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VHF DATA LINK COMMUNICATION CHARACTERISTICS

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16. Abstract

This report describes the results of a series of laboratory, field, and flight test experiments designed to characterize the performance of current VHF communication equipment and the VHF channel relative to the communication of digital data in the ATC environment. The experiments were conducted at data rates of 2400 and 4800 bits per second with minimum-shift-keying (MSK) as the baseband modulation. Laboratory experiments were performed to determine the performance of individual VHF communication equipments and subsystems of equipments in Gaussian noise and simulated multipath environments. Field tests utilizing continuous psuedo-random data streams were conducted at Logan Airport, Boston, to obtain estimates of VHF data link performance in the multipath environment of an airport surface. Flight tests were performed utilizing continuous psuedo-random data streams transmitted air to ground to determine bit and block error rates, received signal level, signal fading characteristics, and geographical coverage. Other parameters that were measured include clock slips, carrier losses, and signal fading due to aircraft maneuvers. A second series of flight tests were performed with a computer controlled experimental VHF data link system. The system was tested in a simplex mode with a single aircraft and utilized formatted messages transmitted ground to air and air to ground. The performance of the system was measured in terms of bit error rate, message transaction failure rate, and message throughput. Error distribution data is presented and analyzed. The results of the test program indicate that VHF data link can provide reliable communications for ATC purposes.

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PREFACE

This report describes the experimentally derived characteristics of the VHF channel and current VHF aeronautical communication equipment relative to their performance in a VHF digital data link system. The project was sponsored by the Federal Aviation Administration, Systems Research and Development Service under the direction of William Hyland and Thomas Williamson.

The material presented in this report represents the efforts of many individuals and organizations. The authors wish to express their appreciation to those persons who played important roles in various phases of this project. A special word of thanks is given to Donald Fehr, FAA/NAFEC, who managed the NAFEC laboratory and flight test contributions to this project. The major contributors to each of the sections of this report are listed below.

<u>Section 2</u>. Laboratory Performance Measurements of VHF Communication Equipment

R. Eaves, DOT/TSC, who wrote the laboratory test plan.

A. Swezeny, FAA/NAFEC, who performed the laboratory tests of the individual VHF communication equipment and many of the laboratory subsystem tests. The material relating to the tests of the individual communication equipment has been excerpted, paraphrased, or abstracted from his report listed as Reference 7.

<u>Section 3</u>. Airport Surface Tests

S. Cantor and R. Gagnon, DOT/TSC, who performed the tests reported in Section 3 and Appendix A.

<u>Section 4</u>. Digital Data Transmission Flight Tests

J. Juroshek and R. Fitz Gerrell, DOC/ITS, who designed the experiment. Mr. Juroshek also assembled the equipment and analyzed the data. The material presented in this section has been excerpted

or paraphrased from Mr. Juroshek's report listed as Reference 11. D. Fehr, A. Swezney, R. Erikson, and J. Bernstein, FAA/NAFEC, who performed the experiments. C. Munofo, FAA/NAFEC, who wrote the data reduction software.

Section 5. Experimental Data Link System Tests

E. Rachlis and J. Goodrow, IOCS, who wrote the software for the Experimental Data Link System. D. Fehr, A. Swezney, R. Erikson, and J. Bernstein, FAA/NAFEC, who performed the flight tests.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

TABLE OF CONTENTS (CONTINUED)

TABLE OF CONTENTS (CONTINUED)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONTINUED)

LIST OF ILLUSTRATIONS (CONTINUED)

LIST OF ILLUSTRATIONS (CONTINUED)

LIST OF ILLUSTRATIONS (CONTINUED)

LIST OF ILLUSTRATIONS (CONTINUED)

LIST OF ILLUSTRATIONS (CONTINUED)

LIST OF ILLUSTRATIONS (CONTINUED)

LIST OF ILLUSTRATIONS (CONTINUED)

LIST OF TABLES

LIST OF TABLES (CONTINUED)

EXECUTIVE SUMMARY

In view of the present overcrowding of radio communication links for air-ground-air Air Traffic Control (ATC) and the anticipated future increases in air traffic, the Systems Research and Development Service of the Federal Aviation Administration assigned to the Department of Transportation/Transportation Systems Center (DOT/TSC) at Cambridge, Massachusetts, the project of investigating the feasibility of digital transmission of ATC information as a means for reducing the present congestion of such communications, and for allowing for future systems growth.

The project, as developed at TSC, involved three concurrent programs: (1) the study of cockpit I/O (Input/Output) requirements; (2) the study of the role of air traffic controllers in such an automated system; and (3) the study of the link characteristics. The present report is concerned only with the link characteristics portion of this project. Potential applications for VHF data link include airport surface control, terminal air traffic control, and en route traffic control.

S.1 OBJECTIVES

The broad objectives of the Link Characteristics Phase of the program were to evaluate the performance of current VHF communication equipment and the VHF channel relative to the communication of digital data in the ATC environment. An additional objective was to develop an experimental data link system to investigate the link management aspects of VHF data link systems. These objectives were met through the performance of a series of laboratory, airport surface, and flight experiments designed to characterize the VHF data link channel.

The VHF communication equipment tested in this program were chosen to be representative of the equipment types currently in service in air carrier and general aviation aircraft and at FAA air traffic control facilities. The minimum shift keying (MSK) technique was selected for the tests because of two outstanding characteristics. First, MSK has the potential for providing performance equivalent to coherent antipodal (coherent phase shift keying) modems under average power constrained conditions. Moreover, MSK has the best constrained spectrum of any modem technique capable of this high level performance. The latter feature is particularly significant in data link applications since it is desired to pass the modem signal through the audio channels of existing aircraft communication equipment at relatively high data rates.

The tests were performed at data rates of 2400 and 4800 bits per second in order to assess throughput gains at the higher data rates versus potential link performance degradation due to bandwidth limitations inherent in some communication equipment designs.

The basic link discipline and message formats used in the data link system experiments were based on the VHF data link system proposed by Aeronautical Radio, Inc. (ARINC), under the guidance of the Airlines Electronic Engineering Committee.

S.2 SUMMARY OF TEST RESULTS

The results of the laboratory, airport surface, and flight tests are summarized in this section.

S.2.1 Summary of Laboratory Test Results

The performance characteristics of a variety of VHF airborne transceivers, ground transmitters, and ground receivers were determined for data link applications at data rates of 2400 and 4800 bits per second. The airborne transceivers included those of the air carrier type (i.e., Aeronautical Radio, Inc., ARINC) and those of the general aviation type. The ground transmitters and receivers tested were those that are in current use by the FAA in air traffic control facilities. The performance characteristics of the ARINC class of transceivers appear better suited to data link applications than the general aviation class of transceivers. However, it was found that with simple modifications the performance characteristics of the general aviation type transceivers can be made compatible with data link requirements. The primary ground transmitter (GRT-21) and receiver (GRR-23) in current use by the FAA appear to be well suited to data link applications.

The performance characteristics of the equipment tested within each equipment user class showed considerable variation. The effect of these performance variations on expected data link performance was determined by testing the transmitters and receivers with the MSK* modem in a Guassian noise environment at data rates of 2400 and 4800 bits per second. The results of these subsystem tests show that the variation in transmitter/receiver performance characteristics can cause performance losses in the range from 0 dB to 6 dB in those cases where the audio bandwidth appears adequate to support MSK operation at a given data rate. However, this performance variation is tolerable for VHF data link applications utilizing MSK modulation. Some of the unmodified general aviation equipment were too narrow in bandwidth to support MSK operation. These latter units can be modified with simple circuit changes to provide large improvement in performance. The results have also shown that receiver filter characteristics having smooth rolloff and bandwidth (-3 dB) of 6.5 to 8 kHz provide the best error performance.

The performance of the MSK modem was determined at baseband, at RF in a Gaussian noise environment, and at RF in a combined Gaussian noise and multipath environment obtained in a channel simulator. The tests were performed at data rates of 2400 to 4800 bits per second. The tests showed that the modem performance was very near the theoretical maximum achievable. It was shown that the modem performance at a data rate of 2400 bits per second was inferior to that of a data rate of 4800 bits per second when measured as a function of energy per bit-to-noise density. The inferior performance at 2400 bps is most likely the result of small signal suppression in the AM detector of the receiver. Signal suppression is experienced at both data rates but is greater at 2400 bps because the IF signal-to-noise is lower at a given energy per

*Minimum shift keying.

bit-to-noise density at the lower data rate. The multipath tests showed that the modem performance was relatively insensitive to Doppler spread rates in the range of up to 40 Hz, which was the maximum tested. Calculations show that Doppler spread rates will not significantly affect modem performance at aircraft cruise velocities. However, the tests showed that modem performance was significantly degraded in the presence of multipath. Modem unlock problems were observed for signal-to-multipath ratios between 6 and 7 dB or smaller. For a signal-to-multipath ratio of 7 dB the modem performance was degraded by approximately 11 dB for a bit error rate of 10^{-4} and on the order of 17 dB for a bit error rate of 10^{-5}. Signal-to-multipath ratios of the order indicated above can occur in airport environments. However, the VHF data link system can be designed to accommodate the multipath and provide acceptable operational performance.

S.2.2 Summary of Airport Surface Test Results

Tests were conducted at Logan International Airport, Boston MA, in order to obtain estimates of potential data link performance in the multipath environment of an airport. These tests were conducted at data rates of 2400 and 4800 bits per second utilizing a continuous pseudo-random data sequence which was MSK modulated onto a VHF carrier and transmitted to an aircraft receiver located in a mobile test van that was driven on the airport surface to simulate a taxiing aircraft or a docked aircraft. The test results showed approximately equal performance at data rates of 2400 and 4800 bits per second. A wide variation in bit error rate was observed as a function of van position on the airport surface. The signal-to-noise ratio available for all the van positions was estimated to exceed 30 dB, and thus uniformly good bit error rate performance should have been observed. The average bit error rate performance ranged between 4×10^{-3}, with many unlocks for obstructed conditions, to 3×10^{-5} for line-of-sight conditions. This variation in performance is indicative of multipath phenomena due to the many large reflective surfaces in the airport environment. The frequency of unlocks observed in the poor propagation areas indicates that the MSK modems will exhibit degraded acquisition performance in these areas.

An analysis of expected data link system performance on the airport surface was performed. This analysis utilized the observed bit error rate data and assumed a polling strategy that allowed up to five retransmissions to deliver a message correctly. The results of this analysis indicate that line-of-sight communication of short messages (200 bits) will typically be accomplished on the first transmission. Long messages (1800 bits) may require retransmissions 2 to 5 percent of the time. Under obstructed conditions, short messages may require retransmission 3 to 5 percent of the time, and long messages will require retransmission 26 to 36 percent of the time. Given a maximum of five retransmissions, short messages will be communicated with high probability. However, a little less than 1 percent of long messages will not be received correctly. Worst case conditions, near some terminal gate areas, will require retransmission of short messages 6 to 9 percent of the time. Long messages will require retransmissions 45 to 59 percent of the time. Again, short messages will be communicated successfully given a maximum of five retransmissions. However, long messages will fail to be received correctly 2 to 7 percent of the time.

It is concluded that for some locations within the airport environment VHF line-of-sight transmissions from a single antenna site may not provide adequate reliability for the delivery of long messages. The percentage of successful message delivery can be significantly improved with ground antenna diversity or hard wire connection to the data link system when aircraft are parked in gate areas with known poor propagation conditions. It is further concluded that similar tests be repeated utilizing an aircraft as the test vehicle in order to verify the results obtained with the van.

Similar, but less extensive tests conducted at UHF indicate that the performance of a UHF data link would be inferior to that of a VHF data link in the airport environment.

S.2.3 Summary of Flight Test Results

Flight tests were performed to determine the characteristics of the VHF channel relevant to the transmission of digital data. A continuous pseudo-random sequence was MSK modulated onto a VHF carrier and transmitted air to ground at data rates of 2400 and 4800 bits per second. Link performance was measured in terms of bit error rate, block error rate, and received signal level. The tests showed that the bit and block error rate performances were nearly identical at data rates of 2400 and 4800 bits per second. The average bit error rate was 6.8×10^{-5} and the average block error rate was 1.2×10^{-2} for block lengths of 1000 bits. The average bit error rate showed an inverse relationship with aircraft slant range from the ground receiver site out to a range of at least 40 nautical miles. The average bit error rate was highest when the aircraft was close to the ground receiver site. The observed depth of signal fading exhibited a similar behavior with the maximum depth of fading occurring when the aircraft was close to the ground receiver site. Both of these observed phenomena are most likely the result of multipath due to ground reflections. Signal fading during aircraft maneuvers was observed to be a complex function of aircraft attitude relative to the receiver. Slow aircraft maneuvers did not appear to cause any abnormal error conditions; however, sudden maneuvers did cause errors. Clock slips and carrier loss indications occurred primarily during weak signal conditions, especially when the aircraft was inbound from locations beyond the radio horizon. However, there were occasions when clock slips occurred during strong signal conditions.

A region of abnormally high bit error rate was observed when the aircraft approached the radio horizon just prior to the loss of signal. The width of this region, described as the near horizon region, varied between 0.5 and 20 nautical miles with an average of 10 nautical miles. The observed radio horizon showed good agreement with that predicted by an air-ground propagation model developed by the Institute of Telecommunication Sciences (ITS) (Reference 12).

A second series of flight tests was performed with a computer-controlled VHF data link system. The VHF computer controlled data link system was tested in a half duplex mode or two-way alternate transmission with the ground system acting as master. The performance of the system was measured in terms of bit error rate, message transaction failure rate, and message throughput. The test results indicate that more than 99 percent of the messages were transmitted error free. Of the messages that had errors 52 percent resulted from failure of the airborne or ground system to respond to valid transmitted messages. The remaining 48 percent of the messages with errors had bit or clock slip errors that were detected by the block check sequence (BCS) error detection scheme. Approximately 48 percent of all messages containing errors detected by the BCS scheme had single bit errors. Analysis of the distribution of the errors indicates that the observed probability of bit error was itself a random variable. An empirical model for the probability of error density is presented which shows that the error density can be modeled by the superposition of several bit error rates that persist for different fractions of the time. The high percentage of no response failures is explained in the context of this model.

Analysis of the bit error rate and message transaction failure rate data for different flight conditions indicate that the link performance relative to average is significantly degraded for the conditions of takeoff and climbout, turning, and approach and landing. Thus a data link system design for ATC operations must consider the total instantaneous aircraft population in a given flight condition along with the link performance characteristics for that flight condition in order to provide the required system capacity in accordance with the required message service times.

A simplified error correction scheme that utilizes the BCS scheme in conjunction with the presently unused character parity bit is recommended to improve the link efficiency. The recommended error correction scheme can correct all the messages containing single bit errors with no increase in system complexity.

The system throughput at 4800 bits per second was nearly double that at 2400 bits per second. The error performance at the two data rates was approximately equal.

S.3 CONCLUSIONS

The results of the present test program indicate, from the technical point of view of air-ground communications, that the VHF data link offers a reliable alternative to the present day voice system for ATC communications. A VHF data link, operating at a data rate of 2400 bits per second, can be implemented utilizing presently available FAA, air carrier, and most general aviation types of VHF communication equipment. Present day FAA and air carrier type VHF communication equipment can support data link operations at a data rate of 4800 bits per second. Present day general aviation type communication equipment, with simple modifications, can also support data link operations at 4800 bits per second.

Some of the significant findings supporting the above major conclusions are summarized in Table S-1.

TABLE S-1. SUMMARY OF CONCLUSIONS

Experimental Parameter	Observed Characteristic	Remarks
Received Signal Strength	On average equal to value predicted by free space path loss calculation. Signal fluctuations about this value caused by multipath and antenna characteristics.	Signals fluctuate +6 dB, -20 dB about theoretical value. Occassional value greater than 6 dB above theoretical attributed to ground reflections.
Signal Fading	Depth of signal fading inversely proportional to distance of aircraft from receiving site. Maximum variation of 20 dB when aircraft 0 to 10 nautical miles (n mi) from site, 8 dB when aircraft 10 to 20 n mi from site, 6.5 dB when aircraft 20 to 30 n mi from site, and 2 dB when aircraft 100 n mi from site.	Signal fading attributed to addition of ground reflections with directly radiated signals. Correlates well with observed bit error rate.
Geographical Coverage	Predicted well by ITS air-ground propagation model. High error density observed as aircraft approaches radio horizon. Region of high error density varies in width between 0.5 to 20 n mi with average of 10 n mi.	Region of high error rate near radio horizon not usable for data link communications.
Bit Error Rate (P_e)	Strong function of aircraft flight condition. Typical nominal average values for various flight phases are: Flight Condition — Nominal Average P_e Airport Surface — 3×10^{-4} Taxi/Climbout — 7.4×10^{-6}	Correlates well with signal fading characteristics. That is, multipath induced fading close to ground site degrades P_e. Link performance is equivalent at 2400 and 4800 bits per second.

TABLE S-1. SUMMARY OF CONCLUSIONS (Continued)

Experimental Parameter	Observed Characteristic	Remarks
Bit Error Rate (P_e) (Cont'd)	<u>Flight Condition</u> — <u>Nominal Average P_e</u> Approach Landing — 1.6×10^{-5} Maneuvers — 4×10^{-5} Level Flight — 4×10^{-6} Overall — 5×10^{-6}	
Message Transaction Failure Rate	More than 99 percent of all message transactions completed error-free. Message transaction failure rate (MTFR) correlates well with P_e as function of flight phase. Nominal average MTFR for 1656 bit messages is: <u>Flight Phase</u> — <u>Nominal Average MTFR</u> Taxi/Climbout — 1.8×10^{-2} Approach/Landing — 3.5×10^{-2} Maneuvers — 2.5×10^{-2} Level Flight — 6×10^{-3} Overall — 8.2×10^{-3}	Link performance is equivalent at 2400 and 4800 bits per second. Throughput essentially doubled at 4800 bits per second.
Error Characteristics	Most message transaction failures were due to No Responses. The No Responses resulted from bit errors in the message heading during periods of high error density. These periods of high error density persisted for durations typically on the order of 2 to 3 seconds.	Polling strategy must be adopted to accommodate the high error density period. An aircraft which does not respond should not be repolled immediately.

TABLE S-1. SUMMARY OF CONCLUSIONS (Concluded)

Experimental Parameter	Observed Characteristic	Remarks
Receiver/ Transmitter Characteristics	Error performance varied with equipment of similar type. FAA and ARINC type equipment adequate for data link use at data rates of 2400 and 4800 bits per second. General aviation equipment, in general, requires simple modification for data link applications, especially at 4800 bits per second.	Variation in performance attributed to intersymbol interference effects due to transmitter/receiver filter characteristics. Best receiver performance obtained with equipment having filter with smooth rolloff and bandwidth (-3 dB) of 6.5 to 8 kHz.

1. INTRODUCTION

In view of the present overcrowding of radio communication links for air-ground-air Air Traffic Control (ATC) and the anticipated future increases in air traffic, the Systems Research and Development Service of the Federal Aviation Administration assigned to the Department of Transportation/Transportation Systems Center (DOT/TSC) at Cambridge, Mass., the project of investigating the feasibility of digital transmission of ATC information as a means for reducing the present congestion of such communications, and for allowing for future systems growth.

The project, as developed at TSC, involved three concurrent programs: (1) the study of cockpit I/O (Input/Output) requirements; (2) the study of the role of air traffic controllers in such an automated system; and (3) study of the link characteristics. The present report is concerned only with the link characteristics program, (3) above, of this project. The results obtained in programs (1) and (2) of the project are covered in separate reports (see References 1, 2, and 3). The broad objectives of the Link Characteristics Phase of the program were to evaluate the performance of current VHF communication equipment and the VHF channel relative to the communication of digital data in the total ATC environment. Potential applications for VHF data link include airport surface traffic control, terminal air traffic control, and en-route traffic control. An additional objective was to develop an experimental data link system to investigate the link management aspects of VHF data link systems. The information derived in satisfying these objectives will provide many of the parameters required for the design of a VHF digital data link system for ATC purposes (See References 4 and 5 for VHF Data link system design requirements.)

A series of laboratory, field and flight experiments were performed to meet these objectives. The following two ground rules were adopted to guide the experiments.

1. Modulation technique was to be limited to consideration of minimum shift keying (MSK) only.

2. Basic link discipline and message format considerations were to be guided by Reference 6, ARINC Project Paper 586, "Air-Ground-Air Data Link System."

These ground rules were adopted to take advantage of previous work in VHF data link systems performed under the direction of the Airlines Electronic Engineering Committee. This previous work had indicated that MSK modulation performed well with existing airborne and FAA communication equipment at 2400 bps and had produced a well documented link discipline and message format.

The laboratory tests were designed to obtain the basic measures of VHF communication equipment characteristics necessary to interpret data link subsystem and system performance data gathered in field and flight tests. The laboratory tests also provided a controlled environment in which to obtain estimates of data link system performance prior to field and flight tests.

The laboratory tests consisted of measurements of significant VHF communication equipment parameters related to the equipment performance in a data link enviroment. VHF equipment tested included airborne transceivers of the air carrier and general aviation type, ground receivers and transmitters of the type used by FAA, MSK modems, and subsystems comprising the above. Measurements performed on the transmitters (including transmitter portions of the transceivers) included passband characteristics (amplitude and phase), harmonic distortion, local oscillator frequency stability, and power rise time. Measurements performed on the receivers (including the receiver portions of the transceivers) included passband characteristics (amplitude and phase), harmonic distortion, local oscillator frequency stability, intermodulation attentuation, adjacent channel selectivity, spurious response attentuation and AGC times. Measurements performed on the minimum shift keying (MSK) modems included bit waveforms, random sequence power spectrum, tone purity and synchronization time. Data link subsystem tests were performed by measuring bit error performance of MSK modulated transmissions through a noisy channel in combination with typical transmitters and receivers at data rates of 2400 and 4800 bits per second.

Field tests were performed at Logan International Airport, Boston, Mass., to obtain measures of expected data link performance in the multipath environment of an airport surface. The tests, conducted at both VHF and UHF frequencies, and at data rates of 2400 and 4800 bits per second, were designed to measure bit error rate, block error rate, signal fading characteristics, and multipath effects as they relate to expected data link coverage on an airport surface.

Flight experiments were performed to obtain measures of the VHF channel relative to the communication of digital data under actual flight conditions. Continuous pseudo-random bit streams were transmitted air to ground and data was collected relating to bit error count, block error count, received signal strength, aircraft position, and aircraft attitude. The flight tests were conducted over a variety of terrain and altitudes. The data was analyzed to determine bit error rate, block error rate, bit error distribution, aircraft attitude effects, and expected geographical coverage for VHF data link.

A second set of flight tests was conducted utilizing an experimental system designed to obtain data relative to the link management functions. The experimental data link system was operated at data rates of 2400 and 4800 bits per second with a link discipline and message format similar to that found in ARINC Project Paper 586, "Air-Ground-Air Data Link System" (Reference 6). Messages consisting of 30, 120, and 220 characters were transmitted in a simplex mode both ground to air and air to ground to a single aircraft. The data link system performance was measured in terms of error statistics based on a BCS error detection scheme, in terms of failure of the system to respond to valid messages, and in terms of message throughput rates.

2. LABORATORY PERFORMANCE MEASUREMENTS OF VHF COMMUNICATION EQUIPMENT

Laboratory tests were performed on a variety of current VHF communication equipments to measure parameters of particular significance to data link system performance. VHF communication equipment tested included airborne transceivers of the air carrier (ARINC) and general aviation type, ground receivers and transmitters of the type currently in use at FAA ATC facilities, MSK modems, and subsystems comprising the above. The equipment that was tested is listed in Table 2-1.

With the exception of the MSK modems, the VHF communication equipment comprising proposed data link systems has been designed primarily for audio use. The performance of this equipment when communicating MSK modulated digital data must be established in order to properly assess expected data link system performance utilizing this equipment. The theoretical MSK spectrum to be passed by the VHF communication equipment is shown in Figure 2-1 for the two data rates of interest, 2400 and 4800 bits per second. A typical energy spectral density for voice signals is shown in the inset for comparison purposes. The portions of the MSK spectrum which are below -20 dB do not contain significant amounts of energy. Thus, for the data link application with the existing VHF audio equipment, the portion of the MSK spectrum of primary concern is confined to the first lobe. A discussion of the MSK modulation technique is given in section 2.3.1.

As can be seen from Table 2-1, the VHF communication equipments tested belong to three distinct user categories: those designed in accordance with ARINC Characteristics (primarily for air carrier use); those designed for general aviation use; and those designed for FAA ATC functions. The equipments designed for air carrier and FAA ATC use provide for relatively wide audio bandwidth when compared to the bandwidth requirements to pass the data link MSK spectrum. In fact, the ARINC equipments were designed or modified to have data link capabilities. The general aviation

TABLE 2-1. VHF COMMUNICATION EQUIPMENT TESTED

QUANTITY	MANUFACTURER AND MODEL	COMMENTS
	TRANSCEIVERS	
1	King KTR-9100A	ARINC Characteristic 566A
2	Bendix RTA-43A	ARINC Characteristic 566A
2	Collins 618M-2B	ARINC Characteristic 546 (Modified for Data Link)
1	Collins 618M-2B	ARINC Characteristic 546
2	BUEC FA-8191	FAA Back-Up Emergency Communication Equipment
1	King KY-195B	General Aviation Equipment
1	NARCO COM-11A	General Aviation Equipment
1	Genave ALPHA-100/360	General Aviation Equipment
	TRANSMITTERS	
1	ITT, A/N GRT-21	FAA ATC Transmitter
1	TV-36	FAA ATC Transmitter
	RECEIVER	
1	ITT, A/N, GRR-23	FAA ATC Receiver
	MODEMS	
2	McDonnell-Douglas MDL-510	2400/4800 Bit Per Second Transmit and Receive Modems

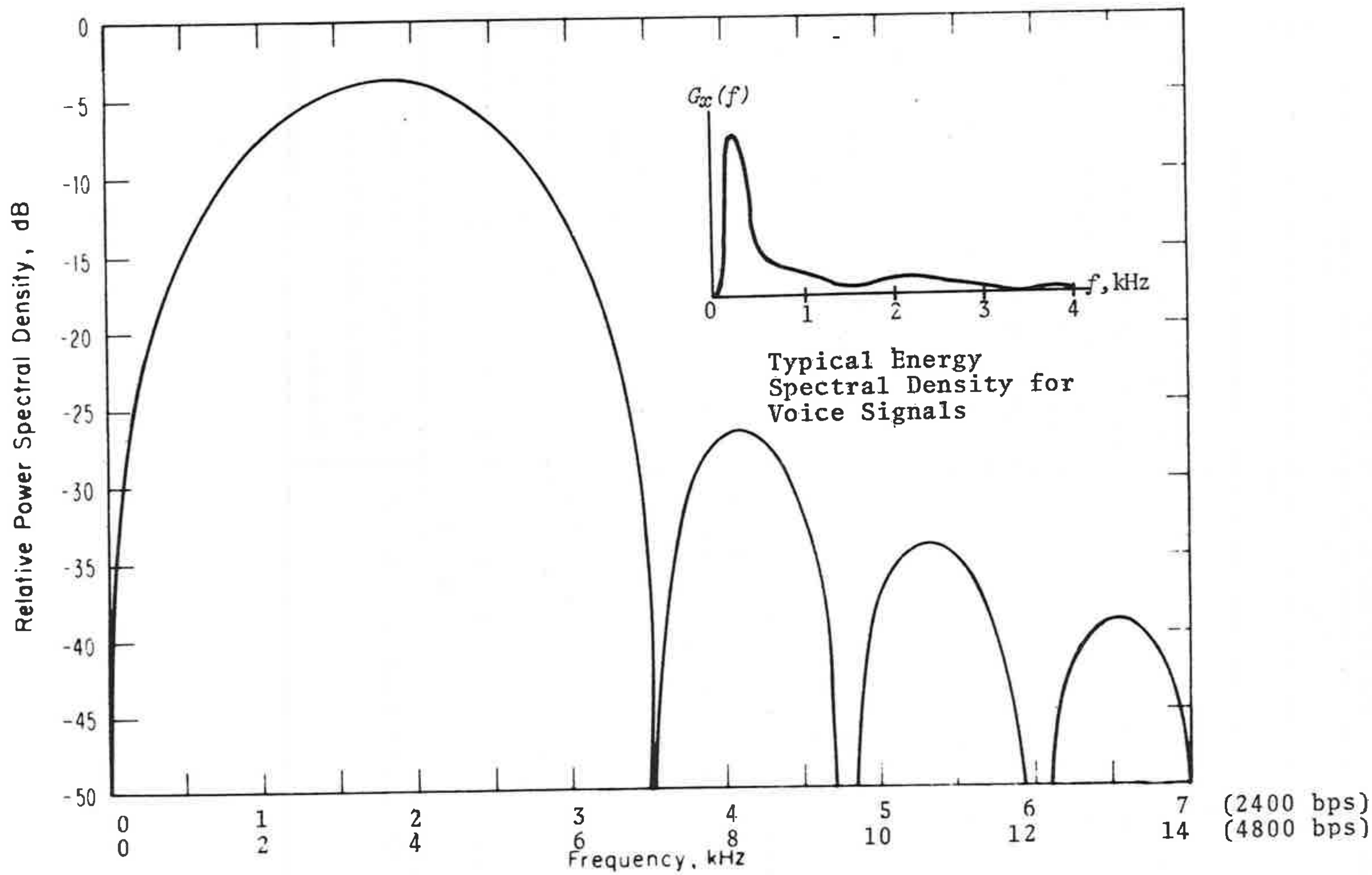


FIGURE 2-1. POWER SPECTRAL DENSITY OF A PHASE-CONTINUOUS, 2400 AND 4800 BIT-PER-SECOND MSK SIGNAL. TRANSMIT TONES ARE 1200 AND 2400 Hz AT 2400 BITS PER SECOND AND 2400 AND 4800 Hz AT 4800 BITS PER SECOND

equipments were designed strictly as minimum cost voice communication devices and as such have limited audio bandwidth relative to the MSK spectrum. Thus, in addition to testing these transceivers in an off-the-shelf condition, minor modifications to increase the audio bandwidth were implemented in order to test this equipment group for data link applications.

Specific modifications to the equipment tested are summarized below.

1. Modifications to the two modified Collins 618M-2B transceivers (ARINC Characteristic 546) listed in Table 2-1 were designed and installed by the manufacturer specifically to minimize switching times. Modifications consisted of replacement of the electromagnetic switching relays with solid state switches. The transceivers were further modified to allow signal reception while the push-to-talk (PTT) and data-link-key lines were grounded.

2. A wide-band audio amplifier was used in the receiver sections of some general aviation type transceivers in order to provide sufficient bandwidth to pass the MSK spectrum. This modification was made to the King, Model KY-195B and the NARCO, Model COM-11-A. In addition, the modulator of the NARCO, COM-11-A was modified by changing capacitor C430 from 10 to 0.5 microfarads to support the wideband data link operation.

2.1 RECEIVER TESTS

Receiver performance characteristic tests were made on the receiver equipment listed in Table 2-1. Parameters considered important to data link system performance were given special attention. Examples of these parameters are receiver AGC attack and decay times, audio delay and distortion, and rf frequency stability and accuracy. In addition, the amplitude and phase characteristics of the receivers are important to an analysis of data link performance, not only because of basic bandwidth considerations, but also because filter shape characteristics (e.g., smooth vs sharp roll-off) determine the extent of intersymbol interference in the data detection process. The receiver tests performed are listed in Table 2-2.

TABLE 2-2. RECEIVER TESTS

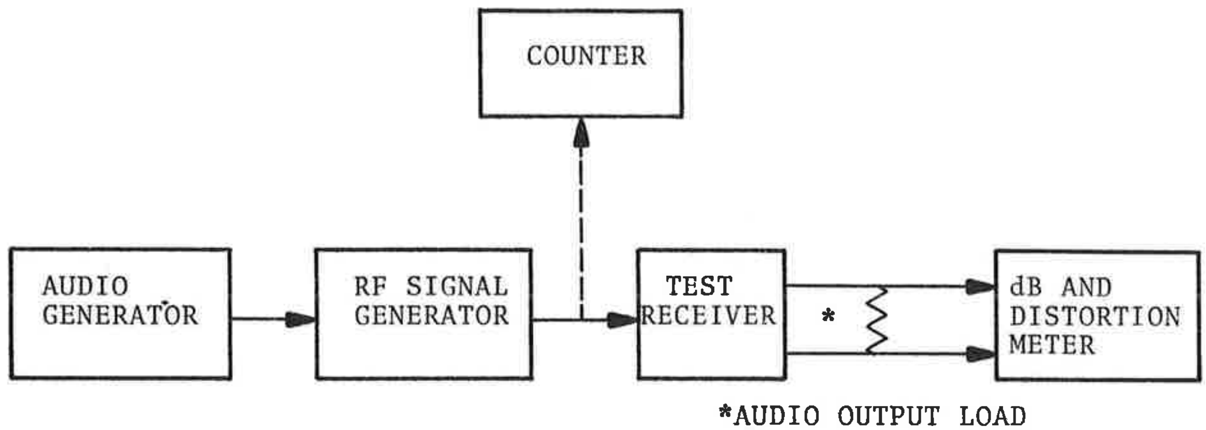
TEST	PURPOSE	REMARKS
1. Pass-Band Characteristics a Amplitude Characteristics b Phase Characteristics	Describes signal distortion resulting from the linear receiver characteristics	Affects Bit Error Rate (P_e) (items 1–3)
2. Harmonic Distortion	Describes distortion resulting from non-linearities in the receiver	
3. Local Oscillator Frequency	Measures the degree to which frequency variations may cause an effective alteration of pass-band characteristics	
4. Intermodulation Attenuation	Gives an indication of the degree to which front end non-linearities will cause signals on other channels to interfere with the desired signal	Provides information on interference which can affect P_e if receiver design or frequency allocations are not suitable (items 4–5)
5. Adjacent Channel Selectivity	Measures the ability of the receiver to discriminate between the desired signal and signals on adjacent channels	
6. Spurious Response Attenuation	Measures the ability of the receiver to reject any undersired signal including images	
7. AGC Attack and Decay Times	Time after signal is first received for receiver output to stabilize so that output will be reliable and time for receiver to return to quiescent state	Contributes to turnaround time
8. Usable Sensitivity	Basic radio performance characteristics. (items 8–11)	
9. Squelch Limit Sensitivity		
10. Quieting Sensitivity		
11. Squelch Threshold Sensitivity		

2.1.1 Receiver Test Setup and Test Procedures

2.1.1.1 Pass-Band Charcteristics - Amplitude and phase characteristics of the receivers listed in Table 2-1 were measured. These measurements were made in order to determine the capability of receivers designed primarily as voice instruments to pass MSK modulated data at 2400 and 4800 bits per second.

Amplitude Characteristics - The test setup to measure the amplitude characteristics ($A(\omega)$) is shown in Figure 2-2. The $A(\omega)$ were measured directly with a dB meter for both 30 percent and 80 percent modulation. The test data were normalized to zero dB at 1000 Hz and plotted. Results of these tests are presented in Figures 2-3 through 2-16 for the 80 percent modulation case. Results for the 30 percent modulation case, which exhibit similar $A(\omega)$, have been omitted from this report for the sake of brevity. The 30 percent modulation test results may be found in Reference 7. Figures 2-3 through 2-5 show the $A(\omega)$ of receiver portions of off-the-shelf transceivers manufactured in accordance with ARINC Characteristic 566A (Ref. 8). These transceivers are designed for data link operation and for operation at 25-kHz channel spacing. The bandwidth of the King 9100A is in excess of 10 kHz. However, the $A(\omega)$ shows a definite ripple at modulation frequencies between 2 and 5 kHz which could contribute to data distortion. The ripple is deeper at 30 percent modulation. The data link audio bandwidths of the two Bendix RTA-43A units are approximately 6.6 and 6.0 kHz respectively. The tone pairs (1200 Hz, 2400 Hz) and (2400 Hz, 4800 Hz) required for MSK modulation at 2400 and 4800 bits per second, respectively, fall within the bandwidth of these receivers. The $A(\omega)$ exhibit a smooth rolloff, which is desirable for data transmission.

Figure 2-6 shows the $A(\omega)$ of the receiver portion of a transceiver manufactured in accordance with ARINC Characteristic 546 (Ref. 9). This transceiver is designed with a data link audio output and is modified for operation at 25-kHz channel spacing.



NOTE: THIS TEST SETUP USED FOR:

USABLE SENSITIVITY
SQUELCH LIMIT SENSITIVITY
QUIETING SENSITIVITY
SQUELCH THRESHOLD SENSITIVITY
SPURIOUS RESPONSE ATTENUATION
HARMONIC DISTORTION
RECEIVER PASS-BAND CHARACTERISTIC

FIGURE 2-2. RECEIVER TEST SETUP 1

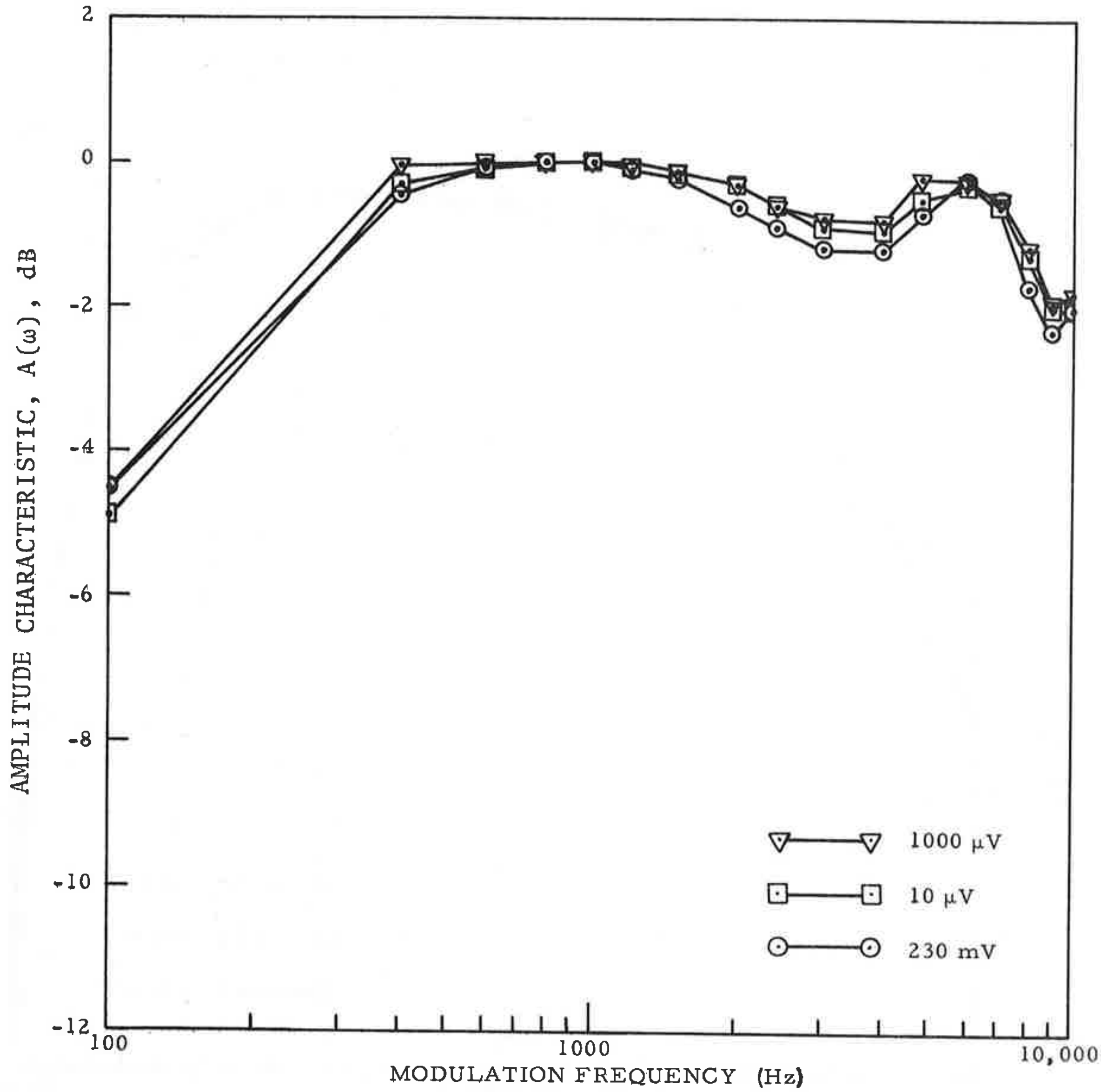


FIGURE 2-3. RECEIVER NORMALIZED DATA LINK AUDIO 80 PERCENT MODULATION, KING, MODEL KTR-9100A, SERIAL NO. 2103

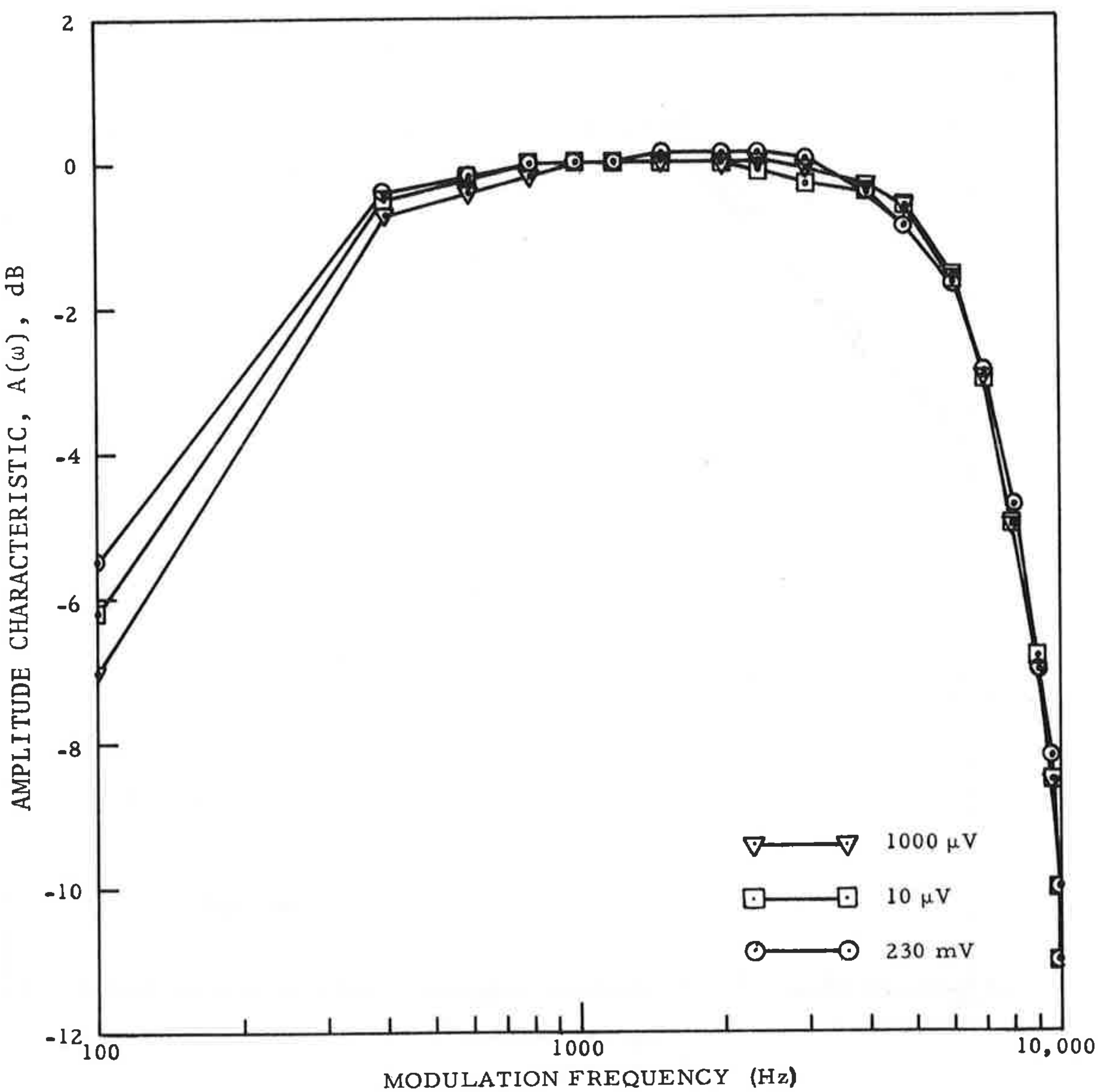


FIGURE 2-4. RECEIVER NORMALIZED DATA LINK AUDIO 80 PERCENT MODULATION, BENDIX, MODEL RTA-43A, SERIAL NO. 1050

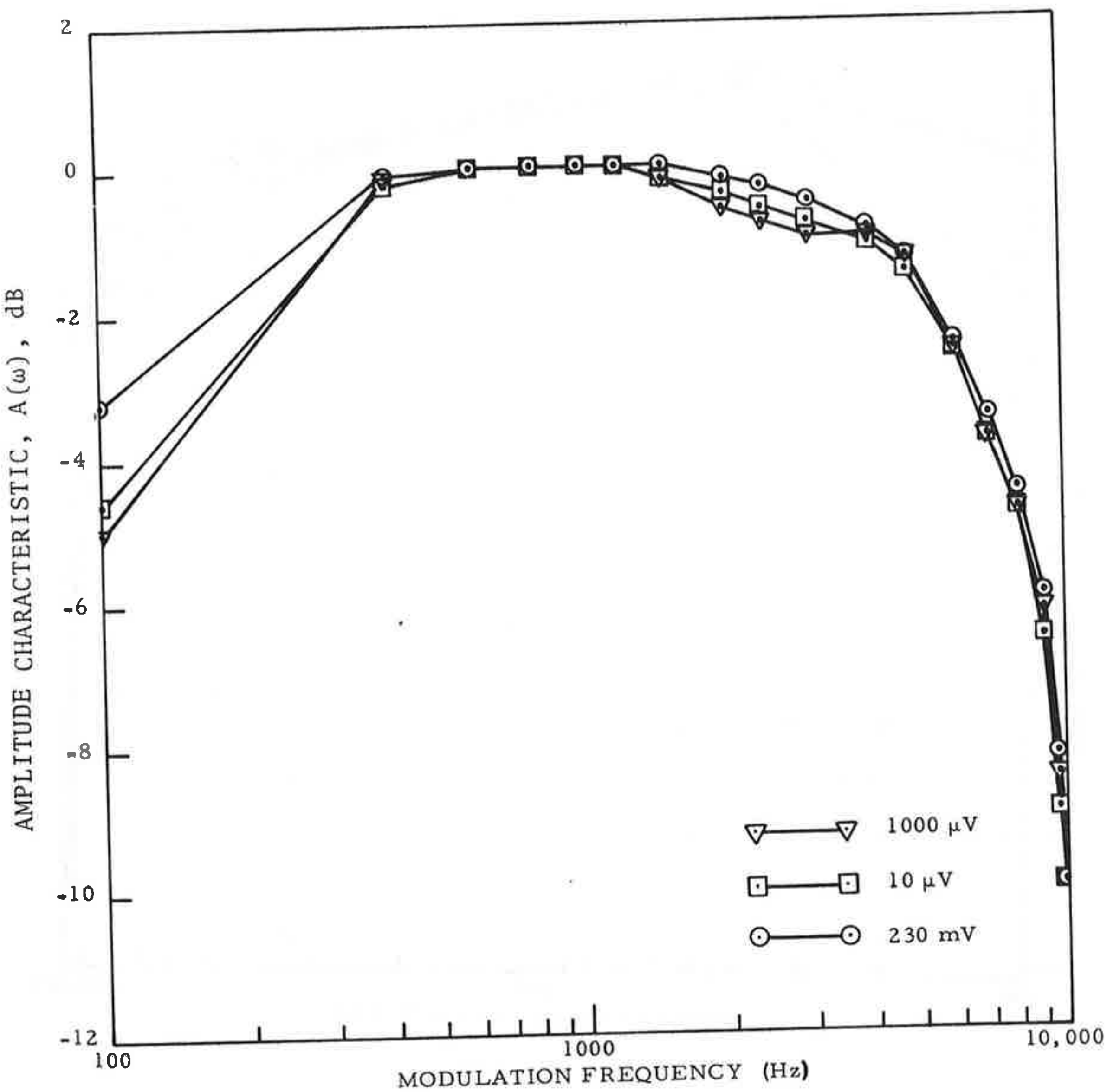


FIGURE 2-5. RECEIVER NORMALIZED DATA LINK AUDIO 80 PERCENT MODULATION, BENDIX, MODEL RTA-43A, SERIAL NO. 1027

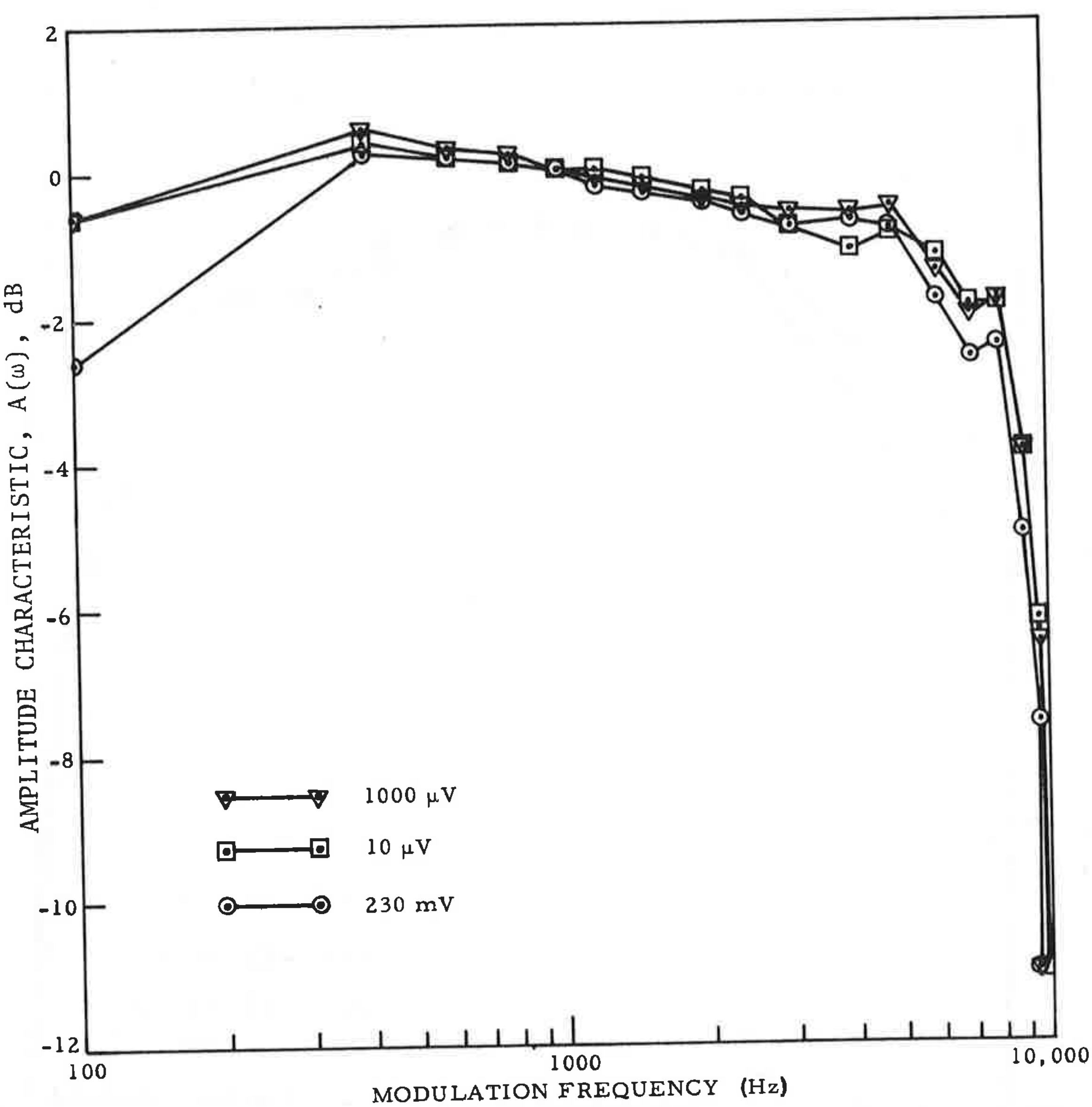


FIGURE 2-6. RECEIVER NORMALIZED DATA LINK AUDIO 80 PERCENT MODULATION, COLLINS, MODEL 618M-2B, SERIAL NO. 4868

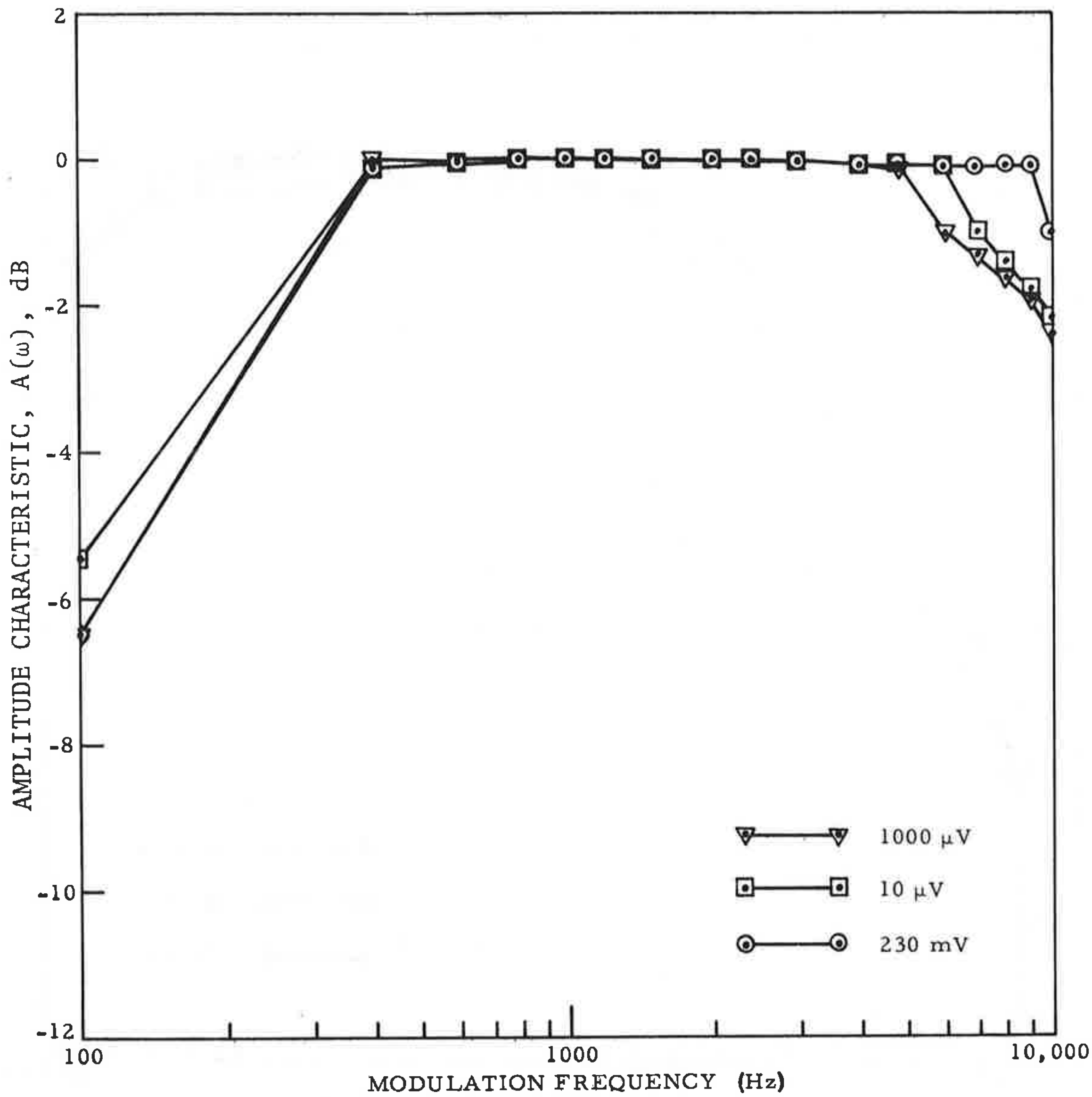


FIGURE 2-7. RECEIVER NORMALIZED DATA LINK AUDIO 80 PERCENT MODULATION, MODIFIED COLLINS, MODEL 618M-2B, SERIAL NO. 2996

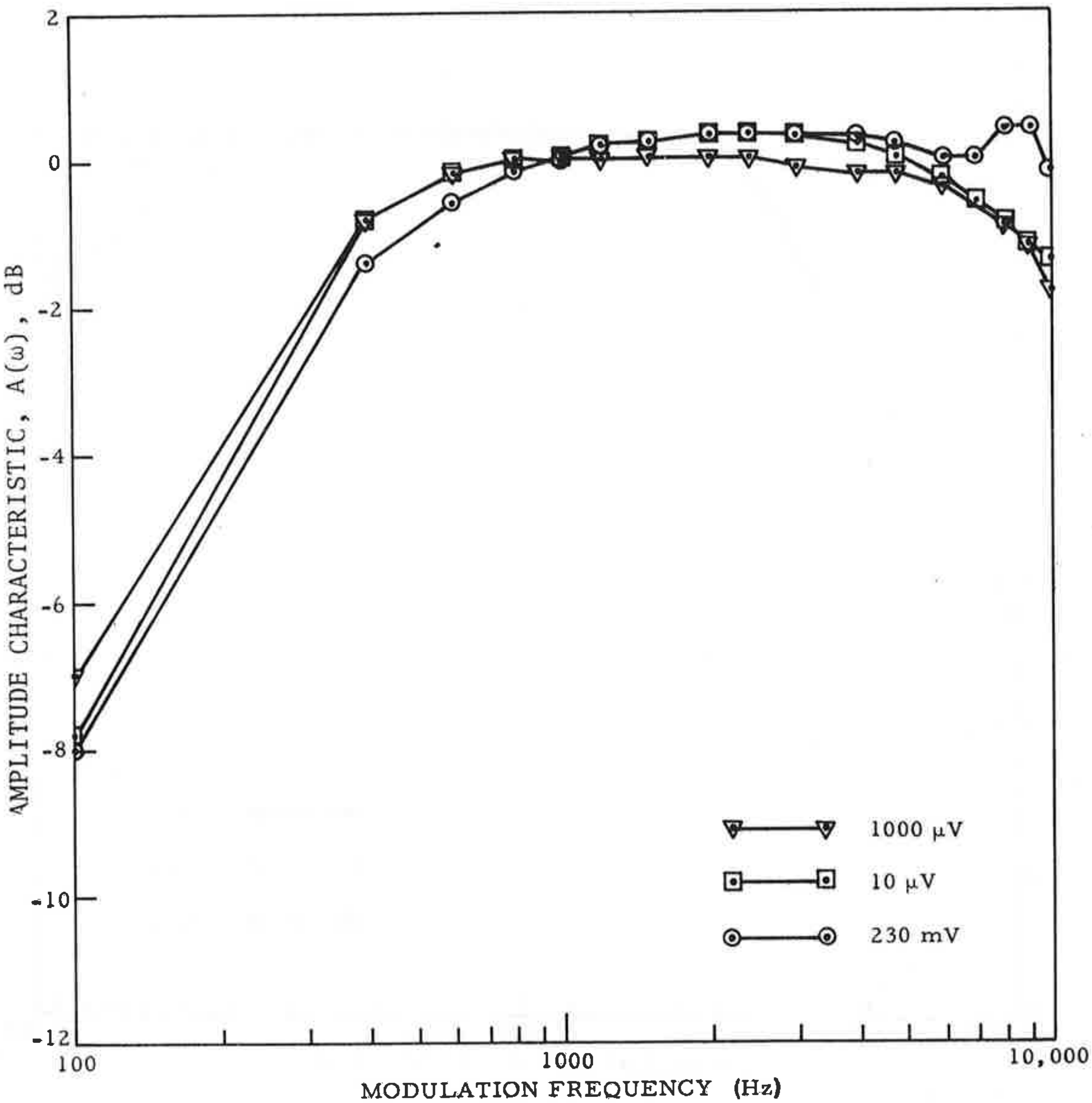


FIGURE 2-8. RECEIVER NORMALIZED DATA LINK AUDIO 80 PERCENT MODULATION, MODIFIED COLLINS, MODEL 618M-2B, SERIAL NO. 2971

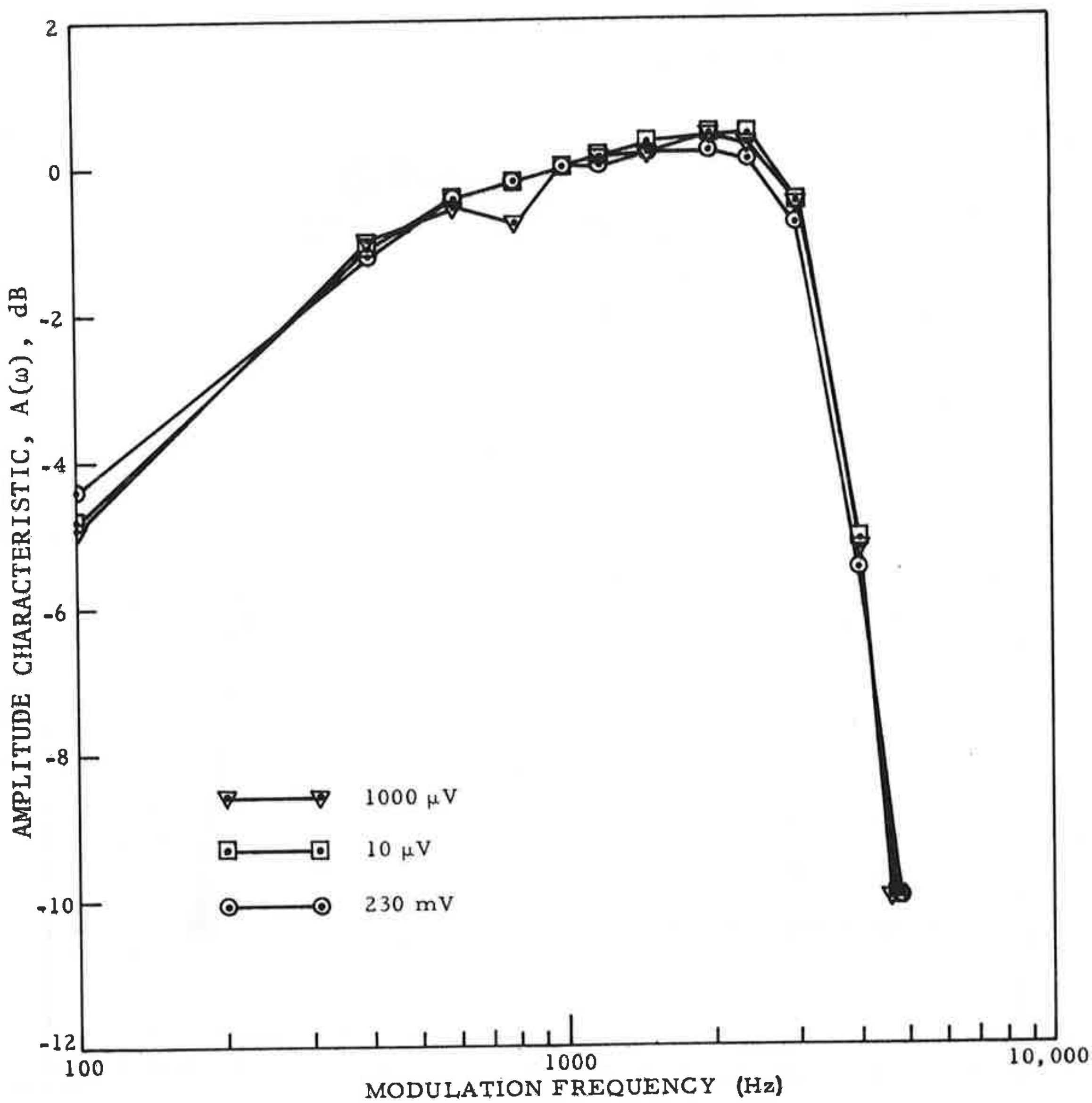


FIGURE 2-9. RECEIVER NORMALIZED AUDIO 80 PERCENT MODULATION, BUEC, MODEL FA-8191, SERIAL NO. 1

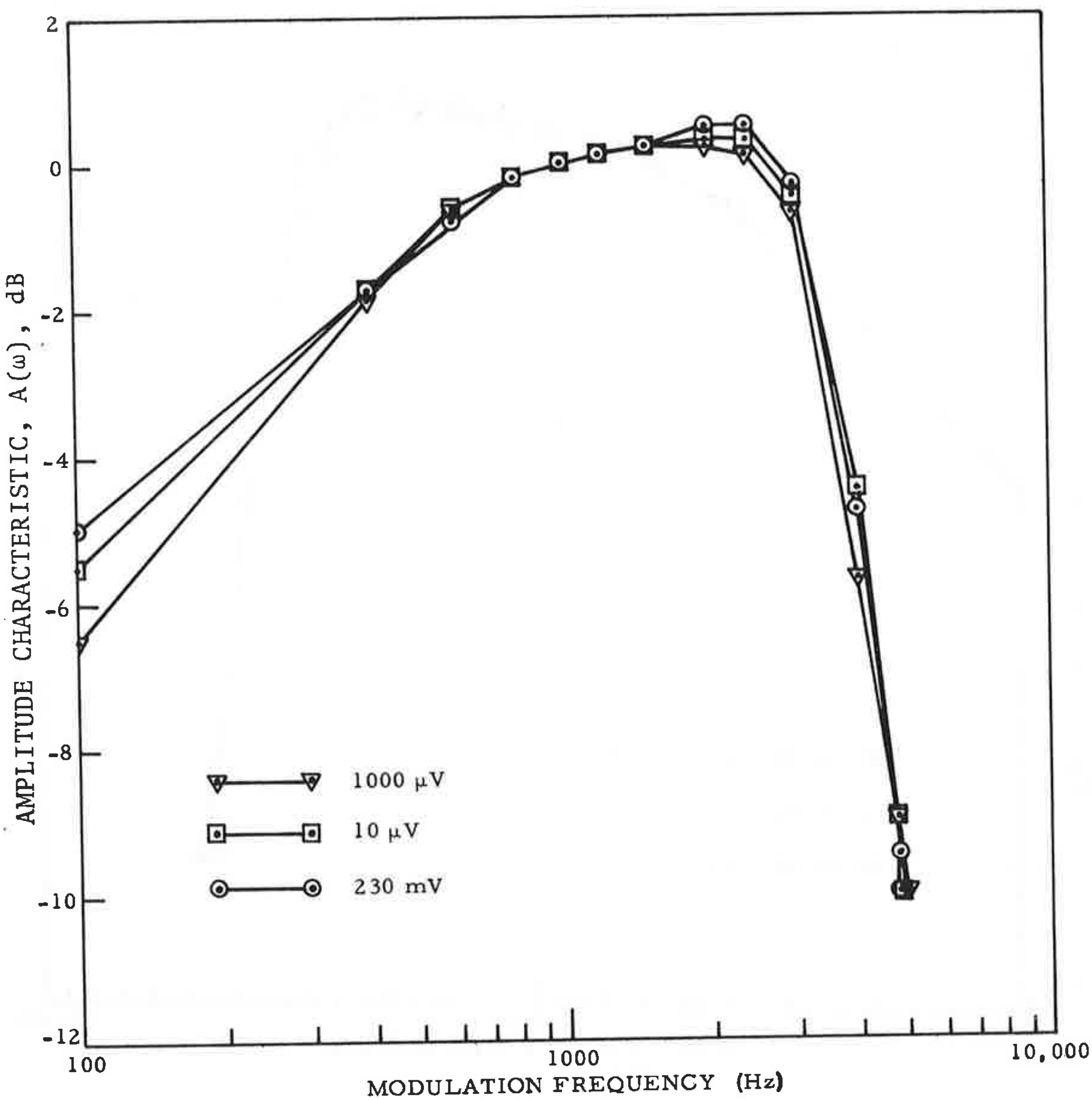


FIGURE 2-10. RECEIVER NORMALIZED AUDIO 80 PERCENT MODULATION, BUEC, MODEL FA-8191, SERIAL NO. 2

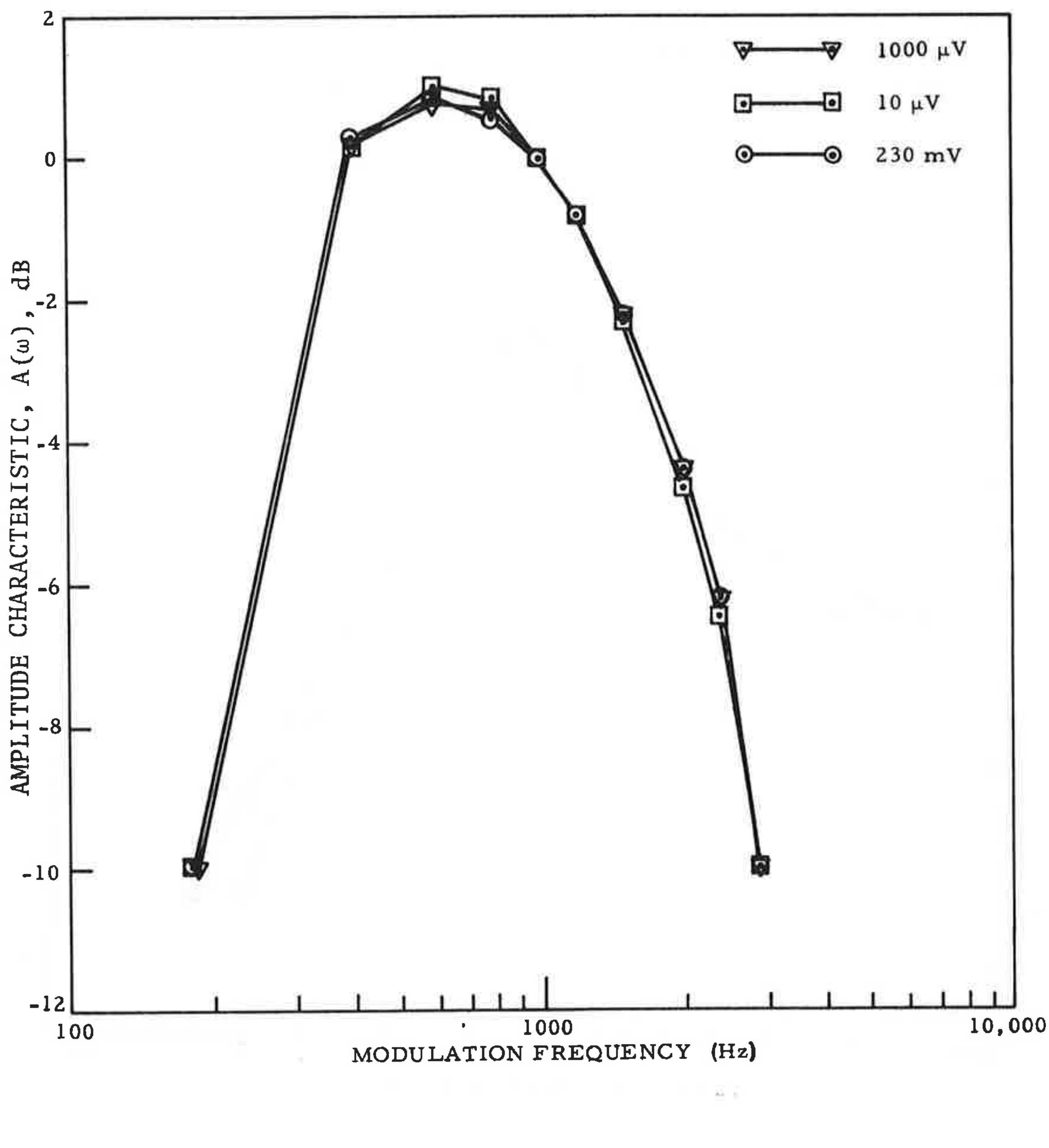


FIGURE 2-11. RECEIVER NORMALIZED AUDIO 80 PERCENT MODULATION, KING, MODEL KY-195B, SERIAL NO. 3145

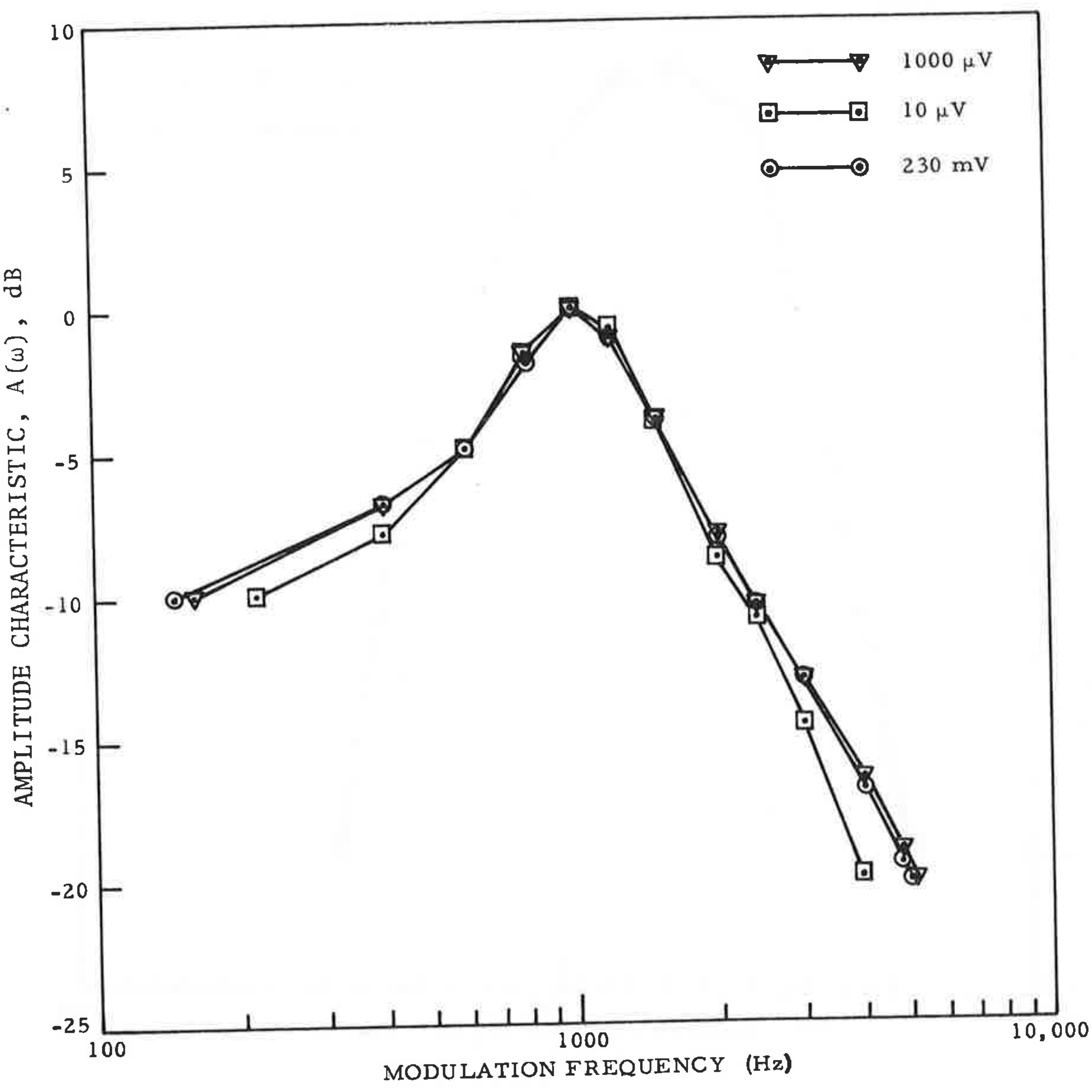


FIGURE 2-12. RECEIVER NORMALIZED AUDIO 80 PERCENT MODULATION, NARCO, MODEL COM-11A

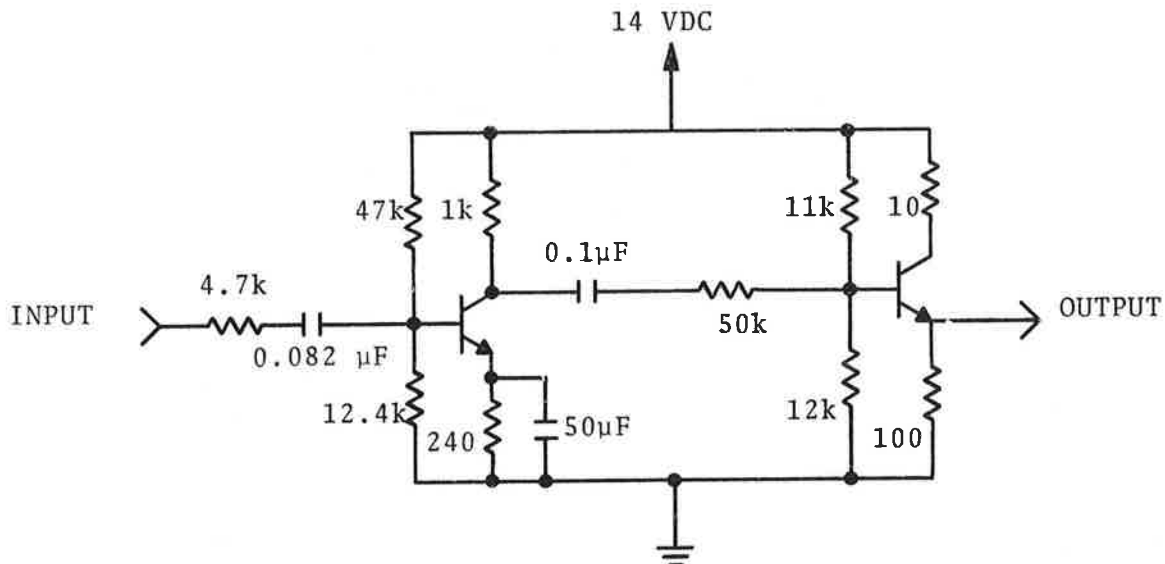


FIGURE 2-13. RECEIVER AUDIO MODIFICATION FOR DATA LINK OUTPUT

NOTE: A modification was used in the test setup to provide this "typical" shaped curve, for reference purposes ONLY. Receiver characteristics were taken from detector TP-410.

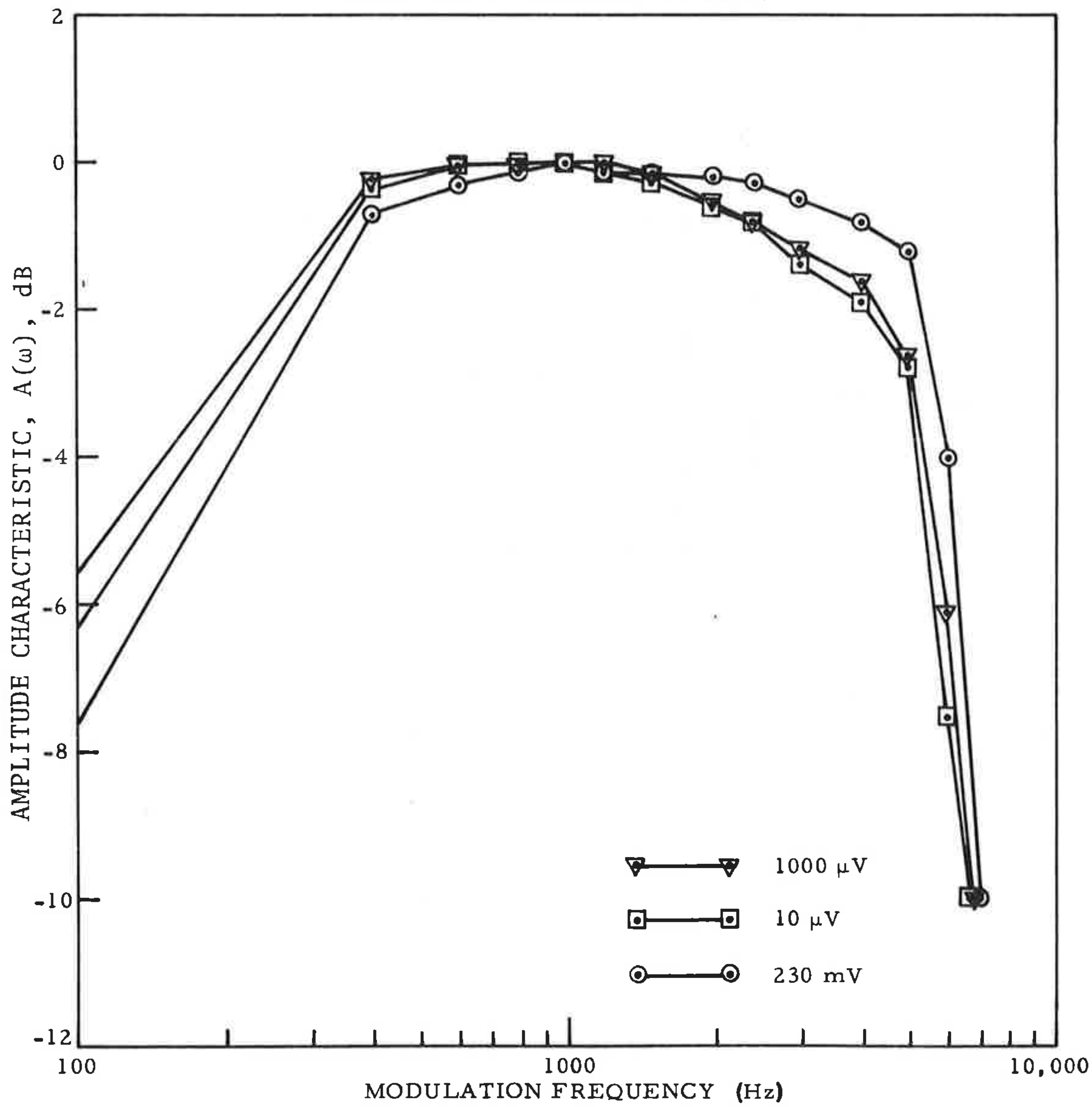


FIGURE 2-14. RECEIVER NORMALIZED MODIFIED AUDIO 80 PERCENT MODULATION, KING, MODEL KY-195B, SERIAL NO. 3145

Note: A modification was used in the test setup to provide this "typical" shaped curve, for reference purposes ONLY. Receiver characteristics were taken from OMNI output.

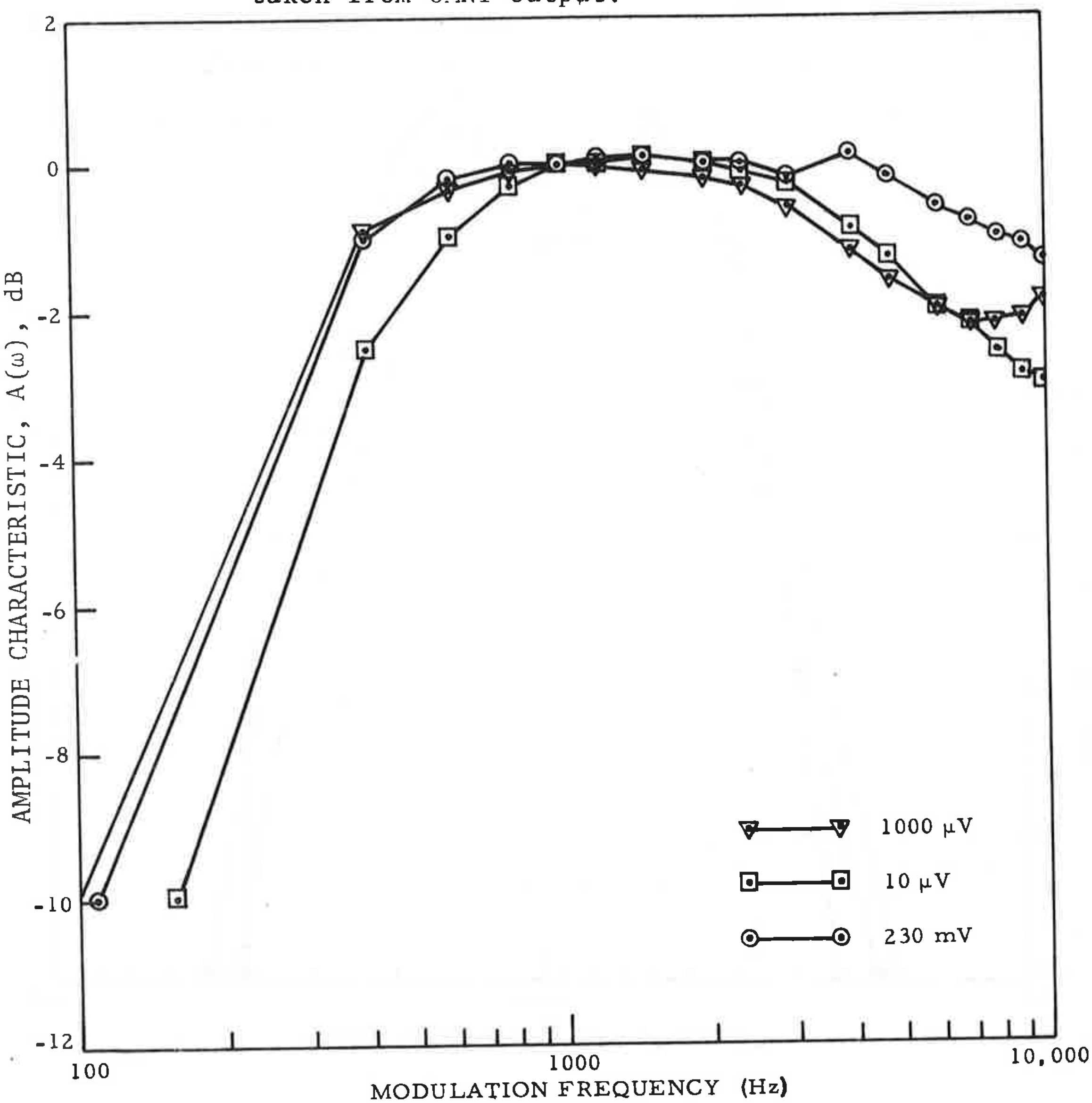


FIGURE 2-15. RECEIVER NORMALIZED MODIFIED AUDIO 80 PERCENT MODULATION, NARCO, MODEL COM-11A

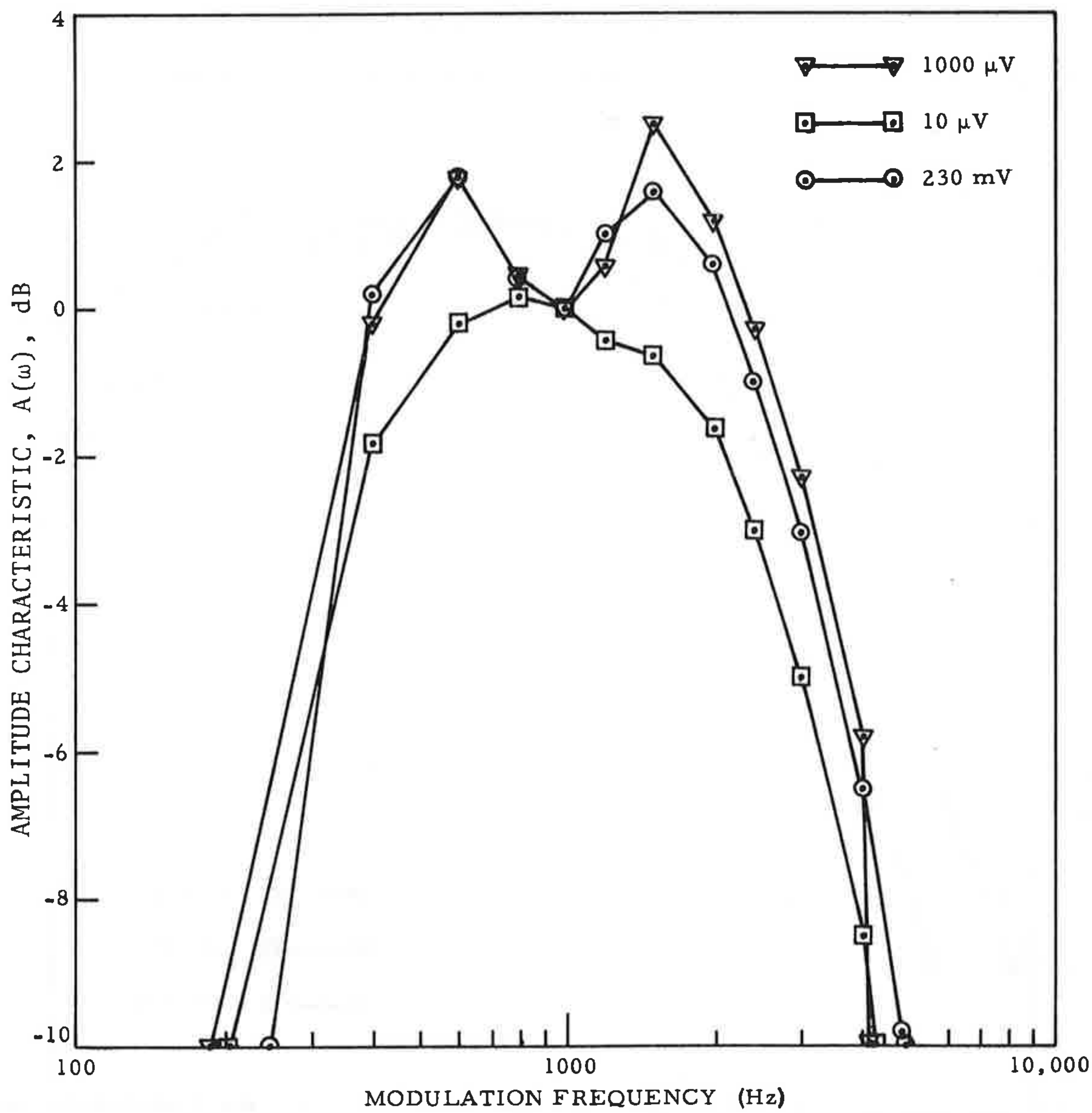


FIGURE 2-16. RECEIVER NORMALIZED AUDIO 80 PERCENT MODULATION, GENAVE, MODEL ALPHA-100/360, SERIAL NO. 43-22

The data link audio bandwidth is approximately 8600 Hz and the MSK tone pairs (1200 Hz, 2400 Hz) and (2400 Hz, 4800 Hz) are well within this bandwidth.

Figures 2-7 and 2-8 show the A(ω) of the receiver portions of transceivers manufactured in accordance with ARINC Characteristic 546 but modified by the manufacturer to enhance data link switching time performance. The modifications consist of the replacement of the standard electromagnetic switching relays with solid state switches and the capability of signal reception while the push-to-talk (PTT) and data-link-key lines are grounded. The data link audio bandwidths for these units exceed 10 kHz which should readily accomodate the MSK spectrum at data rates of 2400 and 4800 bits per second.

Figures 2-9 and 2-10 show the A(ω) of the receiver portions of the FAA's Back-Up Emergency Communication (BUEC) transceivers. Transceivers of this type are presently installed at FAA facilities. The MSK tones of 1200 Hz and 2400 Hz lie within the bandwidth of these transceivers indicating that the receiver portions of these transceivers could be suitable for data link applications at a data rate of 2400 bits per second. However, the proximity of the 2400 Hz tone to the upper limit of the bandwidth could very well yield marginal performance because of the possibility of intersymbol interference effects. Significant errors due to intersymbol interference result when the filter transient response is substantially longer than 1 bit duration. In that case, energy from a given data bit is spread into subsequent bit intervals and acts as interference to the detection of the subsequent bits. The 4800-Hz tone of the MSK spectrum, which represents the entire MSK spectrum for the case of 4800 bits per second data streams containing all marks or all spaces, lies well outside the bandwidth (10 dB down) of these transceivers. The all mark or all space case at 4800 bits per second would be 10 dB below that of the similar case at 2400 bits per second. In addition, the smearing of the filter transient response for the case of randomly occurring MSK marks and spaces would most likely degrade the performance further due to intersymbol interference.

Figures 2-11 and 2-12 show the measured $A(\omega)$ of the receiver portions of two off-the-shelf general aviation transceivers. Note the relatively narrow audio bandwidth when compared to the transceivers manufactured in accordance with ARINC Characteristics (Figures 2-3 through 2-8). However, it should be remembered that these transceivers were not designed with data link applications in mind. For the results shown in Figure 2-11 notice that the 1200-Hz tone of the MSK spectrum (2400 bit-per-second data rate) falls within the receiver bandwidth (1 dB down) whereas the 2400-Hz tone is well outside the bandwidth (more than 6 dB down). Similar observations relative to the results shown in Figure 2-12 reveal that the 1200-Hz tone is within the bandwidth (1 dB down) and the 2400-Hz tone again is well outside the bandwidth (11 dB down) and the response at 4800 Hz is on the order of 18 dB down.

The steady state transceiver error performance for 2400 bit-per-second data streams consisting of all marks or all spaces (corresponds to a pure 2400-Hz tone for the MSK spectrum) would be 5 dB and 10 dB below for the respective transceivers than that for the case of alternating marks and spaces (corresponds to a pure 1200-Hz tone for the MSK spectrum) for the same transceivers. Even worse performance could be expected for realistic data streams consisting of randomly occurring marks and spaces because of the potential for intersymbol interference. For 4800 bit-per-second data streams the error performance can be expected to be very poor since the MSK spectrum lies well outside the bandwidths of the transceivers.

The receiver portions of these two transceivers were modified to demonstrate the types of relatively simple modifications that could be made to increase the audio bandwidth of general aviation transceivers for data link applications. For these test purposes the wide-band OMNI output, designed for VOR use, was picked off and amplified for use as the data link output. The wideband audio amplifier, shown in Figure 2-13 was added to both units. In addition, in the NARCO modulator, capacitor C430 was changed from 10 to 0.5 microfarads. The $A(\omega)$ were repeated with these modifications installed and are shown in Figures 2-14 and 2-15. This modification resulted in a bandwidth increase (measured at the -3 dB points) from 1600 Hz to 4800 Hz for the King transceiver. Notice that the 1200-Hz and 2400-Hz tones now fall within the bandwidth and the 4800-Hz tone is at the upper limit of the bandwidth. Similarly, the bandwidth of the NARCO transceiver was increased from 600 Hz to 9700 Hz and the 1200-Hz, 2400-Hz, and 4800-Hz tones lie within the bandwidth. Thus it would appear that relatively minor modifications can be implemented to increase the bandwidths of the receiver portions of general aviation type transceivers to make them suitable for data link use, at least at 2400 bit-per-second data rates.

Figure 2-16 shows the measured $A(\omega)$ of the receiver portion of a third off-the-shelf general aviation transceiver. It too has a narrow bandwidth (2500 Hz) when compared to the transceivers manufactured in accordance with ARINC Characteristics. The 1200-Hz and 2400-Hz tones of the MSK spectrum both fall within the bandwidth of this transceiver without modification. However, the 2400-Hz tone is at the upper limit of the bandwidth which might result in marginal performance for data link applications at 2400 bit-per-second data rates, particularly when intersymbol interference effects are considered. The 4800-Hz tone falls well outside the bandwidth (greater than 10 dB down) and would seem to preclude satisfactory performance of this transceiver at data rates of 4800 bits per second without modification. In addition, there is a large ripple evident in the passband which could considerably degrade the performance of this receiver at 2400 bits per second.

Figure 2-17 shows the $A(\omega)$ of the FAA's GRR-23 ground receiver. This receiver type is currently the primary FAA audio ground receiver and is installed nationwide in RTR and RCAG sites.

The auxiliary wide-band audio output was utilized as the data link port for this test. Minor modifications to the receiver were required to make it compatible with the data link application. The modifications consisted of the removal of capacitor C41 in the intermediate frequency (IF) amplifier to eliminate distortion. The audio output was taken from capacitor C5 and then to a potentiometer and across a 100-ohm resistive load to provide impedance

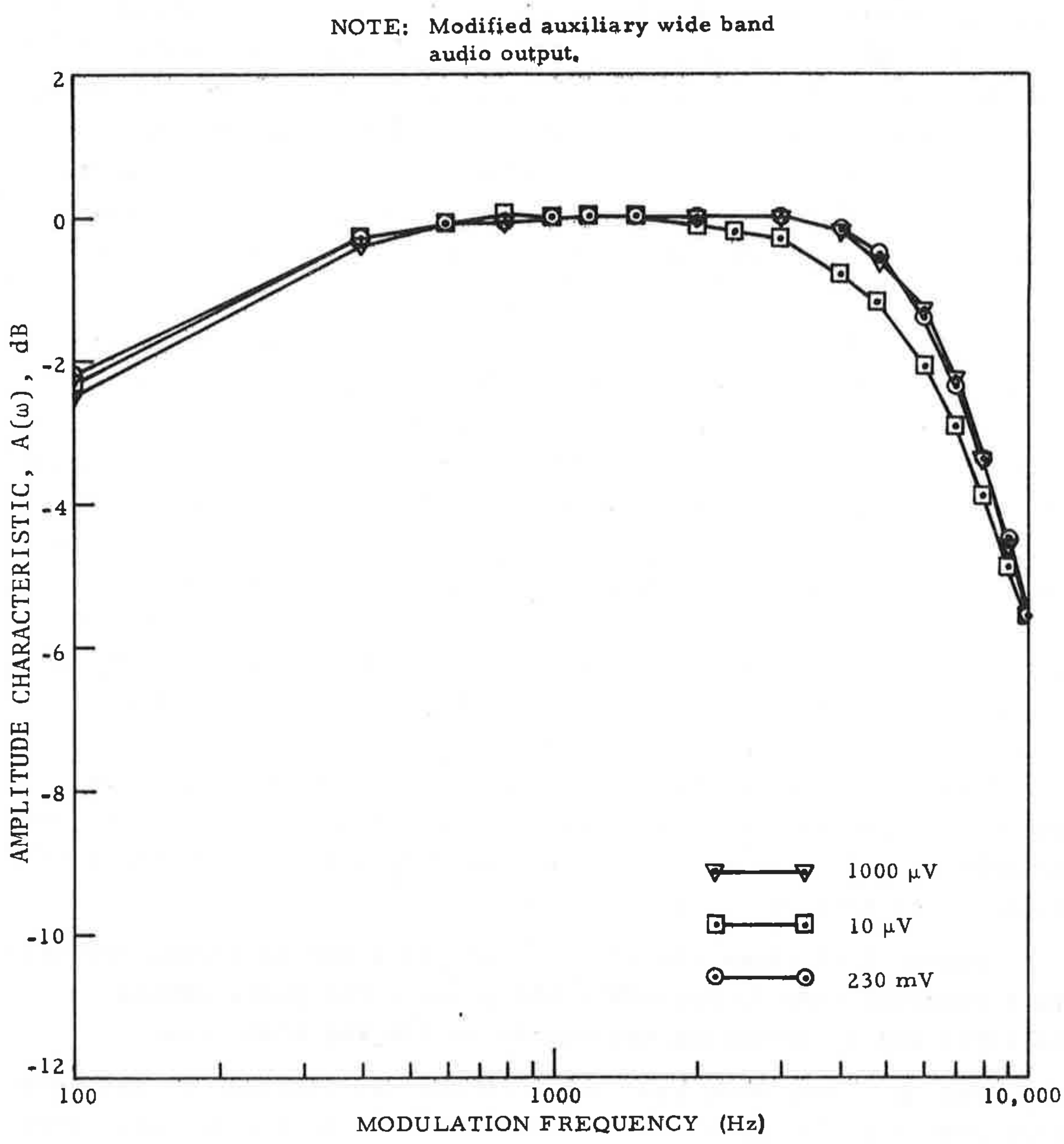


FIGURE 2-17. RECEIVER NORMALIZED MODIFIED AUDIO 80 PERCENT MODULATION, A/N, MODEL GRR-23, SERIAL NO. 4293

matching required by the MSK modem to be used in subsequent tests. In this configuration the receiver bandwidth was approximately 7500 Hz. The tone pairs (1200 Hz, 2400 Hz) and (2400 Hz and 4800 Hz) associated with the MSK modulation for data rates of 2400 and 4800 bits per second respectively, are well within the bandwidth of the receiver. The GRR-23 appears to be well suited for data link applications on the basis of the $A(\omega)$.

Audio Phase Delay Characteristics - Receiver audio delay measurements were performed on the receivers listed in Table 2-1. The test setup for these measurements is shown in Figure 2-18. The results of these measurements are shown in Figures 2-19 through 2-30. The calculated values for the differential time delays at 1200 and 2400 Hz for 2400 bit-per-second MSK and at 2400 and 4800 Hz for 4800 bit-per-second MSK are given in Table 2-3 for the individual receivers. Ideally the audio delay characteristics, as shown in Figures 2-19 through 2-30, should be flat across the bandwidth in order to minimize distortion. That is, the deviation of the delay from the nominal linear value gives rise to distortion, not the absolute value of the delay itself. The amount of differential delay compared to the bit period, expressed as a percentage, is a measure of performance degradation due to this effect. Values of this parameter less than 2 percent indicate good delay distortion characteristics whereas values on the order of 10 percent or more indicate that data performance degradation due to this source is not negligible. The significance of these data relative to data link system performance is discused in section 2.4 below. At this point, it should be noted that neither the amplitude nor the phase (or delay) characteristics of the receiver filter are sufficient to predict data error performance. The combined effect of the amplitude and phase characteristics, or alternatively, the complex transient response, must be known in order to evaluate the intersymbol interference effects.

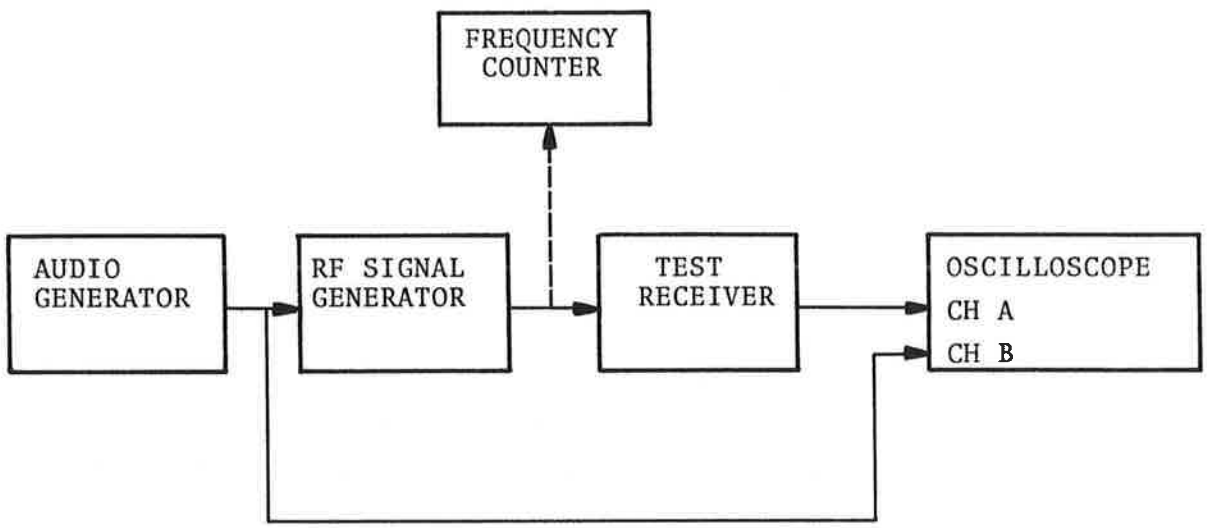


FIGURE 2-18. RECEIVER DIFFERENTIAL PHASE DELAY TEST SETUP

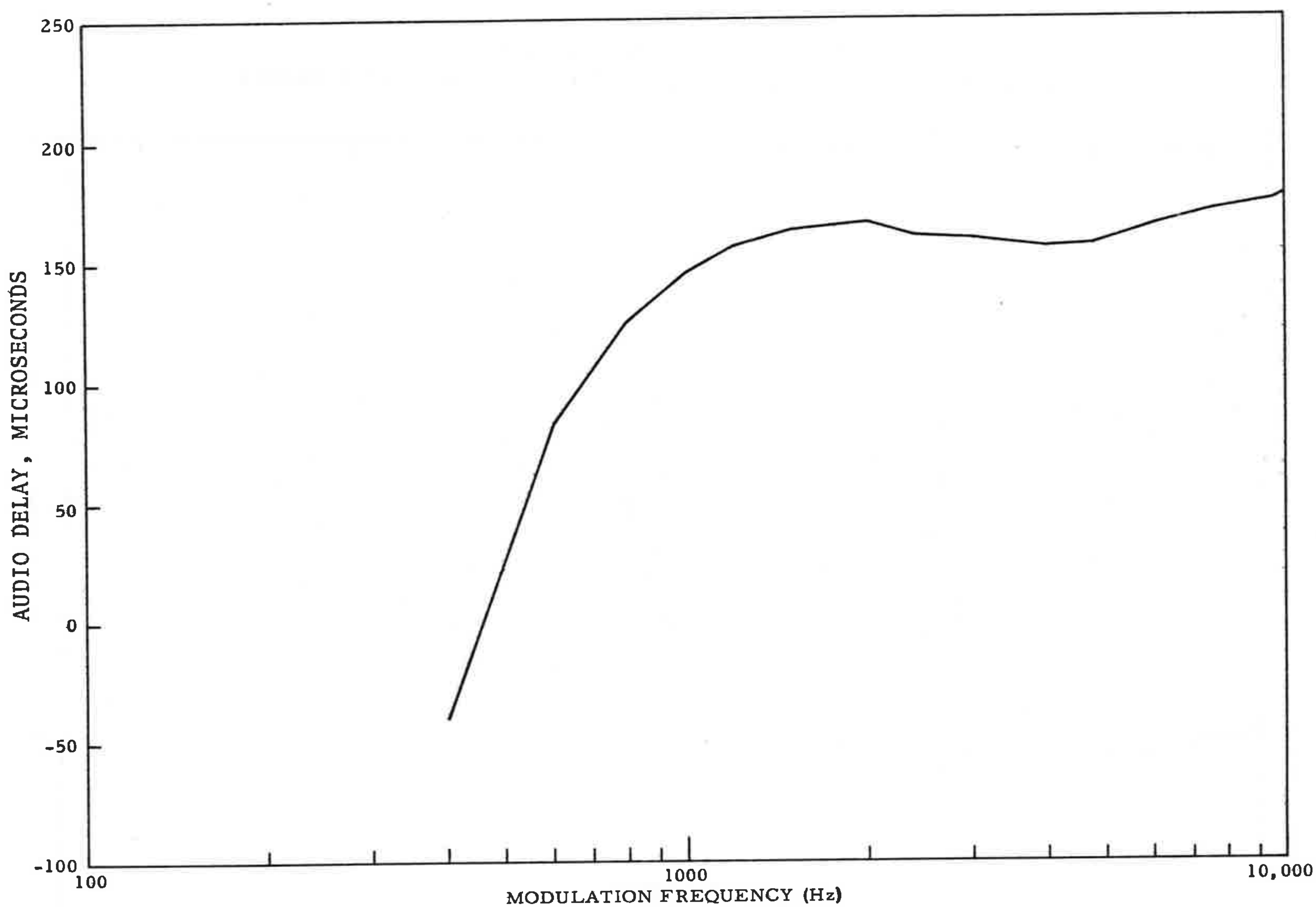


FIGURE 2-19. RECEIVER DATA LINK AUDIO DELAY, KING, MODEL KTR-9100A, SERIAL NO. 2103

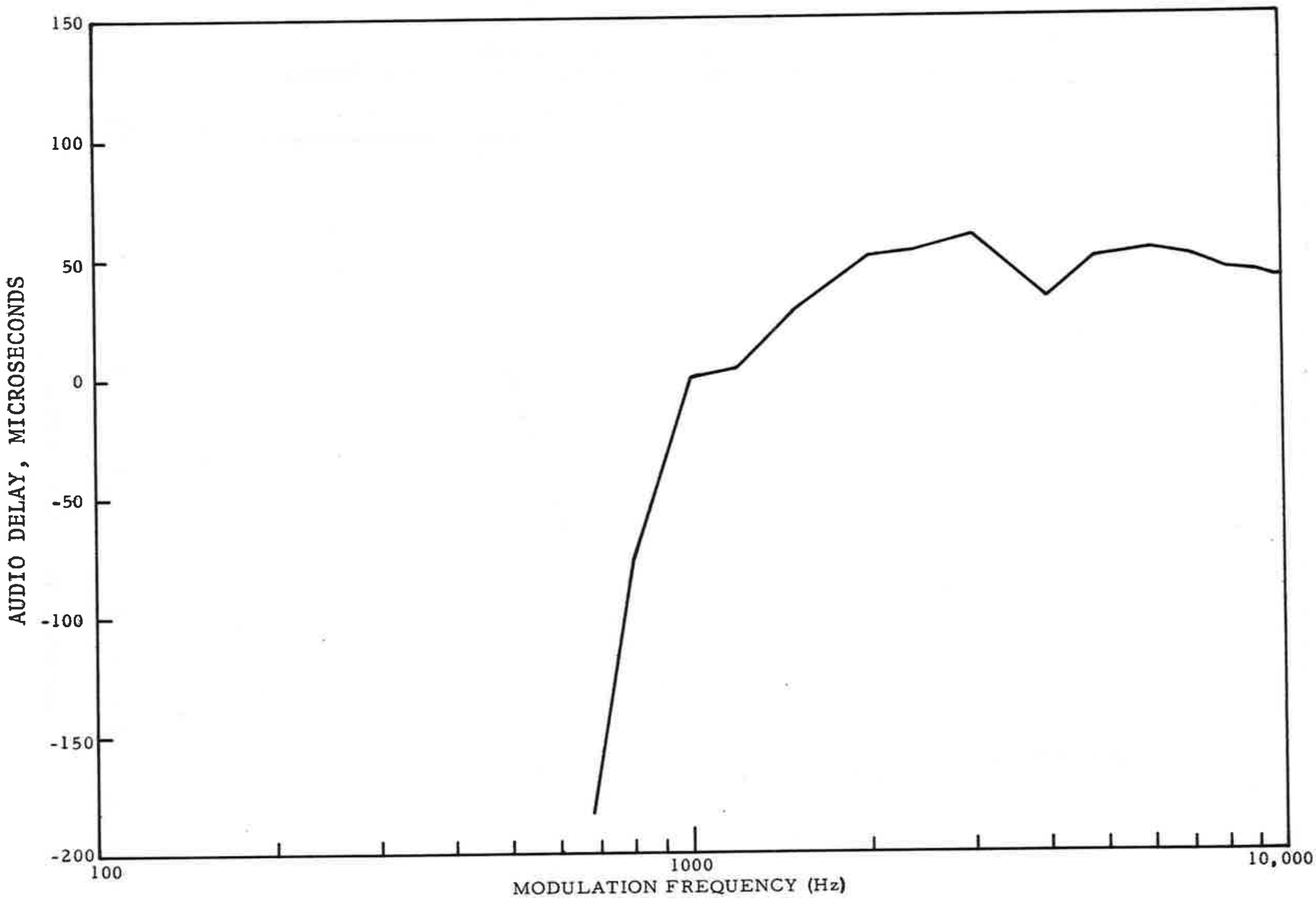


FIGURE 2-20. RECEIVER DATA LINK AUDIO DELAY, BENDIX, MODEL RTA-43A, SERIAL NO. 1050

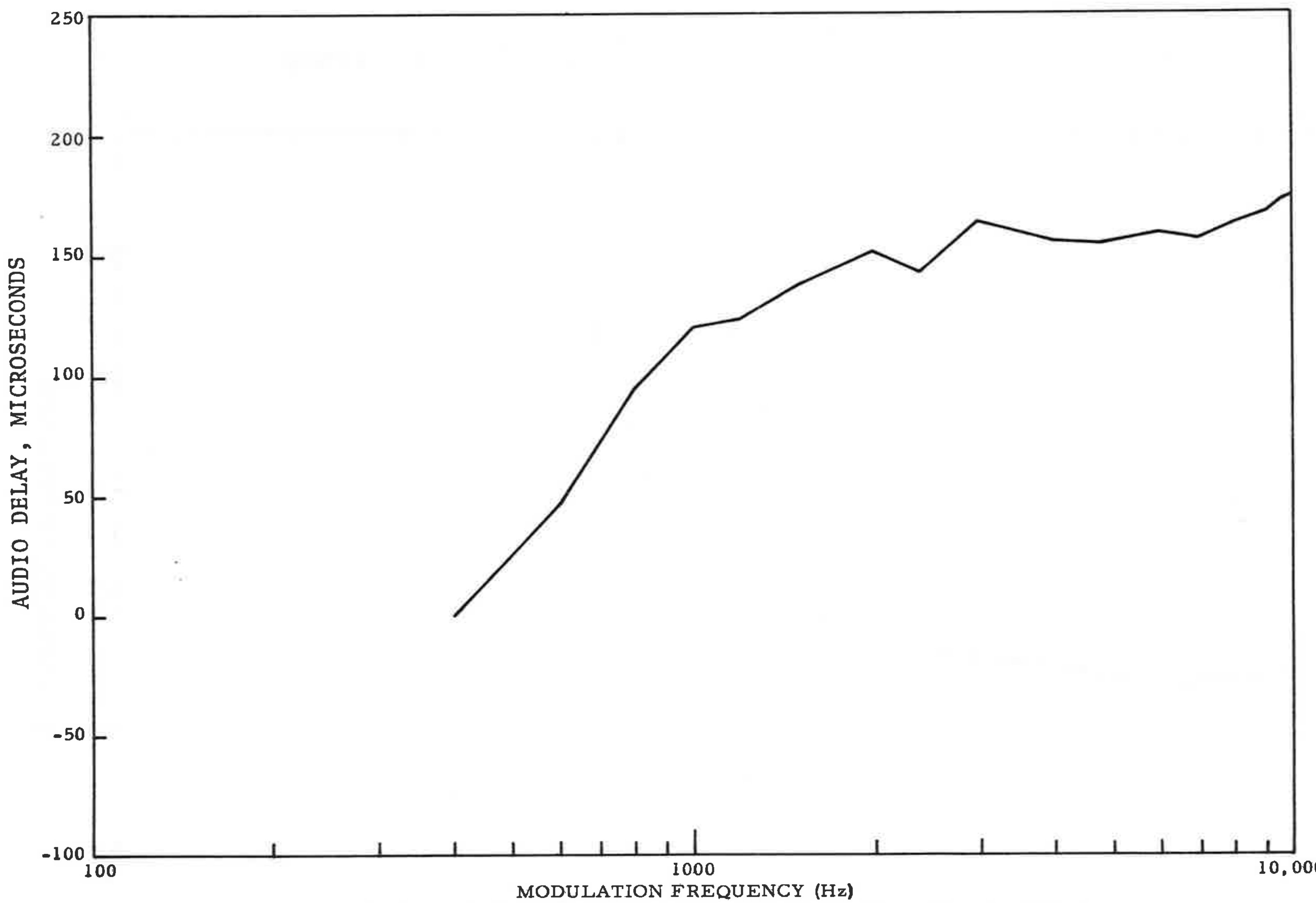


FIGURE 2-21. RECEIVER DATA LINK AUDIO DELAY, BENDIX, MODEL RTA-43A, SERIAL NO. 1027

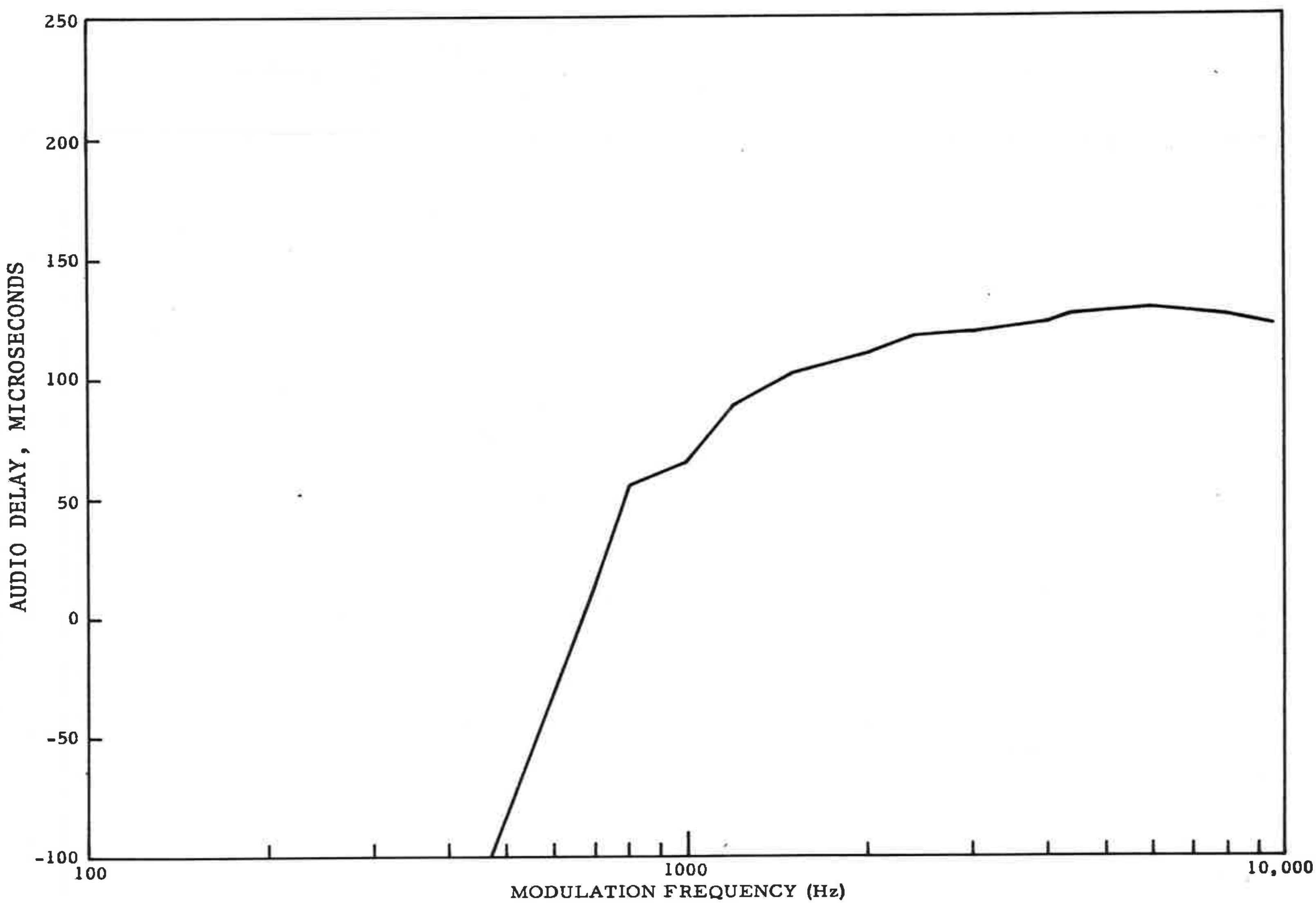


FIGURE 2-22. RECEIVER DATA LINK AUDIO DELAY, MODIFIED COLLINS, MODEL 618M-2B, SERIAL NO. 2971

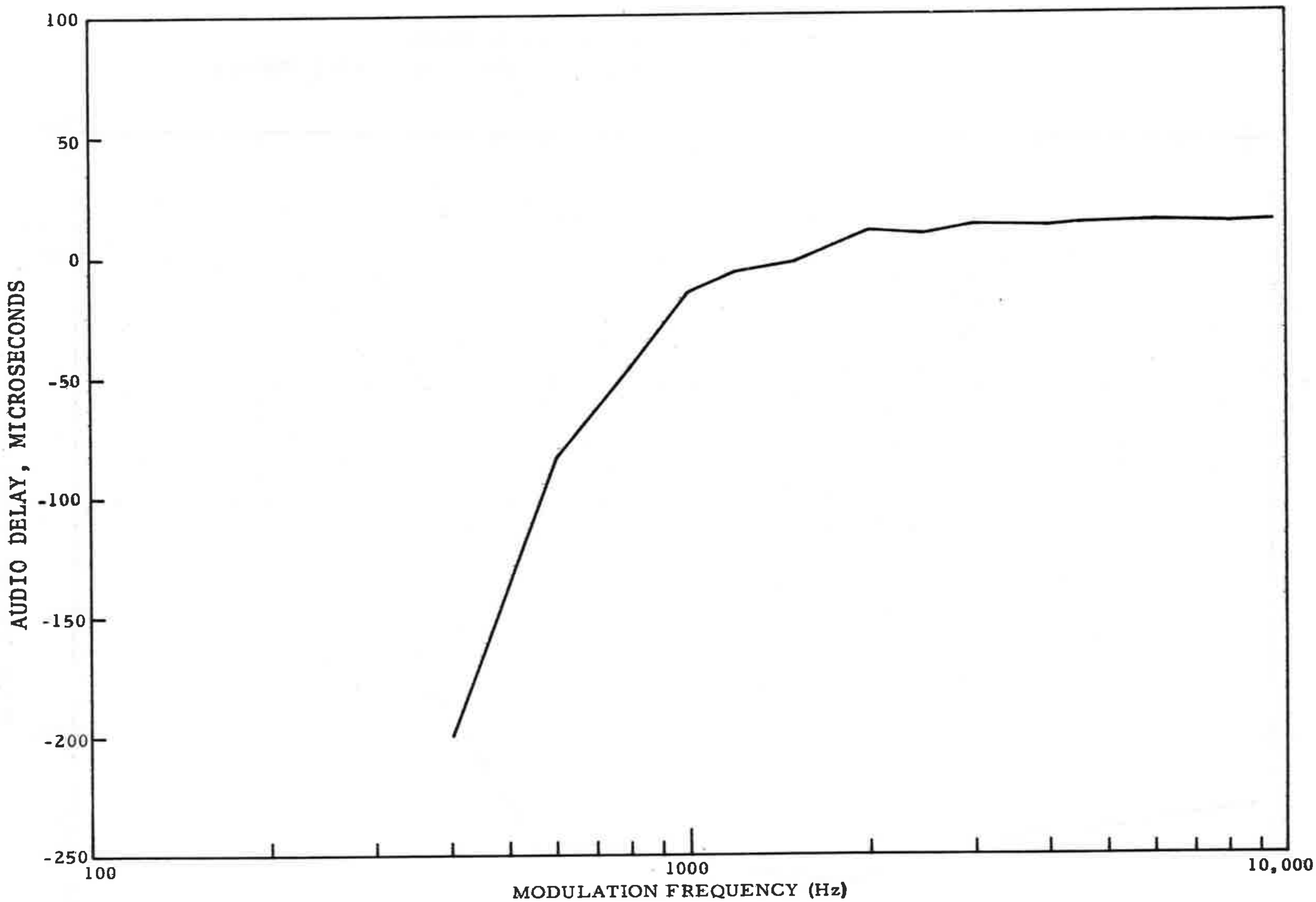


FIGURE 2-23. RECEIVER DATA LINK AUDIO DELAY, MODIFIED COLLINS, MODEL 618M-2B, SERIAL NO. 2996

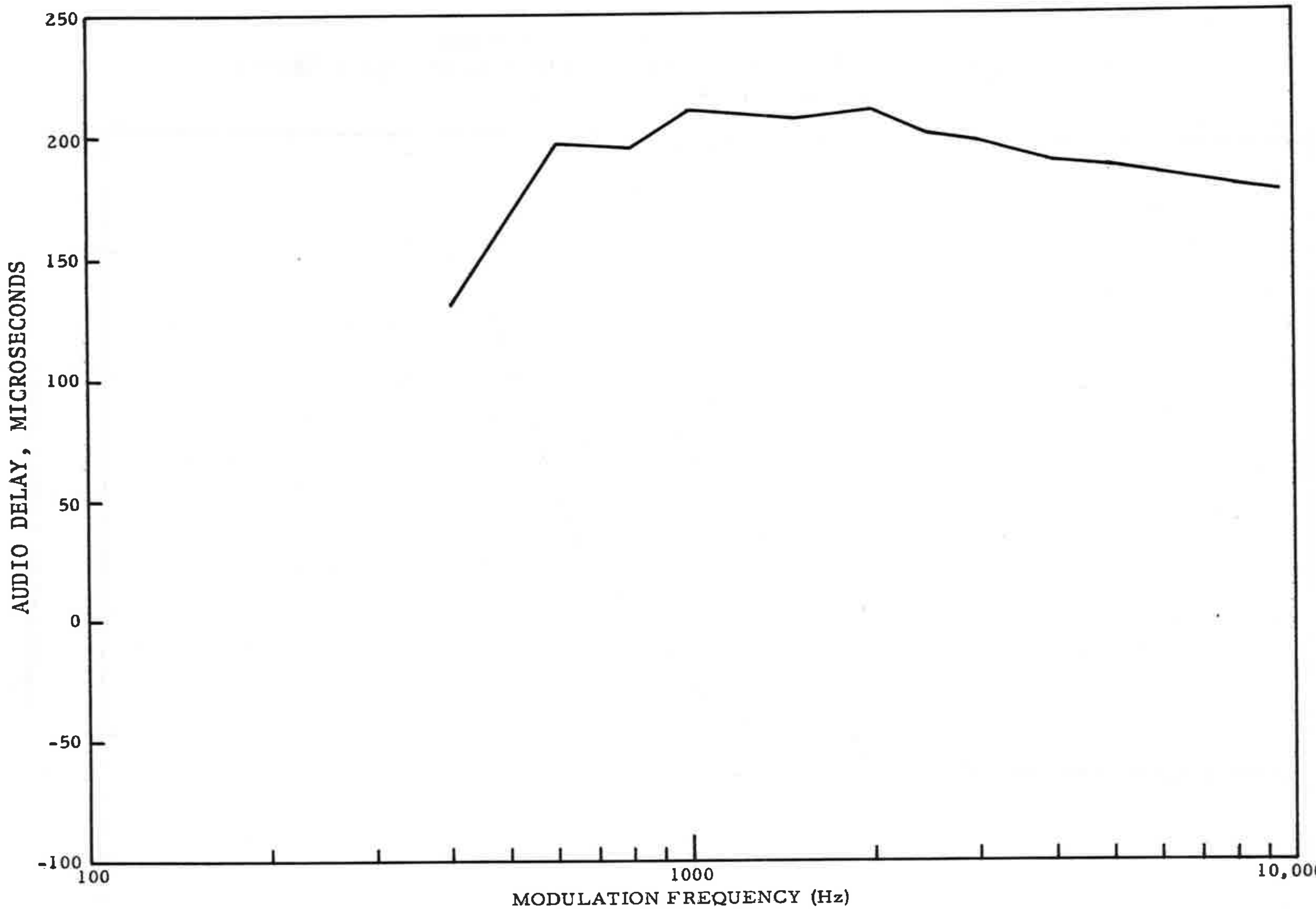


FIGURE 2-24. RECEIVER DATA LINK AUDIO DELAY, COLLINS, MODEL 618M-2B, SERIAL NO. 4868

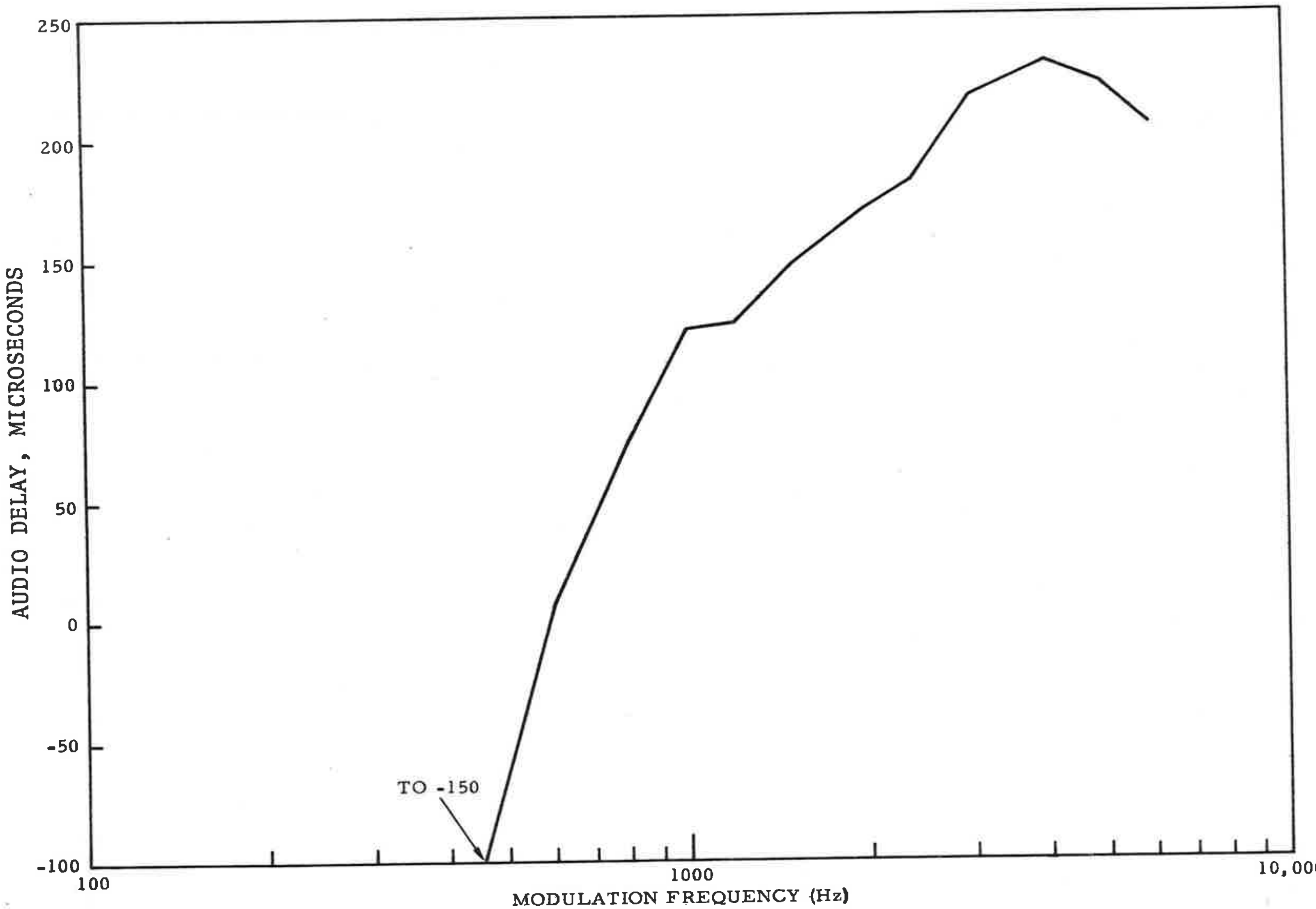


FIGURE 2-25. RECEIVER AUDIO DELAY, BUEC, MODEL FA-8191, SERIAL NO. 1

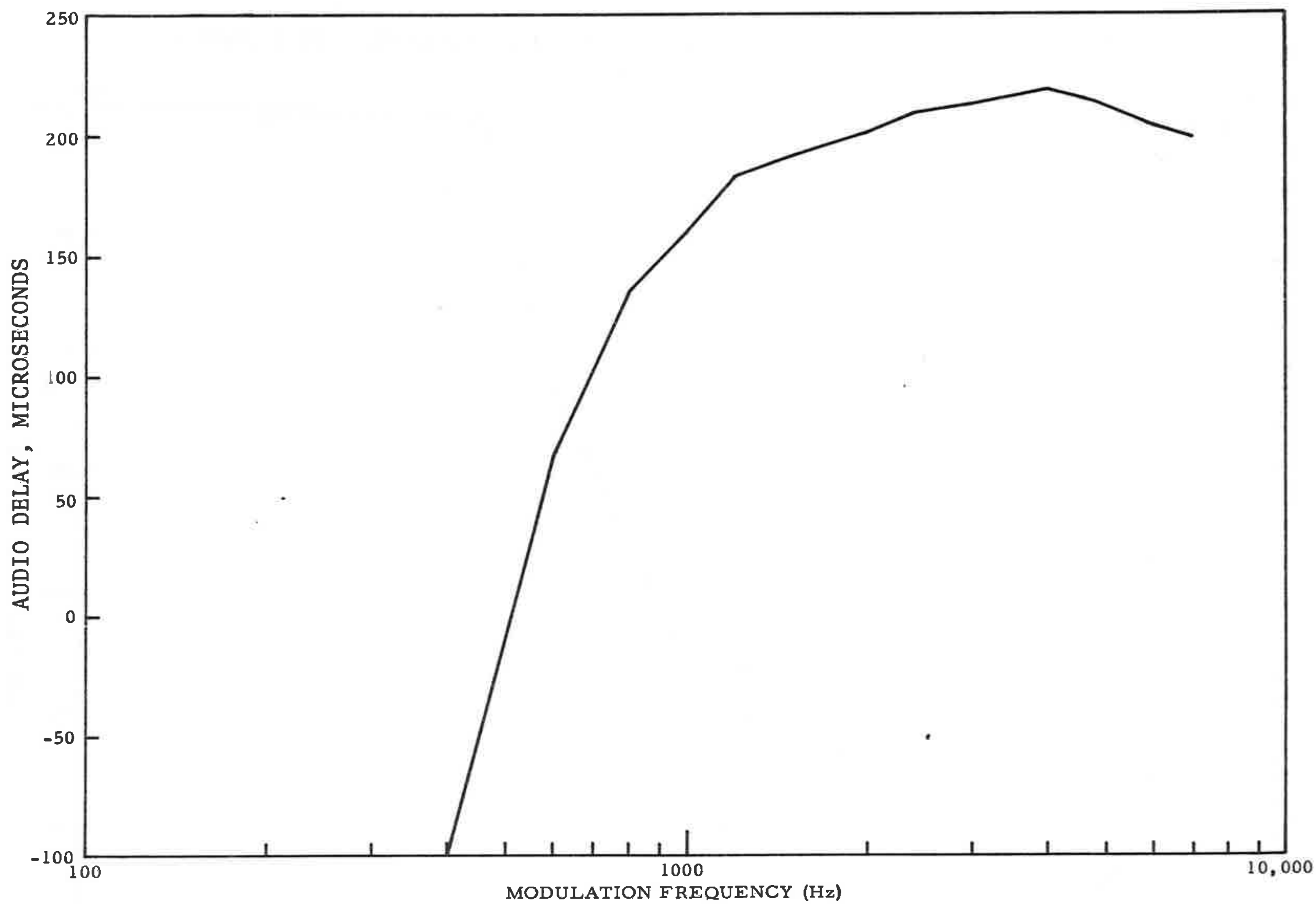


FIGURE 2-26. RECEIVER AUDIO DELAY, BUEC, MODEL FA-8191, SERIAL NO. 2

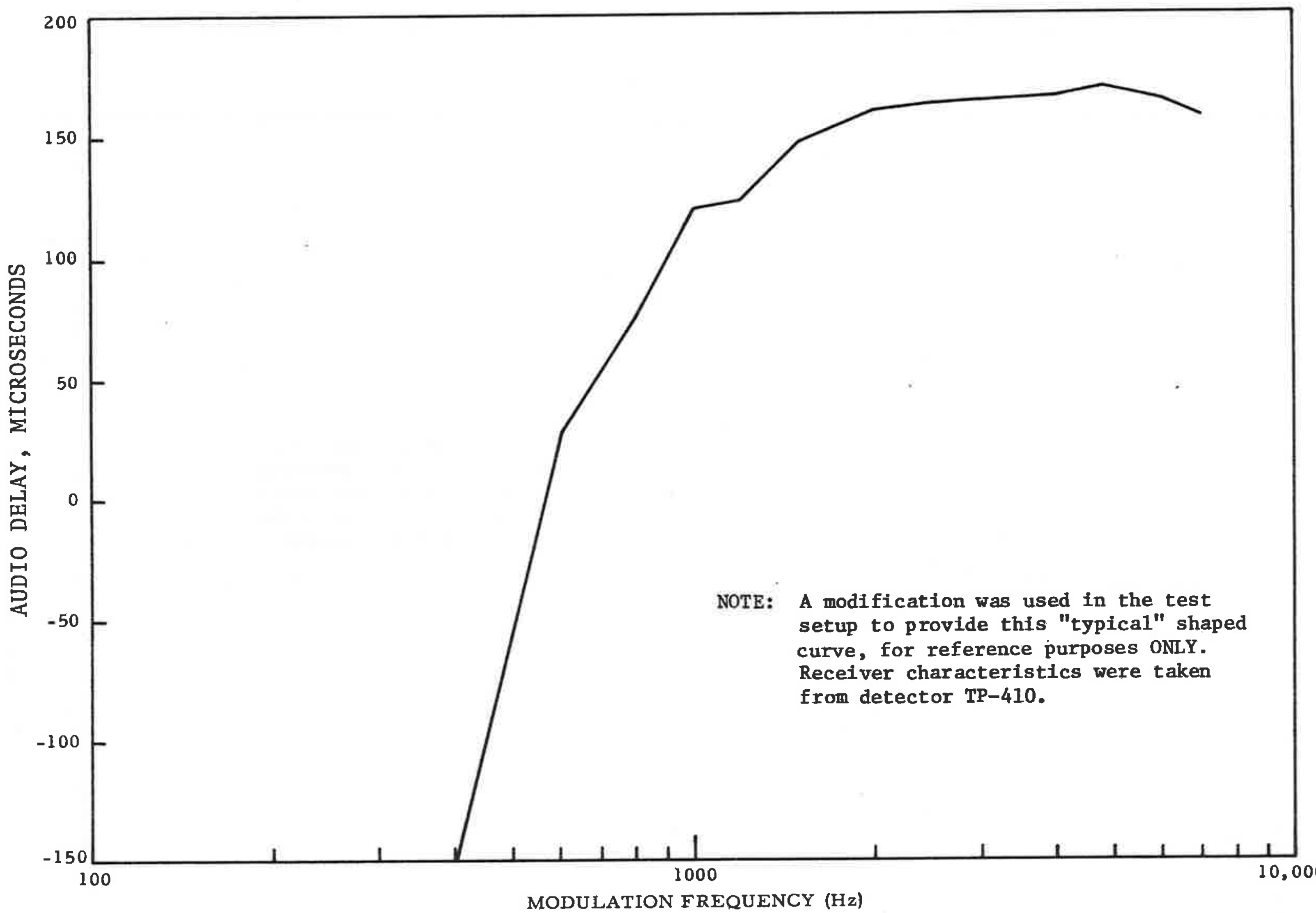


FIGURE 2-27. RECEIVER MODIFIED AUDIO DELAY, KING, MODEL KY-195B, SERIAL NO. 3145

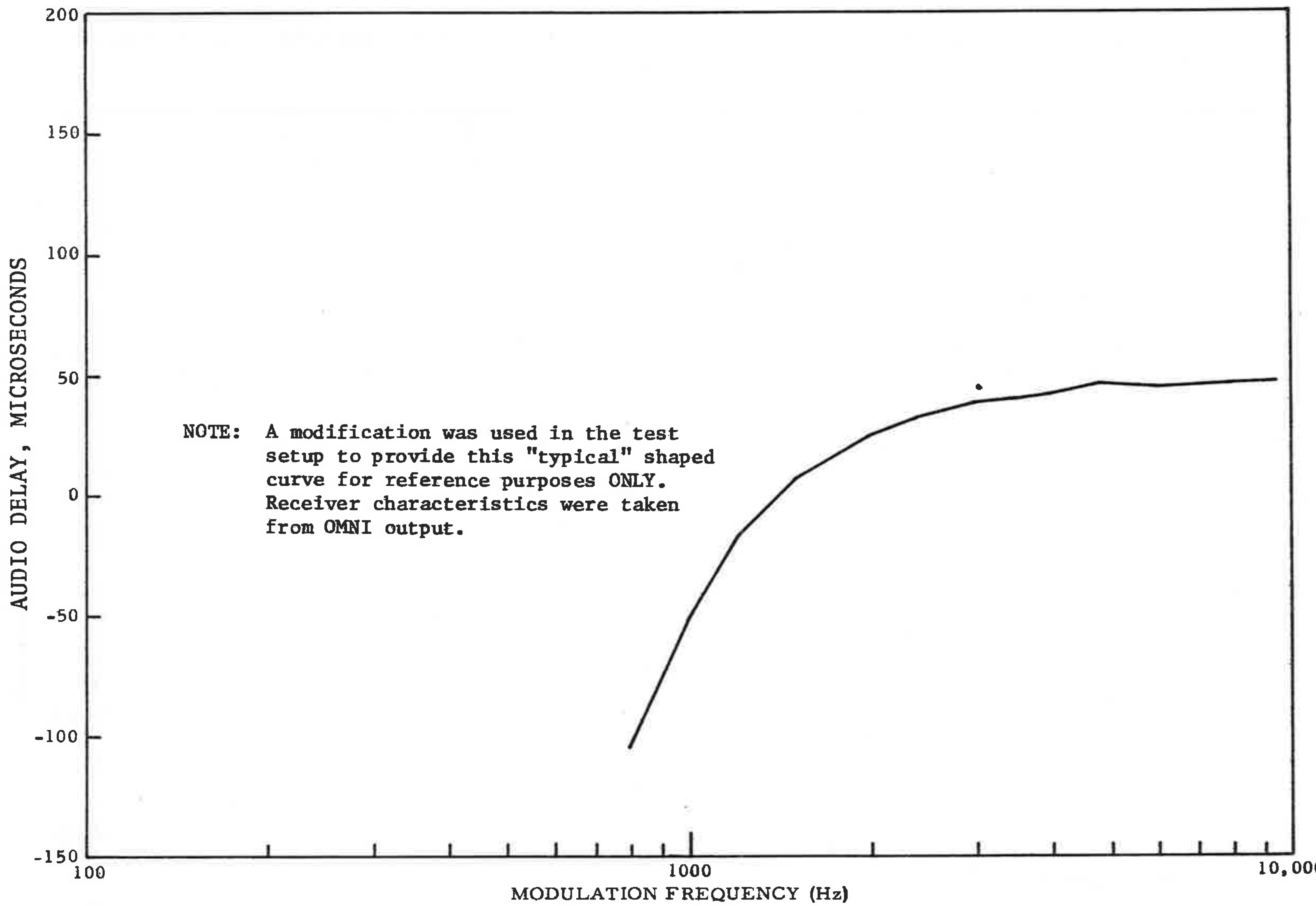


FIGURE 2-28. RECEIVER MODIFIED AUDIO DELAY, NARCO, MODEL COM-11A

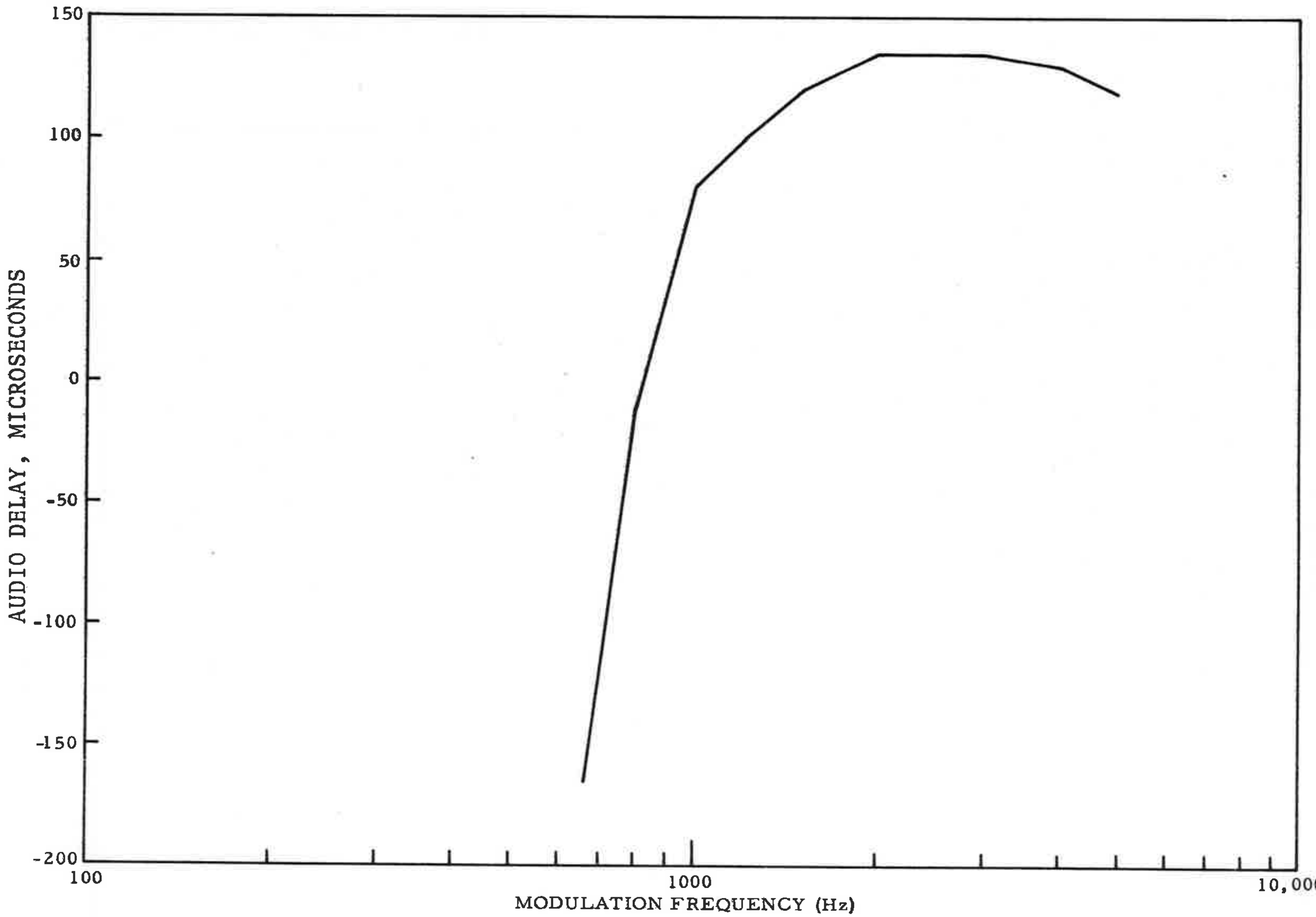


FIGURE 2-29. RECEIVER AUDIO DELAY, GENAVE, MODEL ALPHA-100/360, SERIAL NO. 43-22

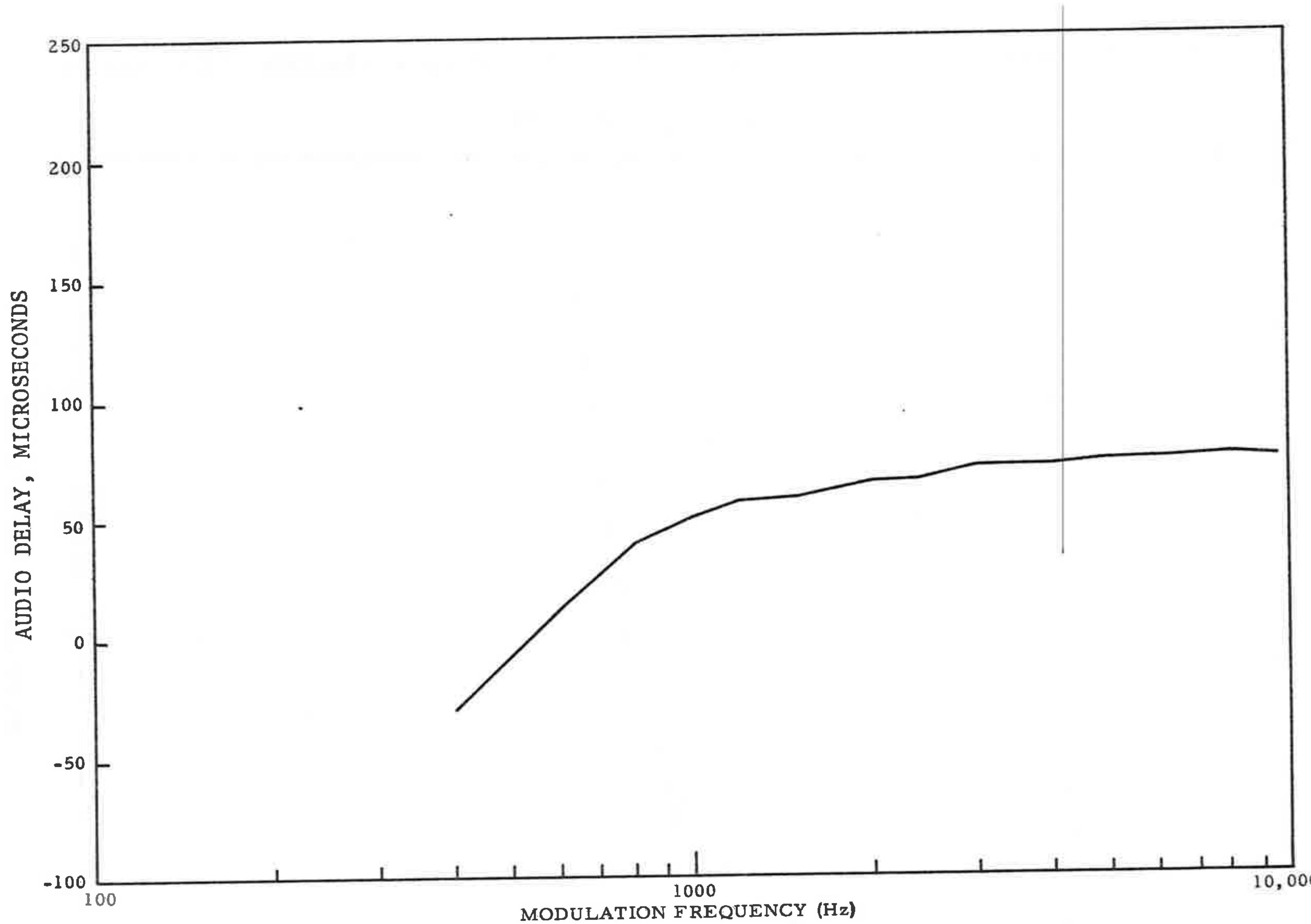


FIGURE 2-30. RECEIVER MODIFIED AUDIO DELAY, A/N, MODEL GRR-23, SERIAL NO. 4293

TABLE 2-3. RECEIVER CHARACTERISTICS

Manufacturer, Model, Serial No.	Usable Sense (µV)	Squelch Limit (µV)	Quieting Sense (µV)	Squelch Threshold (µV)	Oscillator Local Stability (Percent)	Automatic Gain Control		Differential Delay (µs)		Adjacent Channel (dB)	Inter-Modulation (mV)
						Attack (ms)	Decay (ms)	2400	4800		
King, KTR-9100A,	2.1	--	9.6	--	1006 Hz Hi 0.00008	13	70	2.0	1.5	63.0	14.0
Bendix, RTA-43A 1050	1.8	--	6.6	--	50 Hz Lo 0.00003	3.7*	76*	15.0	5.0	74.0	Good Reject
Bendix, RTA-43A 1027	1.6	--	6.1	--	75 Hz Lo 0.00007	13*	--	9.5	6.0	58.0	100.0
Collins, 618M-2B, 2996	1.4	--	7.0	--	100 Hz Lo 0.00007	13	7	14.15	4.6	73.0	37.0
Collins, 618M-2B, 2971	1.5	--	10.0	--	20 Hz Hi 0.000015	15	8	11.66	3.6	64.0	48.0
Collins, 618M-2B, 4868	1.2	--	3.2	--	50 Hz Lo 0.00003	44	--	3.35	6.9	74.5	43.0
BUEC, FA-8191, 1	2.5	--	5.6	0.6	100 Hz Hi 0.000003	36	500	29.50	21.0	56.0	--
BUEC, FA-8191, 2	2.5	--	7.0	2.9	158 Hz Hi 0.000035	44	190	13.0	2.5	57.0	--
King, KY-195B, 3145**	1.3	160	3.0	1.6	1500 Hz Lo 0.00004	32	20	19.5	3.5	71.5	180.0
NARCO COM-11A, **	2.0	75	None	2.0	500 Hz Lo 0.0006	76	138	24.0	7.0	63.0	26.0
GENAVE, ALPHA-100/360	2.7	75	36.0	0.5	1800 Hz Lo 0.0013	6	14	17.5	7.5	60.5	1.8
A/N GRR-23, 4293**	0.7	No over-ride	300.0	1.6	100 Hz Hi 0.00014	22	40	4.5	4.0	76.0	89.0

NOTES: µV = microvolts; ms = milliseconds; mV = millivolts.
* = Automatic gain control to second intermediate frequency.
** = Modified audio.

2.1.1.2 Usable Sensitivity - The usable sensitivity measurements were made on receivers listed in Table 2-1. The test setup for this measurement is shown in Figure 2-2. The usable sensitivity was measured as the minimum vlaue of input signal level from a standard signal source which, with standard test modulation, produced a 12 dB signal plus noise-to-noise ratio at the receiver's audio output. This test was included solely to characterize the basic radio performance. The results are shown in Table 2-3.

2.1.1.3 Squelch Limit Sensitivity - The squelch limit sensitivity measurement was performed on those receivers listed in Table 2-1 that had externally adjustable squelch controls. The squelch limit sensitivity of a receiver is defined as the input signal level from an unmodulated or modulated signal generator that will cause the receiver to switch from a completely quiet state to a completely open state when the squelch control is adjusted to its maximum squelched position. The test setup for this measurement is shown in Figure 2-2. This test was included solely to characterize the basic radio performance. The results of these measurements are presented in Table 2-3.

2.1.1.4 Quieting Sensitivity - The quieting sensitivity measurements were performed on the receivers listed in Table 2-1. The quieting sensitivity of a receiver is defined as the minimum input signal level from an unmodulated signal generator that will cause the background noise of the receiver to be reduced by 20 dB as measured across the standard output load for the receiver. The test setup for these measurements is shown in Figure 2-2. This test was included solely to characterize the basic radio performance. The results of the measurements are shown in Table 2-3.

2.1.1.5 Squelch Threshold Sensitivity - The squelch threshold sensitivity measurements were performed on those receivers listed in Table 2-1 that had externally adjustable squelch controls. The squelch threshold sensitivity of a receiver is defined as the minimum input signal from an unmodulated or modulated signal generator that will cause the receiver to switch from a quiet state to an open state. The test setup for these measurements is shown in Figure 2-2. This test was included solely to characterize the basic radio performance. The results of these measurements are shown in Table 2-3.

2.1.1.6 Local Oscillator Frequency Stability - Measurements of the local oscillator frequency stability were made on the receivers listed in Table 2-1. The test setup for these measurements is shown in Figure 2-31. The local oscillator frequency stability is defined as the extent to which the frequency of the local oscillator signal (or the equivalent thereof in the case of equipments using frequency synthesizers), measured at the point of the injection into the first mixer, is permitted to depart from the reference value. The results of these measurements are presented in Table 2-3.

2.1.1.7 Automatic Gain Control Times - The automatic gain control (AGC) times (attack and decay) were measured for the receivers listed in Table 2-1. The test setup for these measurements is shown in Figure 2-32. The solid state switch and storage oscilloscope were activated simultaneously and the resultant oscilloscope traces photographed for the application (attack) and removal (decay) of input signals of magnitude 3 μV, 1000 μV, and 20 mV. The respective attack and decay times were measured at the point at which the responses reached 90 percent of their steady state value. The AGC attack and decay times are presented in Table 2-3 for the 1000 μV signal case. Results for input signals of 3 μV and 20 mV are presented in Reference 7. Receiver AGC times along with transmitter rise times are significant parameters when considering single channel simplex data link systems because of their contribution to turnaround time and, in turn, system capacity. Long receiver attack times require a high overhead of pre-key characters in the message format in order to effect system synchronization. In addition, long receiver AGC decay times must be accommodated as delays in the data link system architecture to allow for AGC setting when a receiver is in the proximity of other transmitting aircraft on the same channel. That is, no messages can be received

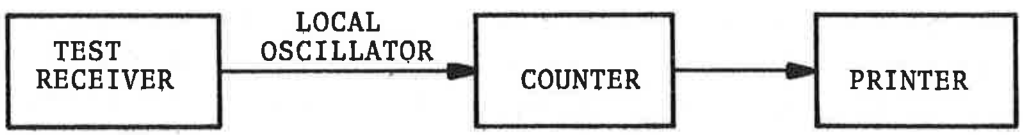


FIGURE 2-31. LOCAL OSCILLATOR FREQUENCY STABILITY TEST SETUP

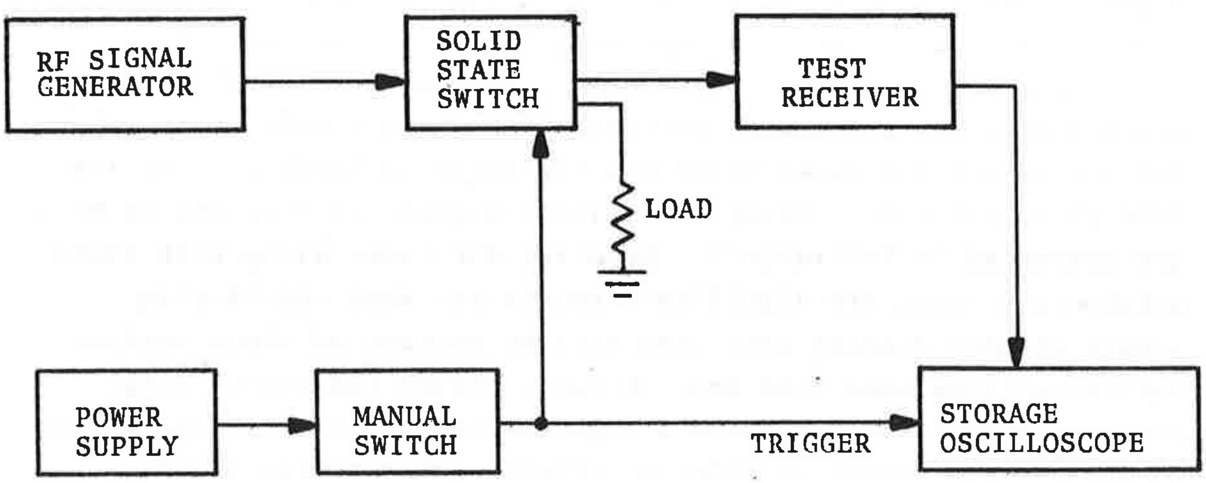


FIGURE 2-32. AUTOMATIC GAIN CONTROL SETTLING TIME TEST SETUP

until the disturbed receiver AGC settles down. This effect is particularly bad when in low signal regions. Furthermore, fast AGC response is helpful when operating under multipath fading conditions. In that case, the AGC decay time must be fast enough to follow the signal down into a fade, or a signal drop-out will result. Similarly, the AGC attack time must be fast enough to follow the signal out of a fade, or the modulation will be lost due to saturation in the IF amplifier.

It is interesting to note that recommended nominal values for receiver AGC attack and decay times for data link applications are 5 ms and 10 to 15 ms respectively (see Reference 8), and none of the receivers tested meet both of these recommended values.

2.1.1.8 Adjacent Channel Selectivity - The adjacent channel selectivity of a receiver is a measure of its ability to differentiate between a desired modulated signal and modulated signals which differ in frequency from the desired signal by the width of one channel. Measurements of this parameter were made on the receivers listed in Table 2-1. The test setup for these measurements is shown in Figure 2-33. The two signal generators were coupled through an isolation tee to the receiver antenna input terminals. Signal generator number 1 was adjusted to give a SINAD (signal + noise + distortion-to-noise + distortion) ratio of 12 dB. Signal generator number 2 was tuned first to the next higher and then to the next lower adjacent channel and the attenuator adjusted until the 12 dB SINAD ratio was decreased to 6 dB. The adjacent channel selectivity was then expressed as the ratio, in dB, of the amplitude of the signal from signal generator number 2 to the amplitude of the signal from signal generator number 1. The smaller of the ratios as determined from the higher or lower adjacent channels was chosen to indicate the adjacent channel selectivity. These values are shown in Table 2-3.

2.1.1.9 Spurious Response Attenuation - The spurious response attenuation of a receiver is a measure of the receiver's ability to reject any undersired signal including images to which it may

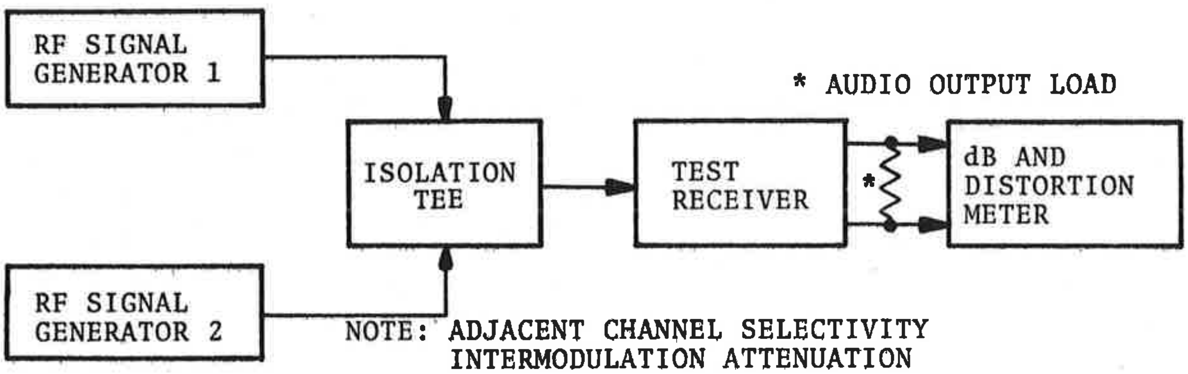


FIGURE 2-33. RECEIVER TEST SETUP 2

respond. The test setup for these measurements is shown in Figure 2-2. The signal generator was varied in frequency from the lowest IF used in the receiver to 1000 MHz. The signal generator output level required to produce 20 dB of quieting for any given response was noted. These measurements excluded subharmonics of the frequency at which the receiver was operated and the frequencies within ± 25 kHz of this frequency. The spurious response attenuation was calculated as the ratio (in dB) of the lowest of the signal generator output levels for any given receiver response to the quieting sensitivity. The results of these measurements are shown in Table 2-4.

2.1.1.10 Receiver Harmonic Distortion - Harmonic distortion measurements were made on the receivers listed in Table 2-1. The test setup for these measurements is shown in Figure 2-2. The distortion measurements were read directly from the distortion meter and plotted. The measurements were made for 30 and 80 percent modulation. Three signal levels were tested: 10 μV; 1000 μV; and 230 mV. In general, for the 1000 μV and 230 mV signal levels, the distortion was greater at 80 percent modulation than at 30 percent modulation. In some cases the distortion for the 10 μV signal input was greater at 30 percent modulation than at 80 percent modulation.* Generally the distortion within the bandwidths of the receivers was less than 20 percent with some greater than 40 percent and some less than 5 percent. The modifications made to the two general aviation transceivers resulted in increased distortion for one receiver and decreased distortion for the other. The results of these measurements are shown plotted in Figures 2-34 through 2-47 for the 80 percent modulation case. The reader is referred to Reference 7 for the plots relating to the 30 percent modulation test results.

*It is likely however, that in this case some of the "distortion" measured was really receiver front-end noise.

TABLE 2-4. RECEIVER SPURIOUS RESPONSE ATTENUATION

Receiver-Manufacturer, Model, Serial No.	MHz	dB	Receiver-Manufacturer, Model, Serial No.	MHz	dB
King, KTR-9100A,	127.00	0.0	King, KY-195B,	125.00	0.0
2103	132.00	78.4	3145	250.00	-58.0
	147.00	82.4		375.00	-76.0
	421.00	83.4			
	538.00	83.9	NARCO, COM-11A	127.000	0
	558.00	81.4		11.980	66
				75.480	100
Bendix, RTA-43A,	127.00	0.0		123.810	93
1050	4.81	101.0		130.210	95
	20.02	100.0		132.990	81
	86.99	77.0		150.940	53
				265.990	66
Bendix, RTA-43A,	127.00	0.0		287.050	84
1027	19.09	98.0		404.060	59
	20.01	89.0		543.930	68
	86.99	75.0		567.860	75
Collins, 618M-2B,	127.00	0.0	GENAVE,	127.00	0
2996	453.00	94.0	ALPHA-100/360	115.661	76
				121.475	70
Collins, 618M-2B,	127.00	0.0		125.024	73
2971	129.12	95.0		127.984	40
	452.99	87.0		129.273	66
				131.025	55
Collins, 618M-2B,	127.00	0.0		138.702	55
4868	124.63	105.0		139.210	82
	125.75	105.0		142.623	76
	126.05	112.0		144.572	83
	126.86	99.0		148.421	73
	126.88	113.0		173.854	66
	453.00	113.0		213.944	85
				277.456	72
BUEC, FA-8191,	127.00	0.0		298.857	77
1	131.73	101.0		302.882	80
				324.335	76
				578.276	55
BUEC, FA-8191,	127.00	0.0			
2	131.73	96.0	A/N, GRR-23,	120.850	0
			4293	None	

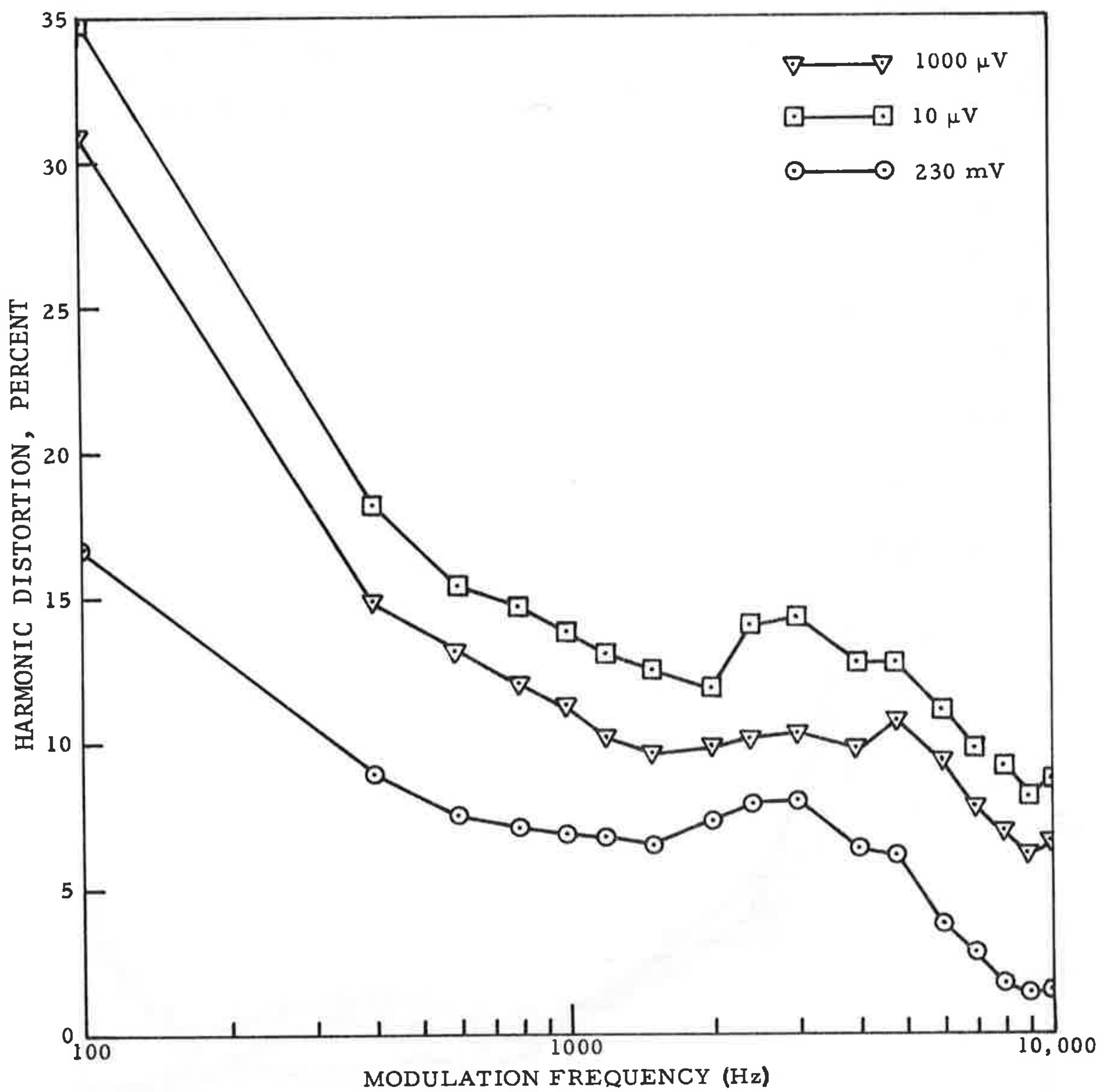


FIGURE 2-34. RECEIVER DATA LINK AUDIO HARMONIC DISTORTION 80 PERCENT MODULATION, KING, MODEL KTR-9100A, SERIAL NO. 2103

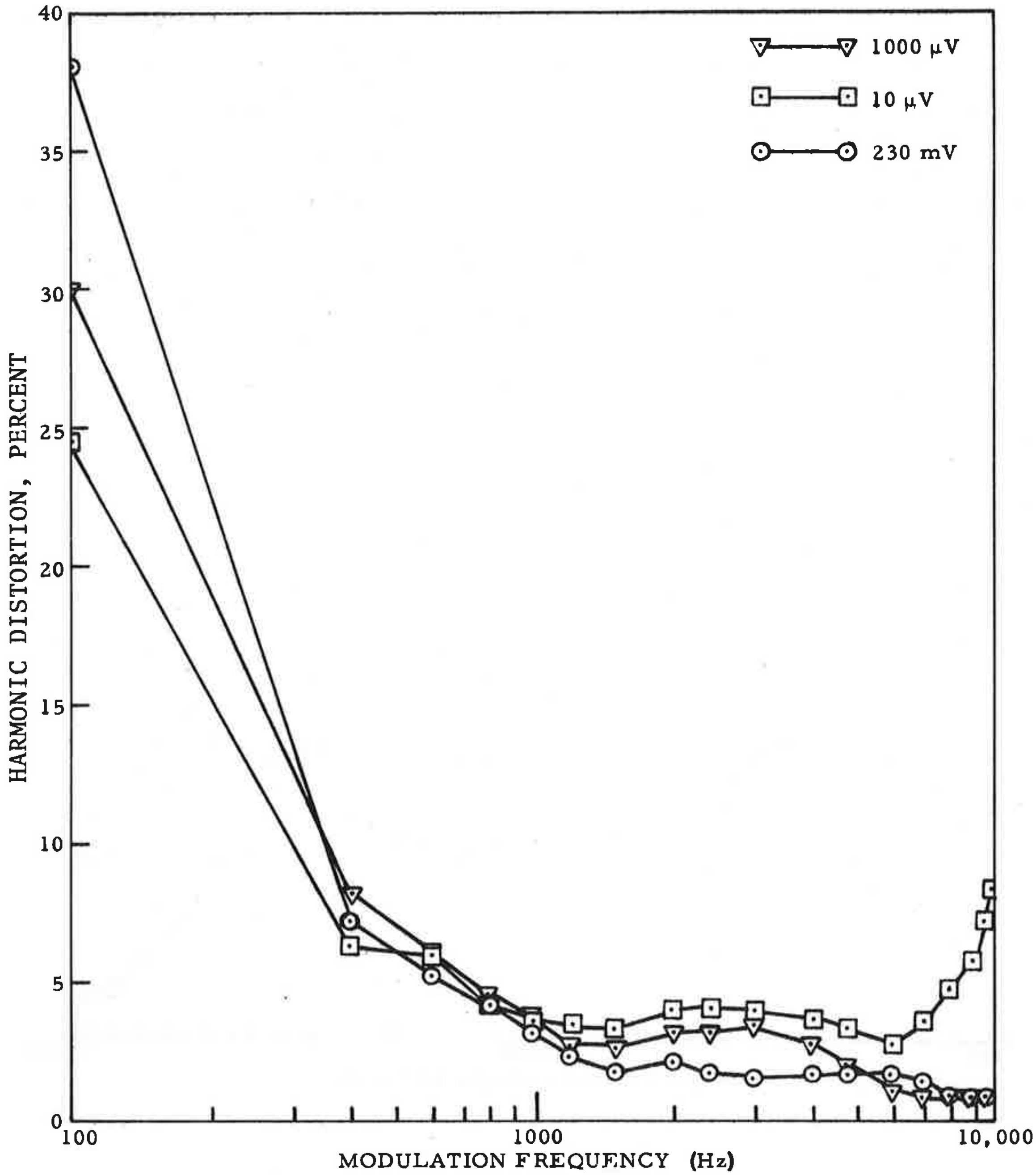


FIGURE 2-35. RECEIVER DATA LINK AUDIO HARMONIC DISTORTION 80 PERCENT MODULATION, BENDIX, MODEL RTA-43A, SERIAL NO. 1050

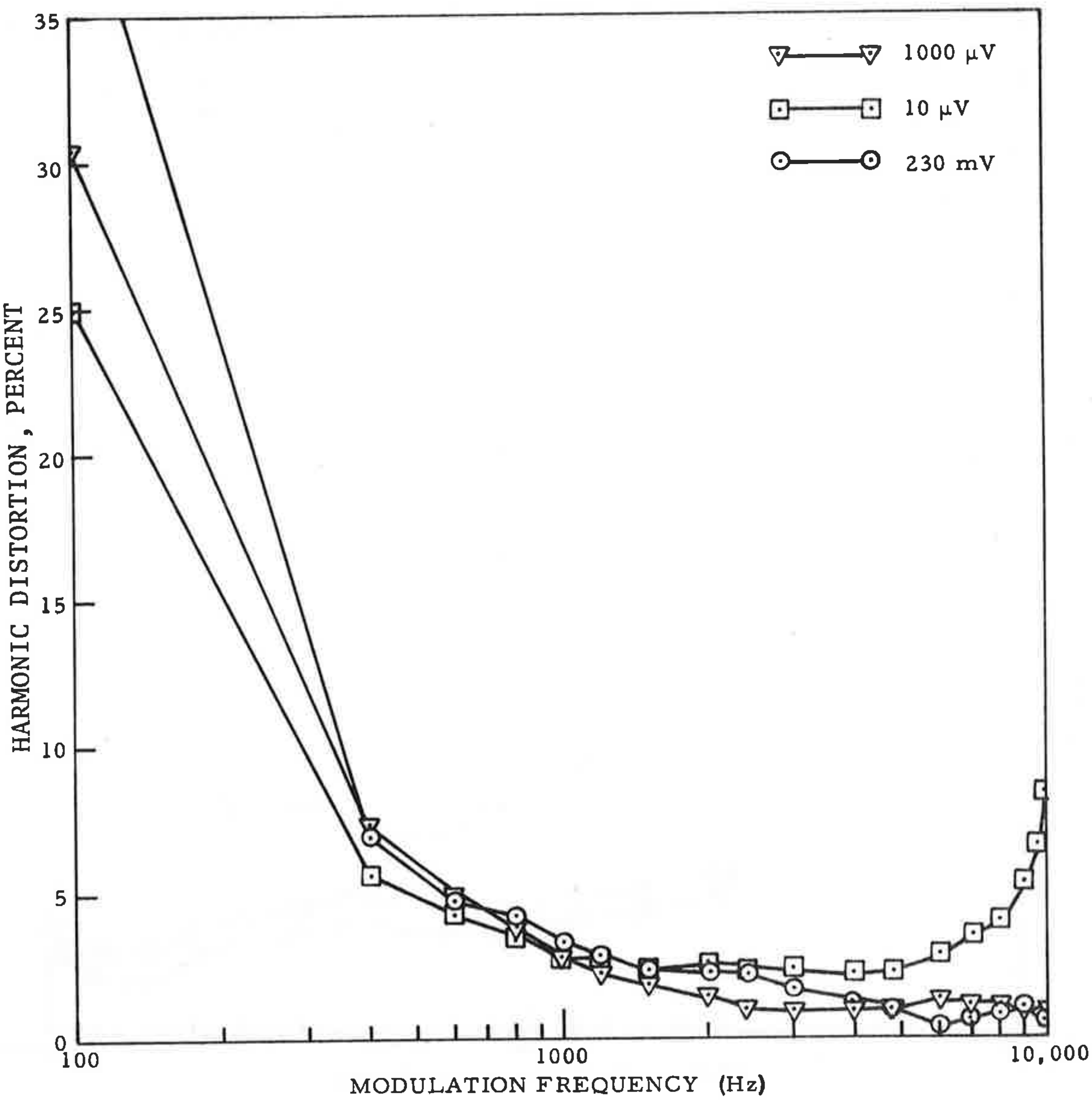


FIGURE 2-36. RECEIVER DATA LINK AUDIO HARMONIC DISTORTION 80 PERCENT MODULATION, BENDIX, MODEL RTA-43A, SERIAL NO. 1027

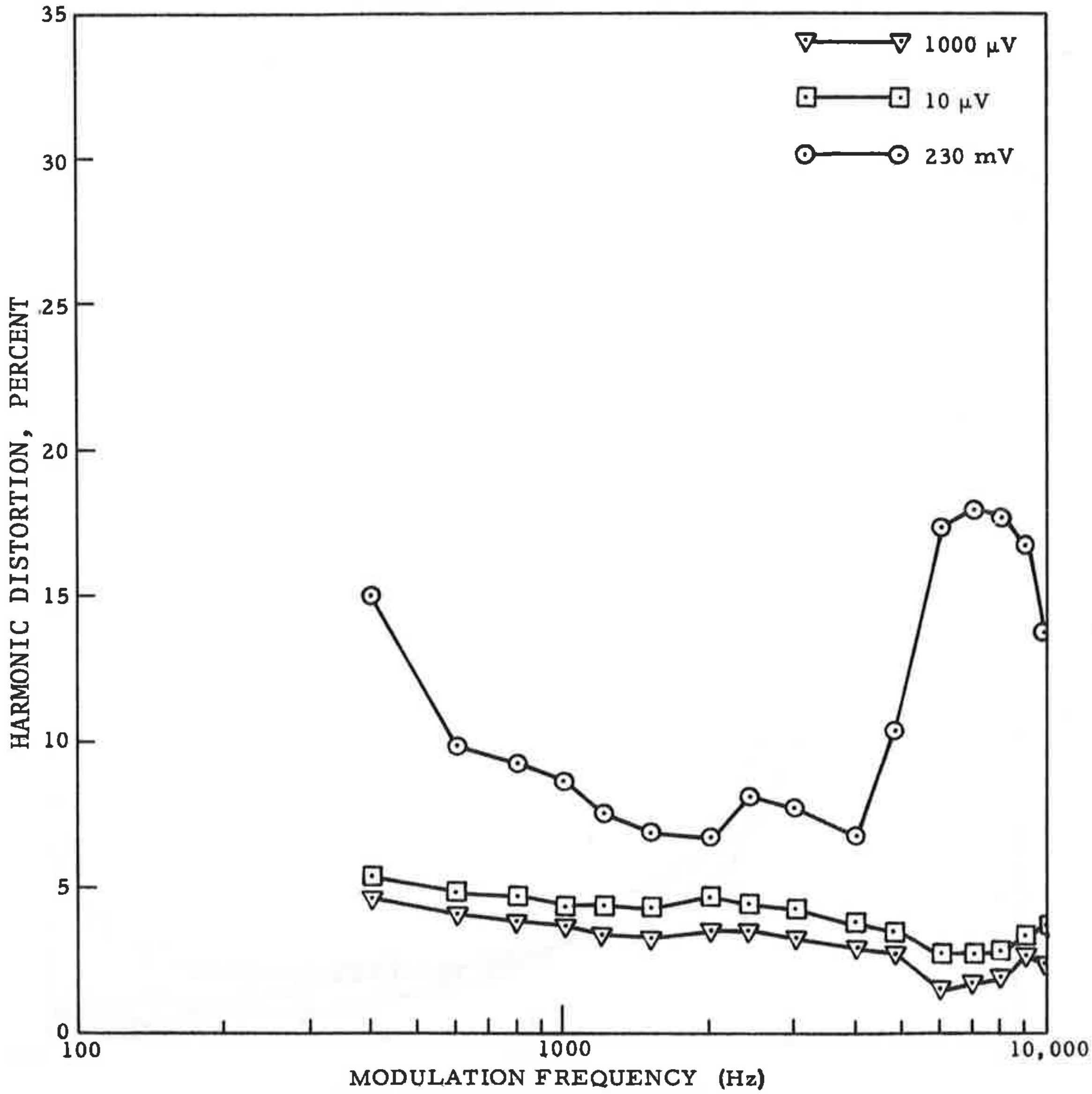


FIGURE 2-37. RECEIVER DATA LINK AUDIO HARMONIC DISTORTION 80 PERCENT MODULATION, MODIFIED COLLINS, MODEL 618M-2B, SERIAL NO. 2996

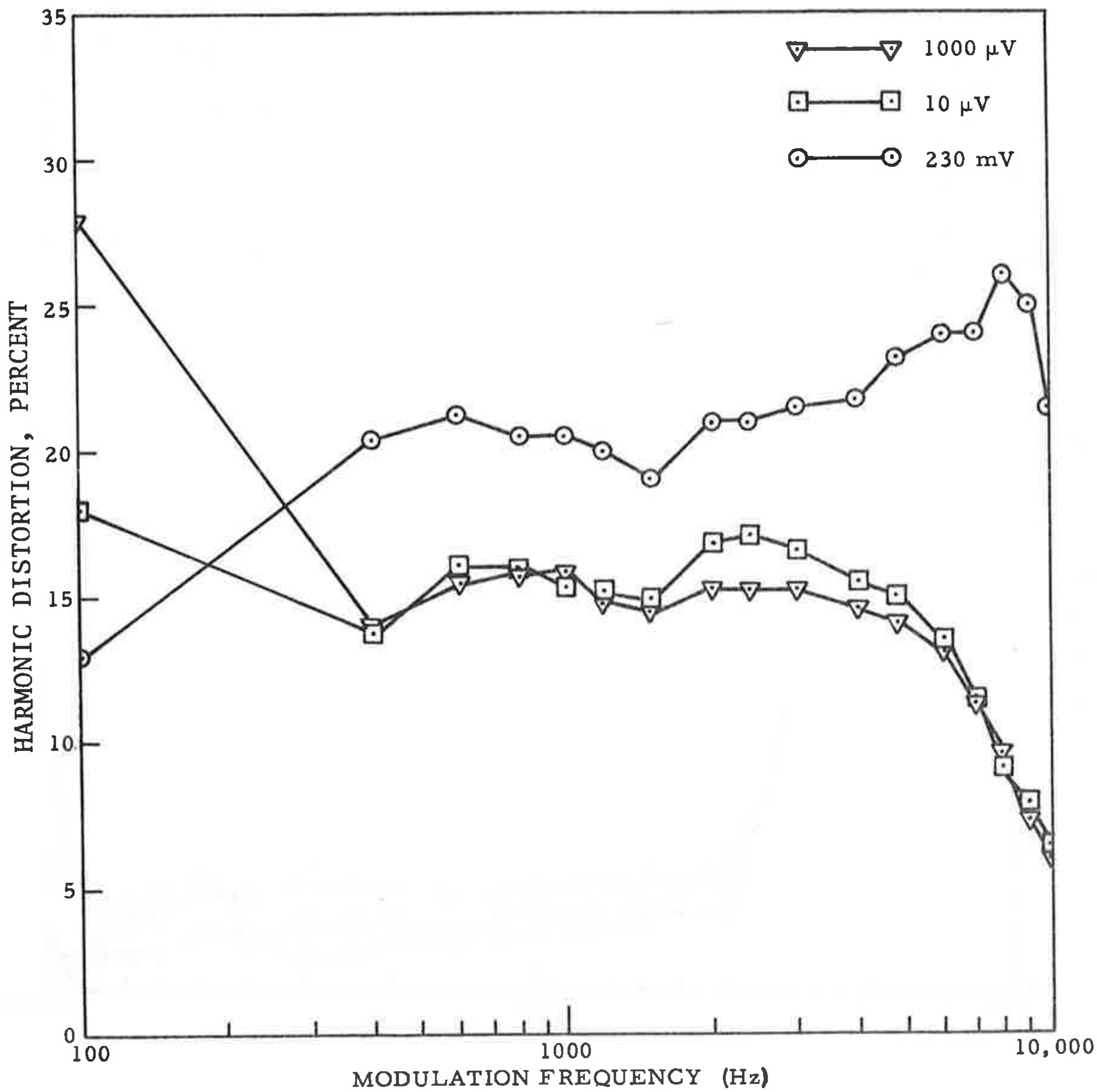


FIGURE 2-38. RECEIVER DATA LINK AUDIO HARMONIC DISTORTION 80 PERCENT MODULATION, MODIFIED COLLINS, MODEL 618M-2B, SERIAL NO. 2971

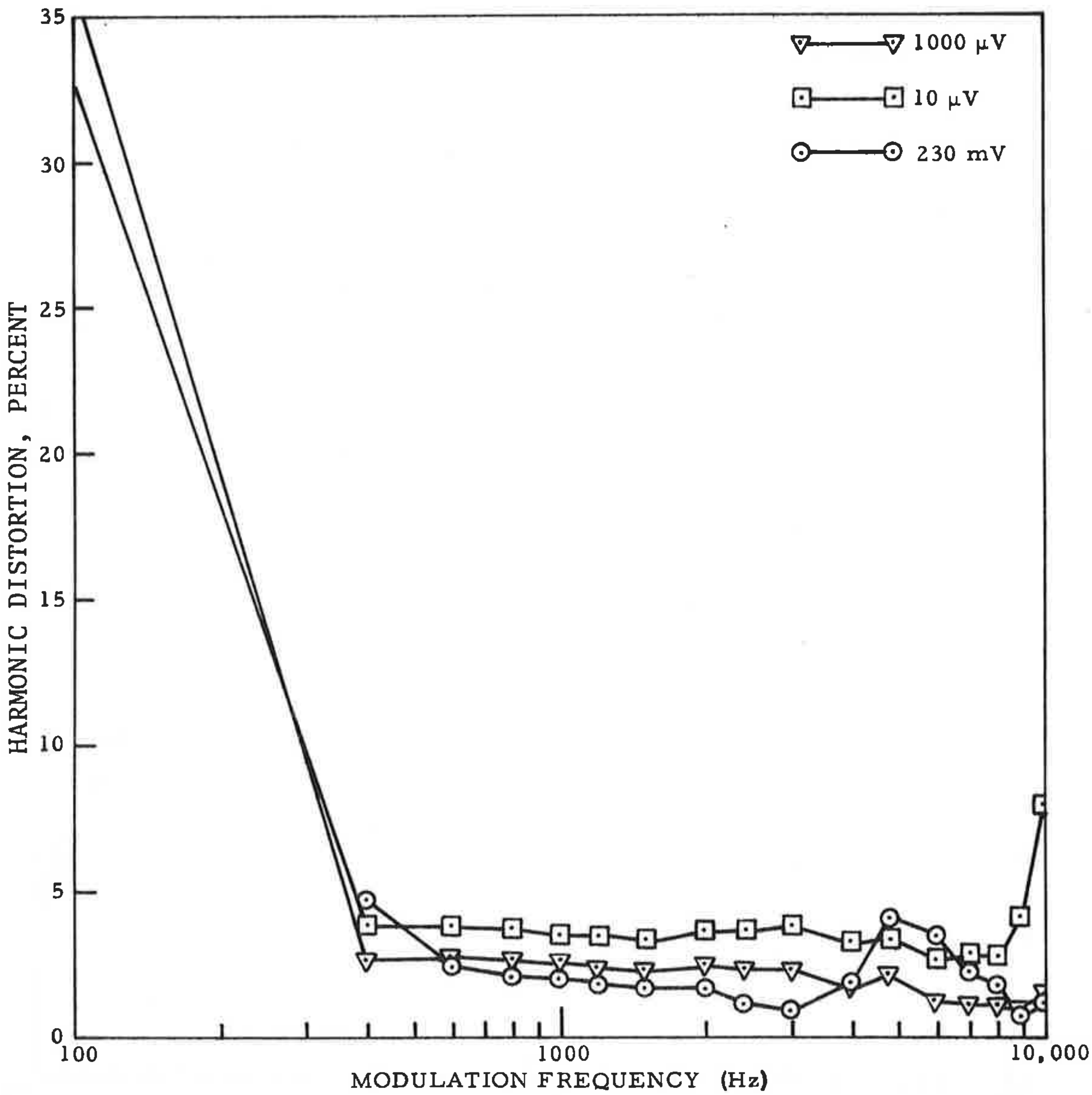


FIGURE 2-39. RECEIVER DATA LINK AUDIO HARMONIC DISTORTION 80 PERCENT MODULATION, MODIFIED COLLINS, MODEL 618M-2B, SERIAL NO. 4868

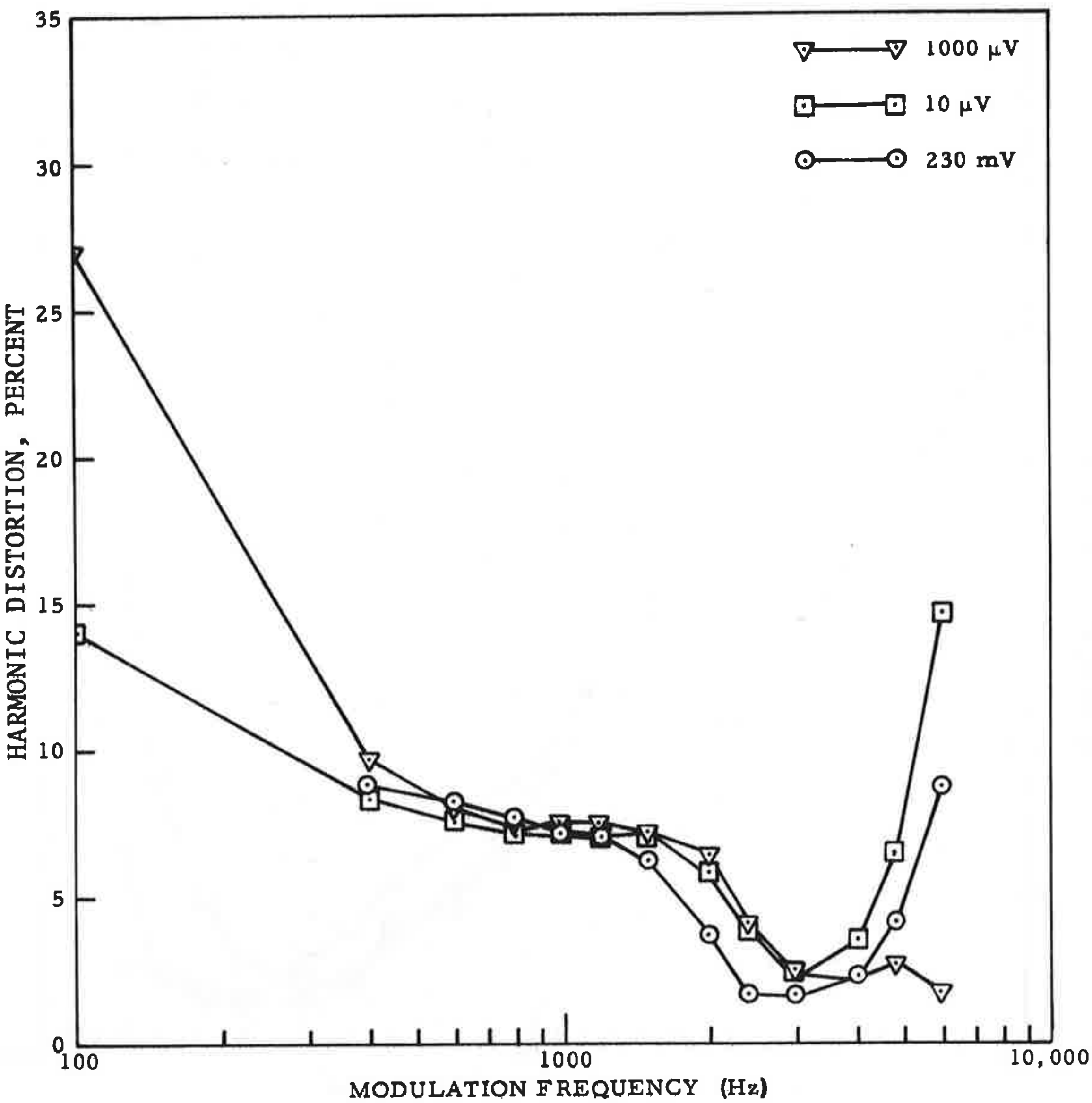


FIGURE 2-40. RECEIVER AUDIO HARMONIC DISTORTION 80 PERCENT MODULATION, BUEC, MODEL FA-8191, SERIAL NO. 1

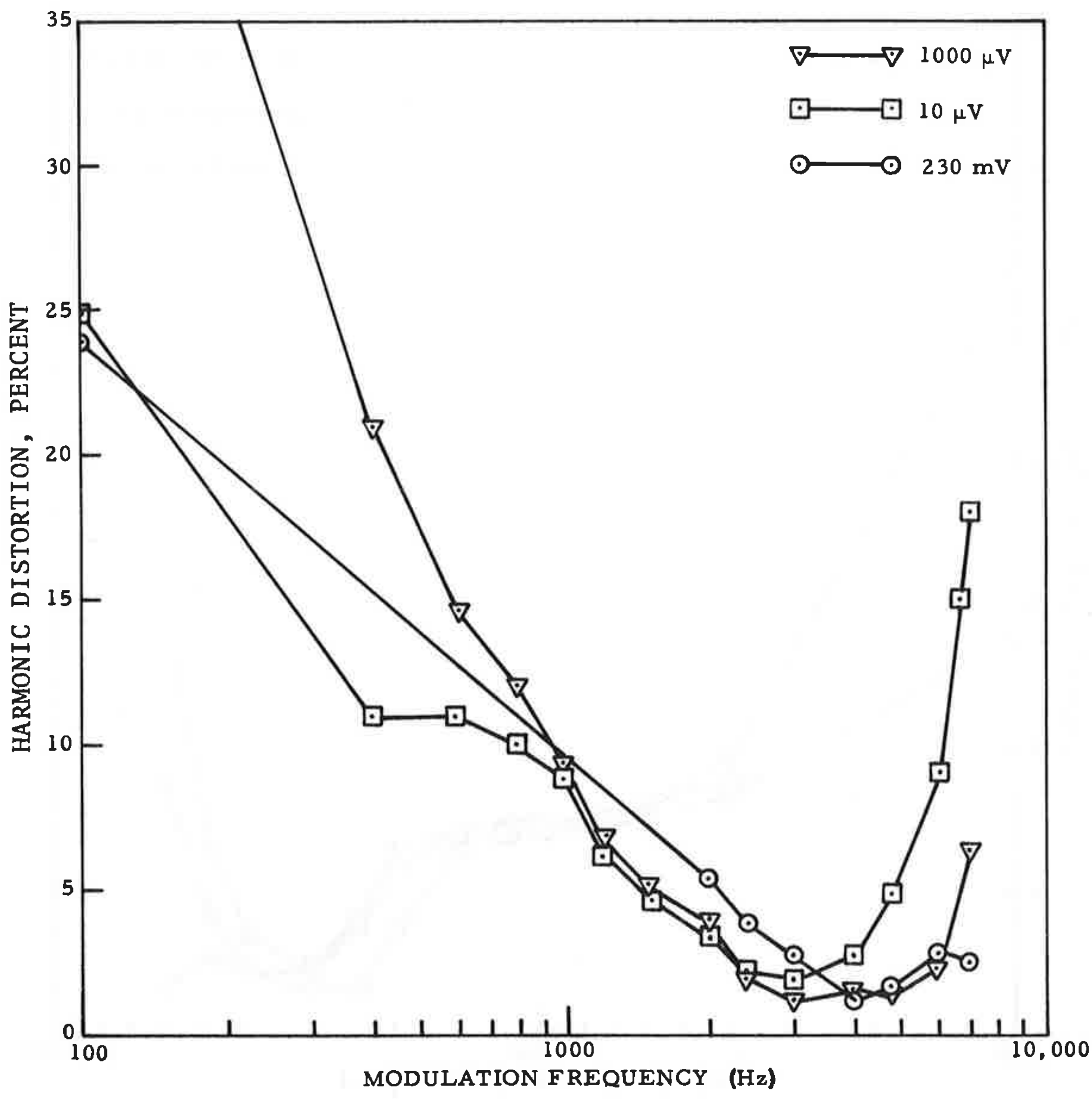


FIGURE 2-41. RECEIVER AUDIO HARMONIC DISTORTION 80 PERCENT MODULATION, BUEC, MODEL FA-8191, SERIAL NO. 2

NOTE: A modification was used in the test setup to provide this "typical" shaped curve, for reference purposes ONLY. Receiver characteristics were taken from detector TP-410.

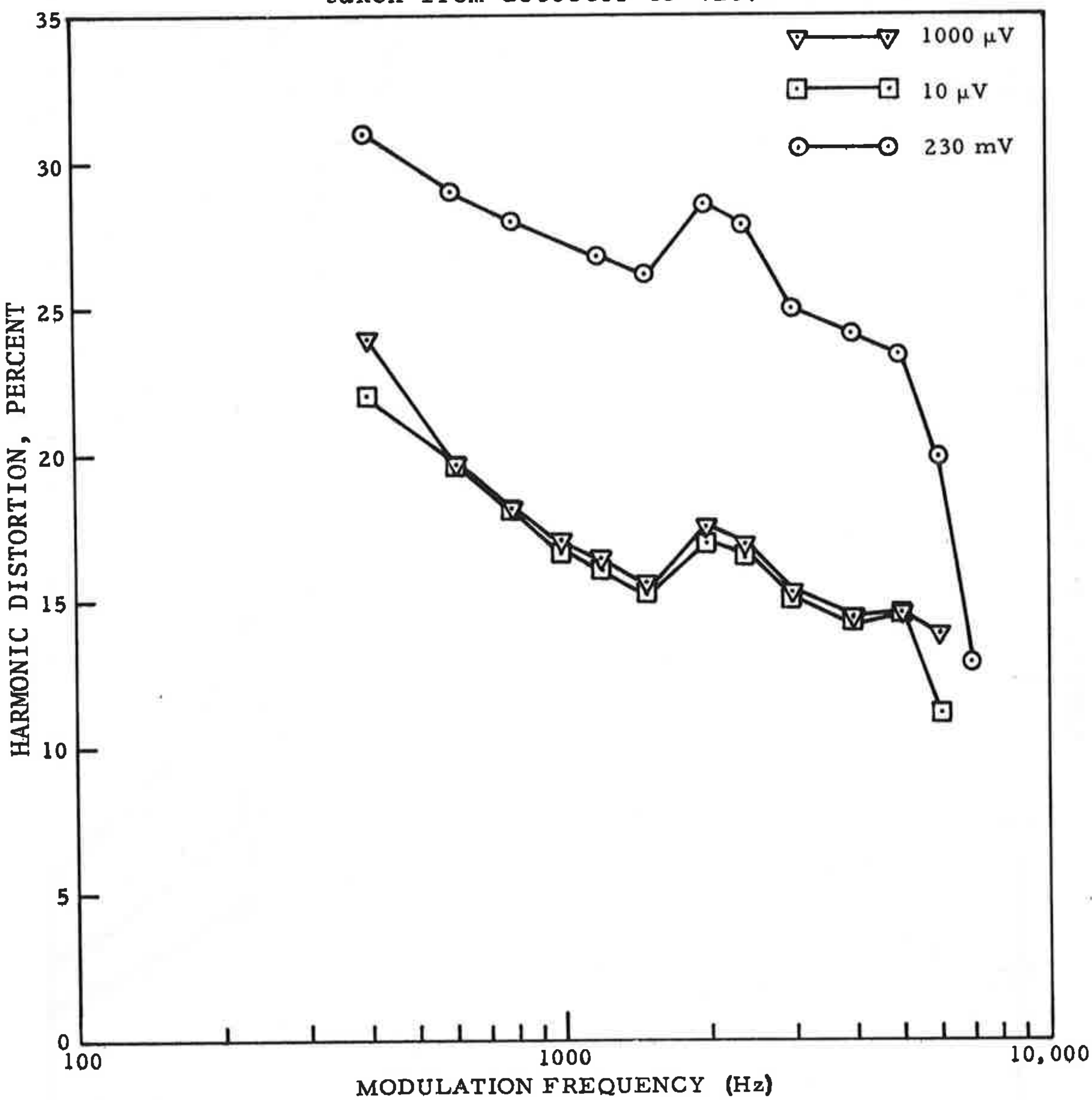


FIGURE 2-42. RECEIVER MODIFIED AUDIO HARMONIC DISTORTION 80 PERCENT MODULATION, KING MODEL KY-195B, SERIAL NO. 3145

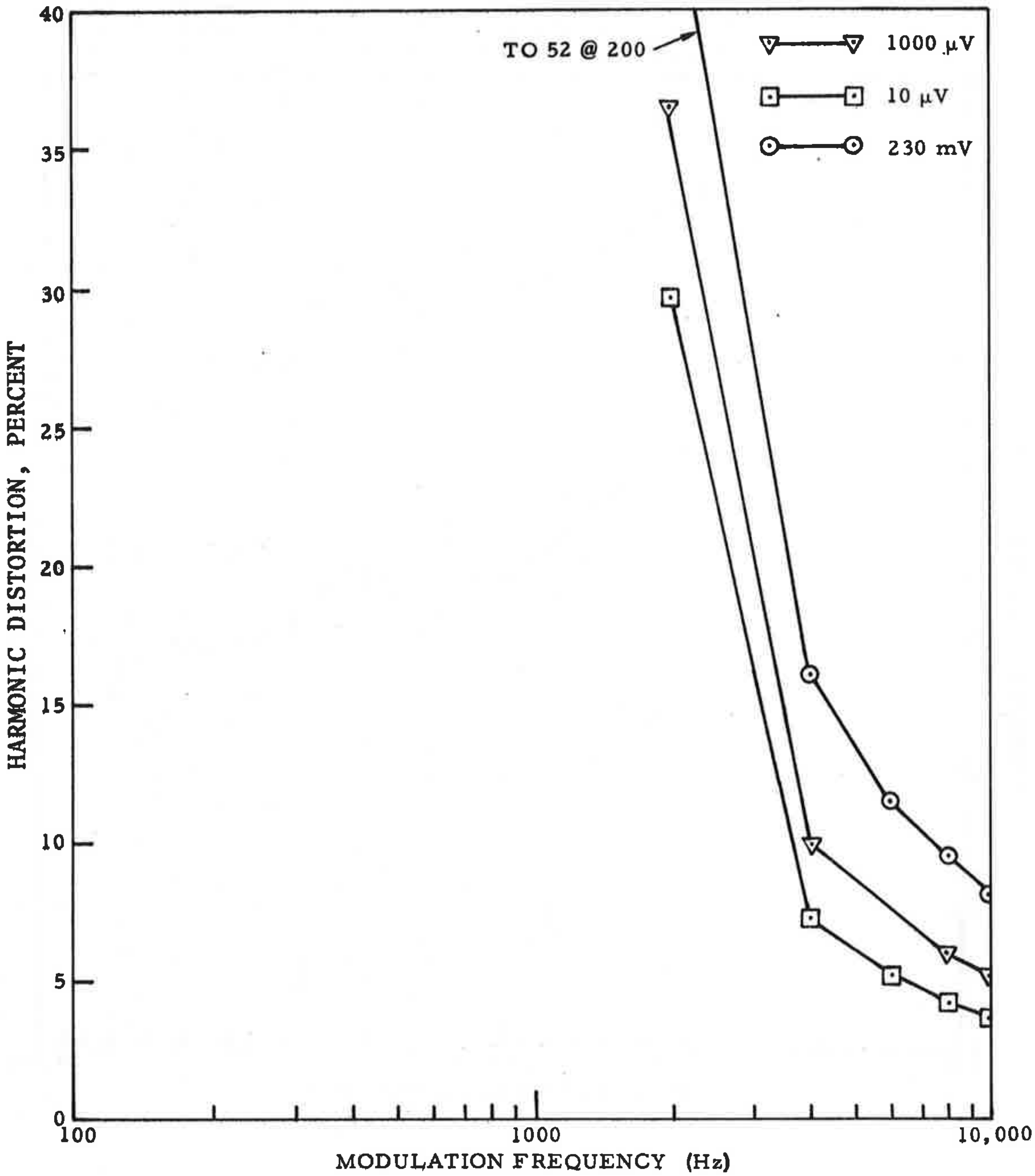


FIGURE 2-43. RECEIVER AUDIO HARMONIC DISTORTION 80 PERCENT MODULATION, KING, MODEL KY-195B, SERIAL NO. 3145

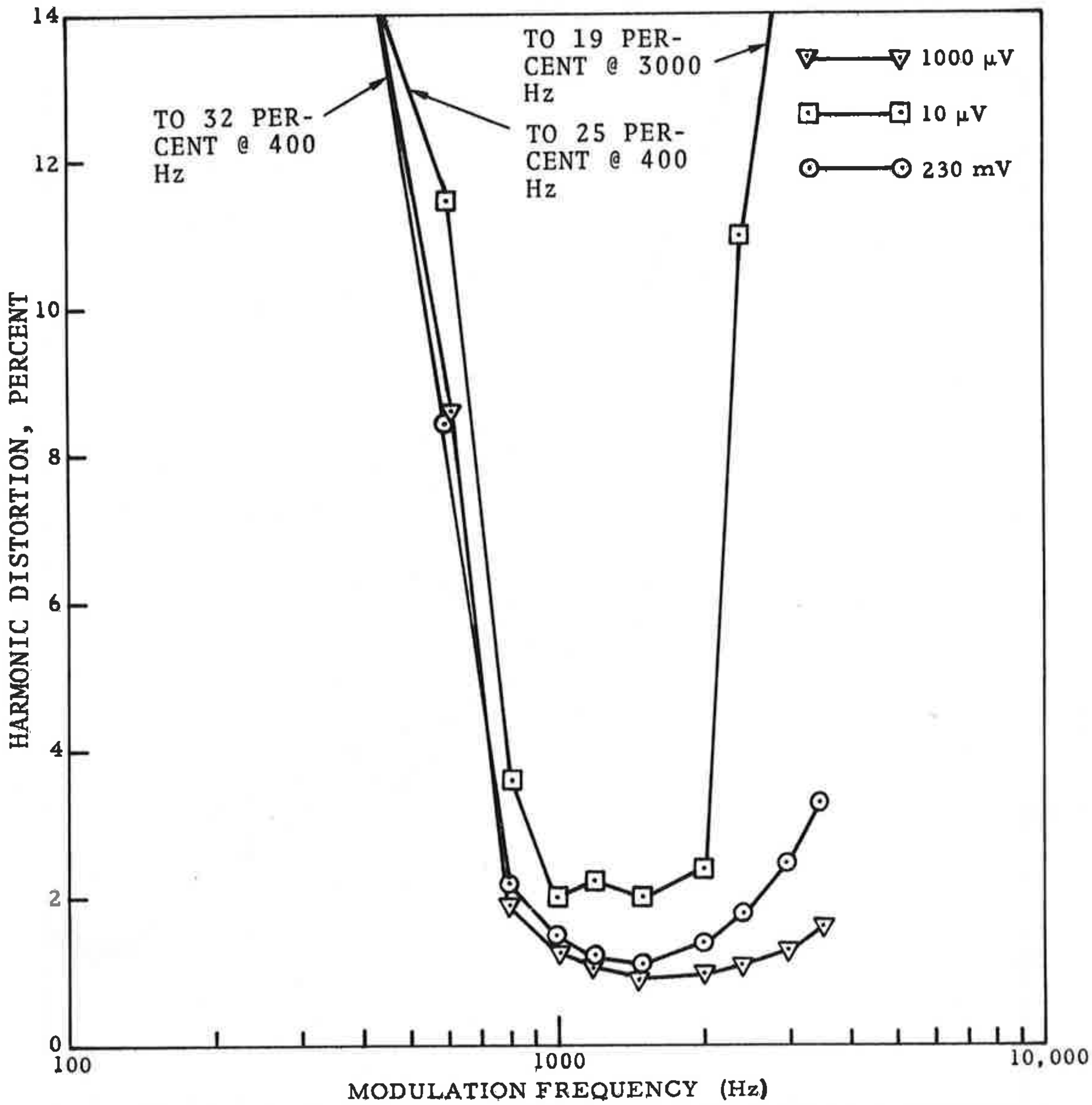


FIGURE 2-44. RECEIVER AUDIO HARMONIC DISTORTION 80 PERCENT MODULATION, NARCO, MODEL COM-11A

Note: A modification was used in the test setup to provide this "typical" shaped curve, for reference purposes ONLY. Receiver characteristics were taken from OMNI output.

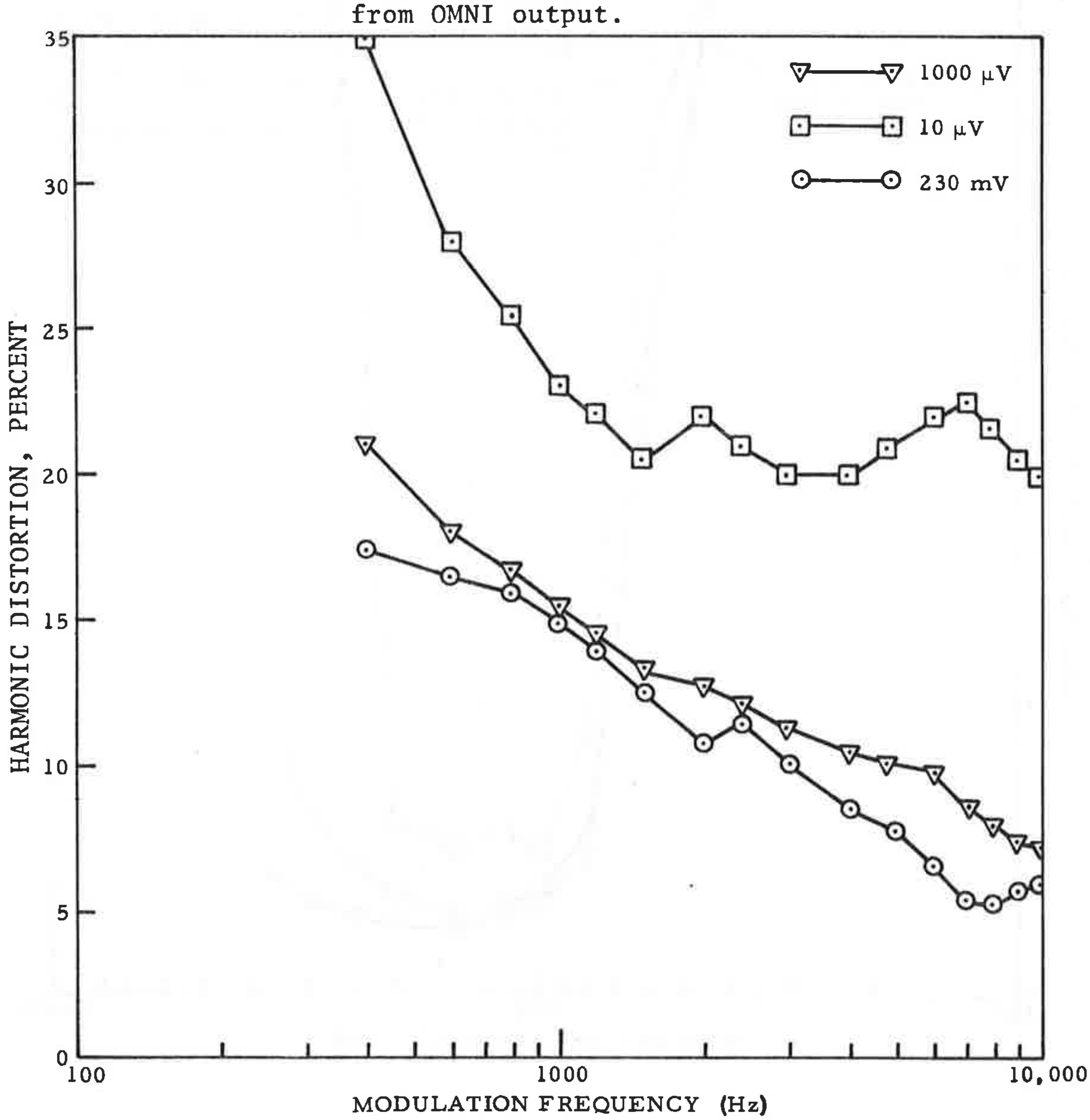


FIGURE 2-45. RECEIVER MODIFIED AUDIO HARMONIC DISTORTION 80 PERCENT MODULATION, NARCO MODEL COM-11A

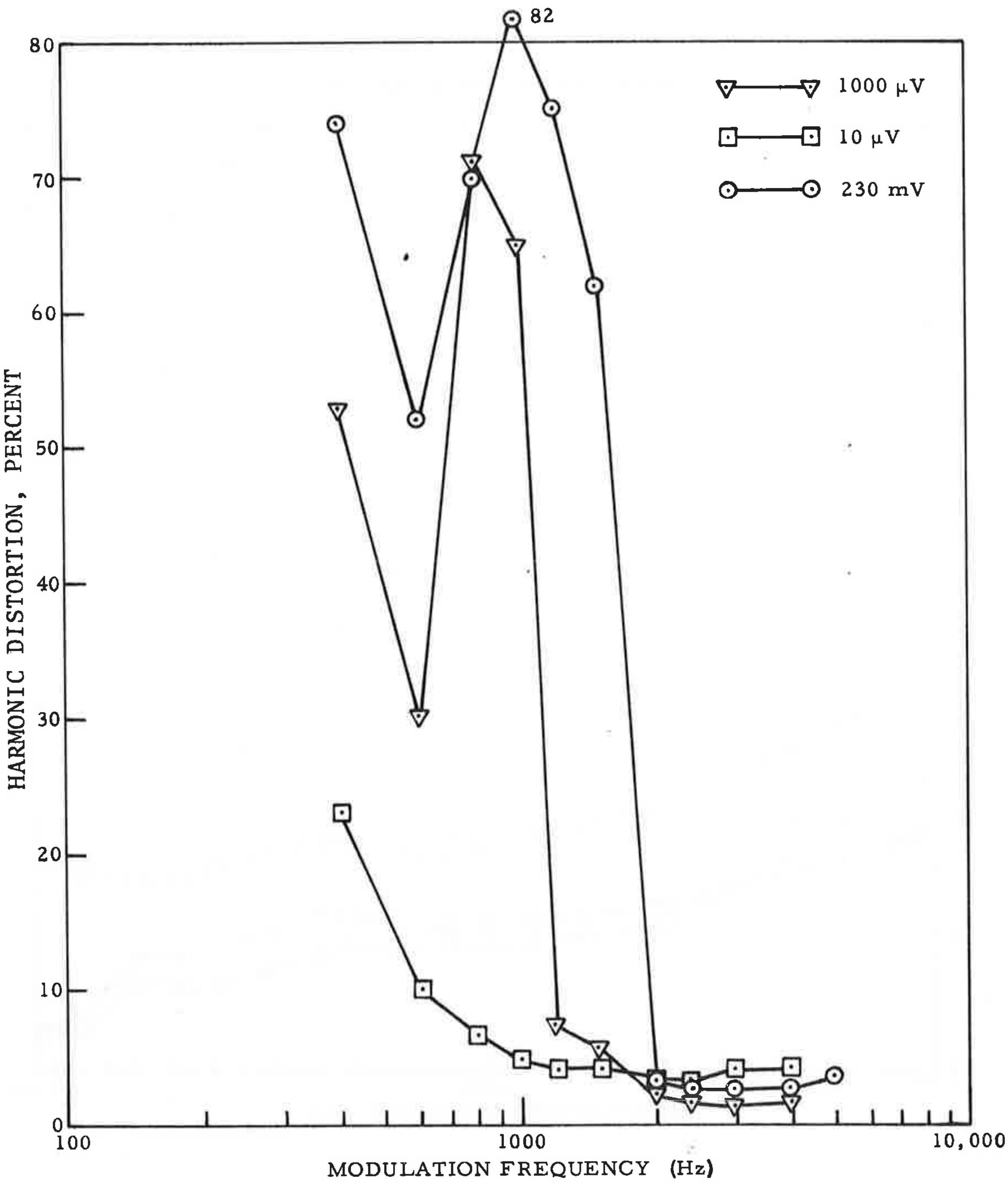


FIGURE 2-46. RECEIVER AUDIO HARMONIC DISTORTION 80 PERCENT MODULATION, GENAVE, MODEL ALPHA-100/360, SERIAL NO. 43-22

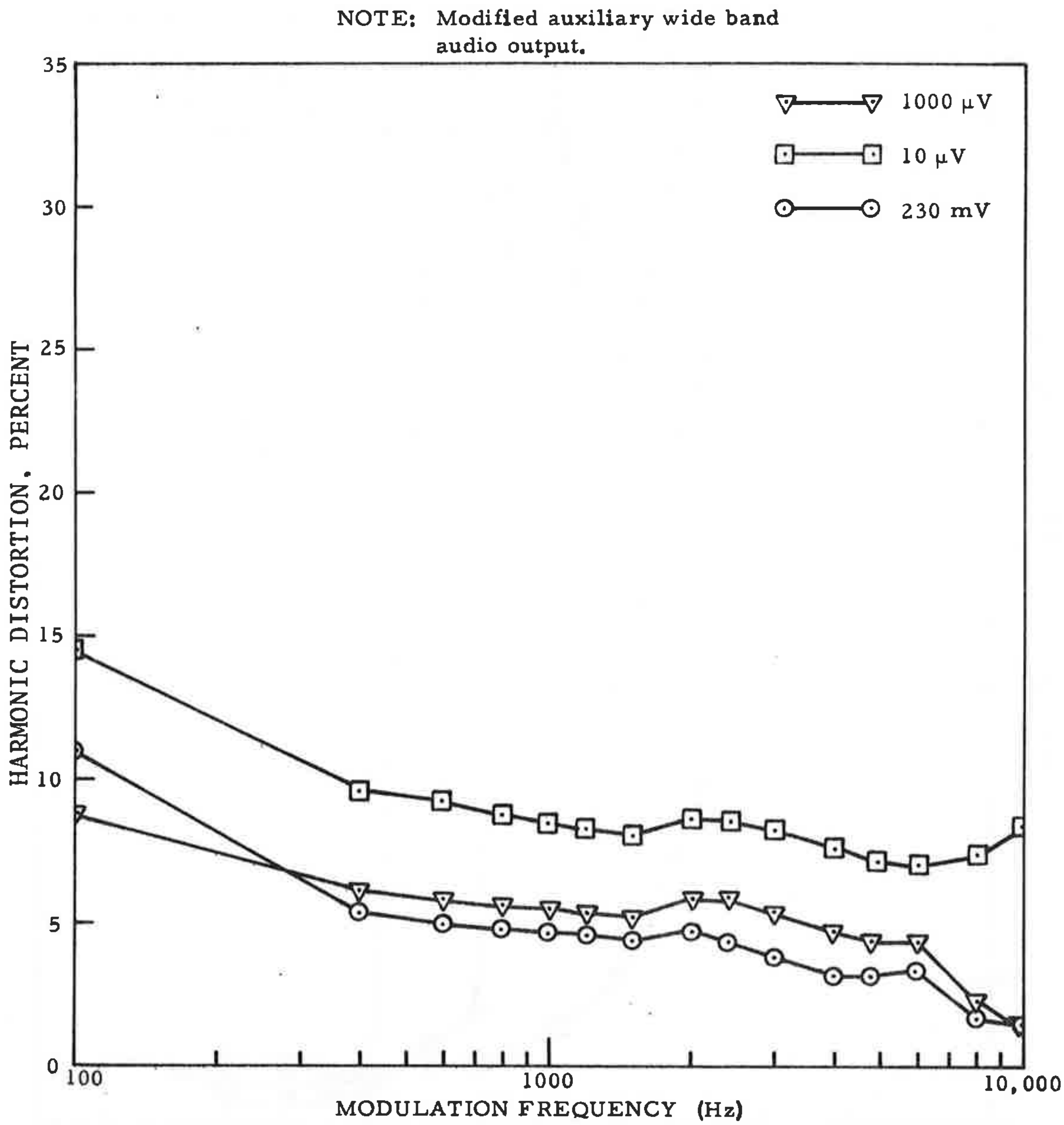


FIGURE 2-47. RECEIVER MODIFIED AUDIO HARMONIC DISTORTION 80 PERCENT MODULATION, A/N, MODEL GRR-23, SERIAL NO. 4293

2.2 TRANSMITTER TESTS

Transmitter performance characteristic tests were made on the transmitter equipment listed in Table 2-1. The tests performed are listed in Table 2-5. The transmitter tests were performed over a representative sample of existing ATC user equipment in order to determine what, if any, limitations this equipment might place on the performance of a data link system.

2.2.1 Transmitter Test Setup and Test Procedures

2.2.1.1 Transmitter Pass-Band Characteristics – Amplitude Characteristics - The test setup used to measure the transmitter amplitude characteristics is shown in Figure 2-48. For each transmitter under test, a reference value of the modulated carrier was established on the oscilloscope at 1000 Hz. Subsequently, a measurement was made of the unmodulated carrier and the difference between the two levels taken to establish the reference modulation signal. The amplitude characteristics $A(\omega)$, in dB normalized to 0 dB at 1000 Hz, were then calculated for each transmitter using the following relationship:

$$A(\omega) = 20 \text{ Log} \left(\frac{a - x}{a_r - x} \right) \qquad (2\text{-}1)$$

where: a = peak-to-peak amplitude of modulated signal as a function of modulation frequency.

x = unmodulated carrier amplitude, peak-to-peak.

a_r = peak-to-peak RF amplitude when modulation is 1000 Hz.

The resulting $A(\omega)$ of the transmitters are shown plotted versus modulation frequency in Figures 2-49 through 2-60.

The transmitter sections of the three transceivers that are in accordance with ARINC Characteristics 566A, Figures 2-49 through 2-51, exhibit considerably different bandwidth characteristics. The measured bandwidths are approximately 2800 Hz (Figure 2-49), 8000 Hz (Figure 2-50), and greater than 10 kHz (Figure 2-51).

TABLE 2-5. TRANSMITTER TESTS

TEST	PURPOSE	REMARKS
1. Passband Characteristics a. Amplitude Characteristics b. Phase Characteristics	To describe potential signal distortion resulting from the linear portion of the transmitter characteristics	Affects Bit Error Rate (P_e)
2. Harmonic Distortion	To describe potential distortion resulting from non-linearities in the transmitter	
3. Local Oscillator Frequency Stability	To measure the degree to which frequency variations may cause an effective alteration of pass-band characteristics	
4. Power Rise Time	To measure time required for transmitter to come up to power	Contributes to turnaround time

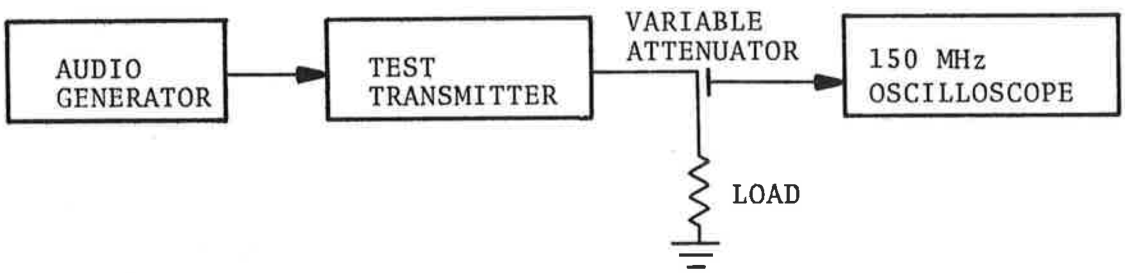


FIGURE 2-48. TRANSMITTER PASS-BAND TEST SETUP

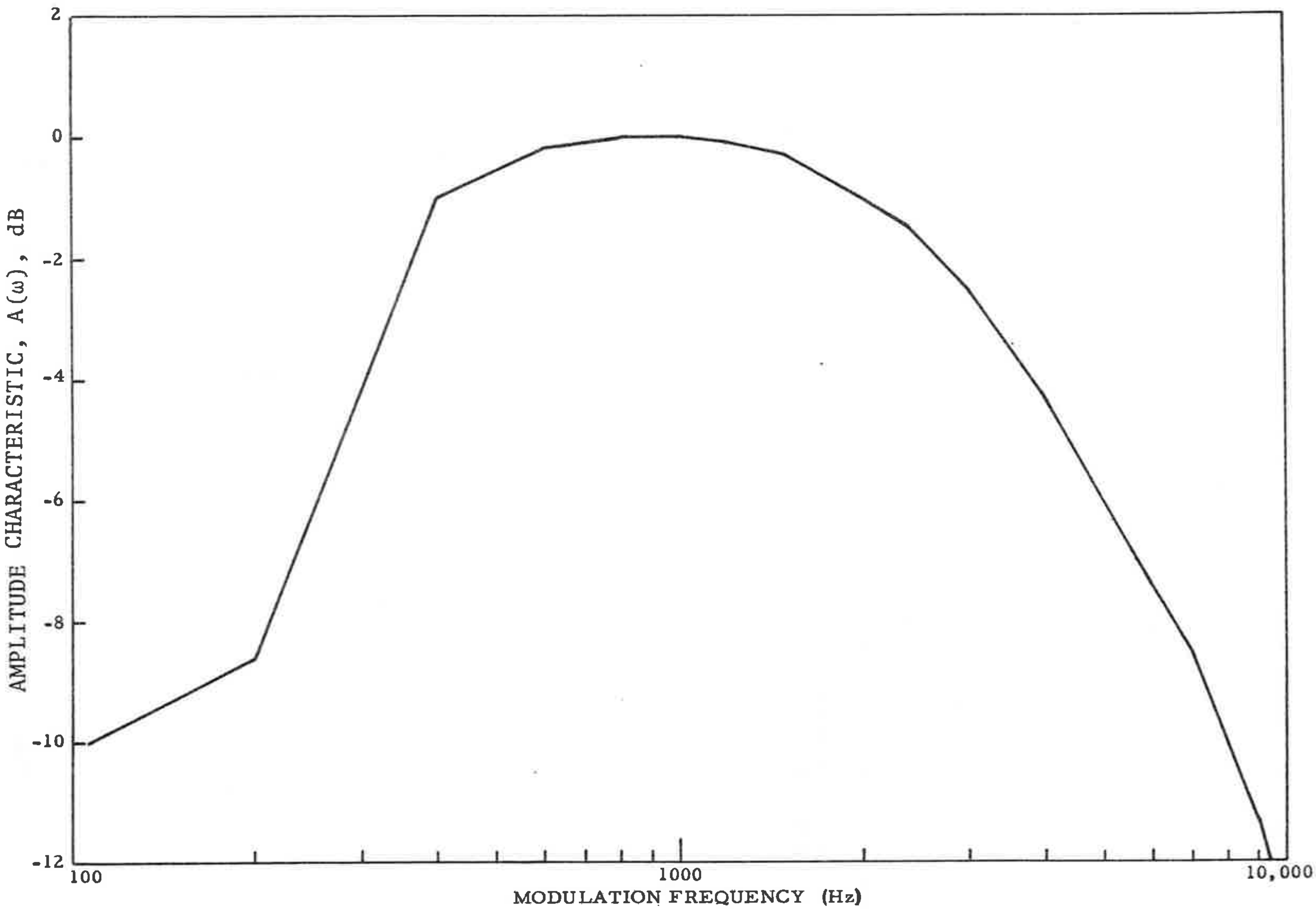


FIGURE 2-49. TRANSMITTER NORMALIZED DATA LINK AUDIO, KING, MODEL KTR-9100A, SERIAL No. 2193

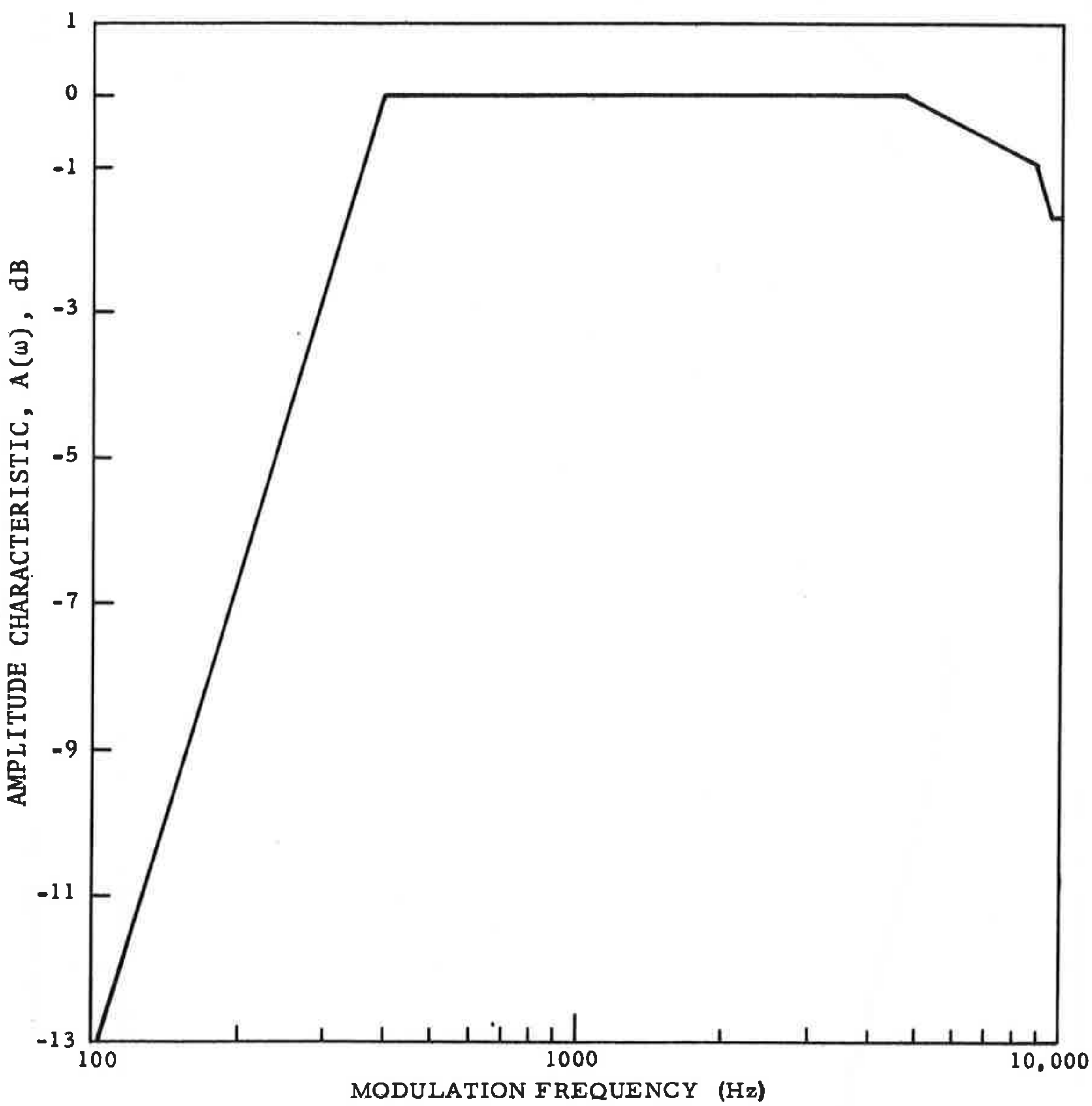


FIGURE 2-50. TRANSMITTER NORMALIZED DATA LINK AUDIO, BENDIX, MODEL RTA-43A, SERIAL NO. 1050

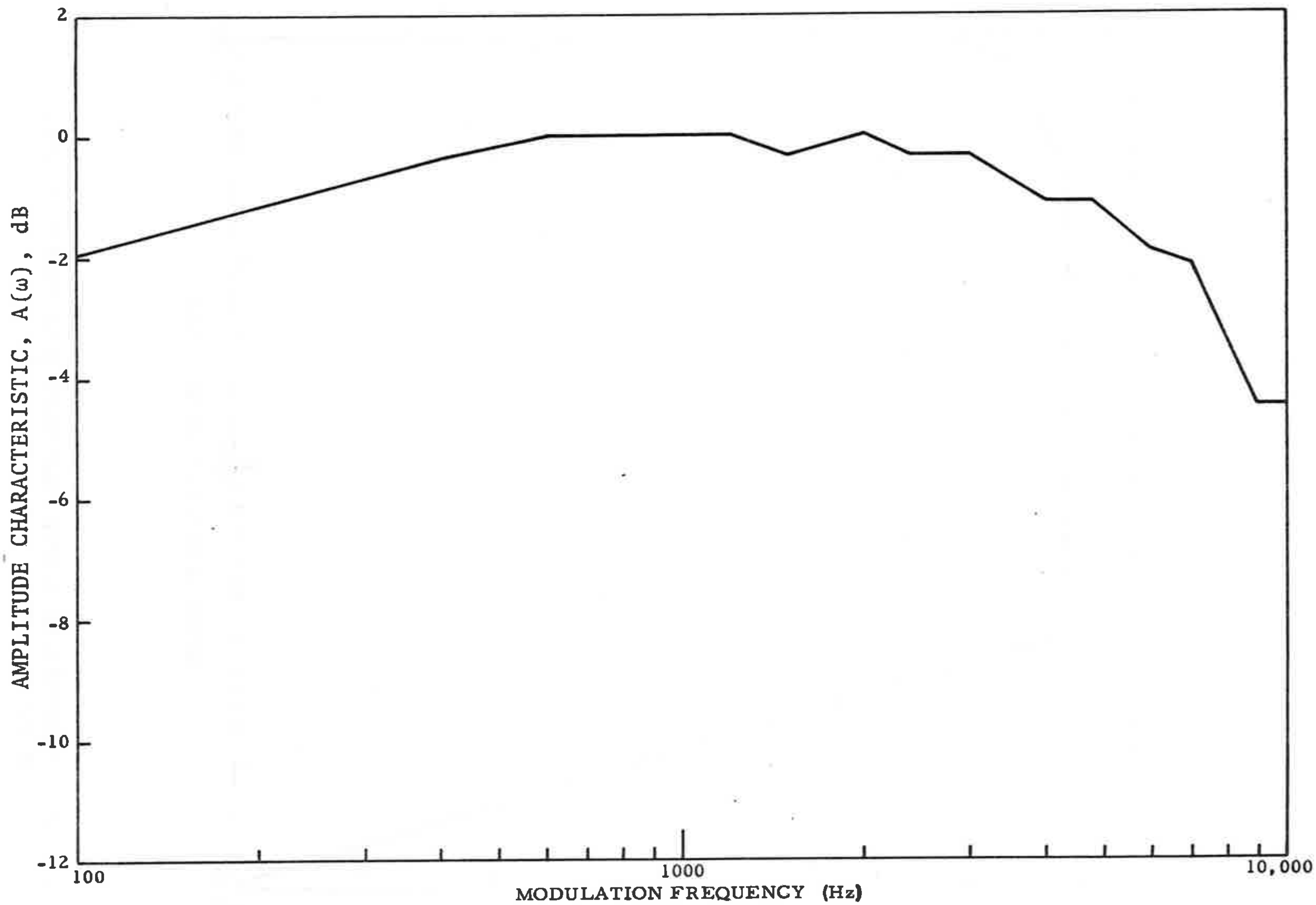


FIGURE 2-51. TRANSMITTER NORMALIZED DATA LINK AUDIO, BENDIX, MODEL RTA-43A, SERIAL NO. 1027

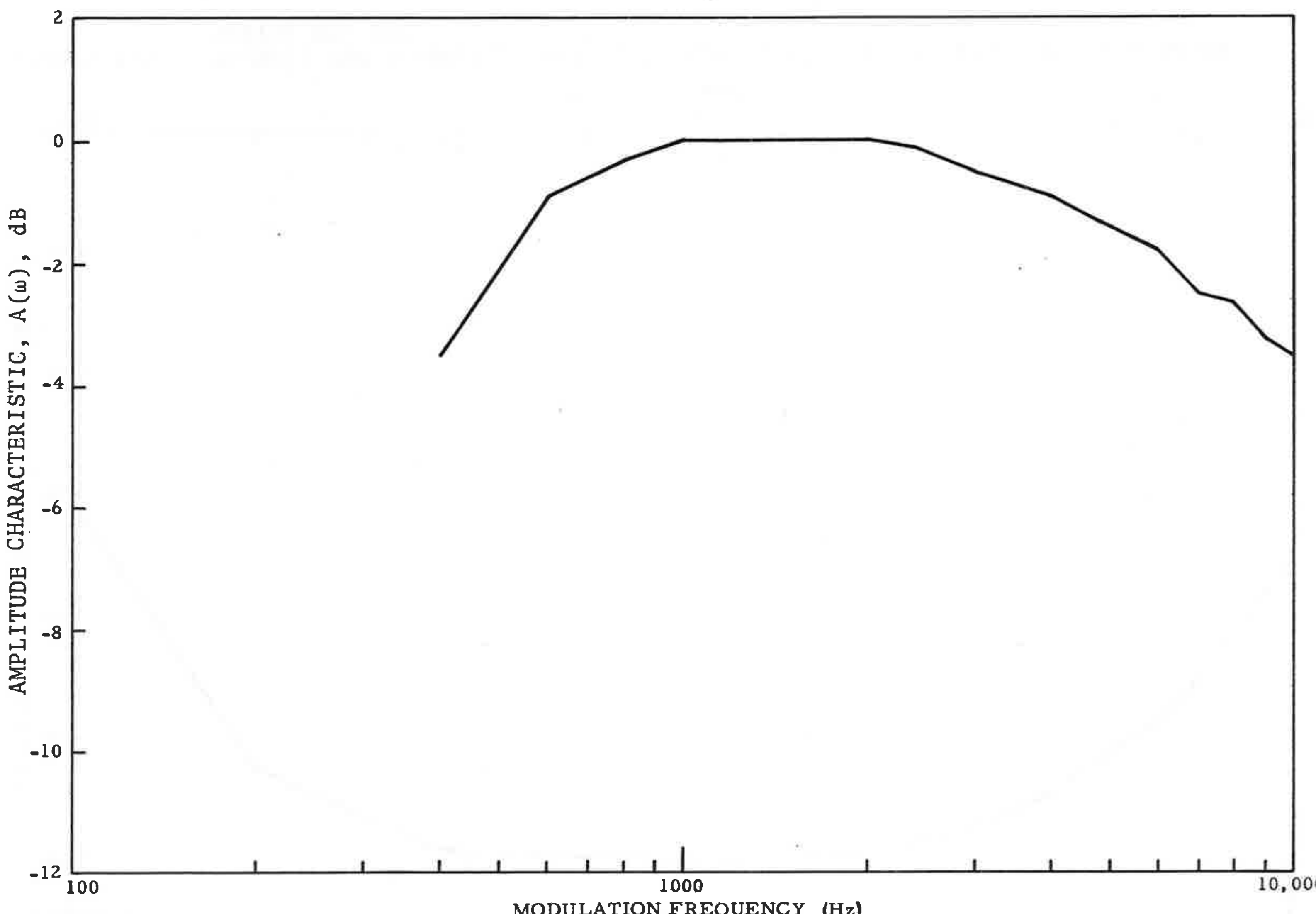


FIGURE 2-52. TRANSMITTER NORMALIZED DATA LINK AUDIO, MODIFIED COLLINS, MODEL 618M-2B, SERIAL NO. 2996

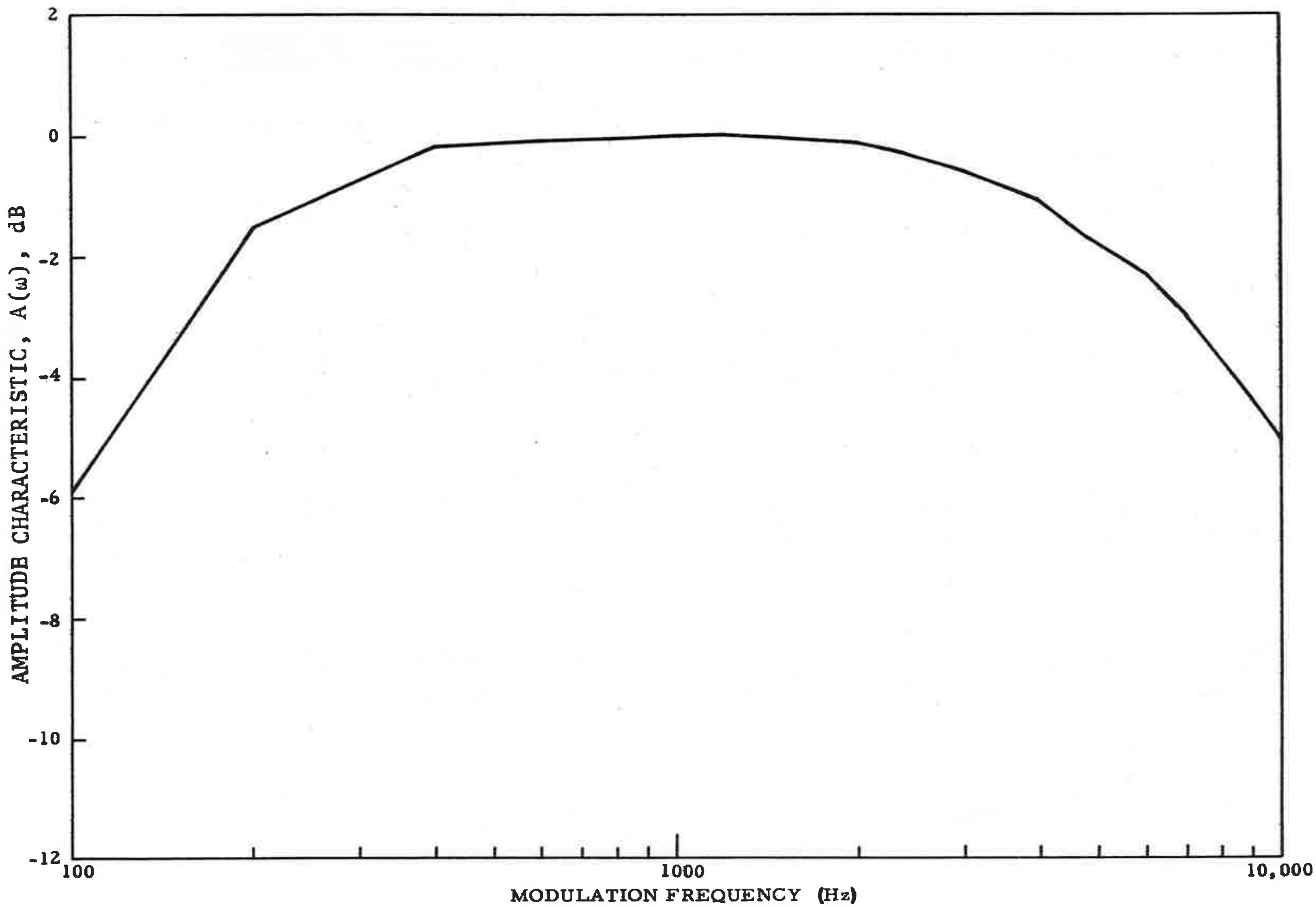


FIGURE 2-53. TRANSMITTER NORMALIZED DATA LINK AUDIO, MODIFIED COLLINS, MODEL 618M-2B, SERIAL NO. 2971

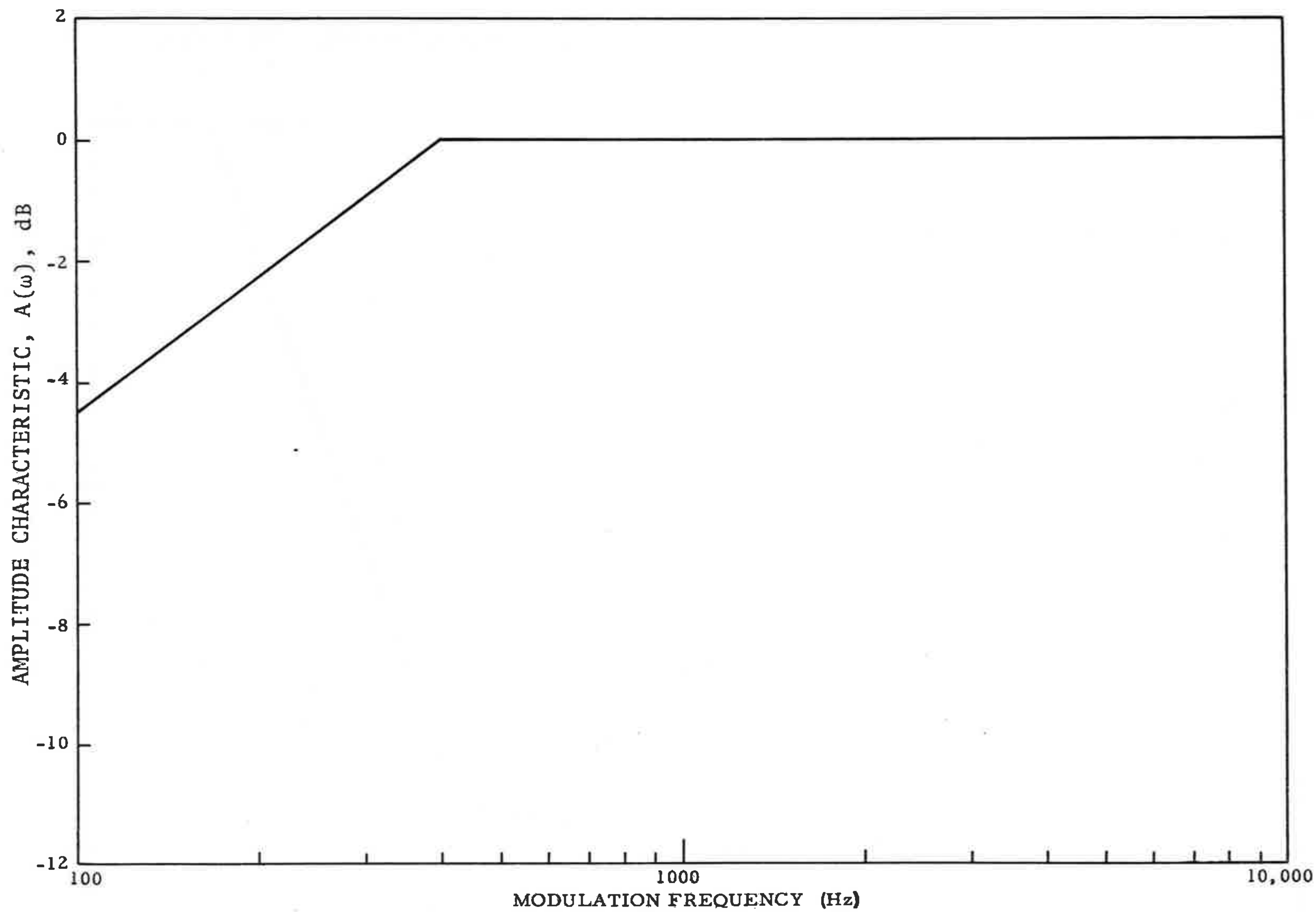


FIGURE 2-54. TRANSMITTER NORMALIZED DATA LINK AUDIO, COLLINS, MODEL 618M-2B, SERIAL NO. 4868

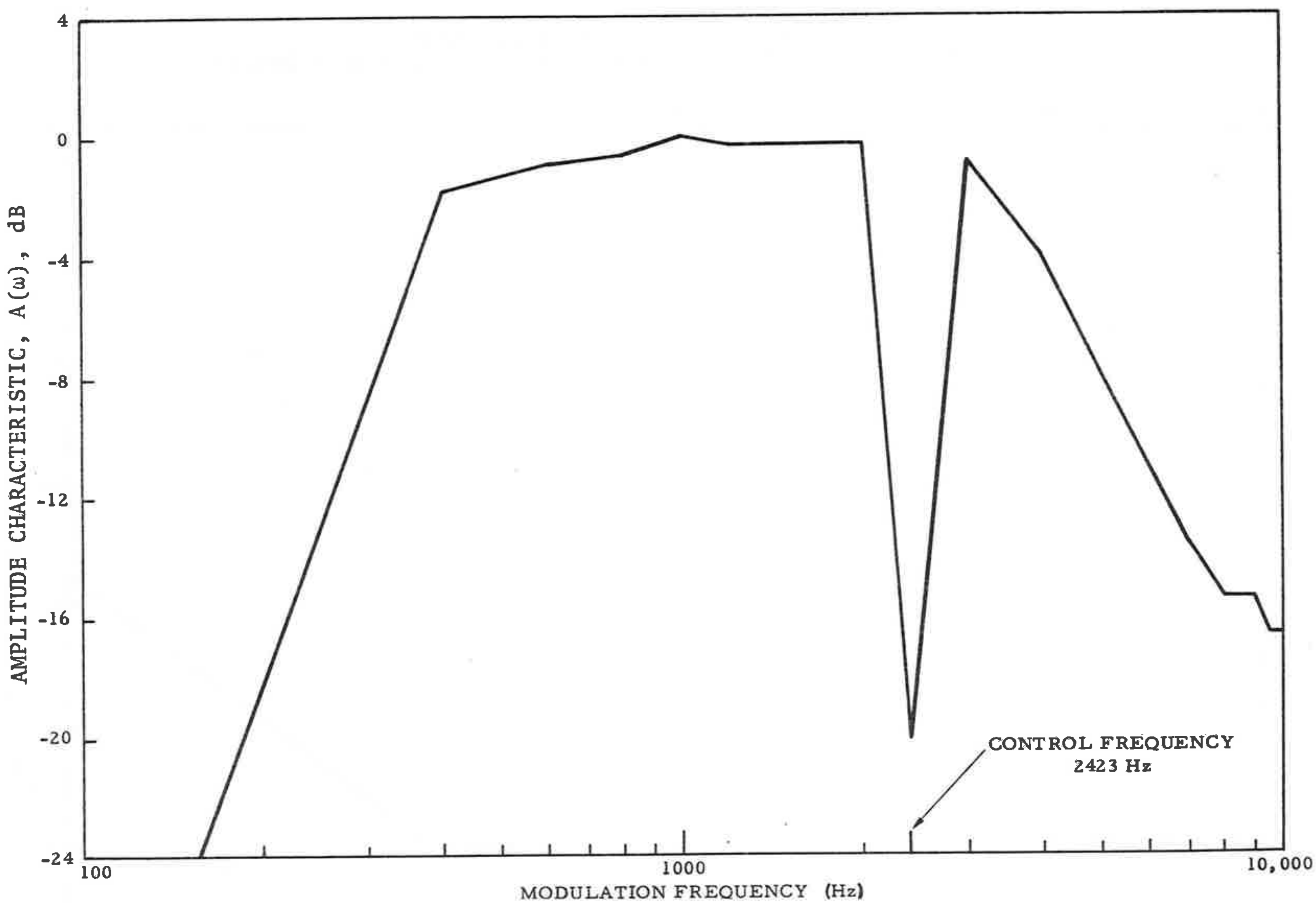


FIGURE 2-55. TRANSMITTER NORMALIZED AUDIO, BUEC, MODEL FA-8191, SERIAL NO. 1

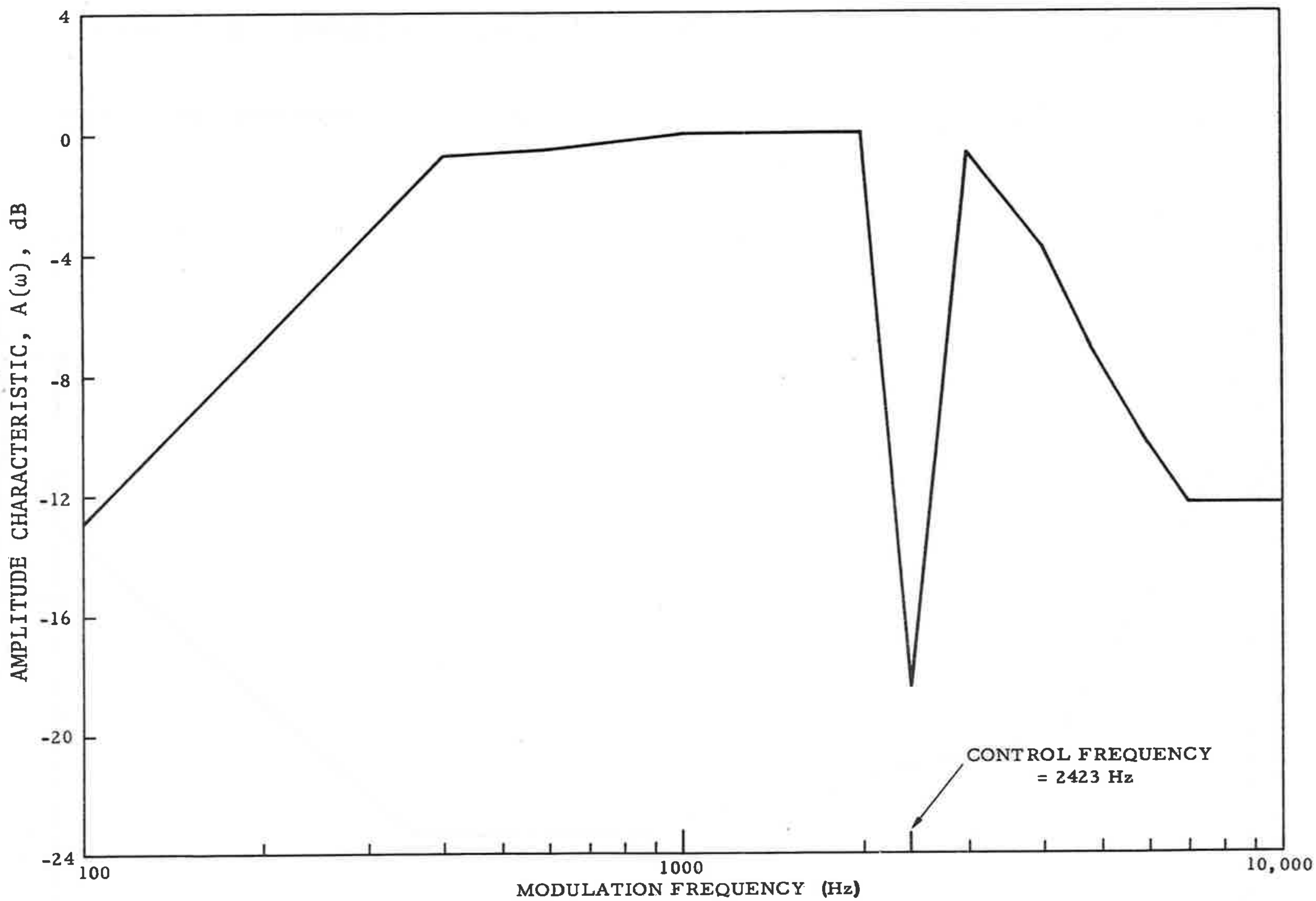


FIGURE 2-56. TRANSMITTER NORMALIZED AUDIO, BUEC, MODEL FA-8191, SERIAL NO. 2

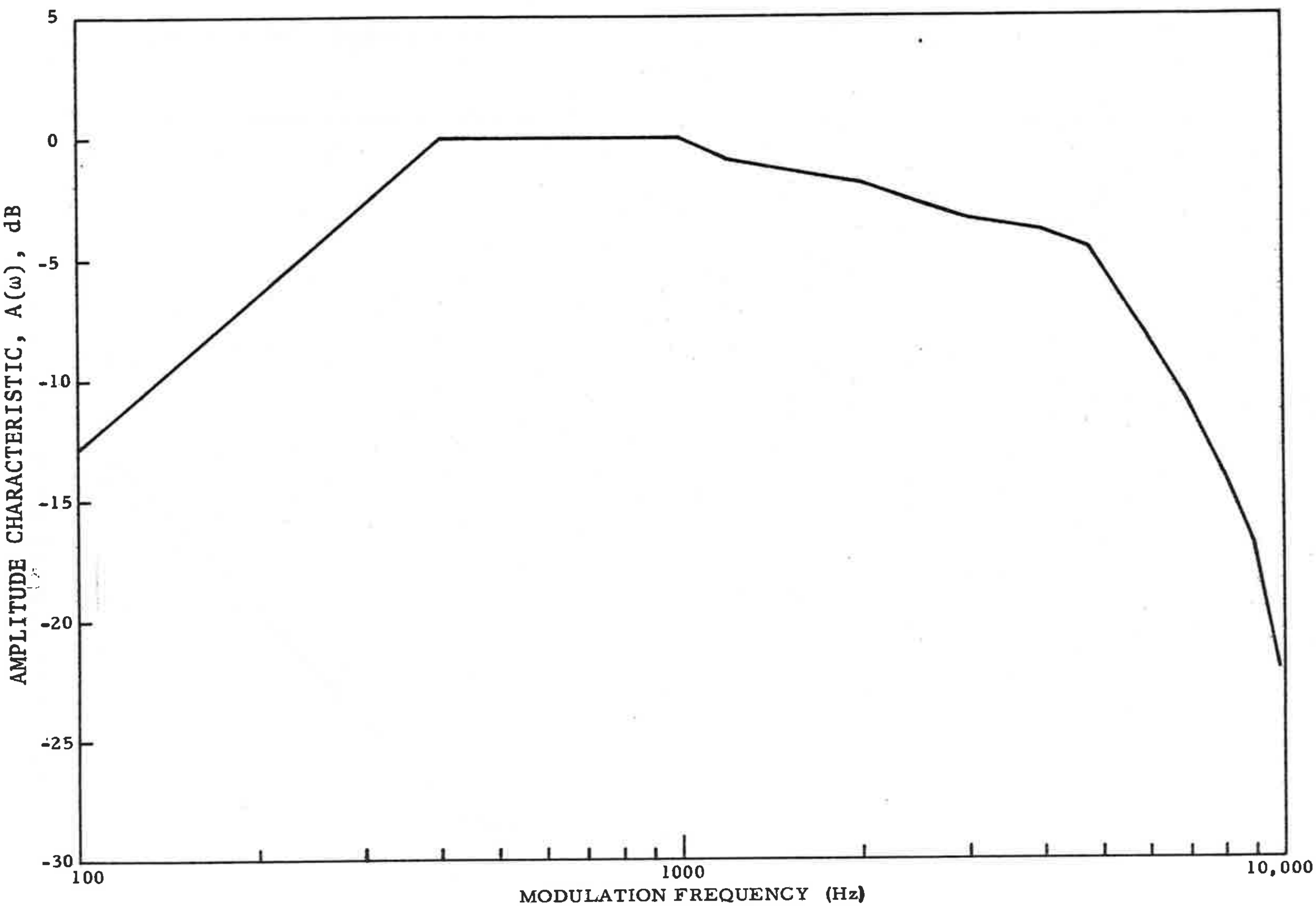


FIGURE 2-57. TRANSMITTER NORMALIZED AUDIO, KING, MODEL KY-195B, SERIAL NO. 3145

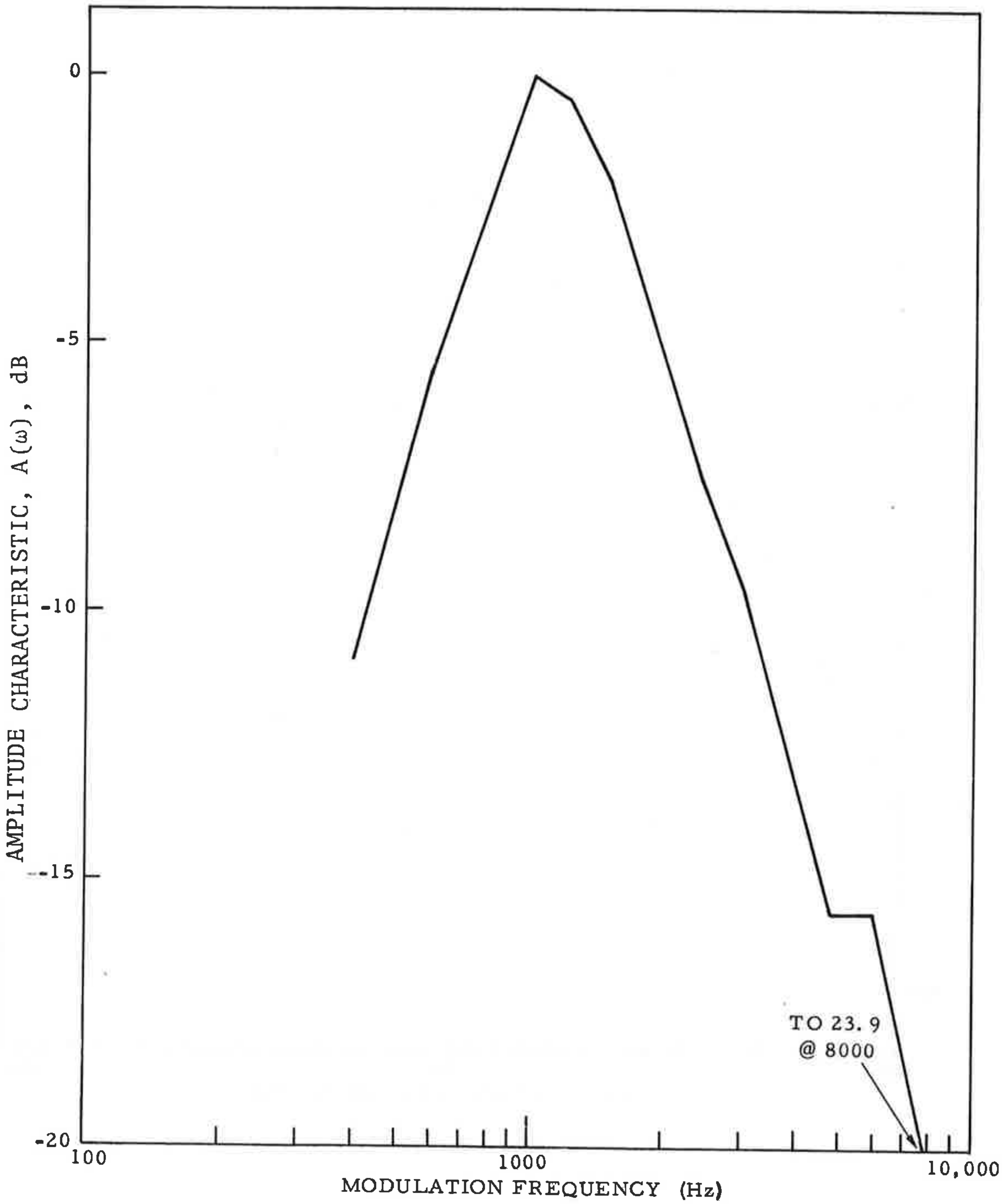


FIGURE 2-58. TRANSMITTER NORMALIZED AUDIO, NARCO, MODEL COM-11A

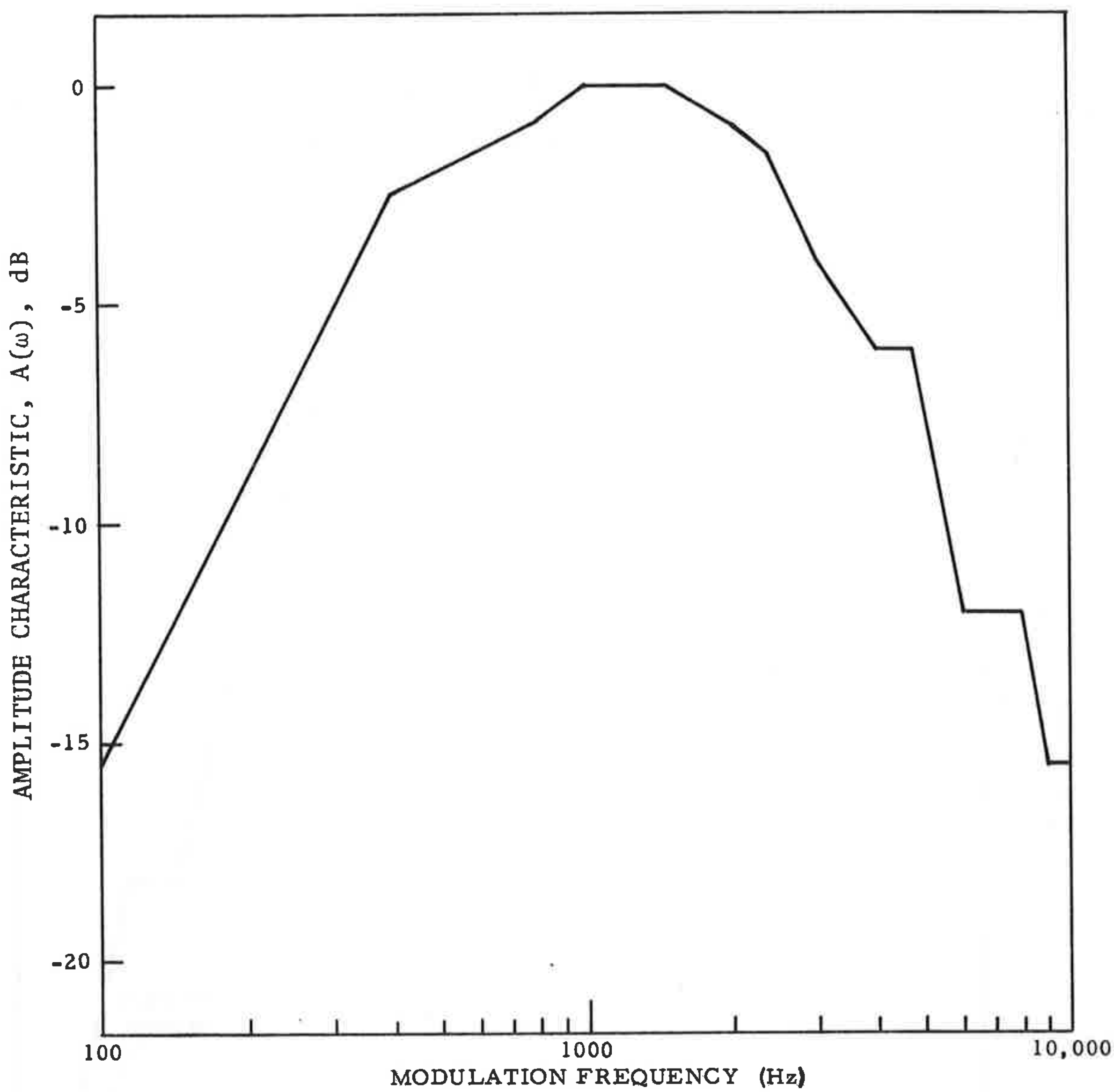


FIGURE 2-59. TRANSMITTER NORMALIZED AUDIO, GENAVE, ALPHA-100/360, SERIAL NO. 43-22

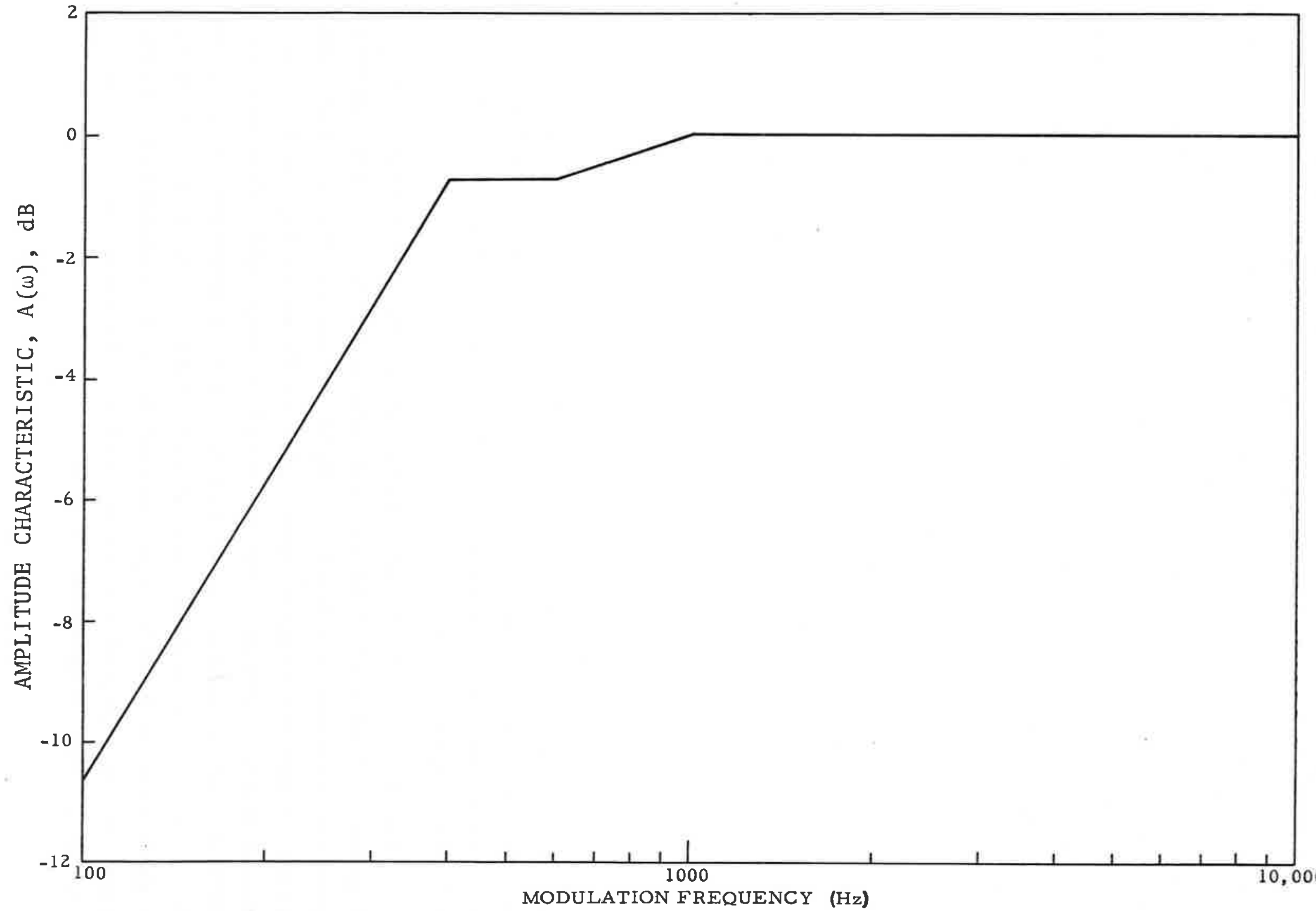


FIGURE 2-60. TRANSMITTER NORMALIZED AUDIO, A/N, MODEL GRT-21, SERIAL NO. 379

The tone pair of 1200 Hz and 2400 Hz for the MSK spectrum at 2400 bits per second falls within the bandwidth of all three transmitters. The tone pair of 2400 Hz and 4800 Hz for the MSK spectrum at 4800 bits per second falls within the bandwidth of the transmitters shown in Figures 2-50 and 2-51. However, the 4800-Hz tone falls outside the bandwidth of the transmitter shown in Figure 2-49. Here the 4800-Hz tone falls in a skirt region and is approximately 6 dB down. The performance of this transmitter at a data rate of 4800 bit per second would be expected to be below that of the transmitters having the characteristics shown in Figures 2-50 and 2-51.

The transmitter sections of the three transceivers that are in accordance with ARINC Characteristics 546, Figures 2-52 through 2-54, have measured bandwidths of approximately 8000 Hz, 6700 Hz, and greater than 10 kHz, respectively. All three of these transmitters accommodate the pairs of the MSK spectrum within the bandwidth at both 2400 and 4800 bits per second and would be expected to perform well at both data rates.

The $A(\omega)$ of the FAA BUEC transmitter shown in Figures 2-55 and 2-56 exhibit a deep notch (20 dB down) at 2423 Hz. This notch results from an active notch filter designed for use with a remote tuning feature of the transmitters. The proximity of the notch to the 2400-Hz tone common to the MSK spectrum at both 2400 and 4800 bit-per-second data rates rules out the use of this equipment for data link applications unless it is modified.

The $A(\omega)$ of the three general aviation transmitters shown in Figures 2-57 through 2-59 exhibit considerably narrower bandwidths than the transmitters built to ARINC characteristics. The bandwidth of the transmitter whose $A(\omega)$ is shown in Figure 2-57 is approximately 2200 Hz. The passband is reasonably flat out to 4800 Hz (approximately 5 dB down). This transmitter would probably function well at a data rate of 2400 bits per second. However, at a data rate of 4800 bits per second loss of transmitted information can be expected due to the relatively steep rolloff that occurs in the vicinity of 4800 Hz.

The bandwidth of the transmitter whose A(ω) is shown in Figure 2-59 is approximately 2300 Hz. This transmitter has an A(ω) similar to that of the transmitter shown in Figure 2-57. Thus, similar comments apply to this transmitter.

The A(ω) of the GRT-21 transmitter is shown in Figure 2-60. This equipment is currently the primary FAA ATC ground transmitter. The bandwidth is in excess of 10 kHz and the amplitude characteristic is within 1 dB of being flat over most of this range. The GRT-21 should perform well for data link applications at data rates of 2400 and 4800 bits per second.

Note that the amplitude balance control on the MSK modem output can be used to compensate for the amplitude imbalance which results from insufficient transmitter bandwidth. However, the effects of intersymbol interference due to insufficient bandwidth are not avoided by the balance adjustment.

Audio Phase Delay Characteristics - Transmitter audio delay measurements were performed on the transmitters listed in Table 2-1. The test setup for these measurements is shown in Figure 2-61. The results of these measurements are shown in Figures 2-62 through 2-73. The values for the differential delay are given in Table 2-5 for the individual transmitters. Ideally, the audio delay characteristics, as shown in Figures 2-62 through 2-73, should be flat across the bandwidth in order to minimize distortion. That is, the deviation of the delay from the nominal linear phase value gives rise to distortion, not the absolute value of the delay itself. The amount of differential delay compared to the bit period, expressed as a percentage, is a measure of performance degradation due to this effect. Values of this parameter less than 2 percent indicate good delay distortion characteristics whereas values on the order of 10 percent or more indicate that data performance degradation due to this effect is not negligible. The significance of these data relative to data link system performance is further discussed in section 2.4 below.

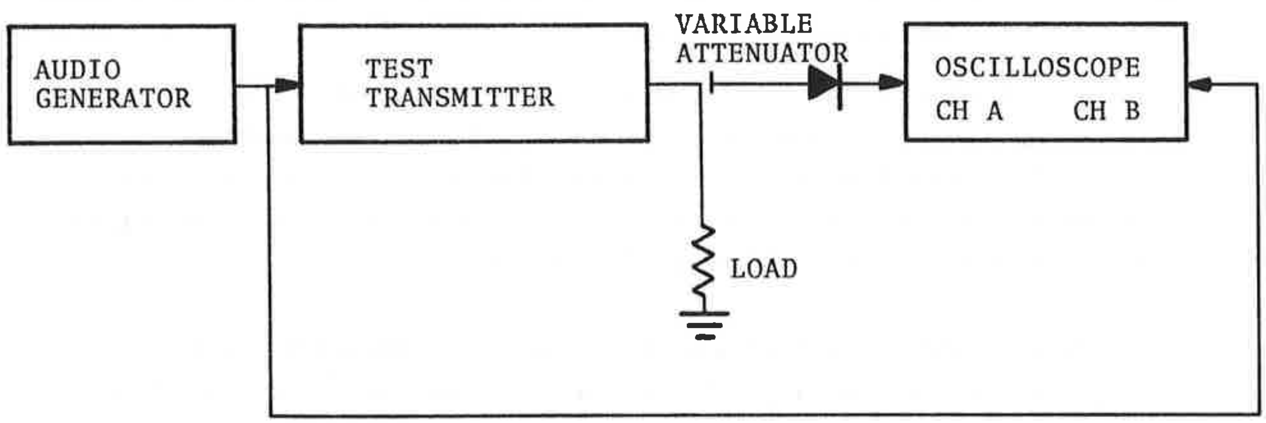


FIGURE 2-61. TRANSMITTER DIFFERENTIAL PHASE DELAY TEST SETUP

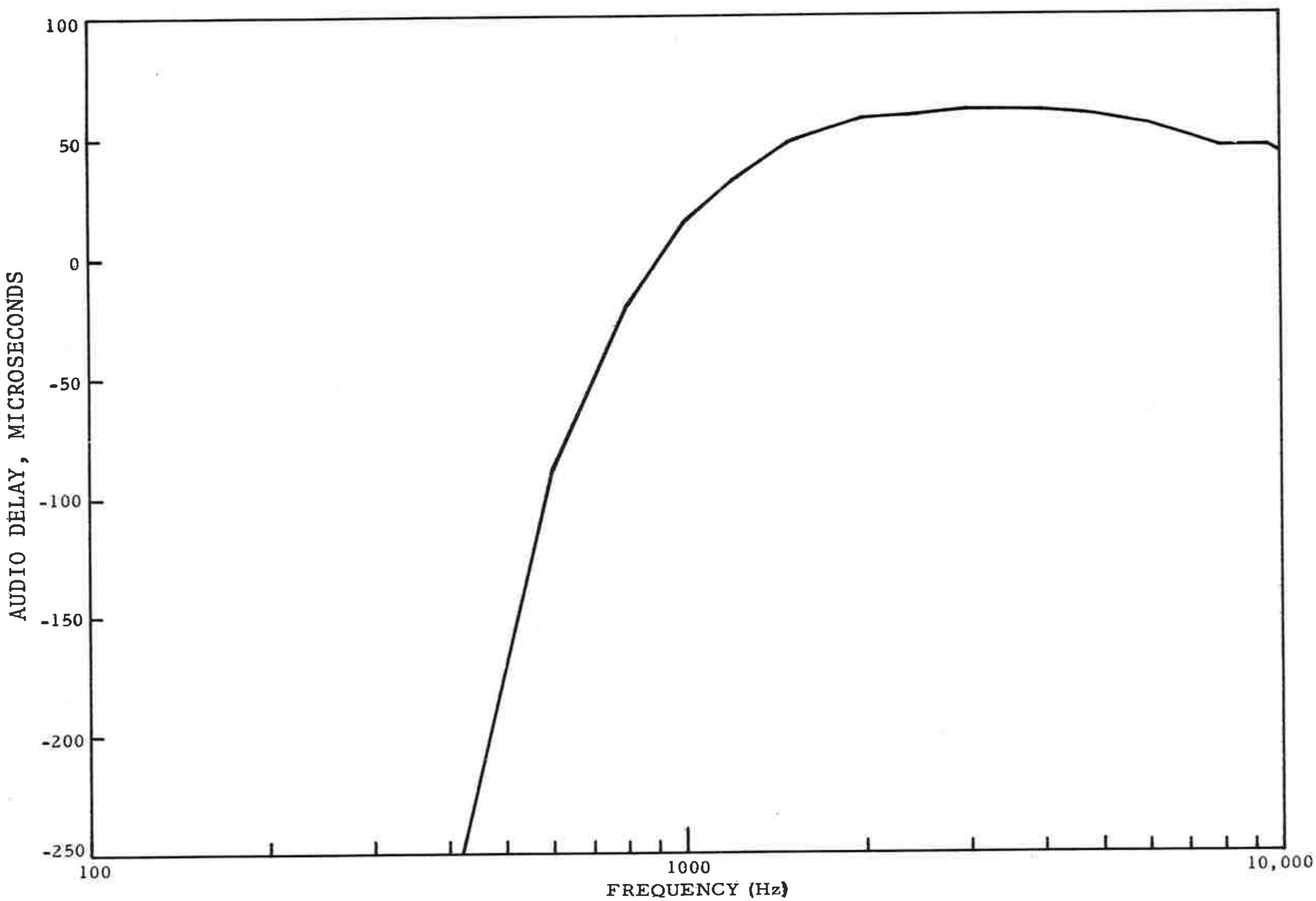


FIGURE 2-62. TRANSMITTER DATA LINK AUDIO DELAY, KING, MODEL KTR-9100A, SERIAL NO. 2103

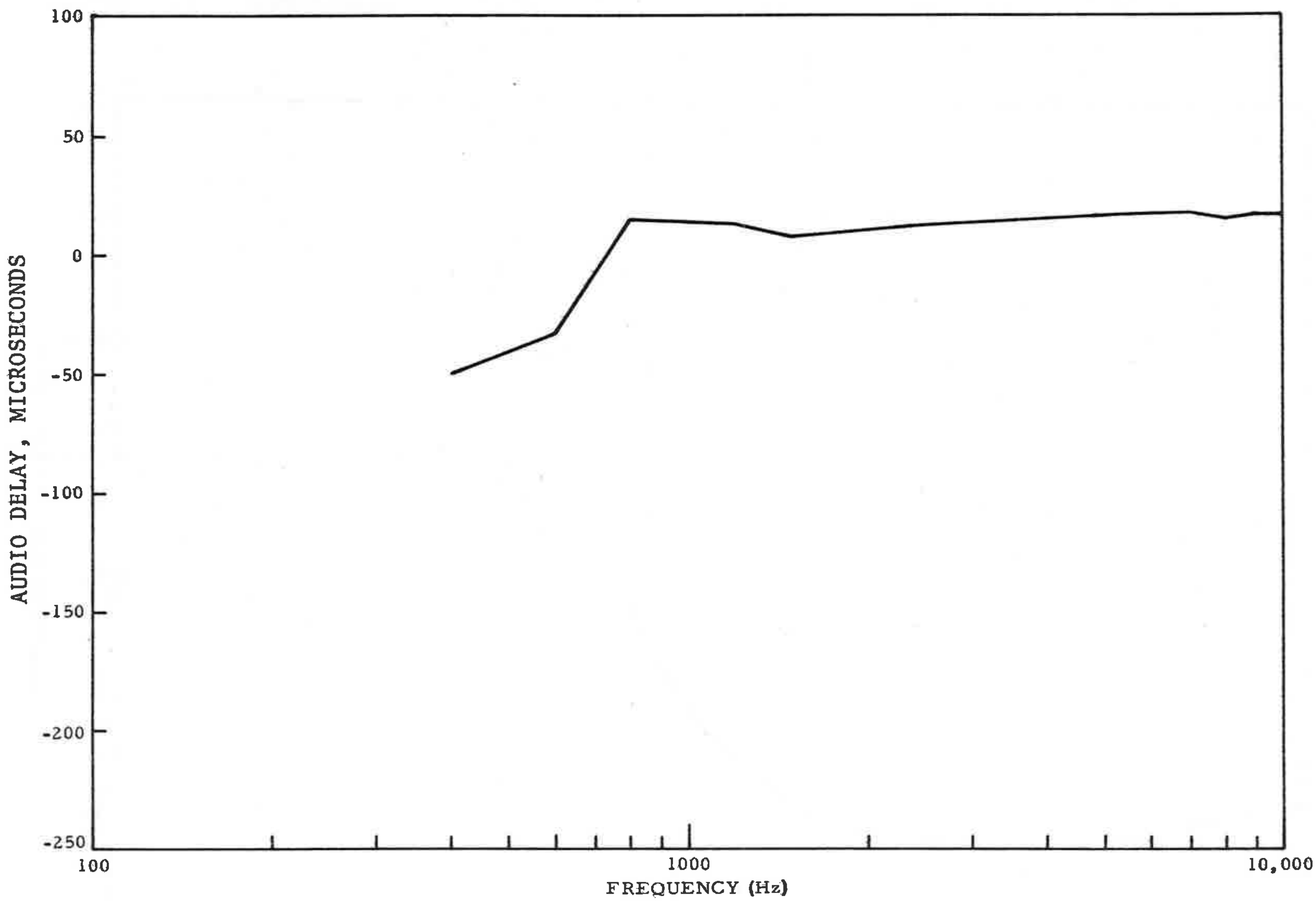


FIGURE 2-63. TRANSMITTER DATA LINK AUDIO DELAY, BENDIX, MODEL RTA-43A, SERIAL NO. 1050

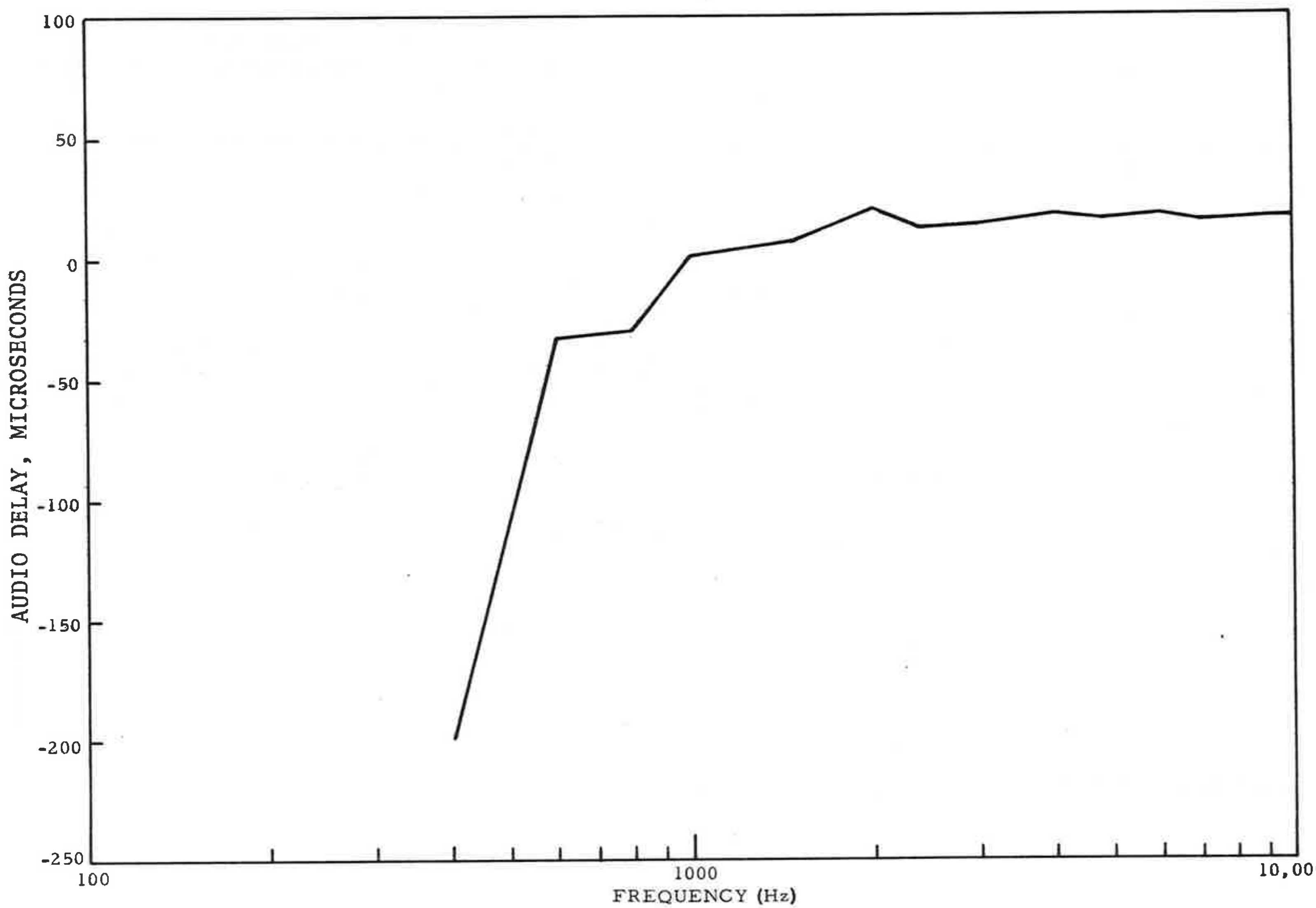


FIGURE 2-64. TRANSMITTER DATA LINK AUDIO DELAY, BENDIX, MODEL RTA-43A, SERIAL NO. 1027

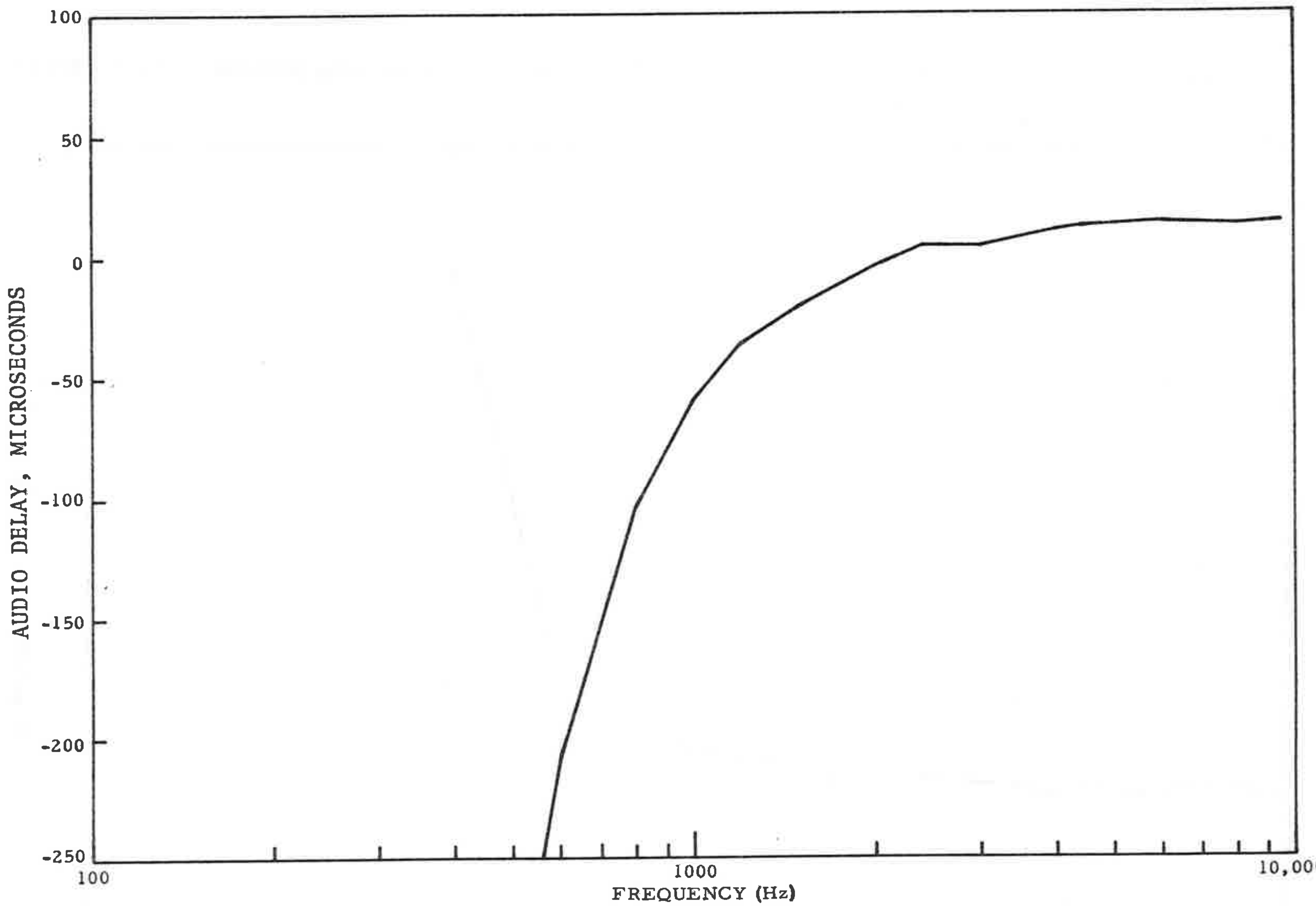


FIGURE 2-65. TRANSMITTER DATA LINK AUDIO DELAY, MODIFIED COLLINS, MODEL 618M-2B, SERIAL NO. 2996

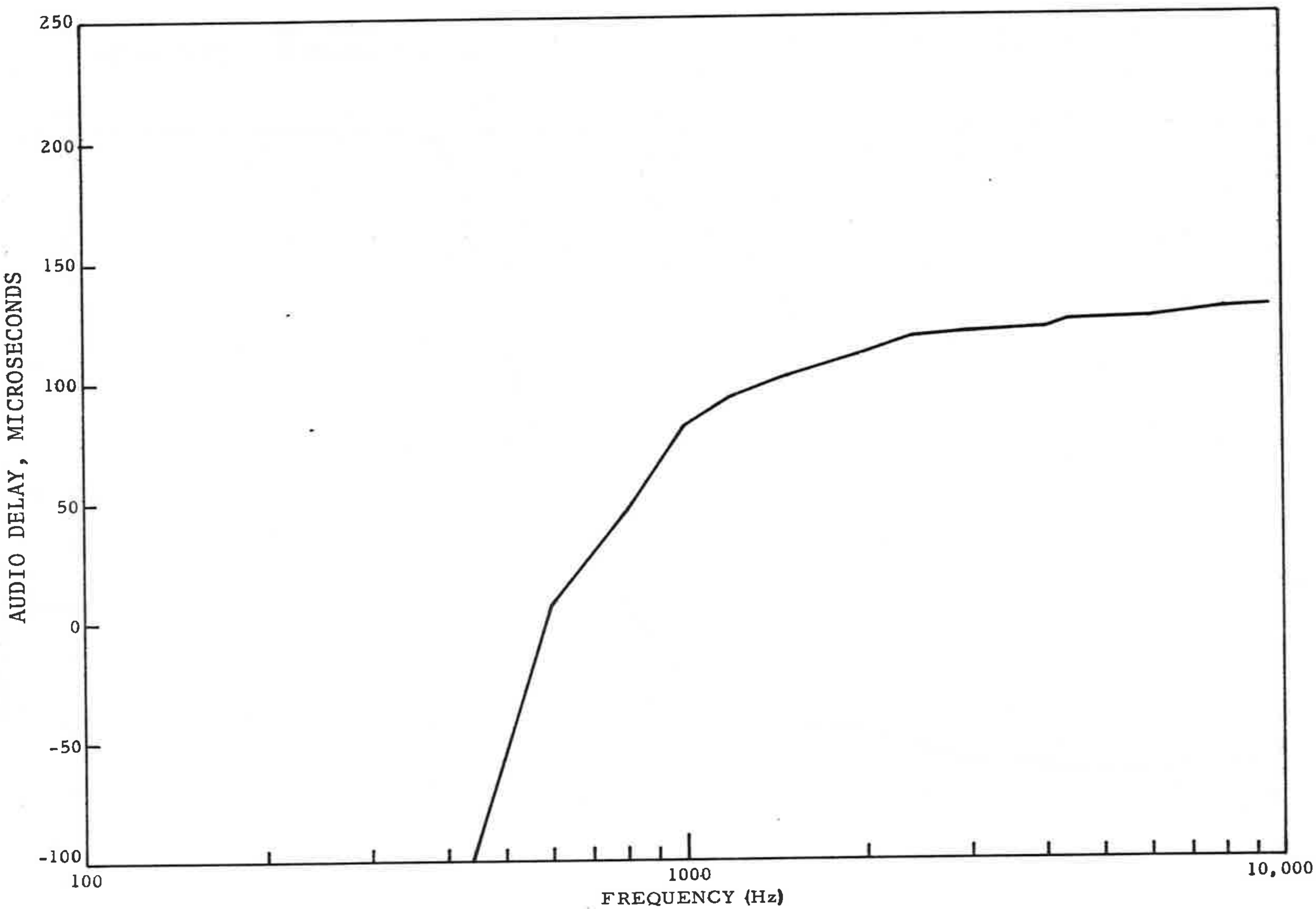


FIGURE 2-66. TRANSMITTER DATA LINK AUDIO DELAY, MODIFIED COLLINS, MODEL 618M-2B, SERIAL NO. 2971

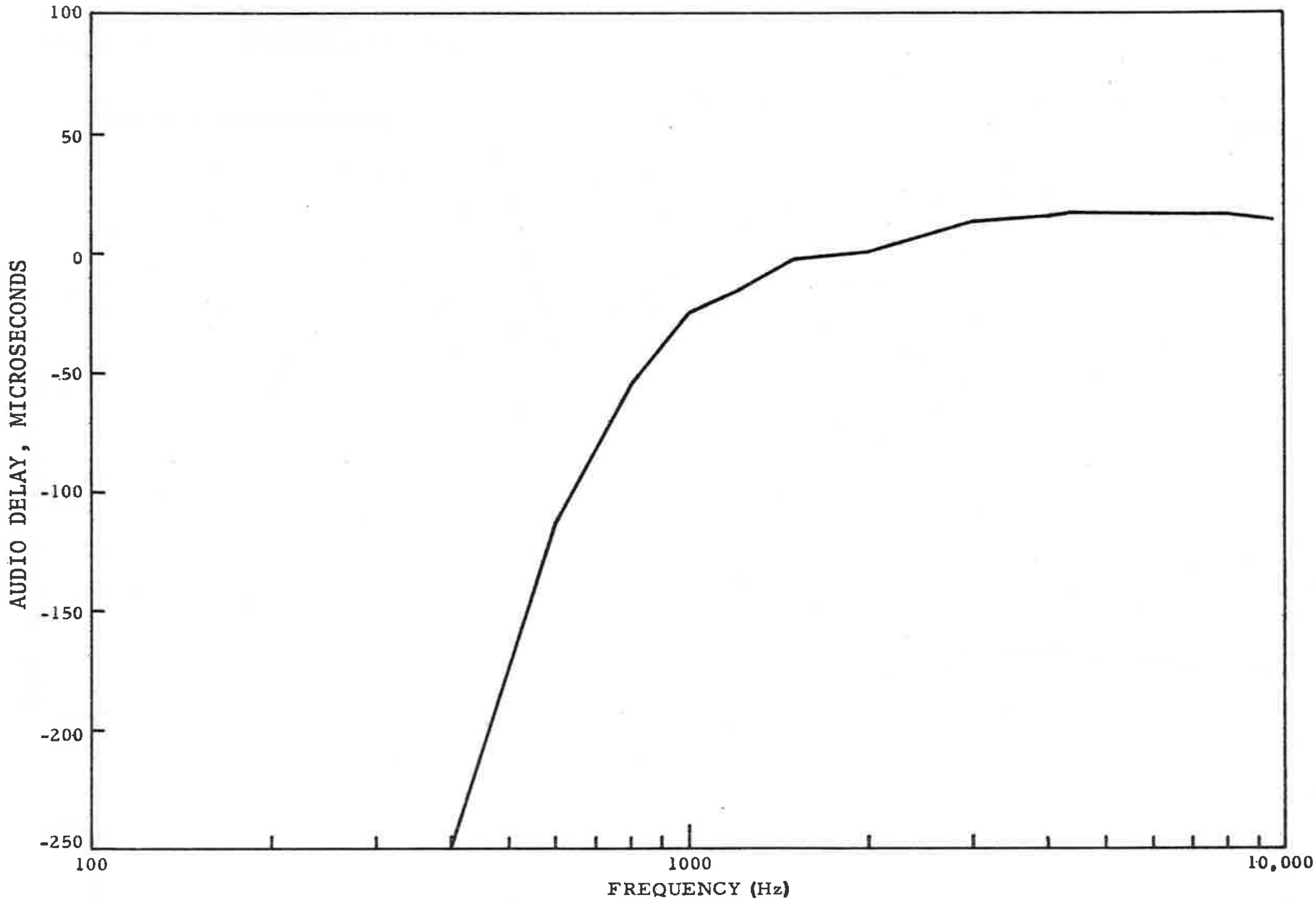


FIGURE 2-67. TRANSMITTER DATA LINK AUDIO DELAY, COLLINS, MODEL 618M-2B, SERIAL NO. 4868

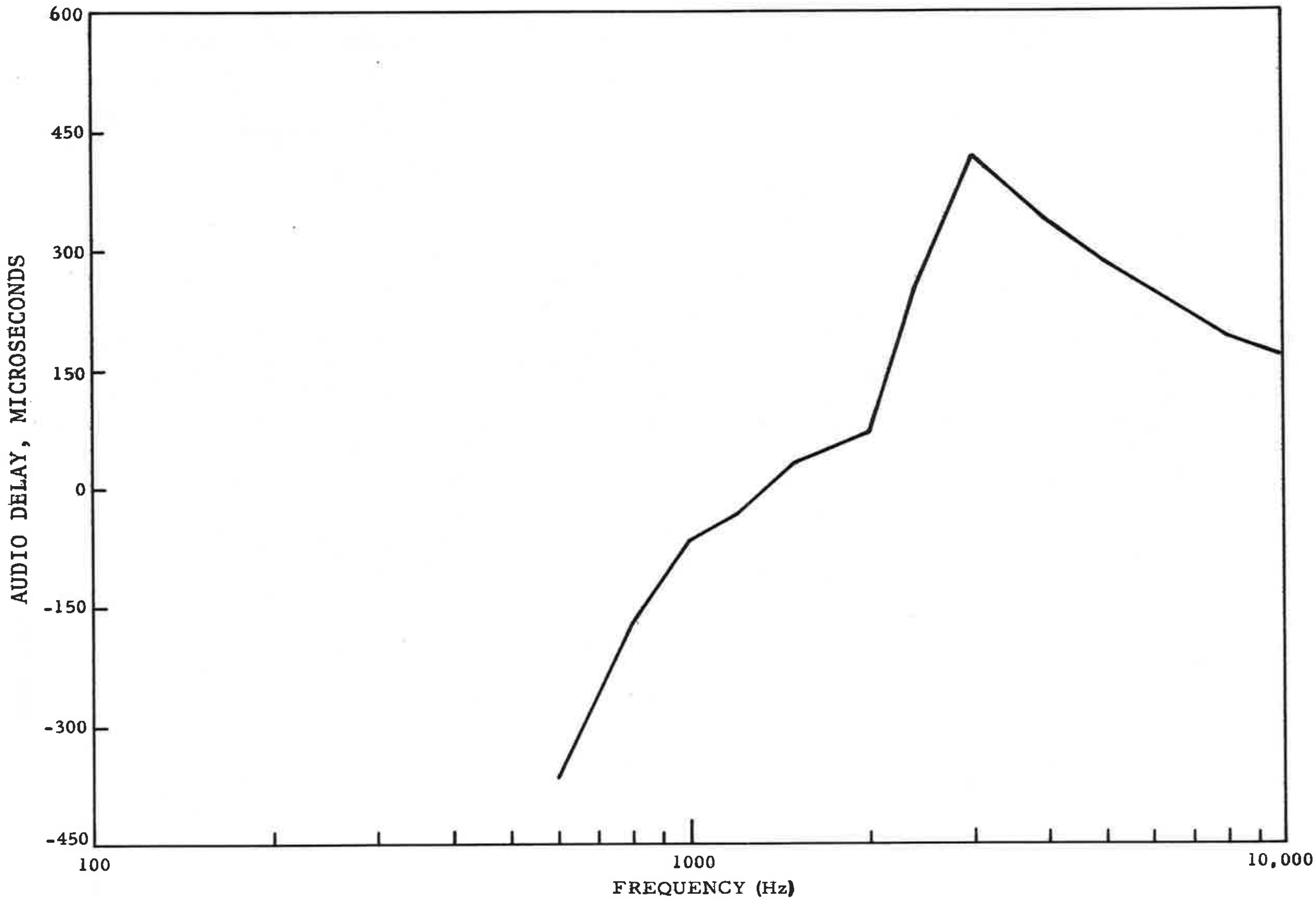


FIGURE 2-68. TRANSMITTER AUDIO DELAY, BUEC, MODEL FA-8191, SERIAL NO. 1

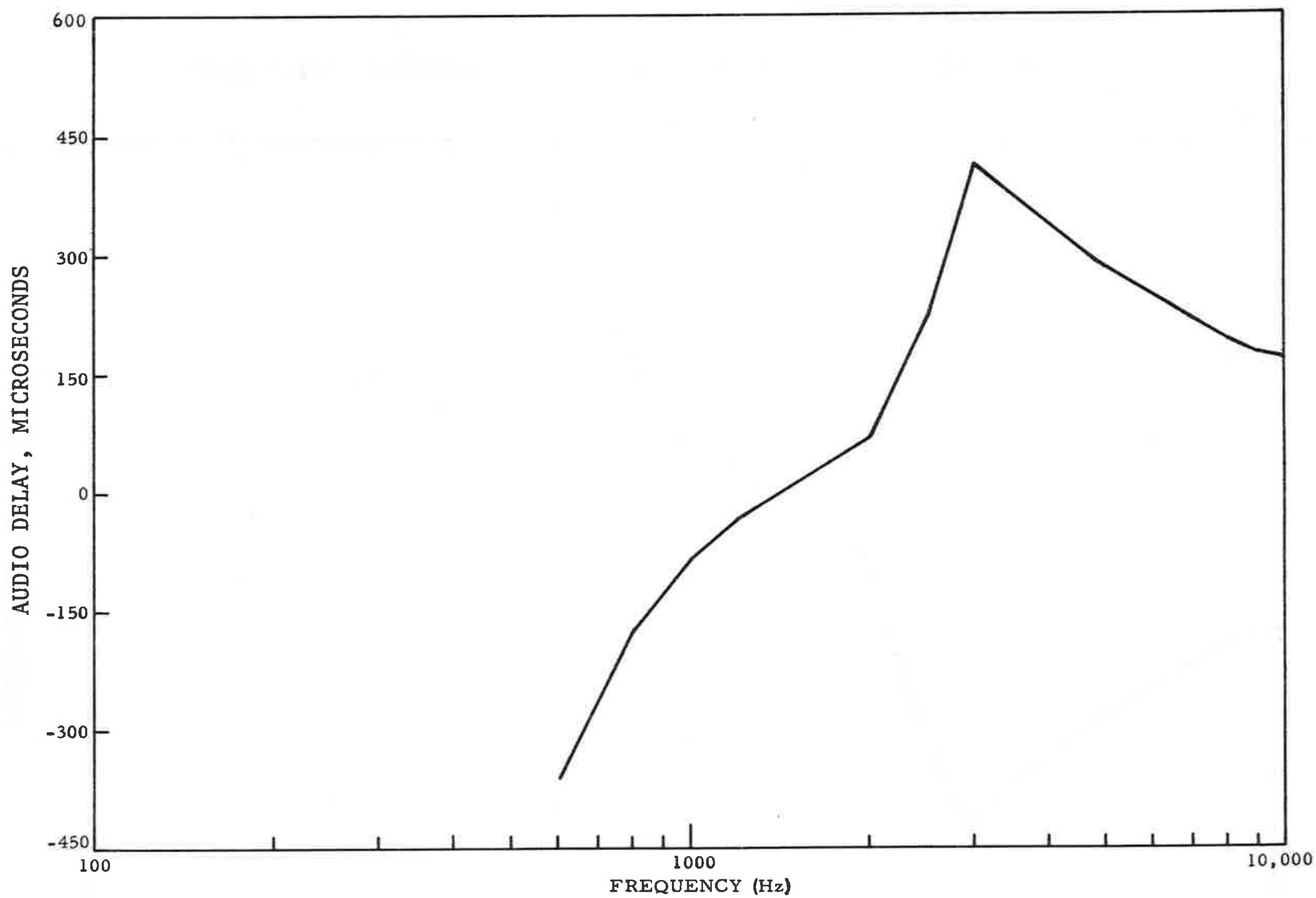


FIGURE 2-69. TRANSMITTER AUDIO DELAY, BUEC, MODEL FA-8191, SERIAL NO. 2

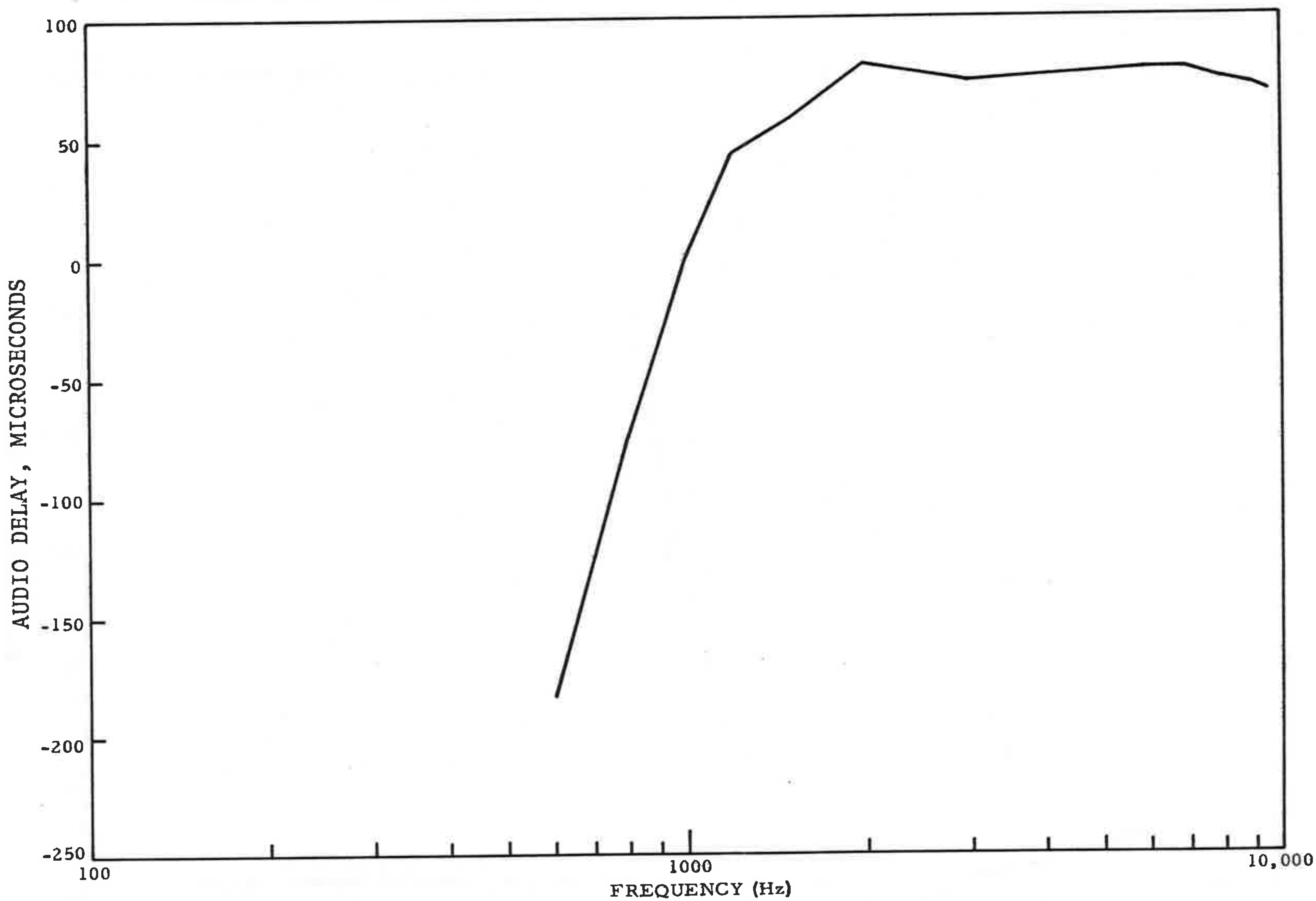


FIGURE 2-70. TRANSMITTER AUDIO DELAY, KING, MODEL KY-195B, SERIAL NO. 3145

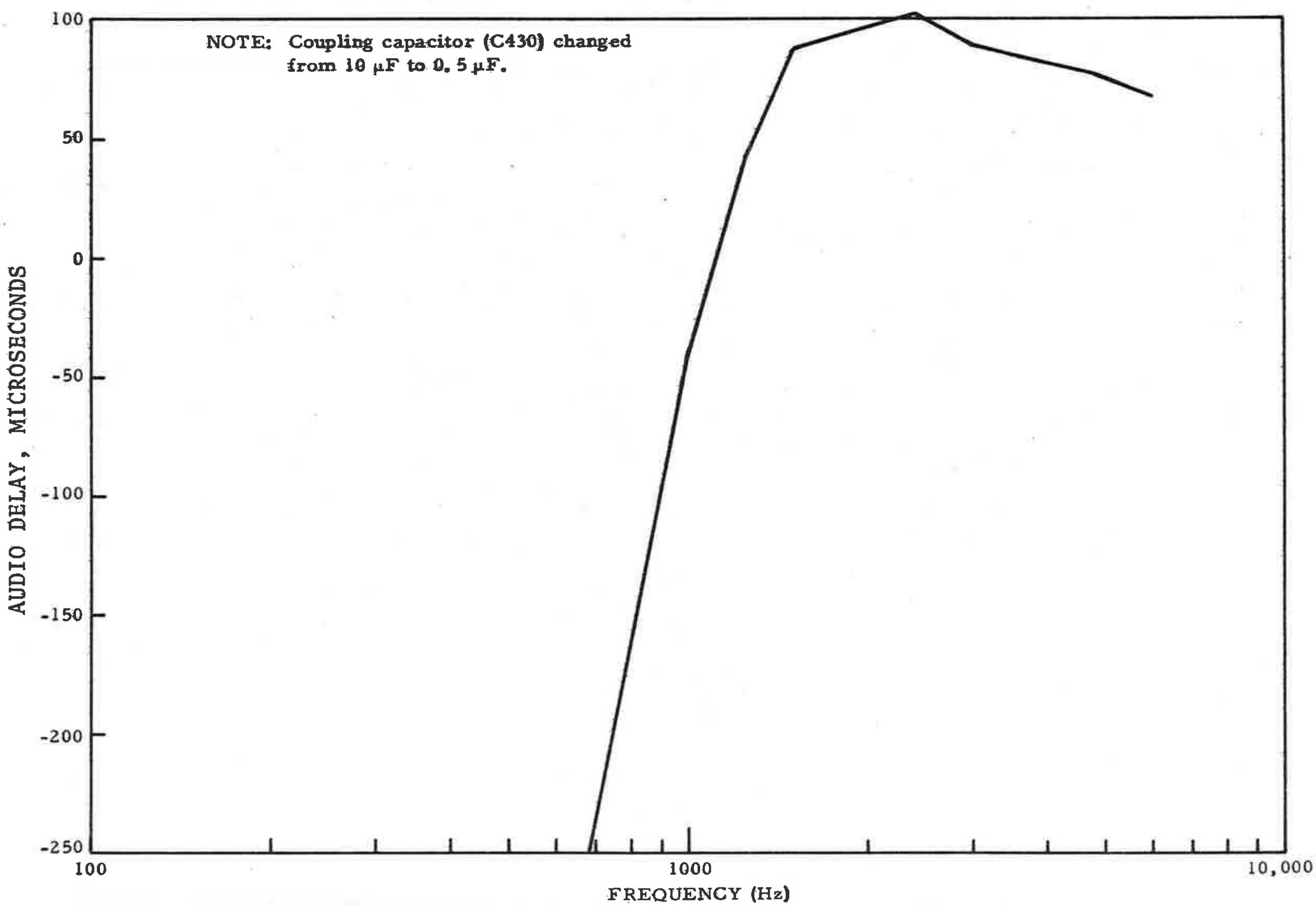


FIGURE 2-71. TRANSMITTER MODIFIED AUDIO DELAY, NARCO, MODEL COM-11A

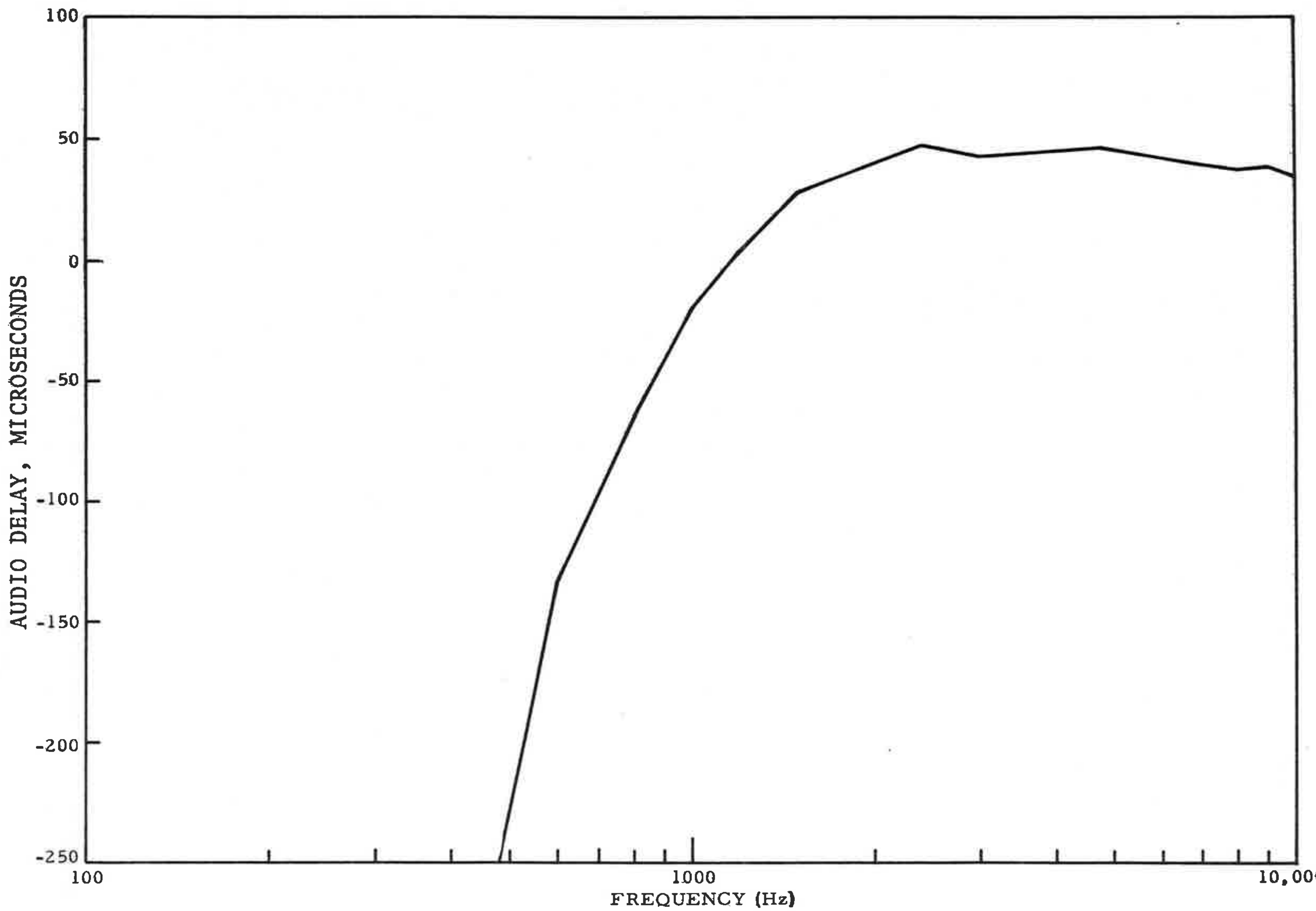


FIGURE 2-72. TRANSMITTER AUDIO DELAY, GENAVE, MODEL ALPHA-100/360, SERIAL NO. 43-22

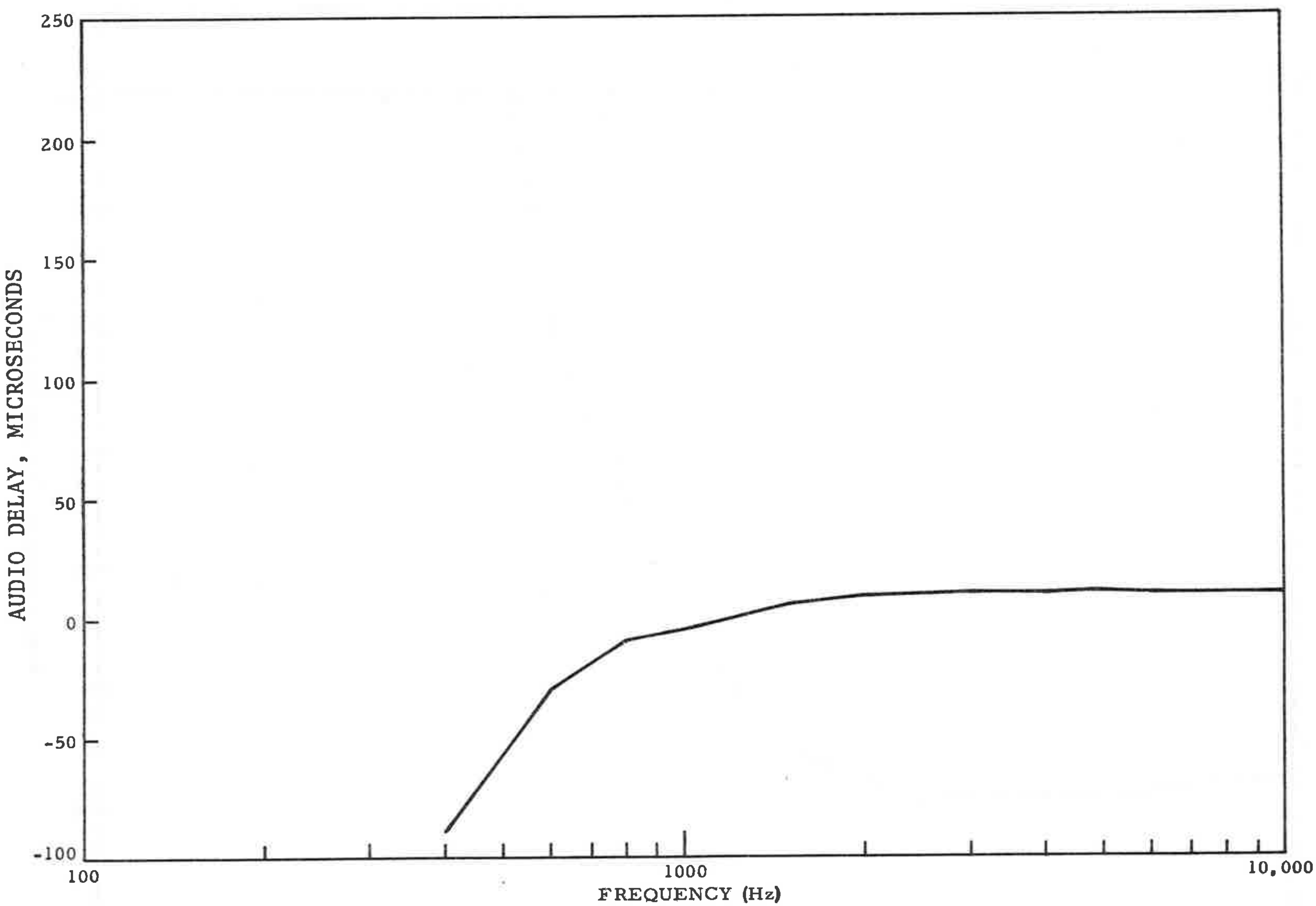


FIGURE 2-73. TRANSMITTER AUDIO DELAY, A/N, MODEL GRT-21, SERIAL NO. 379

2.2.1.2 Transmitter Audio Harmonic Distortion - Harmonic distortion measurements were made on the transmitters and transmitter portions of the equipment listed in Table 2-1. The test setup for these measurements is shown in Figure 2-74. Audio distortion for all transmitters tested was 8 percent or less. The FAA ATC equipment and the transceivers manufactured in accordance with ARINC characteristics exhibited less distortion than did the general aviation transceivers. Complete results of these measurements may be found in Reference 7.

2.2.1.3 Transmitter Frequency Stability - Frequency stability measurements were made on the transmitters and transmitter portions of the equipment listed in Table 2-1. The test setup for these measurements is shown in Figure 2-75. Results of these measurements are shown in Table 2-6. The worst case transmitter stability observed was 0.002 percent.

2.2.1.4 Transmitter Power Rise Time - Transmitter power rise time is one of the parameters of particular interest for data link application. This parameter, along with receiver AGC time, is a major contributor to data link system turnaround time. Transmitter power rise time measurements were made on the transmitter equipment listed in Table 2-1. The measurements were made for normal push-to-talk (PTT) keying and for data link (D/L) keying for those equipments so equipped. The test setup is shown in Figure 2-76. The results of these measurements are shown in Table 2-6 for PTT keying and for D/L keying. The measured values ranged from 450 μsec to 112 msec for PTT keying and from 2.7 msec to 20 msec for D/L keying.

2.2.1.5 Transmitter Spurious Emissions - Transmitter spurious emissions are defined as the energy in the rf output which lies outside the frequency interval of the assigned channel. Spurious emission measurements were made on the transmitters listed in Table 2-1. The test setup for these measurements is shown in Figure 2-77. The transmitter output was measured directly on the spectrum analyzer and the emissions identified by the signal generator setting. The results of these measurements are shown in Table 2-7.

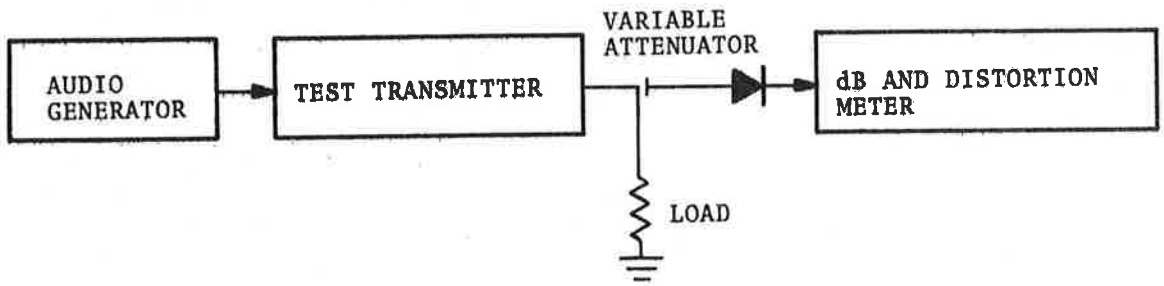


FIGURE 2-74. TRANSMITTER HARMONIC DISTORTION TEST SETUP

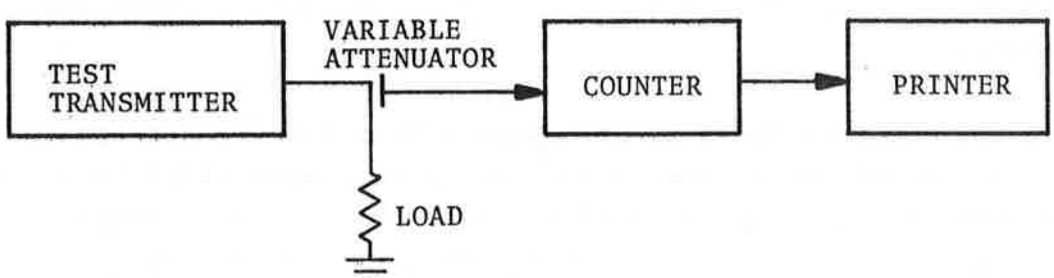


FIGURE 2-75. TRANSMITTER FREQUENCY STABILITY TEST SETUP

TABLE 2-6. TRANSMITTER CHARACTERISTICS

Manufactuer, Model, Serial No.	Transmitter Stability (percent)	Rise Time		Differential Delay	
		PTT	D/L	2400 μsec	4800 μsec
King, KTR-9100A, 2103	133 Hz Hi .00008	78 msec		13.0	0.5
Bendix, RTA-43A 1050	133 Hz Lo .0001	6 msec	15.5 msec	0.5	2.0
Bendix, RTA-43A 1027	260 Hz Lo .0002	3.4 msec	18 msec	4.5	2.0
Collins, 618M-2B, 2996	100 Hz Lo .00007	95 msec	20 msec	20.1	3.55
Collins, 618M-2B, 2971	Transmitter inoperative	100 msec	18 msec	8.19	1.05
Collins, 618M-2B, 4868	5 Hz Lo .00001	96 msec	2.7 msec	11.64	4.55
BUEC, FA-8191, 1	10 Hz Hi .000007	112 msec		141.49	21.5
BUEC, FA-8191, 2	88 Hz Hi .00007	112 msec		126.5	36.5
King, KY-195B, 3145*	2300 Hz Lo .002	10 msec		17.0	0.5
NARCO, COM-11A *	1275 Hz Lo .001	14 msec		29.5	13.0
GENAVE, ALPHA-100/360	1800 Hz Lo .00026	23 msec		22.0	0.5
A/N GRT-21, 379	1400 Hz Hi .0005	450 μsec		4.5	1.0
TV-36,* 1349	1900 Hz Hi .00005	14 msec		0.46	0.27

*Modified Audio PTT Push-to-Talk D/L Data Link

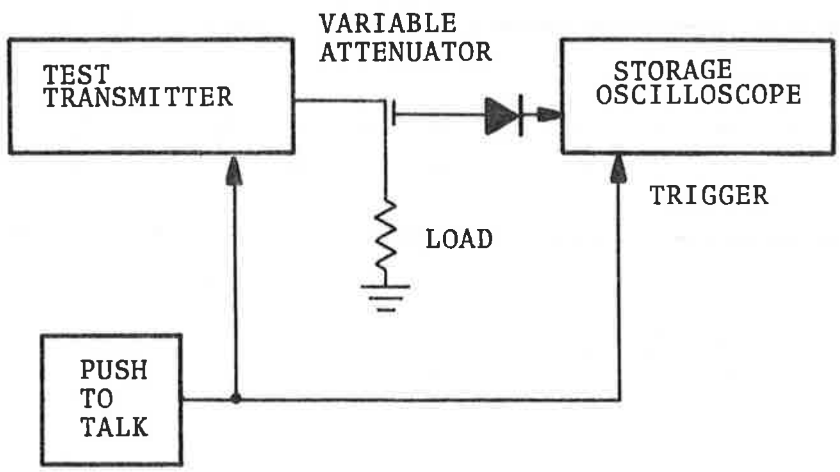


FIGURE 2-76. TRANSMITTER POWER RISE TIME TEST SETUP

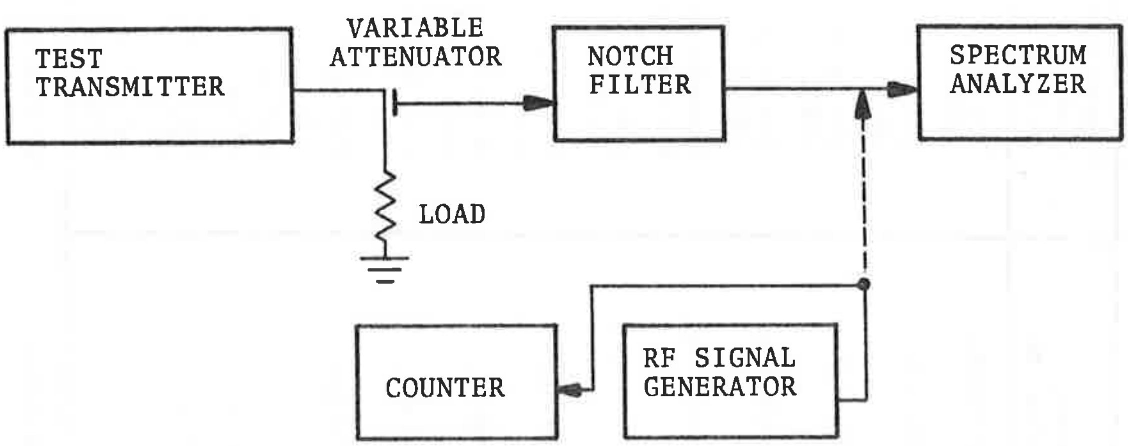


FIGURE 2-77. TRANSMITTER SPURIOUS EMISSION TEST SETUP

TABLE 2-7. TRANSMITTER SPURIOUS EMISSIONS

Transmitter Manufacturer, Model, Serial No.	MHz	dB	Transmitter Manufacturer, Model, Serial No.	MHz	dB
King, KTR-9100A, 2103	125.0 250.0 375.0	0 -58 -76	NARCO, COM-11A	127.0 148.0 254.0	0 -90 -78
Bendix, RTA-43A, 1050	127.0 254.0 381.0	0 -53 -47			
Bendix, RTA-43A, 1027	127.0 254.0 381.0	0 -52 -58	GENAVE, ALPHA-100/360	128.0 106.6 117.6 138.5 149.5 256.0	0 -80 -65 -65 -74 -40
Collins, 618M-2B, 2996	127.0 254.0	0 -62			
Collins, 618M-2B, 2971	Transmitter inoperative				
Collins, 618M-2B, 4868	127.0 254.0 381.0	0 -60 -75			
BUEC, FA-8191, 1	127.0 254.0 381.0	0 -57 -65			
BUEC, FA-8191, 2	127.0 254.0 381.0	0 -58 -65	A/N, GRT-21, 379	120.5 241.0 361.5	0 -84 -85
King, KY-195B, 3145	127.0 63.5 192.0 254.0	0 -93 -90 -81	TV-36, 1349		-80

2.2.2 Summary of Transmitter and Receiver Test Results

The performance characteristics of a variety of VHF airborne transceivers, ground transmitters, and ground receivers were determined for data link applications at data rates of 2400 and 4800 bits per second. The airborne transceivers included those of the ARINC type and those of the general aviation type. The ground transmitters and receivers tested were those that are in current use by the FAA in air traffic control facilities. The performance characteristics of the ARINC class of transceivers appear better suited to data link applications than the general aviation class of transceivers. However, it was found that with simple modifications the performance characteristics of the general aviation type transceivers can be made compatible with data link requirements. The primary ground transmitter and receiver in current use by the FAA appear to be well suited to data link applications.

The performance characteristics of the equipment tested within each equipment user class showed considerable variation. The effect of these performance variations on expected data link performance is demonstrated in section 2.4.

2.3 MSK MODEM TESTS

Laboratory tests were performed on the McDonnell-Douglas MSK modems, model MDL-510, in order to determine the MSK performance in controlled environments of interest. The tests were performed at data rates of 2400 and 4800 bits per second. The modems were tested back-to-back at baseband in a Gaussian noise environment, back-to-back at RF in a Gaussian noise environment, and through a simulated RF channel environment which included Gaussian noise and multipath effects.

The above tests were performed in order to determine actual modem performance relative to theoretical optimum modem performance in the noisy and multipath environments that would be encountered in operational use in flight and on airport surfaces.

2.3.1 Minimum Shift Keying (MSK) Modulation

As stated in Section 1, only the MSK modulation technique was to be considered for this project. This choice of modulation technique was dictated, in part, by a desire for commonality (where possible) with the ARINC Data Link System design in existence at the time this project was initiated. A discussion of this modulation technique is worthwhile at this point in order to gain a firm understanding of the material presented in the remainder of this report.

MSK modulation is one of several modulation techniques which are compatible with the communication equipment constraints imposed by a VHF data link system designed to function in the existing Air Mobile Frequency Band as used by Air Traffic Control. Specifically, the MSK technique can provide nearly optimum (coherent-antipodal) performance under average power constrained conditions. Moreover, the bandwidth of the MSK signal is less than other modulation techniques that will provide similar high performance such as four-phase differential phase-shift keying (4PSK) and split-phase (Manchester) modulation.

2.3.1.1 General Description - Minimum-shift keying (MSK) may be described in the following manner. In each baud, one of four signals will be transmitted. The signals $\pm \cos \pi t/T$ correspond to one of the binary levels, while the signals $\pm \cos 2\pi t/T$ correspond to the other binary level. The bit rate is $1/T$. In either case, the polarity of the transmitted signal is chosen so that the waveform will be continuous at the boundary between adjacent bauds. Thus the modulation is equivalent to continuous-phase frequency-shift keying (FSK) with the mark and space frequencies chosen to give either a whole cycle or a half cycle of sinusoid over the bit interval.

A slight variation on the scheme described above is also possible. In this variation the signaling elements are $\pm \sin \pi t/T$ and $\pm \sin 2\pi t/T$. The performance of these two approaches is identical, but there is a slight difference between the resulting spectra, as shown in Figure 2-78. In particular, the baseband

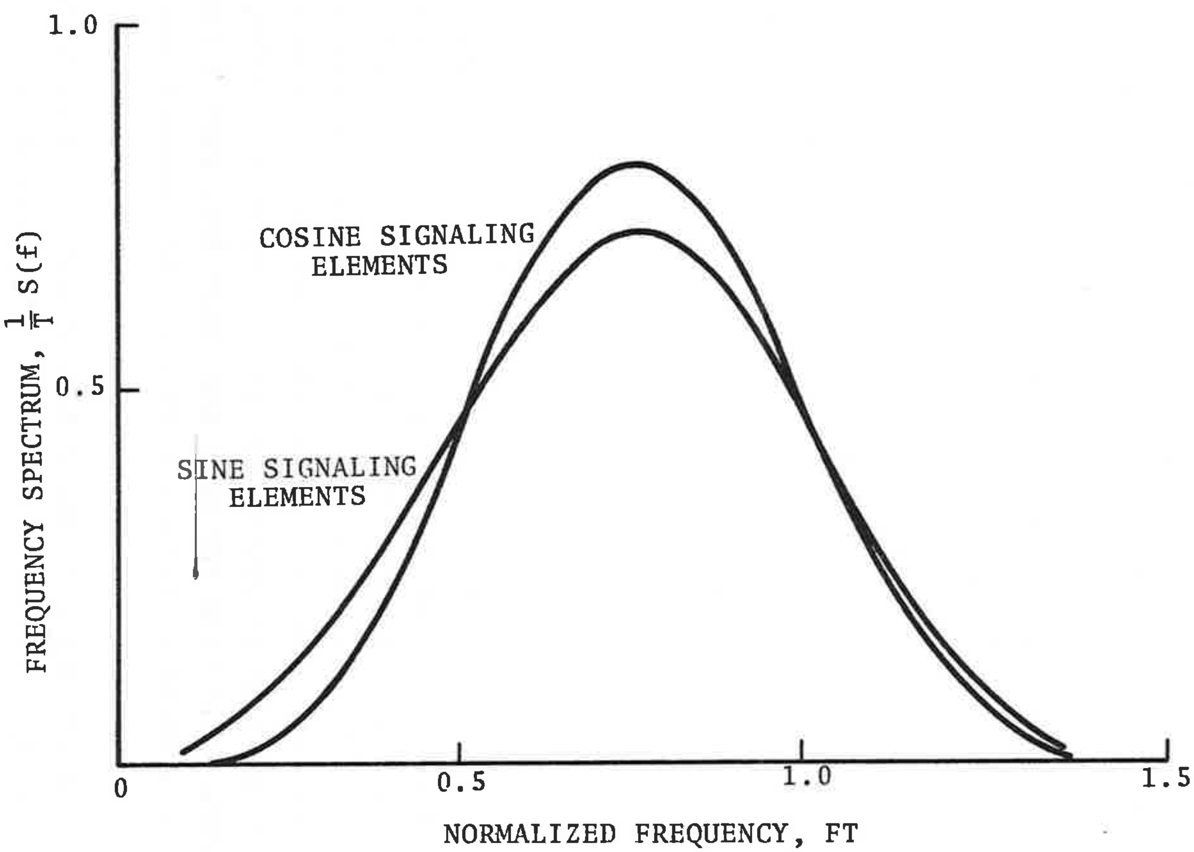


FIGURE 2-78. SPECTRUM OF MINIMUM-SHIFT KEYING

spectrum which results using the cosine signal elements is narrower and it has lower side-lobe levels.* The sine signaling technique is specified for Data Link applications. But, the designation of marks (ones) and spaces (zeros) is different than that given above. Designation of marks as the transmission of $\pm$ sin $\pi t/T$ and spaces as $\pm$ sin $2\pi t/T$ may be interpreted directly as a straightforward FSK system in which the two signaling frequencies are separated by $\Delta f = 1/2$ T. Based on the above interpretation, a receiver can be implemented which employs two matched filters, one tuned to the mark frequency and the other tuned to the space frequency to demodulate the digital data. Alternatively, an FM discriminator can be used for demodulation. In either case, the performance achieved would be relatively poor. Optimum orthogonal FSK performance is achieved with the matched filter approach if, and only if, the separation between mark and space frequencies is an integer multiple of the bit rate (i.e., N/T when N = 1,2,3). Optimum incoherent detection is achieved when the frequency separation is approximately 0.7/T.** Figure 2-79 shows the performances of a variety of signaling systems at baseband.*** Case 1 corresponds to ideal coherent PSK, Case 4 corresponds to discriminator detected FSK with $\Delta f = 1/2$ T, and Case 5 corresponds to discriminator detected FSK with $\Delta f = 0.35/T$. It is clear from Figure 2-79 that if the MSK signals are detected using incoherent FSK techniques, the performance obtained will be inferior to the performance achievable by ideal coherent PSK (coherent binary AM at baseband) by at least 3 dB. An interpretation of MSK in a different light is given in the following section.

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*W.R. Bennet and S.O. Rice, "Spectral Density and Autocorrelation Function Associated With Binary Frequency-Shift Keying," Bell System Technical Journal, 44 (September 1965), 2355-2385.

**Vladimir A. Kotelnikov, A Theory of Optimum Noise Immunity, (R.A. Silverman, trs.) New York: Dover, 1960.

***From William C. Jakes et al., Microwave Mobile Communications, New York: John Wiley and Sons, 1974.

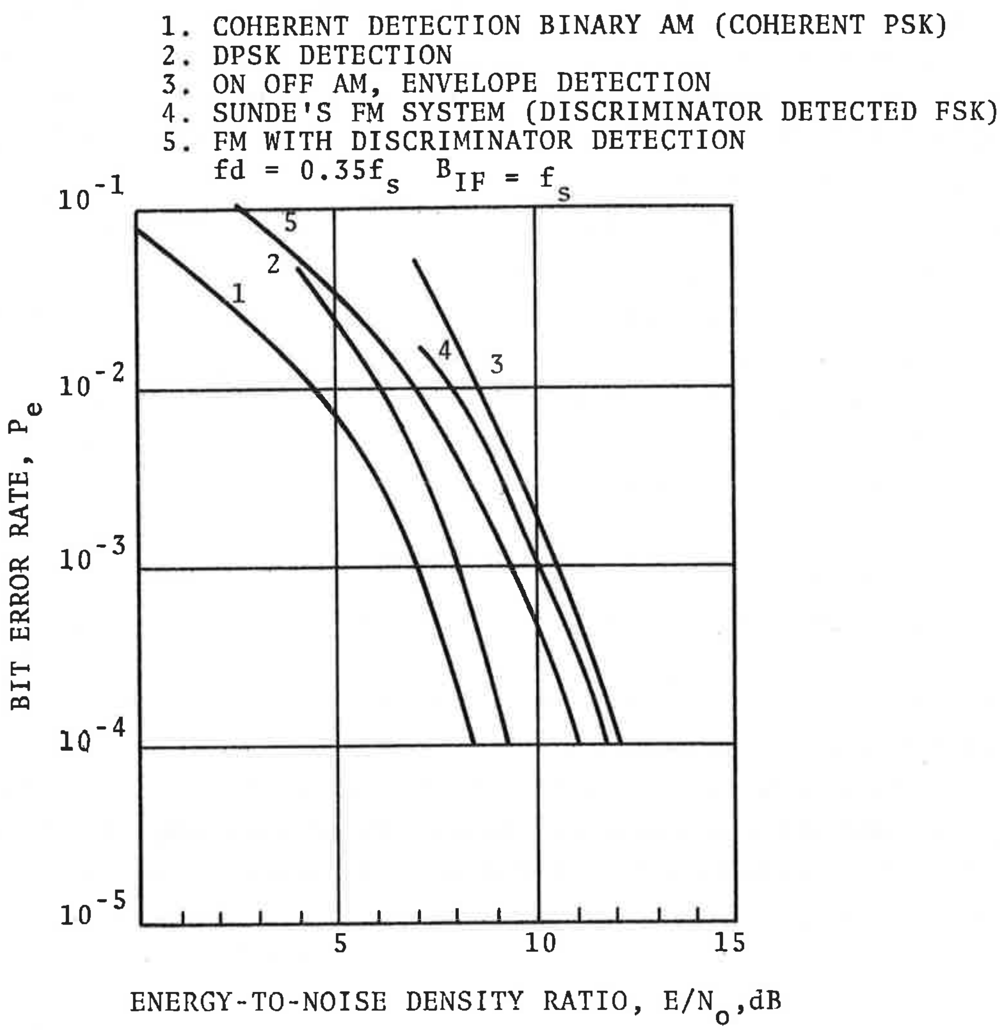


FIGURE 2-79. ERROR PERFORMANCE OF SEVERAL DATA TRANSMISSION TECHNIQUES AT BASEBAND (from Jakes, Microwave Mobile Communications, op. cit.)

2.3.1.2 Coherent Signaling Model - To realize the full performance potential of minimum-shift keying it is necessary to realize that the minimum-shift keyed waveform may be resolved into two orthogonal signals. These signals have been phase-reversal modulated at one-half the bit rate, with alternate data bits modulating each signal separately. The signals are out of phase by one bit interval. At the receiver, separate matched filters may be implemented for each component signal. In this way each bit may be detected with the ideal error probability associated with coherent PSK performance. This coherent signal generation process is illustrated in Figure 2-80. The formulation is as follows: the input data stream is divided into two staggered bit streams, a(t), and b(t). Note a mark (1) corresponds to a(t) or b(t) = +1. Similarly, a space (0) corresponds to a(t) or b(t) = -1. The transmitted MSK waveform is of the form

$$s(t) = a(t) \sin (\pi t/2T) \cos (3\pi t/2T) + b(t) \cos (\pi t/2T) \sin (3\pi t/2T) \quad (2\text{-}2)$$

where: $a(t) = \pm 1$

$b(t) = \pm 1$

Table 2-8 shows the relationship between a(t), b(t) and s(t)

TABLE 2-8. MSK GENERATION

a(t)	b(t)	s(t)
-1 (space)	-1	$-\sin \pi 2t/T$
+1 (mark)	-1	$-\sin \pi t/T$
-1	+1	$+\sin \pi t/T$
+1	+1	$+\sin 2\pi t/T$

Figure 2-80 shows the sequence of operations leading to the generation of the MSK waveform. The data streams $a(t) = \pm 1$ and $b(t) = \pm 1$ modulate the two subcarriers, $\sin (\pi t/2T)$ and $\cos (\pi t/T)$, respectively. The resulting baseband waveforms, $a(t) \sin (\pi t/2T)$

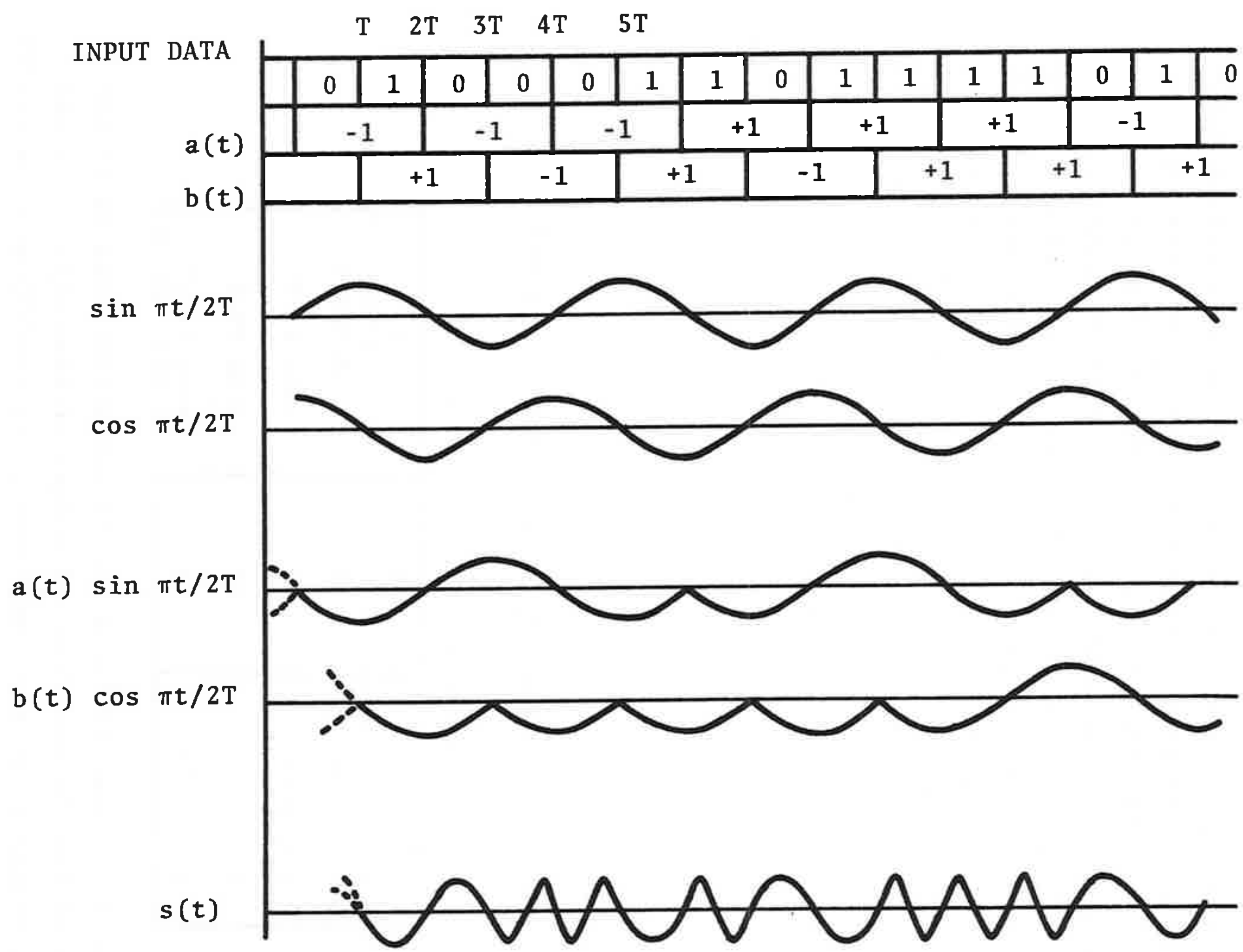


FIGURE 2-80. MSK WAVEFORM GENERATION

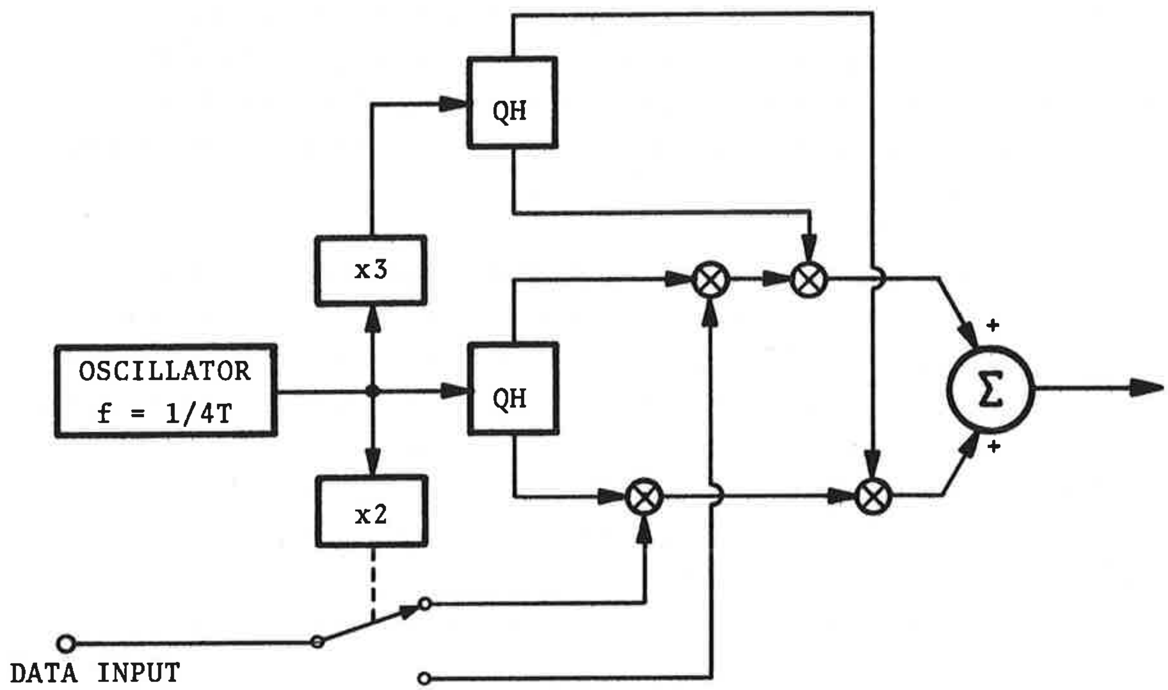
and b(t) cos ($\pi t/2T$) then modulate the quadrature carriers, cos ($3\pi t/2T$) and sin ($3\pi t/2T$), respectively, to form the MSK output, s(t), also shown in Figure 2-80.

Note that the resulting MSK signal structure corresponds exactly in form to the Data Link Structure. Namely, a mark is denoted by a positive-going slope at the end of the baud (bit interval), and a space is denoted by a negative-going slope at the end of the baud.

2.3.1.3 Optimum Coherent Detection of MSK - Optimum detection of the MSK waveform must proceed as follows. The two baseband waveforms must be extracted by synchronous demodulation. Thus, the first step in the detection process is the synthesis of a coherent demodulation reference from the received signal. It should be emphasized that except for the sinusoidal weighting of the bits (e.g., a(t) sin $\pi t/2T$), the MSK signal is exactly the same as Offset 4PSK. Thus, the techniques similar to those employed for 4PSK, a Costas or squaring loop, may be employed for MSK carrier extraction and bit detection.

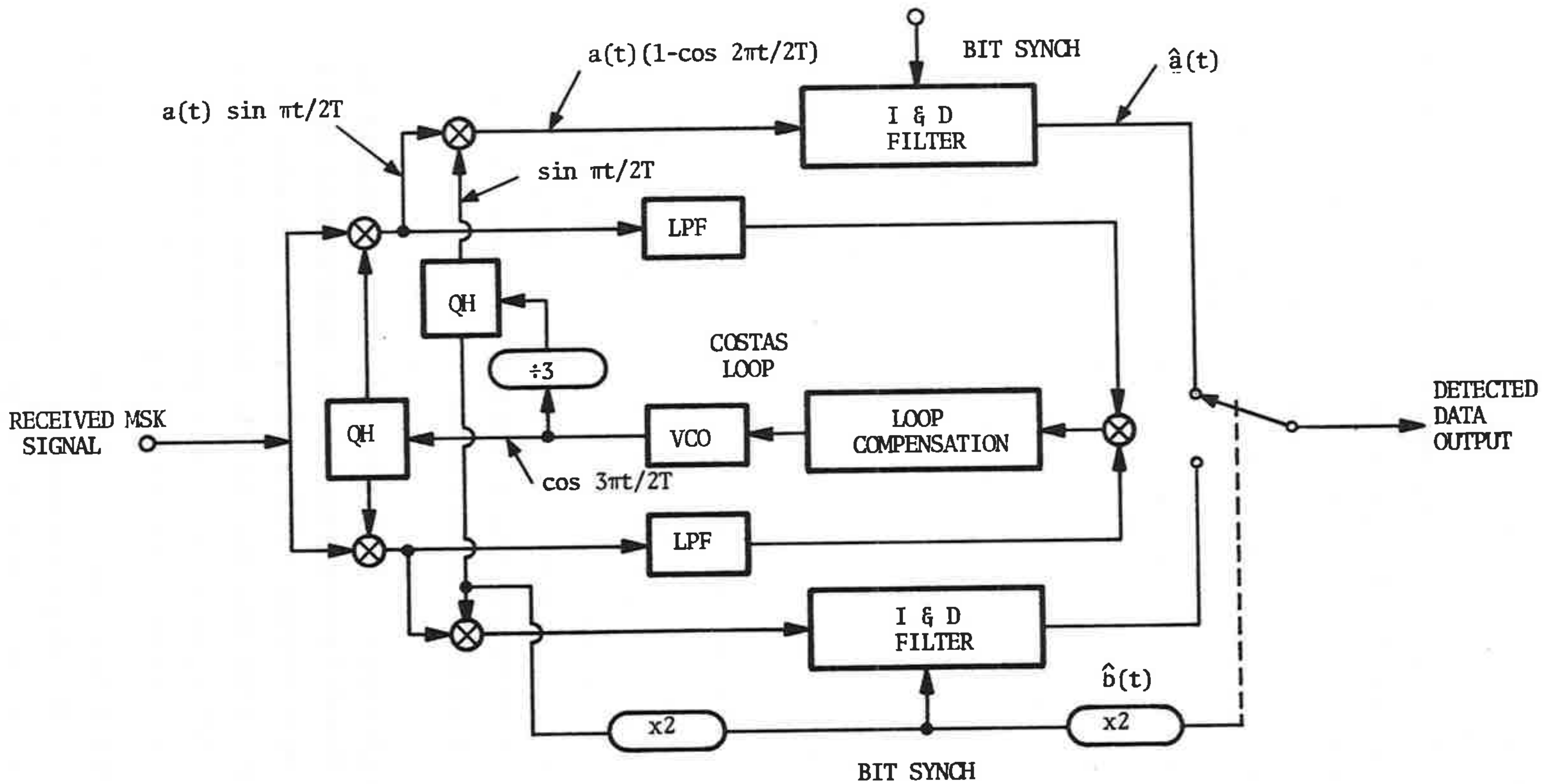
After synchronous demodulation, the two baseband signals must be matched filtered to optimally extract the data streams. In the case of PSK this is accomplished by integrate-and-dump (I & D) filters which constitute matched filters for the PSK's rectangular bit shape. The I & D filtering can be augmented for MSK by premultiplying the demodulated baseband signals by sin $\pi t/2T$ or cos $\pi t/2T$, as appropriate. These weighting functions can be synthesized from the coherent carrier reference or they may be derived using a separate phase locked loop designed for this purpose. Bit synchronization is directly derived by doubling sin $\pi t/2T$ to produce a component at the bit rate of a(t) and b(t), and doubling again to produce a component at the output bit rate.

Block diagrams of a generalized MSK generator and receiver are shown in Figures 2-81 and 2-82. The receiver shown employs a Costas loop to extract the MSK carrier at f = 3/4T. The VCO output, which is the estimate of the received MSK carrier is divided by a factor of 3 to produce an estimate of the MSK subcarrier at



NOTE: QH = QUADRATURE HYBRID
xk = TIMES k FREQUENCY MULTIPLIER
ALL MIXERS ARE BALANCED MODULATORS

FIGURE 2-81. MSK GENERATOR BLOCK DIAGRAM



NOTE: QH = QUADRATURE HYBRID
VCO = VOLTAGE-CONTROLLED OSCILLATOR
xk = FREQUENCY MULTIPLIED BY k
LPF = LOW-PASS FILTER
I&D = INTEGRATE AND DUMP
ALL MIXERS ARE BALANCED MODULATORS

FIGURE 2-82. MSK RECEIVER BLOCK DIAGRAM

$f = 1/4T$. In-phase and quadrature components at the derived sub-carrier frequency are used to weight the demodulated baseband signals. This produces a low-pass component equal to a(t) in one arm (the upper arm) and b(t) in the other arm. To illustrate this operation, assume that the demodulated baseband component in the upper arm is $a(t) \sin \pi t/2T$ and the corresponding baseband component in the lower arm is $b(t) \cos \pi t/2T$. Multiplication by $\sin \pi t/2T$ produces a signal of the form $a(t) - a(t) \cos 2\pi t/2T$ at the input to the I & D filter. The I & D filter integrates over an interval 2T so there is no response to the second term, $a(t) \cos 2\pi t/2T$. It integrates to zero. More important, the I & D filter constitutes a matched filter for the first term, a(t), so the I & D filter output is an optimum estimate of a(t), which is the desired result. A similar operation is carried out in the lower arm to derive an optimum estimate of b(t). These estimates are provided to a switch which is synchronized to the output bit rate to interleave a(t) and b(t), thus producing an output bit stream.

The receiver of Figure 2-82 is simplified in that bit-synch phasing and subcarrier ambiguity resolution processes are not shown. For example, dividing the carrier estimate by 3 does not necessarily produce the subcarrier estimate ($\sin \pi t/2T$) with the correct phase. The ambiguities in the subcarrier and the bit-synch phasing may be resolved during the synch preamble (prekey plus synch characters) which provides data used to initialize the frequency synthesis hardware. Alternatively, a separate phase-locked loop may be implemented to extract the subcarrier unambiguously.

2.3.1.4 Intersymbol Interference - Filtering of the MSK signal at RF or at baseband before demodulation results in intersymbol interference. That is, the signal energy from a given bit interval is spread over succeeding bit intervals due to the transient responses of the filters. Thus, energy from a given bit may cause interference to the detection of several succeeding bits.

The intersymbol interference causes a degradation in bit-error performance. The extent of the degradation depends on the exact characteristics of filters at the transmitter and receiver which operate on the MSK signal. The cascade filter characteristics may be defined in terms of an amplitude and phase response or, equivalently, a complex impulse response. The response of the system to the transmission of a bit is just the convolution of the bit waveform (i.e., sin $\pi t/2T$), with the complex impulse response of the system's filters. The intersymbol interference at any given time is the superposition of the response of the system to all preceding bits. Thus, it is a random variable since the data stream is assumed to be random. The effect of intersymbol interference can be determined via simulation using Monte Carlo methods. The degradation can also be determined analytically. But, in that case, the results achieved are in the form of bounds on the expected degradation. In either case, the system filter characteristics must be well defined. The simulation technique requires that the complex impulse response be defined for each transmitter and receiver combination considered. The analytical approach requires that the rms and peak intersymbol interference be defined. These latter parameters are derived directly from the filter complex impulse response.

The MSK waveform is similar to Offset 4PSK. Therefore, the existing literature on intersymbol interference for Offset 4PSK may be used to derive rough bounds on system performance degradation caused by some standard filters which are typically assumed for analysis such as a 4th-order Butterworth low-pass, etc. However, such bounds will be marginally useful because the actual system filters are sometimes much more irregular, as shown in section 2.1, and because the MSK spectrum is more contained than the PSK spectrum. Section 2.4.2 presents experimental data which show the MSK bit-error-rate performances achieved with a variety of transmitter and receiver combinations.

2.3.2 MSK Modem Description

The McDonnell-Douglas model MDL-510, MSK modem was the only modem tested in the data link project. This modem is divided functionally into a transmit section and a receive section. The transmit section converts NRZ (EIA Standard RS-232C) serial synchronous data signals into MSK audio data signals at 2400 or 4800 bits per second. The data rate is externally selectable by a front panel switch. The transmit section provides the data link interface between a data source, such as a computer output synchronous interface or the receive side of a standard medium speed land line modem, and the audio input to a VHF transmitter. A transmit/receive control line (Push-to-Talk) is also included.

The receive section converts differentially encoded MSK data into RS-232C NRZ data and provides the data link interface between the audio output of the VHF receiver and a computer input synchronous interface, or the transmit side of a standard medium-speed telephone modem. The modem automatically resolves the ambiguous phase of the MSK data resulting from abitrary wiring to/from the radio. Input and output impedances are both 600 ohms, balanced to ground through a transformer. Circuitry is all solid state and diode transistor logic (DTL) flat packs are utilized. There is also a selectable block-check-sequence (BCS) and parity checking feature integral to the modem. This feature was not employed for the tests reported herein. In addition, the modem generates a transmitter key-on signal which may be used to energize a VHF transmitter 10 msec before the transmission of data.

2.3.3 Basic Laboratory Measurement Techniques

This portion of the report describes the measurement techniques employed in the modem tests performed back-to-back at baseband, back-to-back at RF, and through a channel simulator.

Basic modem performance at baseband was measured by transmitting a known psuedo-random sequence from the modulator to the demodulator. At the demodulator, a calibrated amount of noise was added to the modulated signal to produce a desired signal-to-noise ratio. The demodulator output was then processed by an error analyzer to determine the bit error rate (P_e) as a function of signal-to-noise ratio. The laboratory test setup for implementation of this measurement technique is shown in Figure 2-83.

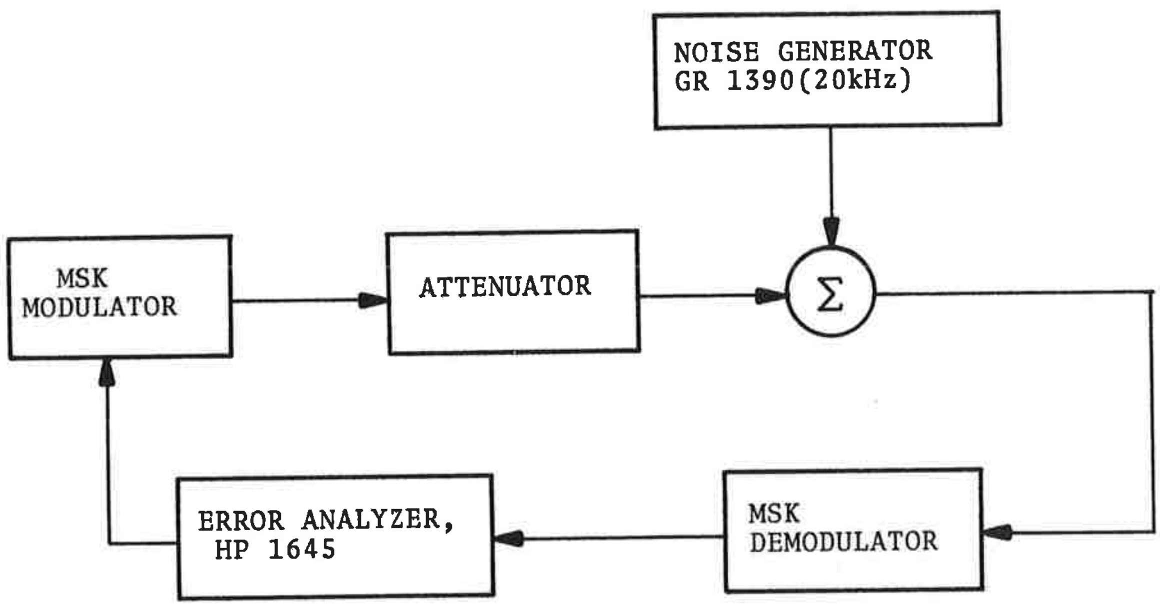


FIGURE 2-83. BASIC MODEM TEST SETUP

The basic modem performance measurement technique was modified to perform the back-to-back tests at RF. First, the MSK modulator output was used to amplitude modulate a VHF carrier so that the signal which was transmitted from the modulator portion of the system to the demodulator portion was a replica of real MSK transmissions. Similarly, a representative airborne type receiver was used (in this case the transceiver used was in accordance with ARINC characteristic 546) to demodulate the AM transmission and provide an input to the demodulator. In this configuration, RF noise was added to the receiver input. The laboratory test setup for implementation of this measurement technique is shown in Figure 2-84.

The addition of the representative data link RF transmission and reception equipment to the basic modem performance measurement scheme improved the realism of the test configuration. In the case of multipath tests, the utilization of RF data signals and the inclusion of representative receivers are essential. Specifically, simulation of multipath distortion cannot be accomplished in any straightforward way using the baseband modem output. On the other hand, this can be accomplished on an RF carrier modulated signal. More important, the IF. characteristics of the receiver and its AGC characteristics directly affect the response of the system to multipath disturbances. These are, of course, included when the tests are conducted at RF.

The multipath performance of the modem was measured with the addition of a multipath simulator to the test setup. The multipath simulator was placed in cascade between the RF modulator output and the receiver input. The simulator was capable of reproducing all of the relevant multipath characteristics of the channel. The laboratory test setup for the modem multipath performance measurement is shown in Figure 2-85. The equipment shown in the figure constitutes a modified modem test configuration as described above. That is, the modulator portion of the modem under test was driven from a psuedo-random data source. The modulator output was used to amplitude modulate an RF carrier in the transmitter subsystem. The resulting RF signal was passed through the channel

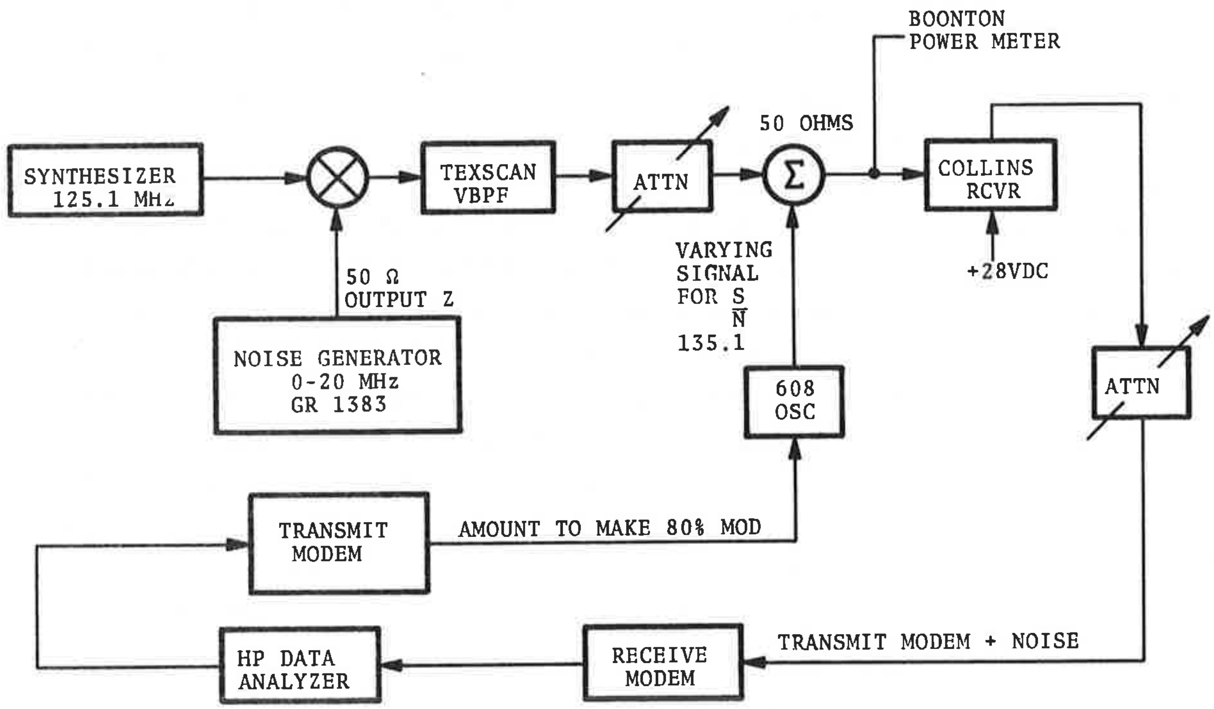


FIGURE 2-84. RF PERFORMANCE TEST SETUP

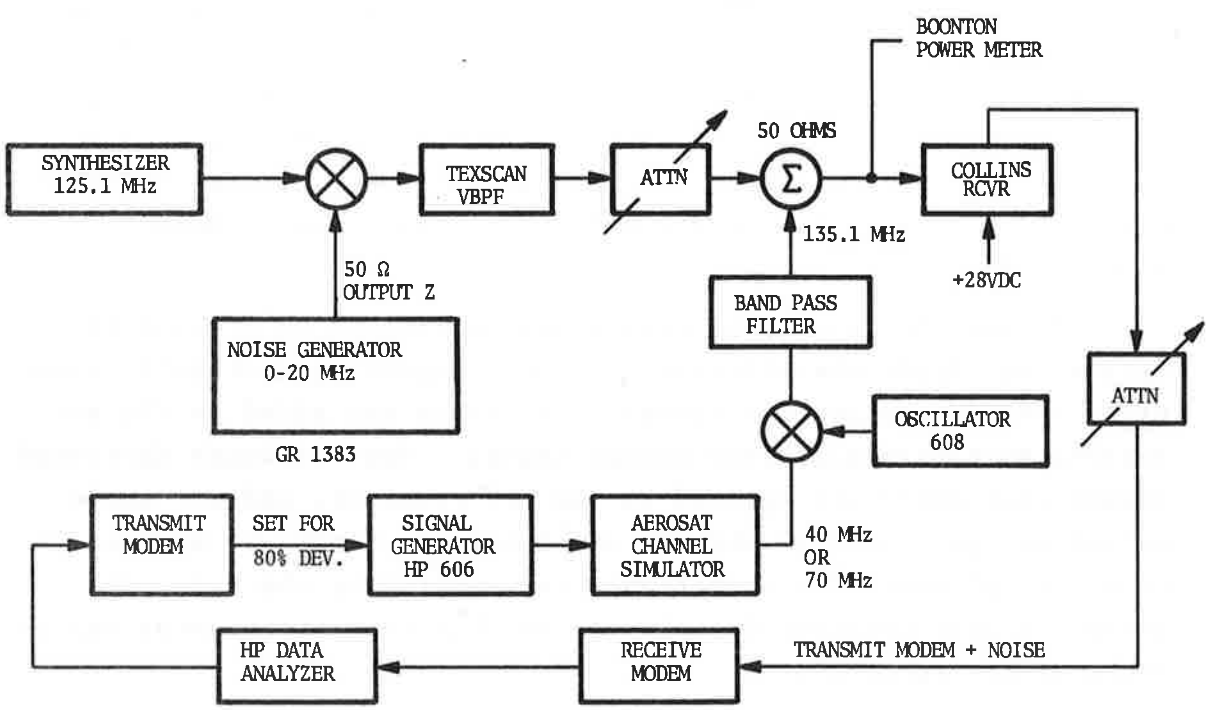


FIGURE 2-85. MULTIPATH PERFORMANCE TEST SETUP

simulator which created multipath distortion with known parameters. Then, a calibrated amount of RF noise was added to the multipath distorted RF signal, and the sum of multipath distorted signal plus noise was provided as input to the receiver. The receiver output was processed by the modem demodulator portion and the output data stream analyzed for bit errors. The error analyzer used in the test setup was a Hewlett-Packard Model 1645A. The receiver used conformed to ARINC Characteristic 546. An ARINC Characteristic 546 transmitter was not used in the test setup because it was not convenient to interface with the available channel simulators at a 40-MHz or 70-MHz (nominal) carrier frequency. Therefore, a laboratory signal generator (Hewlett-Packard Model 606) was used to produce the amplitude-modulated RF carrier. The deviation was set at 80 percent. This approach excludes any effects which may be created by the filtering in standard airborne and ground transmitters. However, these effects are analyzed separately in section 2.4 of this report.

The channel simulators employed for these tests were the DOT playback-channel-simulator system and the Aeronautical Satellite (AEROSAT) Channel Simulator. Figure 2-85 shows the test configuration when the AEROSAT Channel Simulator was used. For the purposes of laboratory testing, it was desired to have channel data with known multipath parameters and with stationary statistics. This channel was created by the AEROSAT Channel Simulator, shown in Figure 2-85.

The AEROSAT Channel Simulator was configured to provide the desired multipath characteristics (i.e., signal-to-multipath ratio, delay spread, and Doppler spread). RF noise was added to the resulting multipath distorted output signal. The multipath distorted signal plus noise was applied to the VHF receiver, and its audio output was processed by the MSK demodulator. Errors as a function of noise and multipath conditions were counted by the error analyzer. A more complete description of this laboratory setup may be found in Reference 10.

Modem performance for the tests depicted in Figures 2-83 through 2-85 was determined as a function of signal-to-noise ratio (S/N) and additionally as a function of signal-to-multipath ratio (S/M) and Doppler spread for the multipath tests (Figure 2-85). The latter two parameters are selectable on the multipath simulator.

The S/N was established by measuring RF signal power (S) in the absence of multipath and RF noise power (N) at RF. Specifically, these parameters were measured at the input to the receiver. The performance results are not plotted as a function of S/N. Instead, they are plotted versus the RF energy-to-noise density ratio (E/N_o). The energy-to-noise density parameter is generally chosen for presentation because the results are then independent of specific filter shapes used in the test equipment.

The energy (E) is simply defined as the RF energy per bit. That is:

$$E = ST \tag{2-3}$$

where: T = bit duration.

The noise density (N_o) is the power spectral density of the noise in the center of the RF channel. The noise spectrum used in the tests was flat over a 4 MHz interval centered on the signal carrier frequency. The noise density is determined by measuring the total noise power output through a filter with known noise bandwidth (B_n). Then

$$N_o = N/B_n \tag{2-4}$$

where:

$$B_n = \left[\frac{1}{2\pi}\int_o^\infty \left|H(\omega)\right|^2 d\omega\right] \Big/ \left|H(\omega_c)\right|^2$$

The integral was evaluated graphically after measuring the frequency response ($H(\omega)$) of the filter used in the given test set-up. The value of the integral was normalized to the value of the power spectral density function at the center frequency $H(\omega_c)$.

2.3.4 Modem Test Results

This section presents the results of the back-to-back modem tests at baseband, the back-to-back modem tests at RF, and the modem multipath performance tests at RF through a simulated channel.

2.3.4.1 Baseband Back-to-Back Test Results - The back-to-back modem tests at baseband were performed with the test setup shown in Figure 2-83. The back-to-back bit error rate is shown in Figure 2-86 for two bit rates, 2400 and 4800 bits per second. Also shown in Figure 2-86 is the theoretical optimum performance for MSK modulation at baseband. The observed performance was very near the optimum achievable (i.e., within 0.5 dB at 4800 bits per second). It is interesting to note that the performance at the lower bit rate was inferior to that at the higher bit rate. In theory, the performance at the two bit rates should be identical when plotted versus E/N_o. There are several possible causes for this effect. It is most probable that this results from a relative degradation of bit synchronization loop performance at the lower bit rate. Note that for a given E/N_o, the S/N in any given bandwidth is lower at lower bit rates. That is, for

$$\frac{E_{2400}}{N_o} = \frac{E_{4800}}{N_o} \tag{2-5}$$

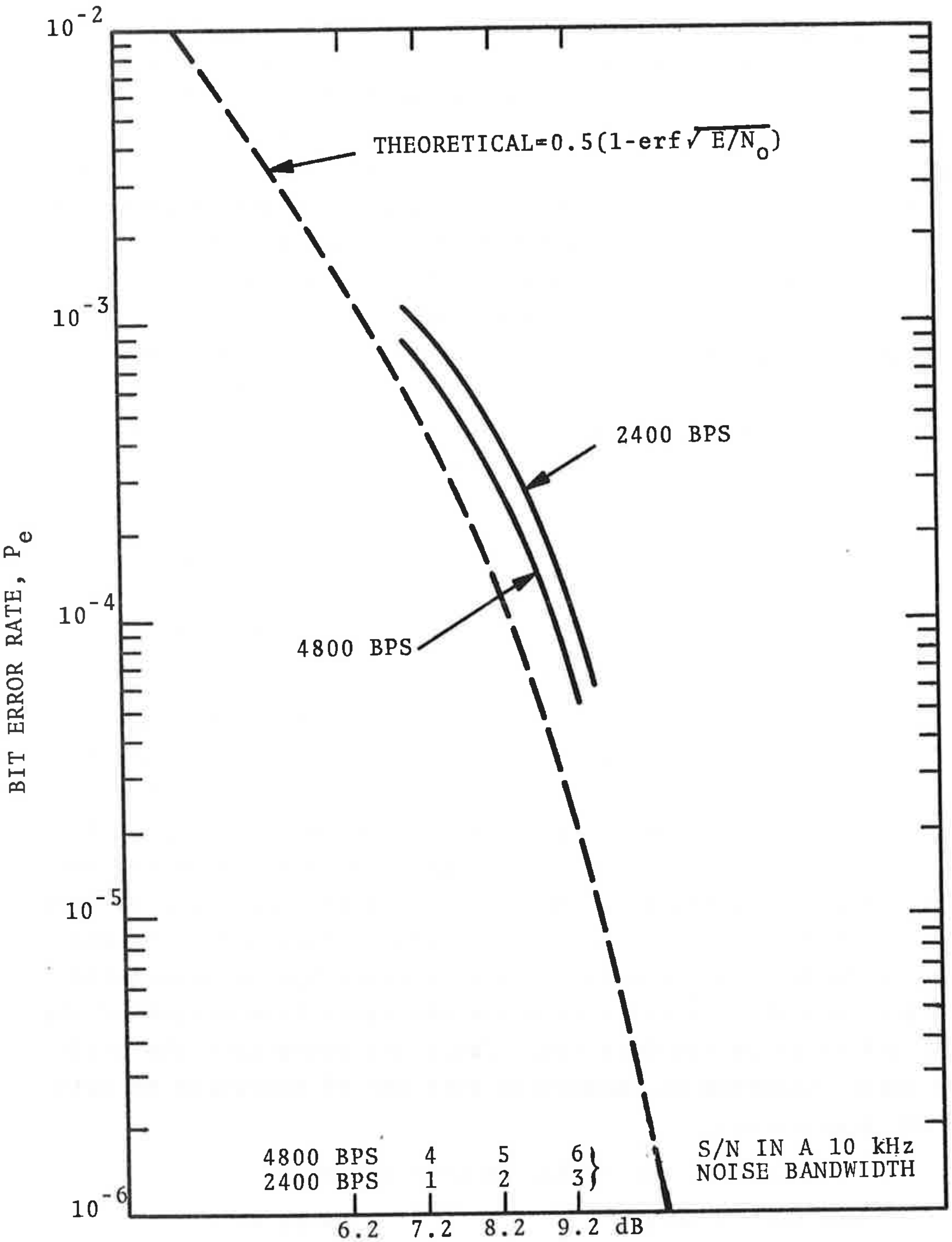
or, recalling that E = ST, Equation (2-3), so

$$\frac{S_{2400}}{2400N_o} = \frac{S_{4800}}{4800N_o} \tag{2-6}$$

or

$$2S_{2400} = S_{4800} \tag{2-7}$$

Thus, it is reasonable to expect larger jitter effects at a lower bit rate given the same E/N_o at both bit rates. Increased jitter in the carrier loops will result in a higher bit error rate (P_e).



ENERGY-TO-NOISE DENSITY RATIO, E/N_o, dB

FIGURE 2-86. BASEBAND BACK-TO-BACK MODEM PERFORMANCE

2.3.4.2 RF Back-To-Back Test Results - The back-to-back modem tests at RF were performed with the test setup shown in Figure 2-84. The receiver is in accordance with ARINC Characteristic 546 and the passband characteristic is shown in Figure 2-6. A signal generator was used to provide the transmitter carrier for these tests. The bit error rate performance is shown by the solid curves in Figure 2-87 for data rates of 2400 and 4800 bits per second. The back-to-back performance (P_e vs. E/N_o) at RF is degraded relative to the back-to-back performance at baseband for a number of reasons. First, the data modulation is only a fraction of the total RF signal power. The test results presented here are based on 80 percent amplitude modulation. Thus, the ratio of power in the modulation to total power is:

$$\frac{m^2}{2+m^2} = \frac{.64}{2.64} \text{ or } -6.15 \text{ dB} \qquad (2\text{-}8)$$

Therefore, the RF performance curves should be shifted at least 6.15 dB to the right relative to the baseband curves.

There are other important sources of performance degradation in addition to the modulation loss just described. For example, the receiver's IF filtering causes the overall filtering of the data to be suboptimum (assuming the modem implements an optimum matched filter detector, then any further filtering is suboptimum by definition). Furthermore, the receiver filtering can give rise to intersymbol interference which degrades performance. In addition, the AM detection process in the receiver has an associated detection loss which results from the nonlinear interaction of the signal and noise in the detector. Table 2-9 summarizes the estimated losses incurred in connection with the RF operation at data link VHF frequencies.

TABLE 2-9. RF OPERATION LOSS ESTIMATES

Modulation Loss	6.15 dB
Filtering Loss	0.5 dB
Detection Loss	1.0 dB
Total	7.65 dB

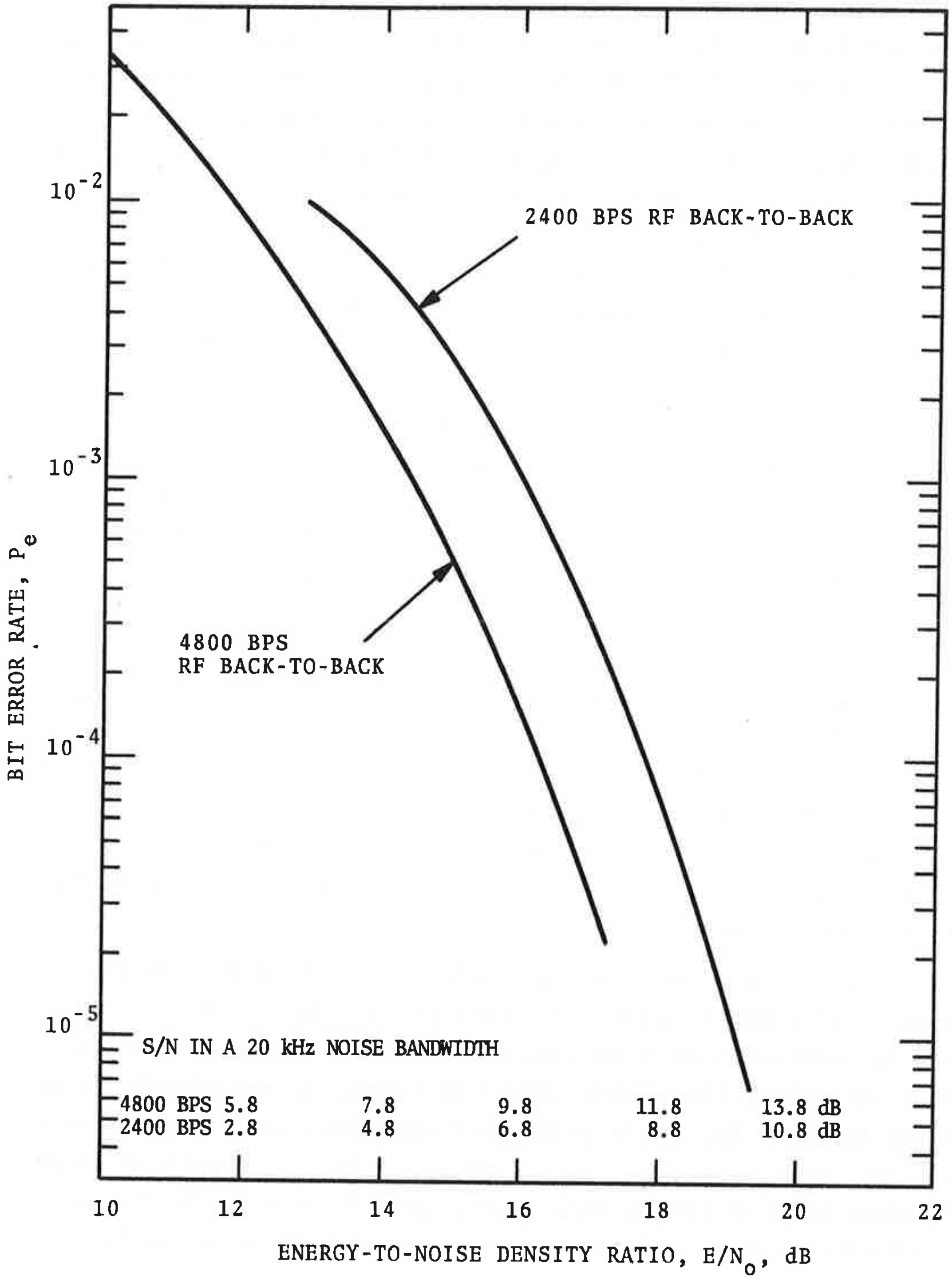


FIGURE 2-87. MODEM RF PERFORMANCE

Thus the modem performance at RF is estimated to be 7.65 dB worse than at baseband. Comparison of the test results at baseband and RF, Figures 2-86 and 2-87, respectively, show good agreement with the analysis. It is interesting to note, however, that the relative performance (at a given E/N_o) at 2400 bits per second (bps) is now more than 1 dB below the 4800-bps results. One would expect that the higher bit rate signal, which has a correspondingly wider bandwidth, would be more degraded by the receiver's IF filtering effect than the lower bit rate signal. The results show clearly that the IF filtering effect of the receiver used for this particular test is quite small as indicated in Table 2-9 and that some other effect has caused the degradation at 2400 bps. In this case, the inferior relative performance at 2400 bps is probably due to small signal suppression in the AM detector of the receiver. Signal suppression is experienced at both data rates but it is greater at 2400 bps because the IF S/N is lower at a given E/N_o at the lower data rate.

2.3.4.3 Simulated Multipath Test Results - Extensive performance testing was carried out using the configuration shown in Figure 2-85. The various ranges of multipath parameters were created by appropriate settings of the AEROSAT Channel Simulator controls. The S/N was obtained by adjusting the noise output of a noise generator which is part of the Playback Simulator. The results are shown in Figure 2-88.

The ranges of parameter variations were limited by equipment performance characteristics. In particular, the tracking jitter induced by multipath effects caused the modem and/or the error analyzer to unlock frequently when the signal-to-multipath ratio (S/M) was below 7 dB. This precluded operation with worse S/M's and it also made it impossible to obtain meaningful data at high E/N_o's when S/M = 6 dB. In that case, unlock occurred before a statistically significant number of errors could be accumulated.

The unlock phenomenon requires careful interpretation in order to obtain a reasonable estimate of modem performance. Unlock of the modem's tracking loop constitutes a catastrophic failure of the

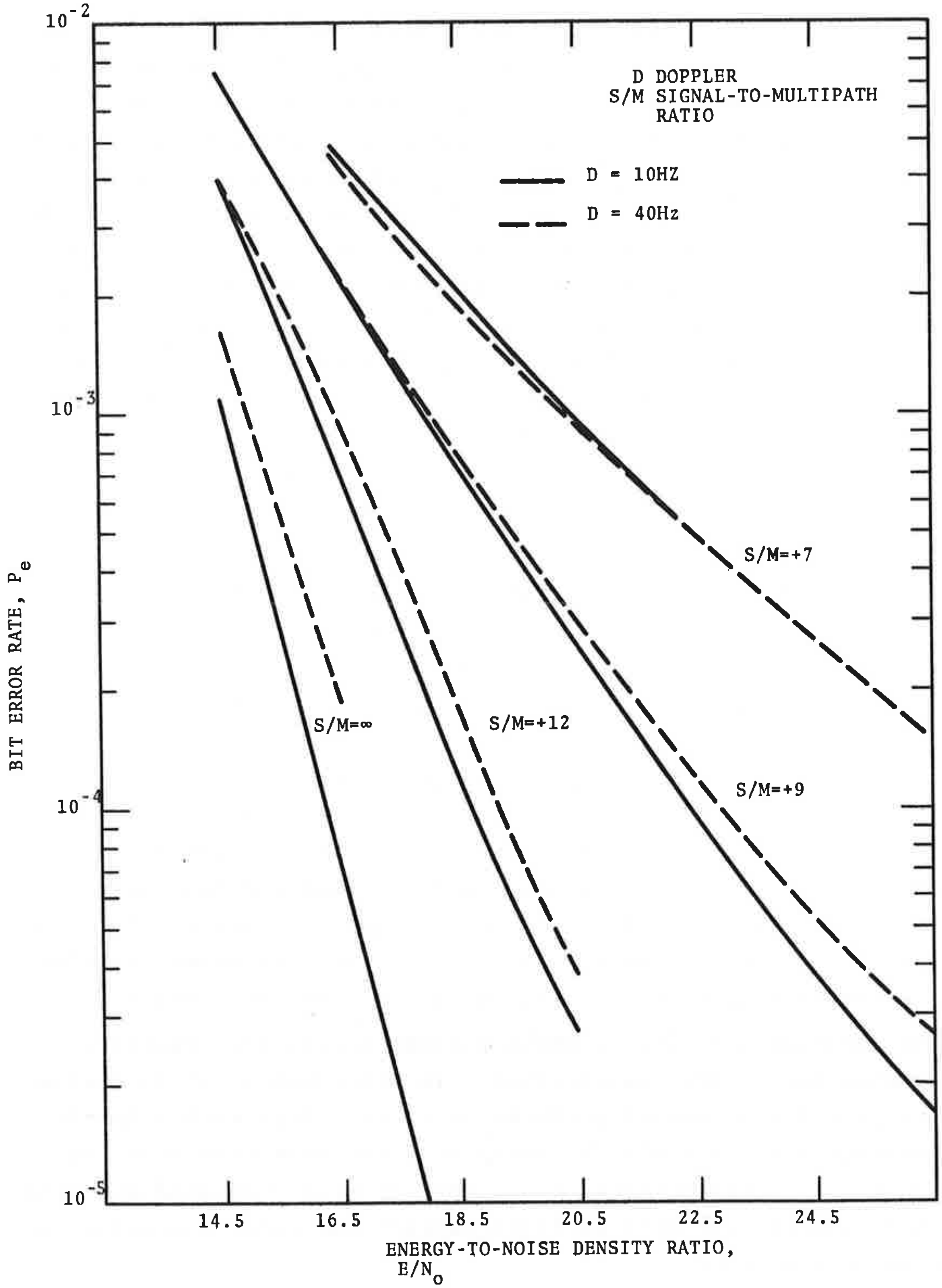


FIGURE 2-88. MODEM MULTIPATH PERFORMANCE

system. During modem unlock the probability of bit error is typically 0.5. If the errors obtained during such intervals were averaged in with the errors obtained during locked conditions, the resulting bit error rate (P_e) performances would be much worse than those shown in Figure 2-88. All data in which unlocks occurred have been excluded for two reasons. First, messages transmitted by a data link system would be short and preceded by synch sequence. Thus, the actual system may not experience the density of unlocks as were encountered in the laboratory. As a test of this hypothesis, the pseudo-random sequence was replaced by a Mark-only, One Mark-One Space, and a Three Mark-One Space pattern. It was informally estimated that under these conditions, unlock occurred slightly less frequently. Given a synch preamble with a large synch energy component and short messages, the working data link system may unlock less frequently in the field.

The second reason for excluding data with unlocks is associated with the characteristics of the Hewlett-Packard Model 1645A Data Error Analyzer. This device is primarily for the detection of errors in data. Therefore, it has special sophsticated circuitry which detects anomalous conditions such as loss-of-carrier or clock slips. When such conditions are detected, the error counting system is gated off so that all errors (except for the first few) which occur during the anomalous conditions are ignored. Furthermore, when the modem unlocks and produces a truly random output data stream (i.e., not all Marks or Spaces) the error analyzer stays in lock and rapidly counts up errors until its error counter overflows. Thus, after less than one second, the error count is useless.

By ignoring any data in which unlocks occur, the resulting performance curves are conservative. In other words, it is reasonable to expect that actual performance in the field with a specified message structure will be somewhat worse than that predicted in Figure 2-88. Furthermore, the unlock problem indicated that the presence of multipath will adversely affect the modem's acquisition (lock-on) performance.

The P_e performance data are plotted for two Doppler spread rates, 10 Hz and 40 Hz. These correspond to velocities on the order of 50 mph and 200 mph at VHF data link carrier frequencies. Figure 2-88 shows that performance is relatively insensitive to Doppler spreads in this range. Note that the 40-Hz data appear to be typically to the right of the 10-Hz data. However, this may be attributed to experimental error because this displacement occurs in the no-multipath (S/M = ∞) case as well. On the other hand, the displacement may result from an actual change in performance of the modem during the test series. The 10-Hz and 40-Hz data were collected on different days. It is possible that performance varied slightly (± 0.25 dB) from day-to-day.

Block error rate was monitored and recorded during all performance measurement runs. The data showed that errors were well distributed and did not occur in long bursts.

2.3.4.4 Discussion of Laboratory Multipath Performance Data - The laboratory performance data of Figure 2-88 show that data link performance will be degraded in the presence of multipath. Specifically, at signal-to-multipath ratios (S/M) less than 6 dB to 7 dB the system does not lock up readily, and after lock is achieved, it will not stay in lock for more than a few seconds. At S/M = 7 dB, the measured degradation in performance is roughly 11 dB with $P_e = 10^{-4}$ and by extrapolating from measured data it is estimated that the degradation is on the order of 17 dB with $P_e = 10^{-5}$. These results exclude the effects of unlock and clock slips. At S/M = 9 dB and $P_e = 10^{-5}$, the degradation is on the order of 10 dB. At S/M = 12 dB and $P_e = 10^{-5}$, the degradation is roughly 4.5 dB. Similarly, at S/M = 12 dB and $P_e = 10^{-4}$, the degradation is roughly 2.5 dB.

These results can be compared with other modems previously tested under similar conditions. Specifically, candidate modems for the AEROSAT system were tested to determine their performance capabilities under multipath conditions. The available data for a high quality differential phase-shift keyed (DPSK) modem shows that with S/M = 11 dB and P = 10^{-5}, the degradation relative to optimum performance is 4 dB. The available data for a high-quality differentially encoded, coherent phase-shift keyed (DECPSK) modem show that, with S/M = 11 dB and $P_e = 10^{-5}$, the degradation relative to optimum is 7 dB. Of course the performance in the absence of multipath for either of these techniques is superior to MSK/AM performance since these designs are not constrained by existing transmitter and receiver characteristics (i.e., high pass channel). MSK/AM performance with and without multipath is compared to the corresponding performance of DPSK and DECPSK systems in Table 2-10.

TABLE 2-10. REQUIRED E/N_o TO ACHIEVE $P_e = 10^{-5}$

Conditions	DPSK	DECPSK	MSK/AM
No Multipath	10.6 dB	10.3 dB	18 dB
S/M = 11 dB	14.6 dB	17.3 dB	24.5 dB

Apart from the basic performance losses incurred due to the characteristics of existing RF equipment (see Table 2-9), Table 2-10 shows that the additional losses due to multipath for MSK are comparable to those of the DPSK system and are less than those of the DECPSK system. It should be pointed out that both the DPSK and DECPSK could operate in stronger multipath environments without experiencing unlock. This capability results from the use of relatively narrow carrier and bit synch tracking loops in these modems. Similar results could probably be obtained with the MSK modem. However, it is possible that the bandwidth of the carrier/ bit synch loop in the MSK modem cannot be reduced beyond its present value because acquisition performance may be seriously degraded. The acquisition performance requirements of the AEROSAT system are not as constraining as those of the VHF data link system.

In summary, Table 2-10 shows the performance of the MSK modulation technique relative to that of DPSK and DECPSK for purposes of comparison. Unfortunately, a discussion of the relative merits of the various techniques is not appropriate since design constraints for the PSK techniques are not the same as those of the VHF data link techniques. Moreover, the flight test data described in

Sections 4 and 5 demonstrate that the suitability of a modem technique for the data link application can not be determined from a simple consideration of noise or noise-plus-multipath performance data.

2.3.5 Summary of Modem Test Results

The performance of the MSK modem was determined at baseband, at RF in a Guassian noise environment, and at RF in a combined Gaussian noise-and-multipath environment obtained with a channel simulator. The tests were performed at data rates of 2400 and 4800 bps. The tests showed that the modem performance was very near the optimum achievable. It was shown that the modem performance at a data rate of 2400 bps was inferior to that at a data rate of 4800 bps at a given energy per bit-to-noise density ratio. The multipath tests showed that the modem performance was significantly degraded in the presence of multipath. Modem unlock problems were observed for an S/M between 6 and 7 dB or less. For an S/M of 7 dB, the modem performance was degraded by approximately 11 dB for a P_e of 10^{-4} and on the order of 17 dB for a P_e of 10^{-5}. The effect of multipath on data error performance was found to be insensitive to Doppler spread rates in the range from 10 Hz to 40 Hz.

2.4 DATA LINK SUBSYSTEM TESTS

End-to-end laboratory tests were performed at RF in a Gaussian noise environment on subsystems of equipment consisting of combinations of receivers and transmitters selected from those listed in Table 2-1 with a pair of MSK modems. The objective of these tests was to determine the sensitivity of data link performance (as measured by bit error rate) to variations in receiver and transmitter characteristics that normally occur in functionally similar equipment produced by a variety of manufacturers.

The observed variation in subsystem performance has been interpreted based on the measured performance characteristics of the individual receivers, transmitters, and modems as presented in sections 2.1, 2.2, and 2.3, respectively, and the resultant intersymbol interference produced by these individual equipment filter characteristics.

2.4.1 The Intersymbol Interference Problem

Intersymbol interference results when energy from preceding bits is spread into succeeding bit intervals. The spread energy constitutes interference in the bit detection process and results in degraded bit error rate performance.

The amount of spreading of a given bit's energy into succeeding bit intervals is determined by the filter characteristics which operate on the bit. It is important to note that the amplitude response does not constitute a complete specification of a given filter's response. Some insight into the intersymbol interference problem can be derived from the amplitude (magnitude) response. However, a more useful and complete filter specification is the filter's transient response. (Of course, this can be derived from the filter's specified amplitude and phase response, or equivalently, from its complex amplitude response, H(s).) In particular, the response of a filter with transient response, h(t), to a single bit symbol $s_b(t)$ is given by:

$$s_t(t) = \int_{-\infty}^{\infty} h(\tau - t)\, s_b(\tau)\, d\tau = \frac{1}{2\pi} \int_{-\infty}^{\infty} H(\omega)\, s_b(\omega)\, e^{j\omega t}\, d\omega \qquad (2\text{-}9)$$

where $s_b(\omega)$ is the amplitude spectrum of a single bit symbol $s_b(t)$.

The filter response $s_t(t)$ is more informative than the amplitude response, but we must know more to predict intersymbol interference effects. First, note that since the duration of $s_t(t)$ may extend into many succeeding bit intervals, the interference in any bit interval depends on many preceding bits. The interference is thus a random variable since the preceding bits are random by definition. For purposes of illustration, let us define a system in which marks (ones) are communicated by transmitting $s_b(t)$ and

and spaces (zeros) are communicated by transmitting $-s_b(t)$. Condider the transmission of a bit stream $a_1, a_2, \ldots a_i, a_N$ where $a_i = \pm 1$ and bit duration is T. The intersymbol interference during the Nth bit interval is given by

$$I_N(t) = \sum_{i=1}^{N-1} a_i \int_{-\infty}^{\infty} h\left(\tau - t + (N-1+i)T\right) s_b(\tau)\, d\tau \qquad (2\text{-}10)$$

The interference as defined above is difficult to deal with analytically. Some researchers try to determine the rms value of I(t) in any bit interval; others attempt to define worst-case interference. Alternatively, the effects of interference can be investigated using computer simulation techniques in which the entire detection process is implemented in the computer. The results of such computer investigations are in the form of rms and worst-case probabilities of bit error due to intersymbol interference as a function of filter characteristics and signal-to-noise ratio (S/N).

It should be emphasized, at this point, that the intersymbol interference does not necessarily cause bit errors. It does reduce the margin for error which results in increased probability of bit error at a given S/N. This effect is illustrated in Figure 2-89 for the case of a baseband Non-Return to Zero (NRZ) bit stream and simple single-pole low pass filtering, Figure 2-89a shows the NRZ waveform before filtering. Figure 2-89b shows the impulse response and the step response of the simple low pass filter. Figure 2-89c shows the response of the filter to the input of Figure 2-89a. The reduction in margin is not clear in Figure 2-89c. However, Figure 2-89d shows the superposition of many such responses. There, the reduction in the minimum distance between the mark and space states at the optimum sampling point is clearly illustrated. Diagrams of the type shown in Figure 2-89d are called "eye opening" diagrams in which the minimum distance is the "eye opening." These displays are easily generated in the laboratory on an oscilloscope. In this way an estimate of the intersymbol

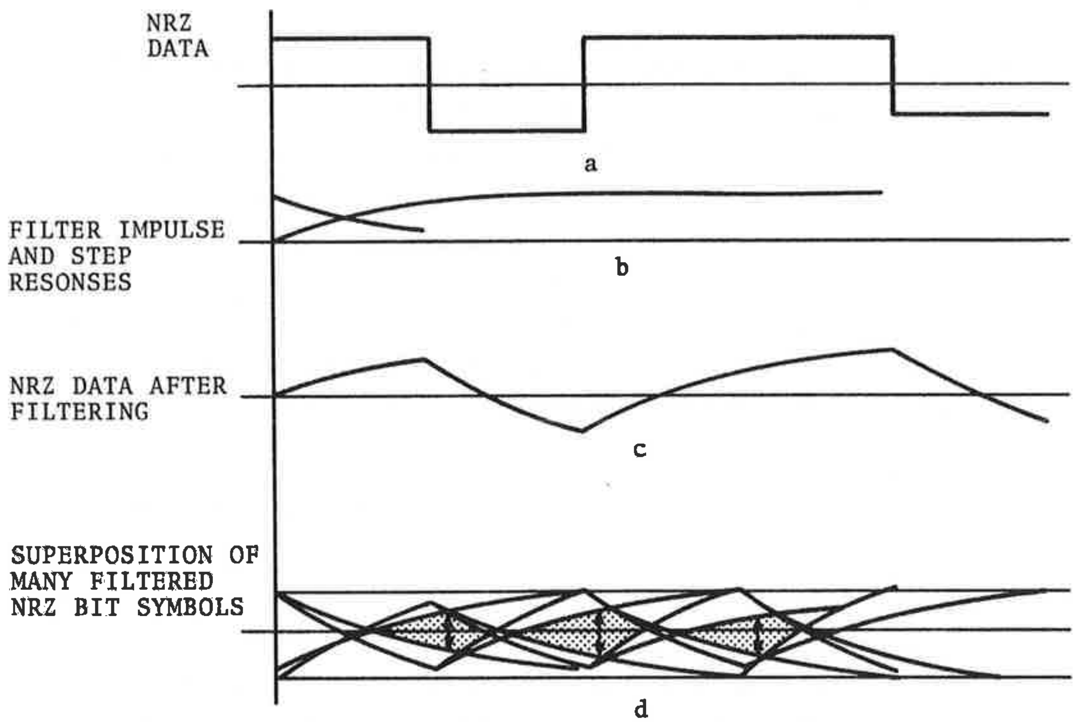


FIGURE 2-89. EFFECT OF FILTERING ON NRZ DATA

interference problem can be obtained experimentally provided that the predetection data signal is accessible.

2.4.1.1 MSK Data Link Characteristics - The data link intersymbol interference problem is substantially more complicated than the situation shown in Figure 2-89. First, the data format consists of orthogonal carriers each of which is modulated by data streams. The data symbols can be interpreted to be of the form $s_b(t) = \left|\sin \pi t/2T\right|$. The MSK baseband waveform is:

$$s(t) = a(t) \sin \pi t/2T \cos 3\pi t/2T + b(t) \cos \pi t/2T \sin 3\pi t/2T \quad (2\text{-}11)$$

where $a(t) = \pm 1$ and $b(t) \pm 1$ are offset data streams. That is, the transitions of a(t) occur in the middle of b(t) bits and vice versa.

While Figure 2-89 addresses a problem in which there is just one data stream, MSK has two. In that case, the energy in one data stream can interfere with the detection of succeeding bits in that stream and it can also spill into the orthogonal channel causing interference there. Cross-talk between the two orthogonal channels can result from dispersive filter characteristics and/or from locking error in the MSK demodulator loop. In any case, the result is the same, intersymbol interference.

The data link system is not a baseband operation. The MSK waveform is amplitude modulated onto a VHF carrier. Filtering takes place at several points in this system. First, the signal may be filtered before modulation onto the VHF carrier. Some slight filtering may take a place at RF before transmission. Significant filtering may occur in the receiver's IF amplifier. Finally, the baseband audio may be filtered in the receiver before the MSK signal is fed out to the MSK demodulation. Of course, there is additional filtering in the MSK demodulator but this is carefully controlled (e.g., matched filtering) and does not result in significant intersymbol interference.

Filtering at RF or IF cannot be characterized by a simple transient response. Instead, the RF or IF filtering may be characterized by a complex impulse response at baseband which is a function not only of the filter characteristics but also the difference between the RF or IF center frequencies and the received signal center frequency. This frequency offset varies with time since the signal carrier frequency is not perfectly stable. As a result, the complex transient response varies with time.

It is clear that complete definition of the filter characteristics of a typical Data Link user channel is a difficult task. Moreover, examination of Equations (2-10) and (2-11) shows that this is just the beginning of the intersymbol interference analytical problem. So many approximations and assumptions are required to reach an analytical solution that the results achieved may be questionable.

2.4.1.2 Filter Characteristics - The analytical problem has been avoided by conducting a series of bit error performance tests with a variety of transmitter and receiver combinations. However, a discussion of the general effects of filtering on intersymbol interference is required to interpret the experimental results obtained.

A filter's amplitude response is usually specified and constrained in order to pass signals with maximum fidelity. Thus, given an end-to-end filter amplitude response which is flat over the MSK signal bandwidth, one may hastily conclude that the MSK signal will be passed without extensive pulse distortion and hence minimum intersymbol interference. In fact, amplitude (magnitude) response does not completely characterize the filter response. As noted above, the phase response must also be specified. A linear phase response over the bandwidth of interest is desired to minimize transient response duration. The phase response may be specified directly (e.g., $\phi(\omega)$ vs. ω), or more typically in terms of a group delay response (e.g., $d\phi(\omega)/d\omega$ vs. ω). A linear phase response corresponds to a flat group delay response.

Unfortunately, flat amplitude response and flat group delay response over a given bandwidth are mutually incompatible requirements. That is, if a low-pass filter with a specified 3-dB bandwidth of BW Hz is desired, the filter with the flattest group delay response with bandwidth BW is one which rolls off gradually starting will below BW. Conversely, filters which cut off sharply at BW will have poor group delay response and hence large pulse distortion and extended transient response. In order to obtain both flat amplitude response and flat group delay response within a signal bandwidth B, the 3 dB bandwidth of the filter must be much wider than the signal bandwidth, B.

The predetection bandwidth cannot be made arbitrarily wide in the case of the MSK system. Note specifically that the energy-to-noise density for acceptable performance assuming 80 percent modulation index is on the order of 18 dB at 4800 bits per second (bps) or 20 dB at 2400 bps. This implies a carrier-to-noise density $C/N_o = E/N_oT = 20 + 33.8 = 53.8$ dB-Hz at 2400 bps. Table 2-11 summarizes the IF S/N's obtained at 2400 bps and 4800 bps assuming IF noise bandwidths of 10 kHz and 20 kHz.

Table 2-11 shows that if the IF bandwidth is increased much beyond 20 kHz, the minimum S/N in the IF filter will be below the threshold of the IF envelope detector. When the detector is below threshold, a significant reduction in post-detection S/N results from small signal suppression effects. This added loss is avoided by making the IF bandwidth narrow enough to ensure that the IF S/N stays above 7 to 10 dB, the threshold level.

TABLE 2-11. IF SIGNAL-TO-NOISE RATIOS

	Bits Per Second	
	2400	4800
Required Energy-to-Noise Density	20 dB	18 dB
Carrier-to-Noise Density	53.8 dB-Hz	54.8 dB-Hz
Signal-to-Noise Ratio in 10 kHz	13.8 dB	14.8 dB
Signal-to-Noise Ratio in 20 kHz	10.8 dB	11.8 dB

Now consider further the problems caused by making the receiver filter very narrow relative to the signal bandwidth. A narrow low-pass filter will attenuate the upper MSK frequency significantly relative to the lower MSK frequency. It is incorrect to conlude that this attenuation is directly related to a loss in bit error rate performance. It should be remembered that the noise in the vicinity of the upper tone is also reduced by the low-pass filtering action. Thus the loss in performance is directly related to the difference between optimum (match filter) filtering and actual filtering. Since it is assumed that the MSK detector subsystem provides nearly optimum filtering, it is concluded that any filter in cascade with the optimum filter will make the system suboptimum. It is the combined filter characteristics of the transmitter and receiver filters in cascade with the detector matched filter that determine this part of the performance degradation. Of course, narrow filters may also cause degradation through intersymbol interference as discussed above. The extent of this latter degradation is a function of the group delay/transient response characteristics of the transmitter-receiver filtering.

2.4.2 Experimentally Derived Bit Error Rate Performance

This portion of the report presents experimentally derived bit error rate performance data and provides a qualitative discussion of the measured results based on the information presented in sections 2.4.1.1 and 2.4.1.2. Table 2-12 summarizes the transmitter receiver modem combinations which were tested. The transmitter/receiver pairings were selected to be representative of that which occurs in present day ATC communications.

2.4.2.1 Test Equipment Configuration - The test setup is shown in Figure 2-90. The operation of the test system was straightforward. A Hewlett-Packard Model 1645A Error Analyzer generated a pseudorandom sequence, which was provided as input to the modulator portion of the MSK modem (MDL 510). The output of the modem was modulated onto a VHF carrier in the transmitter portion of a transreceiver or transmitter. In some cases an AM signal generator was

TABLE 2-12. TRANSMITTER-RECEIVER COMBINATIONS

Transmitter	Receiver	Figure Number
GRT-21	King-9100A	2-91,2-92
GRT-21	Bendix RTA-43A	2-91, 2-92
GRT-21	Collins 618M-2B	2-91, 2-92
GRT-21	King KY-195B	2-91, 2-92
Signal Gen.	NARCO COM 11A	2-93,2-94
Signal Gen.	NARCO COM 11A (modified)	2-93, 2-94
Signal Gen.	Genave, ALPHA-100/360	2-93, 2-94
Segnal Gen.	Collins 618M-2B	2-93, 2-94
King-9100A	GRR-23	2-95, 2-96
Bendix RTA-43A	GRR-23	2-95, 2-96
Collins 618M-2B	GRR-23	2-95, 2-96
NARCO COM11A	Bendix RTA-43A	2-95

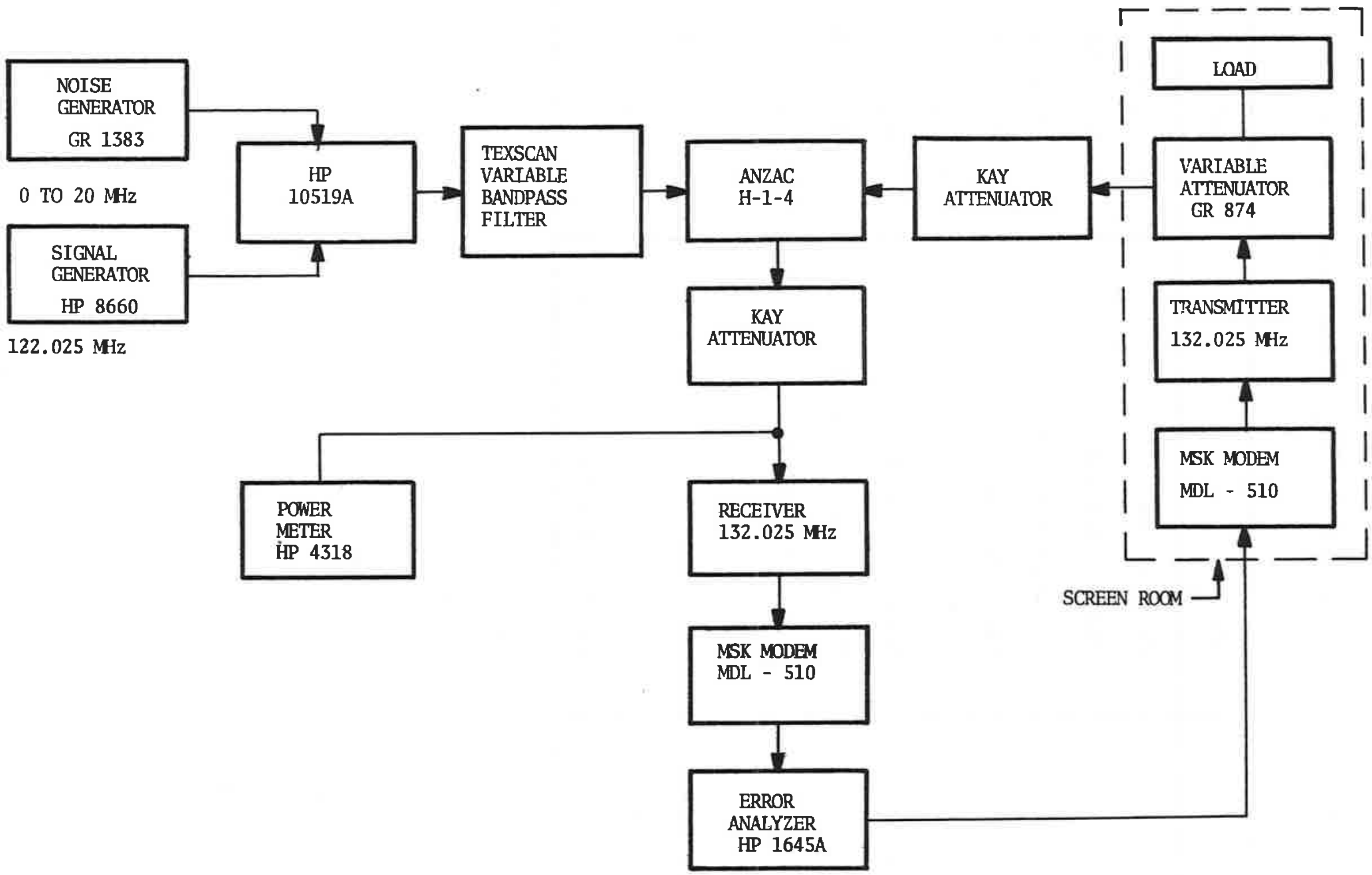


FIGURE 2-90. SUBSYSTEM TEST SETUP

used to create the modulated VHF signal for purpose of comparison and to remove any effects of transmitter filtering.

The VHF output signal was attenuated to a typical received signal level, and a controlled amount of noise was added. The noise was generated by mixing a baseband Gaussian noise process up to VHF in a double-balanced mixer and filtering to create a white Gaussian noise process over a band of approximately 4 MHz centered at the transmitter's output-center frequency. Variable attenuators were used to control the signal-to-noise ratio at the input to the receiver under test.

The baseband output of the receiver was processed by the demodulator portion of a second modem. The modem output was provided to the Hewlett-Packard Model 1645A, where errors were detected and counted.

2.4.2.2 Test Results - Figures 2-91 through 2-96 present the bit error rate performance achieved using the test setup of Figure 2-90. Table 2-12 contains a directory which indexes transmitter-receiver combinations and figure numbers.

Receiver Tests - Figures 2-91 and 2-92 show the performance achieved with the GRT-21 transmitter and the King 9100A, Bendix RTA-43A, Collins 618M-2B, and King KY-195B receivers. Figure 2-91 shows 2400 bit-per-second (bps) performance, and Figure 2-92 shows 4800 bps performance.

At 2400 bps the MSK's spectrum has a width at the -10dB level on the order of 2400 Hz centered at roughly 1800 Hz. Thus it is desired that the transmitter receiver system pass this bandwidth without significant distortion. Examination of Figure 2-4 or 2-5 shows that the Bendix passband characteristic is quite flat over the bandwidth of interest. The Collins passband as shown in Figure 2-7 or 2-8 is even flatter. Nonetheless, the Bendix provided slightly better performance. Examination of Figures 2-20 through 2-23 shows that group delay characteristics are similar for these receivers.

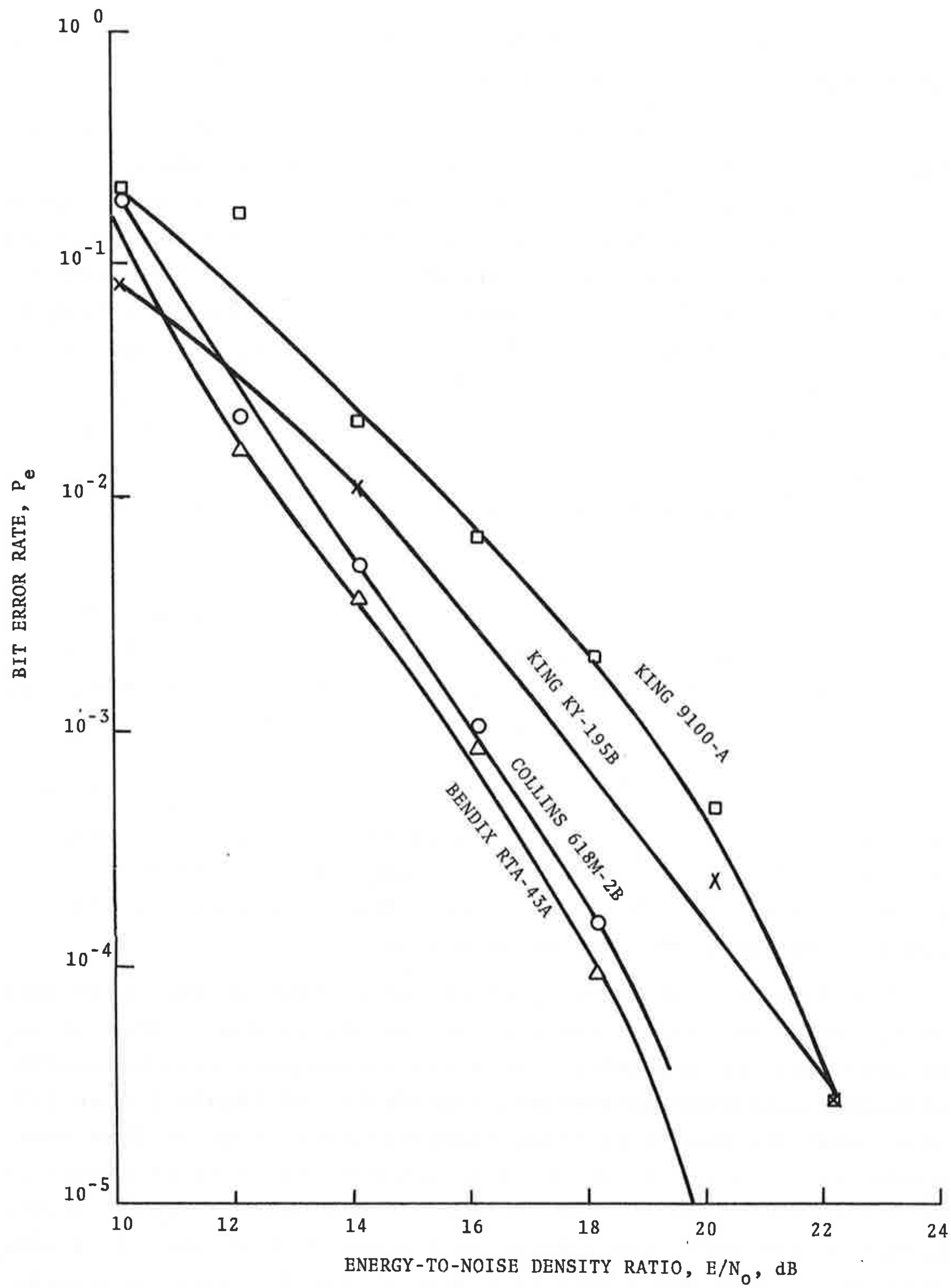


FIGURE 2-91. PERFORMANCE OF KING 9100-A, BENDIX RTA-43A, COLLINS 618M-2B, AND KING KY-195B RECEIVERS WITH GRT-21 TRANSMITTER AT 2400 BPS

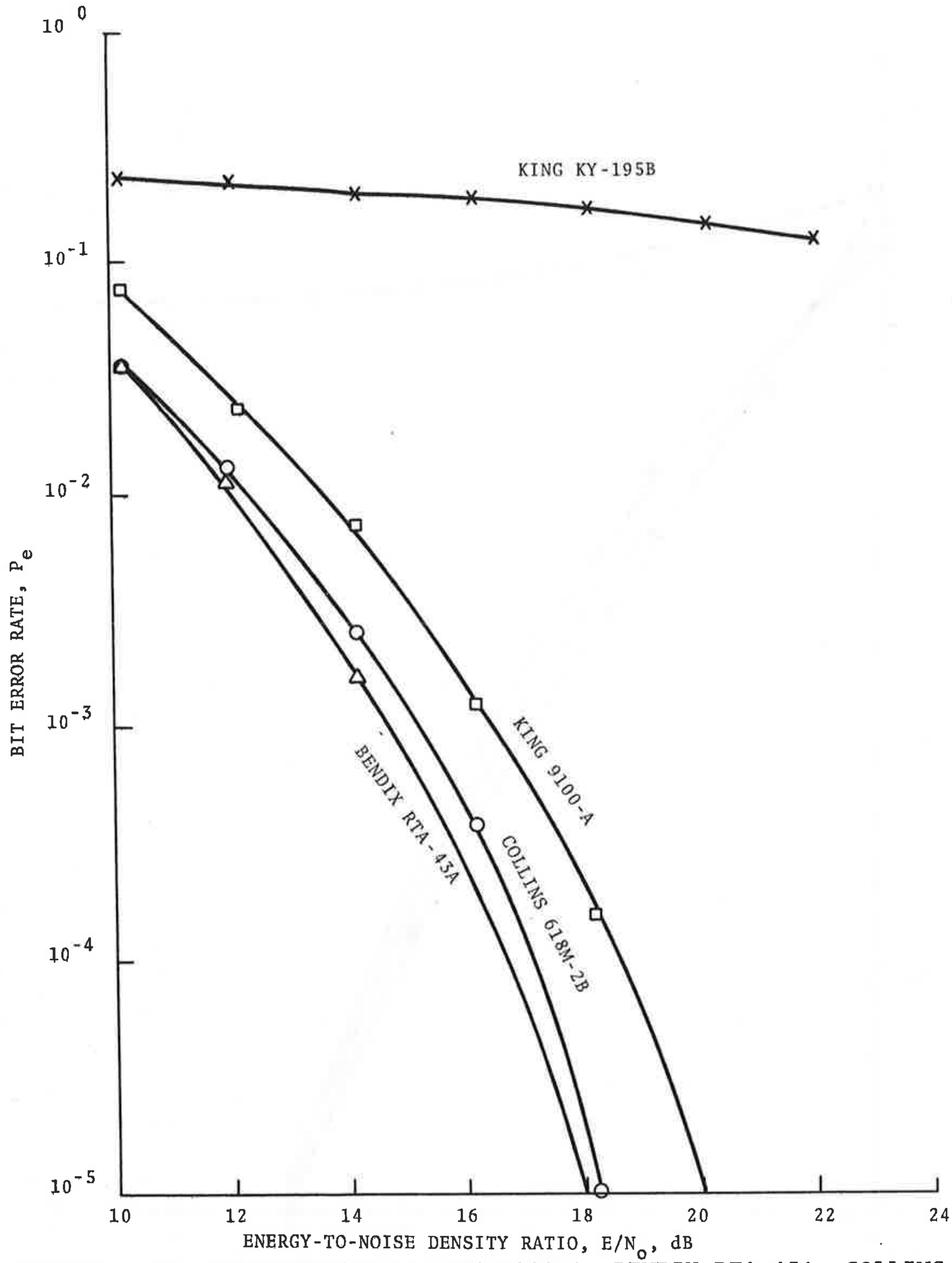


FIGURE 2-92, PERFORMANCE OF KING 9100-A, BENDIX RTA-43A, COLLINS 618M-2B, AND KING KY-195B RECEIVERS WITH GRT-21 TRANSMITTER AT 4800 BPS

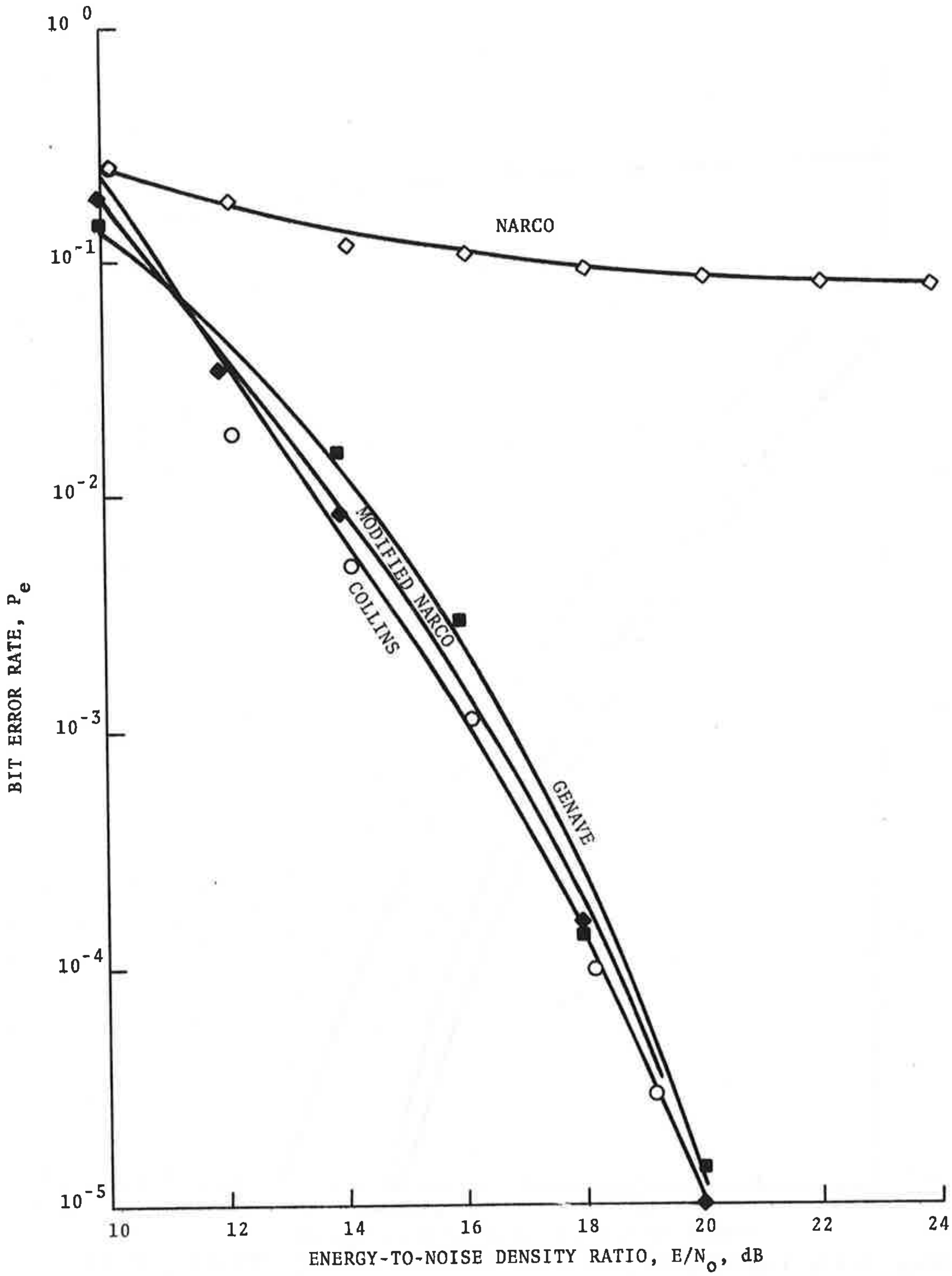


FIGURE 2-93. PERFORMANCE OF NARCO COM-11A, MODIFIED NARCO COM-11A, GENAVE-ALPHA-100/360, AND COLLINS 618M-2B RECEIVERS WITH SIGNAL GENERATOR AT 2400 BPS

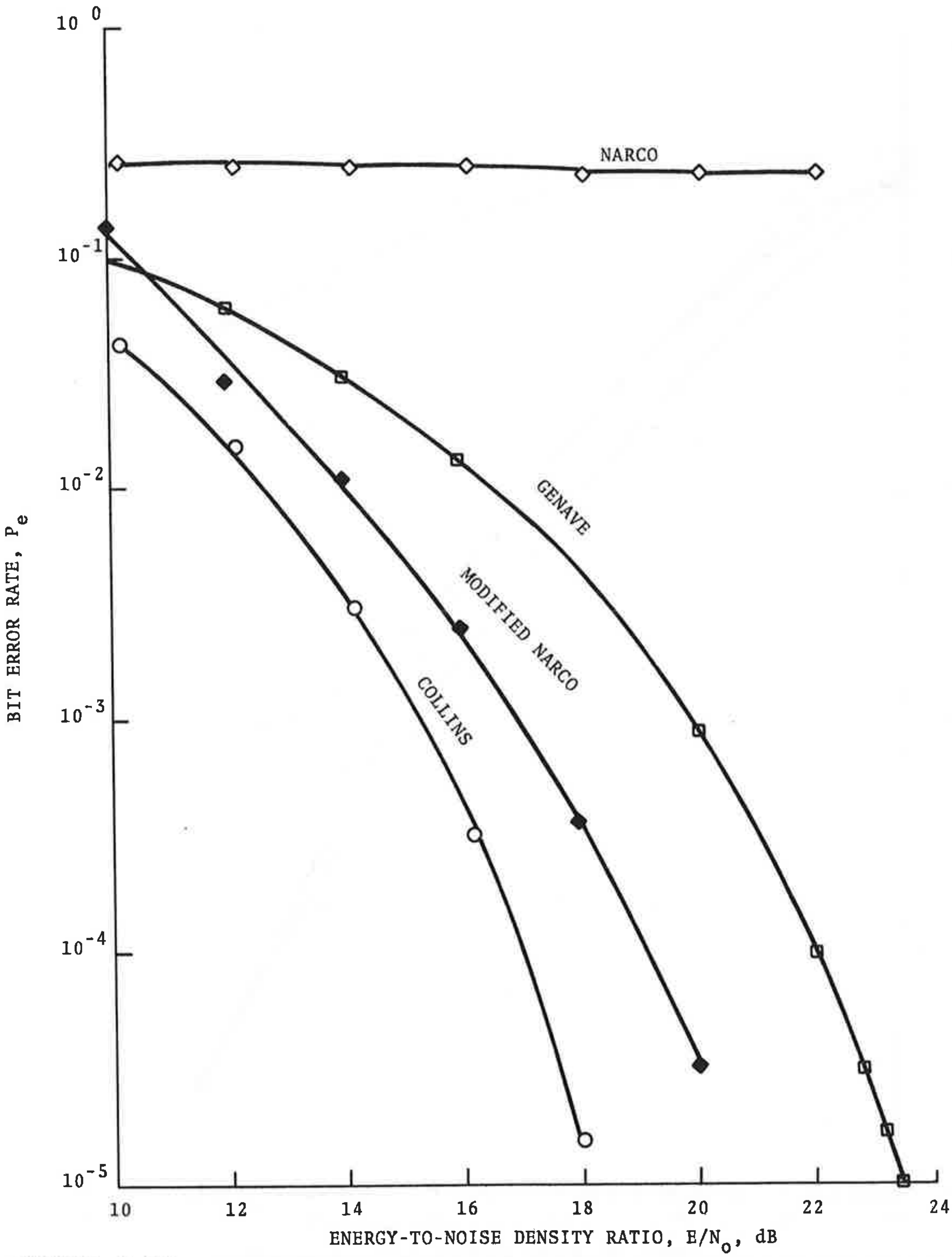


FIGURE 2-94. PERFORMANCE OF NARCO COM-11A, MODIFIED NARCO COM-11A, GENAVE-ALPHA 100/360, AND COLLINS 618M-2B RECEIVERS WITH SIGNAL GENERATOR AT 4800 BPS

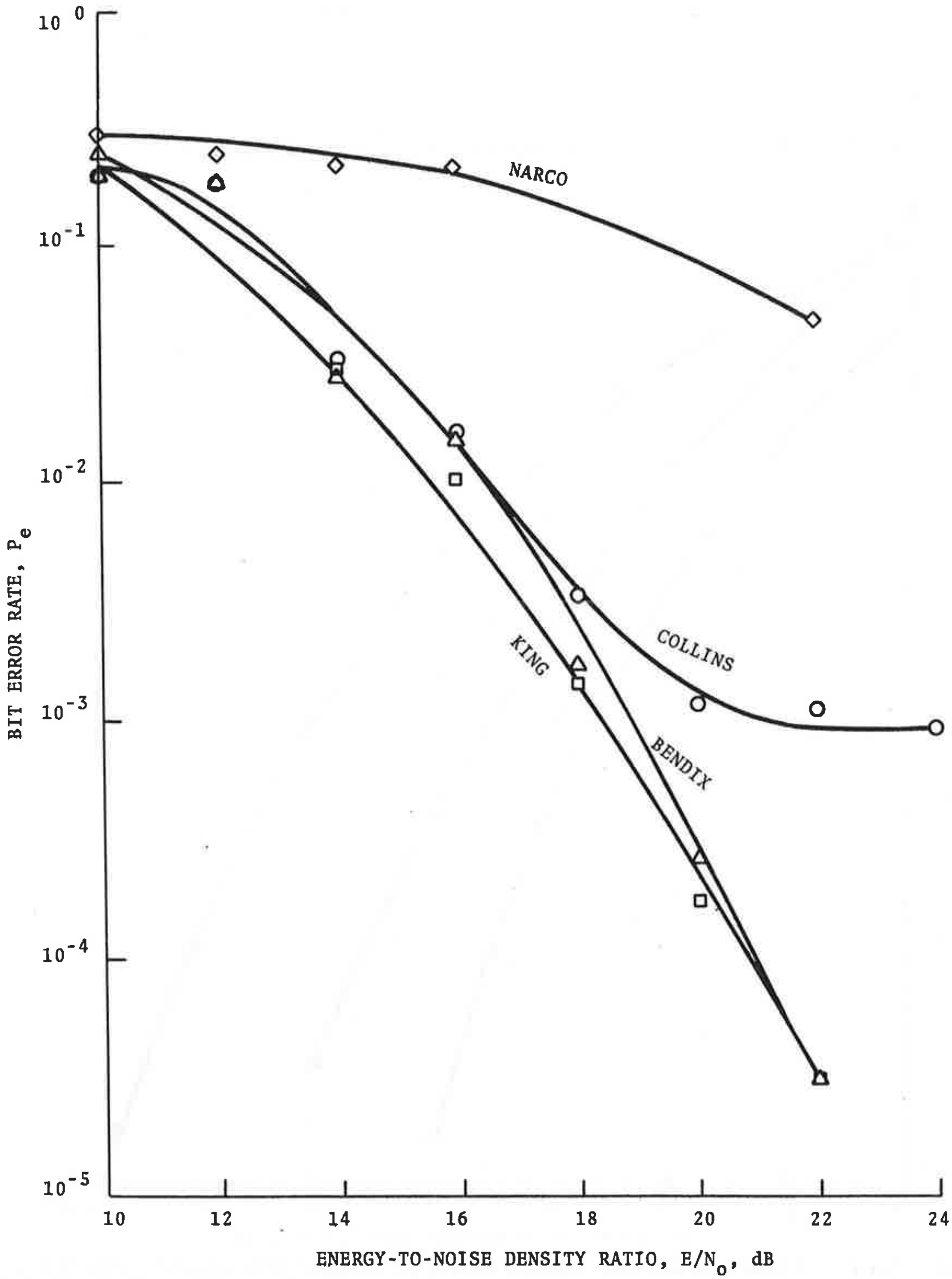


FIGURE 2-95. PERFORMANCE OF KING 9100A, BENDIX RTA-43A, COLLINS 618M-2B, AND NARCO COM11-A TRANSMITTERS AT 2400 BPS

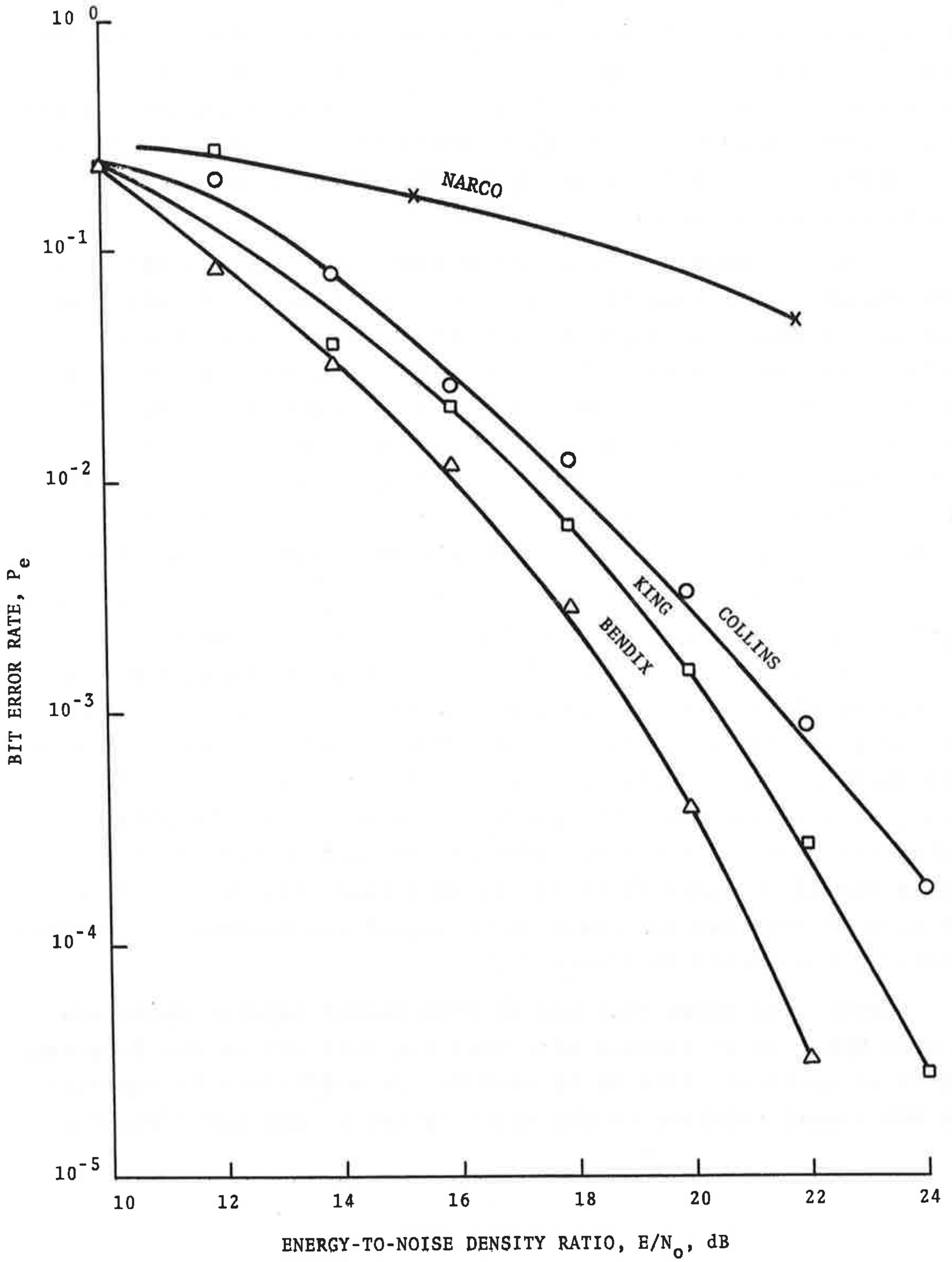


FIGURE 2-96. PERFORMANCE OF KING 9100A, BENDIX RTA-43A, COLLINS 618M-2B, AND NARCO COM 11-A TRANSMITTERS AT 4800 BPS

It is probable that the difference in performance observed is the result of small signal suppression in the Collins AM detector. Since the Collins predetection bandwidth is wider than that of the Bendix, the predetection signal-to-noise ratio (S/N) is lower in the Collins. This means that there could be more small signal suppression in the Collins.

A similar argument could be put forward to explain the lower performance of the King 9100A at 2400 bps. Figure 2-3 indicates that the predetection bandwidth of this unit is wider than the Collins and Bendix units. The King 9100A also has more in-band ripple. This was more evident when the passband characteristic was measured at a lower modulation index (see Ref. 7). However, the in-band ripple did not cause significant group delay distortion. In fact, Figure 2-19 shows that the group delay distortion over the passband of interest is superior to the Bendix or Collins units.

Figure 2-91 shows that the King KY-195B provided better performance than the King 9100A at 2400 bps. This is surprising because the audio response of the King KY-195B is rolling off in the region of interest as shown in Figure 2-11. This may be a case in which the group delay characteristic is relatively flat so that there is little pulse distortion through the filter. It is clear, in any case, that the predetection S/N in the KY-195B is higher than that of the King 9100A or the Collins 618M or the Bendix RTA-43A because it rolls off at a lower frequency. Thus the King KY-195B has the least small signal suppression of the four receivers considered in Figure 2-91.

Figure 2-92 shows that the KY-195B cannot support operation at 4800 bps. It is assumed here that the roll-off in the frequency region of interest, 1200 Hz to 6000 Hz, is sufficient to suppress the MSK signal relative to the noise in the IF and audio stages.

The relative orders of performance of the King 9100A, Collins 618M-2B and Bendix RTA-43A, as shown in Figure 2-92, remain the same at 4800 bps as those shown in Figure 2-91 for 2400 bps. However, note that for a given energy-to-noise density ratio (E/N_o) these three receivers provide better performance at 4800 bps than at 2400 bps. This increase in performance is probably due to better AM detector performance at the higher bit rate. Specifically, at a fixed E/N_o the predetection S/N in a given IF bandwidth is 3 dB higher at 4800 bps relative to 2400 bps. This effect was discussed in connection with Table 2-11 above. There is less small signal suppression at a higher predetection S/N which results in better bit error rate (P_e) at a given E/N_o at the higher bit rate. There is an additional detection effect which also results in better performance (at a given E/N_o) at 4800 bps. Namely, it is a fact that the baseband noise spectrum of an amplitude detected IF noise process is not flat even though the IF noise spectrum may be flat over an appreciable portion of the IF bandwidth. For example, the spectrum of the baseband noise linearly decreases away from zero frequency given an ideal rectangular IF filter characteristic and linear envelope detection. This means that the noise density in the vicinity of the 4800 bps MSK baseband signal is smaller than the noise density in the vicinity of a 2400 bps MSK signal, all other conditions being equal. The result is better performance at 4800 bps relative to 2400 bps at the same E/N_o where E and N_o are determined at the RF input to the receiver.

Figures 2-91 and 2-92 represent tests carried out with the GRT-21 transmitter. The audio characteristics of this unit are flat as shown in Figures 2-60 and 2-73. Thus, it should not contribute any loss in performance relative to the receivers under test.

Figures 2-93 and 2-94 show the results of performance tests of the NARCO COM-11A unmodified and modified to increase audio passband width (see Figure 2-13), the Genave Alpha-100/360, and the Collins 618M-2B. In this case, a signal generator was used to simulate the transmitter portion of the system.

Comparing the Collins performances of Figures 2-93 and 2-94 with the corresponding performances of Figures 2-91 and 2-92, it is clear that the GRT-21 is equivalent to a signal generator in that the filtering effects on the transmitted signal are negligible.

The unmodified NARCO COM-11A is apparently too narrow to pass either the 2400-bps or the 4800-bps MSK signals. The audio output of this system is roughly 10 dB down to 2 kHz, as shown in Figure 2-12. Moreover, it is quite peaked at 1 kHz. For purpose of comparison the KY-195B (Figure 2-11) is roughly 7 dB at 2 kHz and is less peaked.

The Genave Alpha 100/360 provided reasonably good performance at 2400 bps. The audio filtering characteristic shown in Figure 2-16 indicates that the response is only a few dB down at 2.4 kHz. The group delay response shown in Figure 2-29, is also reasonably flat ($\pm$ 30 μsec) over the bandwidth of interest. The Genave performance at 4800 bps was surprisingly good. The audio response is roughly 10 dB down at 4.8 kHz. However, the group delay response in the band from 2400 Hz to 4800 Hz is relatively flat ($\pm$ 15 μsec). This may explain the level of performance achieved at the higher bit rate. In this case intersymbol interference appears to account for a 4 dB loss in performance.

The modified NARCO performance did not follow the pattern previously discussed with respect to the other receivers which have relatively wide audio response. In particular, the 4800 bps performance of the modified NARCO was slightly worse than the 2400 bps performance rather than slightly better. The reason for this discrepancy is not clear. It is probable that the true filter characteristics of the modified NARCO receiver are not clearly presented in Figure 2-15. Note that at low signal levels, the response appears to start rolling off at 2 to 3 kHz. At higher signal levels, this rolloff is partially masked by the AGC action at if. This effect was more clearly evident when the response was measured at a 30 percent deviation. There, the rolloff appeared to begin around 1 to 2 kHz.

Transmitter Tests - Figures 2-95 and 2-96 show the results of NARCO, Collins, Bendix, and King 9100A transmitters with the GRR-23 receiver system. The NARCO COM-11A transmitter was tested with the Bendix RTA-43A, since the NARCO was a 50 kHz channelized unit, and the GRR-23 was fixed tuned to a 25 kHz channel (132.025 MHz).

The audio response and the audio delay characteristics for the GRR-23 receiver used in these tests is shown in Figure 2-97. Since this receiver was designed for 25 kHz channel spacing, the IF bandwidth and audio response are narrower than that shown in Figure 2-17 for the GRR-23 with 50 kHz channel spacing.

The NARCO transmitter was found to be too narrow to support 4800 bps or 2400 bps MSK signals. The passband response of the unmodified NARCO COM-11A transmitter is shown in Figure 2-58.

The performances of the King 9100, Bendix RTA-43A, and Collins 618M-2B transmitters are quite similar at 2400 bps. (It is believed that the divergence of the Collins data at around 20 dB E/N_0 in Figure 2-95 is anomalous. It may have been caused by external noise sources which creased a noise floor during these test runs. Note that the problem is gone in Figure 2-96. The only intentional difference between the test runs of Figure 2-95 and those of Figure 2-96 was the data rate.)

Comparing the performances of Figure 2-95 with those of Figure 2-91, it would appear that the transmitters in combination with the GRR-23 provide performance which is more than 2 dB worse than the best observed; i.e., the GRT-21/Bendix receiver combination. The narrower audio response of the GRR-23 is probably the source of this degradation. The passband, distortion, and group delay characteristics of the GRT-21, Bendix, Collins, and King 9100A transmitters can be compared in an attempt to explain the difference observed in Figures 2-91 and 2-95. The only important performance difference appears to be that the harmonic distortion of the GRT-21 is smaller than the others in the band from 1200 Hz to 2400 Hz. Thus, it is concluded that the GRR-23 used for the modem performance tests was the cause of the performance degradation.

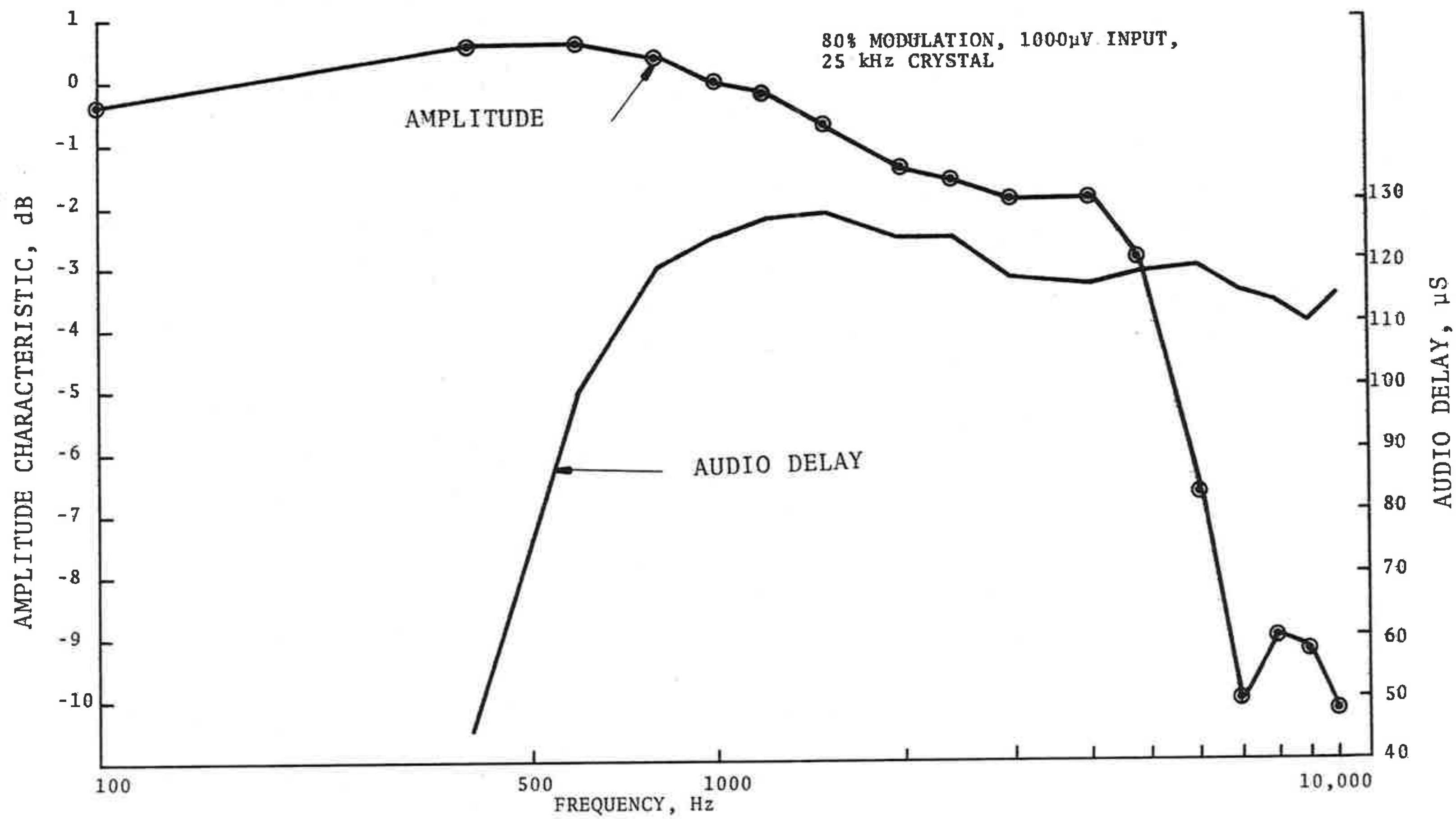


FIGURE 2-97. AUDIO RESPONSE AND PHASE DELAY FOR GRR-23 RECEIVER WITH 25KHz CHANNEL SPACING

This conclusion is supported by the results of the 4800 bps performance tests shown in Figure 2-96. The Bendix → GRR-23 performance is more than 4 dB worse than the GRT-21 → Bendix performance at 4800 bps. This loss in performance cannot be explained based on the passband, distortion, or group delay responses of the Bendix RTA-43A transmitter section. However, the GRR-23 is narrower than the Bendix receiver. The King 9100A transmitter passband is down almost 6 dB at 4800 Hz as shown in Figure 2-49. This could explain part of the performance loss in this case. That is, the higher tone is transmitted at a lower modulation index. However, the passband roll-off was compensated during the error rate tests by the modem symmetry (balance) control, thus transmitter rolloff probably had little effect.

The Collins → GRR-23 performance curve of Figure 2-96 was more than 6 dB down from the GRT-21 → Collins curve of Figure 2-92. Reference to the Collins transmitter passband characteristics of Figure 2-54 shows that this unit is essentially flat from 300 Hz through 10 kHz. Moreover, the phase response of Figure 2-67 is quite satisfactory. The performance degradation shown in Figure 2-96 is due to GRR-23 rolloff as noted above.

2.4.3 Summary of Subsystem Test Results

The results of the transmitter-receiver subsystem tests have shown that these units can cause performance losses in the range from 0 dB to 6 dB in those cases where the audio bandwidth appears adequate to support MSK operation. Some of the unmodified general aviation equipment was too narrow in bandwidth to support MSK operation. These latter units can be simply modified to provide large improvements in performance. The results have also shown that receiver filter characteristics having smooth rolloff and a bandwidth (-3 dB) of 6.5 to 8 kHz provide the best error performance Examples of these receiver filter characteristics are shown in Figures 2-4, 2-5, and 2-17.

3. AIRPORT SURFACE TESTS

Tests were conducted at Logan International Airport, Boston, Mass., during December 1974 in order to obtain estimates of potential data link performance in the multipath environment of an airport. These tests were conducted utilizing an MSK-modulated, continuous pseudo-random data sequence transmitted to a mobile test van driving on the airport surface. The test van is shown parked at the airport transmitter facility (RTR site) in Figure 3-1. A second set of tests employing a different test setup were conducted with the van to compare potential data link performance at VHF and UHF. The results of this comparison along with the analysis of the propagation characteristics at VHF and UHF are reported in Appendix A.

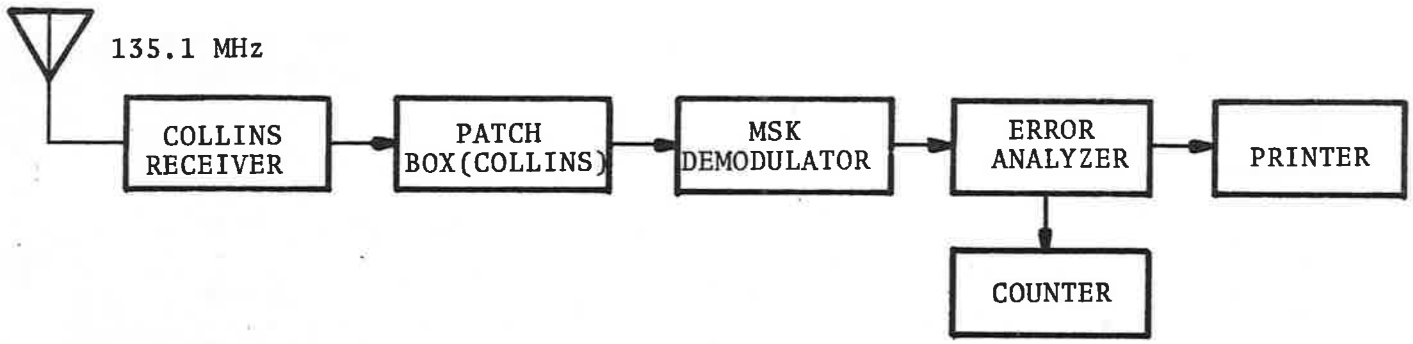
It should be noted that the link performance observed utilizing the van as a test vehicle could differ from that of an aircraft because of differences in vehicle geometry, vehicle speed, and antenna pattern effects. Thus, the results reported in this section should be taken as a first approximation to expected data link performance on an airport surface until verified by tests utilizing an aircraft as the test vehicle.

3.1 TEST CONFIGURATION

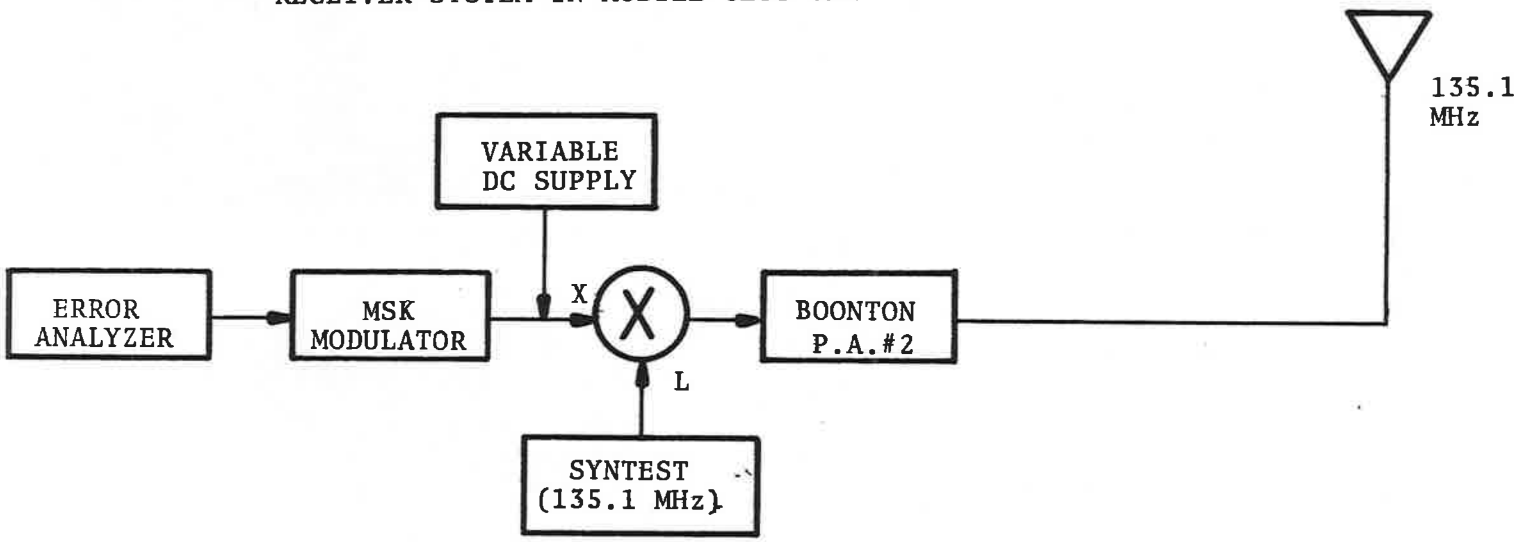
Figure 3-2 shows the test equipment configuration used in these tests. The transmitter system, shown in the lower portion of Figure 3-2, was installed in the transmitter facility at the Remote Transmitter/Receiver (RTR) site at Logan International Airport. The receiver system, shown in the upper portion of Figure 3-2, was installed in a mobile test van.

The transmitter system was used to generate the MSK-modulated signal. The error analyzer generated a pseudo-random sequence at the desired data rate of 2400 or 4800 bits per second. The error analyzer was clocked from the MSK modem and provided pseudo-random data to the MSK modem. The MSK signal was modulated onto a 135.1

FIGURE 3-1. MOBILE TEST VAN AT RTR SITE



RECEIVER SYSTEM IN MOBILE TEST VAN



TRANSMITTER SYSTEM at RTR SITE

FIGURE 3-2. TEST EQUIPMENT CONFIGURATION

MHz carrier to create an 80 percent AM waveform. This signal was amplified to approximately 0.5 watts and applied to an existing FAA broadband omnidirectional VHF antenna which was mounted on the RTR antenna platform.

The upper portion of Figure 3-2 shows the receiver system installed in the mobile test van. The MSK signal was received by a whip antenna mounted on top of the van. The same receiver used in the laboratory tests described in section 2.3.3 (Collins 618M-28) was used here to receive and demodulate the MSK signal. The output of the receiver drove the MSK demodulator which provided the data sequence in a form that was compatible with the Hewlett Packard Error Analyzer. The error analyzer output was printed on a paper tape. In particular, the number of bit errors, block errors, clock slips, and carrier losses in 100,000 bit transmissions were recorded. An event counter was driven from the error analyzer to count the cumulative errors experienced during a test run. This counter accumulated all errors, including those which occurred during the error analyzer's printing cycle. The input to the cumulative error counter was recorded during some of the test runs. A tape recorder was used to provide continuous voice commentary describing test conditions, mobile van location, and any anomalous conditions which occurred during the test runs.

3.2 TEST PROCEDURES

Tests were conducted at Logan International Airport on December 3, 4, and 5, 1974. Preliminary tests were conducted in late November 1974.

The preliminary testing effort provided estimates of the received signal dynamic range for various sectors of the airport. Furthermore, general estimates of the error rates expected for the various sectors were obtained. Based on these preliminary findings four general airport sectors were defined for Logan International Airport. These sectors are listed below:

TWA-International Arrivals Area

Eastern Terminal Area

TWA-Delta-Allegheny-AA Area

Bulkhead Road

These sectors are shown on the map in Figure 3-3.

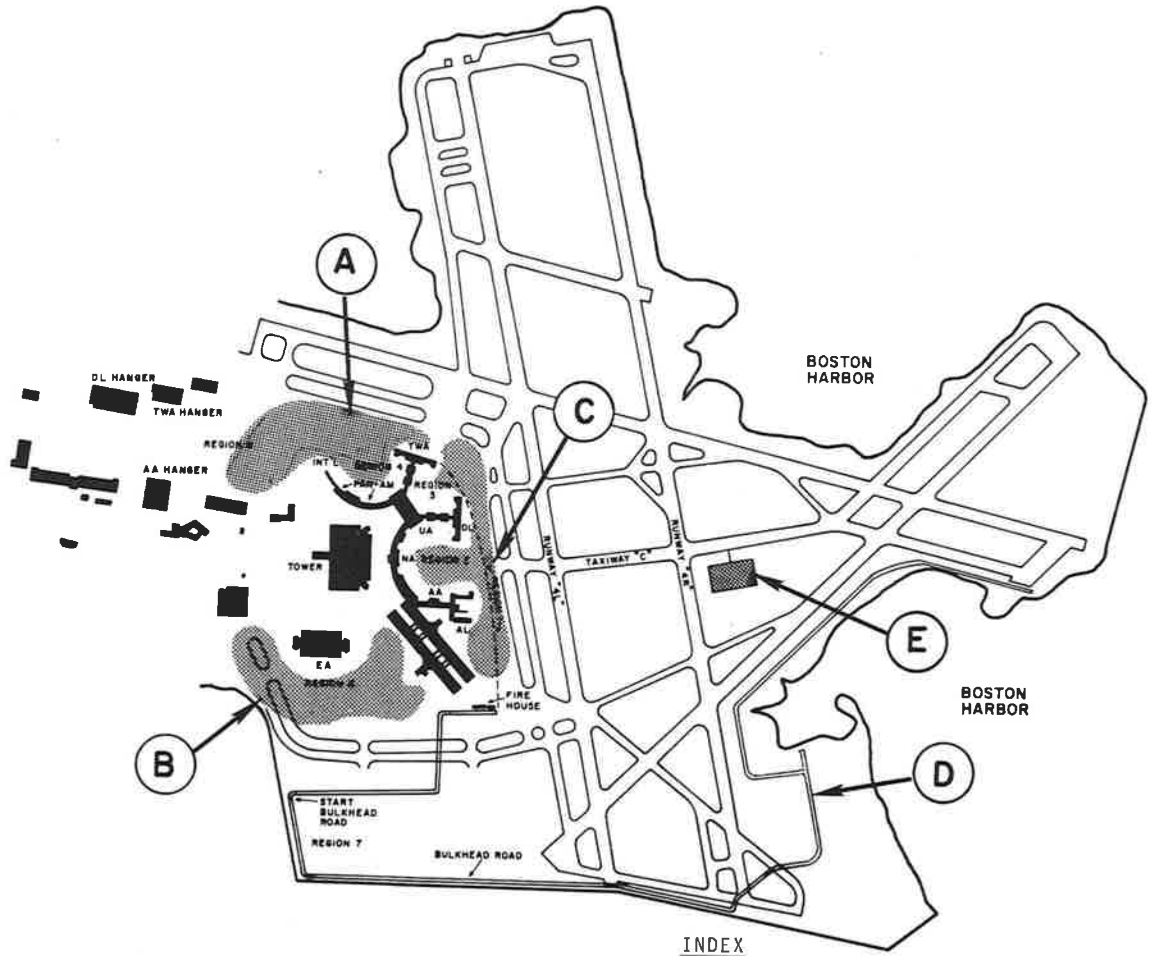
The Bulkhead Road follows the airport boundary along Boston Harbor. Propagation conditions on this road are almost always line-of-sight except for occasional blockages by small buildings such as radar shelters or landing aid equipment shelters.

Line-of-sight to the Eastern Terminal area is blocked by the new American Airline Terminal which was under construction (Dec. 1974). The data taken in this sector were collected in part with the mobile van in close proximity to the buildings and in part on the truck lane. The latter is a roadway marked on the apron area which circumscribes all the terminal areas under consideration here. In any case, the mobile test van followed potential aircraft ground taxi routes at all times. Mobile van velocity varied in the range of 10 to 20 MPH most of the time.

The American-Delta sector is almost always line-of-sight to the RTR site. The exceptions occurred when the line-of-sight was blocked by taxiing aircraft or by large service vehicles. As can be seen from Figure 3-3, the distance to the RTR site is quite small, on the order of 3000 feet.

Most of the TWA-International Arrivals sector is out of line-of-sight from the RTR facility. Again, the mobile test van followed the truck lane for much of the data runs with occasional diversions closer to the terminal buildings. At all times the vehicle followed potential aircraft routes.

The data taking procedure was straightforward. First, all systems were energized and locked up. The printer was started and the cumulative error counter was reset. From time to time during a data run, the MSK modem or the error analyzer lost lock. In that case, the system was reacquired and the cumulative error counter was reset. These events and general comments were noted on a voice tape recorder.



INDEX

A. TWA-INTERNATIONAL ARRIVALS
B. EASTERN TERMINAL AREA
C. TWA-DELTA-ALLEGHENY-AA
D. BULKHEAD ROAD
E. RTR SITE

FIGURE 3-3. LOGAN INTERNATIONAL AIRPORT

3.3 DATA TRANSMISSION TEST RESULTS

MSK data performance was recorded by printing the error analyzer output for each 100,000 bits transmitted and by observing and recording the cumulative error count as a function of mobile test van position. This section presents and discusses bit error results, block error results, and the unlock problem.

3.3.1 Bit Error Performance

The distance from the RTR site to the mobile test van was typically in the range from 3000 ft to 7000 ft. The power output at the RTR site was on the order of 30 dBm effective radiated power (ERP), assuming 3 dB transmitter antenna gain and neglecting cable losses. Received power can be estimated as a function of range using Figure 3-4.* However, note that the axes in Figure 3-4 are calibrated for 70 MHz transmission. Therefore, "receive level dBm," and "receiver level μvolts" should be reduced by 5.7 dB to apply at 135 MHz. On the other hand, the receiver antenna, mounted on the mobile test van, was roughly 12 ft above the terrain instead of 6 ft as assumed for Figure 3-4. To compensate for the increase height, roughly 6 dB should be added to the received power level. In effect, the axis labeling of Figure 3-4 can be used as is for the case under consideration here.

Assuming a transmitter antenna height of 33 ft, the received power level at the 3000-ft range is on the order of -56 dBm, and at 7000 ft it is on the order of -72 dBm.

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*Figure 3-4 shows the propagation loss to be expected on typical links under the conditions specified in the figure. It is assumed in the figure that the terrain is not perfectly flat and to some extent shadowing occurs. The transmitting antenna height is measured with respect to the median terrain height between transmitter and receiver. These curves are based on data taken from NBS TN-101, Rice et al., May 7, 1965.

The noise level can be estimated by assuming an ambient noise figure of 20 dB. Then the noise power in a 20 kHz bandwidth is approximately -111 dB. Thus, the expected signal-to-noise ratio 50 percent of the time at 50 percent of all locations is in the range from 55 dB to 39 dB. This indicates that better than half the time, the system should see extremely high S/N's and therefore should not make any errors.

The results indicated that such high quality performance was never achieved even under line-of-sight conditions in the vicinity of airline terminals.

This effect is illustrated in Table 3-1, which summarizes the bit error rates (P_e) observed on the Bulkhead Road and on the apron in the region from TWA-Delta to the American-Allegheny terminal area.

TABLE 3-1. PERFORMANCE UNDER LINE-OF-SIGHT CONDITIONS

Bits per Second	Probability of Bit Error	Test Duration	Locations
4800	1×10^{-5}	300 sec	RTR to TWA
4800	5.3×10^{-5}	1080 sec	Bulkhead Road and Apron to TWA
2400	1.12×10^{-5}	465 sec	Bulkhead Road
2400	3.96×10^{-6}	210 sec	C Taxiway to TWA
2400	9.6×10^{-6}	130 sec	Delta to Allegheny
2400	3.2×10^{-5}	270 sec	AA Terminal Area
4800	5.1×10^{-5}	375 sec	TWA to New Construction
	3.4×10^{-5}	2830 sec	Weighted Average All Locations

The above data were collected in areas C and D of Figure 3-3. Note that the performance at 4800 bps was not significantly different from the performance at 2400 bps and that the final entry in Table 3-1 averages all data at both bit rates. In the absence of multipath, the required S/N to achieve an error rate on the order of

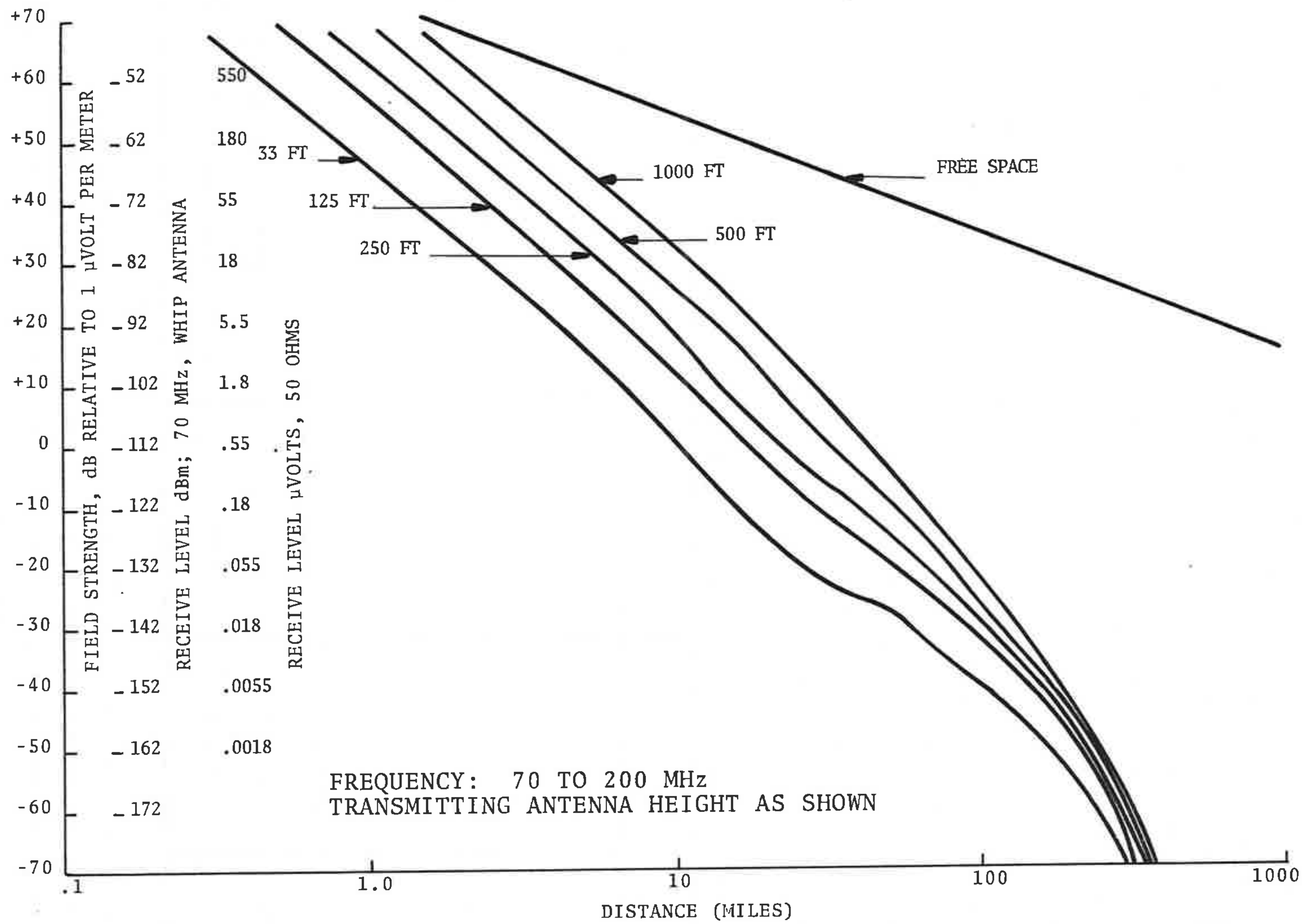


FIGURE 3-4. MEDIAN FIELD STRENGTH (50% TIME AND LOCATION) FROM A TRANSMITTER OF E.R.P. 1 WATT WITH A RECEIVING ANTENNA HEIGHT OF 6 FEET

TABLE 3-3. BIT ERROR RATE (P_e) PERFORMANCE IN THE INTERNATIONAL ARRIVALS TERMINAL AREA

Bits per Second	Probability of Bit Error	Test Duration	Location
4800	4.3×10^{-4}	800 sec	TWA to Int'l Arrivals
4800	1.65×10^{-3}	275 sec	Int'l Arrivals to AA Hangar
2400	9.65×10^{-5}	410 sec	TWA to AA Hangar
2400	1.05×10^{-5}	120 sec	Vicinity AA Hangar
2400	7.4×10^{-4}	40 sec	TWA-Int'l Arrivals
4800	7.42×10^{-4}	1075 sec	Weighted Average (4800)
2400	1.24×10^{-4}	570 sec	Weighted Average (2400)
----	5.28×10^{-4}	1645 sec	Weighted Average All Data

P_e and P_b for this case is plotted in Figure 3-5. The expression for P_b above is simply modified to account for errors occurring in groups of k at a time by assuming that the probability of a group of k errors is approximately P_e/k. Then, the P_b is approximated by

$$P_b \cong 1 - \left(1 - P_e/k\right)^{1000} \qquad (3\text{-}2)$$

for N = 1000. The effect of errors occurring k at a time is to shift the curve of Figure 3-5 to the right by an amount porportional to k.

Figure 3-5 shows some of the laboratory data under various multipath conditions superimposed on the block error curve. In the absence of multipath, the data indicate that errors did occur at random. With multipath present, the data indicate that errors occurred roughly two at a time when P_e was high. They appear to be more random when P_e is low.

3×10^{-5} can be estimated from Figure 2-88 to be $E/N_o \cong 17$ dB. Assuming a bit rate of 2400 bps and an i-f bandwidth of 20 kHz, this corresponds to $S/N \cong 7.8$ dB. The calculated S/N exceeds 39 dB. Thus a fading margin of more than 30 dB is provided.

Since line-of-sight conditions generally prevailed for the values summarized in Table 3-1, it is concluded that performance was significantly degraded by some phenomenon other than receiver front-end noise. Typically, such degradation is caused by multipath and/or ambient noise. Note furthermore that the tabulated results exclude most of the data in which unlocks occurred. Therefore, actual performance is somewhat worse than that presented. The unlock problem is discussed in section 3.3.3 below.

Tables 3-2 and 3-3 summarize results achieved in the Eastern and International Arrivals terminal areas, respectively. Once again the data presented exclude most of the cases in which unlocks occurred.

TABLE 3-2. BIT ERROR RATE (P_e) PERFORMANCE IN THE EASTERN TERMINAL VICINITY

Bits per Second	Probability of Bit Error	Test Duration	Location
4800	8×10^{-4}	725 sec	Eastern Area
2400	5.7×10^{-4}	190 sec	Fire Sta. to E.A.
4800	1.3×10^{-4}	160 sec	Eastern Area
	6.6×10^{-4}	1075 sec	Weighted Average All Locations

3.3.2 Block Error Performance

Given that bit errors occur at random with a bit error rate, P_e, the block error rate, P_b, for a block N bits long is given by

$$P_b = 1 - \left(1 - P_e\right)^N \qquad (3\text{-}1)$$

The error analyzer used in the laboratory and field tests was set to provide blocks with N = 1000. The relationship between random

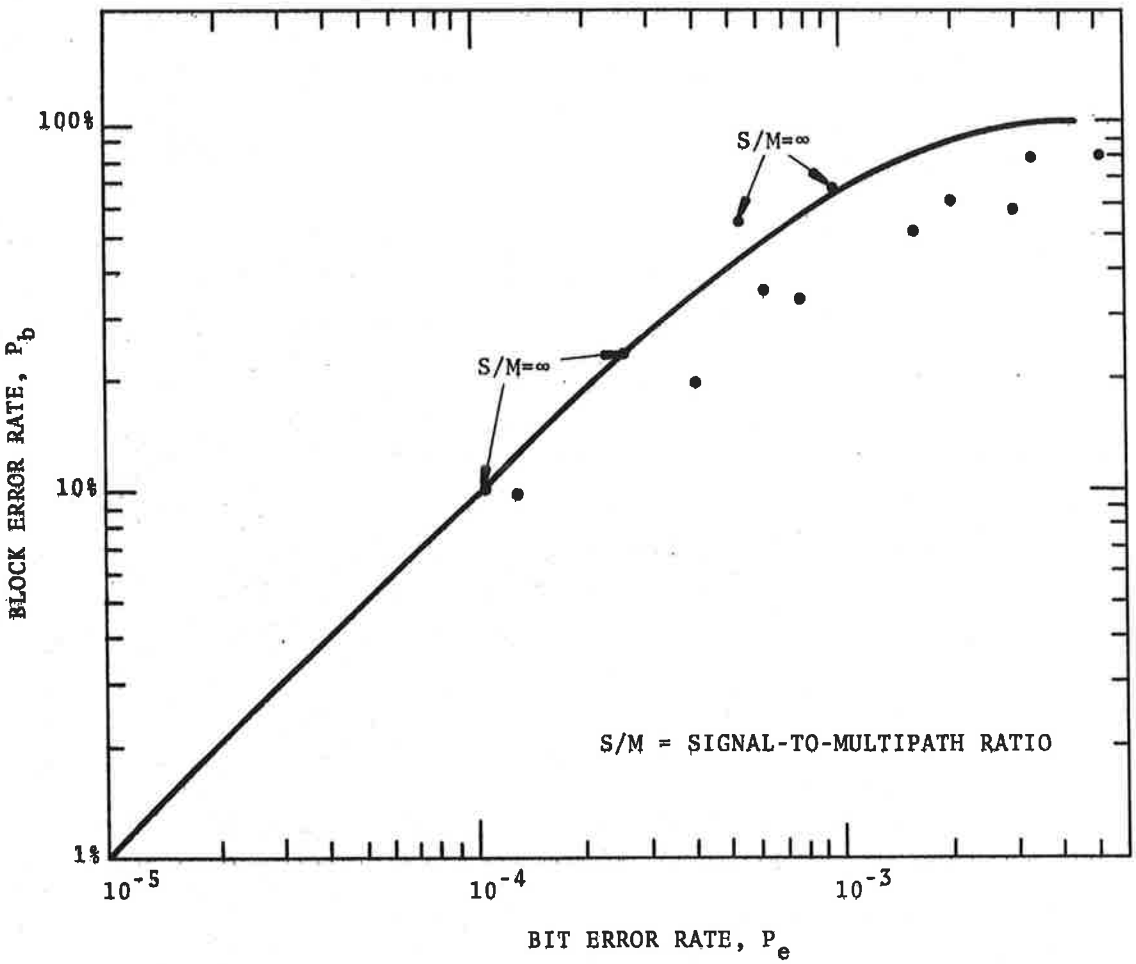


FIGURE 3-5. BLOCK ERROR RATE ANALYSIS OF LABORATORY DATA

Figure 3-6 shows observed P_b as a function of observed P_e for data collected on December 3, 4, and 5, 1974, at Logan International Airport. Each point compares P_e in 100,000 bits to block errors with a 1000 bit block size.

An analysis of these data yielded the results shown in Table 3-4.

TABLE 3-4. BLOCK ERROR ANALYSIS

Number of Consecutive Error	Percentage Occurrence
$k \leq 2$	56
$2 < k \leq 3$	19
$3 < k \leq 4$	6
$4 < k \leq 5$	11
$5 < k$	8

Once again it is noted that the data used to generate Figure 3-6 and Table 3-4 exclude all runs in which unlocks occurred. The field test results were comparable to the laboratory results; i.e., 56 percent of the time errors occurred in clusters of 2 or less.

3.3.3 The Unlock Problem

The unlock problem was easily handled in the laboratory. In that case, any data runs in which unlock occurred were rejected, and a sufficient number of undisturbed runs were performed to derive meaningful statistical results.

The situation in the field was much less controlled. Consider, for example, data collected in the vicinity of the Eastern Airlines terminal on Dec. 3, 1974. A total of 46 data runs of length 100,000 bits were performed. Of these, 16 contained one or more unlock indications; i.e., 35 percent. The bit error rate averaged over all data exceeded 4×10^{-3}. If all data involving unlocks were excluded, the observed error rate was roughly 8×10^{-4} as noted in Table 3-3. The effect on block error analysis was not so severe

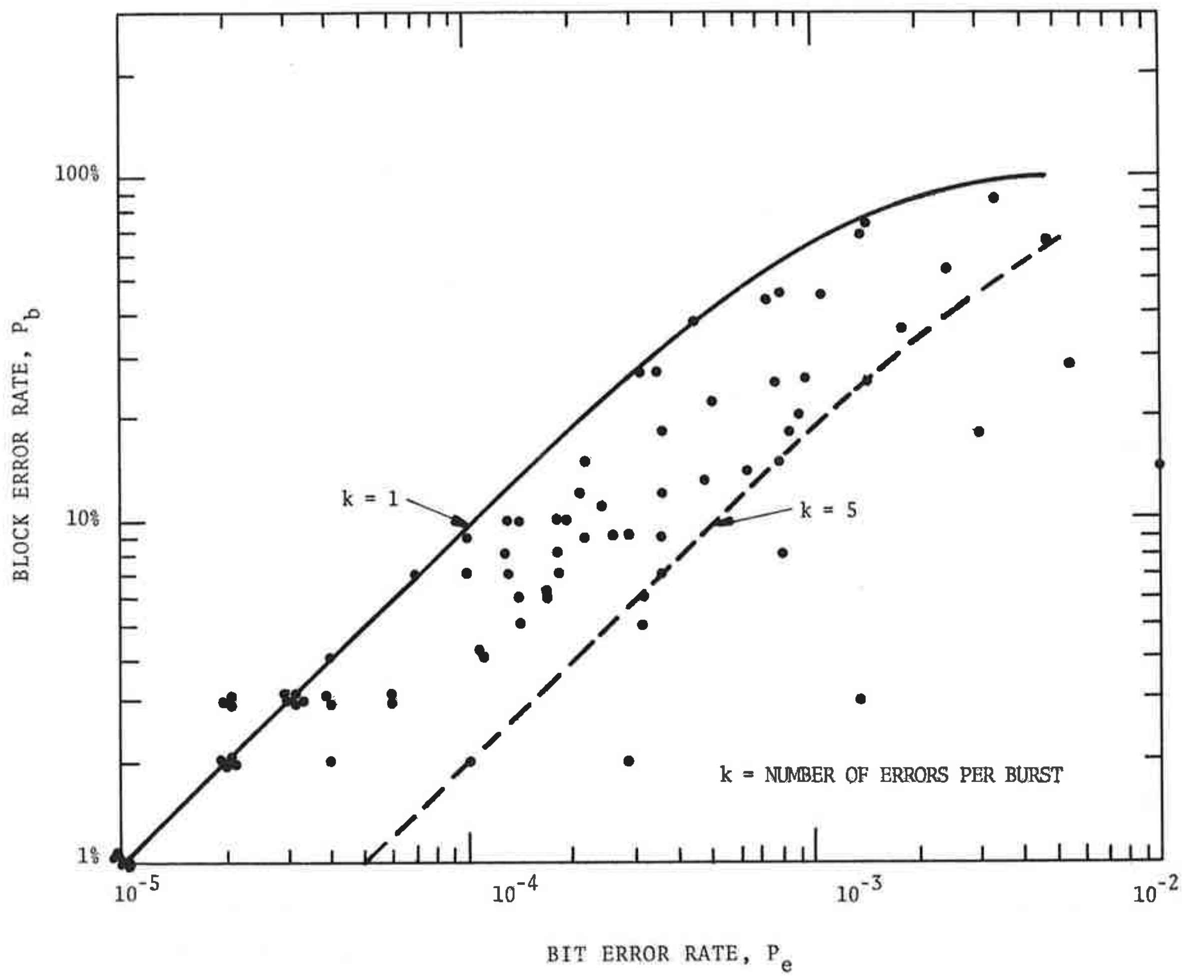


FIGURE 3-6. BLOCK ERROR RATE ANALYSIS OF FIELD TEST DATA

because system unlock caused bursts of errors. Thus, the block error rate including all data was estimated to be 18 percent while the corresponding result excluding data with unlocks was roughly 8 percent.

The data which exclude unlocks will provide somewhat optimistic results when applied to overall system evaluation. On the other hand, the data which include the unlocks are much more unrealistic because these results depend on the reacquisition characteristics of the modem and furthermore include some errors created by the error analysis system. Therefore, such data are rather pessemistic.

The density of unlocks observed in the poor proprgation areas may indicate that the MSK modem will exhibit degraded acquisition performance in these areas. In other words, a system which will not stay in lock under a given set of conditions will probably not be able to acquire under the same conditions. This hypothesis should be tested if possible because failure-to-acquire will have an effect on message retransmission loads and alarm rates.

3.4 DATA LINK PERFORMANCE ANALYSIS

A brief discussion of the projected performance of a data link system in the airport environment is presented below.

3.4.1 Performance Model

The data transmission experiment results described in section 3.3 can be used to derive a baseline link performance model for the purposes of system evaluation. The specific goal of the evaluation is to determine whether significant numbers of retransmissions or alarms will be caused by the presence of multipath in the airport environment.

3.4.1.1 Link Performance - The data of section 3.3 show that in most cases there was no substantial difference in performance observed at 2400 bps or 4800 bps. In the discussion which follows either bit rate can be assumed.

Under line-of-sight conditions, the average bit error rate was on the order of 3×10^{-5} (excluding most unlocks). Figure 3-5 shows that under these conditions bit errors occurred singly or two at a time. When the line-of-sight was obstructed, the expected error rate was on the order of 5×10^{-4}. The errors in this range occurred two at a time or less on the average. Worst case error rates on the order of 1×10^{-3} or more were observed in the vicinity of terminal gate areas. There, errors occurred two or three at a time.

3.4.1.2 Message Characteristics - Data link messages will probably have 17 characters containing administrative data (i.e., overhead). Short messages will contain between 1 and 10 characters. Therefore, for the purposes of analysis, typical short messages will be assumed to have 25 characters or 200 bits. The maximum message text length is 220 characters. Thus, maximum total message length is 237 characters. Therefore, for purposes of analysis, typical long messages will be assumed to have 225 characters or 1800 bits.

Proposed data link system configurations have a capability for detecting transmission errors. When errors are detected a retransmission is requested. The number of retransmissions of a given message is limited by the system monitor algorithms to a value on the order of five. The user modems are also equipped to generate an alarm if the time between successive polls exceeds a value which is determined by the system monitor algorithms. Retransmission requests may increase queuing delays given that a significant number of aircraft are operating under poor propagation conditions. The alarm feature requires the pilot to establish voice contact with the controller when the aircraft is not polled in a routine manner. Thus, an aircraft located in a poor propagation area may have a continuous or frequent alarm condition. The pilot is likely to defeat the system in that case. Alternatively, the ground controllers workload will be increased unecessarily by frequent pilot interrogations given that the pilot does not defeat the system. In general, it is highly desirable to avoid frequent retransmissions or alarms.

3.4.2 Communication Analysis

The effect of decreased bit error rate performance on a typical data link system is considered below.

3.4.2.1 Message Error Rate - Message error rate is computed in the same way that was given for block error rate. That is, the probability of message error given an N bit message, a probability of bit error P_e, and that errors occur k at a time, is

$$P_m = 1 - \left(1 - P_e/K\right)^N \tag{3-3}$$

Furthermore, the probability that a message is not received properly after M retransmission attempts, P_M, is

$$P_M = \left(P_m\right)^M \tag{3-4}$$

These expressions are used below to establish communication performance estimates.

3.4.2.2 Communication Performance Evaluation - Table 3-5 summarizes the communication performance expected under the various conditions encountered during the field tests. Five transmissions are assumed. The results of Table 3-5 exclude the effect of most of the unlocks observed during the field tests and do not account for possible failures-to-acquire.

Table 3-5 shows that line-of-signt communication of short messages will typically be accomplished on the first transmission. Long messages may require retransmissions 2 to 5 percent of the time.

Under obstructed conditions, short messages may require retransmission 3 to 5 percent of the time while long messages will require retransmission 26 to 36 percent of the time. Given a maximum of 5 retransmissions short messages will be communicated with high probability. However, a little less than 1 percent of long messages will not be received.

TABLE 3-5. COMMUNICATION PERFORMANCE ESTIMATES

Line Description	P_e	k	Message Length	P_m	P_M
Line-of-Sight	3×10^{-5}	1	200 bits	6×10^{-3}	7×10^{-12}
Line-of-Sight	3×10^{-5}	2	200 bits	3×10^{-3}	2×10^{-13}
Line-of-Sight	3×10^{-5}	1	1800 bits	5.3×10^{-2}	4×10^{-7}
Line-of-Sight	3×10^{-5}	2	1800 bits	2.6×10^{-2}	1.3×10^{-8}
Obstructed	5×10^{-4}	2	200 bits	4.9×10^{-2}	2.8×10^{-7}
Obstructed	5×10^{-4}	3	200 bits	3.3×10^{-2}	3.8×10^{-8}
Obstructed	5×10^{-4}	2	1800 bits	3.6×10^{-1}	6.3×10^{-3}
Obstructed	5×10^{-4}	3	1800 bits	2.6×10^{-1}	1.2×10^{-3}
Worst Case	1×10^{-3}	2	200 bits	9.5×10^{-2}	7.8×10^{-6}
Worst Case	1×10^{-3}	3	200 bits	6.6×10^{-2}	1.1×10^{-6}
Worst Case	1×10^{-3}	2	1800 bits	5.9×10^{-1}	7.4×10^{-2}
Worst Case	1×10^{-3}	3	1800 bits	4.5×10^{-1}	1.9×10^{-2}

Worst case conditions near terminal gate areas will require retransmission of short messages 6 to 9 percent of the time. Long messages will require retransmission 45 to 59 percent of the time. Again, short messages will be communicated successfully given a maximum of five retransmissions. However, long messages will fail to be accurately received 2 to 7 percent of the time under this constraint.

Interpretation of these results requires more data concerning system utilization. For example, the number of long messages per hour to be transmitted to aircraft in their gate areas could be used to determine system failures per hour. Ground traffic controllers will probably be satisfied with system performance if the number of failures per hour is much less than one. On the other hand, airline users will probably be concerned only with failure rates of the type shown in Table 3-5. Such failure rates should be kept below 1 percent at all locations.

The communication of long messages under obstructed conditions will frequently require at least one retransmission. This could have a significant effect on queuing delay given that such messages constitute a large portion of total message traffic.

Finally, it is important to note that the collected data were averaged over time and location. Thus, some locations may be substantially worse than others at a given time. Changes in weather (ground wetness, humidity), the positions of parked service vehicles and parked aircraft, all affect propagation conditions. Thus, it is reasonable to expect large deviations from the average conditions discussed in this section.

A solution to the potential queue delay problem (multiple retransmissions) resulting from poor propagation conditions that sometimes occur when aircraft are parked close to large structures (at gates) with blockage in the transmission path might require ground antenna diversity or hard wire connections to the data link system.

3.5 SUMMARY OF AIRPORT SURFACE TEST RESULTS

Tests were conducted at Logal International Airport, Boston, Massachusetts, in order to obtain estimates of potential data link performance in the multipath environment of an airport. These tests were conducted at data rates of 2400 and 4800 bits per second (bps) utilizing an MSK modulated, continuous pseudo-random data sequence transmitted to an aircraft receiver located in a mobile test van that was driven on the airport surface. The test results showed approximately equal performance at data rates of 2400 and 4800 bps. A wide variation in bit error rate (P_e) was observed as a function of van position on the airport surface, even though signal fading margins were estimated to exceed 30 dB for all van positions. The average P_e performance ranged between 4×10^{-3}, with many unlocks for obstructed condtions, to 3×10^{-5} for line-of-sight conditions. This variation in performance is indicative of multipath phenomena due to the many large reflective surfaces and obstructions on the airport surface. The density of unlocks observed in the poor propagation areas indicates that the MSK modems will exhibit degraded acquisition performance in these areas.

An analysis of expected data link system performance on the airport surface was performed. This analysis utilized the observed P_e data and assumed a polling strategy that allowed up to 5 retransmissions to deliver a message correctly. The results of this analysis indicate that line-of-sight communication of short messages will typically be accomplished on the first transmission. Long messages may require retransmissions 2 to 5 percent of the time. Under obstructed conditions, short messages may require retransmission 3 to 5 percent of the time while long messages will require retransmission 26 to 36 percent of the time. Given a maximum of five retransmissions, long messages will be communicated with high probability. However a little less than 1 percent of long messages will not be received. Worst case conditions, near terminal gate areas, will require retransmission of short messages 6 to 9 percent of the time. Long messages will require retransmissions 45 to 59 percent of the time. Again, short messages will be communicated successfully given a maximum of five retransmissions. However, long messages will fail to be accurately received 2 to 7 percent of the time.

It is concluded that the percentage of successful message delivery can be significantly improved with ground antenna diversity or hard wire connection to the data link system when aircraft are parked in gate areas with known poor propagation conditions. It is further concluded that similar tests should be repeated at several airports utilizing an aircraft as the test vehicle in order to verify the results obtained with the van at Logan International Airport.

4. DIGITAL DATA TRANSMISSION FLIGHT TESTS

This section summarizes the results of flight tests that were conducted to characterize the VHF channel for the transmission of digital data. These simplified tests, involving no link management logic nor formatted messages, were conducted as a logical prelude to the design and test of an experimental data link system. The flight tests were conducted over a variety of terrain that encompassed mountainous regions, water, coastal regions, and urban areas. The flight tests were flow from the FAA/NAFEC facility on board the FAA owned Gulfstream I aircraft, N-377, shown in Figure 4-1. Continuous psuedo-random sequences were transmitted air-to-ground at data rates of 2400 and 4800 bits per second to the ground receiving site located at NAFEC. No synchronization signals were provided in the data stream. Data collected at the ground station, in the aircraft, and at the EAIR radar tracking facility were merged and analyzed to yield measures of bit and block error rates as a function of aircraft position (slant range and altitude) and aircraft attitude. Geographical coverage was determined from measurements of received signal strength. High error rate regions near the radio horizon were defined. Signal fading was monitored and related to error occurrences as a function of aircraft attitude. A more detailed description of these tests may be found in Reference 11.

4.1 FLIGHT TEST SYSTEM HARDWARE CONFIGURATION

Block diagrams of the airborne and ground site equipment are shown in Figures 4-2 and 4-3, respectively. In the airborne system the continuous psuedo-random sequences were generated by the RANGE RIDER 1200 Modem Test Set, encoded by the MSK modem, and transmitted to the ground site by the King KTR 9100A VHF Transceiver at a frequency of 120.85 MHz. The

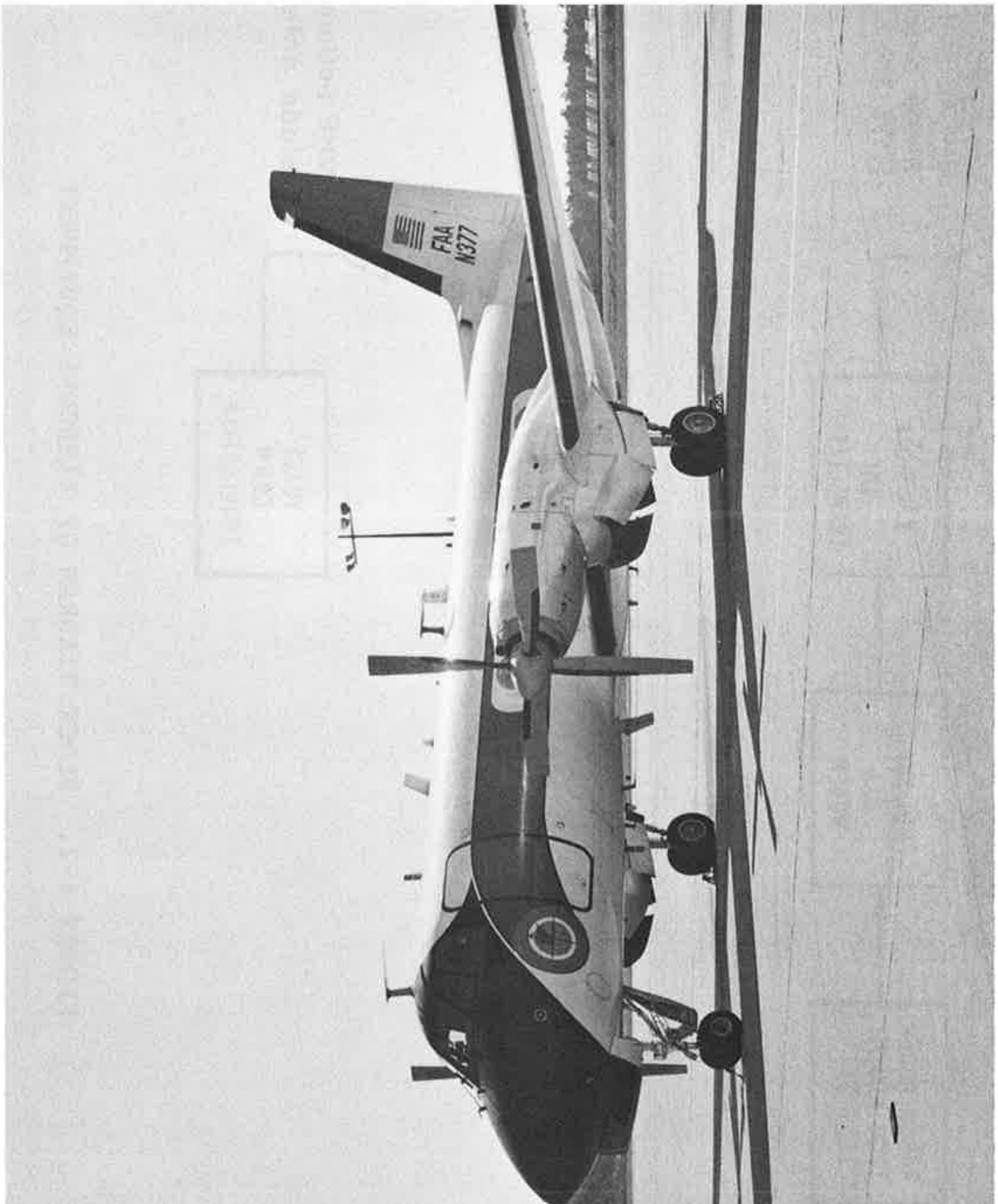


FIGURE 4-1. TEST AIRCRAFT

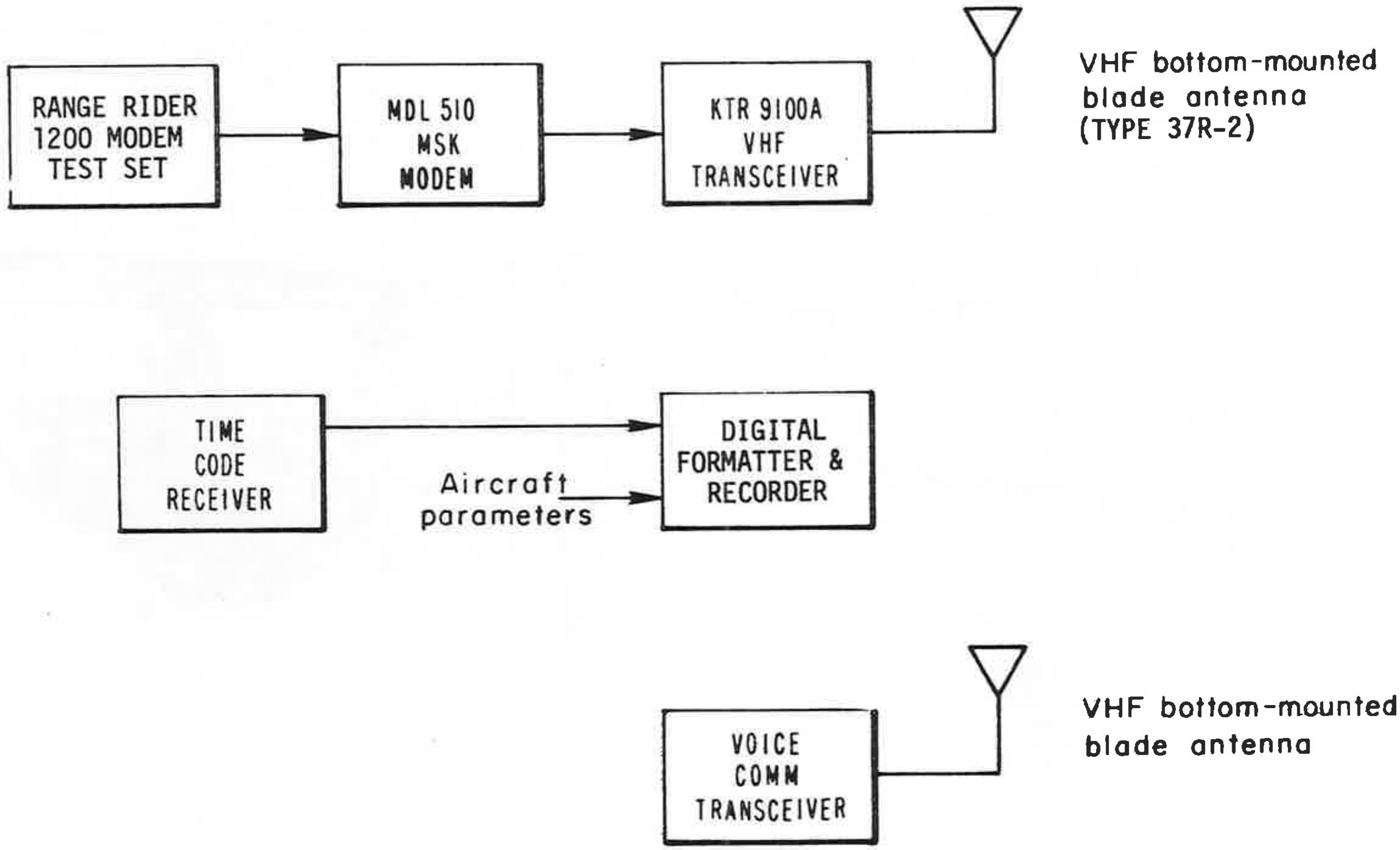


FIGURE 4-2. BLOCK DIAGRAM OF AIRBORNE EQUIPMENT

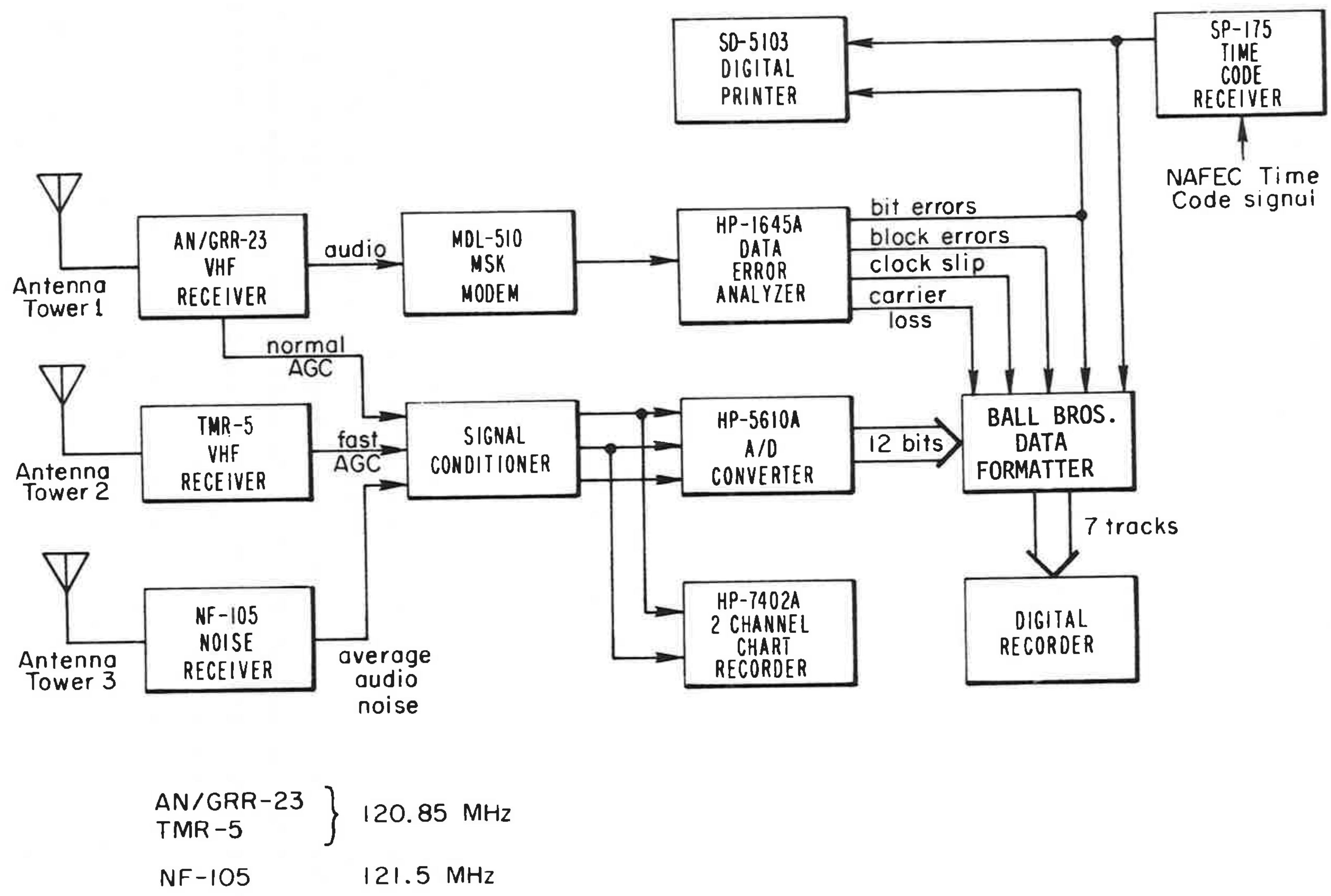


FIGURE 4-3. BLOCK DIAGRAM OF GROUND SITE EQUIPMENT

pseudo-random sequence for these tests was a 1023 bit maximal length shift register code. Aircraft parameters such as altitude, airspeed, roll angle, pitch angle, and heading were recorded in digital format on an Incre-Data digital recording system. The output of the Time Code Receiver, which provided the experiment time reference, was also recorded on the Incre-Data system. The parameters were sampled and recorded at 0.1 second intervals.

At the ground site, the MSK modulated signal was received on both the GRR-23 and TMR-5 receivers. The latter receiver provided a relatively fast AGC output, which was used to record signal fading characteristics. The GRR-23 AGC output was also recorded. The audio output of the GRR-23 receiver was demodulated in the MSK modem and passed through the HP 1645A Data Error Analyzer to detect and identify errors introduced in the transmission of the data stream. The HP 1645A was modified to provide simultaneous, parallel outputs of bit errors, block errors, clock slips, and incidents of carrier loss. The block length was 1000 bits. The output of the Data Error Analyzer was inputted to the Data Formatter where the errors were counted. The AGC outputs of the GRR-23 and TMR-5 receivers along with the Time Code Receiver output were also inputted to the Data Formatter after signal conditioning and conversion to digital data in the A/D Converter. The NF-105 Noise Receiver was tuned to the nearest clear channel (121.50 MHz) to provide an indication of the average ambient noise. The output of the Data Formatter was recorded on a 7 track digital recorder. The data were sampled and recorded at 0.1-second intervals with the exception of the TMR-5 AGC output, which was sampled and recorded at 400 times per second.

The output of the EAIR tracking radar in the form of range, azimuth, and elevation angle along with the Time Code Receiver output was recorded on a separate digital recorder at 10 samples per second.

The resulting three digital data tapes from the airborne, ground site, and tracking radar systems were merged into a single data tape for data reduction purposes.

4.2 EXPERIMENT PROCEDURES

Eleven test flights were conducted between December 1974 and February 1975. The airborne equipment was installed in the cabin of the Gulfstream I aircraft. The aft, bottom-mounted antenna, located at aircraft station 455, was used for these experiments. The ground site equipment was located in NAFEC Building No. 224. The three receiver antennas (Swastika, Type CA-1781) were mounted on separate 60-foot antenna towers, each separated by 80 feet.

The radar track data from the NAFEC EAIR system were offset to the ground station site to provide communication center oriented tracking.

The matrix of flight tests is shown in Table 4-1, and a map showing the approximate flight paths for the tests is shown in Figure 4-4. The actual flight path flown on a given flight consisted of many maneuvers and altitude changes to satisfy the experiment objective to relate communication performance with aircraft maneuvers and to define the radio horizon as a function of altitude and slant range. The flights were conducted up to a maximum altitude of 20,000 feet. Included in the flights were passes over high-noise urban areas such as Philadelphia, ascending spiral flight paths over MacArthur Field on Long Island, and many outbound and inbound interceptions of the radio horizon at various altitudes. Typically, data collection started with the aircraft on the ramp prior to taxi for takeoff and ended when the aircraft returned to the ramp subsequent to landing. Thus, the collected data include data from all portions of a typical flight up to 20,000 feet.

TABLE 4-1. GENERAL SUMMARY OF FLIGHTS

Flight No.	Date	Start Time (EST)	Direction	Max. Distance (n mi)	Max. Altitude	Flight Duration (hr)	Data Rate (bps)	Comments
5	12/6/75	06:02	New York	112	18,049	1.3	2400	Landed McArthur
6	12/12/74	14:30	Scranton	136	20,904	1.2	2400	Landed Philadelphia Int.
7	12/19/74	06:18	Scranton	128	18,158	1.2	2400	
9	12/23/74	13:16	Norfolk	191	17,201	2.6	2400	To Sea Isle Radial
10	1/7/75	09:05	Norfolk	191	16,259	2.4	2400	
11	1/8/75	13:04	New York	112	17,633	1.4	2400	1 mile from McArthur
12	2/11/75	13:25	Norfolk	187	17,015	2.4	4800	
13	2/13/75	09:09	Norfolk	185	16,907	2.1	4800	Landed Cape May
14	2/13/75	13:58	New York	115	16,028	1.5	2400	7500 feet approach to McArthur
15	2/21/75	13:45	Scranton	129	18,845	1.0	4800	Over N. Philadelphia
16	2/21/75	15:05	Scranton	132	18,110	1.1	4800	Over N. Philadelphia

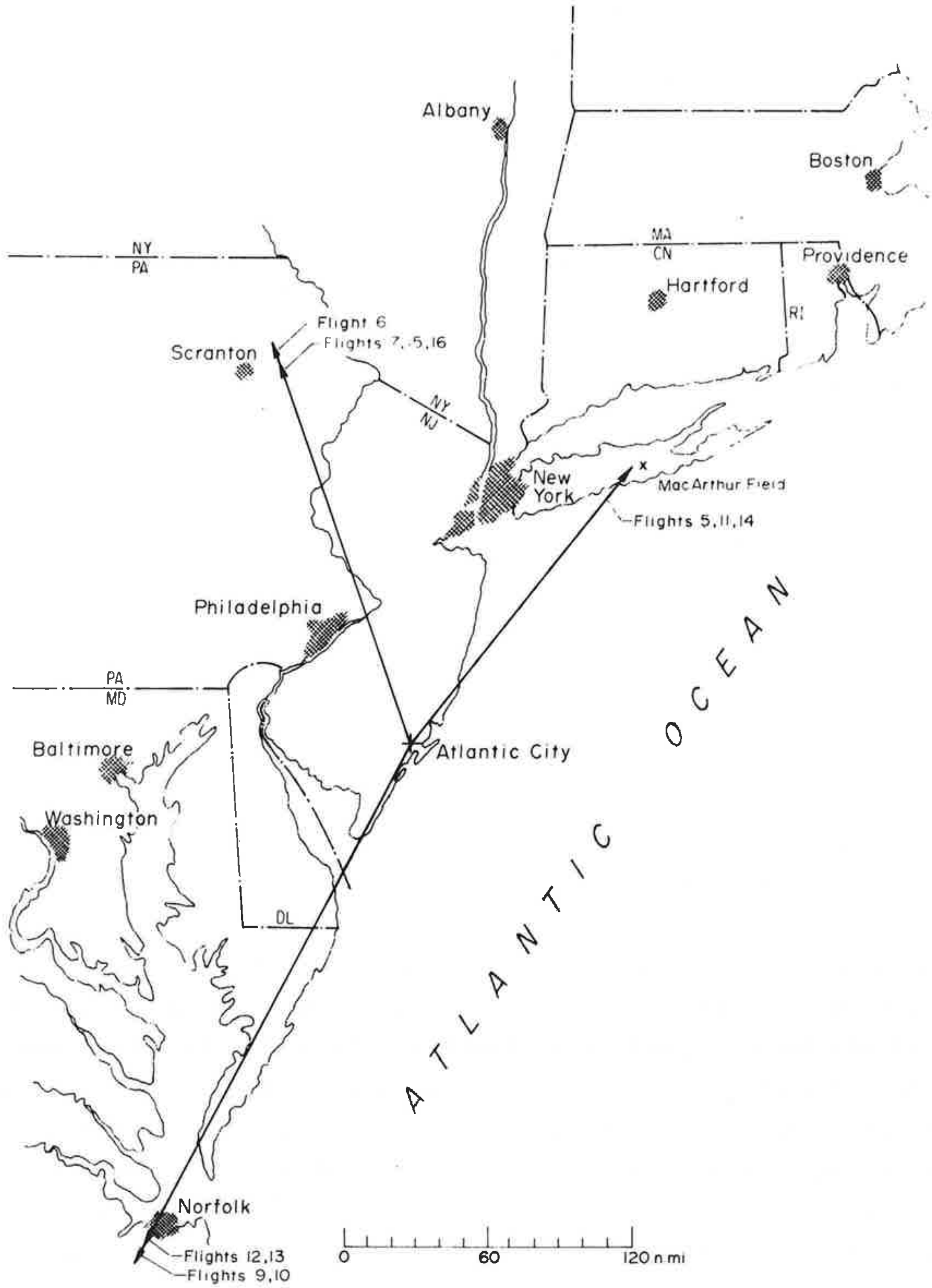


FIGURE 4-4. MAP SHOWING APPROXIMATE FLIGHT PATHS

Portions of the flights extended beyond the range of the tracking radar. Dead reckoning techniques, based on the recorded aircraft parameters (i.e., altitude, heading, speed) were used to reconstruct the flight paths in those regions of flight that were beyond the tracking range of the radar.

4.3 DATA ANALYSIS CONSIDERATIONS

The data tapes from the airborne, ground site, and EAIR radar systems were merged into a single tape by utilizing the reference NAFEC central time recorded on each data tape. The reduced data were analyzed by first removing all error data that occurred when the aircraft was beyond the radio horizon. The second step was to remove all identifiable error data that occurred due to equipment and/or operational problems. For example, the most common equipment error occurred when error counters overflowed due to occasional data clocking problems (the system had several data clocks). Forgetting to turn on certain equipment is an example of a typical operational problem that occasionally led to false error indications.

When analyzing the data, it became apparent that the aircraft encountered a region of high error density prior to interception of the radio horizon. This region of high error density is referred to as the near horizon region in this report. The near horizon region varied in width from 0.5 to 20 nautical miles (average of 10 n mi) and appears to be independent of altitude. Since an operational data link system would not be designed to work out to the radio horizon (some margin of coverage is required for safety reasons), the error data collected while the aircraft was in the near horizon region was removed for the calculation of the average bit and block error rates. The average bit and block error rates calculated in this fashion are more representative of those that might occur in an operational system. It should be noted that the calculated bit and block error rates include the errors resulting from clock slips and carrier loss for the regions of interest (i.e., exclusive of the near and over the horizon regions).

4.4 EXPERIMENT RESULTS

4.4.1 Received Signal Characteristics

Figures 4-5 through 4-8 show the observed average received signal strength as a function of slant range. Each data point on the figures represents the received signal strength averaged over a 10-second period. The solid lines represent theoretical estimates of the received signal level and the radio horizon as a function of altitude. The theoretical estimate of received signal level assuming free space propagation losses is given by:

$$P_R = P_T - 32.45 - 20 \log(f) - 20 \log(1.85d) - L + G \quad (4\text{-}1)$$

Here, P_R is the received signal power in dBW, P_T is the transmitter power (14 dBW), f is the frequency in MHz, and d is the slant range in nautical miles. The terms L and G represent the system losses and gains, respectively. The values of L and G were estimated to be approximately equal for the conditions of this experiment and thus had a net zero contribution to the calculation of received power. The signal level in volts is related to P_R (in watts) by:

$$V = (50 \times P_R)^{\frac{1}{2}} \quad (4\text{-}2)$$

The distance to the radio horizon, d_h (nautical miles), as a function of aircraft altitude, h (feet above mean sea level), was calculated using the approximation:

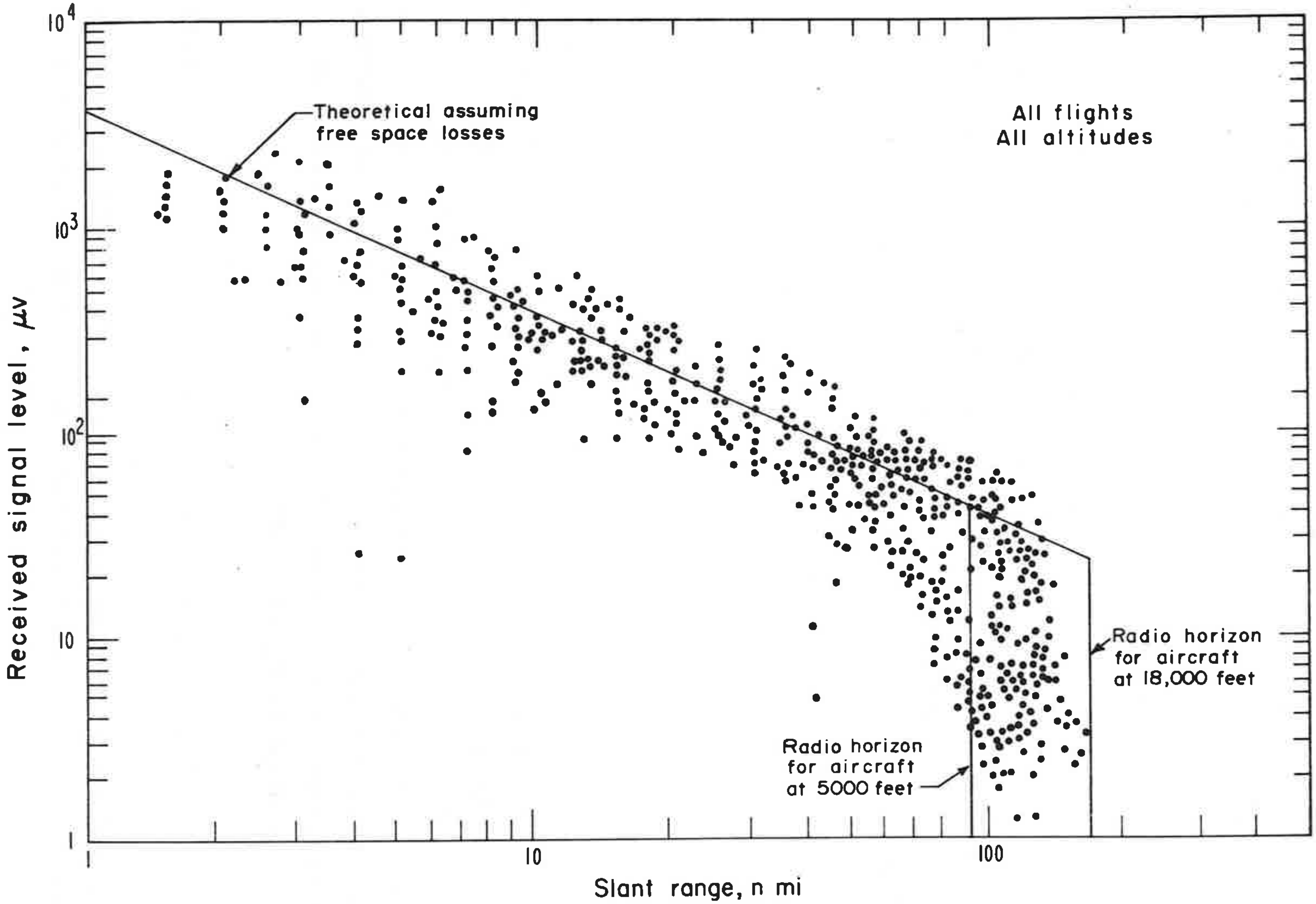


FIGURE 4-5. AVERAGE RECEIVED SIGNAL LEVEL VERSUS SLANT RANGE FOR ALL AIRCRAFT ALTITUDES

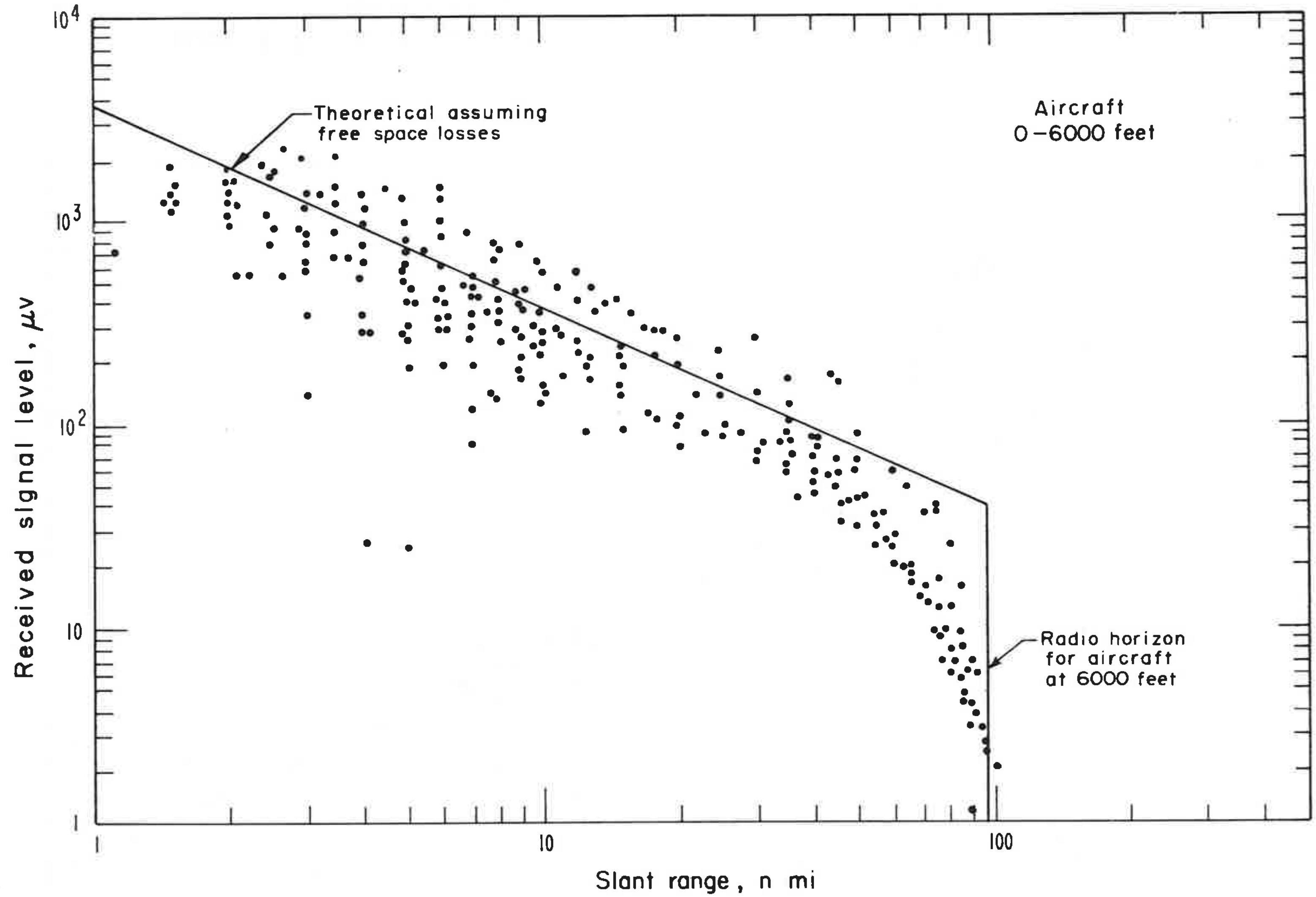


FIGURE 4-6. AVERAGE RECEIVED SIGNAL LEVEL VERSUS SLANT RANGE GIVEN THAT THE AIRCRAFT WAS BETWEEN 0 AND 6000 FT ALTITUDE

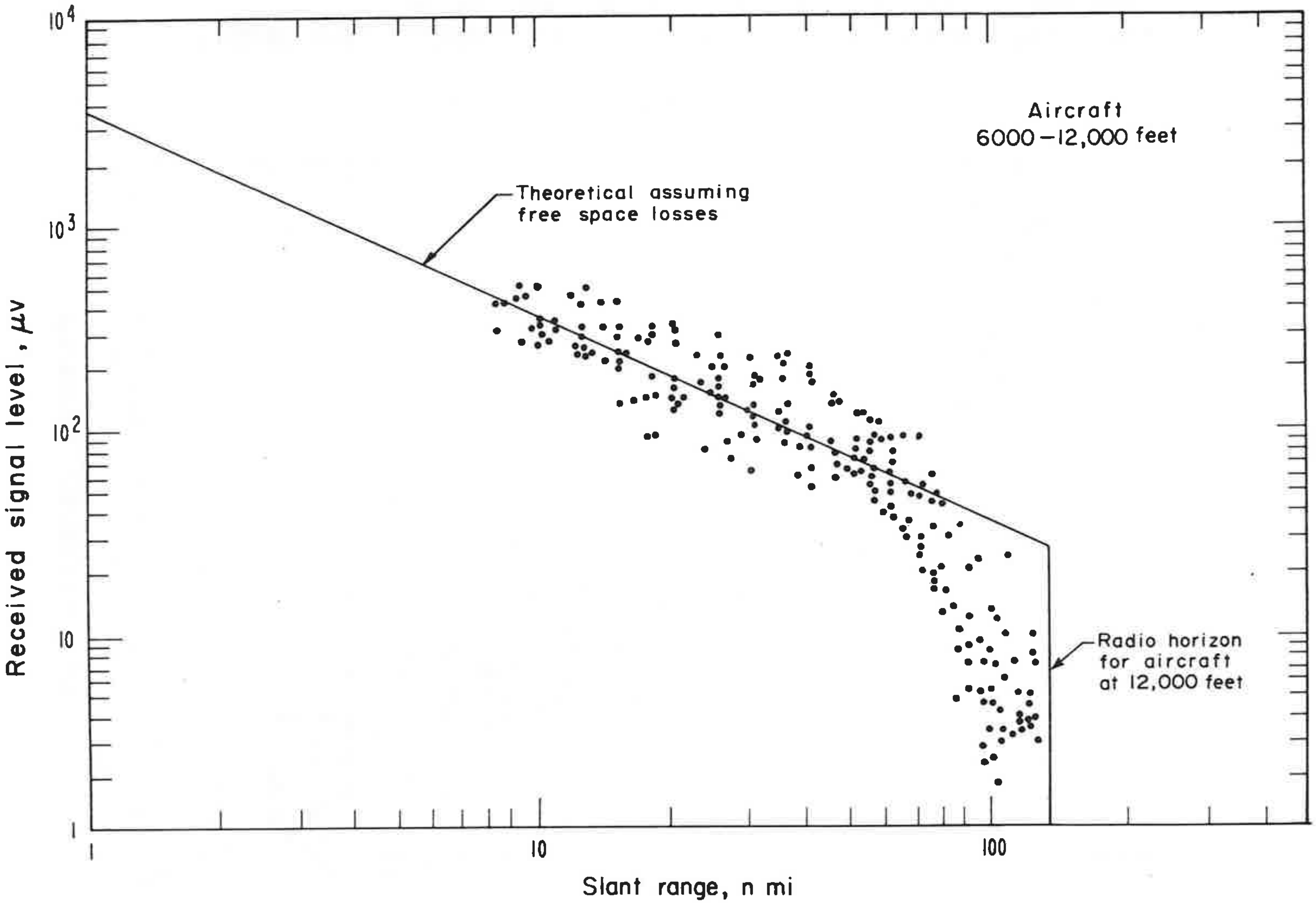


FIGURE 4-7. AVERAGE RECEIVED SIGNAL LEVEL VERSUS SLANT RANGE GIVEN THAT THE AIRCRAFT WAS BETWEEN 6000 FT AND 12,000 FT ALTITUDE

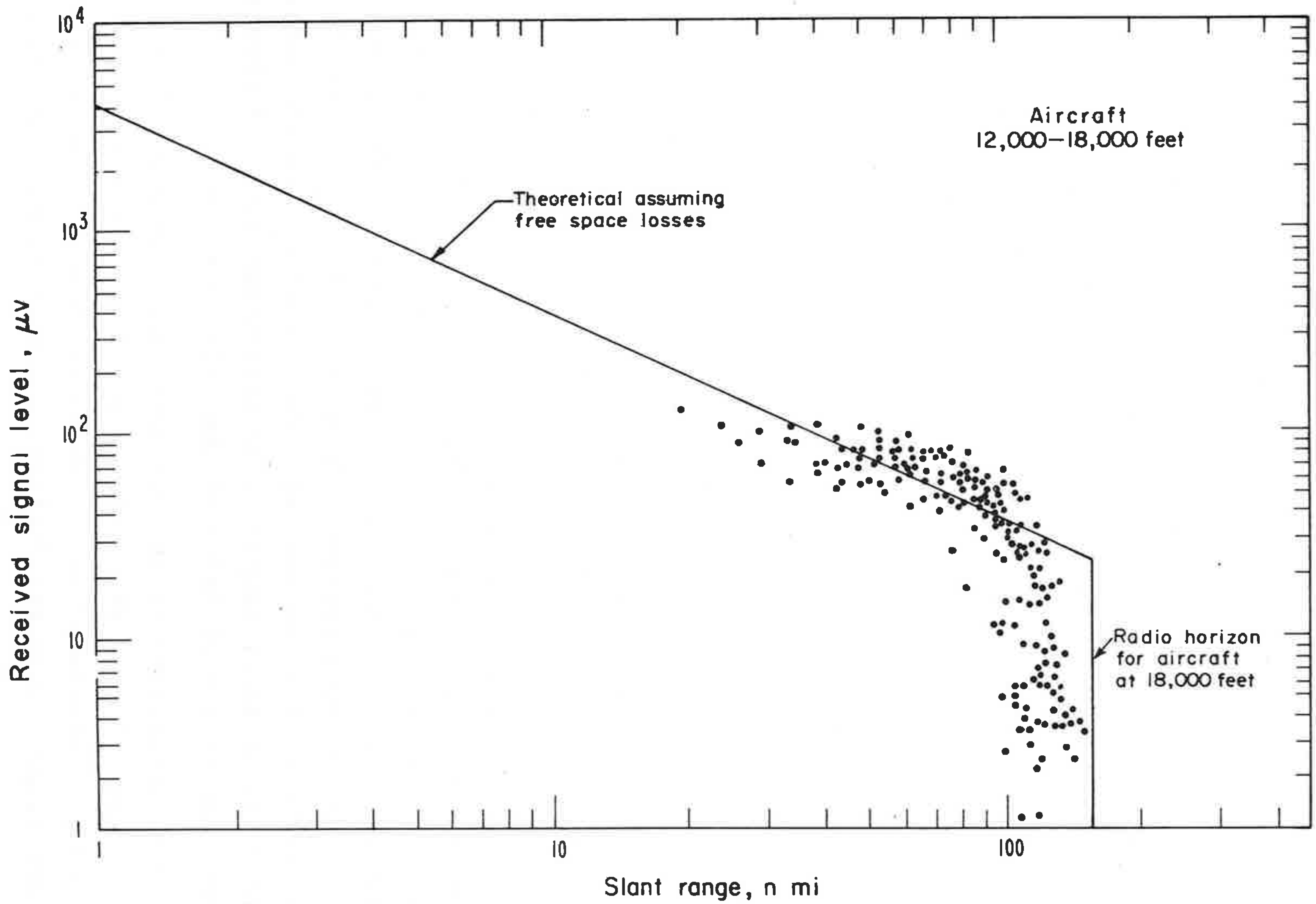


FIGURE 4-8. AVERAGE RECEIVED SIGNAL LEVEL VERSUS SLANT RANGE GIVEN THAT THE AIRCRAFT WAS BETWEEN 12,000 AND 18,000 FT ALTITUDE

$$d_h = .869(2h)^{\frac{1}{2}} \tag{4-3}$$

This approximation assumes an effective earth radius of 4/3 the true earth radius. The approximation also neglects the height of the ground site antenna.

Figure 4-5 shows the average received signal level data for all flights at all altitudes. The theoretical radio horizon is shown for aircraft altitudes of 5,000 feet and 18,000 feet. As can be seen, the experimental data generally agree with the theoretical calculation. The measured signal level is, on the average, equal to the theoretical calculation. The signal level samples that are as much as 6 dB above the theoretical value are probably due to the addition of the ground reflected signal and the direct signal, which can, during favorable conditions, give an increase in signal strength up to 6 dB.

The data are shown plotted in altitude bands of 0 to 6000 feet, 6000 to 12,000 feet, and 12,000 to 18,000 feet in Figures 4-6, 4-7, and 4-8, respectively, in order to show the effects of aircraft altitude on the received signal level. The calculated radio horizon for the higher altitude in each band is shown on the figures. The data agree well with the calculated values of the received signal level and are, on the average, equal to the theoretical value given by the solid lines. The observed received signal level falls off rapidly as the radio horizon is approached. The variations in the average received signal level samples were approximately 17 dB when the aircraft was in the vicinity of the radio horizon.

The variability in the received signal observed in the 10-second period over which the received signal strength was averaged was calculated and is shown in Figure 4-9 as a function of slant range. This variability, known as signal fading, is the maximum change or peak-to-peak variation observed in the 10-second period. Note that the depth of maximum signal fading

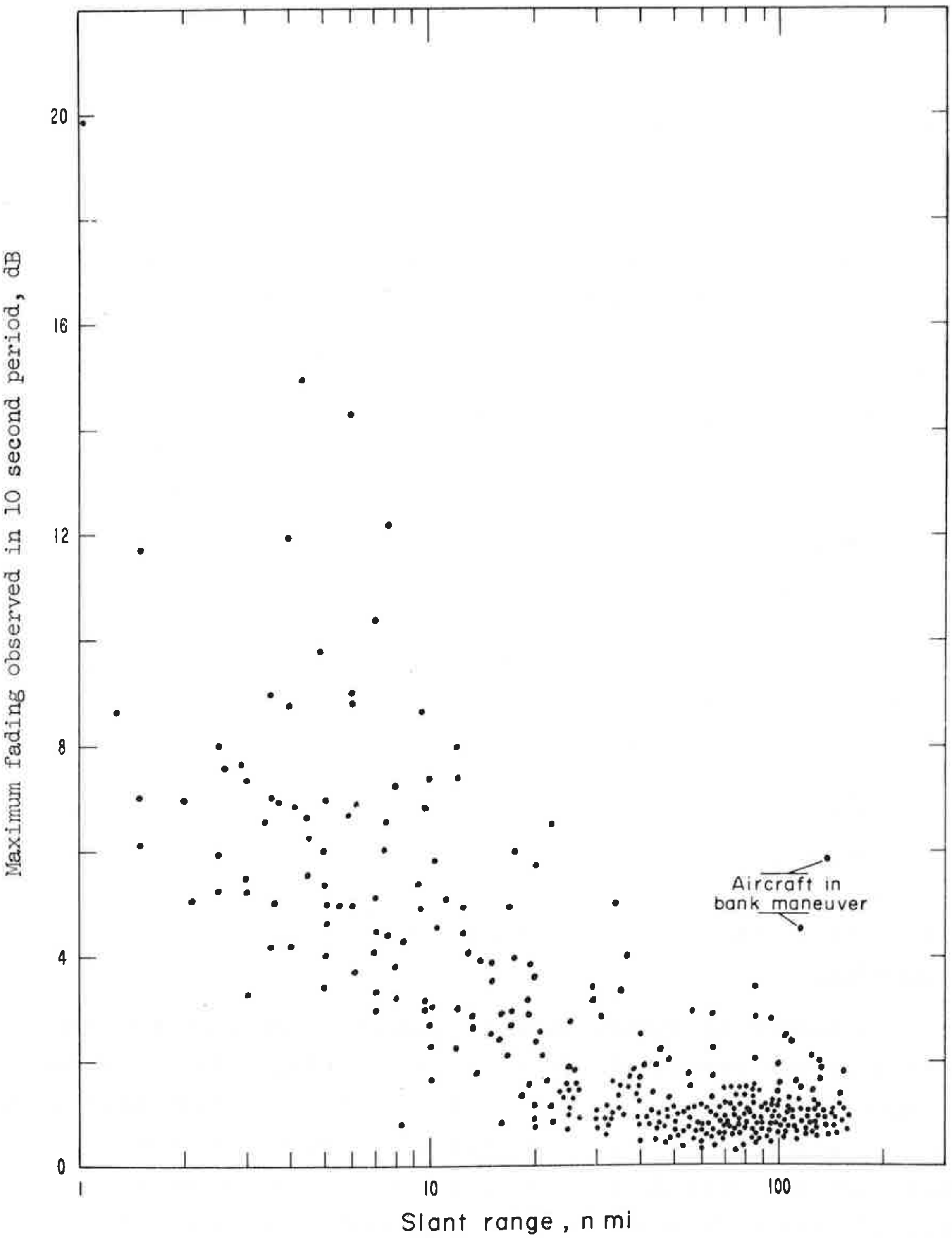


FIGURE 4-9. PEAK-TO-PEAK FADING OBSERVED IN A 10-SECOND PERIOD AS A FUNCTION OF SLANT RANGE

was an inverse function of the slant range. The maximum depth of fades was 20 dB when the aircraft was between 1 and 10 nautical miles (n mi) from the receiver site, 8 dB when the aircraft was between 10 and 20 n mi from the receiving site, and less than 2.5 dB when the aircraft was greater than 100 n mi from the receiving site.

The detailed received signal strength plots shown in Figure 4-10 are typical of the different types of fading structure that were observed during the tests. The upper plot shows the nearly constant conditions that were observed when the aircraft was at large slant ranges from the receiving site. The two lower plots show the relatively deep fading that was observed when the aircraft was close to the receiving site. The close-in behavior is most likely the result of multipath due to the proximity of the aircraft to the ground. A limited analysis of the detailed received signal data indicated that the rate of fading ranged between a fraction of 1 Hz up to a maximum of 2 Hz. The repeatability of the received signal level for similar flight paths was excellent when the test aircraft was at a slant range greater than 30 n mi. However, the received signal level profiles differed significantly for like flight paths when the aircraft was within a slant range of 30 n mi of the receiving site. Again this result is indicative of multipath phenomena.

A number of signal changes (fades) were observed that were a direct result of aircraft maneuvering. Although the changes were obvious, it was difficult to correlate them with any one aircraft attitude parameter. Rather, it appears that signal fading during banking was a complex function of aircraft attitude relative to the ground receiving site. A plot of the signal change as a function of roll angle is shown in Figure 4-11. Selected samples from all flights are

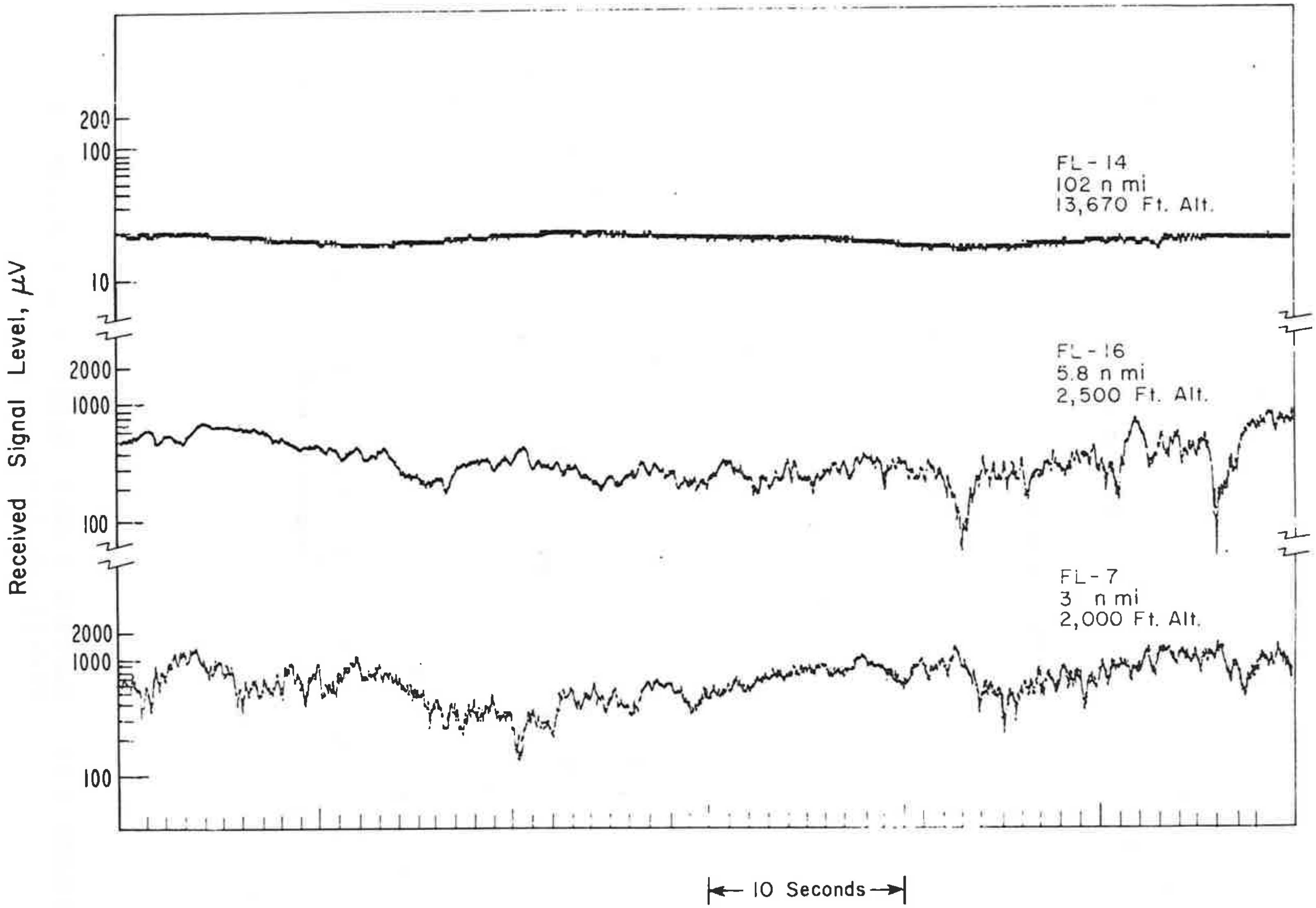


FIGURE 4-10. SAMPLES OF SHORT TERM SIGNAL FADING

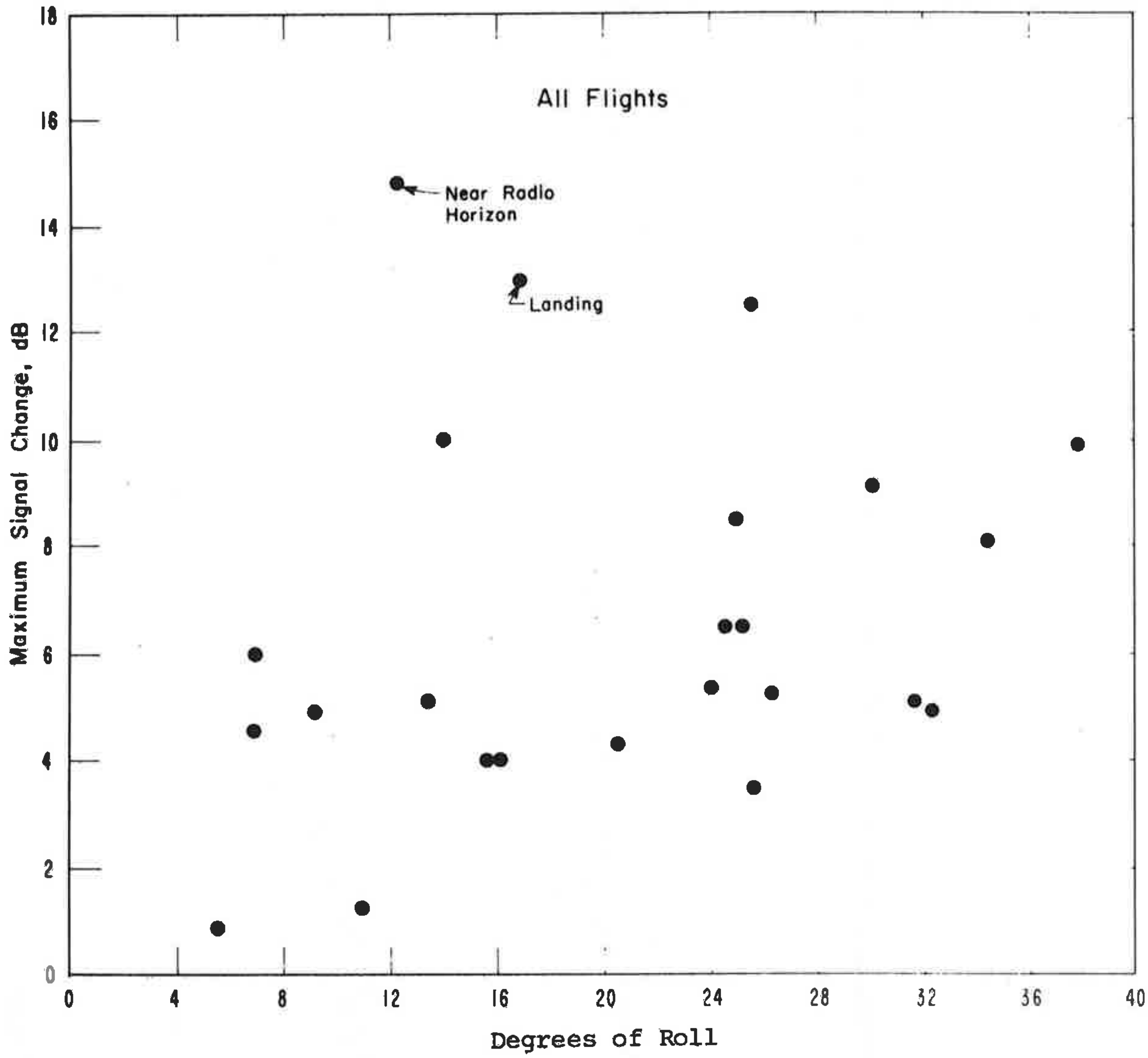


FIGURE 4-11. MAXIMUM SIGNAL CHANGE AS A FUNCTION OF DEGREES OF BANK

included. There is generally no strong dependence between signal change and degrees of roll, although the larger changes tend to occur at higher angles.

4.4.2 Bit and Block Error Rates

The bit and block error rate results were determined by removing error data accumulated due to equipment and operational problems, near horizon effects, and over the horizon effects as described in section 4.3. Figures 4-12 through 4-15 successively show the impact on the average bit error rate (P_e) for each flight due to removal of these accumulated errors. The shaded bars are for the flights at the 4800 bit per second (bps) data rate. Figure 4-15 shows the average P_e for each flight with all the extraneous errors removed. The P_e data are presented in summary form in Figure 4-16 as weighted (with respect to time of each test flight) averages for all the flights for both data rates combined and as a function of data rate. The results indicate that the observed bit error rates are not a function of the two data rates used in this experiment.

The block error rate (P_b) data are presented in a similar fashion in Figures 4-17 through 4-19. The block length is 1000 bits. Figure 4-17 shows the P_b for each flight for the raw data, which includes all extraneous errors. Figure 4-18 shows the P_b for each flight with all the extraneous errors removed. The P_b averaged over all the flights is shown in Figure 4-19 for the raw data and for the data with all extraneous errors removed as a function of data rate. The P_b shows little sensitivity to data rate.

The results of the bit and block error rate measurements are summarized in Table 4-2.

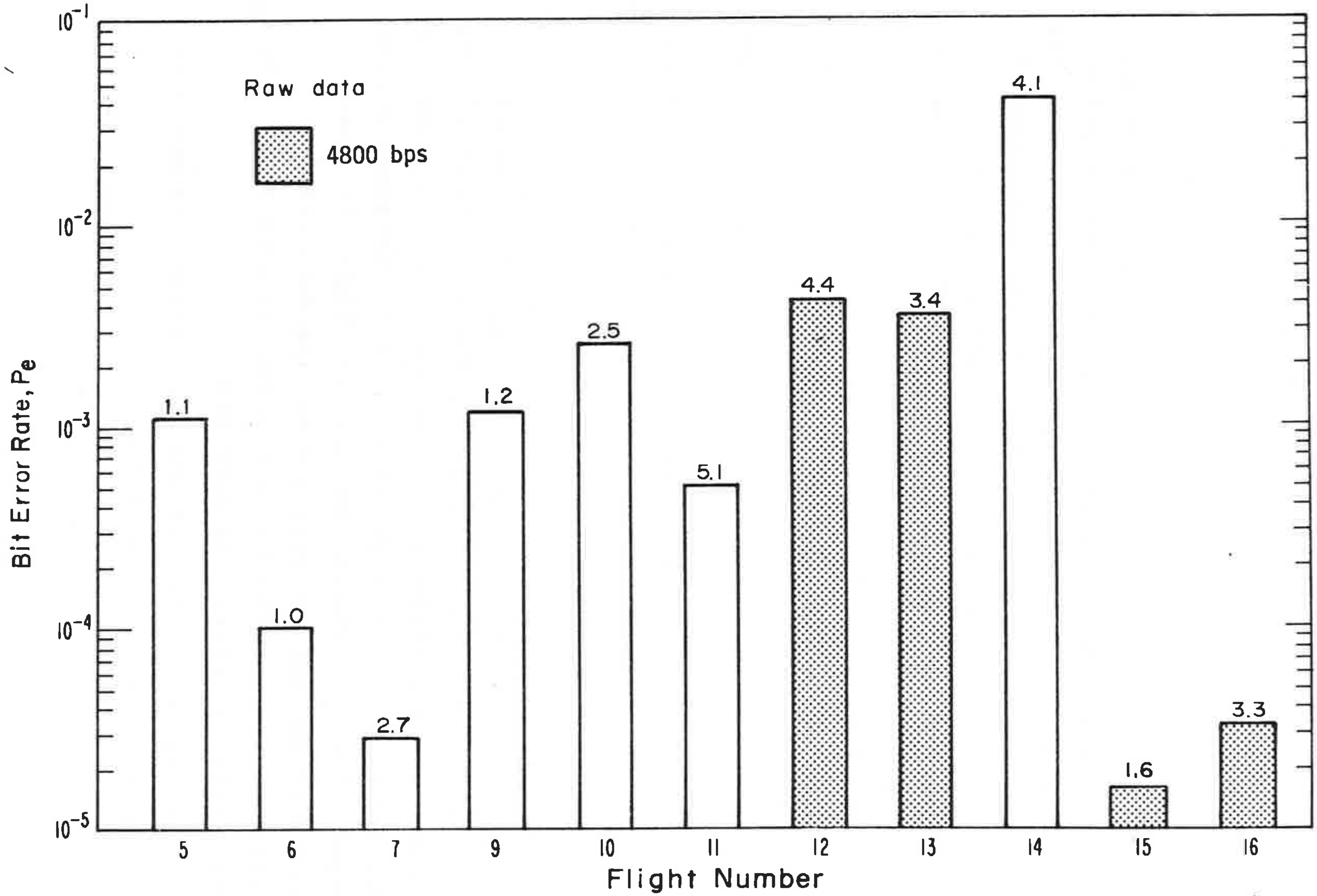


FIGURE 4-12. AVERAGE BIT ERROR RATE FOR EACH FLIGHT USING RAW DATA (INCLUDES ERRORS DUE TO EQUIPMENT AND OPERATIONAL PROBLEMS)

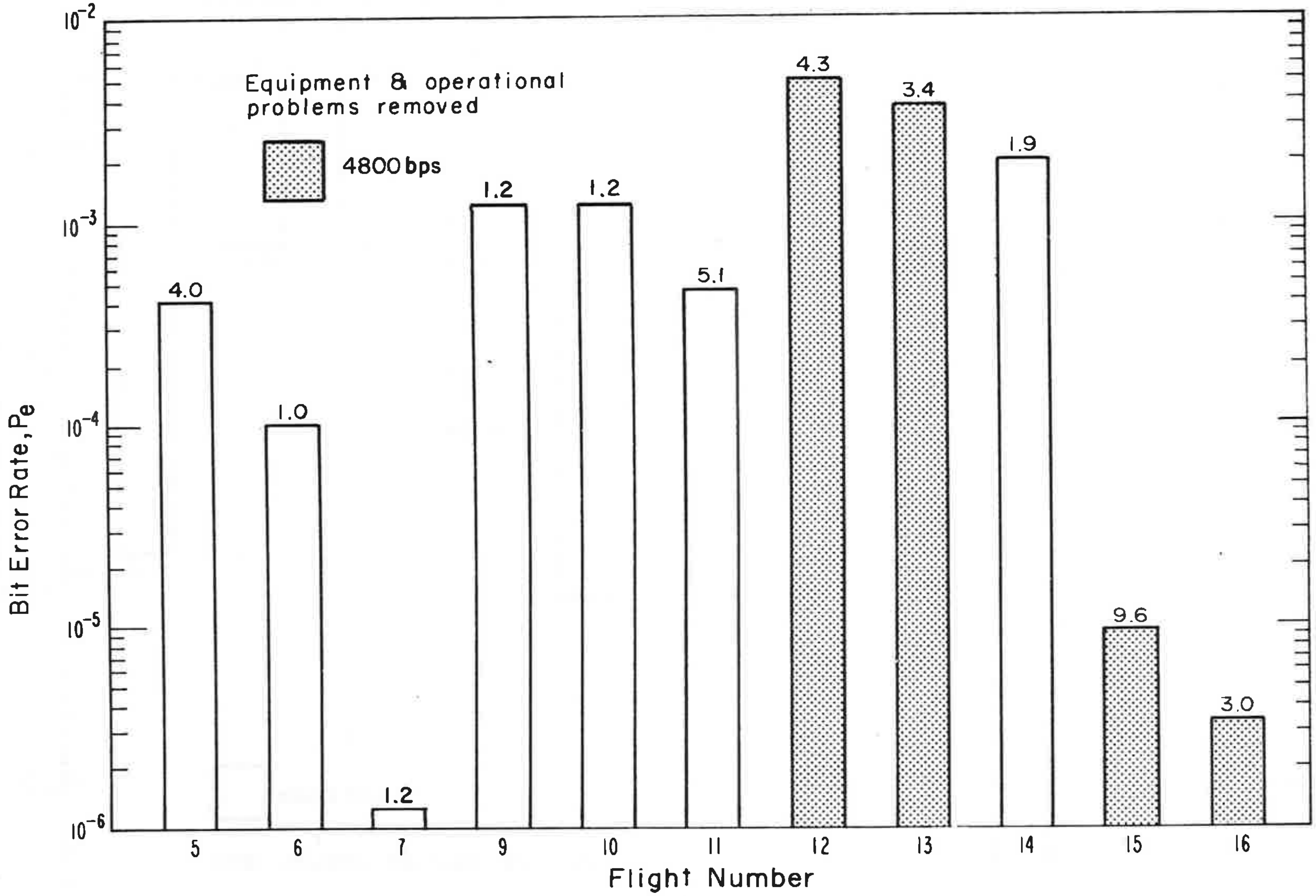


FIGURE 4-13. AVERAGE BIT ERROR RATE FOR EACH FLIGHT WITH EQUIPMENT AND OPERATIONAL PROBLEMS REMOVED

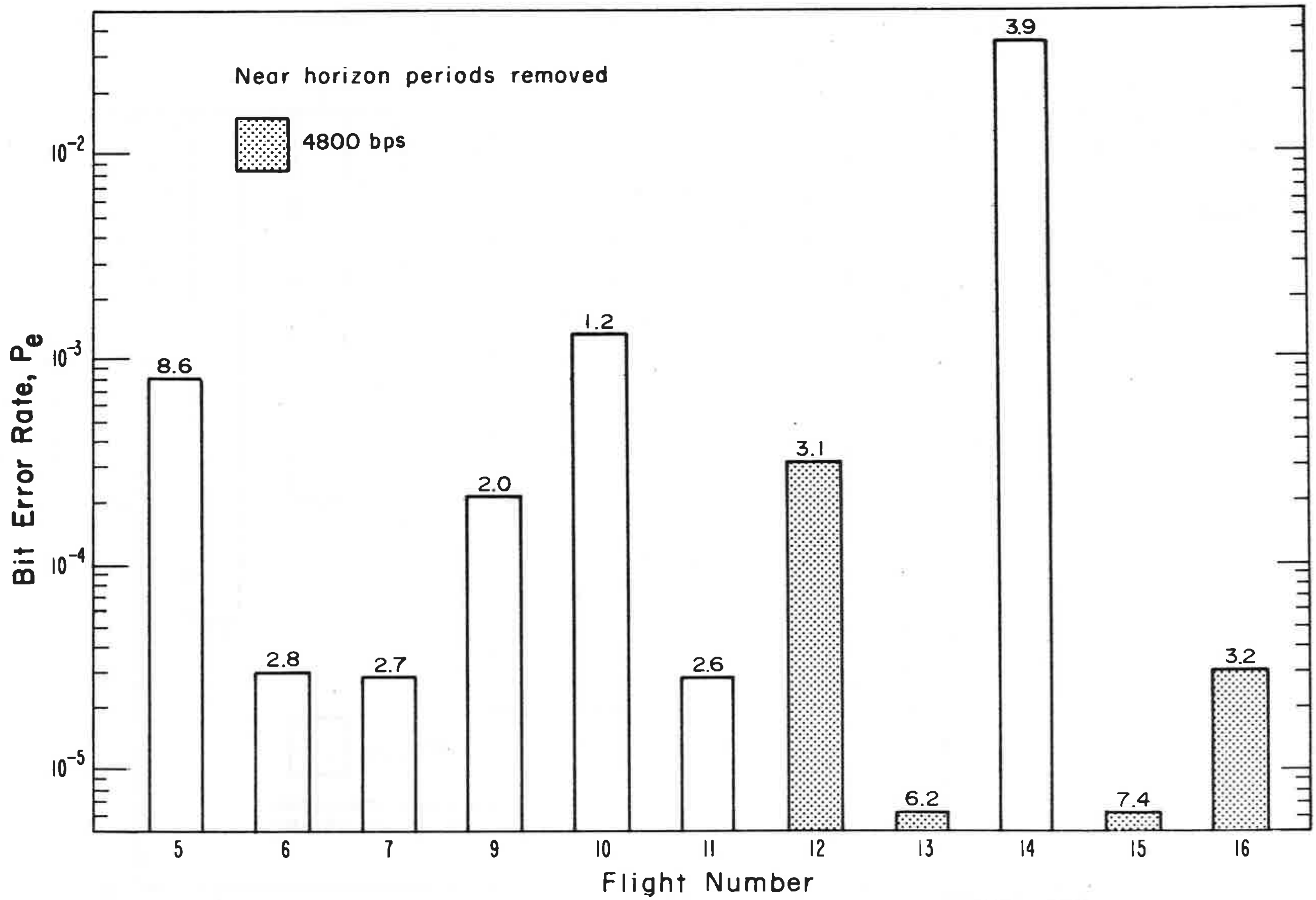


FIGURE 4-14. AVERAGE BIT ERROR RATE FOR EACH FLIGHT WITH NEAR HORIZON PERIODS REMOVED

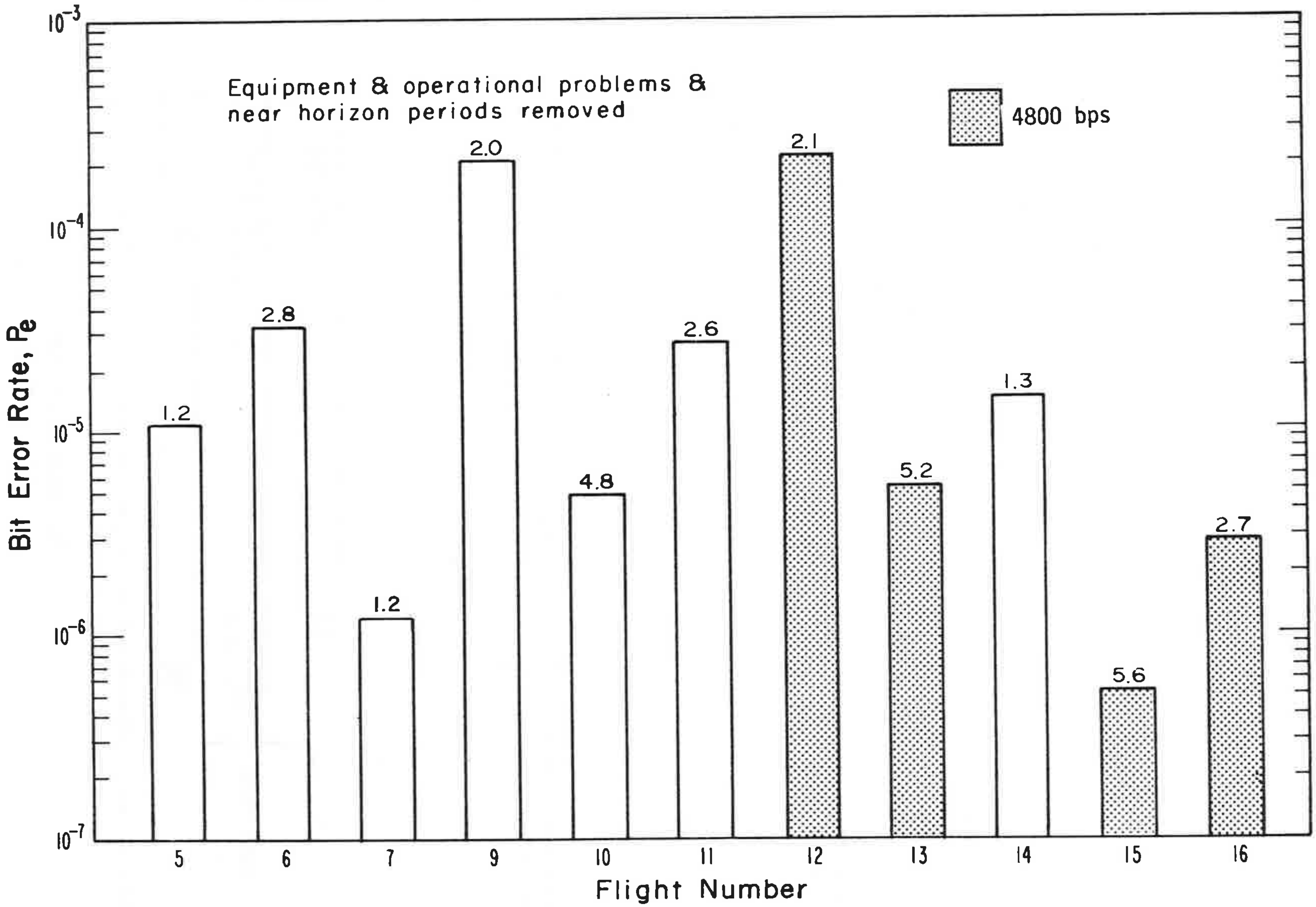


FIGURE 4-15. AVERAGE BIT ERROR RATE FOR EACH FLIGHT WITH EQUIPMENT AND OPERATIONAL PROBLEMS AND NEAR HORIZON PERIODS REMOVED

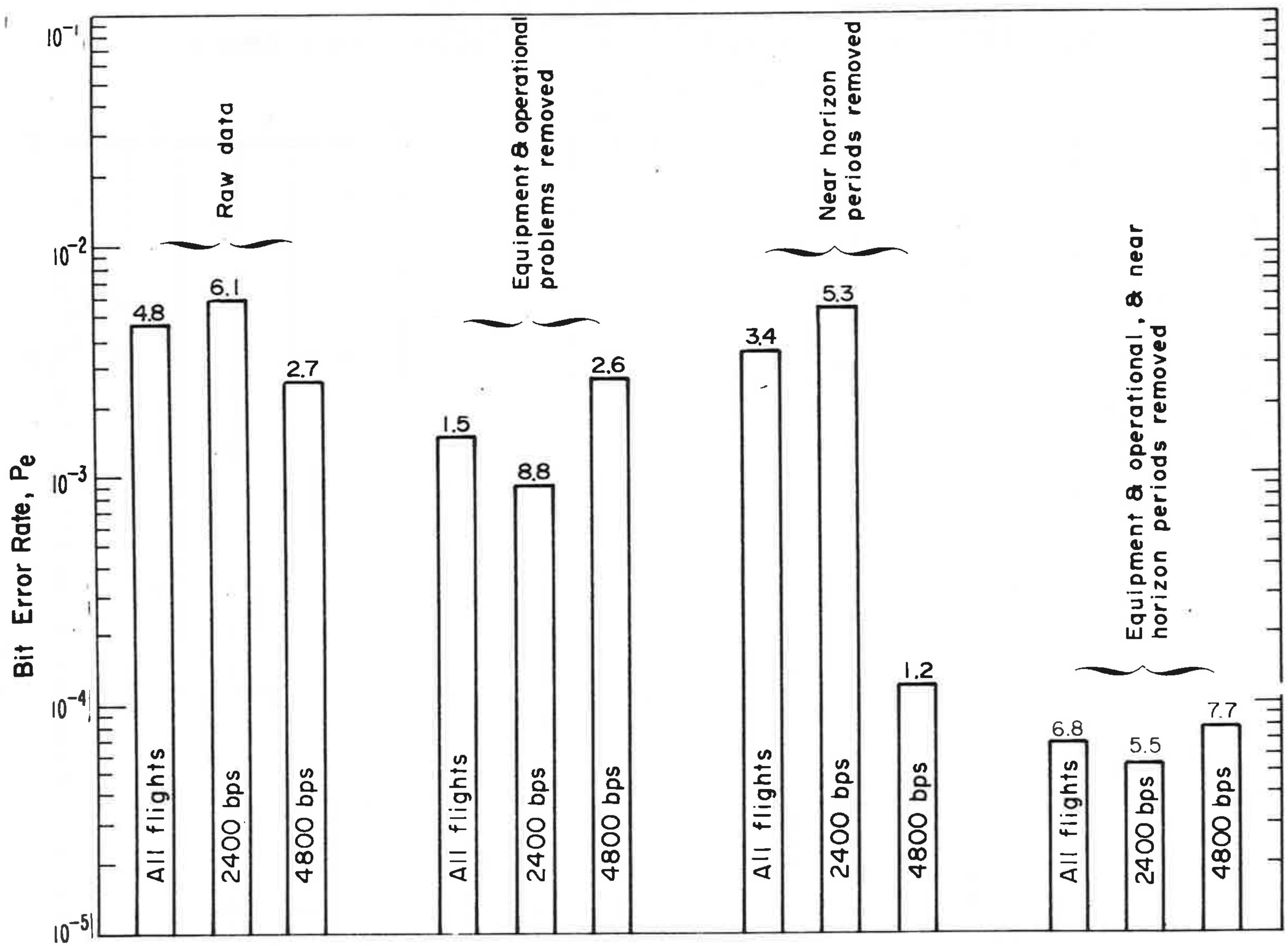


FIGURE 4-16. SUMMARY OF AVERAGE BIT ERROR RATE USING WEIGHTED AVERAGES

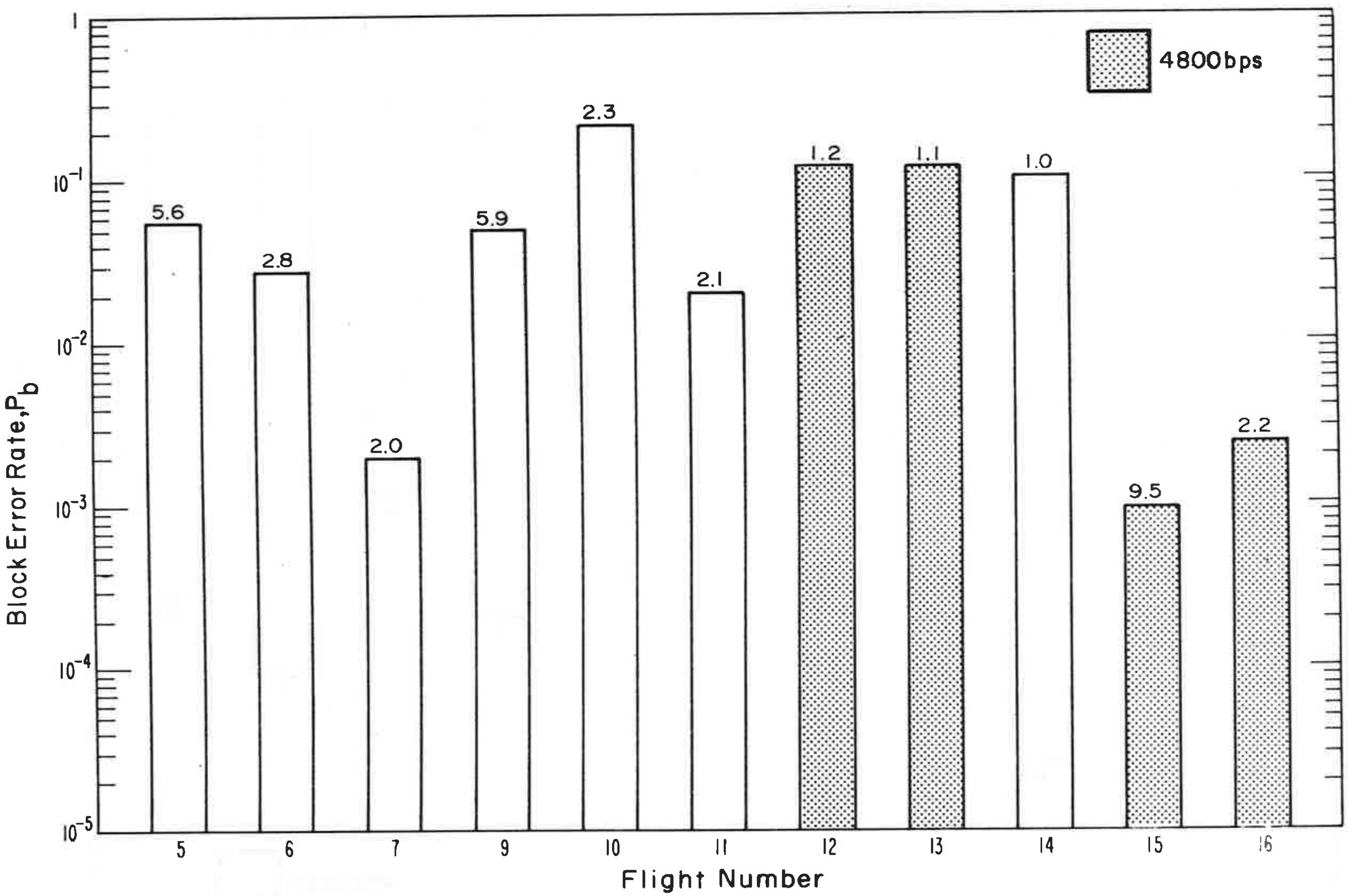


FIGURE 4-17. BLOCK ERROR RATE FOR EACH FLIGHT USING RAW DATA (INCLUDES ERRORS DUE TO EQUIPMENT AND OPERATIONAL PROBLEMS. A BLOCK IS 1000 BITS)

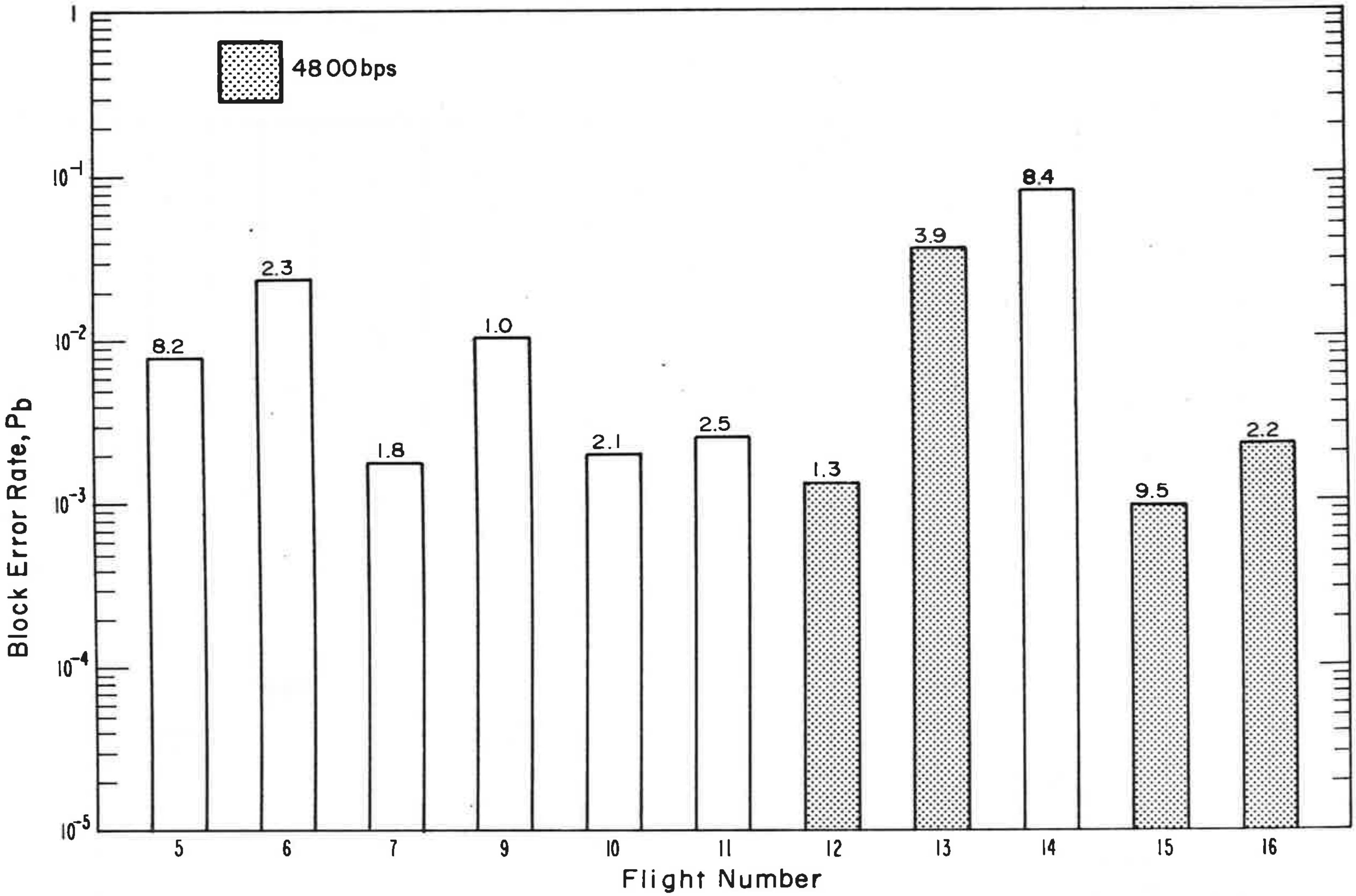


FIGURE 4-18. BLOCK ERROR RATE FOR EACH FLIGHT WITH EQUIPMENT AND OPERATIONAL PROBLEMS AND NEAR HORIZON PERIODS REMOVED (A BLOCK IS 1000 BITS)

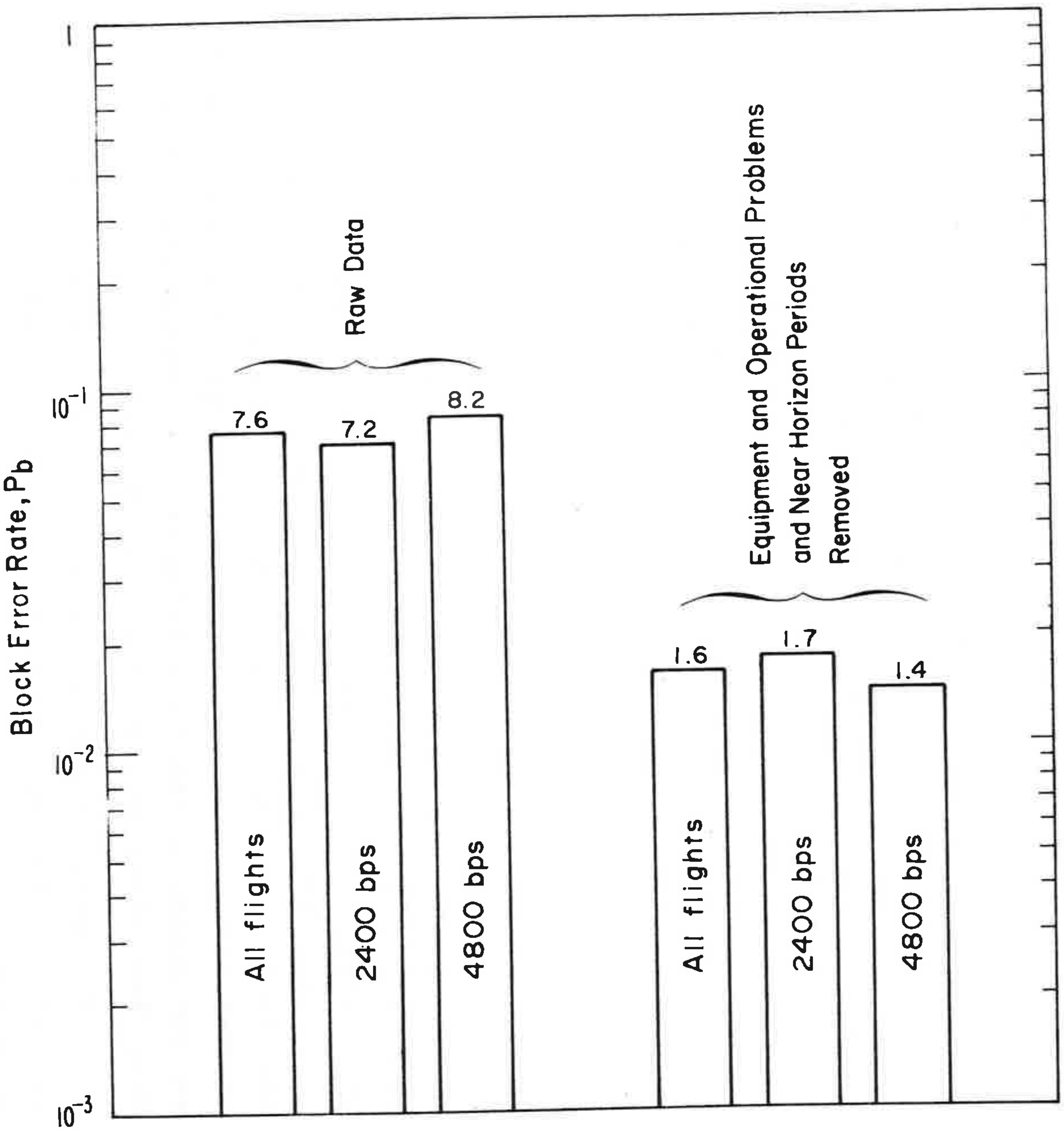


FIGURE 4-19. SUMMARY OF BLOCK ERROR RATES

TABLE 4-2. AVERAGE BIT AND BLOCK ERROR RATES

	2400 BPS	4800 BPS	ALL DATA
$P_e \times 10^{-5}$	5.5	7.7	6.8
$P_b \times 10^{-2}$	1.7	1.4	1.6

The bit error rate (P_e) is shown as a function of aircraft distance from the ground receiving site in Figure 4-20. These data show that within 40 n mi of the ground receiving site the P_e was an inverse function of distance. That is, higher P_e's occurred when the aircraft was within 20 n mi of the receiving site than when the aircraft was between 20 n mi and 40 n mi from the receiving site. This result can be explained as a signal fading (multipath) effect due to the close proximity of the aircraft to large reflecting surfaces on the ground. The signal fading data presented in section 4.4.1 showed the same inverse relationship between depth of fades and aircraft distance from the receiving site. These data support the multipath explanation for the degraded P_e performance with decreasing distance of the aircraft to the receiving site. The inverse relationship of P_e performance and signal fading with decreasing aircraft distance to the receiving site existed out to slant range distances of approximately 40 n mi. Beyond this point the received signal characteristics were very repeatable and exhibited much reduced maximum depths of fades resulting in consistently lower P_e's than those observed with 40 n mi of the receiving site.

The average number of bit errors per block error (N_B) was calculated using the measured average bit and block error rates:

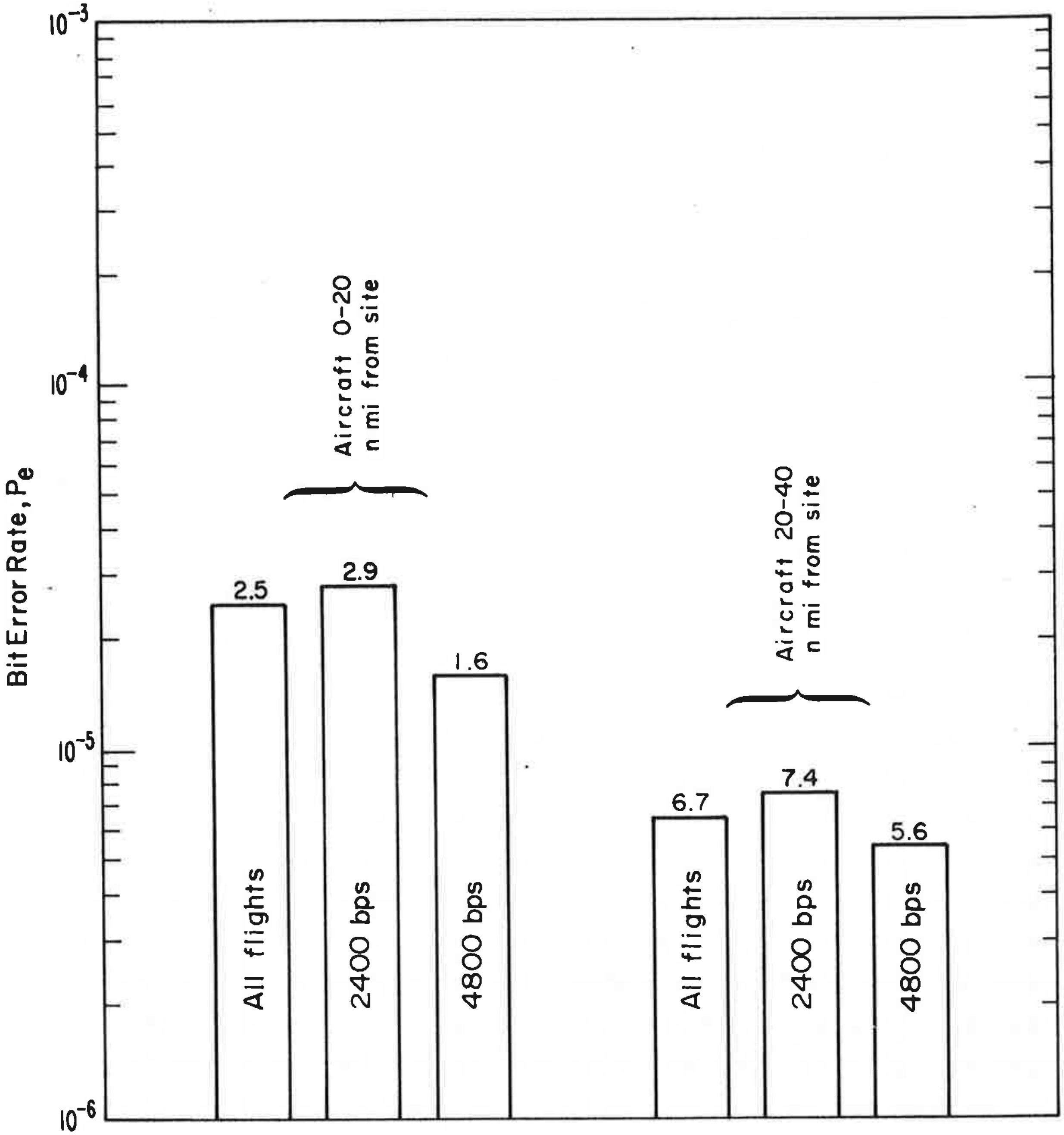


FIGURE 4-20. BIT ERROR RATE AS A FUNCTION OF AIRCRAFT'S DISTANCE FROM SITE (EQUIPMENT AND OPERATIONAL PROBLEMS AND NEAR HORIZON PERIODS REMOVED)

$$N_B = (P_e \times 1000)/P_b \quad (4\text{-}4)$$

which yields:

	N_B
ALL FLIGHTS	2.9
2400 BPS	2.4
4800 BPS	3.9

The quantity N_B is a measure of the average number of bit errors in a block given that the block had one or more errors and that the errors were equally distributed among all the blocks having errors. Error-free blocks were not included in the average.

4.4.3 Distribution of Errors

The distribution of bit errors that occurred in the 1-second data samples are shown in Figures 4-21 and 4-22 for the 2400 and 4800 bps data rates, respectively. These data give the number of bit errors that occurred in 2400 and 4800 bit data blocks, respectively. Errors in the high error density near horizon region and those resulting from equipment or operational problems have been removed. The fractions were computed only for those samples that contained errors; that is, the 1-second samples that had no errors were not included in the computation. Figure 4-21 for the 2400 bps data shows that 68 percent of the 1-second data samples (2400 bit blocks) that had errors had only single bit errors and only 5 percent of the samples had more than 10 errors. Comparison with Figure 4-22 for the 4800 bps data (4800 bit blocks) shows that the probability of having 1 or 2 bit errors was less at 4800 bps than at 2400 bps. However, the proability of 4 bit errors per 1-second sample was greater at 4800 bps than at 2400 bps.

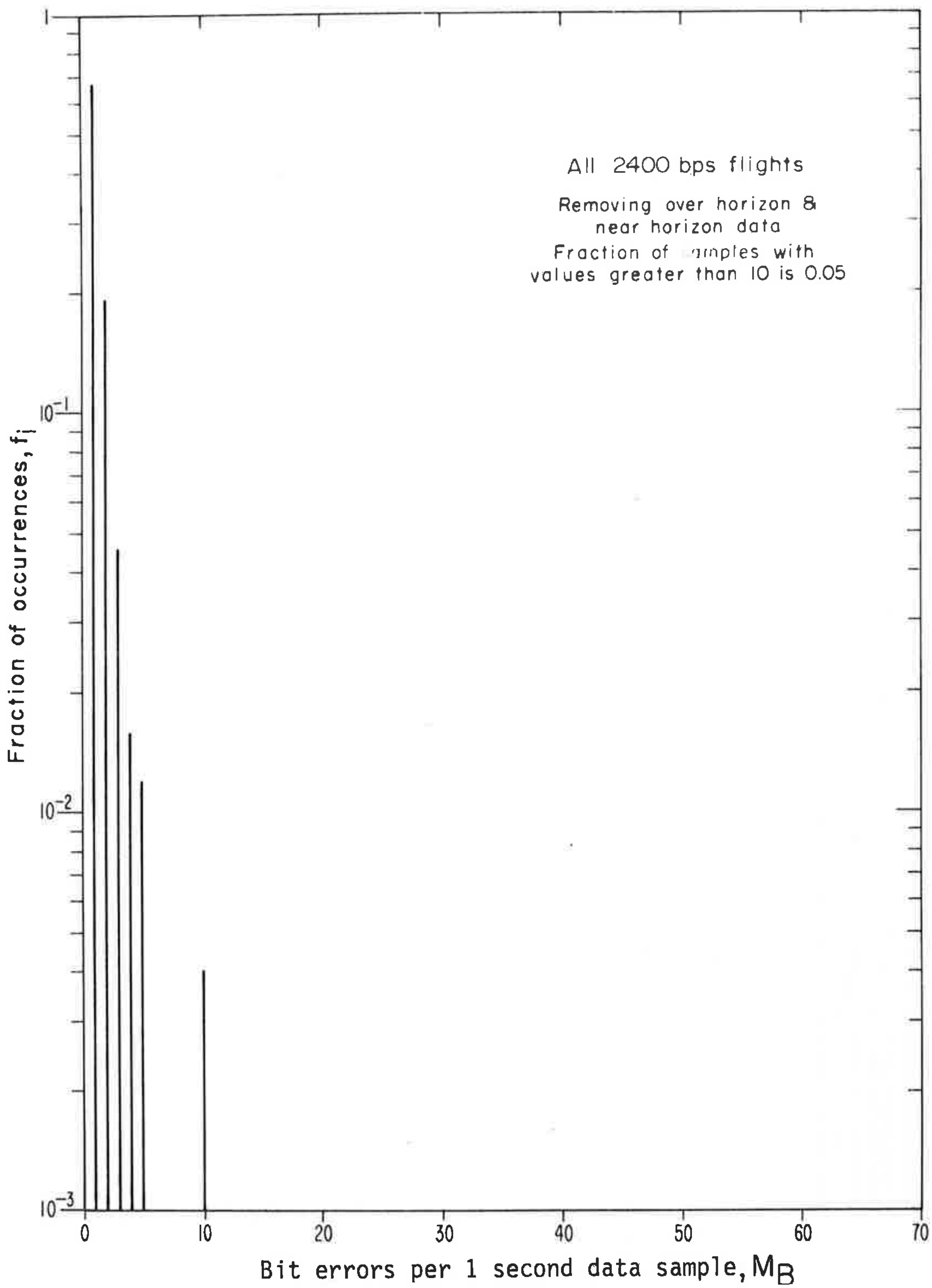


FIGURE 4-21. HISTOGRAM OF NUMBER OF BIT ERRORS PER 1-SECOND DATA SAMPLE FOR ALL 2400 BPS FLIGHTS (EQUIPMENT AND OPERATIONAL PROBLEMS AND NEAR HORIZON PERIODS REMOVED)

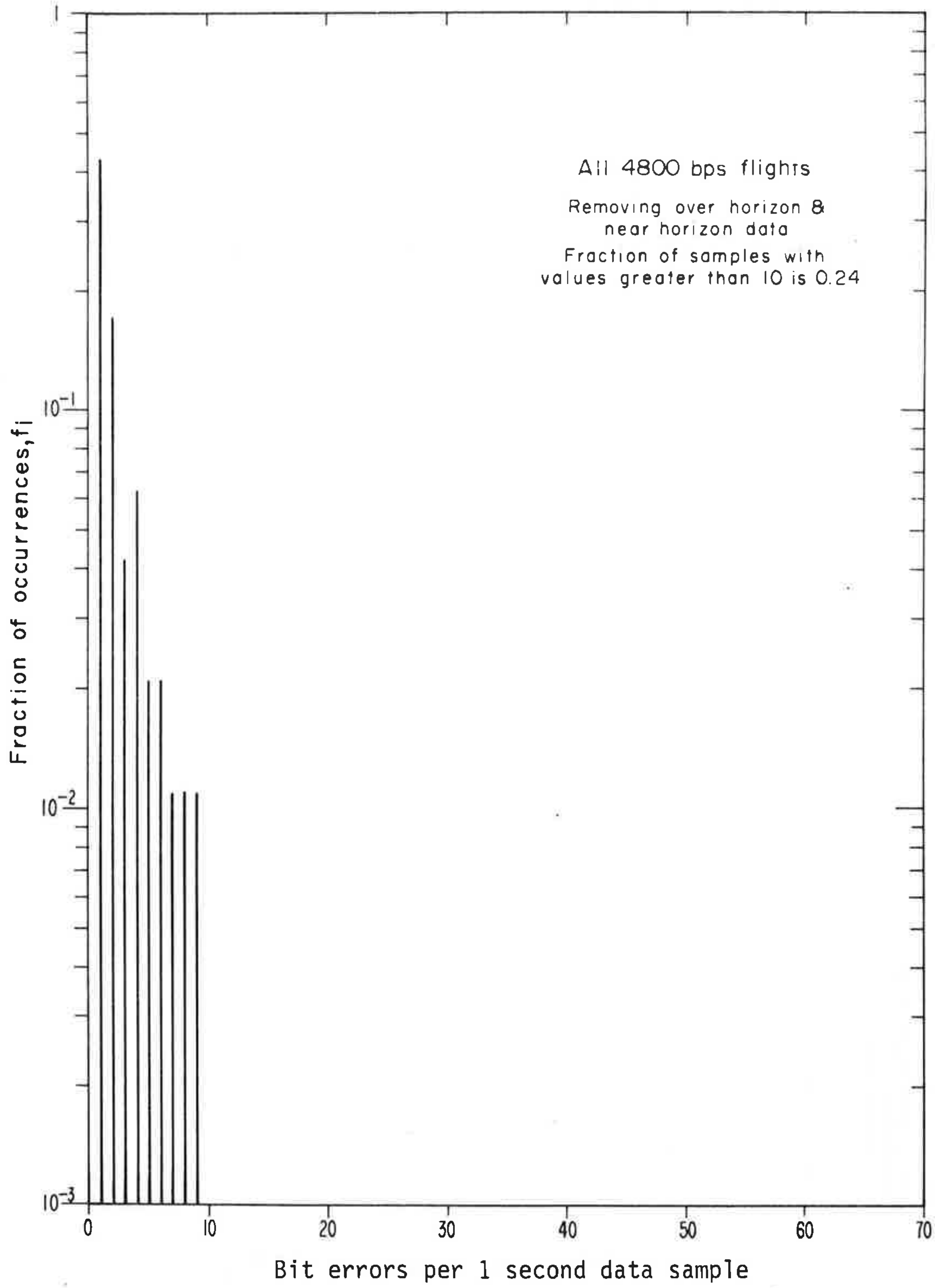


FIGURE 4-22. HISTOGRAM OF NUMBER OF BIT ERRORS PER 1-SECOND DATA SAMPLE FOR ALL 4800 BPS FLIGHTS (EQUIPMENT AND OPERATIONAL PROBLEMS AND NEAR HORIZON PERIODS REMOVED)

The average number of bit errors per 1-second data sample (M_B), given that the data sample had errors, was calculated from the distributions given in Figures 4-21 and 4-22 as follows:

$$M_B = \sum_{i=1}^{\infty} i \cdot f_i \qquad (4\text{-}5)$$

where f_i is the fraction of occurrences shown in Figures 4-21 and 4-22. The results of these calculations are:

	M_B
2400 bps	1.9
4800 bps	4.0

Thus, on the average, if a 1-second data sample had errors, it was likely to have had 2 bit errors at a data rate of 2400 bps or 4 bit errors at a data rate of 4800 bps. The cause of these errors appears to be drop-outs due to multi-path or maneuvers. This subject is discussed further in Section 5 and Appendix C. Recall that the averages include only those 1-second samples in which errors occurred. If a 1-second data sample was chosen at random it would most likely be error free.

The average M_B for block lengths of 2400 and 4800 bits is similar to N_B determined in section 4.4.2 for 1000 bit blocks. The measurements show that N_B was approximately equal to M_B, which means that the average number of bit errors per block, given that the block had one or more errors, was independent of block length over the range of block lengths tested (1000 bits to 4800 bits).

4.4.4 Geographical Coverage

The points where communication was lost on outbound legs, indicated by arrowheads, and reestablished on inbound legs, indicated by circles, are shown as a function of altitude and slant range in Figure 4-23. The length of the leaders attached to the arrowheads and circles represents the extent of the observed near horizon regions for the individual flights; that is, regions of high error density. Also shown in Figure 4-22, for comparison, are the 5 percent and 95 percent availability curves defining the radio horizon as calculated using the ITS propagation model (Ref. 12). The calculations account for the 60-foot receiver antenna height and assume a smooth earth and a 140-dB channel loss. Thus, 90 percent of the time, the 140-dB propagation loss should occur within the two boundaries. The 140-dB propagation loss results in a received signal of 3.5 μV at the ground site receiver. The observed and calculated radio horizons show good agreement with the majority of the observed points falling between the calculated 5 percent and 95 percent availability curves. It is interesting to note that the three most anomolous points (those points at approximately 2000 feet altitude at a slant range between 95 and 110 nautical miles) occurred on over water flights to Long Island. It is possible that overwater propagation anomilies occurred on these flights.

The width of the observed near horizon region as a function of altitude is shown in Figure 4-24. The observed width of this region ranges between 0.5 and 20 n mi. However, based on the small data sample available, there was no strong correlation exhibited between near horizon width and aircraft altitude.

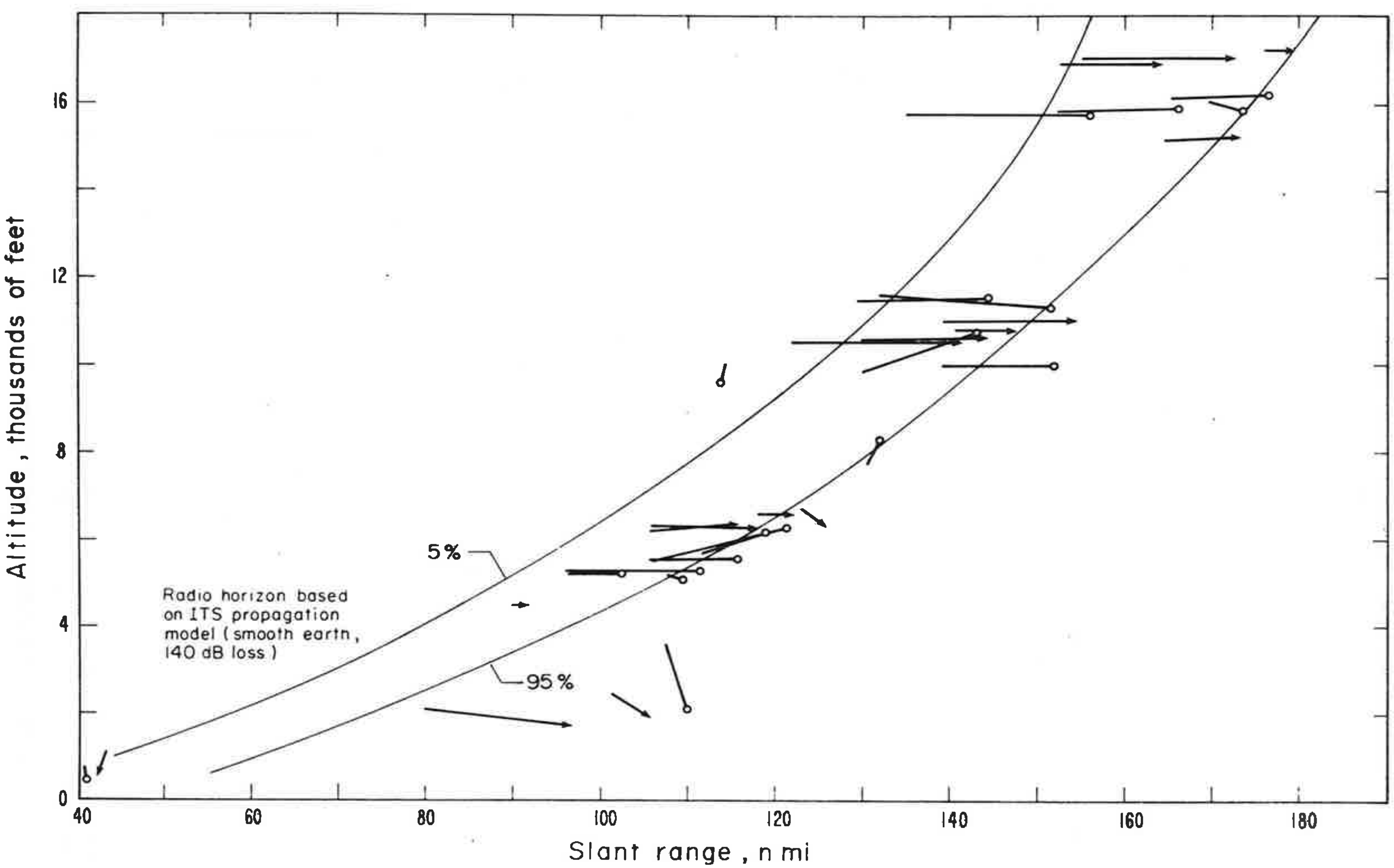


FIGURE 4-23. HIGH ERROR RATE REGIONS AS A FUNCTION OF ALTITUDE AND SLANT RANGE (ARROWS INDICATE LOSS OF SYNC ON OUTBOUND FLIGHTS. CIRCLES INDICATE REESTABLISHING SYNC ON INBOUND FLIGHTS)

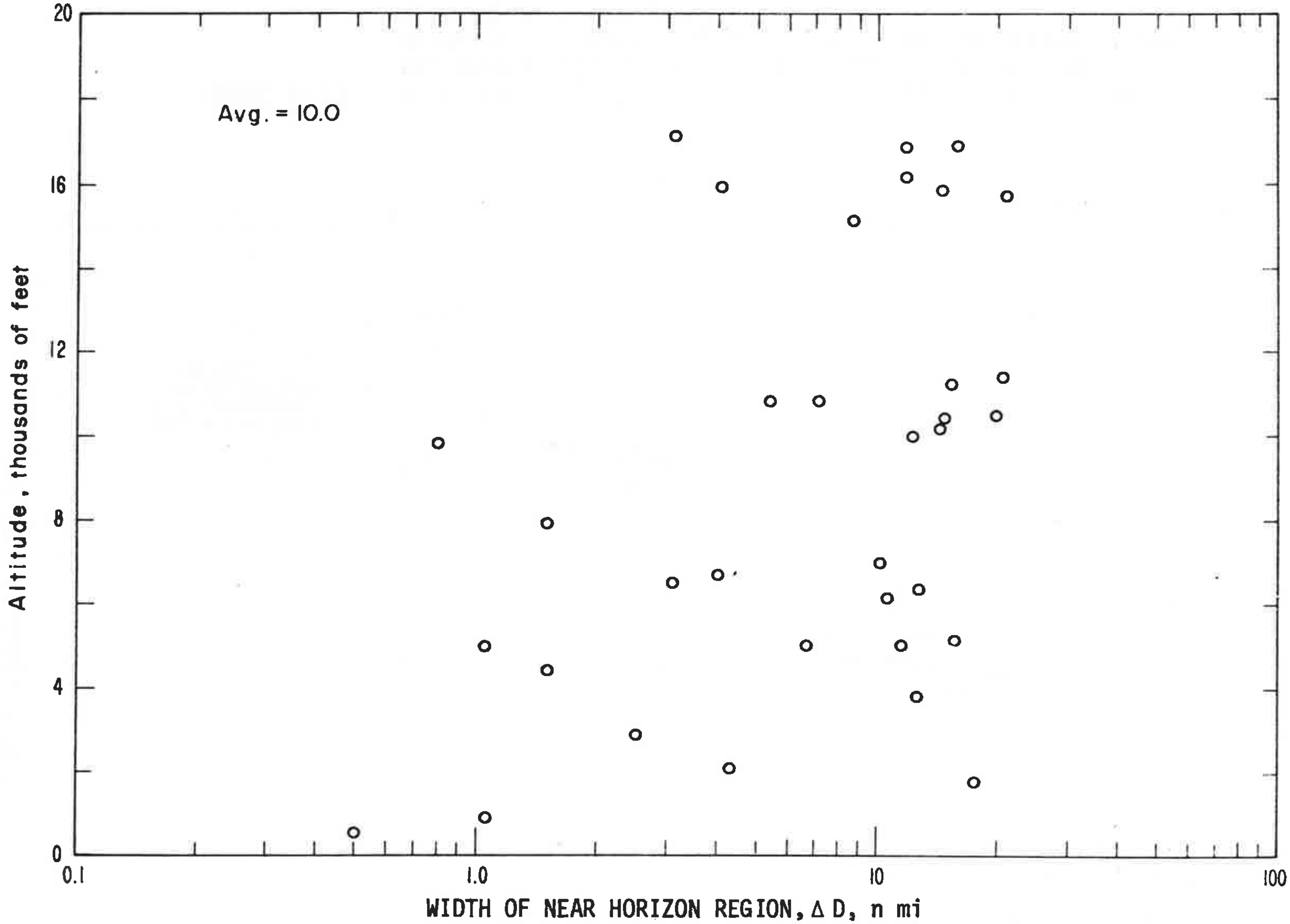


FIGURE 4-24. WIDTH OF NEAR HORIZON REGION AS A FUNCTION OF AIRCRAFT ALTITUDE

The results of this experiment indicate that reliable VHF data link system coverage can be achieved if the system were to be designed to the 5 percent availability curve of the ITS propagation model. That is, communication sector coverage for geographical regions having terrain features similar to those encountered during this experiment could be based on this curve with added margin for safety. Of course the coverage results obtained in this experiment would not apply to geographic regions having vastly different terrain features.

4.4.5 Carrier Loss and Clock Slip

Counts of carrier loss and clock slip were recorded in these experiments. The presence or absence of the carrier was sensed at the MSK modem. The status indication was sent to the data test set where the number of changes was counted. The clock slips, which are an indication of incorrect bit synchronization, were determined by the data test set.

The total count of clock slips and carrier losses for each flight are given in Table 4-3. The column labeled Maximum Received Signal Level denotes the maximum signal level at which clock slips or carrier losses were observed. The maximum number of counts occurred during flight 12 with 928 clock slips and 1892 carrier losses. However, the aircraft was either near or over the horizon for all of these counts. The clock slips or carrier losses occurred primarily when the received signal level was less than 5 μV. Generally, clock slips occurred after a signal outage when the receive modem was trying to reestablish synchronization. Both clock slip and carrier loss occurred primarily during poor signal conditions. However, thirteen occasions were observed when clock slips occurred during relatively good signal conditions (10 to 200 μV). No apparent cause can be attributed to these occurrences since the received signal was relatively constant

TABLE 4-3. SUMMARY OF CLOCK SLIP AND CARRIER LOSS COUNTS

FLIGHT	CLOCK SLIPS	CARRIER LOSSES	MAXIMUM RECEIVED SIGNAL LEVEL
5	40	106	5 μV
6	38	41	5 μV
7	0	0	------
9	572	1136	5 μV
10	326	1245	5 μV
11	58	108	30 μV
12	928	1892	5 μV
13	642	1164	60 μV
14	353	757	200 μV
15	6	12	70 μV
16	29	38	60 μV

and no excessive aircraft maneuvering was observed. Relatively large error bursts, typically 100 bits, were observed when the clock slips occurred. As noted in section 4.4.2, the bit and block error rate calculations include the bit errors resulting from the clock slips and carrier losses that occurred in the good signal region (i.e., exclusive of the near horizon and over-the-horizon regions).

4.4.6 Bit Error Characteristics

Bit errors due to received background noise appear in relatively small bursts, typically 1 to 4 bit errors per burst. Errors during aircraft maneuvering, however, appear in larger bursts, typically 10 to 100 bit errors per burst, and are probably due to the severe signal fades that occur during banking. Signal fades of 15 dB were observed during some banking maneuvers. Another cause of errors during the flights was occasional bursts of errors due to clock slips (loss of synchronization) during good signal conditions when the received signal level was in the 10 to 200 microvolt range.

This problem was only noted on 13 occasions during the entire testing period and could not be correlated to any of the recorded data; however, error bursts of 100 bits were recorded during those periods. Examples of these characteristics are shown in Figure 4-25 where the number of bit errors per 1-second sample are plotted as a function of time for Flight 16. The most likely cause of each of the events is noted on the figure. The causal relationships shown in Figure 4-25 were determined by correlation of the bit error events with measured values of noise, received signal strength, and aircraft attitude. Note that the term "bursts" in this discussion does not necessarily mean that the errors were consecutive. The resolution of the data prevented examination of the errors in sufficient detail to determine whether or not the errors were truly consecutive.

One additional problem that was noted during the flights was that interference occurred when the second bottom-mounted antenna was used for voice reception while the other antenna was simultaneously used for data transmission. Evidently the two antennas did not have sufficient isolation to prevent desensification of the voice receiver by the data transmitter even though the frequencies were widely separated.

4.5 SUMMARY OF RESULTS

Flight tests were performed to determine the characteristics of the VHF channel relative to the transmission of digital data. A continuous MSK modulated, pseudo-random sequence was transmitted air to ground at data rates of 2400 and 4800 bits per second (bps). Link performance was measured in terms of bit error rate (P_e), block error rate (P_b), and received signal level. The tests showed that the bit and block error rate performance was nearly identical at data rates of 2400 and 4800 bps. The average P_e was 6.8×10^{-5} and the average P_b was 1.2×10^{-2}. The average P_e showed an inverse relationship

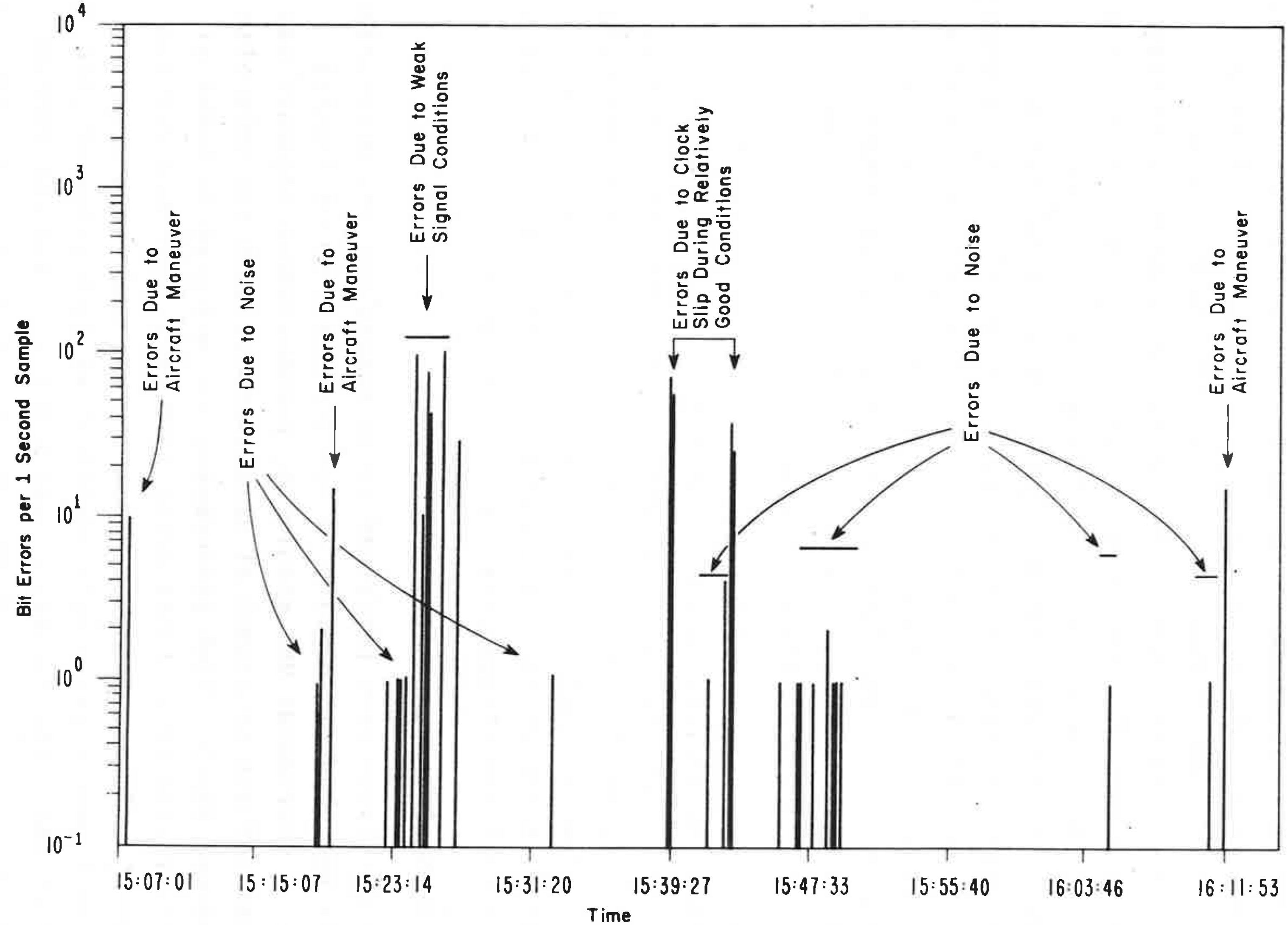


FIGURE 4-25. EXAMPLE SHOWING THE CHARACTERISTICS OF BIT ERRORS FOR FLIGHT 16

with aircraft slant range from the ground receiver site out to a range of at least 40 n mi. The average P_e was highest when the aircraft was close to the ground receiver site. The observed depth of signal fading exhibited a similar behavior with the maximum depth of fading occurring when the aircraft was close to the ground receiver site. Both of these observed phenomena are most likely the result of multipath due to ground reflections. Signal fading during aircraft maneuvers was observed to be a complex function of aircraft attitude relative to the receiver. Slow aircraft maneuvers did not appear to cause any abnormal error conditions; however, sudden maneuvers did cause errors. Clock slips and carrier loss indications occurred primarily during weak signal conditions, especially when the aircraft was inbound from locations beyond the radio horizon. However, there were occasions when clock slips occurred during strong signal conditions.

A region of abnormally high P_e was observed when the aircraft approached the radio horizon just prior to the loss of signal. The width of this region, described as the near horizon region, varied between 0.5 and 20 n mi, with an average of 10 n mi. The observed radio horizon showed good agreement with that predicted by an air-ground propagation model developed by ITS.

5. EXPERIMENTAL DATA LINK SYSTEM TESTS

The Experimental Data Link System was developed in order to demonstrate, in actual flight tests, the performance of a computer-controlled VHF data link system. The objective of the tests was to establish some of the design parameters necessary to perform a system design study for ATC applications of VHF data link. The performance of the system was measured in terms of bit error rate (P_e), message transaction failure rate (MTFR), and message throughput for the system operating in a simplex mode with a single aircraft.

5.1 EXPERIMENTAL DATA LINK TEST CONFIGURATION

The system operated on a master/slave basis with the ground system designated as the master. That is, the airborne system transmitted only in response to correctly addressed ground system generated polls. Messages were generated from message scenarios stored in the ground station computer or by operator keyboard input at the ground station or onboard the aircraft. Continuous message streams were generated automatically by the ground system computer. The message format was similar to that of the proposed ARINC data link system (Reference 6) with minor changes designed to enhance experiment control and data reduction. The transmitted messages were not seen by the flight deck crew and were not utilized to effect ATC commands. Transmission errors were detected by a block check sequence (BCS) scheme. The ground station computer performed a bit-by-bit check on all echo type messages determined to be in error by the BCS scheme in order to identify the exact bit or bits in error for each message. The flight test experiment was performed at data rates of 2400 and 4800 bits per second and for 50 kHz and 25 kHz channel spacings. The system software was configured to gather large quantities of experimental data and to perform many on-line system functions associated with this data gathering in addition to performing the link management functions. These experimental system functions, not normally expected in an operational system, had somewhat of an adverse effect on the message throughput performance of the system due to the increased processing time requirements placed on the computer. Data reduction was accomplished off-line on the ground system computer following completion of the flight tests. The flight tests were flown from the FAA NAFEC facility. The data link ground station was located at NAFEC and the FAA-owned Convair 540, N-103, was used as the test aircraft. The test aircraft is shown in Figure 5-1.

5.1.1 System Hardware Configuration

Block diagrams of the equipment comprising both the ground and airborne portions of the Experimental Data Link System are shown in Figure 5-2. Both ground and airborne systems utilized the TI-960A Minicomputer with 16K of memory and two TI Silent 700 Keyboard/Printer units with Dual Cassette Recorders. The ground and airborne system computers exercised the link management functions of the data link system and managed the collection of the experimental data. The Keyboard/Printer units with Dual Cassette Recorders performed the functions of keyboard inputting, data recording, and link status displaying by printing coded status symbols in real time during the course of the experiments.

An ARINC 566A VHF transceiver, the King 9100A, was used as the airborne communication equipment, while a separate transmitter, the GRT-21, and receiver, the GRR-23, were used for the ground communication equipment.

A bottom-mounted blade antenna, Type 37R-2U, was used on the aircraft and dedicated to the data link transceiver. The airborne data link system was rack-mounted in the cabin

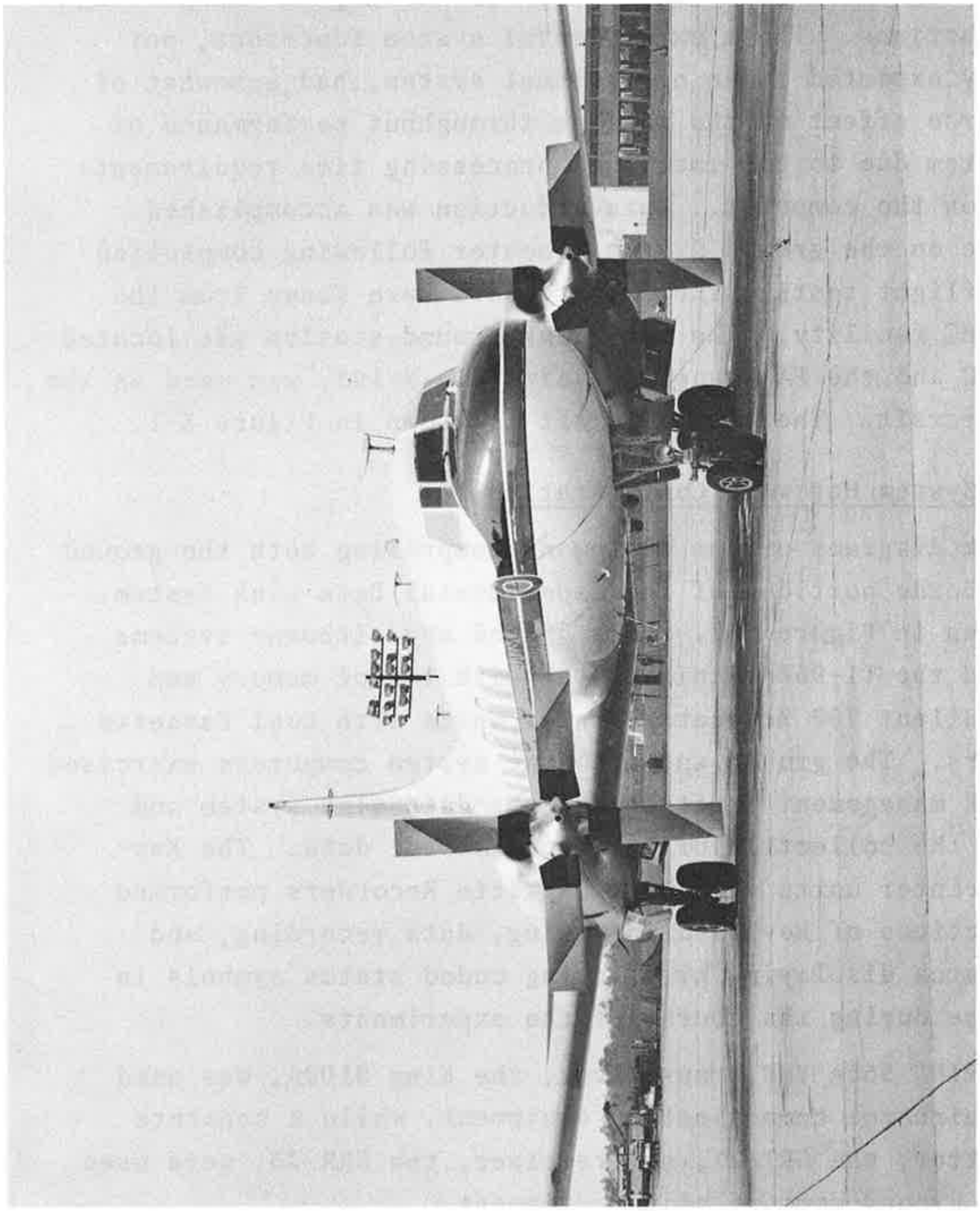


FIGURE 5-1. TEST AIRCRAFT

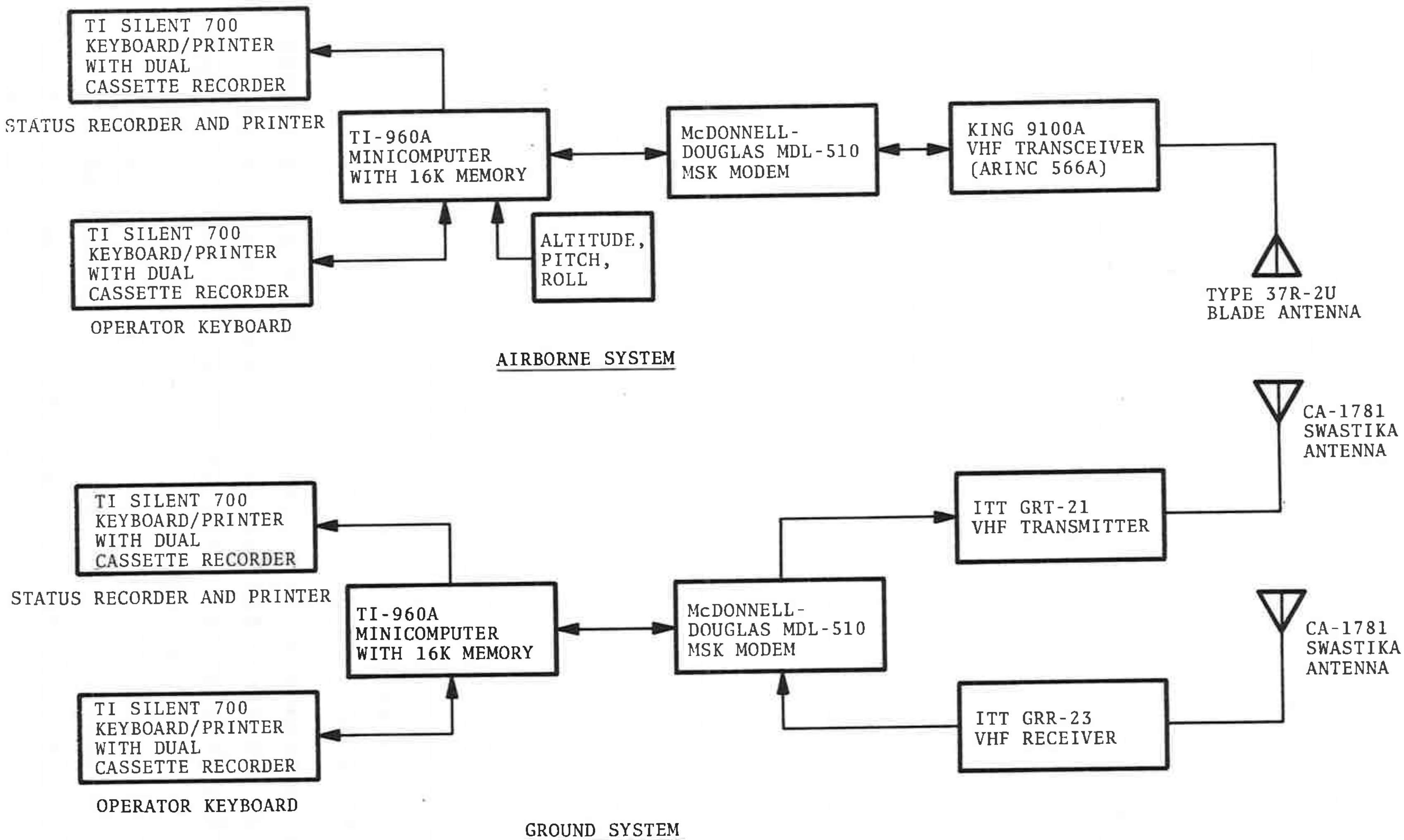


FIGURE 5-2. EXPERIMENTAL DATA LINK SYSTEM BLOCK DIAGRAM

of the test aircraft. The airborne computer was shock-mounted with conventional Lord mounts. The airborne system keyboard was accessible to the airborne system operator from a seated position in the cabin.

Two separate swastika antennas, Type CA-1781, were used for the ground transmitter and receiver. The two swastika antennas were located at the ground station mounted on 60-foot towers separated by 80 feet. A diode-limiting circuit was placed in the receive antenna line to prevent ground receiver saturation when the ground transmitter was activated. The diodes were chosen to limit the maximum received signal level to 200 mV. The ground station was located in NAFEC Building 224, which is approximately 2750 feet, at a bearing of 140^{o}, from the threshold of the 31 end of NAFEC runway 13-31.

Radar tracking was charted for the flight tests to provide correlation of aircraft position with data link performance. The radar track data from the NAFEC EAIR system was offset to the ground station site to provide communication center oriented tracking.

5.1.2 System Functional Description

A brief functional description of the system is given below. Additional information relating to the system description may be found in Appendix B.

The Experimental Data Link System was a polled system operated on a master/slave basis with the ground system designated as the master. The ground system computer dispatched stored-in-memory or keyboard-entered messages to be transmitted to the aircraft. The message format structure was basically in accordance with that of the proposed ARINC message formats (Reference 6) with the following exceptions: (1) five message characters were reserved for message identification to aid in data reduction; and (2) the aircraft identification field was reduced from seven to two characters. In addition, the message format subsequent to the prekey characters was altered because of computer hardware requirements. Two plus (+) characters were inserted following the two bit synchronization characters (+,*). The two bit synchronization characters were then repeated following the two plus (+) characters. This change was made to provide the frame synchronization required by the modem controller board in the computer. The first pair of bit synchronization characters (+,*) were stripped off at the modem and the two plus (+) characters were stripped off at the modem controller. All subsequent characters, starting with the second pair of bit synchronization characters, were passed on to the computer. The individual stored message scenarios, consisting of 30, 120, and 220 characters, were transmitted continuously for the length of time prescribed in the test matrix. That is, the chosen message was transmitted immediately upon receipt of the proper airborne system response to the previous uplinked message. Upon receipt of an uplink message the airborne system checked the message for the proper address, block check sequence (BCS) code, legal message length, and intercharacter times. If the uplink message passed these checks the airborne system transmitted a message containing a technical acknowledgement (ACK) to the ground system. Upon receipt of the ACK, the ground system transmitted the next message in the scenario. If the uplink message failed to pass the checks, the airborne system responded by transmitting a technical nonacknowledgement (NAK) to the ground system. Upon receipt of the NAK, the ground system repeated the previously dispatched message and recorded the error event. This sequence of events was repeated up to three times, at which time the ground system initiated transmission of the next message in the scenario. A similar sequence of events took place if the airborne system failed to respond to a ground-initiated message. If an uplink message did not result in the receipt on the ground of an acceptable response within an allotted time after transmission of the last message bit, the ground system declared that a No Response condition existed and recorded the event. The ground system then repeated the message up to three times or until the airborne system acknowledged receipt of the message; after three tries the ground system initiated transmission of the next message in the scenario. Those messages which failed to start correctly were considered to be No Response cases. There were three conditions which could result in a No Response case: (1) If the modem failed to acquire; (2) if the modem controller failed to acquire; and (3) if the message failed to pass a software acceptance test assuming conditions (1) and (2) above did not apply. To start correctly for condition (3) above, a message received in the computer was required to have the first six consecutive characters free of errors. This really implies that eight consecutive characters were error-free since the modem controller had to be synchronized on the two plus (+) characters in order for the computer to receive the message. This stringent condition replaced the original requirement of the reception of only two error-free characters (SYN, SYN) because of difficulties encountered during bench testing of the system with false starts induced by RF interference caused by other users of the channel assigned to the data link project. The original message start condition was not restored for the flight tests. Thus, the six characters +, *, SYN, SYN, SOH, and a mode character were required to be error-free for the system to accept a message. The time to a No Response declaration was a variable determined in the following manner. Following transmission of the second BCS character to the airborne system, the ground system waited up to 600 ms for a reply. If no reply was received within 600 ms, a No Response was declared. During this time the ground system computer looked for a "+" (plus) character at the beginning of the downlink message. After receipt of the "+" character, the computer then looked for successive receipt of an "*" (asterisk) character, SYN, SYN, SOH, and an acceptable mode character, all following within 5 ms of one another. If the time spacing exceeded 5 ms between any of the six characters, a No Response was declared.

A further condition for the declaration of a No Response was established if a message met the above conditions for acceptability but exceeded 5 ms between any two successive characters following the mode character through the last BCS character.

Diagnostic records with time tags were stored on the cassette tapes for off-line data reduction at the conclusion of the flight tests.

The airborne system performed functions similar to the ground system except that the airborne system functioned as a slave. That is, it responded only to ground-initiated polls such as system entry, time synchronization, or general messages. When there was a keyboard-entered message to transmit, the airborne system appended a special poll request to a conventional message response. Upon receipt of the special poll request the ground system would then ask for the keyboard-entered message from the airborne system. The airborne system recorded aircraft altitude, pitch angle, and roll angle at the time of each received message; i.e., error condition (BCS error or error-free), incorrect aircraft address, illegal message length, and receipt of NAK's.

The ground and airborne system modems provided the transmit/receive switching control for the ground transmitter/receiver and airborne transceiver, respectively.

The MDL-510 MSK Modems, which are capable of generating and checking BCS codes and character parity and detection of the SYN-SYN characters, were used in a completely transparent mode. That is, the modem passed on everything to the computer which did the BCS checking and message start detection. The modem interface with the computer (a printed circuit board in the computer) performed all of the serial-to-parallel and parallel-to-serial packing of bits.

The airborne system computer had a 12-bit A/D converter and multiplexer (computer printed circuit board), which sequentially inputted altitude, pitch, and roll from analog aircraft sensors.

A complete description of the message format and the mode/label scheme may be found in Appendix B.

Software for the Experimental Data Link System was developed under contract by Input-Output Computer Systems Inc., Cambridge MA. The software was written in assembly language. The complete software documentation can be found in Reference 13.

5.1.3 Data Acquisition

The ground and airborne system computers were used to manage the collection of the experimental data. The data were stored on cassettes in the TI Silent 700 Keyboard-Printer recorders. An off-line data reduction program in the ground system computer correlated the airborne and ground system records and printed a reduced data output on the TI Silent 700 Keyboard/Printer.

The system had a special feature called ECHO which, when used with the proper mode character, caused the airborne system to transmit the complete received uplink message, including preamble and postamble, as the downlink message.

The retransmitted (echoed) message was packaged with a new preamble and postamble. This feature allowed a bit-for-bit comparison of the entire uplink message including the original preamble and postamble.

A complete description of the software for data collection and reduction can be found in Reference 13.

5.2 EXPERIMENT PROCEDURES

The flight tests were intended to test the data link system performance at data rates of 2400 and 4800 bits per second at both 25-kHz and 50-kHz channel spacing. It should be recalled that the airborne transceiver, the King 9100A, had 25-kHz channel spacing while the ground receiver, the GRR-23, as normally configured, had 50-kHz channel spacing. However, a filter was available for use with the GRR-23 receiver that allowed it to operate with 25-kHz channel spacing. The characteristics of this filter, compared with the normal 50-kHz channel filter, is shown in Figure 5-3. As can be seen from Figure 5-3, the narrow bandpass filter has poor characteristics relative to bandwidth and smoothness. Thus, hardware limitations required that some of the tests be performed in a hybrid mode relative to 50-kHz channel spacing. That is, the uplink messages were sent to a receiver having 25-kHz channel spacing, and the downlink messages were sent to a receiver having 50-kHz channel spacing. This setup presents a more severe communication test than if both ends of the channel had 50-kHz channel spacing. The tests at 25-kHz channel spacing were performed with the narrow band filter of Figure 5-3 installed in the GRR-23 ground receiver.

The flight test matrix shown in Table 5-1 presents the parameters that were tested in this series of tests. The 11 flights were structured to gather enough data at each test condition to give statistical significance. Message

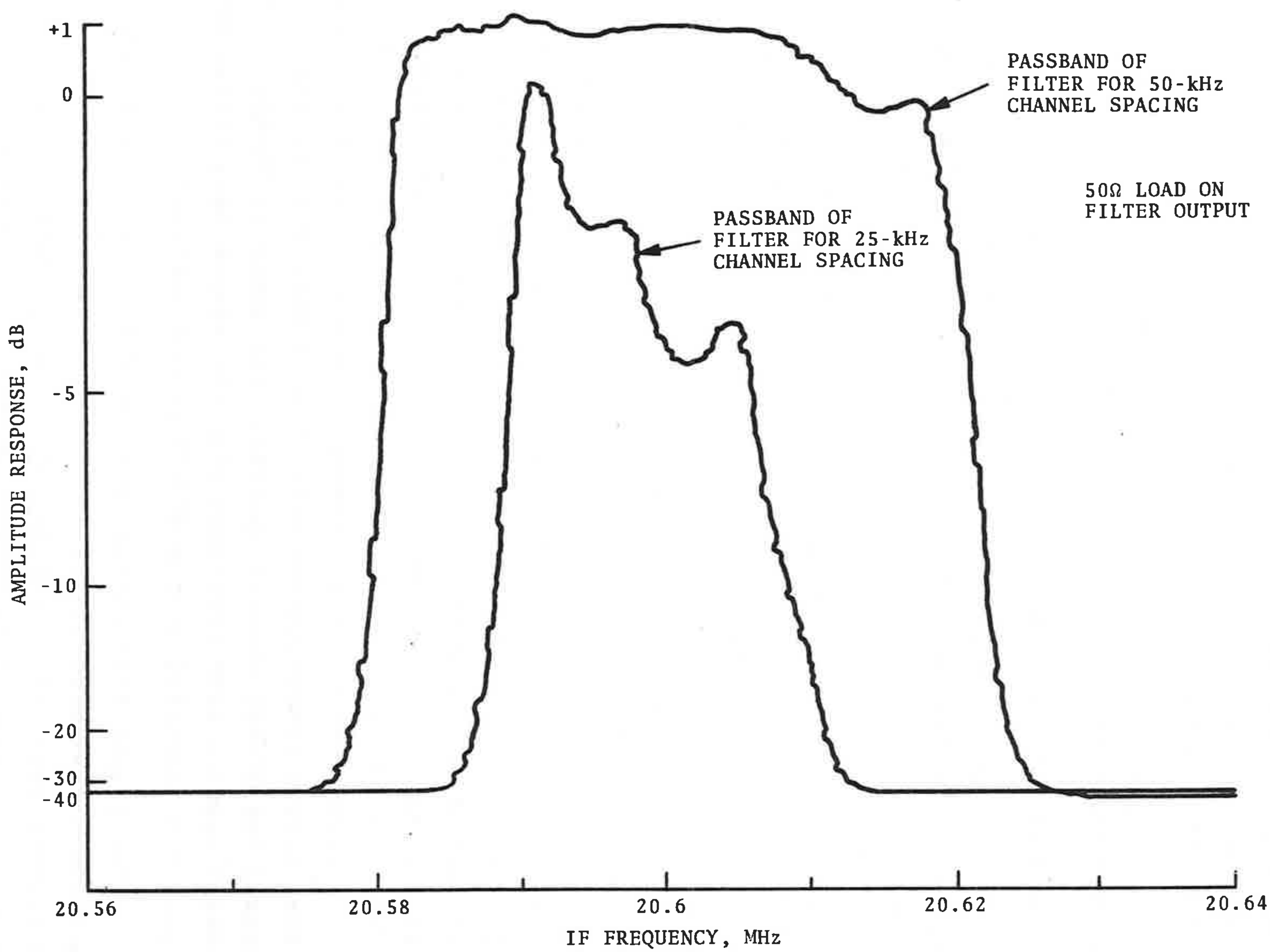


FIGURE 5-3. CHANNEL SPACING FILTER CHARACTERISTICS FOR GRR-23 RECEIVER

TABLE 5-1. EXPERIMENTAL DATA LINK SYSTEM FLIGHT TEST MATRIX

Flight Number	Date	Text Length (Characters)	Message Number	Data Rate	Channel Spacing	Number of Runs	Accumulated Flight Data Time	Mode	Mode Characters
1	6/16/75	220	1	2400	50 kHz	3	4 Hr	Normal	2
2	6/17/75	120	8	2400	50 kHz	3	4 Hr	Normal (Echo)	3, H
3	6/17/75	30	5	4800	50 kHz	2	1 Hr	Normal	2
4*	6/18/75	120	8	4800	50 kHz	3	2.5 Hr	Normal (Echo)	3, H
5	6/18/75	30	5	2400	50 kHz	3	2 Hr	Normal	2
6	6/19/75	220	1	4800	50 kHz	4	2.5 Hr	Normal	2
7	6/19/75	120	8	4800	25 kHz	2	1 Hr	Normal (Echo)	3, H
8	6/19/75	120	8	2400	25 kHz	1	1 Hr	Normal (Echo)	3, H
9	6/20/75	120	8	2400	50 kHz	2	2.5 Hr	Normal (Echo)	3, H
10	6/23/75	30	5	2400	25 kHz	3	2 Hr	Normal	2
11	6/23/75	120	8	4800	50 kHz	3	2 Hr	Normal (Echo)	3, H

*Note - Flight #4 Test was started in mid-air.

Air Route - NAFEC to Sea Isle, V139 to Snow Hill, turn around and return to NAFEC. Approximate Air Speed 290 Knots; Approximate Altitudes of 14,000 and 15,000 feet.

lengths of 30, 120, and 220 characters were chosen as representative of short, medium, and long messages that might be encountered in an operational data link system. The message texts are shown in Figure 5-4. The message character count includes carriage returns, spaces, and line feeds which do not appear in the text. As mentioned previously, those tests listed as having 50-kHz channel spacing actually were a hybrid of 25-kHz and 50-kHz channel spacing. The ground station computer keyboard was used to initialize the data link system for each test. The ground system operator keyed in the data rate, the number of pre-key characters, the number of allowable No Responses, the mode characters, the stored message or series of messages to be used, and any other pertinent data such as existing weather conditions. The data link system was started when the aircraft was on the ramp, for most flights, and run for the entire duration the flight tests until the aircraft returned to the ramp. Thus, data were collected during the taxi portions of the flights.

Eleven test flights were conducted with the airborne system installed on the Convair 540 between June 16, 1975, and June 23, 1975. The flights consisted of from 1 to 4 runs each over a 200-mile course between Atlantic City (ACY), New Jersey, and Snow Hill (SWL), Maryland, at a nominal altitude of 14000 feet and speed of 290 knots. These navigation points are shown boxed in on the map in Figure 5-5. Radar tracks of flights 4, 5, 6, and 9 are shown in Figure 5-6. All turns were 30° standard turns. The ground station communication site is shown on Figure 5-6 as the dot enclosed with a circle and numbered 224. Run lengths were determined by the tape capacity of the cassette recording system. As can be seen from the map in Figure 5-5, the flight paths traversed basically flat sea coast terrain and some bodies of water (e.g., Delaware Bay). Data were collected from the time the aircraft left the ramp until it returned to the ramp.

30 CHARACTER (BYTE) MESSAGE

LAX GROUND 121.8

120 CHARACTER (BYTE) MESSAGE

UA 246 DEPARTURE REPORT RECEIVED

DEPART LAX AT 20 MINUTES AFTER 12A

NOTHING TO REPORT ON AIRCRAFT CONDITION NOW

220 CHARACTER (BYTE) MESSAGE

LA INTERNAT AIRPORT

INFO ZULU CEILING UNLIMITED

VIS 3 MILES IN HAZE AND SMOKE

TEMP 61 DEW POINT 54 WIND 270

AT 14 ALTIMETER 30.10

ILS APPROACH RUNWAYS 24 LEFT AND 24 RIGHT

DEPARTURE RUNWAYS 25 LEFT AND 25 RIGHT

FIGURE 5-4. MESSAGE TEXTS

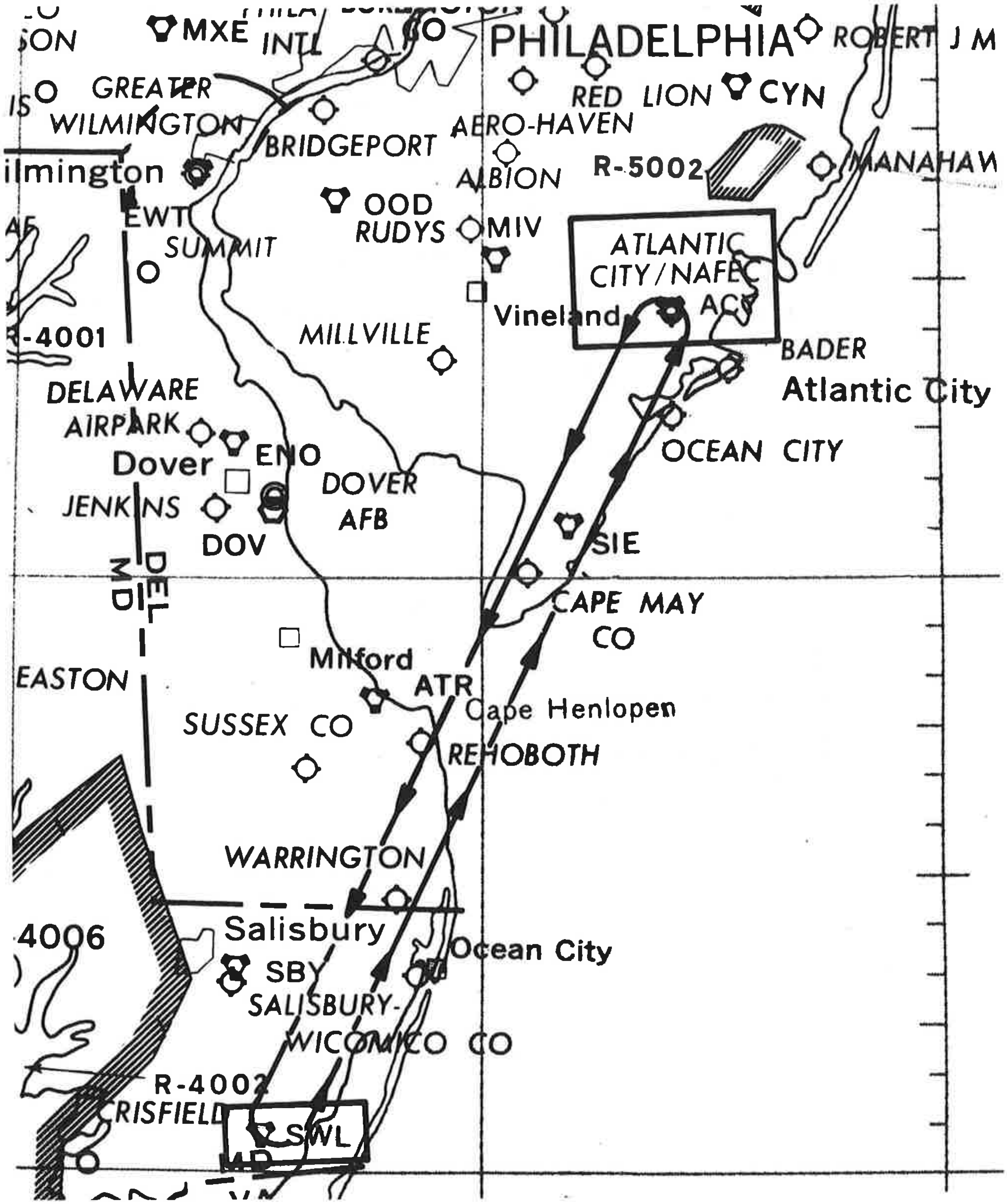


FIGURE 5-5. MAP SHOWING FLIGHT TEST ROUTE

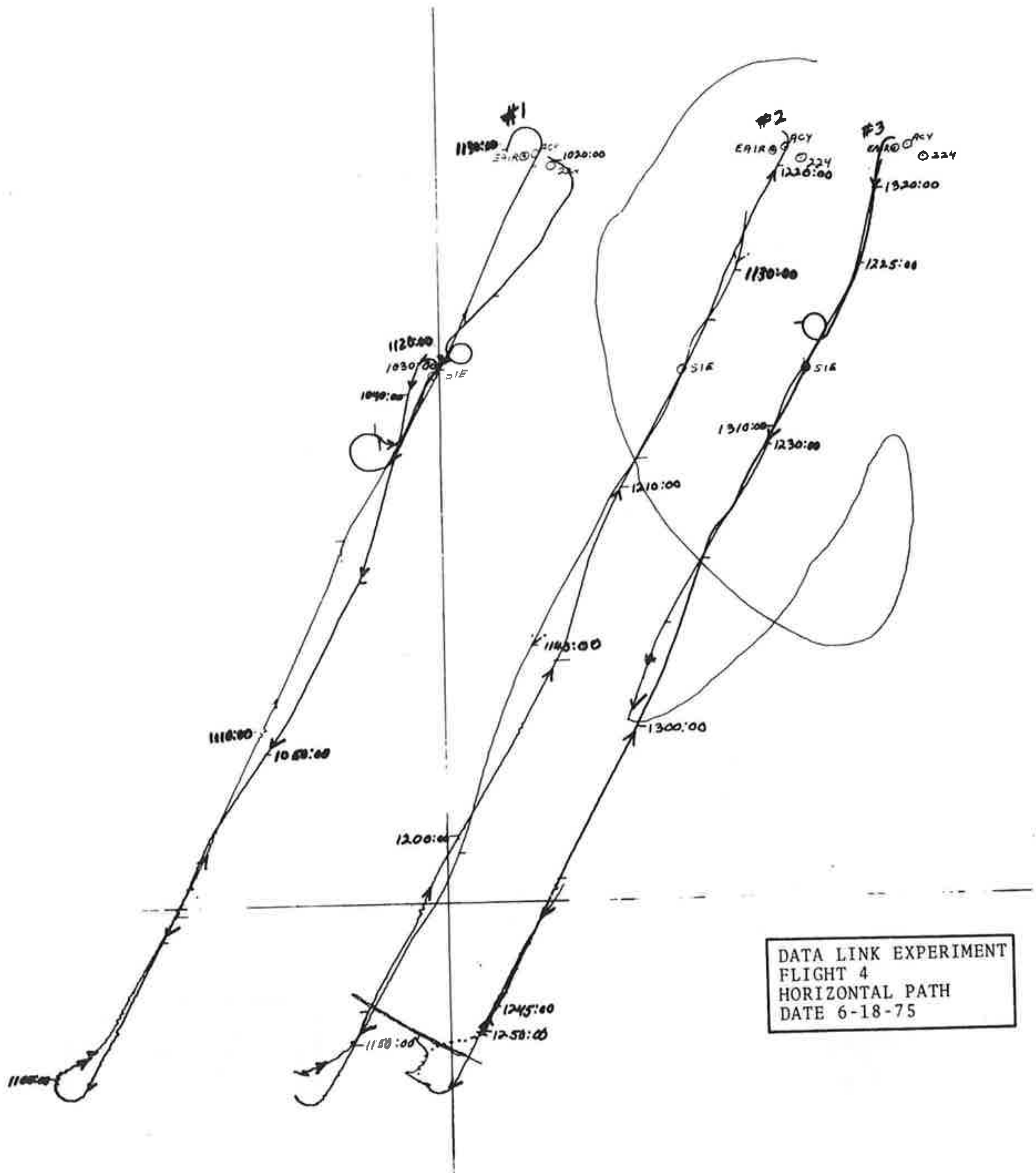


FIGURE 5-6a. RADAR TRACK OF FLIGHT 4

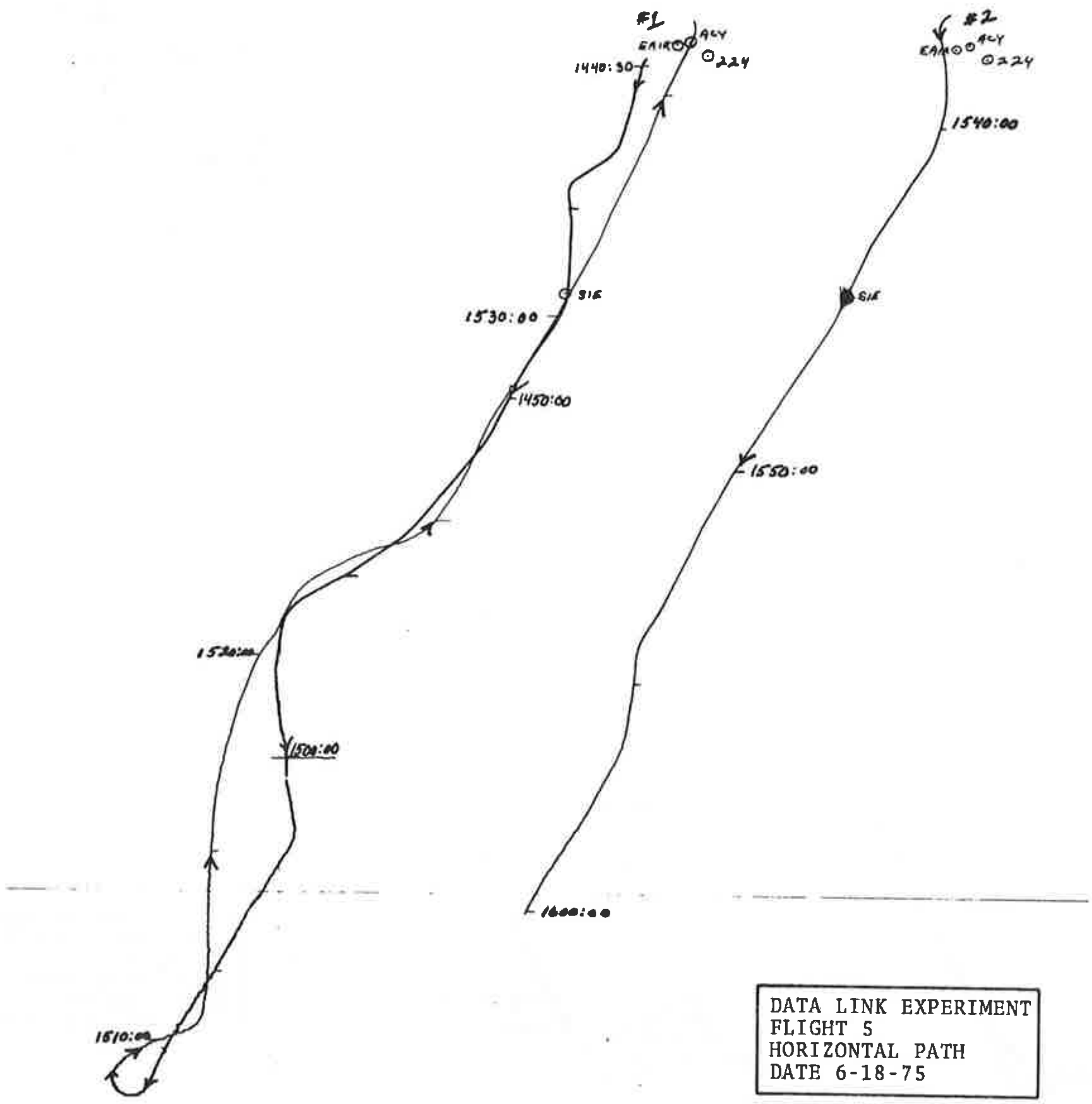


FIGURE 5-6b. RADAR TRACK OF FLIGHT 5

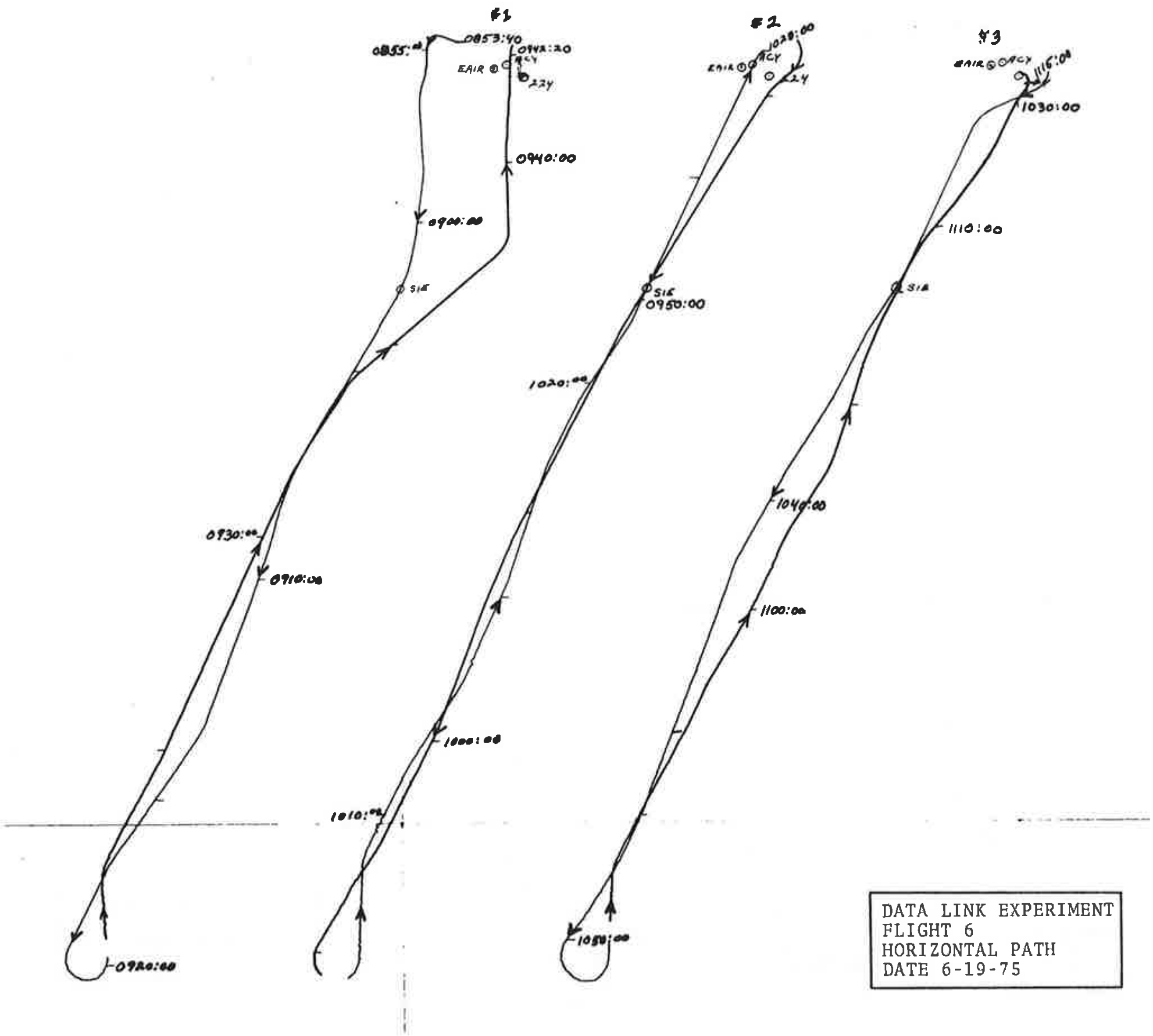
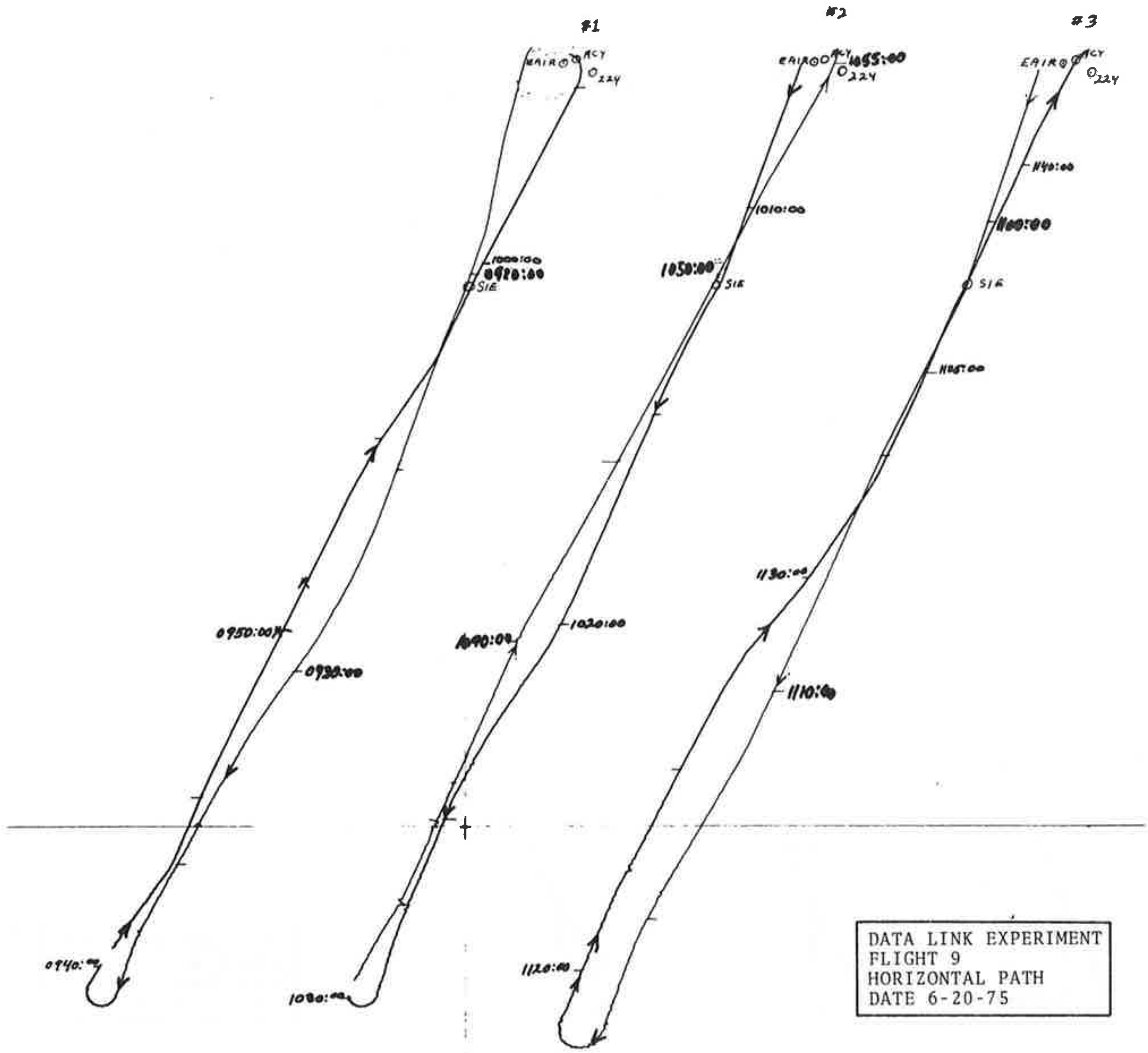


FIGURE 5-6c. RADAR TRACK OF FLIGHT 6



DATA LINK EXPERIMENT
FLIGHT 9
HORIZONTAL PATH
DATE 6-20-75

FIGURE 5-6d. RADAR TRACK OF FLIGHT 9

Thus data were collected during all phases of flight (i.e., taxi, takeoff and climbout, cruise, and approach and landing). The majority of the data were collected for the cruise flight condition. The flight paths were flown to stay within the line-of-sight (LOS) radio horizon to avoid data reduction complexities that would result from averaging over-the-horizon data with LOS data.

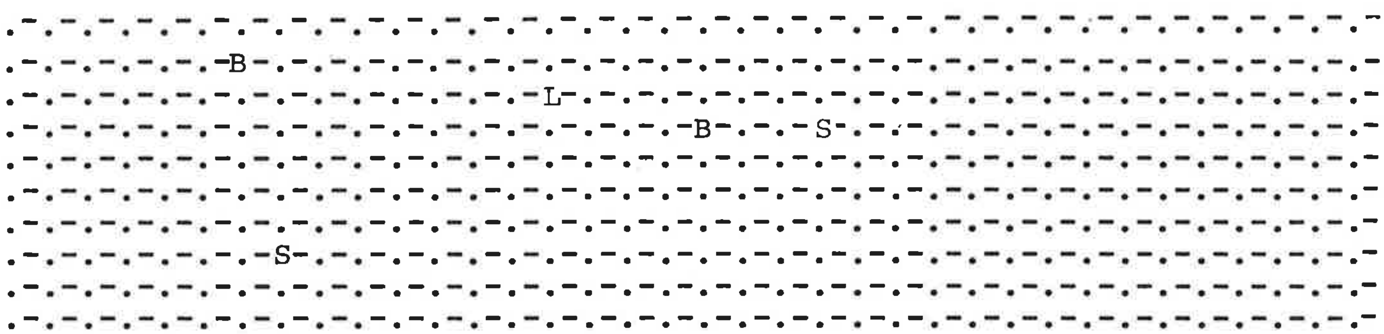
The tests were conducted at a frequency of 126.15 MHz in the Air Mobile Frequency Band. The status of the data link system was displayed to the ground and airborne system operators during the tests on the ground and airborne system printers. Samples of the status records for the airborne and ground systems are shown in Figure 5-7. In these records the dot indicates that a message was received with a proper acknowledgement and good BCS check and a dash indicates that a message was sent. The character B indicates that a message was received having a BCS error. The character L indicates receipt of a message that was too long. The S character indicates receipt of a message that was too short. The W character indicates receipt of a message with an improper address. The R character indicates No Response to a message. The I character indicates receipt of a message with a bit compare error.

5.3 SUMMARIES OF REDUCED DATA

Summaries of the data along with observations for each of the 11 test flights are presented below. For analysis purposes the collected data were divided into five categories: aircraft on the ground, aircraft turning, aircraft in straight and level flight, aircraft landing, and totals for the entire flight.

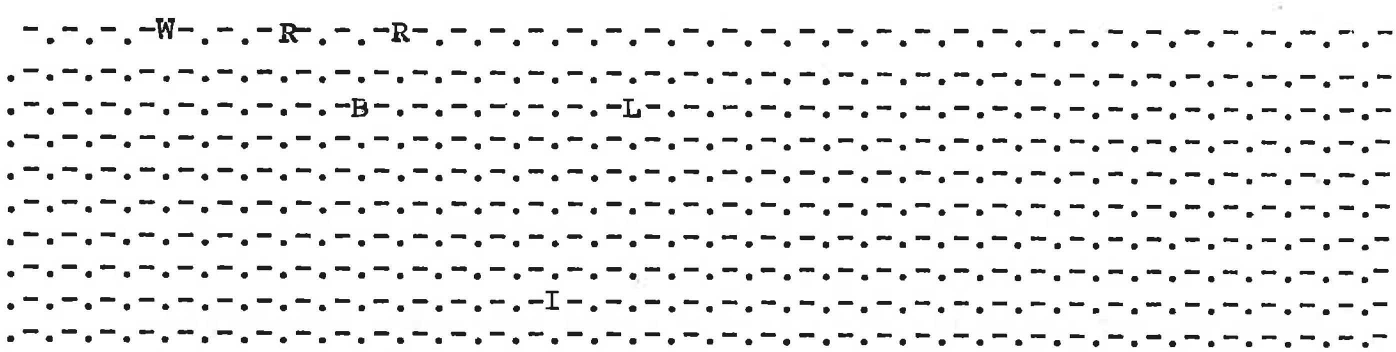
The data summaries are presented in Tables 5-2 through 5-12. These summaries give the number of message transactions attempted, completed, and failed in each of the flight categories.

START OF EXPERIMENT -



(a) PORTION OF TYPICAL AIRBORNE STATUS RECORD

START OF EXPERIMENT -



(b) PORTION OF TYPICAL GROUND STATUS RECORD

FIGURE 5-7. EXAMPLES OF GROUND AND AIRBORNE SYSTEM STATUS RECORDS

TABLE 5-2. FLIGHT 1 DATA SUMMARY

	A/C on the Ground	A/C Turning	A/C Flying Level	A/C Landing	Total
Messages Attempted	112	642	10893	257	11904
Messages Completed	95	559	10841	257	11752
Message Failures (Total)	17	83	52		152
Uplink No Responses	2	41	20		63
Uplink BCS Message Errors/ Number of Bit Errors	14/28	39/294	30/242		83/564
Uplink Long Messages					
Uplink Wrong A/C ID					
Downlink No Responses	3	12	2		17
Downlink BCS Message Errors/ Number of Bit Errors					
Downlink Long Messages					
Downlink Wrong A/C ID					
Number of 3 Repeats	2	20	3		25
Uplink Bit Error Rate ($x10^{-6}$)	132.58	254.78	11.59		24.8
Downlink Bit Error Rate ($x10^{-6}$)					
Message Transaction Failure Rate ($x10^{-3}$)	152	130	4.8		12.77
Expected Message Transaction Failure Rate ($x10^{-3}$)	254.55	489.18	22.253		47.62
Uplink Message Failure Rate ($x10^{-3}$)	142.9	124.6	4.59		12.26
Downlink Message Failure Rate ($x10^{-3}$)	26.79	18.7	0.184		1.43
Messages with Single Bit Errors	6	10	8		24
Messages with Character Slip		2			2
Mean Good Transmission Time (minutes: seconds)					14:40
Maximum Good Transmission Time (minutes: seconds)					34:15
Minimum Good Transmission Time (minutes: seconds)					2:52

Parameters: 2400 bps; 50- kHz channel spacing; 3 repeats on error messages; 30 prekey characters; 220 character message (non-echoed); uplink message = 1920 bits; downlink message = 152 bits; prekey time = 0.0133 seconds; uplink message time = 0.8 seconds; downlink message time = 0.063 seconds.

TABLE 5-3. FLIGHT 2 DATA SUMMARY

	A/C on the Ground	A/C Turning	A/C Flying Level	A/C Landing	Total
Messages Attempted	450	468	8973	225	10116
Messages Completed	445	466	8955	193	10059
Message Failures (Total)	5	2	18	32	57
Uplink No Responses	1		7	1	9
Uplink BCS Message Errors/ Number of Bit Errors	1/1	1/1	8/44	9/35	19/81
Uplink Long Messages					
Uplink Wrong A/C ID					
Downlink No Responses	1	1	2	15	19
Downlink BCS Message Errors/ Number of Bit Errors	2/2			5/25	7/27
Downlink Long Messages				8	
Downlink Wrong A/C ID				1	1
Number of 3 Repeats				4	4
Uplink Bit Error Rate ($x10^{-6}$)	1.99	1.907	4.38	139.5	7.16
Downlink Bit Error Rate ($x10^{-6}$)	3.6			96.47	2.16
Message Transaction Failure Rate ($x10^{-3}$)	11.11	4.27	2.006	142.22	5.63
Expected Message Transaction Failure Rate ($x10^{-3}$)	6.69	2.14	4.9	275.9	10.7
Uplink Message Failure Rate ($x10^{-3}$)	4.44	2.14	1.67	44.4	2.77
Downlink Message Failure Rate ($x10^{-3}$)	6.67	2.14	0.334	128.9	3.56
Messages with Single Bit Errors	3	1	4	2	10
Messages with Character Slip					
Mean Good Transmission Time (minutes: seconds)					14:47
Maximum Good Transmission Time (minutes: seconds)					36:26
Minimum Good Transmission Time (minutes: seconds)					5:42

Parameters: 2400 bps; 50-kHz channel spacing; 3 repeats on error messages; 30 prekey characters; 120 character message (echoed); uplink message = 1120 bits; downlink message = 1240 bits, prekey time = 0.013 seconds; uplink message time = 0.467 seconds; downlink message time = 0.517 seconds.

TABLE 5-4. FLIGHT 3 DATA SUMMARY

	A/C on the Ground	A/C Turning	A/C Flying Level	A/C Landing	Total
Messages Attempted	901	174	7243	601	8919
Messages Completed	898	173	7230	588	8889
Message Failures (Total)	3	1	13	13	30
Uplink No Responses				1	1
Uplink BCS Message Errors/ Number of Bit Errors			1/1	1/1	2/2
Uplink Long Messages					
Uplink Wrong A/C ID					
Downlink No Responses	3	1	8	8	20
Downlink BCS Message Errors/ Number of Bit Errors			4/4	2/6	6/10
Downlink Long Messages					
Downlink Wrong A/C ID				1	1
Number of 3 Repeats				1	1
Uplink Bit Error Rate ($x10^{-6}$)			0.345	4.17	0.56
Downlink Bit Error Rate ($x10^{-6}$)			1.06	19.49	2.16
Message Transaction Failure Rate ($x10^{-3}$)	3.33	5.75	1.79	21.63	3.36
Expected Message Transaction Failure Rate ($x10^{-3}$)			0.69	11.8	1.35
Uplink Message Failure Rate ($x10^{-3}$)			0.14	3.33	0.336
Downlink Message Failure Rate ($x10^{-3}$)	3.33	5.75	1.66	1.66	3.03
Messages with Single Bit Errors			5	2	7
Messages with Character Slip					
Mean Good Transmission Time (minutes: seconds)					6:85
Maximum Good Transmission Time (minutes: seconds)					20:50
Minimum Good Transmission Time (minutes: seconds)					2:26

Parameters: 4800 bps; 50-kHz channel spacing; 3 repeats on error messages; 60 prekey characters; 30 character message (non-echoed); uplink message = 400 bits; downlink message = 152 bits; prekey time = 0.0133 seconds; uplink message time = 0.083 seconds; downlink message time = 0.1083 seconds.

TABLE 5-5. FLIGHT 4 DATA SUMMARY

	A/C on the Ground	A/C Turning	A/C Flying Level	A/C Landing	Total
Messages Attempted		569	9466	454	10489
Messages Completed		550	9342	429	10321
Message Failures (Total)		19	124	25	168
Uplink No Responses			2		2
Uplink BCS Message Errors/ Number of Bit Errors		1	9/7	1/5	11/12
Uplink Long Messages					
Uplink Wrong A/C ID					
Downlink No Responses		17	101	23	141
Downlink BCS Message Errors/ Number of Bit Errors		1/1	8/9	1/3	10/13
Downlink Long Messages			3		3
Downlink Wrong A/C ID			1		1
Number of 3 Repeats			7		7
Uplink Bit Error Rate ($x10^{-6}$)			0.66	9.83	1.02
Downlink Bit Error Rate ($x10^{-6}$)		1.46	0.775	5.6	1.013
Message Transaction Failure Rate ($x10^{-3}$)		33.4	13.1	55.07	16.02
Expected Message Transaction Failure Rate ($x10^{-3}$)		1.8	1.7	17.95	2.4
Uplink Message Failure Rate ($x10^{-3}$)		1.76	1.16	2.2	1.24
Downlink Message Failure Rate ($x10^{-3}$)		31.63	11.94	52.86	14.78
Messages with Single Bit Errors		1	10		11
Messages with Character Slip		1	5		6
Mean Good Transmission Time (minutes: seconds)					7:22
Maximum Good Transmission Time (minutes: seconds)					19:51
Minimum Good Transmission Time (minutes: seconds)					2:28

Parameters: 4800 bps; 50- kHz channel spacing; 3 repeats on error messages; 60 prekey characters; 120 character message (echoed); uplink message = 1120 bits; downlink message = 1240 bits; prekey time = 0.0133 seconds; uplink message time = 0.233 seconds; downlink message time = 0.258 seconds.

TABLE 5-6. FLIGHT 5 DATA SUMMARY

	A/C on the Ground	A/C Turning	A/C Flying Level	A/C Landing	Total
Messages Attempted		347	12470	864	13681
Messages Completed		346	12450	844	13640
Message Failures (Total)		1	20	20	41
Uplink No Responses		1	9	2	12
Uplink BCS Message Errors/ Number of Bit Errors			5/13	9/18	14/31
Uplink Long Messages					
Uplink Wrong A/C ID					
Downlink No Responses			6	7	13
Downlink BCS Message Errors/ Number of Bit Errors				2/6	2/6
Downlink Long Messages					
Downlink Wrong A/C ID					
Number of 3 Repeats			3	4	7
Uplink Bit Error Rate ($x10^{-6}$)			2.608	53.4	5.669
Downlink Bit Error Rate ($x10^{-6}$)				46.168	2.89
Message Transaction Failure Rate ($x10^{-3}$)		2.88	1.604	23.15	2.997
Expected Message Transaction Failure Rate ($x10^{-3}$)			1.04	28.38	2.707
Uplink Message Failure Rate ($x10^{-3}$)			1.12	12.73	1.9
Downlink Message Failure Rate ($x10^{-3}$)			0.48	10.42	1.096
Messages with Single Bit Errors			1	4	5
Messages with Character Slip					
Mean Good Transmission Time (minutes: seconds)					11:93
Maximum Good Transmission Time (minutes: seconds)					20:14
Minimum Good Transmission Time (minutes: seconds)					2:03

Parameters: 2400 bps; 50-kHz channel spacing; 3 repeats on error messages; 30 prekey characters; 30 character message (non-echoed); uplink message = 400 bits; downlink message = 152 bits; prekey time = 0.0133 seconds; uplink message time = 0.167 seconds; downlink message time = 0.063 seconds.

TABLE 5-7. FLIGHT 6 DATA SUMMARY

	A/C on the Ground	A/C Turning	A/C Flying Level	A/C Landing	Total
Messages Attempted	169	678	9876	180	10903
Messages Completed	168	667	9825	178	10838
Message Failures (Total)	1	11	51	2	65
Uplink No Responses			11		11
Uplink BCS Message Errors/ Number of Bit Errors		4/3	19/125		23/128
Uplink Long Messages					
Uplink Wrong A/C ID					
Downlink No Responses		7	21	2	30
Downlink BCS Message Errors/ Number of Bit Errors					
Downlink Long Messages					
Downlink Wrong A/C ID					
Number of 3 Repeats			3		3
Uplink Bit Error Rate ($x10^{-6}$)		2.3	6.6		6.12
Downlink Bit Error Rate ($x10^{-6}$)					
Message Transaction Failure Rate ($x10^{-3}$)	5.9	16.2	5.16	11.1	5.96
Expected Message Transaction Failure Rate ($x10^{-3}$)		4.42	12.67		11.75
Uplink Message Failure Rate ($x10^{-3}$)		5.89	3.04		3.12
Downlink Message Failure Rate ($x10^{-3}$)		10.3	2.13	11.1	2.75
Messages with Single Bit Errors		3	4		7
Messages with Character Slip	1	1	9		11
Mean Good Transmission Time (minutes: seconds)					5:92
Maximum Good Transmission Time (minutes: seconds)					14:28
Minimum Good Transmission Time (minutes: seconds)					0:12

Parameters: 4800 bps; 50-kHz channel spacing; 3 repeats on error messages; 60 prekey characters; 220 character message (non-echoed); uplink message = 1920 bits; downlink message = 152 bits; prekey time = 0.0129 seconds; uplink message time = 0.4 seconds; downlink message time = 0.032 seconds.

TABLE 5-8. FLIGHT 7 DATA SUMMARY

	A/C on the Ground	A/C Turning	A/C Flying Level	A/C Landing	Total
Messages Attempted	126	235	3244		3605
Messages Completed	120	234	3188		3542
Message Failures (Total)	6	1	56		63
Uplink No Responses			10		10
Uplink BCS Message Errors/ Number of Bit Errors			12/28		12/28
Uplink Long Messages					
Uplink Wrong A/C ID					
Downlink No Responses	3		18		21
Downlink BCS Message Errors/ Number of Bit Errors	3/5	1/2	14/21		18/28
Downlink Long Messages			2		2
Downlink Wrong A/C ID					
Number of 3 Repeats			9		9
Uplink Bit Error Rate ($x10^{-6}$)			7.73		6.95
Downlink Bit Error Rate ($x10^{-6}$)	32.78	6.86	6.02		6.99
Message Transaction Failure Rate ($x10^{-3}$)	47.6	4.26	16.03		17.48
Expected Message Transaction Failure Rate ($x10^{-3}$)	40.65	8.506	16.12		16.45
Uplink Message Failure Rate ($x10^{-3}$)			6.78		6.1
Downlink Message Failure Rate ($x10^{-3}$)	47.6	4.26	10.48		11.37
Messages with Single Bit Errors	1		15		16
Messages with Character Slip					2
Mean Good Transmission Time (minutes: seconds)					0:16
Maximum Good Transmission Time (minutes: seconds)					0:55
Minimum Good Transmission Time (minutes: seconds)					0:00

Parameters: 4800 bps; 25-kHz channel spacing; 3 repeats on error messages; 60 prekey characters; 120 character message (echoed); uplink message = 1120 bits; downlink message = 1240 bits; prekey time = 0.0133 seconds; uplink message time = 0.233 seconds; downlink message time = 0.258 seconds.

TABLE 5-9. FLIGHT 8 DATA SUMMARY

	A/C on the Ground	A/C Turning	A/C Flying Level	A/C Landing	Total
Messages Attempted		69	2019	371	2459
Messages Completed		69	2015	370	2454
Message Failures (Total)		0	4	1	5
Uplink No Responses			2	1	3
Uplink BCS Message Errors/ Number of Bit Errors					
Uplink Long Messages					
Uplink Wrong A/C ID					
Downlink No Responses			1		1
Downlink BCS Message Errors/ Number of Bit Errors			1/1		1/1
Downlink Long Messages					
Downlink Wrong A/C ID					
Number of 3 Repeats					
Uplink Bit Error Rate ($x10^{-6}$)					
Downlink Bit Error Rate ($x10^{-6}$)			3.26		2.68
Message Transaction Failure Rate ($x10^{-3}$)			1.98	2.7	2.03
Expected Message Transaction Failure Rate ($x10^{-3}$)			0.496		0.407
Uplink Message Failure Rate ($x10^{-3}$)			0.99	2.7	1.22
Downlink Message Failure Rate ($x10^{-3}$)			0.99		0.813
Messages with Single Bit Errors			1		1
Messages with Character Slip					
Mean Good Transmission Time (minutes: seconds)					12:26
Maximum Good Transmission Time (minutes: seconds)					18:00
Minimum Good Transmission Time (minutes: seconds)					0:57

Parameters: 2400 bps; 25-kHz channel spacing; 3 repeats on error messages; 30 prekey characters; 120 character message (echoed); uplink message = 1120 bits; downlink message = 1240 bits; prekey time = 0.0133 seconds; uplink message time = 0.467 seconds; downlink message time = 0.517 seconds.

TABLE 5-10. FLIGHT 9 DATA SUMMARY

	A/C on the Ground	A/C Turning	A/C Flying Level	A/C Landing	Total
Messages Attempted	315	303	6202	180	7000
Messages Completed	315	299	6192	179	6985
Message Failures (Total)		4	10	1	15
Uplink No Responses			4	1	5
Uplink BCS Message Errors/ Number of Bit Errors		1/4	2/2		3/6
Uplink Long Messages					
Uplink Wrong A/C ID					
Downlink No Responses		2	4		6
Downlink BCS Message Errors/ Number of Bit Errors		1/26			1/26
Downlink Long Messages					
Downlink Wrong A/C ID					
Number of 3 Repeats					
Uplink Bit Error Rate ($x10^{-6}$)		11.79	0.288		0.765
Downlink Bit Error Rate ($x10^{-6}$)		69.7			3
Message Transaction Failure Rate ($x10^{-3}$)		13.2	1.6	5.56	2.14
Expected Message Transaction Failure Rate ($x10^{-3}$)		99.63	0.32		4.58
Uplink Message Failure Rate ($x10^{-3}$)		3.3	0.97	5.56	1.14
Downlink Message Failure Rate ($x10^{-3}$)		9.9	0.64		1
Messages with Single Bit Errors			2		2
Messages with Character Slip					
Mean Good Transmission Time (minutes: seconds)					19:40
Maximum Good Transmission Time (minutes: seconds)					35:27
Minimum Good Transmission Time (minutes: seconds)					2:41

Parameters: 2400 bps; 50-kHz channel spacing; 3 repeats on error messages; 30 prekey characters; 120 character message (echoed); uplink message = 1120 bits; downlink message = 1240 bits; prekey time = 0.0133 seconds; uplink message time = 0.467 seconds; downlink message time- 0.517 seconds.

TABLE 5-11. FLIGHT 10 DATA SUMMARY

	A/C on the Ground	A/C Turning	A/C Flying Level	A/C Landing	Total
Messages Attempted	465	410	11589	1034	13498
Messages Completed	463	409	11584	1034	13490
Message Failures (Total)	2	1	5		8
Uplink No Responses			2		2
Uplink BCS Message Errors/ Number of Bit Errors			2/10		2/10
Uplink Long Messages					
Uplink Wrong A/C ID					
Downlink No Responses	2	1			3
Downlink BCS Message Errors/ Number of Bit Errors					
Downlink Long Messages					
Downlink Wrong A/C ID			1		1
Number of 3 Repeats					
Uplink Bit Error Rate ($x10^{-6}$)			2.16		1.85
Downlink Bit Error Rate ($x10^{-6}$)			0.57		0.487
Message Transaction Failure Rate ($x10^{-3}$)	4.3	2.4	0.43		0.593
Expected Message Transaction Failure Rate ($x10^{-3}$)			0.95		0.814
Uplink Message Failure Rate ($x10^{-3}$)			0.345		0.296
Downlink Message Failure Rate ($x10^{-3}$)	4.3	2.4	0.086		0.296
Messages with Single Bit Errors			1		1
Messages with Character Slip					
Mean Good Transmission Time (minutes: seconds)					14:74
Maximum Good Transmission Time (minutes: seconds)					32:01
Minimum Good Transmission Time (minutes: seconds)					3:11

Parameters: 2400 bps; 25-kHz channel spacing; 3 repeats on error messages; 30 prekey characters; 30 character message (non-echoed); uplink message = 400 bits; downlink message = 152 bits; prekey time = 0.0133 seconds; uplink message time = 0.167 seconds; downlink message time = 0.063 seconds.

TABLE 5-12. FLIGHT 11 DATA SUMMARY

	A/C on the Ground	A/C Turning	A/C Flying Level	A/C Landing	Total
Messages Attempted	373	250	7732	226	8581
Messages Completed	373	211	7556	214	8354
Message Failures (Total)		39	176	12	227
Uplink No Responses		2	23		25
Uplink BCS Message Errors/ Number of Bit Errors		34/57	126/201		160/258
Uplink Long Messages			1		1
Uplink Wrong A/C ID					
Downlink No Responses		2	16	12	30
Downlink BCS Message Errors/ Number of Bit Errors		0	2/4		2/4
Downlink Long Messages		1	8		9
Downlink Wrong A/C ID					
Number of 3 Repeats			11		11
Uplink Bit Error Rate ($x10^{-6}$)		205.2	23.28		26.9
Downlink Bit Error Rate ($x10^{-6}$)			0.42		0.38
Message Transaction Failure Rate ($x10^{-3}$)		156	22.76	53.09	26.45
Expected Message Transaction Failure Rate ($x10^{-3}$)		229.8	26.59		30.6
Uplink Message Failure Rate ($x10^{-3}$)		144	19.4		21.68
Downlink Message Failure Rate ($x10^{-3}$)		12	3.36		4.78
Messages with Single Bit Errors		20	86		106
Messages with Character Slip		1	8		9
Mean Good Transmission Time (minutes: seconds)					8:11
Maximum Good Transmission Time (minutes: seconds)					14:24
Minimum Good Transmission Time (minutes: seconds)					2:23

Parameters: 4800 bps; 50-kHz channel spacing; 3 repeats on error messages; 60 prekey characters; 120 character message (echoed); uplink message = 1120 bits; downlink message = 1240 bits, prekey time = 0.0129 seconds; uplink message time = 0.23 seconds; downlink message time = 0.258 seconds.

The message failures are further defined according to the type of failure and whether it occurred on the uplink or downlink portion of the message transaction. In each type (uplink or downlink) when a message was not received it was categorized as a No Response in accordance with the definitions of section 5.1.2. Messages received with detected BCS errors were categorized as BCS errors. Two special cases of BCS errors were categorized as extra long messages (exceed maximum allowable number of characters) and incorrect aircraft identity. The number of occurrences when the NAK, BCS, and No Response counters reached 3 (the maximum allowed in these tests) is also noted.

Also given on the summary sheets are the values for uplink and downlink bit error rates, message transaction failure rate, expected message transaction failure rate, uplink message failure rate, downlink message failure rate, the number of messages with single bit errors, the number of messages with character slips, the mean good message transaction time, maximum good message transaction time, and the minimum good message transaction time.

The message transaction failure rate (MTFR) was calculated from the ratio of failed message transactions to the total attempted message transactions. That is

$$MTFR = \frac{H}{I} \qquad (5\text{-}1)$$

where

H = number of messages which failed to be completed correctly for any reason. These failures include messages that failed because of BCS failures and No Responses. H is given in the third row of the Flight Summary Tables.

I = The total number of message transactions attempted.

The MTFR was further divided into uplink and downlink message transaction failure rates, UMTFR and DMTFR, respectively.

$$UMTFR = \frac{J}{I} \tag{5-2}$$

where

J = The sum of the number of messages which fail to arrive at the airborne system (i.e., uplink No Responses) and the number that arrive in error.

$$DMTFR = \frac{K}{I - U} \tag{5-3}$$

where

K = The sum of the number of messages which leave the airborne system but fail to arrive at the ground system (i.e., downlink No Response) and the number of messages that arrive at the ground system in error.

U = The number of ground system generated messages that failed to arrive at the airborne system (i.e., uplink No Responses).

The expected message transaction failure rate (EMTFR) is calculated from the observed uplink and downlink bit error rates (P_e and P_e, respectively) and the uplink and downlink message lengths. It is the probability of message failure assuming that bit errors occur randomly (i.e., not correlated). Comparison of this value with the measured values gives an indication of bit error distribution. EMTFR is given by:

$$EMTFR = UP_e \times B + DP_e \times F \qquad (5\text{-}4)$$

where

$$UP_e = \frac{A}{B(I-D)} \qquad (5\text{-}5)$$

where A = number of bit errors observed in uplink messages

B = length of uplink message in bits

D = number of uplink No Responses.

and

$$DP_e = \frac{Q}{F(I-D-W)} \qquad (5\text{-}6)$$

where Q = number of bit errors observed in downlink messages

F = length of downlink message in bits

W = number of downlink No Responses.

Note that the calculation of UP_e and DP_e excludes the No Response messages. Even so, the calculated EMTFR is usually greater than the observed MTFR, indicating that in actual transmissions the bit errors occur in bursts rather than in purely random fashion. However, on several flights there were an unusually large number of No Response occurrences, which caused the MTFR to exceed the EMTFR.

The number of messages with single bit errors are highlighted in the summaries because of their frequent occurrence relative to the total number of BCS errors.

The errors categorized as messages with character slips are those messages having an extra character or a missing character. These errors were most likely the result of computer hardware anomalies (e.g., random failures of the modem controller).

The mean good transmission times represent the average time of successful sequential message transactions for the entire flight. The maximum good transmission time is the maximum length of time the system operated without error. The values given for the minimum good transaction times do not include consecutive successful message transaction blocks of less than 11 message blocks in duration.

5.3.1 Flight 1 Data Summary and Observations

The Flight 1 Data Summary is presented in Table 5-2. A high percentage of messages in error occurred while the aircraft was on the ground. This was probably caused by multipath transmissions. The relatively high occurrence of errors listed under the aircraft turning category can be attributed to the aircraft's disadvantaged antenna position relative to the ground station when making turns. Only a moderate amount of messages in error resulted while the aircraft was in level flight, and no messages in error occurred during landing.

Two error events involving the ETX (end-of-text) character were observed. In one case, a text character was changed into an ETX character by errors causing the airborne system to start transmitting its response while the ground system was still transmitting and could not listen. This resulted in a No Response failure. In the second case, an

ETX character was interpreted late (greater than 5 msec after the last text character) resulting again in a No Response failure.

There were a large number of messages (24) that had only a single bit in error. This accounts for 29 percent of all the BCS errors.

Two events of character slippage were also detected on this flight. These events may be attributed to a hardware failure in the modem computer interface.

The number of uplink No Responses (63) is unexplainably high. Errors in the 6 initial characters could have been the cause of the No Responses. However, the main part of the transmission is composed of 235 characters, and errors in this part produced only 83 error messages. This result indicates that the probability of error in the first 6 characters is 30 times greater than the probability of error in the remaining 235 characters. Only 2 or 3 No Responses should have occurred for statistical consistency. This phenomenon was observed in the majority of the flights. An explanation of this phenomenon will be offered in a later section of this report.

On the first trip around Snow Hill there was a period of 34 minutes and 15 seconds when 1665 consecutive 220-character messages were completed without error. There were other long intervals of error-free message transactions consisting of 1503, 1184, 1117, and 1085 consecutive messages.

5.3.2 Flight 2 Data Summary and Observations

The Flight 2 Data Summary is presented in Table 5-3. During this flight four right-hand standard turns were executed around Snow Hill and three standard left-hand turns were executed around Atlantic City.

Most of the errors observed on this flight occurred during the landing phase, from 3000 feet to touchdown. The airborne system recorded nine error messages, eight of which resulted in reciprocal errors or No Responses in the downlink response.

There were character slips and even half character slips but these were not denoted on the summary sheet since the messages had other errors which were recorded.

The No Response indications on this flight were disproportionately high. There were 28 No Responses compared to 36 other error messages.

5.3.3 Flight 3 Data Summary and Observations

The Flight 3 Data Summary is presented in Table 5-4. Six of the seven messages that were classified as single bit error messages had no text errors, and it was assumed that a single bit error occurred in the BCS code characters.

A single right turn around Snow Hill produced a single No Response.

Nine No Responses and four other error conditions were recorded during the landing phase of the flight.

5.3.4 Flight 4 Data Summary and Observations

The Flight 4 Data Summary is presented in Table 5-5. There were a number of unusual events which were causes of errors on this flight. Due to a computer failure (whether it was hardware or software is unknown), the experiment was restarted while the aircraft was in mid-air (the data gathering starts in mid-air).

There were a large number (141) of downlink No Responses compared to only 2 uplink No Responses. The downlink No Responses seem excessive in number considering that only 25 message failures occurred for all other causes.

Accounting for the large number of the downlink No Responses is difficult on a statistical basis for reasons stated in section 5.3.1., but there were events which can explain some of them. At least the times when the No Responses occurred can be correlated to certain phenomena. Eighteen No Responses occurred during the three right-hand turns around Snow Hill and the three left-hand turns around Atlantic City.

Another group of errors occurred during a sharp descent from 14,000 feet to 4,000 feet when the aircraft had flaps and landing gear down. In a span of 201 attempted message transactions (approximately 186.6 seconds) 67 downlink No Responses and 1 downlink BCS error event occurred. When the flaps and landing gear were raised, error-free message transmissions were resumed. The No Responses were recorded in the ground system even though the messages were accepted error-free in the airborne system and subsequently retransmitted. The message transaction failure rate over this span of flight was $68/201 = 3.38 \times 10^{-1}$. The single BCS error recorded in this span was unusual in that the bit compare record in the ground system showed no errors (messages were echoed on this flight). Thus, it is assumed that there was a single bit error in one of the BCS code characters.

During an earlier phase of the flight, 2 No Responses and 1 other error message was observed when the aircraft pitched down to 18 degrees.

Six downlink No Responses were observed during a 360^{o} turn around Atlantic City prior to landing. These error events are included in the data under the category of Aircraft Turning.

Twenty-three No Responses and two other message errors occurred during the landing phase of the flight.

5.3.5 Flight 5 Data Summary and Observations

The Flight 5 Data Summary is presented in Table 5-6. Only 6 percent of the attempted message transactions for Flight 5 occurred while the aircraft was in the landing phase (below 3500 feet on the approach to NAFEC), yet one-half of all the observed errors on this flight occurred during this time.

It is difficult to explain the 14 No Responses which occurred in a span of 3 minutes while the aircraft was in straight level flight, 50 miles from Atlantic City, 5 minutes prior to initiation of descent.

Two of the observed BCS errors on this flight were the result of single bit errors in the ETX character.

The maximum good transmission time was 20 minutes and 14 seconds.

5.3.6 Flight 6 Data Summary and Observations

The Flight 6 Data Summary is presented in Table 5-7. All the errors listed under the Aircraft Turning category occurred during the turns at Snow Hill. Four uplink BCS errors and seven downlink No Responses were observed. No errors were observed during the turns at Atlantic City.

Five No Responses and three BCS errors were observed when the aircraft was making its descent (iniated at 14,000 feet at 50 miles) to land at ACY. These errors occurred when the aircraft was at 20 miles from ACY.

No downlink BCS errors were observed for the entire flight. However, there were 30 downlink No Response errors.

The maximum good transmission time was 14 minutes and 28 seconds.

5.3.7 Flight 7 Data Summary and Observations

The Flight 7 Data Summary is presented in Table 5-8. The ground station receiver was modified with the narrow band filter (16 kHz), shown in Figure 5-3, to achieve the 25-kHz channel spacing on both uplink and downlink transmissions.

The maximum good transmission time was only 55 seconds. This was the worst observed for all of the flight tests.

5.3.8 Flight 8 Data Summary and Observations

The Flight 8 Data Summary is presented in Table 5-9. This flight test was started in mid-air. The flight test was conducted at a data rate of 2400 bits per second (bps) and the 16-kHz bandpass filter was installed in the ground receiver to achieve 25-kHz channel spacing on the uplink and downlink transmissions. The narrow band filter did not deteriorate the signalling capability as it did at 4800 bps on Flight 7.

No errors occurred during the single turn at Snow Hill.

Only one error, a No Response, was observed during the landing phase of flight.

The maximum good transmission time was 18 minutes.

5.3.9 Flight 9 Data Summary and Observations

The Flight 9 Data Summary is presented in Table 5-10. There were no errors during the takeoff phase of the flight. Only four errors were observed during turns, three at ACY and one at Snow Hill.

One of the errors listed in the Aircraft Flying Straight category occurred when the aircraft was pitched down to 10 degrees. The other errors in this category cannot be explain- by aircraft maneuvers.

The maximum good transmission time was 35 minutes and 27 seconds.

5.3.10 Flight 10 Data Summary and Observations

The Flight 10 Data Summary is presented in Table 5-11. This test, at 25-kHz channel spacing and 2400 bps, yielded very low bit error rates and message failure rates.

Only one error was observed during the turns. This flight had an unusually long, low approach to touchdown. The aircraft was flown at or below 3000 feet from a point 27 miles from ACY to touchdown. The data collected during this time are included in the aircraft landing category in Table 5-11. One of the observed downlink message failures was due to a single bit error in the aircraft ID.

The maximum good message transmission time was 32 minutes and 1 second.

5.3.11 Flight 11 Data Summary and Observations

The Flight 11 Data Summary is presented in Table 5-12. There were an unusually high number (9) of long message errors recorded on the downlink. There were no errors in the text of these messages but the ETX character was missed by the ground system.

A large number (160) of BCS errors occurred on the uplink messages.

5.4 SUMMARY AND ANALYSIS OF TEST DATA

The data for the individual flights are summarized in Table 5-13. The values given in the Total row of Table 5-13 for the uplink and downlink message lengths are averages for the message lengths used in the experiment. The values given

TABLE 5-13. TEST DATA SUMMARY

Flight No.	Experiment Type		Message Transaction			Message Length (bits)		Message Failures				Messages With Single Bit Errors	Messages With Character Slips	Bit Error Rate ($X10^{-6}$)		MTFR ($X10^{-3}$)
	Bit Rate (bps)	Channel Spacing (kHz)	Attempted	Completed	Failed	Uplink	Downlink	Uplink NR	Uplink All Other Errors	Downlink NR	Downlink All Other Errors			Uplink	Downlink	
1	2400	50	11864	11759	155	1920	152	63	83	9	0	24	2	24.8	0	12.8
2	2400	50	10116	10059	57	1120	1240	9	19	17	13	10	0	7.2	2.2	5.6
3	4800	50	8919	8889	30	400	520	1	2	20	7	7	0	0.6	2.2	3.4
4	4800	50	10489	10321	168	1120	1240	2	11	141	14	11	6	1.0	1.0	16.0
5	2400	50	13681	13640	41	400	152	12	14	13	2	5	0	5.6	2.9	3
6	4800	50	10903	10839	65	1920	152	11	23	30	0	7	11	6.1	0	6
7	4800	25	3605	3542	63	1120	1240	10	12	21	20	16	2	7.0	7.0	17.5
8	2400	25	2359	2354	5	1120	152	3	0	1	1	1	0	0	2.7	2.0
9	2400	50	7000	6985	15	1120	1240	5	3	6	1	2	0	0.8	3.0	2.1
10	2400	25	13498	13490	8	400	152	2	2	3	0	1	0	1.8	0.5	0.6
11	4800	50	8581	8354	227	1120	1240	25	161	30	12	106	9	26.9	0.4	26.4
Total			101115	100232	834	1043**	612.5**	143	330	291	70	190	30	8.1**	1.9**	8.2*

*Normalized for an average message transaction length of 1656 bits (total for uplink and downlink)

**Average value

bps = Bits per second

NR = No Response

MTFR = Message Transaction Failure Rate

in the Total row for the uplink and downlink bit error rates (UP_e and DP_e) are averages for all the flights and include data at both 2400 and 4800 bit per second (bps) data rates. The value given in the Total row for the message transaction failure rate (MTFR) is the average for all the flights at both data rates. This average was normalized for an average message transaction length of 1656 bits; i.e., the sum of the averages of the uplink and downlink message lengths used in this experiment.

5.4.1 Analysis of "No Response" Data

The overall data show that a high percentage of the total message failures were due to No Responses. The No Response error condition accounted for 30 percent (143/473) of the message transaction failures on the uplink and 80 percent (291/361) of the message transaction failures on the downlink. Overall, the No Response error condition accounted for 52 percent (434/834) of all the message transaction failures. The majority of the No Responses cannot be accounted for based on a statistical analysis of the observed BCS failures using average observed bit error rates; i.e., the probability of error in the relatively small number of necessary message start bits far exceeds the probability of error observed in the remaining large number of message test bits.

In some of the flights, many No Responses were observed; in others, there were very few. It is hypothesized that No Responses can be caused by two types of effects. First, the modem system may fail to acquire accurately the data link signal baseband carrier and subcarrier, thus producing extraordinarily high error rates during a particular message. Given such high error rates during a particular message, it is likely that errors will occur during the initial 6- character premamble, which will cause a No Response. Alternatively, the No Responses could have resulted from random noise errors occuring during the acquisition preamble. This latter hypothesis was not confirmed when the average error rate for a given flight was used to compute the expected No Response rate. That is, given an average bit error rate for a flight, $\overline{P}_e$, the expected No Response rate (P_{NR}) due to random errors during the first six characters of the messages is just

$$P_{NR} = 1 - (1 - \overline{P_e})^{48}. \qquad (5\text{-}7)$$

In almost all flights the P_{NR} predicted by the above equation was much too low.

It was then hypothesized that a higher bit error rate, P_e, existed in the vicinity of the No Responses and that the No Responses were caused by random errors during these intervals when P_e was abnormally high.

In order to check out this hypothesis, the error rates in all message transactions that immediately preceded and followed each No Response were evaluated for each flight. It was found that in most cases a large percentage of the total bit errors observed for the entire flight occurred in the vicinity of the observed No Responses. This confirms the hypothesis that most of the No Responses are caused by random errors which occur during periods of abnormally high P_e. The data leading to this conclusion are shown in Table 5-14.

The second column in Table 5-14 shows the actual number of errors which occurred immediately before and after the No Responses on a given flight. The third column shows the total number of errors observed on a given flight. On most flights where there were a significant number of errors, it is shown

TABLE 5-14. NO RESPONSE ERROR DATA

Flight No.	No. of Bit Errors Before and After	Total No. Bit Errors	Local Probability of Bit Error	Probability of NR Rate Local P_e	Observed NR Rate
1	286	564	1.9×10^{-3}	8.7×10^{-2}	6.7×10^{-3}
2	42	108	5.1×10^{-4}	2.4×10^{-2}	2.8×10^{-3}
3	11	12	1.5×10^{-3}	7×10^{-2}	2.4×10^{-3}
4	0	24	-	-	1.4×10^{-2}
5	6	37	5.2×10^{-4}	2.46×10^{-2}	1.8×10^{-3}
6	40	128	4.75×10^{-4}	2.25×10^{-2}	3.8×10^{-3}
7	8	59	1×10^{-4}	4.8×10^{-3}	8.6×10^{-3}
8	0	1	-	-	1.6×10^{-3}
9	0	32	-	-	1.6×10^{-3}
10	0	11	-	-	3.7×10^{-4}
11	29	262	1.35×10^{-4}	6.5×10^{-3}	6.4×10^{-3}
Totals	422	1238			

P_e = Bit error rate

NR = No Response

that a large percentage of the errors occurred in the vicinity of the No Responses. In fact, considering all flights, 34 percent of the total number of errors observed occurred immediately before or after the No Responses!

Column four shows the local probability of bit error in the vicinity of No Responses based on the data of column two. Column five shows the probability of message rejection assuming the local bit error rates of column four. These can be compared with the actual No Response probabilities observed during each flight listed in column six.

Most of the predicted No Response probabilities are close to the observed No Response rates. In fact the average predicted No Response rate considering all flights is 2.17×10^{-2} while the observed average No Response rate is 4.55×10^{-3}. Thus, the predictions based on the errors occurring before and after the No Responses are about a factor of 5 higher than the observed rates. This is much closer than the rates predicted based on average bit error probabilities, on the average.

These results indicate that a polling strategy that utilizes immediate message retransmission for unsuccessful messages to a given aircraft would be less efficient than one in which retransmissions to that aircraft are delayed, thereby allowing the aircraft to change from the high error density condition where the probability of correct message reception would be greater. That is, if a message to a given aircraft is unsuccessful, the ground system should service another aircraft before attempting to retransmit the unsuccesful message.

5.4.2 Analysis of BCS Errors

Of the remaining observed message transaction errors (All Other Errors) nearly 48 percent (190/400) of the messages in error contained only a single bit error. This result indicates that a simple error correction scheme might have a significant impact on the VHF link.

The data of Table 5-13 show that the average downlink bit error performance was better than the average uplink bit error performance by a factor of 4. The variation of the uplink bit error performance was significantly greater than that of the downlink bit error performance. This disparity may be the result of an improperly balanced detection circuit in the demodulator section of the uplink modem.

The average uplink and downlink bit error rates (UP_e and DP_e) and the average message transaction failure rate (MTFR) for all flights are given in Table 5-15 according to data rate.

TABLE 5-15. AVERAGE BIT AND MESSAGE TRANSACTION FAILURE RATES

	2400 bps	4800 bps	2400 and 4800 bps Combined
$UP_e \times 10^{-6}$	7.7	8.5	8.1
$DP_e \times 10^{-6}$	2.2	1.7	1.9
MTFR $\times 10^{-3}$	4.0	10.0	8.2

The reader should exercise caution when comparing the values given in Table 5-15 for the Experimental Data Link System with the bit and block error rate data from the Digital Data Transmission Flight Tests given in Table 4-2 and the Airport Surface Tests given in Tables 3-1 through 3-3. Recall that the latter test systems had no equivalent to the No Response filtering process of the Experimental Data Link System. That is, the Experimental Data Link System did not admit a significant number of messages that contained errors (those that failed to pass the test for valid messages), whereas all bit errors contributed to the bit error rate in the systems used in the Digital Data Transmission Flight Tests and the Airport Surface Tests. Thus the bit error rates determined in the tests with the Experimental Data Link System are lower than those determined in the Digital Data Transmission Tests and the Airport Surface Tests. The average message transaction failure rate of 8.2×10^{-3} observed in the tests with the Experimental Data Link System, which includes the No Response errors, agrees reasonably well with the average block error rate of 1.6×10^{-2} (for 1000 bit blocks) observed in the Digital Data Transmission Flight Tests. A discussion of the effect of the No Response filtering on bit error rate is presented in Appendix C.

The average P_e's shown in Table 5-15, which are a measure of the data quality, show little sensitivity to data rate. However, the average MTFR, which is a measure of error distribution, is higher by a factor of more than 2 at 4800 bps than at 2400 bps. This implies that the errors are somewhat more randomly distributed at 4800 bps than at 2400 bps; i.e., conversely, the errors tend to have a more bursty character at 2400 bps than at 4800 bps. It should be recalled that the P_e calculations exclude the effects of No Responses, whereas these effects are included in the calculation of MTFR. Thus, conclusions of error distribution based on this comparison might not be valid. The exclusion of the No Responses from the P_e calculation also causes the apparent 3 orders of magnitude difference between it and the MTFR. (One would expect a difference closer to 2 orders of magnitude.)

The P_e and MTFR data are also shown according to flight phase in Figures 5-8 and 5-9, respectively. The P_e data are shown in Figure 5-8 for uplink and downlink operation for the flight conditions of takeoff, turning, level flight, and landing. The vertical ranges of P_e represent the variation in the observed P_e. The open bars indicate that data points for $P_e=0$ are included in the data.

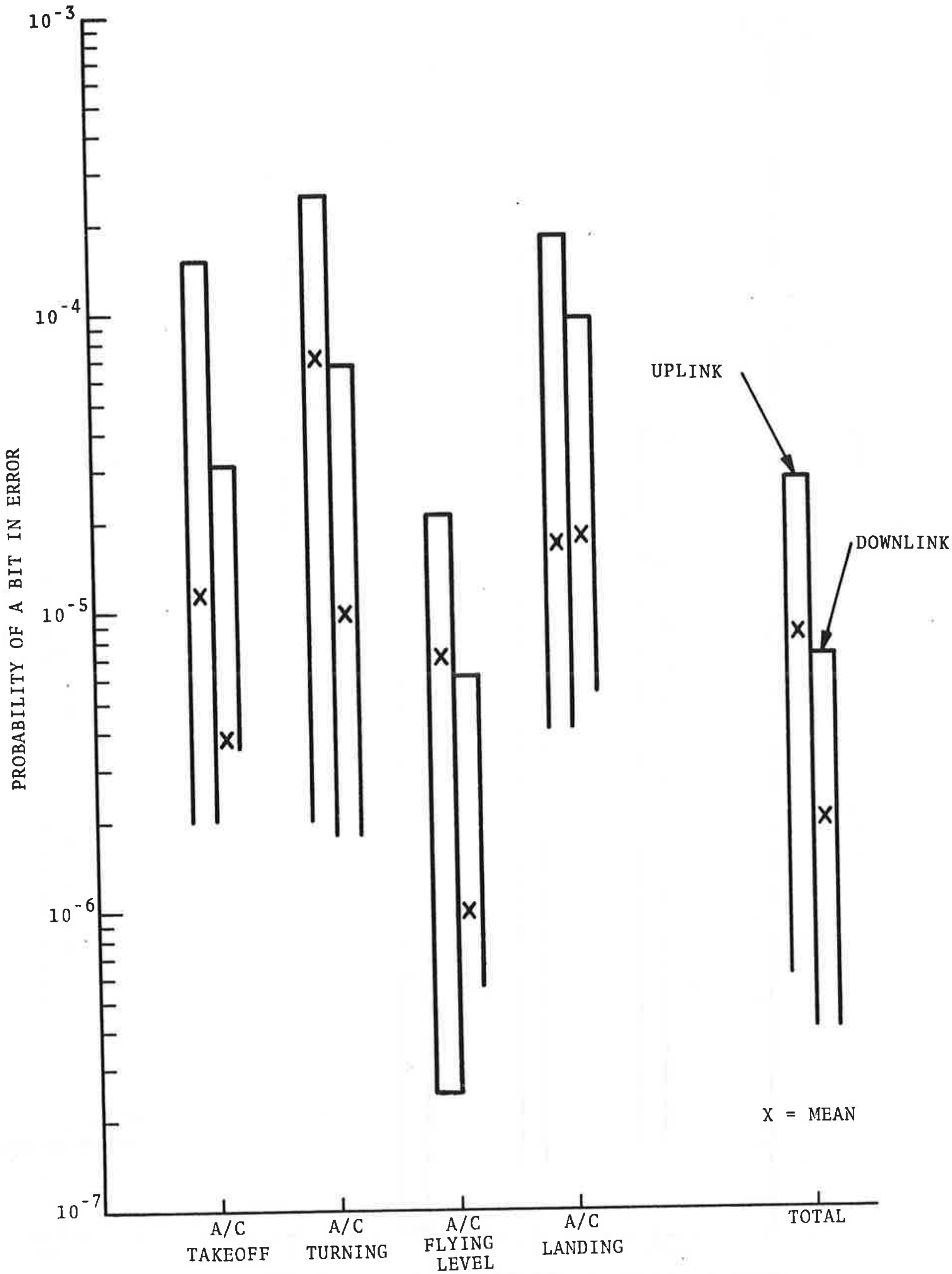


FIGURE 5-8. BIT ERROR RATES, P_e, FOR VARIOUS FLIGHT CONDITIONS

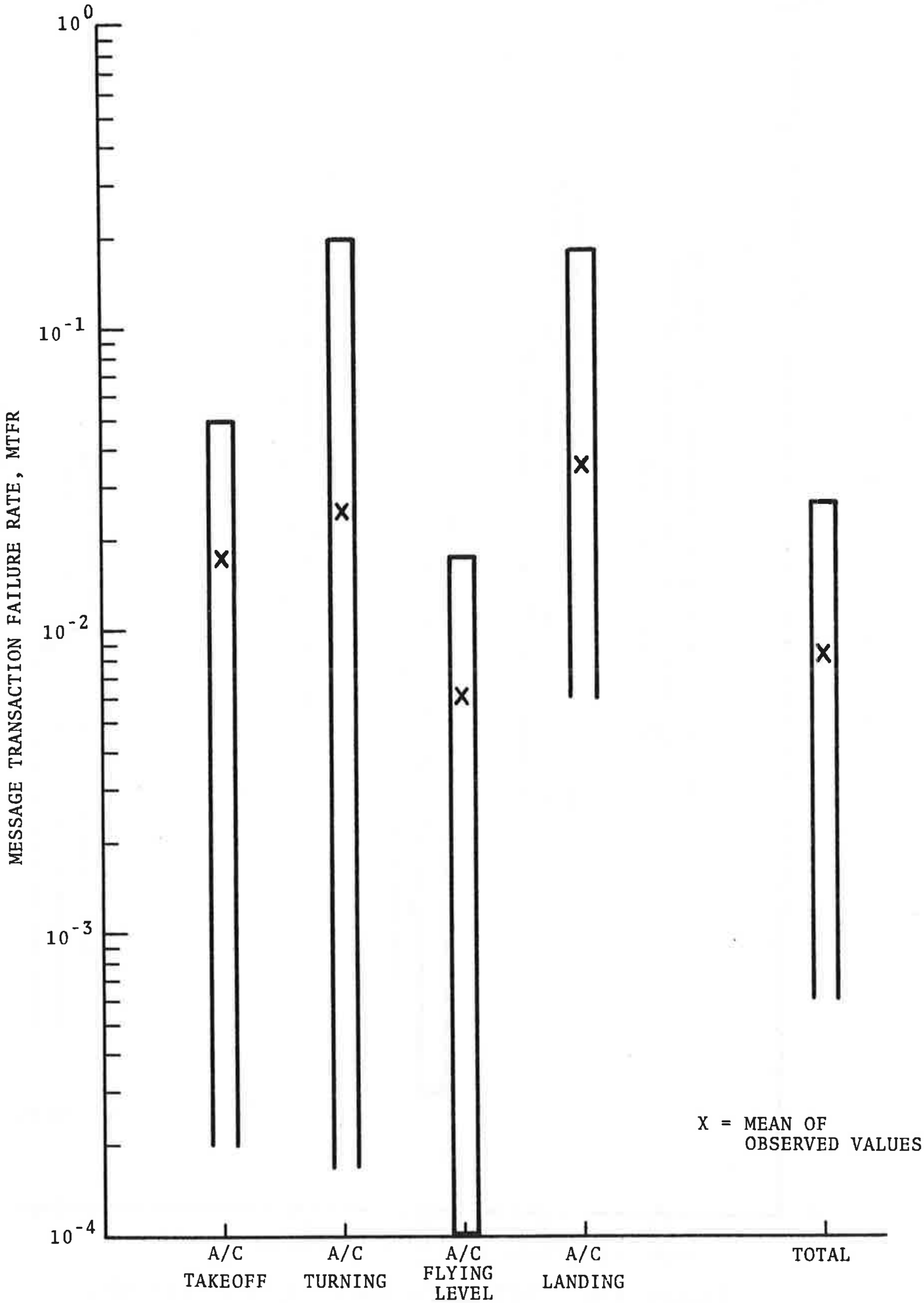


FIGURE 5-9. MESSAGE TRANSACTION FAILURE RATES, MTFR, FOR VARIOUS FLIGHT CONDITIONS

The P_e for the level flight condition are at least an order of magnitude lower than the rates for the other flight conditions. The worst performance occurred for the turning condition. Recall that the same trends were observed in the earlier flight tests reported in Section 4. Also, shown in Figure 5-8 is the mean of observed means of the total P_e data for the individual flights at each flight condition. This shows the data to be heavily weighted by the performance in the level flight condition where most of the data were collected.

Similar results are shown in Figure 5-9 for the MTFR according to flight condition. The lowest MTFR occurred in the level flight condition. The highest MTFR occurred for the landing flight condition. Also shown in Figure 5-9, categorized as Total, is the mean of the observed means of the MTFR for the individual flights. This value is heavily weighted by the data collected in the level flight condition where most of the data were collected.

The results shown in Figures 5-8 and 5-9 (and in Section 4) indicate a potential pitfall in utilizing error performance data averaged over all flight regimes to characterize the link performance for system design purposes. Even though the data from the experiments reported herein are somewhat representative of the percent of time that a given aircraft might spend in a given flight condition on a typical flight and yield relatively good average MTFR, the degraded performance (relative to average) exhibited during the takeoff, turning, and landing phases could have a significant negative impact on system capacity if a data link system were designed based on the overall average performance. In other words, a data link system design for ATC operations must consider the total instantaneous aircraft population in a given flight condition along with the link performance characteristics for that flight condition in order to provide the system capacity (e.g., number of channels) in accordance with the required message volume and message service times.

5.4.3 Error Distribution

The distribution of error bits in the uplink and downlink messages according to bit position within the characters is given in Table 5-16. The bit errors are classified according to whether they were zeros changed to ones or ones changed to zeros. The ratio of the number of zeros changed to ones to the number ones changed to zeros, known as skew, should be approximately 1. Note that this ratio is approximately equal to 2 for the uplink errors and equal to 1 for the downlink errors. The fact that the uplink skew value was not equal to 1 could be the result of minor equipment malfunction in the digital processing portion of the modem.

Distributions of the number of error bits per character are shown in Table 5-17 for the uplink and downlink messages. The number of error-free characters is not shown. The data are presented according to data rate and flight condition. The data totals are shown in histogram fashion in Figure 5-10 for the uplink messages and in Figure 5-11 for the downlink messages. The error distribution per character for those characters containing errors shows somewhat larger tails (i.e., a greater number of bits in error per character) at a data rate of 4800 bps than at 2400 bps for both uplink and downlink messages. There was a greater difference, however, in the relative frequency of occurrence of the number of bit errors per character between the uplink and downlink distributions. The downlink distribution was somewhat more flat than the uplink distribution. Thus, characters containing single bit errors occurred more frequently in the uplink messages than in the downlink messages. The different downlink distribution may result from an insufficient data sample.

TABLE 5-16. DISTRIBUTION OF ERROR BITS ACCORDING TO BIT POSITION WITHIN CHARACTERS

UPLINK ERROR BITS									
Bit Position	7	6	5	4	3	2	1	Totals	
# 0 → 1 Occurrences	46	129	84	110	88	95	118	670	SKEW = $\frac{670}{329} \approx 2$
# 1 → 0 Occurrences	55	19	54	42	56	46	57	329	

DOWNLINK ERROR BITS									
Bit Position	7	6	5	4	3	2	1	Totals	
# 0 → 1 Occurrences	7	8	6	6	11	10	4	52	SKEW = $\frac{52}{52} = 1.0$
# 1 → 0 Occurrences	13	5	4	2	11	7	10	52	

TABLE 5-17. DISTRIBUTION OF NUMBER OF ERROR BITS IN CHARACTERS

Aircraft Attitude and Type Transmission		Bit Rate (Bits Per Second)	Total Number of Bits in Error					
			1	2	3	4	5	≥6
Takeoff	Uplink	2400	26	2				
		4800	1					
	Downlink	2400	3					
		4800	4	2				
Turning	Uplink	2400	219	15	7	6	1	
		4800	43	5	1	1		
	Downlink	2400	15	4	1			
		4800	5	1	1			
Level Flight	Uplink	2400	211	20	6	1	1	
		4800	243	28	14	2	2	
	Downlink	2400	2		1			
		4800	27					
Landing	Uplink	2400	37	9	4			
		4800	5					
	Downlink	2400	28	9	3	1	1	
		4800	9	4				
TOTAL	Uplink	2400	493	46	17	7	2	
		4800	292	33	15	3	2	
	Downlink	2400	48	13	5	1	1	
		4800	45	7	1		1	

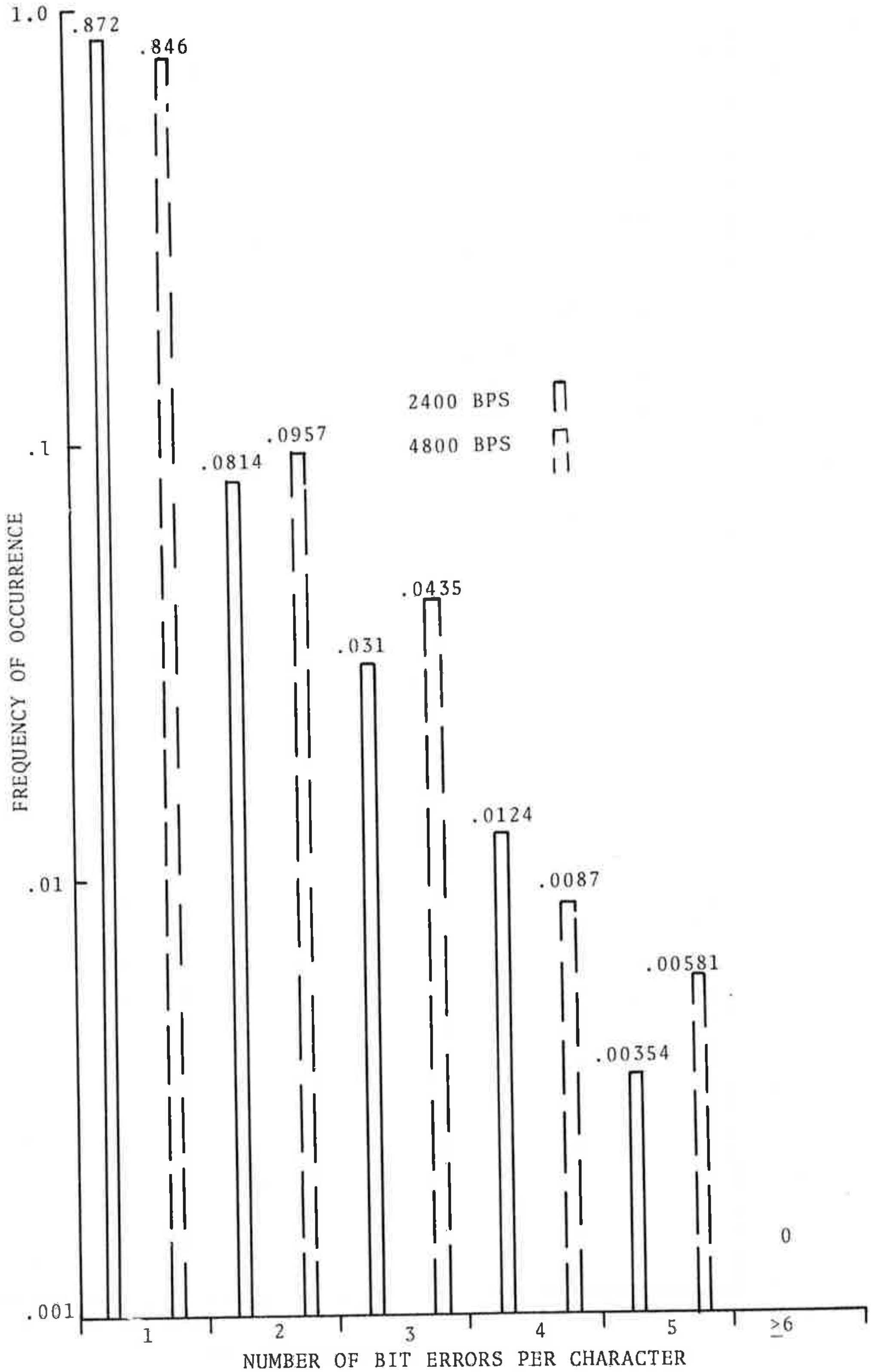


FIGURE 5-10. DISTRIBUTION OF UPLINK BIT ERRORS PER CHARACTER

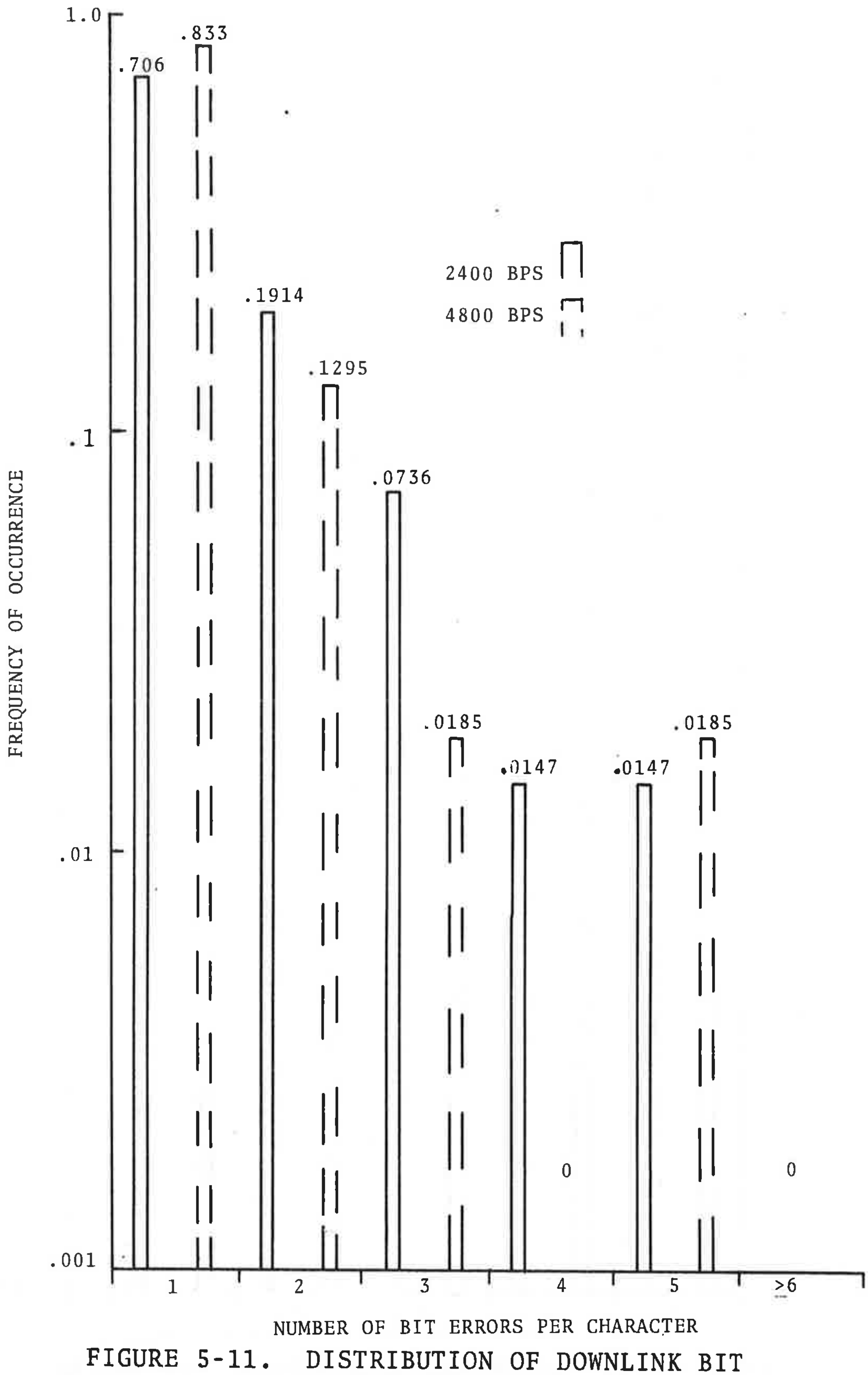


FIGURE 5-11. DISTRIBUTION OF DOWNLINK BIT ERRORS PER CHARACTER

The observed distribution of bit distances between bit errors for messages having two or more errors is shown in Figure 5-12. The distribution was obtained from the combination of all messages containing two or more errors and includes uplink and downlink messages of all message lengths at both 2400 and 4800 bps data rates. The number of messages on which this distribution is based represents 52 percent of the messages that had BCS errors (recall that 48 percent of all messages that had BCS errors had single bit errors). The distribution is presented as a function of the binary count of the bit distances between bit errors. Presented in this fashion, a distance between bit errors of 1 bit indicates that adjacent bits were in error, a distance between bit errors of 2 to 3 bits indicates that there were from 1 to 2 correct bits between the bits in error, etc. The distribution is somewhat biased toward the smaller distances between errors because of the mixture of long and short message lengths included in the statistics.

The observed probability distribution for the number of bit errors per message is shown in Figure 5-13 for all messages and in Figure 5-14 only for messages that had errors. The error statistics used to construct these distributions exclude No Response errors and BCS errors associated with clock slips. The distributions are based on a total of 367 messages that had bit errors detected by the BCS scheme. No attempt was made to determine the distributions as functions of data rate and message length because of the relatively small number of error samples available. The distribution shown in Figure 5-13 is considerably more flat that one would expect if the bit errors were randomly (i.e., binomially) distributed with a fixed probability of bit error.

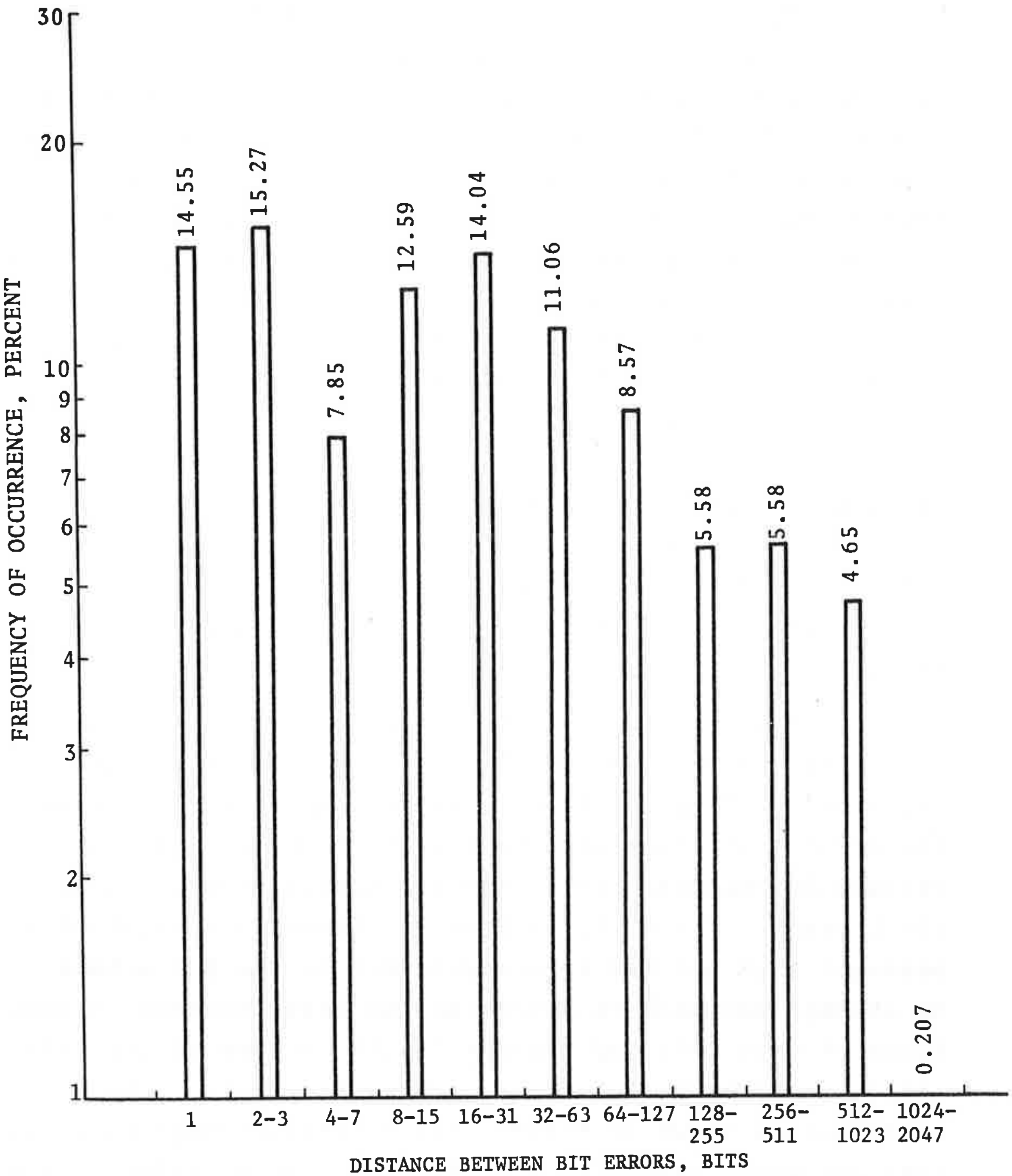


FIGURE 5-12. DISTRIBUTION OF DISTANCES BETWEEN BIT ERRORS FOR MESSAGES HAVING TWO OR MORE ERRORS (UPLINK AND DOWNLINK COMBINED)

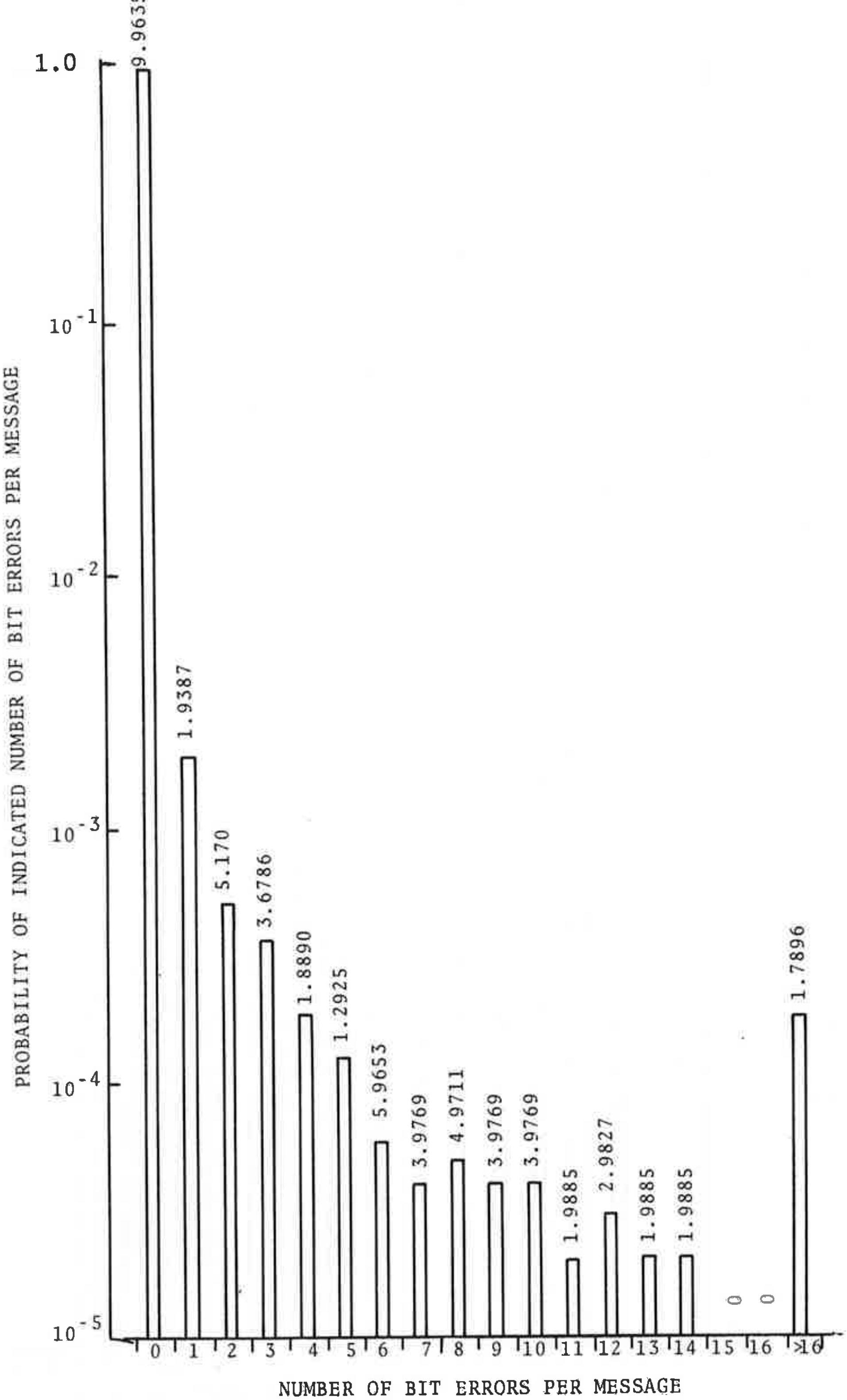


FIGURE 5-13. PROBABILITY DISTRIBUTION OF BIT ERRORS PER MESSAGE FOR ALL MESSAGES

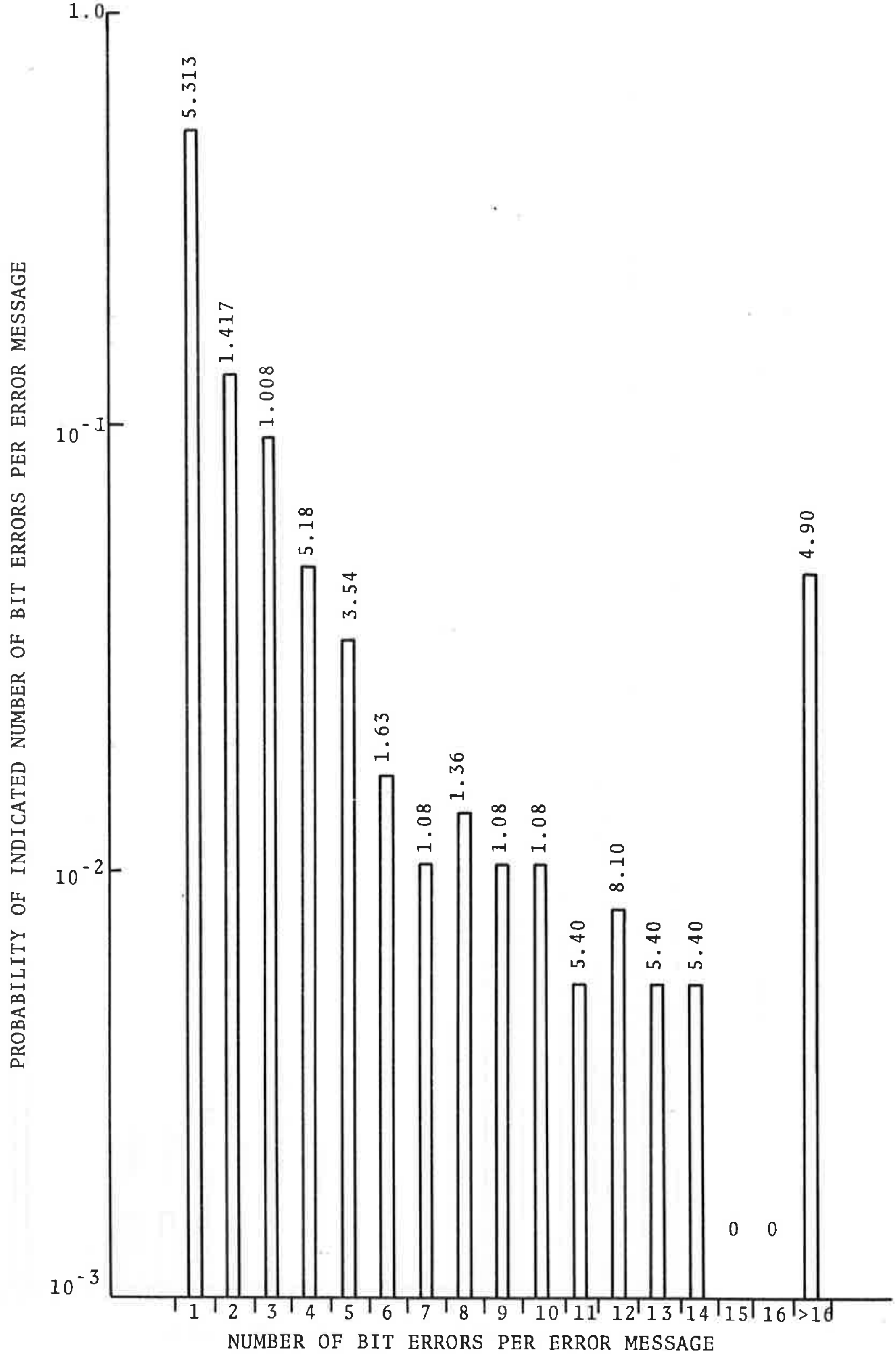


FIGURE 5-14. PROBABILITY DISTRIBUTION OF BIT ERRORS PER MESSAGE FOR MESSAGES WITH ERRORS

For example, the calculated probability for having more than 16 errors in a message containing 1656 bits (the average message length for this experiment from Table 5-13) with a P_e of 5 X 10^{-6} (the average of the observed uplink and down-link P_e from Table 5-13) is less than 4 X 10^{-6} for randomly occurring errors. However, the observed probability for having more than 16 errors in a message was approximately 1.8 X 10^{-4}, which is about 2 orders of magnitude greater than that predicted for the random error case. This result again indicates that a simple random error model does not describe the VHF data link channel. An error model for the VHF data link channel based on the observed data is presented in Appendix C. There it is shown that the probability of bit error is itself a random variable. The probability of bit error was 1 X 10^{-6} for 99.6 percent of the time and in the range of 1 X 10^{-3} to 1 X 10^{-2} for the remaining 0.4 percent of the time. The higher bit error rates, persisting for a small fraction of the time, account for the larger than expected tail in the observed probability of error distribution.

5.4.4 Error Detection Performance

Of particular interest in the distribution of Figure 5-13 is the probability of having more than 16 errors in a message, since this is the condition that yields the possibility of errors going undetected by the particular BCS error detection scheme used in this experiement. The BCS error detection scheme in this experiment utilized the CCITT generator polynomial given by

$$P(X) = 1 + X^5 + X^{12} + X^{16} \qquad (5\text{-}8)$$

This is a class of cyclic codes for error detection described by Peterson in Reference 14. This class of codes is particularly suited to the detection of burst errors. The term burst, as used in this report, refers to any combination of bit errors occurring between the Mode and ETX characters, inclusively, within a message. These are the bits over which the code polynomial, P(X), is applied. As described in Reference 14, the error detection polynomial used in these experiments detects all burst errors of 16 bits or less and a very high percentage of bursts in excess of 16 bits. The fraction of bursts longer than 16 bits that are undetected is 2^{-16} (1.53×10^{-5}). Thus, there is a finite probability, for bursts in excess of 16 bit errors, that an incorrect message was accepted as correct in this experiment. The probability that an incorrect message was accepted as correct (P_D) during this experiment is calculated as follows:

$$P_D = P_a (a > 16) \cdot P_u$$

where

> P_a (a > 16) is the probability of having a burst of errors in excess of 16 bits in a message. The observed value for this experiment was $P_a (a > 16) = 1.7896 \times 10^{-4}$ as shown in Figure 5-13.
>
> P_u is the probability of undetected error for the cyclic code error detection scheme and has a value, as previously indicated, of 1.53×10^{-5}.

Thus, for this experiment, the probability of having accepted an incorrect message as correct is:

$$P_D = 1.7896 \times 10^{-4} \times 1.53 \times 10^{-5} = 2.7381 \times 10^{-9} \qquad (5\text{-}9)$$

This value is approximately 2 orders of magnitude greater than what would be predicted with a simple random error model. This value could be reduced if a higher order code polynomial were to be implemented. However, based on the guidelines given in Reference 15, the value of 2.7381×10^{-9} is an acceptable figure for delivered message error rate. In practical terms, a delivered message error rate of 2.7381×10^{-9} represents one incorrect message every 5.84 years based on a message transaction rate of two messages per second.

The distribution given in Figure 5-14 indicates the error characteristics of those messages that had bit errors, exclusive of clock slips. Thus, of the messages that had detected BCS errors (exclusive of clock slips), 53 percent had single bit errors, 14 percent had two bit errors, etc., and nearly 5 percent had more than 16 bit errors.

5.4.5 Error Correction Considerations

Since a significant percentage of all the messages that had BCS errors in the 11 flights that were run with the Experimental Data Link System had only single bit errors, an improved message transaction rate (throughput) can be achieved with the use of odd (or even) parity per character (or byte) and the Block Check Sequence (BCS) code to produce single bit error correction with no increase in system complexity.

The proposed ARINC 586 Data Link System, Reference 6, provides for odd character parity on all ground-air messages for use on the aircraft for error detection on messages distributed to data link devices within the aircraft. The odd character parity check is not used for error detection on the link transmissions themselves. Consistent with this precedent, the odd character parity check was not used for error detection on ground-air messages in the Experimental Data Link System. If it were to be used in conjunction with the BCS code for all characters, except prekey and the BCS code, then all messages having single bit errors (occurring from the MODE Character, to the BCS codes, inclusively) could be corrected. In addition, the prior characters such as +, *, SYN, SYN, SOH could have odd parity error detection and a degree of character recognizability (i.e., error correction) via comparison with stored correct characters.

The single bit error correction would function in the following manner. Whenever the BCS code check reveals an error and a single character odd parity check indicates an error, a change of one bit of the failed character is made. Then the BCS code check is retried. If it succeeds then the message is considered corrected. If after changes of all eight bits (one at a time, restoring the status whenever the BCS code check fails) of the character in error, the BCS code does not check then the message is considered uncorrectable and the message is retransmitted. Thus the suggested error correction scheme is a hybrid of forward error correction (FEC) and retransmission error correction (RTEC).

If a situation should exist where no odd parity error indications are shown but the generated BCS code does not agree with the received BCS code in a single bit position then the message is considered as uncorrectable and the system reverts to the RTEC mode for error correction.

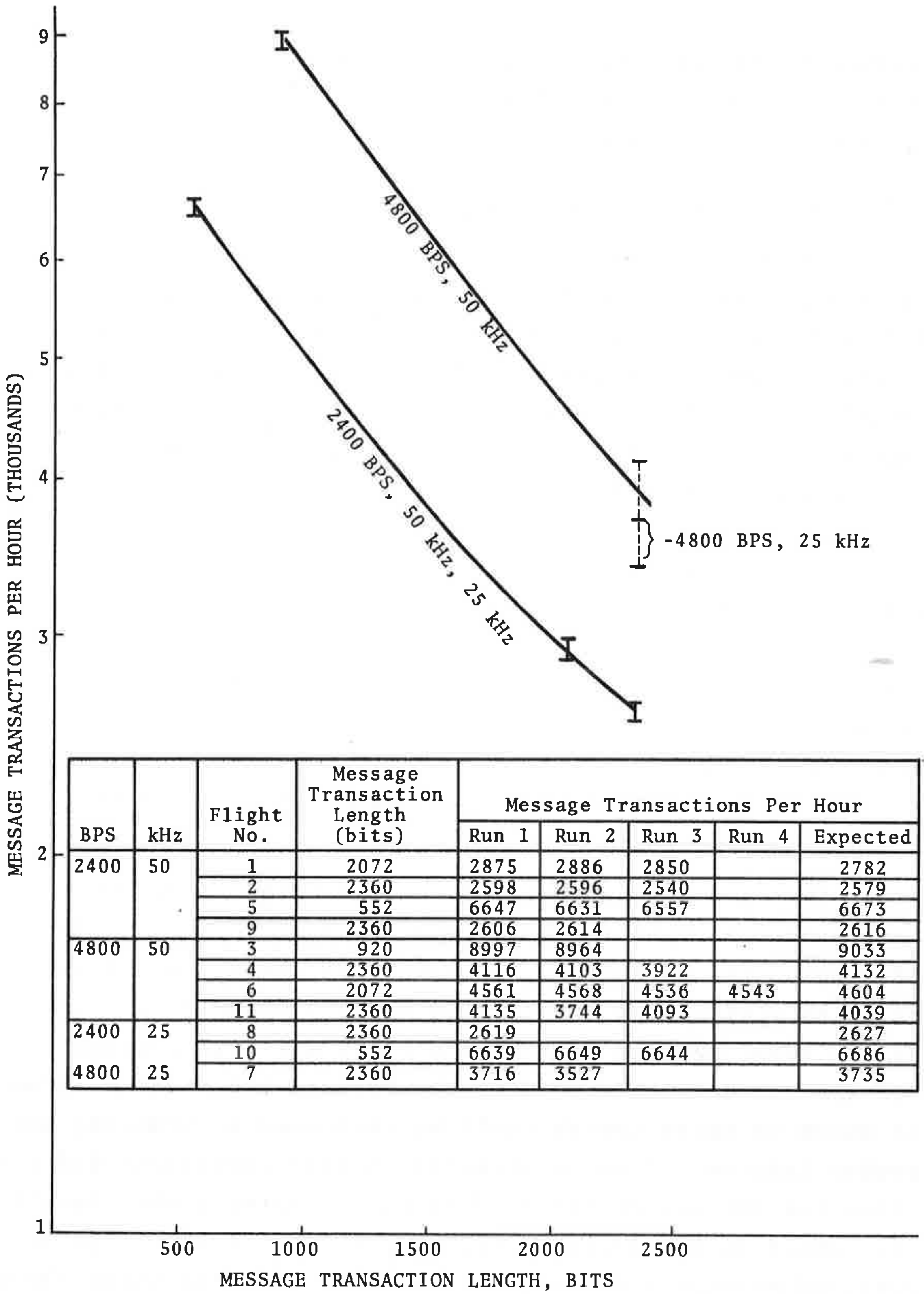
The BCS checking can be done completely by software in a relatively short time in a microprocessor or it can be done with the use of special hardware, which some computer manufacturers supply as optional equipment. In either case single-bit error correction will not add a large burden to the computer.

If a single bit error occurs in the train of characters +, *, SYN, SYN, SOH (i.e., those not checked by the BCS code) then the error can be detected and "corrected" in the following way. The odd parity bit check will usually indicate the erroneous character and if a match with a stored correct character shows that one bit is in error then the message start may be considered as proper.

5.4.6 System Throughput Performance

The observed message transaction rate as a function of message transaction length is given in Figure 5-15 for data rates of 2400 and 4800 bps. The message transaction length is the sum of the uplink and downlink message text lengths, preamble lengths, and postamble lengths. The message transaction length does not include the prekey bits. The data from which the curves were constructed is shown in the table presented in the inset in Figure 5-15. The vertical lines on the curves indicate the spread in the data for the various runs. The portion of the data spread on the 4800 bps curve that is enclosed in braces represents the 25-kHz channel spacing data. Some degradation in throughput occurred for the 25-kHz channel spacing at 4800 bps. This degradation is most likely a result of the poor characteristics of the filter used to obtain the 25-kHz channel spacing in the GRR-23 ground receiver.

The curves show that the message transaction rate was nearly doubled when the data rate was increased from 2400 to 4800 bps. The reason that it was not exactly doubled is that the prekey time (which made up as much as 35 percent of the total message transaction time) was held constant for the two data rates. Thus the message transaction rates as shown in these curves could be increased by reducing the prekey lengths. Time constraints on this experiment did not allow for the collection of data with shorter prekey lengths. Also shown in the table on Figure 5-15 is the value for the expected message transaction rate. The expected value shows good agreement with the observed values. The calculation for the expected value of the message transaction rate was



BPS	kHz	Flight No.	Message Transaction Length (bits)	Message Transactions Per Hour				
				Run 1	Run 2	Run 3	Run 4	Expected
2400	50	1	2072	2875	2886	2850		2782
		2	2360	2598	2596	2540		2579
		5	552	6647	6631	6557		6673
		9	2360	2606	2614			2616
4800	50	3	920	8997	8964			9033
		4	2360	4116	4103	3922		4132
		6	2072	4561	4568	4536	4543	4604
		11	2360	4135	3744	4093		4039
2400	25	8	2360	2619				2627
		10	552	6639	6649	6644		6686
4800	25	7	2360	3716	3527			3735

FIGURE 5-15. MESSAGE TRANSACTION RATE

based on the assumption of randomly distributed errors. This calculation utilizes the expected message transaction failure rates (EMTFR) presented in Tables 5-2 through 5-12. That is, for each flight listed on Figure 5-12,

$$\text{EMTFR} = \frac{\text{No. of Messages Attempted (1-EMTFR)}}{\text{Data Flight Time}} \qquad (5\text{-}10)$$

A comparison of the calculated and observed message transaction times for the 11 flights are shown in Table 5-18 as a function of data rate, uplink message length, and total uplink and downlink message length in bits which includes all prekey, preamble and postamble bits. The calculated transaction times are based solely on the computer times required to transmit the total number of uplink and downlink characters (i.e., prekey, preamble, and text) at the given data rate and do not account for computer processing time and propagation time. Thus the calculated times are ideal times that are not attainable in practice. The observed times are averages of error-free transactions and include computer processing times and propagation times. The variation from this average can be as much as 200 percent during high error conditions. The difference between the calculated transaction time and the observed transaction time is taken to be the computer processing time (the propagation time is negligible).

The large differences between calculated and observed transactions times occur for uplink messages with long texts and when messages are echoed, which produces downlink messages with long texts. In addition, all echoed messages require the ground system computer to perform a bit-by-bit comparison of the echoed message with the original uplinked message before proceeding to the next uplink message. The large data recording task assigned to the ground system

TABLE 5-18. MESSAGE TRANSACTION TIMES

Flight	Data Rate bps	No. of Uplink Message Characters	Total No. of Bits in Message (Uplink and Downlink)	Calculated Transaction Time (Sec)	Observed Transaction Time (Sec)	Difference (Sec)
1	2400	220	2584	1.0766	1.2345	0.157
2	2400	120	2864	1.1866	1.3807	0.194
3	4800	30	1544	0.3216	0.3989	0.077
4	4800	120	3344	0.6933	0.8691	0.176
5	2400	30	1064	0.4433	0.5403	0.097
6	4800	220	3064	0.6383	0.7813	0.143
7	4800	120	3344	0.6933	0.8707	0.177
8	2400	120	2864	1.1866	1.3699	0.172
9	2400	120	2864	1.1866	1.3748	0.188
10	2400	30	1544	0.4433	0.5412	0.098
11	4800	120	3344	0.6933	0.8638	0.170

computer for the performance of this experiment further increased the processing time requirements. The extra processing required to store and process the large quantities of data collected in this experiment does not represent the processing requirements for an operational system. The observed computer processing times for the non-echoed messages are shown in Figure 5-16 as a function of total uplink and downlink message length (including prekey, preamble, and postamble) for the 2400 and 4800 bps data rates. The computer processing times for the echoed messages (flights 2, 4, 7, 8, 9, and 11) fall above the curves for their respective message lengths because of the increased processing requirements for this class of messages. The data of Table 5-18 are shown in a different way in Figure 5-17. Here the observed and calculated message transaction times (including echoed messages) are given as a function of the total number of characters per transaction. The total number of characters per transaction includes the prekey, preamble, and text characters for the uplink and downlink messages. The difference between the observed and calculated curves at each data rate represents the computer processing time. These curves may be used to estimate the sensitivity of the message transaction time of this system to prekey length. For example, if a 4800 bps message containing a total of 250 uplink and downlink characters (this total includes 60 uplink and 60 downlink prekey characters for the conditions of this experiment) were reduced to 190 total characters by reducing the uplink and downlink prekey lengths to 30 characters, the message transaction time (from the observed data curve) would be reduced from 0.508 seconds to 0.390 seconds, resulting in a throughput increase from 7090 messages per hour to 9230 messages per hour. Thus, a 50 percent decrease in the prekey length for this case results in 30 percent increase in the message throughput rate. It should be remembered, however, that there does exist a minimum

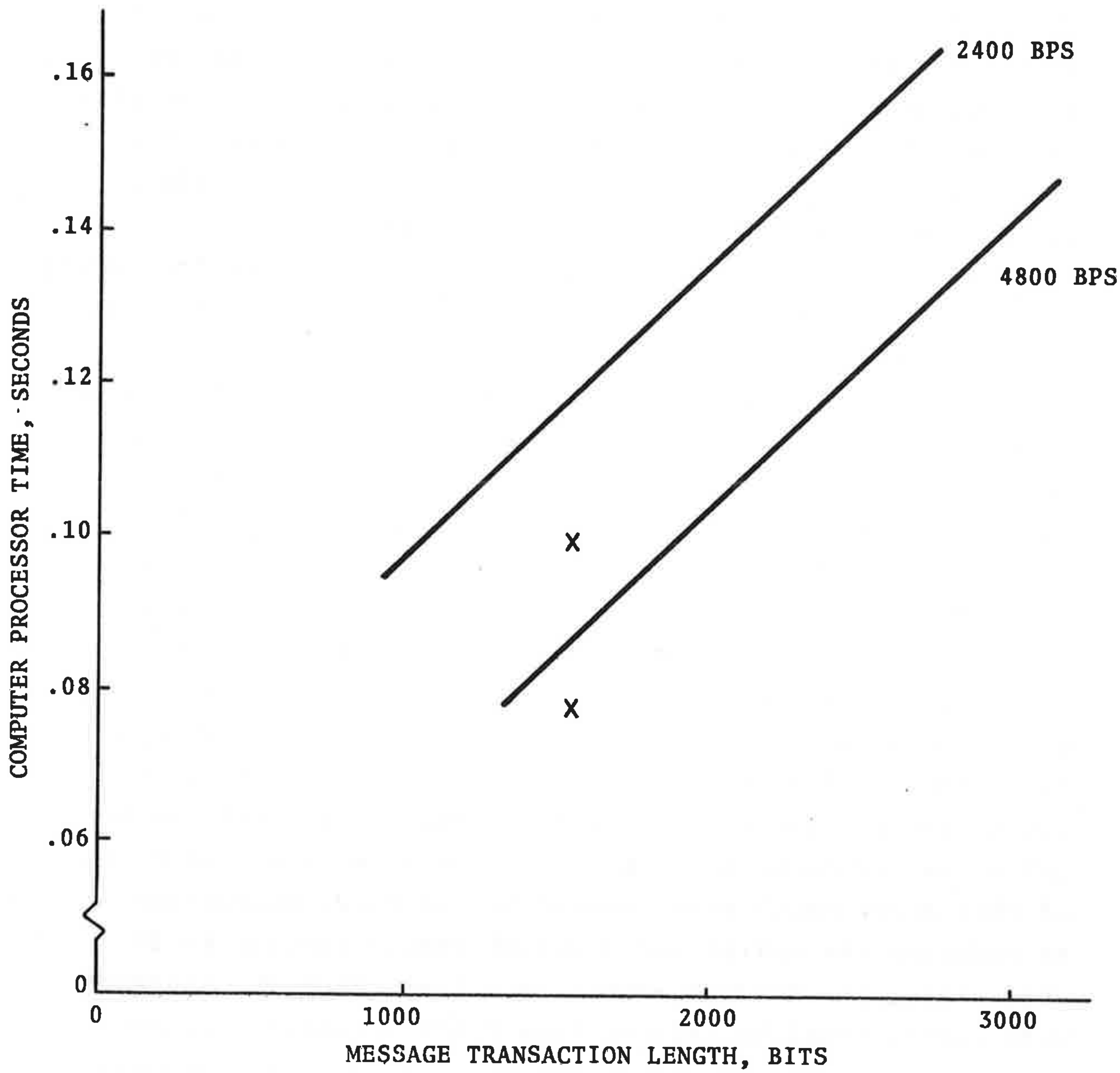


FIGURE 5-16. COMPUTER PROCESSING TIMES FOR NON-ECHOED MESSAGES

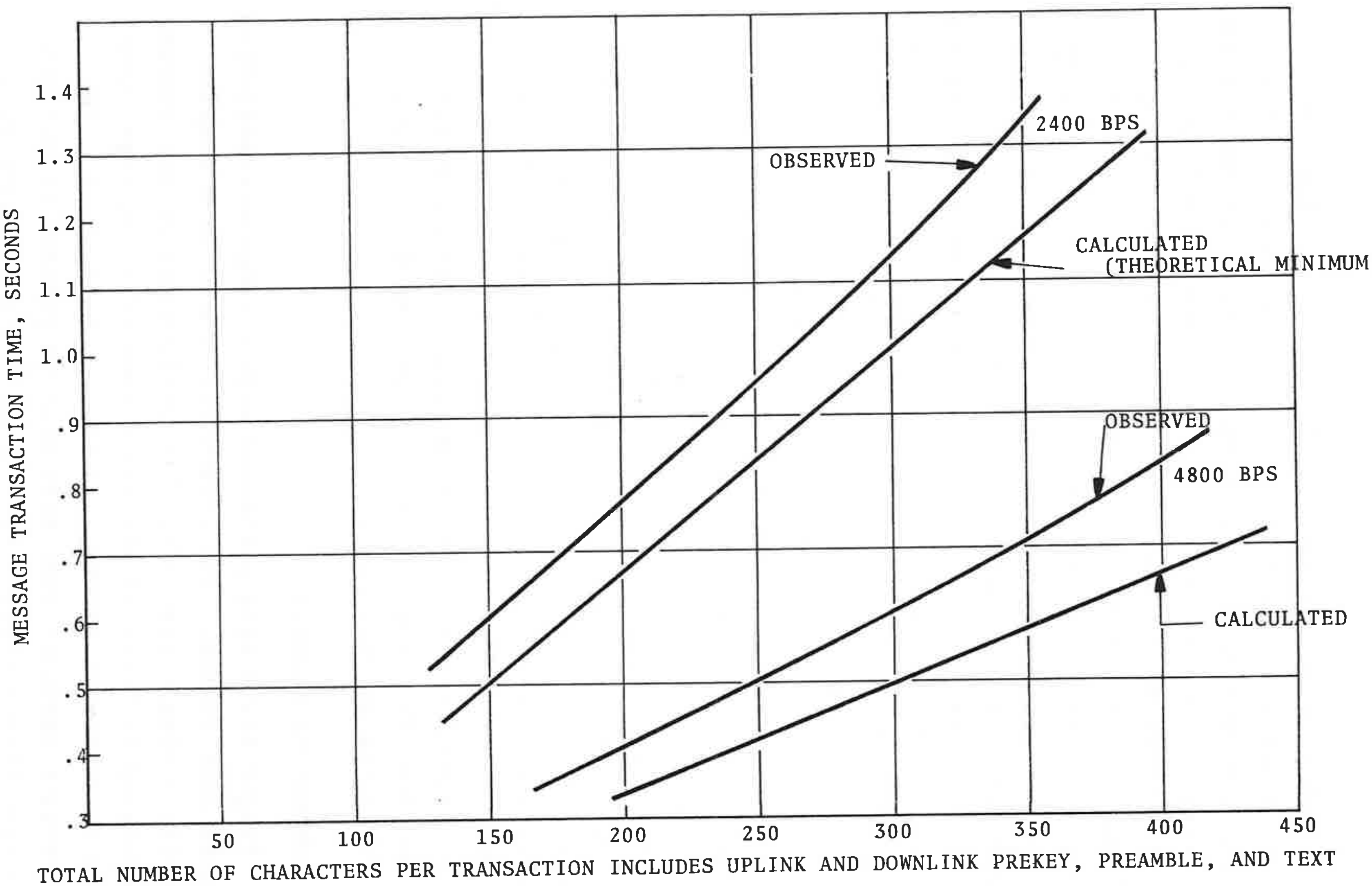


FIGURE 5-17. MESSAGE TRANSACTION TIME

prekey time required by the system hardware (radios and modems) to allow for settling and synchronization. This time is dependent on the individual equipment characteristics comprising a given system and must be chosen based on the slowest performing equipment in the system (the GRR-23, which had a measured AGC attack time of 22 msec., was the slowest equipment in this experiment). The minimum prekey time (or the minimum number of prekey characters as a function of data rate) was not determined for the system configuration used in the flight tests. However, subsequent to the flight tests it was demonstrated in the laboratory that a similar system could reliably acquire messages (average probability of acquisition was approximately 0.995) in prekey times of 3.34 msec. (two character times at 4800 bps) at energy-to-noise density ratios (E/N_o) as low as 12 dB in a Gaussian noise environment. The AGC attack time for the receiver used in these tests was 3.7 msec. The laboratory test setup did not allow testing of shorter prekey times nor testing in a fading environment. The results of these tests are presented in Appendix D. The prekey time of 100 msec. (corresponding to 30 and 60 prekey characters at 2400 and 4800 bps, respectively) chosen for the flight test experiments was intentionally conservative in order to preclude unforeseen problems that would have shortened the data flight time available to this project.

5.5 SUMMARY OF RESULTS

Flight tests were performed with a computer-controlled VHF data link system. The system was tested in a simplex mode with a single aircraft. The performance of the system was measured in terms of bit error rate (P_e), message transaction failure rate (MTFR), and message throughput. The test results indicate that more than 99 percent of the messages were transmitted error-free. Of the messages that had errors, 52 percent resulted from failure of the airborne or ground system to respond to valid transmitted messages. The remaining 48 percent of the messages with errors had bit or clock slip errors that were detected by the block check sequence (BCS) error detection scheme. Approximately 48 percent of all the messages containing errors detected by the BCS scheme had single bit errors. Analysis of the distribution of the errors indicates that the VHF channel cannot be modelled with a random error model. An empirical model for the channel is presented that shows that the channel can be modelled by the superposition of several random error models with corresponding P_e's that persist for different fractions of the time. The high percentage of no response failures is explained in the context of this model.

Analysis of the P_e and MTFR data for different flight conditions indicate that the link performance relative to average is significantly degraded for the conditions of takeoff and climbout, turning, and approach and landing. Thus a data link system design for ATC operations must consider the total instantaneous aircraft population in a given flight condition along with the link performance characteristics for that flight condition in order to provide the required system capacity in accordance with the required message service times.

A simplified error correction scheme that utilizes the BCS scheme in conjunction with the presently unused character parity bit is recommended to improve the link efficiency. The recommended error correction scheme can correct all the messages containing single bit errors with no increase in system complexity.

The system throughput at 4800 bps was nearly double that at 2400 bps. The error performance at the two data rates was approximately equal.

6. CONCLUSIONS

This section presents conclusions relating to the performance characteristics of VHF communication equipment and the VHF Air Mobile Frequency Band relative to their utilization in an MSK modulated VHF data link system. The conclusions listed below are based on data obtained in a series of laboratory, field, and flight tests of data link subsystems and systems.

6.1 DATA LINK PERFORMANCE

VHF data link performance is not dependent upon the bit rate selected. Comparable performance in terms of bit error rate (P_e) and message transaction failure rate (MTFR) was observed for all conditions for either 2400 bps or 4800 bps. Throughput, however, was double at 4800 bps relative to the 2400 bps rate. In addition, digital data performance at either 2400 or 4800 bps with MSK modulation performed equally well for carrier spacings of 25 kHz and 50 kHz.

The VHF data link channel exhibits excellent error performance characteristics the vast majority of the time. The observed channel performance does not warrant radio equipment signal-to-noise ratio performance beyond that achievable with current FAA and ARINC 566A types for successful data link system implementation.

The MSK modulation technique is well suited to VHF data link applications with existing VHF communication equipment. Since the channel exhibits good signal-to-noise properties for the vast majority of the time, less sophisticated modulation techniques might give equivalent performance at a lower implementation cost.

The VHF data link channel exhibits low probabilities of error most of the time. However, in some flight conditions, the probability of bit error is quite high. A model of the probability of error was constructed based on the flight test data collected with the Experimental Data Link System. It was found that the probability of error was 1×10^{-6}, 99.6 percent of the time. During the remaining 0.4 percent of the time the probability of error was in the range of 10^{-3} to 10^{-2}.

6.2 IMPACT OF FLIGHT MANEUVERS

Sizing of VHF data link system for ATC operations (e.g., providing sufficient number of channels) requires consideration of the instantaneous aircraft population at a given flight condition, expected message traffic density at that flight condition, and the average link performance characteristics for the given flight condition. This conclusion is based on the observed wide variation in average bit error rate and message transaction failure rate performance as a function of aircraft flight condition. The average P_e's and MTFR's determined in the tests were significantly worse for the flight conditions of takeoff and climbout, maneuvers, and approach and landing than for the level flight condition. The degraded data link performance observed for taxiing conditions and low altitude flight paths near the ground communication site is attributed to multipath-induced signal fading. The degraded performance observed during maneuvers is attributed to antenna pattern effects which reduce direct path signal gain and may enhance multipath response. Aircraft antenna diversity can be utilized to improve communication performance during maneuvers.

6.3 MESSAGE TRANSACTION PERFORMANCE

More than 99 percent of all messages transmitted in flight tests with an experimental data link system were transmitted error-free. The majority of the message transaction failures (52 percent) were due to No Responses to ground or aircraft generated messages rather than to errors detected by the error detection scheme. The high percentage of message transaction failures due to No Responses is attributed to the observed nature of the VHF channel wherein periods of high error density conditions persist for short periods of time. The periods of high error density can persist for periods of several message transaction times. Messages transmitted under these conditions contain large numbers of errors and are so corrupted that the data link system cannot recognize them as valid messages. This results in the No Responses.

6.4 AIRPORT SURFACE PERFORMANCE

VHF data link can be expected to provide reliable communications over most of an airport surface. Communication performance is degraded by multipath phenomena in certain obstructed areas near large buildings. It was determined for worst case obstructed transmission conditions that a significant number of retransmissions of long messages would be required to provide reliable communication performance. A solution to the potential queue delay problem resulting from multiple retransmissions might require ground antenna diversity to improve worst case propagation conditions or hard wire connections to the data link system when aircraft are parked in gate areas having worst case propagation conditions. This conclusion is based on preliminary tests conducted at one airport using a mobile test van with a nonaircraft antenna. The test results are subject to verification in other airport environments and with an aircraft as the test vehicle.

6.5 POLLING STRATEGY

The polling strategy for VHF data link systems utilizing retransmission error correction techniques should delay retransmission of messages to a given aircraft for which there was no response and instead service a different aircraft, thereby allowing the high error density condition associated with the original transmission attempt to desist before retransmitting the original message. This conclusion is based on the observation that 34 percent of the errors detected by the block check sequence (BCS) error detection scheme occurred immediately prior to or subsequent to the conditions of no response. Thus, if a no response condition is observed, there is a high probability that a high error density condition has been encountered which will result in a number of consecutive messages being in error. Immediate retransmission of messages under these conditions will only degrade system throughput efficiency and contribute to system queue delay.

6.6 ERROR DETECTION

The CCITT generator polynomial given by:

$$P(X) = 1+X^5+X^{12}+X^{16} \tag{6-1}$$

provides adequate error detection capability for VHF data link when implemented with a BCS error detection scheme. The results of the experiments reported herein indicate that a delivered message error rate of approximately 2.7×10^{-9} can be achieved for VHF data link with this implementation of a BCS error detection scheme. This translates into one delivered incorrect message in 5.8 years based on a continuous message transaction rate of 2 messages per second.

Simple error correction schemes combining forward error correction (FEC) and retransmission error correction (RTEC) techniques can be implemented for correcting all messages with single bit errors to improve data link system throughput. An error correction scheme that utilizes character parity checking in conjunction with BCS error detection is suggested for this purpose. The suggested error correction scheme is simply implemented and requires no increase in system complexity. This conclusion is based on the observation that approximately 50 percent of messages having errors in tests conducted with an experimental data link system had single bit errors.

6.7 GEOGRAPHIC COVERAGE

Geographic coverage for VHF data link as a function of aircraft altitude slant range is predicted well by the ITS air-ground propagation model described in Reference 12. The majority of the flight test signal strength data defining the radio horizon fell between the 5 percent and 95 percent availability curves defined by the ITS propagation model. A region of high error density (called the near horizon region) was observed near the actual radio horizon.

The width of this region was observed to vary between 0.5 and 20 n mi for aircraft test altitudes up to 18,000 feet. The average width of this region was 10 n mi. This region plus an additional region sufficient to provide an adequate safety margin should be accounted for when configuring data link system coverage for ATC operations.

6.8 EXISTING VHF EQUIPMENT

Existing FAA primary ATC VHF communication transmitters and receivers and ARINC type airborne transceivers are adequate for data link applications at data rates of 2400 and 4800 bps. The primary FAA ATC receivers are readily modified to function at 25-kHz channel spacing with proper crystal selection. Tests performed on the receiver portions of general aviation transceivers after implementing simple modifications to broaden the passband characteristics showed that this user group of equipment can perform adequately for data link applications at 4800 bps. Similar modifications will be required on the transmitter portions of general aviation transmitters in order to transmit digital data at 2400 and 4800 bps.

Airborne transceivers of the same user group, but of different manufacturers, can give different performance in a data link system even though built to the same specification. Performance differences of 3 to 4 dB were observed in data link subsystem tests of receiver portions of ARINC 566A transceivers. This performance variation is attributed to differences in receiver filter characteristics which results in intersymbol interference. However, because of the nature of the data link channel, equipment performance variations of this order will not significantly affect data link system error rate performance.

Greater extremes of performance variation were exhibited in tests of three unmodified receiver portions of general aviation transceivers: one failed to function at a data rate of 2400 bps and one performed quite well at a data rate of 4800 bps.

Data from these tests indicate that the best data link performance is achieved with receiver filter characteristics having a smooth rolloff and a bandwidth (-3 dB) of 6.5 to 8 kHz.

6.9 MSK MODEM PERFORMANCE

The MSK modem error performance, as determined in laboratory tests in a nonmultipath environment was within 0.5 dB of theoretical maximum performance at a data rate of 4800 bps and less than 1 dB from theoretical maximum performance at a data rate of 2400 bps.

The MSK modem acquisition performance, as observed in limited tests, in a non-multipath environment, showed a probability of acquisition of 0.995 in 3.34 msec.

The MSK modem exhibited significant unlock problems for signal-to-multipath ratios worse than approximately 6 dB in data link subsystem tests performed with a channel simulator. Multipath, as manifested by time selective signal fading, was observed to be a primary source of errors in field tests conducted on an airport surface and in flight tests when the aircraft was taxiing, during climbout, during approach and landing, and during low level maneuvering flight conditions near the ground communication site.

Multipath most seriously effects digital data performance at some locations in the airport environment. Ground antenna diversity or hard wire connections to parked aircraft may be required to successfully communicate at some airport locations. Multipath is a much less serious effect on digital data performance when the aircraft is airborne. Sufficient data link system capacity can be provided in the communication sector design in order to account for any increased polling activity required for successful message delivery to aircraft in low altitude maneuvering flight conditions.

6.10 RADIO AGC TIMES

Sensitivity of data link system throughput to message pre-key time (i.e., number of pre-key characters) does warrant improvement in receiver AGC times and transmitter stabilization times. Maximum system throughput can be achieved if these times are consistent with the acquisition times achievable with the modems.

APPENDIX A
COMPARISON OF DIGITAL DATA TRANSMISSION PERFORMANCE AT VHF AND UHF IN THE AIRPORT ENVIROMENT

This appendix considers the differences in performance to be expected when digital data are transmitted on a UHF carrier instead of a VHF carrier.

A.1 PROPAGATION DIFFERENCES AT VHF AND UHF

There are two sources of propagation differences. First, the scale of terrain anomalies, building and other structures is larger at UHF that at VHF as measured in terms of wavelengths. Second, the velocity of a user aircraft or a moving obstruction is larger at UHF than at VHF as measured in wavelengths per second.

The fact that terrain anomalies, buildings, and structures appear to be larger as measured in terms of wavelengths means that at the higher operating frequency there are more candidates for significant multipath reflection. Stated another way, it is more likely that diffuse multipath will be encountered rather than specular multipath.

The increased scale of velocity at the higher frequency means that for a given actual vehicle velocity, the observed multipath fade rates will be higher.

Thus, when comparing the propagation channel at 118 MHz to 136 MHz to the propagation channel at 300 MHz to 400 MHz, it should be expected that generally lower direct path power-to-multipath power ratios will be observed and that generally higher multipath fading rates will be encountered at the higher carrier frequency.

A.2 SIGNAL-TO-NOISE RATIO DIFFERENCES

In the airport environment, it is reasonable to assume that ambient noise rather than data link system equipment noise will create the system noise floor at VHF. The ambient noise in the 300 MHz to 400 MHz range will be about 10 dB less severe. It is possible, in fact, that in some airpott environments, the receiver noise of a UHF receiver may define the noise floor rather than the ambient noise. In any case, it is reasonable to assume that given the same transmitted power, antenna gains, and propagation losses at both VHF and UHF, and the same IF and postdetection bandwidths, the UHF system will provide a higher signal-to-noise ratio.

Of course, the free-space path loss is higher at the higher frequency. Specifically, the propagation loss is inversely proportional to the square of the frequency. Thus, when comparing the path loss at 300 MHz to that at 120 MHz, the higher frequency will have roughly 8 dB more path loss at a given range. This approximately compensates for the decreased ambient noise at the higher frequency.

Typical signal-to-noise ratios (S/N's) in the airport environment can be estimated as follows: The path loss at a range of 2 kilometers and at 300 MHz is given by:

$$\frac{P_R}{P_T} = G_t G_r \left(\frac{\lambda}{4\pi r}\right)^2 L \qquad \text{(A-1)}$$

with

$G_t = 3\ dB_i$ = transmitter antenna gain

$G_r = 0\ dB_i$ = receiver antenna gain

λ = 1 meter = carrier wavelength

r = 2000 meters = range

L = -1 dB (1/1.26) = system losses.

This yields a path loss of roughly 86 dB. The transmitted power is assumed to be on the order of 40 dBm. Thus, the received power level is roughly 40-86 = -46 dBm. The noise power, P_N in a 20 kHz IF bandwidth (10 kHz baseband bandwidth) is given by

$$P_N = k\ T_0\ (NF)\ B_{IF} \qquad \text{(A-2)}$$

with

K = Boltzmann's constant

T_0 = 290° K

NF = 10 dB = noise figure at 300 MHz

B_{if} = 20 kHz = IF bandwidth.

This yields P_N = -121 dBm. The S/N is thus on the order of 75 dB assuming free-space path loss. As described above, similar results will be achieved at VHF.

Previous analysis has shown that the MSK modem-conventional AM Data Link system starts to have significant numbers of errors when S/N in 20 kHz is on the order of 6 dB at 2400 bps or 9 dB at 4800 bps. This means that in the airport environment assuming free-space propagation conditions, the system has more than 65 dB margin.

In fact, free-space propagation conditions do not prevail in the airport environment. They will be either plane-earth propagation conditions or obstruction limited (diffraction) propagation conditions. Both of these conditions result in lower S/N's than those predicted for free-space conditions.

A.3 SOURCES OF ERROR IN THE AIRPORT ENVIRONMENT

Clearly, signal levels are sufficiently high within several thousand feet of the transmitter so that it is reasonable to conclude that data link signals would be received error-free almost everywhere in the airport environment. That is, no building or structure could provide sufficient shielding to preclude operation.

This conclusion could be true if the received signal level were constant. Instead, it fades due to motion of the receiver (in a vehicle) or due to motion of other vehicles in the vicinity of the transmitter or receiver.

The signal fading has two degrading effects on data link performance. These are discussed next.

A.3.1 AGC Effects

Experimentation at Logan International Airport indicates that VHF signal levels vary over a wide dynamic range. In some regions, fading in excess of 40 dB was observed. Moreover, the fade nulls were sometimes located as close as 3 feet apart. This would result in a 5-Hz fading rate for a vehicle traveling 15 ft/sec.

It is not clear that the receiver's AGC can follow the signal level variations that are extremely rapid in the vicinity of nulls. If the AGC does not normalize the signal level in the presence of this kind of fading then, errors will occur due to the signal drop-outs at the nulls.

The fading rate, and hence the signal level variation rate, is directly proportional to frequency. Thus, it could be concluded that more bits would be lost during signal drop-outs at UHF than at VHF.

A.3.2 Irreducible Error Rate

A more sophisticated analysis uncovers another source of errors due to signal fading. The fading causes spectral smearing of the data signal components, which results in "Mark" signal energy being spread in the "Space" signal's matched filter, and vice versa. In this way the data signal itself develops a self-noise component.

The self-noise created by the signal fading results in an irreducible error rate. That is, an error rate which cannot be reduced by increasing transmitted power. (Increasing the transmitted power increases the signal and the self-noise proportionally.)

The irreducible error rates for most conventional data communication techniques such as FSK, DPSK, PSK, and QPSK are available in the literature. However, the data link modulation technique is a hybrid scheme. In particular, it can be shown that MSK is exactly equivalent to QPSK. Unfortunately this QPSK (MSK) is not sent directly. Instead, it is amplitude modulated onto an RF carrier. Thus, available analyses in the literature do not apply to the MSK system.

For the purposes of illustration, consider the effect of significant signal fading on a DPSK signal. In that case, the irreducible error rate (P_z) is given by*

$$P_z = \frac{1}{2} (f_m T)^2 \qquad \text{(A-3)}$$

*William C. Jakes et al., Microwave Mobile Communications, New York: John Wiley and Sons, 1974.

where

f_m = fade rate ≃ vf_c/c

T = bit duration

At 15 ft/sec and f_c = 130 MHz, f_m ≃ 2 Hz. On the other hand at 15 ft/sec and f_c = 300 MHz, f_m = 4.5. Table A-1 shows the irreducible error rate for these VHF and UHF frequencies for 2400 and 4800 bps data rates.

TABLE A-1. IRREDUCIBLE ERROR RATE

Bit Rate	130 MHz	300 MHz
2400 bps	3.4×10^{-6}	1.7×10^{-5}
4800 bps	8.5×10^{-7}	4.3×10^{-6}

The irreducible error rate increases as the square of the velocity. Thus, for example, the error rate above must be increased by an order of magnitude for vehicle speeds on the order of 45 ft/sec.

It is not unreasonable to assume that similar irreducible error rates are caused by fading in the data link systems.

A.4 EXPERIMENTAL DATA

Some experimental data showing a comparison of performance at 135 MHz versus 275 MHz for digital data transmission were collected by driving a mobile test van on the surface of Logan International Airport, Boston, Mass. These results are shown in Table A-2. The table shows bit error rates (P_e) and block error rates (P_b) observed at three different regions at Logan International Airport. An exact correspondence to the pattern suggested by Table A-1 is not found because vehicle speed could not be controlled due to the nature of the airport activities. Moreover, each region had somewhat different multipath fading characteristics.

Nonetheless, the generally inferior results at UHF predicted by Table A-1 are borne out by the experimental results of Table A-2.

TABLE A-2. EXPERIMENTAL COMPARISON OF PERFORMANCE OF DATA TRANSMISSION AT VHF AND UHF

Type of Error Rate	Region	Bit Rate	VHF Error Rates	UHF Error Rates
P_e (Bit error rate)	A*	4800	6.7×10^{-6}	1.15×10^{-3}
P_b (Block error rate)	A	4800	4×10^{-3}	4.55×10^{-3}
P_e	B**	2400	6.9×10^{-6}	1.49×10^{-3}
P_b	B	2400	3.13×10^{-3}	3.18×10^{-2}
P_e	C***	4800	3.26×10^{-5}	1.95×10^{-4}
P_b	C	4800	7.55×10^{-4}	1.88×10^{-2}

* Region A is an aircraft gate area that has partially obstructed geometric line-of-sight conditions.

** Region B is an aircraft gate area that has totally obstructed geometric line-of-sight conditions.

*** Region C has total geometric line-of-sight conditions.

APPENDIX B
EXPERIMENTAL DATA LINK SYSTEM REQUIREMENTS

This appendix contains the engineering requirements for the development of the software for the Experimental Data Link System. These requirements are presented here to provide additional useful details of the system that do not readily fit into the format of the main text.

B.1 PERFORMANCE

B.1.1 Ground System Performance Characteristics

The ground system shall function as a FFA test bed for the test and evaluation of overall link management techniques for VHF air-ground data links. The ground system shall use a TI-960A Mini-computer, a McDonnell-Douglas MSK Modem capable of operation at 2400 or 4800 bits per second (bps) and a variety of FAA ground receivers and transmitters having 25 and 50 kHz channel spacing. The ground system shall communicate ASCII encoded messages to/from the specified number of airborne systems at 2400 and 4800 bps. The message source shall be from a stored sequence of messages or from a manually inputted message via the teletype. The ground system shall provide the following basic functions realting to data link management:

1. System entry
2. Cyclic and demand access polling
3. Error detection and correction by retransmission
4. Sequence of stored messages

A second but equally important role of the ground system relates to the collection and reduction of experimental data. The functions associated with this role shall include:

1. Error counting, identification, and storage
2. Message turnaround time monitoring
3. Preliminary statistical analysis of data
4. Data printout (cassette and teletype)

B.1.2 Airborne System Performance Characteristics

The Airborne system shall function with the ground system to complete the data link loop. The airborne system peripherals for the baseline system will be limited to two ASR 733 Cassette Keyboard/Printer units. The airborne system shall utilize the TI-960A Minicomputer, McDonnell-Douglas 2400/4800 bps Modem, and available general aviation and ARINC (546, 566, 566A) Transceivers having 25- and 50-kHz channel spacing. The airborne system shall accept and generate ASCII encoded messages at 2400 and 4800 bps. A transparent text capability shall also be provided. The message formats shall be in accordance with section B.2.1.4 of this appendix.

The airborne system shall provide the following basic functions:

1. Recognize and respond to messages having the proper aircraft address
2. Perform block check sequence (BCS) checks
3. Techical acknowledgement/nonacknowledgement (ACK/NAK) recognition and generation
4. Add aircraft identification (ID) to all downlink messages/responses
5. Collect and store data (e.g., identify and store NAK's by message identifier)
6. Store and transmit downlink messages
7. Direct uplink messages to proper peripheral device

B.2 SYSTEM DESIGN AND PERFORMANCE REQUIREMENTS

B.2.1 Link Management Functions

B.2.1.1 Message Priority Structure - All messages shall be of priority 1 (i.e., first in first out). Messages input by the ground system operator shall be handled as soon as current message processing is complete.

B.2.1.2 System Entry Polling - Initially, the airborne system is to be polled by the ground system using a System Entry Poll. This poll has no text in the two-way communication and shall have the format as specified in Tables B-1 and B-2 of this appendix. When the airborne system responds with an ACK its numerical address shall be removed from the System Entry Poll and subsequently be polled via a General Poll. Any subsequent transmitted message that has had a preselected maximum number of No Responses or NAKs shall cause the ground system to initiate transmission of the next message in the scenario. The number of No Responses or NAK errors causing reversion shall be software selectable between 1 and 10.

B.2.1.3 Error Detection and Correction - BCS calculations shall be performed on all uplink and downlink messages. The code polynomial to be implemented is the CCITT polynomial given by $P(x) = 1 + X^5 + X^{12} + X^{16}$. Error correction shall be via retransmission. Limits on the number of retransmissions for any of the above listed error conditions shall be ground system operator selectable with an upper limit of 10. When the number of retransmissions equals the upper limit the ground system will proceed to transmit system entry polls.

TABLE B-1. MESSAGE FORMAT

FUNCTION	ASCII CODE	NO. CHARACTERS
Prekey[1]		1-150
Bit Sync[1]	+	1
Bit Sync[1]	*	1
Character Sync[1]	+	1
Character Sync[1]	+	1
Bit Sync	+	1
Bit Sync	*	1
Character Sync	SYN	1
Character Sync	SYN	1
Start of Heading	SOH	1
Mode	See Table B-2	1
Message Number	Numeric	4
Message Alpha	Alpha	1
Address	Alphanumeric	2
Technical Acknowledgement	ACK/NAK	1
Label Character One	See Table B-2	1
Label Character Two	See Table B-2	1
Start of Text	STX	1
Text		235 max.
End of Text	ETX or ETB	1
Block Check Sequence		1
Block Check Sequence		1

[1]These are timing, modem, and modem controller characters. All characters following these are passed to the computer.

TABLE B-2. MESSAGE LABELS AND MODE CHARACTERS

UPLINK MESSAGE LABELS

Label 1	Label 2
0 System Entry	0 System Entry
E MSG for Printer	Q Other Messages
T Resynch Real Time Clock	
Q Other Messages	

DOWNLINK MESSAGE LABELS

Label 1	Label 2
0 System Entry	0 System Entry
E MSG for Printer	Q Other Messages
R Request for Special General Poll	
Q Other Messages	

MODE CHARACTER

MODE
1 Transparent Text (echo test)
2 Normal Text
3 Normal Text (echo test)
H Transparent text
D System Entry

B.2.1.4 Message Format - Message Element Definitions - The basic air-ground and ground-air message format is given in Table B-1. The selected character set shall conform with the ASCII code except for BCS characters, which shall be permitted to include any bit pattern from the set and are distinguished from control characters by their relative position in the message structure. A type of transparent text capability, specifically, code independent, is included and indicated by a unique mode assignment. All transmissions in both directions shall be least significant bit (LSB) first.

Prekey - The uplink prekey is required to allow the airborne transceiver AGC settling to occur and the airborne modem to stabilize. The downlink prekey is required to allow transceiver switching and transmitter output power to stablilize. The Ground System shall modulate the transmitter during the entire prekey interval. The length of the uplink prekey shall be selectable by a Ground System operator entry over the range of 1 to 150 characters. Each character of the prekey shall consist of eight binary ones with all parity rules being waived.

Bit Sync - There are two bit-sync characters, a "+" followed by a "*". These generate the following bit pattern, LSB first:

(MSB) 0010 1010 1010 1011

Character Sync - There shall be two consecutive "SYN" characters transmitted, LSB first for character sync. This shall generate the following bit pattern:

(MSB) 0001011000010110 (LSB)

Start of Heading - The "SOH" character shall be transmitted LSB first, generating the following bit pattern:

(MSB)00000001(LSB)

Mode - The Ground System shall generate five modes:

Mode	Function
1	Transparent Text with Echo
2	Routine
3	Routine with Echo
D	System Entry
H	Transparent Text

Mode 2 shall be the normally used mode designator and shall be assigned to all uplink messages with the exception of those specified below.

Message Number - Four numeric characters shall be reserved for identification of experimental messages as an aid in data reduction.

Message Alpha - One alpha character (starting with the letter A) shall be appended to the message number for each retransmission of a given message. For each subsequent retransmission, the alpha character shall be alphabetically incremented to indicate the number of times a given message was retransmitted.

Address - The two character address code shall contain a unique address of each destination aircraft in ground-to-air messages or the unique address of the source aircraft in air-to-ground messages.

Label - The first label character denotes the airborne system device (or peripheral) to which an uplink message is intended or from which a downlink message is generated. The second label character denotes the type of message and the format of the downlink reply. The required labels are shown in Table B-2.

Start of Text - In messages without text, there shall be no start of text character. In all other messages, "STX". ((MSB)00000010(LSB)) shall be in this position.

Text - A maximum of 235 characters shall be allowed in the text of any transmission. For transparent text messages (Mode 1 or H) the first 8 bits of the text shall contain the binary count of the equivalent number of transparent 8 bits bytes in the text, including the count character.

End of Text - The first and intermediate blocks of a multiple block message shall terminate with the communication control character "ETB"((MSB) 10010111 (LSB)).

Block Check Sequence (BCS) - BCS shall be initiated by but shall not include the "SOH" character. The calculation shall be terminated by and shall include "ETB" or "ETX" as appropriate. The 16 bits comprising "BCS" may assume any pattern; however, they shall not be treated as ASCII characters by the ground system. The technique used involves forming a code polynominal of the data using the CCITT polynominal $X^{16} + X^{12} + X^5 + 1$. Reference may be made to the Proceedings of the IRE, January 1961 issue, entitled "Cyclic Codes for Error Detection."

Error detection shall be performed in the software. The hardware BCS and parity checking option integral to the McDonnell-Douglas MDL-510 modem will be disabled for this application.

B.2.1.5 Data Link Messages - Message Types - All messages shall be in accordance with the message format given in section B.2.1.4. The messages shall consist of selectable sequences of 8-bit bytes up to a maximum of 235 characters per message and arbitrary bit streams including control characters when operating in mode 1 or H. Message volumes, size distribution, and frequency of occurrence shall be arbitrary within the constraints of the message formats and equipment capabilities.

Message Generation - Uplink messages shall be generated from scenarios stored in the TI-960A Cassette or from manual input via the ASR733 Keyboard.

B.2.1.6 Data Collection and Reduction - Data Collection Requirements - Experimental data shall be collected on the TI-960A Cassette system. Examples of the data to be collected include:

1. NAK counts and identification by message identifier
2. Storage of each NAK'ed message
3. Message turnaround time
4. Data required to calculate bit error rate
5. Data required to calculate message throughput rate

Provisions shall be made to manually enter each set of experimental conditions from the ASR-733 Teletype for storage on the cassette along with the experimental data. Examples of the manually entered data are:

1. Date and place of experiment
2. Ground and airborne equipment list
3. Bit rate
4. Flight path(s) flown
5. Weather conditions
6. Number of prekey characters utilized
7. Other pertinent experiment conditions or remarks.

These inputs shall be updated as required during the course of the experiments.

Data Reduction Requirements - Data reduction shall be performed on the ground system computer following the completion of a given experiment. The experimental data shall be processed with special data reduction software written for the TI-960A Computer.

B.2.1.7 Ground System Hardware Requirements - Computer Subsystem - The ground system subsystem consists of the TI-960 Minicomputer with Cassette and ASR-733 Teletype.

Link Communication Subsystem - The Link Communication Subsystem is comprised of a VHF transmitter, receiver, and associated modem and antennas. The subsystem shall interface with a 2400/4800 baud synchronous interface in the computer.

The modem shall translate the 2400 or 4800 bps binary string to a MSK waveform suitable for transmission over a voice channel and translate such a received waveform back into the corresponding 2400 or 4800 bps binary string. Uplink and downlink transmission shall be in the simplex mode (i.e., a two-way transmission that alternates up and down on a single frequency).

The ground system Link Communication Subsystem shall utilize separate transmit and receive antennas. A request-to-send-data signal from the synchronous interface shall be capable of turning on the transmitter. Similarly, the transmitter shall be capable of forming the squelch signal for the receiver.

The time which the ground system requires for transition between transmit and receive functions and receive and transmit functions shall be consistent with the minimum switching times achievable with the GRR-23 Receiver, the GRT-21 Transmitter, and the airborne system transceiver.

Within three milliseconds after the ground system has received a downlink BCS it shall switch from receive to transmit and initiate the transmitter input for prekey. The prekey input (software selectable) shall continue during transmitter warm-up and the time alloted of airborne transceiver AGC settling. It shall continue after both are complete for a time period sufficient to assume reception of the software selected number of good prekey characters. It is assumed that the transmitter has reached half-power within 15 milliseconds of the signal to switch on, and that this half-power level is adequate for the airborne AGC to commence settling.

The sequence of events for downlink transmission is similar to that for uplink. Within two milliseconds of the uplink BCS, the airborne system shall switch from receive to transmit, and the input for prekey shall be initiated. The prekey input shall continue as the transceiver warms up for transmission and the ground AGC settles, and shall continue after both are complete for a time period sufficient to assure reception of the software selected number of good prekey characters. It is assumed that the ground AGC begins to settle when the transceiver has reached half-power and that settling is complete within 30 milliseconds.

B.2.1.8 Text - Two types of text may be transmitted. "Normal" text consists of 8-bit ASCII code printable characters, punctuation, and printer control characters. The eighth bit shall be zero for these experiments. "Transparent" text may have any bit pattern that follows two rules:

1. The total number of bits is evenly divisible into 8-bit bytes.

2. The first 8-bit byte of text contains the binary count of the number of bytes of text. Note that the number includes the byte containing the count. Each byte may have any bit pattern, with all parity rules being suspended.

B.2.1.9 Modes of Operation - The air/ground system has two modes of operation, controlled by the ground system.

1. In the "normal" mode of operation the only text sent from the airborne system is keyboard-entered messages. Text in either direction is limited to a maximum of 220 8-bit bytes (characters).

2. In the "test" mode, each uplink message is echoed in the downlink reply. In this manner, the ground system may compare the text of the poll to the reply text and identify any errors that occurred in the round trip transmission. Since the message may contain errors when received by the airborne system, it is always downlinked as transparent text. However, the reply is still required to pass the BCS check before being accepted as correct. For completeness of the error checking during data reduction, the entire uplink poll (mode through BCS, inclusive) shall be downlinked as transparent text. The uplink text may be a maximum of 220 bytes, so the reply text may include a maximum of 235 8-bit bytes.

B.2.2 Software Requirements

The software routines shall choose and format each uplink message/poll according to the following procedures:

1. Only a System Entry poll will be sent to an aircraft until it responds with an error-free reply and is placed in the Active A/C list.

2. When an aircraft is on the Active list, messages may be selected from any of three sources:

   a. Manually entered through the keyboard

   b. Special general poll (requested by airborne system)

   c. Stored scenario.

Each time the system selects the next message to be uplinked, it starts at source a., then goes to b., and c. The first message that is found ready to be sent is selected for transmission. A special case of a manually entered message is an instruction to send a "resynch airborne real time clock" message. In this case the current time is uplinked with Mode 2 and labels T, Q.

The airborne system may request a special general poll when it has a keyboard-entered message ready to be downlinked while the system is operating in the test mode. If the ground system receives a reply with label character one set to "R," it will generate a general poll to the aircraft.

3. If a reply is received that contains ACK, then the previous uplink message has been received and so is removed from the message queue.

4. If a reply is not received that indicates that the previous poll was uplinked correctly, then the poll will be retransmitted unless one of the following has occurred for that message:

a. The replies fail the BCS check K times

b. The replies contain a NAK N times

c. No reply is received on L attempts.

The values of L, K, and N are variable over the range 1 through 10 and can be set by the operator. If any of these error limits are met, then the message is discarded and the next message in the scenario is sent.

Each message has a number assigned on a cyclic basis (0000 through 9999) plus a message alpha to facilitate error analysis. When a poll is first sent, it is assigned a number that is one greater than the previous message number, and the message alpha is blank. If the poll is retransmitted, both its number and alpha are incremented. (The alpha goes from blank to A, then B, etc.) The alpha is used to indicate how many retransmissions have occurred for a poll, while the message numbers provide the means for identifying individual transmissions.

Message completeness is assumed when two characters are received after a ETX code. These two characters are the BCS sent by the airborne system. If a message is shorter than a no-text message may be, or longer than the maximum allowed message, it is rejected. In both these cases of incorrect message length, an error message is printed and written on magnetic tape with time, message number, and the message as received.

If the system is operating in the test mode, the received reply is compared bit for bit to the uplink poll to detect any errors that may have occurred in the round trip transmission.

All received messages are checked for proper BCS characters. The detection of any error will cause a message to be printed and a record of the error to be made on the cassette tape (time, msg number, message as received). Failure of a downlink reply to pass the BCS and parity checks will also cause a NAK to be inserted into the next uplink poll. Otherwise an ACK is inserted.

A message generator module produces the messages that are to be transmitted from a stored message scenario when there is no keyboard-entered message and the airborne system has not requested a general poll.

APPENDIX C

PROBABILITY-OF-ERROR MODEL FOR THE DATA LINK SYSTEM

A probability-of-error model for the VHF data link channel is derived and discussed in this appendix. First, the sources of the data used to construct the model are discussed. Then the probability distribution is presented. Finally, the system design implications of the model are considered.

C.1 DATA SOURCES

The data used to construct the probability of error model were collected during the flight tests with the Experimental Data Link System. The data are in the form of error counts per message. In order to get enough data for a statistically significant distribution of error counts per message, it was necessary to accumulate the data from all flights, under all conditions, for both the uplink and downlink messages. An attempt was made to derive a set of error counts per message for each of the flight regimes; i.e. takeoff, level flight, maneuvers, and landing. However, there were insufficient data available to factor the error counts in this way.

As a result, the probability of error model presented here represents the conditions encountered during the tests with the Experimental Data Link System only. The error model can be generally applied provided that it is shown that the distribution of flight conditions encountered during the tests with the Experimental Data Link System are representative of typical data link user aircraft flight profiles. In particular, the message density as a function of user aircraft position must be known in order to determine the applicability of the error model derived below. Nonetheless, the discussion of this appendix serves the important purpose of illustrating the class of error environment in which a VHF data link system must operate.

C.2 ERROR COUNT DATA

Figure C-1 shows the data collected during the flight tests with the Experimental Data Link System. If only one probability of bit error existed throughput the tests, then the probability of n errors per message of length N, P(n/N) would be given by

$$P(n/N) = \frac{N!}{(N-n)!\ n!} P_e^{\,n} (1 - P_e)^{N-n}$$

where

P_e = bit error rate

N = message length

n = number of bit errors/message

The data of Figure C-1 cannot be fitted to the functional relationship above. Instead, it is necessary to assume that P_e is also a random variable. It was assumed, for the sake of illustration, that P_e was a discrete random variable. In this way, it is hypothesized that P_e takes on several different values during the course of the experiment. The data indicate that P_e is quite low, on the order of 1×10^{-6}, almost all the time. On the other hand, analysis based on Equation (C-1) above indicates that with P_e = 1×10^{-6}, the frequency of multiple errors per message can-

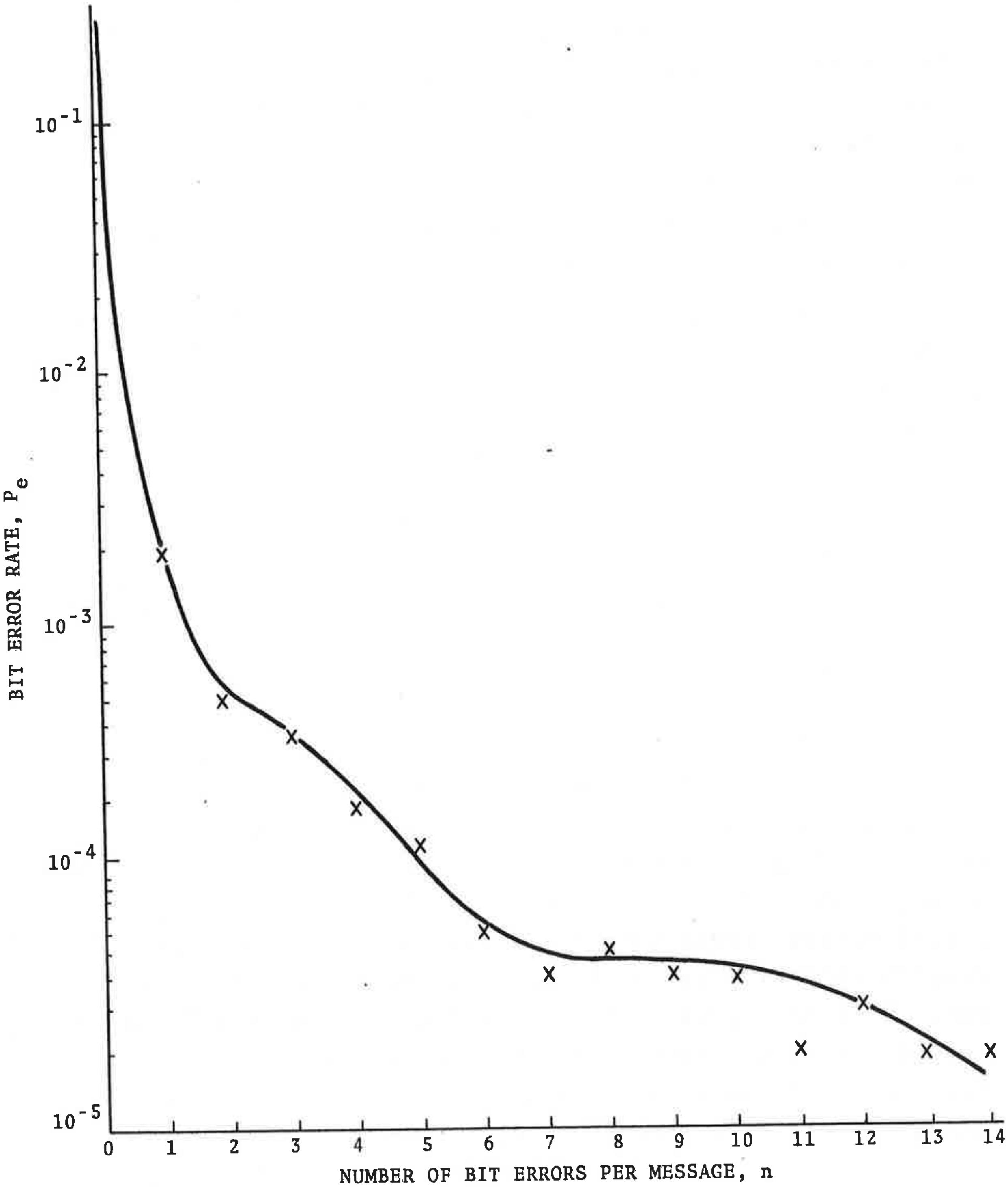


FIGURE C-1. ERROR STATISTICS

not be justified. For example, with n = 10, N = 1600, and $P_e = 1 \times 10^{-6}$, $P(n/N) \simeq 3 \times 10^{-35}$. The data show that 10 errors in 1600 is much more likely. Therefore it is hypothesized that for a small percentage of the total time, the system encounters higher probabilities of error. The task now is to find appropriate probabilities of error and percentages of time during which they persist. Once obtained, it is possible to construct a model for the discrete probability-of-error distribution.

The following constraints will be imposed on the discrete probability density of P_e, $P(P_e)$. The probability density should:

1. Predict the experimentally obtained distribution of bit errors/message
2. Predict the experimentally obtained block error rate
3. Predict the experimentally obtained average bit error rate
4. Account for the Experimental Data Link System operational features which reject messages which have errors in the preamble and heading.

Most of the data required for item 1 are shown in Figure C-1. In addition, the data collected during the experiment showed that the probability of 16 or more bit errors per message was on the order of $P(>16) = 1.79 \times 10^{-4}$. The observed message error rate for an average message length of roughly 1600 bits was 3.97×10^{-3}. The average bit error rate is on the order of 7.37×10^{-6} for all messages communicated during the tests with the Experimental Data Link System. Both of these latter values exclude transactions in which no responses were observed.

Item 4 above is not straightforward. It is noted that the data link system as configured for the test series required that the first 8 characters (64 bits) of the message be received without error or a No Response was recorded and the errors during the body of the transmitted message were not evaluated. This means that the error data of Figure C-1 were pre-screened by the processor so that under high error rate conditions (when it is likely that at least 1 bit out of 64 is in error) the message error characteristics were not evaluated. The error characteristics of Figure C-1 are thus biased in a way which reduces the impact of high error probabilities. Since the message rejection mechanism is known precisely, it is possible to unbias the probability-of-error distribution after a reasonable model is found which fits the biased data of Figure C-1.

C.3 FITTING THE ERROR DATA TO A P_e MODEL

A reasonable fit to the data points in the region $1 \leq n < 7$ in Figure C-1 is obtained when it is assumed that a $P_e \simeq 3 \times 10^{-4}$ persists 0.166 of the time and that a $P_e \simeq 1.5 \times 10^{-3}$ persists 0.17 percent of the time. Similarly, the data in the region $7 \leq n < 15$ suggest that a P_e on the order of 6×10^{-3} persists for 0.035 percent of the time.

Even higher probabilities of error must persist for a small percentage of the time in order to justify the observed frequency of cases in which more than 16 errors are observed in a message. For example, it has been calculated that a $P_e = 1.5 \times 10^{-2}$ will yield the observed P(>16) if this value persists 0.0189 percent of the time.

Next, it will be assumed that most of the time the probability of error is on the order of 1×10^{-6}, as a first approximation. Table C-1 summarizes the P_e model.

TABLE C-1. PROBABILITY-OF-ERROR MODEL

Probability of Error	Percentage of Time	Source
1×10^{-6}	99.6	Estimate
3×10^{-4}	0.166	Figure C-1
1.5×10^{-3}	0.17	Figure C-1
6×10^{-3}	0.035	Figure C-1
1.5×10^{-2}	0.0189	P(>16) Data

The model of Table C-1 indicates that the observed average error probability should be on the order of 9×10^{-6}. This result is certainly close to the actual average observed bit error probability, which is on the order of 7.37×10^{-6} averaged over all data runs.

We can similarly compute the expected average message error rate assuming an average message length of 1600 bits. In particular this is given by

$$P_m = \sum_i [1 - (1 - P_{ei})^{1600}] \cdot W_i \qquad \text{(C-2)}$$

where the P_{ei} are the probabilities of error given in Table C-1 and the W_i are their associated weighting factors. (The weighting factors are of course the percentages-of-time divided by 100.) Following this procedure it is found that the expected message error probability is 4.3×10^{-3}. The actual average message error probability was observed to be roughly 3.97×10^{-3}. Note that the message error probability is less than the message transaction failure rate (MTFR) since it does not include messages for which there was no response.

Thus, the probability-of-error model is almost perfect. It predicts the number of errors per message perfectly. But, the average bit error probability predicted is high by roughly 22 percent, and the predicted message error rate is high by roughly 8 percent.

The discrepancy probably arises from the assumption that the average message length was 1600 bits. In fact, message lengths varied from 152 to 1920 bits. Perhaps if the data collected at each message length had been treated separately and the results averaged, a better fit would have been obtained. Considering the quality of the data (i.e., source of the data points are the result of only one or two events in some cases) such detailed evaluations cannot be justified.

While the model is not exact (e.g., it is a discrete probability density rather than continuous density) it does serve to illustrate the probability of error distribution concept.

The derived model is based on observed BCS errors in the Experimental Data Link System. In order to generalize the results the effects of pre-screening the acquisition preamble must be removed. During the experiment, it was necessary to receive the first 8 characters (64 bits) without error in order to enter the error counting mode. Table C-2 shows the probability of receiving 64 bits without error at the probability of error levels of interest.

TABLE C-2. NO PRESCREEN WEIGHTING FACTORS

P_e	Probability (64 bits correct)	Weighting Factors
1×10^{-6}	0.999936	0.996
3×10^{-4}	0.981	1.69×10^{3}
1.5×10^{-3}	0.908	1.87×10^{-3}
6×10^{-3}	0.68	5.15×10^{-4}
1.5×10^{-2}	0.38	4.97×10^{-4}

Table C-2 also shows the weighting factors that would have been observed if there was no prescreening by the acquisition preamble mechanism. The probability model is shown in Figure C-2.

C.4 INTERPRETATION AND EXTRAPOLATION OF RESULTS

The results of Table C-2 can be used to obtain estimates of error statistics assuming different acquisition word lengths. For example, with no prescreening the observed average error probability can be found from Table C-2 to be 1.485×10^{-5}. That is, removing the effect of prescreening increases the average error rate from 9×10^{-6} to 1.485×10^{-5}, a factor of 1.65. This may explain the generally higher error rates observed during the Digital Data Transmission flight tests (these tests were conducted with a continuous PRN data stream) as compared to the Experimental Data Link System tests.

The same data can be used to evaluate the average message error rate in the absence of prescreening. In order to make these results comparable to the PRN test effort, a message length of 1000 bits will be assumed as was used during the PRN tests. Using the model of Table C-2, the estimated message error rate for a 1000 bit message length is 2.86×10^{-3}. The observed message error rate (i.e., block error rate) during the PRN tests was 1.2×10^{-2}. This indicates that a somewhat different probability of error distribution was in force during the PRN tests. It is noted, for example, that the average error probability predicted by the derived model is somewhat low compared to the results obtained during the PRN tests. It is concluded that the probability model for the PRN test has higher probabilities of error. These are the result of more aircraft maneuvers during the flight tests and more test time in the fringes of

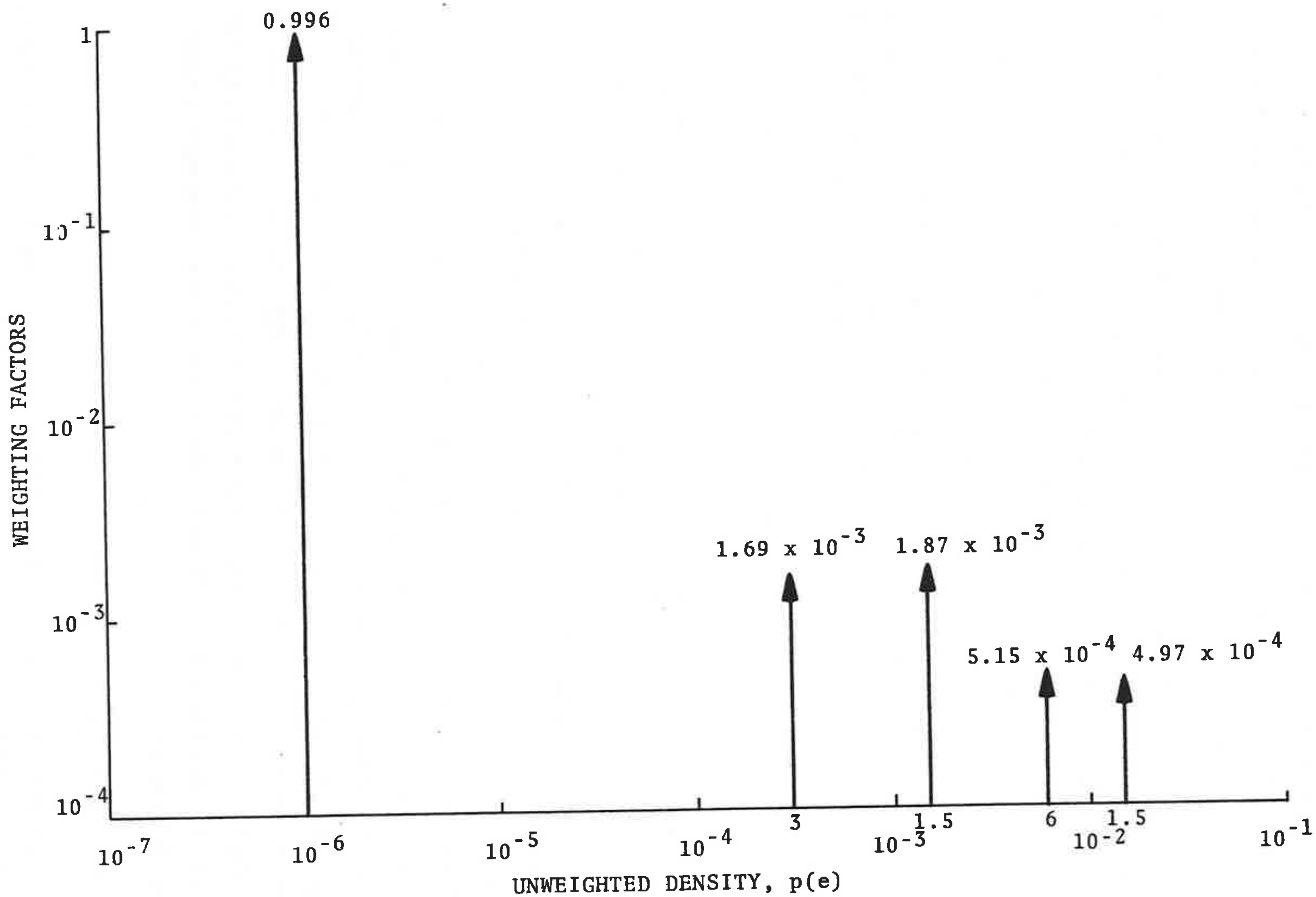


FIGURE C-2. UNWEIGHTED DENSITY, p(e)

the coverage region. Clearly, the flight profile flown during a given test effort has a strong influence on the observed performance of the system under test.

Next the model of Figure C-2 will be used to determine the changes in performance to be expected if the prescreening acquisition word length is reduced from 8 words to 2 words. In that case, the appropriate weighting values are shown in Table C-3.

TABLE C-3. WEIGHTINGS FOR A 2-WORD PRESCREEN

P_e	Probability (16 Bits Correct)	Weighting Factor
1×10^{-6}	0.999984	.996
3×10^{-4}	0.9952	1.69×10^{-3}
1.5×10^{-3}	0.9763	1.82×10^{-3}
6×10^{-3}	0.9082	4.67×10^{-4}
1.5×10^{-2}	0.785	3.9×10^{-4}

The weighting factors for a 2-word heading are not much different from the no prescreen case considered previously. Therefore similar results should be expected. Specifically the average bit error rate is roughly 1.29×10^{-5}. Thus, the increase in average error probability from the 8-word heading case is by a factor of 1.43. The average message error rate is increased from 4.3×10^{-3} to 4.75×10^{-3} or a factor of 1.1. Thus, decreasing the acquisition word length from 8 to 2 will increase average probability of error by 43 percent but it will only increase message error rate by 10 percent.

C.5 CONCLUSIONS

This appendix has presented a discussion of probability of error modelling for typical data link system parameters. The analysis shows that the probability of error must vary as a function of operating conditions in order to obtain the types of error statistics obtained during the course of the the various experimental efforts. A discrete distribution of probabilities of error was derived and presented as a rough model for the probability of error distribution which actually existed during the experiments with the Experimental Data Link System. This model was used to explore the potential effects of system parameter changes and to normalize the results obtained with the Experimental Data Link System so that they could be compared to the results obtained by PRN transmissions during the Digital Data Transmission Flight Test portion of the test program.

APPENDIX D
MSK MODEM ACQUISITION PERFORMANCE TESTS

Tests were conducted to determine the acquisition performance of the MSK modem. Of particular interest were the sensitivity of acquisition performance to prekey length and the response times of the modem's acquisition loop.

D.1 TEST SETUP

The test equipment configuration is shown in Figure D-1. The modems and RF component configurations used for the acquisition experiment were essentially the same as those used for the RF back-to-back tests discussed in Section 2. In this case, however, the modulator was controlled by the Experimental Data Link System ground system computer described in Section 5. Similarly, the demodulator output was provided to the Experimental Data Link System airborne system computer.

An RF switch was added to the VHF Signal Generator output to simulate transmitter "turn-on" which precedes each message transmission.

D.2 TEST SYSTEM OPERATION

The Message Generator computer allowed for the setting of the following parameters:

1. Bit Rate (with corresponding adjustment on modems)
2. Prekey Length
3. Delay between Trial Messages
4. Message Length

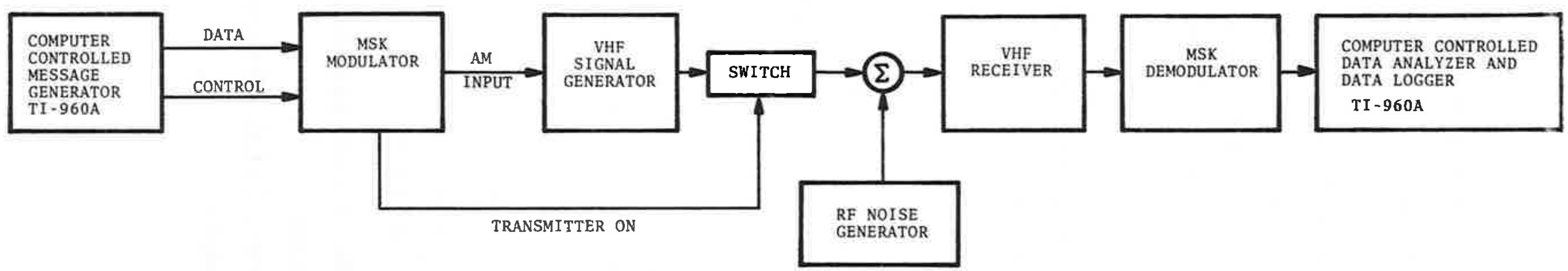


FIGURE D-1. MODEM ACQUISITION TEST SETUP

The transmit modem provided a command signal to the RF switch 10 msec in advance of message transmission. The receiver signal-to-noise ratio was controlled by the setting of the VHF Signal Generator output and the RF noise level.

The Data Analyzer computer (airborne system computer) provided an analysis of the number of no responses per test interval, the number of BCS errors, and the number of acquisition failures.

D.3 TEST RESULTS

Twenty-seven test runs were carried out to determine modem acquisition characteristics. A wide variety of system and operational parameters were employed in the test runs. These are summarized in Table D-1.

TABLE D-1. TEST PARAMETERS

Parameter	Values
Bit Rate	2400 bps and 4800 bps
RF Energy-to-Noise Density	12 dB, 14 dB, 16 dB, 18 dB and ∞
Number of Prekey Bits	0, 5, 10, 20, 30 and 40 bits
Delay Between Runs	0.6 sec, 10 sec, and 30 sec

The results indicate no sensitivity to bit rate, prekey length, or delay between runs. Some sensitivity to E/N_0 was detected. The average probability of acquisition for all runs was 99.5 percent. When E/N_0 is reduced to 12 dB, the average acquisition probability is roughly 96.2 percent.

The apparent lack of sensitivity of acquisition probability to prekey length is explained by the fact that the prekey length could not actually be reduced to 0 under computer control as shown in Table D-1. It appears that the modem always generated a prekey signal during the transmitter turn-on delay. This corresponds to 24 bits and 48 bits of prekey at 2400 bps and 4800 bps, respectively. Note, however, that this hypothesis could not be confirmed during the course of the experimental effort due to the limitations of available equipment.

Modem unlock tests were conducted informally during the experiment effort. For these, it was deduced that the tracking bandwidth (B_t) of the synchronization loop in the modem was on the order of B_t = 200 Hz to 500 Hz.

An informal observation of the loop performance indicated that the loop is probably first order. In that case, the tracking error will be within 5 percent of its final value (18^o tracking error) after $1.5/B_t$ seconds. This corresponds to 7.2 bits at 2400 bits/sec when B_t = 500 or 18 bits when B_t = 200 Hz. Table D-2 summarizes the projected acquisition times, in bits, based on the experimentally determined acquisition loop characteristics.

TABLE D-2. ESTIMATED PREKEY REQUIREMENTS

Estimated Loop Bandwidth	Bit Rate	Prekey Length
200 Hz	2400 bps	18 bits
200 Hz	4800 bps	36 bits
500 Hz	2400 bps	7.2 bits
500 Hz	4800 bps	14.2 bits

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F