THE USE OF DIVERSITY TECHNIQUES TO IMPROVE TRACKING & RECEPTION OF TELEMETRY FROM INSTRUMENTED AIRBORNE VEHICLES

ARTHUR SULLIVAN
ARTHUR SULLIVAN & ASSOCIATES
CHATSWORTH, CALIFORNIA 91311

ABSTRACT

Tracking performance and data reception can be considerably improved by the use of one or more types of diversity in the receiving system.

Various schemes of optimizing signal strength and quality are currently in use. These include polarization, frequency, space, and time diversity. The question of why, when and what kind of system to be used baffles many of us who are required to make mission-dependent decisions. This paper discusses the nature and magnitude of improvement for the various types of diversity. It also discusses which systems should be used for various mission requirements. Methods of combining the diverse signals are adequately discussed in the referenced literature.

INTRODUCTION

Defining the requirements for a system to track airborne vehicles necessitates consideration of the gain of both the receiving antenna and the transmitting antenna. The definition of antenna gain uses, as a reference, an isotropic antenna. Life would be so much simpler if only someone could build an isotropic antenna! In the real world it is not possible to build such a device let alone achieve isotropic coverage on a vehicle.

Most tracking applications require the reception of a signal from a vehicle at all aspect angles of the vehicle. The majority are concerned with tracking either aircraft or missiles.

On an aircraft, the transmitting antennas are usually blade antennas or stub antennas which are linearly polarized. Experience has proven that two antennas are preferable for instrumenting aircraft for tracking. This usually yields large areas of constant signal level at about the isotropic gain level. However, when the aircraft attitude is such that both antennas are visible by the receiving system, large pattern interference nulls are induced. These nulls vary in signal level but can be as deep as 20 dB below isotropic, causing serious fading with attendant data loss or complete loss of track.

The optimum antenna solution for missiles is usually what is called a wrap-around antenna which is a stripline array consisting of many antenna elements. Since many elements are used, regardless of the polarization of each element, the antenna pattern at various angles will be very polarization sensitive. The pattern from a wrap-around antenna has many deep nulls. Fortunately, the position of the nulls and peaks are nearly reversed for orthogonal polarizations. Without diversity, the fading problem while tracking missiles is more severe than while tracking aircraft.

There are four basic types of diversity in use today. These are:

- Polarization Diversity
- Frequency Diversity
- Space Diversity
- Time Diversity

Diversity techniques involve either the combining or selection of two or more receive signals. Time diversity, by its very nature, can only use the selection process, i.e., the two signals are time shared. The methods of combining or selecting signals is well documented in the literature (1), (2), (3), (4). These techniques will not be discussed in this paper. The object of this paper is to discuss the improvements obtainable in the signal quality received from a tracked vehicle for various types of diversity and various mission requirements. Some conclusions are obtained for the choice of the various types of diversity and benefits obtainable for particular mission requirements.

Before considering the various types of diversity, one should consider all the solutions available to solve a particular problem at hand and consider the cost of the various solutions. As an example, assume that the link power budget indicates an additional 3 dB is required to satisfy a particular mission. The requirement can be satisfied by doubling the transmitted power or increasing the antenna size by 41 percent. Either solution yields the required 3 dB. Unfortunately, it is not always that simple. Often it is not practical to increase the power due to physical limitations, heat dissipation or possible interference with other missions.

The choice of the diversity system to use is also dependent upon many factors. It would behoove the system engineer to determine the best solution for the dollar, or to try to evaluate the cost per dB of the various solutions available.

SIMPLE PROBLEMS - SIMPLE SOLUTIONS

If the only tracking problem is one of a varying linear polarization, the simplest, most cost-effective solution is to use a circularly- polarized tracking antenna. However, the 3 dB polarization loss, inherent in circularly-polarized antennas receiving linearly-polarized signals, must be considered. If the 3 dB reduction of signal strength cannot be tolerated it usually can be compensated for by an increase in antenna size or transmitted power or a combination of the two. This approach is far less expensive than implementing polarization diversity, which would require an additional receiver and a diversity combiner. If the tracking problems are more complex such as deep nulls in the received signal caused by antenna pattern interference, multipath, etc., the best solution may found among the diversity techniques.

POLARIZATION DIVERSITY

The maximum improvement obtainable by polarization diversity is commonly experienced in tracking missiles with wrap-around antennas. The major reason for this is that the nulls and peaks are usually interchanged for orthogonal polarizations. While this is not always true, it is true a good percentage of the time. Berns (5) provides a complete discussion of the problems in tracking missiles with wrap-around antennas and the improvements obtainable by the use of polarization diversity. Of all the signal fading problems encountered while tracking wrap-around antennas on missiles, the largest improvements are realized using polarization diversity.

In the Berns paper, a statistical analysis is used to describe the realizable improvements. This, indeed, is the best figure of merit to be used for the <u>missile tracking</u> problem. While polarization diversity affords a maximum improvement of slightly less than 3 dB for an incoming signal of varying polarization orientation (as, for example, in the case of a maneuvering aircraft) due to the elimination of the polarization mismatch, improvements provided by polarization diversity in the reception of signals from missiles are dramatic -- of the order of 10 dB or more -- from reduction of the effects of the deep nulls that exist for any single polarization because of the missile’s wrap-around antenna.

One misconception in tracking both aircraft and missiles is that polarization diversity can considerably reduce multipath nulls since the two apparent sources of signal are not correlated. While this is true at higher elevation angles, the majority of aircraft and missile tracking requirements call for extremely low angle tracking. For angles below the Brewster angle, the reflection coefficient is nearly identical for all polarizations and, therefore, the two sources of signal are indeed correlated. Polarization diversity cannot be used for solving the multipath fading problem. For aircraft tracking, the deep antenna interference nulls cannot be significantly reduced by polarization diversity. This condition will be addressed during the discussion of frequency diversity, which is a more suitable solution.

FREQUENCY DIVERSITY

Frequency diversity is used most often and most effectively for tracking aircraft equipped with two antennas, usually top and bottom. Severe interference nulls exist when both antennas are driven by the same transmitter and both are visible to the tracking antenna. These nulls range from 10 to 20 dB deep. To illustrate the problem, Figure 1 presents the analytical radiation patterns of two blade antennas mounted on the top and bottom of an aircraft. Blade antennas are in common use, not only for aerodynamic considerations, but because they yield a horizontal component which tends to fill in the null that would be present directly above the antenna. Harney (6) achieved about the same results by using stub antennas at a 45º angle. One can see, by Figure 1, that the upper hemisphere is very adequately covered by the upper antenna and the lower hemisphere is very adequately covered by the bottom antenna. If, however, the antennas are at the same frequency, an interference pattern, which is shown in Figure 2, results. Although the selection of antenna locations on the airframe is usually done empirically, Kim and Burnside (7) have developed a numerical solution for predicting the radiation patterns of antennas mounted on curved surfaces. This methodology provides an accurate and efficient means of determining the optimum locations on aircraft.

Using frequency diversity, the antennas operate at two different frequencies and interference nulls are nonexistent. This again, shows that different tracking applications have different solutions. With the missile, where the antenna is an array of many elements, it would not be practical to have a matching number of transmitters. While polarization diversity was clearly the choice for tracking missiles with wrap-around antennas, frequency diversity is the preference for tracking aircraft where omnidirectional coverage is required.

There is another possibility for aircraft tracking with two antennas on the aircraft, and that is the use of time diversity. It is only practical when there is an uplink involved. Time diversity will be discussed later.

Harney discusses, in detail, the problems and improvements associated with the use of frequency diversity for aircraft tracking where omnidirectional coverage is required. He tried a form of time-diversity for his uplink, but abandoned it in favor of a form of space-diversity, using separate airborne receivers for each of the top and bottom-mounted stub antennas, together with AGC-weighted diversity combining. His downlink uses frequency- and polarization-diversity with a separate transmitter feeding each of the two airborne antennas. The ground antenna receives one frequency on one polarization and the other frequency on the orthogonal polarization; each signal is fed to its own receiver, and then to a diversity combiner. These two approaches provide very satisfactory coverage -- both for the uplink and for the downlink.

For the case of tracking maneuvering aircraft, it is clear that frequency diversity is indeed the best solution, offering an advantage in the areas of the nulls of about 15 dB.

At this point, it would appear that achieving optimum results in aircraft tracking necessitates the use of both polarization diversity and frequency diversity. That may be true, but after we look at space diversity we may conclude that a combination of all three would yield the optimum performance. However, budgets being what they are, we must make the most practical selection of options to satisfy the majority of our missions. The practical selection would favor the use of frequency diversity, to eliminate the interference nulls, in combination with a circularly polarized receiving antenna to minimize polarization variations. The deciding factors, as always, are the mission requirements and available funds.

SPACE DIVERSITY

Two or more receiving antennas, located in different areas are required to provide space diversity. Since tracking systems are expensive, the use of space diversity is usually confined to those situations where the target vehicle cannot be continually visible to a single receiving antenna.

There is a lesser known but highly effective use for space diversity. A space diversity system can be configured to reduce the effects of multipath nulls by a substantial amount. Such a system is particularly well suited for low angle tracking over highly reflective terrains, such as water or smooth desert areas. There are missions where multipath nulls of 10 to 20 dB are encountered and cannot be tolerated. To reduce these nulls by increasing the power or increasing the antenna size is not practical, especially from a cost consideration.

To illustrate the multipath problem, a case will be considered of tracking an aircraft over a relatively calm ocean. The parameters chosen were an 8-foot tracking antenna with a reception range, neglecting multipath, of 100 miles. A frequency of 1.435 GHz was used. (Variations in the frequency have very minor effects on the multipath problem in the L and S-band ranges). Polarizations of the tracked antenna and of the reception antenna were both vertical. (At the low angles, the multipath problem is independent of polarization.) A dielectric constant of 70 was chosen for the reflecting terrain, with a conductivity of 5.5, and a surface roughness factor of 1 foot was used. A plot of the range of the receiving antenna located at a height of 25-feet was made. Plots at other heights were then made to determine the alternate antenna height needed to interchange nulls and peaks. The optimum alternate height turned out to be 35-feet. The superimposed plots of the 25 and 35-foot high receiving antenna maximum ranges are shown in Figure 3. Figure 4 shows the resulting maximum range, using space diversity.

There is considerable null pattern improvement from using space diversity. Using the example above, the maximum range for the first null, which is at the horizon, is improved from approximately 45 to 70 miles, or an improvement of 4 dB. The maximum range of the second null is improved from about 25 to 125 miles, or an improvement of 14 dB. The maximum range of the third null is improved from approximately 50 to 155 miles, or an improvement of 9 dB. The maximum range of the fourth null is improved from approximately 75 to 105 miles, or a 3 dB improvement. The range of the fifth null is extended from approximately 85 or 120 miles, or an improvement of 3 dB. For the example chosen, the second null which was at an angle of a little less than 1 degree was the worst case. While the improvement of this null was actually 14 dB and extended the range to 125 miles, the maximum required range for the mission is only 100 miles, resulting in a 12 dB improvement for the mission.

The improvements shown by this example, are relatively frequency independent over the L-band. Figure 5 is the superposition of 1435 MHZ and 1540 MHZ patterns of the antenna and shows there is little change in the position of the nulls.

A detailed study of multipath fading is presented by Geen (9). A multipath computer model was developed and analytic predictions were verified by controlled field tests.

TIME DIVERSITY

For tracking airborne vehicles, time diversity is only practical when there is an uplink to the vehicle, in addition to downlink reception. When this is the case, time diversity can be a very low cost and effective way for signal improvement. The outputs of the receivers on the aircraft are continuously sampled to determine which antenna produces the stronger signal. The transmitter is switched to this antenna, when the differential between the two exceeds a predetermined value. Since, at any given time, only one antenna is radiating no interference nulls are formed.

CONCLUSION

When specifying the requirements for a mission which involves tracking and receiving data from telemetry instrumented airborne vehicles, there are usually options in the parameters involved (except space loss). Normally, the designing engineers have control over the amount of transmitted power, the loss between the transmitter and the transmitting antenna, the type of transmitting antenna, and polarization. They also specify the type of receiving antenna and polarization, losses between the receiving antenna and preamplifier, gain and noise figure of the preamplifier, losses between the preamplifier and the receiver, and the receiver itself. There can be many trade-offs involved such as transmitted power, type and size of antennas, preamplifier noise figure, etc. These trade-offs are usually the result of cost considerations.

If the vehicle being tracked could be instrumented to have a constant effective isotropic radiated power (EIRP) and a constant polarization throughout the mission, then the receiving antenna would utilize the identical polarization and there would be no advantage to any type of diversity. Since this is never the case, and since most operations require tracking through all aspect angles of the tracked vehicle, the systems engineers must consider some form of diversity reception to improve system performance to the maximum extent possible within the constraints of available funding.

Berns (5), has shown the benefits of polarization diversity for missile tracking. There is no question that for missile tracking polarization diversity should always be used. There will still be trade-offs on transmitted power, antenna gain, preamplifier noise figure, etc., but unquestionably, the benefits to be obtained from polarization diversity offer the best buy for the dollar.

For aircraft tracking, the received signal is nearly always linearly polarized. The orientation of the linear polarization however, is varying as a function of the aircraft maneuvers. The problem of the varying linear polarization can be solved using either a circularly polarized tracking antenna or polarization diversity. Polarization diversity affords a gain increase of a little less than 3 dB. The decision to use polarization diversity is therefore purely one of cost. Usually, if a 3 dB improvement is required, it can be had by other means for lower cost. This is not always the case and should be evaluated for every requirement.

For tracking aircraft where omnidirectional telemetry coverage of the vehicle is required, Harney (6), has shown that frequency diversity is the obvious choice for this requirement. Again, the magnitude of the interference nulls for this situation is such that frequency diversity yields the lowest possible cost to obtain the required performance. The selection of antennas and their location on the aircraft is extremely important. The proper location of the antennas can be determined by modeling techniques or by analysis. Kim and Burnside (7) have developed analyses applicable to solving this problem.

For most tracking operations, multipath is not a severe problem. When the terrain is rough, particularly with vegetation, the multipath will be negligible. Smooth terrain, however, does present a problem. About the worst case encountered is that of tracking over smooth water and, next to that, tracking over a smooth desert. Since the use of space diversity requires at least two completely separate antennas, it is very seldom used because of cost. There are times, however, when space diversity should be used and is the most cost-effective means of satisfying mission requirements. Again, this can only be determined by the particular mission requirements. As an example, doubling the size of the tracking antenna will achieve a 6 dB improvement. For small antennas doubling the size is less expensive than purchasing two antennas. When two antennas are required, they need to only be about 71% of the diameter of the one antenna system for the same gain (equal area). The two antennas can be mounted on the same pedestal. The pedestal required would be larger than the single antenna approach. The choice of a single pedestal or two pedestals again is determined by cost. Different mission requirements will have different solutions.

At about an 8-foot diameter, the cost of doubling the size becomes comparable with purchasing two separate antennas. The lowest cost approach changes from increasing antenna size to using two separate antennas. It is relatively easy to analyze the effects of multipath for a particular mission requirement; see Chandler (8) or Geen (9). Anytime the reflecting terrain is smooth, this analysis should definitely be performed to determine the magnitude of the multipath problem. Usually polarization diversity is of no help because the tracking requirements are for angles lower than the Brewster angle. For example, at

L-band the lowest possible Brewster angle is 5.8 degrees. Most operations require tracking below this angle. When severe multipath nulls exist, space diversity should certainly be considered and, usually, will afford the optimum solution or the best buy for the dollar. This is especially true if the link budget indicates the need for a large antenna in the absence of multipath.

The decision of when to use time diversity is usually quite simple. If the operation includes an uplink it is cost effective to use time diversity to avoid the problems of interference nulls. Since most tracking requirements do not have an uplink, time diversity is very seldom used.

ACKNOWLEDGMENTS

The author wishes to express his thanks to the following: Mo Kaloi of Pacific Missile Test Center, Pt. Mugu, CA, for his many valuable contributions; D. Kruszenski and R. A. Potter, both of Electro-Magnetic Processes, Inc., Chatsworth, CA, for editing and for many valuable suggestions; and C. W. Chandler, also of Electro-Magnetic Processes, Inc., for helpful advice and for plotting the figures.

REFERENCES

1) Brennan, D.G., “Linear Diversity Combining Techniques,” Proceedings International Telemetering Conference, June 1959, PP 105-1101.

2) Streich, R.G., et. al., “Dynamic Requirements for Diversity Combiners,” Proceedings International Telemetering Conference, October 1972, PP 635-642.

3) Hill, E.R., “AM/AGC Weighted Pre-detection Diversity Combiner,” Proceedings International Telemetering Conference, October 1977, PP 215-233.

4) Busch, Charles E., “A Symmetric Telemetry Diversity Combiner System,” Proceedings International Telemetering Conference, October 1988, PP 177-182.

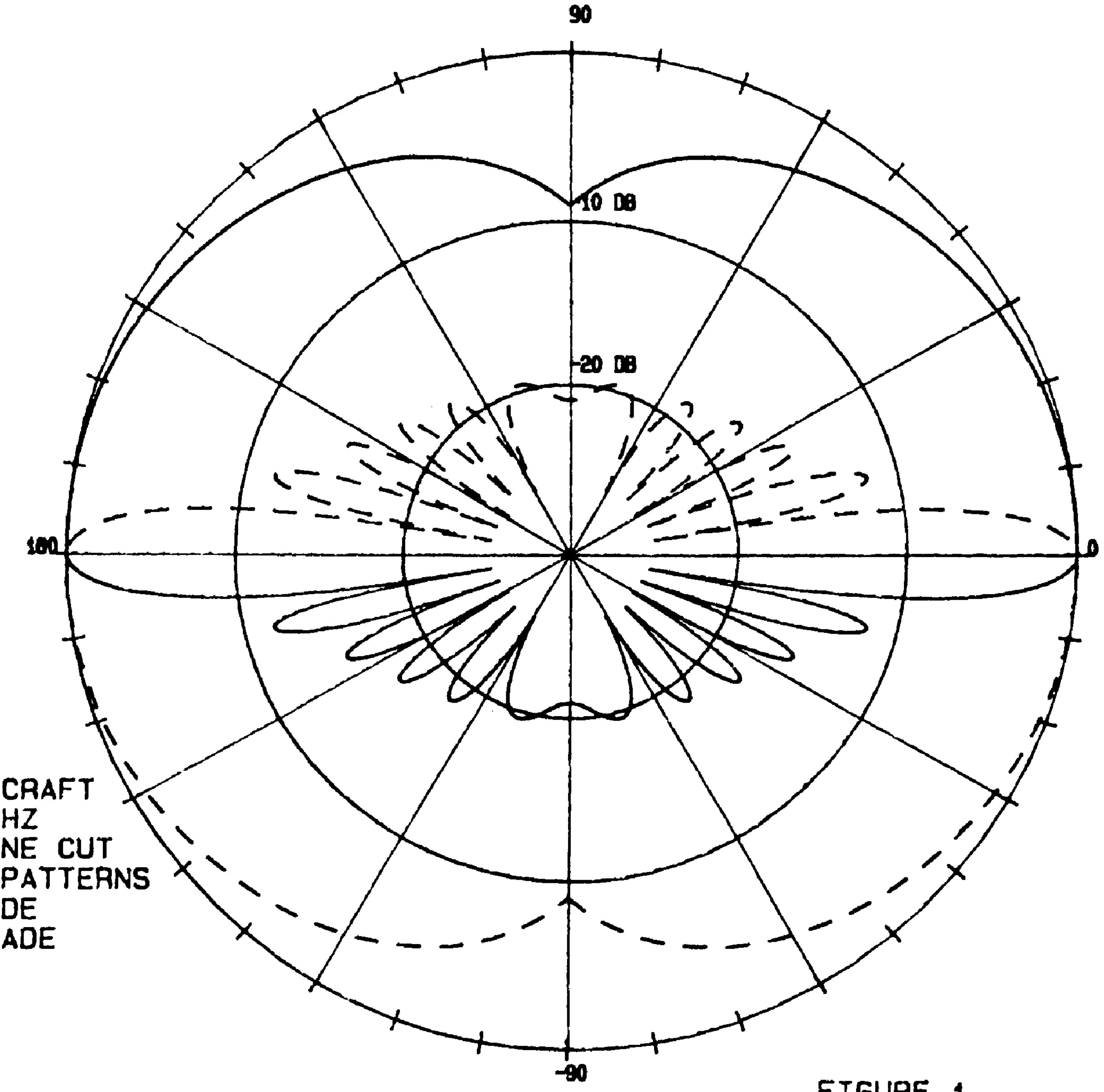
5) Berns, K.L., “Benefits of Polarization Diversity Reception,” Proceedings International Telemetering Conference, October 1984, PP 627-642.

6) Harney, Paul F., “Diversity Techniques for Omnidirectional Telemetry Coverage of the HiMat Research Vehicle,” Proceedings International Telemetering Conference, 1981, PG. 649.

7) Kim, Jacob J., Burnside, Walter D., “Simulation and Analysis of Antennas Radiating in a Complex Environment,” IEEE Transactions on Antennas and Propagation, April 1986, Vol. AP34, No. 4.

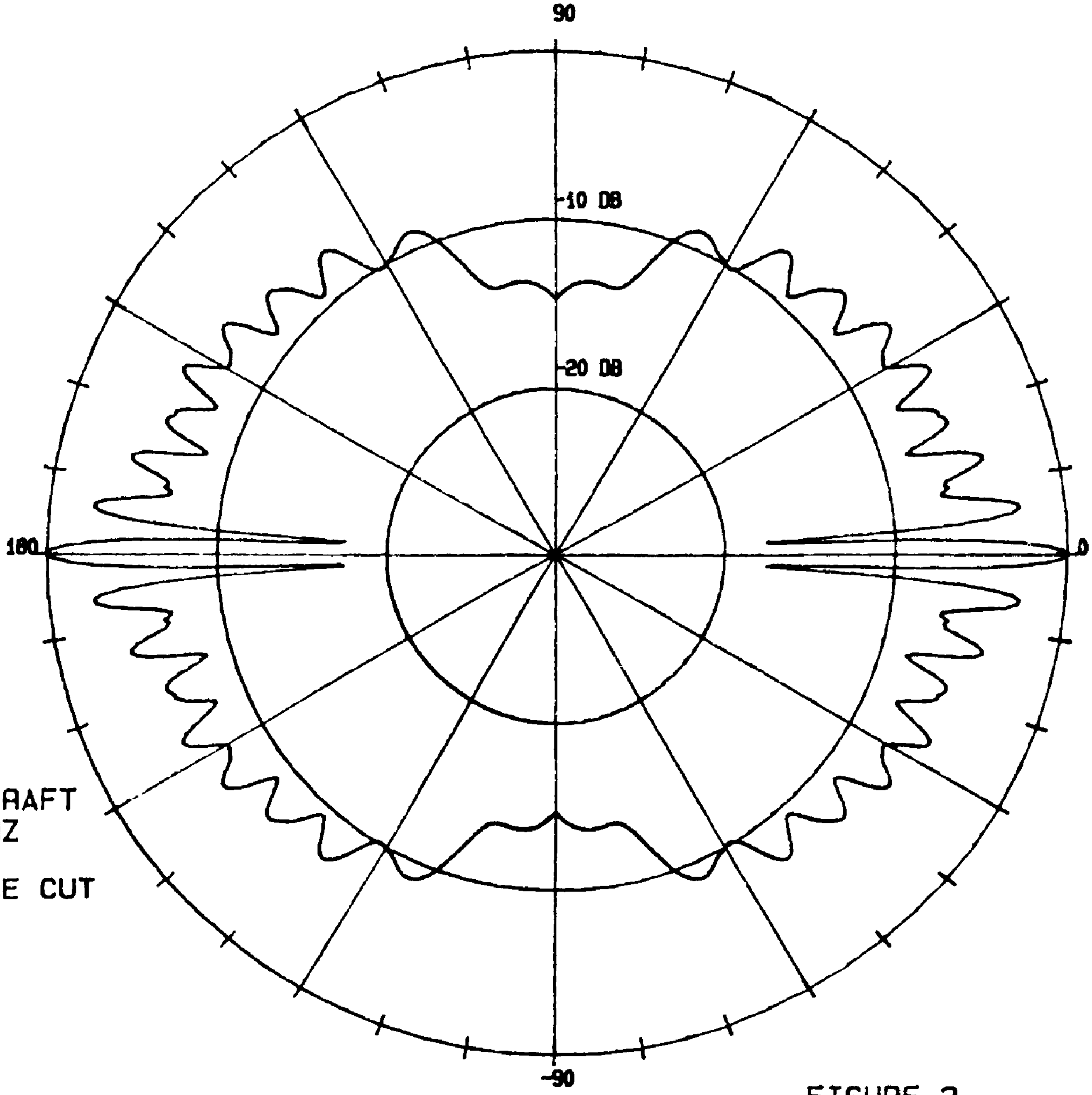
8) Chandler, Charles W., “Terrain Reflection Effects on Data Reception from Airborne Vehicles,” Proceedings International Telemetering Conference, October 1980.

9) Geen, David, “A space-combining approach to the multipath problem,” Report NSWC TR89-15, Naval Surface Warfare Center, Dahlgren, Virginia, April 1989.



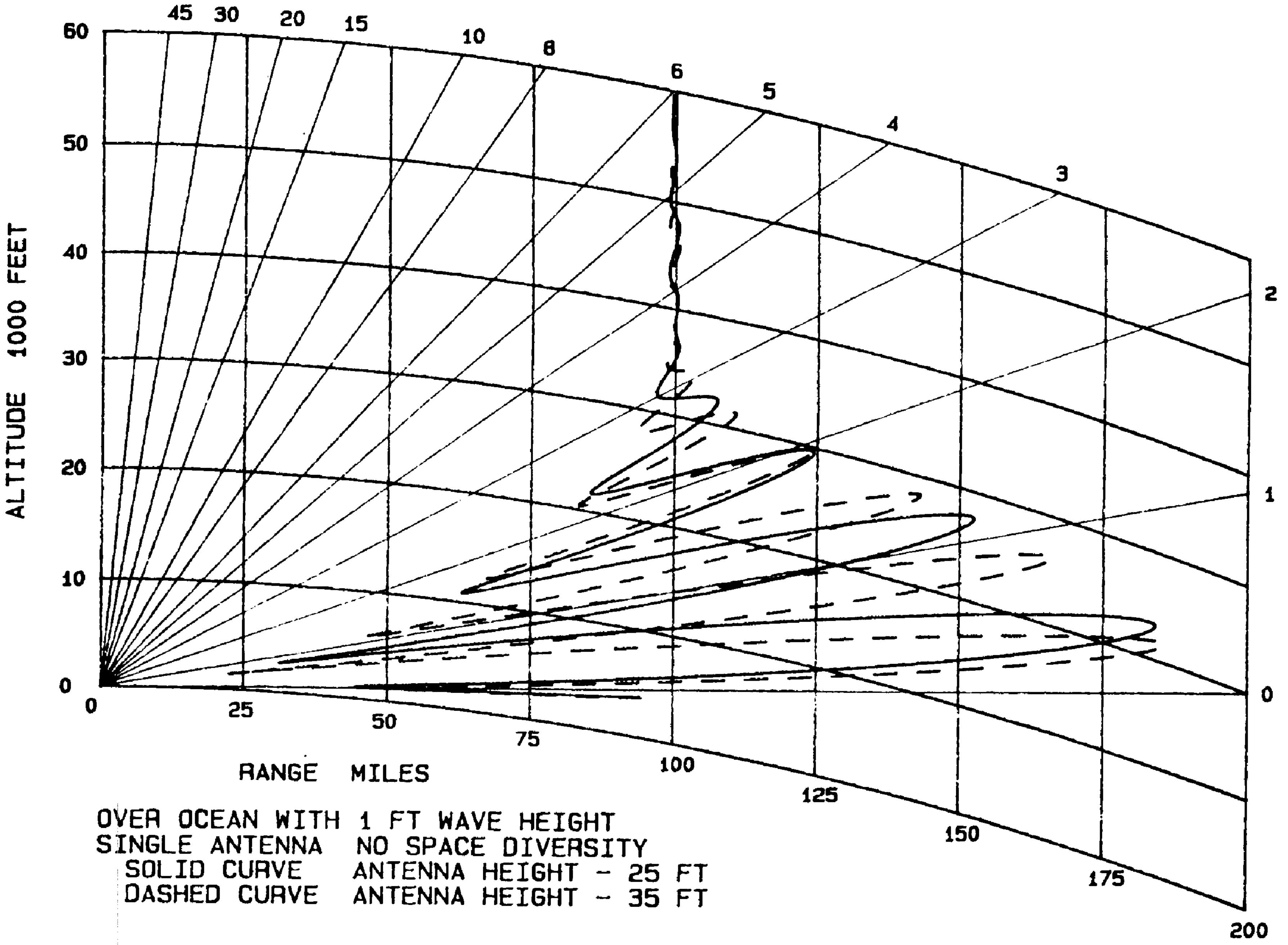
TWO BLADES ON AIRCRAFT
FREQUENCY 1435 MHZ
PITCH OR ROLL PLANE CUT
INDIVIDUAL BLADE PATTERNS
SOLID - UPPER BLADE
DASHED - LOWER BLADE

FIGURE 1



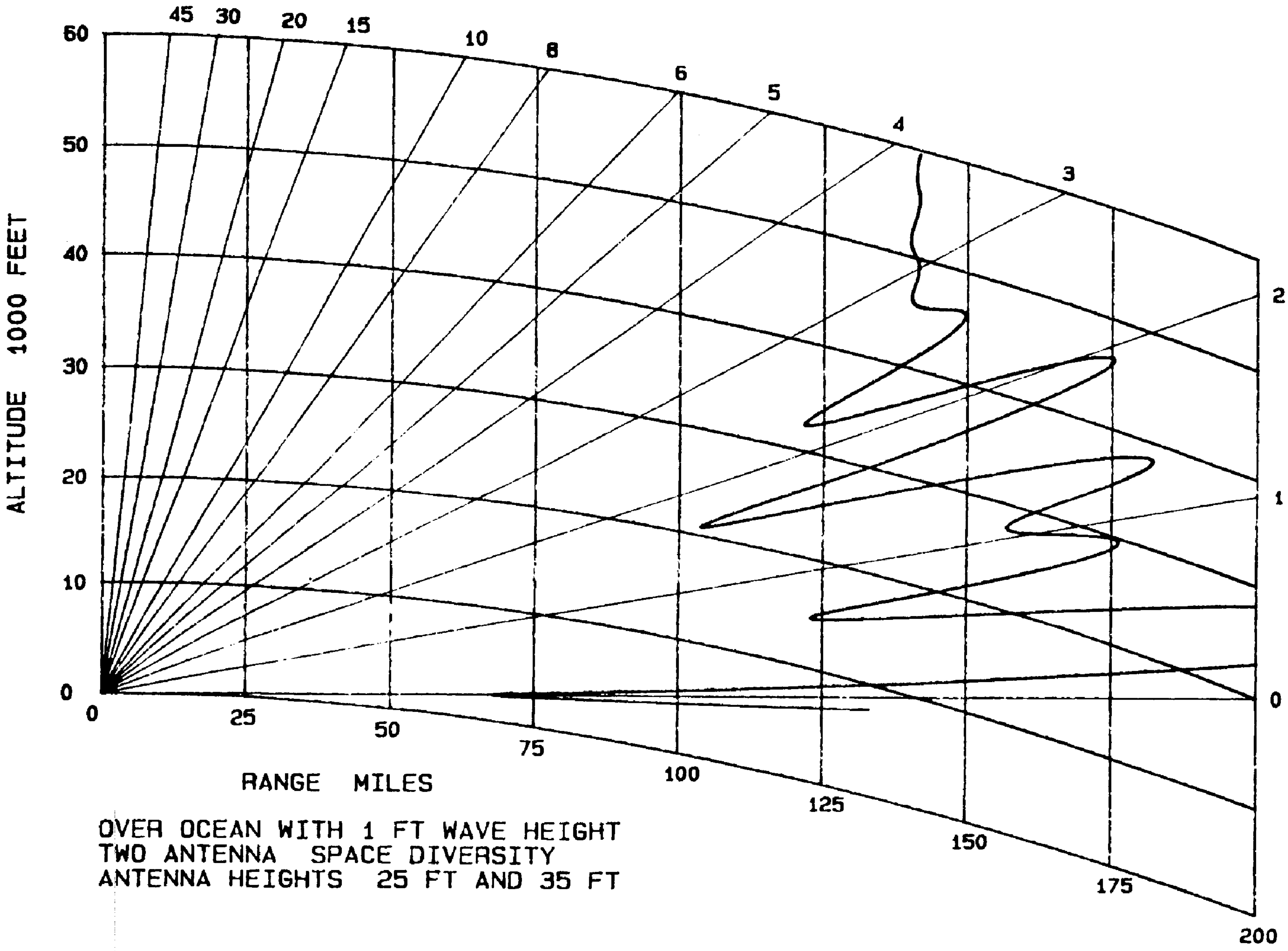
TWO BLADES ON AIRCRAFT
FREQUENCY 1435 MHZ
ARRAY PATTERN
PITCH OR ROLL PLANE CUT

FIGURE 2



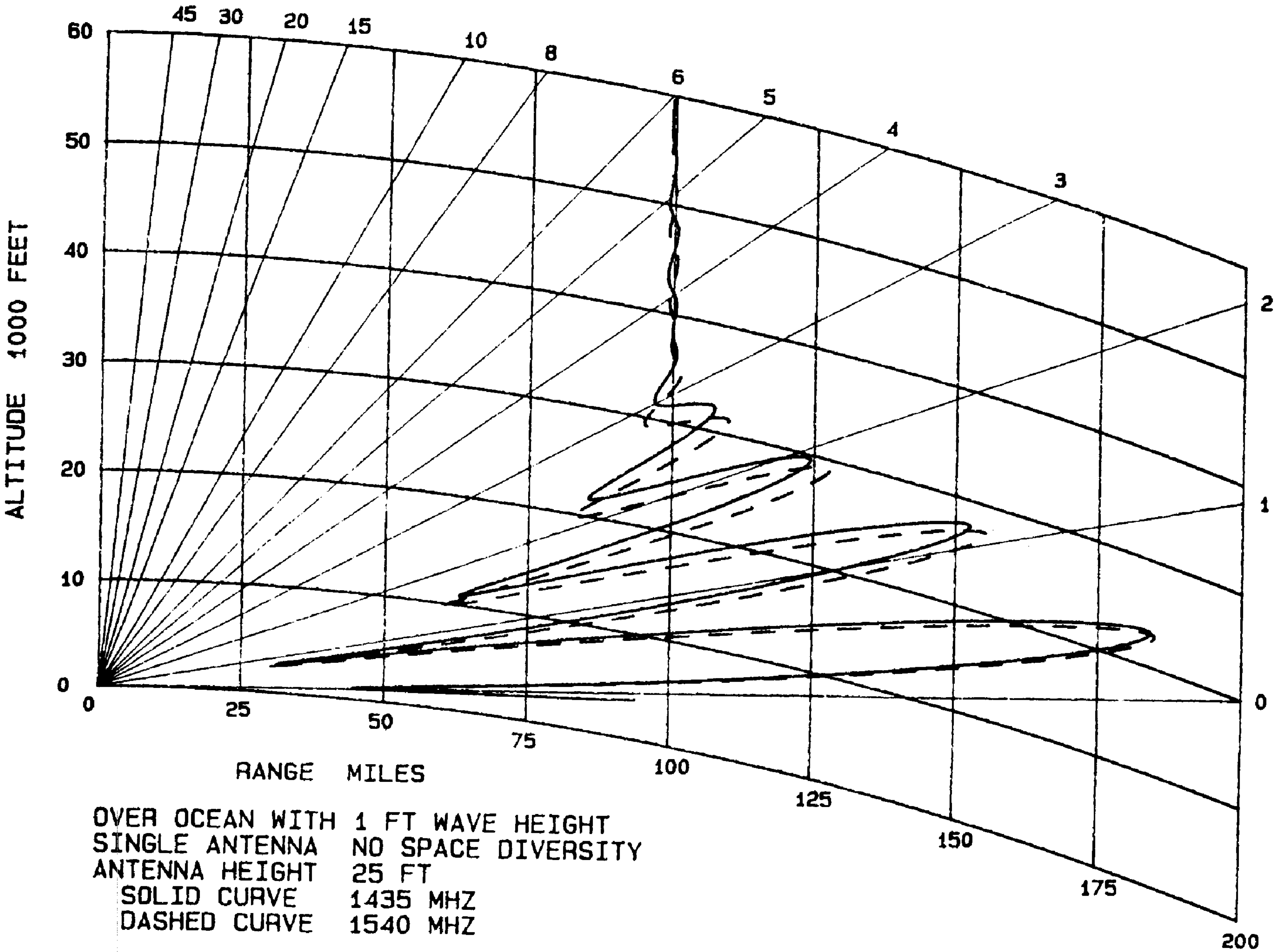
OVER OCEAN WITH 1 FT WAVE HEIGHT
SINGLE ANTENNA NO SPACE DIVERSITY
SOLID CURVE ANTENNA HEIGHT - 25 FT
DASHED CURVE ANTENNA HEIGHT - 35 FT

FIGURE 3



OVER OCEAN WITH 1 FT WAVE HEIGHT
TWO ANTENNA SPACE DIVERSITY
ANTENNA HEIGHTS 25 FT AND 35 FT

FIGURE 4



OVER OCEAN WITH 1 FT WAVE HEIGHT
SINGLE ANTENNA NO SPACE DIVERSITY
ANTENNA HEIGHT 25 FT
SOLID CURVE 1435 MHZ
DASHED CURVE 1540 MHZ

FIGURE 5