

# Antenna Basics

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## Antenna Fundamentals

Lets get right down to the study of antennas and **Antenna Basics**. Suppose one day you're walking down the street and a kind but impatient person runs up and asks you to design an antenna for them. "Sure", you quickly reply, adding "what is the desired frequency, gain, bandwidth, impedance, and polarization?"

Or perhaps you have never heard of (or are a little rusty) on the above parameters. Well then, you've come to the right place. Before we can design an antenna or discuss antenna types, we must understand the basics of antennas, which are the fundamental parameters that characterize an antenna.

So let us learn something. We'll start with frequency and step through radiation patterns, directivity and gain, and ultimately close with an explanation on why antennas radiate. Jump ahead if this is already familiar to you.

## [Frequency](#)

The basics of sinusoids (sine and cosine waves), wavelength, frequency and the speed of light.

## [More Advanced Frequency Information](#)

A discussion on how all waveforms in the universe are made up of the sum of sinusoids (simple waves) This helps explain why in antenna theory we always discuss wavelength and frequency no matter what signal (information) we want to transmit.

## [Frequency Bands](#)

No discussion on antenna fundamentals is complete without a real-world list of frequency bands.

## [Radiation Pattern](#)

The radiation pattern for an antenna is defined on this page. We have 3D graphs of real antenna radiation patterns, with a discussion on isotropic, omnidirectional and directional radiation patterns. Radiation patterns are of the utmost importance in the discussion of antenna basics.

## [Field Regions](#)

The introduction to antennas continues with a discussion of Field Regions. The Far Field, Near Field and Fresnel Regions for an antenna is presented.

## [Directivity](#)

Directivity is fundamental to antennas. It is a measure of how "directional" an antenna's radiation pattern is.

## [Efficiency and Antenna Gain](#)

An antenna's efficiency is a measure of how much power is radiated by the antenna relative to the antenna input power. The subject of Antenna Basics also includes a discussion of Antenna Gain, which is real power radiated in a particular direction.

## [Beamwidths and Sidelobes](#)

An antenna's radiation pattern in the far field is often characterized by its beamwidth and sidelobe levels. This introduction to antennas illustrates this with an example.

## [Impedance](#)

Antenna Impedance is presented as the ratio of voltage to current at the antenna's terminals. Low- and High-Frequency models are presented for transmission lines. The fundamentals of antenna theory requires that the antenna be "impedance matched" to the transmission line or the antenna will not radiate. The concept of VSWR is introduced as a measure of how well matched an antenna is.

## [Bandwidth](#)

The bandwidth of an antenna is the frequency range over which the antenna radiates. The bandwidth can be defined in different ways; this page presents an introduction to antenna bandwidth.

## [Polarization of Waves](#)

All electromagnetic plane waves have an associated polarization. The antenna concepts of Linear, Circular and elliptical polarization are presented.

## [Polarization of Antennas](#)

Antennas are also classified by their polarization; this defines the type of plane wave polarization the antenna is most sensitive to. This is a fundamental antenna concept.

## [Effective Aperture](#)

Effective aperture is a basic antenna concept that is a measure of the power captured by an antenna from a plane wave. Effective aperture can be expressed as a function of the antenna gain and the wavelength of interest.

## [Friis Transmission Equation](#)

Friis Transmission Formula is the most fundamental equation of antenna theory. This equation relates transmit power, antenna gains, distance and wavelength to received power. This page is a must-read for those interested in antenna theory.

## [Antenna Temperature](#)

Antenna Temperature is a property of an antenna and the environment it operates in. It is a measure of the noise received by the antenna due to thermal (or temperature) effects.

## [Why do Antennas Radiate?](#)

The antenna basics section concludes with a discussion of Why Antennas Radiate. The idea here is to explain the physical concepts that produce radiation in terms of electrons flowing on a wire.

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After concluding the study of Antenna Fundamentals, the next step in the understanding of antenna theory is to move on to the [types of antennas](#) page, where basic antenna types are discussed. You will find that the understanding of the above concepts is crucial for understanding real antennas.

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# Frequency

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**Frequency** is one of the most important concepts in the universe and to antenna theory, which we will see. But fortunately, it isn't too complicated.

## Beginner Level (or preliminaries):

Antennas function by transmitting or receiving electromagnetic (EM) waves. Examples of these electromagnetic waves include the light from the sun and the waves received by your cell phone or radio. Your eyes are basically "receiving antennas" that pick up electromagnetic waves that are of a particular frequency. The colors that you see (red, green, blue) are each waves of different frequencies that your eyes can detect.



All electromagnetic waves propagate at the same speed in air or in space. This speed (the speed of light) is roughly 671 million miles per hour (1 billion kilometers per hour). This is roughly a million times faster than the speed of sound (which is about 761 miles per hour at sea level). The speed of light will be denoted as  $c$  in the equations that follow. We like to use "SI" units in science (length measured in meters, time in seconds, mass in kilograms), so we will forever remember that:

speed of light is a constant  
function of frequency times  
wavelength

Before defining frequency, we must define what a "electromagnetic wave" is. This is an [electric field](#) that travels away from some source (an antenna, the sun, a radio tower, whatever). A traveling electric field has an associated [magnetic field](#) with it, and the two make up an electromagnetic wave.

The universe allows these waves to take any shape. The most important shape though is the sinusoidal wave, which is plotted in Figure 1. EM waves vary with space (position) and time. The spatial variation is given in Figure 1, and the the temporal (time) variation is given in Figure 2.

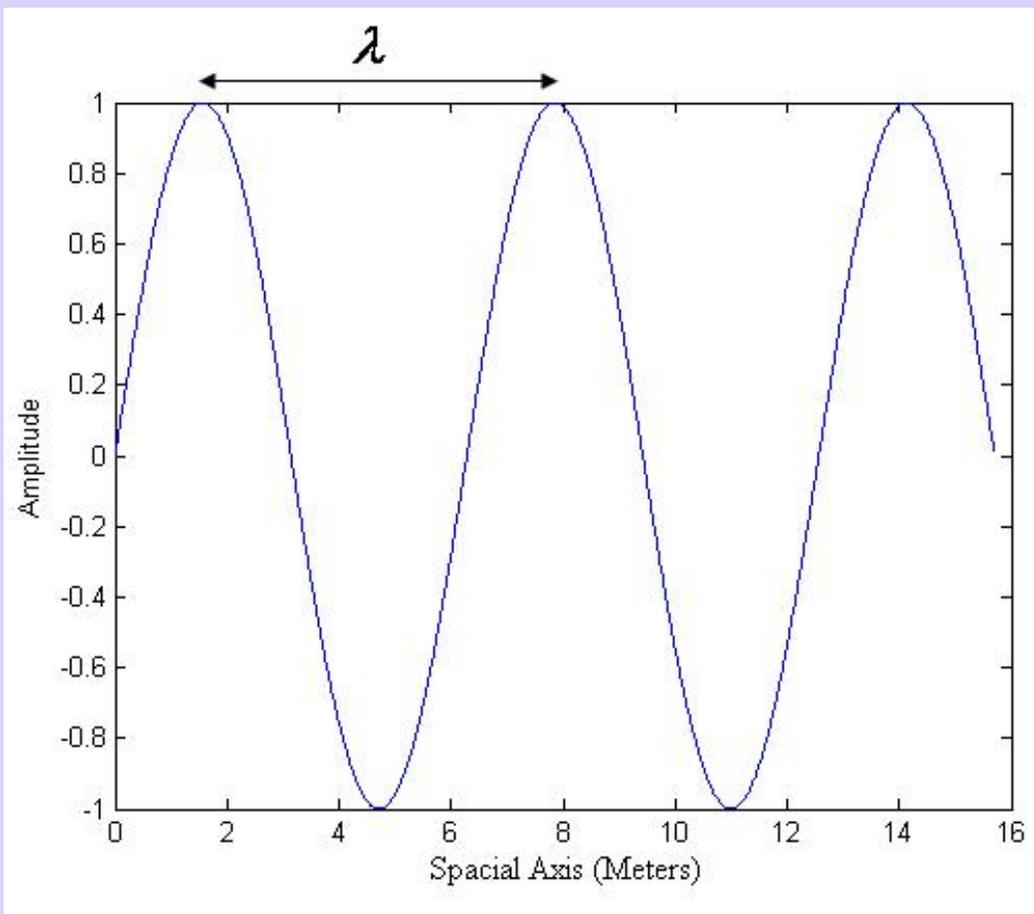


Figure 1. A Sinusoidal Wave plotted as a function of position.

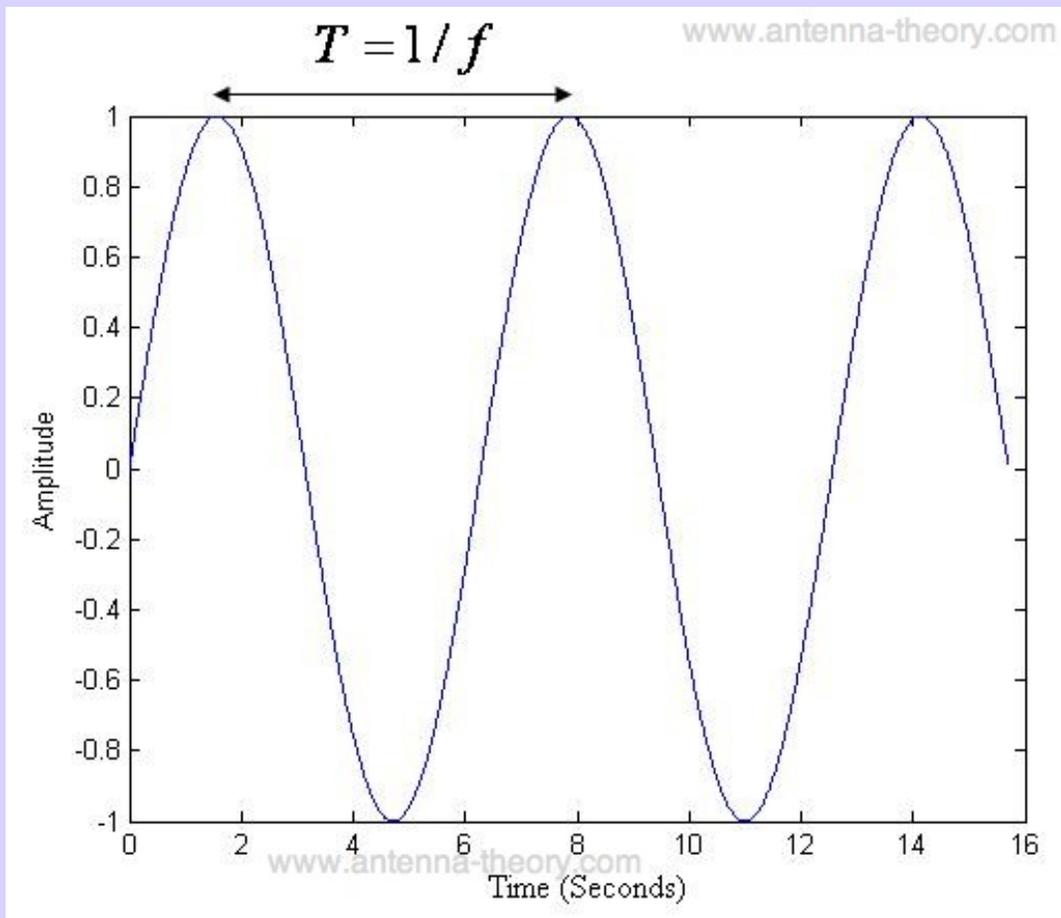


Figure 2. A Sinusoidal Wave plotted as a function of time.

The wave is periodic, it repeats itself every  $T$  seconds. Plotted as a function in space, it repeats itself every **wavelength** meters, which we will call the wavelength. The frequency (written  $f$ ) is simply the number of complete cycles the wave completes (viewed as a function of time) in one second (two hundred cycles per second is written 200 Hz, or 200 "Hertz"). Mathematically this is written as:

frequency is the number of  
cycles per second (Hertz)

How fast someone walks depends on the size of the steps they take (the wavelength) multiplied by the rate at which they take steps (the frequency). The speed that the waves travel is how fast the waves are oscillating in time ( $f$ ) multiplied by the size of the step the waves are taken per period (**wavelength**). The equation that relates frequency, wavelength and the speed of light can be tattooed on your forehead:

$$c = f\lambda$$

Basically, the frequency is just a measure of how fast the wave is oscillating. And since all EM waves travel at the same speed, the faster it oscillates the shorter the wavelength. And a longer wavelength implies a slower frequency.

This may sound stupid, and actually it probably should. When I was young I remember scientists discussing frequency and I could never see why it mattered. But it is of fundamental importance, as will be explained in the "more advanced" section on frequency.

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## Frequency - More Advanced Concepts

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Why is frequency so fundamental? To really understand that, we must introduce one of the coolest mathematical ideas ever (seriously), and that is 'Fourier Analysis'. I had a class on Fourier Analysis in grad school at Stanford University, and the professor referred to these concepts as 'one of the fundamental secrets of the universe'.

Let's start with a question. What is the frequency of the following waveform?

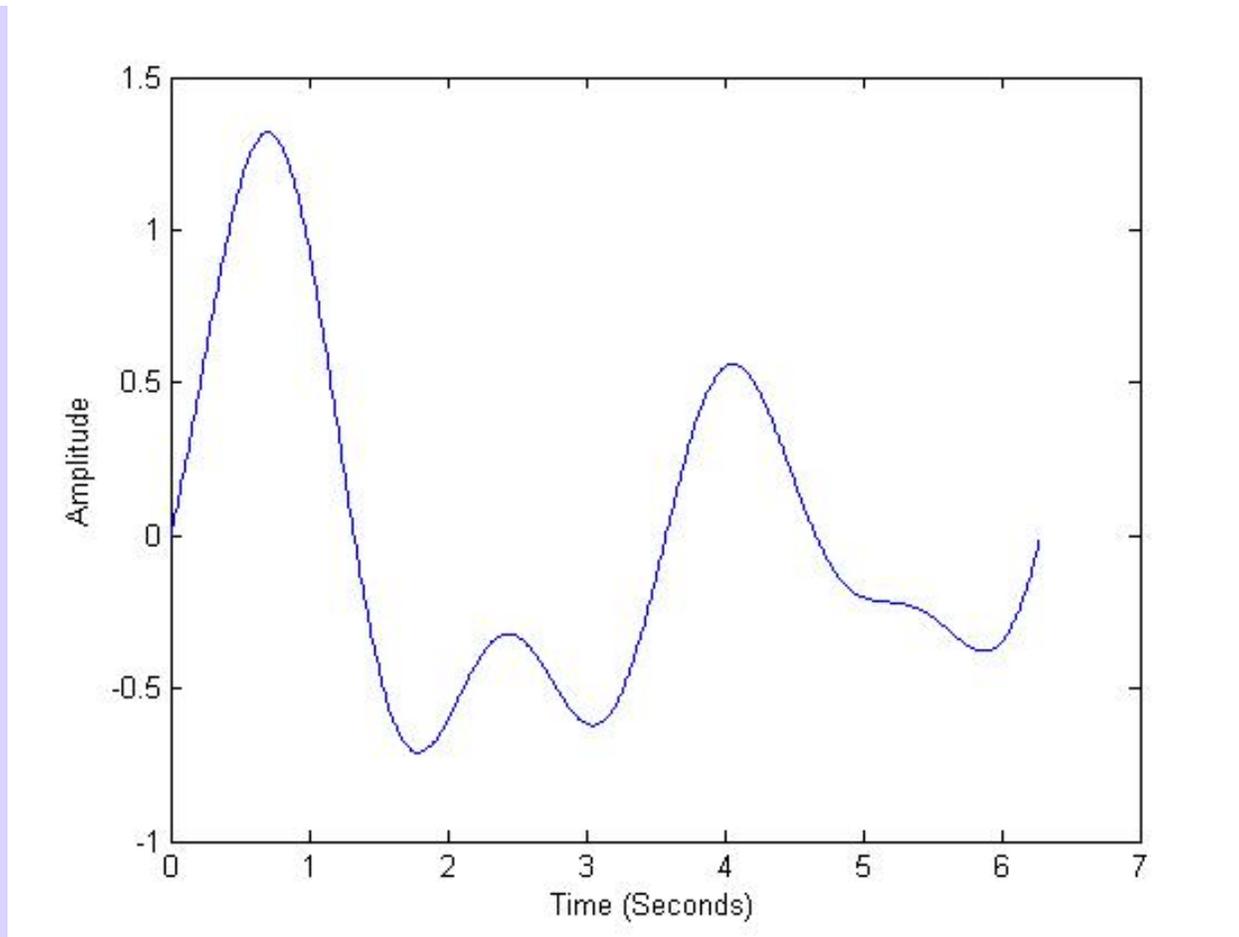


Figure 1. A simple waveform.

Well, you'd look for what the period is and realize that it isn't periodic over the plotted region. Then you'd tell me the question was stupid. But here we go:

**One of the Fundamental Secrets of the Universe**

All waveforms, no matter what you scribble or observe in the universe, are actually just the sum of simple sinusoids of different frequencies.

As an example, let's break down the waveform in Figure 1 into its 'building blocks' or the its frequencies. This decomposition can be done with a [Fourier transform](#) (or Fourier series for periodic waveforms). The first component is a sinusoidal wave with period  $T=6.28$  ( $2\pi$ ) and amplitude 0.3, as shown in Figure 2.

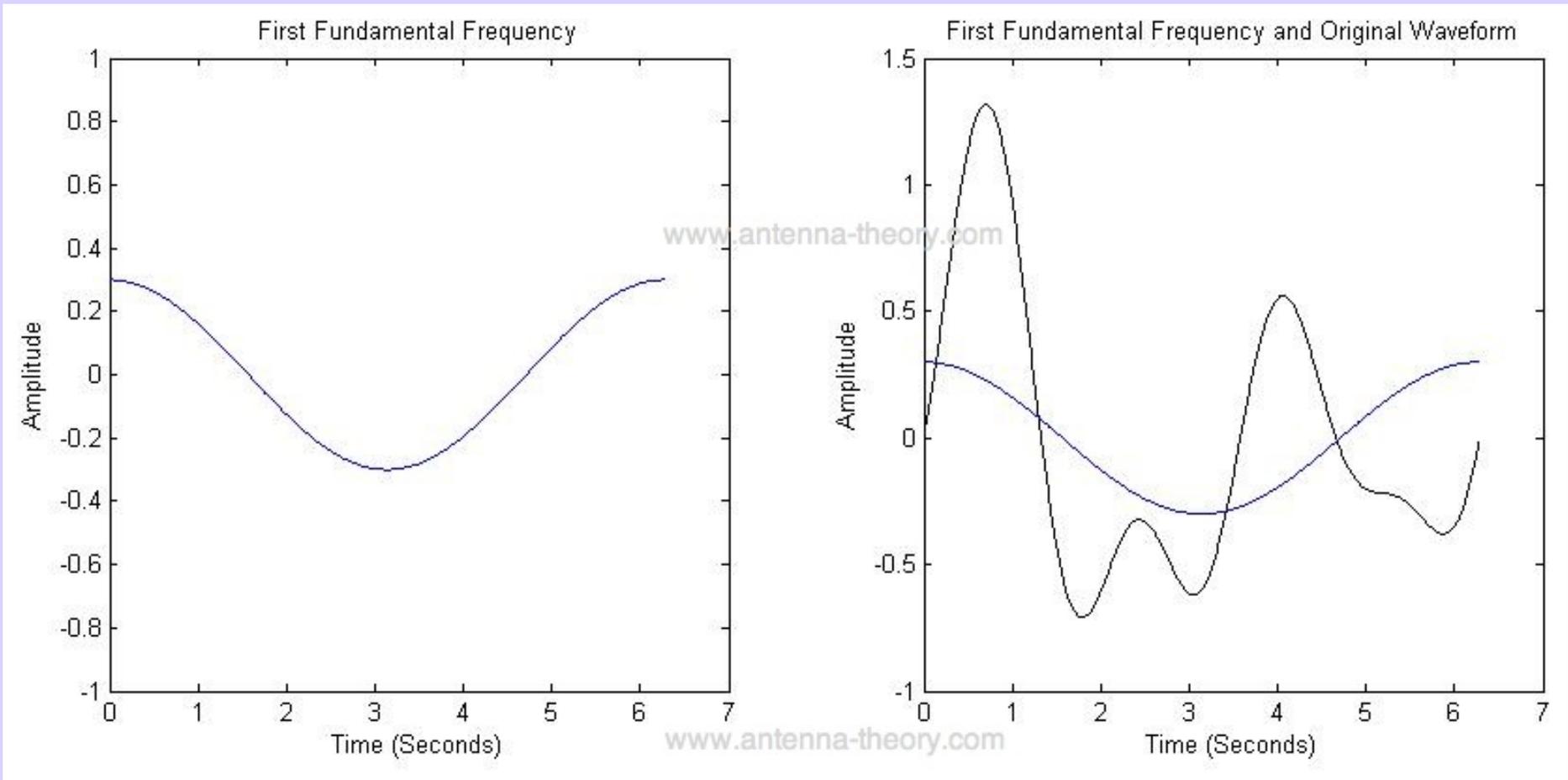


Figure 2. First fundamental frequency (left) and original waveform (right) compared.

The second frequency will have a period half as long as the first (twice the frequency). The second component is shown on the left in Figure 3, along with the sum of the first two frequencies compared to the original waveform.

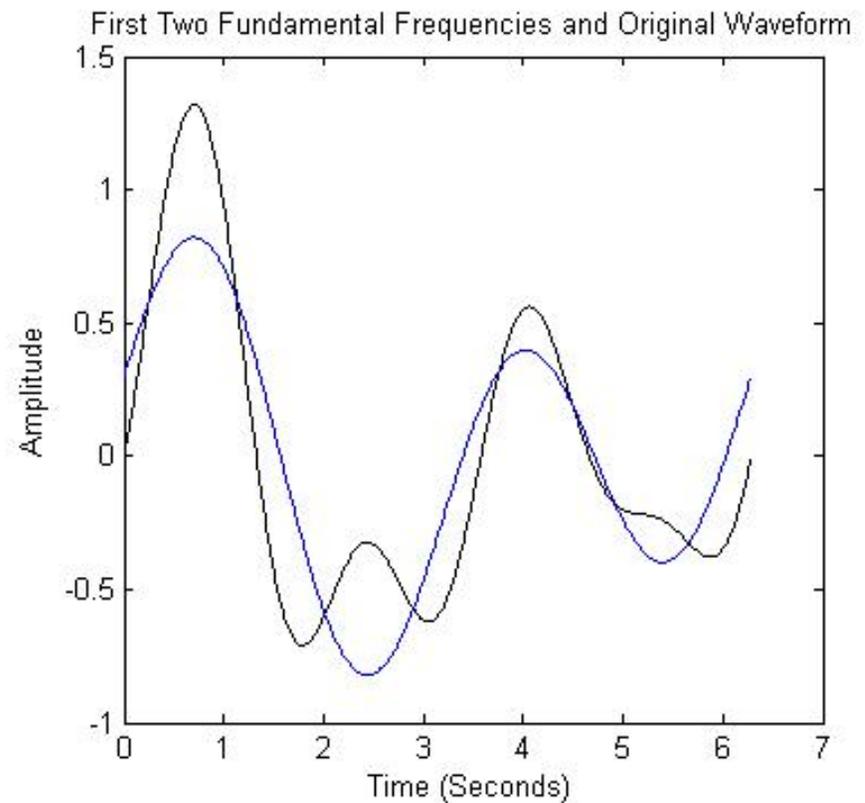
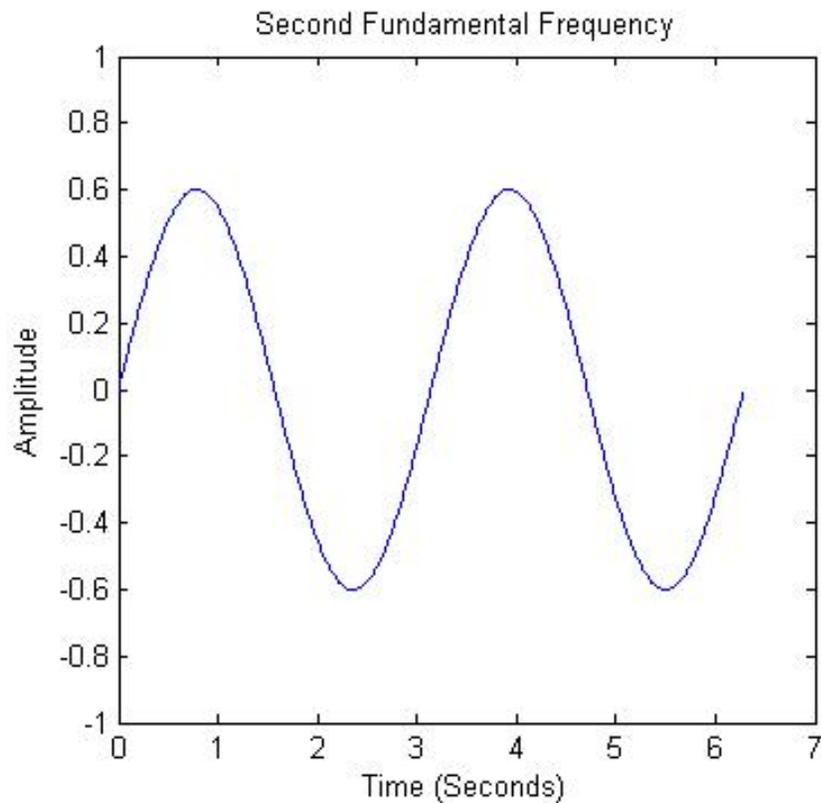


Figure 3. Second fundamental frequency (left) and original waveform compared with the first two frequency components.

We see that the sum of the first two frequencies is starting to look like the original waveform. The third frequency component is 3 times the frequency as the first. The sum of the first 3 components are shown in Figure 4.

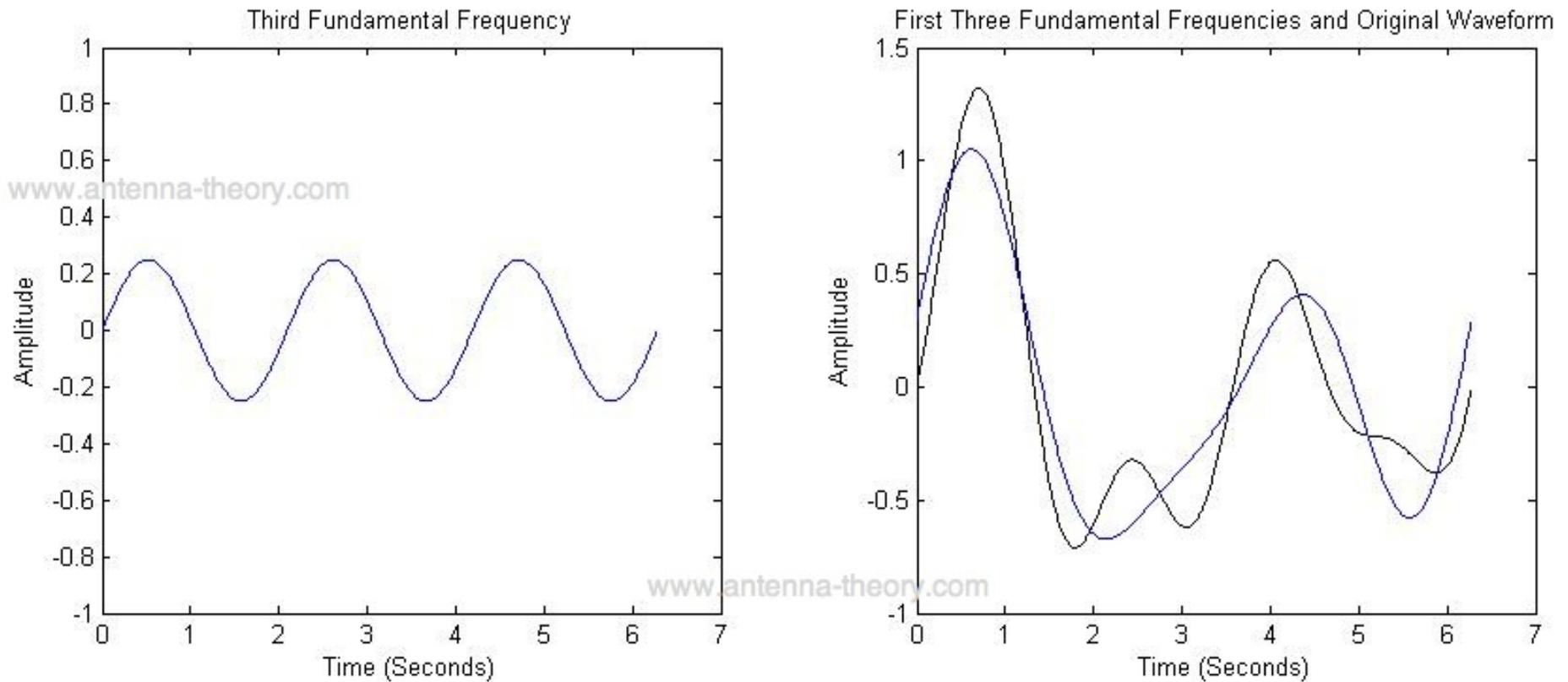


Figure 4. Third fundamental frequency (left) and original waveform compared with the first three frequency components.

Finally, adding in the fourth frequency component, we get the original waveform, shown in Figure 5.

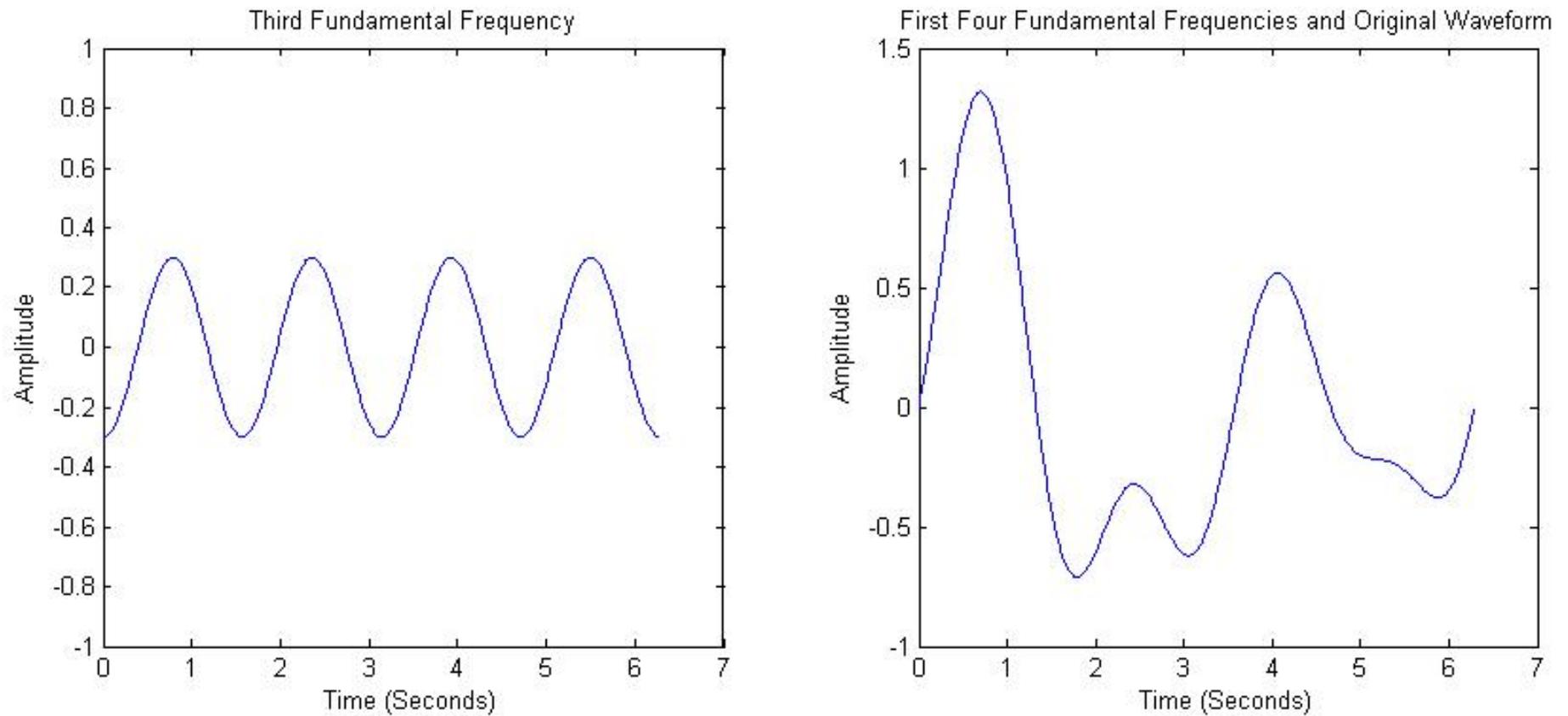


Figure 5. Fourth fundamental frequency (left) and original waveform compared with the first four frequency components (overlapped).

While this seems made up, it is true for all waveforms. This goes for TV signals, cell phone signals, the sound waves that travel when you speak. In general, waveforms are not made up of a discrete number of frequencies, but rather a continuous range of frequencies.

Hence, for all of antenna theory, we will frequency be discussing wavelength of frequency. Actual antennas radiate real world signals - data from the internet over WIFI, speech signals, etc etc etc. However, since every piece of information in the universe can be decomposed into sine and cosine components of varying frequencies, we always discuss antennas in terms of the wavelength it operates at or the frequency we are using.

As a further consequence of this, the power an antenna can transmit is divided into frequency regions, or

frequency bands. In the next section, we'll look at what we can say about these frequency bands.

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# Frequency Bands

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How can your cell phone and your television work at the same time? Both use antennas to receive information from electromagnetic waves, so why isn't there a problem?

The answer goes back to the fundamental secret of the universe. No matter what information you want to send, that waveform can be represented as the sum of a range of frequencies. By the use of modulation (which in a nutshell shifts the frequency range of the waveform to be sent to a higher frequency band), the waveforms can be relocated to separate frequency bands.

As an example, cell phones that use the PCS (Personal Communications Service) band have their signals shifted to 1850-1900 MHz. Television is broadcast primarily at 54-216 MHz. FM radio operates between 87.5-108 MHz.

The set of all frequencies is referred to as "the spectrum". Cell phone companies have to pay big money to get access to part of the spectrum. For instance, AT&T has to bid on a slice of the spectrum with the FCC, for the "right" to transmit information within that band. The transmission of EM energy is greatly regulated. When AT&T is sold a slice of the spectrum, they can not transmit energy at any other band (technically, the amount transmitted must be below some threshold in adjacent bands).

The **Bandwidth** of a signal is the difference between the signals high and low frequencies. For instance, a signal transmitting between 40 and 50 MHz has a bandwidth of 10 MHz. This means that the energy of the signal is contained between 40 and 50 MHz (and the energy in any other frequency range is negligible).

We'll wrap up with a table of frequency bands along with the corresponding wavelengths. From the table, we see that VHF is in the range 30-300 [MHz](#) (30 Million-300 Million cycles per second). At the very least then, if someone says they need a "VHF antenna", you should now understand that the antenna should transmit or receive electromagnetic waves that have a frequency of 30-300 MHz.

Frequency Band Name	Frequency Range	Wavelength (Meters)	Application
Extremely Low Frequency (ELF)	3-30 Hz	10,000-100,000 km	Underwater Communication
Super Low Frequency (SLF)	30-300 Hz	1,000-10,000 km	AC Power (though not a transmitted wave)

Ultra Low Frequency (ULF)	300-3000 Hz	100-1,000 km	
Very Low Frequency (VLF)	3-30 kHz	10-100 km	Navigational Beacons
Low Frequency (LF)	30-300 kHz	1-10 km	AM Radio
Medium Frequency (MF)	300-3000 kHz	100-1,000 m	Aviation and AM Radio
High Frequency (HF)	3-30 MHz	10-100 m	Shortwave Radio
Very High Frequency (VHF)	30-300 MHz	1-10 m	FM Radio
Ultra High Frequency (UHF)	300-3000 MHz	10-100 cm	Television, Mobile Phones, GPS
Super High Frequency (SHF)	3-30 GHz	1-10 cm	Satellite Links, Wireless Communication
Extremely High Frequency (EHF)	30-300 GHz	1-10 mm	Astronomy, Remote Sensing
Visible Spectrum	400-790 THz ( $4 \cdot 10^{14}$ - $7.9 \cdot 10^{14}$ )	380-750 nm (nanometers)	Human Eye

**Table 1. Frequency Bands**

Basically the frequency bands each range over from the lowest frequency to 10 times the lowest frequency. Antenna engineers further divide the bands into things like "X-band" and "Ku-band". That is the basics of frequency. To understand at a more advanced level, read on, or move to the next topic.

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# Radiation Pattern

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A **radiation pattern** defines the variation of the power radiated by an antenna as a function of the direction away from the antenna. This power variation as a function of the arrival angle is observed in the antenna's [far field](#).

As an example, consider the 3-dimensional radiation pattern in Figure 1, plotted in [decibels \(dB\)](#) .

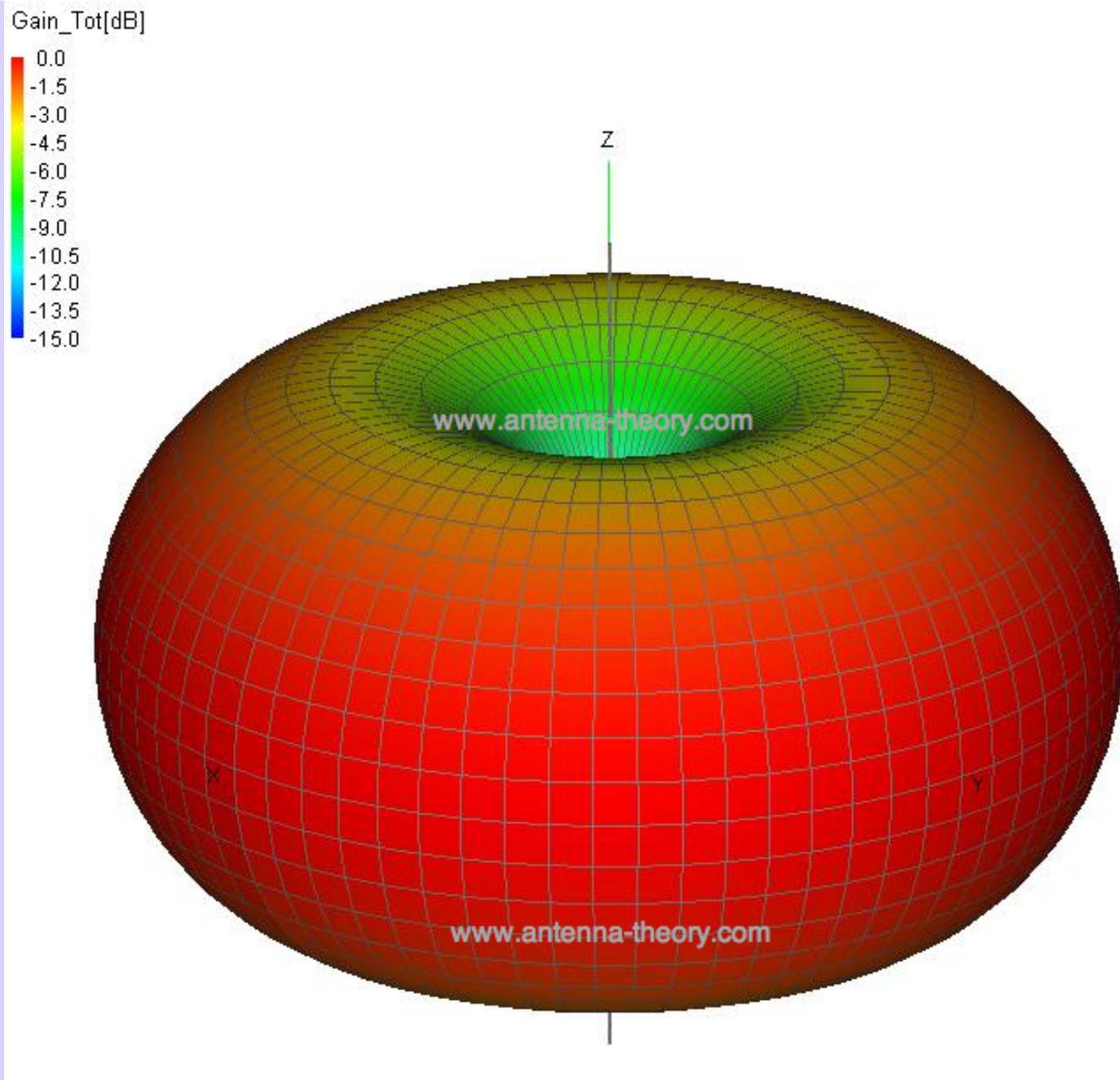


Figure 1. Example radiation pattern for an Antenna (generated with FEKO software).

This is an example of a donut shaped or toroidal radiation pattern. In this case, along the z-axis,

which would correspond to the radiation directly overhead the antenna, there is very little power transmitted. In the x-y plane (perpendicular to the z-axis), the radiation is maximum. These plots are useful for visualizing which directions the antenna radiates.

Typically, because it is simpler, the radiation patterns are plotted in 2-d. In this case, the patterns are given as "slices" through the 3d plane. The same pattern in Figure 1 is plotted

in Figure 2. Standard spherical coordinates are used, where polar angle theta for plots in spherical coordinates is the angle measured off the z-axis, and phi, the azimuth angle of spherical coordinates in antenna patterns is the angle measured counterclockwise off the x-axis.

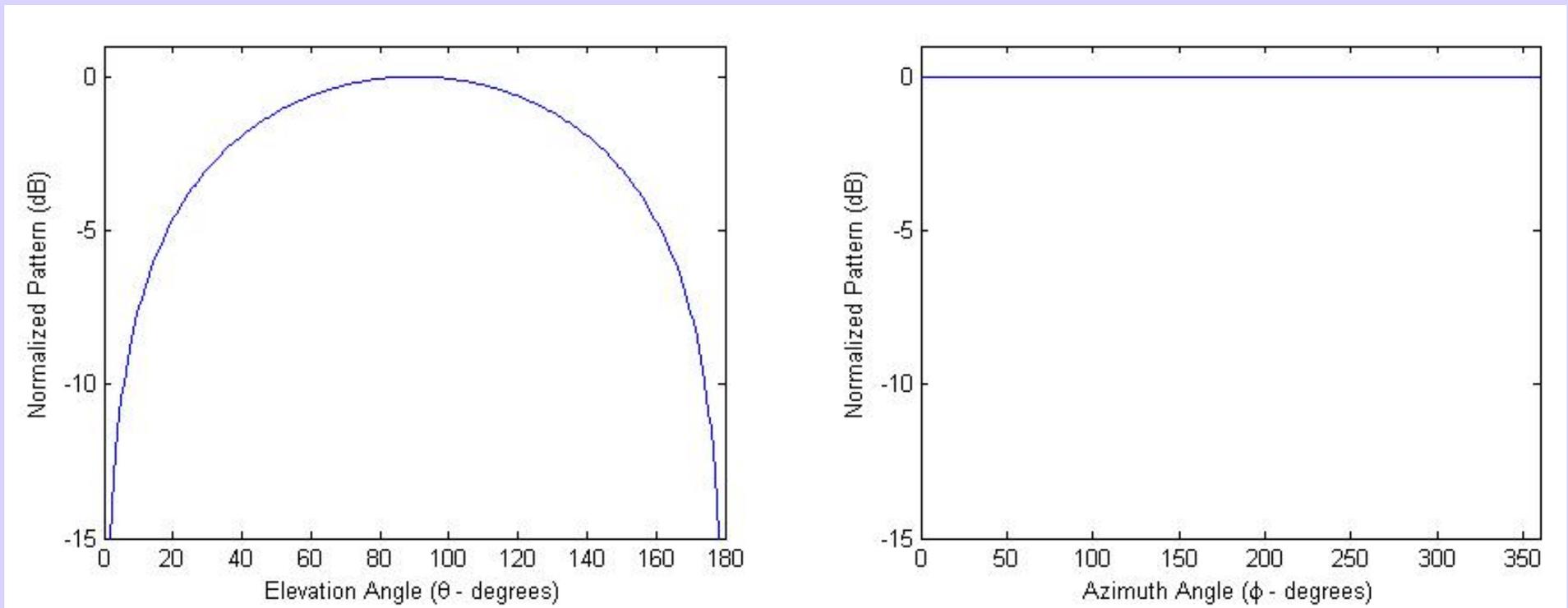


Figure 2. Two-dimensional Radiation Patterns.

If you're unfamiliar with radiation patterns or spherical coordinates, it may take a while to see that Figure 2 represents the same radiation pattern as shown in Figure 1. The radiation pattern on the left in Figure 2 is the elevation pattern, which represents the plot of the radiation pattern as a function of the angle measured off the z-axis (for a fixed azimuth angle). Observing Figure 1, we see that the radiation pattern is minimum at 0 and 180 degrees and becomes maximum broadside to the antenna (90 degrees off the z-axis). This corresponds to the plot on the left in Figure 2.

The radiation pattern on the right in Figure 2 is the azimuthal plot. It is a function of the azimuthal angle for a fixed polar angle (90 degrees off the z-axis in this case). Since the radiation pattern in Figure 1 is symmetrical around the z-axis, this plot appears as a constant in Figure 2.

A pattern is "isotropic" if the radiation pattern is the same in all directions. Antennas with isotropic radiation patterns don't exist in practice, but are sometimes discussed as a means of comparison with real antennas.

Some antennas may also be described as "omnidirectional", which for an actual antenna means that the radiation pattern is isotropic in a single plane (as in Figure 1 above for the x-y plane, or the radiation pattern on the right in Figure 2). Examples of omnidirectional antennas include [the dipole antenna](#) and the [slot antenna](#).

The third category of antennas are "directional", which do not have a symmetry in the radiation pattern. These antennas typically have a single peak direction in the radiation pattern; this is the direction where the bulk of the radiated power travels. These antennas are very common; examples of antennas with highly directional radiation patterns include the [dish antenna](#) and the [slotted waveguide antenna](#). An example of a highly directional radiation pattern (from a dish antenna) is shown in Figure 3:

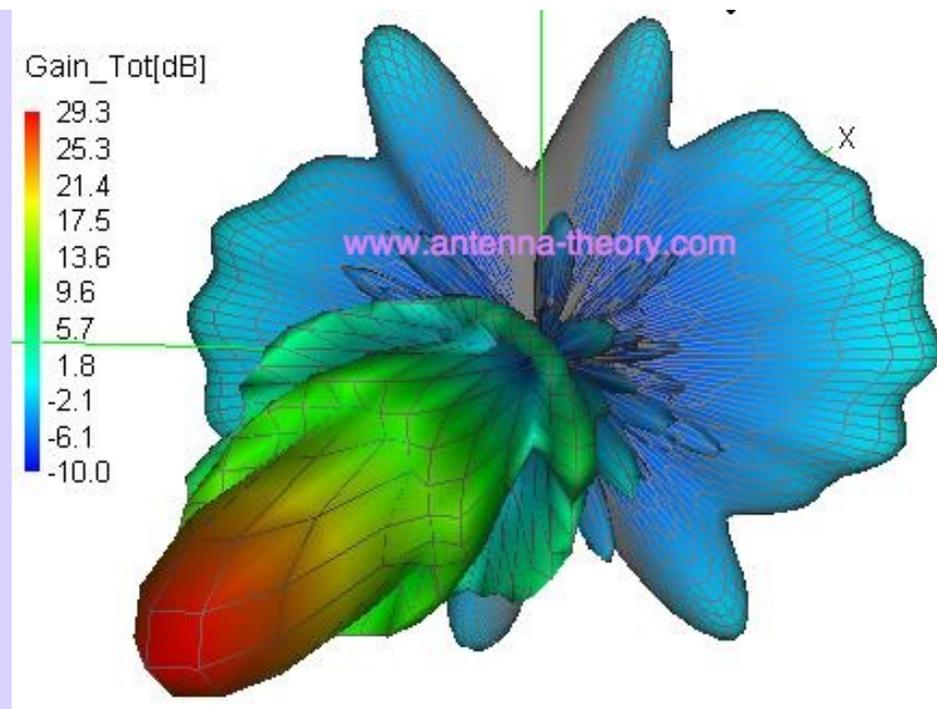


Figure 3. Directional Radiation Pattern for the Dish Antenna.

In summary, the radiation pattern is a plot which allows us to visualize where the antenna transmits or receives power.

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# Field Regions

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The fields surrounding an antenna are divided into 3 principle regions:

- [Reactive Near Field](#)
- [Radiating Near Field or Fresnel Region](#)
- [Far Field or Fraunhofer Region](#)

The far field region is the most important, as this determines the antenna's radiation pattern. Also, antennas are used to communicate wirelessly from long distances, so this is the region of operation for most antennas. We will start with this region.

## Far Field (Fraunhofer) Region

The far field is the region far from the antenna, as you might suspect. In this region, the radiation pattern does not change shape with distance (although the fields still die off as  $1/R$ , the power density dies off as  $1/R^2$ ). Also, this region is dominated by radiated fields, with the E- and H-fields orthogonal to each other and the direction of propagation as with plane waves.

If the maximum linear dimension of an antenna is  $D$ , then the following 3 conditions must all be satisfied to be in the far field region:

$$R > \frac{2D^2}{\lambda}$$

[Equation 1]

$$R \gg D$$

[Equation 2]

$$R \gg \lambda$$

[Equation 3]

The first and second equation above ensure that the power radiated in a given direction from distinct parts of the antenna are approximately parallel (see Figure 1). This helps ensure the fields in the far-field region behave like plane waves. Note that  $\gg$  means "much much greater than" and is typically assumed satisfied if the left side is 10 times larger than the right side.

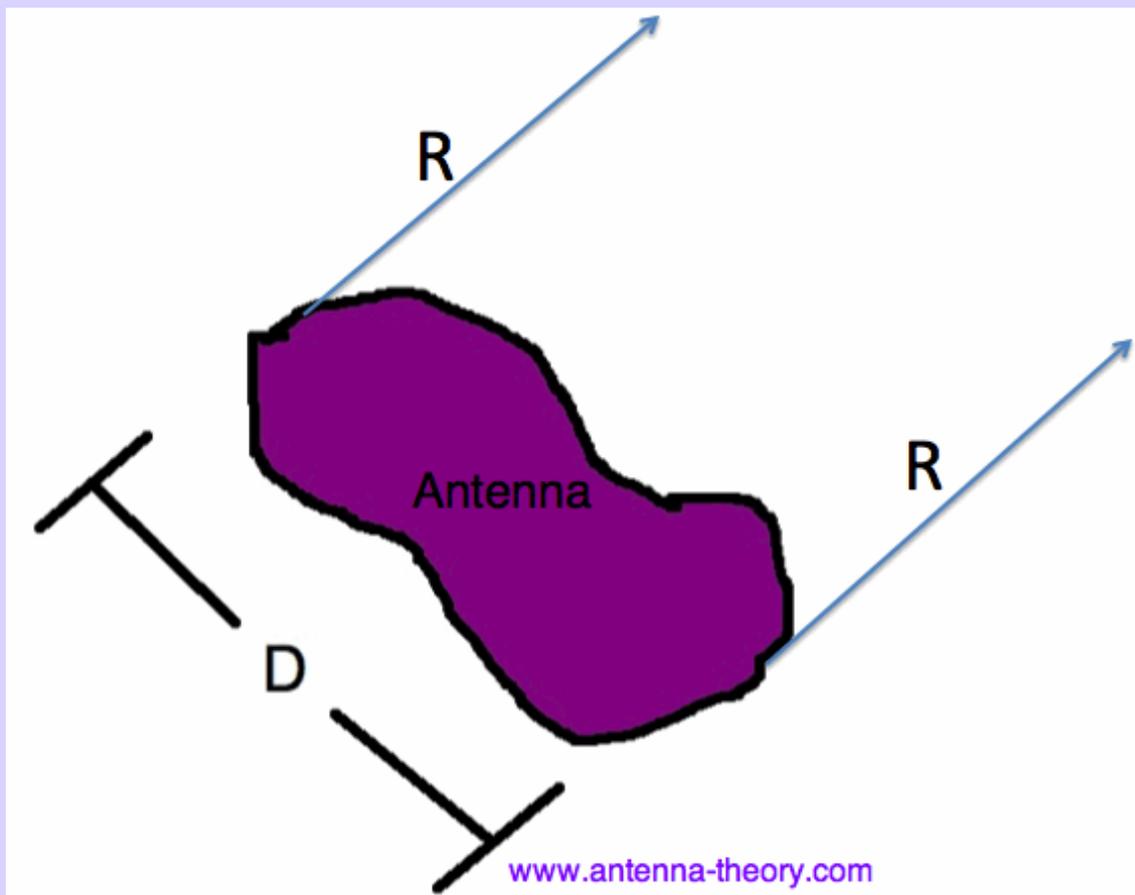


Figure 1. The Rays from any Point on the Antenna are Approximately Parallel in the Far Field.

Finally, where does the third far-field equation come from? Near a radiating antenna, there are reactive fields (see reactive near field region, below), that typically have the [E-fields](#) and [H-fields](#) die off with distance as  $\frac{1}{r^2}$  and  $\frac{1}{r^3}$ . The third equation above ensures that these near fields are gone, and we are left with the radiating fields, which fall off with distance as  $\frac{1}{r}$ .

The far-field region is sometimes referred to as the Fraunhofer region, a carryover term from optics.

## Reactive Near Field Region

In the immediate vicinity of the antenna, we have the reactive near field. In this region, the fields are predominately reactive fields, which means the E- and H- fields are out of phase by 90 degrees to each other (recall that for propagating or radiating fields, the fields are orthogonal (perpendicular) but are in phase).

The boundary of this region is commonly given as:

$$\frac{2D^2}{\lambda}$$

## Radiating Near Field (Fresnel) Region

The radiating near field or Fresnel region is the region between the near and far fields. In this region, the reactive fields are not dominant; the radiating fields begin to emerge. However, unlike the Far Field region, here the shape of the radiation pattern may vary appreciably with distance.

The region is commonly given by:

fresnel region for antennas

Note that depending on the values of  $R$  and the wavelength, this field may or may not exist.

Finally, the above can be summarized via the following diagram:

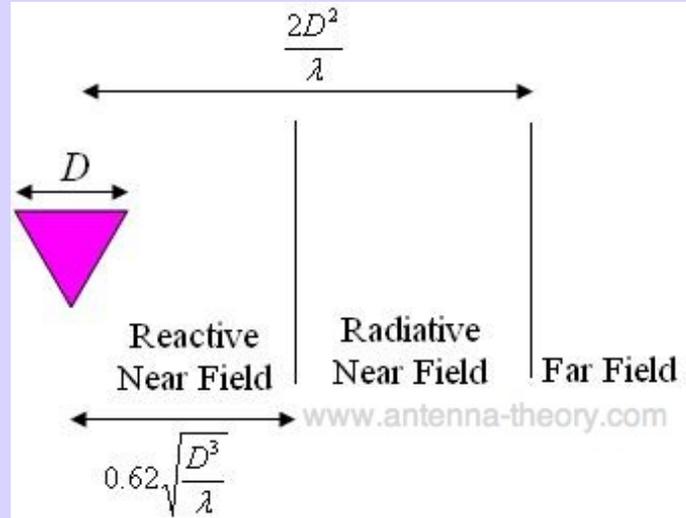


Figure 2. Illustration of the Field Regions for an Antenna of Maximum Linear Dimension  $D$ .

Next we'll look at numerically describing the directionality of an antenna's radiation pattern.

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# Directivity

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**Directivity** is a fundamental antenna parameter. It is a measure of how 'directional' an antenna's radiation pattern is. An antenna that radiates equally in all directions would have effectively zero directionality, and the directivity of this type of antenna would be 1 (or 0 dB).

**[Silly side note: When a directivity is specified for an antenna, what is meant is 'peak directivity'. Directivity is technically a function of angle, but the angular variation is described by its radiation pattern. Hence, directivity throughout this page will mean peak directivity, because it is rarely used in another context.]**

An antenna's normalized radiation pattern can be written as a function in [spherical coordinates](#):

radiation pattern for  
directivity

**[Equation 1]**

A normalized radiation pattern is the same as a radiation pattern; it is just scaled in magnitude such that the peak (maximum value) of the magnitude of the radiation pattern ( $F$  in equation [1]) is equal to 1. Mathematically, the formula for directivity ( $D$ ) is written as:

$$D = \frac{1}{\frac{1}{4\pi} \int_0^{2\pi} \int_0^{\pi} |F(\theta, \phi)|^2 \sin \theta d\theta d\phi}$$

This equation for directivity might look complicated, but the numerator is the maximum value of  $F$ , and the denominator just represents the "average power radiated over all directions". This equation then is just a measure of the peak value of radiated power divided by the average, which gives the directivity of the antenna.

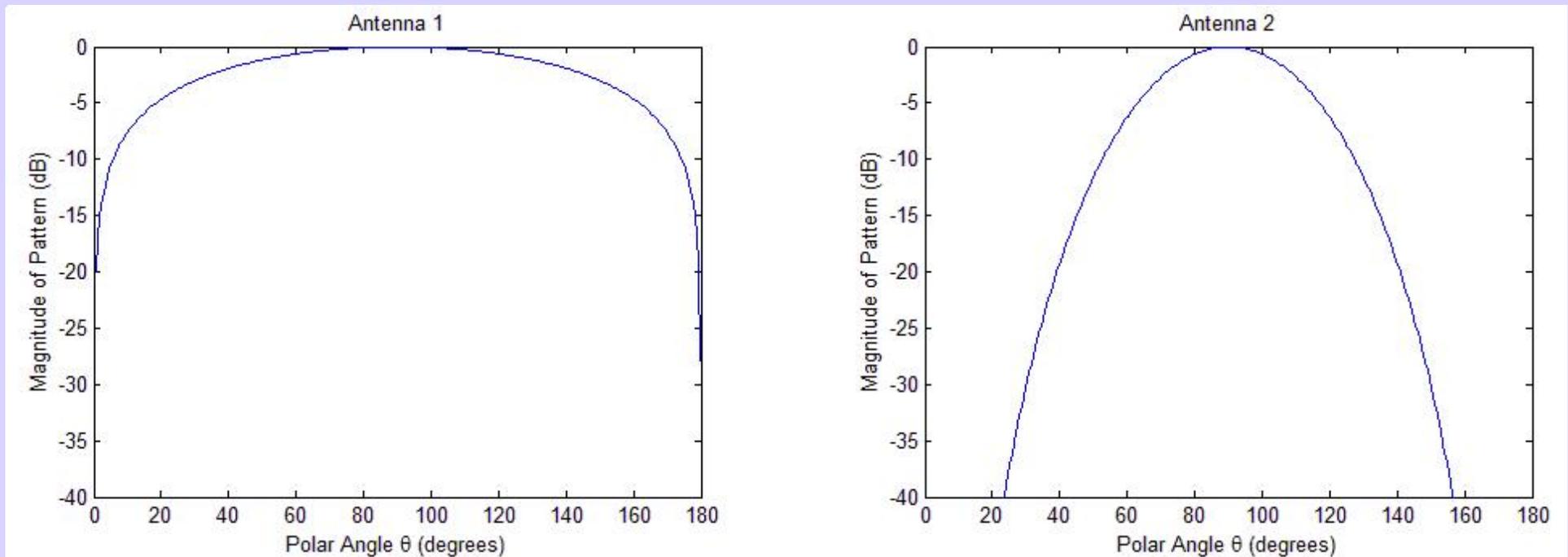
## Directivity Example

As an example consider two antennas, one with radiation patterns given by:

$\text{directivity 1}$     **Antenna 1**

$\text{directivity 2}$     **Antenna 2**

These radiation patterns are plotted in Figure 1. Note that the patterns are only a function of the polar angle  $\text{polar angle theta}$ , and not a function of the azimuth angle (uniform in azimuth). The radiation pattern for antenna 1 is less directional than that for antenna 2; hence we expect the directivity to be lower.



## Figure 1. Plots of Radiation Patterns for Antennas. Which has the higher directivity?.

Using Equation [1], we can figure out which antenna has the higher directivity. But to check your understanding, you should think about Figure 1 and what directivity is, and determine which has a higher directivity without using any mathematics.

The results of the directivity calculation, using Equation [1]:

The directivity is calculated for Antenna 1 to be 1.273 (1.05 dB).

The directivity is calculated for Antenna 2 to be 2.707 (4.32 dB).

Again, increased directivity implies a more 'focused' or 'directional' antenna. In words, Antenna 2 receives 2.707 times more power in its peak direction than an isotropic antenna would receive. Antenna 1 would receive 1.273 times the power of an isotropic antenna. The isotropic antenna is used as a common reference, even though no isotropic antennas exist.

Antennas for cell phones should have a low directivity because the signal can come from any direction, and the antenna should pick it up. In contrast, satellite dish antennas have a very high directivity, because they are to receive signals from a fixed direction. As an example, if you get a directTV dish, they will tell you where to point it such that the antenna will receive the signal.

Finally, we'll conclude with a list of antenna types and their directivities, to give you an idea of what is seen in practice.

As you can see from the above table, the directivity of an antenna can vary over several order of magnitude. Hence, it is important to understand directivity in choosing the best antenna for your specific application. If you need to transmit or receive energy from a wide variety of directions (example: car radio, mobile phones, computer wifi), then you should design an antenna with a low directivity. Conversely, if you are doing remote sensing, or targeted power transfer (example: received signal from a mountain top), you want a high directivity antenna, to maximize power transfer and reduce signal from unwanted directions.

### **A Little Bit of Antenna Design**

Let's say we decide that we want an antenna with a low directivity. How do we accomplish this?

The general rule in Antenna Theory is that you need an electrically small antenna to produce low directivity. That is, if you use an antenna with a total size of 0.25 - 0.5 wavelength for directivity (a quarter- to a half-

wavelength in size), then you will minimize directivity. That is, [half-wave dipole antennas](#) or [half-wavelength slot antennas](#) typically have directivities less than 3 dB, which is about as low of a directivity as you can obtain in practice. Ultimately, we can't make antennas much smaller than a quarter-wavelength without sacrificing [antenna efficiency](#) (the next topic) and [antenna bandwidth](#).

Conversely, for antennas with a high directivity, we'll need antennas that are many wavelengths in size. That is, antennas such as [dish \(or satellite\) antennas](#) and [horn antennas](#) have high directivity, in part because they are many wavelengths long.

**Why is this? [I don't know how to explain this without getting mathematical, sorry!] Ultimately, it has to do with the properties of the Fourier Transform. When you take the Fourier Transform of a short pulse, you get a broad frequency spectrum. The analogy is present in determining the radiation pattern of an antenna: the pattern can be thought of as the Fourier Transform of the antenna's current or voltage distribution. As a result, small antennas have broad radiation patterns (low directivity), and antennas with large uniform voltage or current distributions have very directional patterns (and thus, a high directivity).**

Now that we know what directivity is, we can move on to the next antenna concept, gain.

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Antenna Type	Typical Directivity	Typical Directivity (dB)
<a href="#">Short Dipole Antenna</a>	1.5	1.76
<a href="#">Half-Wave Dipole Antenna</a>	1.64	2.15
<a href="#">Patch (Microstrip) Antenna</a>	3.2-6.3	5-8
<a href="#">Horn Antenna</a>	10-100	10-20

<a href="#">Dish Antenna</a>	10-10,000	10-40
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# Antenna Efficiency and Antenna Gain

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On this page, we'll introduce two fundamental antenna parameters: antenna efficiency and antenna gain.

## Antenna Efficiency

The **efficiency** of an antenna relates the power delivered to the antenna and the power radiated or dissipated within the antenna. A high efficiency antenna has most of the power present at the antenna's input radiated away. A low efficiency antenna has most of the power absorbed as losses within the antenna, or reflected away due to impedance mismatch.

[Side Note: [Antenna Impedance](#) is discussed in a later section. Impedance Mismatch is simply power reflected from an antenna because its impedance is not the correct value; hence, "impedance mismatch". ]

The losses associated within an antenna are typically the conduction losses (due to finite conductivity of the antenna) and dielectric losses (due to conduction within a dielectric which may be present within an antenna).

The antenna efficiency (or radiation efficiency) can be written as the ratio of the radiated power to the input power of the antenna:

$$\epsilon_R = \frac{P_{\text{radiated}}}{P_{\text{input}}}$$

[Equation 1]

Efficiency is ultimately a ratio, giving a number between 0 and 1. Efficiency is very often quoted in terms of a percentage; for example, an efficiency of 0.5 is the same as 50%. Antenna efficiency is also frequently quoted in [decibels \(dB\)](#); an efficiency of 0.1 is 10% or (-10 dB), and an efficiency of 0.5 or 50% is -3 dB.

Equation [1] is sometimes referred to as the antenna's radiation efficiency. This distinguishes it from another sometimes-used term, called an antenna's "total efficiency". The total efficiency of an antenna is the radiation efficiency multiplied by the impedance mismatch loss of the antenna, when connected to a transmission line or receiver (radio or transmitter). This can be summarized in Equation [2], where  $\epsilon_T$  is the antenna's total efficiency,  $M_L$  is the antenna's loss due to impedance mismatch, and  $\epsilon_R$  is the antenna's radiation efficiency.

$$\epsilon_T = M_L \cdot \epsilon_R$$

[Equation 2]

Since  $M_L$  is always a number between 0 and 1, the total antenna efficiency is always less than the antenna's radiation efficiency. Said another way, the radiation efficiency is the same as the total antenna efficiency if there was no loss due to impedance mismatch.

Efficiency is one of the most important antenna parameters. It can be very close to 100% (or 0 dB) for dish, horn antennas, or half-wavelength dipoles with no lossy materials around them. Mobile phone antennas, or wifi antennas in consumer electronics products, typically have efficiencies from 20%-70% (-7 to -1.5 dB). The losses are often due to the electronics and materials that surround the antennas; these tend to absorb some of the radiated power (converting the energy to heat), which lowers the efficiency of the antenna. Car radio antennas can have a total antenna efficiency of -20 dB (1% efficiency) at the AM radio frequencies; this is because the antennas are much smaller than a half-wavelength at the operational frequency, which greatly lowers antenna efficiency. The radio link is maintained because the AM Broadcast tower uses a very high transmit power.

Improving impedance mismatch loss is discussed in the [Smith Charts and impedance matching](#) section. Impedance matching can greatly improve the efficiency of an antenna.

## Antenna Gain

The term **Antenna Gain** describes how much power is transmitted in the direction of peak radiation to that of an isotropic source. **Antenna gain** is more commonly quoted in a real antenna's specification sheet because it takes into account the actual losses that occur.

An antenna with a gain of 3 dB means that the power received far from the antenna will be 3 dB higher (twice as much) than what would be received from a lossless isotropic antenna with the same input power.

Antenna Gain is sometimes discussed as a function of angle, but when a single number is quoted the gain is the 'peak gain' over all directions. Antenna Gain ( $G$ ) can be related to [directivity](#) ( $D$ ) by:

$$G = \epsilon_R D$$

[Equation 3]

The gain of a real antenna can be as high as 40-50 dB for very large dish antennas (although this is rare). Directivity can be as low as 1.76 dB for a real antenna (example: [short dipole antenna](#)), but can never theoretically be less than 0 dB. However, the peak gain of an antenna can be arbitrarily low because of losses or low efficiency. Electrically small antennas (small relative to the wavelength of the frequency that the antenna operates at) can be very inefficient, with antenna gains lower than -10 dB (even without accounting for impedance mismatch loss).

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## Beamwidths and Sidelobe Levels

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In addition to [directivity](#), the [radiation patterns of antennas](#) are also characterized by their beamwidths and sidelobe levels (if applicable).

These concepts can be easily illustrated. Consider the radiation pattern given by:

$$R(\theta) = \sin \theta \frac{\sin\left(4\left(\theta - \frac{\pi}{2}\right)\right)}{4\left(\theta - \frac{\pi}{2}\right)}$$

This pattern is actually fairly easy to generate using [Antenna Arrays](#), as will be seen in that section. The 3-dimensional view of this radiation pattern is given in Figure 1.

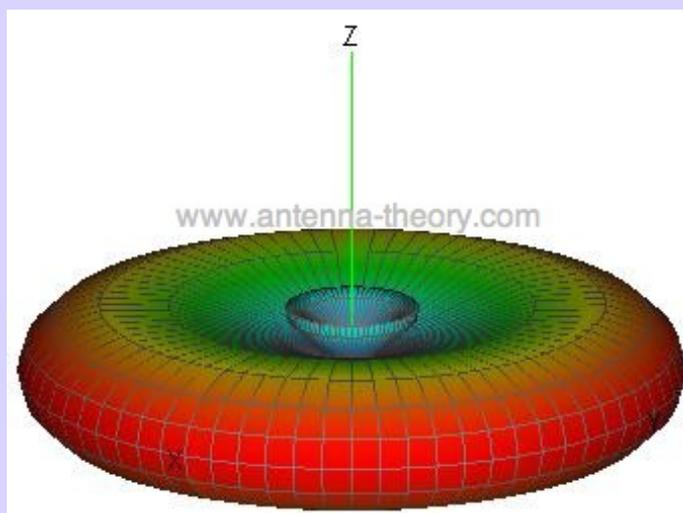


Figure 1. 3D Radiation Pattern.

The polar (polar angle measured off of z-axis) plot is given by:

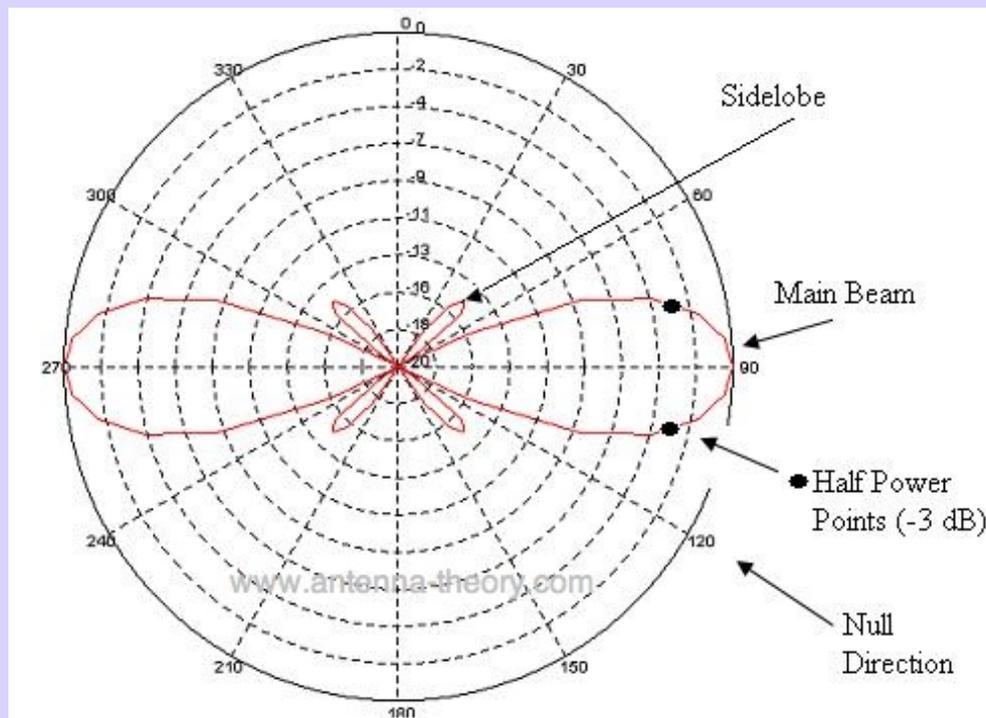


Figure 2. Polar Radiation Pattern.

The **main beam** is the region around the direction of maximum radiation (usually the region that is within 3 dB of the peak of the main beam). The main beam in Figure 2 is centered at 90 degrees.

The **sidelobes** are smaller beams that are away from the main beam. These sidelobes are usually radiation in undesired directions which can never be completely eliminated. The sidelobes in Figure 2 occur at roughly 45 and 135 degrees.

The **Half Power Beamwidth (HPBW)** is the angular separation in which the magnitude of the radiation pattern decrease by 50% (or -3 dB) from the peak of the main beam. From Figure 2, the pattern decreases to -3 dB at 77.7 and 102.3 degrees. Hence the HPBW is  $102.3 - 77.7 = 24.6$  degrees.

Another commonly quoted beamwidth is the **Null to Null Beamwidth**. This is the angular separation from which the magnitude of the radiation pattern decreases to zero (negative infinity dB) away from the main beam. From Figure 2, the pattern goes to zero (or minus infinity) at 60 degrees and 120 degrees. Hence, the Null-Null Beamwidth is  $120 - 60 = 60$  degrees.

Finally, the **Sidelobe Level** is another important parameter used to characterize radiation patterns. The sidelobe level is the maximum value of the sidelobes (away from the main beam). From Figure 2, the Sidelobe Level (*SLL*) is -14.5 dB.

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## Antenna Impedance

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Antenna **impedance** relates the voltage to the current at the input to the antenna. This is extremely important as we will see.

Let's say an antenna has an impedance of 50 ohms. This means that if a sinusoidal voltage is applied at the antenna terminals with an amplitude of 1 Volt, then the current will have an amplitude of  $1/50 = 0.02$  Amps. Since the impedance is a real number, the voltage is in-phase with the current.

Alternatively, suppose the impedance is given by a complex number, say  $Z=50 + j*50$  ohms.

Note that "j" is the square root of -1. Imaginary numbers are there to give phase information. If the impedance is entirely real [ $Z=50 + j*0$ ], then the voltage and current are exactly in time-phase. If the impedance is entirely imaginary [ $Z=0 + j*50$ ], then the voltage leads the current by 90 degrees in phase.

If  $Z=50 + j*50$ , then the impedance has a magnitude equal to:



The phase will be equal to:



This means the phase of the current will lag the voltage by 45 degrees. That is, the current waveform is delayed relative to the voltage waveform. To spell it out, if the voltage (with frequency  $f$ ) at the antenna terminals is given by



The electric current will then be equal to:

$$I(t) = \frac{1}{70.71} \cos\left(2\pi ft - \frac{\pi}{180} \cdot 45\right)$$

Hence, antenna impedance is a simple concept. Impedance relates the voltage and current at the input to the antenna. The real part of the antenna impedance represents power that is either radiated away or absorbed within the antenna. The imaginary part of the impedance represents power that is stored in the near field of the antenna. This is non-radiated power. An antenna with a real input impedance (zero imaginary part) is said to be resonant. Note that the impedance of an antenna will vary with frequency.

While simple, we will now explain why this is important, considering both the low frequency and high frequency cases.

### Low Frequency

When we are dealing with low frequencies, the transmission line that connects the transmitter or receiver to the antenna is short. Short in antenna theory always means "relative to a wavelength". Hence, 5 meters could be short or very long, depending on what frequency we are operating at. At 60 Hz, the wavelength is about 3100 miles, so the transmission line can almost always be neglected. However, at 2 GHz, the wavelength is 15 cm, so the little length of line within your cell phone can often be considered a 'long line'. Basically, if the line length is less than a tenth of a wavelength, it is reasonably considered a short line.

Consider an antenna (which is represented as an impedance given by  $Z_A$ ) hooked up to a voltage source (of magnitude  $V$ ) with source impedance given by  $Z_S$ . The equivalent circuit of this is shown in Figure 1.

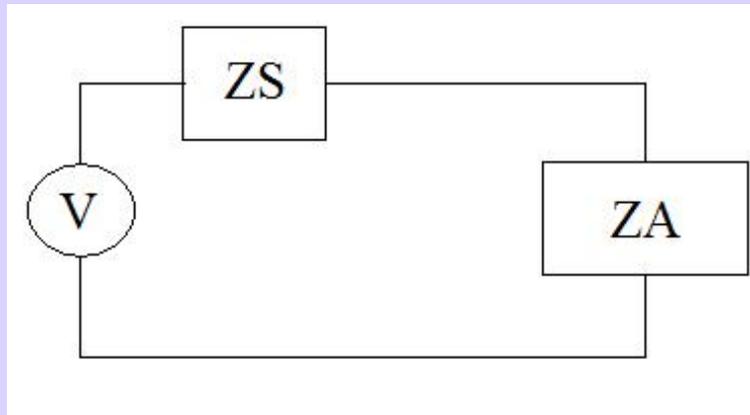


Figure 1. Circuit model of an antenna connected to a voltage source.

From circuit theory, we know that  $P=I*V$ . The power that is delivered to the antenna is:



If  $Z_A$  is much smaller in magnitude than  $Z_S$ , then no power will be delivered to the antenna and it won't transmit or receive energy. If  $Z_A$  is much larger in magnitude than  $Z_S$ , then no power will be delivered as well.

For maximum power to be transferred from the generator to the antenna, the ideal value for the antenna impedance is given by:



The  $*$  in the above equation represents complex conjugate. So if  $Z_S=30+j*30$  ohms, then for maximum power transfer the antenna should impedance  $Z_A=30-j*30$  ohms. Typically, the source impedance is real (imaginary part equals zero), in which case maximum power transfer occurs when  $Z_A=Z_S$ .

Hence, we now know that for an antenna to work properly, its impedance must not be too large or too small. It turns out that this is one of the fundamental design parameters for an antenna, and it isn't always easy to design an antenna with the right impedance - particularly over a wide frequency range.

## High Frequency

This section will be a little more advanced. In low-frequency circuit theory, the wires that connect

things don't matter. Once the wires become a significant fraction of a wavelength, they make things very different. For instance, a short circuit has an impedance of zero ohms. However, if the impedance is measured at the end of a quarter wavelength transmission line, the impedance appears to be infinite, even though there is a dc conduction path.

In general, the transmission line will transform the impedance of an antenna, making it very difficult to deliver power, unless the antenna is matched to the transmission line. Consider the situation shown in Figure 2. The impedance is to be measured at the end of a transmission line (with characteristic impedance  $Z_0$ ) and Length  $L$ . The end of the transmission line is hooked to an antenna with impedance  $Z_A$ .

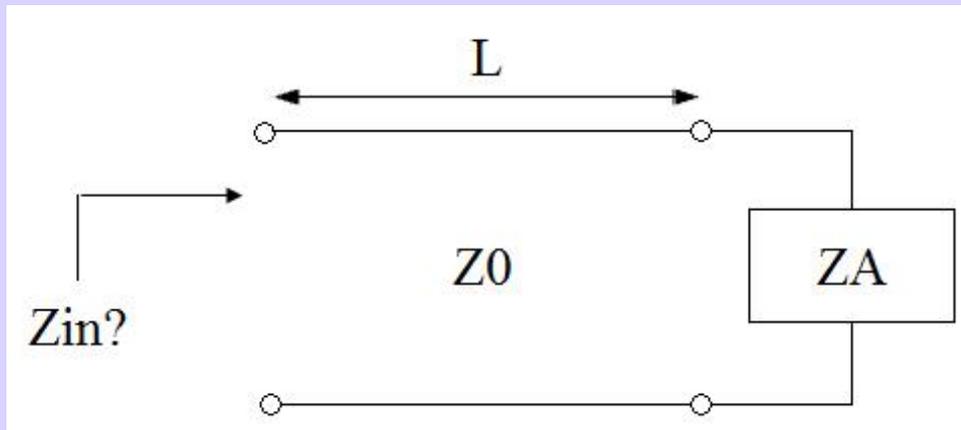


Figure 2. High Frequency Example.

It turns out (after studying transmission line theory for a while), that the input impedance  $Z_{in}$  is given by:

$$Z_{in} = Z_0 \frac{Z_A + jZ_0 \cdot \tan\left(\frac{2\pi f}{c} L\right)}{Z_0 + jZ_A \cdot \tan\left(\frac{2\pi f}{c} L\right)}$$

This is a little formidable for an equation to understand at a glance. However, the happy thing is:

**If the antenna is matched to the transmission line ( $Z_A=Z_0$ ), then the input impedance does not depend on the length of the transmission line.**

This makes things much simpler. If the antenna is not matched, the input impedance will vary widely with the length of the transmission line. And if the input impedance isn't well matched to the source impedance, not very much power will be delivered to the antenna. This power ends up being reflected back to the generator, which can be a problem in itself (especially if high power is transmitted). This loss of power is known as *impedance mismatch*. Hence, we see that having a tuned impedance for an antenna is extremely important. For more information on transmission lines, see the [transmission line tutorial](#).

## VSWR

We see that an antenna's impedance is important for minimizing impedance-mismatch loss. A

poorly matched antenna will not radiate power. This can be somewhat alleviated via [impedance matching](#), although this doesn't always work over a sufficient bandwidth (bandwidth is the next topic).

A common measure of how well matched the antenna is to the transmission line or receiver is known as the Voltage Standing Wave Ratio (VSWR). VSWR is a real number that is always greater than or equal to 1. A VSWR of 1 indicates no mismatch loss (the antenna is perfectly matched to the tx line). Higher values of VSWR indicate more mismatch loss.

As an example of common VSWR values, a VSWR of 3.0 indicates about 75% of the power is delivered to the antenna (1.25 dB of mismatch loss); a VSWR of 7.0 indicates 44% of the power is delivered to the antenna (3.6 dB of mismatch loss). A VSWR of 6 or more is pretty high and will generally need to be improved.

The parameter VSWR sounds like an overly complicated concept; however, power reflected by an antenna on a transmission line interferes with the forward travelling power - and this creates a standing voltage wave - which can be numerically evaluated by the quantity Voltage Standing Wave Ratio (VSWR). For more information, see the page on [VSWR and VSWR Specifications](#).

In the next section on antenna basics, we'll look at the very important antenna parameter known as bandwidth.

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# Bandwidth

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**Bandwidth** is another fundamental antenna parameter. Bandwidth describes the range of [frequencies](#) over which the antenna can properly radiate or receive energy. Often, the desired bandwidth is one of the determining parameters used to decide upon an antenna. For instance, many antenna types have very narrow bandwidths and cannot be used for wideband operation.

Bandwidth is typically quoted in terms of [VSWR](#). For instance, an antenna may be described as operating at 100-400 MHz with a  $VSWR < 1.5$ . This statement implies that the reflection coefficient is less than 0.2 across the quoted frequency range. Hence, of the power delivered to the antenna, only 4% of the power is reflected back to the transmitter. Alternatively, the return loss  $S_{11} = 20 \cdot \log_{10}(0.2) = -13.98$  dB.

Note that the above does not imply that 96% of the power delivered to the antenna is transmitted in the form of EM radiation; losses must still be taken into account.

Also, the [radiation pattern](#) will vary with frequency. In general, the shape of the radiation pattern does not change radically.

There are also other criteria which may be used to characterize bandwidth. This may be the polarization over a certain range, for instance, an antenna may be described as having circular polarization with an [axial ratio](#)  $< 3$  dB (less than 3 dB) from 1.4-1.6 GHz. This polarization bandwidth sets the range over which the antenna's operation is approximately circularly polarized.

The bandwidth is often specified in terms of its [Fractional Bandwidth \(FBW\)](#). The FBW is the ratio of the frequency range (highest frequency minus lowest frequency) divided by the center frequency. The [antenna Q](#) also relates to bandwidth (higher Q is lower bandwidth, and vice versa).

To give some concrete examples of bandwidth, here is a table of the bandwidths for common antenna types. This will answer such questions as "what is the bandwidth of a dipole antenna?" and "which antenna has a higher bandwidth - a patch or a spiral antenna?". For a fair comparison, we set the center frequency for each antenna to 1 GHz (1000 MHz).

Table I. The Bandwidth for Several Common Antennas.

Antenna	Center Frequency	Frequency Range	Fractional Bandwidth	Ratio	Percentage Bandwidth
Patch	1000 MHz	985-1015 MHz	0.03	1.0305:1	3%
Dipole	1000 MHz	960-1040 MHz	0.08	1.083:1	8%
<a href="http://www.antenna-theory.com">www.antenna-theory.com</a>					
Horn	1000 MHz	154-1848 MHz	1.694	12:1	169.40%
Spiral	1000 MHz	95-1900 MHz	1.805	20:1	180.50%

As can be seen from Table I, the bandwidth for antennas can vary widely. [Patch \(Microstrip\) Antennas](#) are very low bandwidth, while [spiral antennas](#) have a very large bandwidth.

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# Polarization - EM Waves and Antennas

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## Polarization of Plane Waves

**Polarization** (or Polarisation for our British friends) is one of the fundamental characteristics of any antenna. First we'll need to understand polarization of plane waves, then we'll walk through the main types of antenna polarization.

### Linear Polarization

Let's start by understanding the polarization of a plane electromagnetic wave.

A plane electromagnetic (EM) wave is characterized by travelling in a single direction (with no field variation in the two orthogonal directions). In this case, the electric field and the magnetic field are perpendicular to each other and to the direction the plane wave is propagating. As an example, consider the single frequency E-field given by equation (1), where the field is traveling in the +z-direction, the E-field is oriented in the +x-direction, and the magnetic field is in the +y-direction.

description of plane wave  
propagating in the y-  
direction

In equation (1), the symbol unit vector is a unit vector (a vector with a length of one), which says that the E-field "points" in the x-direction.

A plane wave is illustrated graphically in Figure 1.

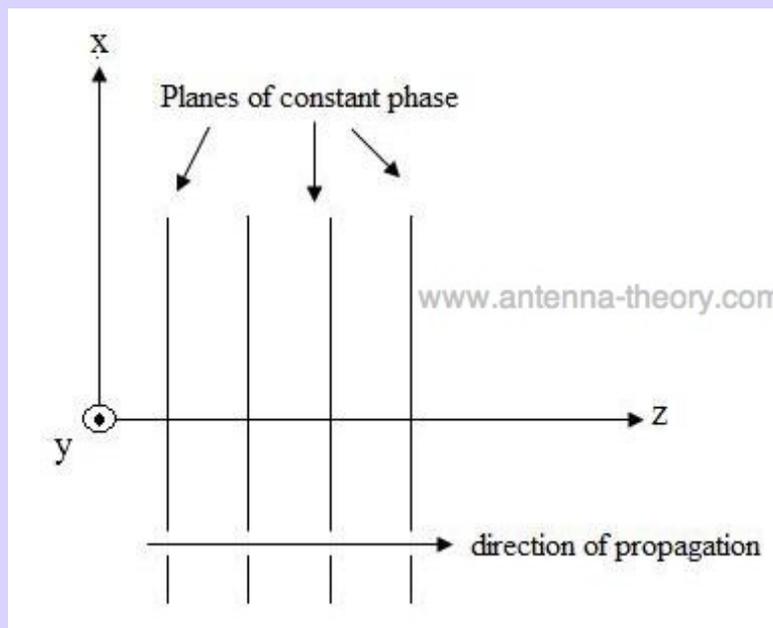
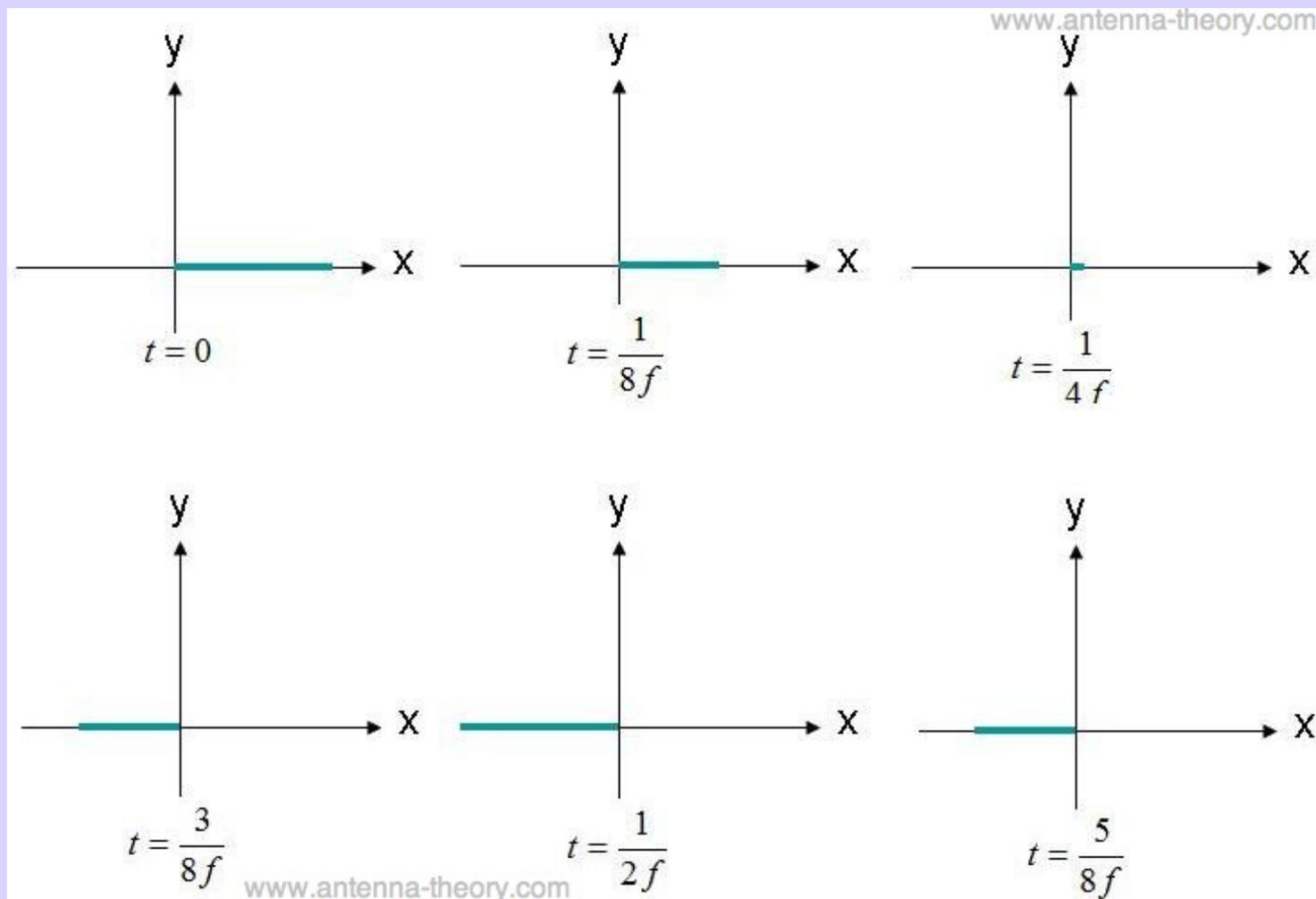


Figure 1. Graphical representation of E-field travelling in +z-direction.

**Polarization** is the figure that the E-field traces out while propagating. As an example, consider the E-field observed at  $(x,y,z)=(0,0,0)$  as a function of time for the plane wave described by equation (1) above. The amplitude of this field is plotted in Figure 2 at several instances of time. The field is oscillating at frequency  $f$ .

Figure 2. Observation of E-field at  $(x,y,z)=(0,0,0)$  at different times.

Observed at the origin, the E-field oscillates back and forth in magnitude, always directed along the x-axis. Because the E-field stays along a single line, this field would be said to be **linearly polarized**. In addition, if the x-axis was parallel to the ground, this field could also be described as "horizontally polarized" (or sometimes h-pole in the industry). If the field was oriented along the y-axis, this wave would be said to be "vertically polarized" (or v-pole).

A linearly polarized wave does not need to be along the horizontal or vertical axis. For instance, a wave with an E-field constrained to lie along the line shown in Figure 3 would also be linearly polarized.

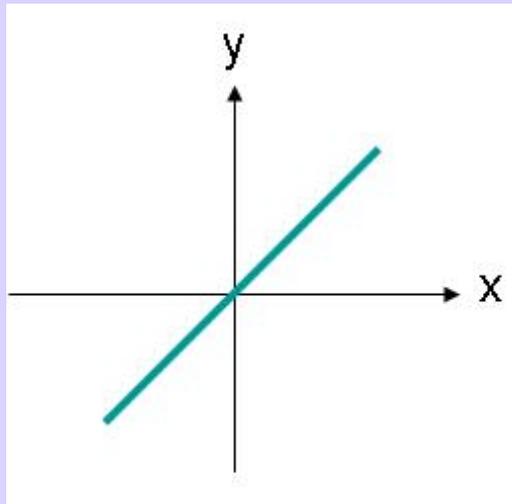


Figure 3. Locus of E-field amplitudes for a linearly polarized wave at an angle.

The E-field in Figure 3 could be described by equation (2). The E-field now has an x- and y-component, equal in magnitude.

linear polarized wave  
described by E-field  
components

One thing to notice about equation (2) is that the x- and y-components of the E-field are in phase - they both have the same magnitude and vary at the same rate.

## Circular Polarization

Suppose now that the E-field of a plane wave was given by equation (3):

mathematical description of  
E-field in a circularly  
polarized field

In this case, the x- and y- components are 90 degrees out of phase. If the field is observed at  $(x,y,z)=(0,0,0)$  again as before, the plot of the E-field versus time would appear as shown in Figure 4.

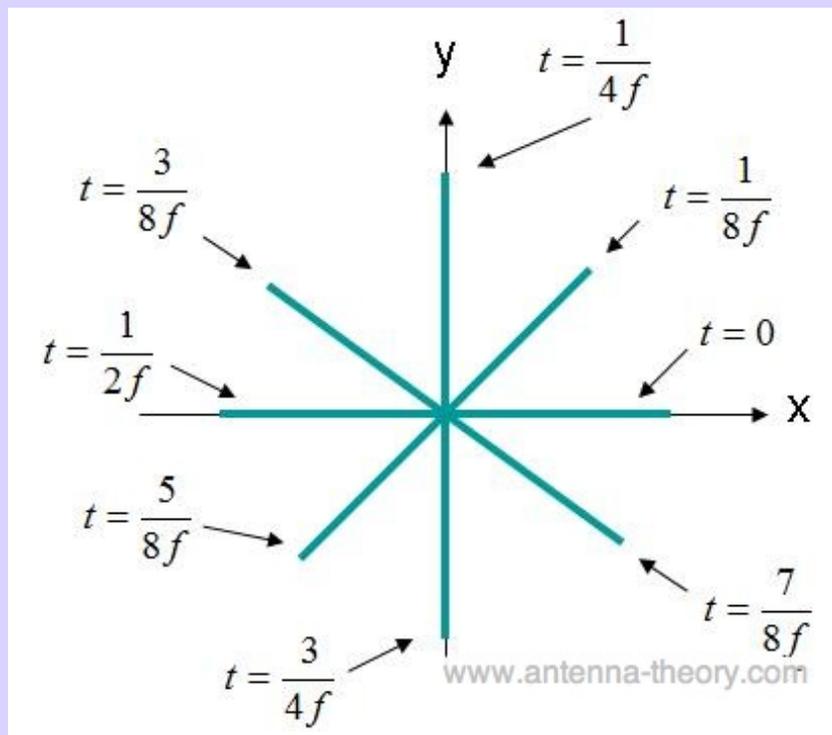


Figure 4. E-field strength at  $(x,y,z)=(0,0,0)$  for field of Eq. (3).

The E-field in Figure 4 rotates in a circle. This type of field is described as a **circularly polarized** wave. To have circular polarization, the following criteria must be met:

#### Criteria for Circular Polarization

- The E-field must have two orthogonal (perpendicular) components.
- The E-field's orthogonal components must have equal magnitude.
- The orthogonal components must be 90 degrees out of phase.

If the wave in Figure 4 is travelling out of the screen, the field is rotating in the counter-clockwise direction and is said to be **Right Hand Circularly Polarized (RHCP)**. If the fields were rotating in the clockwise direction, the field would be **Left Hand Circularly Polarized (LHCP)**.

## Elliptical Polarization

If the E-field has two perpendicular components that are out of phase by 90 degrees but are not equal in magnitude, the field will end up **Elliptically Polarized**. Consider the plane wave travelling in the +z-direction, with E-field described by equation (4):

description of elliptical polarizations in equation form

The locus of points that the tip of the E-field vector would assume is given in Figure 5.

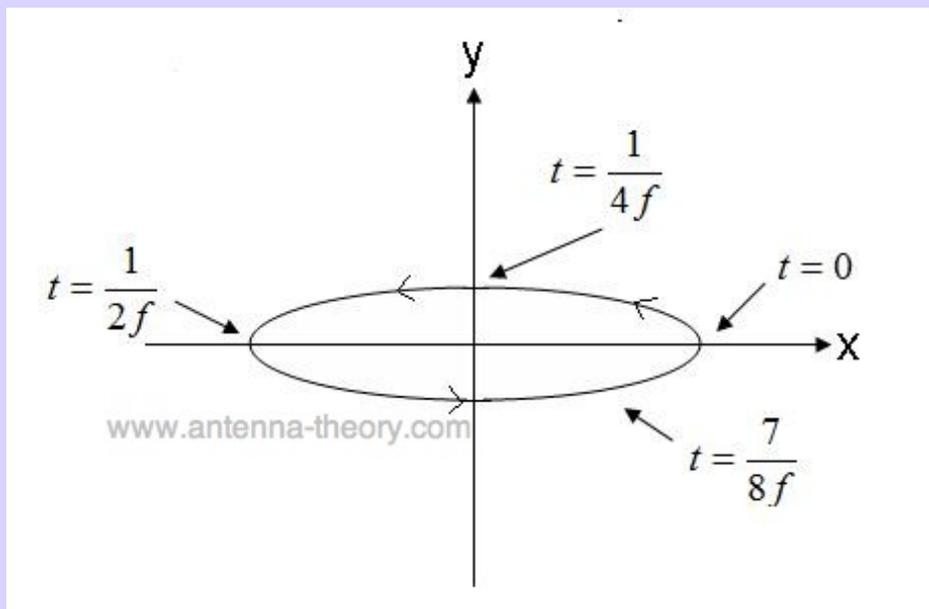


Figure 5. Tip of E-field for elliptical polarized wave of Eq. (4).

The field in Figure 5, travels in the counter-clockwise direction, and if travelling out of the screen would be **Right Hand Elliptically Polarized**. If the E-field vector was rotating in the opposite direction, the field would be **Left Hand Elliptically Polarized**.

In addition, elliptical polarization is defined by its eccentricity, which is the ratio of the major and minor axis amplitudes. For instance, the eccentricity of the wave given by equation (4) is  $1/0.3 = 3.33$ . Elliptically polarized waves are further described by the direction of the major axis. The wave of equation (4) has a major axis given by the x-axis. Note that the major axis can be at any angle in the plane, it does not need to coincide with the x-, y-, or z-axis. Finally, note that circular polarization and linear polarization are both special cases of elliptical polarization. An elliptically polarized wave with an eccentricity of 1.0 is a circularly polarized wave; an elliptically polarized wave with an infinite eccentricity is a linearly polarized wave.

In the next section, we will use the knowledge of plane-wave polarization to characterize and understand antennas.

## Polarization of Antennas

Now that we are aware of the polarization of plane-wave EM fields, **antenna polarization** is straightforward to define.

The polarization of an antenna is the polarization of the radiated fields produced by an antenna, evaluated in the far field. Hence, antennas are often classified as "Linearly Polarized" or a "Right Hand Circularly Polarized Antenna".

This simple concept is important for antenna to antenna communication. First, a horizontally polarized antenna will not communicate with a vertically polarized antenna. Due to the reciprocity theorem, antennas transmit and receive in exactly the same manner. Hence, a vertically polarized antenna transmits and receives vertically polarized fields. Consequently, if a horizontally polarized antenna is trying to communicate with a vertically polarized antenna, there will be no reception.

In general, for two linearly polarized antennas that are rotated from each other by an angle  $\alpha$ , the power loss due to this polarization mismatch will be described by the *Polarization Loss Factor* (PLF):

### Polarization Loss Factor

Hence, if both antennas have the same polarization, the angle between their radiated E-fields is zero and there is no power loss due to polarization mismatch. If one antenna is vertically polarized and the other is horizontally polarized, the angle is 90 degrees and no power will be transferred.

As a side note, this explains why moving the cell phone on your head to a different angle can sometimes increase reception. Cell phone antennas are often linearly polarized, so rotating the phone can often match the polarization of the phone and thus increase reception.

Circular polarization is a desirable characteristic for many antennas. Two antennas that are both circularly polarized do not suffer signal loss due to polarization mismatch. Antennas used in GPS systems are Right Hand Circularly Polarized.

Suppose now that a linearly polarized antenna is trying to receive a circularly polarized wave. Equivalently, suppose a circularly polarized antenna is trying to receive a linearly polarized wave. What is the resulting *Polarization Loss Factor*?

Recall that circular polarization is really two orthogonal linear polarized waves 90 degrees out of phase. Hence, a linearly polarized (LP) antenna will simply pick up the in-phase component of the circularly polarized (CP) wave. As a result, the LP antenna will have a polarization mismatch loss of 0.5 (-3dB), no matter what the angle the LP antenna is rotated to. Therefore:

### PLF for circular to linear polarization or polarisation

The Polarization Loss Factor is sometimes referred to as polarization efficiency, antenna mismatch factor, or antenna receiving factor. All of these names refer to the same concept.

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## Effective Area (Effective Aperture)

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A useful parameter calculating the receive power of an antenna is the **effective area** or **effective aperture**. Assume that a plane wave with the same polarization as the receive antenna is incident upon the antenna. Further assume that the wave is travelling towards the antenna in the antenna's direction of maximum radiation (the direction from which the most power would be received).

Then the *effective aperture* parameter describes how much power is captured from a given plane wave. Let  $p$  be the power density of the plane wave (in  $\text{W}/\text{m}^2$ ). If  $P_t$  represents the power (in Watts) at the antennas terminals available to the antenna's receiver, then:

$$P_t = p A_e$$

Hence, the effective area simply represents how much power is captured from the plane wave and delivered by the antenna. This area factors in the losses intrinsic to the antenna (ohmic losses, dielectric losses, etc.).

A general relation for the effective aperture in terms of the peak [antenna gain](#) ( $G$ ) of any antenna is given by:

effective aperture as a  
function of peak gain and  
wavelength

Effective aperture or effective area can be measured on actual antennas by comparison with a known antenna with a given effective aperture, or by calculation using the measured gain and the above equation.

Effective aperture will be a useful concept for calculating received power from a plane wave. To see this in action, go to the next section on the Friis transmission formula.

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Next Topic: [Friis Transmission Formula](#)

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# The Friis Equation

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On this page, we introduce one of the most fundamental equations in antenna theory, the **Friis Transmission Equation**. The Friis Transmission Equation is used to calculate the power received from one antenna (with gain  $G1$ ), when transmitted from another antenna (with gain  $G2$ ), separated by a distance  $R$ , and operating at frequency  $f$  or wavelength  $\lambda$ . This page is worth reading a couple times and should be fully understood.

## Derivation of Friis Transmission Formula

To begin the derivation of the Friis Equation, consider two antennas in free space (no obstructions nearby) separated by a distance  $R$ :

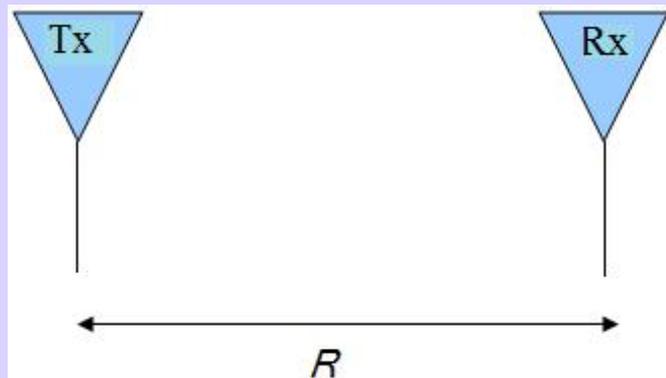


Figure 1. Transmit (Tx) and Receive (Rx) Antennas separated by  $R$ .

Assume that [friis transmission formula](#) Watts of total power are delivered to the transmit antenna. For the moment, assume that the transmit antenna is omnidirectional, lossless, and that the receive antenna is in the far field of the transmit antenna. Then the power density  $p$  (in Watts per square meter) of the plane wave incident on the receive antenna a distance  $R$  from the transmit antenna is given by:

$$\text{friis transmission formula}$$

If the transmit antenna has an [antenna gain](#) in the direction of the receive antenna given by  $G_1$ , then the power density equation above becomes:

$$\text{antennas}$$

The gain term factors in the directionality and losses of a real antenna. Assume now that the receive antenna has an effective aperture given by [antenna theory](#). Then the power received by this antenna [antenna tutorial](#) is given by:

$$\text{Friis}$$

Since the effective aperture for any antenna can also be expressed as:

effective aperture

The resulting received power can be written as:

received power from Friis  
Transmission Formula

**[Equation 1]**

This is known as the ***Friis Transmission Formula***. It relates the free space path loss, antenna gains and wavelength to the received and transmit powers. This is one of the fundamental equations in antenna theory, and should be remembered (as well as the derivation above).

Another useful form of the Friis Transmission Equation is given in Equation [2]. Since wavelength and frequency  $f$  are related by the speed of light  $c$  (see [intro to frequency page](#)), we have the Friis Transmission Formula in terms of frequency:

$$P_R = \frac{P_T G_T G_R c^2}{(4\pi R f)^2}$$

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**[Equation 2]**

Equation [2] shows that more power is lost at higher frequencies. This is a fundamental result of the Friis Transmission Equation. This means that for antennas with specified gains, the energy transfer will be highest at lower frequencies. The difference between the power received and the power transmitted is known as *path loss*. Said in a different way, Friis Transmission Equation says that the path loss is higher for higher frequencies.

The importance of this result from the Friis Transmission Formula cannot be overstated. This is why mobile phones generally operate at less than 2 GHz. There may be more frequency spectrum available at higher frequencies, but the associated path loss will not enable quality reception. As a further consequence of Friis Transmission Equation, suppose you are asked about 60 GHz antennas. Noting that this frequency is very high, you might state that the path loss will be too high for long range communication - and you are absolutely correct. At very high frequencies (60 GHz is sometimes referred to as the mm (millimeter wave) region), the path loss is very high, so only point-to-point communication is possible. This occurs when the receiver and transmitter are in the same room, and facing each other.

As a further corollary of Friis Transmission Formula, do you think the mobile phone operators are happy about the new LTE (4G) band, that operates at 700MHz? The answer is yes: this is a lower frequency than antennas traditionally operate at, but from Equation [2], we note that the path loss will therefore be lower as well. Hence, they can "cover more ground" with this frequency spectrum, and a Verizon Wireless executive recently called this "high quality spectrum", precisely for this reason.

*Side Note: On the other hand, the cell phone makers will have to fit an antenna with a larger wavelength in a compact device (lower frequency = larger wavelength), so the antenna designer's job got a little more complicated!*

Finally, if the antennas are not polarization matched, the above received power could be multiplied by

the [Polarization Loss Factor](#) (*PLF*) to properly account for this mismatch. Equation [2] above can be altered to produce a generalized Friis Transmission Formula, which includes polarization mismatch:

$$P_R = (PLF) \cdot \frac{P_T G_T G_R c^2}{(4\pi R f)^2} \quad \text{[Equation 3]}$$

See also [decibel math](#), which can greatly simplify the calculation of the Friis Transmission Equation.

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# Antenna Temperature

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**Antenna Temperature** ( $T_A$ ) is a parameter that describes how much noise an antenna produces in a given environment. This temperature is not the physical temperature of the antenna. Moreover, an antenna does not have an intrinsic "antenna temperature" associated with it; rather the temperature depends on its gain pattern and the thermal environment that it is placed in. Antenna temperature is also sometimes referred to as **Antenna Noise Temperature**.

To define the environment, we'll introduce a temperature distribution - this is the temperature in every direction away from the antenna in spherical coordinates. For instance, the night sky is roughly 4 Kelvin; the value of the temperature pattern in the direction of the Earth's ground is the physical temperature of the Earth's ground. This temperature distribution will be written as  $T(\theta, \phi)$ . Hence, an antenna's temperature will vary depending on whether it is directional and pointed into space or staring into the sun.

For an antenna with a [radiation pattern](#) given by  $R(\theta, \phi)$ , the noise temperature is mathematically defined as:

$$T_A = \frac{1}{4\pi} \int_0^{2\pi} \int_0^{\pi} R(\theta, \phi) T(\theta, \phi) \sin \theta d\theta d\phi$$

This states that the temperature surrounding the antenna is integrated over the entire sphere, and weighted by the antenna's radiation pattern. Hence, an isotropic antenna would have a noise temperature that is the average of all temperatures around the antenna; for a perfectly directional antenna (with a pencil beam), the antenna temperature will only depend on the temperature in which the antenna is "looking".

The noise power received from an antenna at temperature  $T_A$  can be expressed in terms of the [bandwidth](#) ( $B$ ) the antenna (and its receiver) are operating over:

$$P_{TA} = KT_A B$$

In the above,  $K$  is Boltzmann's constant ( $1.38 * 10^{-23}$  [Joules/Kelvin = J/K]). The receiver also has a temperature associated with it ( $T_R$ ), and the total system temperature (antenna plus receiver) has a combined temperature given by  $T_{sys} = T_A + T_R$ . This temperature can be used in the above equation to find the total noise power of the system. These concepts begin to illustrate how antenna engineers must understand receivers and the associated electronics, because the resulting systems very much depend on each other.

A parameter often encountered in specification sheets for antennas that operate in certain environments

is the ratio of [gain](#) of the antenna divided by the antenna temperature (or system temperature if a receiver is specified). This parameter is written as  $G/T$ , and has units of dB/Kelvin [dB/K].

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## Why do Antennas Radiate?

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Obtaining an intuitive idea for why antennas radiate is helpful in understanding the fundamentals of antennas. On this page, I'll attempt to give a low-key explanation with no regard to mathematics on how and why antennas radiate electromagnetic fields.

First, let's start with some basic physics. There is electric charge - this is a quantity of nature (like mass or weight or density) that every object possesses. You and I are most likely electrically neutral - we don't have a net charge that is positive or negative. There exists in every atom in the universe particles that contain positive and negative charge (protons and electrons, respectively). Some materials (like metals) that are very electrically conductive have loosely bound electrons. Hence, when a voltage is applied across a metal, the electrons travel around a circuit - this flow of electrons is electric current (measured in Amps).

Let us get back to charge for a moment. Suppose that for some reason, there is a negatively charged particle sitting somewhere in space. The universe has decided, for unknown reasons, that all charged particles will have an associated electric field with them. This is illustrated in Figure 1.

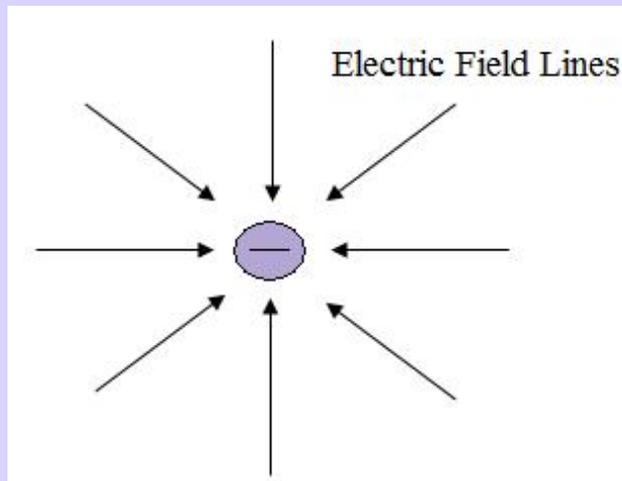


Figure 1. A negative charge has an associated Electric Field with it, everywhere in space.

So this negatively charged particle produces an [electric field](#) around it, everywhere in space. The Electric Field is a vector quantity - it has a magnitude (how strong the field strength is) and a direction (which direction does the field point). The field strength dies off (becomes smaller in magnitude) as you move away from the charge. Further, the magnitude of the E-field depends on how much charge exists. If the charge is positive, the E-field lines point away from the charge.

Now, suppose someone came up and punched the charge with their fist, for the fun of it. The charge would accelerate and travel away at a constant velocity. How would the universe react in this situation?

The universe has also decided (again, for no apparent reason) that disturbances due to moving (or accelerating) charges will propagate away from the charge at the speed of light -  $c_0 = 300,000,000$  meters/second. This means the electric fields around the charge will be disturbed, and this

disturbance propagates away from the charge. This is illustrated in Figure 2.

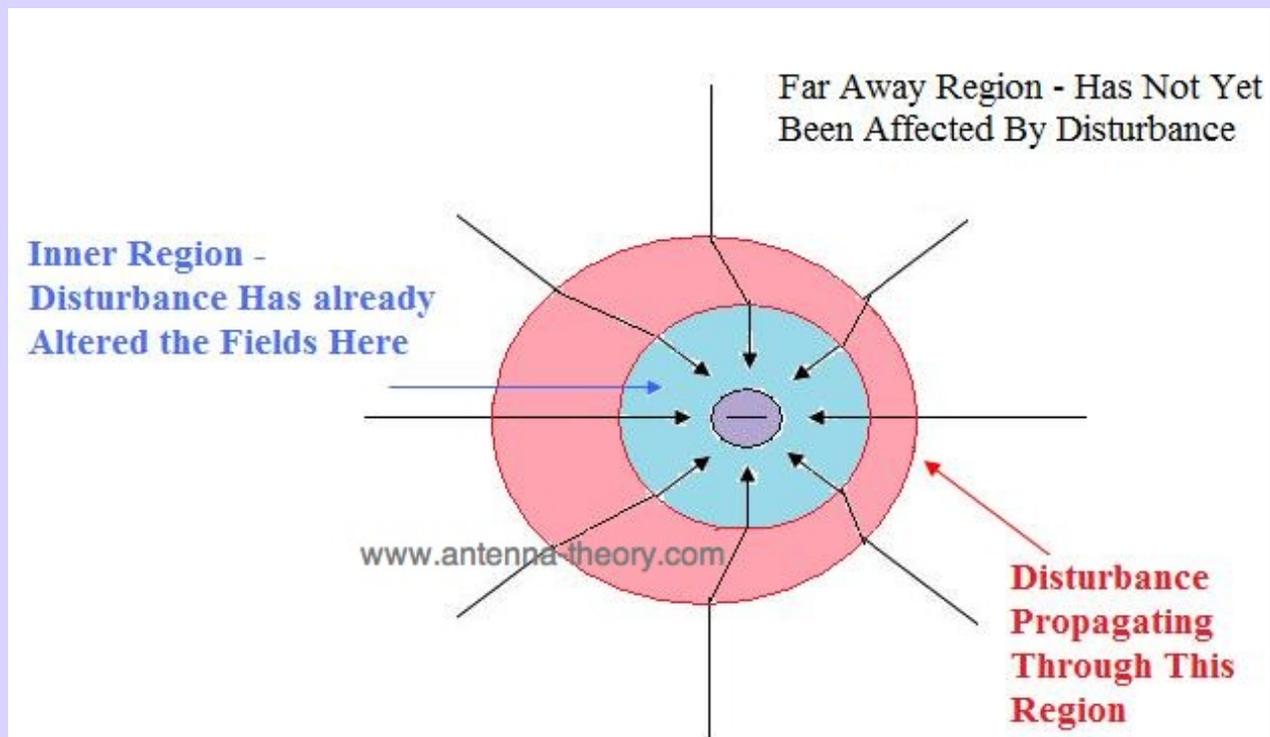


Figure 2. The E-fields when the charge is accelerated.

Once the charge is accelerated, the fields need to re-align themselves. Remember, the fields want to surround the charge exactly as they did in Figure 1. However, the fields can only respond to events at the speed of light. Hence, if a point is very far away from the charge, it will take time for the disturbance (or change in electric fields) to propagate to the point. This is illustrated in Figure 2.

In Figure 2, we have 3 regions. In the light blue (inner) region, the fields close to the charge have readapted themselves and now line up as they do in Figure 1. In the white region (outermost), the fields are still undisturbed and have the same magnitude and direction as they would if the charge had not moved. In the pink region, the fields are changing - from their old magnitude and direction to their new magnitude and direction.

Hence, we have arrived at the fundamental reason for radiation - the fields change because charges are accelerated. The fields always try to align themselves as in Figure 1 around charges. If we can produce a moving set of charges (this is simply electric current), then we will have radiation.

Now, you may have some questions. First - if all accelerating electric charges radiate, then the wires that connect my computer to the wall should be antennas, correct? The charges on them are oscillating at 60 Hertz as the current travels so this should yield radiation, correct?

**Answer:** Yes. Your wires do act as antennas. However, they are very poor antennas. The reason (among other things), is that the wires that carry power to your computer are a transmission line - they carry current to your computer (which travels to one of your battery's terminals and out the other terminal) and then they carry the current away from your computer (all current travels in a circuit or loop). Hence, the radiation from one wire is cancelled by the current flowing in the adjacent wire (that is travelling the opposite direction).

Another question that will arise is - if its so simple, then everything could be an antenna. Why don't I just use a metal paper clip as an antenna, hook it up to my receiver and then forget all about [antenna theory](#)?

**Answer:** A paper clip could definitely act as an antenna if you get current flowing on the antenna. However, it is not so simple to do this. The [impedance](#) of the paper clip will control how much power your receiver or transmitter could deliver to the paper clip (i.e. whether or not you could get any current flowing on the paper clip at all). The impedance will depend on what [frequency](#) you are operating at. Hence, the paper clip will work at certain frequencies as an antenna. However, you will have to know much more about antennas before you can say when and it may work in a given situation.

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In summary, all radiation is caused by accelerating charges which produce changing electric fields. And due to [Maxwell's Equations](#), changing electric fields give rise to changing [magnetic fields](#), and hence we have electromagnetic radiation. The subject of antenna theory is concerned with transferring power from your receiver (the energy is contained in voltages and currents) into electromagnetic radiation (where the energy is contained in the E- and H-fields) travelling away from the antenna. This requires the impedance of your antenna to be roughly matched to your receiver, and that the currents that cause radiation add up in-phase (that is, they don't cancel each other out as they would in a transmission line). A multitude of antenna types produce ways of achieving this, and you can find descriptions about them on the [antenna list](#) page.

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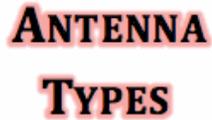
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# Antenna Types

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In this section, we'll introduce the fundamental antenna types. Almost every antenna in the world can be understood as some combination or derivative of the antennas listed on this page. We'll start with the simplest of all antennas, the short-dipole antenna (which is basically a short wire), and work our way through to the more complicated antennas.

The logo consists of the word "ANTENNA" in a bold, black, serif font with a red outline, positioned above the word "TYPES" in a similar bold, black, serif font with a red outline. The text is centered within a white rectangular box.

## Wire Antennas

[Short Dipole Antenna](#)

[Dipole Antenna](#)

[Half-Wave Dipole](#)

[Broadband Dipoles](#)

[Monopole Antenna](#)

[Folded Dipole Antenna](#)

[Small Loop Antenna](#)

## Travelling Wave Antennas

[Helical Antennas](#)

[Yagi-Uda Antennas](#)

[Spiral Antennas](#)

## Other Antennas

[NFC Antennas](#)

## Microstrip Antennas

[Rectangular Microstrip \(Patch\) Antennas](#)

[Planar Inverted-F Antennas \(PIFA\)](#)

## Reflector Antennas

[Corner Reflector](#)

[Parabolic Reflector \(Dish Antenna\)](#)

## Aperture Antennas

[Slot Antenna](#)

[Cavity-Backed Slot Antenna](#)

[Inverted-F Antenna](#)

[Slotted Waveguide Antenna](#)

[Horn Antenna](#)

[Vivaldi Antenna](#)

[Telescopes](#)

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[Types of Antennas](#)

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[Smith Charts and Impedance Matching](#)

[Antenna Engineering Careers](#)

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This website is intended to be a source of knowledge for learning about and understanding **antennas**. The goal is to present a comprehensive tutorial on **antennas**. In the spirit of Einstein:

"Everything should be made as simple as possible, but not simpler."

This website will strive to make **antennas** understandable, without unnecessary complexity.

A photograph of an antenna testing chamber (anechoic chamber) with a robot arm holding a probe. The chamber walls are covered in pyramidal absorbers.

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About this Site:

Antennas and Antenna Theory has always been a fascinating subject for me, and it is this excitement that leads me to present this tutorial. In my life, I have found that once I thoroughly understand a subject, I am amazed at how simple it seems, despite the initial complexity. This I have found true for a wide range of activities, be it riding a motorcycle, learning about antennas, or understanding physical phenomena such as electromagnetics. With that in mind, I endeavor to write this Antenna Theory website in the simplest of all possible manners.

Specifically, consider this statement: *Complexity is not a sign of intelligence; simplify*. I have found this to a priceless amount of wisdom. In that regard, one need not know the intricacies of Lebesgue integration or complex integrals involving Cauchy residues in order to fully understand Antenna Theory. In fact, most people who focus on the mathematical intricacies of [Maxwell's Equations](#) tend to be poor practicing antenna engineers (probably because they try to write code or derive integrals instead of put a product together). The subject of Antennas is best understood intuitively; this is in stark contrast to the methods in University, where complex math pervades every page. I do not think this approach effectively teaches antenna theory. In these pages you will not find rigorous mathematical analysis which only apply in the simplest of antenna cases (and are ultimately artificial for the real world); I will try to state facts and a minimum of math except where necessary. I also try to avoid making things unnecessarily

complicated. For instance, [VSWR](#) stands for *Voltage Standing Wave Ratio*, and sounds very complicated. But it is simply a measure of how much power is reflected from an antenna. Avoiding unnecessary complexity is a lifelong goal of mine.

About me:

I am a practicing antenna engineer, with a PhD in antennas and I have worked for many years in defense, university and the consumer electronics field as an antenna engineer. My dissertation in pdf form is available here: [Antenna Arrays: Performance Limits and Geometry Optimization](#).

Other Projects:

A daylight saving time project entitled [when does the time change](#), and a "Where are the?" website, for discussion based location, as in [Where are the Maldives?](#).