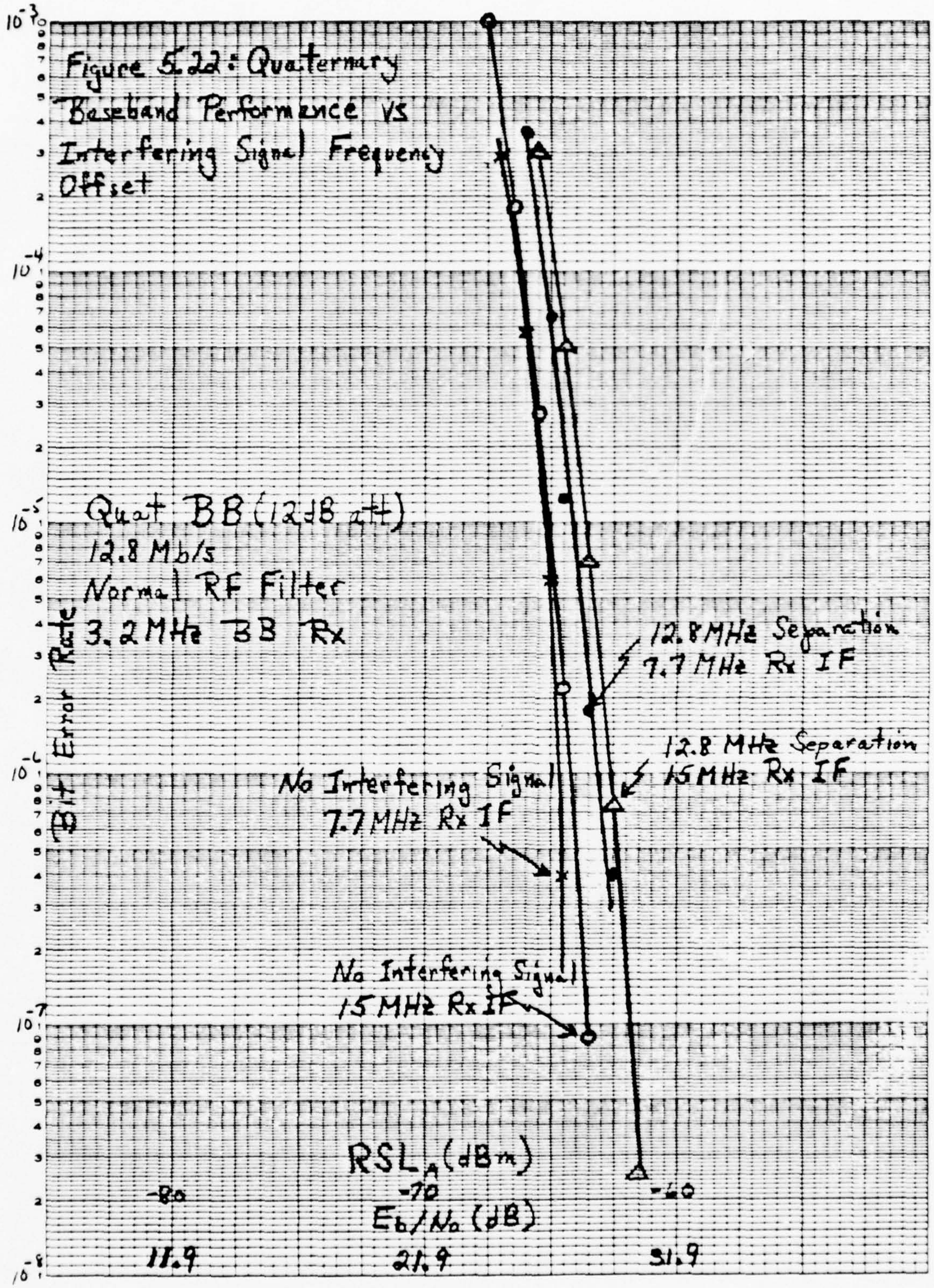


Figure 5.22: Quaternary Baseband Performance vs Interfering Signal Frequency Offset
Quat BB (12 dB att)
12.8 Mb/s
Normal RF Filter
3.2 MHz BB Rx
12.8 MHz Separation
7.7 MHz Rx IF
12.8 MHz Separation
15 MHz Rx IF
No Interfering Signal
7.7 MHz Rx IF
No Interfering Signal
15 MHz Rx IF
Bit Error Rate
RSL (dBm)
-80
-70
-60
Eb/No (dB)
11.9
21.9
31.9

nearly a 50% error rate over the entire range when the offset was 6.4 MHz. When an unmodulated carrier at 12.8 MHz frequency separation was used, an irreducible error rate of 1.5×10^{-5} was evidenced. With modulation and 12.8 MHz separation the measured degradation from the no interference case at a 1×10^{-7} error rate is only 1.9 dB for the 1 bps/Hz case and slightly less for the 2 bps/Hz case. Since Figure 5.4 shows almost identical performance for the 7.7 MHz and 15 MHz IF filters at 2 bps/Hz it was felt one may be preferable to the other under the conditions tested. As can be seen from the data the IF filter selection (of the two tested) makes little difference.

Unless a user is operating outside authorized bandwidths or under very unusual atmospheric conditions, the separation of an interfering signal will exceed the separations investigated and will cause even less degradation. than that shown in the figures. Operationally, such interfering signals on other frequencies should cause no problems for the modem.

5.13.3 FDM Signals

Having seen that digital traffic in adjacent bandwidths should be of no consequence, the effects of analog and digital traffic in adjacent bandwidths are considered. Analog FDM signal conditions are as described in Section 4.10.3.

Figure 5.23 shows the FDM signal's effect on the baseband modem's 1 bps/Hz performance. If the FDM signal is offset sufficiently, minimal to no performance loss occurs. Clearly 12.8 MHz offset is not sufficient; an irreducible error of about 2.5×10^{-4} occurs. When the data is compared to Figure 4.17, the comparable figure for the QPSK modem, it is evident that the baseband modem is more susceptible to interference from an analog source. Nonetheless, when the

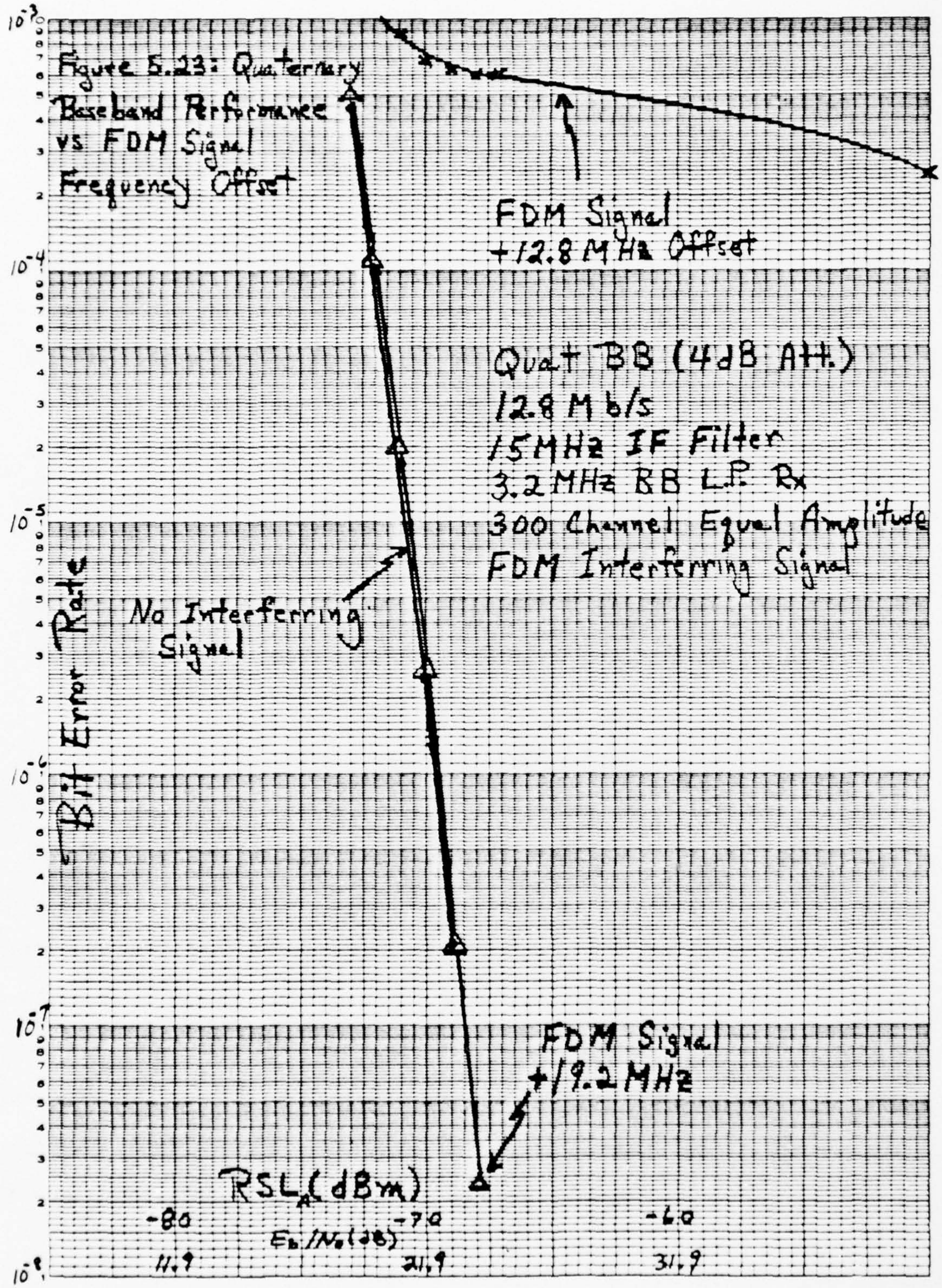


Figure 5.23: Quaternary Baseband Performance vs FDM Signal Frequency Offset
FDM Signal
+12.8 MHz Offset
Quat BB (4dB Att.)
12.8 Mb/s
15MHz IF Filter
3.2MHz BB L.P. Rx
300 Channel Equal Amplitude
FDM Interferring Signal
No Interferring Signal
Bit Error Rate
FDM Signal
+19.2 MHz
RSL (dBm)
-80
-70
-60
Eb/No(dB)
11.9
21.9
31.9

FDM signal was offset by 19.2 MHz no degradation whatsoever was observed in the baseband case. Hence, no operational problems with the modem are expected due to the analog transmission.

Next, the effects of digital traffic on analog FDM is addressed for the quaternary baseband modem at 1 bps/Hz operation. The experimental results are given in Figures 5.24a and b. They indicate a somewhat higher degradation in NPR than was evidenced when the QPSK modem was used. But operational frequency separations are sufficient to permit analog and digital transmission in adjacent channels with little or no degradation.

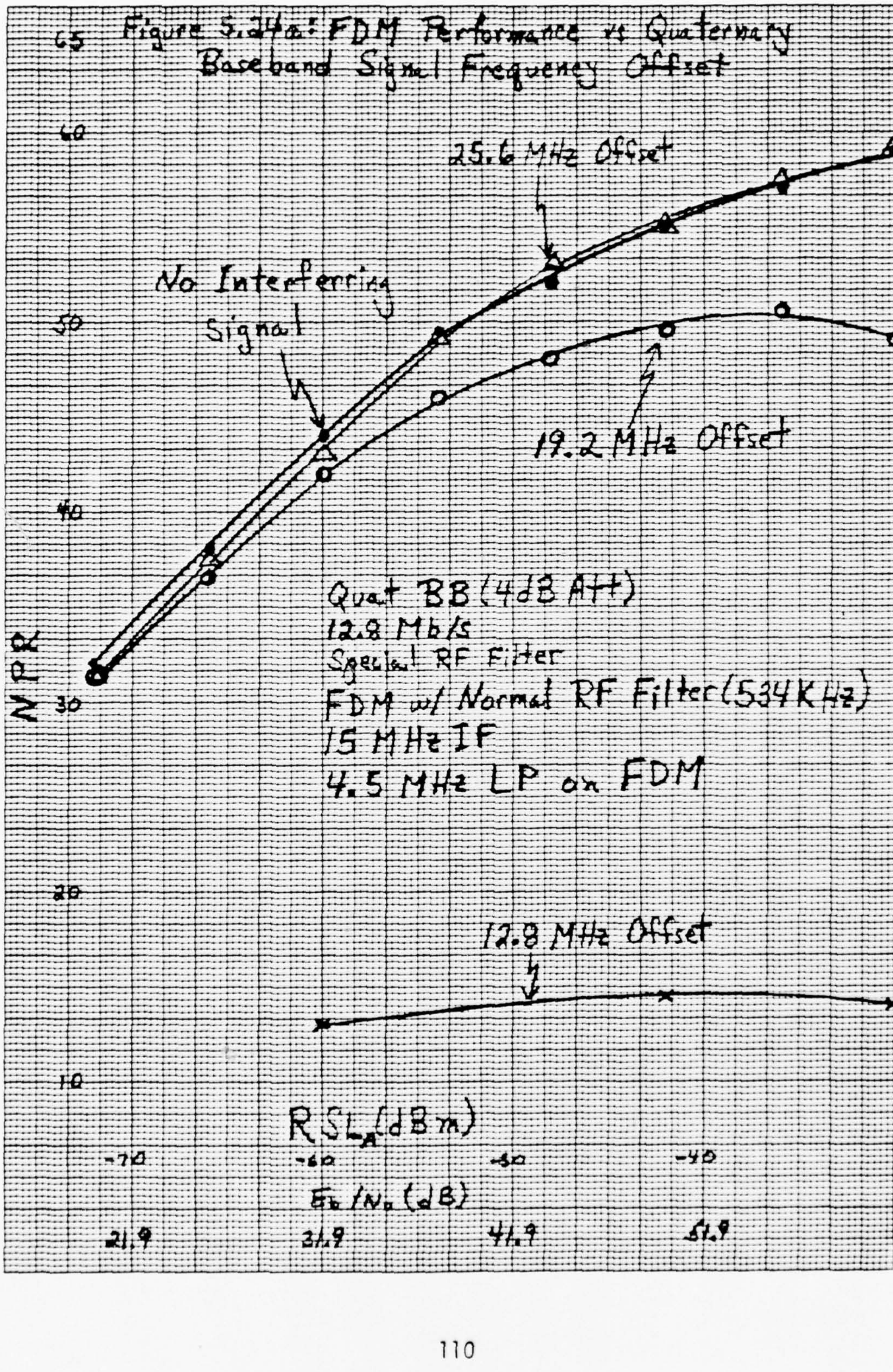


Figure 5.24a: FDM Performance vs Quaternary Baseband Signal Frequency Offset
65
60
50
40
30
20
10
25.6 MHz Offset
No Interferring Signal
19.2 MHz Offset
Quat BB (4dB Att)
12.8 Mb/s
Special RF Filter
FDM w/ Normal RF Filter (534KHz)
15 MHz IF
4.5 MHz LP on FDM
12.8 MHz Offset
NPR
RSL$_A$ (dBm)
-70
-60
-50
-40
E_b/N_o (dB)
21.9
31.9
41.9
51.9

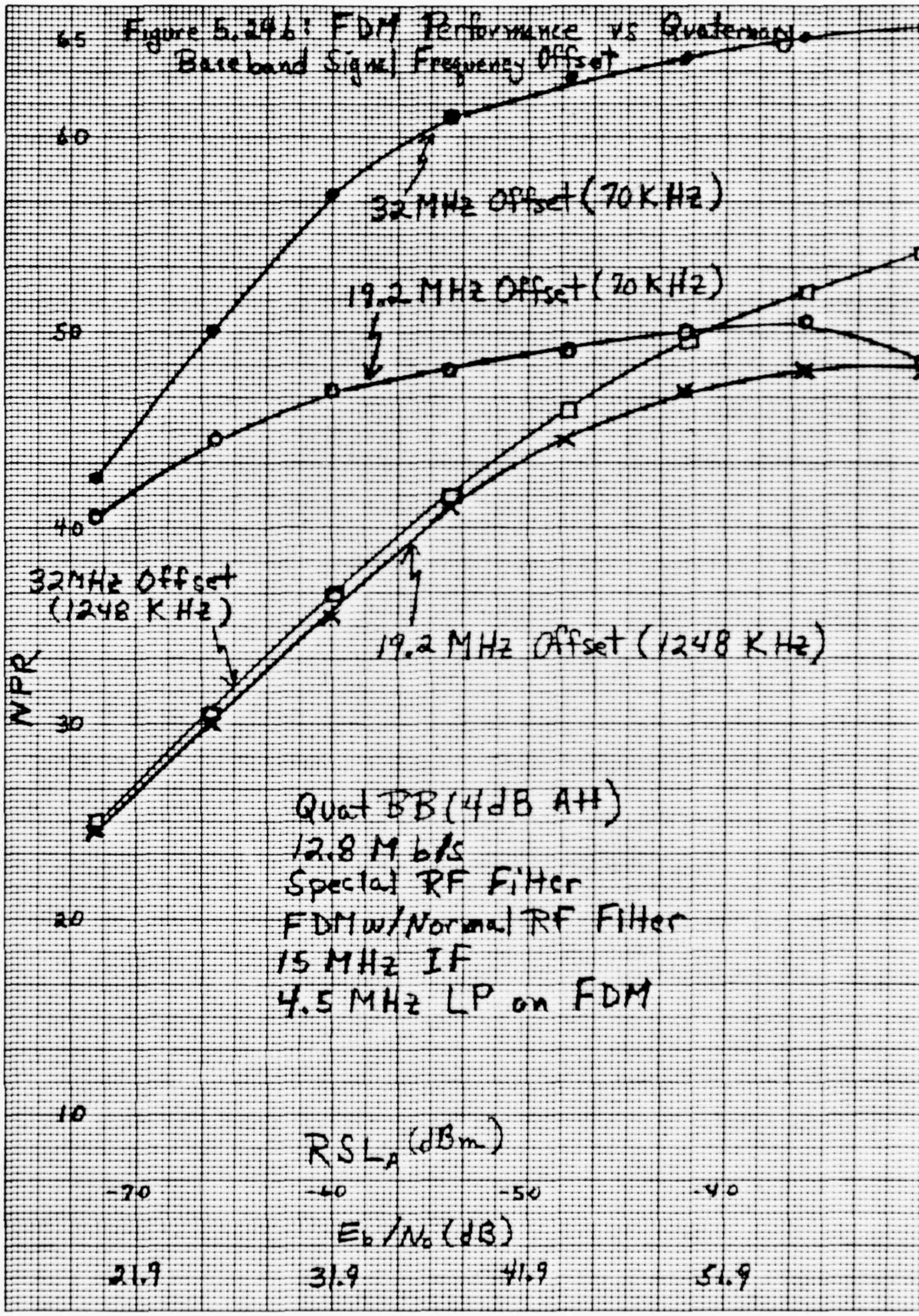


Figure 5.24b: FDM Performance vs Quaternary Baseband Signal Frequency Offset
65
60
50
40
30
20
10
NPR
32 MHz Offset (70 KHz)
19.2 MHz Offset (70 KHz)
32MHz Offset (1248 KHz)
19.2 MHz Offset (1248 KHz)
Quat BB (4dB Att)
12.8 Mb/s
Special RF Filter
FDM w/Normal RF Filter
15 MHz IF
4.5 MHz LP on FDM
RSL$_A$ (dBm)
-70
-60
-50
-40
E_b/N_o (dB)
21.9
31.9
41.9
51.9

SECTION 6

SYSTEM TESTS

6.0 Introduction

The performance of various parts of future type digital network configurations has thus far been described in this report and the various other Phase I interim technical reports. Particular emphasis in the previous sections has been given to performance evaluations of the two modem types when the microwave radio and link parameters are varied.

This section describes the results obtained when the digital equipments were tandemed. Certain incompatibilities were surfaced which necessitated equipment modifications. These incompatibilities and the overall system test results and conclusions are addressed here.

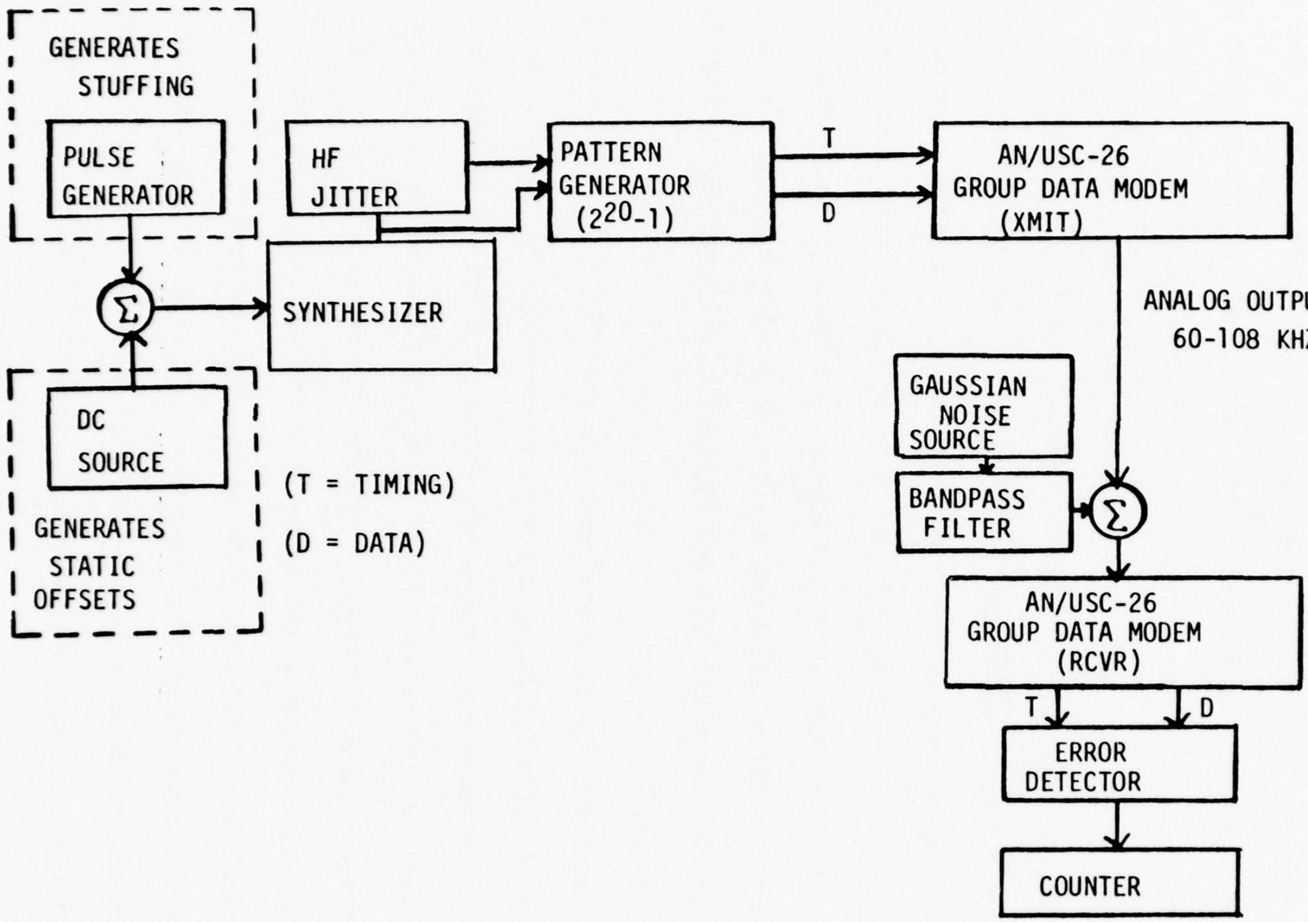
6.1 AN/USC-26 - AN/GSC-24 Interface

The AN/USC-26 GDM and the AN/GSC-24 ATDM were two equipments specifically identified by DCA as requiring testing under the program. Initial attempts to interface these equipments uncovered major compatibility problems. The cause was the relationship between the asynchronous stuffing technique used in the ATDM and the extremely tight rate recovery circuitry in the GDM. Comments are made relative to the engineering design models (EDM's) of the ATDM, which were to be used in the system tests, and to the production models ATDM which were not yet available during the Phase I tests.

In early testing with the EDM the GDM could not track the phase variations at the ATDM output. These phase variations result from the technique used within the ATDM to provide the asynchronous capability. Bits from the data source are placed in an elastic buffer at the input of the ATDM. The data bits are removed from the buffer at a fixed sampling rate determined by the ATDM configuration. When the incoming rate is higher than the sampling rate, the excess bits which accumulate in the buffer are removed and transferred to the demultiplexer through the overhead channel then stuffed back into the correct position in the output bit stream. The stuffing action causes an instantaneous 2π phase step. For input rates below the sample rate, the buffer begins to empty so one bit is occasionally deliberately sampled twice. At the demux side the redundant bit is removed, again causing a 2π phase step. The demux smoothing buffer in the EDM, which is controlled by a first order digital phase locked loop (DPLL), smooths these phase steps by spreading them out over a 768 bit interval (effectively a 2π in 768 bit time phase slew rate). Specifically, for rates up to 512 Kbps it increases (or decreases) the length of every 32nd bit by 1/24th of a bit time until a full bit time is added (or deleted). Above 512 Kbps a 1/12th bit time correction is made at 64 bit intervals.

When the GDM was interfaced with the ATDM using this smoothing technique loss of bit count integrity resulted even with the modem connected back-to-back. A short test program was then run on the GDM to determine its response to various slew rates. The test configuration is shown in Figure 6.1. The worst case and, therefore, compatibility determining rate is 153.6 Kbps. The bandlimited noise on the analog side was set at a level which provided a typical 1×10^{-5} bit error rate in back-to-back operation at the 153.6 Kbps rate and different rates of slewing were applied on the digital side. The test results are shown in Figure 6.2. Bit error rate versus E_b/N_o performance results were also obtained and are plotted in Figure 6.3. From the curves a

FIGURE 6.1: GDM PERFORMANCE VS SLEW RATE TEST CONFIGURATION



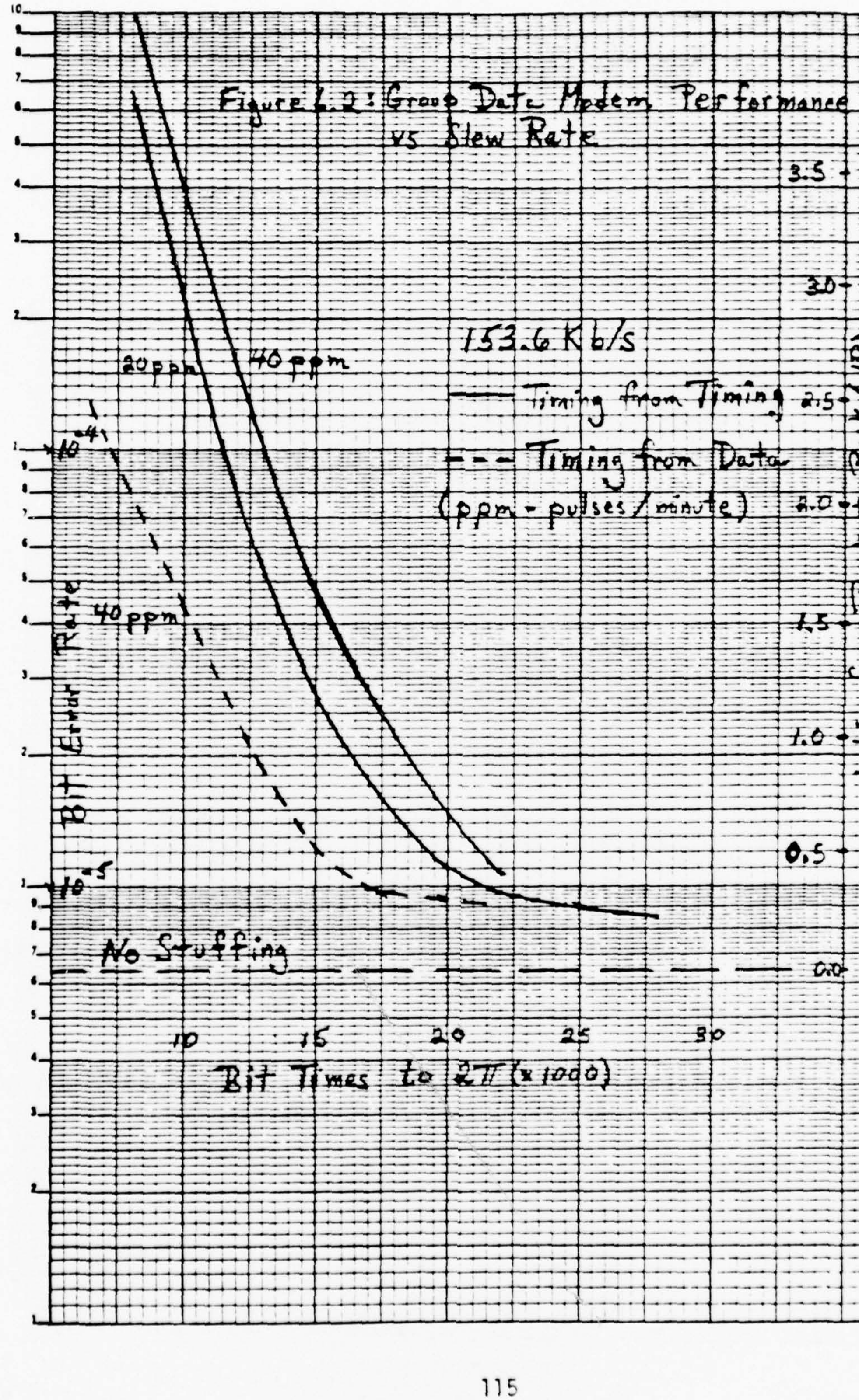


Figure 2.2: Group Data Modem Performance vs Slew Rate
153.6 Kb/s
20 ppm
40 ppm
40 ppm
Timing from Timing
Timing from Data
(ppm - pulses/minute)
10^{-4}
10^{-5}
No Stuffing
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
10
15
20
25
30
Bit Times to 2π (x 1000)
Bit Error Rate
Degradation from Back-to-Back (dB)

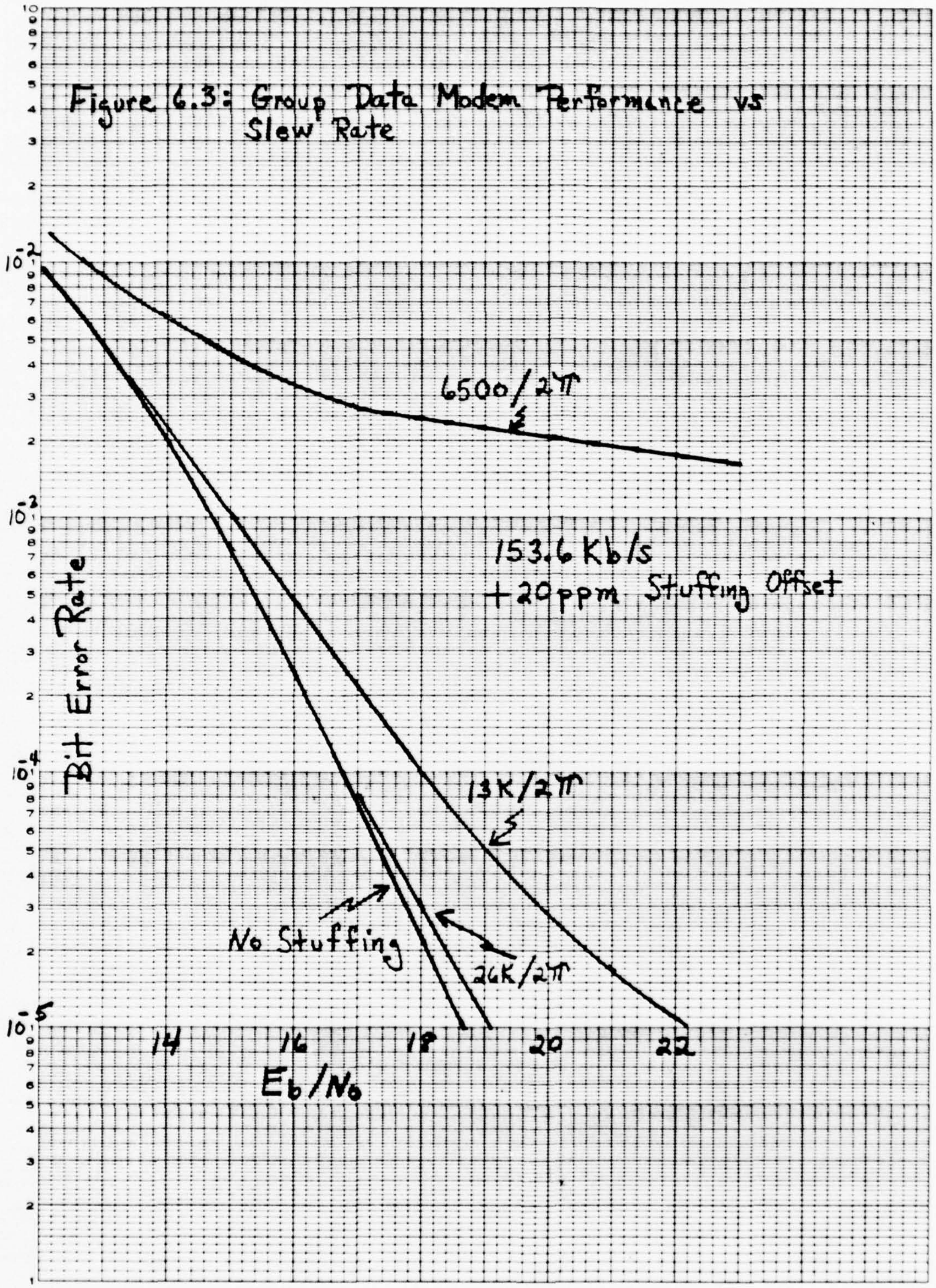


Figure 6.3: Group Data Modem Performance vs Slew Rate
6500/2π
153.6 Kb/s
+20ppm Stuffing Offset
13K/2π
No Stuffing
26K/2π
Bit Error Rate
Eb/No
14
16
18
20
22
10-2
10-3
10-4
10-5

slew rate of 2π in 20,000 bit times was determined as the minimum allowable for satisfactory operation with the USC-26, and even at that rate there is some performance degradation. At the 2π in 768 rate, performance would clearly be unacceptable even if timing synchronization could be established. The GDM required slew rate is more than an order of magnitude more critical than other units which typically interface with the ATDM. However, such a characteristic is typical of high efficiency synchronous data modems: efficiency is obtained by the use of very tight phase lock loops (PLL's).

In the production version ATDM an analog PLL was employed for smoothing but the design cannot be pushed far enough to give smoothing to 2π in 20,000 bit times. To establish interface compatibility between the ATDM and the GDM a special smoothing buffer was designed for the ATDM which is card for card replaceable with the ATDM's general purpose buffer. Concurrent with the Phase I system testing a breadboard version of this special buffer was tested with satisfactory results. Detailed compatibility testing was subsequently carried out under the ATDM program and the results verified that the interface incompatibility has been overcome.

Because of the unavailability of an ATDM with the special buffer during Phase I testing no configurations tested entail a use of the AN/USC-26 Group Data Modem. Nonetheless, the testing subsequently conducted under the ATDM program demonstrated the production model is compatible with the GDM provided the special smoothing buffer is used.

6.2 AN/GSC-24 General Interface

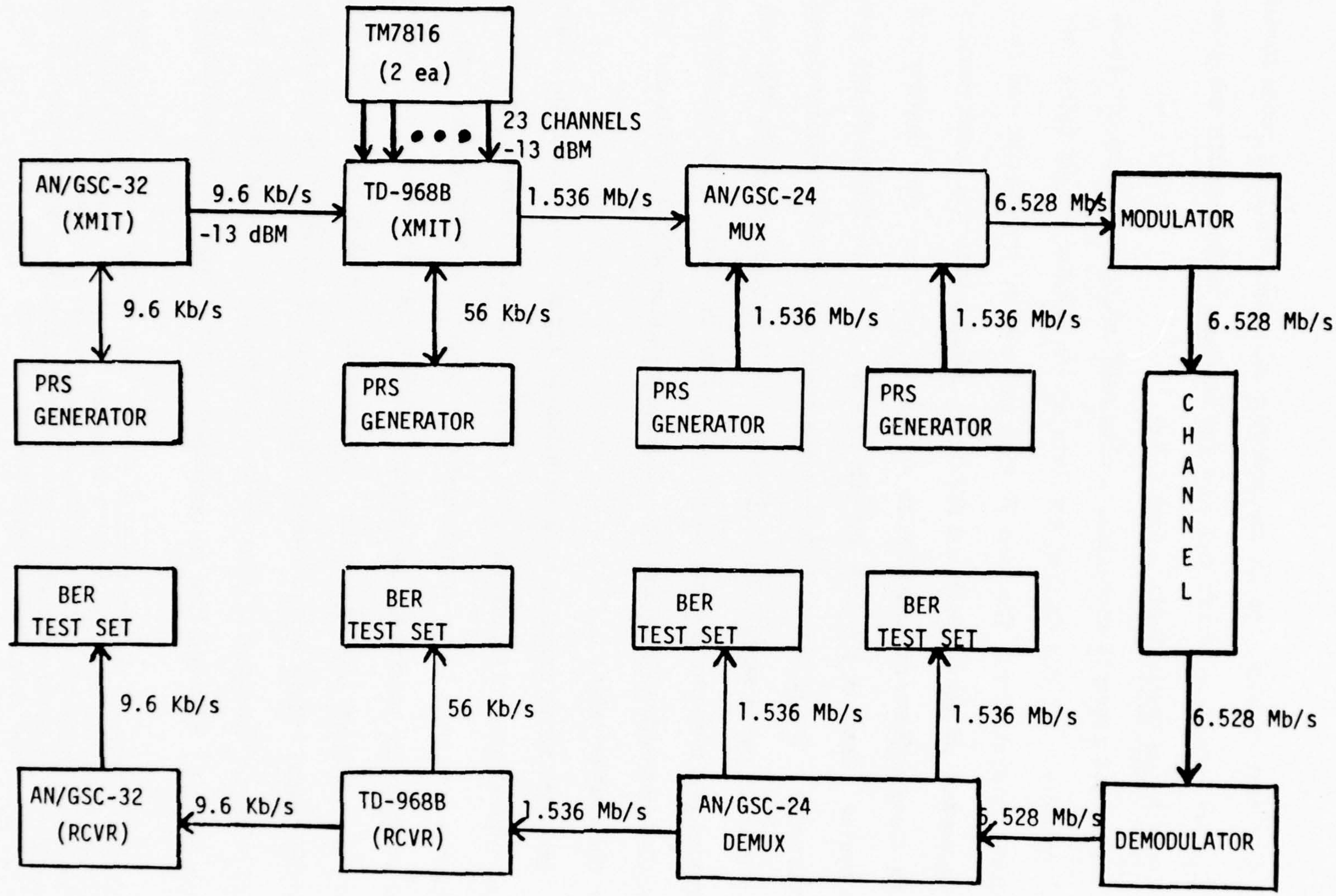
The above interfacing problem was not the only one surfaced involving the AN/GSC-24. Other problems, which did not preclude testing but presented certain initial test setup difficulties, occurred. These are described in [4]. Once interface was accomplished the test results presented in [4] along with those to be presented in this section show the ATDM to be an extremely versatile high level multiplex system capable of presenting a transparent window for end-to-end communication requirements.

6.3 System Test Configuration

After the basic system interface problems were overcome, the equipments were tandemed in various ways to simulate operational network configurations. Figure 6.4 depicts, in a general way, the type of configurations evaluated. The AN/GSC-32 Voice/Data Modem is a wireline modem chosen over other possible modems purely on an availability basis. Its characteristics are given in [15]. The Marconi TM 7816's are 12 channel noise generators. The pseudo random sequence generators and bit error rate test sets pairs represent various bit error rate test equipments -- specifically, the IIC BERT 901, Tau Tron S-130C, HP 1645A and an AN/GSC-24 Test Set. The modem used for modulation and demodulation of the multiplexed bit stream was either the QPSK or quaternary baseband modem addressed in the preceding sections. The term channel is used in the very generalized sense; it includes everything between the modulator and demodulator. This may be just the radio and simulator rack or it may include transmissions between sites where intermediate sites may contain various digital equipments.

All the system tests involved the general configuration; however, all the equipments were not necessarily connected for all tests. Additionally, in some tests the TD 968B transmitter and receiver were in the same unit whereas in others different units were used. It will be seen these two cases led to

FIGURE 6.4: SYSTEM TEST CONFIGURATION



very different results. As in the previous sections, the QPSK modem system results are considered first and then the baseband modem results are given.

6.4 QPSK Modem System Tests - Single Hop

Figure 6.5 presents test results obtained* using the system configuration of Figure 6.4 where the channel consists of the simulator rack being used for frequency translation. The same TD 968B was used as transmitter and receiver. The agreement of the TD 968B and AN/GSC-24 results with the modem results shows these equipments introduce no additional bit error rate degradation into the system. That is the ATDM and PCM by themself or in tandem do not degrade performance. The AN/GSC-32 modem causes about a 1 dB or approximately an order of magnitude performance loss. Since the 56 Kbps mode of the TD 968B has not degraded performance, theloss is attributed to the wireline modem and/or the wireline modem/TD 968B interface. This degradation will be evidenced throughout the system tests.

One additional point is made relative to Figure 6.5. Prior to this test some intermittent difficulties with regard to carrier recovery and some performance loss were being experienced with one of the QPSK modems. The unit was returned to the contractor for repair. During the repair some improvements were incorporated into the modem. The results here when compared to the earlier data, Figure 4.3, shows an improvement of about 1.5 dB for the same conditions. Consequently, the modem after modification yielded just about what might be expected from an optimized system. Some of the subsequent curves

*Modem performance points given in system test configuration curves are obtained for each point using the modem's internal test mode immediately after completing data acquisition at a particular received signal level. Modem performance could not be obtained during system data acquisition because the bit stream into the modem consisted of multiplexed bit streams.

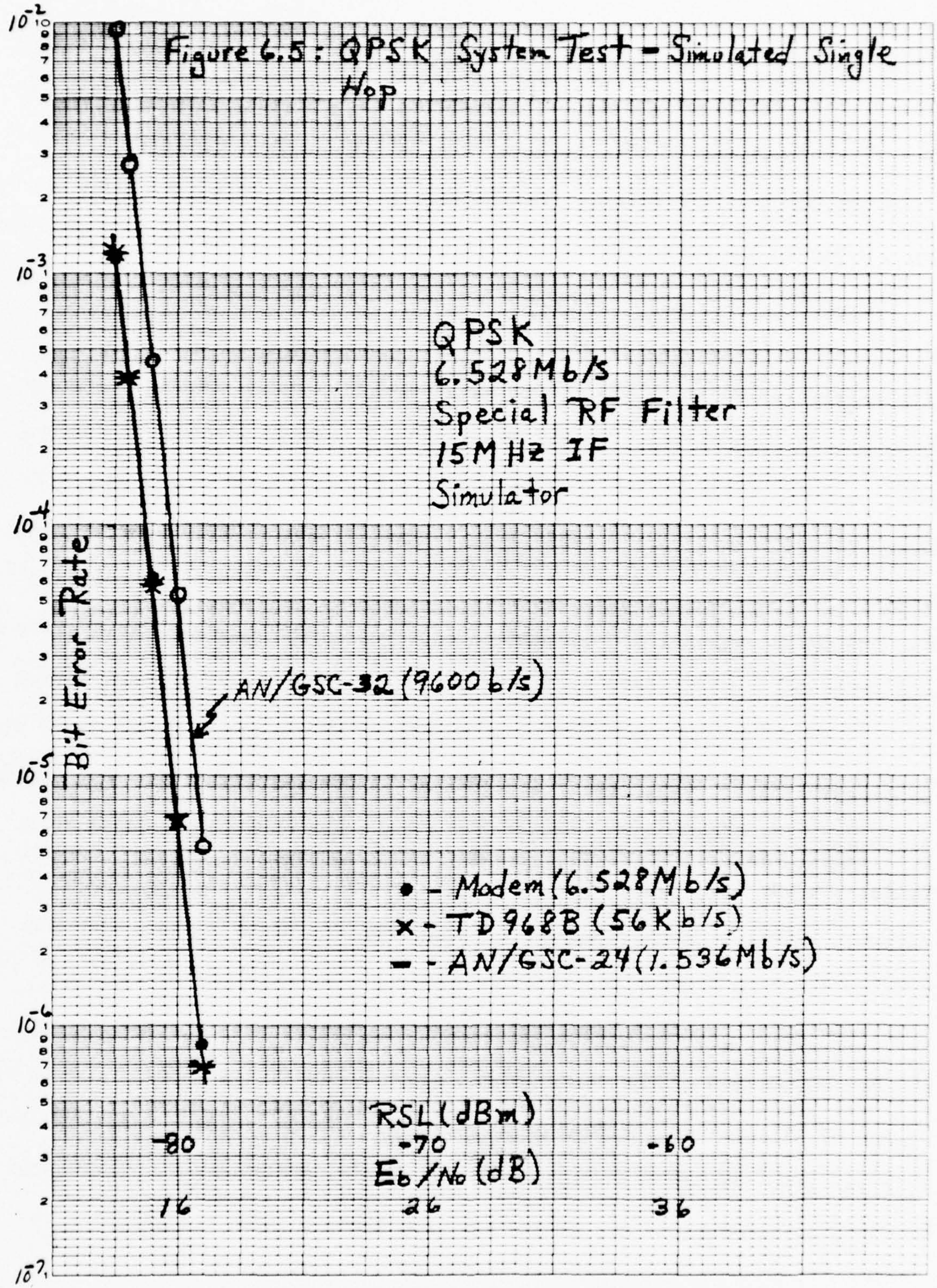


Figure 6.5: QPSK System Test - Simulated Single Hop
QPSK
6.528Mb/s
Special RF Filter
15MHz IF
Simulator
Bit Error Rate
AN/GSC-32 (9600 b/s)
• - Modem (6.528Mb/s)
x - TD968B (56Kb/s)
▬ - AN/GSC-24 (1.536Mb/s)
RSL (dBm)
-80
-70
-60
Eb/No (dB)
16
26
36
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7

involved performance with the other QPSK unit or the repaired unit at a time when a small amount of degradation was occurring. As such a slight improvement (1 or 2 dB) may be obtainable in some of the curves. However, the important point is the relative performance of the PCM, ATDM, and modem equipments given on the same curves.

Figure 6.6 shows performance for the actual single hop case. Of course in this case, since the equipment is located at different sites, the TD 968B transmitter and receiver are not in the same unit. Additionally, the normal RF filter is used in this and all the remaining tests. Performance for the modem and GSC-24 remain the same; however, there is a very significant difference in the PCM equipment's performance. The bit error rate in either direction for the 56 Kbps channel without signal attenuation is worse than $1x10^{-3}$. The drastic degradation in performance relative to the essentially error-free operation for the case of a single TD 968B unit being used for transmission and reception reflects the problem of stability of the phase locked loops used to generate the 56 KHz clocks. The problem is identified in [3]. The problem was reported to the equipment developer and changes were incorporated to eliminate the problem. Although this fix was incorporated too late to enable checkout under the Phase I tests, tests at the contractor's plant show the problem has been eliminated.

6.5 <u>QPSK Modem System Tests - Two Hops</u>

By attenuation of the transmitted signal by use of the simulator assembly an RSL of -71 dBm was obtained at Stockbridge. Radio loopback was then used to obtain the two hop test conditions for obtaining Figure 6.7. The system performance conclusions are consistent with those pointed out relative to

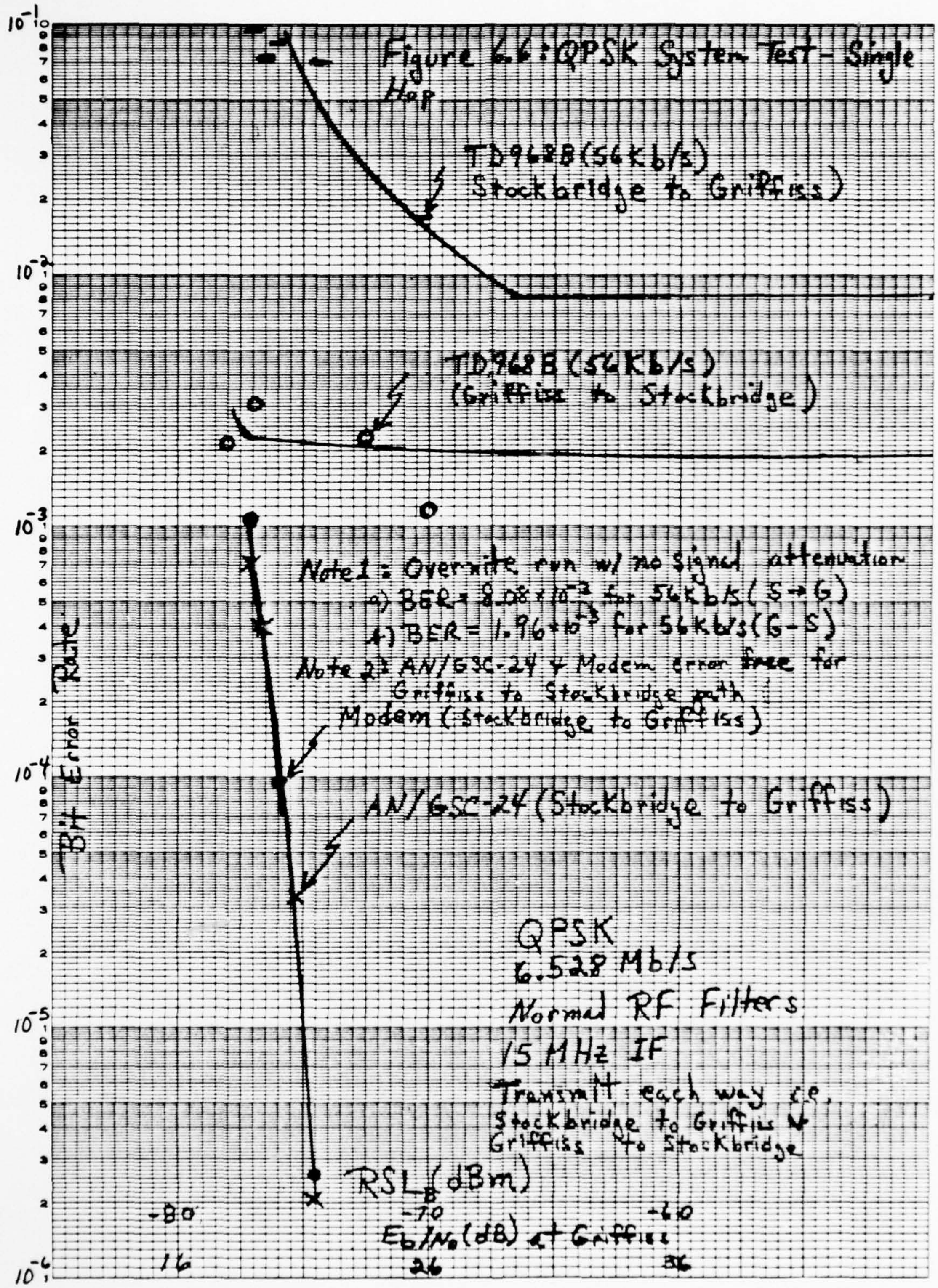


Figure 6.6: QPSK System Test - Single Hop
TD968B (56Kb/s) Stockbridge to Griffiss)
TD968B (56Kb/s) (Griffiss to Stockbridge)
Note 1: Overwrite run w/ no signal attenuation
a) BER = 8.08×10-3 for 56Kb/s (S→G)
b) BER = 1.96×10-3 for 56Kb/s (G-S)
Note 2: AN/GSC-24 & Modem error free for Griffiss to Stockbridge path
Modem (Stockbridge to Griffiss)
AN/GSC-24 (Stockbridge to Griffiss)
QPSK
6.528 Mb/s
Normal RF Filters
15 MHz IF
Transmit each way i.e. Stockbridge to Griffiss & Griffiss to Stockbridge
RSL (dBm)
-80
-70
-60
Eb/No (dB) at Griffiss
16
26
36
Bit Error Rate
10-1
10-2
10-3
10-4
10-5
10-6

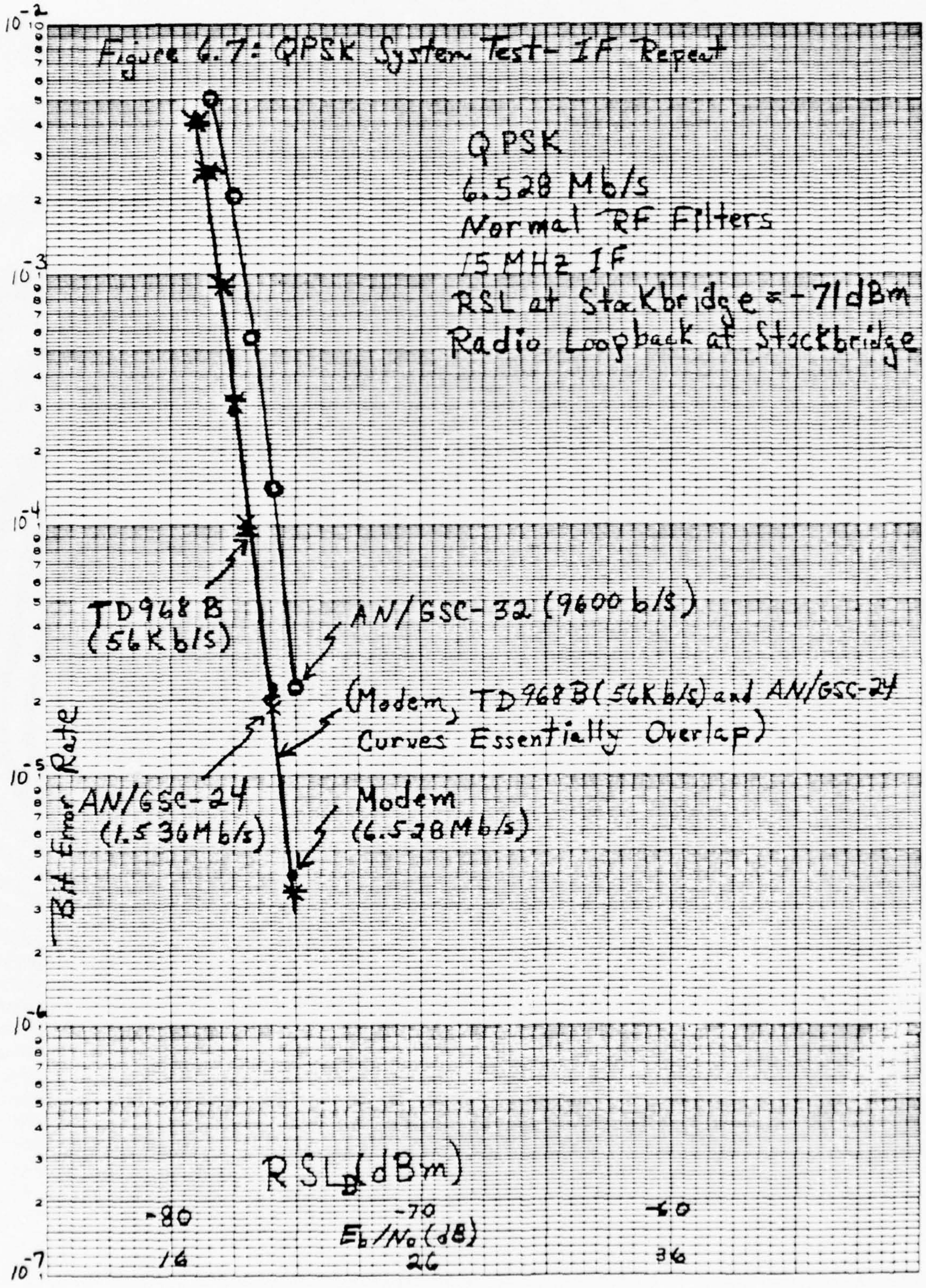


Figure 6.7: QPSK System Test- IF Repeat
QPSK
6.528 Mb/s
Normal RF Filters
15 MHz IF
RSL at Stockbridge = -71dBm
Radio Loopback at Stockbridge
TD968 B
(56Kb/S)
AN/GSC-32 (9600 b/s)
(Modem, TD968B(56Kb/s) and AN/GSC-24
Curves Essentially Overlap)
AN/GSC-24
(1.536Mb/s)
Modem
(6.528Mb/s)
Bit Error Rate
RSL (dBm)
-80
-70
-60
E_b/N_o (dB)
16
26
36

Figures 6.5 and 6.6. Obviously, only one TD968B was used. It is apparent that two-hop repeater operation without regeneration does not inherently cause excessive degradation. Of course such operation is possible only if no drop or insert is required. Additionally, the conclusions of Section 4.5 apply and so such operation would rarely be warranted.

From the above one would certainly expect that regenerative operation can also be used. However, since regeneration may be done for dropping and inserting data, regenerative operation performance was obtained for the case that the demultiplexed data was inserted into the multiplexer and then regenerated. The results shown in Figures 6.8 and 6.9 verify operation under such conditions is very feasible. Because of the presence of additional digital equipments for dropping and inserting data, the conditions tested are more stringent than those present when one regenerates merely to enhance the signal. The necessity of dropping and inserting precludes the possibility of simply using IF repeaters.

6.6 Quaternary Baseband Modem System Tests - Single Hop

Figures 6.10 and 6.11 present test results obtained using the quaternary baseband modem operating at a 1 bps/Hz transmitted spectral occupancy. Since prior results, Figure 5.8, indicated the 7.7 MHz IF filter yielded performance superior to the 15 MHz filter, performance was assessed for the 7.7 MHz single hop case, Figure 6.10, and also for the 15 MHz case, Figure 6.11. In the later case performance is shown with and without the modem scrambler being used. The relative performance for the two filter cases remains just about the same as before (Figure 5.8). In spite of the fact that the narrower IF filter yields better performance it was decided to use the 15 MHz filter in the

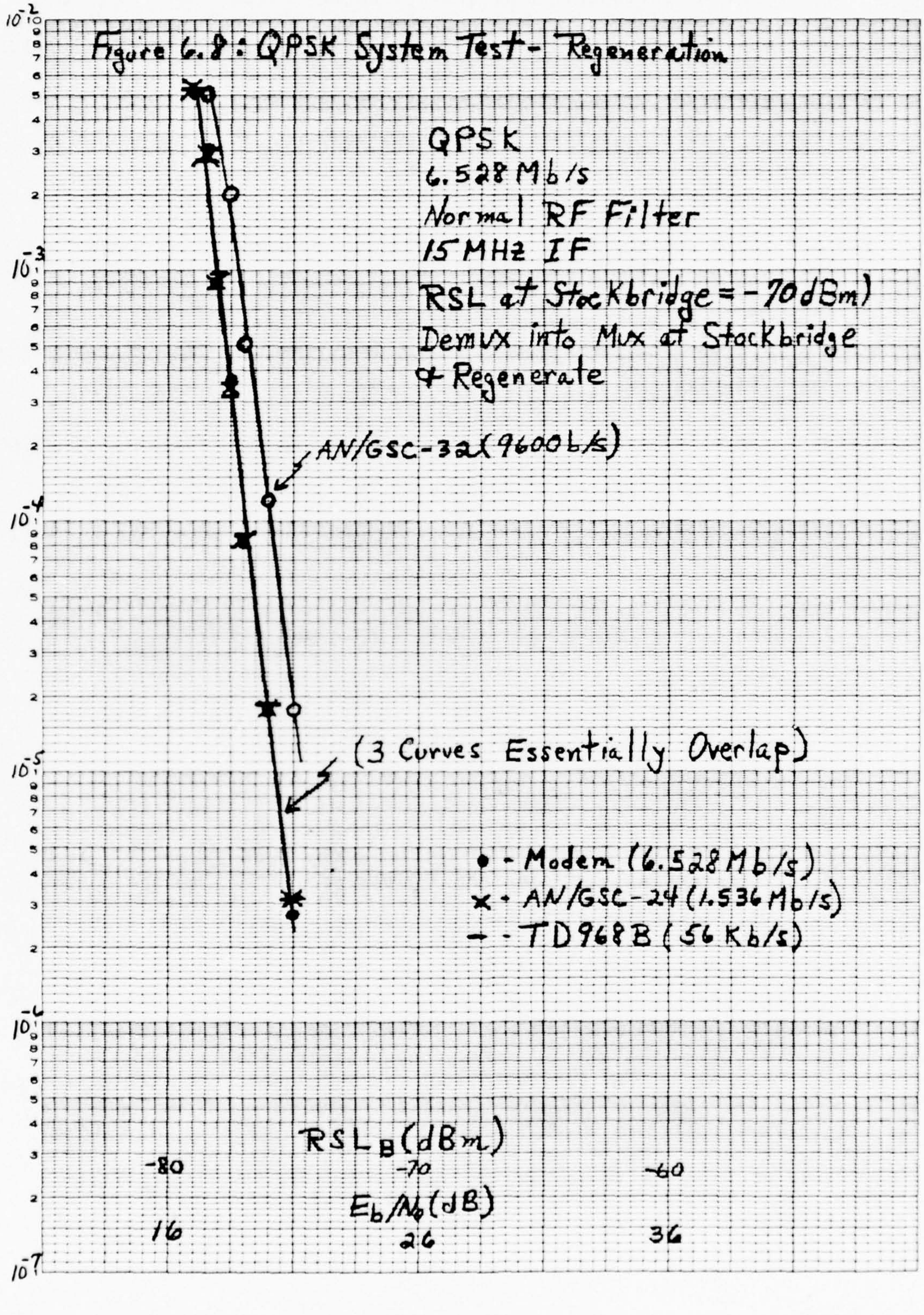


Figure 6.8: QPSK System Test - Regeneration
QPSK
6.528 Mb/s
Normal RF Filter
15 MHz IF
RSL at Stockbridge = -70 dBm)
Demux into Mux at Stockbridge
& Regenerate
AN/GSC-32 (9600 b/s)
(3 Curves Essentially Overlap)
• - Modem (6.528 Mb/s)
× - AN/GSC-24 (1.536 Mb/s)
— - TD968B (56 Kb/s)
RSL_B (dBm)
-80
-70
-60
Eb/No (dB)
16
26
36
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7

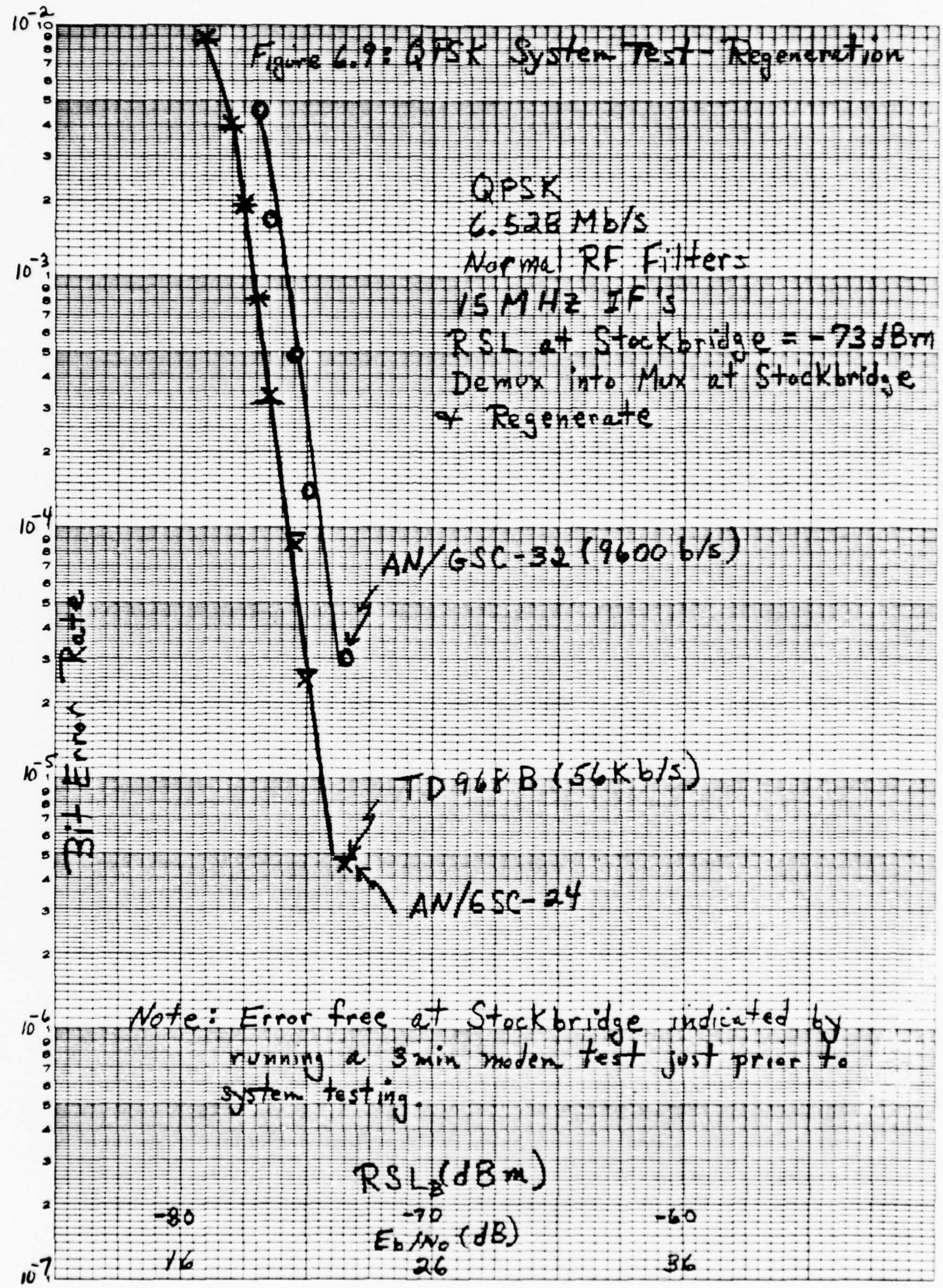


Figure 6.9: QPSK System Test - Regeneration
QPSK
6.528 Mb/s
Normal RF Filters
15 MHZ IF's
RSL at Stockbridge = -73 dBm
Demux into Mux at Stockbridge
& Regenerate
AN/GSC-32 (9600 b/s)
TD 968 B (56 Kb/s)
AN/GSC-24
Bit Error Rate
Note: Error free at Stockbridge indicated by running a 3 min modem test just prior to system testing.
RSL$_B$ (dBm)
-80
-70
-60
Eb/No (dB)
16
26
36
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}

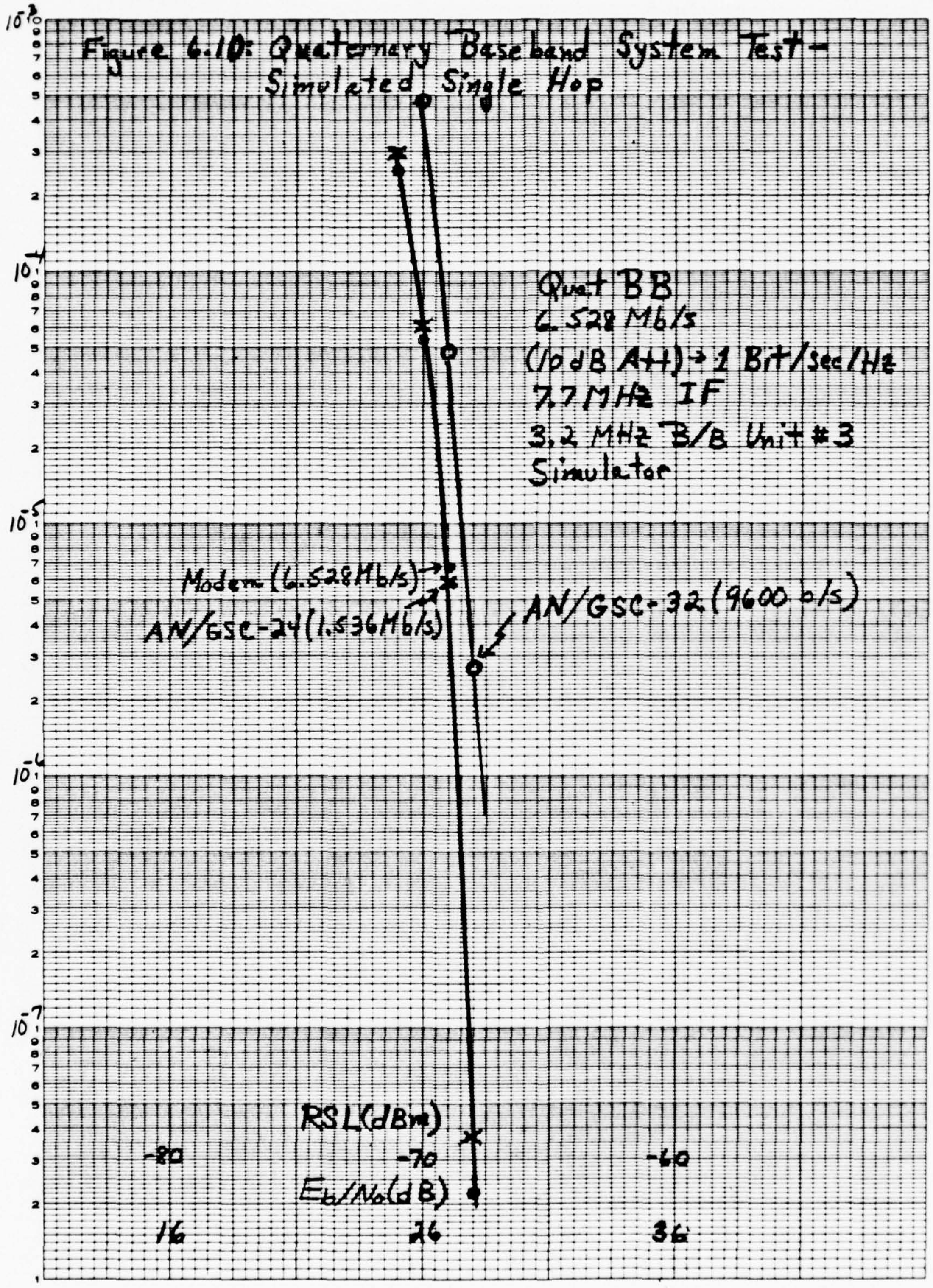


Figure 6.10: Quaternary Baseband System Test -
Simulated Single Hop
Quat BB
6.528 Mb/s
(10 dB Att) → 1 Bit/sec/Hz
7.7 MHz IF
3.2 MHz B/B Unit #3
Simulator
Modem (6.528 Mb/s)
AN/GSC-24 (1.536 Mb/s)
AN/GSC-32 (9600 b/s)
RSL (dBm)
-80
-70
-60
Eb/No (dB)
16
26
36

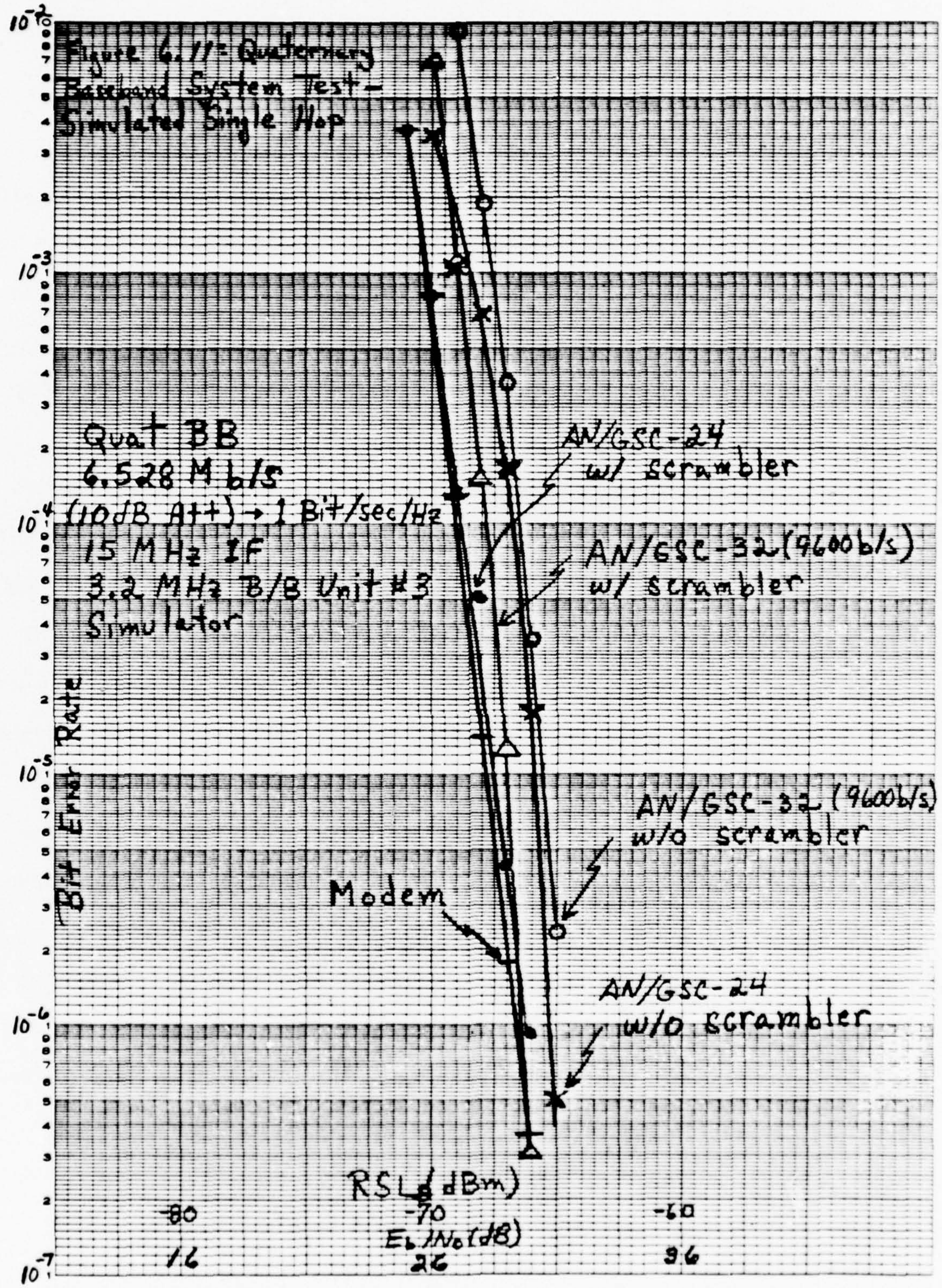


Figure 6.11: Quaternary Baseband System Test — Simulated Single Hop
Quat BB
6.528 Mb/s
(10 dB Att) → 1 Bit/sec/Hz
15 MHz IF
3.2 MHz B/B Unit #3
Simulator
AN/GSC-24
w/ scrambler
AN/GSC-32 (9600 b/s)
w/ scrambler
AN/GSC-32 (9600 b/s)
w/o scrambler
Modem
AN/GSC-24
w/o scrambler
Bit Error Rate
RSL (dBm)
-80
-70
-60
Eb/No (dB)
1.6
26
9.6

subsequent tests. This action was taken since the 15 MHz filter is a standard IF filter for the LC-8D radios whereas the 7.7 MHz filter is non-standard having been constructed especially for use with the QPSK modem.

Figure 6.11, in addition to showing basic system performance results, also illustrates some other important points. At the higher performance levels the degradation in performance between the AN/GSC-32 and the other equipments is decreased. In practice, the loss in the wireline modem performance due to the microwave hop should be negligible under operational channel conditions when compared to degradations caused in the wireline portion. Consequently, a detailed analysis of the cause of degradation in the AN/GSC-32 modem performance was not undertaken.

The relative performance shown for operation with and without the scrambler for data randomization has a very practical implication. Theoretically, if the data entering the modem was random, the scrambler would cause an approximate 3 to 1 increase in bit error rate (exactly 3 to 1 if all errors occur independently). The test results show the unscrambled operation is actually about 1.5 dB worse. This would seem to indicate the data is not random. Figures 6.12a, b and c show this to be the case. Figure 6.12a shows the jagged spectrum that arises without any data input and no scrambling. In the absence of an input the GSC-24 automatically furnishes a constant "one" output. Therefore, for Figure 6.12a the input to the modem is a constant "one" value except for the variations caused by the synchronization framing patterns. When data is furnished as indicated in Figure 6.12b some of the jaggedness is eliminated; however, a dominant frequency spike is still in evidence. If another 1.536 Mb/s input stream were inserted, the spike would be significantly reduced

Figure 6.12a: RF Spectrum without Scrambler - System Configuration

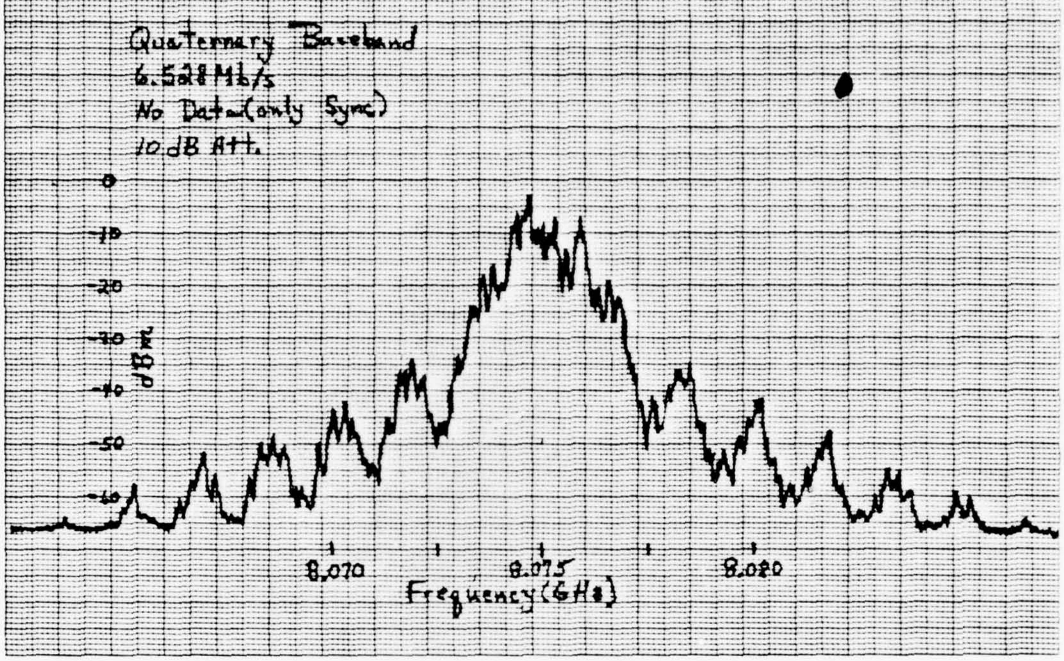
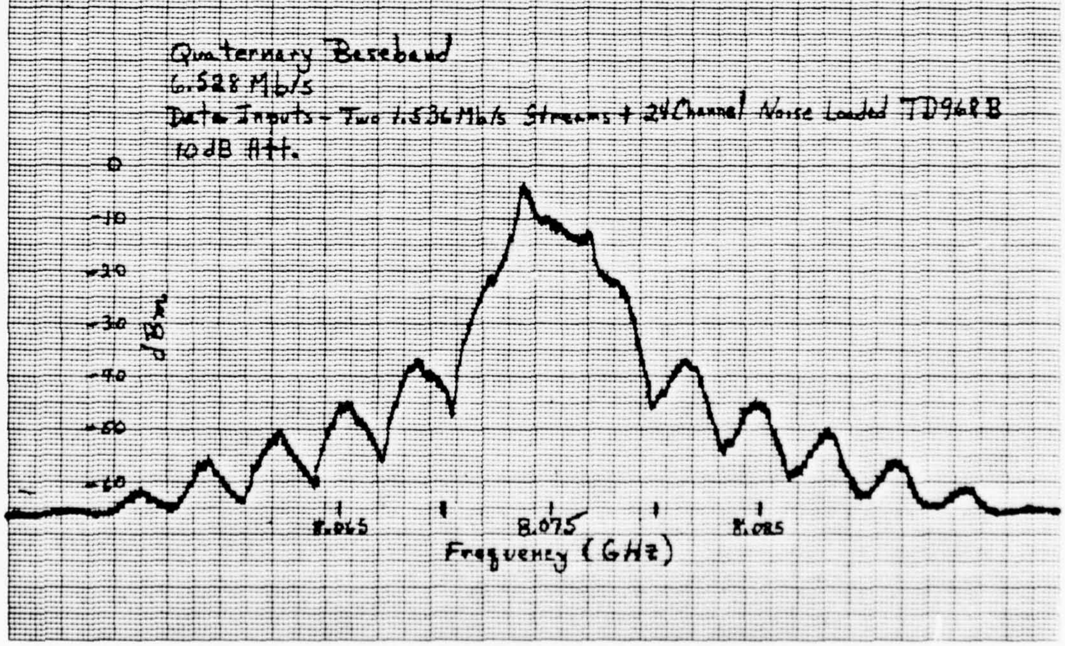


Figure 6.12b: RF Spectrum without Scrambler - System Configuration



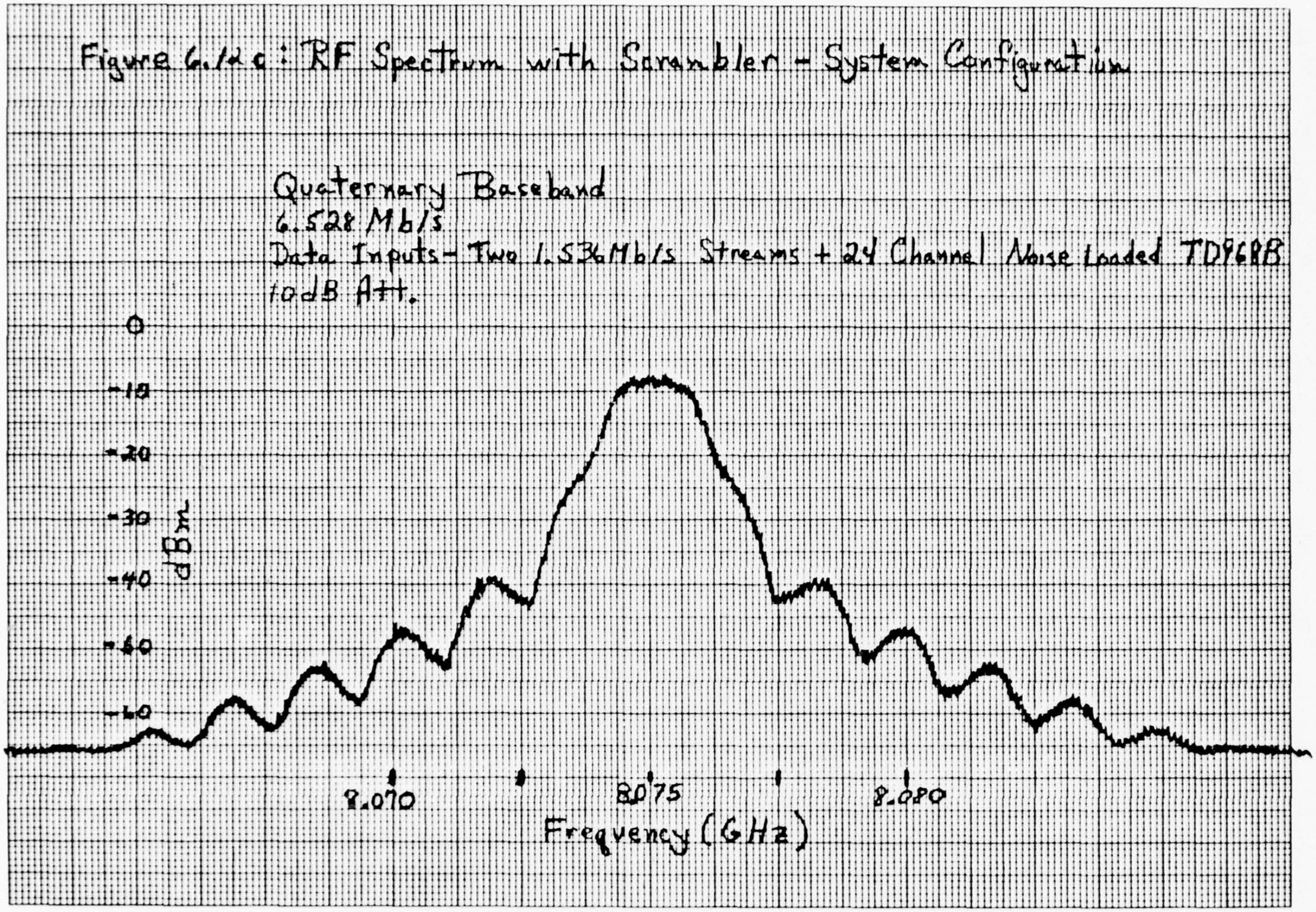


Figure 6.12c: RF Spectrum with Scrambler - System Configuration

because of the increased data randomness. Figure 6.12c shows the RF spectrum with data inputs identical to those used to obtain Figure 6.12b only in this case the modem's scrambler is utilized. To further ascertain the effects of the scrambler a spectral plot was obtained with no data inputs only with the scrambler on. The plot was indistinguishable from Figure 6.12c. That is, as long as the scrambler is used no spectral spikes are evidenced.

The predominance of a particular level can degrade modem performance by causing a bias in the reference voltage circuitry. Operationally, there is no reason to assume a system will be fully loaded or even if it is that the data will necessarily be random. The degradation in modem performance induced by non-random data is seen in Figure 6.11. The most one can lose with a three tap randomizer is an increase in error rate by a multiplicative factor of 3. In the example, a failure to use the randomizer caused a loss of about 1.5 dB. As such, because of the enhancement in performance in certain situations, the use of scrambling is recommended.

6.7 Quaternary Baseband System Tests - Two Hops

Figure 6.13 gives results for the 2 hop case with radio loopback at Stockbridge. The slightly better performance of the modem is attributed to the fact that channel conditions were slowly improving. To obtain statistically valid data for the 9600 bps modem data for each point required that data be acquired over a period of time. Thus, for a given attenuator setting one would expect some improvement at the end of the run. Attributing the small differences to this cause the data is consistent with previous results.

Figure 6.14 treats the two hop regenerative case. With the exception that the baseband modem replaces the QPSK modem, conditions are identical to those

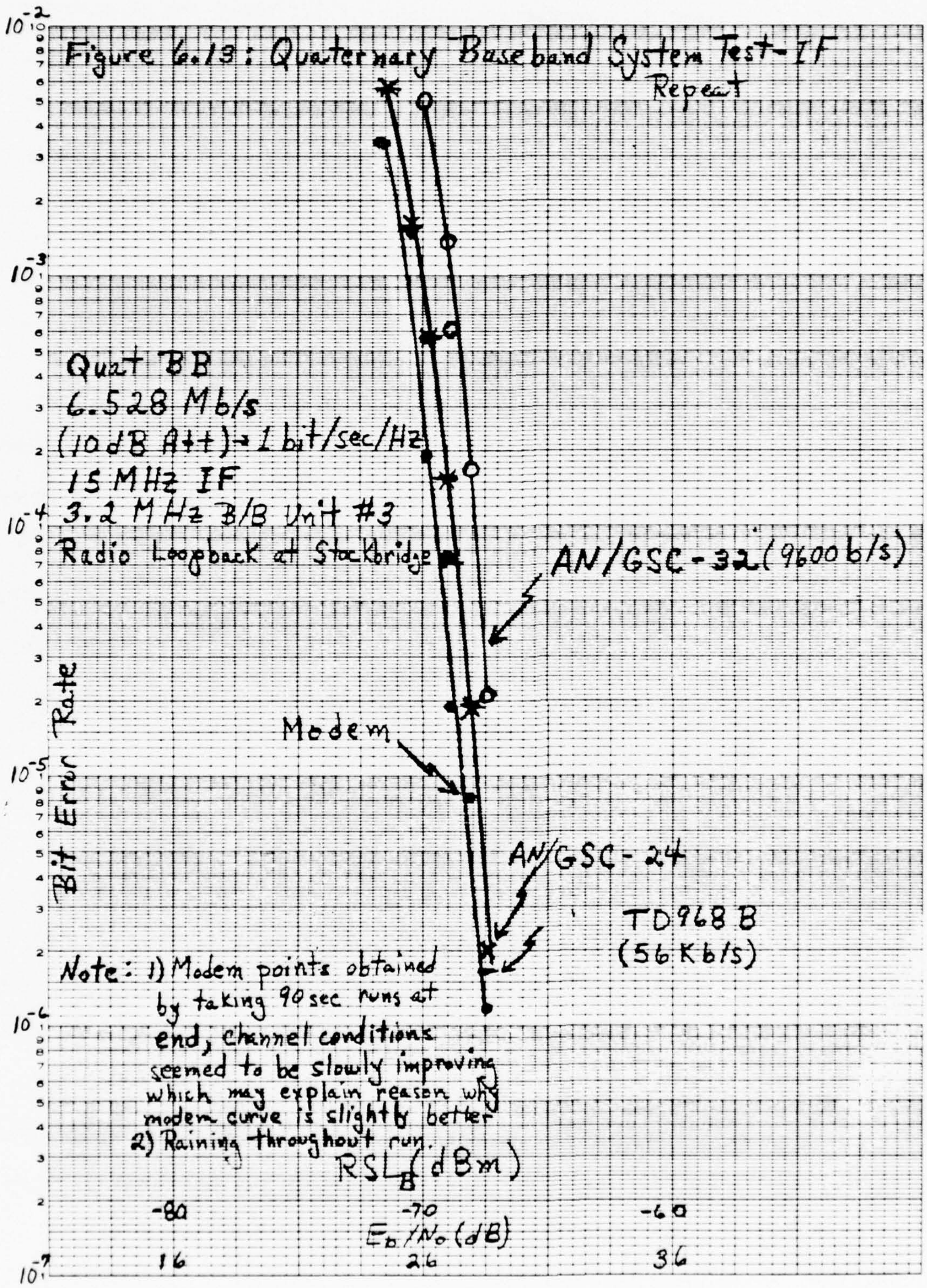


Figure 6.13: Quaternary Baseband System Test-IF
Repeat
Quat BB
6.528 Mb/s
(10 dB Att) → 1 bit/sec/Hz
15 MHz IF
3.2 MHz B/B Unit #3
Radio Loopback at Stockbridge
AN/GSC-32 (9600 b/s)
Modem
AN/GSC-24
TD968 B
(56 Kb/s)
Note: 1) Modem points obtained by taking 90 sec runs at end, channel conditions seemed to be slowly improving which may explain reason why modem curve is slightly better
2) Raining throughout run.
Bit Error Rate
RSL (dBm)
-80
-70
-60
Eb/No (dB)
16
26
36
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7

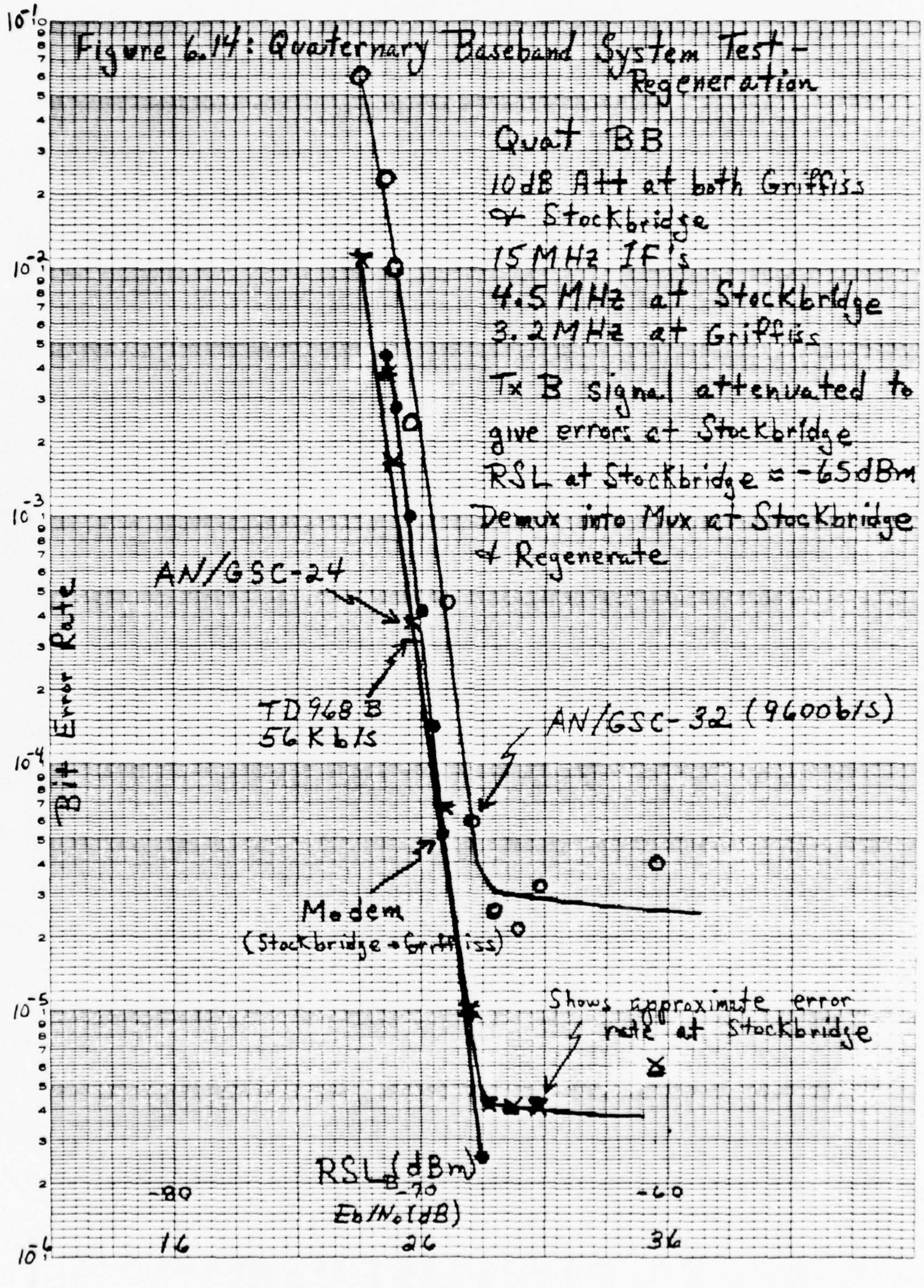


Figure 6.14: Quaternary Baseband System Test - Regeneration
Quat BB
10dB Att at both Griffiss & Stockbridge
15MHz IF's
4.5 MHz at Stockbridge
3.2MHz at Griffiss
Tx B signal attenuated to give errors at Stockbridge
RSL at Stockbridge ≈ -65dBm
Demux into Mux at Stockbridge & Regenerate
AN/GSC-24
TD 968 B
56 Kb/s
AN/GSC-32 (9600b/s)
Modem
(Stockbridge - Griffiss)
Shows approximate error rate at Stockbridge
Bit Error Rate
RSL (dBm)
-80
-70
-60
Eb/No (dB)
16
26
36

used for obtaining Figures 6.8 and 6.9. In this case the transmitted signal could be attenuated sufficiently to obtain errors at Stockbridge. At an RSL = -65 dBm at Stockbridge the data reveals an error rate of approximately 4×10^{-6} for the GSC-24 and 56 Kbps mode of the TD968B. Taking into account a 0.5 dB difference in radio noise figures, Figure 5.8 yields an error rate of 7×10^{-6} for the modem at the corresponding E_b/N_o showing excellent agreement with previous results. The overall results are as expected and do verify the acceptability of regenerative operation in the case where dropping and inserting is present.

6.8 Diversity Switching Effects

The principal function of the receiver IF switch module within the LC-8D radio is to monitor the AGC voltage in each of the two diversity channels and select the channel having the larger signal. Under the rather stringent performance standards established for DCS microwave links the occurrence of a large number of errors during a switch could cause severe problems in meeting the standards, particularly if the switch causes additional errors or loss of synchronization in subsequent equipments.

6.8.1 Switching Errors

The number of errors due to diversity switching is affected by the demodulation technique, switch times and differential delay times on the two diversity channels.

Table 6.1 lists the average number of errors caused by switching for the two types of modems at various transmission rates. The testing was performed at the Griffiss site with radio loopback from the Stockbridge test annex. Switching was obtained by varying the B receiver's RSL via the simulator assembly. Care was taken to insure switching occurred at an RSL which resulted in error-free performance under normal one channel operation. The averaging is taken over 10 switches in each direction.

TABLE 6.1: Receiver IF Switching Errors

Rate (Mbps)	QPSK Errors (Avg)	Quat BB Errors (Avg)
12.8	256	240
11.0	177	193
9.0	90	73
8.0	54	19
6.4	25	8
1.536	11	2

The effect of a differential delay on the channels was then addressed. This test was carried out on the QPSK modem at a rate of 8.0288 Mbps. Delays were inserted by the use of cables. Table 6.2 gives the results. It is

TABLE 6.2: Switching Errors with Delay (8.0288 Mbps)

Delay (% of Symbol)	Errors (A→B)	Errors (B→A)	Errors (Avg)
0	55	59	57
.27	52	65	58.5
.39	60	76	68
.43	104	119	111.5

concluded that delay of one channel relative to the other (multipath) will cause some errors during switching but this should not be a severe problem with regards to the modem.

6.8.2 Synchronization During Switching

The effects of switching on subsequent equipments in the system configuration was investigated. Under normal operation switching caused no problems. The errors were distributed among the bit error rate test equipments in a manner consistant with the bit rate of the data source. Testing was conducted for the 6.528Mbps configuration and an 8.0288 Mbps configuration. The sum of averages of the errors was consistent with the average modem error rate. Next, cables were used to insert various delay times and the GSC-24 framing lite was monitored for synchronization. A bit rate of 6.528 Mbps yields a baud rate of 3.264 M symbols per second and a symbol duration of 306 nanoseconds. With a differential delay of 145 nanoseconds, 47% of a baud, no loss of bit count integrity (BCI) occurred in 100 switches, 50 in each direction. Increasing the delay to 151 nanoseconds, 49.3% of a baud, BCI was lost only 5 times in 100 switchings. With a delay of 153 nanoseconds, 50% of a baud, BCI was lost 42 times in 100 switching. For the 8.088 Mbps rate with differential delay of 47% of a baud BCI was not lost in 25 switches from channel A to B but it was lost 17 out of 25 times when switching from B to A. With a differential delay of 43% of a baud no loss of BCI was experienced. It is concluded that as long as the differential delay is somewhat less than half a symbol baud, BCI will be maintained. However, as seen in Table 6.2, the number of errors will increase with increasing differential delay.

6.9 Acquisition Times

It has just been seen that under normal circumstances maintenance of synchronization presents no problem. Initial acquisition will now be addressed. The synchronization technique for the TD968 is described in [3]. Test points were determined within the PCM for monitoring the initial sync confidence counter incrementation (which may actually be caused by a false sync pattern) and for monitoring when the confidence counter reaches five (sync acquisition acceptance). The Williard Code Sync Technique was used because of its demonstrated superiority over the Bell Code [3]. The TD968 acquisition time of 1.5 milliseconds shown in Figure 14 of [3] is actually the time to initial sync indication. In the absence of false sync or a false rejection of correct sync actual sync acceptance occurs a fixed time later. At the 1.536 Mbps TD968 rate the fixed time is 6.2 milliseconds which when added to the 1.5 millisecond value yields a 7.7 milliseconds sync acquisition time. The acquisition time for the AN/GSC-24 is generally less than 1000 bits except for very high error rate conditions [4]. Consequently, at the 6.528 Mbps ATDM rate the acquisition time will be about 0.15 microseconds, a negligible amount when compared to the 7.7 milliseconds time for the TD968.

Clock recovery time for the quaternary baseband modem and clock and carrier recovery times for the repaired and improved QPSK modem (Section 6.4) were ascertained. Measurement time started at the time the signal reached the demodulator input and ended when acquisition was obtained. Monitor points are readily available on the demodulator module for these points. The test was conducted with the general system configuration of Figure 6.4 with the exception that the TD968 either had no loading or 24 channel noise loading. The simulator channel was used under essentially error-free conditions.

For the QPSK system clock recovery time with or without noise loading was between 16 and 17 milliseconds for 40 measurements for each noise case. The averages were 16.3 milliseconds loaded and 16.2 milliseconds unloaded. Carrier recovery times measured at the same time averaged 25.75 milliseconds loaded and 24.95 milliseconds unloaded. Since both clock and carrier recovery are required for acquisition, the maximum of the two measurements is the actual acquisition time. Averaging out the 40 reading for each noise condition yields QPSK demodulator acquisition times of 28.8 milliseconds loaded and 24.95 milliseconds unloaded. The carrier oscillator circuitry's cycle equals 112 milliseconds. Since carrier acquisition is accomplished on either a positive or negative level transition and the demodulator input occurs randomly with respect to the oscillator the average time to carrier acquisition should be 112/4 = 28 milliseconds. This time is independent of the data rate. Assuming acquisition on the first transition, which should occur except under extremely poor channel conditions, the worse case acquisition time is 56 milliseconds.

For the quaternary baseband system, with 10 dB attenuation at 6.528 Mbps to yield 1 bps/Hz operation, the clock acquisition time using the internal test mode of the modem and going through the simulator averaged 2.4 milliseconds. A modem rate of 12.8 Mbps with 4 dB modem signal attenuation was then used to ascertain if the acquisition time was significantly altered by rate. At this rate the average acquisition time was 2.66 milliseconds. The received signal was attenuated to a level yielding a bit error rate of $2x10^{-4}$. The clock average acquisition time became 2.84 milliseconds*.

Ideally the total sync acquisition time of the tandemed system will equal the sum of the sync times of the individual equipments. Total sync time is

*Acquisition data at the 12.8 Mbps rate under degraded conditions was also obtained for the QPSK modem; however, this data was discarded because it used the faulty QPSK modem prior to its repair and improvement. The validity of the data is questioned.

understood here to be the time from when the signal enters the demodulator to the time the TD968 sync confidence counter reaches a count of five. Table 6.3 lists the values obtained. The expected times to sync based upon summing

TABLE 6.3: Total Synchronization Time (Milliseconds)

Modem	BER	24 Chan Loading	No Loading
QPSK	error free	35.1	37.25
Quat BB	error free	10.27	9.98
Quat BB	9.56×10^{-5}	10.61	-----
Quat BB	9.85×10^{-4}	11.07	11.09
Quat BB	1.98×10^{-3}	11.43	10.98
Quat BB	3.85×10^{-3}	11.83	11.04
Quat BB	7.80×10^{-3}	11.83	11.43
Quat BB	1.55×10^{-2}	12.54	12.01
Quat BB	3.10×10^{-2}	15.72	13.93
Quat BB	.124	*	*

* AN/GSC-24 will not sync for over a few seconds.

the individual sync times are 36.5 milliseconds (loaded) and 32.65 milliseconds (unloaded) for the QPSK system and 10.1 milliseconds for the quaternary baseband modem. The baseband demodulator acquisition time was obtained using the internal test mode which should be analogous to the 24 channel loading condition as far as the TD968 is concerned.

The excellent agreement between Table 6.3 and the summed synchronization times shows the total sync times are indeed the sum of the individual sync times. Furthermore, a quite high error rate should not increase the acquisition time to a large extent.

SECTION 7

SUMMARY

7.0 Bandwidth

When using QPSK modems over FDM type microwave radios IF transmit filtering by itself does not provide sufficient truncation to permit operation at 1 bps/Hz of RF (99%) bandwidth when using the radio's normal RF filter unless power is reduced. Reducing power is generally unacceptable because it causes an attendant loss in fade margin; the usually quoted required 40 dB fade margin will not be obtainable. Satisfaction of the 99% power bandwidth criterion requires the replacement of the normal RF transmit filter with one of narrower bandwidth when using a QPSK modem.

The situation for a remodulation radio is quite different. For multilevel AM in general, and for the quaternary baseband modem in particular, an attenuation of the modulator output, which affects a change in deviation, represents an extremely economical and effective method of controlling the RF transmit bandwidth. Transmit low pass filtering, having only a secondary effect on occupancy in comparison to modem signal attenuation, is not required for spectral truncation. But such filtering can yield a performance improvement and may be desirable if fade margins are not sufficient.

7.1 Modem Performance and Selection

Performance-wise with proper transmit and receive filtering digital traffic can be effectively passed over microwave heterodyne and remodulating configured radios by the use of the QPSK and quaternary baseband modems, respectively. In fact, digital traffic is much less sensitive to signal impairing conditions than analog traffic. Simulated conditions which would prohibit the transmission of analog traffic caused very little degradation in the quality of the digital traffic.

Bit error rate versus E_b/N_0 considerations favor the use of the QPSK modem for 1 bps/Hz operation where possible. However, economics would seem to favor the use of the baseband modem since it entails no modification of the radios' RF filters. On long hops fade margins might tend to indicate the need for the higher performance modem. On short hops fade margins would tend to be very adequate, thereby permitting the use of the more economical alternative of the baseband modem.

With regard to analog regeneration the losses due to multi-hops were seen to be somewhat larger under baseband operation. When coupled with the fact that the baseband performance is inferior to performance with the QPSK modem this implies an analog repeat when using the baseband modem is less advisable than multi-hop repeatering with the QPSK modem. In general analog repeating is not recommended for either modem. But in very rare situations it may be used on some short hops particularly if the QPSK modem is used with a heterodyne radio configuration.

The LC-8D is capable of being configured for either heterodyne or remodulation operation and so one has an option. However, certain fielded radios, such as the AN/FRC-80 and AN/FRC-155 through AN/FRC-162, have no IF interface capability and, therefore, must be operated with a baseband modem. When an option is available the trade-offs between performance and economics must be assessed.

In essence the modem selection may be dictated by exclusion; baseband interface may be required. In other cases selection involves a trade-off between performance and economics.

7.2 System Tests

The system tests did reveal some incompatibilities. Modifications were required in the ATDM to permit its interface with the Group Data Modem and in the TD968B to permit end-to-end transmission using the 56 kbps mode. However, once initial compatibilities were established the equipments preceding the modulator and following the demodulator operate essentially error free. Under non-degraded channel conditions system tests were ran with each modem type over three day periods without error. When channel conditions were intentionally degraded the error rates obtained for all equipments except for the wireline modems were essentially the same as the error rate of the modems. The AN/GSC-32's performance was close to an order of magnitude poorer at a given level.

The basic quality of the digital traffic under the system configuration would seem to depend solely upon the performance of the modem. The test results show excellent performance is attainable.

With the modems tested high quality digital traffic can be transmitted over fielded FDM type microwave radios with a much greater immunity to degradations in radio alignments or channel interference conditions than can analog traffic. The advanced digital communications equipments tested in conjunction with the modems and radio rapidly acquire synchronization and operate essentially error free. There should be little or no difficulties with the introduction of such equipments into the DCS.

7.3 Present Status

Thus far this section has summarized the overall conclusions resulting from the analysis of the test data obtained under the DCS Digital Systems Evaluation Phase I Program. During the test, analysis and documentation period additional relevant work has occurred. As such it is worthwhile to conclude with an assessment of the general status of digital communication over the line-of-sight microwave media and an indication of the problem areas presently under investigation.

Communications in the US are, for the most part, leased; outside the US communications are US Government owned and operated. LOS microwave allocations for the US in foreign countries are in the 4.4 - 5.0 and 7.1 to 8.4 GHz bands. Bandwidths allocated are typically 7.0 MHz. If greater bandwidths are required two contiguous 7.0 MHz authorizations are given to obtain 14 MHz. No bandwidths greater than 14 MHz are ever granted.

Present requirements indicate that up to 28 Mb/s will have to be communicated in a 14 MHz RF bandwidth with expectations of requirements for twice that rate in the next ten years. This works out to bandwidth efficiencies of 2 bps/Hz in the near term and 4 bps/Hz in the long term.

During the past two years a new spectrum standard was developed for digital microwave in the US. Until 1974 microwave frequency allocations were authorized based upon 99% bandwidths. With the advent of digital microwave and the potential for increased congestion and interference, a new standard was issued by the FCC termed "Docket 19311". This standard, although providing lower interference levels out of band than 99%, provides more of a challenge to the digital microwave radio designer because it is more restrictive. This standard has been accepted by the military for use in the US and there are strong indications that it will be required in the DCS worldwide.

The previously discussed efficiencies must meet Docket 19311 without substantially increasing the output power, acquiring new repeater sites, or using new frequency bands.

Digital radios are presently fielded in the US which meet 1 to 1.5 bps/Hz at 11 GHz in a 40 MHz bandwidth. The links on which these radios are employed are typically shorter than the average link in the DCS which can exceed 70 miles. The transfer of technology from 11 GHz and 40 MHz bandwidths to 8 GHz and 14 MHz is not straightforward due to the more restrictive filters required.

Laboratory models of digital radios which meet 2 bps/Hz at 8 GHz have been built. Power outputs are limited to 2 watts. This results from the insertion loss of the RF filters used in certain radios and in other radios, is due to the "quasi-linear" nature of the modulation techniques employed. The latter approach was utilized as a compromise between linearity available and the 2 bps/Hz efficiency requirement.

As indicated above, state-of-the-art in linear amplification at 8 GHz is in the 1-2 watt range. To obtain higher power outputs nonlinear amplifiers such as travelling wave tubes (TWT's) are required. This causes modulation technique designs to be constant envelope, thus not requiring linear amplification. Constant envelope techniques such as FSK or PSK are not as spectrally efficient as techniques which utilize amplitude modulation. The task for the technique designer is therefore significantly more difficult. RADC is addressing, with present programs, obtaining two bits/sec/Hz efficiency with five watt power outputs or greater using constant envelope techniques. The studies indicate that the modulation technique which appears most promising is 4 frequency phase-continuous FSK.

Obtaining bandwidth efficiencies higher than two bps/Hz through non-linear devices appears somewhat tenuous. Essentially a ten dB performance penalty is paid for each one bps/Hz increase in efficiency. To obtain four bps/Hz for example with a constant envelope technique would require a signal to noise ratio of 40 dB. Fade margins are not sufficient to yield the required availability at this signal to noise ratio within existing power constraints. Two alternatives are in order: (1) development of more linear devices with higher power outputs to accomodate more spectrally efficient modulation techniques; or (2) use of cross polarization.

Use of linear modulation techniques will of course require linear amplification at 8 GHz. At least 5 watts output will be required. It is hoped that linear power amplifiers will be available in the future, but their absence represents a problem at this time. In anticipation of such developments linear modulation techniques are being explored to better define the degree to which the 4 bps/Hz requirement could be met with linear amplifiers.

Cross-polarization also has the potential to provide four bps/Hz by transmitting data on both horizontal and vertical polarizations at the same carrier frequency. Although this is a viable alternative it does suffer from media conditions such as rain and multipath which increase the cross-polarization interface. For DCS application, with a 99.995% availability requirement, cross-polarization could not be directly applied. However, at RADC algorithms which could be used for interference reduction are being investigated. Computer simulations to date have been quite successful and an implementation program is planned for the near future.

The use of diversity in a digital microwave system is somewhat different than in an analog microwave system. Typically, diversity in analog systems is either dual space or dual frequency (with one known military installation quad-diversity). Combining is either maximal ratio or selection type. When digital microwave systems are introduced the diversity problem becomes more complex. Delay variations over the path must be taken into account so that if the diversity path is used extra bits are not inserted nor bits lost. If this occurs, equipment beyond the receiver will lose bit count integrity (BCI) and information flow will be interrupted until resynchronization is accomplished.

SECTION 8

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METRIC SYSTEM

BASE UNITS:

Quantity	Unit	SI Symbol	Formula
length	metre	m	...
mass	kilogram	kg	...
time	second	s	...
electric current	ampere	A	...
thermodynamic temperature	kelvin	K	...
amount of substance	mole	mol	...
luminous intensity	candela	cd	...

SUPPLEMENTARY UNITS:

plane angle	radian	rad	...
solid angle	steradian	sr	...

DERIVED UNITS:

Acceleration	metre per second squared	...	m/s
activity (of a radioactive source)	disintegration per second	...	(disintegration)/s
angular acceleration	radian per second squared	...	rad/s
angular velocity	radian per second	...	rad/s
area	square metre	...	m
density	kilogram per cubic metre	...	kg/m
electric capacitance	farad	F	A·s/V
electrical conductance	siemens	S	A/V
electric field strength	volt per metre	...	V/m
electric inductance	henry	H	V·s/A
electric potential difference	volt	V	W/A
electric resistance	ohm		V/A
electromotive force	volt	V	W/A
energy	joule	J	N·m
entropy	joule per kelvin	...	J/K
force	newton	N	kg·m/s
frequency	hertz	Hz	(cycle)/s
illuminance	lux	lx	lm/m
luminance	candela per square metre	...	cd/m
luminous flux	lumen	lm	cd·sr
magnetic field strength	ampere per metre	...	A/m
magnetic flux	weber	Wb	V·s
magnetic flux density	tesla	T	Wb/m
magnetomotive force	ampere	A	...
power	watt	W	J/s
pressure	pascal	Pa	N/m
quantity of electricity	coulomb	C	A·s
quantity of heat	joule	J	N·m
radiant intensity	watt per steradian	...	W/sr
specific heat	joule per kilogram-kelvin	...	J/kg·K
stress	pascal	Pa	N/m
thermal conductivity	watt per metre-kelvin	...	W/m·K
velocity	metre per second	...	m/s
viscosity, dynamic	pascal-second	...	Pa·s
viscosity, kinematic	square metre per second	...	m/s
voltage	volt	V	W/A
volume	cubic metre	...	m
wavenumber	reciprocal metre	...	(wave)/m
work	joule	J	N·m

SI PREFIXES:

Multiplication Factors	Prefix	SI Symbol
1 000 000 000 000 = 10^{12}	tera	T
1 000 000 000 = 10^{9}	giga	G
1 000 000 = 10^{6}	mega	M
1 000 = 10^{3}	kilo	k
100 = 10^{2}	hecto*	h
10 = 10^{1}	deka*	da
0.1 = 10^{-1}	deci*	d
0.01 = 10^{-2}	centi*	c
0.001 = 10^{-3}	milli	m
0.000 001 = 10^{-6}	micro	μ
0.000 000 001 = 10^{-9}	nano	n
0.000 000 000 001 = 10^{-12}	pico	p
0.000 000 000 000 001 = 10^{-15}	femto	f
0.000 000 000 000 000 001 = 10^{-18}	atto	a

* To be avoided where possible.

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