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PERFORMANCE RESULTS OF SOME CANDIDATE FRENCH MODEMS FOR THE AERONAUTICAL SATELLITE COMMUNICATION CHANNEL

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16. Abstract

Five candidate data, voice, and ranging modems were evaluated by the AEROSAT channel simulation facility to determine applicability for use in the aeronautical satellite communication channel for air traffic control. The modems were supplied by Telecommunications Radio-electriques et Telephoniques of Paris, France. The modems' performance were evaluated as a function of carrier to noise ratio, carrier to multipath ratio, doppler frequency, and relative doppler frequency. The results are presented herein.

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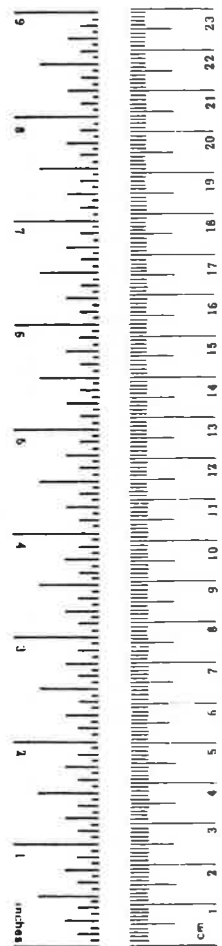
METRIC CONVERSION FACTORS

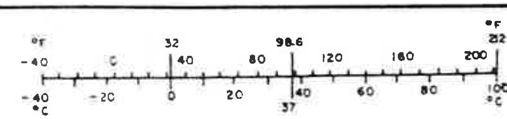
Approximate Conversions to Metric Measures

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



CONTENTS

2. MODEM EVALUATION

General

The laboratory evaluation of modems to be used for AEROSAT must involve consideration of the channel through which the modems must interface. Thus it was desirable to use a channel simulator (see Section 3) to be able to control, under laboratory conditions, those parameters which would influence modem operation. The laboratory evaluation equipment will thus be briefly described in this section.

With reference to Figures 1 and 2, the output of the noise source from 2-1000 MHz is amplified and then bandpass filtered through a filter 625 kHz wide centered at 70 MHz. The output of this filter then goes to the noise level control attenuator, and is then further amplified to bring up the level to be compatible with modems whose outputs are 0 dBm. It is necessary to split the amplifiers since two stages of amplification before the bandpass filter would saturate the second amplifier. On the signal side, the modulator output goes to the simulator where multipath is added along with any desired doppler; the signal is then sent back from the simulator to the attenuator which sets carrier level. Both signal and noise are summed and further amplified to a level compatible with the demodulator input requirements. At the output is a switch allowing the experimenter to measure C/N_o. Switching ATT_N, the attenuator in the noise path, maximum attenuation allows signal power to be measured in the absence of noise. Then restoring ATT_N to zero and switching in maximum attenuation of ATT_C, the attenuator in the signal path, allows noise power to be measured in a bandwidth of 625 kHz. The RF power meter measures the average values in each case. The C/N_o is then computed from the following equation:

$$C/N_o = P_{C_{dBm}} - P_{N_{dBm}} + 58 \text{ dBHz}.$$

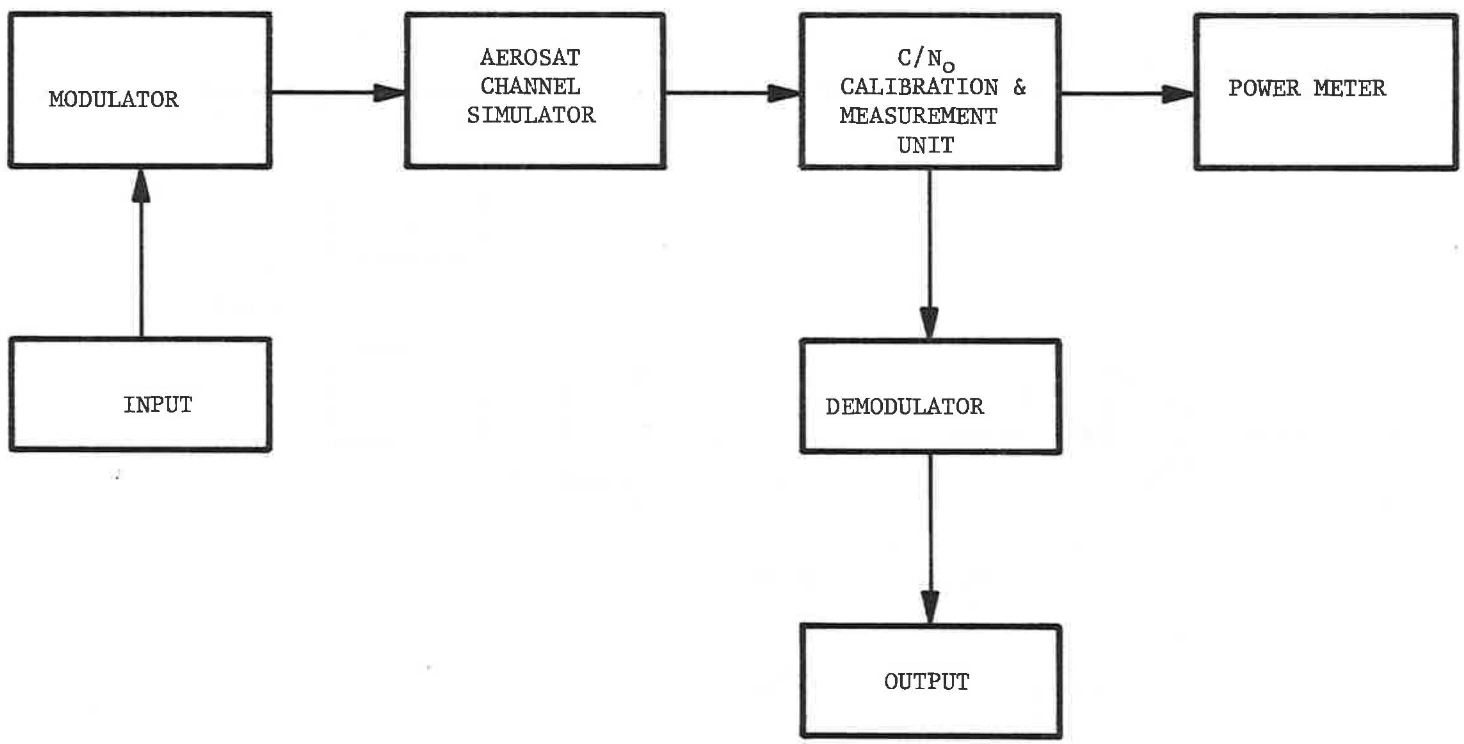


FIGURE 1. BLOCK DIAGRAM - GENERAL MODEM EVALUATION SYSTEM

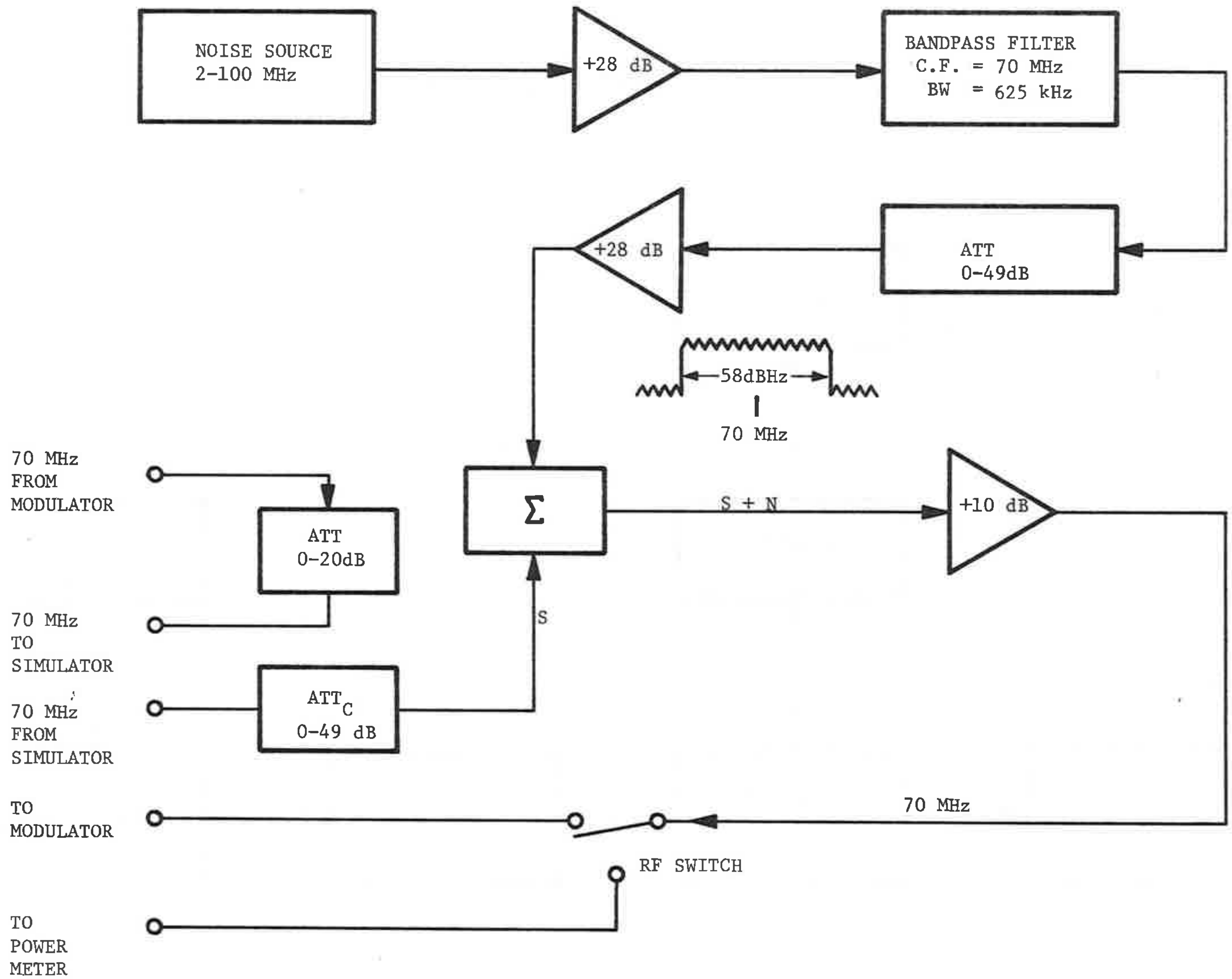


FIGURE 2. BLOCK DIAGRAM - C/N_o MEASUREMENT AND CALIBRATION UNIT

Once a reference value of C/N_o is established, C/N_o is calibrated and can be changed in one dB steps by varying ATT_C or ATT_N. The C/N_o measurement and calibration unit is shown in Figure 3.

2.1 DATA EVALUATION

A block diagram of the laboratory setup used to evaluate the performance of the TDMA data modem is shown in Figure 4. The setup used in evaluating the 50/4800 baud data modem is shown in Figure 5. The TDMA system consisting of the test unit, the 19.2 k bps interface unit, and the modulator and demodulator are pictured in Figures 6, 7 and 8. Note the presence of the level shifting network in Figure 4. The data error analyzer operates on TTL levels (5 volts for high, 0 volt for low) whereas the T.R.T. test unit inputs and outputs at $\pm$ 10 volts. Since the 50/4800 baud modem operates at TTL levels, the level shifting network was not necessary for this modem. See picture of 50/4800 Baud modem, Figure 9.)

The evaluation of data performance fundamentally involves determination of the presence of a transmitted bit, and thus determination of the accuracy of the modem in correctly demodulating the incoming data as a function of C/N_o. The data analyzer transmits a pseudo-random noise (PRN) sequence to the modem at a rate established by the clock being sent by the modem to the code generator (part of the error analyzer). The detected bits from the demodulator are sent to the analyzer, along with the reconstituted clock; the analyzer, upon establishing synchronization between the internally generated code and the received code, makes a bit by bit comparison between the two codes. Any discrepancies are errors which are counted until the analyzer is commanded to stop. Thus a probability of error can be easily established as:

$$P_e = \frac{\text{Errors}}{\text{Bit Rate x } \Delta t} ,$$

where Δt = interval over which the errors are counted. Thus P_e versus C/N_o is established. The data are collected in real time

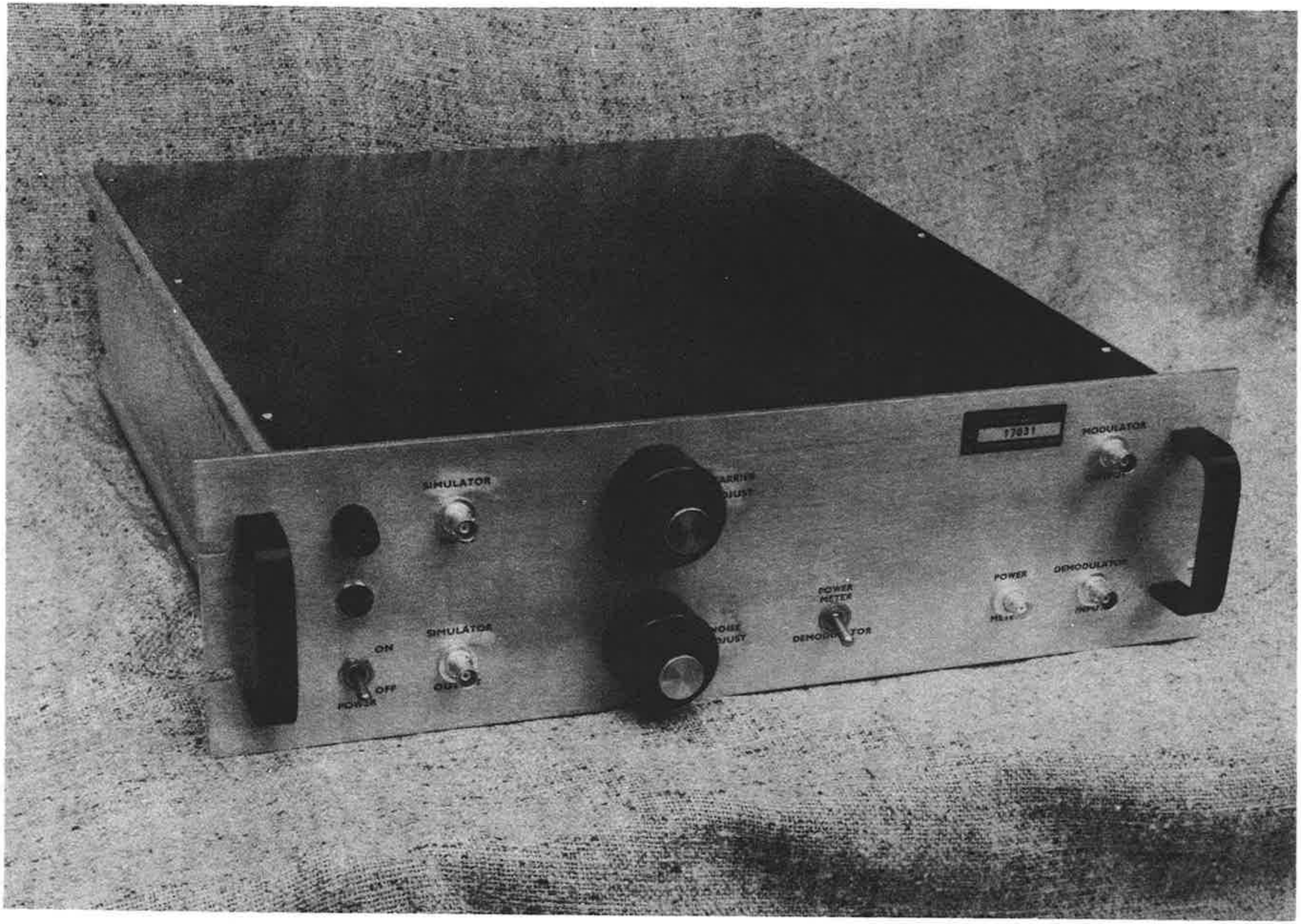


FIGURE 3. C/N_0 CALIBRATION AND MEASUREMENT UNIT

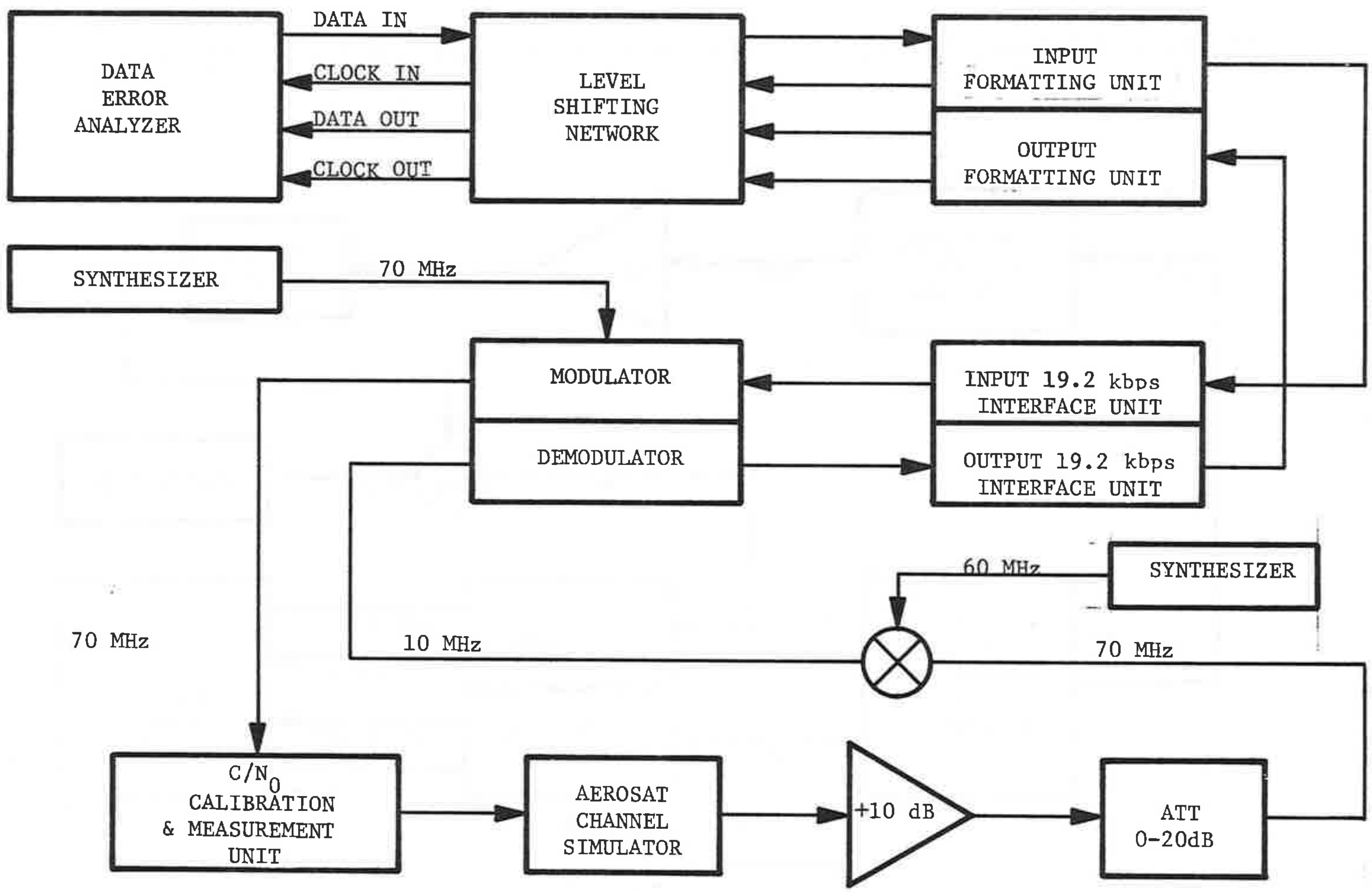


FIGURE 4. BLOCK DIAGRAM - TDMA MODEM DATA PERFORMANCE EVALUATION

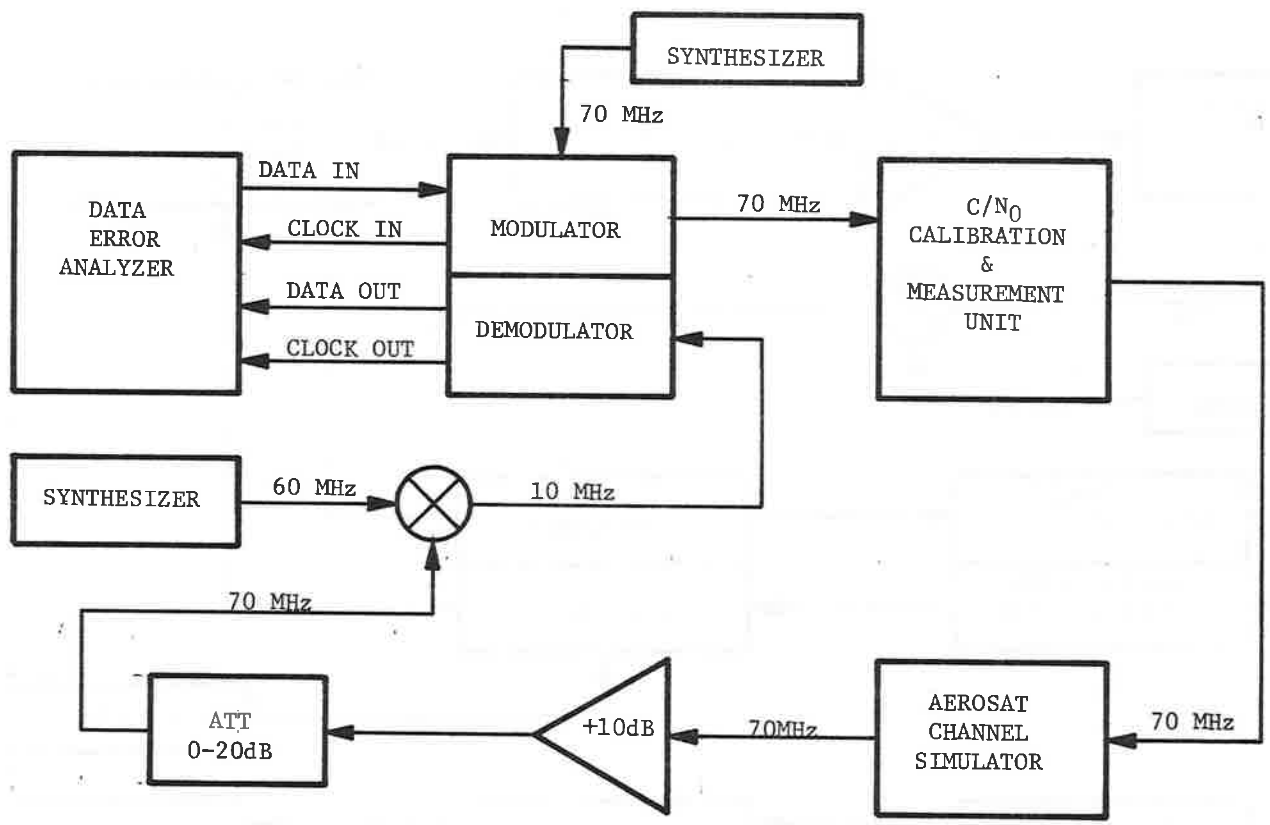


FIGURE 5. BLOCK DIAGRAM - 50/4800 BAUD MODEM DATA PERFORMANCE EVALUATION

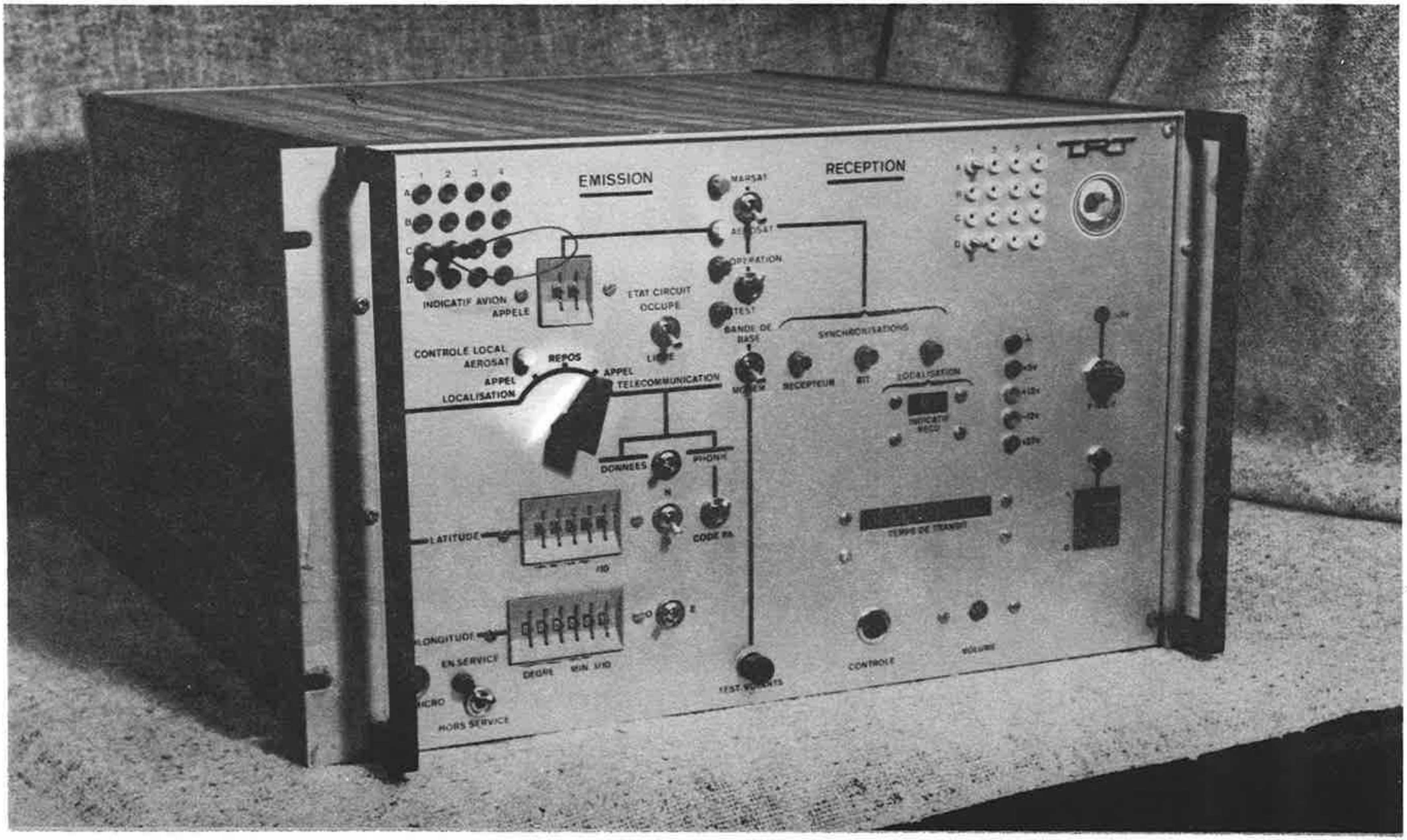


FIGURE 6. TDMA TEST UNIT

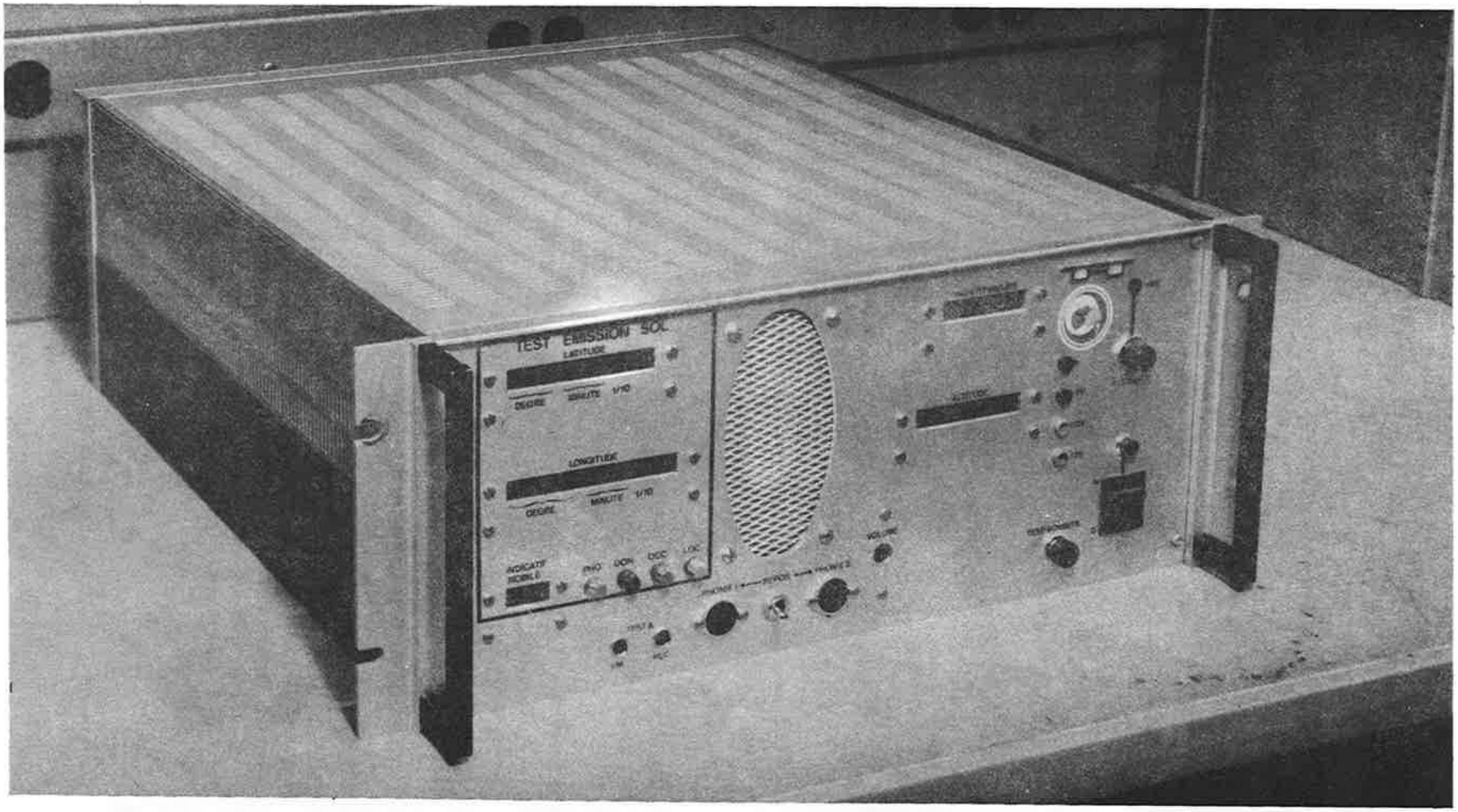


FIGURE 7. TDMA 19.2 kbps INTERFACE UNIT

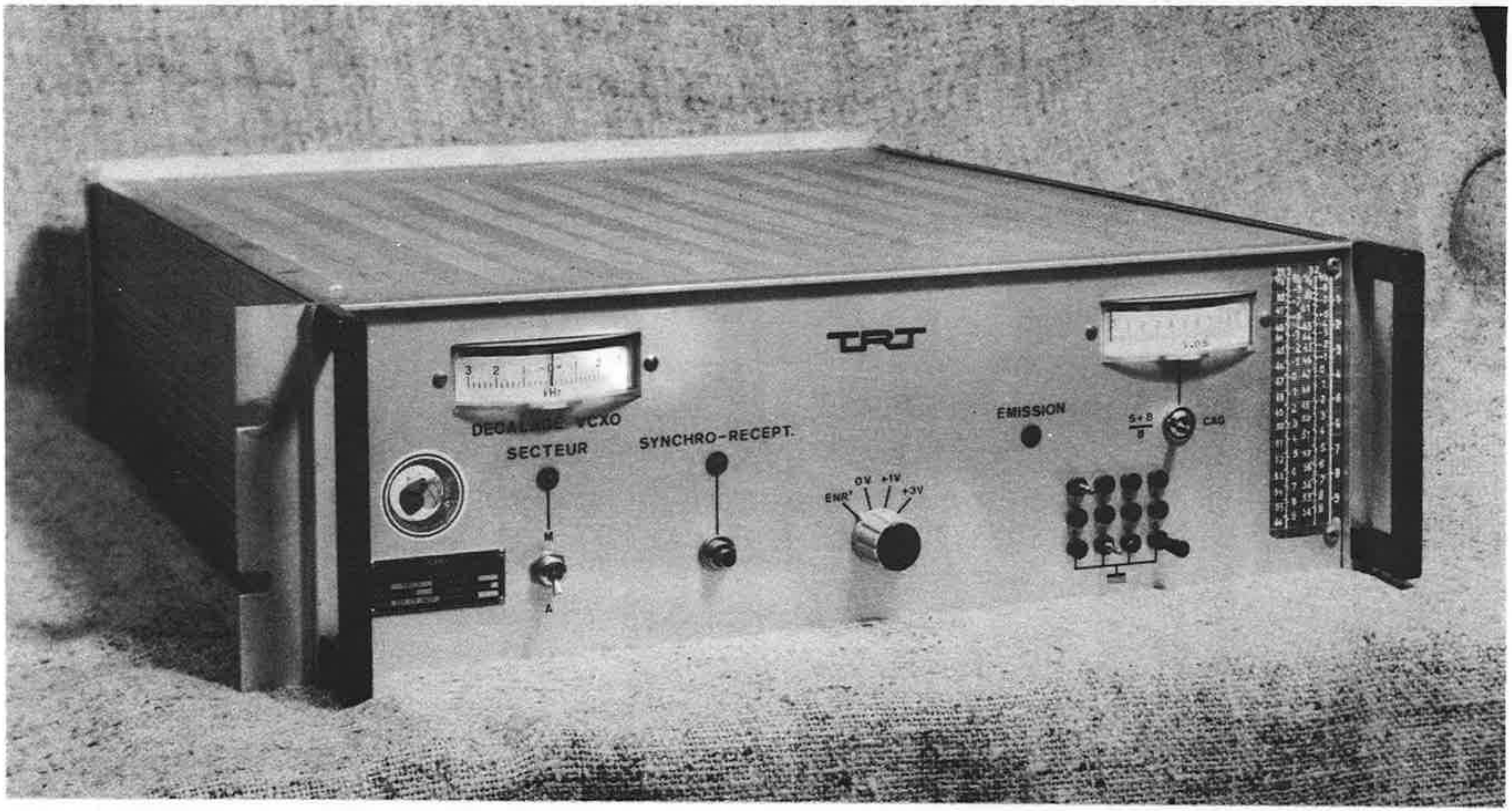


FIGURE 8. TDMA MODULATOR AND DEMODULATOR

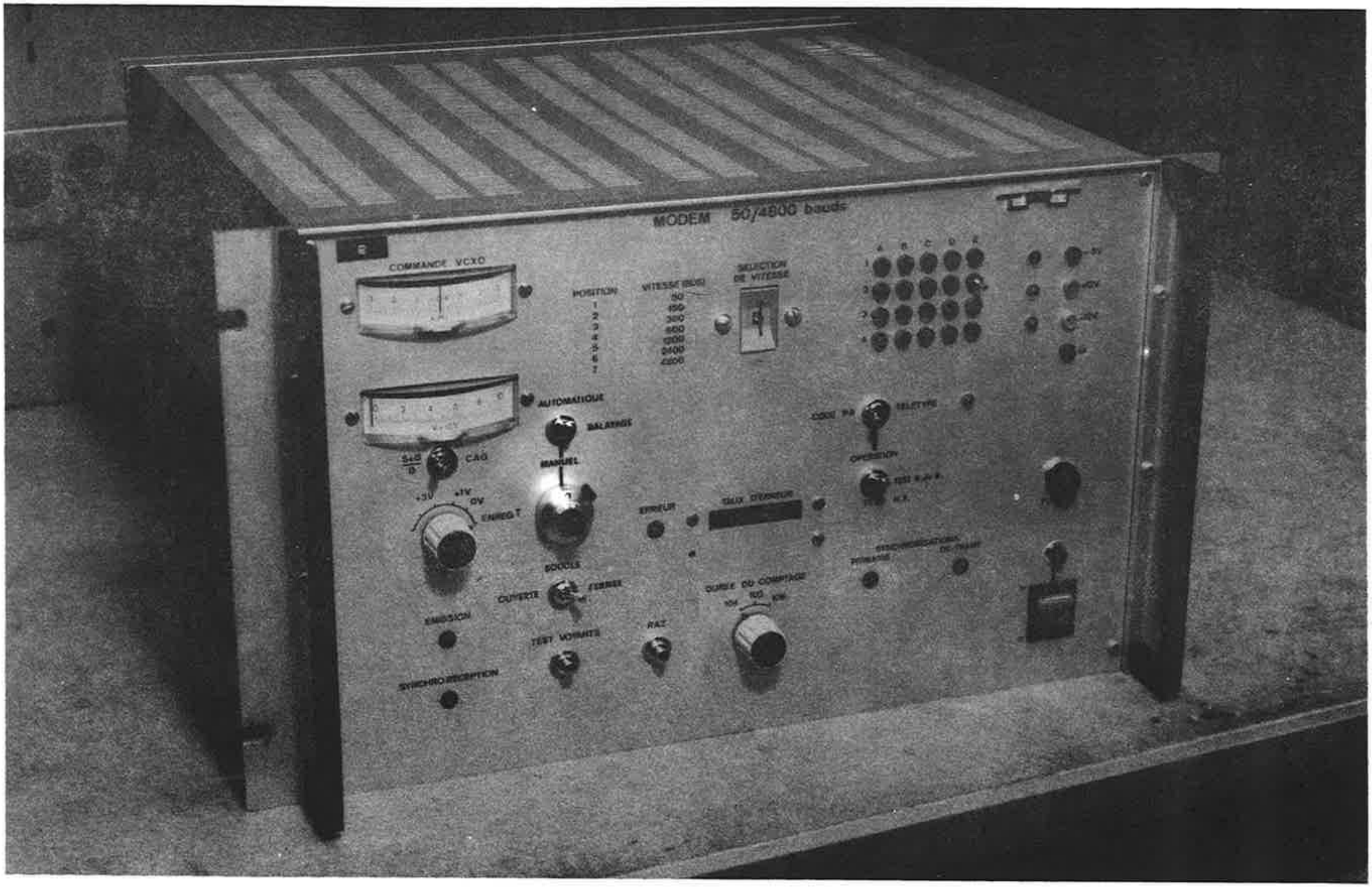


FIGURE 9. 50/4800 BAUD MODEM

and BER's (P_e) obtained immediately. No lengthy or costly error analysis is required to obtain this P_e data. If burst error statistics are desired non-real time processing is required, but this is of a straightforward nature.

2.2 VOICE EVALUATION

A block diagram of the laboratory setup used to evaluate the performance of the voice modem is shown in Figure 10. The evaluation of voice modems required inputting a voice signal and modulating it onto a carrier, transmission of the carrier to the demodulator after the addition of multipath, doppler, relative doppler and noise; receiving the demodulated audio; and establishing a criterion of intelligibility. For these tests recorded lists of phonetically balanced (PB) word lists were played from tape into the TRT test unit input, sent to the 19.2 k bps interface unit, and to the modulator where the 70 MHz IF frequency was sent through the simulator and noise generation circuitry to be received by the demodulator, then on to the output 19.2 k bps interface unit, output test unit and onto the output tape recorder. A series of tapes was recorded (400 words per tape in 50 word lists) as a function of C/N_o and simulator parameters.

Tapes with recorded PB words are sent to an evaluation facility which employs a panel of trained listeners who score the tapes. To obtain a percent intelligibility the number of correctly interpreted words is divided by the total number of words times 100%. Since a panel may consist of ten or fifteen listeners an average intelligibility as a function of C/N_o is established along with a standard deviation. The whole process involves recording the words on tape, sending the tapes to the listener facility, waiting the required time for evaluation, and compiling the intelligibility scores. Thus, the process is somewhat more complicated than that required for obtaining B.E.R.s in the data modem case.

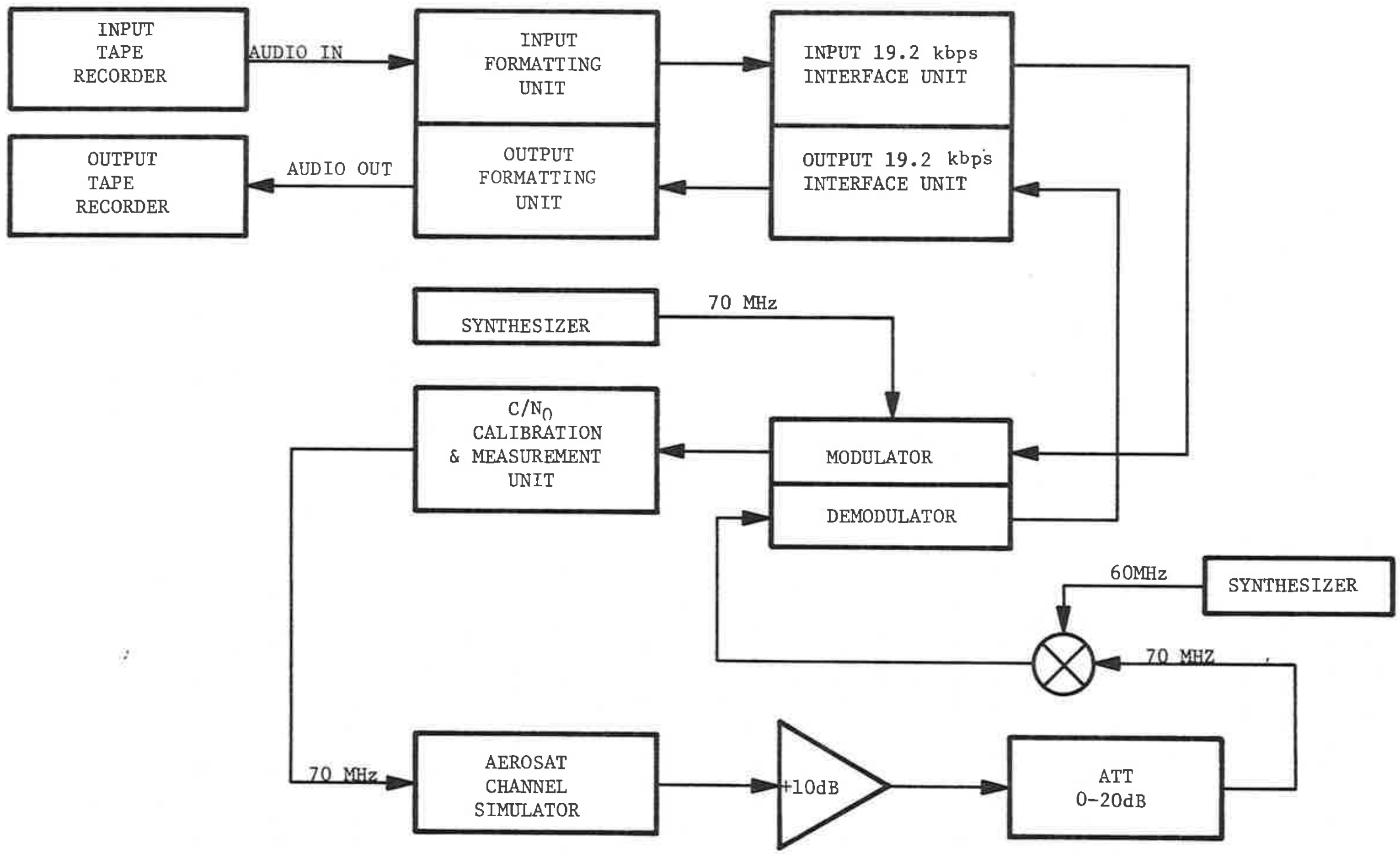


FIGURE 10. BLOCK DIAGRAM - TDMA MODEM VOICE PERFORMANCE EVALUATION

2.3 RANGING EVALUATION

A block diagram of the laboratory procedure used to evaluate the performance of the ranging modem is shown in Figure 11. Determination of range requires accurate determination of the time taken for a pulse to go from point A to B. Since the distance from ground station to satellite is known, the only unknown is the satellite to aircraft distance. If the total time for a pulse to go from ground station to aircraft is $T + t_{sat}$ where T = time from satellite to aircraft and t_{sat} the time from ground station to satellite then the distance from satellite to aircraft is

$$d = v \times T ,$$

where v=c= velocity of light = 3×10^8 m/sec.
Note that if $\Delta t = 1$ nsec $= 10^{-9}$ sec then

$$d = 3 \times 10^8 \times 10^{-9} = .3\text{m}$$

Thus, a 1 ns error in timing is equivalent to a 1 foot error in position determination.

From Figure 11 it is seen that the signal flow is generally the same as for the data and voice signals. Here the ranging pulse, T_1, is transmitted and Δt seconds later, at T_2, enters the computing counter where the value $\Delta t + \delta t$ is outputed. δt is the error in the measurement resulting from pulse jitter. It is important to compute the r.m.s. phase jitter ($\sigma_{r.m.s.}$) of the range signal to establish the range accuracy. The computing counter performs the required calculation by inputing a program from the keyboard. The counter computes $\Delta t + \delta t$ one thousand times and computes the r.m.s. phase jitter. Thus, r.m.s. phase jitter, which is a measure of the accuracy of the system, can be plotted as a function of C/N_0. The results of the tests performed on the ranging modem are presented this way.

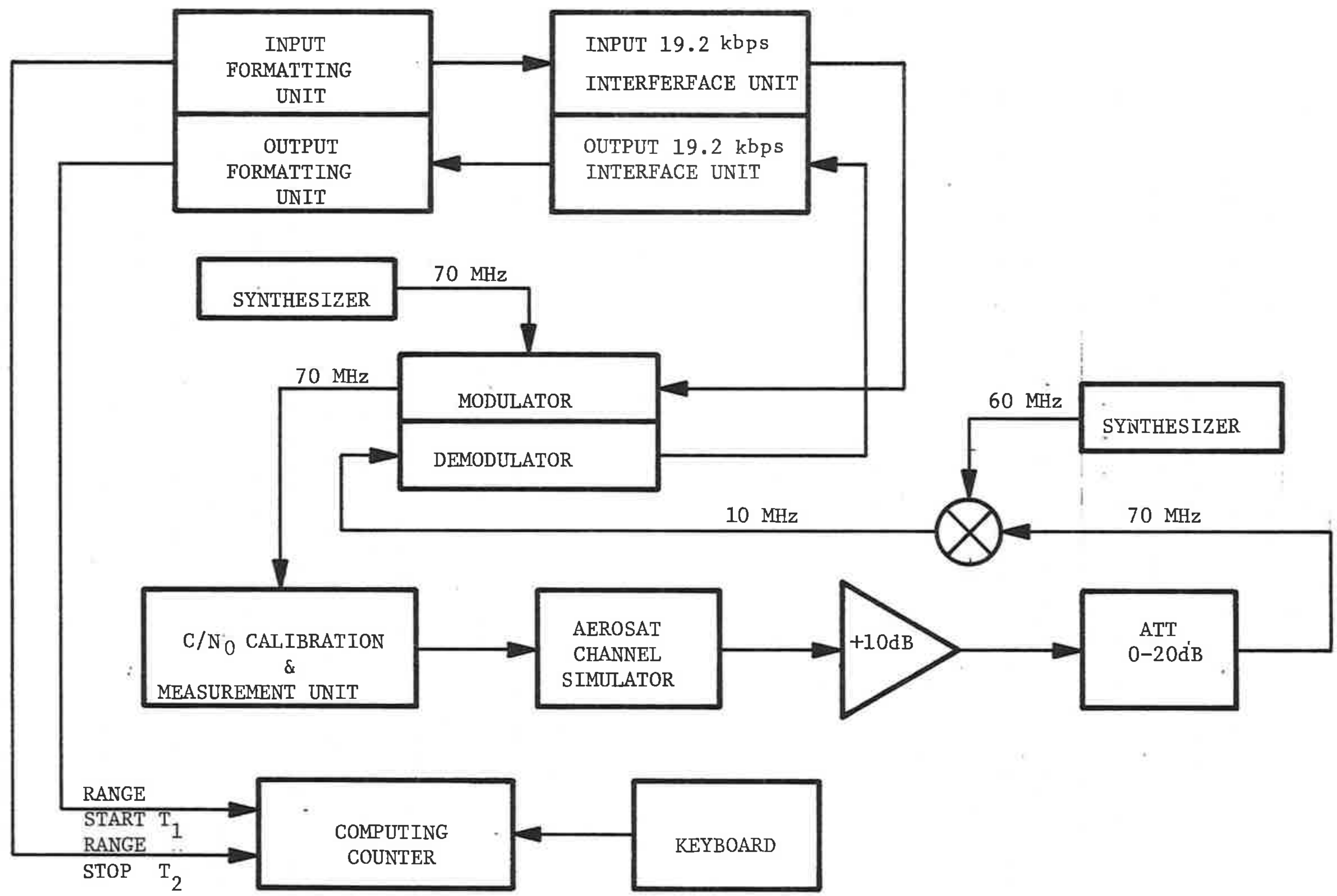


FIGURE 11. BLOCK DIAGRAM - TDMA MODEM RANGING PERFORMANCE EVALUATION

3. AEROSAT CHANNEL SIMULATION FACILITY

The AEROSAT Channel Simulation Facility was established to evaluate candidate modems for use in AEROSAT. The adequate evaluation of the performance of a system designed to operate from satellite to aircraft without resorting to extensive flight tests requires the use of a laboratory instrument to simulate this particular link. The channel simulation facility has such a simulator which forms the core of the facility. See Ref. 1.

The channel simulator (see Figure 12 and Figure 13) simulates the communication channel existing between satellite and aircraft. This channel is characterized by a number of parameters which can vary according to sea conditions and relative geometry between aircraft and satellite. See. Figure 14. The channel simulator accounts for the effects of variation of carrier to multipath ratio (C/M), the relation between the power received in the direct path signal to the aircraft and that received as a reflection off the earth's surface. It also accounts for the time delay between these two signals, along with doppler frequency and relative doppler frequency effects. Multipath bandwidths from 10 Hz to 2000 Hz, and group delays of 5μs, 30μs and 55μ are available.

The effects of doppler frequency shift, caused by aircraft movement in relation to the satellite are simulated, as are the effects of relative doppler frequency shift, corresponding to altitude changes. Doppler frequencies of up to ± 1000 Hz and relative doppler frequencies of up to ± 100 Hz are available. A multipath spread "profile" can be set up by using the simulator's tapped delay line with five taps, 2 μs apart. The output of each tap is mixed with noise in a complex process, in phase and quadrature, to produce multipath; the power output of each as well as the bandwidth is controllable. All may be summed together to produce a complex multipath profile. At the output of the simulator the signal plus multipath are added to gaussian white noise which simulates receiver front end noise. The channel simulator

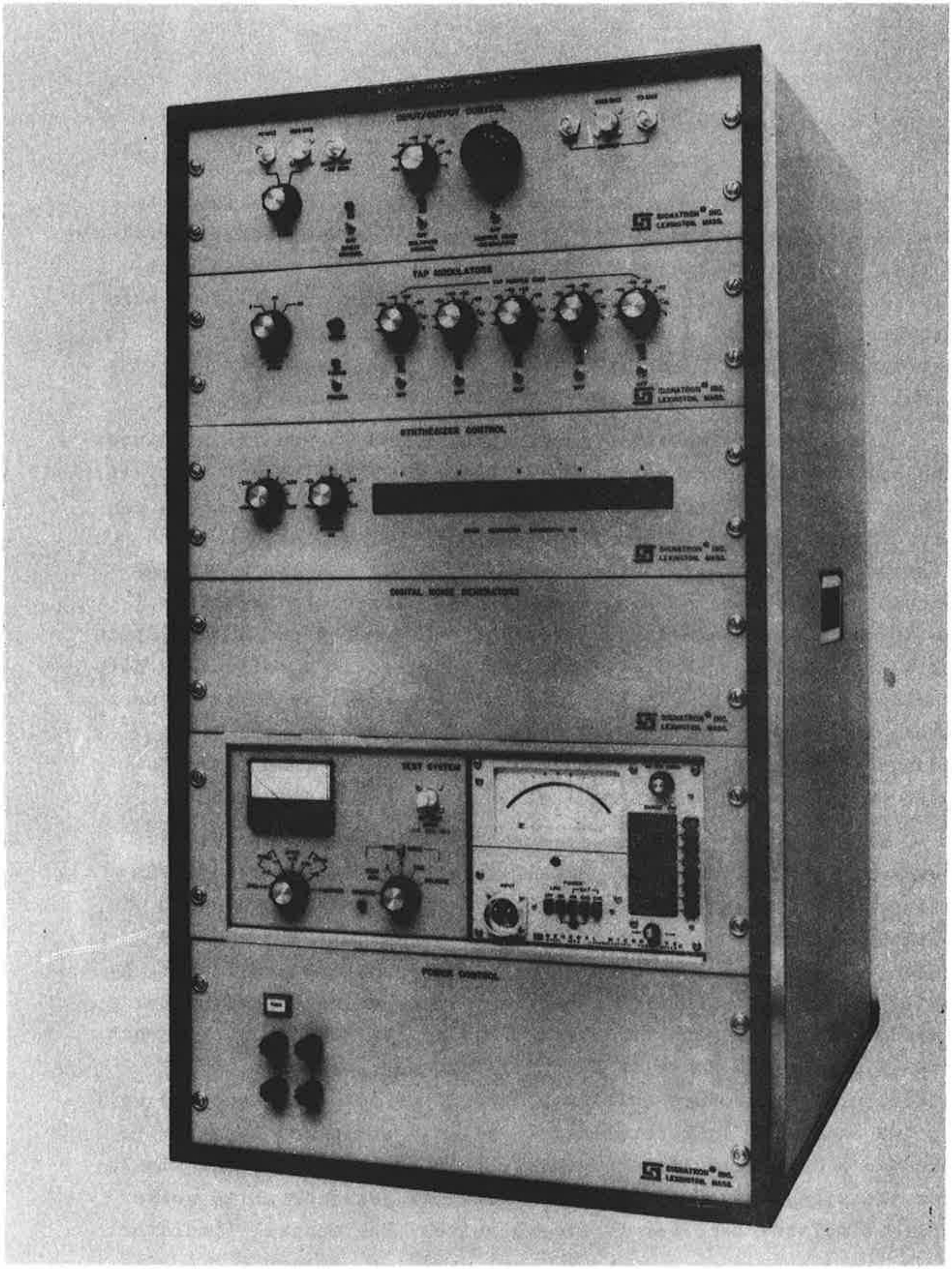


FIGURE 12. AEROSAT CHANNEL SIMULATOR

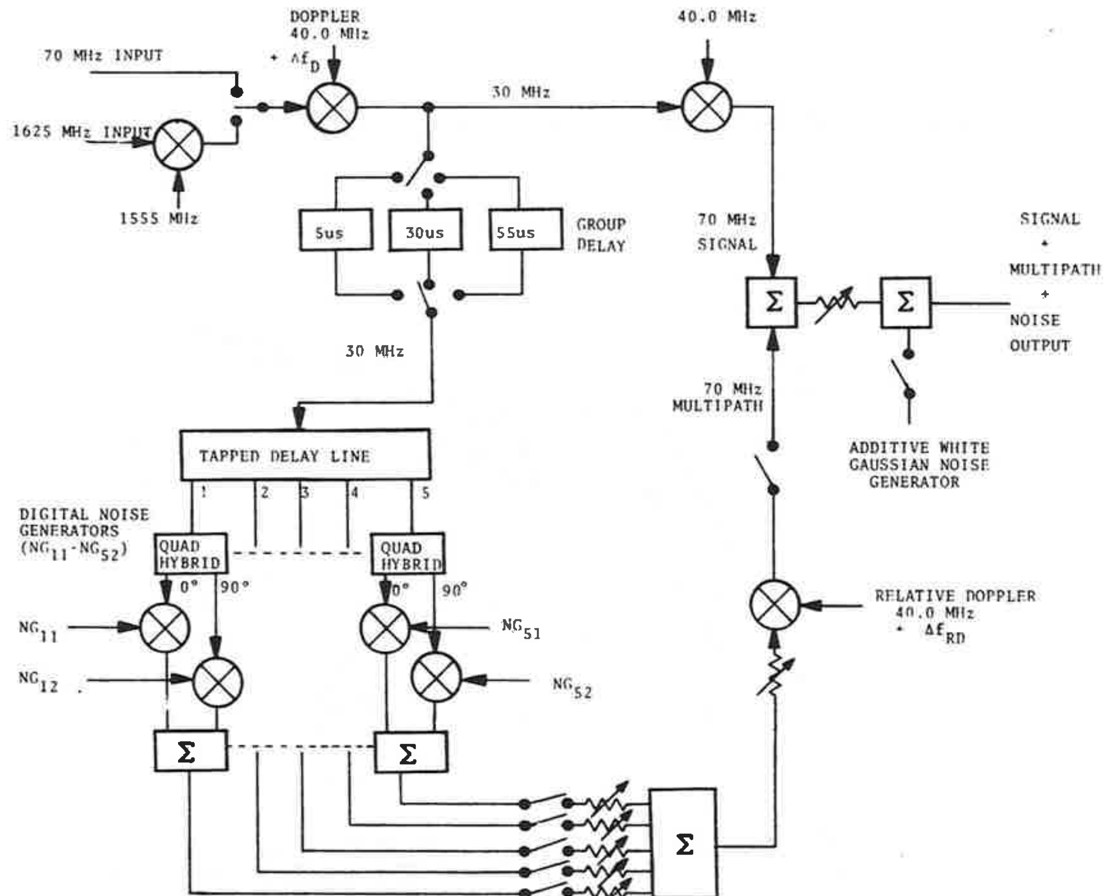


FIGURE 13. MULTIPATH SIMULATOR BLOCK DIAGRAM

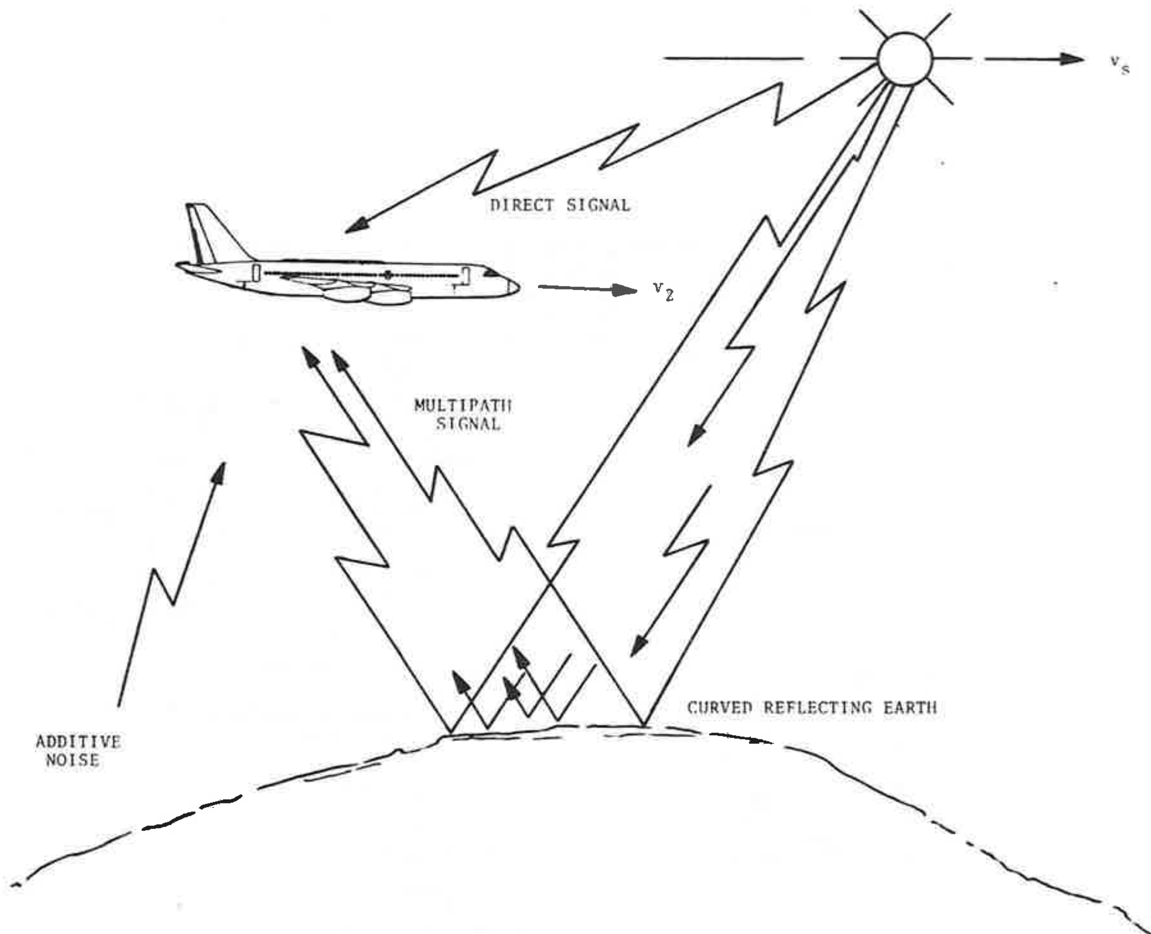


FIGURE 14. AEROSAT COMMUNICATION CHANNEL GEOMETRY

offers an inexpensive way to evaluate modems which must operate in the AEROSAT environment. Earlier results of tests performed using the simulator and presented in Refs. 2 and 3.

4. TDMA MODEM

4.1 ORTHOGONAL CODING MODEM

This modem is a DECPSK modem which uses data coding to improve the BER performance and offer burst error correcting to combat the type of errors caused by multipath. This is achieved by spreading the signal energy.

The coding used is an orthogonal code called a first order Reed Muller code (See Ref. 4). Data vectors are formed from blocks of input data bits. Then a correspondence is established between each data vector and a code vector. The code vectors are formed such that all form an orthogonal set. The code vectors are determined by the channel bandwidth which for AEROSAT is considered to be 19.2 kHz which results in a transmission bit rate to data bit rate ratio of 16 (for 1200 bps data). A synchronization code is also established. Here, one quarter of the 19.2 kHz is dedicated for synchronization code transmission while three quarters or 14.4 k bps is dedicated to the code vector bit rate. The code vectors are generated such that a Reed Muller code of the first order results. The frame synchronization code is a pseudo random code of length 1024 which is inserted every 64 code vectors or 3072 bits. Thus a basic pattern of 1024 bits of frame code followed by 64 code vectors (3072 bits) is established. The coded data is applied to the input of the modulator along with a reference 70 MHz signal to produce a modulated 70 MHz psk system.

The 70 MHz to the demodulator is mixed down to 10 MHz to provide input to the demodulator, which has a 3 dB input filter bandwidth of 100 kHz; the demodulator consists of a Costas loop with damping ratio of .7 and loop noise bandwidth of 18.5 Hz. This is followed by a bit synchronizer consisting of an analog loop and a digital loop. The data frequency is extracted from the analog loop, and bit synchronization is obtained from the digital loop. Data are first detected with a matched filter which is implemented as an integrate and dump network. Then the data are processed to find the frame code so that the code vectors may be decoded. Via a series of buffers, registers, and timing networks the original data is coded and outputed at 1200 bps.

4.2 MAJORITY CODING MODEM

This modem is a DECPSK modem which transmits 1200 bps information by using majority coding at a chip rate of 19.2 k bps.

The incoming data are sectioned into 57 bit blocks. The 57 bit blocks are passed through a feedback shift register encoder (polynominal $x^6 + x + 1$) to create a 6 bit parity check code to form a 63 bit block. This block is majority encoded to length 693 bits by eleven bits of 1010... etc. if the bit is a 1 and 0101... etc. if the bit is a zero. Added to these 693 bits are 219 bits of frame synchronization to obtain a total of 912 bits. The bits are then differentially encoded to avoid phase ambiguity and modulated onto a 70 MHz carrier (external reference) to result in a majority coded differentially encoded phased shift keying output at 70 MHz.

The demodulator receives a 10 MHz input (mixed down from 70 MHz via a mixer and L.O. of 60 MHz). The demodulator itself consists of a Costas loop. This is followed by bit synchronization, data extraction and decoding. First it is necessary to obtain frame synchronization. As the bits are received they are placed in a temporary register until the 219 bit frame code arrives (56 errors can be tolerated).

At frame synchronization the majority decoder is started. After decoding the bits are applied to an error correcting network which can correct one error. This is performed every 63 bits. Finally the original data is reconstituted from the 63 bit blocks and outputed at the original 1200 bps.

4.3 VOICE MODEM

The voice modem uses the delta modulation technique at 19.2 k bps. In general, the input is encoded such that at the sampling times if the sign of the difference signal is positive a "1" is sent and "0" if the sign is negative.

It is possible that the slope of the input signal is too great to be accurately followed by the reconstructed waveform and the system is overloaded. To prevent this an analog pulse amplitude modulator is used which adapts sample height to a short term mean input signal slope, thus resulting in an improved quality without increasing the sampling rate. At the demodulator, after detection by Costas loop, the digital stream is decoded, filtered and the original analog voice signal reconstituted.

4.4 RANGING MODEM

The system was designed to synchronously time division multiplex the ranging signal at 19.2 k bps with a supervisory signal at 6.4 k bps resulting in an overall transmission rate of 25.6 k bps. In the air to ground direction the two were separated and the ranging signal alone was sent at 19.2 k bps. Thus the results here are for the ranging modem at 19.2 k bps.

The ranging modem uses majority coding modulated onto a 70 MHz carrier. The input to the demodulator is at 10 MHz. The range measurement is just the time delay between the transmitted code and the received code. To perform the rms phase jitter measurement the ranging code clocks are used, one to start the computing counter and one to stop it. The time between the two leading edges is thus the measurement.

5. 50/4800 BAUD MODEM

The 50/4800 Baud Modem, belonging to the French Administration, CNES, was built to operate with ATS-6 mainly for maritime applications. It is a data modem that can operate at data rates of 50, 150, 300, 600, 1200, 2400 and 4800 bps, which are front panel selectable by a thumbwheel switch. The model uses coherent demodulation with differential encoding to solve the phase ambiguity problem.

The modulator is simple. It consists of a ring modulator which on one side receives an externally generated 70 MHz carrier and on the other bipolar data of $\pm$ V volts which has been differentially encoded. The output 70 MHz is either in phase or out of phase with the 70 MHz carrier depending on the polarity of the data. There is then amplification to provide a 70 MHz, DECPSK signal.

The demodulator consists of a Costas loop, bit synchronizer and data detector. The input to the demodulator is a 10 MHz DECPSK signal which passes through a filter, whose 3 dB bandwidth is $\pm$ 50 kHz, to limit noise, followed by automatic gain control. The demodulation is done by a Costas loop whose filter is 300 Hz wide for bit rates of 50, 150 and 300 bps and 3 kHz for the higher bit rates. The loop noise bandwidth of the phase lock loop is about 8 Hz. The loop sweeps until phase synchronization is established.

The bit synchronizer consisting of a digital and an analog loop extracts the clock from the received data. The analog loop is a second order loop extracting the data. The digital loop is a first order loop which provides the correct phasing of the data clock.

Data detection is achieved with an integrate and dump filter which corresponds to the matched filter for a rectangular pulse in gaussian white noise. A decision is made as to the bit polarity. After data detection the bits go through differential decoding to establish the original data stream.

6. RESULTS - ORTHOGONAL CODING MODEM

Results of the performance of the T.R.T data modem with orthogonal coding are shown in Figures 15-20. Figure 15 is a reference curve. It contains theoretical curves and laboratory performance curves. Curve A of Figure 15 is the theoretical DECPSK performance at 1200 bps without coding. Curve B of Figure 15 is the theoretical DECPSK performance at 1200 bps for an orthogonal coding system. Curves C and D of Figure 15 are the performance curves of the modem, Curve C obtained from the tests performed at TSC and Curve D from earlier test results obtained at the T.R.T. facilities in France. It is seen that curves C and D track within experimental error. It is also seen that at 38 dBHz curves A and C cross. Below 38 dBHz coding degrades the system performance when compared to an uncoded system. There are too many errors that have to be corrected to make coding worthwhile. Above 38 dBHz there is steady improvement over an uncoded system until at 40 dBHz there is 1 dB improvement over the theoretical performance of an uncoded system. The actual data performance curve of an uncoded system lies 0.2 to 0.6 dB away from theoretical; see Reference 2 and Reference 3. Thus, comparing the two curves at the BER = 10^{-5} point, there is approximately 1.5 dB difference. Thus, we can conclude that orthogonal coding does offer improvement in system performance at higher C/N_o's by using more R.F. bandwidth. These curves (A, B and C) are repeated for reference in the other graphs presented for this modem i.e., 16, 17, 18 and 19.

Tests were performed on the modem with the addition of multipath at a C/M = 5 dB with the multipath energy spread over 10 Hz, 100 Hz and 1000 Hz respectively. From Figure 16 it is seen that the P_e never exceeds 10^{-3}. In Figure 17 the C/M = 8 dB with the same three bandwidths. With multipath bandwidths of 10 Hz and 100 Hz the P_e is no better than 3×10^{-4} at 46 dBHz. However, when the multipath energy is scattered over 1000 Hz a P_e of 1.5×10^{-5} at 44 dBHz is seen. In Figure 18 results of data tests

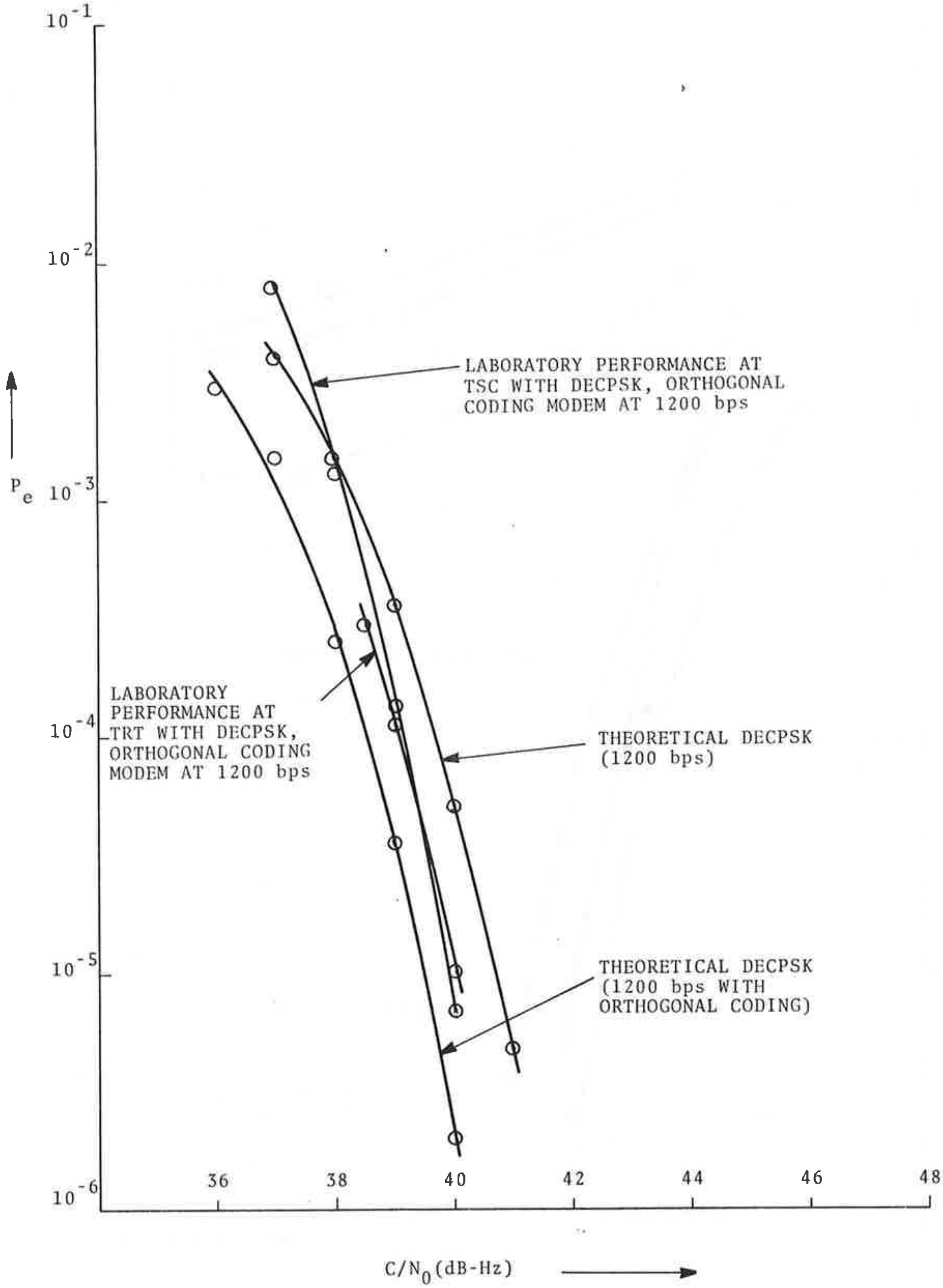


FIGURE 15. PROBABILITY OF BIT ERROR VS. C/N_0 FOR ORTHOGONAL CODING MODEM AT 1200 bps

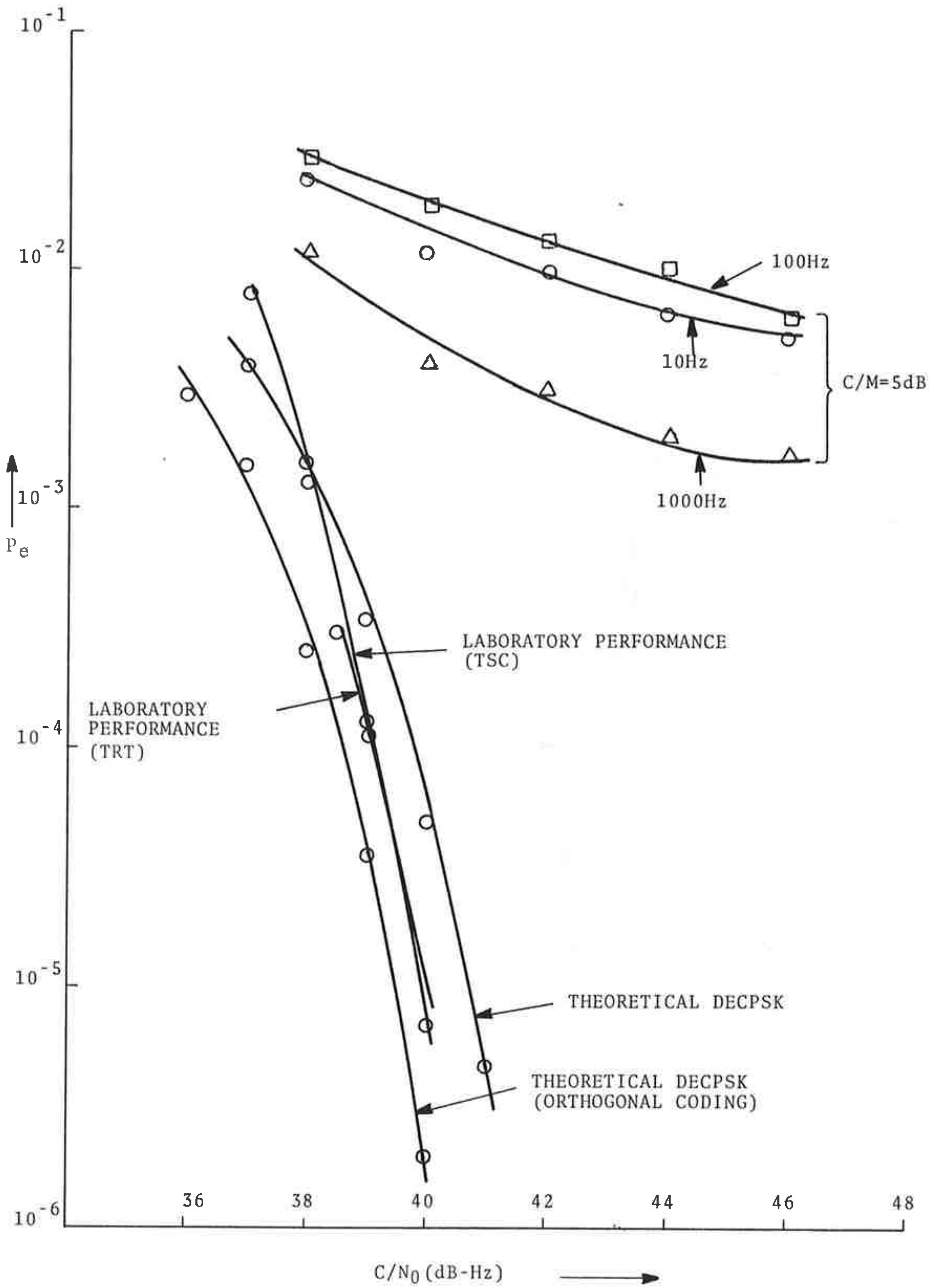


FIGURE 16. PROBABILITY OF BIT ERROR VS. C/N_0 FOR ORTHOGONAL CODING MODEM AT 1200 bps WITH MULTIPATH

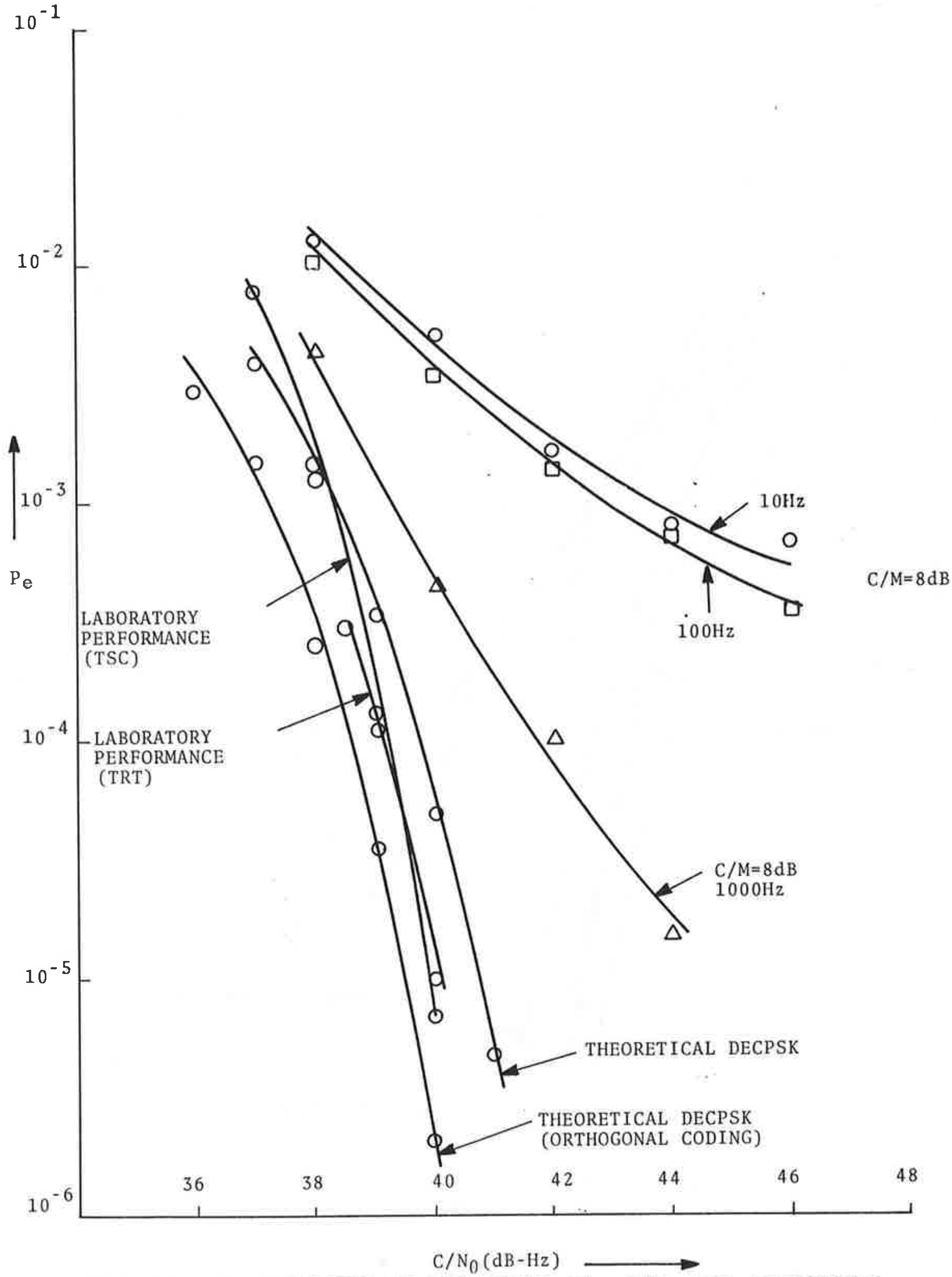


FIGURE 17. PROBABILITY OF BIT ERROR VS. C/N_0 FOR ORTHOGONAL CODING MODEM AT 1200 bps WITH MULTIPATH

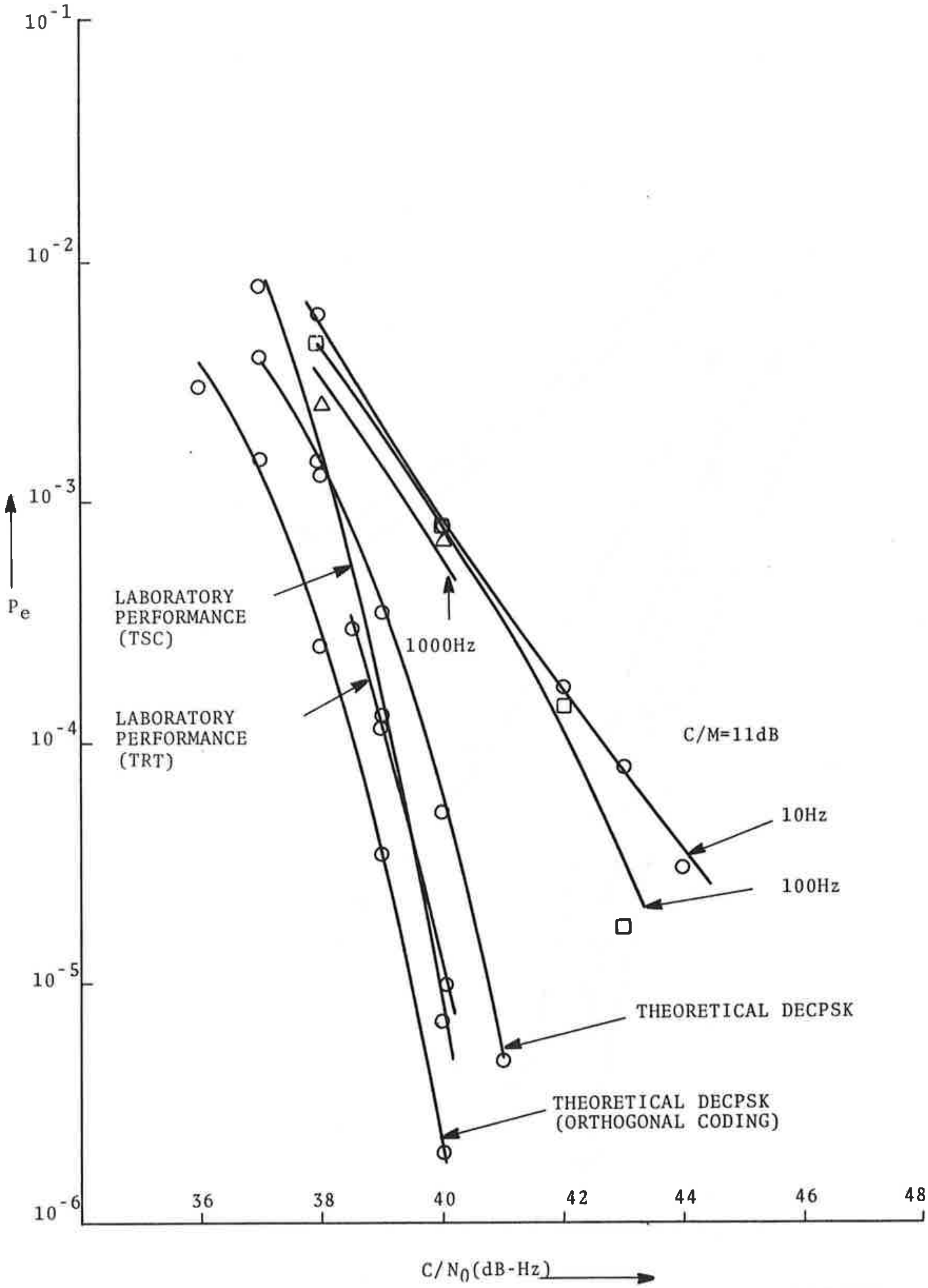


FIGURE 18. PROBABILITY OF BIT ERROR VS. C/N_0 FOR ORTHOGONAL CODING MODEM AT 1200 bps WITH MULTIPATH

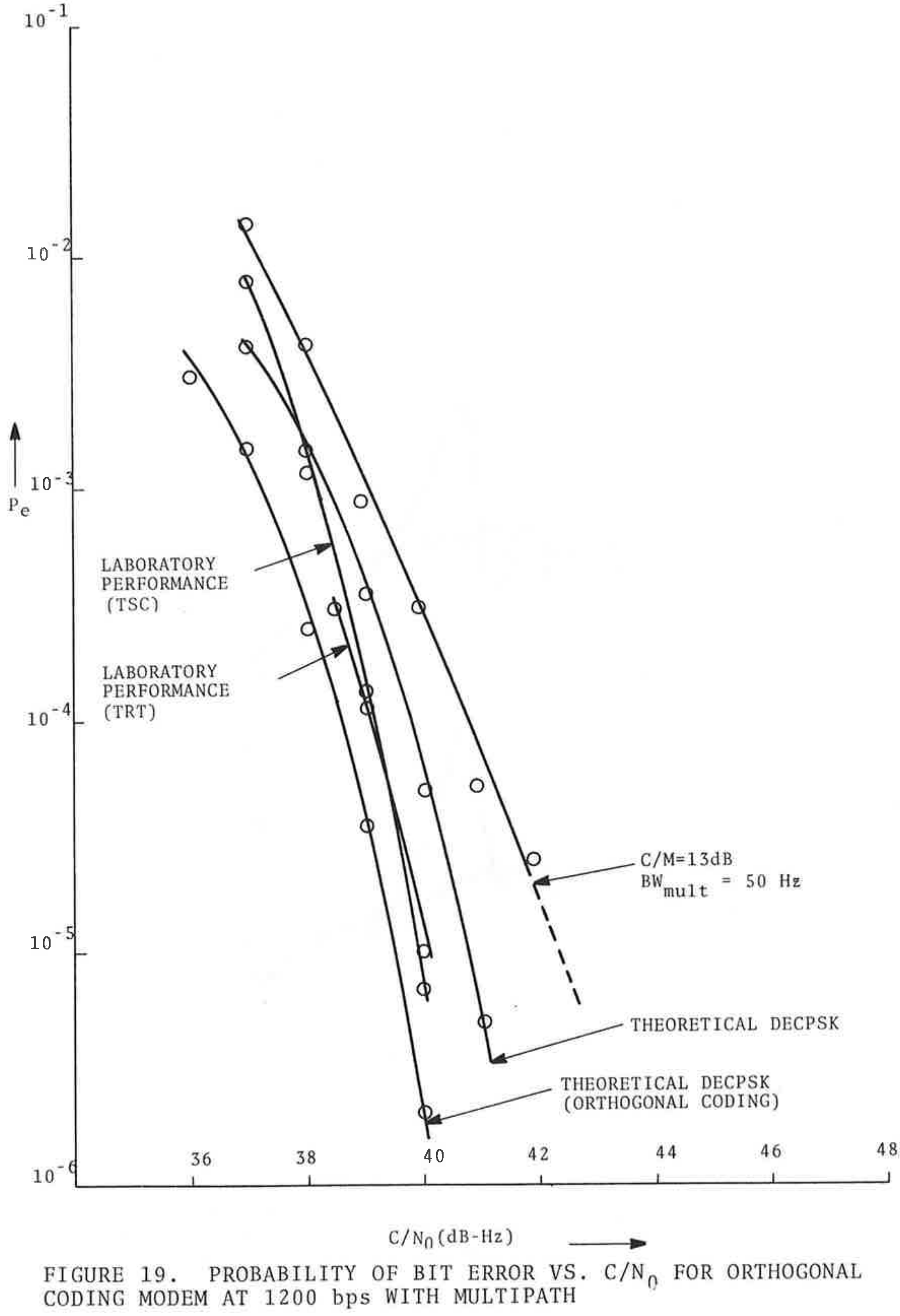


FIGURE 19. PROBABILITY OF BIT ERROR VS. C/N_0 FOR ORTHOGONAL CODING MODEM AT 1200 bps WITH MULTIPATH

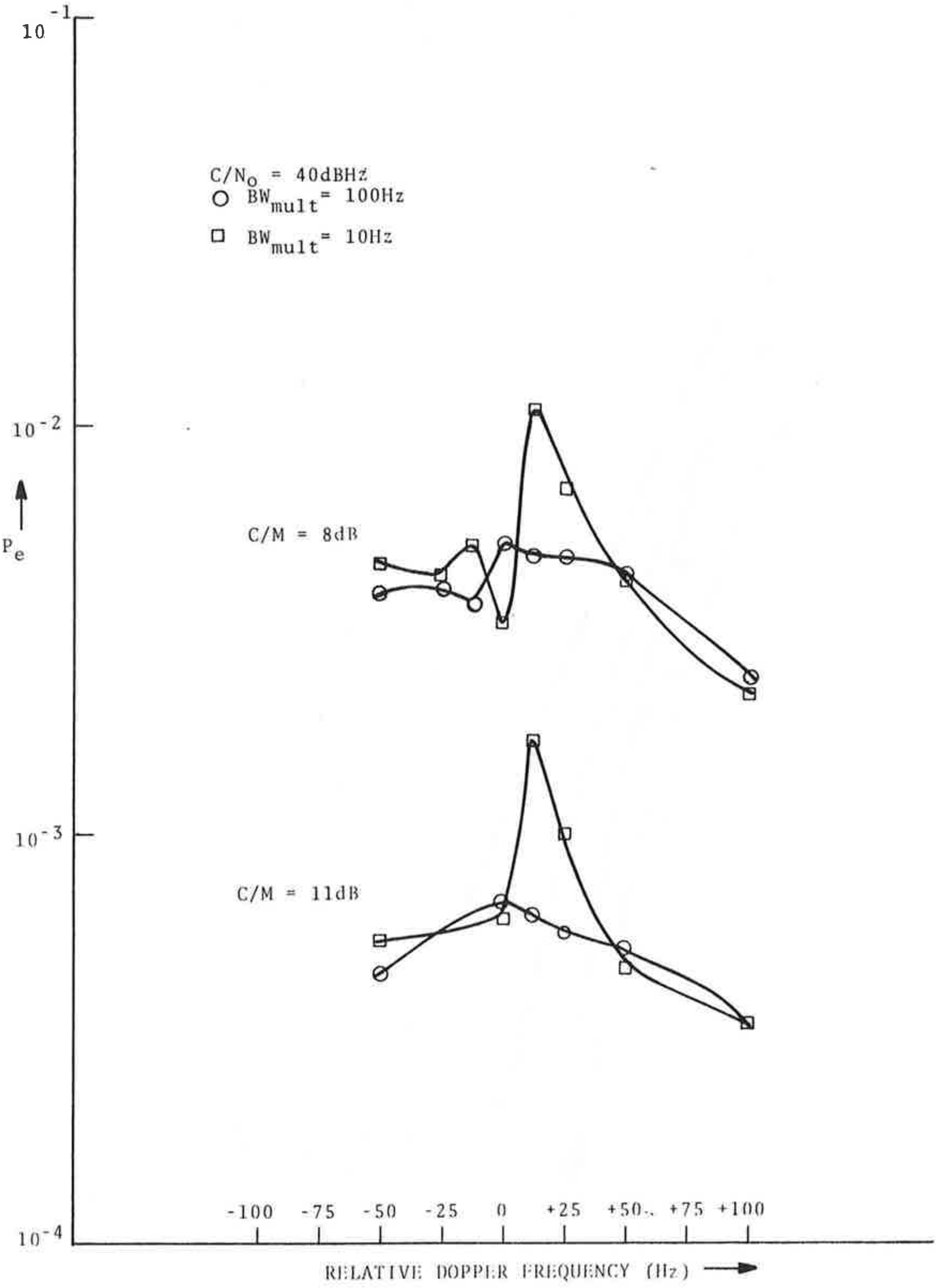


FIGURE 20. BIT ERROR RATE PERFORMANCE VS. RELATIVE DOPPLER FREQUENCY FOR DECPSK ORTHOGONAL CODING MODEM

are presented which were performed when C/M = 11 dB. Three curves are again presented. When the multipath energy is spread over 10 Hz and 100 Hz P_e's of 1.5 x 10^{-4} are realized at 42 dBHz. When the multipath bandwidth is increased to 1000 Hz a P_e of 3 x 10^{-5} is realized at 40 dBHz. It is also seen that this particular curve is only .5 dB away from the performance curve resulting when the modem is subjected to a white noise environment only. Figure 19 presents the modem performance with the C/M = 13 dB in a 50 Hz bandwidth. Extrapolation of this data shows a P_e of 10^{-5} at 42.2 dBHz. Figure 20 is a plot of P_e versus relative doppler frequency at 40 dBHz for two different conditions of multipath. Both show variation in P_e as relative doppler changes. However, the greatest change is at 12 Hz of relative doppler when the multipath bandwidth is 10 Hz. No variation was seen in P_e as a function of relative doppler frequency when the multipath bandwidth was 1000 Hz.

Comparison of the results of these data tests with those performed on other modems show that orthogonal coding does improve the performance in a multipath environment. Table 1 compares the performance of Hybrid 1 of Reference 2 at various C/N_o's and C/M's to the orthogonal coding modem. At C/M = 5 dB with 10 Hz and 100 Hz multipath bandwidths little difference exists in performance. With a 1000 Hz multipath bandwidth a better performance results with the coded system, but the 1000 Hz bandwidth is also the less likely. With C/M = 8 dB, better multipath rejective is evident with the coded system especially at higher C/N_o. The same is true at C/M = 11 dB, only more so, since the errors are more random and thus more easily corrected.

TABLE 1. COMPARISON OF UNCODED DECPSK MODEM WITH ORTHOGONALLY CODED DECPSK MODEM

C/No (dBHz)	BW / Mult / Modem	$\frac{C}{M}$ = 5 dB 10 Hz	$\frac{C}{M}$ = 5 dB 100 Hz	$\frac{C}{M}$ = 5 dB 1000 Hz	$\frac{C}{M}$ = 8 dB 10 Hz	$\frac{C}{M}$ = 8 dB 100 Hz	$\frac{C}{M}$ = 8 dB 1000 Hz	$\frac{C}{M}$ = 11 dB 10 Hz	$\frac{C}{M}$ = 11 dB 100 Hz	$\frac{C}{M}$ = 11 dB 1000 Hz
38	*M1	$2.5x10^{-2}$	$3.8x10^{-2}$	$4.7x10^{-2}$	$1.4x10^{-2}$	$1.3x10^{-2}$	$1.2x10^{-2}$	$7.1x10^{-3}$	$7x10^{-3}$	$6.2x10^{-3}$
	**M2	$2.5x10^{-2}$	$2.9x10^{-2}$	$1.3x10^{-2}$	$1.3x10^{-2}$	$1x10^{-2}$	$4.5x10^{-3}$	$6x10^{-3}$	$4.7x10^{-3}$	$2.6x10^{-3}$
40	M1	$1.7x10^{-2}$	$2.3x10^{-2}$	$3x10^{-2}$	10^{-2}	$8x10^{-3}$	$7x10^{-3}$	$1.8x10^{-3}$	$1.7x10^{-3}$	$1.5x10^{-3}$
	M2	$1.2x10^{-2}$	$1.8x10^{-2}$	$4x10^{-3}$	$5x10^{-3}$	$3.5x10^{-3}$	$4.5x10^{-4}$	$8x10^{-4}$	$8x10^{-4}$	$5x10^{-5}$
42	M1	10^{-2}	$1.5x10^{-2}$	$2x10^{-2}$	$5.2x10^{-3}$	$3.6x10^{-3}$	$3x10^{-3}$	$4.9x10^{-3}$	$4.8x10^{-3}$	$3x10^{-3}$
	M2	10^{-2}	$1.3x10^{-2}$	$3x10^{-3}$	$1.7x10^{-3}$	$1.4x10^{-3}$	10^{-4}	$1.8x10^{-4}$	$1.4x10^{-4}$	$<10^{-6}$ (extra-polated)
44	M1	$6.2x10^{-3}$	$1.2x10^{-2}$	$1.8x10^{-2}$	$2.7x10^{-3}$	$1.8x10^{-3}$	$1.3x10^{-3}$	$1.5x10^{-4}$	$1.4x10^{-4}$	$6x10^{-4}$
	M2	$6.4x10^{-3}$	10^{-2}	$2x10^{-3}$	$8x10^{-4}$	$7x10^{-4}$	$1.5x10^{-5}$	$3x10^{-5}$	$5x10^{-6}$ (extra-polated)	---------

*DECPSK modem without coding.

**Orthogonally coded DECPSK modem.

7. RESULTS -- MAJORITY CODING MODEM

The results of tests performed are presented in Figure 21. With no multipath a B.E.R. of 10^{-3} is obtained at 40 dBHz, 2 x 10^{-4} at 41 dBHz, and 10^{-5} at 42 dBHz, all about 1 dB or $1\frac{1}{2}$ dB away from theoretical, which is shown as a reference at the left. The other curves are B.E.R. performance when subjected to multipath at C/M = 11 dB. For a multipath bandwidth of 10 Hz modem acquisition was not possible much below 42 dBHz; for 100 Hz, 41 dBHZ. Modem operation using a C/M of 8 dB or less was not possible since the modem could not establish bit synchronization long enough to obtain any useful data.

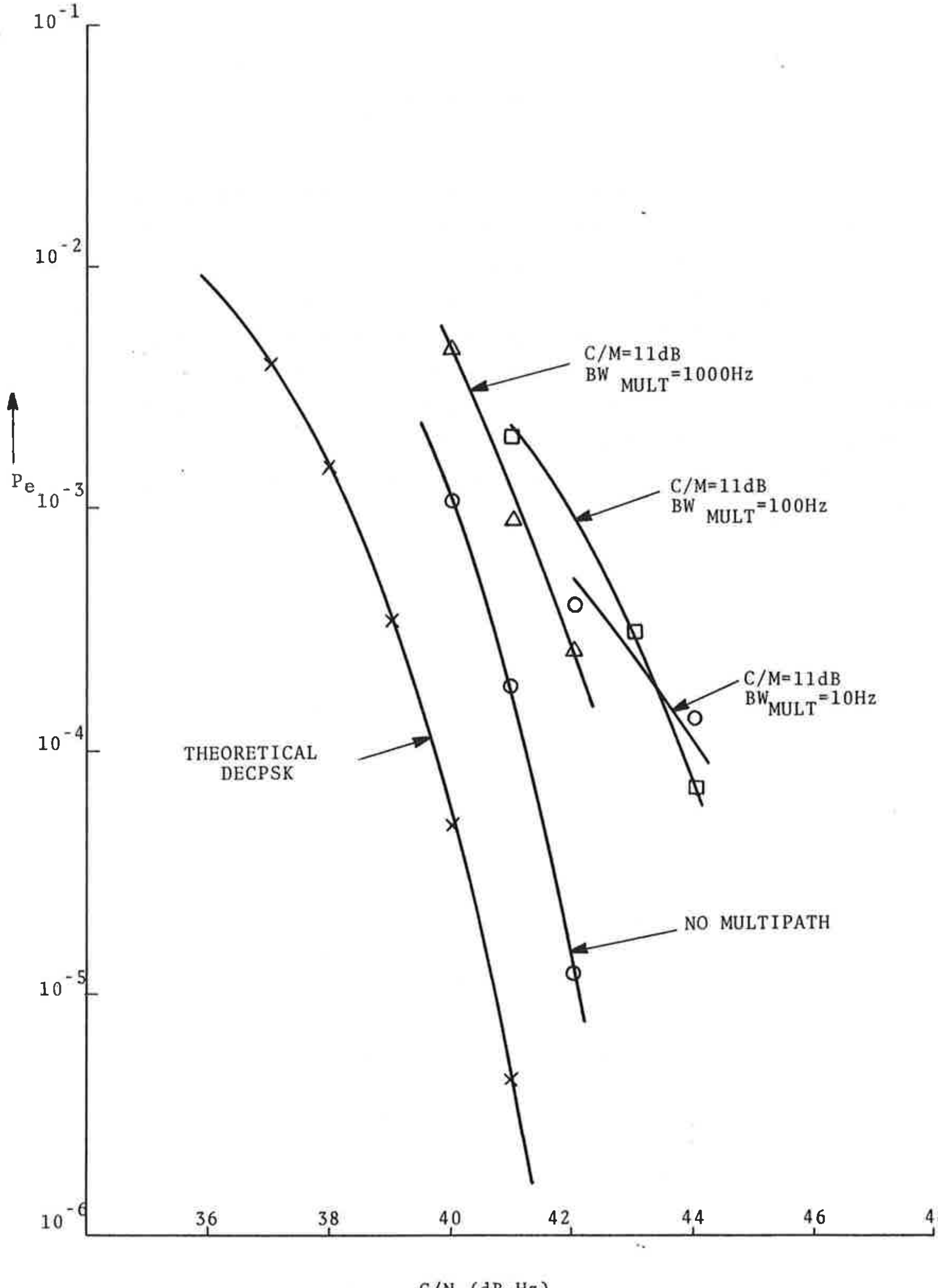


FIGURE 21. PROBABILITY OF BIT ERROR VS. C/N_0 FOR MAJORITY CODING MODEM AT 1200 bps WITH AND WITHOUT MULTIPATH

8. RESULTS -- VOICE MODEM

Results of the tests performed to evaluate the performance of the voice modem are presented in Figure 22. Each point represents the average score of nine or ten listeners each listening to 250 PB words. From Figure 22, it is seen that there is little difference between the curves especially at higher C/N_o, say 46 dBHz and above. Note that one curve represents average voice intelligibility for the modem in the absence of multipath, a high elevation angle situation for instance; another for a C/M = 11 dB, lower elevation angle and some multipath; another for a C/M = 5 dB, moderate interference, a low elevation angle situation. All the multipath tests were performed using a 10 Hz bandwidth. Voice modems are usually much less susceptible to multipath than data modems because of the redundancies in speech. At a high multipath situation, C/M = 5 dB, there is some degradation in performance but nothing like the effect that multipath produces on the P_e for data modems. The lowest value of C/N_o used was 40.5 dBHz since at 39.5 dBHz the modem could not acquire lock nor remain in lock.

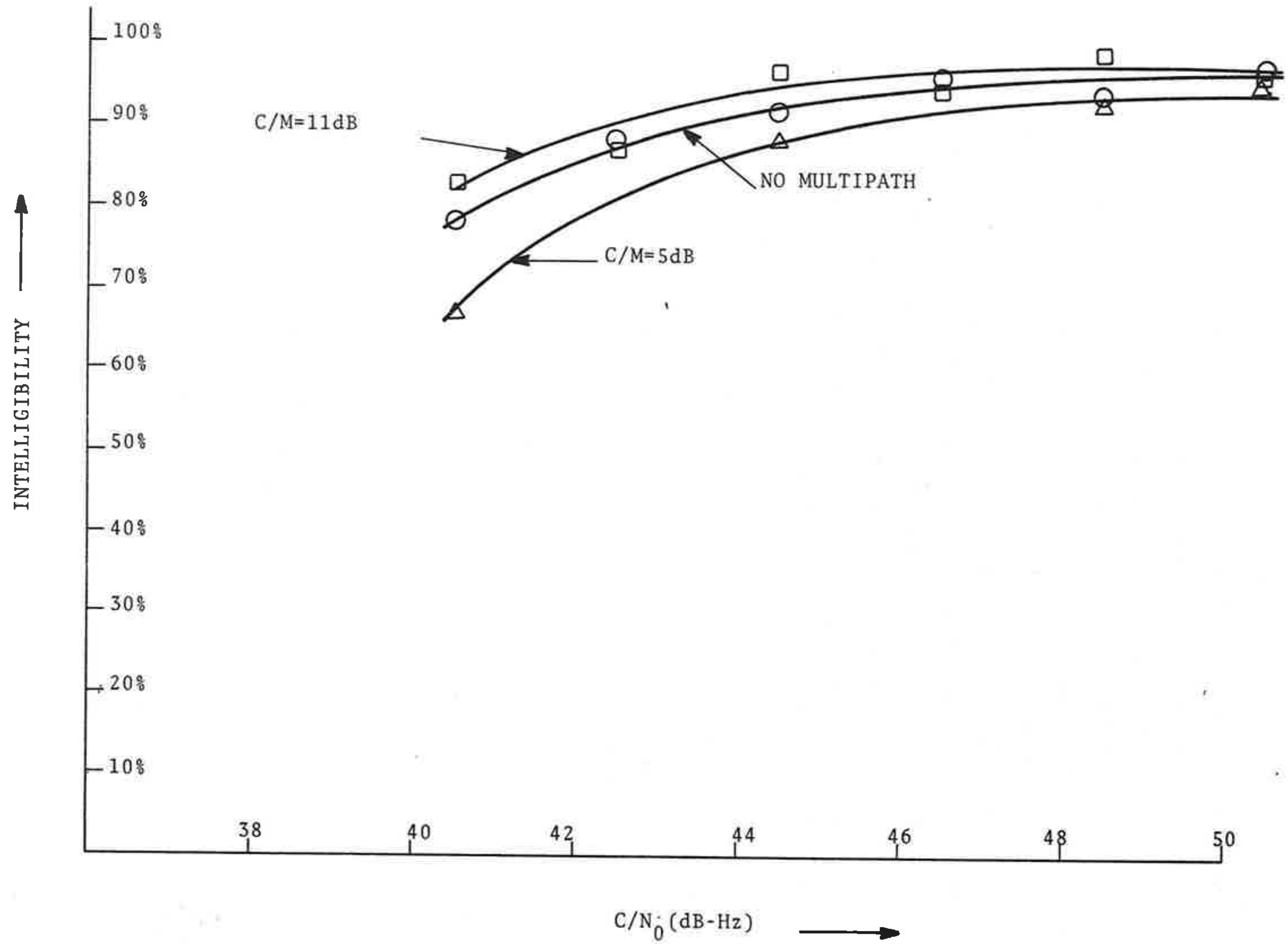


FIGURE 22. INTELLIGIBILITY VS C/N_0 FOR TRT TDMA VOICE MODEM

9. RESULTS -- RANGING MODEM

The results of the tests performed on the ranging modem are shown in Figures 23 through 26. In Figure 23, it is seen that the phase jitter varies between 240 nsec at 50 dBHz to 930 nsec at 37 dBHz when the modem is operated in a straight gaussian white noise environment. When the modem is subjected to multipath some degradation in performance occurs at C/M = 11 dB for multipath bandwidths of 100 Hz and 1000 Hz but the overall effect is not severe. However, when the multipath is spread over 10 Hz there is a large change in performance seen. Above 39 dBHz the phase jitter remains at approximately 800 nsec with no further improvement seen at higher C/N_o. When the C/M = 8 dB, Figure 24, the change in phase jitter from the no multipath condition is greater than that obtained by using C/M = 11 dB. This is certainly as expected since the multipath is greater. Again, a multipath bandwidth of 10 Hz creates results which are very bad compared with the bandwidths of 100 Hz and 1000 Hz. In fact, at a C/M = 8 dB with BW = 10 Hz the modem will not operate below 44 dBHz. With C/M = 5 dB, Figure 25, the degradation of the modem performance is still greater. Also with C/M = 5 dB and a 10 Hz multipath bandwidth the modem will not operate at all. In all cases, C/M = 5, C/M = 8 and C/M = 11 dB the deviation from the no multipath case, at bandwidths of 100 Hz and 1000 Hz, is greater as C/N_o increases. This is as expected since at low C/N_o the gaussian noise becomes the predominating effect. Thus, at higher C/N_o the multipath effect is seen more clearly. Although a C/M = 5 dB results in worse overall performance than a C/M = 11 dB the resultant performance of the modem is not all that much perturbed when the multipath bandwidths are 100 Hz and 1000 Hz. The operation is certainly tolerable. If a larger signal bandwidth were used the $\sigma_{r.m.s.}$ would be proportionally less. See Ref. 3 and Ref. 5.

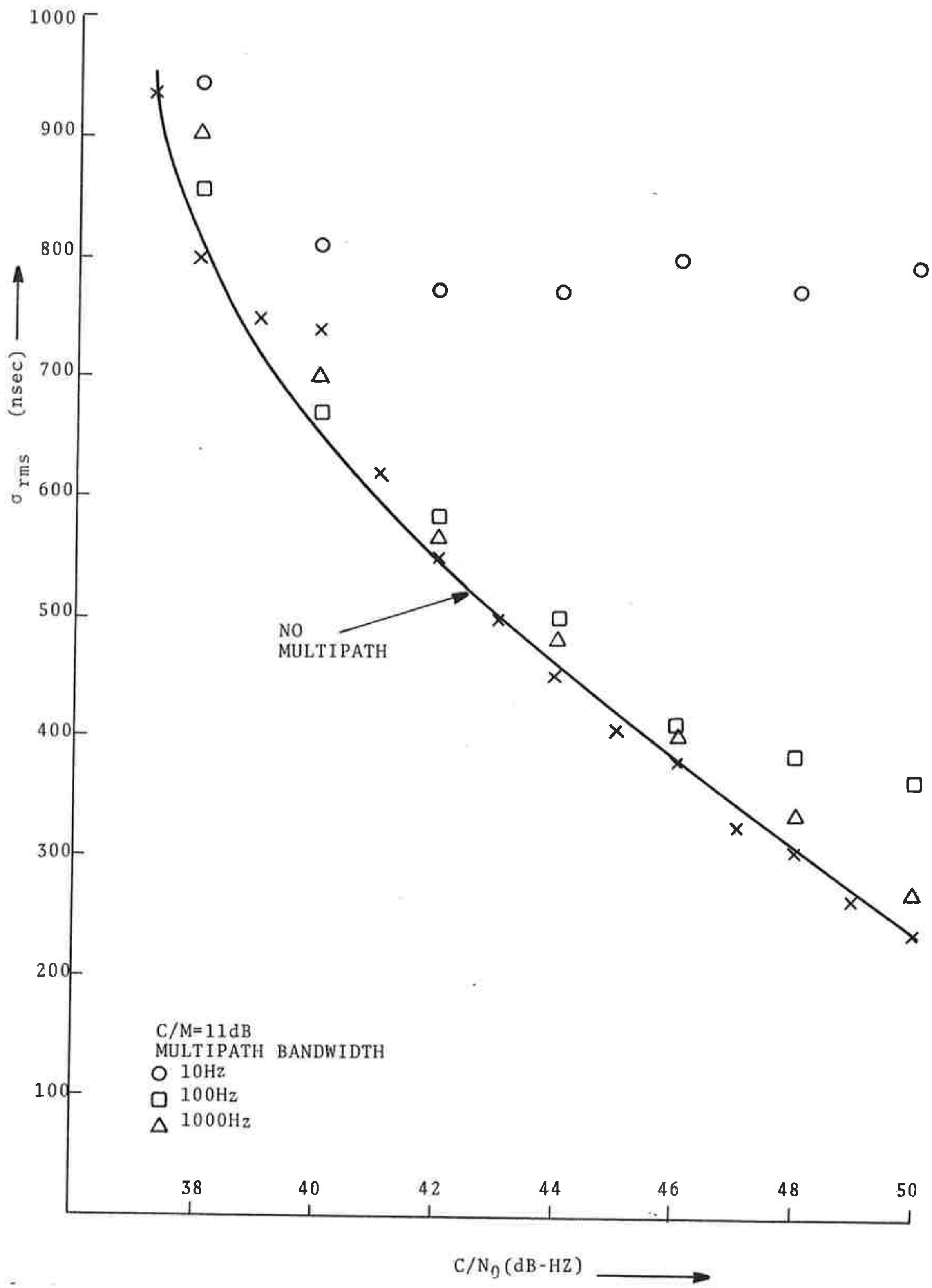


FIGURE 23. RMS PHASE JITTER VS. C/N_0 FOR RANGING MODEM

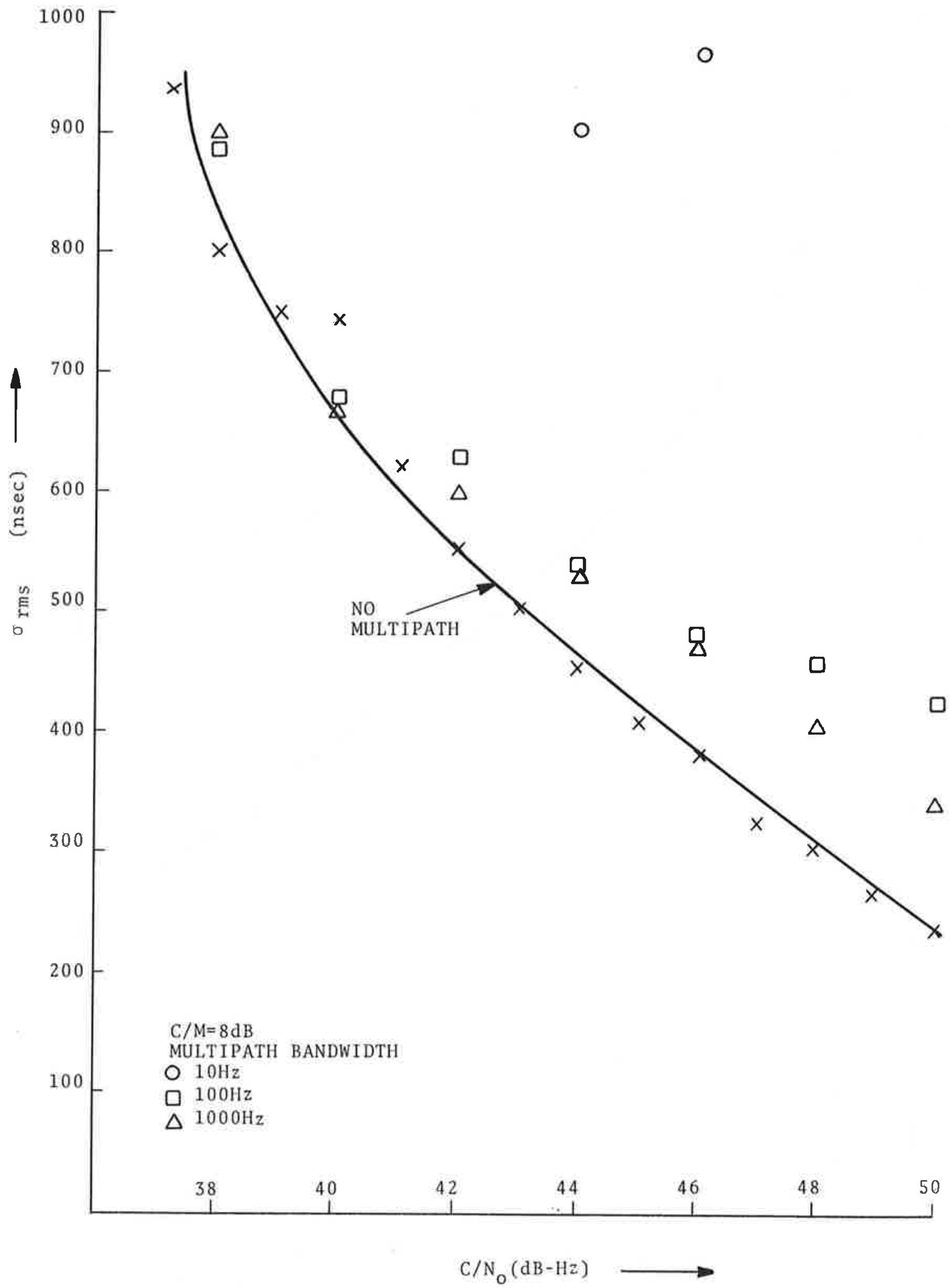


FIGURE 24. RMS PHASE JITTER VS. C/N_0 FOR RANGING MODEM

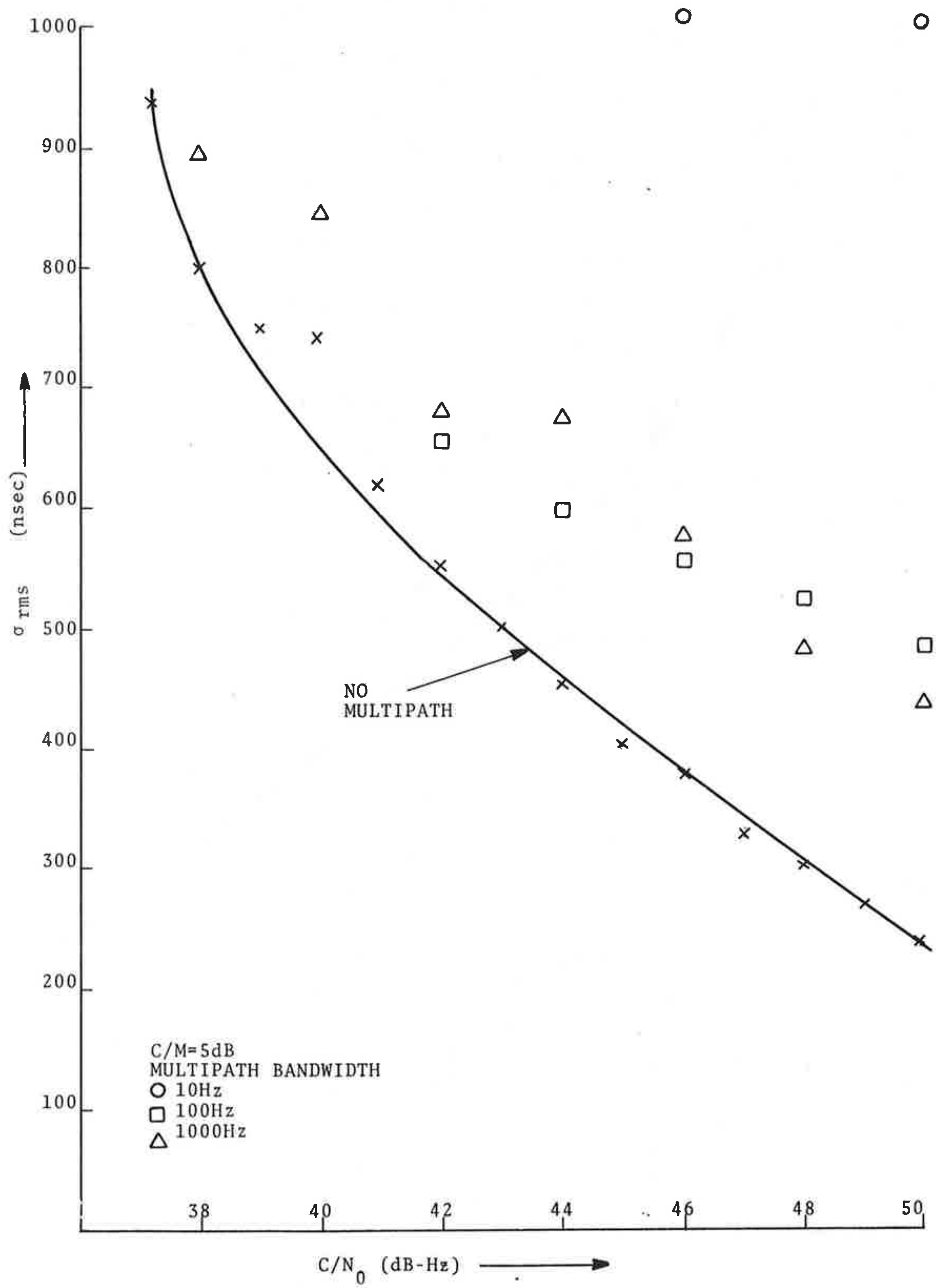


FIGURE 25. RMS PHASE JITTER VS. C/N_0 FOR RANGING MODEM

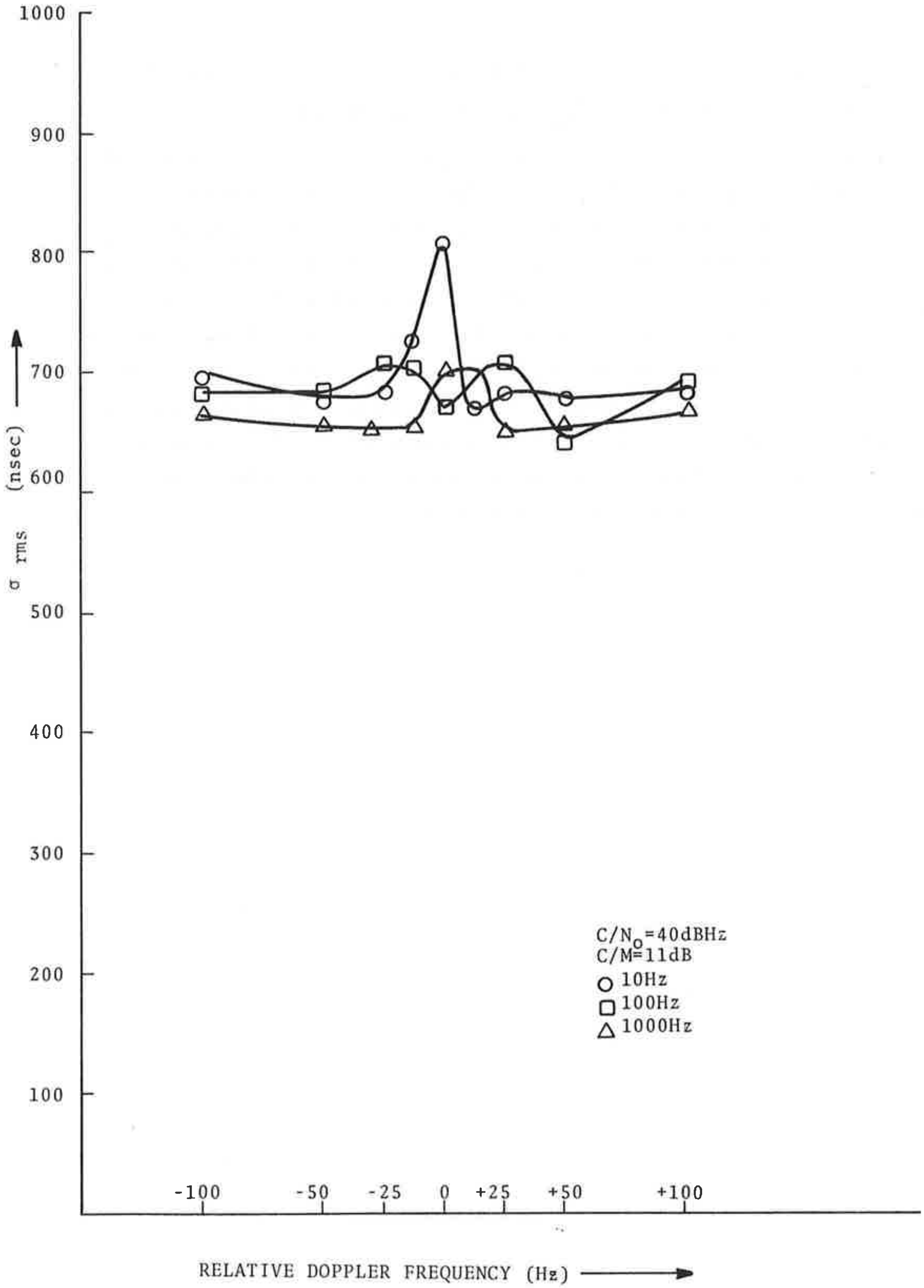


FIGURE 26. RMS PHASE JITTER VS. RELATIVE DOPPLER FREQUENCY FOR TRT RANGING MODEM

However, multipath in a 10 Hz bandwidth results in a quite serious deviation in performance from the no multipath case.

In Figure 26 the effects of relative doppler are presented. The C/N_o used was 40 dBHz at a C/M = 11 dB. The variation in phase jitter as a function of relative doppler for a given C/N_o, C/M and multipath bandwidth is small. In fact, for the case of BW_{mult} = 10 Hz there is some slight improvement with relative doppler, from 800 nsec to 700 nsec which, in terms of accuracy in feet, is an improvement in uncertainty of 100 feet in 800 feet. For the ranging tests we conclude that relative doppler plays a small part. Variation in doppler frequency of up to ± 1000 Hz resulted in no change in modem performance and is thus just mentioned and not presented in graph form.

10. RESULTS -- 50/4800 BAUD DATA MODEM

The results of the tests performed on the 50/4800 Baud Data Modem are shown in Figures 27-32, 33-38 and 39-44. The modem was tested at 600 bps, 1200 bps and 2400 bps with and without various amounts of multipath. Results are also presented depicting the modem bit error rate performance as a function of relative doppler frequency.

In Figure 27, P_e vs. C/N_o at 600 bps, it is seen that the laboratory performance curve (no multipath) lies .8 dB from theoretical and .2 dB from the same tests performed by T.R.T. at their facility in France. When multipath is added to the channel, see Figures 28-32, degradation in P_e occurs depending on the severity of the multipath signal. It is seen for C/M = 5 dB that even at 43 dBHz the P_e is not much better than 3×10^{-3} and, in the case of a 100 Hz multipath bandwidth, not much better than 10^{-2}. A C/M = 8 dB at 43 or 44 dBHz results in performance in the range of P_e of 2×10^{-4} to 10^{-3} with slow improvement as C/N_o increases. A C/M of 11 dB in either a 10 Hz or 100 Hz multipath bandwidth results in a 10^{-4} P_e at an extrapolated value of 41.5 dBHz. Further extrapolation of the data shows that a 10^{-5} P_e is perhaps possible at C/N_o of 45 dBHz.

Figure 32 shows the effect that relative doppler frequency plays in the determination of P_e. If the satellite elevation angle is 10° a relative doppler frequency of 12 Hz corresponds to an aircraft altitude change of 22 ft/sec. See Reference 2. However, it should be realized that the time constant of the initial acquisition loop of this modem is fifteen minutes for a sweep range of ± 5 kHz about the center frequency. Thus the modem is better suited to maritime applications. At a C/N_o of 35 dBHz with light mulitpath of C/M = 11 in a 100 Hz bandwidth, a factor of 2 degradation in P_e occurs at -50 Hz. A shift of -50 Hz corresponds to a change in altitude at a rate of 90 ft/sec at an elevation angle of 10°. It is seen that there is a rather complex process involving the change in P_e as a function of relative doppler. However, it is noted the most serious change in P_e takes place for relative doppler frequencies up to $\pm$ 50 Hz. This is true for most of the curves of P_e versus relative doppler.

Figures 33-37 and 38 show, respectively, P_e vs. C/N_o with various multipath parameters and P_e vs. relative doppler frequency at 1200 bps. The shape of the curves in Figures 33-37 is the same as in Figures 27-31. That is, for a given S/N the B.E.R. performance is generally the same under the same multipath conditions. Turning to Figure 38 it is seen that there is once again a complex relationship between P_e and the relative doppler frequency. There is a greater degradation in P_e because the S/N is greater than that of Figure 32. At higher S/N's the masking effect of the noise is less noticeable. The greatest changes in P_e are seen for relative doppler frequencies of approximately $\pm$ 12 Hz.

In Figures 39-43 P_e vs. C/N_o is plotted for 2400 bps. Once again the performance curves are generally the same as for the other two data rates of this modem. Also looking at Figure 44 there is the same tendency for a large degradation in P_e when the relative doppler frequency is $\pm$ 50 Hz or so. At this rate there is less variation when the multipath bandwidth is 100 Hz than 10 Hz and practically no change in P_e versus relative doppler when the multipath bandwidth is 1000 Hz.

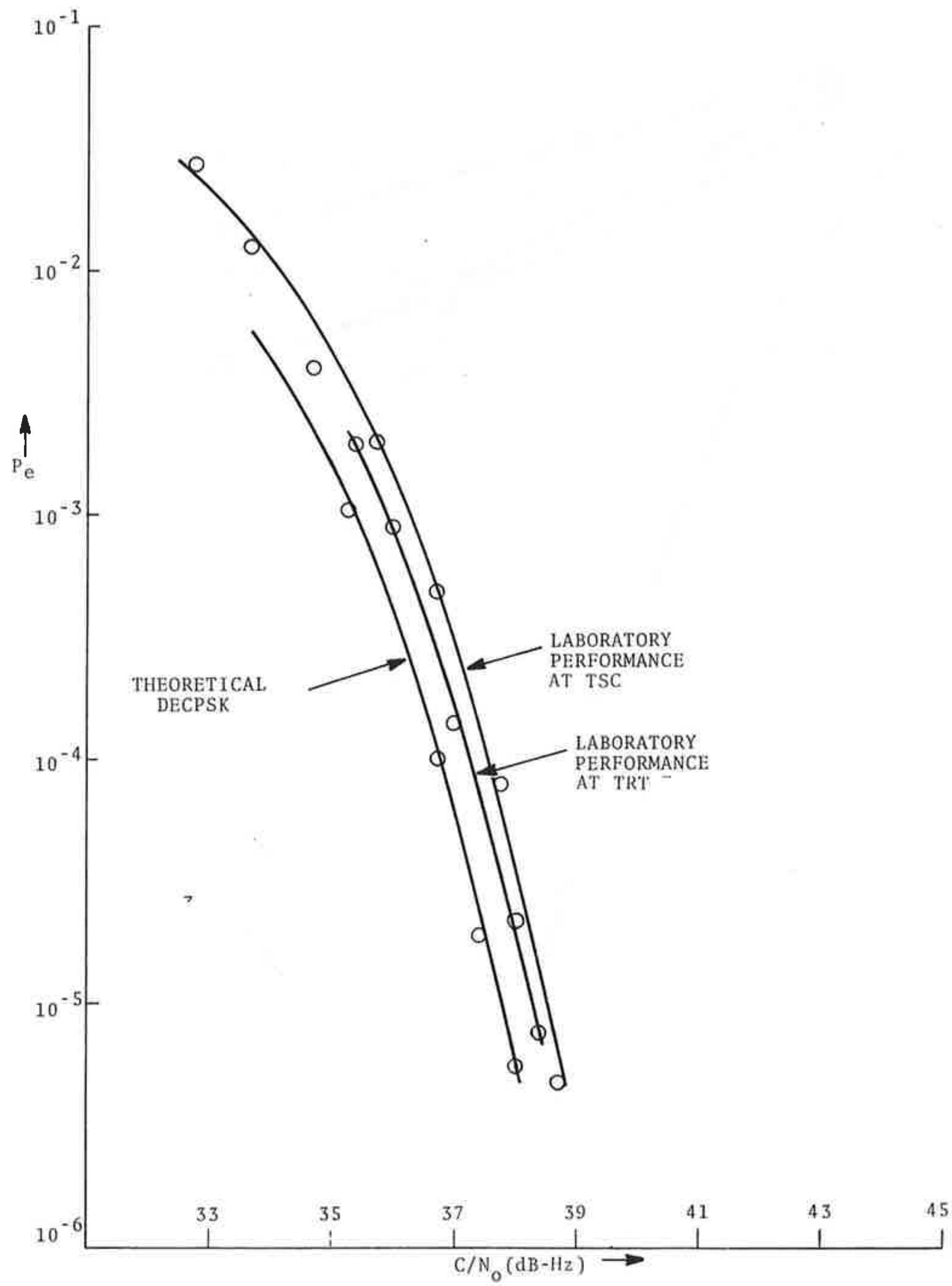


FIGURE 27. PROBABILITY OF BIT ERROR VS. C/N_0 FOR 50/4800 BAUD MODEM AT 600 bps

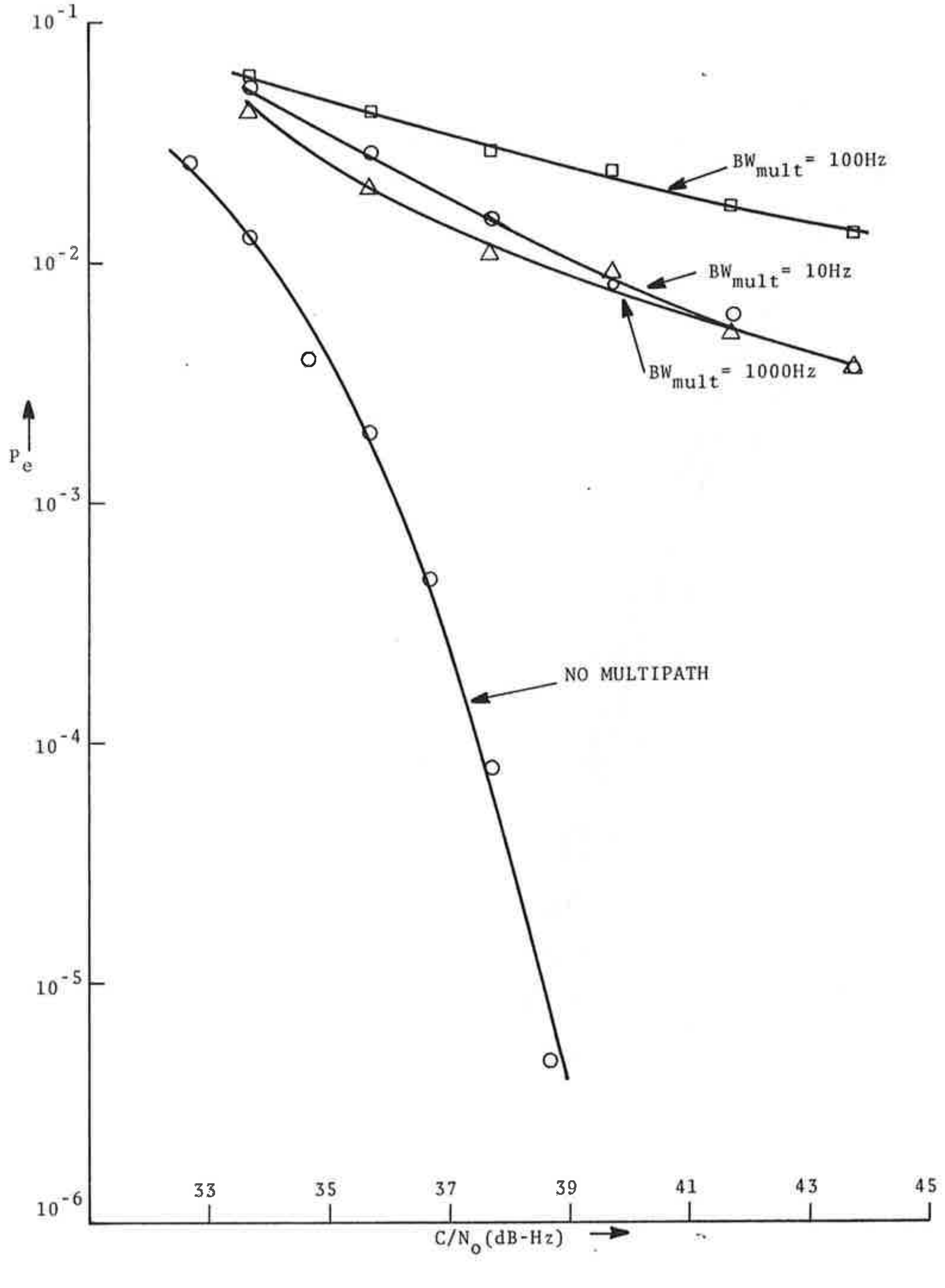


FIGURE 28. PROBABILITY OF BIT ERROR VS. C/N_0 FOR 50/4800 BAUD MODEM AT 600 bps WITH MULTIPATH AT $C/M \cong 5$ dB

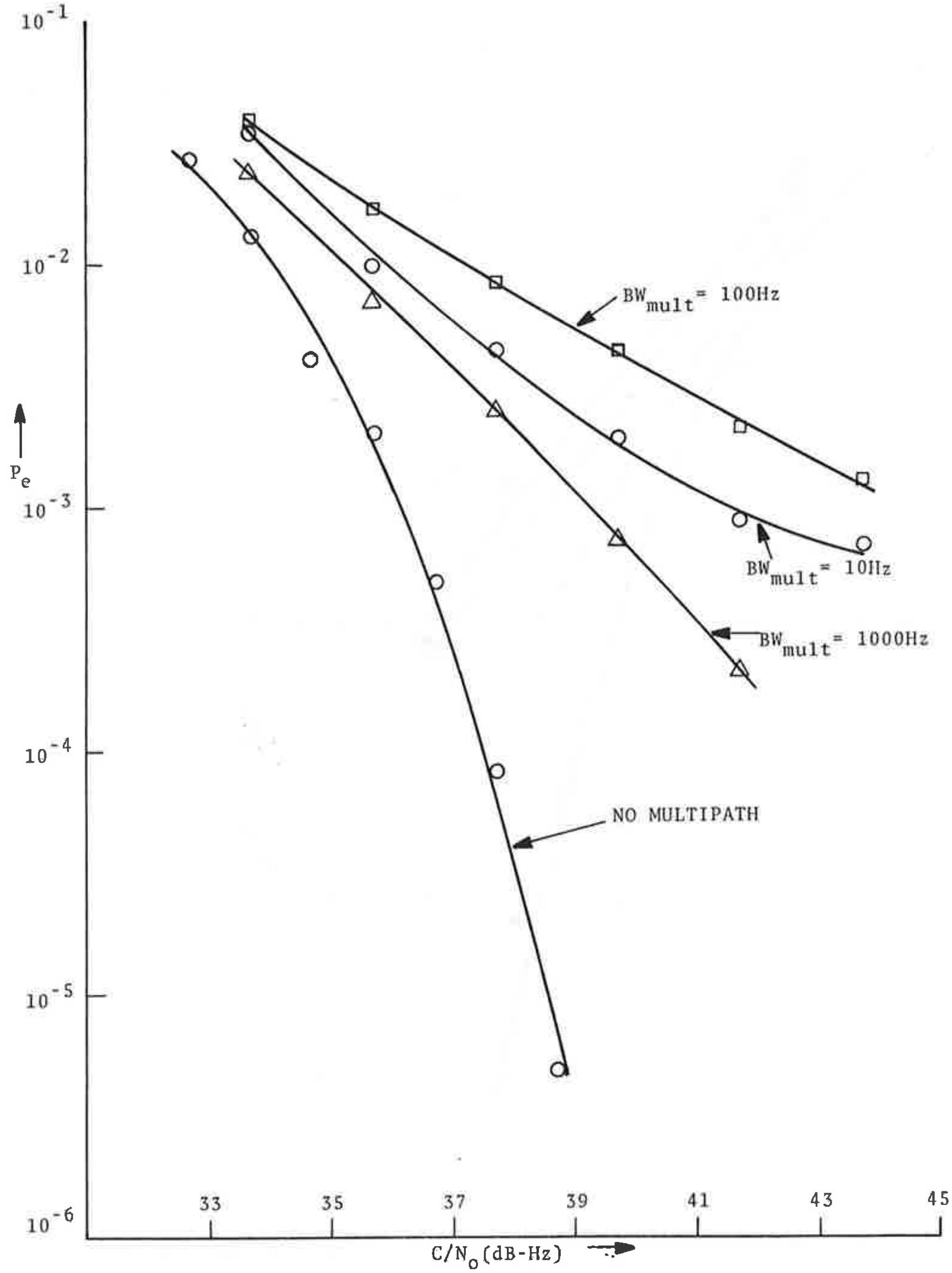


FIGURE 29. PROBABILITY OF BIT ERROR VS. C/N_0 FOR 50/4800 BAUD MODEM AT 600 bps WITH MULTIPATH AT C/M = 8 dB

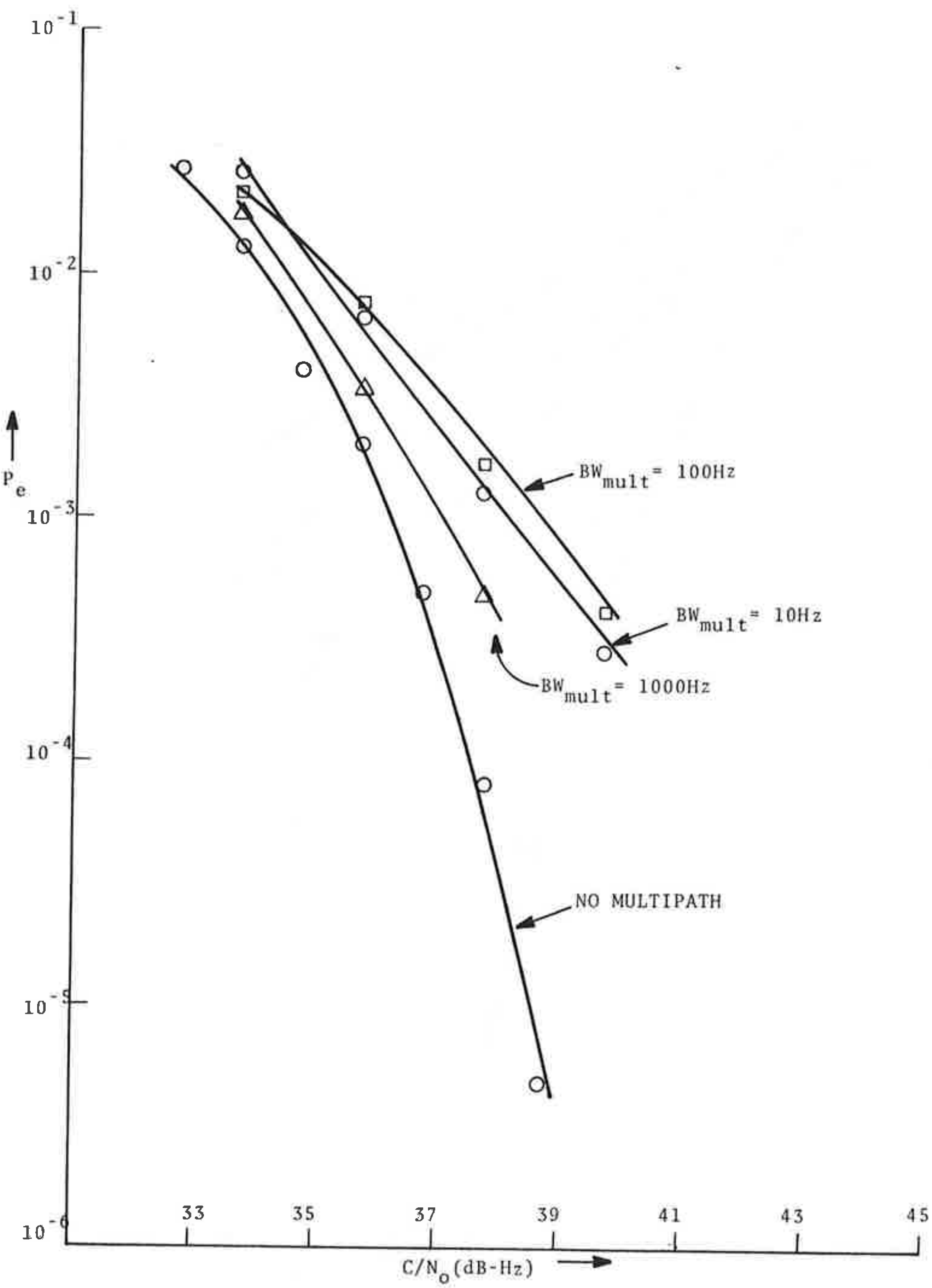


FIGURE 30. PROBABILITY OF BIT ERROR VS. C/N_0 FOR 50/4800 BAUD MODEM AT 600 bps WITH MULTIPATH AT C/M = 11 dB

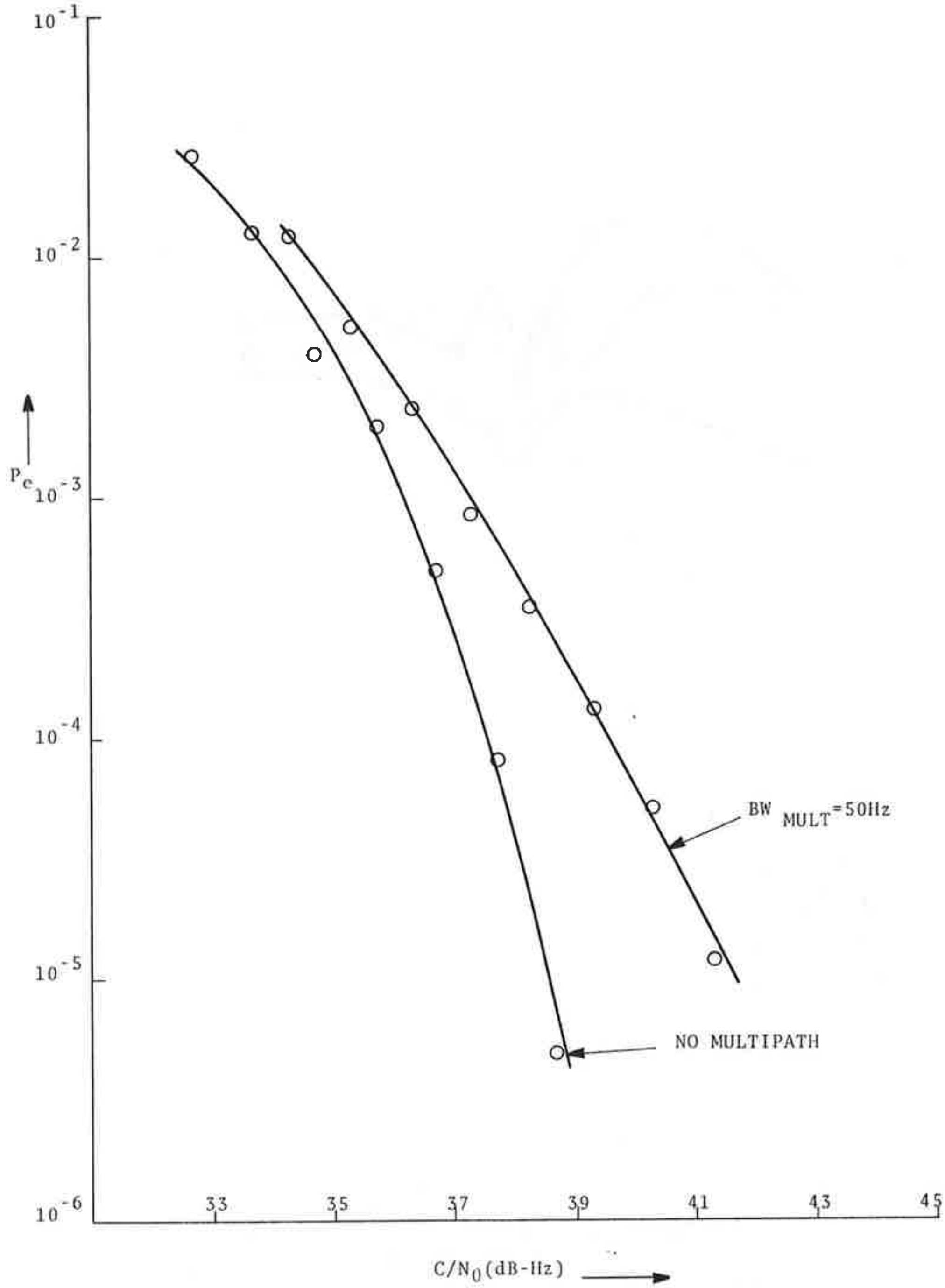


FIGURE 31. PROBABILITY OF BIT ERROR VS. C/N_0 FOR 50/4800 BAUD MODEM AT 600 bps WITH MULTIPATH AT C/M ≈ 13 dB

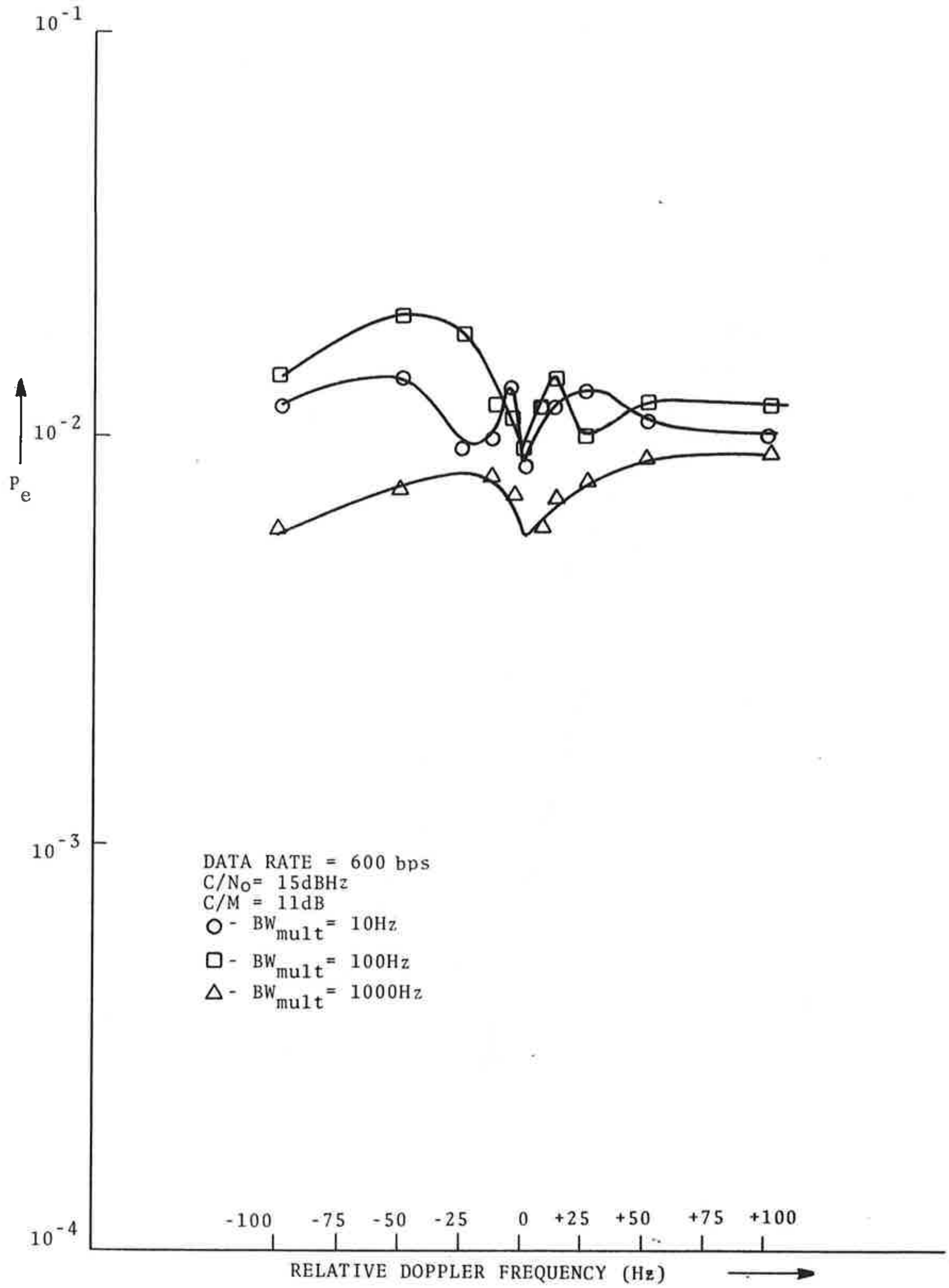


FIGURE 32. PROBABILITY OF BIT ERROR VS. RELATIVE DOPPLER FREQUENCY FOR 50/4800 BAUD MODEM

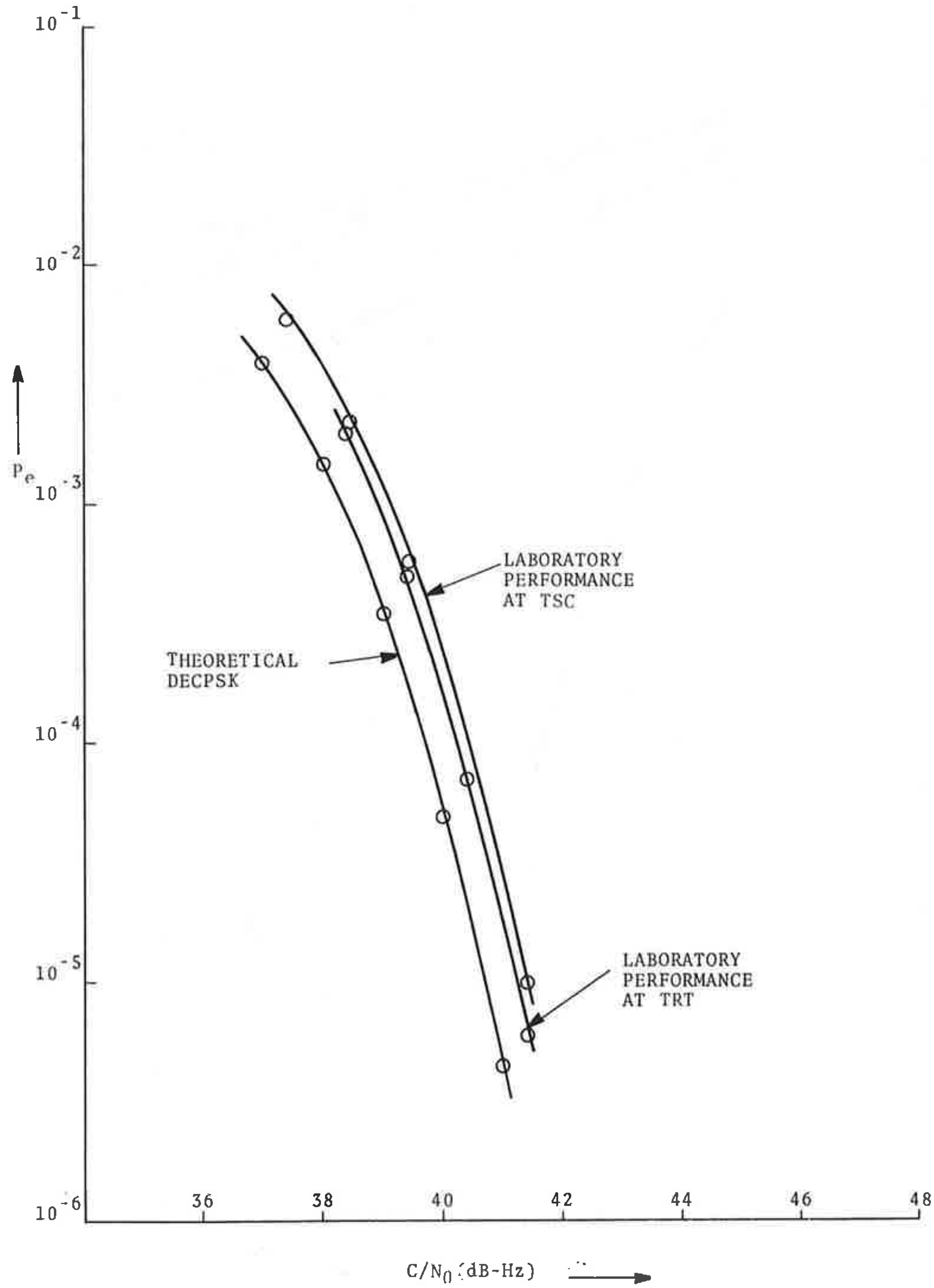


FIGURE 33. PROBABILITY OF BIT ERROR VS. C/N_0 FOR 50/4800 BAUD MODEM AT 1200 bps

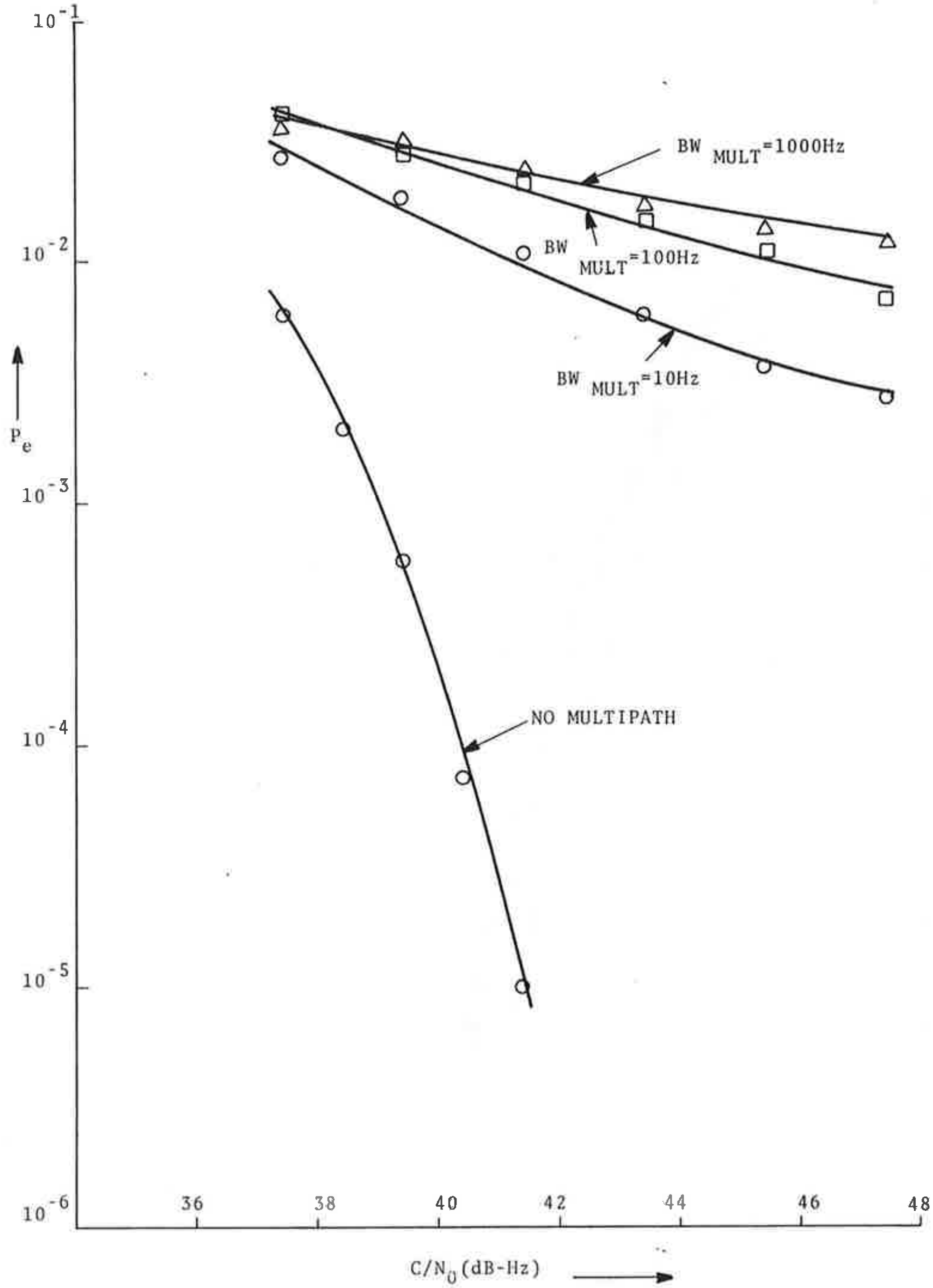


FIGURE 34. PROBABILITY OF BIT ERROR VS. C/N_0 FOR 50/4800 BAUD MODEM AT 1200 bps WITH MULTIPATH AT C/M = 5 dB

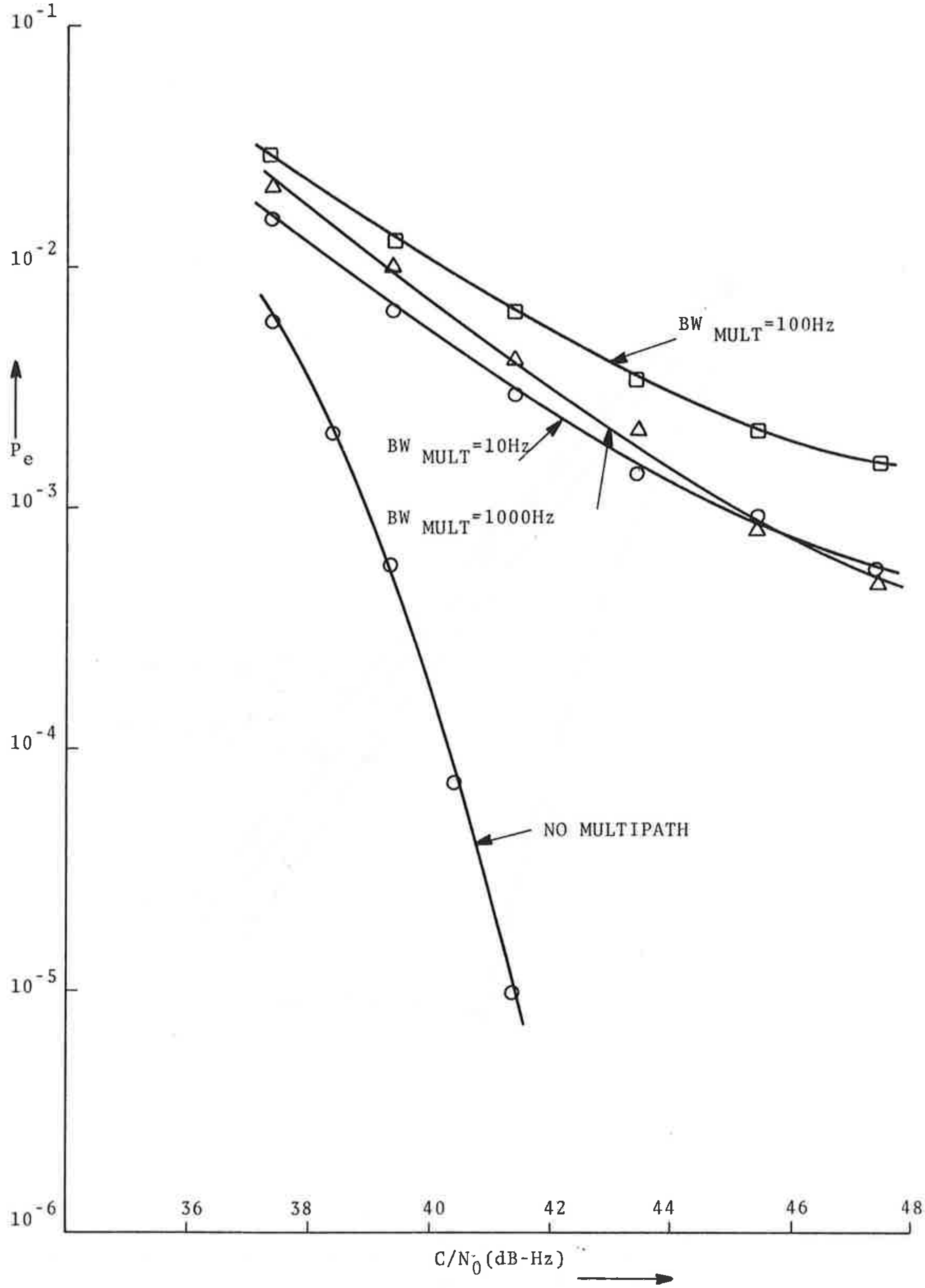


FIGURE 35. PROBABILITY OF BIT ERROR VS. C/N_0 FOR 50/4800 BAUD MODEM AT 1200 bps WITH MULTIPATH AT C/M = 8 dB

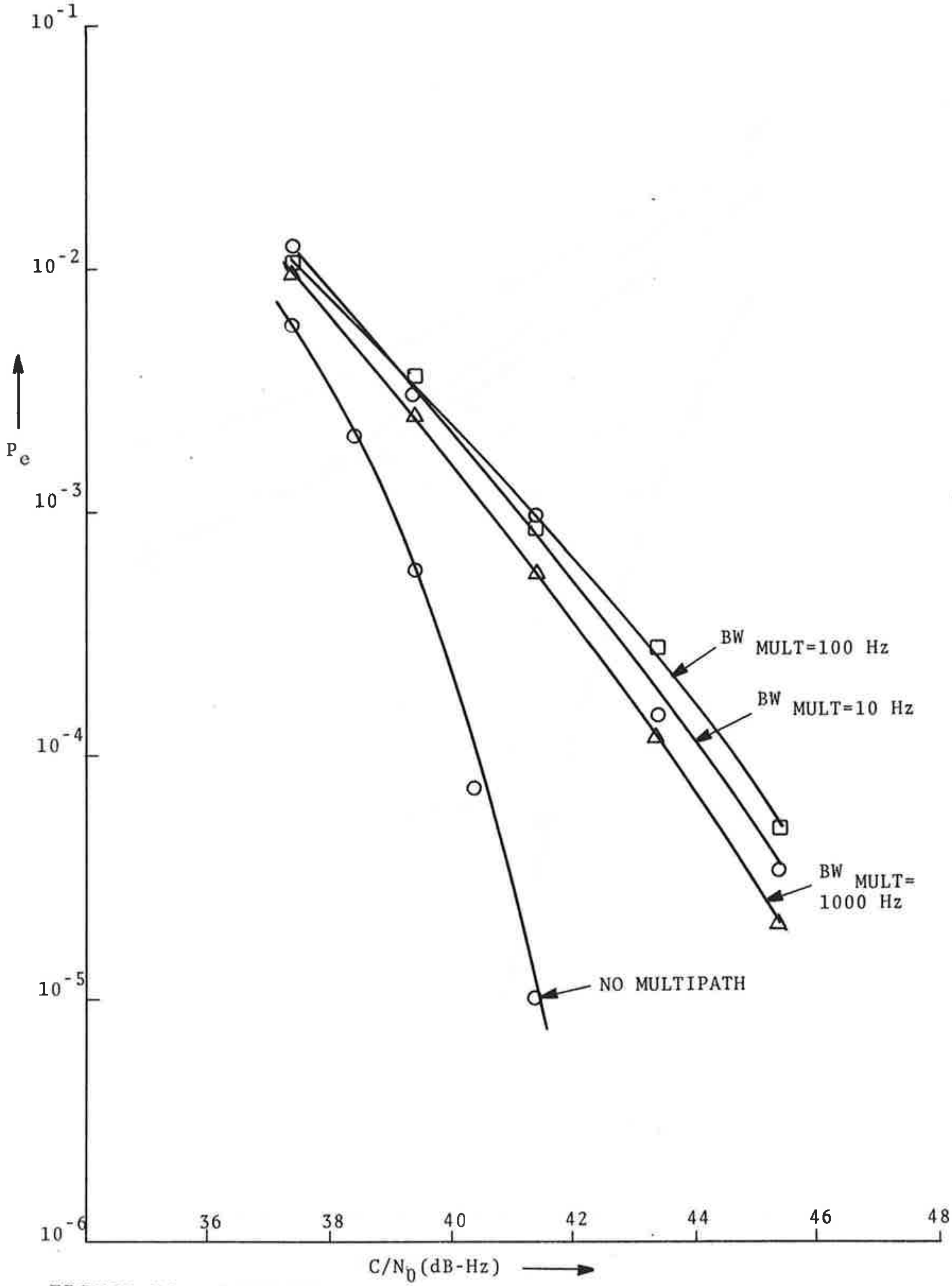


FIGURE 36. PROBABILITY OF BIT ERROR VS. C/N_0 FOR 50/4800 BAUD MODEM AT 1200 bps WITH MULTIPATH AT C/M = 11 dB

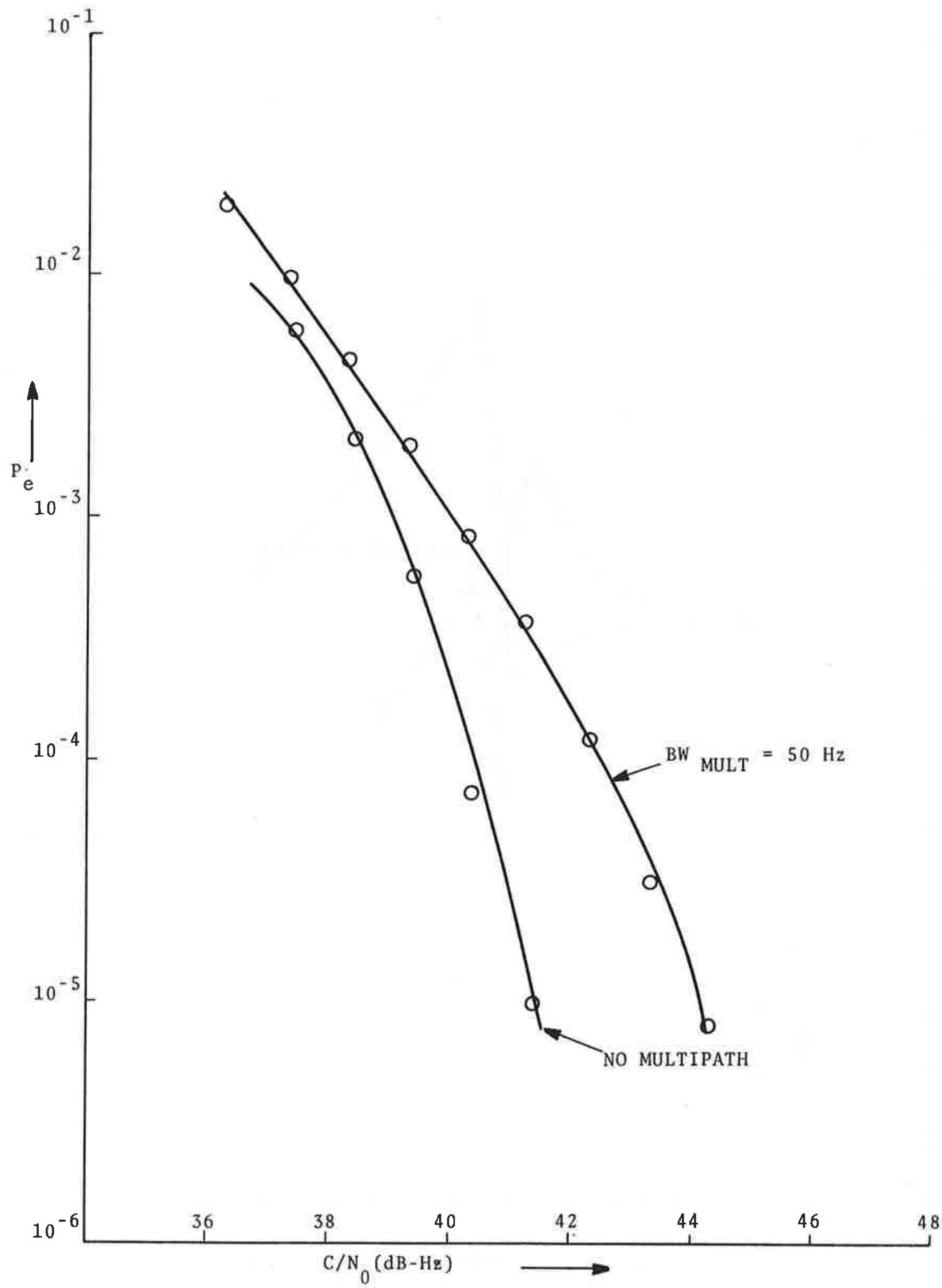


FIGURE 37. PROBABILITY OF BIT ERROR VS. C/N_0 FOR 50/4800 BAUD MODEM AT 1200 bps WITH MULTIPATH AT C/M_0 = 13 dB

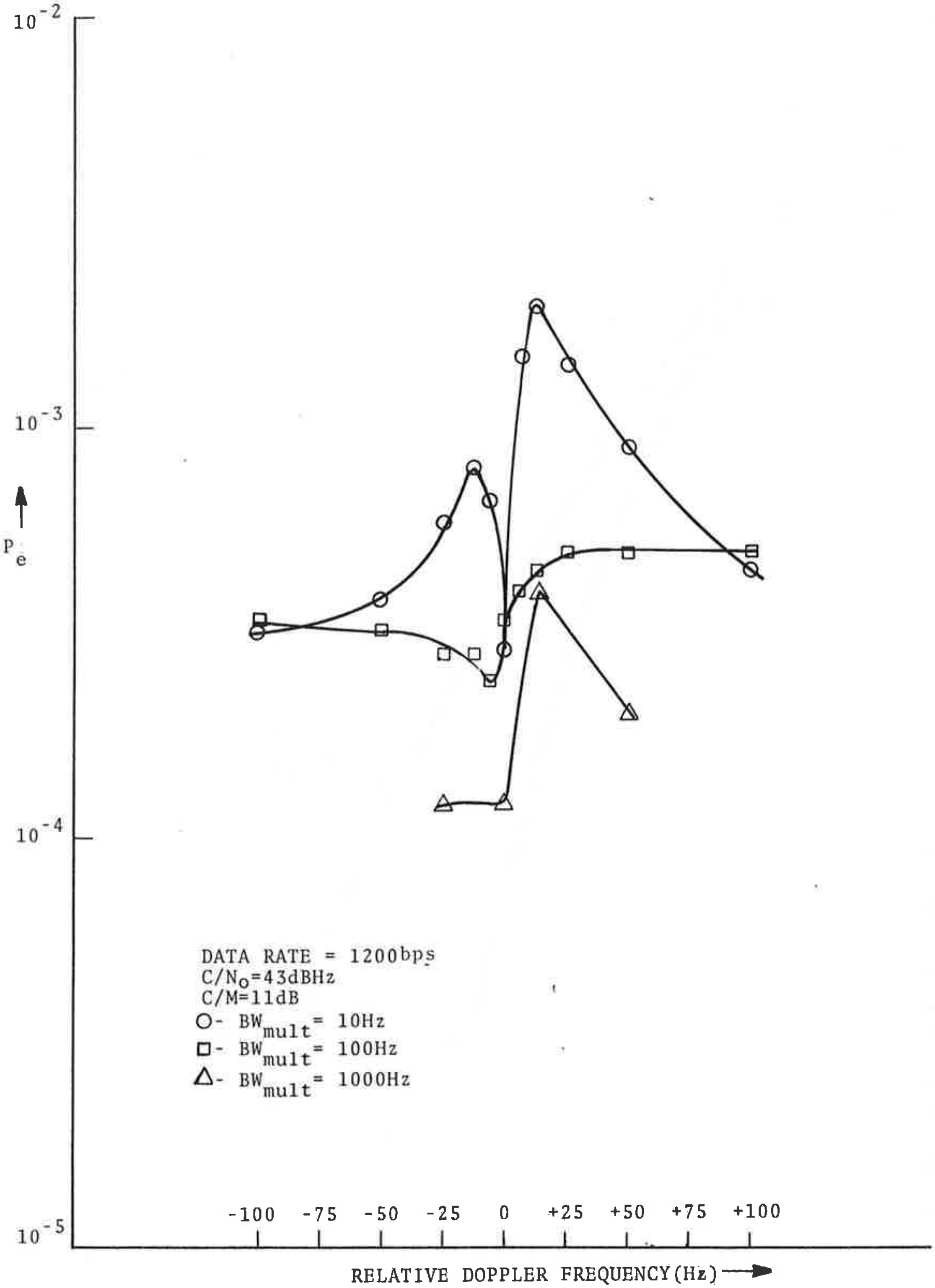


FIGURE 38. PROBABILITY OF BIT ERROR VS. RELATIVE DOPPLER FREQUENCY FOR 50/4800 BAUD MODEM

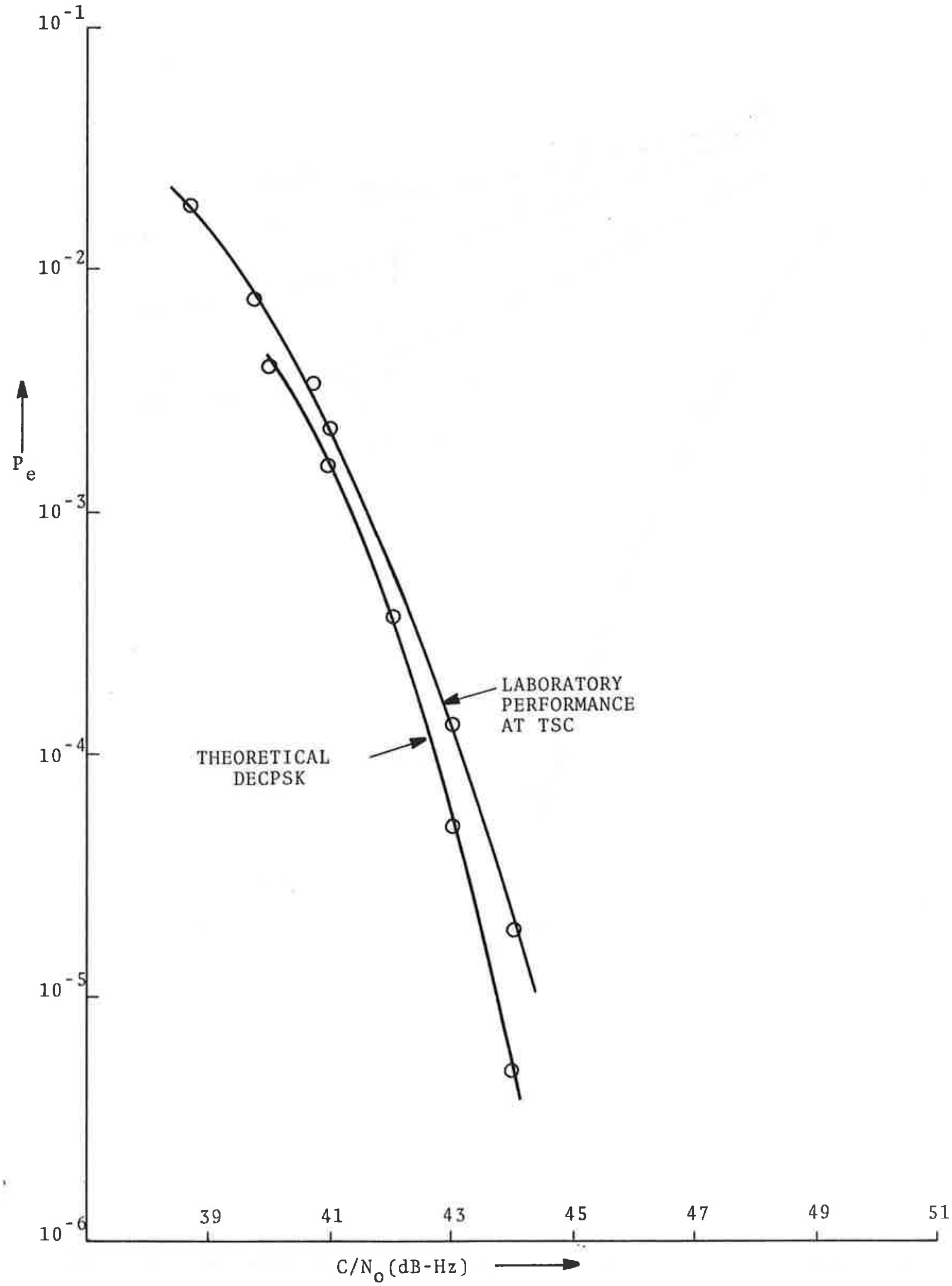


FIGURE 39. PROBABILITY OF BIT ERROR VS. C/N_0 FOR 50/4800 BAUD MODEM AT 2400 bps

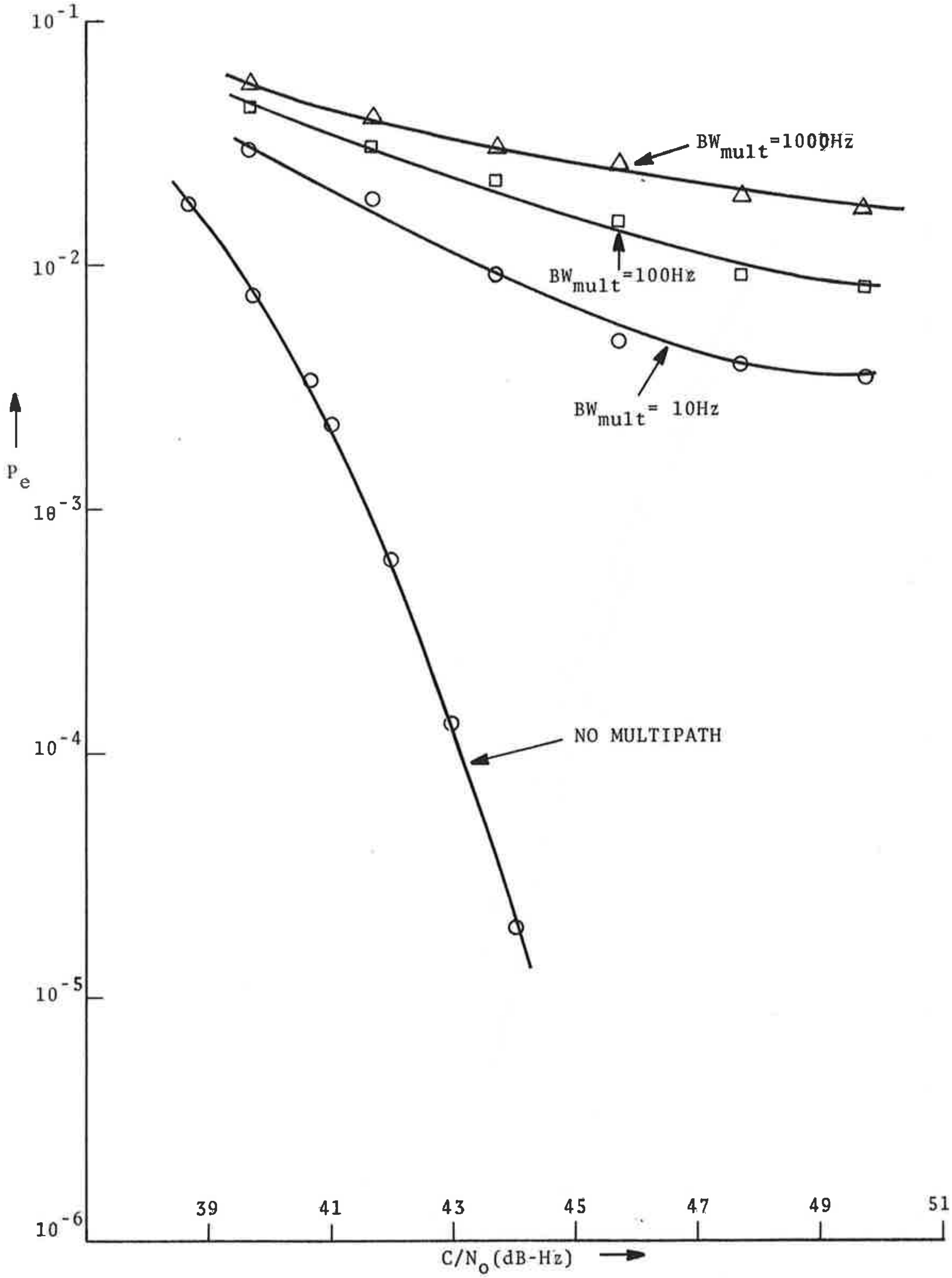


FIGURE 40. PROBABILITY OF BIT ERROR VS. C/N_0 FOR 50/4800 BAUD MODEM AT 2400 bps WITH MULTIPATH AT C/M = 5 dB

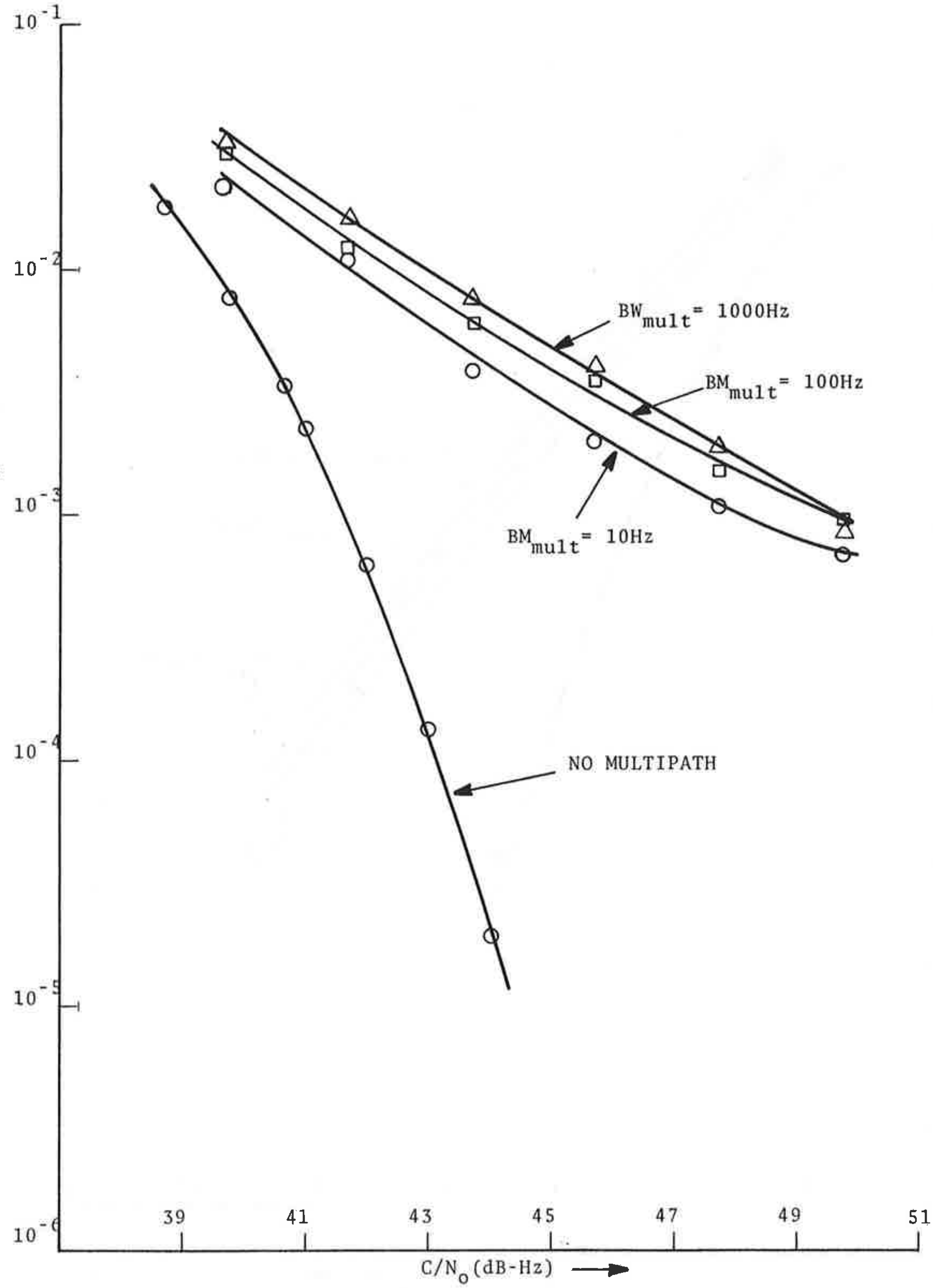


FIGURE 41. PROBABILITY OF BIT ERROR VS. C/N_0 for 50/4800 BAUD MODEM AT 2400 bps WITH MULTIPATH AT C/M = 8 dB

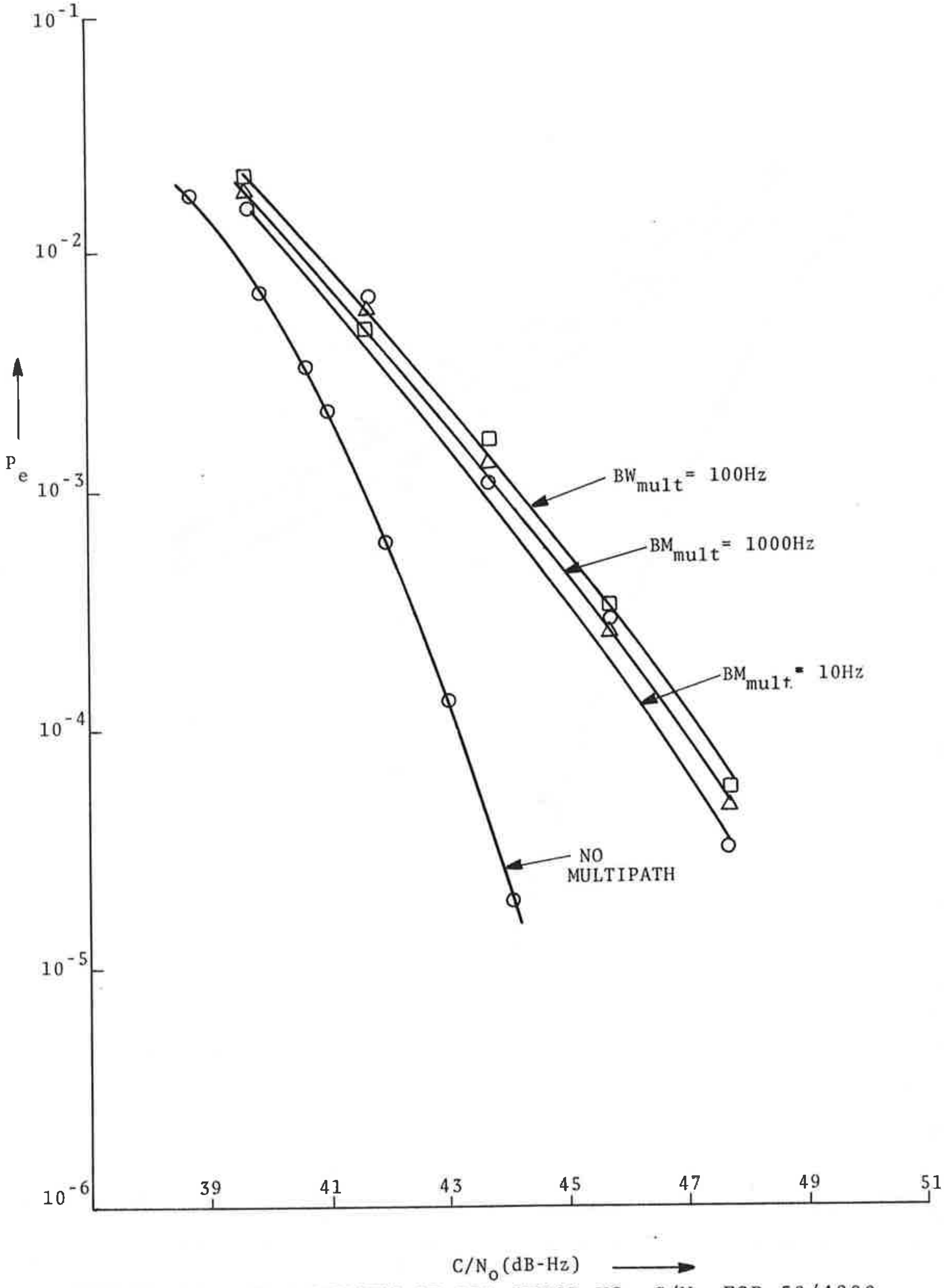


FIGURE 42. PROBABILITY OF BIT ERROR VS. C/N_o FOR 50/4800 BAUD MODEM AT 2400 bps WITH MULTIPATH AT C/M = 11 dB

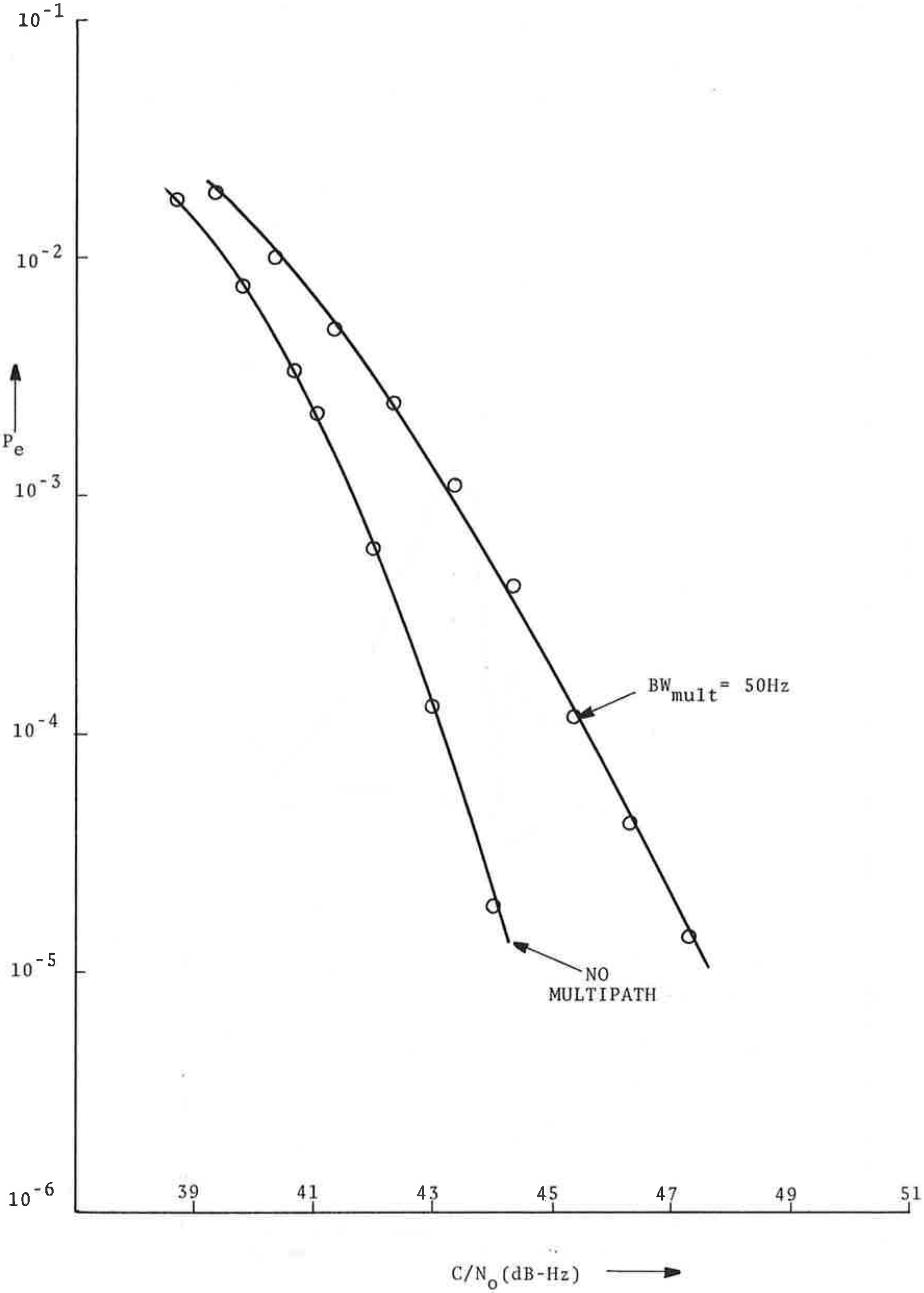


FIGURE 43. PROBABILITY OF BIT ERROR VS. C/N_0 FOR 50/4800 BAUD MODEM AT 2400 bps WITH MULTIPATH AT C/M = 13 dB

slow tracking loop the modem required a long time to reacquire lock once the doppler was added. This modem may have more application in the marine area than in the aeronautical environment.

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