In this assessment the effects of inclination angles and orbit altitudes on pfd computation were investigated separately. The results of these calculations for a single satellite are shown in Figures 13 through 16. The curves marked A, B, C, and D in these figures represent orbit altitudes 300, 500, 800, and 1200 km, respectively. Curve E in these figures represents the CCIR interference noise criteria for systems in the Fixed Service. The results shown indicate that, regardless of orbit altitude, the interference from satellites to radio-relays in the Fixed Service is more serious at low inclination angles. Also the level of interference increases as the altitude of satellite orbit increases. Since the curves shown in Figures 13 through 16 do not cross each other at least in the important region above 0.1 percent of time, it may be stated that the effects of orbit altitudes and orbit inclination angles are independent. Based on these results, worst case interference to radio-relays in the Fixed Service from a low orbit satellite occurs when it is in an orbit with high altitude and low inclination angle. However, the increase in interference level due to low inclination angles occurs in the region of the interference curve which has no effect on the determination of pfd limits.

A glance at Figures 13 through 16 indicates that the separation between the criterion curve E and the interference curves A, B, C, and D is larger for higher percentages of time. This is true for all the inclination angles and the various orbit altitudes used in the calculations of the data in Figure 13 through 16. This result is significant and leads to the fact that the interference from the satellites in low orbit is more pronounced at low inclination angles. The data shown in Figures 13 to 16 were for the hypothetical case where one satellite was assumed to be in orbit. The purpose of the data was to show the effect of inclination angle on the interference received from satellites in non-geostationary orbits. A significant point to be made is that interference received from satellites in non-geostationary orbit is negligible for percentage of time greater than 5%.

Now consider the case of a trendline that experiences interference from satellites in the geostationary and non-geostationary orbits. Clearly, the effect of interference from satellites in both geostationary and non-geostationary orbits is more serious when satellites in non-geostationary orbits have low inclination angles. Assuming that a trendline located at 40 degrees latitude is experiencing 1000 pW of interference from satellites in geostationary orbit, the interference from satellites in non-geostationary orbits was calculated and the results was added to the 1000 pw of interference. The results found for this combination are shown graphically in Figure 17. In this calculation eight satellites were assumed to be divided evenly in four non-geostationary orbits with 20 degrees inclination angle. The four orbits each having two satellites were in altitudes 300, 500, 800, and 1200 km. The data in Figure 17 shows that the effect of interference from satellites in non-geostationary orbits is negligible for percentage of time greater than 5%.

An examination of the data in Figure 17 suggests that the pfd limits for satellites in non-geostationary orbit may be raised by only 8 dB (the dB difference between CCIR curve and the curve showing the calculated interference at 0.5% of time). But in reality, this is not the case. Figure 18 shows the interference received by the same trendline from satellites in

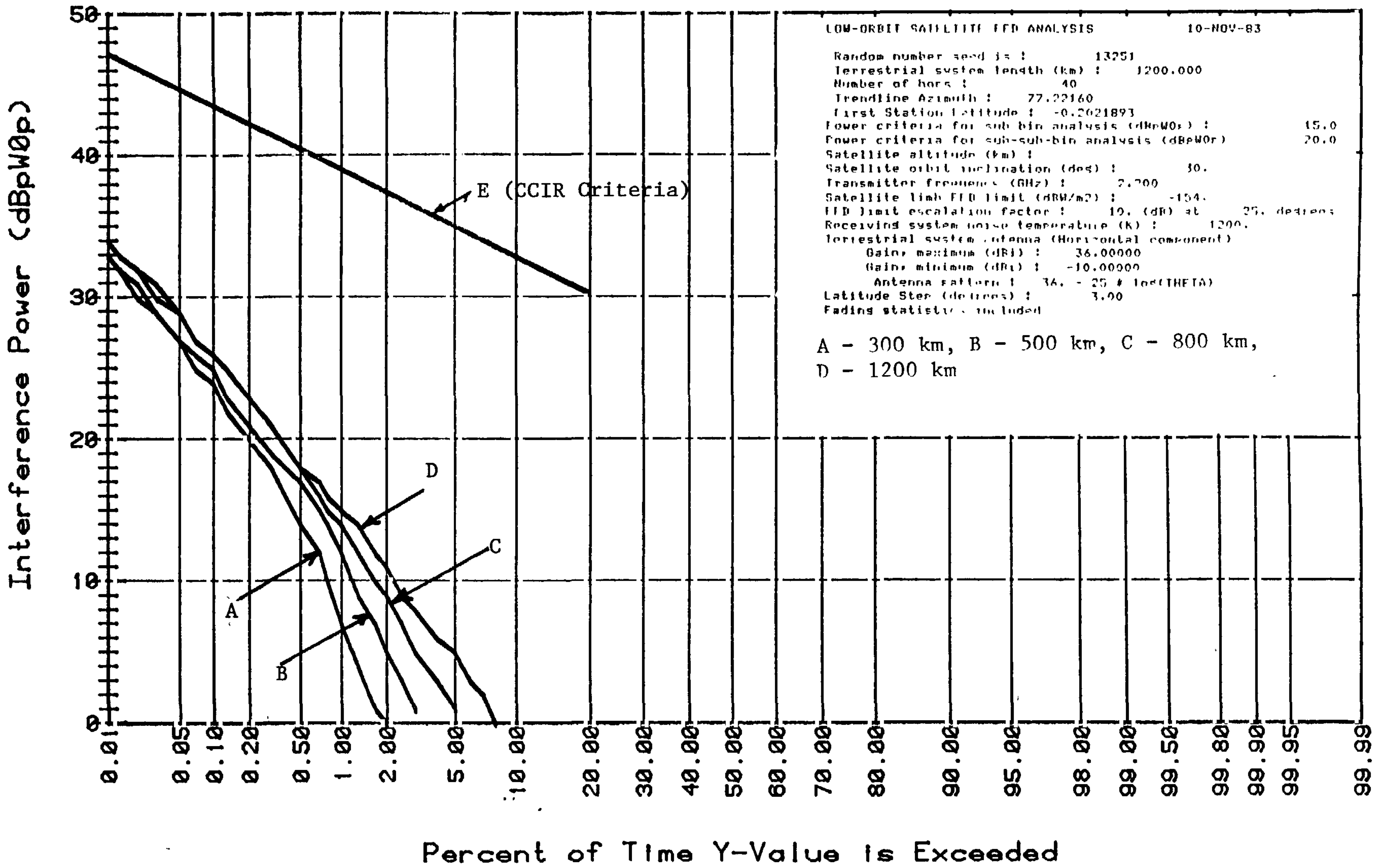

Figure 13 Interference Calculcation for Inclination Angle Equal to 10 Degrees

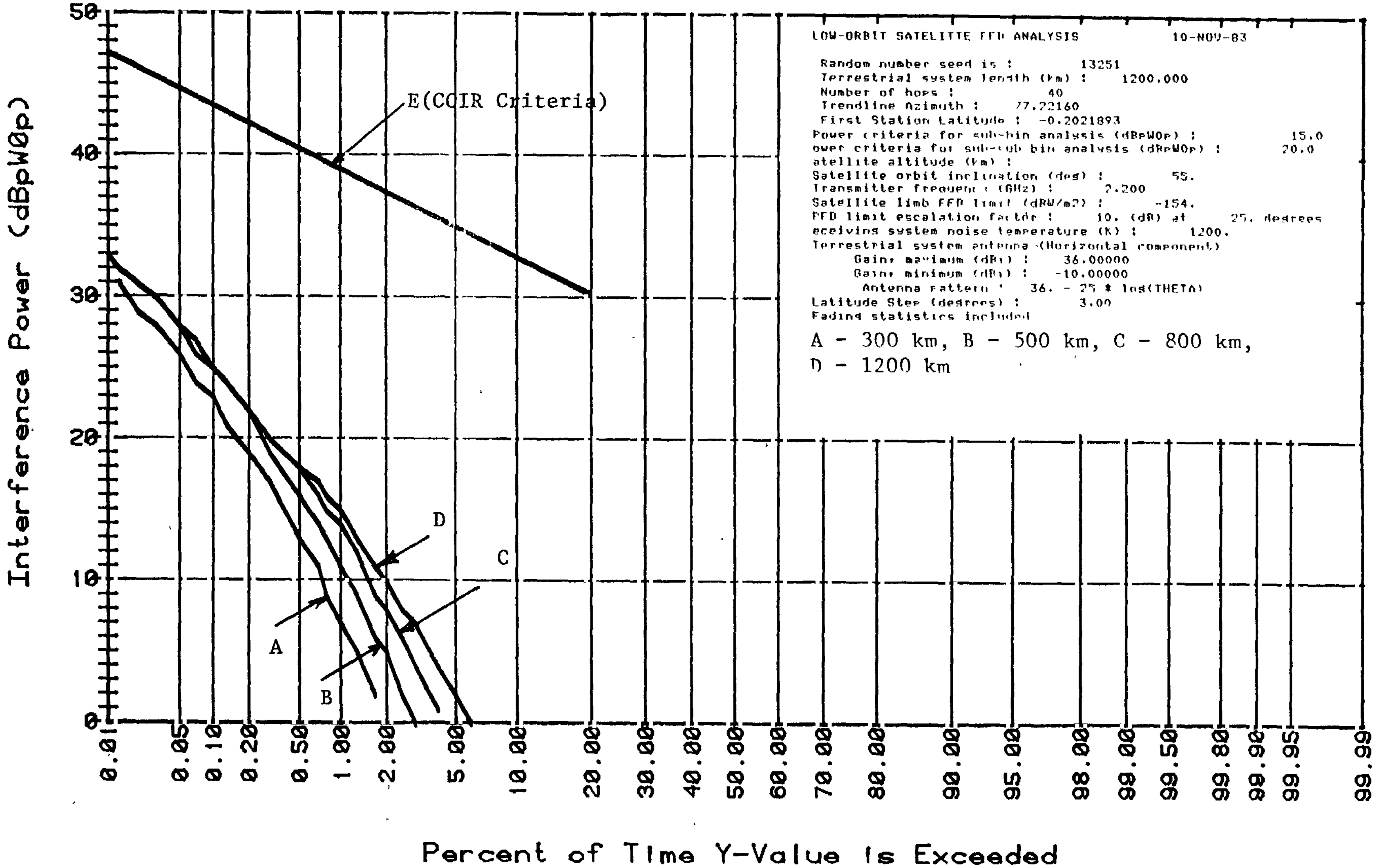

Figure 14 Interference Calculation for Inclination Angle Equal to 30 Degrees

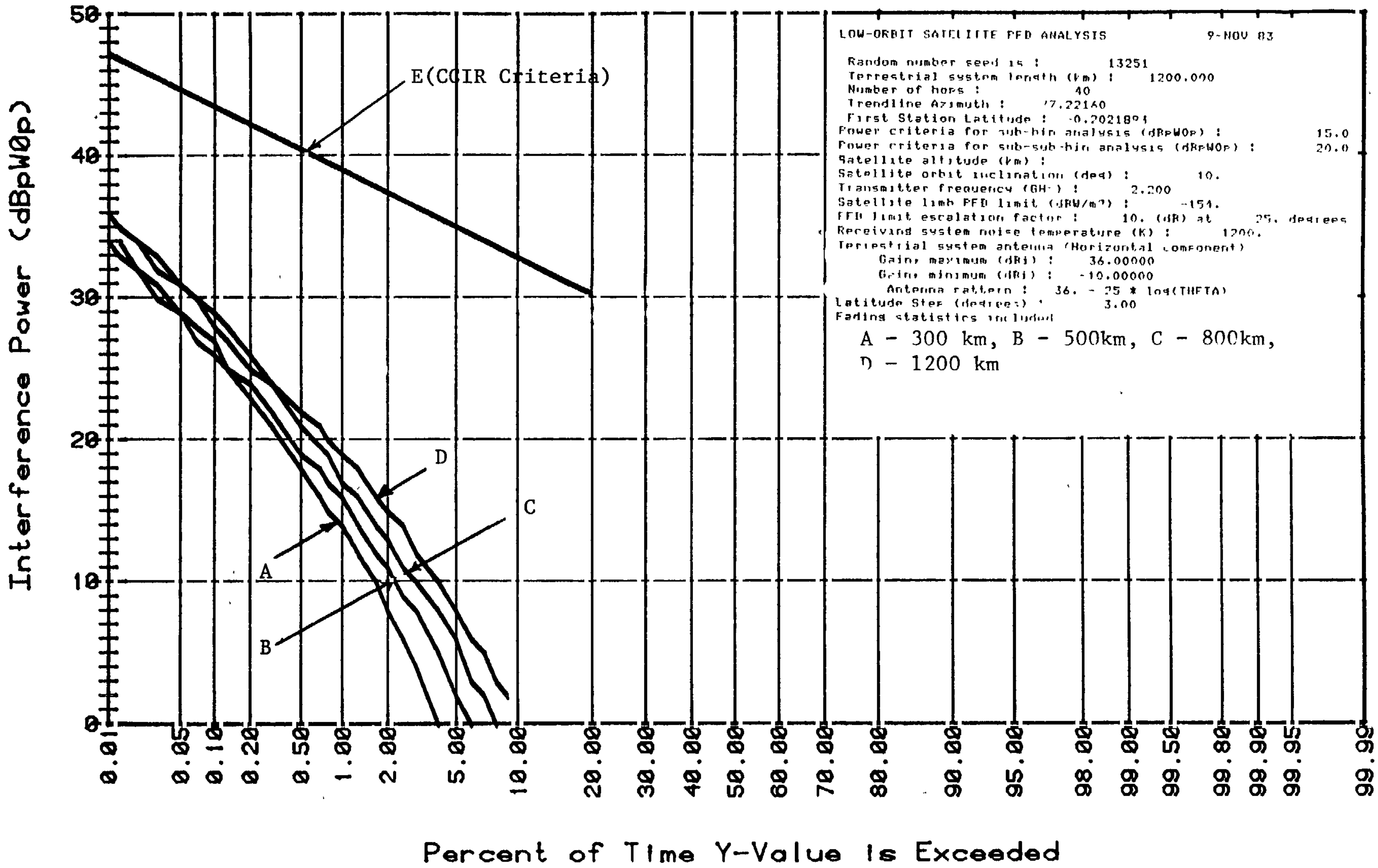

Figure 15 Interference Calculation for Inclination Angle Equal To 55 Degrees

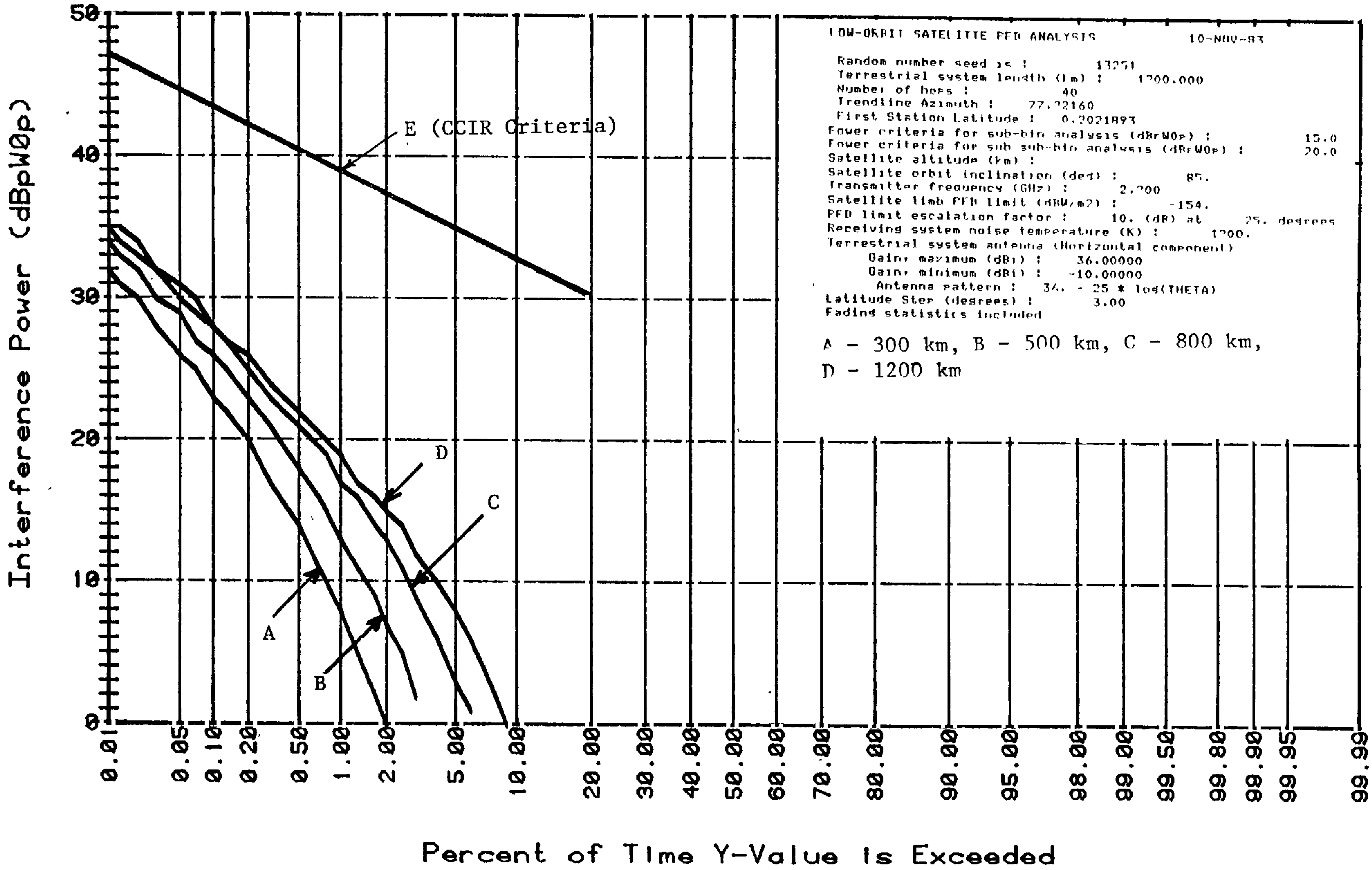

Figure 16 Interference Calculations for Inclination Angle Equal to 85 Degrees

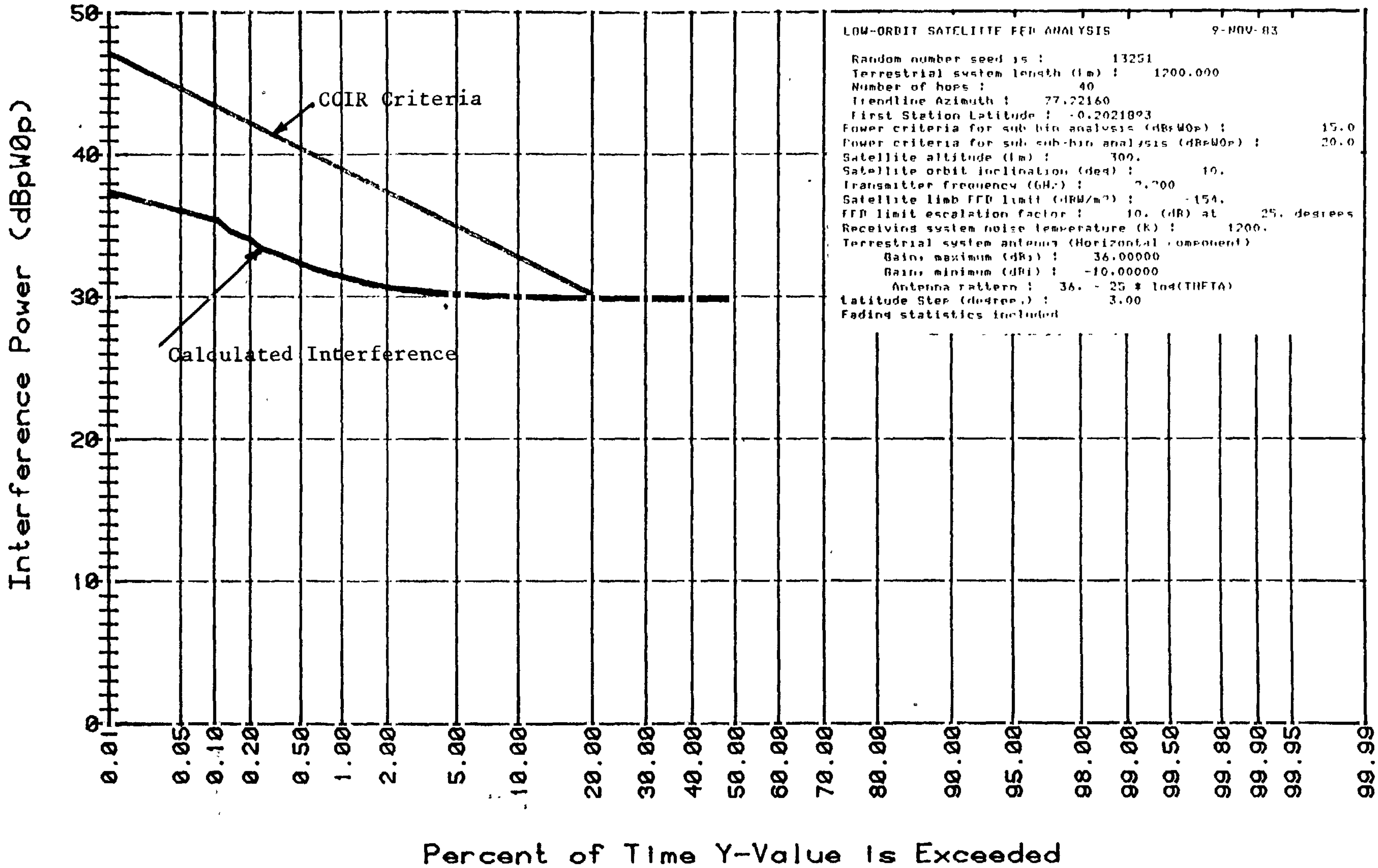

FIGURE 17: Combined Interference from Satellites in Both Geostationary and Non-Geostationary Orbits

Figure 17 except that in the latter 1000 pW of interference from satellites in the geostationary orbit was not added to the results. Note that again the results in Figure 17 shows that this time the pfd limits from satellites in non-geostationary orbit may be raised by 14 dB (again considering the level of interference at 0.5 percent of time). Had we added 14 dB to pfd limits and included 1000 pW of interference from geostationary orbit, the results would have been 40.4 dB compared with 40 dB recommended by the CCIR. Therefore, the combined curve for interference shown in Figure 17 should be interpreted correctly and care should be exercised in using this curve for calculating pfd limits for satellites in non-geostationary orbits. The results in Figures 17 and 18 indicate that pfd limits for satellites in non-geostationary orbits may be thought of as being independent from the limits for satellites in geostationary orbit and can be calculated separately.

As was mentioned above, to determine multiple-orbit effects on pfd limits, the NGM computer program was modified to conduct the analysis using satellites in various orbits of different altitudes. To calculate these effects it was assumed that there were a total of eight satellites visible simultaneously by the radio-relays in the Fixed Service in 2025-2300 MHz frequency range. This assumption is consistent with the results given in Part 1 of this report. Since the orbit altitudes in this frequency range vary from 300 to 1200 km, for the computational purposes it was assumed that there are two satellites in each of the four orbits with the altitudes of 300, 500, 800, and 1200 km. The eight satellites were evenly divided among the four orbits. Curve E in Figure 18 represents the interference noise criteria established by the CCIR (Rec. 357-3). Data in Figure 19 shows that the pfd limits for satellites in non-geostationary orbits may be raised by 14 dB. This method of calculation is more realistic and the assumption that all the satellites remain in the highest orbit visible to terrestrial radio-receivers is very conservative and results in more restrictive pfd limits.

SYSTEMS USING TROPOSPHERIC TRANSMISSION

Internationally, there are several systems which use tropospheric transmission in or near the 2025-2300 MHz frequency range. However, in the United States the use of the 2200-2290 MHz band is limited to line-of-sight transmission for Government users and the 2290-2300 MHz band is not sufficient for accommodating any long-haul tropospheric transmission in other administrations. But the emissions from U.S. satellites are not always confined to the U.S. boundaries and power flux limits are required to protect the systems using tropospheric transmission in other administrations. Provisions in No. 2560 of the ITU Radio Regulations specify limits for the protection of the systems which are designed to operate using tropospheric transmission. Transhorizon receivers generally have lower noise temperatures than the receivers used in line-of-sight operation. Transhorizon systems use very high gain antennas with narrower beamwidth and low off-axis gain. Compared to systems using line-of-sight transmission, transhorizon systems use fewer receivers in a trendline of similar length. Hence, there are fewer interference entries in a transhorizon system.

A realistic power flux limit for the protection of transhorizon system was not determined here. There exists no recommendation by the CCIR for the noise power level to transhorizon systems from the systems in the Fixed Satellite Service. The derivation of -168 dBW in any 4 kHz bandwidth was

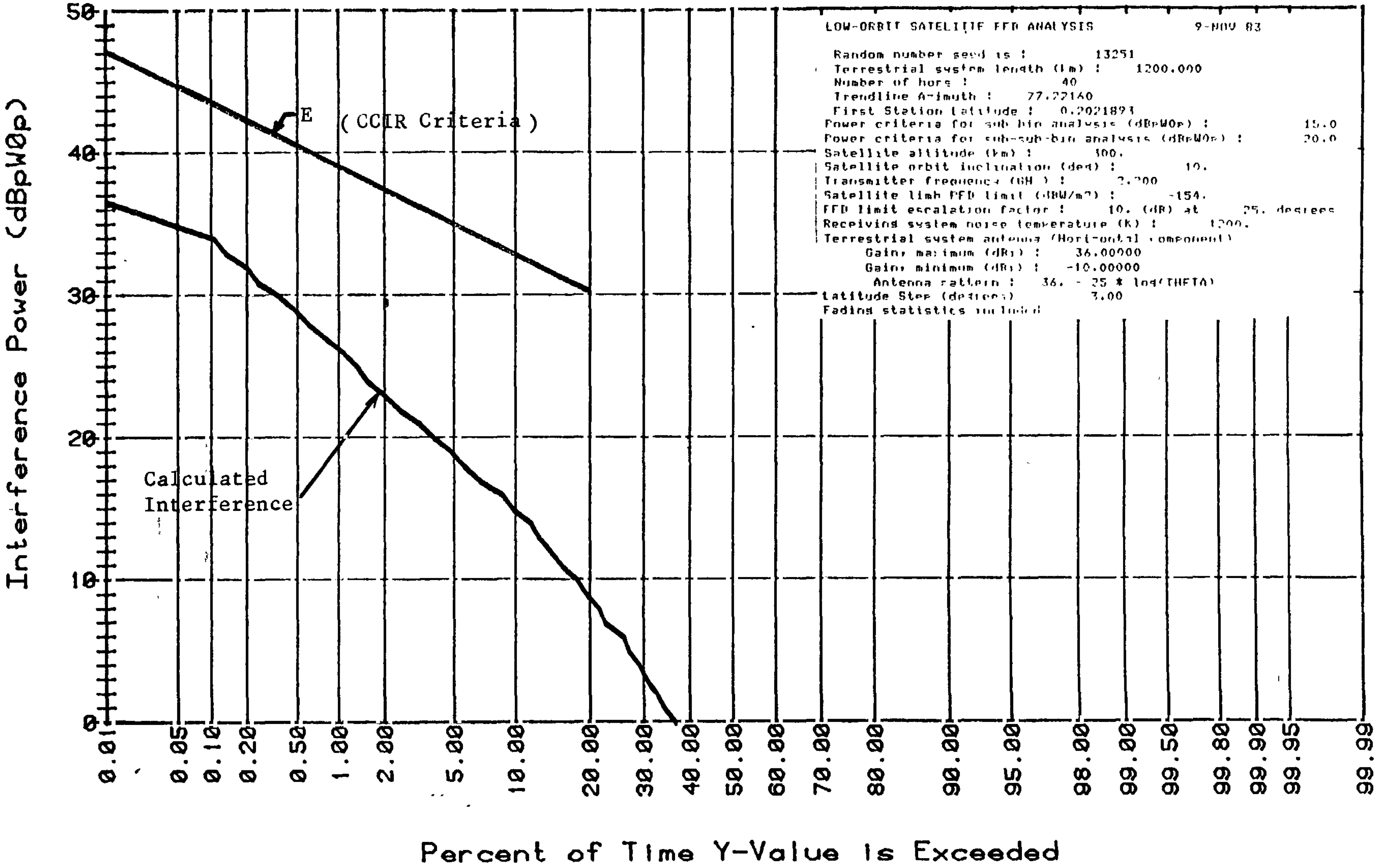

FIGURE 18: Interference from Satellites in Non-Geostationary Orbits.

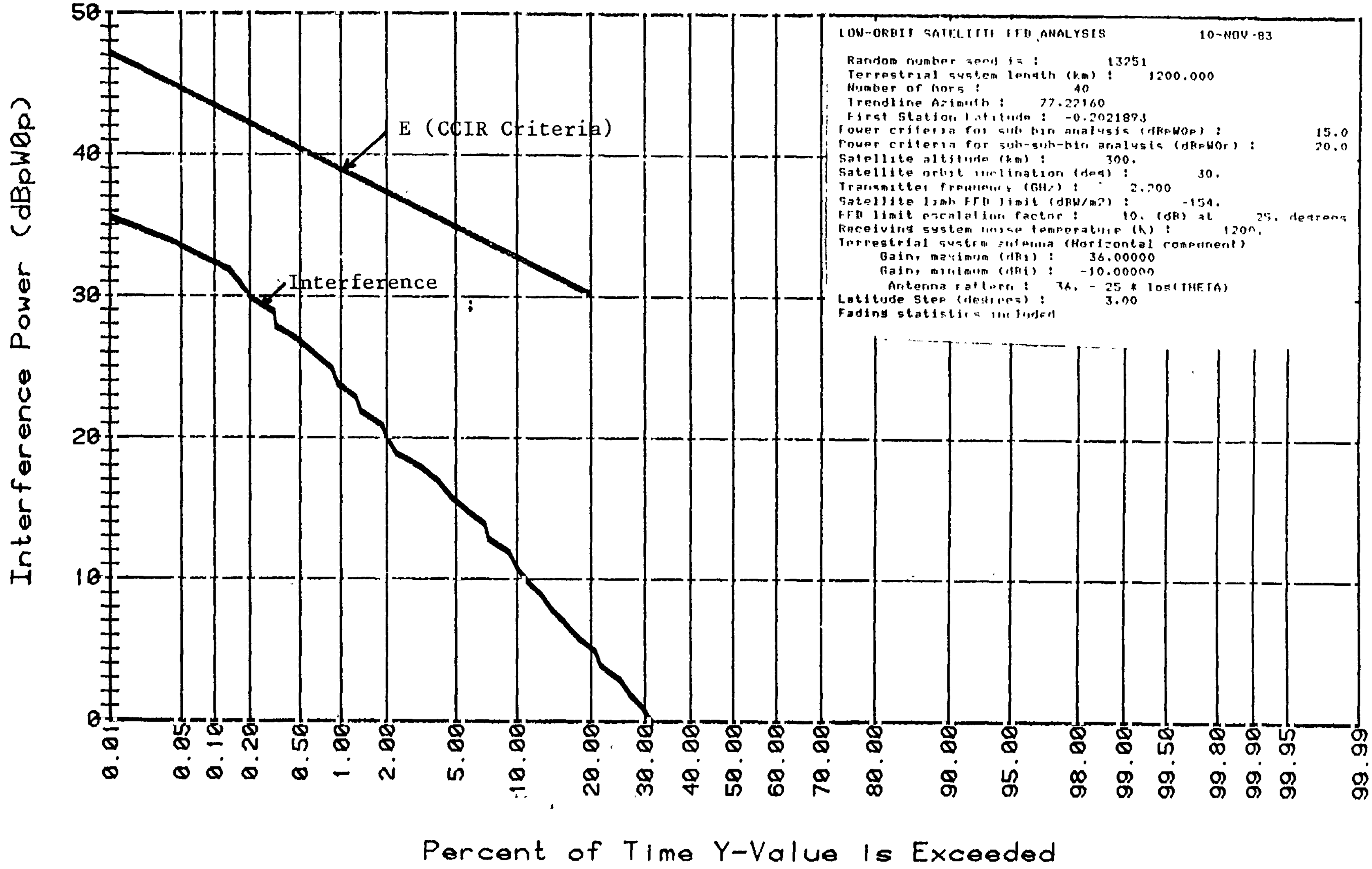

FIGURE 19: Interference Curve for 8 Satellites in Low Orbits Varying in Altitudes from 300-1200 km

considered both in Annex 6-2D and Annex 8-4B of the CCIR Report of the Special Joint Meeting of 1971, Part II. Annex 6-2D is discussed by Watson (McHugh E, Watson) as follows.

"INTERFERENCE FROM ERS SPACE STATIONS TO
TRANS-HORIZON RADIO-RELAY RECEIVERS (M/227)

"The following hypothetical example at 8 GHz is developed to illustrate some aspects of sharing between trans-horizon radio-relay systems and low altitude inclined orbit satellite systems such as an ERS system.

Trans-horizon radio-relay systems have system noise temperatures as low as 300 K. To protect the most sensitive receiver, under the assumption that interference is allowed to equal thermal noise, the maximum allowable interference level at the receiver input will be -167.3 dBW in 4 kHz."

A summary of derivation of -167.3 dBW in 4 kHz is as follows:

k (Boltsman Constant)	-228.6 (dBW)
300K	24.8 (dB)
	-203.8 (dBW)
4 kHz	36.0 (dB)
	-167.8 dBW/4 kHz

Obviously, -167.8 corresponds to the noise level of the receiver and communication systems generally are designed to operate far above these noise levels considering multipath and atmospheric effects. The GM computer program, originally, was used for calculating the pfd limits for protecting terrestrial line-of-sight radio-relay systems. These systems generally use antennas pointed in the direction of the horizontal plane. As a result, the computer model does not take into account an inclination angle of antennas in the vertical plane which could be used by transhorizon systems. In addition, the pointing angles and the direction of trendlines are calculated statistically by the computer model. The use of the computer model in calculating power flux limit for systems using transhorizon transmission will yield an approximate result. Modification to the computer program should be made after a review of the characteristics of trendlines using trans-horizon transmission. A more detailed analysis, however, must await the determination of interference noise limit by the CCIR for satellites to protect the systems using tropospheric transmission.

DIGITAL SYSTEMS

Both GM and NGM computer programs consider only the potential interference from satellites in geostationary and non-geostationary orbits, respectively, to the analog terrestrial systems in the Fixed Service. There are a large number of digital systems in the 2025-2300 MHz frequency range which are now in operation by both Government and non-Government users.

Relative to analog systems, digital radios are more recent and had to be designed to function properly in the analog environment. Historically, digital systems used in radio telephony have followed the design guidelines previously set by the CCIR for analog radios. For example, the Hypothetical Reference Circuit for analog FDM/FM radios is identical to the Hypothetical Reference Digital Circuit established by the CCITT for digital radio-relay systems. This historical observation is not surprising, since the facts are that the digital radio should interface with their analog counterparts and that the environment once established by and for the analog radios could not be rearranged to accommodate any new systems with characteristics requiring a different environment. The pfd limits set by the CCIR are among the elements in the electromagnetic environment which were in place to protect the analog systems in the Fixed Service.

Efforts have been made by the CCIR to provide some design guidelines specially suited for the digital systems. For example, Recommendation 557 states "... that the concept of unavailability of a Hypothetical Reference Digital Path should be as follows: in at least one direction of transmission, one or both of the two following conditions occur for at least 10 consecutive seconds...: 1. The digital signal is interrupted (i.e. alignment or timing is lost). 2. The error rate is greater than 10^{-3}." More recent attempts were made by the CCIR to establish more definite guidelines for the bit-error-rate in digital systems, but no unanimous agreement has been achieved through the CCIR and, in addition, there exists no criteria for interference noise from satellites to the digital systems. Despite the ruggedness which had been used in the design of the digital system in this frequency range, it was found advantageous to conduct a cursory analysis to assess, approximately, the degree of protection that the digital systems in the 2025-2300 MHz frequency now have.

In the analysis given here, let us assume that the bit-error-rate (ber) has to be less than 10^{-3} and that this is the limiting value. The characteristics of the digital systems vary with the modulation schemes used and the performance of these systems are sensitive to these characteristics. Variations in modulation schemes are often to accommodate marketing features which appeal to system users. For example, one system uses quadrature amplitude modulation (a form of amplitude shift keying) and another system uses quadrature phase shift keying modulation. Despite apparent variation of modulation schemes used by different manufacturers, every system must be designed with sufficient flexibility; and, in general, it may be stated that all the modulation schemes used in the digital equipment may be described by the three basic forms of modulation, i.e. Amplitude Shift Keying (ASK), Phase Shift Keying (PSK), and Frequency Shift Keying (FSK). Coherent detection has been assumed in the analysis. As far as signal-to-noise ratio and its relation to ber are concerned, it may be possible to consider a system to be in one of the three categories of modulation mentioned above. The relationship between ber and signal-to-noise ratio may be used to estimate the degree of protection afforded for the digital systems in the 2025-2300 MHz frequency range.

It has been shown (Newhouse, 1981) that with continuous interference signals, noise and CW generally produce the two extremes, i.e., noise causes the worst and CW interference causes the least degradation in performance of a digital radio reciever. Hence, Gaussian noise being the worse case interference may be used to calculate the ber which a system may have to endure under severe interference. Therefore, if the signal-to-noise ratio for a system is such that it can function in the presence of Gaussian noise, then the system may be assumed to be compatible with other interference sources whose effects on the system are always less than that caused by the Gaussian noise.

Three computer programs were prepared in order to calculate the signal-to-noise ratio as a function of ber for the three modulation techniques (ASK, PSK, and FSK) used by digital systems. The results of the calculations are shown in Figures 20, 21, and 22. The curves in these figures are for M = 2, 4, 6, and 8. Generally, signal-to-noise ratio of a radio-relay receiver is greater than approximately 33 dB under faded condition in a channel. (The acceptable criteria for signal-to-noise ratio set by the Bell Systems is 33 dB). Using 26-43.5 dB signal-to-noise ratio at the input to receiver demodulator as an operational parameter, the data in Figures 20, 21, and 22 indicate that ber for all types of modulation techniques used for digital systems will be less than 10^{-3}.

The cursory analysis given above indicates that if digital systems in the 2025-2300 MHz frequency range were designed to operate in the analog environment, they can function properly under the guidelines set by the CCIR. At this time when no criteria for interference from satellites to digital systems are available, the discussions on ber and the fact that digital systems have been designed to operate in the analog environment may be sufficient to state that the digital systems are protected against interference from satellites if the pfd limits from these satellites provide protection of the analog systems in the 2025-2300 MHz frequency range.

Receiver Transfer Function

In Part 1 of this report, a qualitative analysis was conducted which gave an estimate of the approximation in the receiver transfer function (May and Pagones, 1973)

$$\frac{i_c}{n_c} = \frac{i_4}{n_4} \tag{2}$$

where i_c and n_c are interference and free space noise power in a channel, respectively, and i_4 and n_4 are the interference and noise power, respectively, in a 4 kHz bandwidth at receiver input. For the analysis given here N is equal to 25 pW as indicated in CCIR Report 387-1. Equation (2) was used in both GM and NGM computer programs. A quantitative analysis was conducted here using a convolution technique in order to determine the inaccuracy involved in using Equation (2) for the determination of pfd limits in the 2025-2300 MHz frequency range.

A more exact form of Equation (2) may be written

$$\frac{i_c}{n_c} = k(\Delta f, m) \frac{i_4}{n_4} \tag{3}$$

where k is a function of frequency separation, Δf, and modulation index, m, of the desired signal. In addition, function k can vary from one channel to

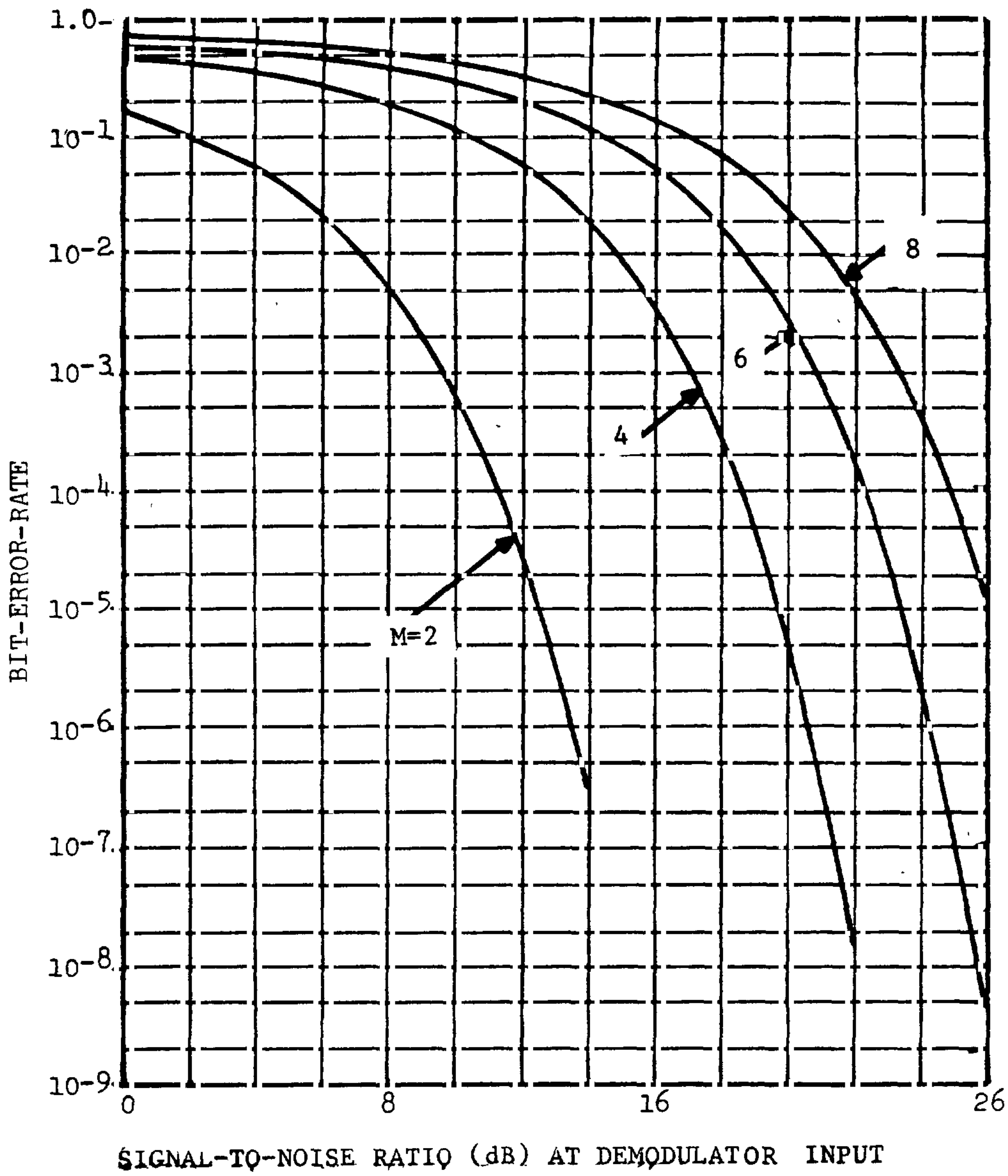

Figure 20. Probability of Bit-Error-Rate vs. Signal-to-Noise Ratio for ASK Modulation

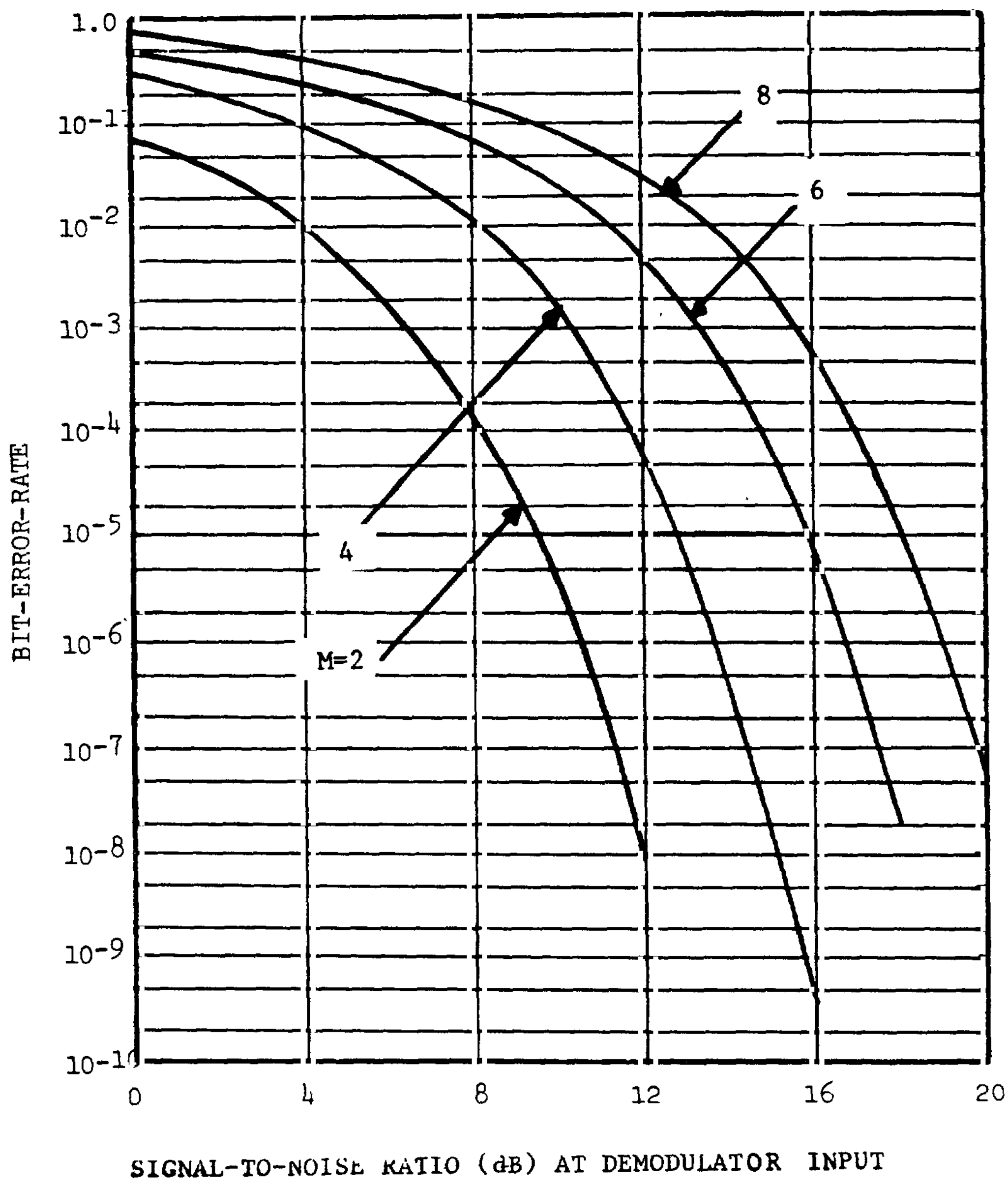

Figure 21. Probability of Bit-Error-Rate vs. Signal-to-Noise Ratio for PSK Modulation.

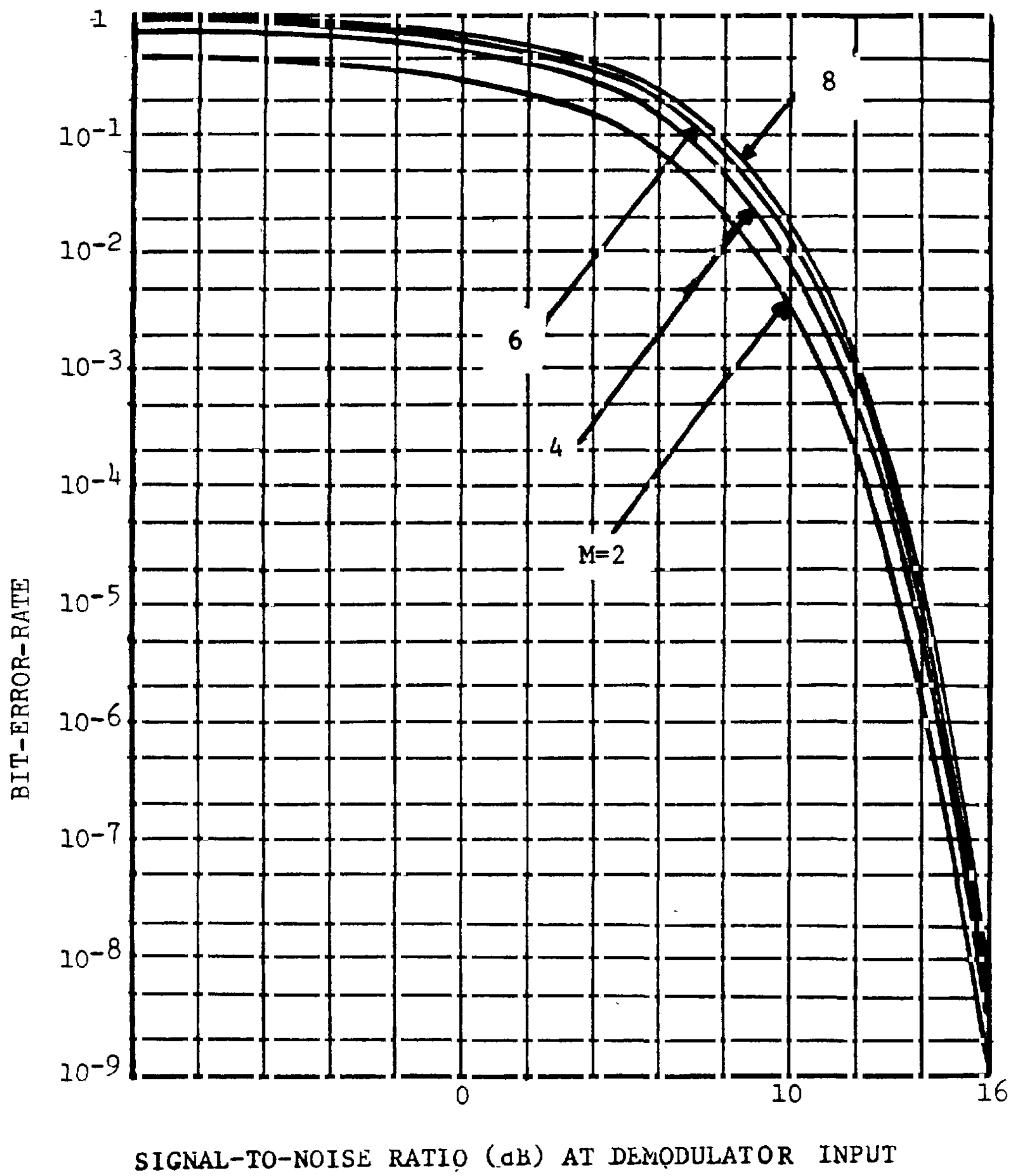

Figure 22. Probability of Bit-Error-Rate vs. Signal-to-Noise Ratio for FSK Modulation.

another in a receiver. The parameters i_c, n_c, i_4, and n_4, are defined above. Evaluation of function k is desired. Comparison of Equations (3) and (2) indicates that function k in Equation (2) was set equal to unity. This is a conservative approach and the underlying assumption is that interference spectrum is flat and noiselike. For the modulation indices used by the systems in the Fixed Service operating in the 2025-2300 MHz frequency range the value of k = 1 constitutes an upper bound.

For large modulation indices, m > 1.5, an FDM/FM spectrum assumes a Gaussian shape. For low modulation indices, m < .1, the spectrum becomes discontinuous with a predominant residual carrier. For these two extreme cases, function k may be evaluated using closed form expressions. However, signals with intermediate modulation indicies the problem is more difficult and the function k should be determined using convolution of the desired and undesired emission spectrums. The construction of the solution is as follows:

We begin by invoking the concept of noise-power ratio (npr). In this report NPR = 10 log (npr). In the absence of interference npr for a receiver loaded with a particular level of noise test signal, may be defined as the ratio of the noise power in an arbitrarily small bandwidth of the passband to the noise power in the same bandwidth within a stop-band. A mathematical expression for npr may be derived as follows; npr resulting from interference is, among other factors, directly proportional to the carrier-to-interference ratio. Mathematically npr as related to signal-to-interference ratio in a channel and carrier-to-interference (c/i) ratio at the input to the IF may be expressed by the relationship derived in Bulletin No. 10-C (Electronics Industries Association, 1976).

$$(c/i)dB = NLR/CH - 10\log i_c + 87.5 - NPR \quad (4)$$

where i_c was defined earlier. The desired signal level in Equation (4) was offset relative to the zero reference level by an amount given by the noise loading ratio per channel (NLR/CH). Derived from the FCC loading equation, the NLR/CH in dBm0 is given by:

$$NLR/CH = \begin{cases} -15 & N > 240 \\ -1-6\log N & 60 < N<240 \\ 2.6-8\log N & 12 < N<60 \end{cases}$$

where N is the number of voice channels. In Equation (4) signal is a test tone with zero dBm level and constant 87.5 is psophometrically weighted noise reference (-90 + 2.5 = -87.5) in a channel. A different form of Equation (4) is given in CCIR Report 388-3. The interference power i_c is obtained using expression:

$$10\log i_c = 87.5 - B - (c/i)_{dB} \quad (5)$$

An interesting feature of Equation (5) is the term B which is given by CCIR Report 388-3.

$$B = 10\log\left[(s/i_c)/(c/i)\right] \quad (5a)$$

where

- s : test signal power in a telephone channel = 1 mW,
- i_c : interference power in a telephone channel (bandwidth 3.1 kHz),
- c : power of the wanted signal carrier (W),
- i : power of the interfering signal carrier (W).

Using Equations (4) and (5) relationship between B and NPR may be found:

$$B = NPR - NLR/CH \quad (6)$$

Equation (6) states that B is different from NPR by a constant (NLR/CH). NLR/CH is a constant for given number of channels for a receiver. Another word B may be evaluated after NPR has been determined. Before discussing the evaluation of NPR let us write NPR in the following forms using Equations (5a) and (6):

$$(npr)_i \sim (s/i)_o/(c/i)_{in} \quad (7)$$

when interference is present and when noise is the source of impairment in the receiver:

$$(npr)_n \sim (s/i)_o/(c/n)_{in} \quad (8)$$

Subscripts i and n in Equations (7) and (8) refer to interference and noise, respectively, and subscripts o and i_n indicate output and input, respectively. The reason for the symbol $\sim$ used in Equations (7) and (8) is that we have neglected the term NLR/CH in these equations. Dividing Equation (8) by Equation (7) we obtain

$$\frac{(npr)_n}{(npr)_i} = \frac{i_c}{n_c} \cdot \frac{n_{in}}{i_{in}} \quad (9)$$

Note that Equation (9) resembles Equation (3) except that the ratio of i_4/n_4 in Equation (3) is replaced by i_{in}/n_{in} in Equation (9). A method of converting i_{in}/n_{in} to i_4/n_4 is as follows. Assuming the noise at the input to the receiver be flat a linear realtionship between n_{in} and n_4 may be obtained.

$$n_{in} = n_4 \, BW_n/4000 \quad (10)$$

when BW_n is the noise bandwidth of the receiver. The interference signal is never flat and i_{in} may be concentrated in certain sections of the interference spectrum density. Sections of spectrum where concentration of power is higher contribute most to evaluation of npr and the impairment of radio channels.