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Effects of Amplitude Distortions and IF Equalization on Satellite Communication System Bit-Error Rate Performance

Robert J. Kerczewski and Gene Fujikawa
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

James S. Svoboda
Sverdrup Technology, Inc.
NASA Lewis Research Center Group
Cleveland, Ohio

and

Paul J. Lizanich
Analex Corporation
NASA Lewis Research Center
Cleveland, Ohio

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COMMUNICATION SYSTEM BIT-ERROR RATE PERFORMANCE

Robert J. Kerczewski and Gene Fujikawa
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

James S. Svoboda*
Sverdrup Technology, Inc.
NASA Lewis Research Center Group
Cleveland, Ohio 44135

Paul J. Lizanich†
Analex Corporation
NASA Lewis Research Center
Cleveland, Ohio 44135

Abstract

Satellite communications links are subject to distortions which result in an amplitude versus frequency response which deviates from the ideal flat response. Such distortions result from propagation effects such as multipath fading and scintillation and from transponder and ground terminal hardware imperfections. Laboratory experiments performed at NASA Lewis Research Center measured the bit-error rate (BER) degradation resulting from several types of amplitude response distortions. Additional tests measured the amount of BER improvement obtained by flattening the amplitude response of a distorted laboratory-simulated satellite channel. This paper presents the results of these experiments.

Introduction

For a digital communication link, an amplitude response which is a constant function of frequency represents the ideal, distortionless case.[1] In a satellite communication link, the amplitude response is often distorted by atmospheric and propagation effects such as scintillation, rain attenuation, and multipath fading. Cumulative effects of less-than-ideal responses of satellite transponder and ground terminal hardware and antennas contribute additional distortion to the amplitude response of the system. Measurements performed at NASA Lewis Research Center on an experimental hardware-simulated 30/20 GHz satellite communication link indicate that the amplitude response of the system is among the most important RF parameters in terms of the effect on bit-error rate (BER).[2]

At NASA Lewis, experiments were performed to quantify the effects of amplitude distortion on the BER of a satellite communication system. NASA's Systems Integration, Test and Evaluation (SITE) satellite communication system simulator was used to simulate system amplitude distortion and the effectiveness of fixed IF amplitude equalization in improving degraded links. In one set of experiments, a tunable IF equalizer was used to simulate a number of amplitude distortions representing some of the types of distortions found in real systems. The resulting BER degradations caused by the simulated distortions were measured. In a second set of experiments, the equalizer was used to improve the amplitude response of several degraded channels of the system simulator, with the resulting BER improvement measured.

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The following sections will describe the test systems and equipment, review the types of amplitude distortions simulated, and describe the experiments performed and results obtained.

Description of Test System

A block diagram of NASA Lewis's SITE satellite communication system simulator is shown in Fig. 1. It consists of a satellite transponder, ground terminal up/down converters, ground terminal digital subsystems, and an experiment control computer. The satellite transponder portion contains two hardware channels interconnected through an IF matrix switch. The transponder operates at an uplink frequency of 27.5 to 30.0 GHz and a downlink frequency of 17.7 to 20.2 GHz. Seventeen matrix switch crosspoints and two 20 GHz power amplifiers at various operating points provide a large number of combinations resulting in various system amplitude responses. The ground terminal up/down converters, with variable local oscillators, provide access to the entire 2.5 GHz bandwidth. The ground terminal digital subsystem contains the modems and digital control necessary to measure BER.

The modems used for the experiments described in this paper are 220 Mbps serial minimum shift keyed (SMSK) modems built by Motorola, Government Electronics Group.[3-5] SMSK is theoretically equivalent to BPSK or QPSK in bit-error rate performance versus energy-per-bit to noise power density ratio (E_b/N_o), but is more spectrally efficient. The main lobe of the spectrum contains 99 percent of the data energy; the bandwidth of the main lobe is 50 percent wider than QPSK but is 25 percent narrower than BPSK. The out of band (sidelobe) energy is significantly less than either BPSK or QPSK, thus SMSK is more robust when encountering adjacent channel interference.

The 220 Mbps modulator block diagram is shown in Fig. 2. It is basically a BPSK modulator with the carrier frequency f_c offset from the center frequency f_o by one-fourth of the data rate, T, i.e., $f_c = f_o - 1/4T$ Hz. A bandpass conversion filter, consisting of a quadrature hybrid and power summer followed by a two-pole Butterworth bandpass filter, realizes the SMSK modulated signal. A plot of the modulator output spectrum is shown in Fig. 3.

The block diagram of the 220 Mbps demodulator is shown in Fig. 4. The basic structure of the demodulator is essentially the reverse of the modulator structure. It consists of an input bandpass matched filter, followed by the coherent demodulator, and a lowpass filter to eliminate the double frequency components at the mixer output. Automatic gain control (AGC) circuitry is provided to allow for burst-to-burst baseband signal variation over a 20 dB dynamic range.

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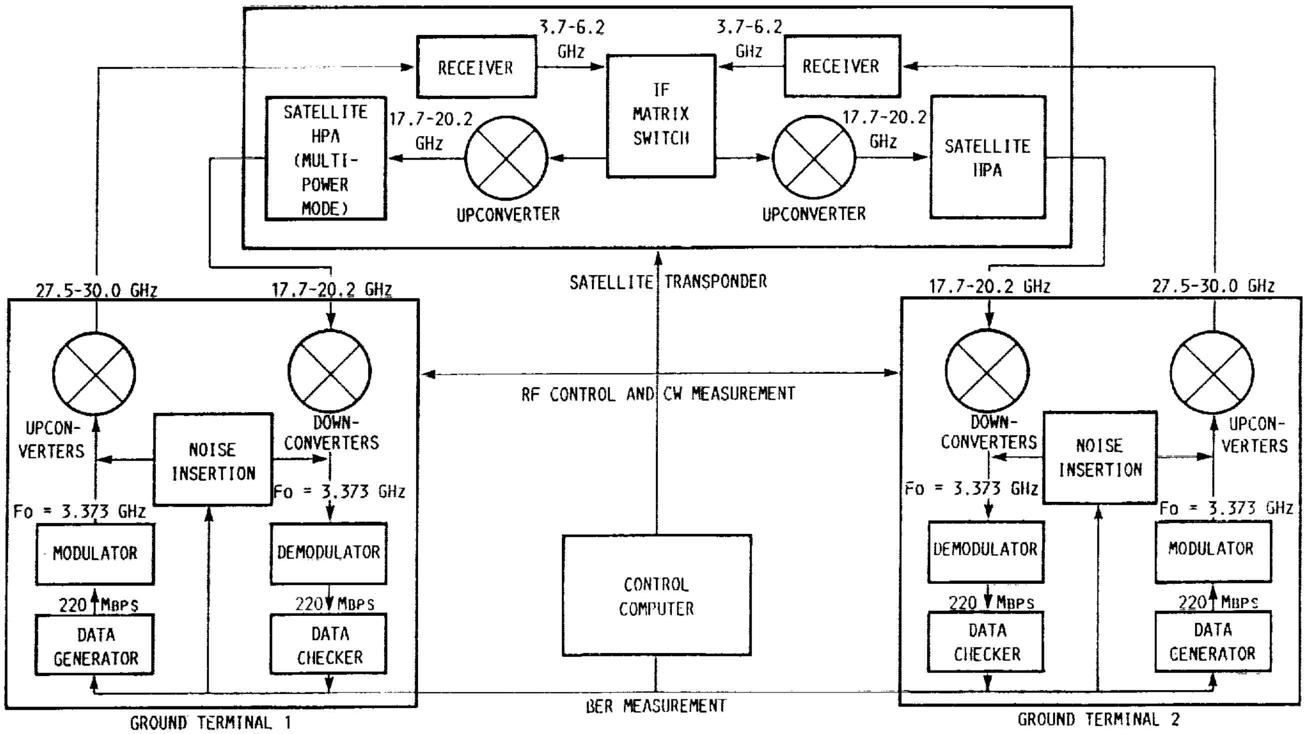

FIGURE 1. - SITE SATELLITE COMMUNICATION SYSTEM SIMULATOR BLOCK DIAGRAM.

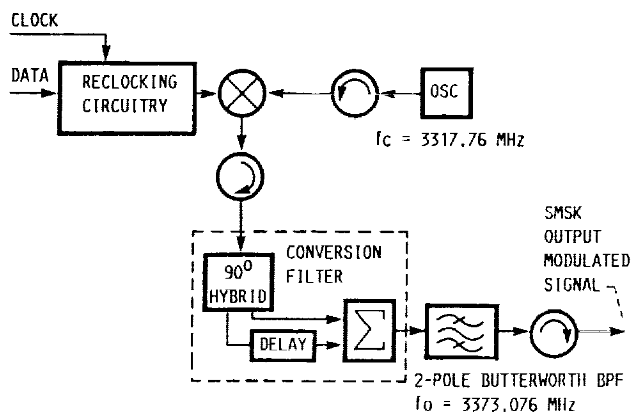

FIGURE 2. - 220 MBPS MOTOROLA SMSK MODULATOR BLOCK DIAGRAM.

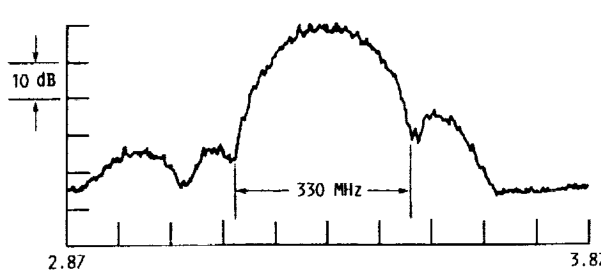

FIGURE 3. - 220 MBPS SMSK SPECTRUM.

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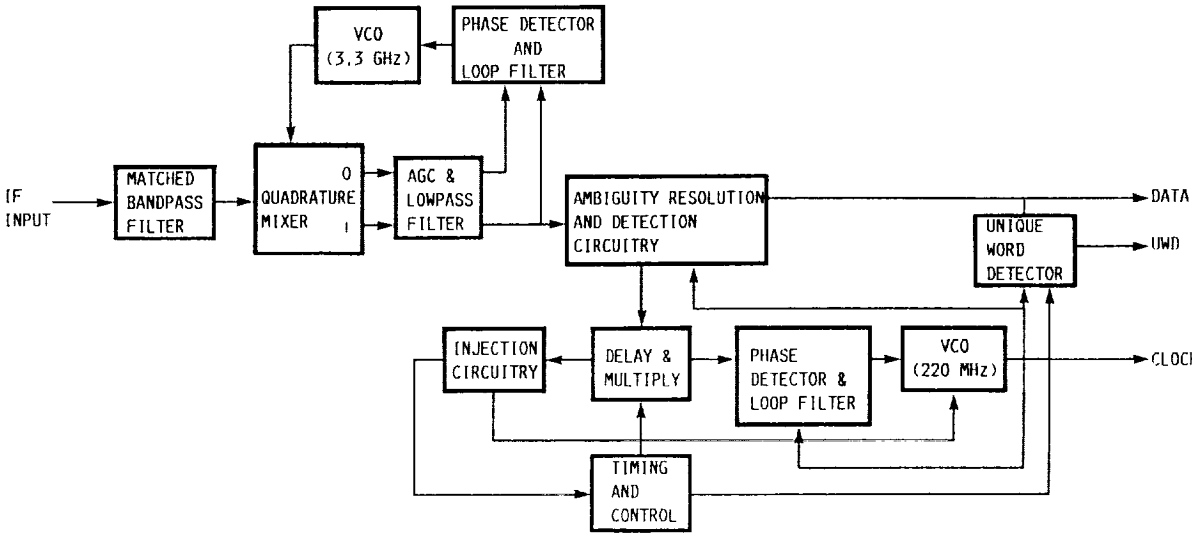

FIGURE 4. - 220 MBPS MOTOROLA SMSK DEMODULATOR BLOCK DIAGRAM.

Carrier synchronization is implemented by the use of a Costas loop which derives a filtered phase error signal that is used to correct the phase of the 3.3 GHz VCO. To remove phase ambiguity (presence of stable lock points at 0° and 180°) in the carrier acquisition loop, injection locking of an unmodulated carrier is done. This unmodulated carrier is sent as a portion of the preamble in a TDMA system. Bit timing is accomplished by transition tracking, which measures the timing error between the local clock and the measured transition times of the demodulated baseband data, and uses this error to pull the local clock into synchronization.

For each experimental situation a complete BER curve is measured as a function of E_b/N_o. The modulator accepts a pseudorandom bit stream at 220 Mbps. The received, demodulated bit stream is compared to a regenerated version of the transmitted bit stream and bit-errors are detected and counted. Under control of the experiment control computer, calibrated amounts of noise are added to the received modulated signal at the demodulator input. The E_b/N_o is increased in 1 dB increments until a BER = 10^{-8} is attained, at which time the measurement is ended. For purposes of measuring and calibrating noise power, a channel bandwidth of 330 MHz is assumed. This bandwidth represents the width of the main spectral lobe for SMSK modulation operating at a data rate of 220 Mbps (Fig. 2). Detailed explanations of the measurement hardware and procedures are given in Refs. 11 and 12.

The IF equalizer used to simulate amplitude distortions and equalize the laboratory system simulator is a 10-section mechanically tunable filter device built by Innowave, Inc. Each equalizer section is a resonator with two adjustments which allow both the center frequency and the attenuation of the resonator to be varied. A single resonator can be tuned to produce an amplitude notch at a desired frequency and depth, or the resonators can be used in combination to produce desired shapes across a passband of 3.2 to 3.55 GHz.

Amplitude Distortions in Satellite Communication Systems

The two major sources of amplitude distortions in satellite communications systems are propagation effects and hardware imperfections. The simulation of these distortions was based upon the characteristics of real systems to the extent possible given the limitations of the hardware used for the experiments. Propagation effects were simulated by induced amplitude distortion produced by the tunable IF equalizer. The hardware imperfections were simulated by both induced amplitude distortion using the equalizer and by real imperfect hardware in the SITE simulation system.

Satellite Link Propagation Effects

The propagation characteristics of the transmission path are important when considering the design and operation of a satellite communications system. Many factors have been cited as significant in space communications applications operating in the atmospheric windows up to 100 GHz. These include signal attenuation due to scattering or absorption, depolarization, scintillation or atmospheric multipath fading, angle of arrival fluctuations, etc.[6] Multipath fading has been shown to cause distortions on terrestrial digital links. This effect is frequency selective across the channel bandwidth under operation. Previous research using beacons in the 30/20 GHz range have indicated that multipath effects are insignificant for wideband satellite communications systems operating at frequencies above 10 GHz, except when operating at low elevation angles (<15°).[7] However, it remains of interest to determine if such frequency selective distortions have any pronounced effect on a digitally modulated signal transmitted through a simulated satellite channel.

It has been shown that the amplitude characteristic during a wideband multipath fading period is

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basically a notch (minimum) at a selected frequency.[9] This minimum in the signal power is also accompanied by a maximum or minimum in group delay distortion. Since this paper is primarily interested in the amplitude characteristics, the delay distortion will not be discussed any further. The amplitude characteristics which represent the propagation fading effects are primarily the notch and slope distortions. The amplitude distortion simulated by the IF equalizers in the induced distortion experiments are to represent those propagation effects.

Satellite Link Hardware Imperfections

A satellite communications link contains a cascade of numerous components including both passive devices such as filters, multiplexers, and antennas and active devices such as receivers, up/down converters, and power amplifiers. The SITE system (Fig. 1) contains several major contributors to amplitude distortion: the satellite receiver, matrix switch, satellite HPA, and ground terminal up/down converters. These major components were built under proof-of-concept technology development programs. Thus, their amplitude responses are somewhat more degraded than would be expected in an operational system. Additional elements (not shown in Fig. 1) including filters, couplers, and driver amplifiers contribute smaller amounts of degradation.

The amplitude distortions which result from the various system components, when combined, yield a wide variety of system distortion shapes. However, these shapes are mainly a combination of three basic distortions: ripple, parabolic, and slope. The ripple distortions originate mostly from filter and matching network circuits, and especially from mismatches between adjacent components. Parabolic distortion results from filters and other bandlimiting components. Amplitude slope can be produced by any component, and usually occurs when the component is being operated near its design band edge.

The induced distortion experiments, in addition to simulating propagation effects, also simulated the three basic hardware-induced distortions just described. The IF equalization tests took advantage of the degraded amplitude responses resulting from the proof-of-concept components in the SITE system. Thus, the general problem of hardware-induced amplitude distortion was investigated by the two experiments described below.

Induced Distortion Tests

The induced distortion tests attempted to simulate some of the amplitude distortions resulting from propagation effects and hardware imperfections as described previously. In these tests, a variety of amplitude distortions were deliberately induced by the adjustable IF equalizer, which was then used to simulate a distorted satellite channel.

The equalizer was adjusted while viewing its amplitude response on a network analyzer. Examples of the resulting amplitude responses, as plotted from the network analyzer, are shown in Figs. 5 to 8. Four types of distortions were induced: ripple, slope, parabolic, and notch. The ripple distortions were obtained by adjusting several of the equalizer's resonators at equal intervals across the passband. For the 3-ripple case (Fig. 5), four resonators were tuned to give three positive peaks (at f_o and $f_o \pm 110$ MHz) and four negative peaks (at $f_o \pm 55$ MHz and $f_o \pm 165$ MHz). Ripples with two, four, and five positive peaks were similarly obtained. Positive and negative slopes (Fig. 6) were obtained by tuning a combination of resonators across the band to give either a rising or falling slope. Parabolic distortions are shown in Fig. 7. The upward opening parabola required a number of resonators tuned in combination, while the downward opening parabola required resonators placed at each end of the band. For all of these cases, the amount of distortion, as measured by the difference between the highest and lowest in-band amplitude, was varied as shown in Table 1. The magnitude of each distortion was increased until the equalizer tunability limit was reached. In some cases, adding additional distortion produced a negligible increase in BER degradation or caused a complete failure of the

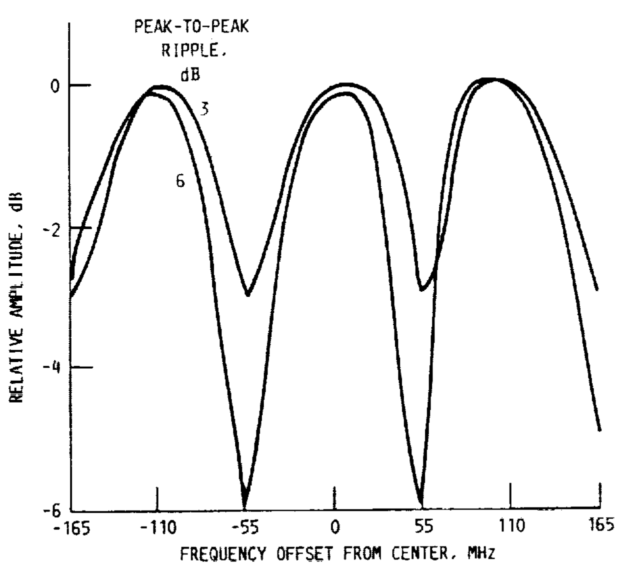

FIGURE 5. - MEASURED AMPLITUDE RESPONSES FOR INDUCED 3-RIPPLE DISTORTION.

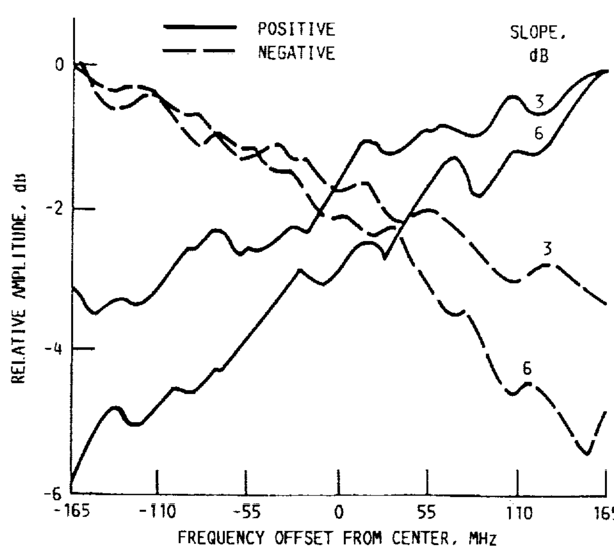

FIGURE 6. - MEASURED AMPLITUDE RESPONSES FOR INDUCED POSITIVE AND NEGATIVE SLOPE DISTORTIONS.

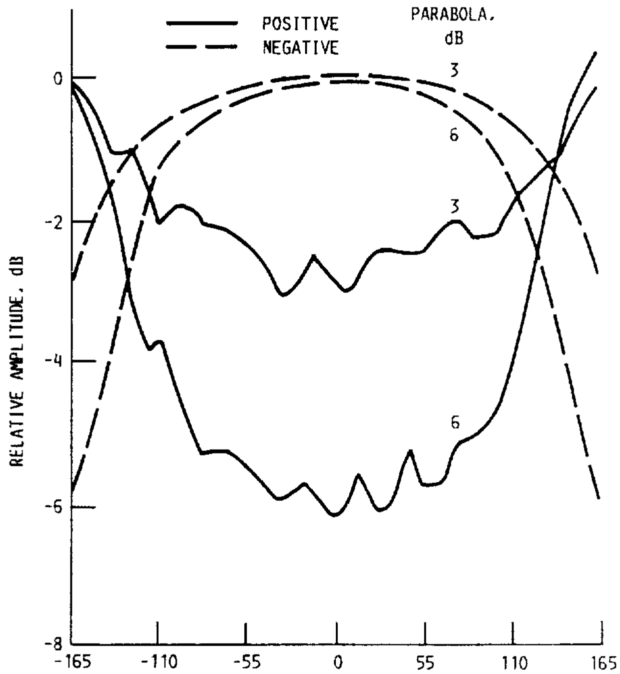

FIGURE 7. - MEASURED AMPLITUDE RESPONSES FOR INDUCED PARABOLIC DISTORTIONS.

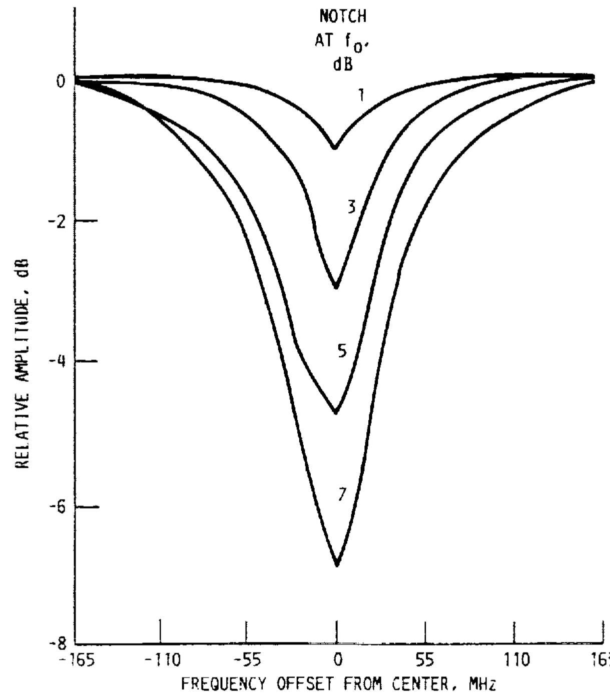

FIGURE 8. - MEASURED AMPLITUDE RESPONSE FOR INDUCED NOTCH DISTORTION.

TABLE I
TEST RESULTS FOR INDUCED DISTORTION

TYPE OF DISTORTION	MAGNITUDE OF DISTORTION [dB]	BER DEGRADATION (@ BER=10^{-7}) [dB]	TYPE OF DISTORTION	MAGNITUDE OF DISTORTION [dB]	BER DEGRADATION (@ BER=10^{-7}) [dB]
None		0.81	Notch 3.353 GHz	6	3.09
2-Ripple	3	2.24	3.375 GHz	6	2.86
	6	4.33	3.408 GHz	6	4.60
3-Ripple	1	1.21	3.430 GHz	6	4.81
	2	1.64	3.463 GHz	6	2.51
	3	2.13	3.485 GHz	6	1.62
	4	3.28	3.518 GHz	6	1.18
	5	6.15	3.540 GHz	6	0.95
	6	8.11	Notch 3.320 GHz	1	0.89
4-Ripple	3	2.24		2	1.05
5-Ripple	3	2.17		3	1.64
Positive Slope	3	0.89		4	1.77
	4	0.90		5	2.33
	5	0.86		6	3.02
	6	1.04		7	3.55
	7	0.93		8	5.25
	8	1.45		12	9.71
	12	1.86	Notch 3.375 GHz	1	1.11
	15	3.14		2	1.48
Negative Slope	3	1.75		3	1.92
	6	1.51		4	2.43
	12	2.69		5	2.10
Upward Parabola	3	1.25		6	2.86
	4	0.93		7	3.88
	6	0.88		8	5.29
Downward Parabola	3	0.74		10	5.19
	4	0.82	Notch 3.430 GHz	1	1.53
	6	0.88		2	1.86
	8	0.92		3	2.69
Notch 3.210 GHz	6	1.13		4	3.18
3.243 GHz	6	1.00		5	3.96
3.265 GHz	6	1.02		6	4.81
3.298 GHz	6	1.97		7	5.27
3.320 GHz	6	3.02		8	6.76

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demodulator (i.e., 50 percent BER), in which case no further increase in distortion was attempted.

The notch distortions were generally the easiest to obtain, since they usually required only one or two resonators to be tuned. The first set of notch tests involved moving a 6 dB notch across the passband from 3.21 to 3.54 GHz. A second set of tests involved placing a notch of varying depth at a fixed frequency. This was done at three frequencies: the band center, f_o, 3.375 GHz, and $f_o \pm 1/4T$ Hz, corresponding to 3.32 and 3.43 GHz, respectively. An example of how the SMSK spectrum is distorted by a notch is shown in Fig. 9, for a 10 dB notch at the band center frequency.

After obtaining the desired distortion pattern, the equalizer was connected to the test system as shown in Fig. 10(a), simulating an amplitude distorted satellite channel. A BER curve was measured for each of 66 distortions. The results of these measurements are given in Table 1 and are discussed below.

Results of Induced Distortion Tests

The induced distortion tests resulted in 66 measured BER versus E_b/N_o curves. An example of these curves is shown in Fig. 11. In this example an amplitude notch of varying depth was induced at the center of the test band (3.375 GHz). The BER curves measured for each of several notch depths are plotted. The curves move away from the ideal SMSK curve as the depth of the notch increases, indicating an increasingly degraded BER. The degradation of each curve with respect to the ideal curve can be conveniently quantified by measuring the additional amount of E_b/N_o required to maintain a given BER, compared to the E_b/N_o required for the ideal curve. Using a BER of 10^{-6} as a reference, the BER degradation measured for each of the 66 induced distortion is listed in Table 1. The first entry in the table represents the distortionless case, where the BER degradation of 0.81 dB results from modem implementation losses. The results for each type of induced distortion will now be discussed.

Several variations of amplitude ripple were induced, referred to by the number of positive amplitude peaks occurring in-band. Thus, the 2-ripple case has two positive peaks, the 3-ripple case has three positive peaks, etc. For the

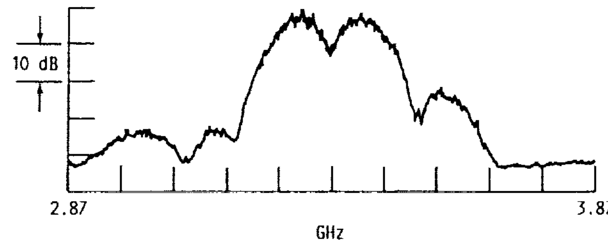

FIGURE 9. - EXAMPLE OF AN SMSK SPECTRUM DISTORTED BY A 10 dB NOTCH AT THE BAND CENTER FREQUENCY.

3-ripple case, the amount of ripple was varied from 1 to 6 dB. The resulting BER degradation is plotted in Fig. 12 as a function of peak-to-peak ripple depth. Slight degradation is observed until the ripple depth reaches 4 dB, at which time the BER degradation begins to increase rapidly. For the 2-, 4-, and 5-ripple cases, measurements made for a 3 dB ripple show a similar degradation to the 3-ripple case. A measurement made for the 2-ripple case at 6 dB depth, however, shows significantly less degradation than the 3-ripple case at 6 dB. We believe this is due to the location of the negative amplitude peaks at $f_o \pm 1/4T$ (±55 MHz) from the center frequency. These two frequencies are significant for SMSK modulation. At $f_o - 1/4\,T$ the carrier, f_c, is located and there are no data transitions, corresponding to transmission of a sequence of consecutive ones or zeros. Transmission of a 1-0-1-0. . . data sequence results in the instantaneous frequency $f_o + 1/4T$.[4] Thus, the 3-ripple case affects both the carrier tracking and phase transitions.

The BER degradation measured for amplitude slope is plotted in Fig. 13. Very little degradation was observed due to either positive or negative slope. For the positive slope, virtually no additional degradation (compared to the distortionless case) occurred until an 8 dB slope was induced. Even for a 15 dB slope, the additional degradation was only 2 dB. The degradation due to a negative slope was 0.5 to 0.9 dB greater than for a positive slope, still relatively minor compared to other distortion types.

Parabolic distortions produced even less degradation than the amplitude slope distortions. Figure 14 shows that the BER degradation due to parabolic slope is practically negligible. This is a

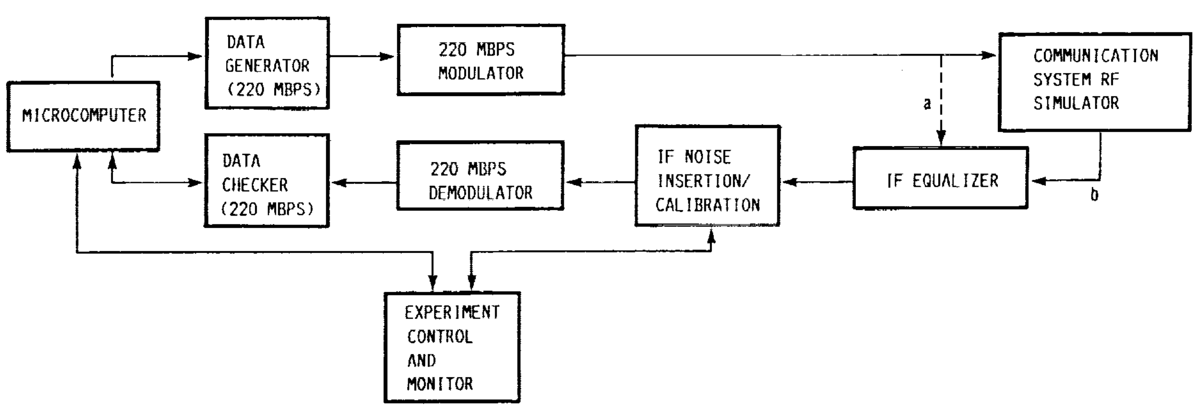

FIGURE 10. - BLOCK DIAGRAM OF BIT-ERROR RATE MEASUREMENT SETUP. WITH THE RF SIMULATOR BYPASSED (a), THE IF EQUALIZER INDUCED AN AMPLITUDE DISTORTION. IN EQUALIZATION TESTS (b), THE IF EQUALIZER IS USED TO FLATTEN THE AMPLITUDE DISTORTIONS CAUSED BY THE RF SIMULATOR.

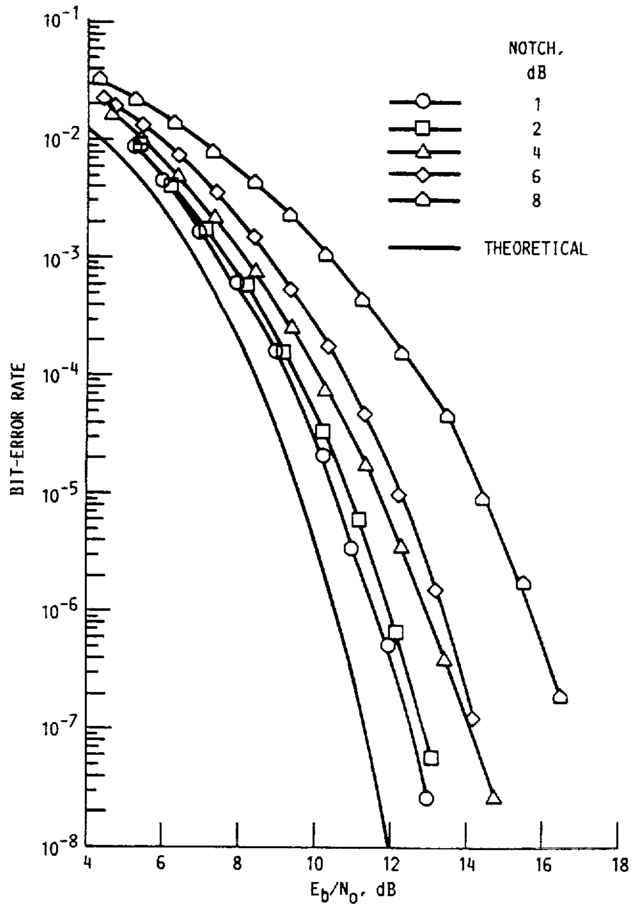

FIGURE 11. - BER CURVES FOR A NOTCH AT 3.375 GHz.

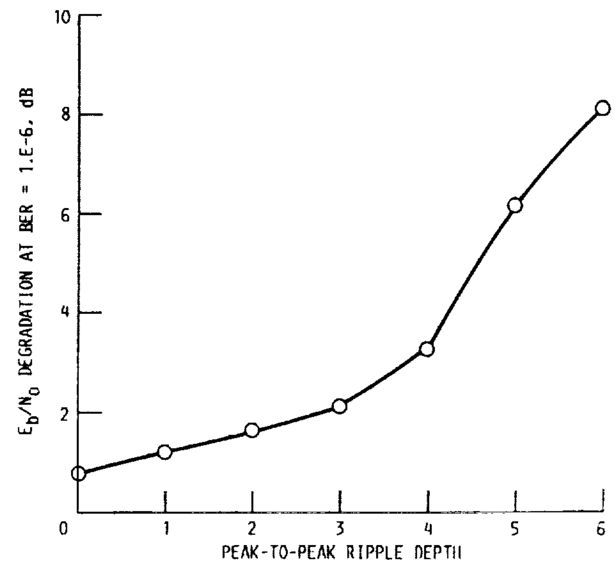

FIGURE 12. - BER DEGRADATION AS A FUNCTION OF RIPPLE DEPTH (IN dB) FOR 3-RIPPLE AMPLITUDE DISTORTION.

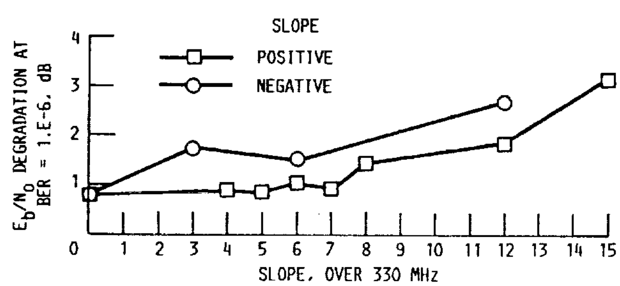

FIGURE 13. - BER DEGRADATION AS A FUNCTION OF AMPLITUDE SLOPE, dB.

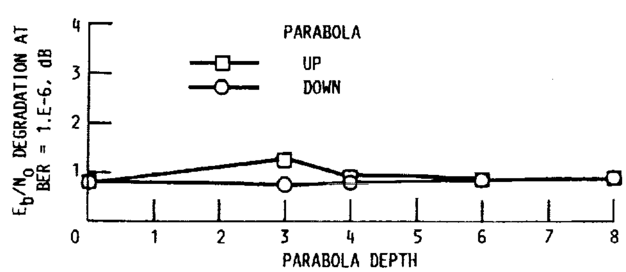

FIGURE 14. - BER DEGRADATION AS A FUNCTION OF PARABOLA DEPTH (IN dB) FOR PARABOLIC AMPLITUDE DISTORTION.

significant result, since channel filtering in a system often degrades BER due to a parabolic response which results in distortion at the band edges. For SMSK, very little signal power resides at the band edges, since nearly all the of the power is concentrated in the main spectral lobe. This most probably accounts for the negligible degradation caused by the parabolic distortion. This result also is similar to results found for group delay distortion at the band edges for SMSK in a previous study,[13] where it was found that group delay distortions at the band edges do not affect the BER for an SMSK satellite channel.

The most interesting results were produced by the induced amplitude notch distortions. In the first set of notch tests, a 6 dB notch was induced at a number of frequencies across the band, from 3.21 to 3.54 GHz. Figure 15 shows the BER degradation resulting from a 6 dB notch as a function of frequency offset from f_o. Degradation caused by notches near the band edges is negligible. As notches are moved toward the center of the band the degradation increases, peaking at approximately $f_o \pm 55$ MHz, corresponding to the $\pm 1/4T$ frequencies. The degradation for a 6 dB notch was about 3 dB at -55 MHz and 5 dB at +55 MHz, indicating that detection of the 1-0-1-0. . . phase transitions is particularly sensitive to this type of distortion. In contrast, the group delay distortion study[13] indicated that group delay distortions at the -55 MHz frequency produced much more BER degradation than group delay distortions at +55 MHz.

In the second set of notch tests, notches of varying depth were induced at three frequencies of interest: 3.32, 3.375, and 3.43 GHz, corresponding to f_o - 55 MHz, f_o, and f_o + 55 MHz, respectively. These results are plotted in Fig. 16. For the

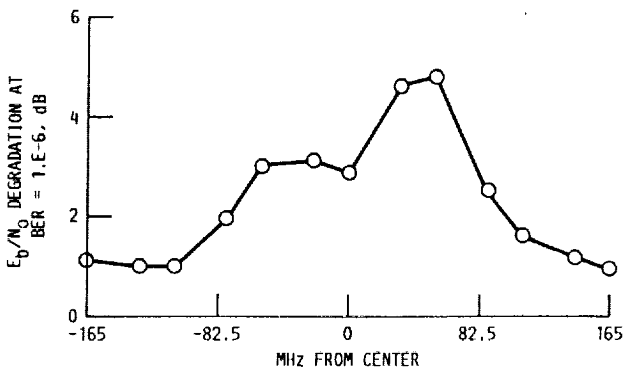

FIGURE 15. - BER DEGRADATION AS A FUNCTION OF FREQUENCY OFFSET FROM CENTER FOR A 6 dB NOTCH.

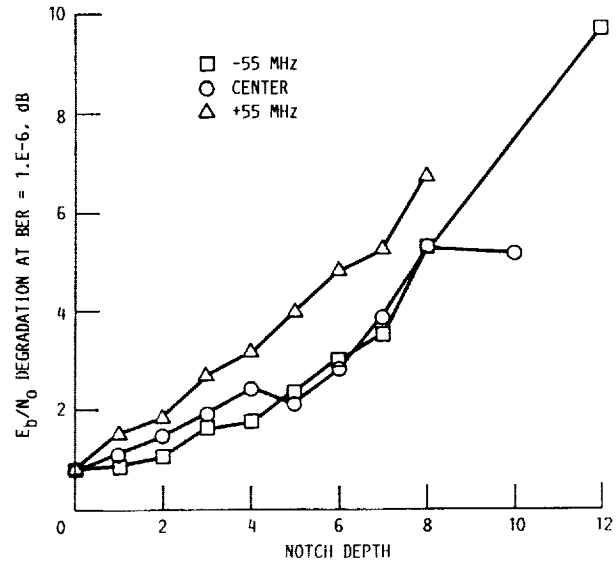

FIGURE 16. - BER DEGRADATION AS A FUNCTION OF NOTCH DEPTH (IN dB) FOR NOTCHES AT f_0-55 MHz, f_0, AND f_0+55 MHz.

f_0 - 55 MHz and f_0 notches the additional BER degradation compared to the distortionless case is small, less than 1.5 dB, up to a notch depth of 5 dB. For deeper notches, the degradation increases more rapidly, at a rate of 1 dB of degradation per decibel of notch depth. For the f_0 + 55 MHz notch the degradation is 1 to 2 dB greater than for notches at the other two frequencies for corresponding notch depths. This again indicates the greater sensitivity to amplitude distortion at f_0 + 55 MHz.

In summary, the induced amplitude distortion experiments indicate that the BER degradation is dependent on both the type of distortion and its location in frequency with respect to the modulated spectrum. The slope and parabolic distortions contribute negligible degradation. The ripple distortions, representing the most common type of distortion attributable to system hardware, cause significant distortion when the peak-to-peak ripple becomes greater than 3 dB. Degradation is most severe when the negative ripple peaks occur at ±1/4T from the center frequency. Notch distortion, which represents multipath propagation effects, create degradation which is also a function of relative frequency. Notches approaching the center of the spectrum create more degradation than those at the band edges. For the SMSK modulation, notches at the frequency f_0 + 1/4T cause the greatest distortion per decibel of notch depth.

Link Equalization Tests

The SITE communications system simulator provided the opportunity to test the effectiveness of fixed IF amplitude equalization in improving the BER performance of a satellite channel. As applied to a real system, this procedure assumes that there are constant amplitude distortions resulting from system hardware which can be improved permanently by using a fixed amplitude equalizer.

The SITE system simulator has four variable parameters which can be manipulated in search of candidate channels for equalization. These parameters are the operating frequency band, matrix switch crosspoint, TWT operating point, i.e., linear, saturated, and 1 dB compression, and TWT power mode. The TWT used in the transponder is a multipower mode TWT/power processor with three distinct power output modes designated: low, medium, and high. In selecting six combinations of these parameters for equalization tests, the frequency band used remained constant (f_0 = 29.528 GHz uplink and 19.728 GHz downlink). The TWT was operated in low and medium power modes at 1 dB compression and linear operating points, and five different matrix switch crosspoints were used.

Seven equalization tests were performed using the six channel parameter combinations described above. In each case, a swept CW amplitude measurement was made over the link from the ground terminal transmit IF to the ground terminal receive IF (or from the modulator output to the demodulator input). Thus, the distorted amplitude response seen by the SMSK demodulator was measured. A BER measurement was performed on the unequalized link. The IF equalizer was adjusted to flatten the amplitude response of the distorted channel to the extent possible and inserted in front of the SMSK demodulator, as shown in Fig. 10(b). The swept CW and BER measurements were repeated on the equalized channel to complete the test. For one of the six channel parameter combinations, two equalization tests were performed; a partial equalization to observe incremental BER improvement, followed by further equalization to obtain the best possible amplitude response and BER improvement.

Results of Link Equalization Tests

Results for the seven link equalization tests are summarized in Table 2. A qualitative description of the amplitude distortion and the channel configuration are given in the first two columns. The third and fourth columns list the peak amplitude distortion, measured by subtracting the minimum in-band amplitude from the maximum, before and after equalization. The final columns give the BER degradation before and after equalization, and the measured BER improvement due to equalization.

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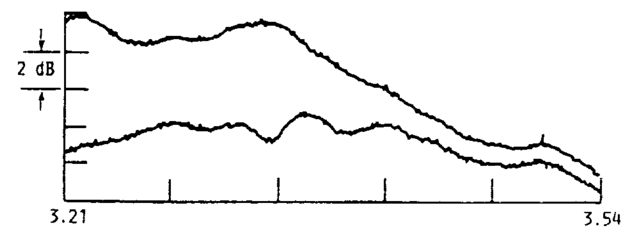
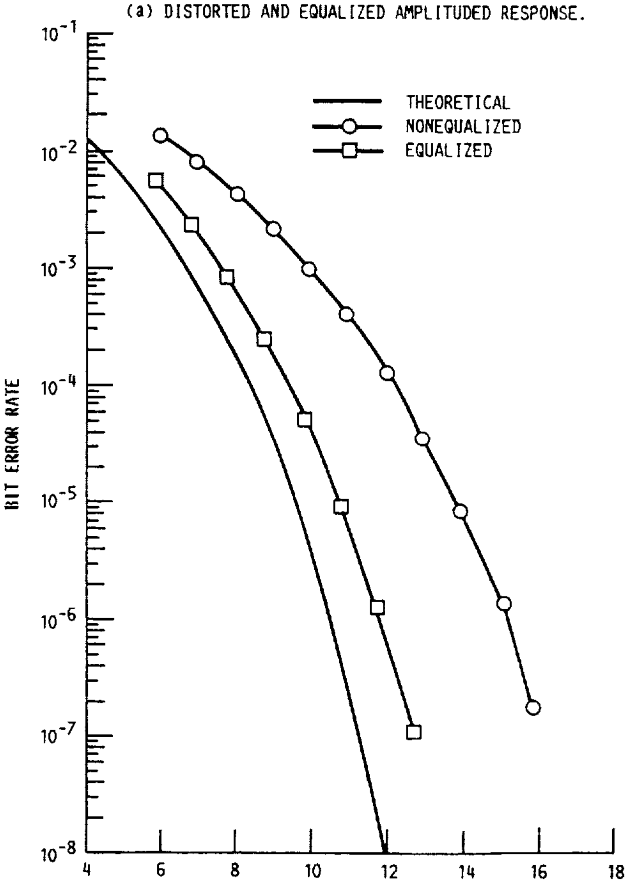
TABLE II
TEST RESULTS FOR LINK EQUALIZATION

DESCRIPTION OF CHANNEL AMPLITUDE DISTORTION	CHANNEL CONFIGURATION	PK TO PK AMPLITUDE DISTORTION (dB) BEFORE EQ.	PK TO PK AMPLITUDE DISTORTION (dB) AFTER EQ.	BER DEGRADATION at 10^{-6} (dB) BEFORE EQ.	BER DEGRADATION at 10^{-6} (dB) AFTER EQ.	BER IMPROVEMENT DUE TO EQUALIZATION (dB)
5 dB Linear Drop 3.34–3.48 GHz 2.7 dB Linear Rise 3.24–3.34 GHz	Med Mode, Linear Cross Point 3–3	5.0	1.7	2.9	1.0	1.9
8 dB Linear Drop 3.34–3.54 GHz Nearly Flat 3.21–3.32 GHz (FIG 17)	Low Mode, Linear Cross Point 4–3	8.0	4.0	4.7	1.3	3.4
6 dB Linear Drop 3.32–3.47 GHz Nearly Flat 3.21–3.32 GHz	Med Mode, 1 dB Cross Point 4–3	6.0	4.0	4.0	0.9	3.1
3 dB Ripple, Peaks at 3.34 GHz and 3.42 GHz	Low Mode, Linear Cross Point 5–5	4.0	2.0	1.5	1.0	0.5
2–3 dB Ripples, Peaks at 3.34, 3.42, and 3.52 GHz	Med Mode, 1 dB Cross Point 6–6	4.0	2.0	1.8	1.8	0.0
5 dB Linear Drop 3.32–3.47 GHz 2 dB Valley 3.21–3.32 GHz (FIG 18)	Low Mode, Linear Cross Point 6–3	5.0	3.5	3.3	2.2	1.1
5 dB Linear Drop 3.32–3.47 GHz 2 dB Valley 3.21–3.32 GHz (FIG 18)	Low Mode, Linear Cross Point 6–3	5.0	3.0	3.3	1.1	2.2

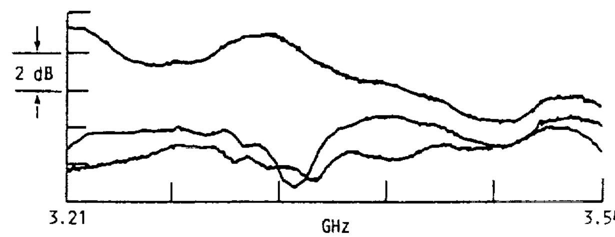


(a) DISTORTED AND EQUALIZED AMPLITUDED RESPONSE.

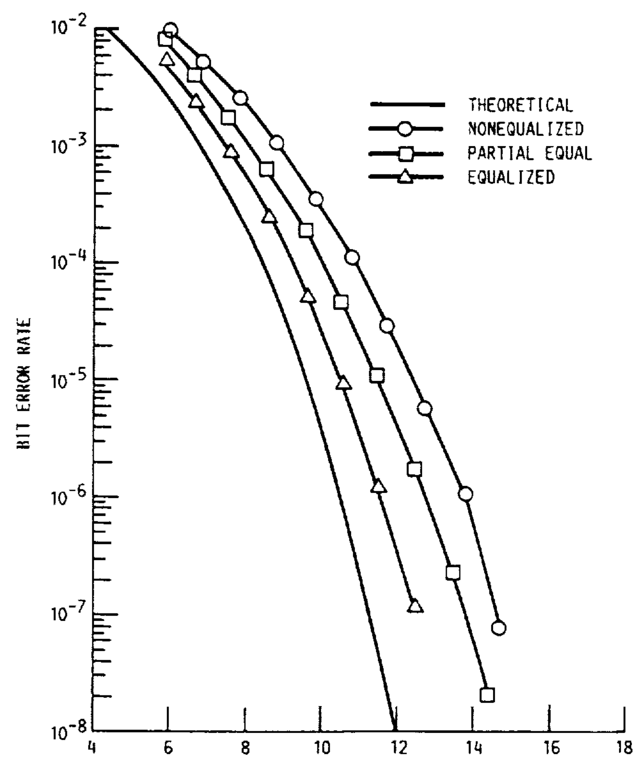


(b) DISTORTED AND EQUALIZED BER CURVES.

FIGURE 17. - EXAMPLE OF LINK EQUALIZATION TEST RESULTS. (TWT LOW MODE, LINEAR; CROSSPOINT 4-3).



(a) DISTORTED, PARTIALLY EQUALIZED, AND FULLY EQUALIZED AMPLITUDE RESPONSE.



(b) DISTORTED, PARTIALLY EQUALIZED, AND FULLY EQUALIZED BER CURVES.

FIGURE 18. - EXAMPLE OF LINK EQUALIZATION TEST RESULTS. (TWT LOW MODE, LINEAR; CROSSPOINT 6-3).

Examples of plotted link equalization results are shown in Figs. 17 and 18. In Fig. 17(a), the swept CW amplitude response before and after equalization is plotted, for the channel configured with the transponder TWT operated linearly in the low power mode using matrix switch crosspoint 4-3. Significant improvement of the amplitude response was obtained with the equalizer. The BER performance, plotted in Fig. 17(b), shows 3.4 dB of improvement (at BER = 10^{-6}) due to equalization. In Fig. 18(a), with the TWT operated linearly in the low power mode using matrix switch crosspoint 6-3, two levels of equalization were attempted. The top curve is the amplitude response for the unequalized channel. The middle curve shows the first equalization attempt, which improved the original response but added a 3 dB notch at 3.35 GHz. The lower curve in the figure is the final equalization, with the notch essentially removed. The resulting BER curves, Fig. 18(b), show that the partial equalization resulted in a 1.1 dB improvement in BER performance and the final equalization attempt yielded an additional 1.1 dB of improvement.

Improved BER performance was observed in six of the seven equalization tests. The improvement ranged from 0.5 to 3.4 dB, and was proportional to the amount of distortion in the unequalized channel. In the one test in which no improvement was obtained, the equalization applied resulted in only a modest improvement in amplitude response, reducing the depth of a 3-ripple response by about 1 dB. The induced distortion tests for the 3-ripple case indicated only a modest improvement in BER for this case. The measured results showed an identical BER performance before and after equalization.

Conclusions

The results of the induced distortion tests indicate that the BER degradation resulting from amplitude distortions are related to the type of distortion and its location in frequency relative to the modulated spectrum. Distortions occurring at the band edges were negligible, as were pure slope and parabolic distortions. Distortions occurring toward the center of the modulated spectrum caused degradation which was proportional to the magnitude of the amplitude distortion.

Of particular importance was the result that notch distortions significantly affect the BER when they occur at the frequencies corresponding to $f_o \pm 1/4T$, or one-fourth of the data rate above and below the center frequency of the modulated spectrum. For SMSK modulation, these two frequencies correspond to the instantaneous frequencies occurring during alternating bit sequences (1-0-1-0. . . at +1/4T) or consecutive bit sequences (0-0-0. . . or 1-1-1. . . at -1/4T). For other modulation schemes, the sensitivity to notch distortions will depend on the structure of the modulated spectrum, particularly the instantaneous frequencies occurring during the transition of bits or groups of bits.

Multipath propagation effects generally manifest themselves in frequency selective notches such as those simulated in the induced distortion tests. The tests results show that, depending on the frequency of the notch relative to the modulated spectrum, notches greater than 6 dB in depth can cause severe BER degradation. Above 6 dB, each 1 dB increase in notch depth caused approximately 1 dB of additional BER degradation.

The hardware portion of a satellite link will inevitably contribute amplitude distortion to the channel. The induced distortion tests and the link equalization tests have shown that some amount of amplitude distortion is tolerable without seriously degrading the BER. Ripples up to 2 dB in depth contribute no more than 1 dB of BER degradation. For SMSK modulation, distortions occurring near the band edges can be ignored.

The link equalization tests demonstrated that significant improvement in BER can be obtained in degraded channels through equalization. For fixed amplitude distortions resulting from hardware imperfections, a fixed equalizer placed in the ground terminal IF path or in the satellite transponder itself can restore the BER performance to a level approaching the undistorted case. For time-varying distortions due to atmospheric effects, adaptive equalization could be employed to obtain similar BER improvement.

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16. Abstract

Satellite communications links are subject to distortions which result in an amplitude versus frequency response which deviates from the ideal flat response. Such distortions result from propagation effects such as multipath fading and scintillation and from transponder and ground terminal hardware imperfections. Laboratory experiments performed at NASA Lewis Research Center measured the bit-error rate (BER) degradation resulting from several types of amplitude response distortions. Additional tests measured the amount of BER improvement obtained by flattening the amplitude response of a distorted laboratory-simulated satellite channel. This paper presents the results of these experiments.

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