USE OF POLARIZATION, ANGLE, HEIGHT, AND FREQUENCY DIVERSITY DURING MULTIPATH FADING TO IMPROVE TELEMETRY RECEPTION ABOARD SHIP

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ABSTRACT

Methods to improve reception during multipath fading of telemetry data received aboard ships participating in missile exercises include various diversity techniques. Among these techniques are polarization, angle, height, and frequency diversity. In this paper, a two-ray multipath model is used to investigate the various techniques and determine the merits of each. Possible ways of implementing the promising ones are discussed.

Key words: multipath fading, diversity techniques, telemetry link.

INTRODUCTION

Shipboard reception of telemetry from missiles at low elevation angles can result in loss of data because of multipath propagation. As data rates and distances increase, communication link margin decreases, leaving none left to offset the effects of multipath fades. This is especially true when a small receiving antenna is used aboard ship. Various diversity techniques have been examined over the past few years to increase received signal during multipath propagation.(1,2) The purpose of this investigation is to examine the applicability of polarization, angle, height, and frequency diversity to the shipboard receiving station and determine which diversity methods (or combinations of methods) will result in link improvements.

MULTIPATH MODEL

An ideal one-way communication link has one path between the transmitting antenna (source) and the receiving antenna. The electromagnetic wave travels along this path, and the received signal may be calculated by using the Friis transmission equation. Multipath propagation occurs when additional paths allow additional signals from the source to arrive at the receiving antenna. In general, the lengths of the paths are not equal and thus result in differences among the arrival times of the signals. These time differences result in phase differences among the signals that sometimes cause the signals to subtract from one another, resulting in low signal (a null) at the output of the receiving antenna.

For this investigation, a two-ray multipath model was used as shown in Figure 1. One ray follows the direct path, and the other follows the path reflecting off the water at grazing angle ψ. The field component reflected off the water is the field component incident to the water multiplied by the reflection coefficient, ρ, for seawater and for the proper polarization. At the receiving antenna, the total signal is a combination of the direct-path field component (signal) and the reflected-path field component (signal). Field attenuation due to 1/R in the Friis equation is essentially the same for both the direct- and reflected-path signals; therefore, the difference between the lengths of the direct and reflected paths affects only the relative phase of the two signals.

The following assumptions are made to simplify the multipath model: the reflecting surface is assumed to be smooth and flat, allowing use of theoretical values for ρ and simplifying the geometry. The angle α is very small, resulting in the magnitude and polarization of the direct-path and reflected-path signals being equal to each other as the signals leave the transmitting antenna and resulting in zero phase difference between them. The carrier frequency is 2250 MHZ, nominal. The telemetry modulation type is narrowband FM; consequently, results at the carrier frequency apply throughout the bandwidth of the signal. (Wide-bandwidth signals are a special case considered under Frequency Diversity.)

In the resulting model, the direct-path signal has a coefficient of 1 and the reflected-path signal has a coefficient $\rho e^{j\theta}$, where ρ is the reflection coefficient for seawater and θ is the phase shift caused by path difference. The total signal at the antenna (in the frequency domain) is given by:(3,4)

$$S = 1 + \rho(\omega_o,\psi) \cdot \exp\left(-j\frac{2\omega_o hH}{cD}\right) \tag{1}$$

where

$\rho(\omega_0,\psi)$ = reflection coefficient at frequency ω_0 and grazing angle ψ for either horizontal or vertical polarization

ω_0 = carrier frequency (rad/s)

ψ = grazing angle (deg)

h = height of the receiving antenna (m)

H = height of the transmitting antenna (m)

c = speed of light (m/s)

D = range of the transmitting antenna (m)

The signal at the output of the receiving antenna is the vector sum of the direct-path and reflected-path components multiplied by the gain of the receiving antenna at the respective incident angles (superposition). The total signal at the output of the antenna is given by

$$S_T(\omega_o) = \sqrt{G(\phi_d)} + \sqrt{G(\phi_r)} \cdot \rho(\omega_o, \psi) \cdot \exp\left(-j\frac{2\omega_o hH}{cD}\right) \tag{2}$$

where

$S_T(\omega_0)$ = voltage at the output of the receiving antenna at frequency ω_0

$G(\Phi_d)$ = receiving antenna gain for the direct-path signal

$G(\Phi_r)$ = receiving antenna gain for the reflected-path signal

Φ_d = angle of the direct path referenced to boresight

Φ_r = angle of the reflected path referenced to boresight

Equation 2 must be used twice (once for each polarization) to compute the horizontal polarized signal and the vertical polarized signal at the output of the antenna. Proper weighting must be used for each polarization depending on the polarization of the transmitted wave. The total received power is the sum of each received signal squared.

DIVERSITY METHODS

Polarization, height, angle, and frequency diversity were investigated to determine their effectiveness in increasing received signal during multipath fading. Polarization diversity uses the polarization of the transmitted wave and receiving antenna as well as the reflection coefficient to advantage. Height diversity and angle diversity are closely related and vary receiving antenna height and antenna pointing angle, respectively, to advantage. Frequency diversity uses multiple frequencies or a wide signal bandwidth to advantage.

In most of the methods, more than one output signal would be available from the antenna system (e.g., horizontal and vertical polarization). The outputs would then be combined in a multiple-channel receiver/combiner to yield the best signal. Such an optimal combiner is assumed in the following discussion, but details of its operation are beyond the scope of this paper.

POLARIZATION DIVERSITY

First, polarization diversity in the multipath-free environment is considered. The polarization of the transmitted wave depends on the transmitting antenna polarization and the attitude of the antenna. Since attitude may change considerably during flight, any attempt to control transmitting antenna polarization does not ensure a given polarization at the receiving antenna. Thus, a robust solution is to receive orthogonal-polarized signals and optimally combine them. In this solution, a dual-polarized receiving antenna and optimum receiver/combiner function together to yield a receiving antenna whose polarization matches the incoming wave polarization in real-time.

Next, the effects of multipath propagation are considered. Equation 2 is used first for horizontal polarization and then for vertical polarization to determine the total received signal. Figure 2 shows the magnitude of ρ as a function of ψ for both polarizations. It can be seen that $|\rho|$ is approximately one for all angles of ψ (horizontal polarization); this results in 6 dB peaks and deep nulls for all angles of ψ as shown in Figure 3 for $h = 12$ meters. It can also be seen that $|\rho|$ varies considerably as a function of ψ (vertical polarization); this results in smaller peaks and nulls as shown in Figure 3. Not shown is the phase of ρ as a function of ψ. For horizontal polarization, it is always approximately -180 deg; for vertical polarization, it varies from -180 deg at $\psi = 0$ deg, to -90 deg at $\psi = 6$ deg, and then toward 0 deg for large values of ψ. The consequence of this phase difference between polarizations is that the horizontal reflected signal will not be in phase with the vertical reflected signal for ψ greater than a few degrees. This results in the nulls (and peaks) of the total horizontal signal occurring at different times than the nulls (and peaks) of the total vertical signal. As ψ decreases toward 0 deg, it can be seen that the nulls for both polarizations start to correlate, and at $\psi = 0$ deg, they occur simultaneously; this is apparent in Figure 3.

The following techniques might be used to exploit the above behavior. First, if the transmitting polarization can be controlled (which it usually cannot), use vertical polarization for transmitting and receiving; signal nulls are not deep for vertical polarization except at very low grazing angles. Second, transmit, receive, and optimally combine both polarizations; the combined signal will have no nulls above

ψ = 6 deg because the horizontal and vertical nulls are uncorrelated. But below 6 deg, nulls will get deeper as ψ decreases toward 0 deg because the phases of the two reflection coefficients approach -180 deg and $|\rho|$ for vertical polarization approaches one.

HEIGHT DIVERSITY

Height diversity is a method of locating antennas at different heights to increase the total received signal during multipath fading. Its effectiveness can be visualized by plotting received signal level versus receiving antenna height. Using Equation 1, a family of curves, one curve for each value of ψ, is plotted in Figures 4 and 5 for horizontal and vertical polarization, respectively. Figures 4 and 5 can be described as interference patterns that result from the direct- and reflected-path signals reinforcing and interfering with each other. Note that the received signal at a given height h depends on ψ so that the received signal from an antenna placed at that height will increase and decrease as the interference pattern runs past the antenna due to the changing ψ. One can see that a movable antenna could avoid the pattern nulls by adjusting its height dynamically as ψ changes.

Figures 4 and 5 also show two horizontal lines, A and B, located at the heights of two antennas. One can see that for ψ = 2.5 deg, one or both of the antennas will receive sufficient signal because both are not in signal nulls simultaneously. As ψ decreases to 1.75 deg, both antennas are in adjacent nulls, and the received signal from both antennas is insufficient. When ψ decreases below 1.75 deg, both antennas begin to move away from being in simultaneous nulls, and total received signal increases.

Total received power is plotted versus ψ for two antennas at 13- and 14-m heights (separation equals 1 m) in Figure 6. It can be seen that this value of separation results in good signal for $\psi > 1.5$ deg, but that the null depths gradually increase as ψ decreases. If the antenna heights are varied but the separation distance is fixed, a family of curves will result. If the nulls of each curve are connected, an envelope will be constructed, which is shown by the dashed line in Figure 6. Figure 7 is a plot of several envelopes for cases of antenna separation from 0.5 to 2 m. It can be seen that different values of separation result in different ranges of ψ in which nulls are weak or deep. Height diversity may be combined with angle diversity as described at the end of the following section on angle diversity.

ANGLE DIVERSITY

Angle diversity is the method of pointing the antenna to increase the received signal. One example, the limited-elevation method, is a technique of limiting the antenna in elevation near the horizon so that the direct-path signal enters the antenna near the main beam peak, but the reflected-path signal enters down on the main beam near the first null. The output of the antenna may be calculated using superposition. When the direct-path signal and reflected-path signal are out of phase at the antenna, the output of the antenna is the direct-path signal multiplied by the peak main-beam gain, minus the reflected-path signal multiplied by the main-beam gain at the incident angle. Thus, the reflected-path signal is reduced in amplitude by the antenna pattern, which results in only a mild signal null.

Another example, the monopulse-combining method, is a method of optimally combining the sum signal and elevation error signal from a monopulse antenna. An analysis in Reference 5 shows that it is equivalent to combining the outputs of two wide-beam antennas spaced vertically a small distance apart. This results in a two-element electronic phased array antenna that automatically changes and moves its antenna pattern to obtain the greatest signal, regardless of fine mechanical pointing (i.e., automatic tracking). Thus, the antenna and optimum receiver/combiner function together to yield an antenna that electronically points in the direction of the incoming wave. This has the advantage of being able to track the incoming wavefront in real-time.

Figure 8 shows a plot of signal level versus phase shift of the reflected-path signal for three cases: normal sum-channel reception, limited-elevation method, and monopulse-combining method. It can be seen that the sum-channel reception has a deep null while the other two methods do not. Also, the null depth using the other two methods is very close, but the peaks are significantly different.

Reference 4 outlines a method using angle diversity and height diversity to yield a combined signal that reduces the effects of multipath fading better than either diversity technique alone. Figure 9 shows an example of total received power for three cases: angle diversity, height diversity, and both.

FREQUENCY DIVERSITY

Frequency diversity is a method of using multiple or spread frequencies to reduce the effects of multipath. Looking at Equation 1, it can be seen that the received signal is a function of frequency. Previously, analysis of the received signal has assumed that it is at a single frequency; however, this is not exactly true because a signal that contains information also has bandwidth. The signal bandwidth depends on the information rate, coding, modulation, etc.

The spectral components of the received signal will be changed in magnitude and phase due to the filtering effects of multipath. The magnitude of the received signal from Equation 1 is plotted as a function of frequency in Figure 10 for a receiving antenna located at a height of 13 m and with a grazing angle of 5 deg (horizontal polarization). It can be seen that the received signal is a periodic function of frequency; the 6-dB bandwidth is approximately 90 MHZ and the 6-dB null width is approximately 45 MHZ. As both h and ψ decrease, the pattern moves to the right and expands, increasing the bandwidth and the null width. Methods using multiple carriers or spectrum-spreading modulation methods may be used to allow energy to be received regardless of the location (in frequency) of the null. As bandwidths increase, techniques such as adaptive filtering may be used to offset the filtering effects of multipath fading.

CONCLUSIONS

Of the four diversity techniques considered, polarization diversity is the most easily implemented and results in signal improvement even when multipath propagation is not a factor. Thus, it should be implemented by using dual-polarized antennas and receiver/combiners when possible.

Strategies using angle diversity and height diversity should be developed using the receiving antenna capabilities and available assets (receivers and antennas). One strategy might use limited-elevation positioning of a large antenna and an additional smaller antenna. Another strategy might use the monopulse-combining method when the receiving antenna is located high on the ship. These diversity techniques show promise in reducing the detrimental effects of multipath fading at a reasonable cost.

Frequency diversity techniques are very complicated in that they involve the transmitting end as well as the receiving end of the communication link. At the present time, these techniques do not appear justified for our application; however, in the future, they may become necessary for the missile-to-ship telemetry link.

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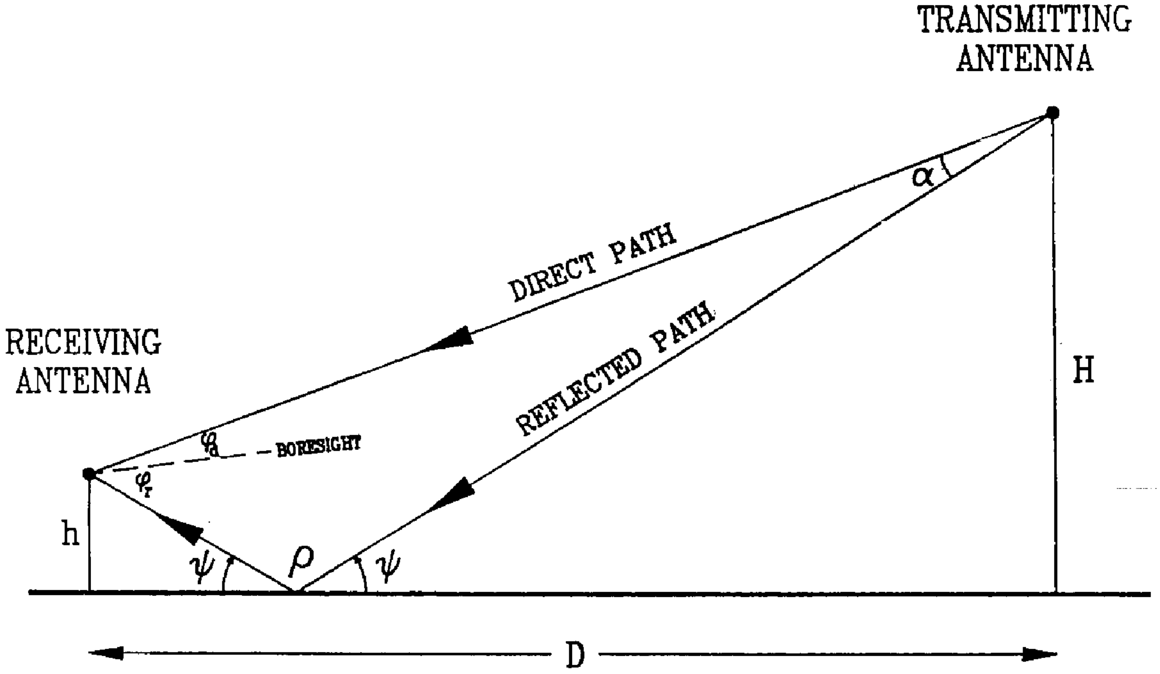

Figure 1. FLAT-EARTH MULTIPATH MODEL

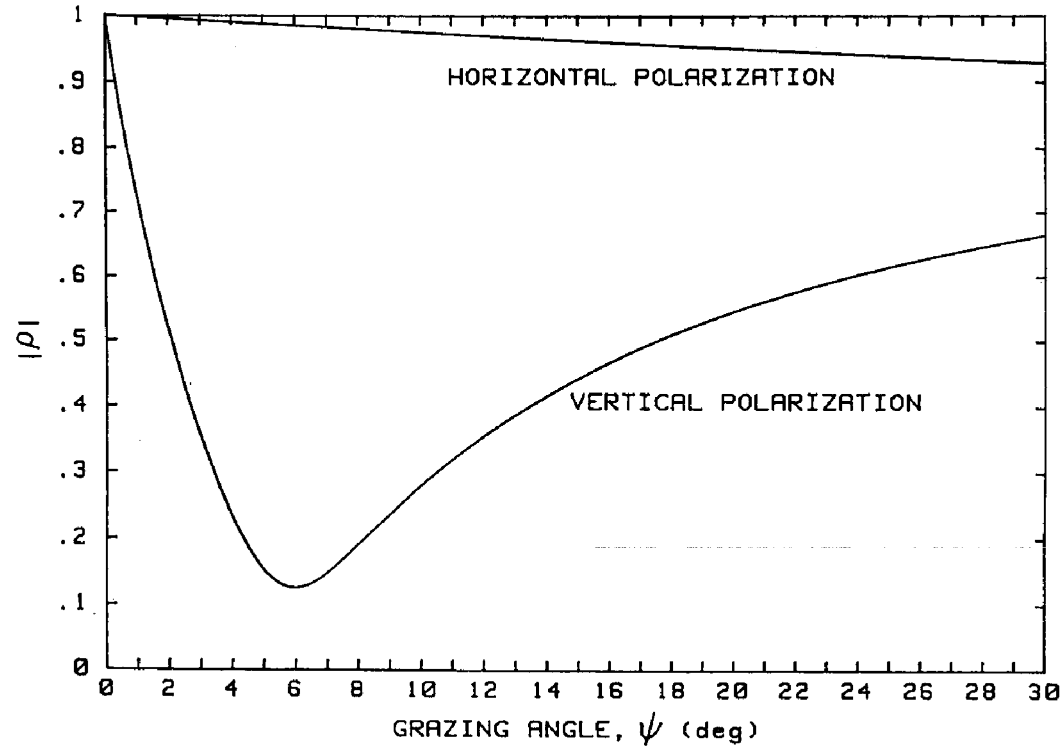

Figure 2. MAGNITUDE OF REFLECTION COEFFICIENT VS GRAZING ANGLE

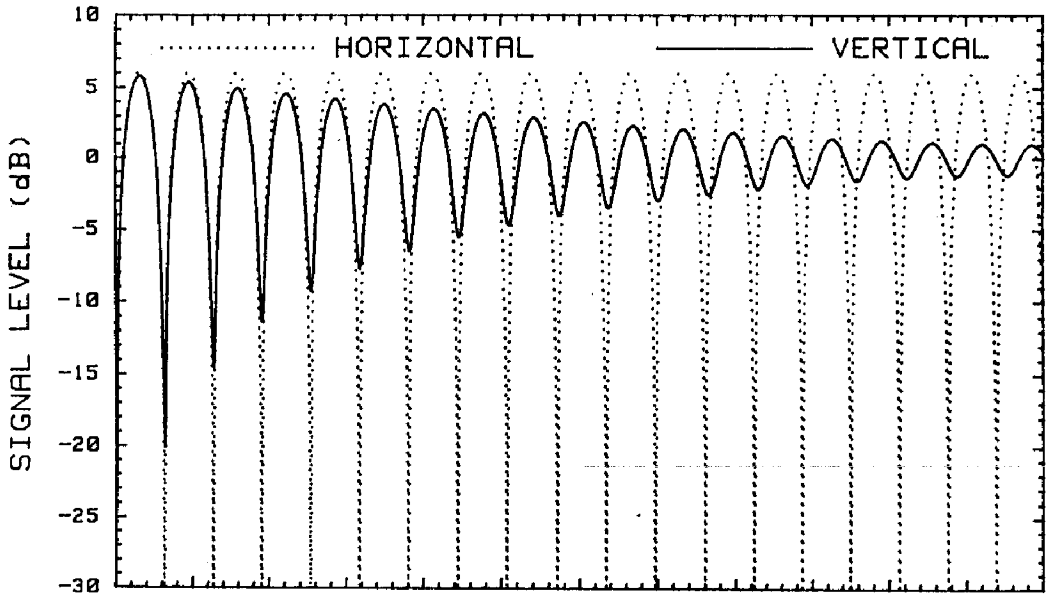

Figure 3. RECEIVED SIGNAL VS GRAZING ANGLE

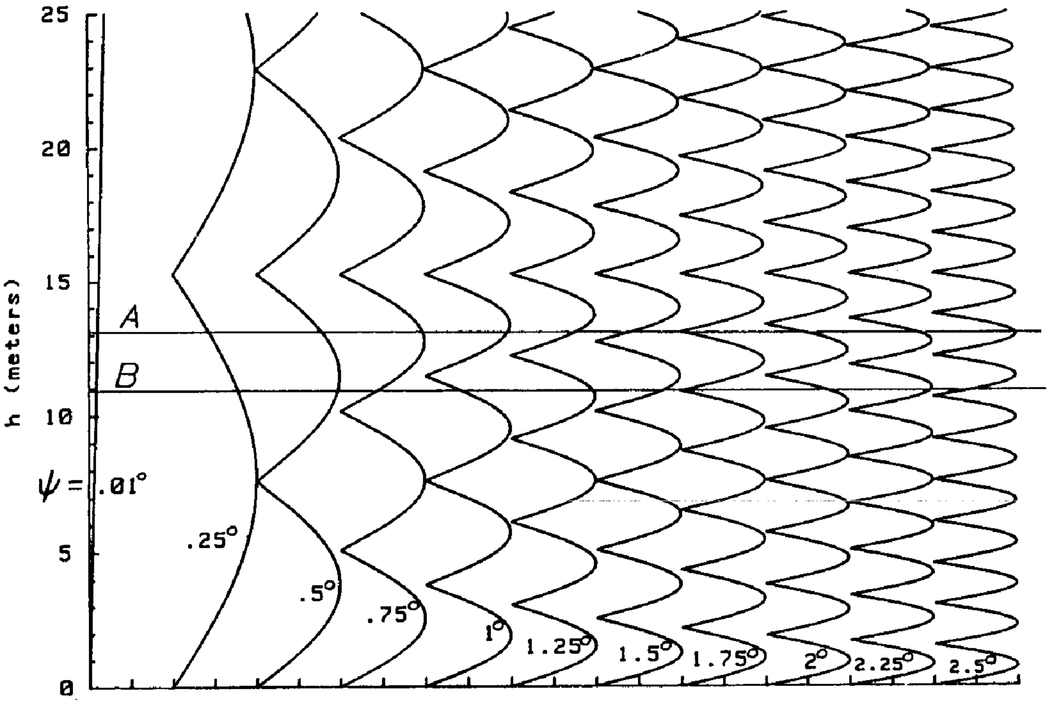

Figure 4. RECEIVED SIGNAL AS A FUNCTION OF h FOR HORIZONTAL POLARIZATION

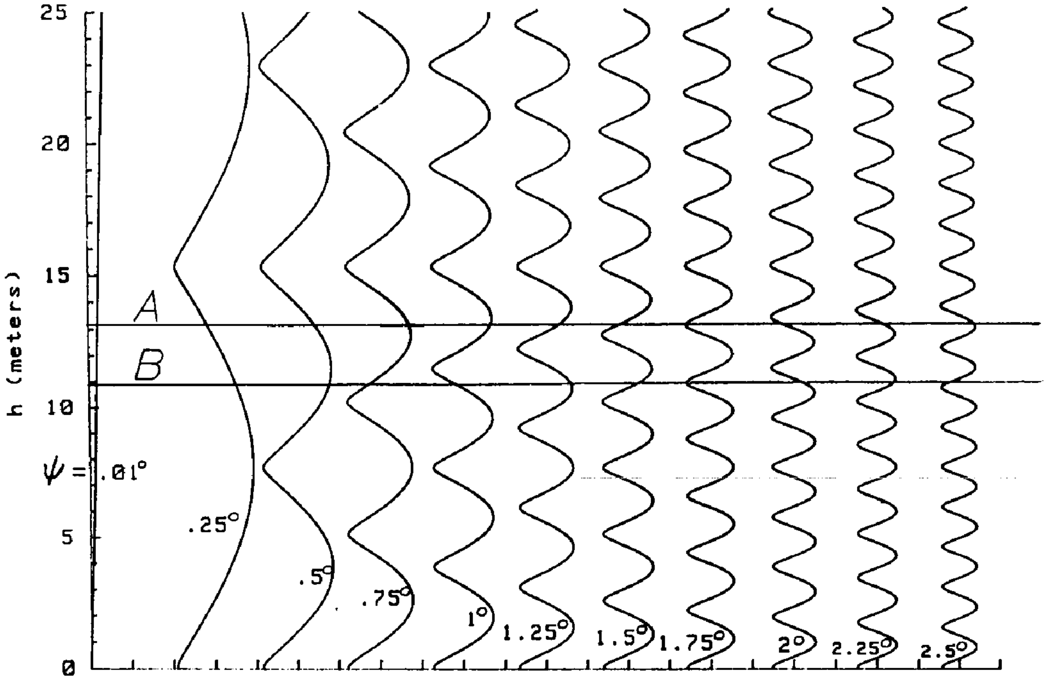

Figure 5. RECEIVED SIGNAL AS A FUNCTION OF h FOR VERTICAL POLARIZATION

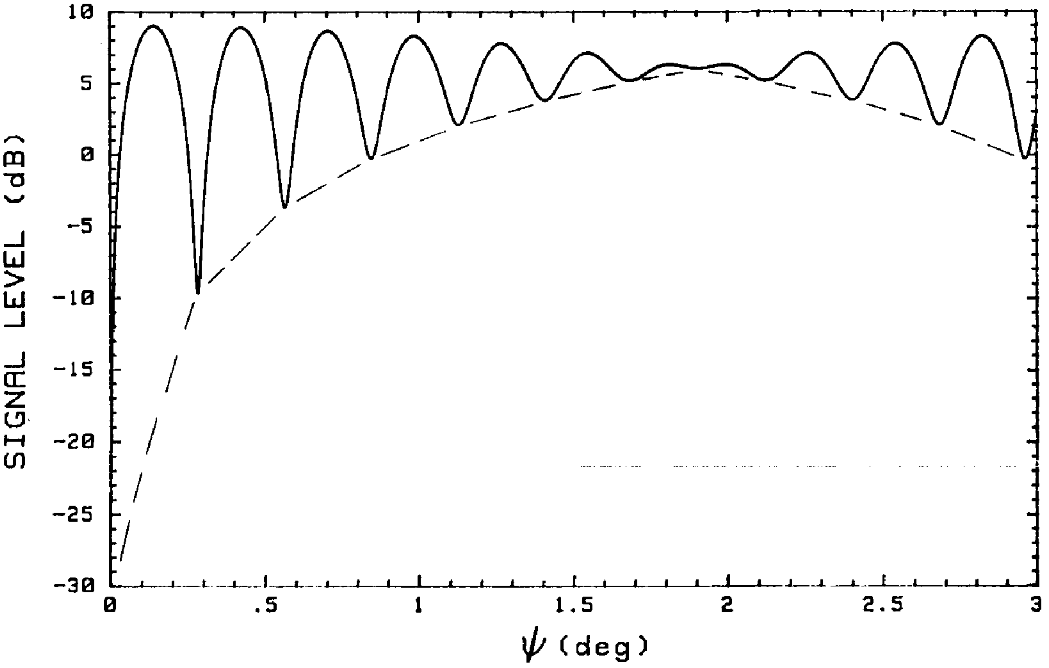

Figure 6. TOTAL RECEIVED POWER FOR TWO ANTENNAS SEPARATED BY 1 METER

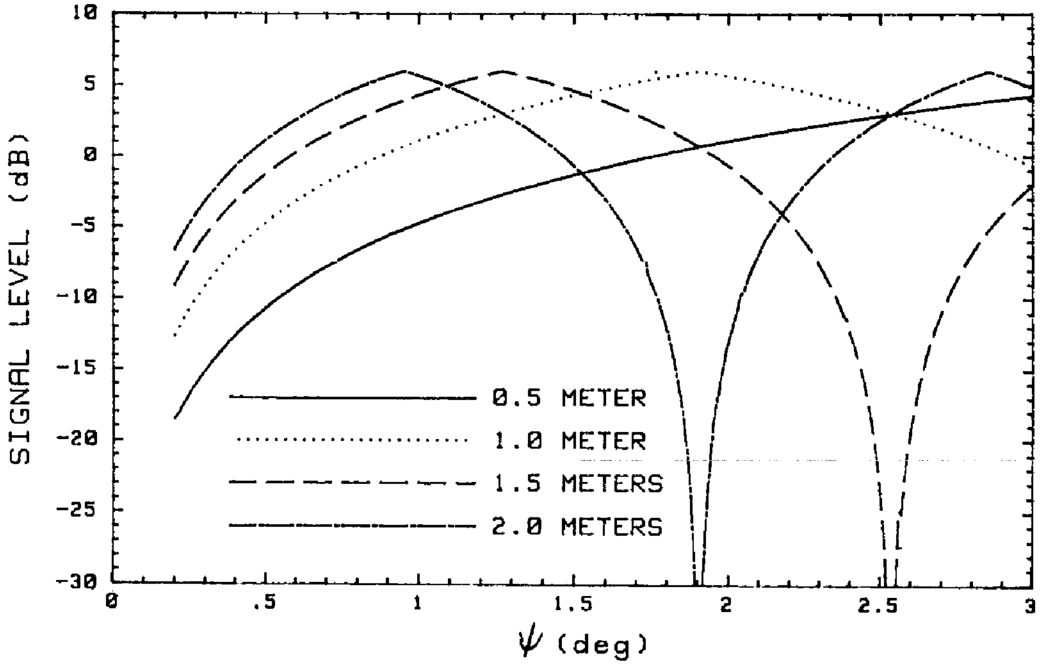

Figure 7. ENVELOPES OF TOTAL RECEIVED POWER FOR TWO SEPARATED ANTENNAS

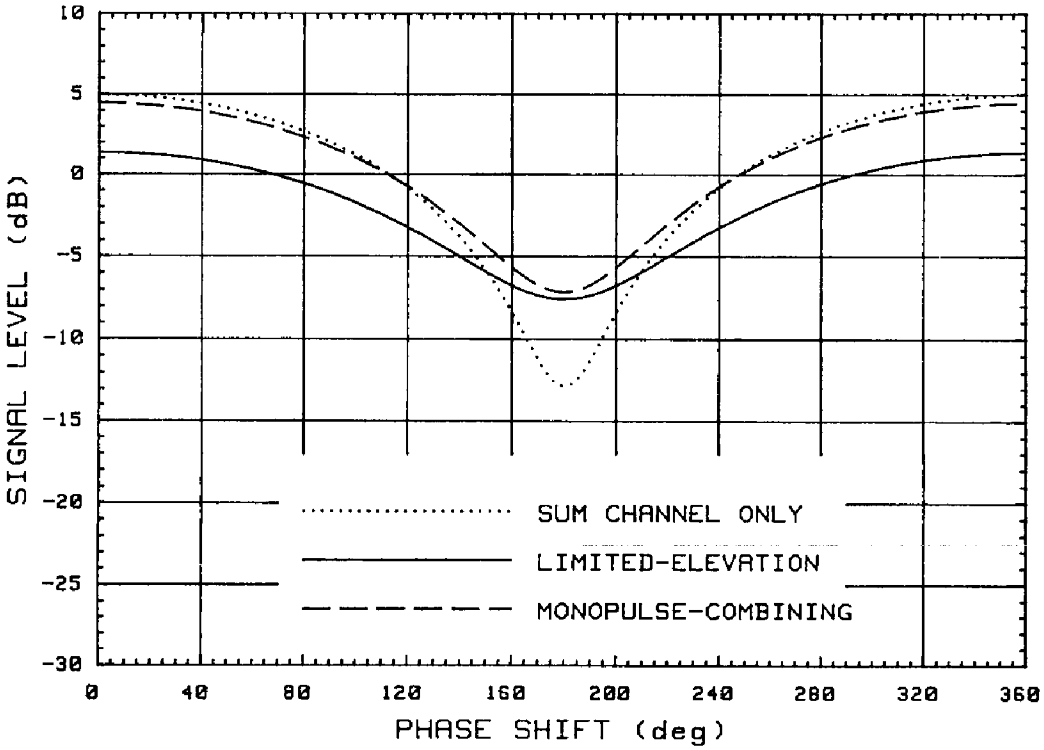

Figure 8. SIGNAL LEVEL VS PHASE SHIFT USING ANGLE DIVERSITY

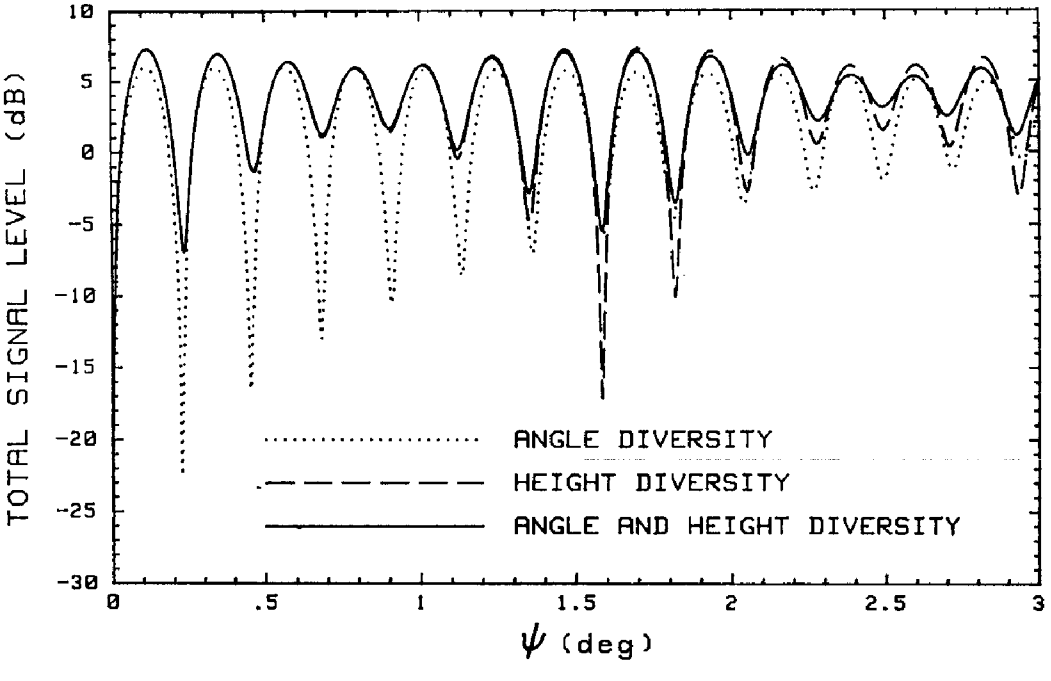

Figure 9. TOTAL RECEIVED POWER VS GRAZING ANGLE FOR ANGLE & HEIGHT DIVERSITY

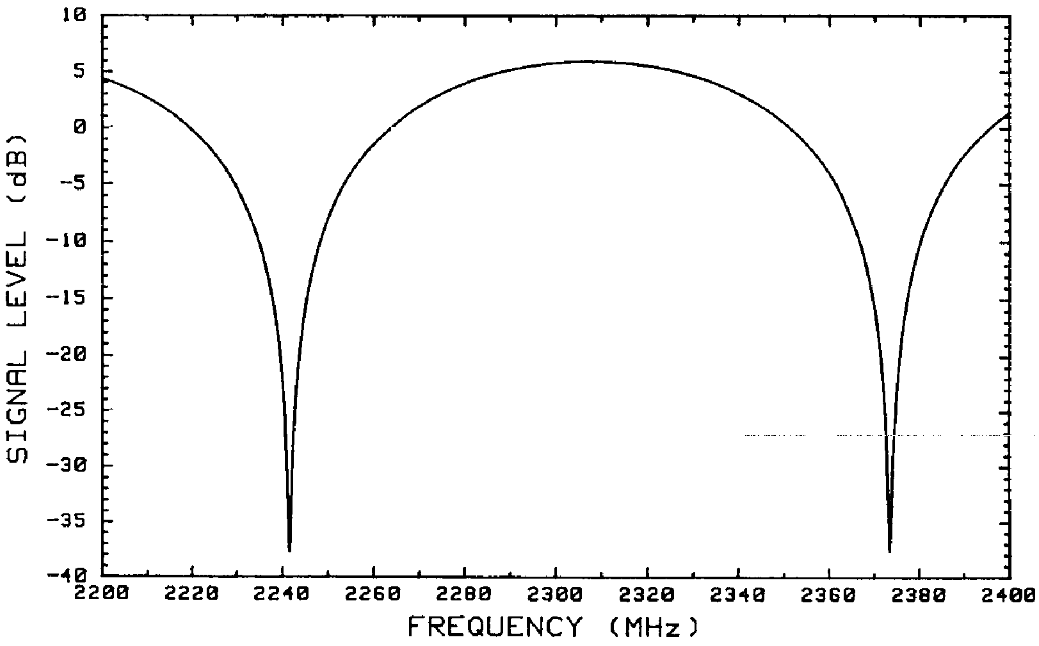

Figure 10. SIGNAL LEVEL VS FREQUENCY FOR A SINGLE ANTENNA