# Telemetry Antenna Patterns for Single and Multi-Element Arrays

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June 7, 1990

## Abstract

The use of multiple antennas (or multiport) antennas for vehicular telemetry causes patterns to result which are unknown and not well understood by the telemetry designer. When the antenna ports are separated by distances of more than a half wavelength, the resulting patterns are rarely what was intended. The antenna plotting program, an extension of a earlier University of Utah antenna plotting routine, allows rapid creation of patterns for up to 30 (or more) antennas of like polarization displaced from each other in all three axes. Single-port antennas are modeled as compound antennas to produce the observed pattern, and combinations of these single-port antennas are then plotted. Case studies are shown for an aircraft and a missile body.

## 1 Introduction

Missiles and aircraft[1] have antennas added for the purpose of telemetry, range safety, and transponders not intended for inclusion in the tactical version of the same equipment. Typical antennas are the blade and flush types made as microstrip, stripline, or the larger cavity-backed radiators. Consequently, antennas are relegated to less-than-perfect locations, and required to be small and of inconsequential wind resistance. It is often desired to have near-omnidirectional coverage from such antennas,[2] so more than one antenna, or a multipart antenna is used.

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* The computer program `anplot90` was written and tested by the author at the University of Utah Department of Electrical Engineering in December, 1989.

[1] Referred to collectively as "vehicles", for lack of a more descriptive name. Basically any source without a fixed location with respect to the ground station is considered to be a vehicle.

[2] Whether omnidirectional coverage is the best choice is another matter, which will be discussed later in this paper.

Unfortunately, the individual antenna elements produce patterns that are seldom well characterized by their manufacturers. These patterns also are affected by the size and orientation of the vehicle on which they are mounted, and the testing of even a single antenna on a large vehicle is a complex undertaking. If more than one antenna is used, especially if the antennas are more than $\lambda/2$ apart, the resulting patterns have many lobes and nulls. As a result of limited understanding of the process involved, the intended pattern is rarely produced, and the actual pattern rarely known.

Equally unfortunately, no IRIG documents address telemetry antennas directly.[3] Since manufacturer-supplied data is not generally very lucid, the perception that either antenna patterns are trivial or everybody knows the factors involved is strong. This paper is the first in a series of literature on the subject to fill the gaps and cite examples of what, and what not, to do.

## 2 Notation and Coördinate System

For any of this to make sense, a notation for things like "up" and "down" must be agreed upon. This is less simple than it seems when a vehicle moving in three-dimensional space is being considered. Most standard measurement techniques assume that the antenna under test is moved in relation to a fixed reference antenna.

### 2.1 Vehicle

For the purposes of this paper, the vehicle is presumed to be cylindrical in shape, and travelling (unless otherwise noted) on a straight and level course along its long axis, noted as $\hat{z}$. As viewed from the tail, the $\hat{y}$-axis is to the right. The $\hat{x}$-axis is up. Note that the references for up and right are with respect to the vehicle, and not to the vehicle's position in space, which can vary. Blade antennas, when mounted on this theoretical model, are aimed in such a way that they appear as fins, with their leading edge swept backward in the $\hat{z}$-axis.

### 2.2 Antenna

Coordinates for the antenna itself are such that the antenna is a monopole or dipole array oriented along the $\hat{z}$ axis, with the $\hat{x}y$ plane perpendicular to the antenna. The angle 2 is then the angle from the $\hat{x}y$ plane to the $\hat{z}$ axis, and thus has the range ±90°. The angle in the $\hat{x}y$ plane is measured as an azimuth such that if the antenna protrudes from the earth, 2 = 0° with angles increasing clockwise. Note that the axes for the antennas and for the

[3] The existing IRIG antenna documentation deals exclusively with high-gain receiving antennas, and is concerned with testing rather than recommending characteristics. The Telemetry Group [TG] of the Range Commanders' Council [RCC] is working on some documents to fill this need.

vehicle may be different, and in general do not have their origins at the same place; also the origin and orientation of an array of antennas must be specified.

## 3 Polarization

Telemetry receiving antennas, especially of the high-gain variety, are almost universally circularly polarized.[4] Telemetry transmitting antennas, on the other hand, are generally of linear polarization, with the polarization axis in the $\vec{z}$ direction as defined above. The thinking [1] is that, although a 3 dB loss occurs because of this polarization mismatch, the vehicle can roll or tumble to any position of its own $\vec{z}$ -axis and never be cross-polarized with respect to the receiver.[5]

## 4 The Problem

It is generally desired to have omnidirectional, or at least toroidal, transmitting coverage from the vehicle. This is complicated not only by the shape of the vehicle and the size and locations of the antennas, which are generally far from optimal, but also by the shape and shielding due to nearby objects during all or part of the test.[6] The solution to these problems often involves use of multiple antennas, each of which has a radiation pattern of its own, and all of which combine to make the actual pattern, which is often nothing like what was desired or intended.[7] Since these composite patterns are seldom calculated nor measured, problems often don’t surface until the vehicle is fielded, and the designers are reluctant to change anything. Even if a pattern is calculated or measured, phase differences due to cable length tolerances may alter the pattern significantly.

The important thing to note is that field strength at any point is due to the magnitude and phase of all antennas—they do not simply add together to make the total field strength.

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[4] If a single polarization is used, it is generally RHP; if polarization diversity is used on a single antenna, LHP may also be present.

[5] This can be a quite satisfactory arrangement in many circumstances, but not when the test vehicle is a low altitude and the receiver is above it (possibly airborne), because reflections from the ground are mixed with the direct signals and multipath reception results.

[6] Examples of such shields include the launch aircraft, launch tubes, and the ground. Some of these objects remain in the same relative position throughout the vehicle’s mission, and some don’t.

[7] In particular, antennas spaced by more than half a wavelength produce pattern lobes—including nulls that might be infinitely deep.

## 5 Solution

By modeling the individual antennas, and then combining the patterns algebraically, it's possible to calculate and plot any trial combination in a matter of minutes. When a good pattern is found, it's then possible to "tweek" the characteristics slightly to determine sensitivity of the system to manufacturing tolerances.

## 6 Mathematical Basis

The power density from a dipole oriented along the Ƶ -axis as described above is given [4, eq'n. 2.80] by the expression

$$\vec{\mathcal{P}} = \frac{1}{2} \times \eta \times \left(\frac{I_m}{2\pi r_o}\right)^2 \times \left\{\frac{\cos(kh \times \cos\theta) - \cos(kh)}{\sin\theta}\right\}^2 \times \vec{r} \qquad (1)$$

where $\vec{\mathcal{P}}$ is output power, *O* is the impedance of space in the medium (normally air or vacuum, almost identical) and taken to be 120π = 377Ω, $I_m$ is the driving-point current, Ᵽ is a unit vector to make the power be directed away from the antenna in all directions, kh is the distance from the feedpoint to the ("electrical") end of the antenna, and $r_o$ is the distance between the antenna and the observation point. The dimensions of $\mathcal{P}$ are hence in watts per square meter, assuming that $r_o$ is expressed in meters. Note that there is no dependence on *N*, but there is a dependence on *2*. As a consequence, for any nonzero value of kh, no power can ever be radiated at *2* = 90°, thus a truly omnidirectional ("isotropic") antenna cannot exist.[8]

When two or more dipoles (or monopoles) of the same orientation are operated simultaneously, their combined effect at a distant receiver is not due to the slight differences in distance between the individual antennas, because even though the power density decreases with the square of the distance to the individual antennas, this small distance difference is insignificant in what we call the "far field". However, differences in the excitation currents for each antenna and differences in the electrical length kh of each antenna cause obvious differences in the values of $\mathcal{P}$ for each element in the array. These differences are such that the contributions of each antenna can be added by direct superposition. However: Differences in phase between the driving currents (if differences exist), and differences in phase caused by antenna spacings as viewed from a measurement point in the sphere defined by *2* and *N* (which must exist, since two antennas cannot be in the same space) have a significant effect on the pattern.

[8] At *2* = 0° (1) produces a value which can be shown to approach unity as a limit.

In the far field, each antenna, no matter what its size, looks like a point source, with energy radiating out of a point generally taken to be the base of the antenna.[9] To determine the power radiating in any direction, the contribution due to each antenna in power and relative transmitting phase, adjusted for space phase differences, is summed in accordance with equation (1).

## 7 The **`anplot90`** Program

The `anplot90` antenna plotting routine[6] used to generate the plots shown here is a program written in the C language updating and extending a program originally written in FORTRAN 66 by Dr. Om P. Gandhi of the University of Utah. When linked to the plotting routine `<PLOT 79>`,[10] smooth 1080-point plots of antenna patterns can be generated for any angle above or below the plane normal to the antennas' elements. Copies of the program and supporting documentation may be obtained from the author, or by anonymous file transfer from the Electrical Engineering Department of the University of Utah.

## 8 Blade Antennas

The blade antenna, while not exactly vertically polarized, can be considered as a first assumption to be a quarter-wave monopole oriented vertically to the surface of the vehicle on which it is mounted. The radiation pattern of such an antenna on an infinite ground plane is known, as shown in Figure 1. The bottom half of the trace (shown as a dotted line) is not "real", and no energy is directed below the ground plane. Since the vehicle body is not an infinite ground plane, and is not even flat,[11] the actual transmitting pattern will be a cross between the pattern of Figure 1 and the pattern of an isolated (i.e., no ground plane) dipole in space, which is a figure-eight, as shown in Figure 2. The actual shape of the vertically-polarized portion of the blade antenna's output will appear something like Figure 3, with the disparity between the upper and lower halves depending on the curvature of the vehicle. In any event, no vertically-polarized power is transmitted directly upwards, and a larger (perhaps much larger) gap exists below.

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[9] The exact point is less obvious with antennas that are not dipoles, but since it's the distance between the radiating points that matters, this is not a problem in practice.

[10] The `<PLOT 79>` system, developed jointly by the University of Utah and the Autonomous University of Mexico is in common use.

[11] Ground-plane flatness may be a fairly-accurate assumption in the Ƶ direction, but almost never in the radial direction at the short wavelengths involved.

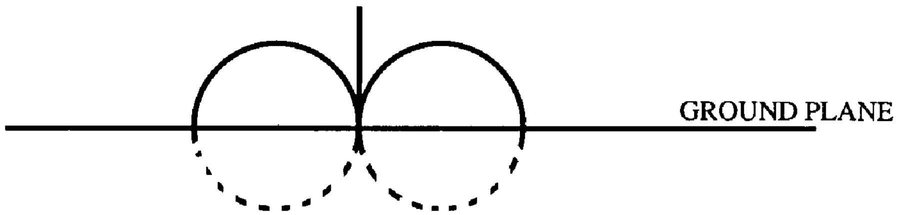


Figure 1: The radiation of pattern an antenna on an infinite ground plane

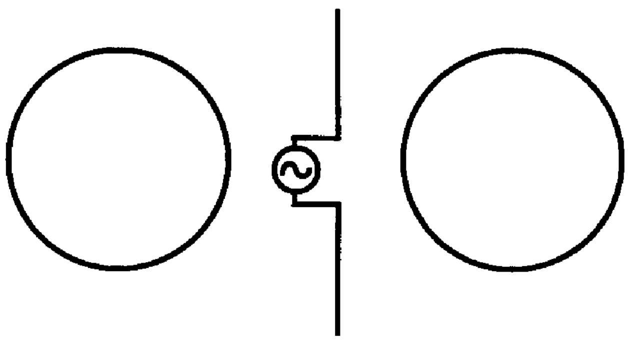

Figure 2: The pattern of an isolated dipole in space

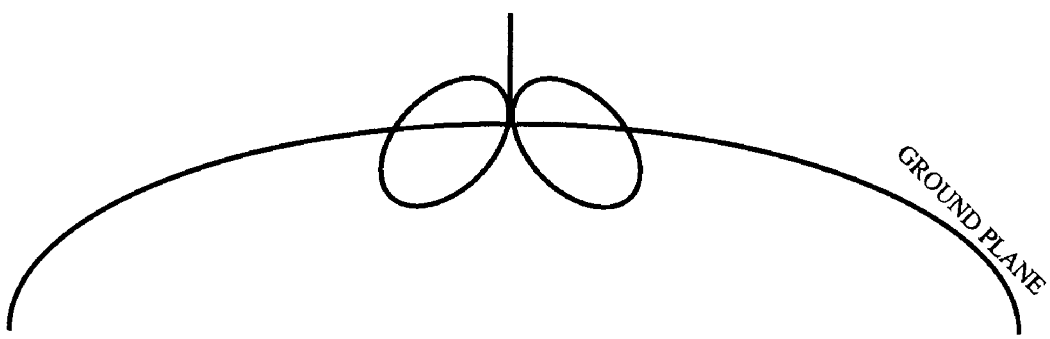


Figure 3: Blade antenna output

The horizontally-polarized output of the blade antenna, resulting from the tilt in the active element inside the blade, produces a cardioid pattern when viewed from the tail or nose of the vehicle (the vehicle's Ƶ axis). Because the tilt angle is relatively small and the vehicle essentially behaves as a reflector, the main purpose served by the horizontal component is to create a null-fill directly above the antenna. Since the tilt angle that creates the horizontal pattern is the same on all antennas in a multi-element array,[12] and since the polarization of the vertical component depends on whether that particular element is pointed up or down, the user is best advised to not count on the horizontal component being of much use.

[12] Aerodynamics generally won't permit any other orientation.

## 9 Flush Antennas

Flush antennas disturb the air stream of the vehicle less than do blades, but if the antenna type involves a cavity back requires a large hole in the vehicle body; stripline and microstrip antennas can be machined in flush, or do protrude from 1/64" to 1/4" from the vehicle.

### 9.1 Polarization

Typically, flush antennas are linearly polarized with the polarization axis along the $z$-direction of the vehicle. In the case of stripline construction, such antennas are identified by the radiating slots which run transverse to the $z$-axis because of the nature of slot antennas.[5, §14-18] Cavity-backed antennas may have linear or circular polarization.

### 9.2 Radiating Pattern

The radiating pattern of a flush-mounted antenna on a flat surface (infinite ground plane, etc.) is as shown in Figure 4. Maximum radiation is in the direction normal to the ground plane; zero radiation occurs at the ground plane and below it, and at ±45° the radiated energy is reduced by 3 dB with respect to maximum. If the vehicle diameter is small compared to a wavelength, the radiating pattern is essentially omnidirectional in the $xy$ plane.[7] When the diameter of the vehicle is a significant part of a wavelength or several wavelengths as in the cases considered here, the pattern becomes a cardioid, as shown in Figure 5. This pattern may be modeled as a pair of antennas with equal driving currents and pleases, with one at the vehicle surface and one inward toward the center. The pattern shown in Figure 5 shows the result of a model with 90 electrical degrees of spacing; the pattern and centroid location become more omnidirectional as the vehicle diameter decreases. The model using the pattern of Figure 5 works fairly well for most missile telemetry

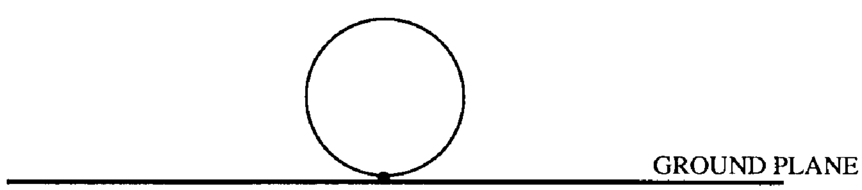


Figure 4: Flush-mounted antenna

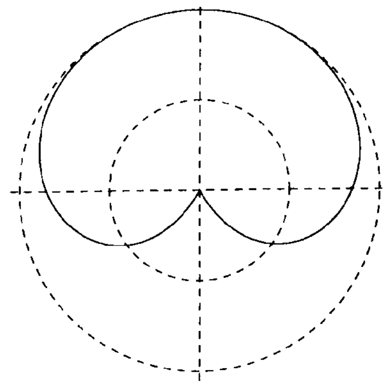

Figure 5: Cardioid

## 10 Desired Patterns

Users often express a desire for omnidirectional coverage from telemetry antennas. Not only is true omnidirectional coverage an impossibility,[4, 5] but it is seldom a good choice.[13] For example, on vehicles such as rockets and missiles, coverage to the rear is complicated by the signal passing through ionized gases from the motor. Coverage to the front implies locating the receiving station at a point at which the rocket is heading—an unpleasant place to be. Toroidal coverage, such as that provided by a dipole oriented along the vehicle Z-axis might be as close to omnidirectional coverage as would ever be needed.

If the vehicle will always be observed from a more restricted angle (say from below) a more focused pattern allows the possibility of antenna gain. In situations where the vehicle telemetry signal is received from above (a low-flying missile being received by a chase plane, for example), ground reflection of the signal may at times be stronger than the direct signal, causing data losses even while the receiver indicates a strong signal. Consequently, if the downward coverage is not required for any other purpose, link quality is improved by eliminating it.[14]

Yet another desired pattern, typically for aircraft, is one in which a strong signal is transmitted downward, but "enough" signal is transmitted upward and sideways that the aircraft can be received from all aspects. Typically this is accomplished by use of two antennas, one on the top and one on the bottom of the fuselage, and possibly displaced from each other in the Z-axis. Since these antennas are many wavelengths apart, the resulting patterns differ from the desired patterns considerably.

[13] For other uses, such as range safety devices, which may need to be exercised if a vehicle should tumble, for example, may actually require an omnidirectional pickup. In such instances, omnidirectional coverage is provided through use of multiple antennas and receivers.

[14] Ground reflections can also be eliminated by use of circularly-polarized antennas for both the transmitter and receiver. Reflected signals are produced with the opposite polarization ("mirror images") and are rejected.

## 11 Multi-Element Arrays

Knowing the pattern of any given antenna type, and the model necessary to produce a similar pattern using dipoles, it is possible to produce patterns for specific antenna arrangements. In this section, several practical problems are solved using `anplot90`. The examples are representative of the capabilities of the program.

### 11.1 Aircraft Antennas

A typical aircraft telemetry link uses the L-band frequencies (1435-1535 MHZ) and has upper and lower antennas on the fuselage center line. The cables to each antenna are of random length, so the phase relationship between the two antennas is arbitrary. If by some miracle the two antennas were fed in phase, the result in the vertical polarization sense would be 180° out because the antennas point in opposite directions.

> Two antennas operating on 1500 MHZ are placed in opposite phase (one pointed up, one pointed down) and separated by 23 feet in the $\hat{z}$ direction and four feet in $\hat{y}$. (a) What is the transmitting pattern for the combination in the $\hat{x}y$ (yaw) plane, assuming the two antennas are driven in phase? (b) What is the result of using a 90/10 power splitting arrangement?

At 1500 MHZ, the wavelength is 20 cm. The 23-foot $\hat{z}$-displacement thus represents 34.615 wavelengths, and the displacement between the antenna bases[15] is 6.02 wavelengths. The resulting pattern is shown in Figure 6. If the two antennas were not in phase, the resulting pattern would be different in some respects, but the point is that the pattern has infinite nulls due to phase cancellation all over the place! If the antennas are fed in a 9:1 ratio (generally with the lower antenna getting 90% of the power), cancellations are impossible—at worst, 80% of the expected dipole output is produced, as shown in Figure 7.

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[15] Since the two antennas are pointed in opposite directions, a measurement between their bases might be slightly less than the electrical separation between the antennas. This effect may be important in some instances, but can be shown not to be important here.

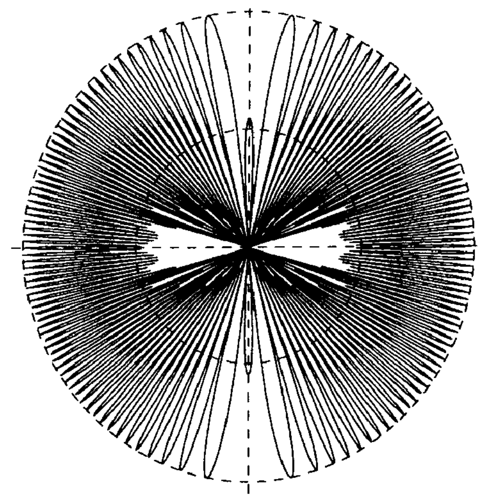

Figure 6: Radiation centers of two antennas in phase (20 dB plot)

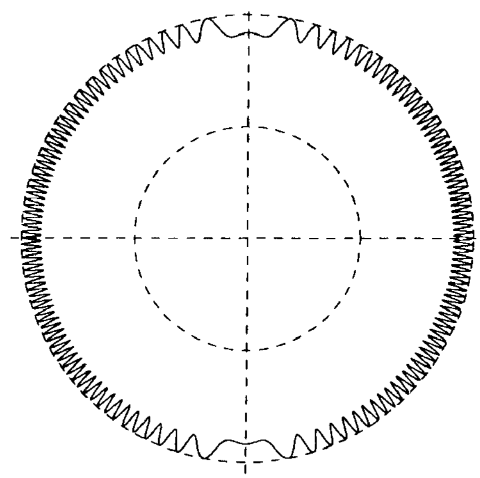

Figure 7: Radiation centers of two antennas, phase 9:1 split (20 dB plot)

### 11.2 Cardioid pattern

To generate the needed cardioid pattern in the $xy$-plane to produce the effect of a slot antenna on a cylinder of typical size, we consider the following problem:

> Two identical antennas fed equal base currents are spaced 90° apart and fed 90° apart in phase. What is the resulting pattern?

The pattern produced resembles Figure 5 as desired. The plot shows that the maximum output, where the signals from the two antennas reinforce, is upward (i.e., away from the vehicle body), and that an infinite null is produced where the two antennas oppose on the opposite side.

Note that the phase of the second element leads the first element. As a consequence, the power from the first element has undergone a 90-degree delay as a result of its travel through space toward the second element, and the two signals consequently cancel in that direction. Reversing the phase arrangement would direct the pattern downward.

## 11.3 Compound Cardioid antenna

This problem is more complex, and typical of the type actually encountered in the field.

> Two surface-mounting antennas are placed on the top and bottom of a missile whose diameter is 20 3/8 inches. Operating frequency is 2204.5 MHZ. The antennas produce a polarization along the missile's Ƶ axis, and can each be modeled as cardioids of the type described in the previous example. The "radiation center" of each element can be taken as the midpoint between the two elements of the simple cardioid, $\lambda/8$ from either element.
>
> What are the results when the two antennas are fed equal power and in phase? What are the results when the two antennas are fed 180°out of phase? What are the results if the two antennas are fed in phase, but the lower antenna has its input signal attenuated by 10 dB (a) with the antennas in phase and (b) with the antennas 180° out of phase? © If a 10 dB pad is inserted in the line to the lower antenna, what pattern results?

At 2204.5 MHZ, wavelength in air is 13.608 cm. The missile diameter is thus 3.80294 wavelengths, which is the separation between the two elements. Then the radiation centers of the two antennas are separated from each other by this diameter. The coordinates (0,0,0) are taken to be the centerline of the vehicle for symmetry, but this is not a requirement, and the choice of the spatial reference will not alter the data.

The resulting patterns are shown in Figures 8-10. If the intent was to produce an antenna with a reasonably omnidirectional pattern in the Ƶ-axis, the choice of two antennas fails miserably. If the two are fed in phase (the first condition), the antennas reinforce at the points exactly between them, but there are two notches of infinite depth close by. Besides the notches, there are four dips of slightly greater than 10 dB intensity as well. Going to a 180° phase reversal between the elements lowers the maximum radiation intensity slightly, but moves the infinite nulls to the $N = \pm 90°$ points, produces four nulls of about 13 dB depth, and four more of about 8 dB depth. The use of a pad and either type of phasing flattens out the coverage in the upper hemisphere, but makes a serious mess in the lower hemisphere. One antenna, with a cardioid pattern, produces a smoother pattern than any combination of two antennas tried. To get a pattern without nulls takes a minimum of about 14 antennas, which can be shown with this technique.

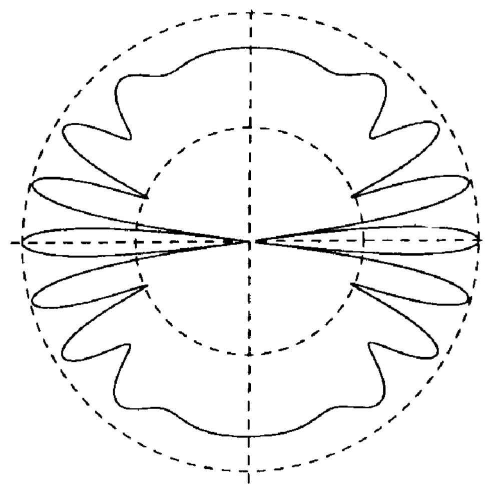

Figure 8: Radiation centers of two antennas in phase (20 dB plot)

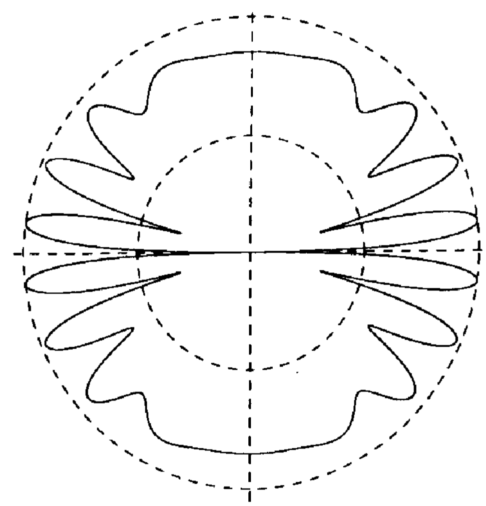

Figure 9: Radiation centers of two antennas, 180° out of phase (20 dB plot)

## 12 Conclusions

The two most-common antenna systems that do not work, and suggested systems that do work were examined here. In any system where more than one antenna is to be used for desired coverage, especially where the antenna elements are widely separated, it behooves the designer to verify that the pattern likely to be produced is the one intended.

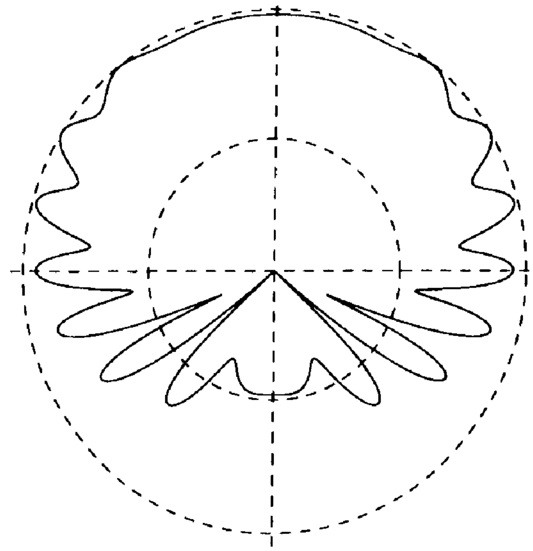

Figure 10: Radiation centers of two antennas, phase 10:1 split (20 dB plot)

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