General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

Produced by the NASA Center for Aerospace Information (CASI)

CR-128515

COMMUNICATIONS TERMINAL BREADBOARD

FINAL REPORT

BREADBOARD Final Report (Hughes Aircraft
Co.) Jul. 1972 37 p   N72-30150
                              CSCL 17B
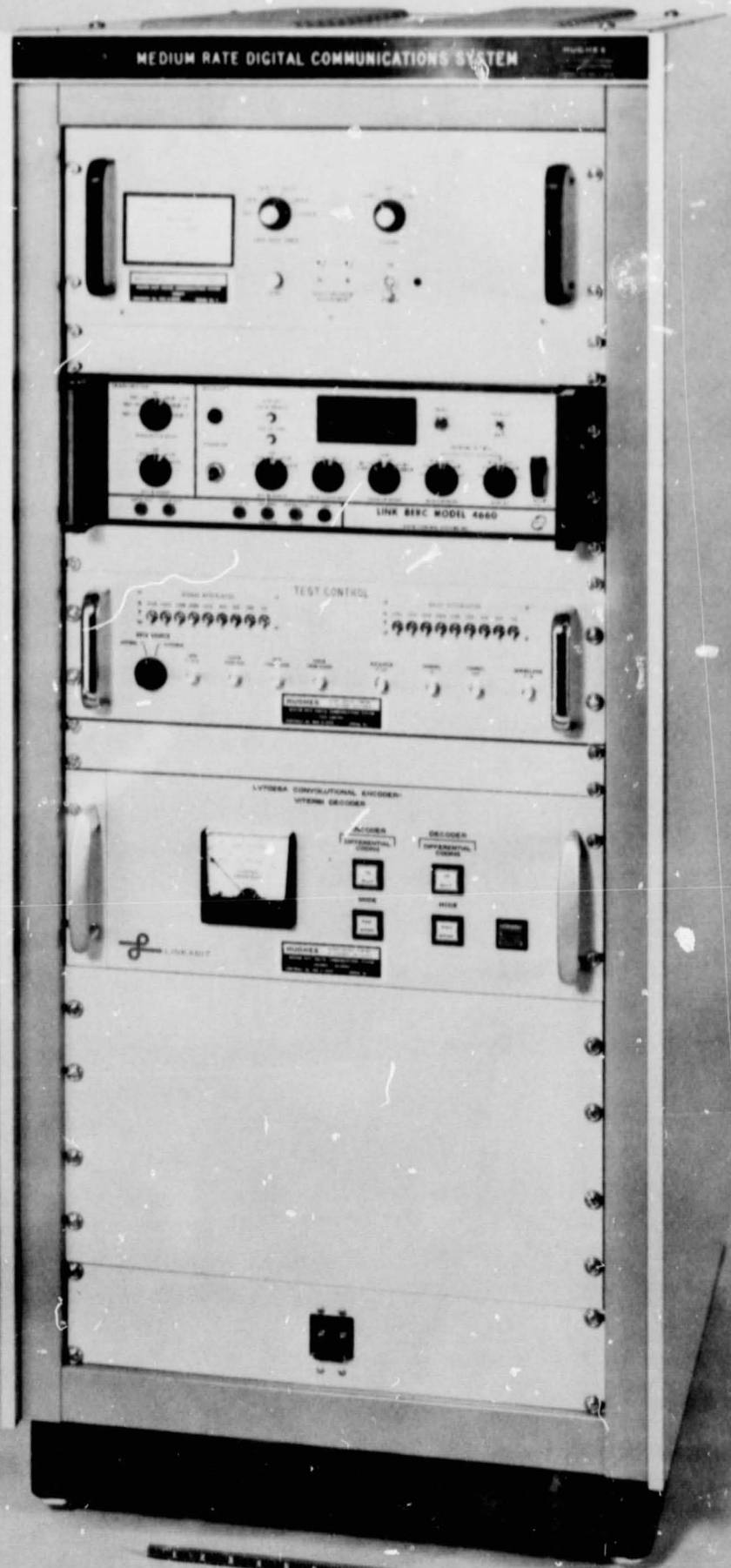
                                    Unclas
                              G3/07 39631

HUGHES

HUGHES AIRCRAFT COMPANY
SPACE AND COMMUNICATIONS GROUP
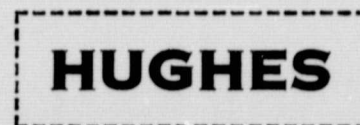
SCG 20481R

MEDIUM RATE DIGITAL COMMUNICATIONS SYSTEM

LINK BERC MODEL 4660

TEST CONTROL

LV7000A CONVOLUTIONAL ENCODER-
VITERBI DECODER

COMMUNICATIONS TERMINAL BREADBOARD

FINAL REPORT

NASA Contract No. NAS 9-12019

CONTENTS

1. INTRODUCTION AND SUMMARY

Hughes has developed a baseline design of a digital communications link between an advanced manned spacecraft (AMS) and an earth terminal via an Intelsat IV type communications satellite used as a geosynchronous orbiting relay station. Hughes has also fabricated, integrated, and tested those elements of the terminals at each end of the link which as a group are designated as a medium rate digital communications system (MRDCS).

In the baseline link design, the information-carrying capacity of the link was estimated for both the forward direction (earth terminal to AMS) and the return direction, based upon orbital geometry, relay satellite characteristics, terminal characteristics, and the improvement that can be achieved by the use of convolutional coding/Viterbi decoding techniques. A summary description of the baseline communications design is given in Section 2.

The MRDCS consists of a two-phase phase shift keyed modem, a convolutional encoder/Viterbi decoder, a test set capable of generating a pseudo-noise (PN) code and comparing a received data stream with the original PN code for measuring error rates, and various other components needed to integrate the above. The transmit portion of the MRDCS is capable of accepting an NRZ data stream at any one of six predetermined data rates, differentially encoding the data, and biphase modulating a 70 MHz IF carrier with the data. The differentially encoded data may be placed directly onto the carrier or convolutionally encoded within the MRDCS before modulating the carrier. The receive portion of the MRDCS performs the converse operations, accepting a modulated 70 MHz carrier, demodulating the signal, and decoding the data. It outputs an NRZ data stream and a synchronous clock signal to the user data sink. The NRZ input can be selected from an external data source or from the test set. When the PN input from the test set is used, the received data stream is tested for errors by the test set.

The modem and the encoder/decoder were procured in accordance with Hughes performance specifications from Magnavox Research Laboratories, Inc., and Linkabit Corporation, respectively. A Data Control Systems, Inc., link bit error rate calculator (BERC), Model 4660, was selected as the test set. The three major components of the MRDCS (modem, encoder/decoder, and test set) can be used independently in a variety of

1

experiments other than the baseline communications link for which the MRDCS was designed.

Section 3 provides a brief description of the MRDCS, an evaluation of its performance, and a discussion of equipment anomalies experienced during the integration and testing of the MRDCS. Section 4 presents brief synopses of the effort spent on each of the tasks defined in the contract statement of work.

2. BASELINE COMMUNICATIONS LINK DESIGN

The communications link between advanced manned spacecraft (AMS) and an earth terminal via an Intelsat IV type communications satellite (or relay satellite), conceptually illustrated in Figure 1, is representative of a typical data relay satellite application. The terminals at either end of the link are functionally equivalent in that each must accept input data from a local source, process such data before modulating it onto a carrier and transmitting it to the relay, and then must perform the converse operations on the signal received from the repeater, as shown schematically in Figure 2. However, the implementation constraints for the two terminals are radically different because of the difference in environment and available support with which each must operate.

In this application, the link design is constrained to the use of a repeater with predetermined characteristics and, to a large extent, to existing designs of earth terminals, at least with respect to their RF transmit and receive capabilities. Therefore, the design freedom of the RF portion of the link lies in the determination of the RF characteristics of the AMS terminal and the signal levels at which the relay will operate. As discussed in greater detail later, the AMS terminal will be typically limited in power and antenna gain relative to that of the earth terminal, and the "return" link (AMS-to-ground) signal will be weak in comparison to that of the forward link. This requires that the level of the forward link signal be controlled so as not to suppress the return signal. Assumed AMS terminal characteristics and repeater signal level considerations were used in determining the channel capacity (in terms of bit rate) of both the forward and reverse links over the range of geometric relationships possible between the AMS and the relay satellite. The results were used in selecting the data rates at which, the communications terminal breadboard (CTB) would be designed to operate.

It was also established that the link design would consider only digital data sources with biphase modulation of the carrier. Consideration was given to maximizing the performance by the use of convolutional encoding and Viterbi decoding. Although the MRDCS coding parameter selection was largely limited by available hardware designs, a review of the improvement to be obtained over a range of the parameters was traded off against the corresponding cost and implementation complexity. It was concluded that the selected parameters represented close to an optimum set in the sense of
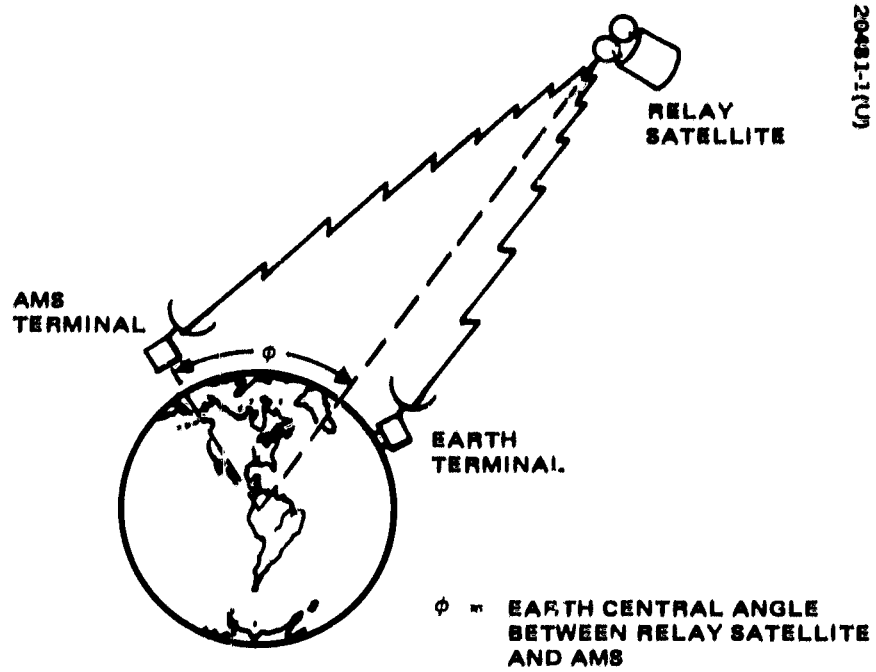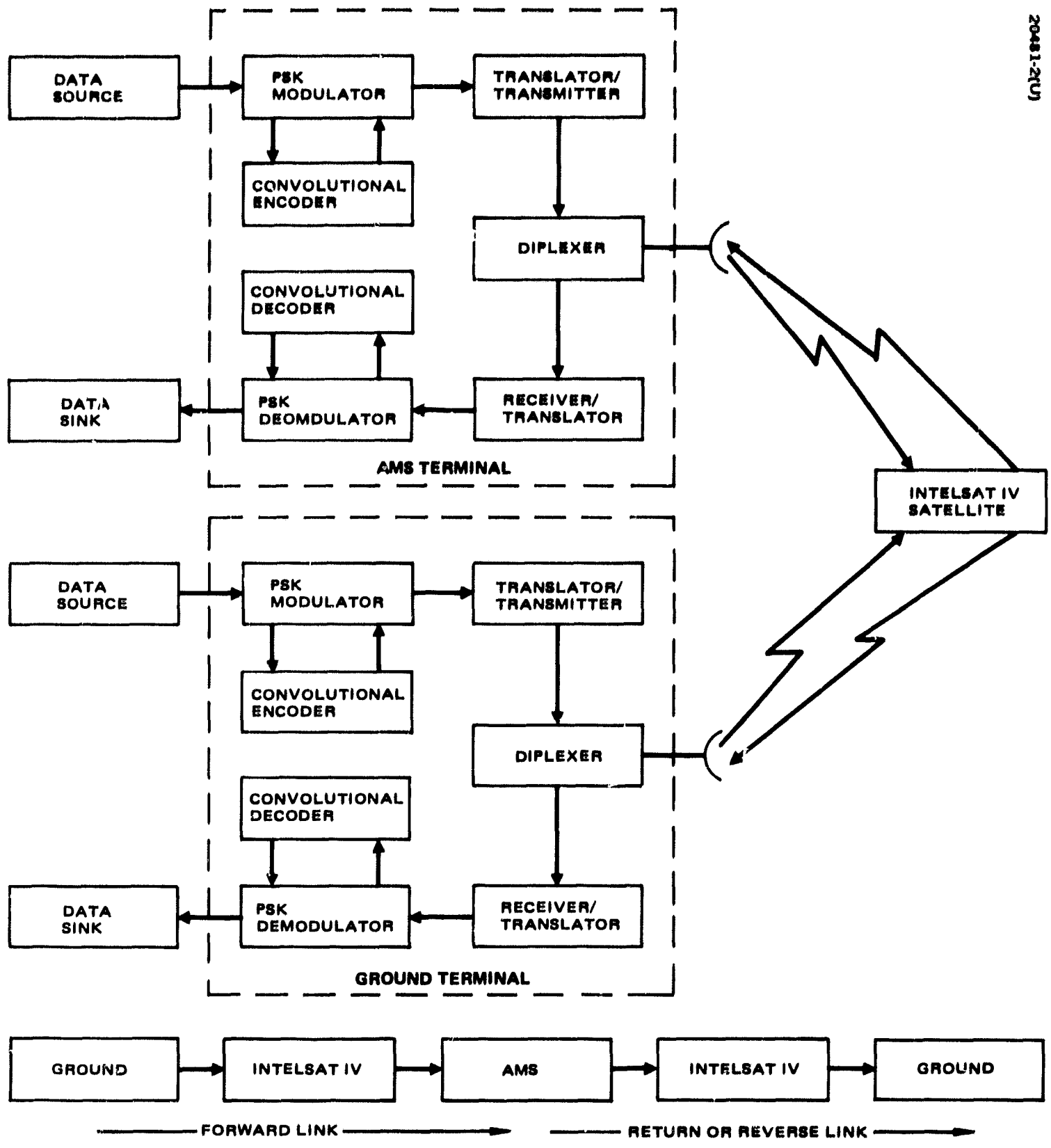
3

Figure 1.   AMS to Ground Communications
Link

Figure 2. AMS Two-Way Communications Link

performance improvement relative to cost and implementation complexity. A summary of the channel capacity determination and the coding parameter selection is given in the following paragraphs. More detailed reports are included in Reference 1 and in Monthly Progress Reports 1 and 2 and their appendices.

2.1 CHANNEL CAPACITY

A key consideration in determin'ng the capacity of the return link is the signal levels at which the forward and return signals pass through the relay satellite repeater, since the smaller of two signals in a nonlinear repeater may be substantially suppressed when the repeater is operated at or near saturation. The data shown in Figure 3 were obtained from measurements made on an actual Intelsat IV repeater channel.

For this study, it was assumed that the AMS transmitter would have a maximum potential EIRP of 57 dBw (corresponding to a 100 watt transmitter, a 6 foot diameter antenna, and a line loss of 1 dB between transmitter and antenna). The corresponding incident power level received by the relay is approximately 20 to 25 dB below the level required to saturate the relay repeater and is thus a small signal in comparison to the forward signal, which could easily provide sufficient power to saturate the repeater. The selected forward link signal level indicated in Figure 3 (repeater output power 5 dB below saturation) results in only a 2 dB suppression of the return link signal. Larger forward link signals would rapidly degrade the return link,whereas little improvement in the return link can be obtained by further reducing the forward link signal.

Using the selected repeater forward link operating level and the relay repeater gain and antenn· characteristics, the forward and return link budgets of Tables 1 and 2, respectively, were developed for a geometry in which the AMS is along the nadir of the relay satellite (angle ϕ of Figure 1 equal to zero).

For the forward link (Table 1), the high level signal from the ground eliminates virtually all noise in the link to the relay and the only link noise of significance is that seen at the AMS receiver, with an assumed system noise temperature of 2000°K. A potential improvement of 3 dB (1000°K) is considered in the right-hand column of Table 1, labeled "Variation". The other large variant indicated in the table is the relay EIRP. Should there be a requirement for increased capacity in the forward link for limited periods, a 5 dB improvement can be achieved by driving the repeater to saturation at the expense of serious degradation in the return link.

The nominal power-to-noise ratio for the forward link is about 54 dB. This corresponds to a data rate of 25.7 x 10^3 bps at an error rate of less
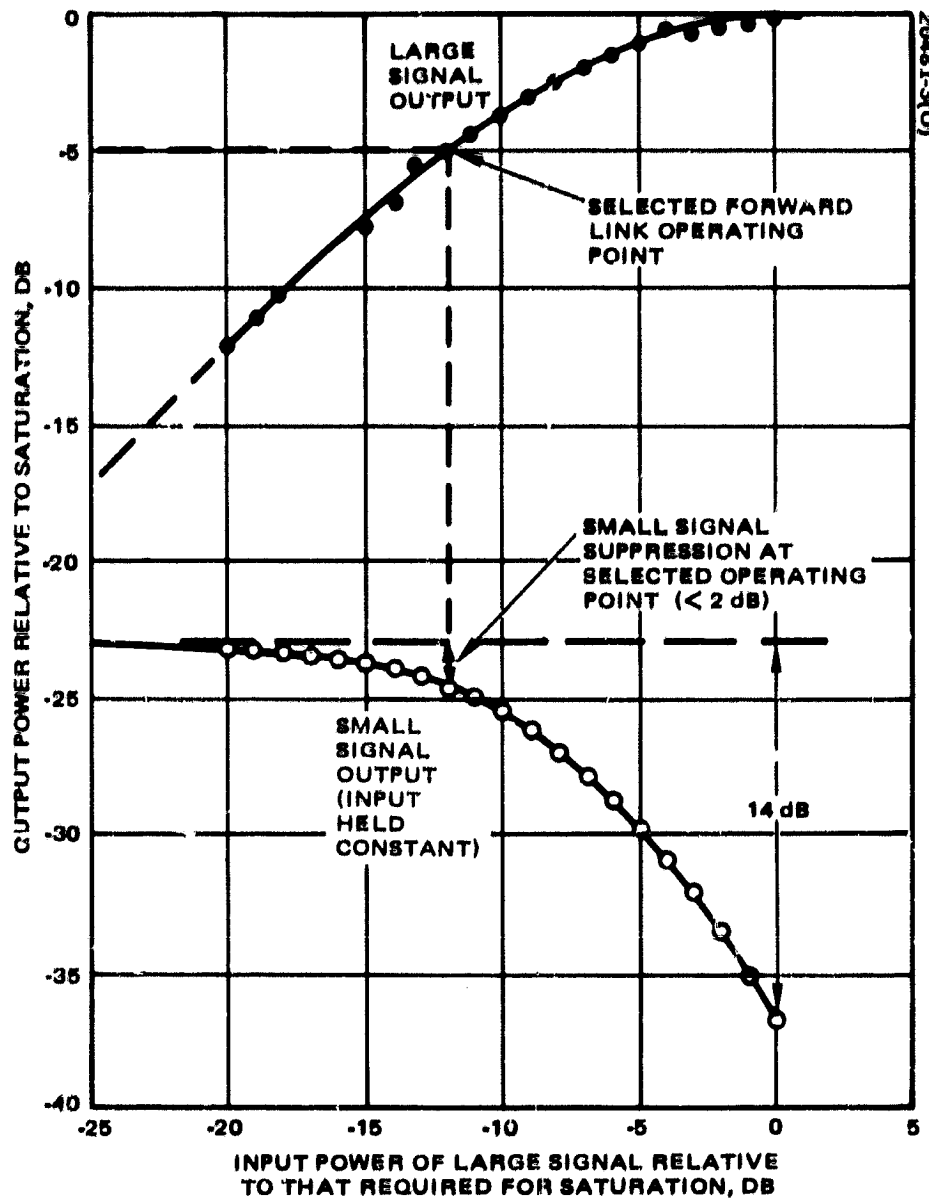
6

Figure 3. Small Signal Suppression in Intelsat IV Repeater Channel

TABLE 1. FORWARD LINK BUDGET FOR $\phi = 0$

Parameter	Value, dB	Variation, dB
Intelsat IV EIRP (5 dB backoff)	+20.0 dBw	+5.0 to -3.0
Path loss (f ≈ 3900 MHz)	-195.3	±0.5
AMS antenna gain (6 foot dish)	+35.0	+0.5 to -1.5
Polarization loss	-0.2	----
AMS line loss	-1.0	-0.5
Received carrier power, P	-141.5 dBw	+6.0 to -5.0
AMS noise temperature (2000°K)	+33.0	+1.0 to -3.0
Boltzmann's constant	-228.6	
Noise density, η	-195.6 dBw/Hz	+1.0 to -3.0
P/η	54.1 dB-Hz	+9.0 to -6.0

than 10^{-5}, based upon theoretical performance with $\triangle$PSK modulation ($E_b/N_0 \approx 10$ dB)*. As the separation angle, ϕ, between the AMS and the relay satellite increases, the link capacity decreases because of the increased range between the two vehicles and off-axis loss of antenna gain in the relay satellite. The variation with separation angle is shown in Figure 4 as the curve labeled "Nominal — No Coding".

For the return link, relay repeater noise, signal suppression and power transfer characteristics, and atmosphere effects between the relay and the earth terminal must be considered in addition to those affecting the forward link capacity. These are all shown in the link budget of Table 2, with a resultant power-to-noise ratio of 66 dB, equivalent to a data rate of 4×10^5 bps at an error rate of less than 10^{-5} for theoretical $\triangle$PSK modulation ($E_b/N_0 = 10$ dB). The return link performance has the same sensitivity to separation angle as does the forward link, as indicated by the curve labeled "Nominal — No Coding" in Figure 5.

The use of convolutional encoding will permit operation at a lower received bit energy-to-noise density ratio (E_b/N_0). For the coding parameters used in the MRDCS (constraint length K = 7, coding rate R = 1/2, and soft-decision quantization Q = 8), data obtained from a simulation performed by NASA (Reference 2) indicate an improvement of 5.5 dB in link capacity over that theoretically achievable with coherent PSK. However, manufacturers of coding equipment and modems report that actual performance is

---

*E_b refers to signal energy per kit, E_s refers to signal energy per symbol and is equal to $E_b R$ when the data are encoded at a code rate R, and N_0 is the one-sided spectral density of the noise (assumed to have a gaussian distribution).

TABLE 2. RETURN LINK BUDGET FOR φ = 0

| Parameter	Nominal Value, dB	Variation, dB
AMS transmitter output power	+20.0 dBw	
AMS line loss	-1.0	-0.5
AMS antenna gain	+38.0	±1.0
AMS EIRP	57.0 dBw	+1.0 to -1.5
$4\pi R^2$, dB m^2	-162.0	±1.22
Polarization loss	-0.2	
AMS antenna point loss	-1.0	
Received flux density, dBw/m^2	-106.2	+2.22 to -1.72
Intelsat IV noise temperature (2600°K)	+34.2	
Boltzmann's constant	-228.6	
Intelsat IV noise density	-194.4 dBw/Hz	
Single carrier repeater output EIRP	+2.0 dBw	
Signal suppression due to forward link signal	-2.0	±1.0
Path loss to ground station	-196.7	
Pointing and polarization loss	-0.3	-0.2
Atmospheric loss	-2.0	-3.0
Ground antenna gain	+57.0	-1.0
Received carrier power at ground station, P_G	-142.0 dBw	+3.2 to -6.9
Transmitter noise density output with 1 dB suppression	-90.2 dBw/Hz	
Intelsat IV antenna gain	+20.7	
Transmitted noise density EIRP	-69.5 dBw/Hz	
Path, polarization, and pointing losses (see above)	-197.0	-0.2
Atmospheric loss	-1.0	-3.0
Ground antenna gain	+57.0	-1.0
Received noise density, η_1	-210.5 dBw/Hz	-4.2
Ground station receiver noise density, η_2 (T = 50°K)	-211.6 dBw/Hz	
Total noise density, $\eta = \eta_1 + \eta_2$	-208.0 dBw/Hz	-2.1
P_G/η	66.0 dB-Hz	+3.2 to -4.8

9
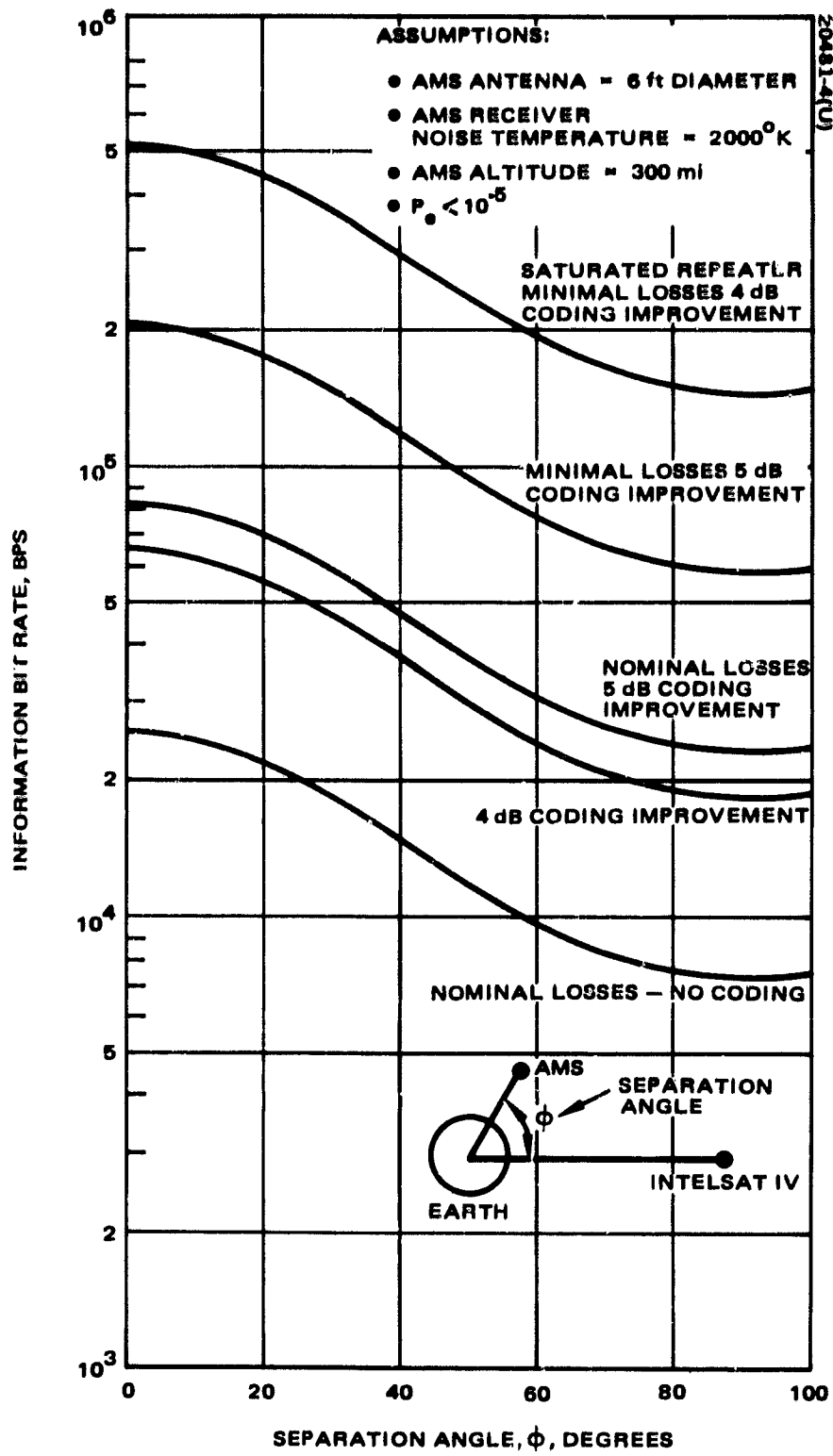
Figure 4. Forward Link Capacity (Ground to AMS Via Intelsat IV)
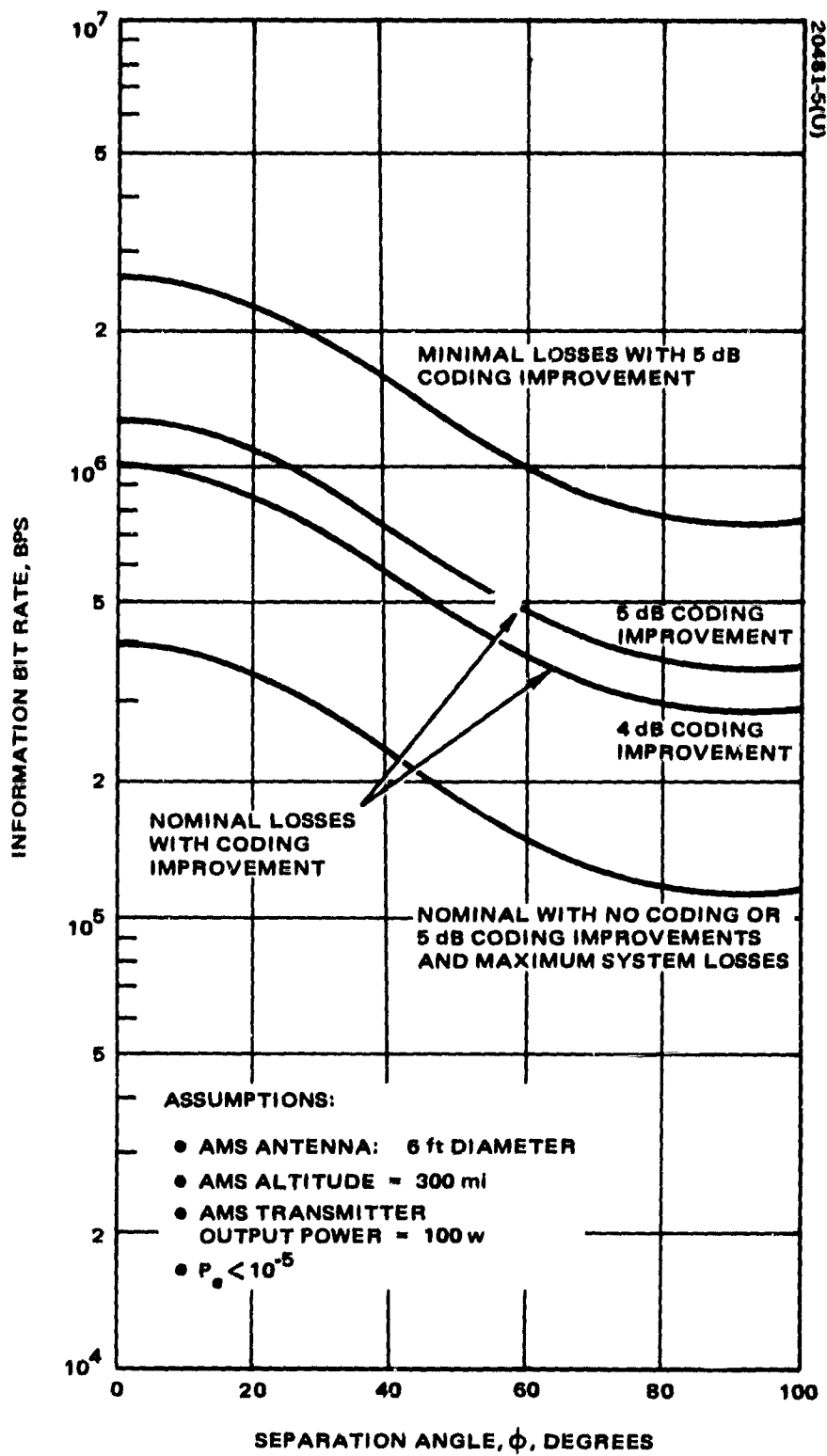
10

Figure 5. Return Link Capacity (AMS to Ground Via Intelsat IV)

11

approximately 1 dB less than the theoretical. Thus, it is expected that with the above coding parameters, the improvement will be between 4 and 5 dB.

Link Capacity and MRDCS Data Rate Selection

The improvement expected with coding is shown in Figures 4 and 5 for the forward and return links, respectively. For the return link, the maximum bit rate that can be obtained over a major portion of every AMS orbit is on the order of 1.0 to 1.5×10^6 bps. For nominal link performance with 5 dB coding improvement, 3×10^5 bps can be achieved whenever the AMS and the relay satellite are mutually visible.

The forward link capacity for minimal losses but with the normally backed-off repeater output is limited to approximately 80 to 100 kbps. With nominal link losses, the capacity is 20 kbps during mutual visibility.

Discussion with NASA/MSC personnel resulted in a choice of 19.2 kbps for the minimum bit rate. This is currently used for delta modulation of a single voice channel. The other five selectable bit rates are obtained by multiplying 19.2 kbps by a factor of 2^n, all of which are in accordance with IRIG standards. The other five rates selected are 38.4, 76.8, 307.2, 614.4, and 1228.8 kbps; this range covers the link capacities of both the forward and return links.

2.2 SELECTION OF CODING PARAMETERS

As indicated in the preceding link analysis, the use of an error correcting coding scheme is essential in increasing link capacity. Earlier techniques primarily used block codes, but convolutional codes can result in lower bit error rate for a given energy per bit-to-noise density ratio (E_b/N_o), and may permit simpler decoder implementation. However, even for convolutional codes, practical considerations in implementing a decoder limit the achievable performance.

Two convolutional decoding approaches available are sequential decoding and Viterbi decoding. Sequential decoding has the advantage that large coding improvement gains can be achieved with implementable decoding algorithms by using codes with long constraint lengths. These algorithms are probabilistic in nature, with the resultant requirement for a large input buffer to prevent loss of data. For any finite buffer capacity, there will be a non-zero probability of buffer overflow resulting in a loss of data. Whenever such an overflow occurs, the decoder must be reinitialized, with a corresponding loss of data for the period required to restore the buffer.

12

Viterbi decoding has been selected for the CTB link simulation for the following reasons:

1) Real time decoding is possible, eliminating the need for an input buffer.

2) The Viterbi algorithm is self-synchronizing and does not require periodic reinitialization.

The three parameters which must be specified for the Viterbi decoding algorithm are the code rate, R, the constraint length, K, and the number of quantization levels, Q. The values selected for the MRDCS decoder are R = 1/2, K = 7, and Q = 8. Although this selection was largely predicated upon the availability of hardware with these parameters, the sensitivity of performance to these parameter values, as discussed below, suggests that the improvements in performance attainable at higher values of these parameters is small in comparison to the increased equipment complexity (and cost) required to implement them.

Code Rate (1/V)

The error correcting capability of a coding scheme obviously increases as the number of symbol bits per information bit (V) increases. (Code rate is defined as the reciprocal of this number, or R = 1/V.) However, the bandwidth required to support a given information rate is directly proportional to V, and the number of computations required for decoding also increases with V. The advantage of lower code rates is that the required E_b/N_0 is decreased, permitting the transmission of higher data rates for a given power or lower power for a given data rate. Another complexity which results from lowering the code rate is that the energy per symbol, E_s, seen by the demodulator, carrier, and bit synchronizer loops is directly proportional to the product of energy per bit and code rate, or $(E_s/N_0) = (E_b/N_0)/V$. This means that the signal acquisition and tracking threshold required of the modem decreases somewhat more rapidly than does the code rate 1/V.

Simulation studies (reported in Reference 3) have shown that a decrease in the code rate from one-half to one-third results in a reduction of the required E_b/N_0 on the order of 0.3 to 0.5 dB, or an increase in data rate for a fixed error rate and transmitting power of about 7 to 12 percent. However, the corresponding increase in decoding complexity relative to a code rate of one-half is about 17 percent[*], as obtained from the formula $(46 + 2^V \log_2 V)/50$, also given in Reference 3. For larger values of V, the improvement in performance relative to the increased decoding complexity diminishes rapidly.

---

[*]Relative complexity, derived from Reference 3, applies only to the decoder. In many cases, there is a corresponding increase in complexity in the demodulator.

Code Constraint Length, K

The required E_b/N_o for a fixed bit error rate can be decreased by increasing the constraint length, K; the improvement is about 0.4 dB per unit increase in K. This corresponds to an increase in data rate for a given power and error rate of about 10 percent per unit of constraint length. However, the relative decoder complexity given by $2^{(K-1)}K$ in Reference 3 increases much more rapidly with K than does the link capacity. At present, the greatest constraint length which can be practically implemented in a Viterbi decoder is about ten. For a code rate of one-half, K = 7 is a particularly good choice because the optimum code for this constraint length results in a minimum free distance* of ten. To achieve a minimum free distance greater than ten, the constraint length would have to be increased to at least nine, with a corresponding increase in decoder complexity by greater than a factor of 4. Although it is difficult to show quantitatively, engineering judgment suggests that the improvement in performance relative to increased complexity rapidly diminishes with further increases in constraint length.

Another advantage of selecting K = 7 is that the optimum code for this constraint length al o happens to be a transparent code; i.e., if the input to the decoder is inverted, the decoder output will be inverted. This is a desirable feature because there is ambiguity with respect to sign in the data output from the demodulator to the decoder. Although the same ambiguity carries through the decoder, its output, in the form of a differentially encoded data stream, is insensitive to the sign ambiguity.

Quantization Level, Q

For coded data streams in an additive white gaussian noise channel (AWGN), a "hard-decision" (Q = 2) decoder has been shown in simulations to be about 2 dB poorer (in E_b/N_o) than the theoretically optimum performance achievable. At Q = 8, the performance is improved by about 1.75 dB or to within 0.25 dB of optimum. This improvement corresponds to about a 50 percent increase in data rate for a fixed power and error rate, as compared to a maximum increase of about 58 percent which would result from achieving the full 2 dB improvement theoretically possible. Gain of any portion of the theoretically remaining 8 percent can be achieved only at significant increases in complexity.

---

*Minimum free distance is used as a measure of the error-correcting capability of a code. It is defined in Reference 3.

14

3. MRDCS INTEGRATION AND TEST

The MRDCS generally performed as expected. The measured error rates met the specification except for one case involving the highest data rate (1228.8 kbps) and soft-decision decoding, as discussed in subsection 3.4. The system has the specified capability to acquire a signal in the presence of noise.

In those cases where performance anomalies were encountered, possible causes were considered and ways to avoid them in future coded systems are suggested. The anomalies are not severe enough to detract significantly from the usefulness or performance of the system.

During integration and testing of the MRDCS, problems were encountered in interfacing the modem and encoder/decoder; this is understandable since soft-decision modems and decoders are relatively new in digital communications systems. Considerable effort was expended in trying to understand and correct the interface problems, as reported in subsection 3.2.

3.1 SYSTEM DESCRIPTION

The MRDCS consists primarily of three components: a two-phase PSK modem, a convolutional encoder/Viterbi decoder, and a bit error rate calculator (BERC). The functional connections between these components and an external data source and sink are shown in Figure 6. The shaded blocks represent components of the MRDCS. The system can operate at any one of six data rates: 19.2, 38.4, 76.8, 307.2, 614.4, or 1228.8 kbps. It can also operate in three convolutionally coded modes and in an uncoded mode. The three convolutionally coded modes involve identical encoding but differ in the number of quantization levels presented to the decoder: a hard-decision mode in which the decoder makes decisions based on data having 2 levels of quantization ($Q = 2$), and two soft-decision modes in which the data supplied to the decoder has 4 and 8 levels of quantization, i.e., $Q = 4$ and $Q = 8$, respectively.

The BERC (or CTB test set) generates a PN sequence of length 2047 bits, which serves as an NRZ data source. In addition, it compares the decoded NRZ data with a regenerated replica of the original PN sequence and
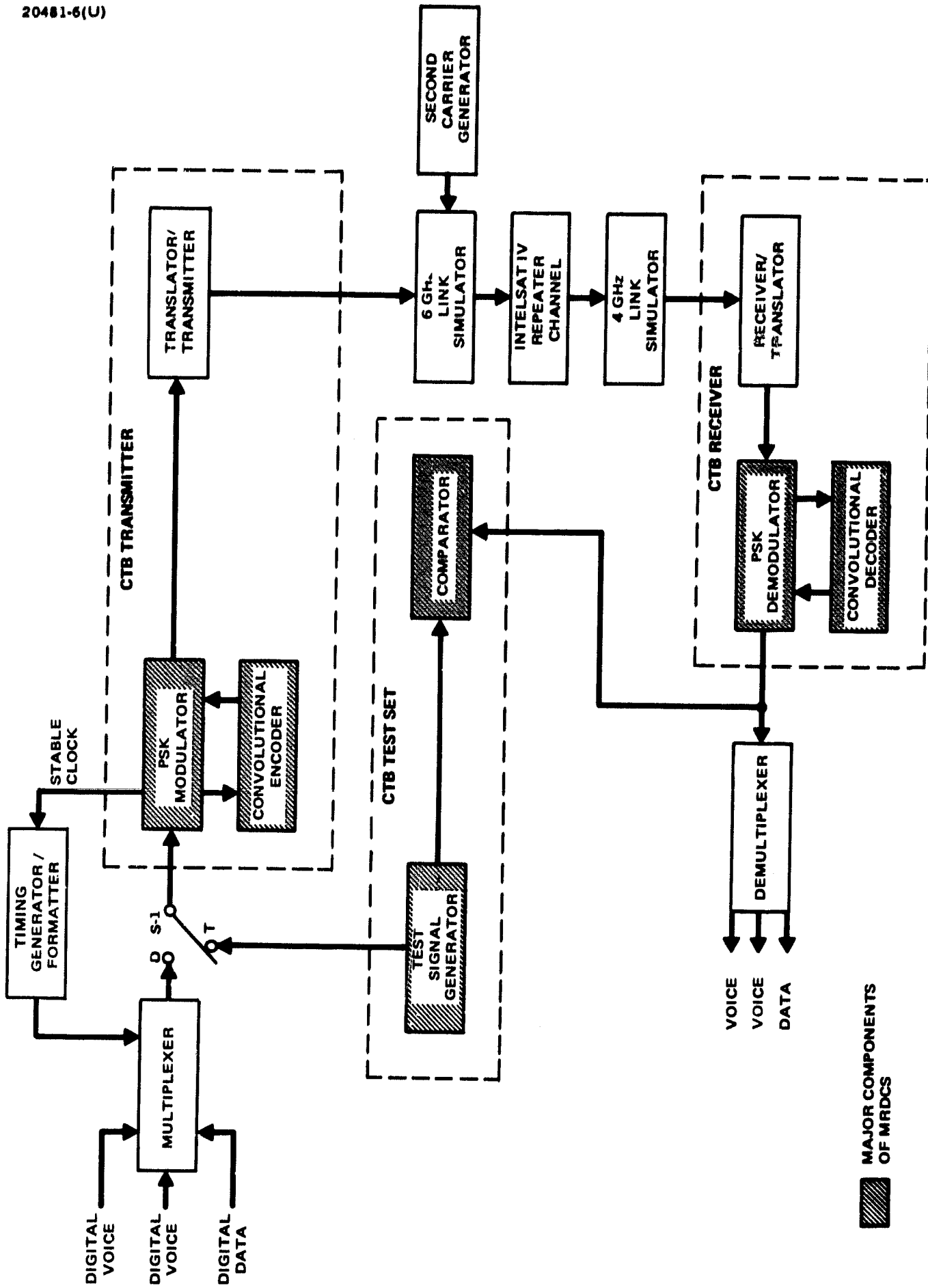
15

Figure 6.   MRDCS and Intelsat IV Repeater/Link Simulator Functional Block Diagram

16

counts the errors contained in the recovered data. Bit error rate, obtained by dividing the number of errors by the total number of bits in the measurement time interval, is displayed by a three-place decimal readout on the BERC front panel.

The modem is two-phase PSK with the modulator output at a center frequency of 70 MHz and a nominal power level of +10 dBm into 50 ohms. The demodulator requires an input power level between -75 and -25 dBm into 50 ohms. The modem receiver uses a Costas loop to provide a phase reference for coherent demodulation and an integrate-and-dump circuit for detection. To operate at the low signal-to-noise ratios expected with convolutional encoding, the Costas loop must be narrowband, which restricts the frequency offset that can be acquired. As a result, the modem must go through a rather slow frequency search program in acquiring the signal, with the Costas loop VCO searching through a large number of relatively small frequency steps. This slow acquisition process is characteristic of modems for this type of an application.

Bit timing for the MRDCS is normally established by a stable clock generated by the modem modulator at the selected data rate. This clock is provided to the NRZ data source, as shown in Figures 6 and 7. In the event that the NRZ data source has its own clock, the modem can derive bit timing from the NRZ data if the data rate is within ±0.4 percent of the selected nominal data rate. Signal flow through the MRDCS is indicated in Figure 8. A detailed description of the operation of the system is contained in References 4 and 5.

3.2 SYSTEM INTEGRATION

There were two phases of the system integration task for the MRDCS. First, the modem and encoder/decoder underwent individual tests. Subsequently, the system components were interconnected as shown in Figure 7, and interface problems were discovered and corrected.

Modem Checkout

The modem was tested by the modem subcontractor prior to delivery to Hughes. These performance tests were for the uncoded mode and verified that the error rate and signal acquisition capability of the modem were satisfactory. After delivery to Hughes, the performance tests were repeated with consistent results.

Two modem component failures occurred during integration and test. Shortly after delivery of the unit to Hughes, an operational amplifier on the sync demodulator board failed. A few weeks later, a tunnel diode on the clock acquisition board failed (probably inadvertently damaged during tests). Also, during the acceptance test of the MRDCS, the entire sync demodulator
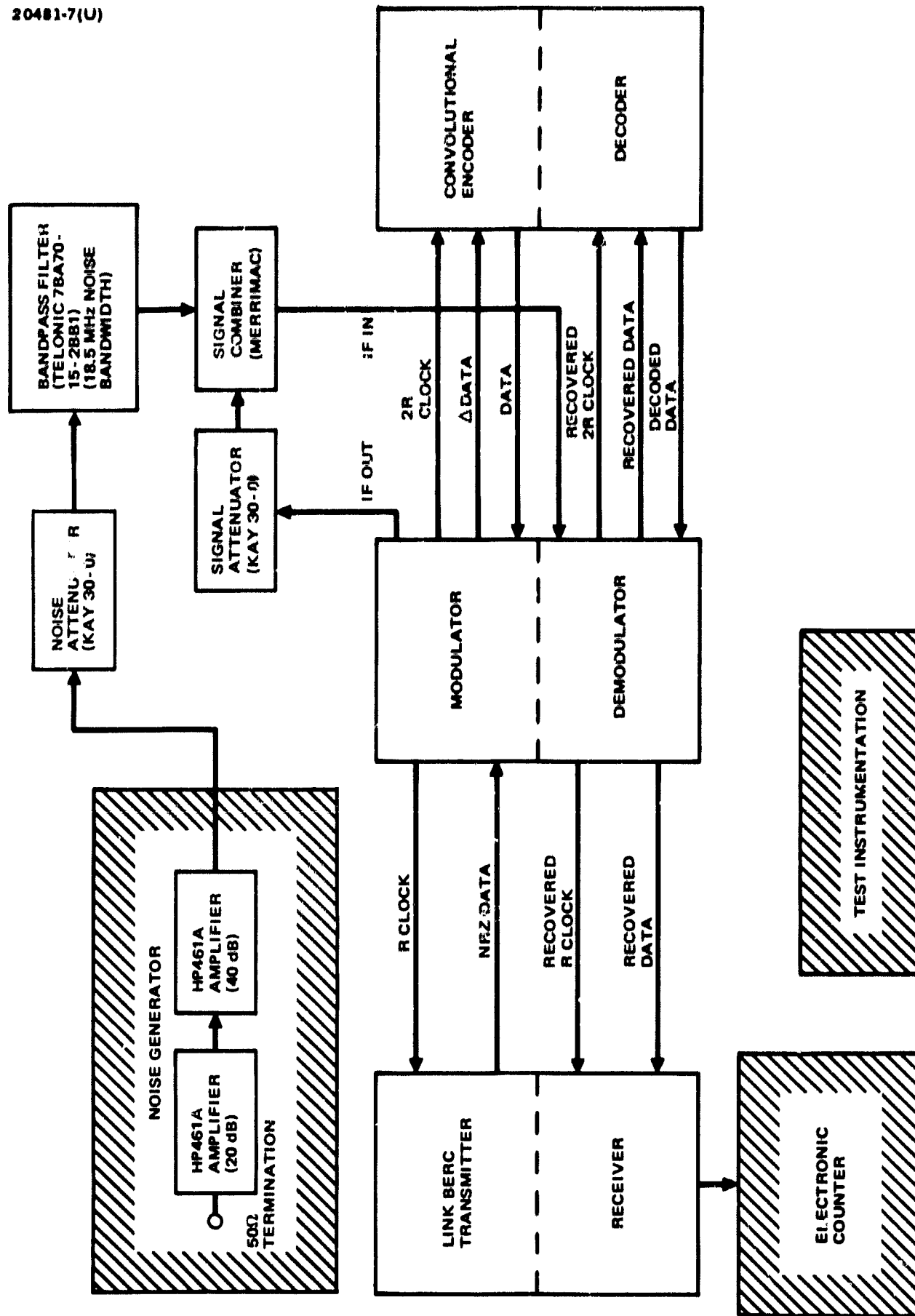
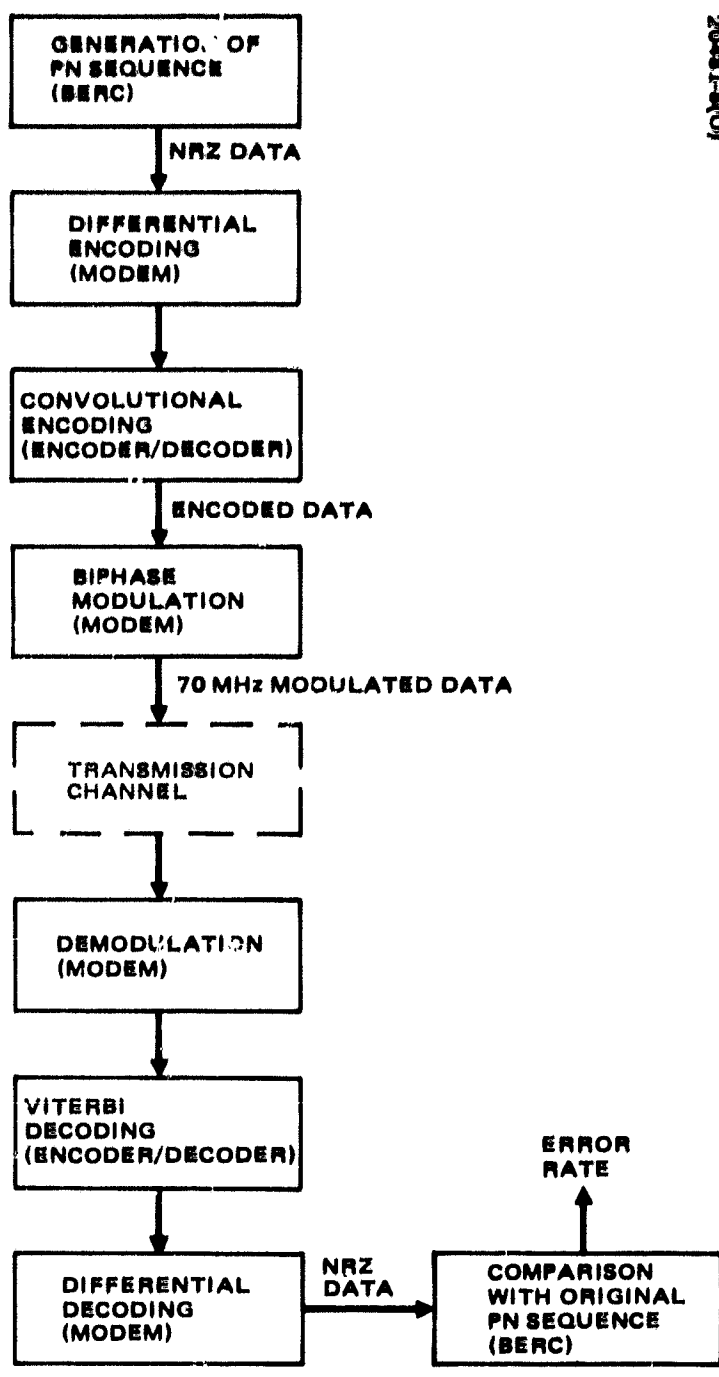Figure 7. Error Rate Test Setup

18

Figure 8. Signal Flow Through MRDCS

board was replaced because the modem had been unable to acqui.·e a signal at sufficiently low signal-to-noise ratio. Replacing the board corrected this problem. The fault in the original board was not definitely established but was probably caused by the failure of a relay used to select the bandwidth of a low-pass filter in the Costas loop corresponding to the selected data rate.

Encoder/Decoder Checkout

The convolutional encoder/Viterbi decoder was tested by the encoder/decoder subcontractor using simulated quantized gaussian noise. However, their noise generator was unable to simulate gaussian noise at values of E_b/N_0 greater than about 4 dB. For $E_b/N_0 \leq 4$ dB, the measured error rates met the specification requirement. After the unit was delivered to Hughes, a wiring mistake in the circuit that receives the least significant data bit from the modem was discovered. The effect of this mistake was that the least significant bit was ignored by the decoder, so that it really was operating in the $Q = 4$ mode. Very likely, the decoder was also operating in the $Q = 4$ mode when the error rate tests were made by the subcontractor, so the data taken at that time are not valid for the $Q = 8$ mode.

Operation of Total System

When the system components were first connected as shown in Figure 7, error rates in both the $Q = 2$ and $Q = 8$ modes appeared to meet specification requirements. After the previously mentioned wiring mistake in the encoder/decoder was discovered and corrected, the error rate in the $Q = 8$ mode did not behave as expected when operating at the highest dat. rate (1228.8 kbps). At high values of signal-to-noise ratio, performance in the $Q = 8$ mode deteriorated relative to theoretical performance to the extent that it was no better than for $Q = 2$. This anomaly, illustrated in Figure 9, is discussed in more detail in subsection 3.3.

In an effort to understand the anomaly for $Q = 8$, the integrate-and-dump detector and analog-to-digital converter in the modem were examined. The thresholds for the analog-to-digital conversion were fixed at approximately 0, ±0.3, ±0.6, and ±0.9 volt. The output of the integrate-and-dump circuit (which is adjustable around 1.0 volt by modem front panel controls) were sampled at the end of each symbol and compared to the fixed threshold to determine in which of the 8 quantization intervals it fit. The integrate-and-dump output showed some anomalies. The amplitude of positive integrations differed by as much as 0.1 volt from the negative integrations. Also, both positive and negative integrations had variations in amplitude which can be partially explained by intersymbol interference. The total variation in amplitude of the integrate-and-dump outputs was about 0.2 volt, which is significant relative to the 0.3 volt spacing between threshold levels of the analog-to-digital converter. It is reasonable to expect that these amplitude variations would cause some deterioration in decoder performance for the $Q = 8$ mode; however, it is not evident that they would cause as much deterioration as was observed.
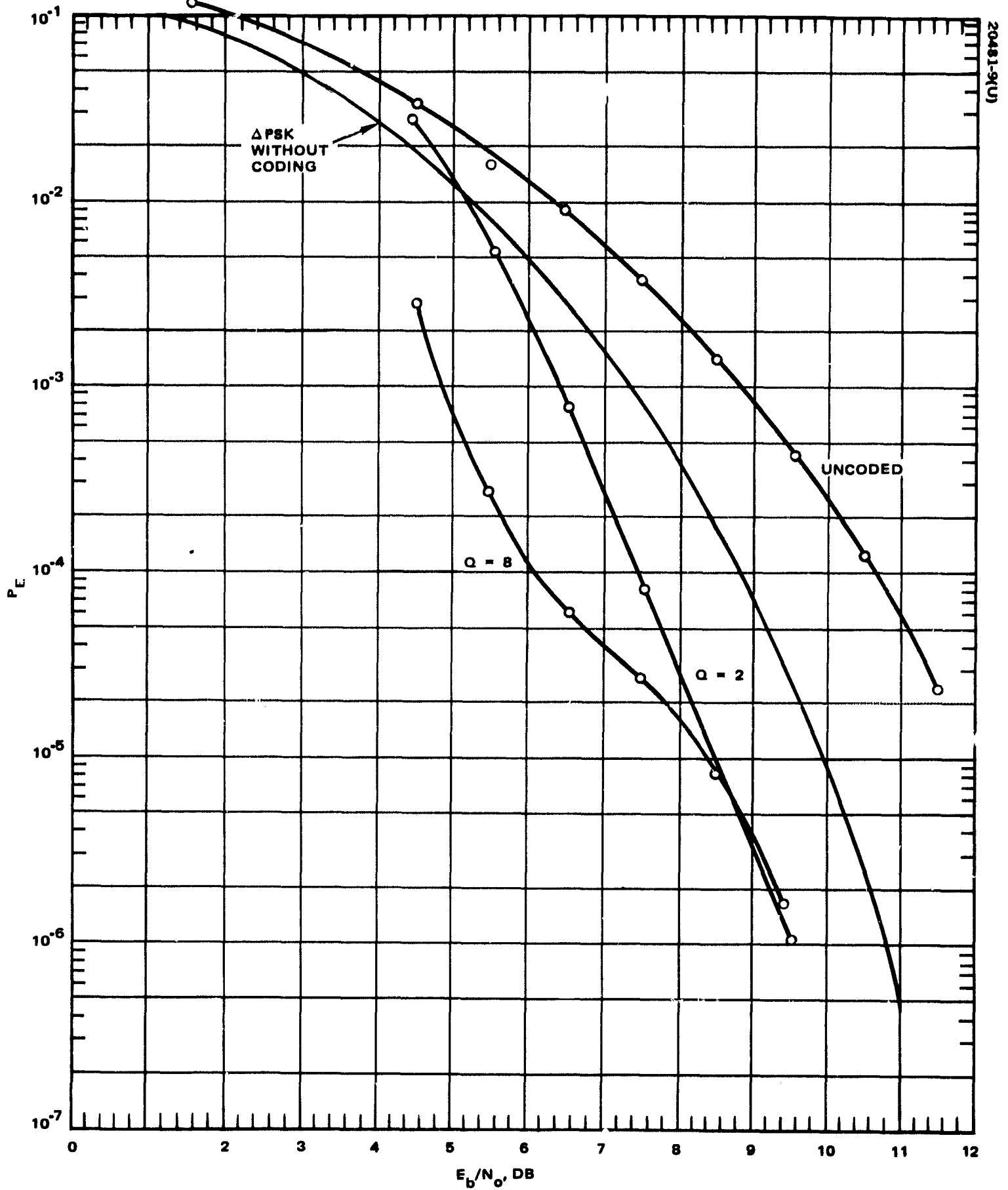
20

Figure 9. MRDCS Error Rate Performance

21

3.3 PERFORMANCE TEST RESULTS

The results discussed here were obtained during the acceptance test performed 27-29 June 1972. They agree closely with previous test data taken by Hughes. The performance tests consisted basically of: 1) acquisition tests intended to verify that the system is capable of acquiring a signal within the specified time period at the specified signal-to-noise ratio and 2) error rate tests at the various data rates and operating modes.

Modem Acquisition

The use of coding in the MRDCS places a stringent requirement on the modem since signal acquisition must be accomplished at low signal-to-noise ratios. Convolutional encoding/decoding can be used to provide improved performance at signal-to-noise ratios, E_b/N_o, as low as 4 dB; therefore, for a rate 1/2 code, the modem used in conjunction with the encoder/decoder must be capable of acquiring and maintaining carrier and symbol synchronization for E_s/N_o as low as 1 dB.* The basic requirement is that the modem be capable of acquiring carrier and symbol synchronization under the condition that $E_s/N_o \geq 1$ dB (except at 19.2 kbps, where E_s/N_o is 4 dB or greater**) satisfied at all six data rates.

In addition, tests were conducted at nominal data rates of 38.4 and 1228.8 kbps to see if acquisition was possible under the condition that the nominal data rate has a static offset of ±0.4 percent. At 1228.8 kbps, acquisition was accomplished at $E_s/N_o = 1.5$ dB.

At 38.4 kbps, it was necessary to increase E_s/N_o to about 2.5 dB before acquisition was possible. The results and conditions of the acquisition tests are fully described in the End Item Test Plan (Reference 5).

Error Rates

A summary of the error rate performance of the system at each of the six data rates is given below. Complete test results are given in Reference 5.

1) 19.2 kbps — Measured error rates in the uncoded mode were within 1 dB of theoretical over the range 1 dB $\leq E_b/N_o \leq$ 10 dB. At a bit error rate of 10^{-5}, the coding improvement was 3.5 dB for the hard-decision (Q = 2) mode and about 4.8 dB for the soft decision (Q = 8) mode.

---

*Symbol refers to one of the two transmitted signal elements corresponding to a data bit.

**At 19.2 kbps, the modem is required to operate only down to E_b/N_o of 4 dB because of an implementation problem. To operate down to 1 dB, it would be necessary to add another switchable filter to the sync demodulator board and there was insufficient room on the board for another filter.

2) 38.4, 76.8, 307.2, and 614.4 kbps — In the uncoded mode, error rates were within approximately 1.4 dB of theoretical over the range 1 dB $\leq E_b/N_o \leq$ 10 dB. At a bit error rate of 10^{-5}, coding improvement was approximately 3.7 dB for $Q = 2$ and 5.6 dB for $Q = 8$.

3) 1228.8 kbps — In the uncoded mode, error rates were within 1.6 dB of theoretical for 1 dB $\leq E_b/N_o \leq$ 10 dB. At a bit error rate of 10^{-5}, coding improvement was about 3.3 dB for both $Q = 2$ and $Q = 8$ modes. At $P_e = 10^{-4}$, coding improvement was 3.1 dB for $Q = 2$ and 4.4 dB for $Q = 8$.

Allowing for the accuracy of measuring E_b/N_o, the error rate performance was within specification requirements except for operation in the $Q = 8$ mode at 1228.8 kbps. Results of previous error rate tests conducted at Hughes verified that satisfactory performance was achieved at 1228.8 kbps while operating in the $Q = 4$ mode instead of $Q = 8$.

3.4 PERFORMANCE ANOMALIES

Two major anomalies were observed in the operation of the MRDCS: 1) the error rate was relatively high at large signal level for the three lowest data rates, and 2) at the highest data rate, error rate performance in the soft-decision ($Q = 8$) mode deteriorated to that of hard-decision ($Q = 2$) for high signal-to-noise ratios. The first anomaly is probably not important since operation at high signal level is normally not as critical as operation at low levels. The second anomaly can be partially avoided by operating in the $Q = 4$ mode at the highest data rate. The $Q = 4$ mode has performance which is about 0.5 dB poorer than theoretical $Q = 8$ performance, satisfying the requirement for $Q = 8$ performance. Thus, these two anomalies will probably not detract significantly from the usefulness of the system.

Degraded Error Rate Performance at High Signal Level

At the three lower data rates (19.2, 38.4, and 76.8 kbps), there is noticeable degradation in modem error rate performance at signal power levels exceeding about -50 dBm. The carrier acquisition capability of the modem is also somewhat degraded for these data rates at the higher signal power levels. The probable cause of this degradation is limiting in the 70 MHz preamplifier of the modem demodulator. For example, at 19.2 kbps, the noise power (measured in the filter bandpass) at the preamplifier input can be as much as 30 dB above the signal power. Thus, for signal levels exceeding -50 dBm, the input level to the preamplifier can be more than -20 dBm, which exceeds the upper end of its operating range. To correct this problem, a modem demodulator redesign could be considered where the AGC range is extended above the present level of -25 dBm.

Degraded Error Rate Performance in Soft-Decision (Q = 8) Mode

The error rate performance in the Q = 8 mode deteriorates at high signal-to-noise ratio to the extent that it approaches that of Q = 2, as can be seen from Figure 9. (The data were taken during the MRDCS acceptance test.) Although this deterioration is more pronounced at the highest data rate, 1228.8 kbps, it is also noticeable at the lower data rates.

Figure 10 shows error rate data at 614.4 kbps taken on 10 June 1972 with the same test setup and procedure as used for the acceptance test. This figure illustrates the anomaly because it includes data for the Q = 4 mode as well as for Q = 4 and Q = 8.

Notice from Figure 10 that the hard-decision (Q = 2) error rate curve behaves as expected, giving about 3 dB coding improvement at a bit error rate of 10^{-5}. This is typical behavior in the Q = 2 mode at all of the data rates.

Notice also that the Q = 4 mode provides an additional 1.5 to 1.8 dB coding improvement relative to Q = 2, which is slightly more than expected. Theoretically, Q = 4 should be 1.2 to 1.5 dB better than Q = 2. The difference between measured and theoretical coding improvement is small enough to be within measurement accuracy.

The behavior of the Q = 8 mode is not understood. As seen from Figure 10, for $E_b/N_0 \geq 6$ dB the error rate for Q = 8 is worse than for Q = 4, and for higher signal-to-noise ratios approaches Q = 2 (hard-decision). One explanation for this behavior is that it is caused by intersymbol interference or other irregularities in the demodulated data from the modem. However, this would probably not account for the fact that the Q = 4 mode continues to work well at high values of E_b/N_0. Another explanation is that the decoder is not operating properly at high values of E_b/N_0. One way to determine if the decoder is causing the problem is to generate quantized gaussian noise at baseband and operate the decoder separate from the modem. However, it is difficult to generate quantized noise at high signal-to-noise ratios. The encoder/decoder subcontractor's simulator can go only up to about $E_b/N_0 = 4$ dB, below the range where difficulty was encountered. The subcontractor's opinions concerning the causes of the problem are contained in the appendix.

The informal test results previously given to NASA* showed error rates for Q = 2 and Q = 8. However, those measurements were made before it was discovered that the Q = 8 mode was operating as though it were in the Q = 4 mode because the least significant data bit was being ignored by the decoder. The measurements made at that time are valid for the Q = 4 mode but not for Q = 8. In almost all cases, these measured error rates (Q = 4) satisfied the Hughes specification on operation in the Q = 8 soft-decision mode.

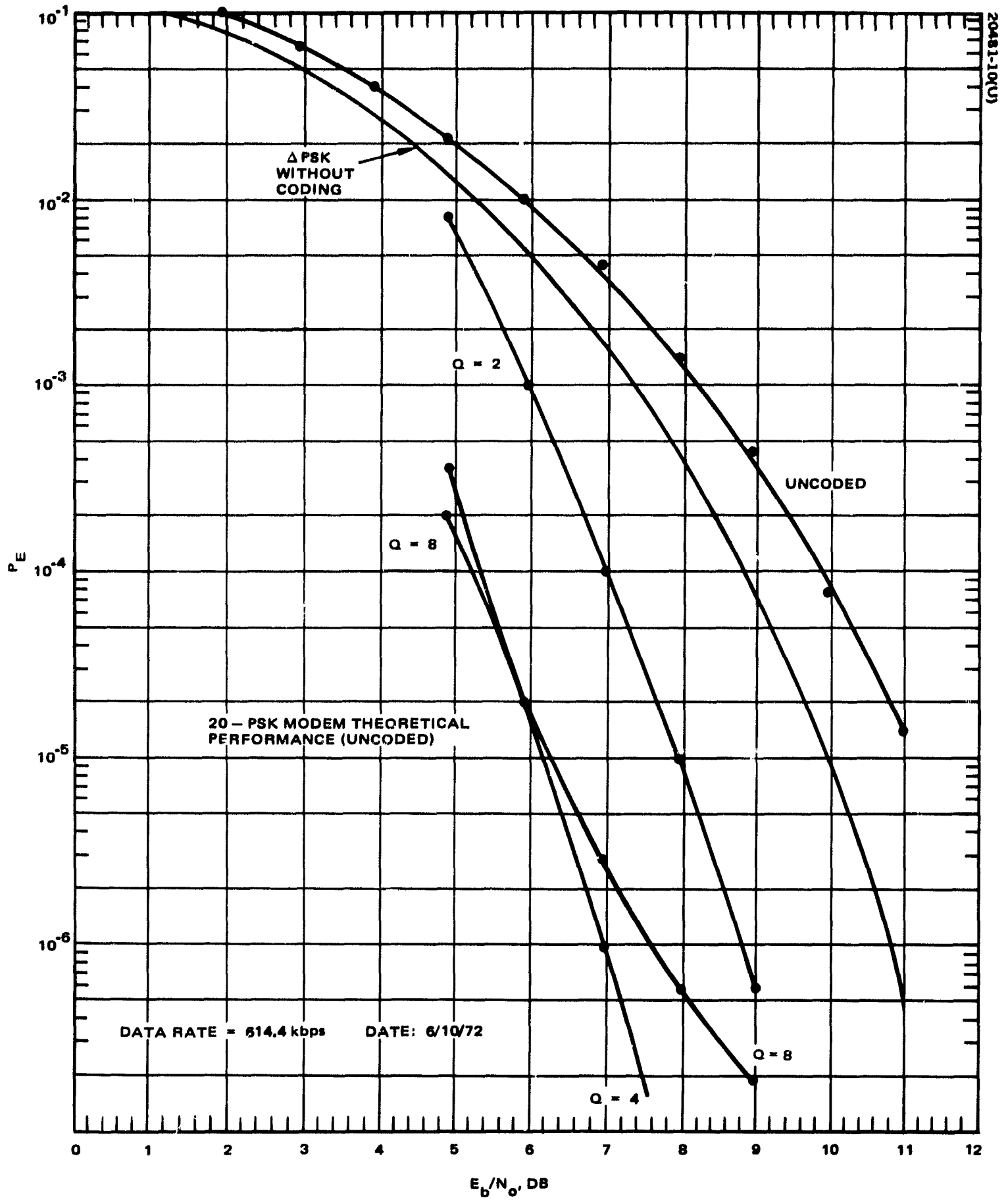*Test results were given to W. E. Teasdale of NASA during his visit to Hughes in May 1972.

Figure 10.   Error Rate Data at 614.4 kbps

25

3.5 SUGGESTIONS FOR SPECIFYING FUTURE CODED SYSTEMS

The following suggestions are based on Hughes experience in integrating and testing the MRDCS:

1) The decoder should be tested by itself over the entire operating range of signal-to-noise ratio using simulated quantized noise. This was not done for the MRDCS because a noise simulator that operates at $E_b/N_0 > 4$ dB was not available. Linkabit Corporation, who furnished the decoder, is currently building a simulator capable of achieving an E_b/N_o of 6 dB.

2) The output of the integrate-and-dump detector of the modem receiver should be more carefully controlled. Specification of amplitude variations of the integrate-and-dump outputs should ensure that such variations are small compared to the threshold spacing of the analog-to-digital converter. (This is more critical for a modem used with a quantized output; the MRDCS modem was designed for hard-decision with an add-on analog-to-digital converter as a modification for the MRDCS.)

3) If intersymbol interference or amplitude variations in the integrate-and-dump output of the modem cannot be carefully controlled, selection of $Q = 4$ might be a better choice than $Q = 8$. Although $Q = 8$ has theoretical performance about 0.5 dB superior to $Q = 4$, some of this advantage is lost if the data supplied to the decoder have errors in the least significant bit caused by amplitude variation in the integrate-and-dump output.

4. TASK SYNOPSES

Each paragraph of this section is referenced to tasks itemized in the contract statement of work.

4.1 ITEM I, TASK 1 — ORIENTATION AND DATA ASSIMILATION

During the first month of this contract effort, and as required thereafter, data furnished by NASA/MSC were reviewed by project personnel to familiarize themselves with the results of prior and current work performed in the area of convolutional encoding by and for NASA. The principal documents included in this review include References 2 and 6 through 11.

4.2 ITEM I, TASK 2 — BASELINE LINK DESIGN

This task was involved with the development of a baseline link design for communicating between an advanced manned spacecraft (AMS) and the earth via a relay satellite. It was initially established that the relay satellite would have the characteristics of an Intelsat IV communications satellite, and that the link analysis should consider performance with inputs from and outputs to either the AMS or the earth terminal in the form of digital data. Preliminary forward (earth terminal to AMS) and return link performance was reported in the July 1971 and the August 1971 Monthly Progress Reports, respectively, and the overall performance was included in Reference 1. A summary of the baseline design performance is given in Section 2 of this report.

4.3 ITEM I, TASK 3 — SIGNAL ANALYSES AND CHANNEL PERFORMANCE MAXIMIZATION

This task was primarily concerned with the performance of the baseband portion of the CTB. Using the data developed under Contract NAS 9-10409, it was agreed with NASA that this task should assume that the input to the CTB would be a single digital bit stream. Tradeoff studies were performed comparing the performance improvement which could be achieved as a function of coding parameters for convolutionally encoded data. The

results were reported in Reference 1 and in Section 2 of this report. Reference 12 is the Hughes Specification for the convolutional encoder/Viterbi decoder.

4.4 ITEM I, TASK 4 — EQUIPMENT DESIGN AND PERFORMANCE SPECIFICATION

The principal effort under this task was the preparation of the subject document and associated procurement specifications for the implementation of the equipment to be furnished under this task; the procurement specifications were furnished to NASA as appendices to the Equipment Design and Performance Specification.

The work statement for this task also required a review of the selection of the convolutional coding parameters. This was reported in Reference 1 and in Section 2.2 of this report.

4.5 ITEM II

Item II covers the requirements for the design, fabrication, procurement, integration, and test of the several components which as a group have been designated the MRDCS. Integration and testing of the MRDCS was completed in June 1972, with the testing performed in accordance with the End Item Test Plan (Reference 5), observed by the NASA technical monitor, and the equipment was turned over to the Government for shipment to NASA/MSC. The completed End Item Test Plan was forwarded to NASA 10 July 1972.

REFERENCES

1. Functional Link Design for a Communications Terminal Breadboard, Hughes Ref. No. 4092G/38/C4356, December 1971.

2. B.H. Batson, R.W. Moorehead, and S. Z.H. Taqvi, Simulation Results for the Viberbi Decoding Algorithm, NASA Technical Report, February 1971.

3. K.S. Gilhousen, et al., Coding Systems Study for High Data Rate Telemetry Links, NASA Report 114278, Linkabit Corporation, January 1971.

4. Final Breadboard Design for a Communications Terminal Breadboard, Hughes Ref. No. 4092G/45/C4356, 31 January 1972.

5. End Item Test Plan, Medium Rate Digital Communications System, Communications Terminal Breadboard, Hughes Ref. No. 4092G/52/ C4356, 30 May 1972.

6. W.H. Ng, Self Synchronizing Convolutional Codes and Branch Synchronization, Lockheed Electronics Company Report, 30 October 1970.

7. S. Z.H. Taqvi, Branch Synchronization Schemes for Convolutional Codes, LEC HASD 642D0823247, 8 July 1970.

8. Potential Applications of Digital Techniques to Apollo Unified S-Band Communications System, Final Report, Martin Marietta Corporation, February 1970.

9. S. Z. H. Taqvi, Computer Identification of Catastrophic Convolutional Codes, Lockheed Electronics Company Report, 16 December 1970.

10. S. Z. H. Taqvi, Computer Analysis of Noise for Coding Simulation Applications, LEC Document 642D-823246, 19 June 1970.

11. B.H. Batson, C. K. Land, and R. W. Moorehead, Low-Rate Communications Utilizing Digital Coding and Modulation, NASA Report.

12. "Convolutional Encoder/Decoder", Hughes Specification TB-E/D-PS, 17 September 1971.

29

APPENDIX

COMMENTS ON VITERBI DECODER ANOMALIES

LINKABIT CORPORATION   10453 ROSELLE STREET UNIVERSITY INDUSTRIAL PARK SAN DIEGO, CALIFORNIA 92121 714-453-7007

13 July 1972

Mr. L. M. Gould
Hughes Aircraft Company
Space and Communications Group
P. O. Box 92919 - Airport Station
Los Angeles, CA 90009
366/1022

Reference: 40926/53/C4356

Dear Mr. Gould:

This is in answer to your letter concerning the two anomalies observed in the operation of the LINKABIT LV7026 Convolutional Encoder/ Viterbi Decoder in conjunction with the Magnavox soft decision modem.

It is our opinion that both anomalies are due directly to inaccuracies in the analog-to-digital conversion performed in the modem and/or in the AGC loop. This opinion is based on several points.

Extensive computer simulations down to output error rates of 10^{-5} indicate, of course, that these phenomena should not occur. However, these simulations have been carried out under the assumption that the modem is perfect, i.e., the thresholds are placed in their proper locations. The effect of imperfect AGC has also been simulated. The main results are that AGC errors of less than 3 dB cause very little performance degradation, while errors of more than 3 dB cause significant errors. A 9 dB AGC error, for example, causes a degradation equivalent to a 1 dB decrease in E_b/N_o. Thus, imperfect AGC can cause degradation in soft decision performance while not affecting hard decision performance.

More significant is the fact that the LV7026 has been operated with two other soft decision modems; one at Radiation, Inc., Melbourne, Florida, and the other at NASA Ames. In both cases the performance curves were very close to the simulation results after correcting for modem losses. This indicates that there is no basic design error in the LV7026.

The phenomena of performance improvement when the least significant bit is removed has been observed in one other situation; namely,

31

Mr. L. M. Gould   13 July 1972
Hughes Aircraft Company

when operating the LV7026 with our in-house digital noise generator.
This generator simulates a Gaussian channel in a digital fashion and
generates soft decision output data. At the higher E_b/N_o values,
above 4 dB, the generator output is known to give a   poor repre-
sentation of the Gaussian channel. This is primarily because the
data used to generate the soft decision bits was truncated at 8 bits,
whereas it should have been extended to 12 or 16 bits. (A new digi-
tal noise generator is being designed which uses 16 bits and will give
an accurate representation at E_b/N_o values up to 6 dB). In the region
where the generator is known to   be inaccurate, there are one or
two settings at which removal of the least significant bit improves
performance. This leads us to believe that the equivalent phenomenon
observed at Hughes is due to inaccuracies in the modem A/D converter.

Several weeks ago, I spent several hours at Hughes observing
the operation of the LV7026 with the modem. One point in evidence
was that the two magnitude bits from the modem (i.e., the two least
significant bits), were data dependent. This data dependence could
be varied by varying the A/D converter threshold within the modem.
With a properly operating A/D converter and AGC loop, there should
be no data dependence among the soft decision output lists. This, in
our estimation, is further evidence that the problem areas are in the
modem rather than the decoder.

Another phenomenon observed during this demonstration was the
relative sensitivity of the Q=8 and Q=4 modes to internal modem timing.
Specifically, the decoder error rate seemed to be highly sensitive to
the internal modem timing in the Q=8 mode, and relatively insensitive
in the Q=4 mode, especially at 1.7208 Mbps. This could indicate that,
not only are there A/D converter inaccuracies, but that there is also
an intersymbol intersymbol interference effect present. The published
performance curves assume no intersymbol interference, and the presence
of intersymbol interference is known to degrade performance somewhat.

In order to determine without doubt whether the source of the
anomalies is the modem, it will be necessary to measure the distribu-
tions of the soft decision modem outputs. Of primary interest are the
joint distributions among the three outputs. These measurements should
be made at several data rates and for several threshold settings.
Furthermore, distributions should also be measured between adjacent
bits to determine if intersymbol interference effects are present.

I am convinced, for the above reasons, that such measurements
will indicate modem malfunction. However, should this not be the case,
LINKABIT will gladly reconsider the situation and take whatever correc-
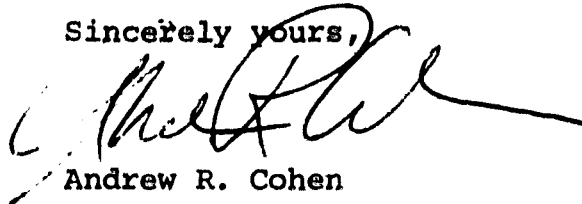tive measures are required.

Mr. L. M. Gould   13 July 1972
Hughes Aircraft Company

        I am very interested in seeing the results of the tests, and I
would appreciate your sending me any data which will become available.

        Please let me know if I can be of further assistance.

                                        Sincerely yours,

                                        Andrew R. Cohen

/sa