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# TIL-TEK Antenna Seminar

This seminar was developed by Hector Boudreau with formatting assistance from Eileen Boudreau.  
Some diagrams were provided by Rene Duville and the International Wireless Packaging Consortium (IWPC).



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**Solutions that Work**

**Affordable Quality**

**ISO 9001:94**

**Reliability**

**Service**



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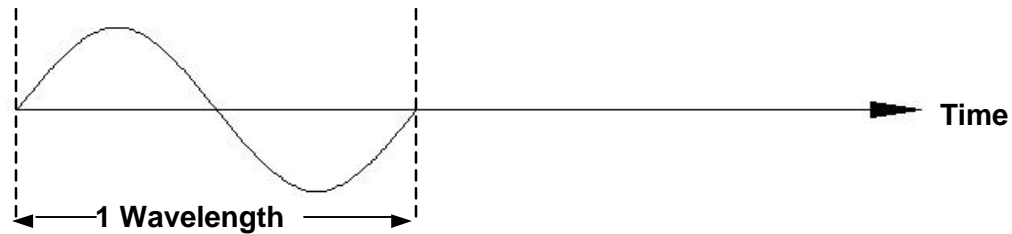
## Antenna Seminar



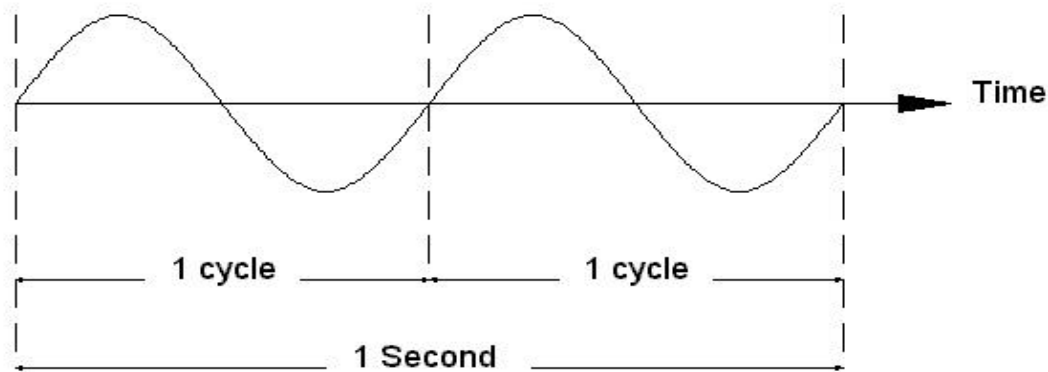
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## Frequency, Wavelength and Velocity

Radio waves oscillate (alternate from plus to minus) This variation from plus to minus is called a cycle, since it repeats itself



The number of cycles that the radio wave goes through in one second is called the frequency (f)



Frequency  $f = 2$  cycles per second or 2 Hertz Hz



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## Frequency, Wavelength and Velocity

Instead of saying “**cycles per second**”, we use the word **Hertz** (abbreviated **Hz**) in honour of Heinrich Hertz who discovered radio waves. Also, since we are dealing with high frequencies, we use prefixes like **kilo** (1,000), **Mega** (1,000,000) and **Giga** (1,000,000,000) in front of Hertz, to further simplify the terminology.

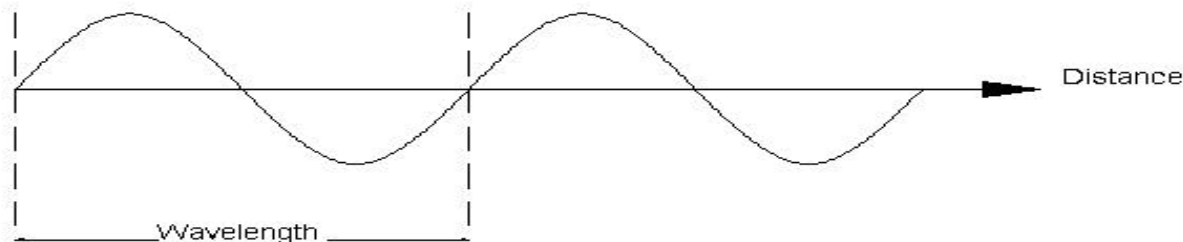
5 cycles per second = 5 **Hz**

5,000 cycles per second = 5 **kHz**

5,000,000 cycles per second = 5 **MHz**

5,000,000,000 cycles per second = 5 **GHz**

We know that radio waves travel at the speed of light (~186,000 miles per sec. Or  $3 \times 10^8$  meters per sec.) and we can measure the frequency of the radio waves, therefore we can find out how far the wave travels in 1 cycle by dividing its' speed by its' frequency. We call this a **wavelength** (abbreviated ?)



<u>Frequency</u>	<u>Wavelength</u>
150 MHz	2.0 m
900 MHz	33.3cm
2.4 GHz	12.5cm
5.8 GHz	52cm



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## **The Decibel**

The decibel (dB) is a ratio, measured in logarithm, used to measure quantity. A dB has no dimensions.

The decibel is used to compare one power (or voltage level) to another.

**Ratio in dB =  $10\log_{10}$  (Power Ratio) =  $20\log_{10}$  (Voltage Ratio)**

(Power is proportional to the voltage squared)

20 dB means a power ratio of  $10^2$  to 1 or 1,000:1

10 dB means a power ratio of 10 to 1 or 100:1

0 dB means a power ratio of 1 to 1 or 1:1

Because the dB is a ratio, it is dimensionless, however many times reference is made to the unit that is made as a ratio.

e.g. dBm in the case of milliwatts

20 dBm means 100:1 over 1 milliwatt or 100mW

e.g. converting 4W into dBm

$$10\log_{10} \frac{4000\text{mW}}{1\text{mW}} = 36 \text{ dBm}$$

Later on we will see that if an antenna has twice the power gain of a half wave dipole (an antenna used as a standard reference), that is a power ratio of 2 over the 1/2 wave dipole, then the antenna is said to have a gain of 3dBd. (3db over the 1/2 wave dipole)

$$10\log 2=3$$

A +3dB gain represents a doubling of power while a -3dB loss represents 1/2 of the power



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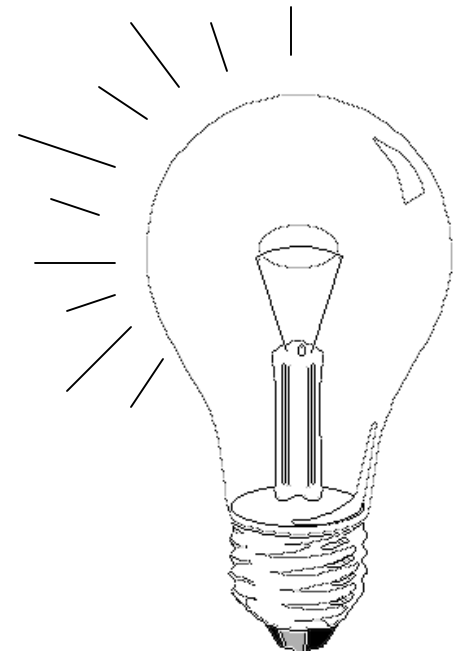
## **What is an Antenna**

An antenna is a device which transforms electromagnetic signals from a transmission line, into electromagnetic waves radiating into free space, (transmit mode) and also collects electromagnetic waves, transforming them into electromagnetic signals and sends them to the transmission line. (receive mode) This is all the antenna is designed to do; it is a passive device. Antennas do not amplify, they simply focus radio energy.

Antennas work equally well whether transmitting or receiving radio energy. (Reciprocity) For example, when measuring the radiation patterns of an antenna on a test range, the antenna under test can be either transmitting or receiving radio waves.

A transmitting antenna is sometimes compared to a light source (another form of radiation) to help in visualizing such antenna parameters as radiation pattern and gain.

Another common analogy is to compare an antenna to a sprinkler at the end of a hose. There is only so much water coming out of the hose but we can spread the water out or focus it to throw the water farther in a specific direction. The total is the same. The spray is different.



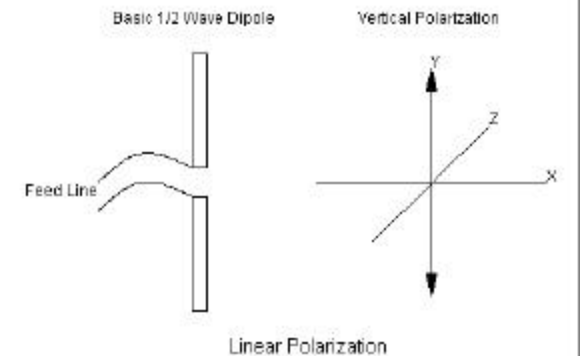


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## Polarization

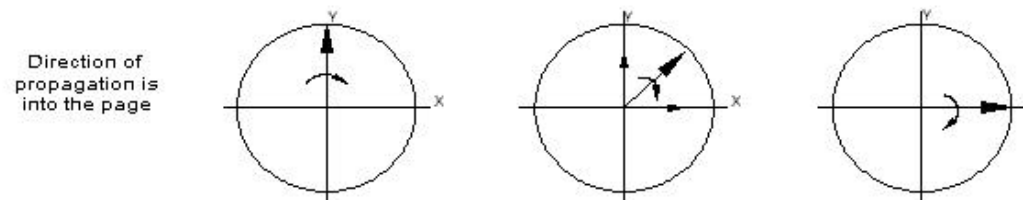
The radiated electromagnetic wave from a transmitting antenna is characterized by the complex Poynting vector  $\mathbf{E} \times \mathbf{H}$  in which  $\mathbf{E}$  is the electric field and  $\mathbf{H}$  is the magnetic field. Polarization describes the orientation of the radiated wave's electric field.

**Linear Polarization**: The electric field vector lies on a straight line that is either vertical (vertical polarization), horizontal (horizontal polarization) or on a 45° angle (slant polarization). If the radiating elements are dipoles, the polarization simply refers to how the elements are oriented or positioned. If the radiating elements are vertical, then the antenna has vertical polarization and if horizontal, it has horizontal polarization.



**Circular Polarization**: Two orthogonal linearly polarized waves of equal amplitude and 90 degrees out of phase are radiated simultaneously. The electric field vectors rotate around a circle. If the horizontal  $\mathbf{E}$  field vector leads the vertical  $\mathbf{E}$  field vector as seen in the direction of rotation, the polarization is said to be Clockwise Circular (right-hand circular polarization). If the horizontal  $\mathbf{E}$  field vector lags the vertical  $\mathbf{E}$  field vector as seen in the direction of rotation, the polarization is said to be Counterclockwise Circular (left-hand circular polarization).

Clockwise Circular Polarization



Right Hand Circular Polarization (Courtesy IWPC)





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## **Polarization**

If we use a linearly polarized antenna to measure the pattern radiated by a circularly polarized antenna, the relative pattern will not change but the absolute values of signals measured will be down by 3dB since we are only measuring one of the “two orthogonal linearly polarized waves” that are radiated by the circularly polarized antenna. Antenna polarization characteristics are kept constant in the main beam, but vary in the side lobes.

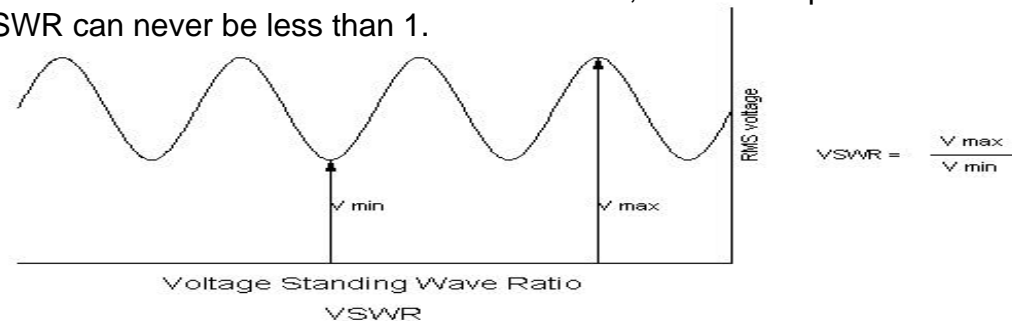
The skipping-rope analogy is often used to explain polarization. Consider the case of a skipping-rope with one end tied to a wall and a person holding the loose end. When the loose end of the skipping-rope is “flipped” up and down, a wave is generated in the rope that travels towards the wall in a vertical plane (vertical polarization). If the skipping-rope is flipped sideways, the wave travels in a horizontal plane (horizontal polarization). If the loose end of the skipping-rope is simultaneously flipped and rotated clockwise, the resultant wave travels towards the wall along a helical path (right hand circular polarization).



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## Input Impedance, VSWR and Return Loss

Input impedance is defined as the impedance presented by the antenna at its terminals or the ratio of the voltage to current at its terminals. If the antenna is perfectly matched to the transmission line (impedance presented by the antenna is the same as the characteristic impedance of the transmission line), then all the energy that reaches the antenna is radiated. If the two are not matched, the antenna will not accept all the power from the transmission line. The part it does not accept is reflected back and forth between the transmitter and the antenna. This sets up a fixed wave pattern along the line which we can measure and which is called the **voltage standing wave ratio (VSWR)**. The VSWR (ratio of maximum voltage to the minimum voltage along the line) expresses the degree of match between the transmission line and the antenna. When the VSWR is 1 to 1 (1:1) the match is perfect and all the power that reaches the antenna is radiated. When the VSWR is 1.5:1, 96% of the power that reaches the antenna is radiated. By definition VSWR can never be less than 1.



**Return Loss** is another way of expressing mismatch. It is a logarithmic ratio measured in dB that compares the power reflected by the antenna to the power that is fed into the antenna from the transmission line. The relationship between VSWR and return loss is the following:

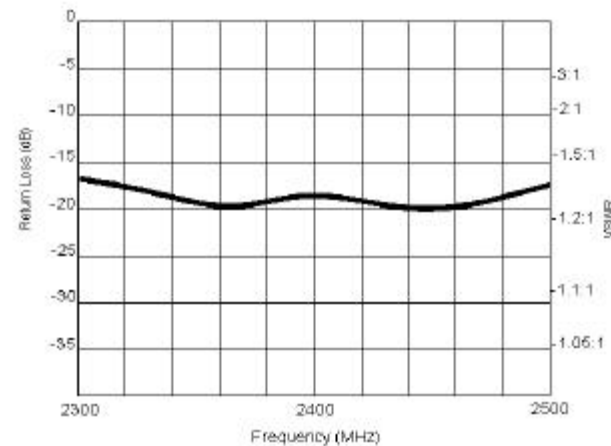
$$RL \text{ (in dB)} = 20 \log_{10} \frac{VSWR + 1}{VSWR - 1}$$

Return loss can be measured at the frequencies of interest only (i.e. transmit and receive frequencies) but most of the time it is measured/plotted as a continuous graph of return loss versus frequency for the entire operating frequency range of the antenna (the input signal to the antenna is “swept” across the frequency band of interest).



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## Input Impedance, VSWR and Return Loss



Return Loss and VSWR vs. Frequency

Return loss is a good description of what happens, that is, power is injected into the antenna, the power reflected by the antenna is measured and the “loss” that the signal has encountered in the process is calculated. There are many published mismatch loss tables that relate VSWR to return loss to transmission mismatch loss (transmitted power that is lost because of the imperfect match between the antenna and the transmission line).

VSWR	Return Loss	Transmission Loss
1:1	?	0dB
1.2:1	-20.8dB	-0.1dB
1.5:1	-14.0dB	-0.5dB
2.0:1	-9.5dB	-1.3dB

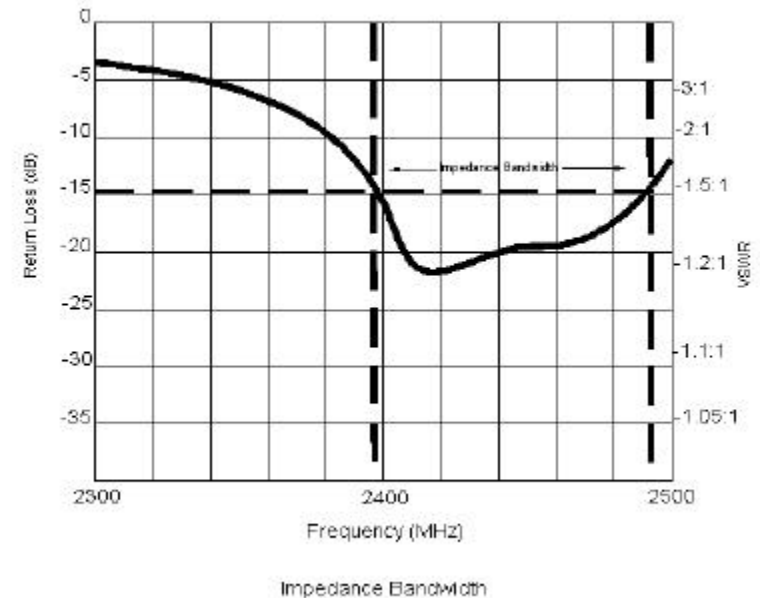


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## **Bandwidth**

The bandwidth of an antenna refers to the range of frequencies over which the antenna can operate satisfactorily.

It is usually defined by impedance mismatch (impedance bandwidth) but it can also be defined by pattern features such as gain, sidelobe level, beamwidth, etc. (All these pattern features do change over the bandwidth of an antenna).



The radio spectrum is divided into frequency bands that are reserved for specific applications (e.g. the ISM band between 2400 MHz and 2483 MHz). Operators want to be able to buy antennas that operate satisfactorily anywhere in the band of interest so that they don't have to specify the transmit and receive frequencies each time they install a new system. They also want their spare antennas to be useful for all their installed systems.

Antenna designers quickly assess the feasibility of an antenna requirement by expressing the required bandwidth as a percentage of the centre frequency of the band. Different types of antennas have different bandwidth limitations.

e.g. ISM band between 2400 and 2483 MHz

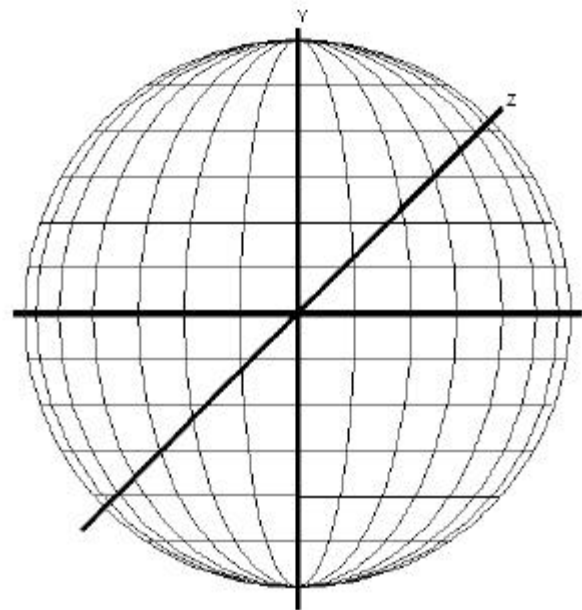
$$\frac{(2483-2400)}{2441.5} \times 100 = 3.4\% \text{ bandwidth}$$



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## Isotropic Radiator

As is the case for all measurements (height, volume, weight, distance, etc.), we need a reference from which we can describe the directive properties of practical antennas. The reference used is the isotropic radiator. This is an imaginary point source which radiates equally well in all directions. The electromagnetic waves from this antenna can be thought of as radiating outward in the shape of a sphere.



Isotropic Radiator

In essence, the isotropic radiator is like a “lowest common denominator”. All practical antennas will have gain when compared to an isotropic radiator. This gain is achieved by focusing the radiated energy in one or more particular directions (remember that an antenna is a passive device).



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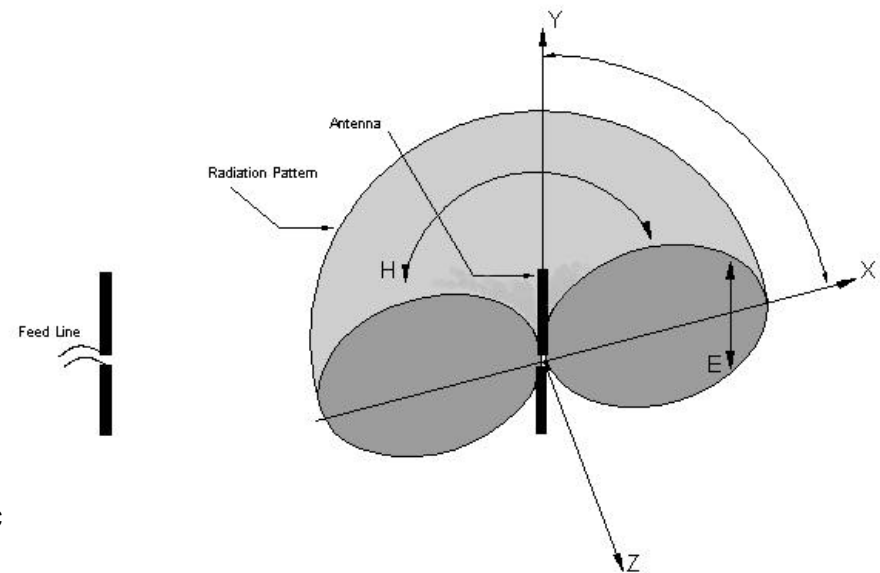
## Radiating Elements and the Half-Wave Dipole

Antennas consist of one or more radiating elements configured in such a way (stacked one above the other, placed against a reflective backplate, etc.) as to give the desired radiation characteristics. The three most common radiating elements are the dipole, the patch and the slot.

We will only cover the half-wave dipole in this course because it will serve to illustrate our purpose and it is another “reference” used by antenna engineers. In general, the half-wave dipole (half a wavelength long) is used as a reference below 1 GHz and the isotropic radiator is used as a reference above 1 GHz when specifying the gain of an antenna (gain is expressed in dBd below 1 GHz and in dBi above 1 GHz).

The half-wave dipole is simply a straight conductor of wire, rod, or tubing that is one-half wavelength long (electrically) and generally is fed in the middle. It radiates at maximum intensity in the middle of the dipole at right angles to its length and at minimum intensity at its ends.

The half-wave dipole is cut or adjusted in length to the desired frequency because it radiates best when it is resonant at that frequency (current distribution along it is maximum in the middle and falls to zero at the ends). This adjusted electrical half wavelength is generally a few percent shorter than the physical half wavelength in order to allow for what is called “end effect” of the conductor. When used as a reference, the half-wave dipole is said to have unity gain (gain of 1 or the same gain as any other half-wave dipole). A half-wave dipole has 2.15 dB of gain when compared to an isotropic radiator (0 dBd = 2.15 dBi).



Half Wave Dipole



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## **Far- Field Region**

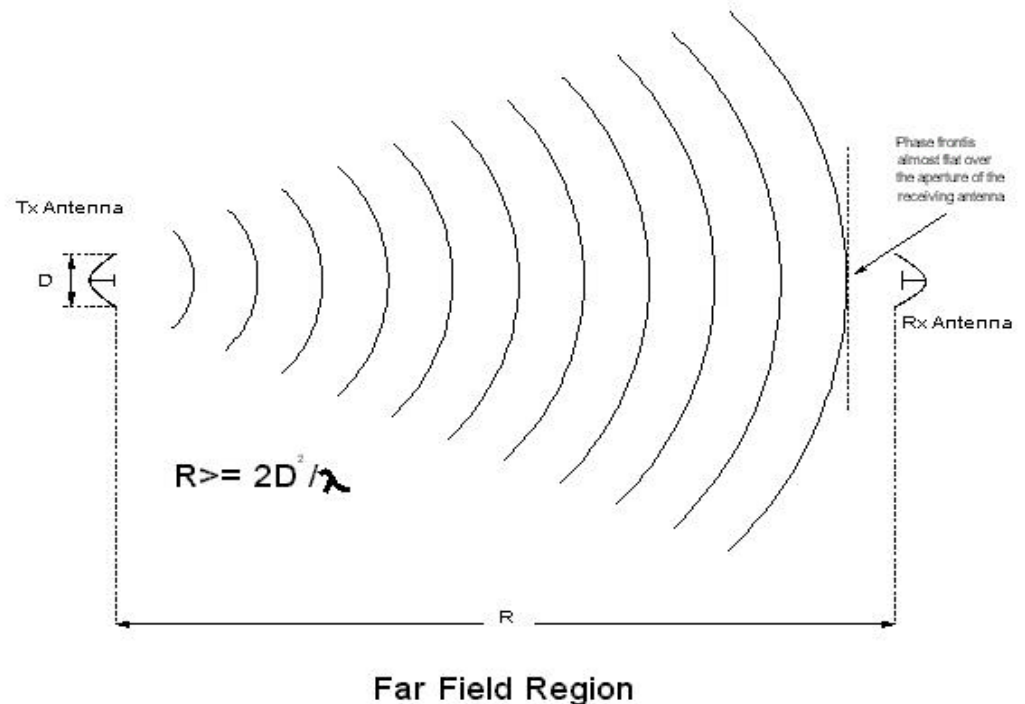
To a receiving antenna far enough in a horizontal direction from a radiating point source (three-dimensional pattern is a sphere) or a half-wave dipole (three-dimensional pattern is a fat doughnut), the wavefront will appear flat for all practical purposes (the radiating waves have spread so much that over the relatively small area of the receiving antenna the wavefront appears to be a wall of energy moving outwards at the speed of light).

In radio engineering, we are only interested in the far-field region where the phase of the radiating field is well behaved (polarization characteristics are kept constant in the main beam). The boundary between near-field and far-field is a function of both the transmit antenna aperture and the frequency of operation.

The criterion  $R > 10$  is used for small antennas.

$D$  is the largest dimension in the transmit antenna aperture.

In the far-field region the fields decay as  $1/R$  and the radiation pattern is independent of  $R$  (the shape of the radiation pattern can be determined by measurements at any point in the far field region).





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## **Radiation Pattern**

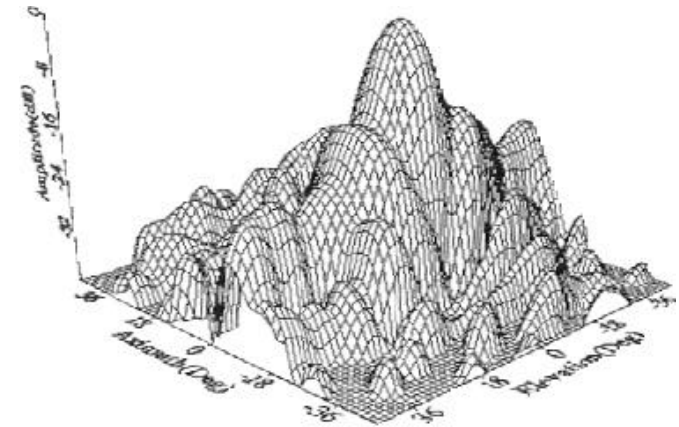
The pattern of an antenna can be measured in transmit or receive mode. The radiation pattern is determined in the far-field region for constant radial distance and frequency. All antennas have a three dimensional pattern.

Because it is not practical to measure a three-dimensional pattern, a number of two-dimensional patterns are measured. A two-dimensional pattern is referred to as a pattern cut.

The radiation from an isotropic radiator is equal in all directions and the radiation pattern is a sphere. If we cut the sphere vertically, we would have the vertical pattern and it would be a circle. If we cut the sphere horizontally, we would have the horizontal pattern and it too would be a circle.

The radiation pattern of a half-wave dipole mounted vertically is a “fat doughnut”. Its horizontal pattern is a circle and its vertical pattern is a fat figure eight lying on its side.

Antenna performance is typically described in terms of principal E-plane and principal H-plane patterns. For a linearly polarized antenna, the E-plane is the plane containing the Electric field vector and the direction of maximum radiation and the H-plane is the plane containing the Magnetic field vector and the direction of maximum radiation.



Radiation Pattern

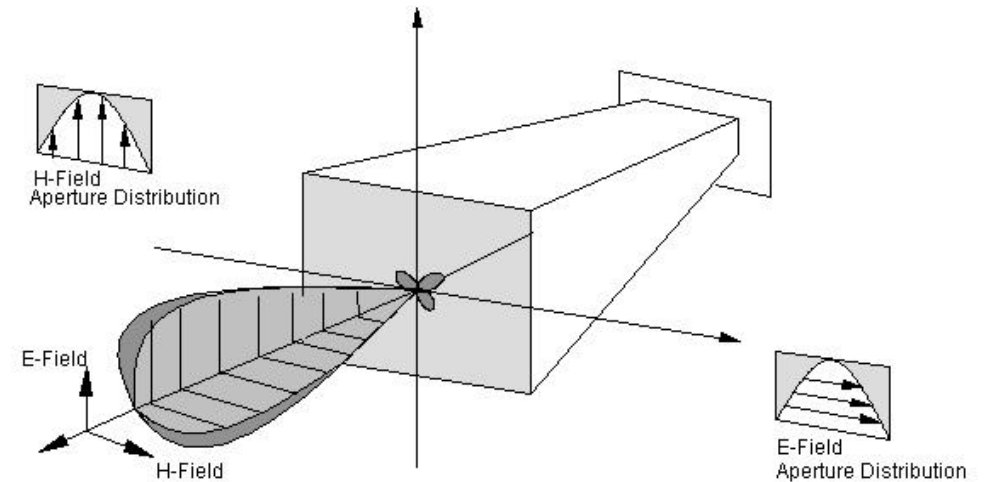




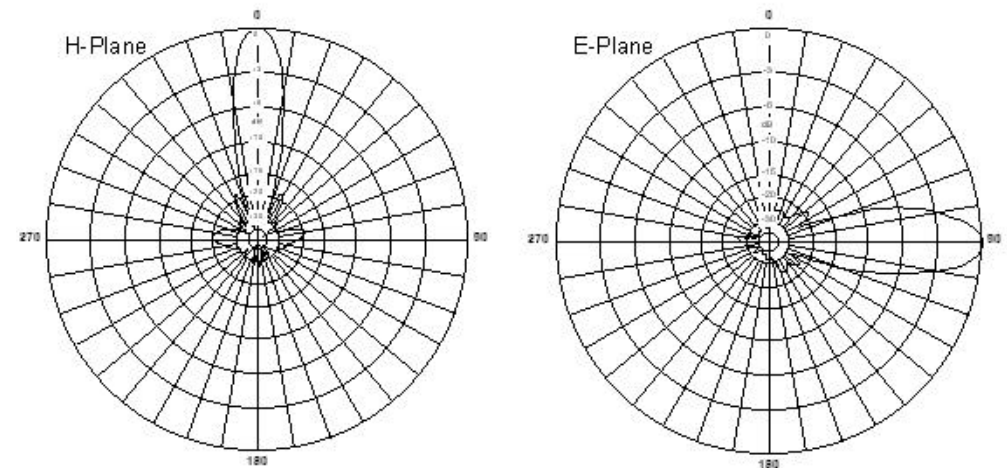
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## Radiation Pattern

Most of the time, principal plane patterns are plotted on a relative scale (maximum gain measured is plotted as the reference level (0 dB level) with all other measurements being negative). The principal plane patterns give no indication of the absolute gain of the antenna. Absolute gain (in dBi or dBd) is measured by comparing the gain of the antenna under test to a Standard Gain antenna.



**E & H Planes**



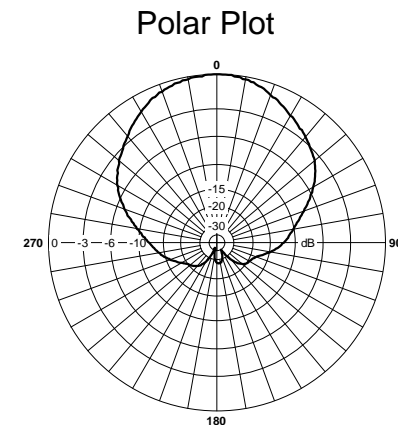
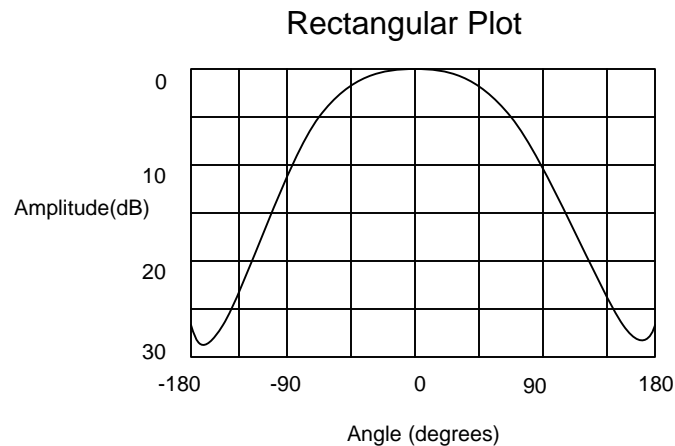
**Principal Plane Patterns**



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## **Radiation Pattern**

Principal plane patterns are plotted in either rectangular coordinates or in polar coordinates with polar plots being the most popular.



## **Rectangular and Polar Coordinates**

Measured radiation patterns (real life) are almost never symmetrical (if you fold them over along the direction of maximum radiation, the two sides don't match exactly). Often they are plotted on a non-linear log scale in order to obtain better resolution in the main lobe area (or to make the sidelobes appear smaller!!).

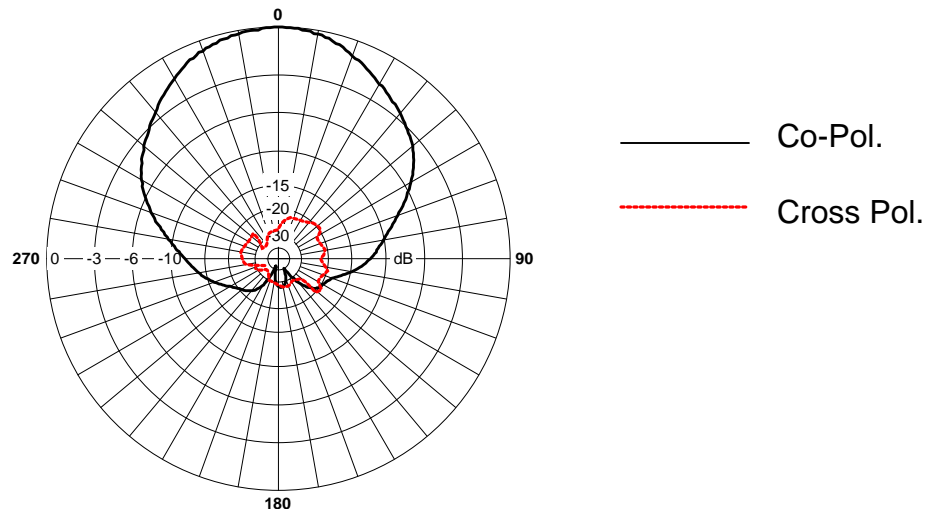


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## **Cross- Polarization Discrimination**

Cross-polarization discrimination is the measure of discrimination to oppositely polarized electromagnetic waves (e.g. the discrimination that a vertically polarized antenna has to horizontally polarized radio waves or the discrimination that a right-hand polarized antenna has to left-hand polarized radio waves).

When plotted along with the principal plane pattern of the antenna on a relative dB scale, cross-polarization discrimination is simply the difference between the co-polarized level and the cross-polarized level in any given direction.



**Cross Polarization Discrimination**

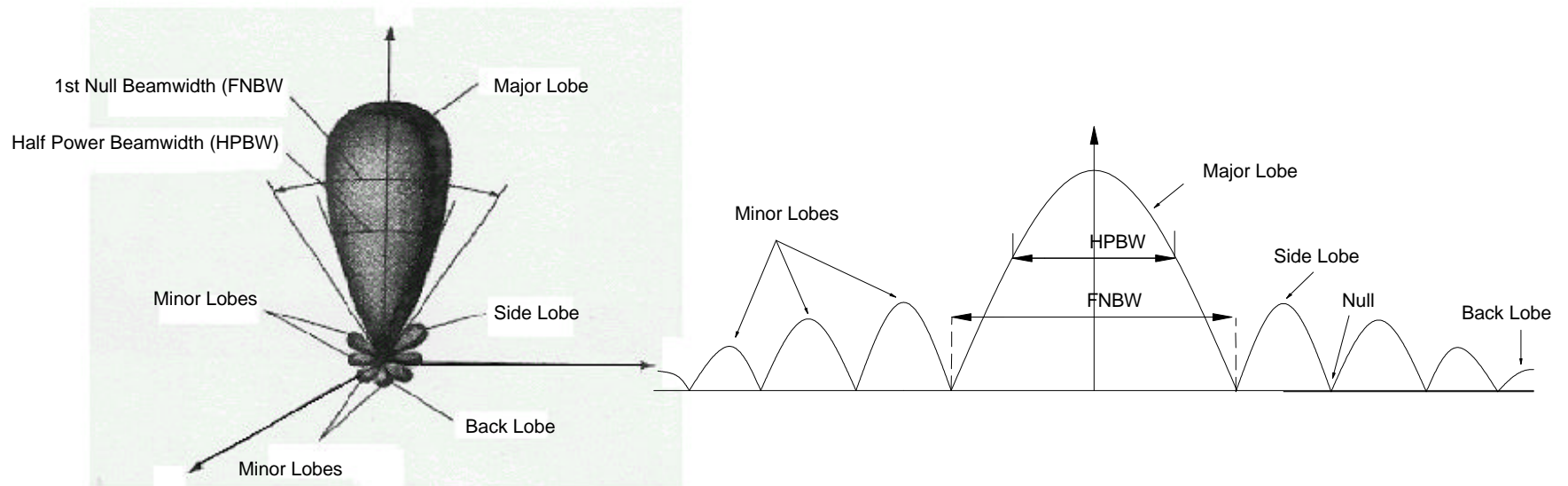
In general, cross-polarization discrimination is specified in terms of its minimum value (in dB) anywhere within the 3 dB beamwidth of the antenna.



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## Pattern Lobes

A radiation pattern consists of a major lobe (referred to as the main beam) and a number of minor lobes. Generally, the minor lobes on each side of the main beam are referred to as the sidelobes and the lobe directly opposite the main beam is referred to as the back lobe. The regions of relatively weak radiation intensity between lobes are called “nulls”.



**Pattern Lobes**



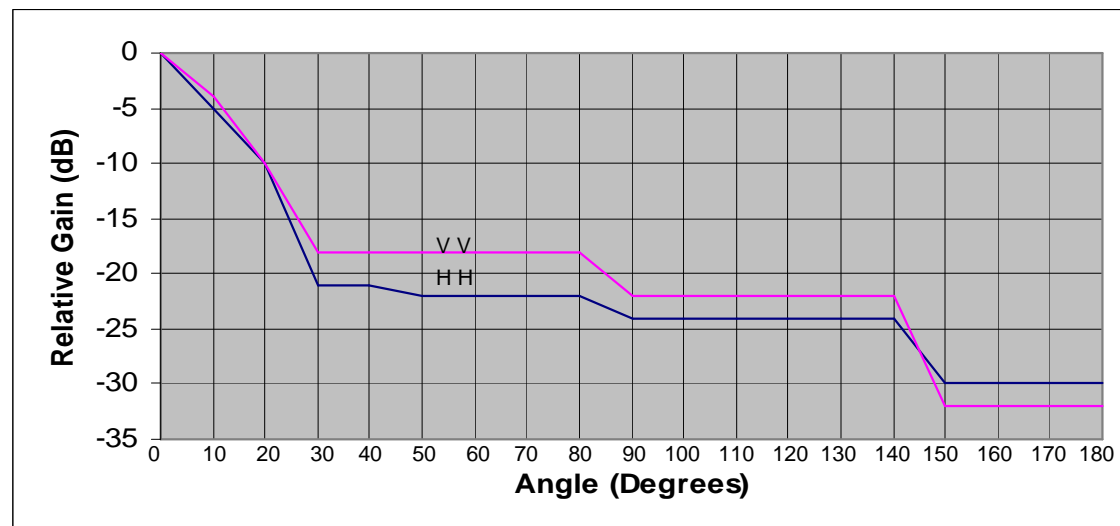
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### **Pattern Lobes (Cont'd.)**

The radiation pattern of an ideal directional antenna would have a major lobe and no minor lobes. Minor lobes serve no useful purpose and should never be counted upon to do useful work when designing a system because their amplitude, shape, position and polarization characteristics all vary over the bandwidth of the antenna. On the other hand, you must keep them in mind when doing interference studies because they do represent gain for an interference signal on the right frequency coming from the right (wrong) direction.

Since the shape and amplitude of pattern lobes change slightly with frequency across the bandwidth of an antenna, Radiation Pattern Envelopes are usually used for interference studies. A radiation pattern envelope is a line graph showing the maximum gain across the bandwidth of the antenna that can be expected at any frequency (usually the pattern is measured at the low, middle and high frequencies, the patterns are superimposed and the pattern envelope is drawn from one maximum to the other.)

**Radiation Pattern Envelope**





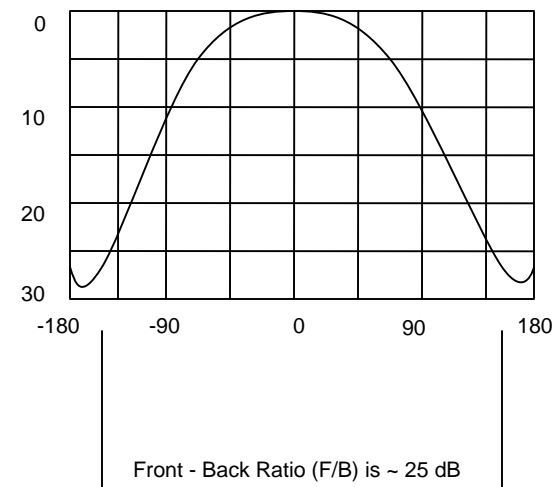
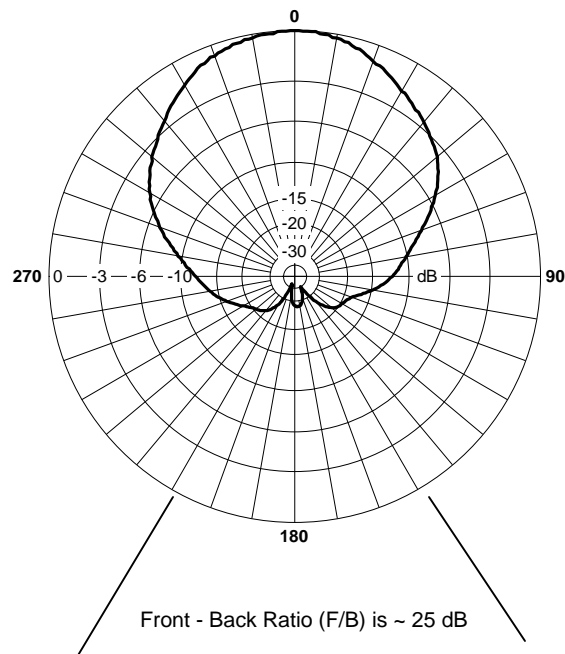
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## Front-to-Back Ratio

Front-to-back ratio is a measure of the radiation intensity at the back of a directional or sectoral antenna (back lobe).

The front-to-back ratio of an antenna is defined as the ratio of the power transmitted in (or received from) the main beam of the antenna to the power transmitted in (or received from) the back lobe.

When the principal plane pattern is plotted on a relative dB scale, the front-to-back ratio is the difference (in dB) between the level of the main beam and the level of the back lobe. In general, the level of the back lobe is taken as the maximum level in a direction  $180 \pm 30$  degrees from the direction of maximum radiation.



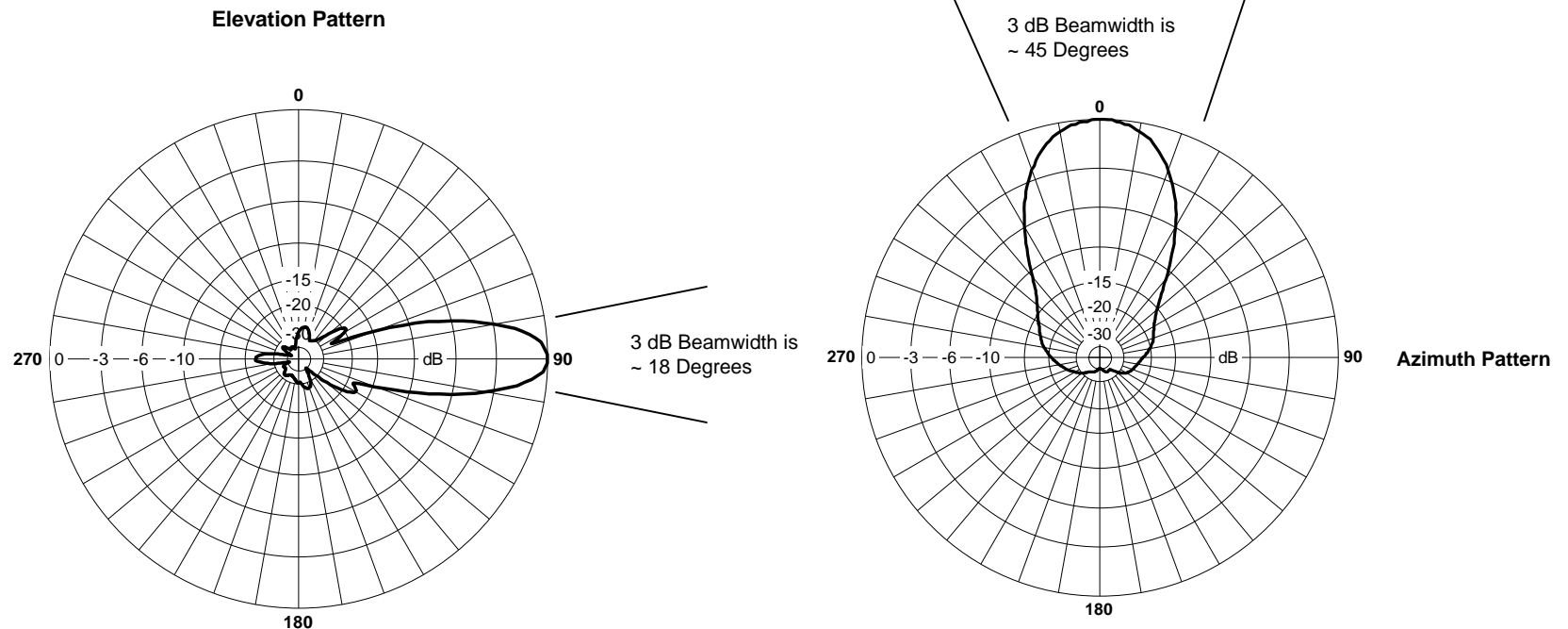


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## Beamwidth

The main beam in a radiation pattern is the lobe containing the direction of maximum radiation intensity. The half power (3 dB) beamwidth is the angle between the two points on the main beam where the radiation intensity is down to half the maximum value (3 dB down on a dB scale).

When designing point-to-multipoint systems, it is very important that all outstation (CPE) locations fall with the 3 dB beamwidths of the central station antenna, both in azimuth and in elevation. It is also very important to keep in mind that the beamwidths of an antenna will change slightly over the frequency band for which the antenna was designed.





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## Directivity and Gain

The directivity of an antenna is a measure of the extent to which the received or transmitted energy is concentrated in the main beam of the antenna pattern. It is defined as the ratio of the antenna radiation intensity in a specific direction in space to the radiation intensity of an isotropic radiator for the same radiated power. There are cases in which the term directivity is used in connotation with its maximum value.

The gain of an antenna is closely related to its directivity, but takes into consideration the losses in the antenna (conduction losses and dielectric losses) as well as its directional capabilities. By definition it is equal to 4 times the ratio of the maximum radiation intensity to the net power accepted by the antenna at its terminals. The antenna efficiency is the ratio of directivity to gain.

Gain is measured on a far-field outdoor test range by comparing the gain of the antenna under test to that of a pre-calibrated Standard Gain antenna.

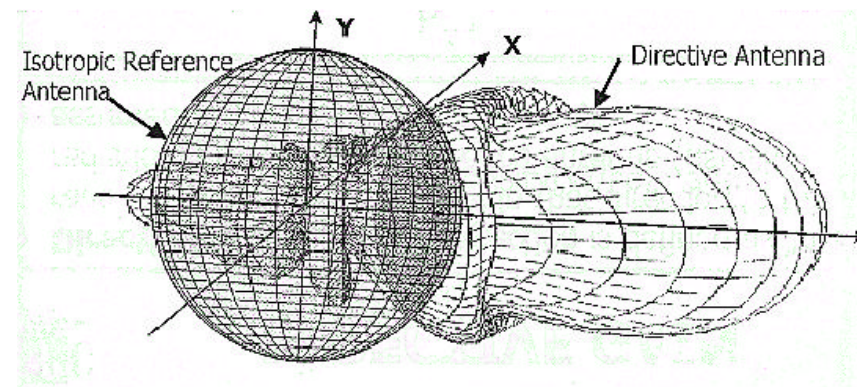
$$G = 10 \log_{10} \frac{4}{\lambda^2} A_e$$

where G= antenna gain in dB

$\lambda$  = operating wavelength in meters

$A_e$  = effective aperture in square meters

If we double the length of the aperture, the gain of the antenna is doubled (i.e. the gain increases by 3 dB).







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### **Directivity and Gain (Cont'd.)**

A useful approximation to quickly determine the gain of an antenna is:

$$G = 10 \log_{10} \frac{36,000}{E_{BW} \times H_{BW}}$$

where

G = antenna gain in dBi

H<sub>BW</sub> = H-plane beamwidth in degrees

E<sub>BW</sub> = E-plane beamwidth in degrees

e.g.

E-plane beamwidth = 8°

H-plane beamwidth = 360° (vertically polarized omni)

$$G = 10 \log_{10} \frac{36000}{8 \times 360} = 11 \text{ dBi}$$

Note: This formula neglects conduction losses and dielectric losses, which are typically 0.5 to 1.5 dB, depending on the antenna type.



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## **Effective Radiated Power**

Effective Isotropic Radiated Power (EIRP) is a figure of merit for the net radiated power in a given direction. It is equal to the product of the power supplied to a transmitting antenna and the antenna gain in a given direction relative to an isotropic radiator, expressed in watts.

Effective Radiated Power (ERP) is similar, but is relative to a half-wave dipole (instead of an isotropic radiator).

e.g. Transmitter Output Power = 4 watts = 36 dBm  
Transmission Line Loss = 2 dB  
Antenna Gain = 10 dBd

$$\text{ERP} = 36 - 2 + 10 = 44 \text{ dBm} = 25 \text{ watts}$$

A word of caution about dBm. You cannot add dBm to dBm. The two powers must first be converted to watts, then added and the sum reconverted to dBm.

e.g..  
 $10 \text{ dBm} + 10 \text{ dBm} = 20 \text{ dBm}$   
 $10 \text{ dBm} = 10 \text{ mW}$   
 $10 \text{ mW} + 10 \text{ mW} = 20 \text{ mW}$   
 $20 \text{ mW} = 10 \log_{10} (20/1) = 13 \text{ dBm}$

$10 \text{ dBm} + 10 \text{ dB} = 20 \text{ dBm}$   
 $30 \text{ dBm} - 10 \text{ dB} = 20 \text{ dBm}$   
 $30 \text{ dB} + 10 \text{ dB} = 40 \text{ dB}$   
 $30 \text{ dB} - 10 \text{ dB} = 20 \text{ dB}$



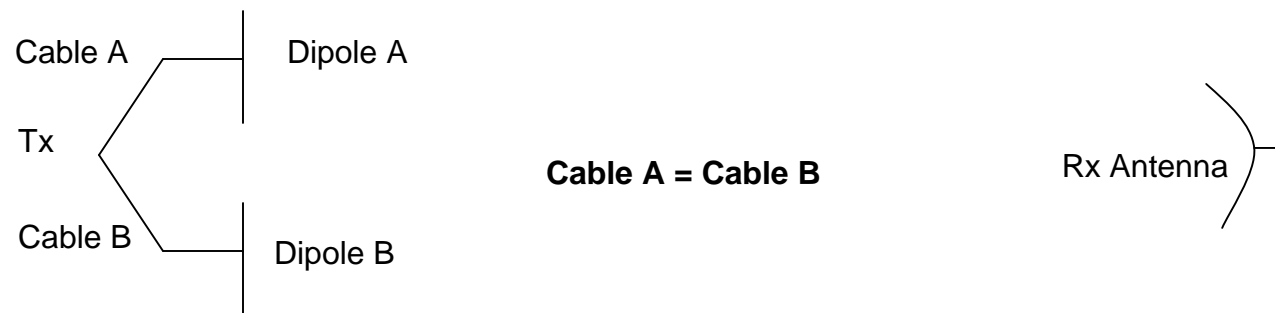
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## Pattern Shaping

Antenna gain is achieved by changing the shape of the pattern to put the radiation where you want it (shaping the pattern). It's like a sprinkler. There's only so much water coming out of the hose. We can distribute the water in a circle or we can adjust the sprinkler head to throw the water further and put more into a given spot, but there's the same total amount of water always.

**Phasing:** One way to shape an antenna pattern is by making the phase of the current on one element different than the phase of the current on another element (input signals to the two elements are at different points in their cycle). This causes the radiation from the two elements to be in or out of phase as seen from a point at some distance from the two elements (far-field).

Consider the case of two dipoles positioned vertically one above the other and separated a distance of around one wavelength between their centres. If the two dipoles are connected by cables of the same length to a transmitter, the power from the transmitter will arrive at each dipole at the same instant and the dipoles will start radiating in the same direction at the same time. An antenna several kilometers away from each dipole will receive the two waves exactly together and they will add up to give a stronger signal. The two dipoles are “in phase”.



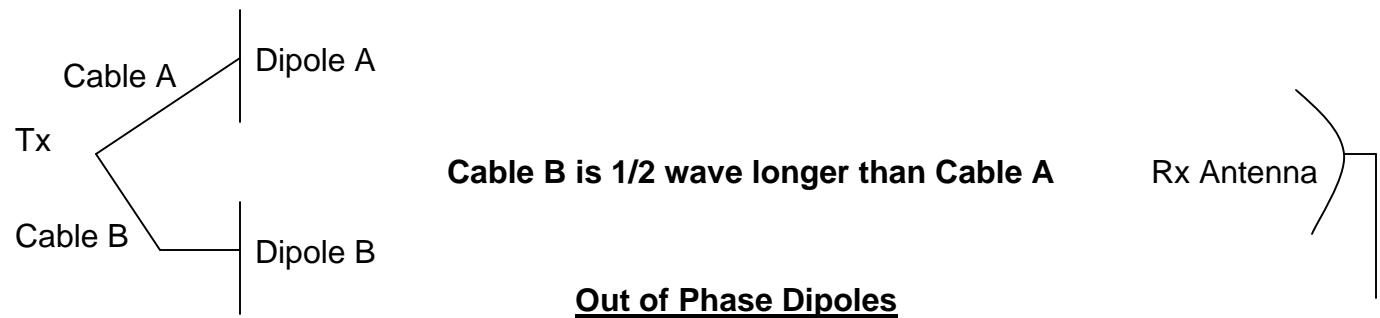
**In Phase Dipoles**



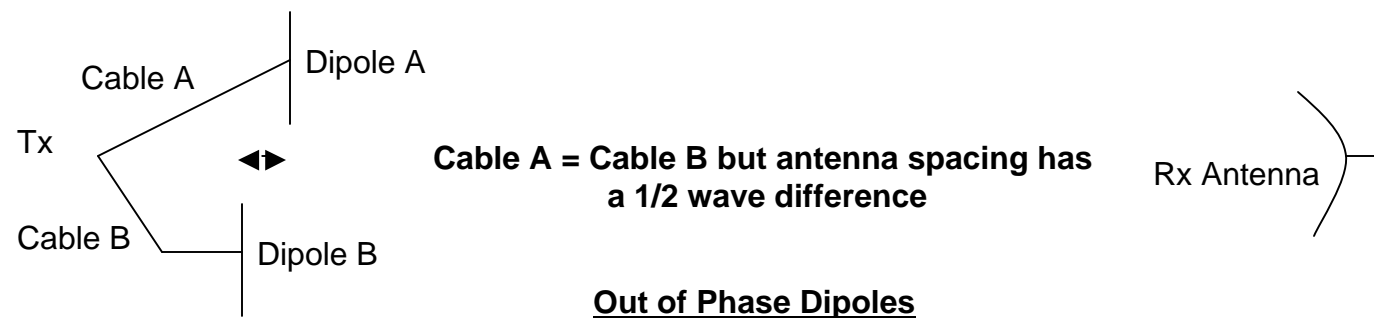
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## Pattern Shaping

If cable B in the example below is lengthened by one-half wavelength or any odd multiple of a half-wavelength ( $1/2$ ,  $3/2$ ,  $5/2$ , etc.), the power from the transmitter will arrive at dipole B half a cycle later than dipole A. Consequently, radiation from dipole B will arrive at the receive antenna out of phase with radiation from dipole A and the two waves will cancel out. The two dipoles are “out of phase”.



The same “out of phase” cancellation would occur if the cable lengths were kept the same but dipole B was moved half a wavelength closer to the receive antenna. Then the radiation from dipole A would arrive at the receive antenna half a cycle later than that from dipole B. When B was going plus, A would be going minus and the received signals would cancel out.

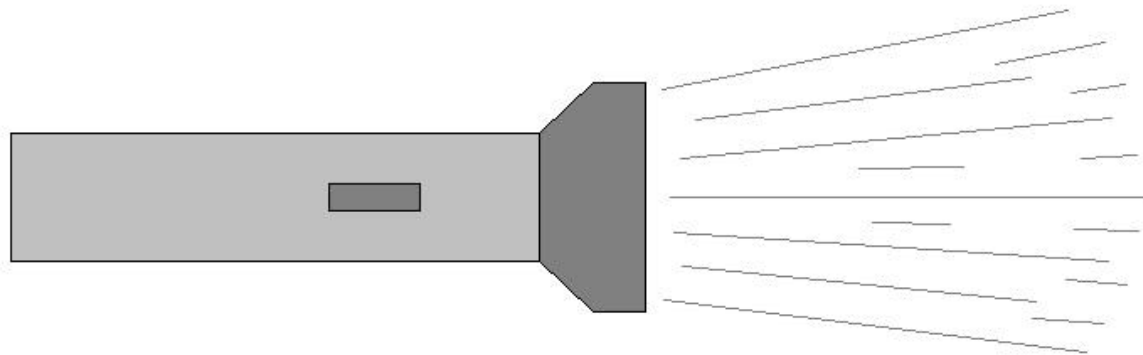




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## **Pattern Shaping**

**Reflectors:** Another way to shape a pattern is by using a metal reflector (solid or wire mesh) to block the radiation in an unwanted direction and redirect it in the desired direction, in much the same way as a mirrored surface is used to focus the light emitted by the bulb in a flashlight.



We know from theory and experiment that if a dipole is spaced a quarter wavelength in front of a metal reflector, the radiation which would normally go to the rear is redirected to the front to form a directional lobe (directional antenna). The larger the size of the metal reflector, to a point, the narrower this lobe becomes. We say that the antenna has narrowed its beamwidth or increased its gain. In effect, the dipole serves to illuminate the reflector and then the reflector radiates on transmit and collects on receive.



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## **Vertically Polarized Omnidirectional Antenna**

There is no truly omnidirectional antenna in practice - the isotropic radiator only exists in theory. The term omnidirectional antenna is used to describe an antenna that radiates equally well in all directions in the azimuth (horizontal) pattern. The half-wave dipole when mounted vertically is an omnidirectional antenna. Its three dimensional pattern is a large fat doughnut resulting in a horizontal pattern that is circular and a vertical pattern that is a fat figure eight lying on its side.

Having decided on an omnidirectional pattern (horizontal pattern that is circular), one way to get gain in a vertically polarized omnidirectional antenna is to stack vertical dipoles above each other (increasing the vertical size or aperture) and feed these dipoles with power, in such a fashion that the radiation from the individual dipoles will add together at a distant point. Also, we must connect the dipoles together so that they will match into the transmission line if we want to get the most radiated power out of the antenna. Most radiated power is obtained when the dipoles are lined up vertically (collinear) with optimum spacing between them and fed with equal power that arrives at the dipoles at the same instant. This type of antenna is called a collinear phased array and is the most common type of omnidirectional gain antenna.

The elevation (vertical) half power (3 dB) beamwidth of a vertically mounted half-wave dipole is 78 degrees and its input impedance is 72 ohms. If we stack two half-wave dipoles vertically, the elevation beamwidth will be reduced to half (39 degrees) and the gain will increase by 3 dB. If we double the number of half-wave dipoles again to four, the elevation beamwidth will be halved again to 19.5 degrees and the gain will increase by another 3 dB (gain of 6 dBd).

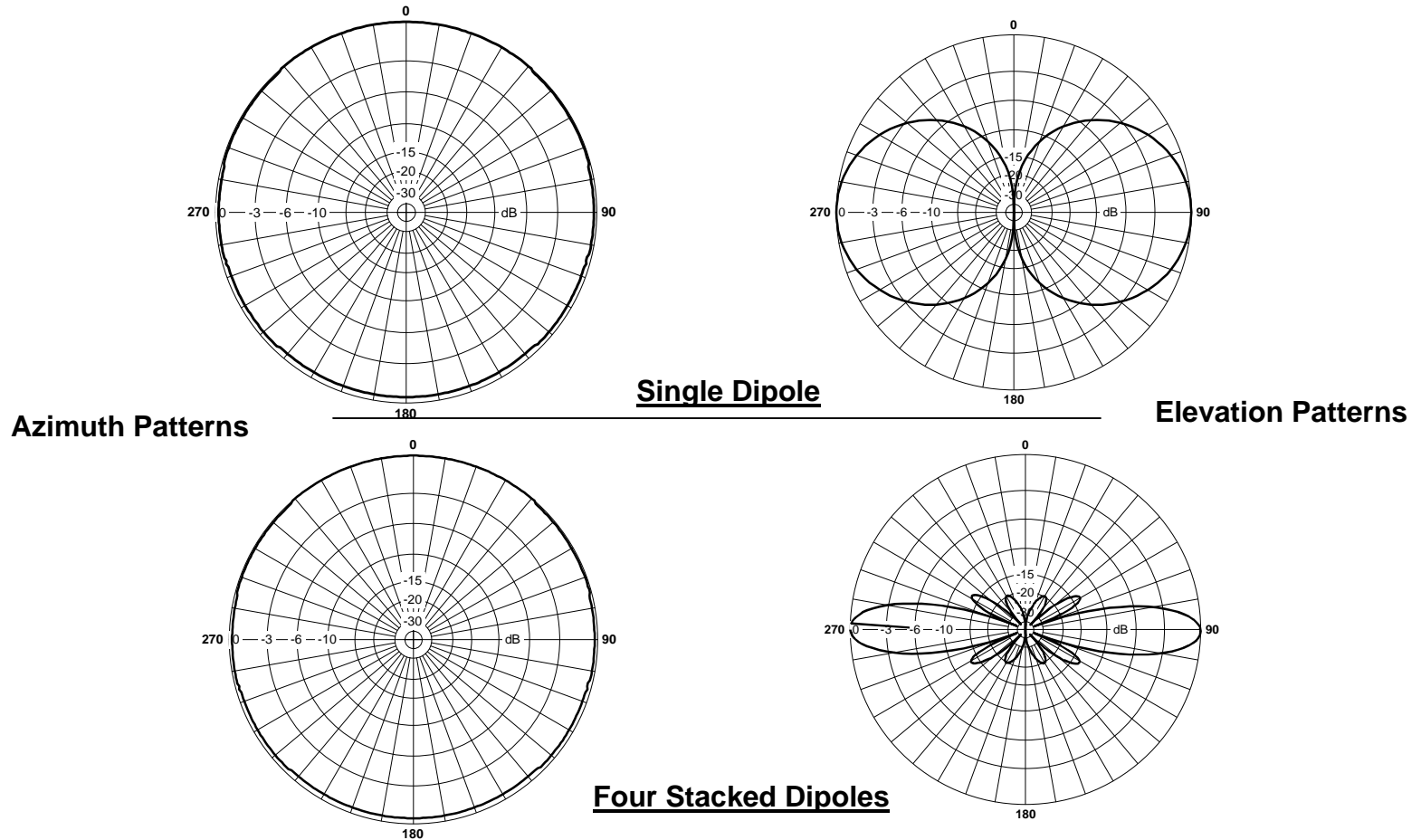
<u>No. of Half-Wave Dipoles</u>	<u>Vertical Beamwidth (degrees)</u>	<u>Gain (dBd)</u>
1	78	0
2	39	3
4	19.5	6
8	9.75	9

In real life an 8 dBd (10 dBi) omnidirectional antenna has a vertical beamwidth of only 8 degrees, because of the losses in the antenna (conduction losses and dielectric losses) and the power lost in the minor lobes.



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## Vertically Polarized Omnidirectional Antenna



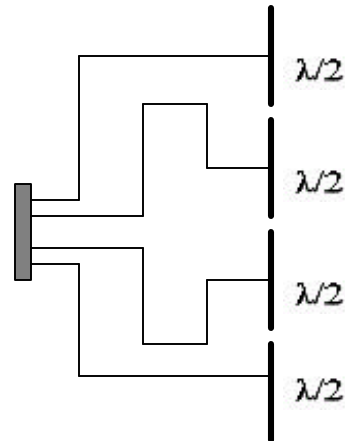
The two basic types of feeds used in collinear arrays are the parallel feed where the dipoles are fed individually from a common point (usually in the middle of the antenna) and the series feed where the dipoles are fed in sequence using phasing coils.



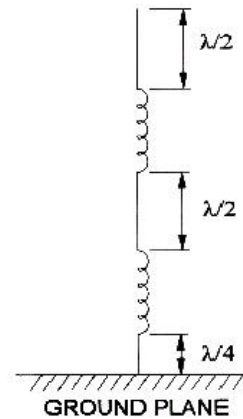
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## Vertically Polarized Omnidirectional Antenna

Parallel or Corporate Feed



Series Feed



### Series and Parallel Feeds

The gain that can be obtained in a given physical length or aperture is slightly less for a series feed because the top dipoles get less power (contribute less to the gain of the antenna). For all practical purposes, however, the effective gain of a collinear array is dependent upon the aperture which in turn is largely dependent upon the physical length of the array.

If all the dipoles are fed the same amount of power in a parallel feed, then the gain is maximized and the sidelobes (vertical pattern) are about 13 dB down from the main beam. If the feed is tapered (less power fed to the end elements), the beamwidth increases (less gain) but the sidelobes are reduced.

A series fed collinear, apart from having slightly less gain for a given physical length, will have less bandwidth because the phasing sections create a phase error in the power to the end dipoles as the frequency is varied on each side of the resonant (centre) frequency.



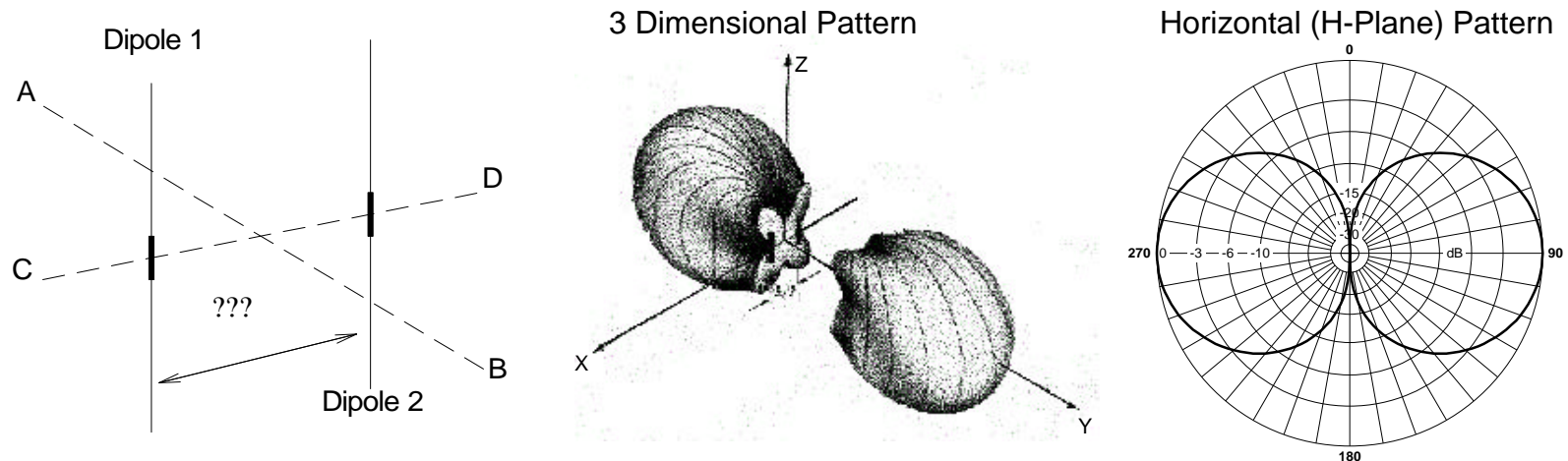


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## Horizontally Polarized Omnidirectional Antenna

It is relatively easy to make a vertically polarized omnidirectional antenna with gain because a half-wave dipole mounted vertically has an omnidirectional pattern to start with. It is considerably harder to make a horizontally polarized omnidirectional antenna.

Consider the case of two half-wave dipoles spaced horizontally apart one-half wavelength and fed in phase.



## Vertical Half-Wave Dipoles Spaced 1/2 Wave Apart



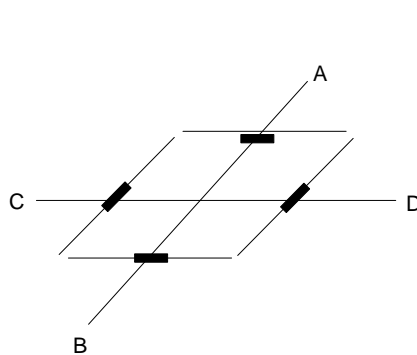
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## Horizontally Polarized Omnidirectional Antenna (Cont'd.)

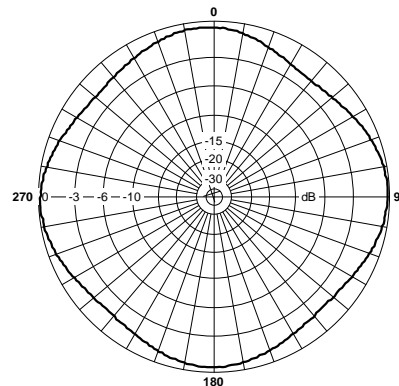
To a receive antenna in the far-field and along line AB, the two dipoles are equal distances. The radiation from the two dipoles will, therefore, arrive along this line at the same time (in phase) to produce an increase. Along line CD, however, there is a difference of one-half wavelength (out of phase) and the radiation along this line will cancel and make a null. The resultant horizontal pattern then is a figure eight.

One way to get a horizontally polarized omnidirectional pattern is by mounting four half-wave dipoles horizontally so as to form a square. If the spacing between dipoles are such that the horizontal patterns of two adjacent dipoles cross over around the -6 dB points, then the resultant horizontal pattern will be circular for all practical purposes. (It will have a “squarish” look but the differences between maximums and minimum will be acceptable.)

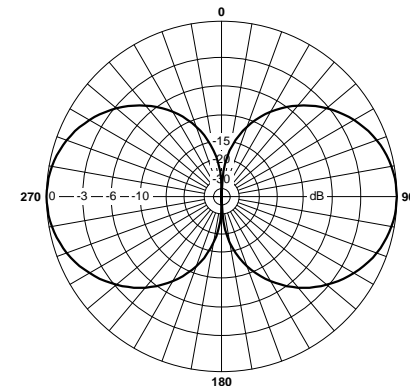
What we have done can be compared to bending a horizontal half-wave dipole into a loop. It is reasonable then, to expect that the vertical pattern of our four-dipole array will be a “fat figure eight” lying on its side. To get more gain, we now have to do the same thing we did in the case of a vertically polarized omnidirectional antenna, that is, stack arrays of four dipoles vertically. Again, in real life a 10 dBi horizontally polarized omnidirectional antenna has a vertical beamwidth of about 8 degrees.



4 Horizontal Dipoles



Horizontal (E-Plane) Pattern



Elevation (H-Plane) Pattern



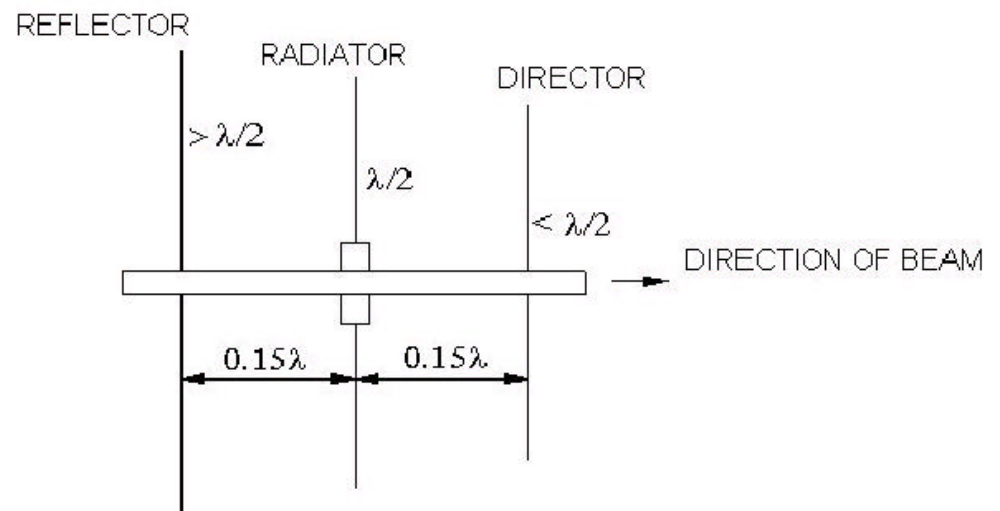
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## Directional Antennas

In an omnidirectional gain antenna, the horizontal pattern is circular and gain is achieved by stacking dipoles vertically in order to compress the vertical pattern. In a directional antenna, gain is primarily achieved by shaping the horizontal and vertical patterns. This is done either by adding a reflector behind the elements or by stacking elements (dipoles) horizontally (or both in the case of high gain directionals).

**Yagi Antenna:** The Yagi antenna has many forms and variations but generally consists of at least two elements and more often three elements. The basic elements of the three-element Yagi are a radiator, a reflector, and a director. The director element is in front of the radiator (a half-wave dipole) while the reflector element is behind the radiator. The director element is slightly shorter than the radiator while the reflector element is slightly longer. These lengths and spacing (between 0.1 and 0.2 ) from the radiator determine the conditions which form the radiated power into a directional lobe to give the antenna its gain.

To increase the gain of the three-element Yagi, you have to add additional directors in front of the first director. In order to increase the gain by 3dB, you have to add directors of the proper length (generally, each additional director is shorter than the previous one) and spacing to effectively double the overall length of the antenna. The additional elements narrow the bandwidth of the antenna.

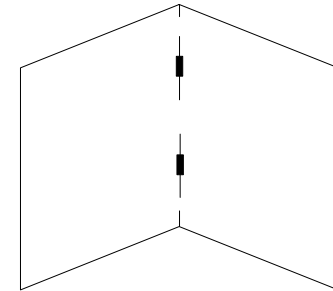




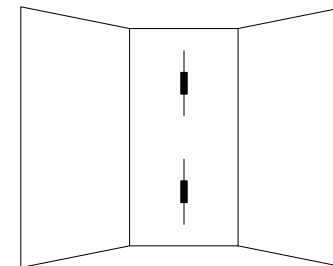
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## Directional Antennas (Cont'd.)

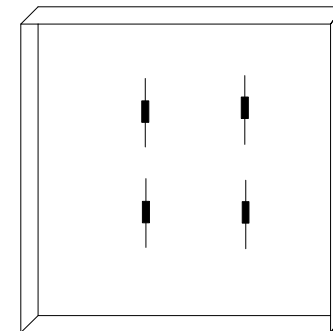
**Corner Reflector Antenna:** This is a special case of a dipole in front of a reflector where a reflector of the proper size is bent into an angle, (usually 90 or 60 degrees) and the dipole is located a certain distance from the angle intersection. The beamwidth and gain depend on the relationship of reflector size, angle and dipole position. The reflector can be made of wire mesh or vertical rods spaced close enough so as to obtain nearly the same effect as a continuous reflector (rods must be parallel to the dipole and less than  $1/8$  wave apart)



**Trough Reflector Antenna:** The trough reflector antenna is basically a truncated corner reflector. The main reason for going to this shape is to reduce the depth of the antenna.



**Panel Antenna:** The panel antenna is basically a trough reflector antenna whose sides have been brought in until they are at right angle to the back plane. The ends are then added to complete the "box" and make it easier to install a radome over the elements. The ends have no appreciable effect on the electrical performance of the antennas.

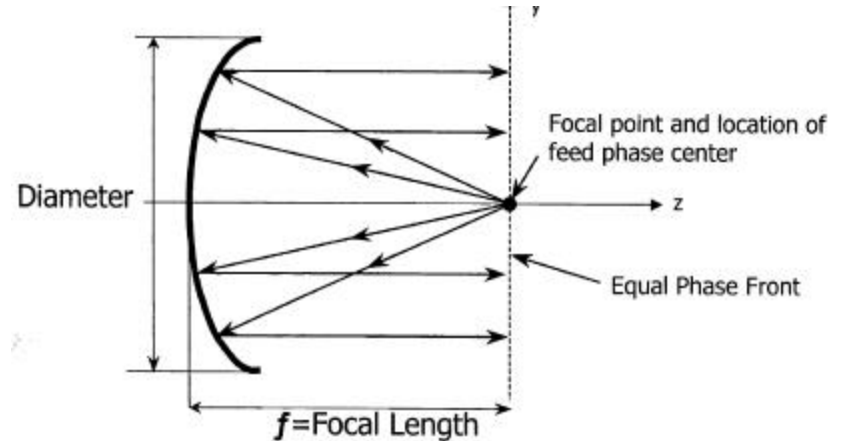




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## Directional Antennas Cont'd

**Parabolic Antenna:** This antenna consists of a dish-like reflector with a parabolic shape and a primary radiator feed at the focal point of the reflector. In the transmit mode, signals leaving the focal point and reflecting off any point on the parabola have the same phase as from any other point on the reflector.



The gain of a parabolic antenna depends upon its size, frequency and illumination. Maximum gain would occur if the illumination was uniform in phase and equal in amplitude across the aperture of the parabola; however, in practice this is not the case. The amplitude and phase illumination errors, spillover loss, reflector surface tolerance error and other losses reduce the gain to slightly over one half of this value (between 58 to 63 percent with 55 percent guaranteed by most manufacturers).

$$G \text{ (in dBi)} = 10 \log_{10} 4 \frac{A}{\lambda^2}$$

Where A = area of parabolic aperture

$\lambda$  = wavelength of operating frequency

n = efficiency factor

The half power (3 dB) beamwidth is given by the equation

$$\text{HPBW} = 70 \frac{\lambda}{D}$$

When installing the feed in a grid parabolic antenna, you must ensure that the dipole is parallel to the rods in the parabolic reflector. (If the dipole is at right angle to the rods, the gain will be reduced by 15 dB or more.)



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### **Sectoral Antennas**

Sometimes, in point-to-multipoint systems, the outstations (subscribers) are not distributed in a full circle around the base station. They can be concentrated in one or more sectors. Using an omnidirectional antenna in these cases would be a waste of power. It is better to concentrate the available power in the sector(s) where the subscribers are located.

A sectoral antenna is a base station antenna that focuses the radiated power in a given sector ( horizontal pattern). Sectoral antennas are named according to their 3 dB beamwidth (the horizontal pattern of a 90° Sectoral would have a 3 dB beamwidth of ninety degrees). They come in all sizes, horizontal beamwidths and gains (these three parameters are closely related).

An adjustable sectoral antenna is a sectoral antenna whose horizontal beamwidth can be adjusted in the field on an installed antenna (usually to 2 or 3 preset values). The horizontal beamwidth is usually adjusted mechanically by swinging the side panels in/out or by moving them forward/backward. Its versatility, plus the fact that the number of spare antennas required in a network are greatly reduced, make this antenna a very popular choice amongst system designers.

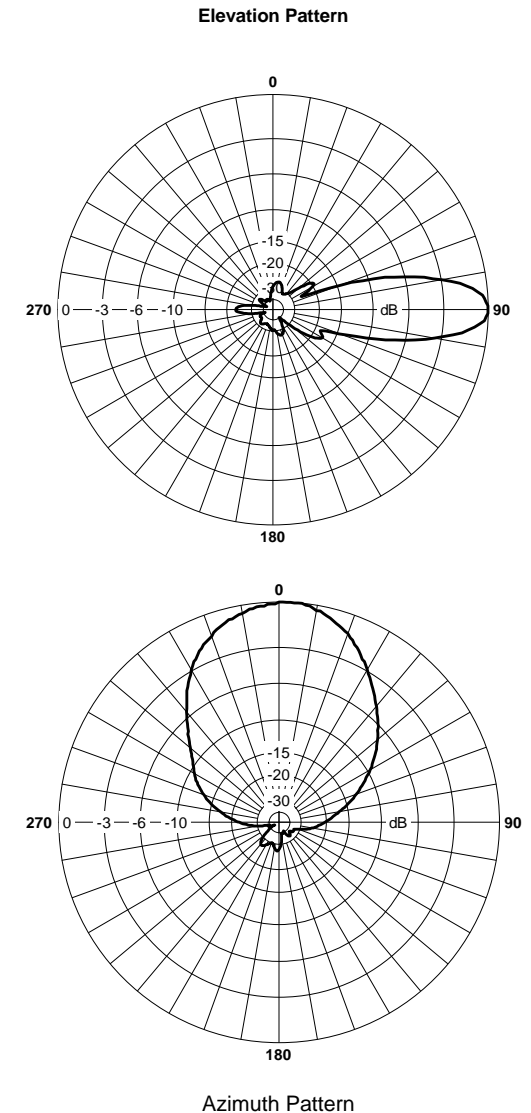
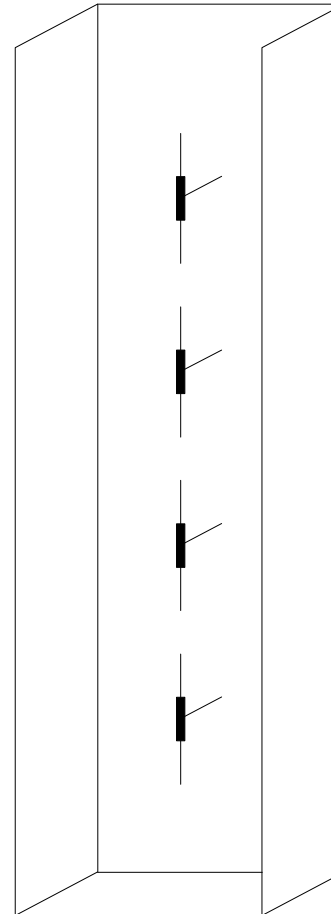


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## Sectoral Antennas

The required horizontal beamwidth is achieved by stacking dipoles horizontally and/or by shaping the reflector (as discussed in the section on directional antennas). Then the gain is increased by stacking dipoles vertically to compress the vertical pattern (as discussed in the sections on omnidirectional antennas). Hence, we can draw the following general conclusions:

- 1) If a 10 dBi omnidirectional antenna has 8 dipoles stacked vertically, then a 10 dBi 180° sectoral antenna will only have 4 dipoles stacked vertically and the vertical beamwidth of the sectoral antenna will be double that of the omnidirectional antenna.
- 2) In order to increase the gain of a 90 degree sectoral antenna by 3 dB, you have to double its length (reduce its vertical beamwidth by half).
- 3) If an adjustable sectoral antenna has a gain of 10 dBi when set to 180 degrees, then it will have a gain of 13 dBi when set to 90 degrees and the vertical pattern will be virtually identical at the two settings.

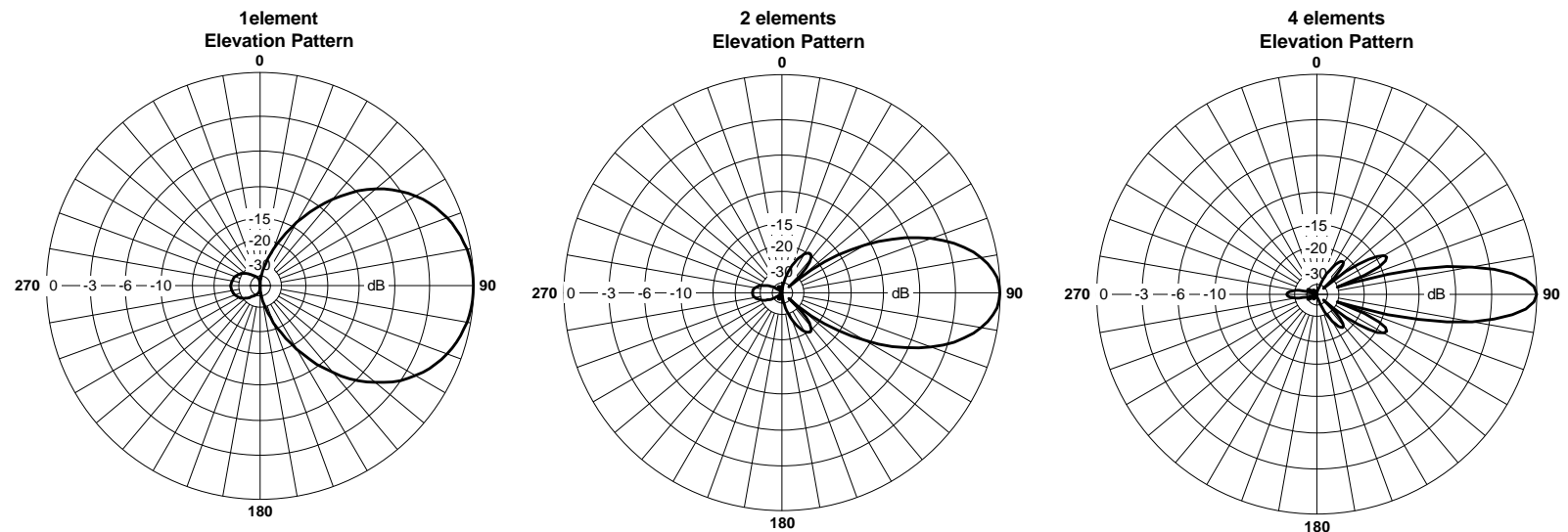




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## Additional Gain by Stacking Directional Antennas

Additional gain can be obtained by stacking directional antennas vertically in line. The net effect is to compress the vertical pattern giving optimum utilization of the power in a certain direction (the horizontal pattern of the array is the same as that of the individual antennas). Of course, they must be phased together correctly and matched into the transmission line in order to get maximum gain. Stacking two identical antennas will increase the gain by 3 dB (reduce the vertical beamwidth by half). The effective height of the antenna array above ground is the physical centre of the array.







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## Omnidirectional Coverage Using Sectoral Antennas

It is best to start by recalling the basic laws of physics that we have covered:

1) Gain is increased in an omnidirectional antenna by “squeezing” the vertical pattern (more power is radiated in the horizontal direction, therefore, less power can be radiated above and below the antenna). An antenna is a passive device; no new energy is created. A fixed amount of energy is being re-directed in the required direction. By now we should have an idea of the vertical beamwidths of omnidirectional antennas.

<u>Gain (dBi)</u>	<u>Vertical Beamwidth (degrees)</u>
7	16
10	8
13	4
16	2

2) A useful approximation to quickly determine the gain of any antenna is:

$$G \text{ (in dBi)} = 10 \log_{10} \frac{36,000}{E_{BW} \times H_{BW}}$$

3) If we only need to cover a 90° sector along the azimuth, then a 13 dBi sectoral will have an elevation beamwidth that is 4 times larger than that of a 13 dBi omni. Typical vertical beamwidths of 90° sectoral antennas are as follows:

<u>Gain (dBi)</u>	<u>Vertical Beamwidth (degrees)</u>
13	16
16	8
19	4

(The gain/beamwidth relationship does not follow exactly like this in practice because of losses.)

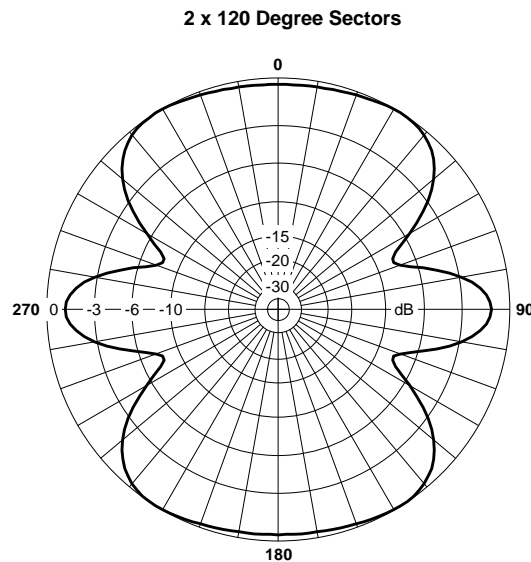
On the surface, it would appear that we can make a 13 dBi omni with 16 degrees of vertical beamwidth out of four 90° sectorals. Not so! In order to feed the four sectorals, we have to split the power coming from the transmission line in four (power to each sectoral is 6 dB lower than the power coming out of the transmission line). The effective radiated power has decreased by 6 dB; therefore, in order to get 13 dBi omnidirectional coverage, you have to start with 19 dBi sectorals, and guess what, they have a 4 degree vertical beamwidth, the same as a 13 dBi omnidirectional antenna.



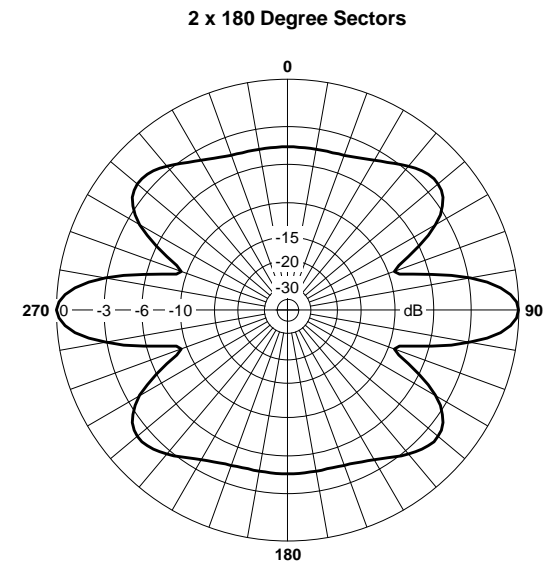
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## **Omnidirectional Coverage Using Sectoral Antennas (Cont'd.)**

In real life, however, things are not quite that simple. In the regions where the horizontal patterns of two sectorals overlap, there are points where the signal coming from one sectoral is out of phase with the signal coming from the other sectoral. At other points in this region, the two signals are in-phase. This creates a ripple in the resultant omnidirectional pattern in the regions where the individual sectoral patterns overlap. Experiments have shown that this ripple is minimized when the individual sectoral patterns are overlapped at their -6dB point (6 dB down from the main beam maximum). Consequently, if you want to make an omnidirectional antenna out of two sectorals, better to use two 120° sectorals than two 180° sectorals. Also, ideally these two sectorals should be mounted back-to-back. The further apart they are mounted (because of physical limitations), the greater the number of ripples there will be in the resultant pattern. Note the apparent loss in gain in the directions of the main beams for the 180° sectorals (0° and 180° azimuth). This is because the front-to-back ratio for the 180° sectorals was only 15 dB to start with whilst that for the 120° sectors was 22 dB.



### **Back to Back Sectors**





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### **Side Mounted Antennas**

We have seen that if we put a reflector behind an array of dipoles, we can block the radiation in the direction of the reflector and re-direct it to form a directional pattern. We have also seen that a wire mesh can work as well as a solid reflector. We should be conscious of these facts when installing antennas on metal towers.

Mounting a directional antenna on a metal tower poses no problem. The radiation is directed out from the tower and the tower has little effect upon the pattern or gain. Mounting an omnidirectional antenna on the side of a metal tower is a different thing. The tower is excited by the currents radiated into it and re-directs the radiation into a “directional” pattern. The resultant far-field pattern will have a null in the direction of the tower and many ripples. The number of ripples and the depths of nulls depend on the operating frequency, the polarization of the antenna, the dimensions of the tower members and other factors.

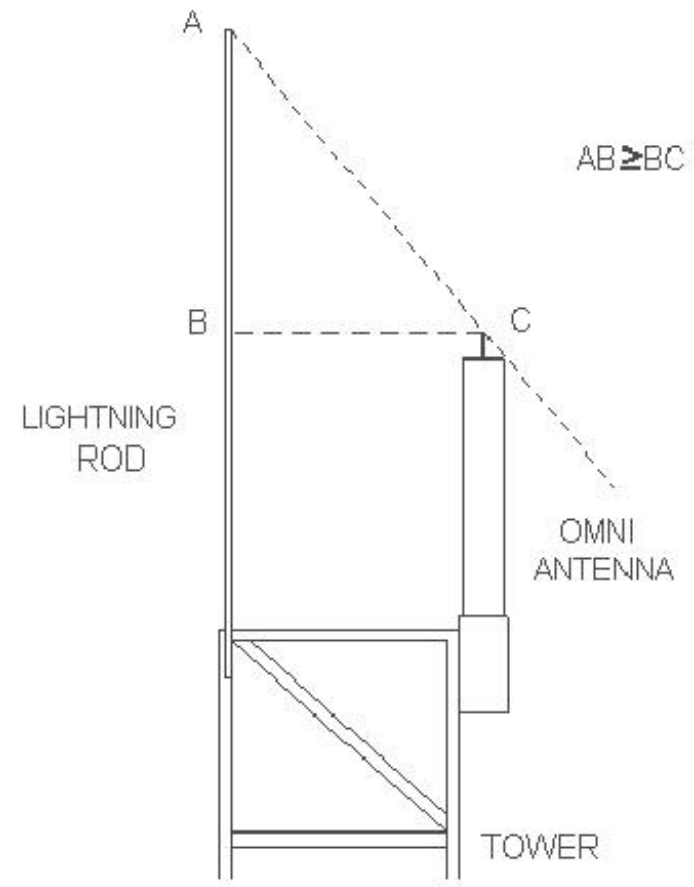
Before mounting an omnidirectional antenna on the side of a metal structure, ask the antenna manufacturer to run a computer simulation of the resultant pattern. You may be better off using an array of sectorals!



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### Omnidirectional Pattern Ripple Due to a Lightning Rod

Omnidirectional antennas should be mounted on top of towers, clear of all obstructions. The problem is that there are few omnidirectional antennas on the market today that will withstand a direct lightning strike (even if the conductive path between the top of the antenna and its base can withstand the very large currents produced by a direct strike, the air inside the radome will be ionized heating it to very high temperatures and causing an explosion that will destroy the radome). The alternative then, is to install a lightning rod beside the omnidirectional antenna. If the top of the lightning rod is above the top of the antenna by the same amount that the two are separated horizontally, then the lightning rod will provide a “cone of protection” for the antenna.



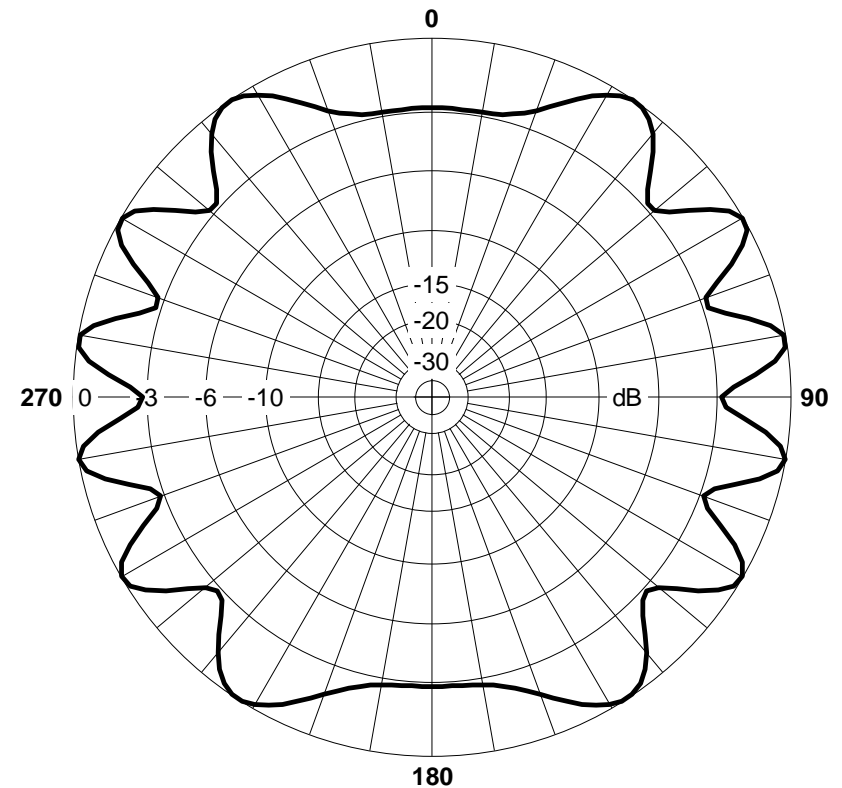


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### Omnidirectional Pattern Ripple Due to a Lightning Rod (Cont'd.)

A separate lightning rod does have an effect on the horizontal pattern of an omnidirectional antenna. The lightning rod scatters the electromagnetic field of the antenna, causing a ripple in the far-field horizontal pattern (the net effect of electromagnetic scattering is to increase the gain in some directions and decrease it in others). The resultant peak-to-peak ripple is dependent on the operating frequency, the diameter of the lightning rod and the distance between the lightning rod and the antenna (See TIL-TEK Application Note No. 3). The effect of scattering is different for vertical and horizontal polarization (the ripple is less for horizontal polarization and becomes negligible when the circumference of the lightning rod is less than one wavelength).

**Pattern Ripple Due to a Lightning Rod  
(4 Wavelengths From Antenna)**



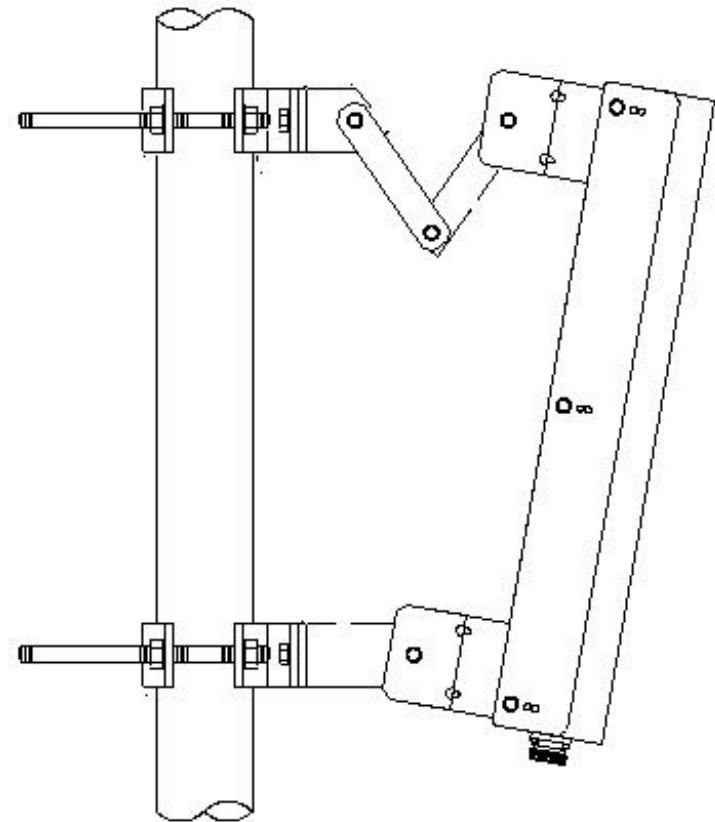


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## **Downtilting the Main Beam of an Antenna**

Downtilt is a term usually applied to Omnis' and sectorals. It refers to tilting the main beam downward away from the horizon. The same process with directional antennas is usually referred to as orientation. High gain directionals have to be carefully adjusted (oriented) both in azimuth and elevation.

**Mechanical Downtilt:** The main beam is tilted downward by physically tilting the antenna away from the vertical. Mechanical downtilt does not apply to Omnis', unless of course, half of your subscribers are Martians. It really only applies to sectoral antennas that have narrow horizontal beamwidths (60 degrees or less). If one takes a sheet of paper on which the horizontal pattern of a 180° sectoral has been drawn and physically tilts the pattern downwards, it will immediately become apparent that if the pattern is tilted 5 degrees at the front, the sides (3 dB points) will not tilt at all. The narrower the azimuth pattern, the more uniform the tilt will be across the 3 dB beamwidth of the antenna.

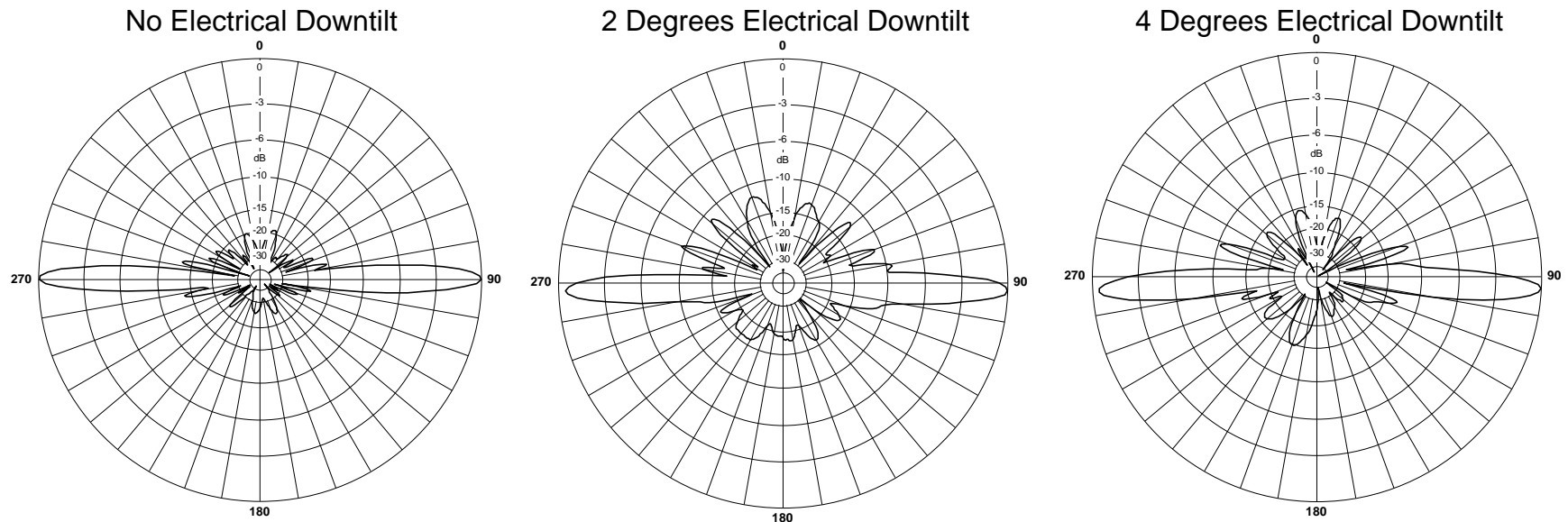




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## Downtilting the Main Beam of an Antenna (Cont'd.)

Electrical Downtilt: The main beam is tilted downwards electrically by feeding the elements (dipoles) of the array with currents of different phase. The advantage of electrical downtilt over mechanical downtilt is that the beam is tilted evenly over the entire beamwidth of the antenna (for a given operating frequency). Usually, the sidelobes (in the vertical pattern of the antenna) increase as the amount of electrical downtilt is increased. The resulting loss in gain is not a problem but the power radiated by the upper sidelobe may cause interference in neighbouring systems. For this reason, system designers like to see the upper sidelobe thirty degrees or more above the main beam. Another imperfection encountered in real life is that electrical downtilt is not constant over the operating bandwidth of the antenna. It does vary slightly with frequency.



## Electrical Downtilt in Omnidirectional Antennas





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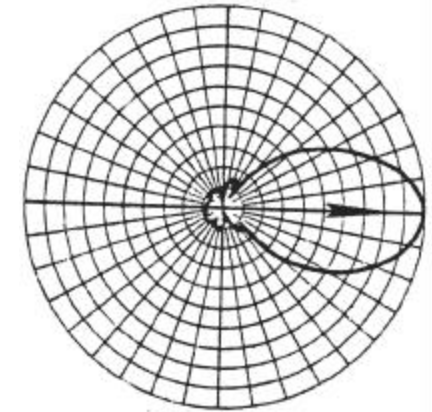
## Effect of Ice on Antenna Performance

Ice affects the performance of all antennas to some degree and the problem gets more serious the higher the frequency. The dipole elements in an antenna transform electromagnetic signals into electromagnetic waves radiating into free space. The impedance of free space is 377 ohms. If the air immediately surrounding the dipole elements is replaced by ice which has a lower impedance than air, then the impedance match and radiation patterns of the antenna will change. These changes become progressively worse as the ice loading increases.

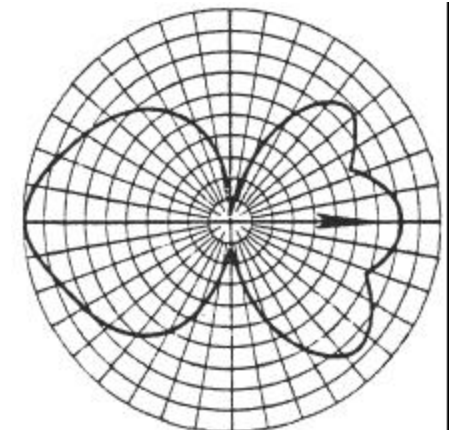
Antenna elements are usually encased in a plastic protective housing (radome). This provides an air space between the elements and ice casing so that the lower impedance of the ice layer has only a small effect on the radiators. Detuning is greatly reduced but radiation pattern distortion may still be encountered (detuning reduces usable antenna bandwidth). For a given ice thickness, deviation from nominal performance values become worse as frequency increases.

Yagi antennas are particularly sensitive to icing if the radiator and first two directors are not covered with a radome (their directivity can even be reversed under severe icing conditions). Icing on the elements of a yagi has the same effect as if the directors were lengthened. When the electrical length of the directors become greater than one-half wavelength, they become reflectors and the yagi antenna is no longer a directional antenna. The radiation pattern of the antenna changes and the sidelobes grow as the ice builds up on the elements.

It makes perfect sense that a "traveling wave" type of antenna like the yagi (where icing has the same effect as lengthening the elements) will be much more sensitive to icing than a "reflector" type of antenna, especially if the latter has a radome protecting the air space in front of the elements. In areas where severe icing and wet snow are common, it is prudent to install a full radome over solid parabolic antennas, to use panel antennas instead of corner reflectors, and to stay away from grid parabolics.



No Ice



0.2" Radial Ice

**10 Element Yagi at 502 MHz**





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### **Radome Pressurization**

Most antenna radomes are unpressurized. This means that they are “splash proof” so that water from rain or melting snow will not enter them freely but they are not sealed against moisture. As such they must have a drain hole at the bottom so that if water does enter, it will not accumulate inside the antenna. One way water gets inside a radome is by warm humid air entering the radome during the day and when it cools off at night the water vapour in the air condenses producing water droplets on the inside surfaces of the antenna. Sometimes the space inside the radome is filled with closed-cell foam in order to minimize this process (condensation).

Some antennas (e.g. high power broadcast antennas) have pressurized radomes. The radome is pressurized (less than 10 lb./in<sup>2</sup>) through the transmission line using dry air or nitrogen. In effect, the transmission line (air dielectric) and antenna become one pressurized system. In this case, the radome is sealed against moisture. The fact that the air inside the transmission line/radome is higher in pressure than that on the outside ensures that water will not get into this system through condensation.



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## **Antenna Installation Practices**

Do not go for gain indiscriminately. Choose an omnidirectional antenna that has an elevation beamwidth sufficient to cover all the subscribers, both near and far away (See TIL-TEK application Note No. 1). When installing a high gain directional antenna on a tower, make sure that the tower specifications (tilt and sway) are rigid enough to handle the 3 dB beamwidths of the antenna.

If you have to use a large diameter transmission line (7/8 inch and larger) between the antenna and transmitter in order to reduce losses, use a jumper cable between the antenna and transmission line in order to reduce the stress on the antenna connector.

Most antenna problems are caused by coaxial cable connections that loosen due to vibration, allowing moisture to penetrate the connector interface. Weatherproof all outdoor connections. This can be done by applying several layers of rubber vulcanizing tape over the connection and then covering that with good (low temperature) electrical tape (See TIL-TEK application Note No. 2).

Drainage is very important with unpressurized radomes. Make sure that the drain hole is on the bottom and that it has not been blocked during installation (when sealing the antenna connector).



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### **dB's are Expensive**

Try to get an appreciation for antenna specifications by comparing the specifications of different manufacturers for a particular type of antenna. What manufacturers put down as specifications on their data sheets represents a good compromise for the money. Increasing gain, reducing sidelobe levels, increasing bandwidth or increasing return loss may require a redesign of the antenna resulting in an increase in price. Never hesitate to contact the antenna manufacturers for additional information if you need help in designing a system.



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## **Application Notes**

### **Antenna Far Field Distance**

The antenna far field distance is generally considered to be the smallest distance from the antenna at which the radiation pattern is well formed. The standard formula for the antenna far field distance,  $r$ , is:

$$r = 2D^2/\lambda, \text{ where}$$

$D$  = maximum of antenna length, width or height  
 $\lambda$  = wavelength

and  $r$ ,  $D$  and  $\lambda$  are in the same units (e.g. meters, feet or inches)

The wavelength,  $\lambda$ , is:

$$\begin{aligned}\lambda &= 299.8/f \text{ MHz meters} \\ &= 983.6/f \text{ MHz feet} \\ &= 11803/f \text{ MHz inches} \\ f \text{ MHz} &= \text{frequency in MHz}\end{aligned}$$



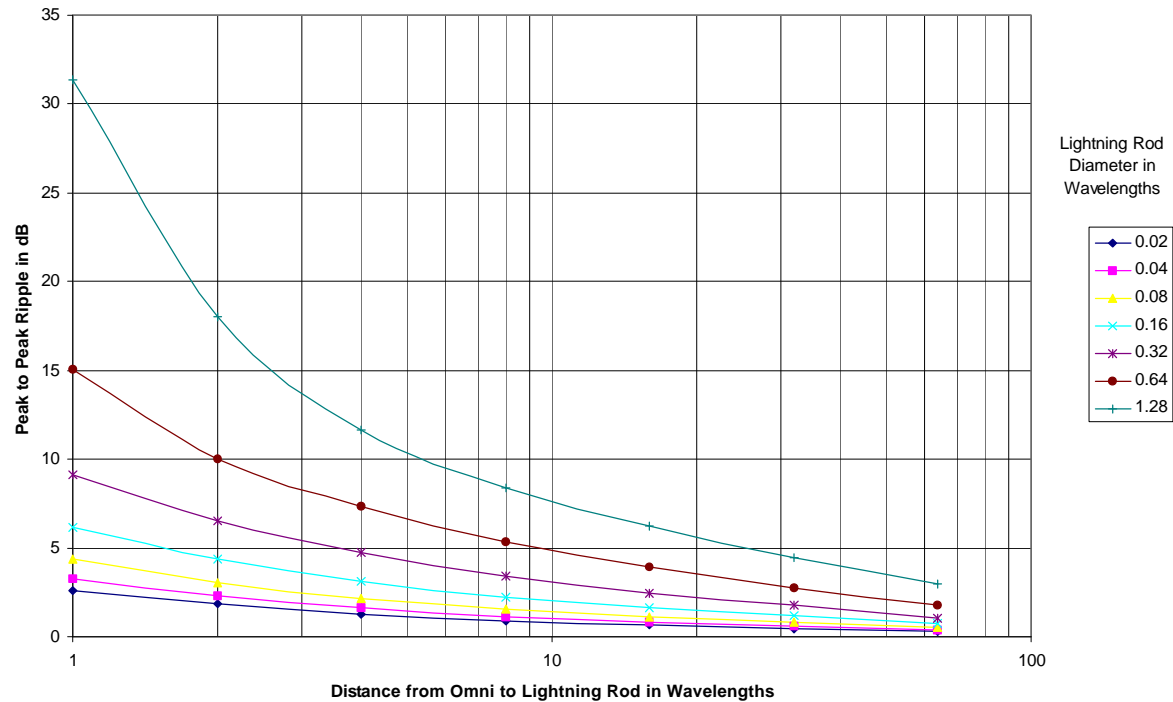
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## Application Notes

### Omni Pattern ripple Due to A Lightning Rod

The typical omnidirectional antenna is situated at the top of a tower beside a lightning rod. The lightning rod will scatter the electromagnetic field of the antenna, causing a ripple in the far-field azimuth pattern. This note shows how much ripple will occur. The effect is different for vertical and horizontal polarization.

Ripple in an Omni Pattern due to a Lightning Rod



$$\text{Wavelength, } \lambda_m = 299.8 / f \text{ MHz}$$
$$\lambda_{\text{inches}} = 11,803 / f \text{ MHz}$$



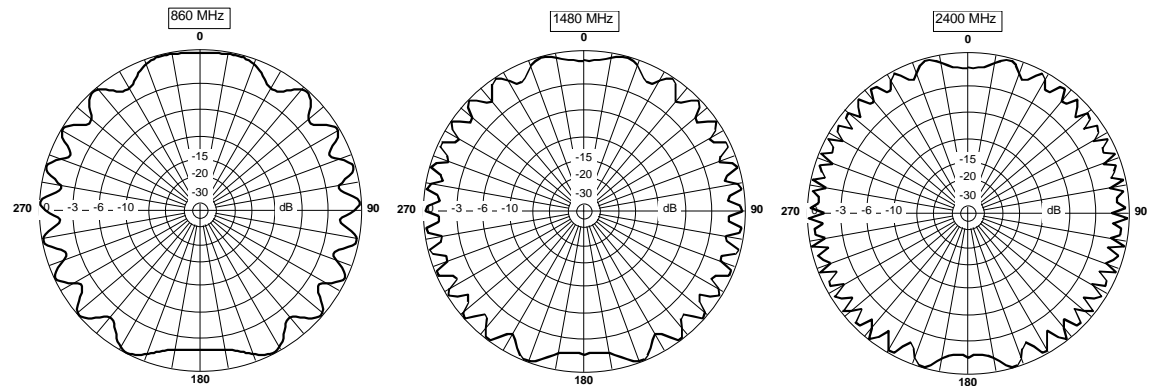
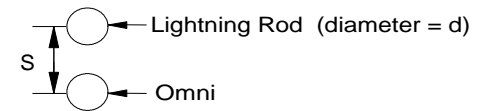
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## Application Notes

### Omni Pattern ripple Due to A Lightning Rod (Cont'd)

Relative positions of the lightning rod are shown. The nominal gain of the antenna (data sheet specification) would be represented by a line on the average of the ripple, i.e. the net effect of electromagnetic scattering is to increase the gain in some directions and to decrease it in others.

**s = 1.5m    d = 16 mm (5/8")**



**s = 1.5m    d = 38 mm (1.5")**

