

ELECTROMAGNETIC RADIATION CHARACTERISTICS

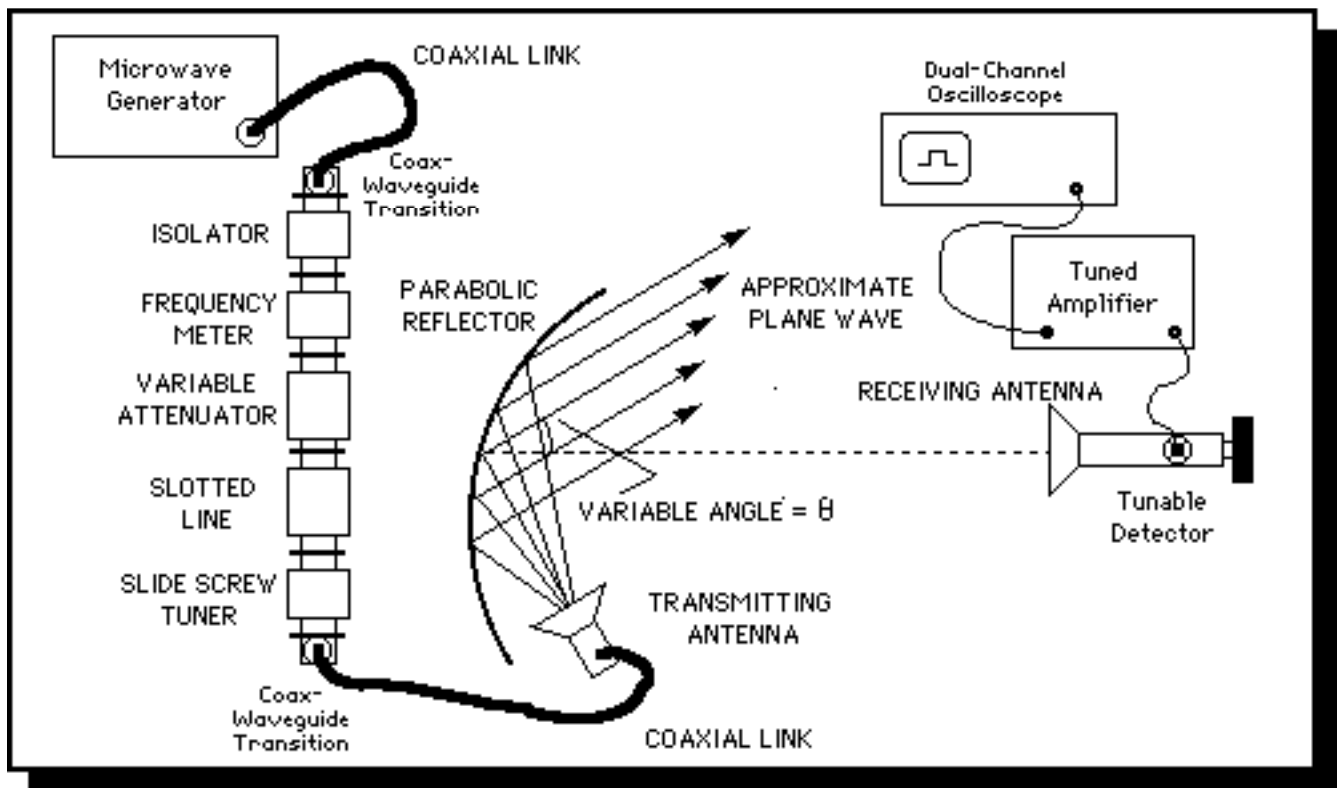
Microwave Antenna Measurements

OBJECTIVE:

To study the radiation patterns and other characteristics of a variety of electromagnetic radiators (antennas).

EXPERIMENTAL METHODS¹

EXPERIMENTAL SETUP:



EQUIPMENT:

Sweep signal generator: 8 -12 GHz, Dorado International Corp. Model G4-197
Low-noise preamplifier, Stanford Research Systems, Model SR560
60 MHz Dual-channel oscilloscope, Tektronix, Model 2213A
Microwave isolator, Bomac Laboratories, Model BLF-30
Slotted line section, Hewlett-Packard, Model 809B
Variable attenuator, Hewlett-Packard, Model X382A
Slide screw tuner, Hewlett-Packard, Model X870A
Frequency meter, FXR, Model X401B

¹ See Chapter 16, Antenna Measurements, in *Antenna Theory* (Second Edition), Constantine A. Balanis, ISBN 0-471-59268-4.

Detector mount, Hewlett-Packard, Model X485B
 and microwave crystal diode detectors, 1N21B or 1N23B
 Parabolic reflector (18 inch aperture diameter), Edmund Scientific
 Center-fed reflector antenna (30 cm diameter aperture), homemade
 Set of two small (5.4 cm x 7.3 cm) pyramidal horn antennas, Narda, Model 640
 Large aperture (9 cm x 15 cm) pyramidal horn antennas, homemade
 Endfire helical antenna, homemade
 Microstrip patch antenna, homemade
 Three element array antenna driver, homemade
 Set of rotatable wooden antenna stands), homemade
 Wooden frame for CATR reflector, homemade
 Two waveguide *twist* sections
 Flexible inspection light
 Sheets (24 x 24 inch) of microwave anechoic material
 Miscellaneous test parts including: waveguide and coax components and transistors; wire
 and aluminum foil; *etc.*

GENERAL COMMENTS:

The experimental setup, illustrated above, provides a means for studying the radiation patterns and other characteristics of electromagnetic antennas. In real-world engineering, such a configuration would be called a *antenna range*.² As you will discover, precise and unambiguous antenna measurements are quite difficult and time consuming. In particular, it is often difficult to clearly isolate the direct radiation from the transmitting antenna and radiation scattered from proximate reflecting objects such as buildings, furniture, people, *etc.*. Thus, real-world antenna ranges are elaborate and costly facilities.³ At high frequencies, isolation from the effects of *range clutter* may be achieved in carefully constructed compact, anechoic chambers. However, at frequencies below one GHz, anechoic chambers are impractical and one must look for a sizable chunk of flat, uninhabited real estate.⁴

Of course, the advantage of using microwave radiation for such experiments is the convenience of small size and, since Maxwell's equations are scaleable, the results obtained are, in most respects, completely general. Following common engineering practice, the ES151 antenna range is configured to study antennas in the receiving mode. As shown, the receiving test antenna is mounted in a rotatable wooden stand and irradiated with a *reasonable approximation* of a plane wave.⁵ This plane wave is obtained by collimating the

² To quote from Balanis (Section 16.1, in *Antenna Theory*)

"...it is usually most convenient to perform antenna measurements with the antenna in its receiving mode. If the antenna is reciprocal, the receiving mode characteristics (gain, radiation pattern, *etc.*) are identical to those transmitted by the antenna. The ideal condition for measuring far-field radiation characteristics then, is the illumination of the test antenna by plane waves: uniform amplitude and phase. Although this ideal condition is not achievable, it can be approximated by separating the test antenna from the illumination source by a large distance on an outdoor range. At large radii, the curvature of the spherical phase front produced by the source antenna is small over the test antenna aperture. ...In addition to phasefront curvature due to finite separation distances, reflections from the ground and nearby objects are possible sources of degradation of the test antenna illumination."

³ See, for example,

http://euler.ece.uiuc.edu/public_html/picture_archive/dtu/chamber.jpg

⁴ See, for example,

http://euler.ece.uiuc.edu/public_html/picture_archive/npl/calib.gif

output of a transmitting antenna which is excited by a microwave signal derived from a variable frequency generator operating in the range of, approximately, 8 - 12 GHz (X-band).⁶ An isolator is incorporated in the transmitter circuit to shield the generator from any potential deleterious "downstream" impedance effects and to insure stable operation. The frequency meter, obviously, provides a means of measuring the frequency of the generator's output, if necessary. The calibrated variable attenuator, in turn, allows for the precise adjustment of the relative radiated power from the antenna and, thus, effectuates the *substitution* or *constant-power-to-the-detector* measurement strategy which we have used in earlier experiments. The slotted line section provides a means, if necessary, for measuring the power reflected from the transmitting antenna. Finally, the slide screw tuner provides a means for matching the impedance of the antenna to obtain maximum radiative output. For the purpose of detection, the transmitted signal is amplitude modulated at an audio frequency (1 kHz). The modulated beam from the transmitting antenna impinges on the receiving antenna and is conveyed by waveguide or coaxial line to a crystal detector (demodulator). After amplification, the received, demodulated signal is displayed on one channel of the dual-channel scope.

EXPERIMENTAL MEASUREMENTS AND OBSERVATIONS:

ESTABLISHING THE COMPACT ANTENNA TEST RANGE (CATR):⁷

The first task is to establish a Compact Antenna Test Range (CATR) using one of the Narda, Model 640 pyramidal horn antennas (an industry standard; see the attached specification sheet) as an offset feed antenna and an 18 inch parabolic reflector as the CATR reflector.

⁵ Recall that in the lecture notes entitled *Receiving Antenna Characteristics*, we showed (*viz.*, Equation [7]) that when an antenna in its receiving mode is irradiated by a plane wave of magnitude \vec{E}_{inc} and wave vector $\hat{\mathbf{k}}$, the received open-circuit voltage is given by

$$V_R(\omega) = -\vec{E}_{inc} \cdot \hat{\mathbf{k}} \times \hat{\mathbf{k}} \times \frac{1}{I_T} \vec{N}_{trans}(\omega)$$

where $\vec{N}_{trans}(\omega)$ is the antenna's far-field current transform.

⁶ Precisely the frequency range is 8.15 to 1205 GHz.

⁷ Again to quote from Balanis (Section 16.2.3, in *Antenna Theory*)

"A Compact Antenna Test Range (CATR) is a collimating device which generates nearly planar wavefronts in a very short distance.....Some attempts have been made to use dielectric lenses as collimators, but generally the name compact antenna test range refers to one or more curved metal reflectors which perform the collimating function. Compact antenna test ranges are essentially very large reflector antennas designed to optimize the planar characteristics of the fields in the near-field of the aperture. Compact range configurations are often designated according to their analogous reflector antenna configurations: parabolic, Cassegrain, Gregorian, and so forth.

"One compact range configuration is that...where a source antenna is used as an offset feed that illuminates a paraboloidal reflector, which converts the impinging spherical wave to plane wave. Geometrical Optics (GO) is used ... to illustrate general CATR operation. The rays from a feed antenna can ... be viewed as emanating from a point at its phase center. When the phase center of the feed is located at the prime focus of a parabolic reflector, all rays that are reflected by the reflector and arrive at a plane transverse to the axis of the parabola have traveled an equal distance.Therefore, the field at the aperture of the reflector has a uniform phase; i.e., that of a plane wave.

"The major drawbacks of compact ranges are aperture blockage, direct radiation from the source to the test antenna, diffractions from the edges of the reflector and feed support, depolarization coupling between the two antennas and wall reflections. The use of an offset feed eliminates aperture blockage and reduces diffraction.

Viewing a distant light source through the center hole in the parabolic reflector, find the approximate location of the image of the light source and, thus, the location of the reflector's focal plane. (As a convenient reference, you will find it helpful to define the aperture plane with one or more lengths of fine thread running across the aperture and taped to the edges of the reflector.)

Mount the horn feed antenna in one of the rotatable wooden stands and the parabolic reflector in its wooden frame. Excite the feed antenna with an AM signal at 10 GHz. Probe Since it has the highest directivity, use the center-fed reflector antenna (mounted in the other rotatable wooden stand) as a test probe in setting up the CATR.

Adjust the positions and orientations of the feed and reflector to achieve the best possible **quiet zone** at the position of test antenna.⁸ In adjusting the position of the feed, it is important to know that the position of the phase center of a pyramidal horn antenna varies with flare angle and wavelength.⁹ For the Narda standard horn with flare angle of approximately 15° the phase center is on the horn axis and within ± 3 mm of the horn aperture.

The filament of the bulb in the flexible head inspection light is a convenient point source of light. In aligning and visualizing the operation of the CATR, you may find it helpful to deploy this point source of light at the microwave phase center of the feed horn and observe its visual image.

General precautions:

- **Be sure to always tune the receiving crystal detector for maximum response!**
- **Be sure to always tune the slide screw tuner to obtain maximum transmitter output!**
- **Use the anechoic sheets to test for and to screen out the effects of spurious reflections!**

⁸ Continuing to quote from Balanis (Section 16.2.3, in *Antenna Theory*

A perfect plane wave would be produced by a CATR if the reflector has an ideal parabolic curvature, is infinite in size and is fed by a point source located at its focus. Of course CATR reflectors are of finite size, and their surfaces have imperfection; thus the test zone fields they produce can only approximate plane waves. Although there are different configurations of CATR, their test zone fields have some common characteristics. The usable portion of the test zone consists nearly planar wavefronts and is referred to as the "quiet zone." Outside the quiet zone, the amplitude of the fields decrease rapidly as a function of distance transverse to the range axis. The size of the quiet zone is typically about 50%-60% of the dimensions of the main reflector."

⁹ See Section 13.10 in *Antenna Theory* (Second Edition), Constantine A. Balanis.

ANTENNA MEASUREMENTS

Calibration Standard: Narda Pyramidal Horn Antenna, Model 640

Our goal is to determine the radiation patterns and, in particular, the **directive gain**¹⁰ of a number of different antennas by measuring the angular dependence of the received signal. The study of pyramidal horn antennas, represent a good starting point, since their behavior is quite reproducible and they are essentially engineering or industry standards (see attached spec sheets). In particular, for the Narda horn we know the beam width (28°) and the midband gain (16.5 dB) with reference to that elusive fictional standard, the *isotropic radiator* (see end of this write-up for an explanation of antenna terms). Thus having measured the characteristics of our Narda, Model 640 horn in our antenna range, we can use it as a local standard of reference for other antenna measurements.

Measurement:

Mount the Model 640 antenna in the receiver stand. By rotating the receiving antenna in the E-plane and adjusting the variable attenuator to maintain constant-power-to-the-detector, determine the angular response at 10 GHz in the E-plane.

Remount the transmitting and receiving antennas using the two waveguide twist sections. Again, by rotating the receiving antenna in the H-plane and adjusting the variable attenuator to maintain constant-power-to-the-detector, determine the angular response at 10 GHz in the H-plane.

Assess the degree of beam depolarization associated with reflection from the CATR reflector.

Report:

- Plot the E- and H-plane angular responses of Model 640.
- From these plots deduct values for the nominal angular beam widths of Model 640.
- Comment on the degree of beam depolarization associated with reflection from the CATR reflector.

Homemade Large Aperture Horn Antenna

Measurement:

Mount the homemade large aperture horn antenna in the receiver stand. By rotating this receiving antenna in the E-plane and adjusting the variable attenuator to maintain constant-power-to-the-detector, determine the in the angular response at 10 GHz in the E-plane. Also by maintaining constant-power-to-the-detector strategy, determine the directive gain of this antenna with reference to Model 640.

Report:

- Plot the in the E-plane angular response of this antenna.
- From this plot deduct a value for the nominal angular beam width of this large aperture antenna.
- By comparing this beam width result with that for Model 640, estimate how the angular width of the radiation pattern varies with horn size.

¹⁰ See end of this write-up for an explanation of antenna terms such as the **power gain** and **relative gain** of a given antenna in a given direction.

- Report your estimates of the directive gain of this antenna with reference to Model 640 and with reference to an isotropic radiator.

Center-fed Reflector Antenna

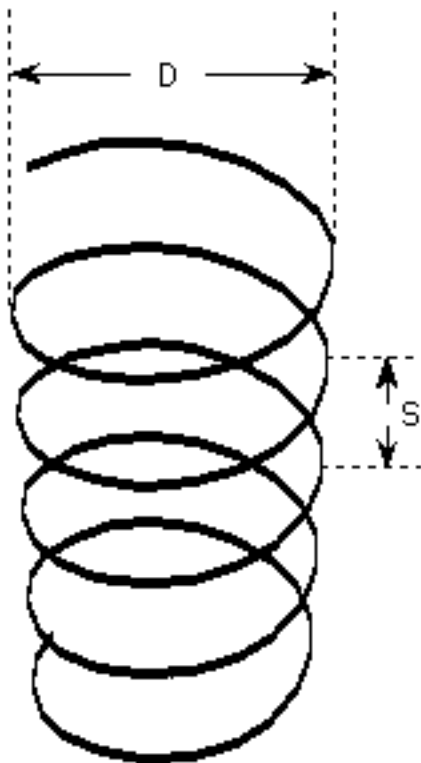
Measurement:

Remount the homemade center-fed reflector antenna in the receiver stand. By rotating this receiving antenna in the E-plane and adjusting the variable attenuator to maintain constant-power-to-the-detector, determine the angular response at 10 GHz of this antenna. Also by maintaining constant-power-to-the-detector strategy, determine the directive gain of this antenna with reference to Model 640.

Report:

- Plot the in the E-plane angular response of this antenna.
- From this plot deduct a value for its nominal angular beam width.
- Report your estimates of the directive gain of this antenna with reference to Model 640 and with reference to an isotropic radiator.

Helical Antennas



$$C = D$$

Helical Antenna Characteristics

Parameters:

$$\text{Pitch angle: } \tan^{-1} \frac{S}{D} = \tan^{-1} \frac{S}{C}$$

$$\text{Length of helix: } L = N S$$

$$\text{Length of wire: } L_N = N L_0 = N \sqrt{S^2 + C^2}$$

Normal (broadside) mode: $L_N = N L_0 \ll$

Polarization varies with , but when $C = \sqrt{2} S$ the radiation is circularly polarized in all directions!

Axial (endfire) mode: S and C are large fractions of (typically $12^\circ < < 14^\circ$)

In particular, obtain circular polarization when

$$\frac{3}{4} < C < \frac{4}{3} \quad \text{and} \quad S \frac{1}{4}$$

Helical antennas are an interest, simple and quite useful class of wide bandwidth antennas. The radiation characteristics of helical antennas can be varied by controlling the size of its geometrical parameters with respect to the radiated wavelength (see table above). In particular, when the pitch angle approaches zero the helix becomes a

stack of magnetic dipoles with radiated H field parallel to the axis of the helix. But when θ approaches 90° the helix becomes a long electric dipole with radiated E field parallel to the axis of the helix.

Of the many possible variants, the axial or endfire mode of a helical antenna is perhaps the most useful and it is the one we study here.

Measurement:

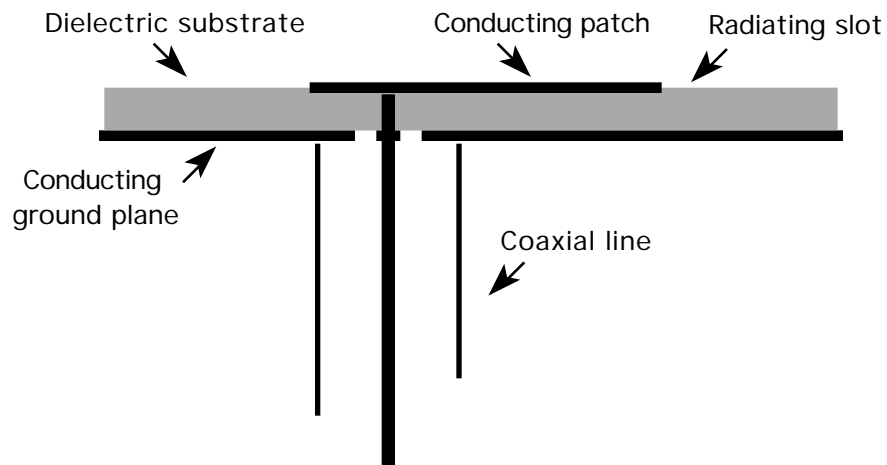
Mount the endfire helical antenna in the receiver stand. By rotating the antenna in the E-plane and adjusting the variable attenuator to maintain constant-power-to-the-detector, determine the angular response at 10 GHz in the E-plane of the antenna. Also by maintaining constant-power-to-the-detector strategy, determine the directive gain of this antenna with reference to Model 640.

Report:

- Plot the angular response of this antenna.
- From this plot deduct a value for its nominal angular beam width.
- Report your estimates of the directive gain of this antenna with reference to Model 640 and with reference to an isotropic radiator.

Microstrip Patch Antennas

Microstrip patch antennas are very simple structures that are becoming increasingly popular in applications where low-profile is a key concern.¹¹ A cross sectional view of a coax-fed patch antenna is illustrated below. It is, essentially, an unterminated length of microstrip transmission line (parallel plate waveguide). For best operation the thickness of dielectric substrate should be a very small fraction of the radiated wavelength (usually between 0.003 and 0.05). The most useful mode of operation occurs when the excitation frequency is such that there is a voltage maximum (open circuit) at the *radiating slot*. Under these circumstance there is a maximum in the radiation of the antenna **normal to the planar surface of the patch!**



Measurement:

¹¹ On display in the Cruft Basement Laboratory is a commercial version of a flat microwave (2.5 to 2.7 GHz) receiving antenna (Antennas America Inc., Model MMDS1414) which has been designed for MMDS (Multichannel Microwave Distribution Service) applications. Such “piazza box” antennas figure prominently in descriptions of advanced mobile and fixed-point wireless services.

Mount the microstrip patch antennas in the receiver stand and orient it so that the patch is normal to direction of the plane wave from the CATR reflector. By the varying the frequency of the microwave signal generator, find a frequency or range of frequencies at which the antenna is sensitive in the normal direction. At this frequency, rotate the antenna in the E-plane to determine the main features of the angular response -- viz., determine the angular width and strength of the peak response normal to the patch as well the angular location and strength of other maxim .

Report:

- Report and discuss your findings.

Three-element Antenna Array: Traveling Wave

The three element array driver is a section of waveguide with equally spaced ($d = 12.85$ cm) coupling ports. You may recall that the endfire condition for array is that the phase between elements must be ¹²

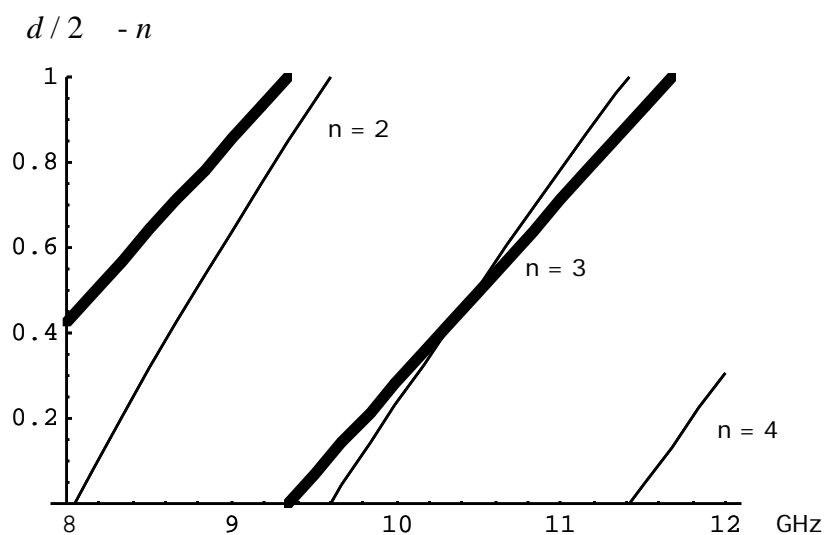
Measurement:

With the three element array driver line terminated in a matching impedance each element is excited equally by a traveling wave and the phase delay between the elements is given by βd where β is the propagation constant in the waveguide and d is distance between elements. $d=12.85$ In X-band waveguide

$$\frac{\beta}{k} = \frac{\sqrt{f^2 - f_{co}^2}}{f} \quad \text{where} \quad f_{co} = 6.557 \text{ GHz}$$

or

$$\frac{\beta}{k} = \sqrt{1 - \left(\frac{f_{co}}{f}\right)^2} \quad \text{where} \quad f_{co} = 4.572 \text{ cm}.$$



Mount the three-element antenna array in the receiver stand. By rotating this receiving antenna and adjusting the variable attenuator to maintain constant-power-

¹² See the lecture notes entitled *Antenna Arrays in the Far-Field Approximation*.

to-the-detector, determine the angular response at 10 GHz in the E-plane of the antenna. , measure the radiation pattern of the one apertures. Then measure the radiation pattern of the three aperture array over a range of frequencies which incorporates a value of $d = (2n + 1)/2$. Also by maintaining constant-power-to-the-detector strategy, determine the directive gain of this antenna with reference to Model 640.

Report:

- Plot the angular response of this antenna.
- From this plot deduct a value for the nominal angular beam width of this antenna.
- Report your estimates of the directive gain of this antenna with reference to Model 640 and with reference to an isotropic radiator.

SOME ANTENNA TERMS:

Antenna radiation pattern: An antenna radiation pattern or antenna pattern is defined as "a mathematical function or graphical representation of the radiation properties of the antenna as a function of space coordinates. In most cases, the radiation pattern is determined in the far-field region (*i.e.* in the region where electric and magnetic fields vary inversely with distance) and is represented as a function of the directional coordinates." The radiation property of most concern is the two- or three-dimensional spatial distribution of radiated energy as a function of an observer's position along a path or surface of constant distance from the antenna. A trace of the received power at a constant distance is called a power pattern. A graph of the spatial variation of the electric or magnetic field along a constant distance path, is called a field pattern.

Isotropic antenna: An isotropic antenna is defined as "a hypothetical lossless antenna having equal radiation in all directions." Clearly, an isotropic antenna is a fictitious entity, since even the simplest Hertzian antenna has some degree of directivity. Although hypothetical and not physically realizable, an isotropic radiator is taken as a reference for expressing the directional properties of actual antennas.

Directional antenna: A directional antenna is one "having the property of radiating or receiving electromagnetic waves more effectively in some directions than in others. " The term is usually applied to an antenna whose maximum directivity is significantly greater than that of a linear dipole antenna.

Omnidirectional antenna: An omnidirectional antenna is an antenna having a radiation pattern which is nondirectional in a plane. For example, a linear dipole has uniform power flow in any plane perpendicular to the axis of the dipole and the maximum power flow is in the equatorial plane.

Directivity: The directivity of a transmitting antenna is defined as the ratio of the radiation intensity flowing in a given direction to the radiation intensity averaged over all direction. The average radiation intensity is equal to the total power radiated by the antenna divided by 4π . If the direction is not specified, the direction of maximum radiation intensity is usually implied. Directivity is some times referred to as **directive gain**.

Absolute gain: The absolute gain of a transmitting antenna in a given direction is defined as the ratio of the radiation intensity flowing in that direction to the radiation intensity that would be obtained if the power accepted by the antenna were radiated isotropically. If the direction is not specified, the direction of maximum radiation intensity is usually implied. (Absolute gain is

closely related to directivity, but it takes into account the efficiency of antenna as well as its direction characteristics. To distinguish it, the absolute gain is some times referred to as **power gain**.)

Relative gain: The relative gain of a transmitting antenna in a given direction is defined as the ratio of the absolute gain of the antenna in the given direction to the absolute gain of a reference antenna in the same direction. The power input to the two antennas must be the same.

Efficiency: The efficiency of a transmitting antenna is the ratio of the total radiated power radiated by the antenna to the input power to the antenna.

Effective area (aperature): The effective area or aperature of a receiving antenna in a given direction is defined as the ratio of the available power at the terminals of the antenna to the radiation intensity of a plane wave incident on the antenna in the given direction. If the direction is not specified, the direction of maximum radiation intensity is usually implied. It can be shown, that when an isotropic area is used as a receiving antenna its effective area is the wavelength squared divided by 4 . Thus, the gain of a receiving antenna is the ratio of the antennas effective area to that of an isotropic antenna -- i.e. $G_g = 4 A / \lambda^2$.

Antenna factor: The ratio of the magnitude of the electric field incident upon a receiving antenna to the voltage developed at the antenna's output connector (assuming a 50 ohm coaxial connector) is called the antenna factor. The antenna factor is clearly related to the gain of antenna, but is often found to be the most convenience parameter for use in the monitoring of electromagnetic emissions.

$$AF = \sqrt{\frac{30}{50}} \frac{4}{\lambda} \frac{1}{\sqrt{G}} = \frac{9.734}{(\text{meters})} \frac{1}{\sqrt{G}}$$