Chapter 1
ANTENNA FUNDAMENTALS

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Introduction

Antenna gain is essential for microwave communication — since it helps both transmitting and receiving, it is doubly valuable. Practical microwave antennas provide high gain within the range of amateur fabrication skills and budgets.

Three types of microwave antennas meet these criteria: horns, lenses, and dishes. Horns are simple, foolproof, and easy to build; a 10 GHz horn with 17 dB of gain fits in the palm of a hand. Metal-plate lenses[1] are easy to build, light in weight, and non-critical to adjust. Finally, dishes can provide extremely high gain; a 2-foot dish at 10 GHz has more than 30 dB of gain, and much larger dishes are available.

These high gains are only achievable if the antennas are properly implemented. I will try to explain the fundamentals using pictures and graphics as an aid to understanding. In addition, a computer program, **HDL_ANT**, is available for the difficult calculations and details. Finally, I will discuss microwave antenna measurement, so that antenna performance may be verified.

ANTENNA BASICS

Before we talk about specific microwave antennas, there a few common terms that must be defined and explained:

Aperture

The aperture of an antenna is the area that captures energy from a passing radio wave. For a dish antenna, it is not surprising that the aperture is the size of the reflector, and for a horn, the aperture is the area of the mouth of the horn. Wire antennas are not so simple — a thin dipole has almost no area, but its aperture is roughly an ellipse[2] with an area of about 0.13 λ^2, and Yagi-Uda antennas have even larger apertures.

Gain

The hypothetical isotropic antenna is a point source that radiates equally in all directions. Any real antenna will radiate more energy in some directions than in others. Since it cannot create energy, the total power radiated is the same as an isotropic antenna driven from the same transmitter; in some directions it radiates more energy than an isotropic antenna, so in others it must radiate less energy. The gain of an antenna in a given direction is the amount of energy radiated in that direction compared to the energy an isotropic antenna would radiate in the same direction when driven with the same input power. Usually we are only interested in the maximum gain — the direction in which the antenna is radiating most of the power.

An antenna with a large aperture has more gain than a smaller one; just as it captures more energy from a passing radio wave, it also radiates more energy in that direction. Gain may be calculated as

$$G_{dBi} = 10\log_{10}\left(\eta\frac{4\pi}{\lambda^2}A\right)$$

with reference to an isotropic radiator; $\boldsymbol{h}$ is the efficiency of the antenna.

Efficiency

Consider a dish antenna pointed at an isotropic antenna transmitting some distance away. We know that the isotropic antenna radiates uniformly in all directions, so it is a simple(!) matter of spherical geometry to calculate how much of that power should be arriving at the dish over its whole aperture. Now we measure how much power is being received from the dish (at the electrical connection to the feed) — never greater than is arriving at the aperture. The ratio of power received to power arriving is the aperture efficiency.

How much efficiency should we expect? For dishes, all the books say that 55% is reasonable, and 70 to 80% is possible with very good feeds. Several ham articles have calculated gain based on 65% efficiency, but I haven't found measured data to support any of these numbers. On the other hand, KI4VE[3] suggests that the amateur is lucky to achieve 45-50% efficiency with a small dish and a typical “coffee-can” feed.

For horns and lenses, 50% efficiency is also cited as typical. Thus we should expect the same gain from any of these antennas if the aperture area is the same.

Reciprocity

If we transmit alternately with a smaller and a larger dish, is there any reason that the relative power received at a distant antenna would be any different than the relative power received by the two dishes? No, but a mathematical proof [4,5] is surprisingly difficult. Transmitting and receiving gains and antenna patterns are identical.

However, the relative noise received by different types of antennas may differ, even with identical antenna gains. Thus, the received signal-to-noise ratio may be better with one type of antenna compared to another.

Directivity and Beamwidth

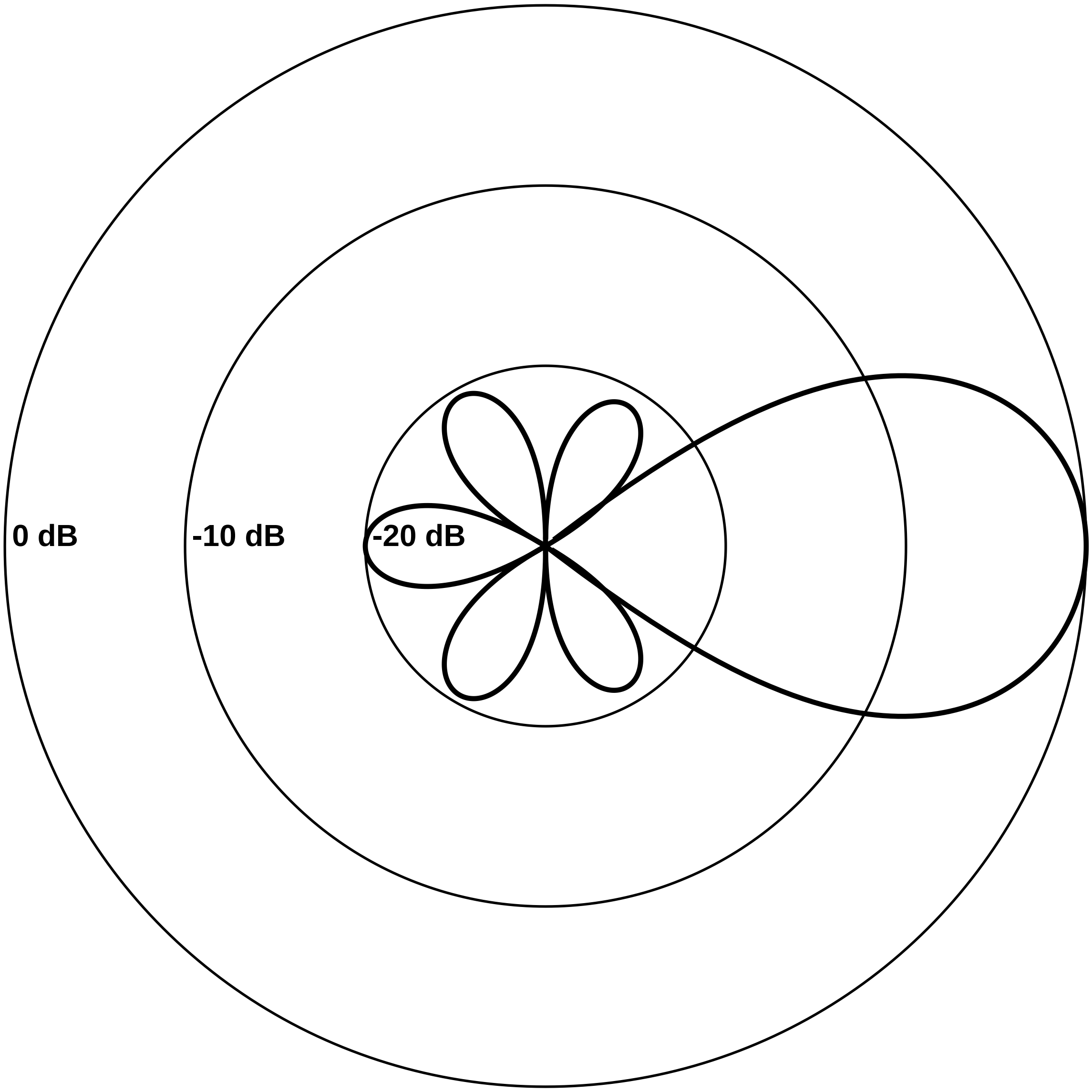
Suppose an antenna has 20 dB of gain in some direction. That means it is radiating 100 times as much power in that direction compared to radiation from an isotropic source, which is uniformly distributed over the surface of an arbitrarily large sphere which encloses it. If all the energy from the 20 dB gain antenna were beamed from the center of that same sphere, then it would pass through an area 100 times smaller than the total surface of the sphere. Since there are 41,253 solid degrees in a sphere, the radiation must be concentrated in 1/100th of that, or roughly 20 degrees beamwidth. The larger the gain, the smaller the beamwidth.

The directivity of an antenna is the maximum gain of the antenna compared with its gain averaged in all directions. It is calculated by calculating the gain, using the previous formula, with 100% efficiency.

Sidelobes

No antenna is able to radiate all the energy in one preferred direction. Some is inevitably radiated in other directions. Often there are small peaks and valleys in the radiated energy as we look in different directions (Figure 1-1). The peaks are referred to as sidelobes, commonly specified in *dB down from the main lobe*, or preferred direction.

Are sidelobes important? Let's suppose that we could make an antenna with a 1 degree beamwidth, and in all other directions the average radiation was 40 dB down from the main lobe. This seems like a pretty good antenna! Yet when we do the calculation, only 19.5% of the energy is in the main lobe, with the rest in the other $\frac{41252}{41253}$ of a sphere. Obviously the maximum efficiency this antenna can have is 19.5%.



Typical Antenna Pattern with Sidelobes

Figure 1-1

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E-plane and H-plane

An antenna is a transducer which converts voltage and current on a transmission line into an electromagnetic field in space, consisting of an electric field and a magnetic field travelling at right angles to each other. An ordinary dipole creates electric field, creating a pattern with larger amplitude in planes which include the dipole. The electric field travels in the E-plane; the H-plane, perpendicular to it, is the field in which the magnetic field travels. When we refer to polarization of an antenna, we are referring to the E-plane. However, for three-dimensional antennas like horns, dishes, and lenses, it is important to consider both the E-plane and the H-plane, in order to fully utilize the antenna and achieve maximum gain.

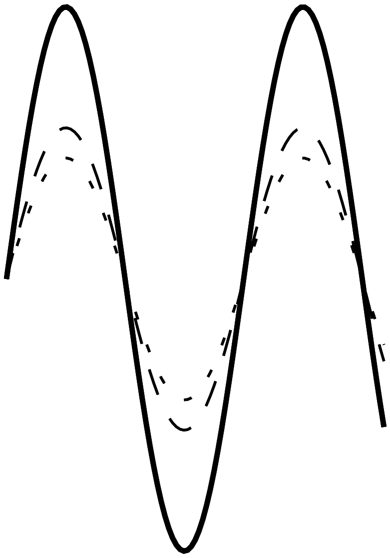
Phase Center

The antenna pattern in Figure 1-1, and most other illustrations of antenna patterns, shows only amplitude, or average power. This is all we need to consider for most applications, but for antennas which are like optical systems, like lenses and dishes, we must also be concerned with phase, the variation in the signal as a function of time. RF and microwave signals are AC, alternating current, with voltage and current that vary sinusoidally (like waves) with time. Figure 1-2a shows several sine waves, all at the same frequency, the rate at which they vary with time.

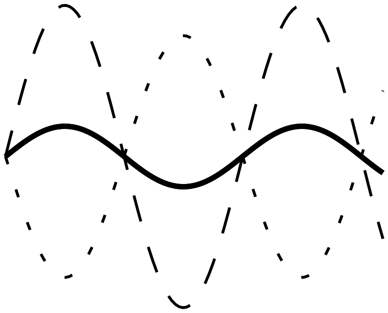
Let's think about a simple example: a child's swing. We've all both ridden and pushed one at some time. If we push the swing just as it starts to move away from us, it swings higher each time. If we add a second pusher at the other end, it will increase faster. Now if we tie a rope to the swing seat and each pusher takes an end, we can try to add energy to the swing throughout its cycle. This will work as long as we keep the pulling synchronized with the motion of the swing, but if we get *out of phase*, we will drag it down rather than sending it higher.

The motion of a swing is periodic, and the height of the swing varies with time in a pattern similar to a sine wave of voltage or current. Look at a sine wave in Figure 1-2a, considering the highest point of the waveform the height the swing travels forward, and the lowest point as the height the swing travels backward, both repeating with time. If there are two swings side-by-side and both swings arrive at their peak at the same time, they are in phase, as in Figure 1-2a.

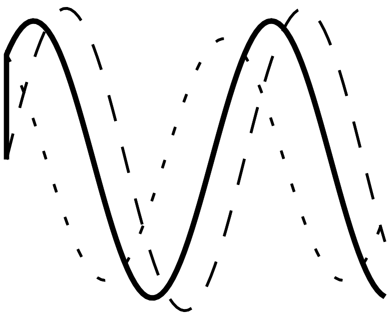
When two electromagnetic waves arrive at a point in space and impinge on an antenna, their relative phase is combined to create a voltage. If they have the same phase, their voltages add together; in Figure 1-2a, the two dashed waveforms are in phase and add together to form the solid waveform. On the other hand, when signals are exactly out of phase, the addition of positive voltage to negative voltage leaves only the difference, as shown in Figure 1-2b. If the phase difference between the two signals is partially out of phase, then the resultant waveform is found by adding the voltage of each at each point in



(a) In phase - addition

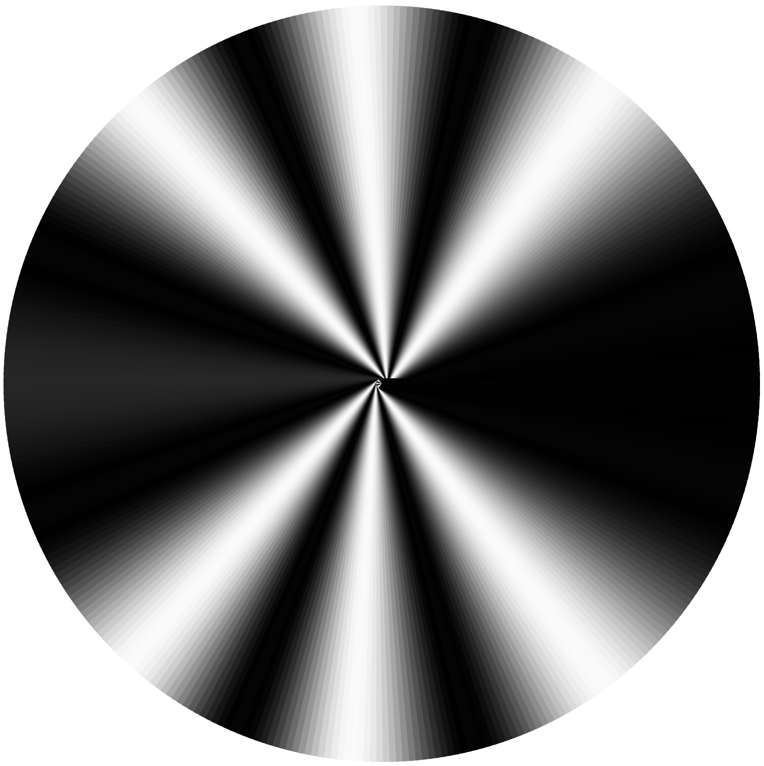


(b) Out of phase - cancellation



(c) 120 degree phase difference

(d) Point source - single phase center



(e) Two sources - interference pattern

Figure 1-2. Phase and Phase Center

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time; one example is shown in Figure 1-2c. Notice that the amplitude of the resultant waveform is dependent on the phase difference between the two signals.

If our signal source is a point source, then all waves are coming from that one point in space. Each wave has a wavefront, like a wave arriving on a beach. The wavefront from the perfect point source has a spherical shape. Consider its *amplitude*. First, we place an antenna and power meter at some distance from the source and take a reading, then when we move the antenna around to other places that create exactly the same power reading, we will draw a sphere around the source. Thus, the amplitude has a uniform distribution like Figure 1-2d; dark areas have higher amplitude than lighter areas, and the amplitude decreases as we move away from the source according to the inverse square law described below (the shading is shown in steps for emphasis, but is really a continuous smooth function).

The *phase* of this wavefront as it propagates in space appears to also have a spherical shape. If frozen in time, one sphere would represent a positive peak of a sine wave. One half wavelength inside would be another sphere representing a negative peak of the sine wave, and another half wave inside again is a positive peak. The *phase center* of an antenna is the apparent place from which the signal emanates based on the center of a sphere of constant phase.

However, no real antenna is small enough to be a point source, so the radiation must appear to emanate from a larger area. If we consider a simple case, where the radiation appears to come from two points, then two signals will arrive at each point in space. A point in space is typically farther from one radiating point than from the other, and since the time it takes for each signal to arrive depends on the distance to each of the radiating points, there will be a phase difference between the two signals. This phase difference will be different at each point in space, depending on the relative distances, and the amplitude of the resultant signal at each point depends on the phase difference. An example of a pattern created by two radiating sources is shown in Figure 1-2e, where the dark areas have the greatest amplitude due to the two signals arriving in phase and the light areas are areas where phase cancellation, like Figure1-2b, has reduced the amplitude.

A well designed feed for a dish or lens has a single phase center, so the radiation appears to emanate from a single point source. This must be so, for at least the main beam, the part of the pattern that illuminates the dish or lens. Away from this main beam, the phase center may move around and appear as multiple points, due to stray reflections and surface currents affecting the radiation pattern. However, since these other directions do not illuminate the dish or lens, they can be ignored.

Inverse Square Law

As two antennas are moved farther apart, received power decreases in proportion to the square of the distance between them; when the distance is doubled, only 1/4 as much power is received, a reduction of 6 dB. This is because the area illuminated by a given beamwidth angle increases as the square of the distance from the source, so the power per unit area must decrease by the same ratio, the square of the distance. Since the area of the receiving antenna has not changed, the received power must decrease proportionally.

The phase center pattern in Figure 1-2e does *not* include the effect of inverse square law in the pattern, in order to emphasize the phase cancellation. The effect of including inverse square law would be to lighten the pattern as distance from the phase center increased.

Path Loss

We can estimate the path loss between two antennas, a transmitting antenna (gain = $\mathbf{G_T}$**)** and a receiving antenna (gain = $\mathbf{G_{R)}}$, using a convenient form of the Friis transmission loss equation[6] :

$$\text{Loss}\,(dB) = 10 \cdot \log\left(\frac{4\boldsymbol{p}\text{d}}{\boldsymbol{l}}\right)^2 - \text{G}_\text{T}\,(dBi) - \text{G}_\text{R}\,(dBi)$$

where the path length **d** is the distance between the two antennas.

Free Lunch

Since gain is proportional to aperture, larger antennas have more gain than smaller antennas,and poor efficiency can only make a small antenna worse. In spite of various dubious claims by antenna designers and manufacturers, "There's no such thing as a free lunch." [7]

However, a large antenna with poor efficiency is a waste of metal and money.

Recommended Reading

For those interested in pursuing a deeper understanding of antennas, a number of books are available. A good starting point is the *The ARRL Antenna Book* and *The ARRL UHF/Microwave Experimenter's Manual*. Then there are the classic antenna books, by Kraus [2], Silver [4], and Jasik [8]. Lo and Lee [5] have edited a more recent antenna handbook, and Love has compiled most of the significant papers on horns [9] and dishes [10,11] For those interested in computer programming for antenna design, Sletten [11] provides a number of routines. Be warned that the math gets pretty dense once you get beyond the ARRL books.

Summary

This concludes our quick tour through basic antenna concepts and definitions. Now let's apply these concepts to understanding actual microwave antennas, starting with horns.

HDL_ANT Computer Program

The intent of the **HDL_ANT** program is to aid in design of microwave antennas, not to be a whizzy graphics program. The program does the necessary calculations needed to implement a horn, dish, or lens antenna, or to design an antenna range and correct the gain measurements. The basic data is entered interactively and results are presented in tabular form. If you like the results, a table of data or a template may be saved to a file for printing or further processing; if not, try another run with new data.

The C++ source code is also included, for those who wish to enhance it or simply to examine the more complex calculations not shown in the text. It has been compiled with Borland C++ version 3.1 and version 4.5, and is available for downloading.

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