REPORT 762-2

EFFECTS OF MULTIPATH ON DIGITAL TRANSMISSION OVER LINKS IN THE MARITIME MOBILE-SATELLITE SERVICE

(Study Programme 17A/8)

(1978-1982)

1. Introduction

The effects of multipath propagation on digital transmission have been theoretically analyzed and experimentally evaluated.

The theoretical analysis performed by Japan results in a prediction of error rate performance for two-phase coherent PSK and two-frequency non-coherent FSK modulations.

The theoretical analysis carried out by the United States gives the error rate for differential coherent phase-shift keying (DCPSK); the results of United States experiments with the ATS-6 satellite determine the range of multipath values used in the theoretical model. The calculated error rate is compared with measurements made using a laboratory channel simulator.

The tests performed in 1975 by France with the ATS-6 satellite have made it possible to obtain curves representing the bit error ratio for two-phase PSK digital transmission for different satellite elevation angles.

In tests performed in 1979 by the Federal Republic of Germany with the aid of the Marisat tracking beacon, the amplitude and phase response of the satellite-to-ship multipath signal was recorded on-board ship for various receiving antennas and elevation angles. The recordings were used to control a laboratory channel simulator (the stored channel principle) to determine the fading margin for various data transmission methods. The amplitude response was statistically evaluated and compared with theoretical models.

2. Theoretical analyses

2.1 *Rice-Nakagami or m-distribution*

2.1.1 *General*

This work assumes that the amplitude distribution of the sea-reflected signal follows the *m*-distribution function and derives the probability distribution for the fading amplitude [Nakagami, 1960]; this distribution is also known as the Rice-Nakagami distribution and is general enough to describe most fading phenomena including Rayleigh fading.

An example of the *m*-distribution using "*m*" as a parameter is shown in Fig. 1. It should be noted that this figure represents one-sided Gaussian fading when $m = ½$ and Rayleigh fading when $m = 1$, where m is the inverse of the normalized variance of the reflected signal amplitude squared.

2.1.2 *Probability of error*

The probability of error, $p(\rho, C/M, m)$, corresponding to the Rice-Nakagami distribution has also been derived [Mizuno *et al.*, 1975] for the cases two-phase coherent PSK and two-frequency non-coherent FSK. In this notation ρ is the energy per bit-to-noise power density ratio (E/N_0) at the demodulator, and C/M is the direct signal-to-multipath signal power ratio.

2.1.3 *Results of calculations*

Figures 2 to 4 illustrate the bit error ratio characteristics calculated using the analytic methods referenced above.

Figure 5 shows the relation between direct signal-to-multipath signal power ratio and the equivalent degradation value of carrier-to-noise power ratio. The equivalent degradation value is the difference in the E/N_0 values required to obtain a bit error ratio of 10^{-5} in the presence of thermal noise, between the case when a sea-reflected signal exists and the case when no reflected signal exists. In other words, it corresponds to the fading margin to be assigned for multipath interference for the particular modulations discussed.

The following can be concluded from Fig. 5:

- When C/M is constant, the degradation due to the multipath effect increases as m decreases.
- When the fading is deep or m is smaller than 1, the equivalent degradation value of E/N_0 for the two-phase coherent PSK is larger than that for the two-frequency non-coherent FSK.
- For a given m, the required margin necessary to achieve a bit error ratio (BER) of 10^{-5}, represented as a degradation of E/N_0 in Fig. 5, increases as C/M decreases. For a C/M of 12 dB and $m = ½$, which corresponds to a Gaussian scatter process for the multipath, an increase in signal of about 11 dB is required to give the same bit error ratio for a two-phase coherent PSK receiver as is obtained in the presence of thermal noise alone. It may also be noted in this case that a small decrease in the direct signal to multipath ratio, C/M, produces a large increase in required margin.

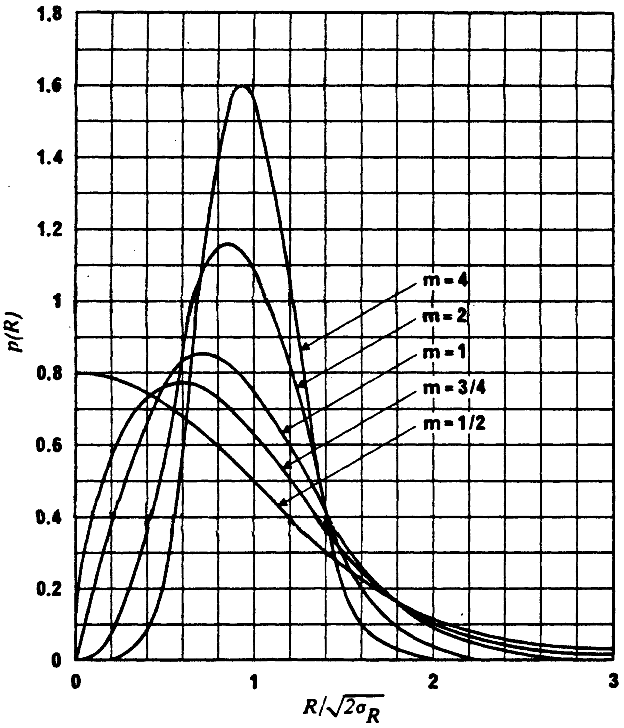

FIGURE 1 — *m-distribution*

R: amplitude of the reflected signal
σ_R: r.m.s. value of the reflected signal

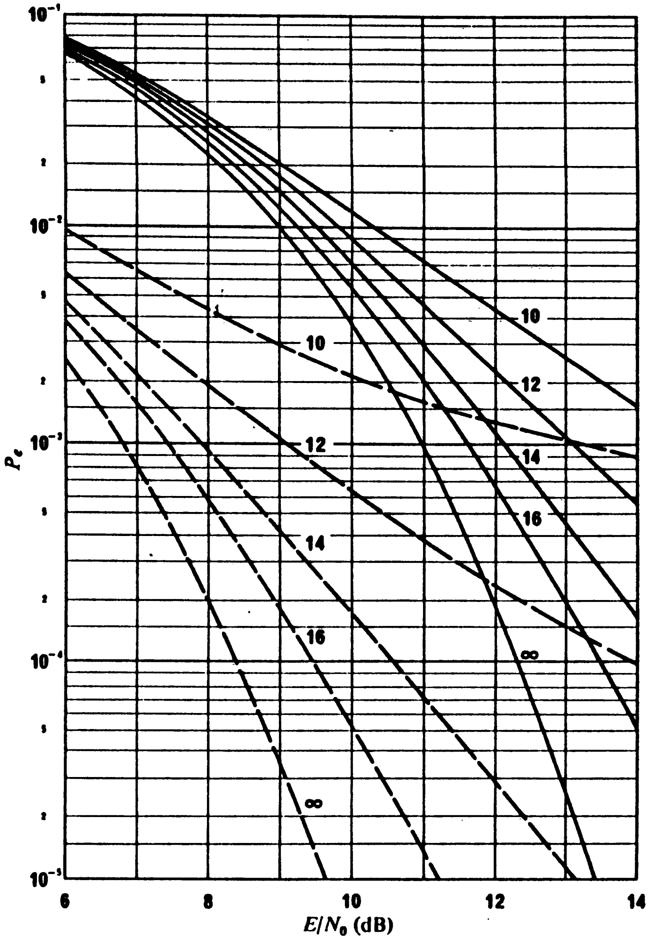

FIGURE 2 — *Error probability for the two-phase coherent PSK and the two-frequency non-coherent FSK (m = ½)*
(Parameter is C/M, in dB)

– – – – 2CPSK
——— 2NFSK

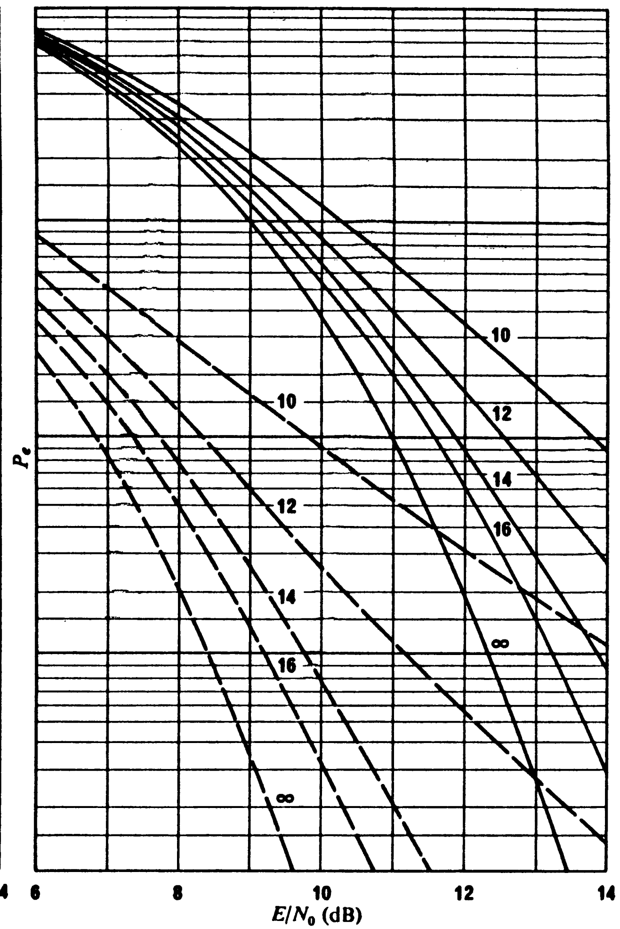

FIGURE 3 — *Error probability for the two-phase coherent PSK and the two-frequency non-coherent FSK (m = 1)*
(Parameter is C/M, in dB)

– – – – 2CPSK
——— 2NFSK

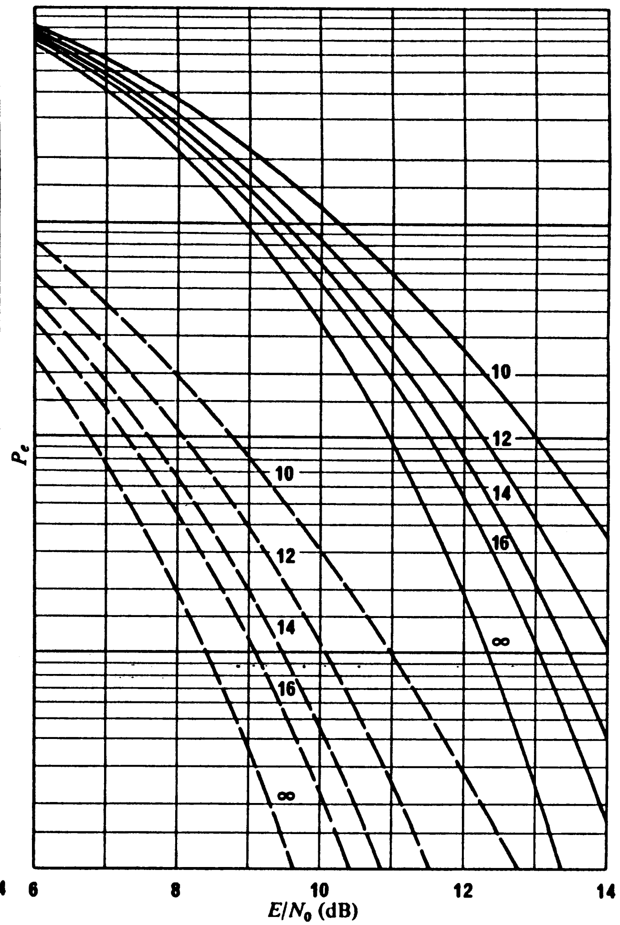

FIGURE 4 — *Error probability for the two-phase coherent PSK and the two-frequency non-coherent FSK (m = 4)*
(Parameter is C/M, in dB)

– – – – 2CPSK
——— 2NFSK

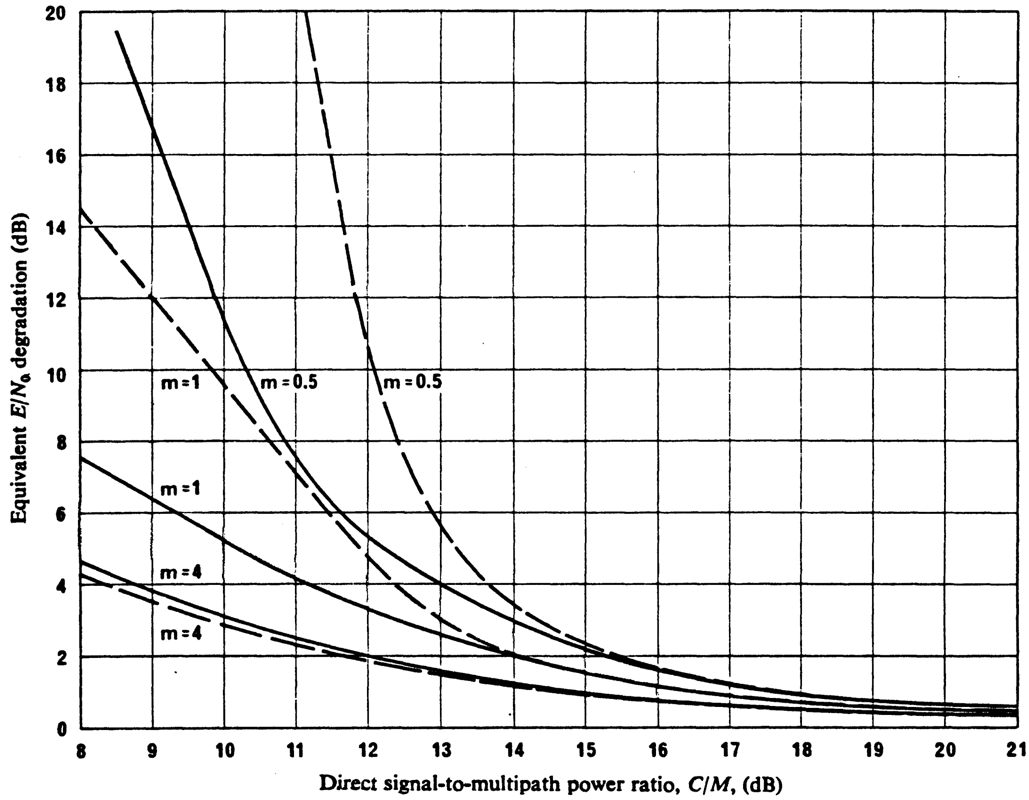

FIGURE 5 — *Equivalent degradation of E/N_0*
($BER = 10^{-5}$)

— — — 2CPSK

——— 2NFSK

2.2 *Modestino-Mui analysis*

2.2.1 *General*

The maritime satellite channel can be modelled as shown in Fig. 6. This model is based on previous analytical studies [Salwen, 1972].

The channel model of Fig. 6 can accommodate either specular or diffuse multipath reflection conditions. As the multipath becomes more specular in nature, the mean-square multipath power (M) tends to increase while the bandwidths of the in-phase and quadrature components of the complex envelope which characterize the multipath envelope tend to zero.

The data collected during the ATS-6 maritime satellite tests support the conclusion that the reflected multipath is diffuse. In particular, it was found that the multipath energy arrives from a broad region on the ocean's surface rather than from the multipath specular reflection point.

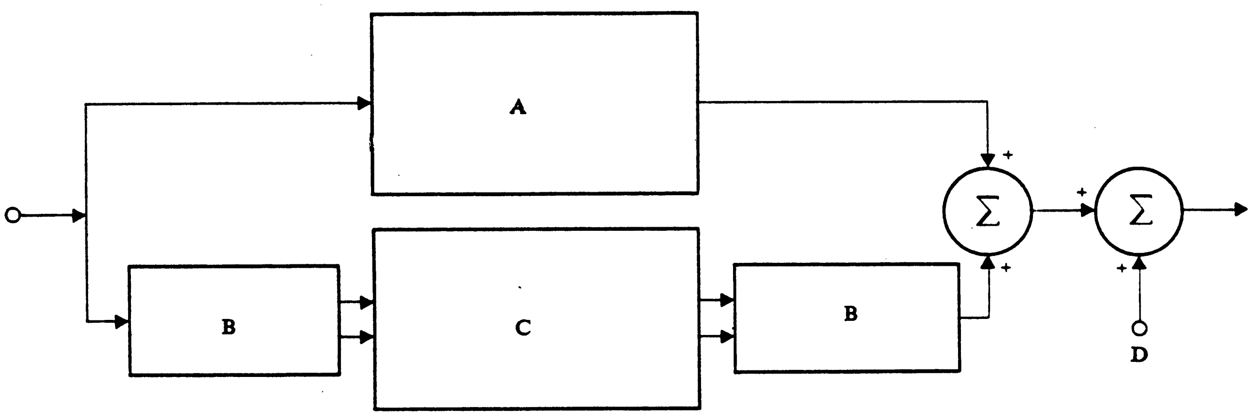

FIGURE 6 — *Channel model representative of a satellite-ship link*

A: direct path (constant complex gain factor)

B: quad hybrid

C: multipath (time varying complex gain factor)

D: $n(t)$ (noise)

2.2.2 *Probability of error*

The probability of bit error for a coherent PSK system in which there is a slowly varying carrier tracking error and a slowly fading amplitude (the fade is slow relative to the bit rate), has been derived [Modestino and Mui, 1976] for the case of two-phase coherent PSK. Their results are extended to the DCPSK case by noting that the probability of bit error for DCPSK is approximately $2P_b$ when $P_b \ll 1$.

2.2.3 *Results of calculations*

Figure 7 shows the expected value of the probability of bit error for DECPSK as a function of C/N_0 and C/M which are obtained by digital computer solution of the theoretically derived expression [Modestino and Mui, 1976]. The curves shown in Fig. 7 assume a 15 dB signal-to-noise ratio in the carrier tracking loop. At that level, carrier tracking errors have very little effect on probability of bit error.

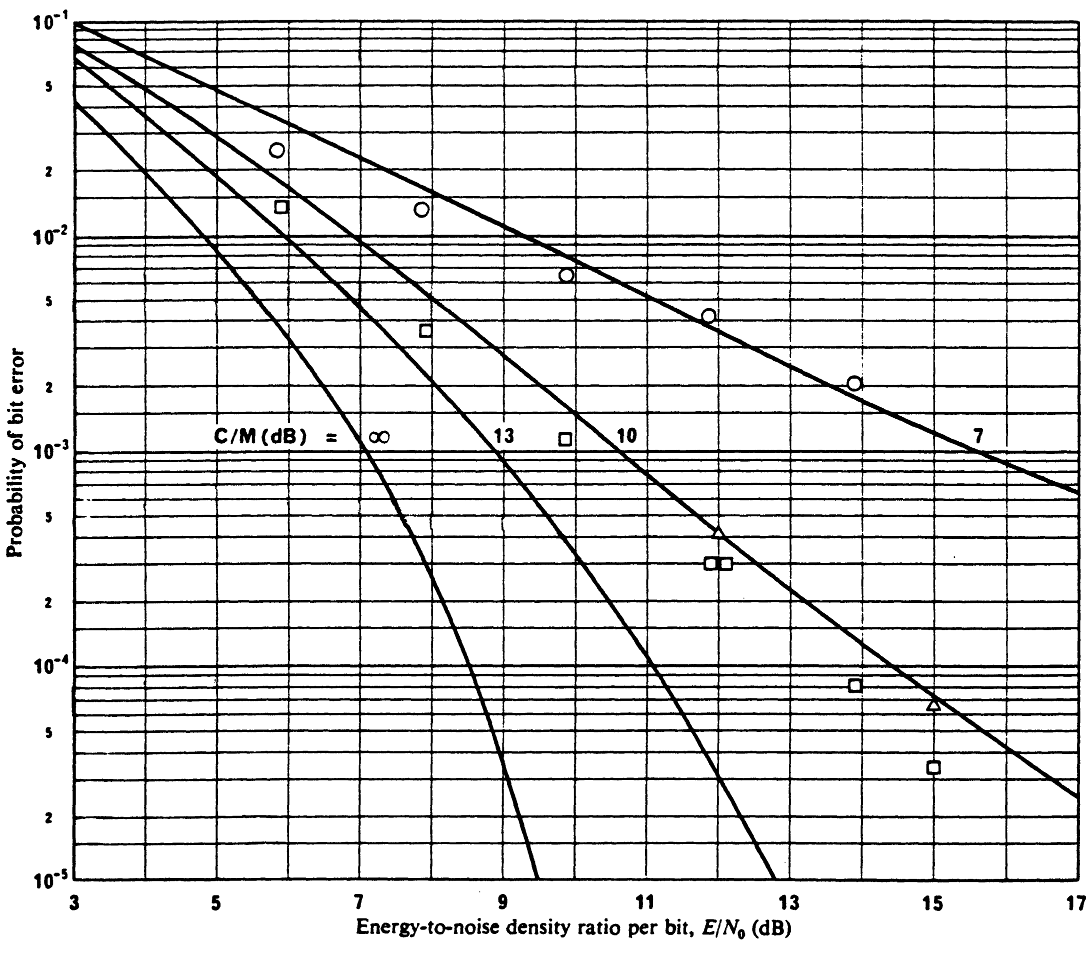

FIGURE 7 – *Performance of DCPSK modem at 1200 bit/s in multipack with simulator*

Notes:

— Solid curves are theoretical results with Doppler spread (fading rate) much less than bit rate.

— Simulator data: ○ $C/M = 8$ dB

△ $C/M = 10$ dB

□ $C/M = 11$ dB

3. Experimental results

3.1 *Tests performed by United States with ATS-6 and with channel simulator*

3.1.1 *Tests performed by United States with ATS-6*

Figure 8 shows the observed multipath power, relative to the power in the direct path signal for data collected during the ATS-6 tests. The relative multipath power is in the range from 5.7 dB to 8.8 dB. These values exclude antenna discrimination effects but do include polarization discrimination effects. The actual *C/M* ratios observed, including the antenna directivity factor, were typically 10 dB or greater. However, in some cases, *C/M* ratios as low as 6 dB were measured [Engels *et al.*, 1976].

Table I summarizes the averaged multipath data collected at low elevation angles during the ATS-6 maritime satellite tests. The ship antenna has a 35° beamwidth.

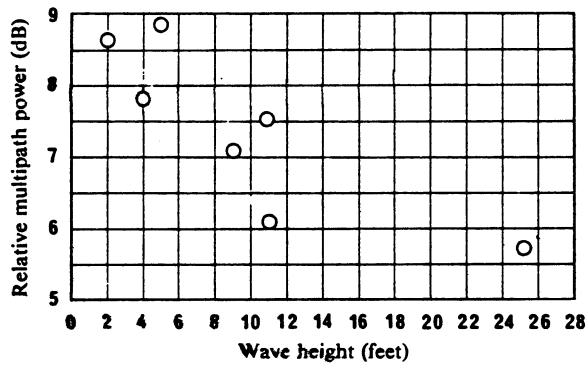

FIGURE 8 — *Dependence of relative multipath power on sea surface wave height*

TABLE I - *ATS-6 Multipath data*

Satellite elevation (°)	Sea condition (peak to through) (m)	Date	C/M (dB)	−20 dB linewidth (Hz)
8.2	2.4-3.0	13 November, 1974	10.02	4.5
8.3	7.5	14 November, 1974	8.65	5.35
8.4	3.0-3.6	15 November, 1974	9.1	4.55
16.9	1.2	19 November, 1974	14.2	5.5
16.9	3.3	20 November, 1974	14.76	3.75
17.0	1.5	21 November, 1974	16.2	4.47
17.0	0.6	31 March 1975	15.65	3.35

3.1.2 *Tests performed by United States with channel simulator*

The analysis outlined in § 2.2 was tested experimentally using a DCPSK modem and a laboratory channel simulator; the results obtained are superimposed on the theoretical results in Fig. 7. [Salwen and Duncombe, 1975; Salwen, 1975]. There is close agreement between theoretical and experimental data. The experimental results of Fig. 7 are for the best modem tested in an extensive laboratory test effort [Salwen and Duncombe, 1975]. The performance of other DCPSK modems tested was substantially worse under simulated multipath conditions.

The margins required to achieve 10^{-4} and 10^{-5} error rates can be derived for a DECPSK modem based on the results shown in Fig. 8. These margins are shown in Table II.

TABLE II – *C/N_0 margins*

C/M (dB)	Margin (dB) for $P_e = 10^{-4}$	Margin (dB) for $P_e = 10^{-5}$
13	2.5	3.2
11	5.3	7.4
10	5.5	9
8	–	30 (estimated)

Under the best conditions, a 5 dB margin would permit 10^{-5} error rate performance when C/M was on the order of 12 dB. However, in most cases a larger margin would be required in order to allow for other performance degradation factors such as:

- antenna pointing error,
- ionospheric losses,
- atmospheric losses,
- modem performance degradation (in presence of multipath).

3.2 *Tests performed by France with the ATS-6 satellite*

3.2.1 *Type of transmission*

A two-phase PSK 19.2 kbit/s digital channel transmitted through the ATS-6 satellite was received on board a ship operating off the Azores. A pseudo-random sequence transmitted on this channel was compared with an undisturbed sequence in order to determine the bit error ratio.

3.2.2 *Ship antenna*

The antenna used was a quadhelix antenna with a maximum gain of about 20 dB and a half power beamwidth of 14°. The height of the antenna above the sea was about 20 m. The antenna was stabilized to about 1°, using a vertical reference and the ship's gyrocompass.

3.2.3 *Sea conditions*

The measurements were carried out under rough sea conditions corresponding to a mean peak-to-peak wave height of about 3 m.

3.2.4 *Results obtained*

Figure 9 shows the bit error ratio curves for two-phase coherent PSK as a function of the E/N_0 expressed in dB, for elevation angles of 5°, 10°, 15° and 20°. It also shows the theoretical curve for the performance in presence of thermal noise only.

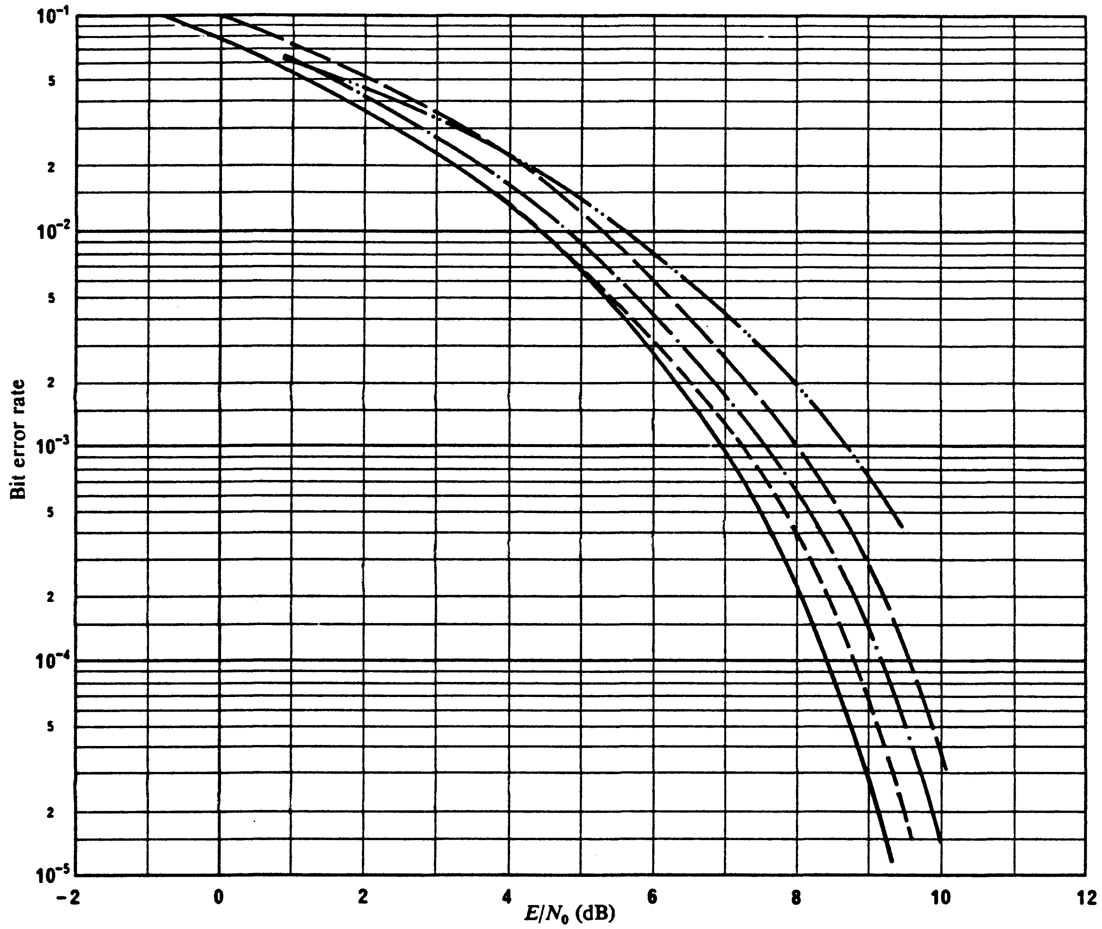

FIGURE 9 — *Effect of the elevation angle on the error / rate*

Test curves:
- ———— Theoretical curve
- —··— Elevation angle 5°
- — — — Elevation angle 10°
- —·—·— Elevation angle 15°
- - - - - - Elevation angle 20°

3.2.5 *Comparison of experiment and theory*

In order to directly compare the experimental and theoretical results, it is necessary to have a knowledge of *m* and the direct signal to multipath ratio.

Using the parameters given in the example of 2.1, a theoretical system margin of 11 dB is required, assuming no antenna discrimination. For a satellite elevation of 5°, both the direct and reflected signals will arrive within the main beam of the high gain antenna of the experiment. Extrapolating the 5° curve of Fig. 9, the measured degradation in E/N_0 for a bit error ratio of 10^{-5} is approximately 2.5 dB.

Substantial multipath discrimination in addition to that given by the antenna must have contributed to give this low value. The assumption made above regarding practical values for *m* and *C/M* require validation by further experiment.

3.3 *Tests performed by the Federal Republic of Germany with MARECS and with the stored channel method*

3.3.1 *Description of the stored channel methods*

Communication to and from ships via geostationary satellites is complicated by both multipath propagation at the sea's surface and antenna tracking requirements. In the case of the relatively large antennas used up to now, very little degradation was caused by fading occurring at elevation angles greater than 5°. Smaller antennas, in view of their broad beamwidth, do not require accurate tracking but lead to greater degradation. Limited information was available on the deterioration of the transmission quality to be expected due to multipath propagation. As it is extremely difficult to reproduce fading under realistic conditions, the stored channel principle was employed. During field trials the signal response of the channel with respect to amplitude and phase was recorded on board ship and evaluated at a laboratory. The channel was modelled as shown in Fig. 10. The correlations between the model's parameters and the various antenna types, sea conditions and elevation angles were also determined at the laboratory. By using the recorded fading to control a channel simulator it is possible to accurately reproduce the signal amplitude and phase response of the fading.

The addition of noise permits a comparison between various modulation and coding methods at a variable signal-to-noise ratio. At the laboratory, the bit error ratios and the required fading margin of various transmission methods were determined for various sea conditions and elevation angles (0°-28°) with different antennas and tracking mechanisms [Schweikert *et al.*, 1980].

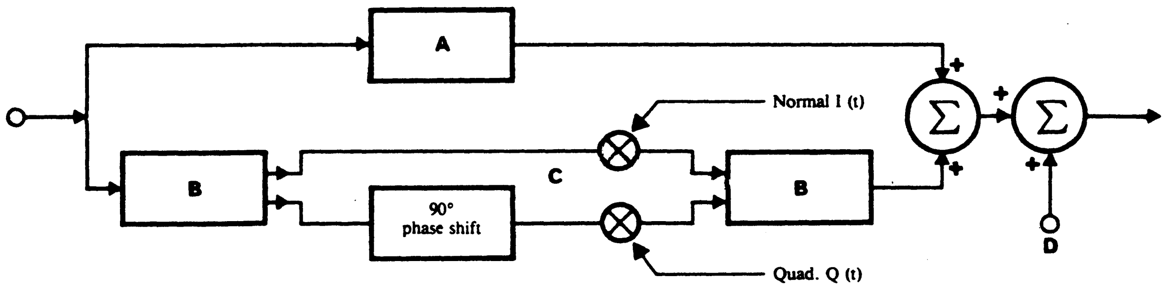

FIGURE 10 – *Channel model representative of a satellite-ship link*

A: direct path (constant complex gain factor)
B: quad hybrid
C: multipath (time varying complex gain factor, normal and quadrature component)
D: $n(t)$ (noise)

3.3.2 *Field trials with standard C antennas*

Field trials were performed from January to March 1983 on board the RV "Gauss" of the "Deutsches Hydrographisches Institut DHI". Four different antennas with gains ranging from 3 dB to 14 dB and three receivers were used, in parallel, to receive a CW-signal transmitted from Villafranca (Spain) earth station via the Atlantic Ocean Marecs satellite. The power of the CW-signal was the equivalent power of at least ten FM voice channels (e.i.r.p. 28 dBW). The baseband normal and quadrature components from the three receivers were recorded on board the ship for elevations between 4° and 30° and sea states between 1 m and 6 m wave height (open-sea conditions). Three 80-hour periods of recordings were made [Hagenauer *et al.*, 1984].

3.3.3 *Statistical evaluations and channel model*

In the laboratory, all the tapes were digitized and a broad variety of statistical evaluation took place on a mainframe computer. The results [Hagenauer *et al.*, 1984] of these evaluations show the following:

- the standard C-maritime channel can be modelled by a Rice-Nakagami fading model with a direct signal of power C and a diffuse scattered signal of mean power M. No significant reflected specular components have been observed;
- the Rice-Nakagami parameter C/M at the edge of satellite coverage (5° elevation) is 8 to 9.5 dB for all antennas and increases with elevation depending on the antenna (see Fig. 11);
- the influence of sea state is insignificant compared to elevation;
- the range of power fluctuations (fading range) at 5° elevation angle is:

  14 dB for 98%
  19 dB for 99.8%
- the fading bandwidth at 5° elevation angle (width of power density spectrum) is approximately:

  0.5 to 1 Hz (3 dB bandwidth)
  5 Hz (20 dB bandwidth) (see Fig. 12);
- average duration of a fade at -3 dB to -5 dB thresholds below average signal power is approximately 0.1 s;
- fading and connection time statistics are available and give a sufficient description of the channel in the time domain. Figure 13 gives some significant results;
- Doppler offsets (see Note) with this medium-size ship (1600 tons) were found to be of the order of ± 10 Hz with a rate of 1 Hz/s.

Note. – It should be noted that Doppler offsets observed by a ship are a function of the relative velocity of the satellite with respect to the ship and the coast earth station (see Report 214).

3.3.4 *Tests of 2-PSK modems with uncoded data transmission*

3.3.4.1 *Modems*

Four different 2-PSK modems have been tested for the maritime channel. To ensure comparability, the channel data rate was fixed at 1200 bit/s and differential encoding was used for phase ambiguity resolution.

The modems tested were:

(a) coherent Costas receiver,

(b) coherent tuned filter receiver,

(c) DCPSK receiver,

(d) Costas/AFC receiver.

3.3.4.2 *Bandwidths*

For all receivers, the filter and loop bandwidths have been optimized either by computer simulation during design or by on-line optimization during testing.

For synthetic Rayleigh fading receiver (a) performed best at high S/N (35 dB) and receiver (d) gave best performance at low S/N (20 dB). Contrary to the theoretical curves which assume perfect phase synchronization, the performance curves levelled out to a BER of 10^{-4} at S/N of 35 dB due to phase variations.

3.3.4.3 *Receivers*

For the stored channels receiver (d) performed best because it was able to track phase and frequency variations on the link. The fading margins are shown in Table III. The next best receiver was the (c) receiver.

3.3.4.4 *Conclusions*

In conclusion, the measured results on modem performance via the stored channel, showed that probably the most appropriate choice among those tested was a combined coherent Costas/AFC or a differential coherent (DPSK) receiver. If FEC is used, the selection of the receivers is less critical, because at channel error rates of 5×10^{-3} to 10^{-2} the receiver performance differs only by 1 dB. The results given in Table III apply only to the modems tested. It may be noted that use of FEC and/or other techniques would reduce the required margin and therefore reduce the required satellite and ship-earth station e.i.r.p. (see Report 921).

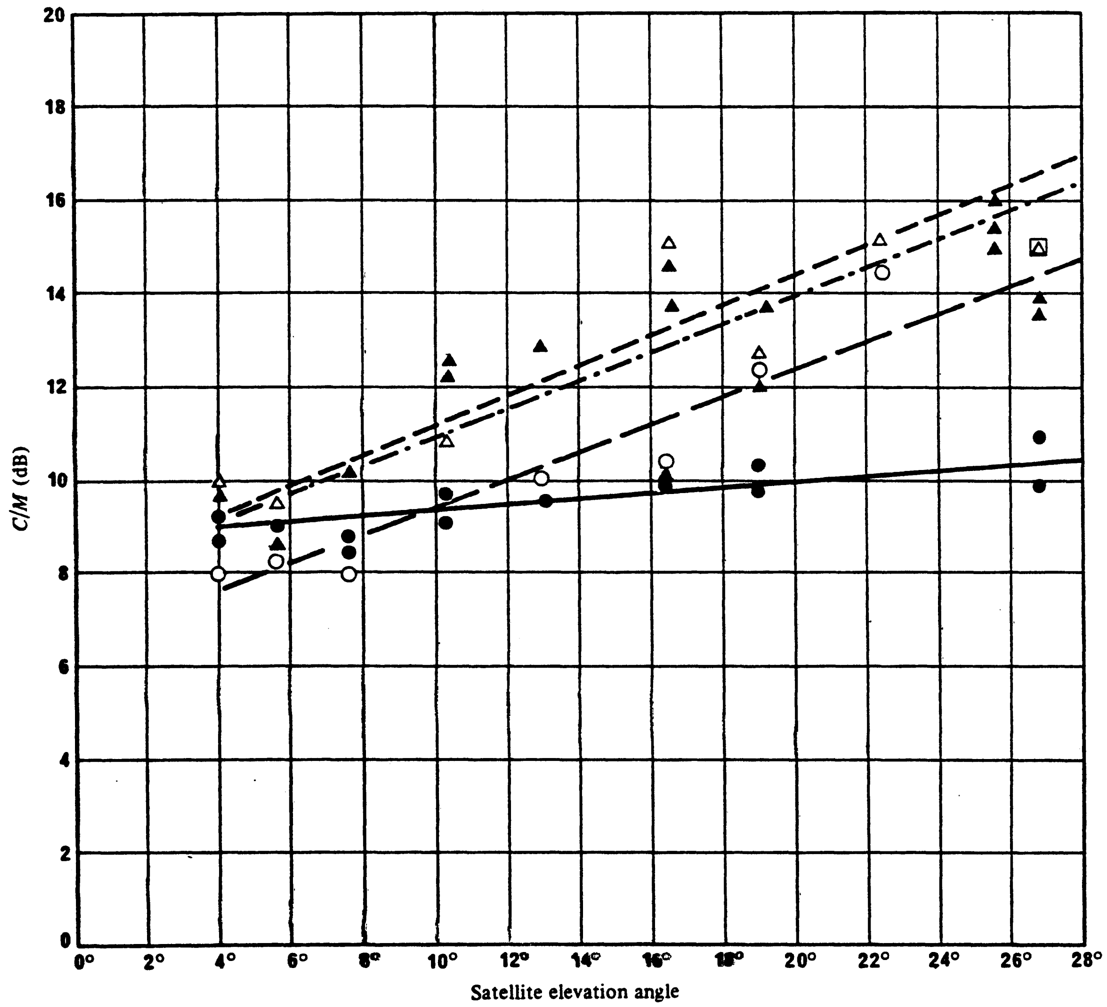

FIGURE 11 – *Direct-to-multipath signal power ratio C/M in dB as a function of satellite elevation angle*

● Measured —— Best fit	C3 antenna, 3 dB gain
○ Measured — — Best fit	C5 antenna, 5 dB gain
▲ Measured —·—·— Best fit	C11 antenna, 11 dB gain
△ Measured – – – – Best fit	C14 antenna, 14 dB gain

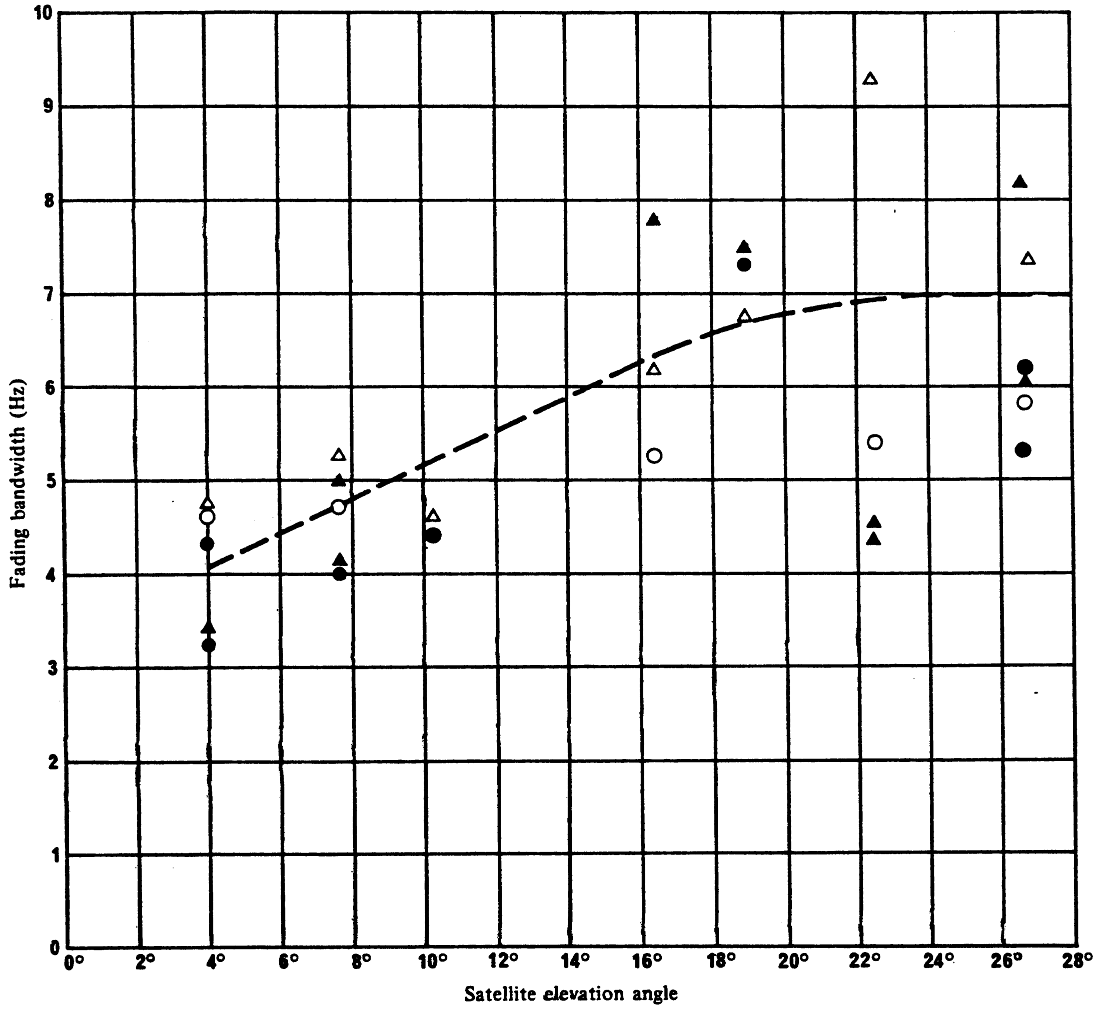

FIGURE 12 – *The 20 dB fading bandwidth in Hz as a function of satellite elevation angle*

- ● C3 antenna, 3 dB gain
- ○ C5 antenna, 5 dB gain
- ▲ C11 antenna, 11 dB gain
- △ C14 antenna, 14 dB gain

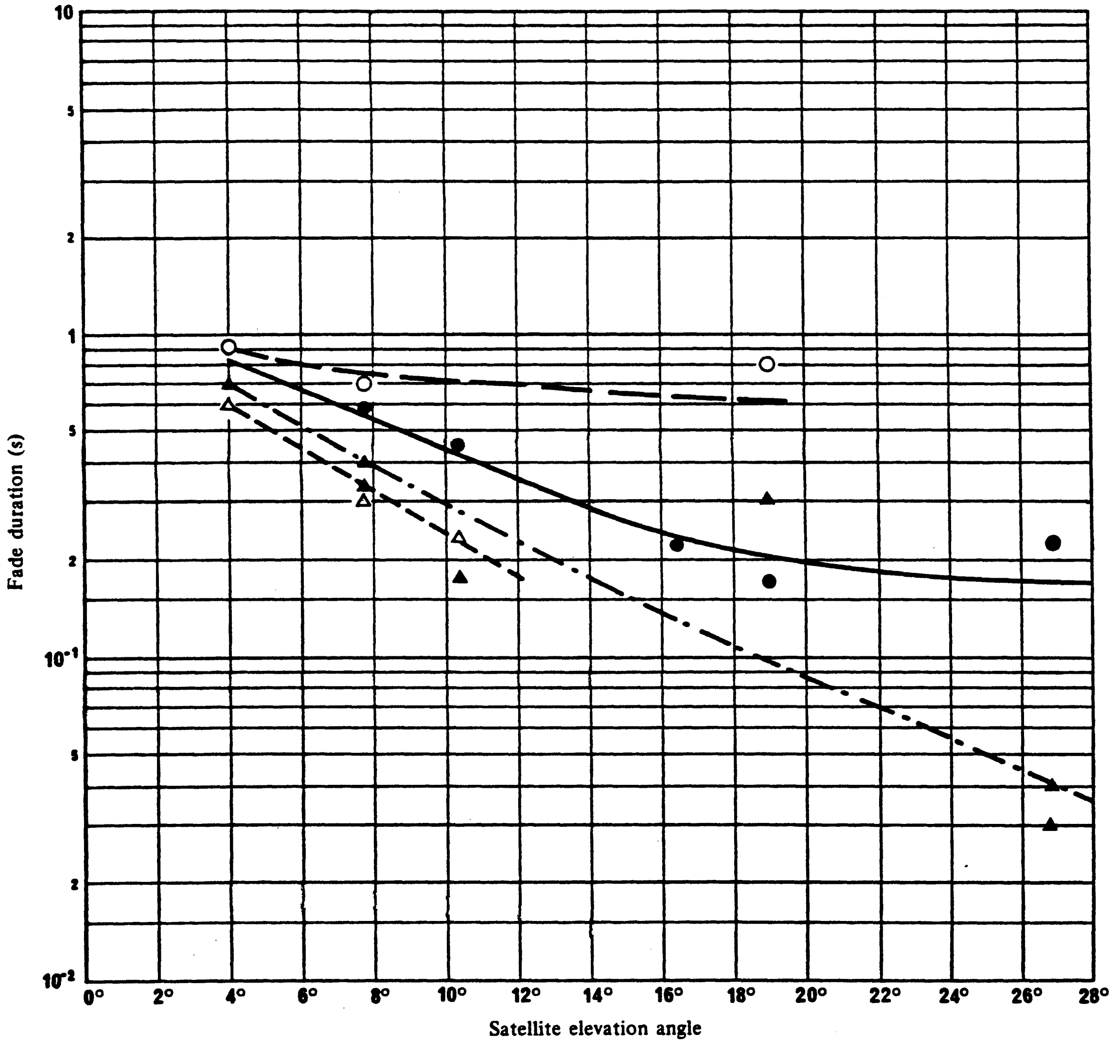

FIGURE 13 – *Maximum duration of fades (5 dB below mean power) in 99.9% of time as a function of satellite elevation angle*

●	Measured	C3 antenna, 3 dB gain
————	Best fit	
○	Measured	C5 antenna, 5 dB gain
—— ——	Best fit	
▲	Measured	C11 antenna, 11 dB gain
—·—·	Best fit	
△	Measured	C14 antenna, 14 dB gain
– – – –	Best fit	

TABLE III – *Required E_b/N_0 and fading margin for different antennas and elevation angles (Costas/AFC 2-PSK receiver)*

Antenna gain (dB)	Elevation angle (degrees)	Required E_b/N_0 faded (dB)		Required E_b/N_0 non-faded (dB)		Required long-term fade margin (dB)	
		BER = 10^{-4}	BER = 10^{-5}	BER = 10^{-4}	BER = 10^{-5}	BER = 10^{-4}	BER = 10^{-5}
3	4	19	25	10	11	9	14
	19	14	18	10	11	4	7
5	4	20	30	10	11	10	19
11	4	18	33	10	11	8	22
	19	12	14	10	11	2	3

Note. – The antennas used in these measurements were unstabilized and satellite pointing was carried out by hand.

4. Conclusions

The effect of the sea-reflected multipath interference on the received bit error ratio characteristics of binary coherent PSK and non-coherent FSK signals was theoretically examined by Japan assuming that the amplitude distribution of sea-reflected signals follows the *m*-distribution. The *m*-distribution can deal with almost all types of fading phenomena caused by specular reflected signals or by Gaussian reflected signals. The methods outlined and the figures shown in § 2.1 are useful in estimating the fading margin, although the value of m and C/M must be determined by experiments.

Theoretical analysis and experimental data obtained by the United States with ATS-6 using a 35° beamwidth shipboard antenna indicate that a margin of 5 dB will make possible a $P_e = 10^{-5}$ when $C/M = 12$ dB under ideal conditions. It is likely that under realistic conditions, a 5 dB margin will allow for $P_e = 10^{-5}$ when C/M is greater than about 14 dB. This multipath level (or less) was typically obtained when the elevation angle to the satellite was equal to one half the antenna beamwidth (or more).

The experimental curves given in Fig. 9 obtained by France with ATS-6, illustrate the effect of multipath upon the bit error ratio with the 20 dB gain antenna used. The test curves deviate from the thermal noise curve by a value (in dB) which increases as the elevation angle decreases, as theory predicts. The average additional power requirements due to multipath over that required for no multipath for a bit error ratio of between 10^{-3} and 10^{-4} are found to be the following:

- elevation angle 5°: 2 dB,
- elevation angle 10°: 1 dB,
- elevation angle 15° or more: 0.5 dB approximately.

The performance of the two-phase PSK digital modulation was significantly aided by the discrimination achieved by the 20 dB stabilized antenna.

The stored channel principle was used in the tests performed by the Federal Republic of Germany with MARECS in 1983. A comparison between the transmission of data via satellite and via the recorded channel at the laboratory as well as an evaluation of the amplitude statistics confirmed the usability of the stored channel and the Rice-Nakagami fading model.

The following values were found to be typical for a standard B antenna at 5° elevation:

- $C/M = 9$ dB
- a fading margin of 8 dB in the case of 2-PSK-modulated data transmission and a bit error ratio of BER = 10^{-4}.

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