TECHNIQUES FOR USE IN A SATELLITE MULTIPATH
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TECHNICAL MEMORANDUM

A REVIEW OF MODULATION TECHNIQUES FOR USE IN A SATELLITE MULTIPATH ENVIRONMENT

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ABSTRACT

Satellite communication relays have been suggested for use in numerous communication links. When the transmitter - receiver terminals are sufficiently large so that they have antennas with moderately high directivity then nearly all of the time the channel can be modeled as a well-behaved additive white Gaussian noise channel. Unfortunately, when one terminal in a two terminal satellite relay link lacks antenna directivity the simplicity of the white Gaussian noise channel is lost. When such is the case, an efficient design has to take into account multipath effects due to the reflection of signal energy off the Earth's surface which interferes with the direct path signal at the receiver. An example of a communication link in which antenna directivity cannot be achieved by one of the terminals, is a ground station that is used to communicate with several low orbiting satellites (e.g. the TDRS system proposed for NASA). In this memorandum the communication systems designed for such a channel are reviewed.

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DATE: September 30, 1970

FROM: L. Schuchman

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TECHNICAL MEMORANDUM

INTRODUCTION

Satellite communication relays have been suggested for use in numerous communication links. When the transmitter - receiver terminals are sufficiently large so that they have antennas which have substantial directivity and gain, then nearly all of the time the channel can be modeled as an additive white Gaussian noise channel. Since the additive white Gaussian noise channel is the most studied channel in communication theory, because of its relative simplicity, a great deal of analytic power can be brought to bear in the efficient design of any particular system. Unfortunately, when at least one terminal, in a two terminal satellite relay link lacks antenna directivity, the simplicity of the white Gaussian noise channel is lost. When such is the case an efficient design has to take into account multipath effects due to the reflection of signal energy off the Earth's surface which interferes with the direct path signal at the receiver. A situation in which this occurs is depicted in Figure 1. Figure 1 illustrates two real channels in which antenna directivity cannot be achieved by one of the terminals. In one channel a ground station talks to aircraft through a satellite relay, while in the other, a ground station talks to a low orbiting (or several low orbiting) satellites as in the TDRS system proposed for NASA. In this memorandum we restrict our attention to the case where an Earth reflected signal exists.

The channel to be discussed is thus not white nor Gaussian. The reflected signal causes a significant complication, as we shall see, so that the analysis and design of a communication system for such a channel is not simple.

MODELING THE REFLECTED SIGNAL

Beckmann & Spizzichino[1] have written what is now the classic text on the scattering of electromagnetic waves from rough surfaces. The authors model the scattering as a two dimensional statistical distribution of its height above a

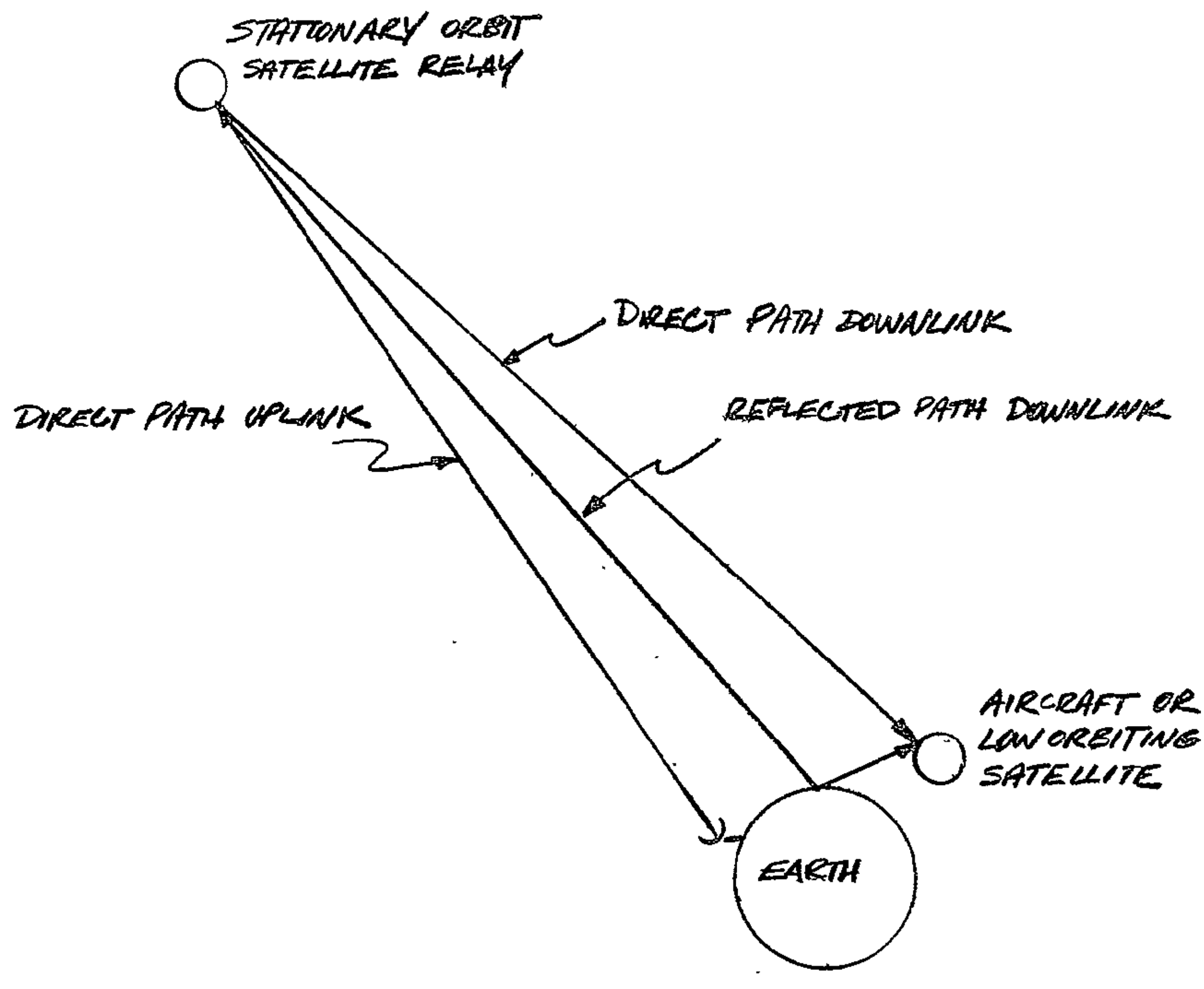

Fig 1. A Satellite Relay Communication System in which multipath effects have to be accounted for.

certain mean level. The model is based upon a number of simplifications such as the neglecting of multiple scattering and assuming a particular model for the surface roughness, e.g., random variations in height given by a particular statistical distribution. It is also pointed out by Beckmann that several other models exist and they are outlined in Chapter 6 of the referenced work.

It is beyond the scope of this memorandum to evaluate the merits of the several differing models. It is, however, valid to conclude that accurate modeling of the Earth's surface scattering of electric and magnetic waves is extremely complex, but as will be seen shortly for grazing angles that are not too small the Beckmann - Spizzichino model appears to roughly predict the average behavior of the Earth-reflected signal. It, therefore, must be kept in mind that the performance predictions of communication systems whose design is based on this model of the reflection will not be as accurate as those made for systems operating in additive white Gaussian noise channels.

S. H. Durrani and H. Staras[2,3] have extended the work of Beckmann and Spizzichino to determine the Average Scattered Power, the Fade Rate and the Coherence Bandwidth of the reflected signal in a paper dealing with communication between a stationary satellite and low-altitude spacecraft.

In determining the performance of a communication system in this type of channel it is necessary to know the reflected power relative to the direct path transmitted power. Using the Beckmann - Spizzichino model they determined the relative scattered reflective power as a function of target aspect angle for different values of spacecraft orbits (The target aspect angle is defined in Figure 2*). These results are presented in Figure 3.

It can be seen that their work predicts increasing reflected power with a decreasing target orbit altitude and a decreasing aspect angle A. In addition, it can be seen that the vertically polarized signals generate less reflected scattered power than horizontally polarized signals.

The fade rate of the received signal is important since fade rates that are slower than transmitted data rates cause conditions which are less desirable than those in which the reverse

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*In the literature both the target aspect angle and the grazing angle are used. The grazing angle is the complement of the angle of incidence defined in Figure 2 and is inversely related to the target aspect angle.

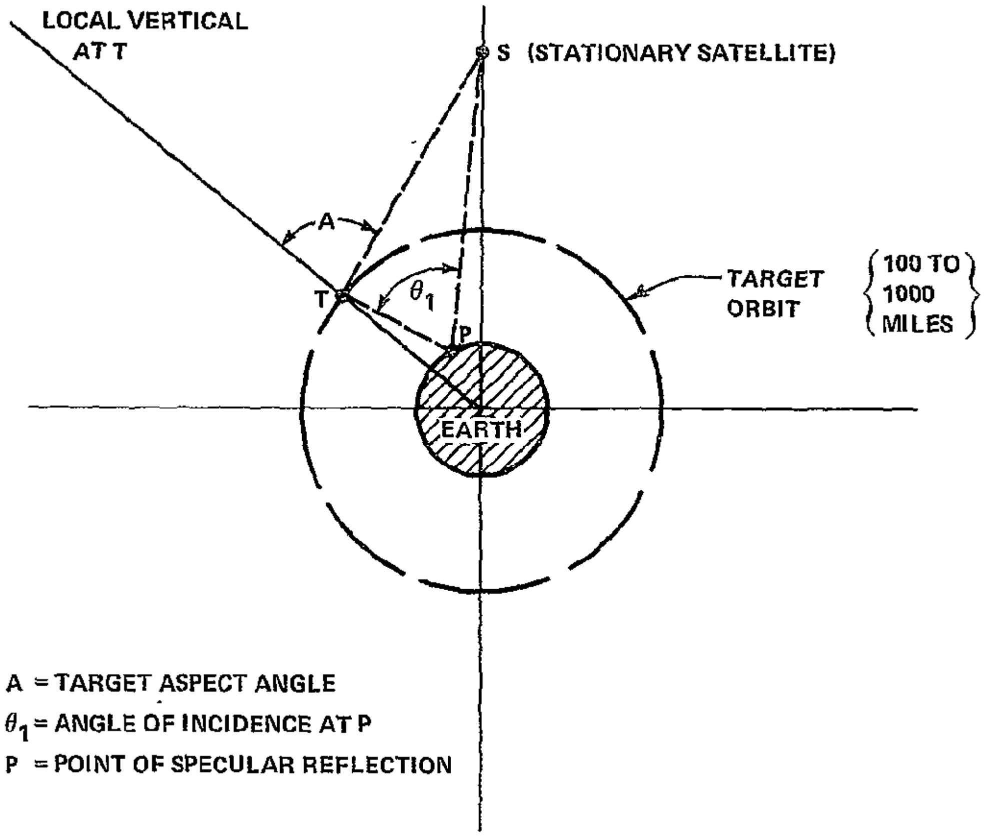

FIGURE 2 - GEOMETRY FOR LOW ORBITING SPACECRAFT AND STATIONARY SATELLITE COMMUNICATION CHANNEL

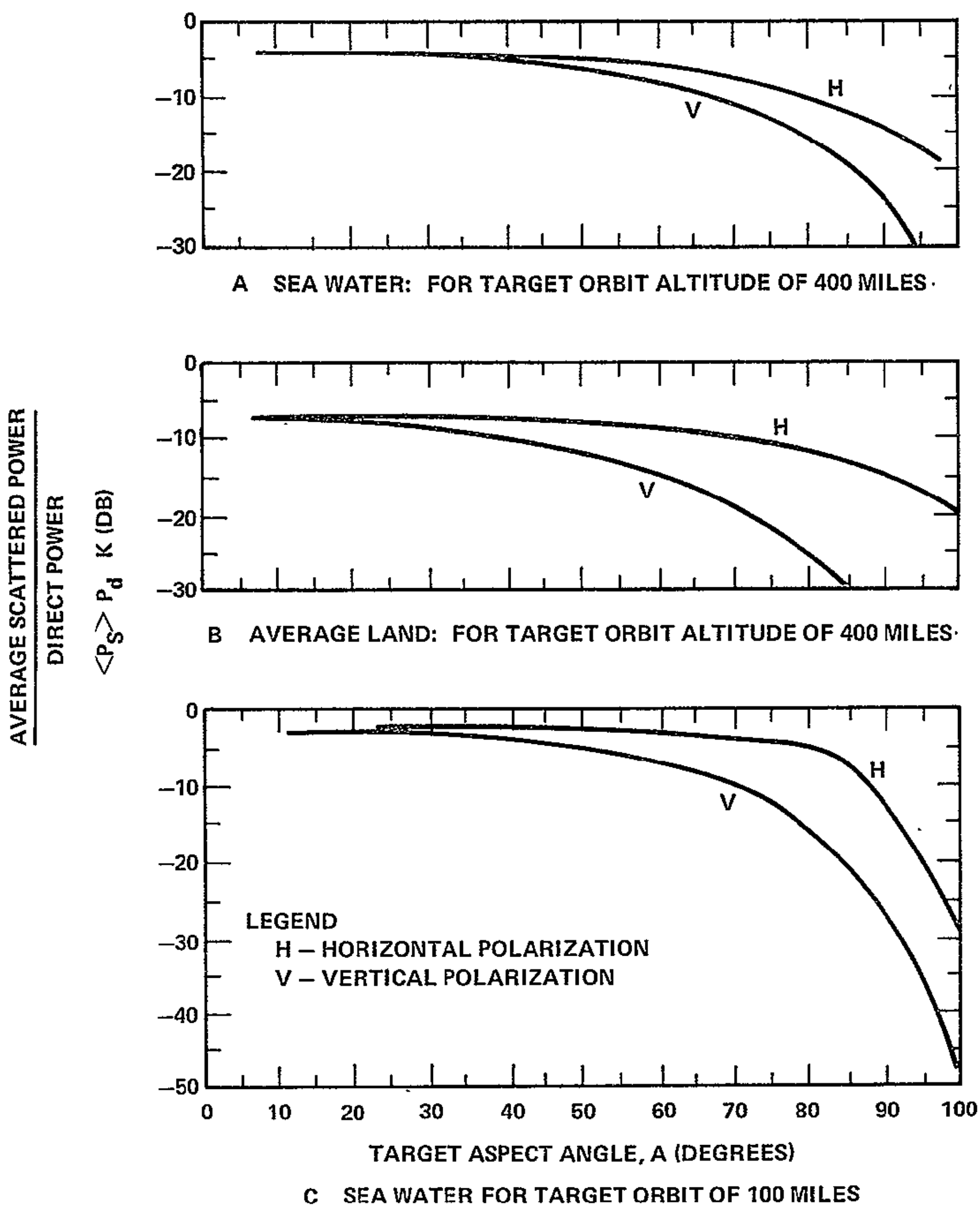

FIGURE 3 - AVERAGE SCATTERED POWER (NORMALIZED) RECEIVED AT THE REPEATER (TAKEN FROM REFERENCE 2)

is true (see Reference 4 and 5 for a detailed discussion of this point). In Figure 4 we see that as the aspect angle increases the fade bandwidth decreases. To put this another way, we see that the fade rate increases as the grazing angle increases.

Finally, the referenced authors derive an expression for the coherence bandwidth which measures the correlation in bandwidth of the received signal. The authors show that for target heights of 100 and 400 miles and a grazing angle of 90° the coherence bandwidth is 63.4 Khz and 20.7 KHz respectively. On the other hand, for a 0° grazing angle, the bandwidth is found to be on the order of 2 KHz. The coherence bandwidth limits the traffic bandwidth that can be supported in the presence of multipath since a wider traffic bandwidth will result in significant time spreading of the signal. Thus, one would be faced with problems of intersymbol interference.

To see how the analytical model predicts actual performance, results from experimental work was sought. Unfortunately in the target range of 100 to 1000 miles there was none that could be found. However, Jordan[6,7] had investigated the effects of the Earth's reflections on an Aircraft - Satellite UHF link when the aircraft was flying at 25,000 ft. His results are presented in Figures 5 and 6.

In Figure 5 the relative reflective power is plotted as a function of the grazing angle. The measurements were made both over land and water and the dark lines in the graph are the analytical predictions for a smooth sea. Thus one can see that there is little correlation between the experimental points and these graphs even for low grazing angles where the theory would imply specular reflection.* In Figure 6 the received signal bandwidth is plotted as a function of the grazing angle. It can be seen that the phenomena, predicted by the theory of an increasing fade rate with an increasing grazing angle, occurs.

Thus we conclude that we have a diffuse reflection whose fade rate increases with increasing grazing angles but whose relative average power and actual power cannot be predicted very precisely.

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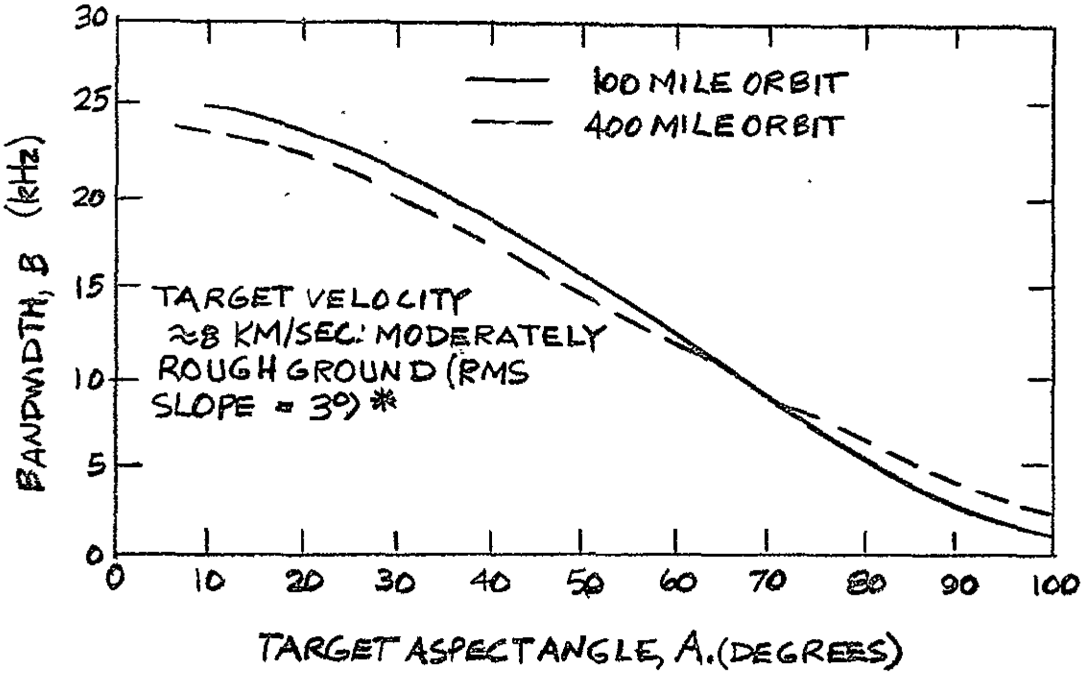
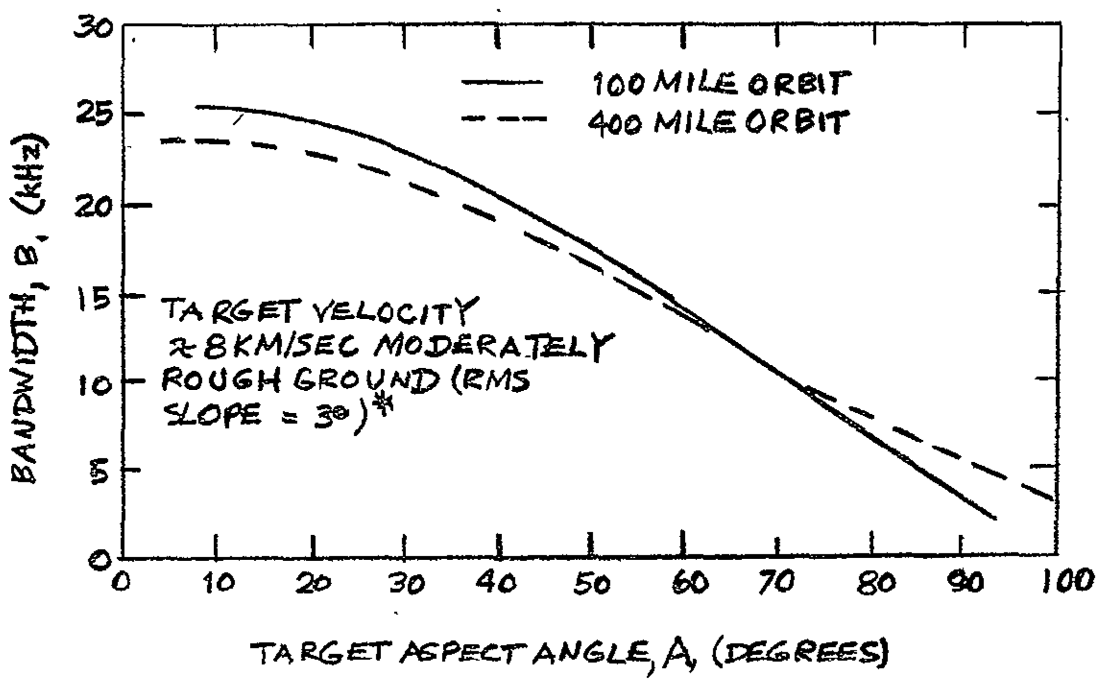
*For a smooth sea the reflection is specular.



A. CASE I. TARGET ORBIT IN THE PLANE OF THE TARGET, SATELLITE, AND EARTH CENTER.



B. CASE II. TARGET ORBIT PERPENDICULAR TO THE PLANE OF THE TARGET SATELLITE AND EARTH CENTER

Fig. 4 — Bandwidth of scattered signal.
(Approximate bandwidth of fading signal)
(Taken from reference 3)

* 8 KM/SEC ≈ VELOCITY OF A TARGET AT LOW FLYING ORBIT

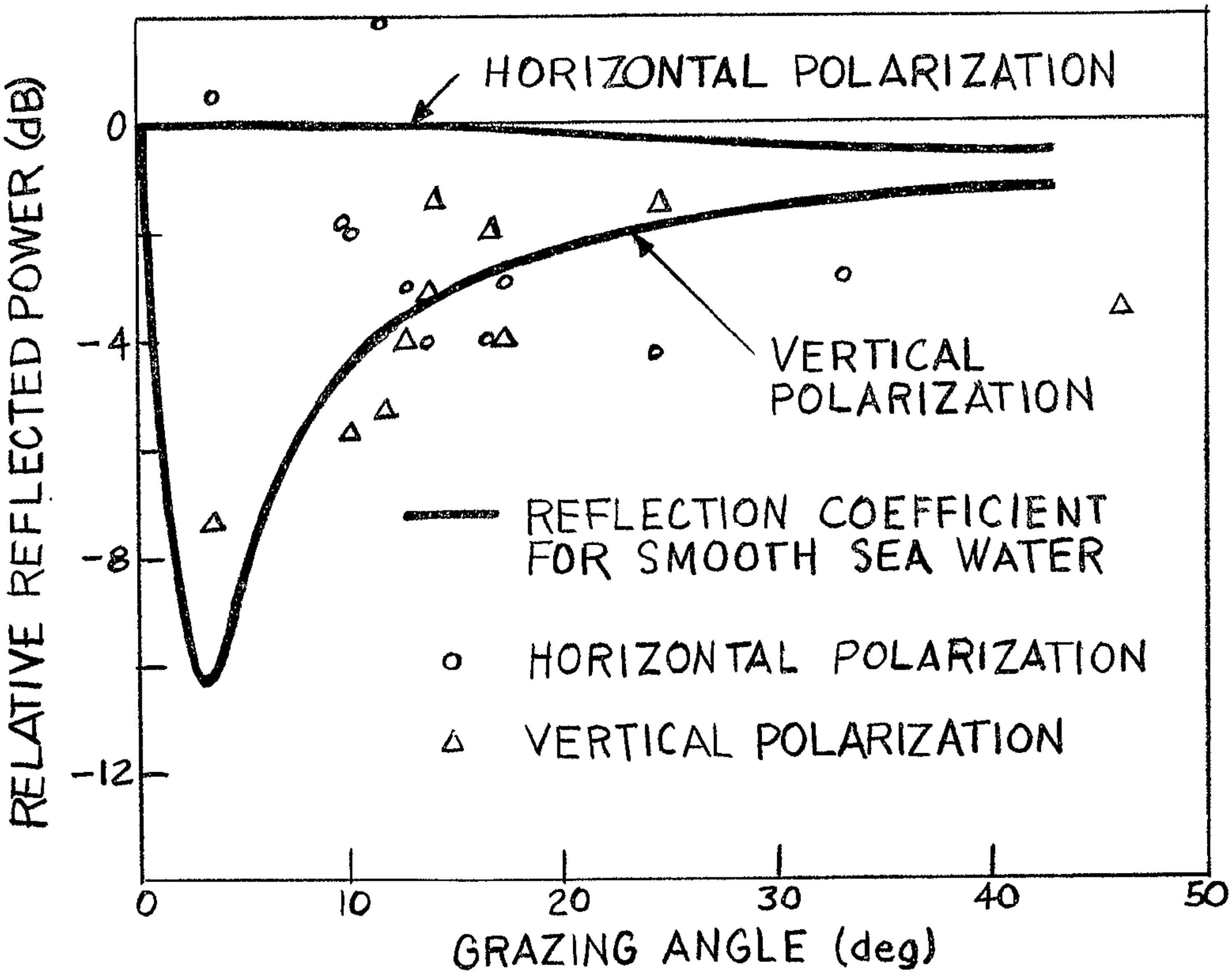


Fig. 5 (Taken from reference 6)

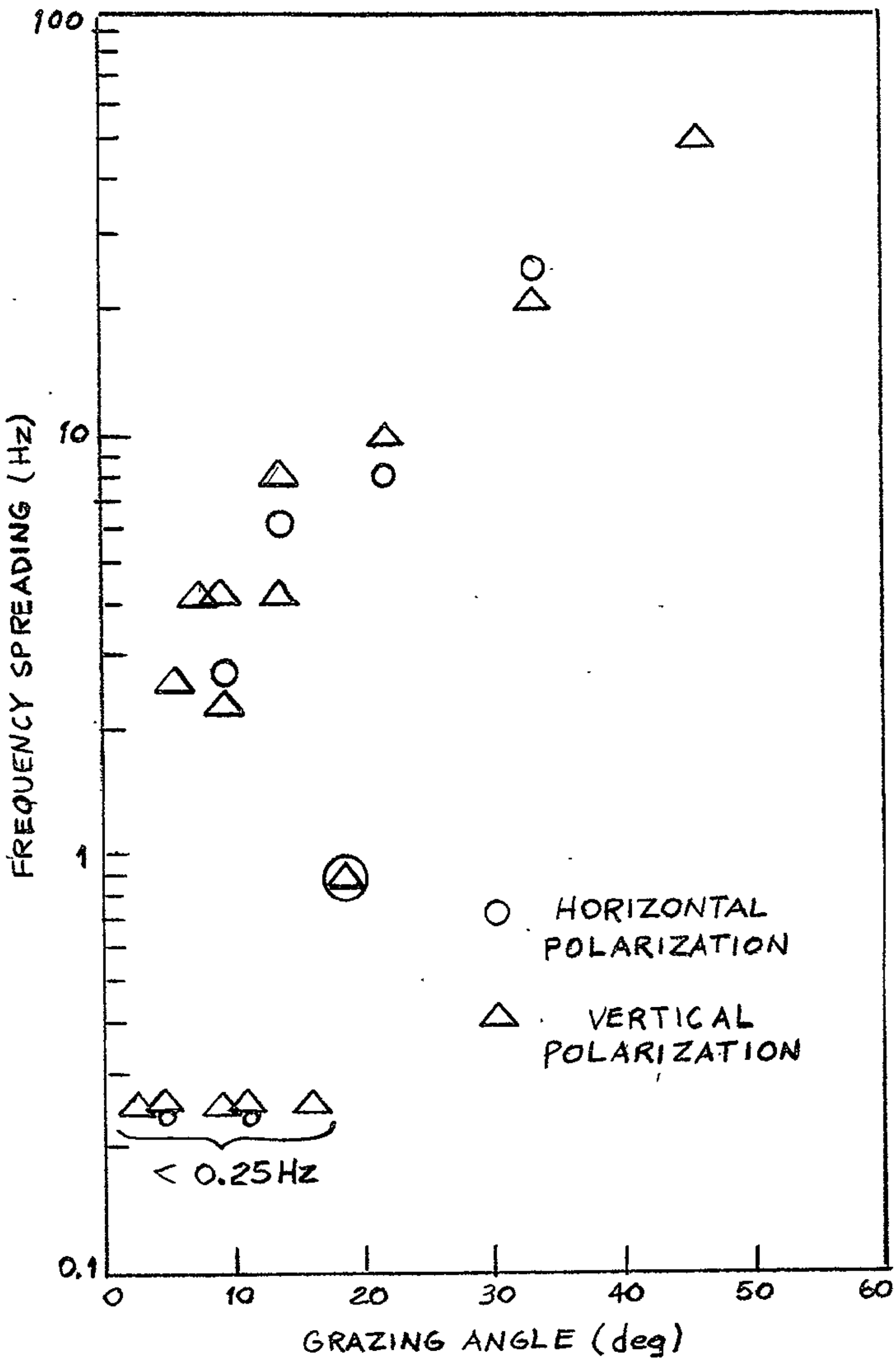


Fig. 6 (Taken from reference 6)

PERFORMANCE OF NON-COHERENT DIGITAL SYSTEMS IN A THREE COMPONENT - TWO PATH CHANNEL

As we shall shortly see, many analysts have approached the communication problem from a somewhat complementary manner to that which we have been discussing. Instead of being concerned with the exact values for reflected power and fade rates, a parametric study was made wherein the reflected signal was assumed to have a Rician distribution. That is, the reflection was assumed to have a specular component and a diffuse component whose envelope had a Rayleigh distribution. This model was consistent with the theory developed by Beckmann and Spizzichino.

J. Jones[8] has determined the performance of an optimum non-coherent FSK communication system for this channel.

In a non-coherent FSK modulation system, binary information is transmitted on one of two frequencies. The detector in the receiver measures the energy in the envelope of the output of two bandpass filters over a bit interval whose center frequencies are identical to the two possible frequencies transmitted. These energy measures are compared and a decision made that a given frequency was sent if its representative energy measure is greatest. Jones looked at the case where the reflected signal is delayed more than a bit interval due to the large path it has to travel. Some of his key results are presented in Figures 7, 8, 9, and 10 under the assumption of no doppler.

Figure 7 describes the performance when the total reflected signal (here denoted as the interference) is specular and where the interference falls totally in the 1 filter if a 0 was sent (alternate filter) over a bit interval. Figures 3 and 9 describe the case for a completely diffuse reflection while Figure 10 demonstrates how diversity can improve the system performance. The results show that a diffuse reflection falling in the alternate filter is the worst case since for a given diversity value it produces an irreducible error. It is to be noted that Jones assumed the bandwidth of the diffuse reflection to be identical to the transmitted signal and to have a white spectral density. In addition Jones showed that the 3 db improvement that Differential Phase Shift Keying (DPSK) has over FSK in an additive white Gaussian noise channel carries over to this channel.

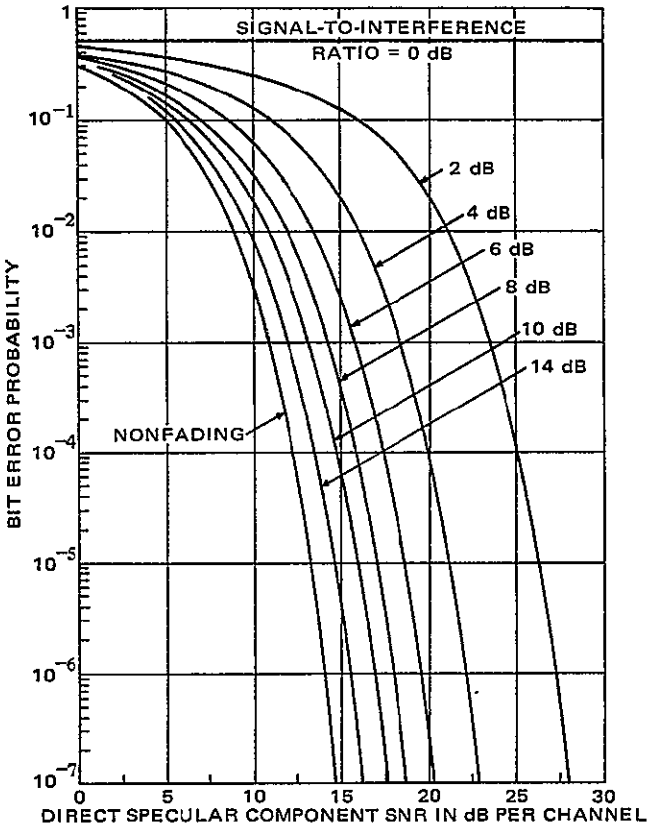


Figure 7 - Two-ray specular; reflected component in alternate filter. (order of diversity = 1)*

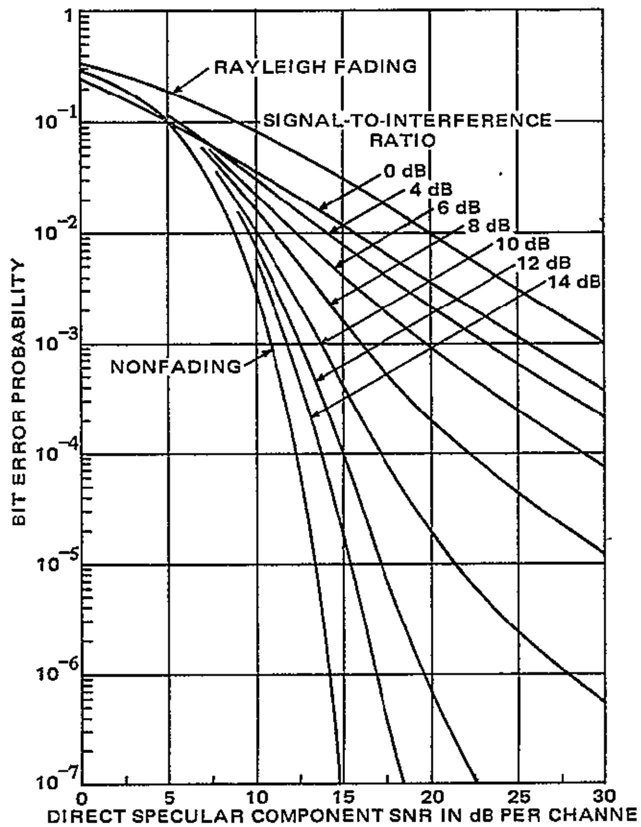


Figure 8 - Rician fading; diffuse component in same filter. (Order of diversity = 1)*

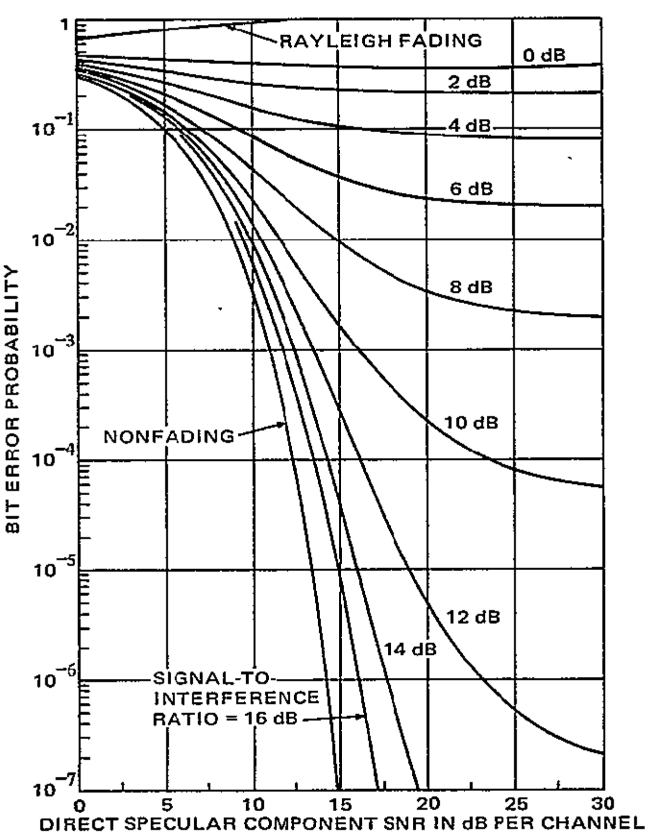


Figure 9 - Rician fading; diffuse component in alternate filter. (Order of diversity = 1)*

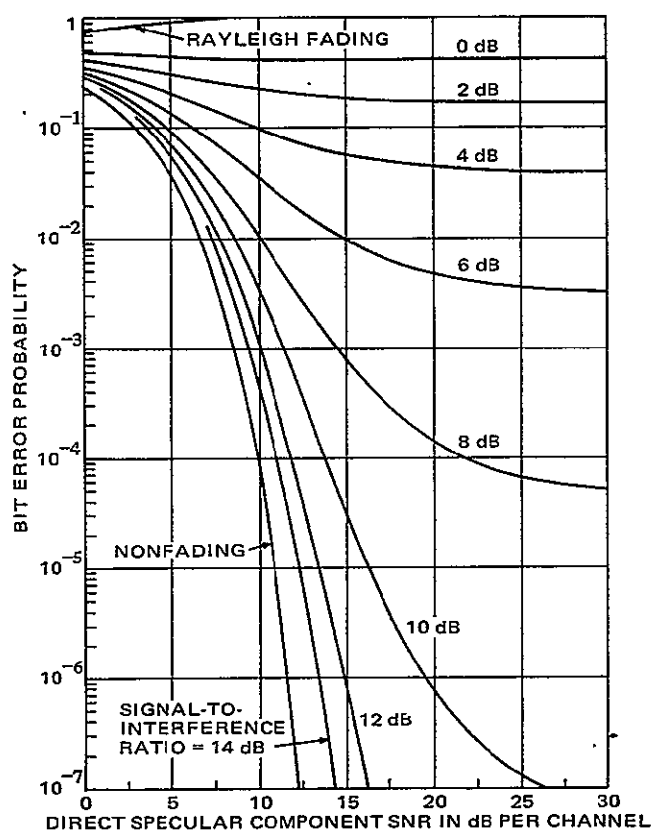


Figure 10 - Rician fading; diffuse component in alternate filter. (Order of diversity = 2)*

* Taken from reference 8.

Schuchman[5,6] has extended the work of Jones by looking at the slow fading case, and including doppler variation. The model of a Rician reflection does not put any restriction on the second order statistics of the received signal so that all fade rates are equally valid. Schuchman in one case assumed the fade bandwidth to be not so wide as the information bandwidth but sufficiently narrow that it would be constant over several bit intervals. Thus it was still valid to look at the average bit error probability as a measure of predicted performance for the system. It is interesting that in comparing the results obtained by Schuchman with those of Jones, they are essentially identical for the no doppler variation case. When doppler is considered, Schuchman widened the prediction bandwidth of the receiver to allow for the doppler, but this also meant allowing in more additive white Gaussian noise. It was shown, however, that for this case, conclusions obtained for the no doppler case carried over identically, except that now more transmitter power was required to overcome the effects of the additional white noise power.

To conclude, the work of Jones and Schuchman has shown that a non-coherent communication system in a three component-two path channel could be used to transmit information provided one was willing to pay the very high energy and bandwidth penalties this channel requires.

Continuous FSK and Differential Phase Shift Keying (DPSK) modulation schemes are simple and well known. However, there are other more sophisticated non-coherent systems that can be specifically designed for this channel. The several schemes can be divided into two major categories. In the first, bursts of information are transmitted with less than 100% duty factor, such that the maximum delayed reflection is received before the next direct path pulse is received. An additional constraint is that the maximum pulse width be sufficiently narrow that the minimum delayed reflection is not detected simultaneously with the direct transmission. This system is illustrated in Figure 11. It has the advantage that there is no irreducible error rate as in the continuous FSK and DPSK systems. On the other hand the system is constrained by the maximum and minimum delays experienced on the channel. More information can be transmitted in such a scheme by driving a voltage controlled carrier oscillator with a saw tooth function. Such a system is described in Figure 12.

In the systems described we have been concerned only with the transmission of information from one target to a satellite relay. In reality, systems are designed where numerous users access a satellite relay simultaneously. For the systems described, this can easily be done by orthogonal frequency assignments.

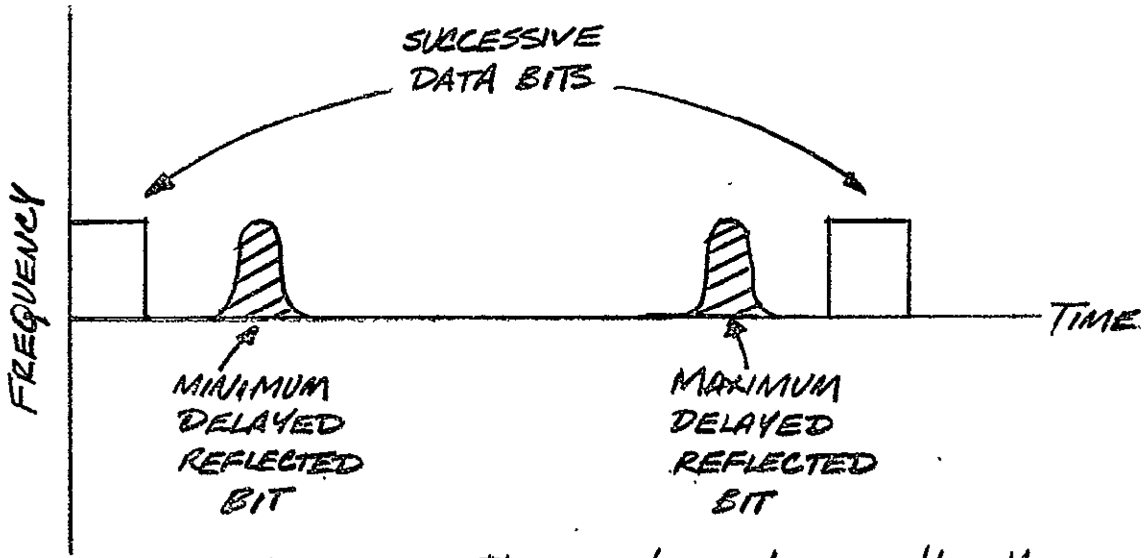


Fig 11. Transmitting and avoiding multipath

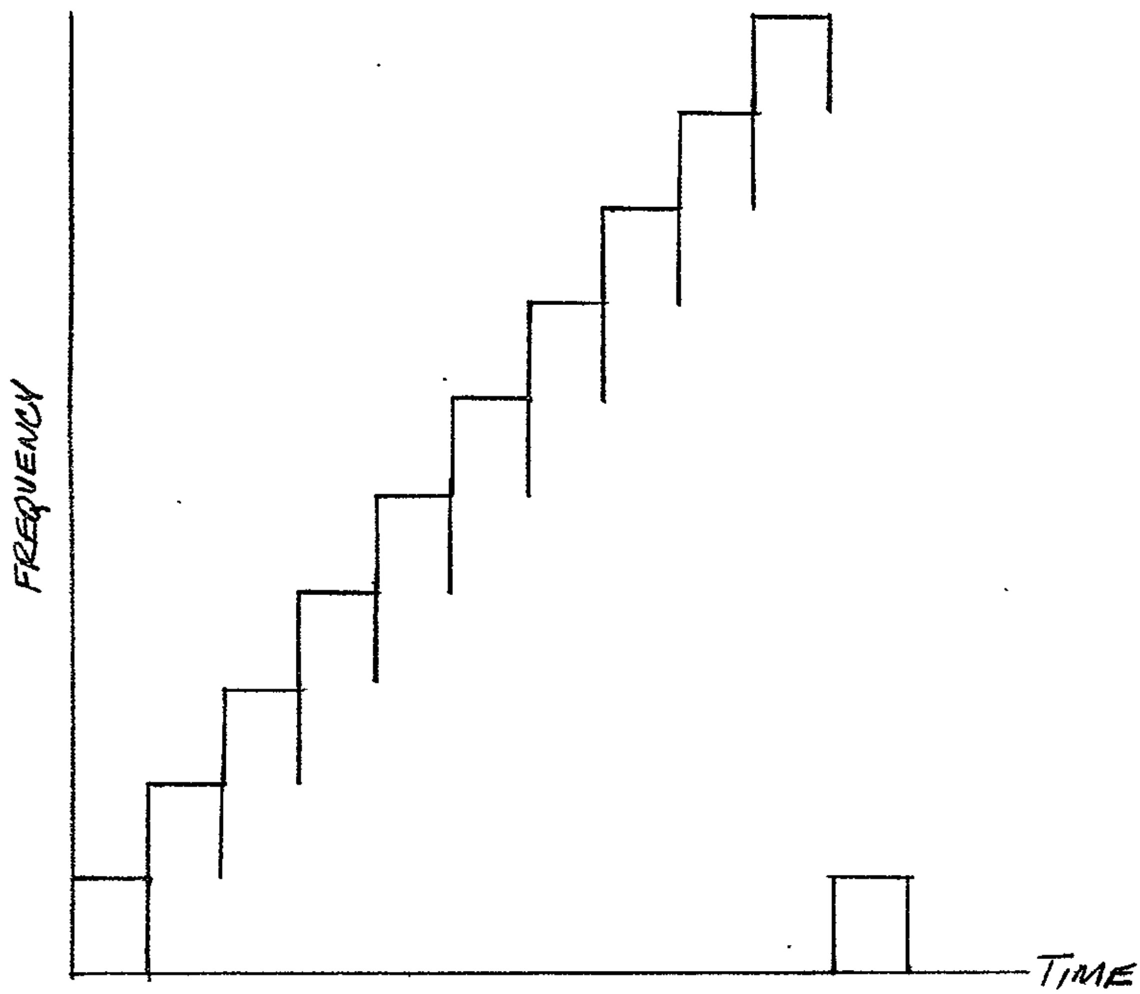


Fig 12. Transmitting continuously and avoiding multipath

The second category of systems we now discuss allow all multiple access users to communicate in the same bandwidth. In such schemes a transmitter modulates a PN sequences which in turn phase modulates an RF carrier. The PN sequence acts as an address so that the receiver can automatically determine which of the many transmissions on the air is the one it should detect. Such PN codes must have very good autocorrelation properties and excellent cross correlation properties. That is two nonsynchronous PN codes must have a near zero cross correlation while each PN code must have an autocorrelation function that approaches a delta function. Codes such as Anderson[9,10] and Gold[11] codes have this property. These systems operate efficiently by whitening the reflections and other addressed PN codes through correlation techniques and reducing this self-system-noise by a processing gain proportional to the ratio of the RF bandwidth to information bandwidth. Thus the wider the RF bandwidth is made the better the system operates. In addition such a system is somewhat more flexible in that more users can be assigned to use the system. This is particularly true if each user does not use the system continuously but rather in a random manner and with a relatively low duty factor.

The PN sequence systems are used for a more significant reason. It is usually the case that in addition to communication information, range information is also required. In terms of the communication system performance if the self noise of the system can be kept relatively small then the PN system will be expected to perform nearly as well as the non-coherent continuous DPSK or FSK system. Note that in a non-coherent PN system each of the PN pulses will be sent by either DPSK or FSK. Since in an additive white Gaussian noise channel the PN system can do no better than continuous DPSK or FSK we would expect similar findings for this three component - two path channel. The big advantage of the PN system is in obtaining range data. Range data can be extracted from the PN sequence with the aid of a delay lock loop. Using this device the range accuracy becomes inversely proportional to the chip width of the PN sequence. Thus, as the bandwidth of the PN sequence increases, the accuracy of the range data increases. In the continuous DPSK or FSK system the range accuracy is proportional to the information chip width. Thus, the idea of using PN systems is to maintain the performance of the communication system while significantly increasing the target range accuracy over that which can be obtained by the simpler DPSK or FSK system.

To conclude this section we see that the two-path three component channel can be made in a relatively efficient manner provided there is sufficient bandwidth available.

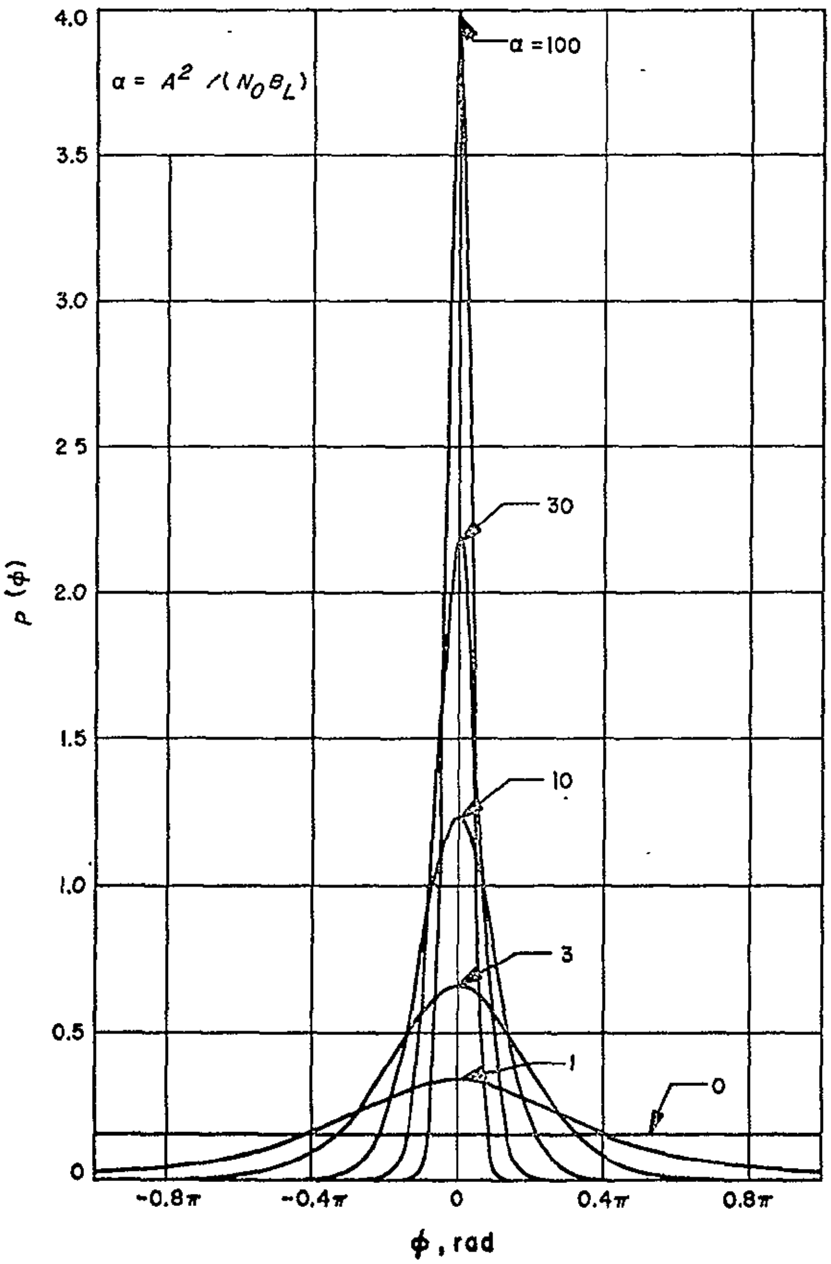


Fig 13 First-order-loop steady-state probability densities $p(\phi)$ as a function of phase error (ϕ) for several values of loop SNR's (α). (Taken from reference 12)

COHERENT COMMUNICATION

The most accurate range information that can be obtained for the smallest cost in bandwidth can be obtained in a coherent communication system. Thus, if coherence can be maintained in the two path - three component channel such a system would be a more efficient system.

Viterbi[12] has described the behavior of the phase-locked loop in a rigorous manner. He showed that ideal coherent detection cannot be achieved since the receiver device (a phase-locked loop) which estimates the transmitted phase could not do it perfectly due to noise in the system. Viterbi showed that there is a stationary phase error in the system which was a function of the carrier power and phase-lock loop bandwidth. His results are reproduced in Figure 13. He then described an optimum partially-coherent detector and estimated its performance with the use of Figure 13. Little has been done with the Viterbi receiver, but Lindsey[14] has estimated the performance of an ordinary phase locked loop with the use of Figure 13. In addition, Schuchman[15] has shown the relationship between acquisition time, time to acquire, and loop signal to noise ratio for a first order loop. The question now remains to see if these referenced results can be extended to the fading channel. Blain and Balcewicz[16] have shown experimentally that such an extension can be made when the reflected bandwidth is of the order of the signal bandwidth or greater. Their results are presented in Figure 14.

Several researchers[11,16] have proposed PN systems for the two-path three-component channel. For such a system the fading and multiple access effects must be accounted for. Unfortunately the effect of the multiple access users on a particular loop's carrier to loop-bandwidth ratio was not determined. It would appear to me that this would severely limit the acquisition and cycle slipping properties of the loop since there is no processing gain in the loop circuit that would eliminate the effects of other strong signals.

Hekimian[16] has proposed a system that avoids the multipath and is a variation of the one described in Figure 11. His system takes advantage of the fact that for different target altitudes the minimum and maximum delay values vary. This can be seen in Table I where the reflected signals delay is given as a function of grazing angle for two different target altitude values. Hekimian uses this information to vary the pulse widths at each altitude increment while the duty factor is kept constant. This allows for a more efficient use of bandwidth over the system described in Figure 11. However, the system is somewhat complicated by the need to know the target altitude.

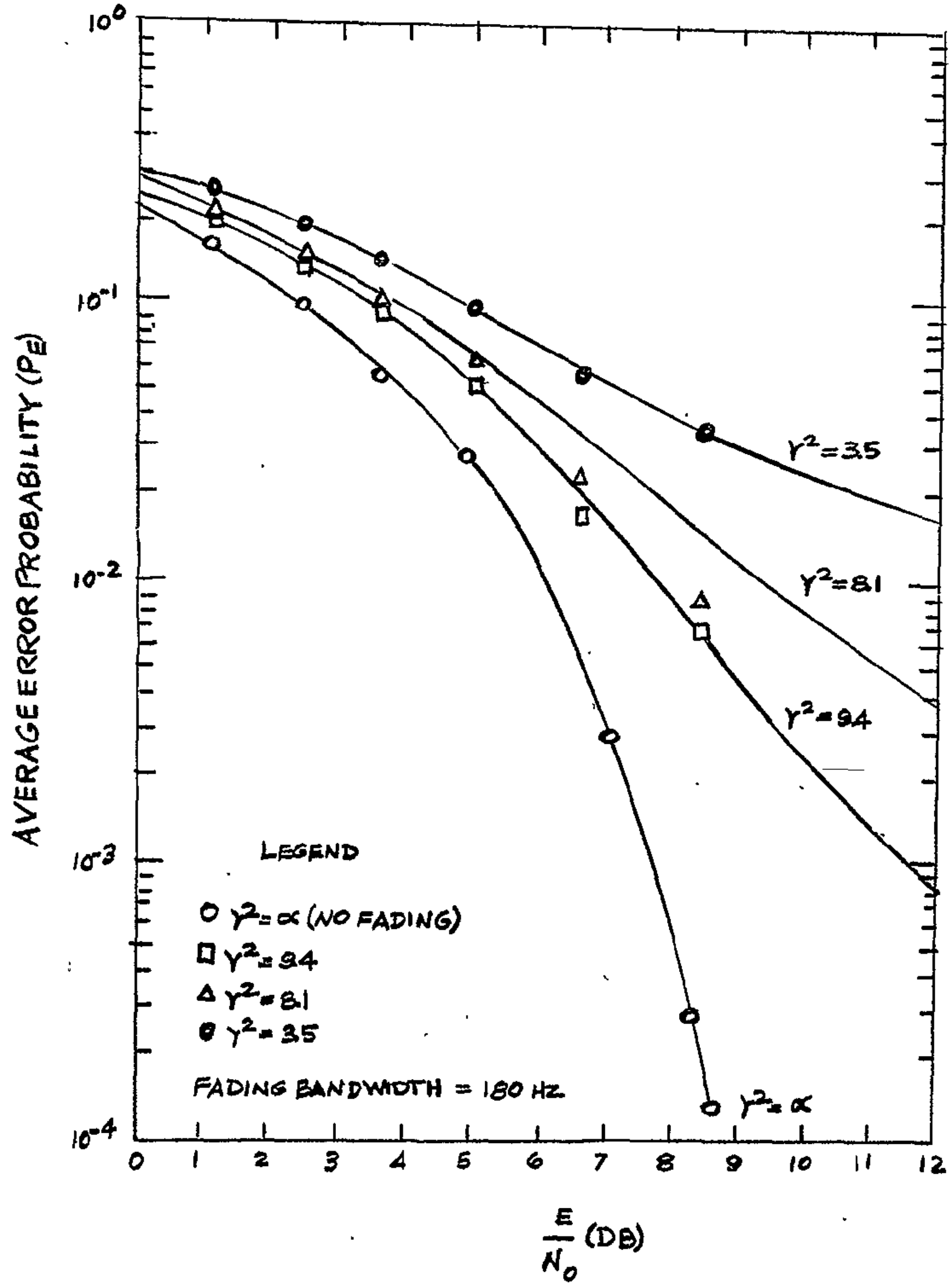


Fig 14. Average Error Probability vs Energy-to-Noise Ratio for Fading Bandwidth Equal to the Loop Bandwidth (Taken from Reference 16)

TABLE 1

Path Delay as a Function of Grazing Angle for two Values of Target Altitude

Target Altitude 100 n.m.

Grazing Angle (Radians)	Delay (Millisecs)
.004	.00013
.03	.008
.045	.017
.154	.131
.287	.302
.443	.495
.614	.688
.794	.865
.982	1.018
1.175	1.136
1.37	1.209
1.57	1.234

Target Altitude 1000 n.m.

Grazing Angle (Radians)	Delay (Millisecs)
.0526	.069
.0788	.175
.09485	.25
.1914	.9
.295	1.9
.407	3.2
.528	4.6
.657	6.2
.795	7.8
.940	9.2
1.091	10.5
1.25	11.5
1.41	12.13
1.57	12.34

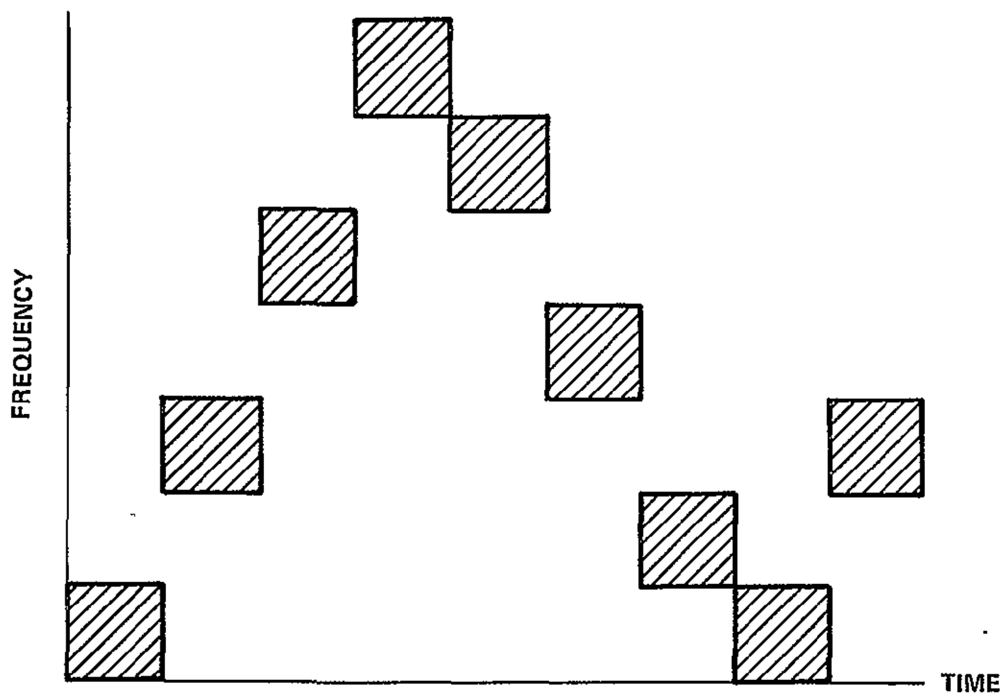


FIGURE 15 - AVOIDANCE OF MULTIPATH, WHILE TRANSMITTING CONTINUOUSLY IN TIME, BY A FREQUENCY SAWTOOTH HOPPING TECHNIQUE

Except for the complexity of the system due to the requirement that the target altitude must be known the system appears to be reasonable. However, the gating of the phase locked loop input may cause the loop to lose lock during the off periods. The effects of such gating should be experimentally determined.

A simple variation of this system is described by Figure 12. This system operates at a 100% duty factor and requires no knowledge of the target altitude. Here, too, the phase locked loop's ability to maintain lock may be questioned since the saw tooth discontinuity in driving the VCO may cause problems.

A slight variation of the last idea in which an attempt is made to reduce the discontinuity in the saw tooth VCO drive is depicted in Figure 15. Here we see that the trade off has been to exchange the large discontinuity in the saw tooth drive for a series of much smaller step discontinuities. It is difficult to say which of these several techniques, if any, will perform efficiently. However, since the possible malfunction of the phase-locked loop being considered will not be caused by the channel, it appears that the effects of gating or saw tooth driving of an oscillator can easily be demonstrated in a laboratory. Thus, it appears that such an experiment is warranted if a proper evaluation of a system that attempts to avoid multipath is to be made.

CONCLUSION

To summarize, it would appear that a coherent system that avoids multipath would be the most efficient. However, such a system has two problems. The range of operation of such a system is limited by the maximum and minimum delays in the reflected path, and there is some question that the gating or saw tooth driving of the oscillator in the phase lock loop may cause serious cycle slipping problems. This latter problem can be resolved easily by an experimental investigation. If such a system were operated non-coherently the range data would be less accurate, since the phase information would be destroyed. However, the accuracy of the system would be inversely proportional to the transmitted pulse width rather than the larger information pulse width.

The major advantages of the PN sequence appears to be the following: it can operate over a wide tracking range, and it is more flexible when there are a large number of low duty cycle users. In addition, it appears that with sufficient bandwidth both communication and range data can be obtained.

It is interesting to point out that when the grazing angle is so small that path delay is negligible, then for the non-coherent PN system, performance can be obtained from graphs such as Figure 8 since the no delay case is equivalent in FSK to having the reflection fall in the same filter when very large delays occur. As was pointed out by both Jones and Schuchman, this is not as severe a problem as having the reflection fall in the alternate filter. Thus, it would appear the communication at low grazing angles in a two-path three component channel is less difficult than communicating at higher angles as long as a direct path signal can be maintained. One word of caution is, however, needed. At such low grazing angles, the dependence on the model assumed for the Earth's surface becomes more significant. As we have seen, this can mean that results based on the Rician reflections model may not be very accurate.

2034-LS-pjr

L. Schuchman

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