Wave Propagation

Bruce C. Gabrielson, PhD

Security Engineering Services
5005 Bayside Rd.
Chesapeake Beach, MD 20732
ses@blackmagic.com

Field Theory

Current flow through a conductive substance creates an electromagnetic field around the substance as shown in Figure 1. The field is made up of mutually perpendicular electric and magnetic waves of varying strengths (intensities) called E fields and H fields respectively. These field strengths are vector quantities, having both magnitude and direction. Neither field can exist independently: whenever there exists a magnetic field, an electric field also exists. Radio waves are defined as moving electromagnetic fields with E and H field components at right angles to each other, and having velocity in the direction of travel.

WAVE CREATION

Current flow through a conductive substance creates an electromagnetic field around the substance
The field is made up of mutually perpendicular electric and magnetic waves.
Neither field can exist independently.

FIELD TYPES

Static and induction fields associated with the collapse of stored energy are called "near" fields.

The radiation field due to current flow is called the "far" field.

Static fields vary inversely as the third power of the distance from their source.

If the current flowing through the conductor is a sinusoidal varying or pulsed current, the electromagnetic field around the conductor will expand and contract, and a portion of the energy stored in the field will be radiated away from the current path. The greater the low frequency component of current flow, the greater the magnetic field strength.

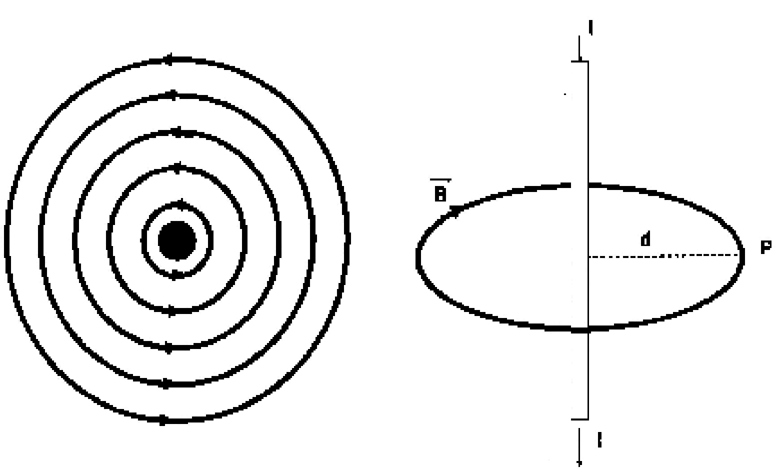


Figure 1 - Fields & Current Flow Around a Conductor

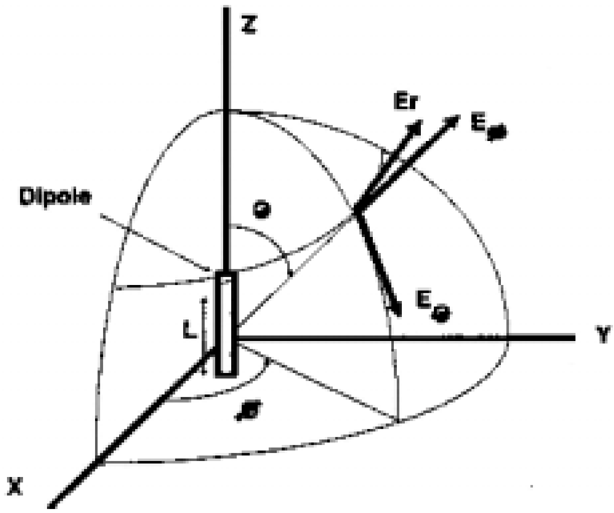


Figure 2 - Wire Source

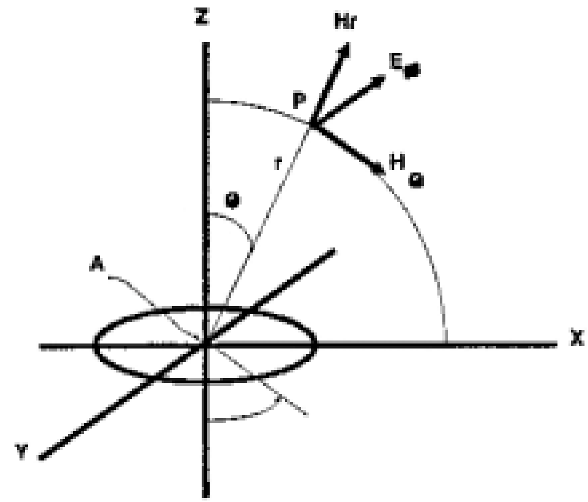


Figure 3 - Loop Source

> ***HOW IT HAPPENS***
>
> ***If the current flowing through the conductor is sinusoidal, the E-field around the conductor will expand and contract.***
>
> ***As the E-field expands and collapses, completely closed loops of E-flux lines are formed and "pushed" into space by subsequent expanding flux lines.***

As the E-field expands and collapses, completely closed loops of E-flux lines are formed and "pushed" into space by subsequent expanding flux lines. The radiated E-field generates its own accompanying H-field since there can be no conductive current in free space, the radiated E-field acts as a displacement current which generates the H-field. Figure 2 and 3 show the resulting fields associated with a loop and a wire source. Individual field components can be calculated from the equations of Figure 4. Figure 5 shows the components of an electromagnetic wave including direction of travel and orientation.

$$\text{for } r \ll \frac{\lambda}{2\pi} = \sqrt{\frac{\mu}{\varepsilon}} = 120\pi = 377\ \Omega$$

$$H_\phi = \frac{ID\pi \sin\theta}{\lambda^2}\left[\left(\frac{\lambda}{2\pi r}\right)^2 \sin\psi + \left(\frac{\lambda}{2\pi r}\right)\cos\psi\right]$$

$$E_\theta = \frac{Z_o ID\pi \sin\theta}{\lambda^2}\left[-\left(\frac{\lambda}{2\pi r}\right)^3 \cos\psi - \left(\frac{\lambda}{2\pi r}\right)^2 \sin\psi + \left(\frac{\lambda}{2\pi r}\right)\cos\psi\right]$$

$$E_r = \frac{2 Z_o ID\pi \cos\theta}{\lambda^2}\left[\left(\frac{\lambda}{2\pi r}\right)^3 \cos\psi + \left(\frac{\lambda}{2\pi r}\right)^2 \sin\psi\right]$$

where
Z_o = free space impedance
I = current in short wire (doublet)
D = length of short wire doublet in which $D << \lambda$
θ = zenith angle to radial distance r
λ = wavelength corresponding to frequency, $f = c/\lambda$
r = distance from short wire doublet to measuring or observation point
Ψ = $2\pi r/\lambda - \omega t$
t = time = $1/f$
c = 3×10^8 m/sec
ω = radial frequency = $2\pi f$

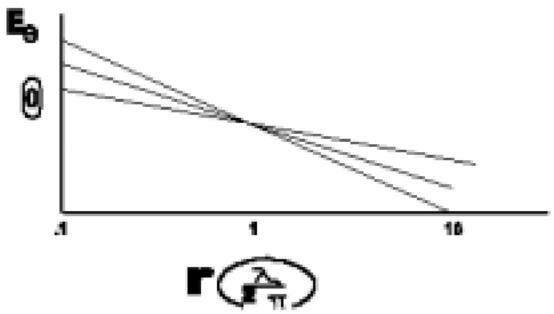


Figure 4 - For Field Component Calculations

The fluctuating energy produces an induction field associated with the stored energy, and a radiation field. The static and induction fields are called "near" fields, and the radiation field is called the "far" field. Figure 6 describes the near and far field relationship in terms of the transition point. Figure 7 describes individual fields in terms of wave impedance. The static field varies inversely as the third power of the distance from the antenna, so that it becomes negligible at distances greater than about one one-hundredth (1/100) of a wavelength from the radiating source.

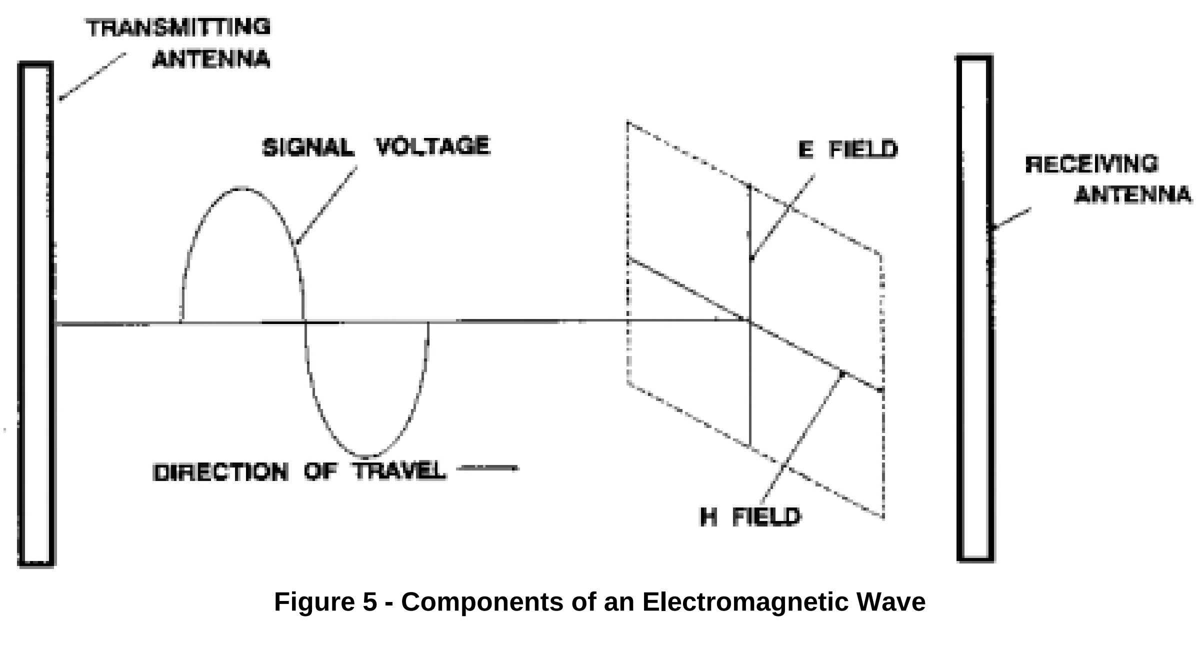


Figure 5 - Components of an Electromagnetic Wave

Power Transmission

Standard propagation relates to delivering power to a conductive object which in turn, based on the object's loading with respect to free space impedance, delivers this power through the expanding and contracting fields to another conductive object located at some other point. For power transmission, antennas are used to match the impedance of the transmission source to that of free space.

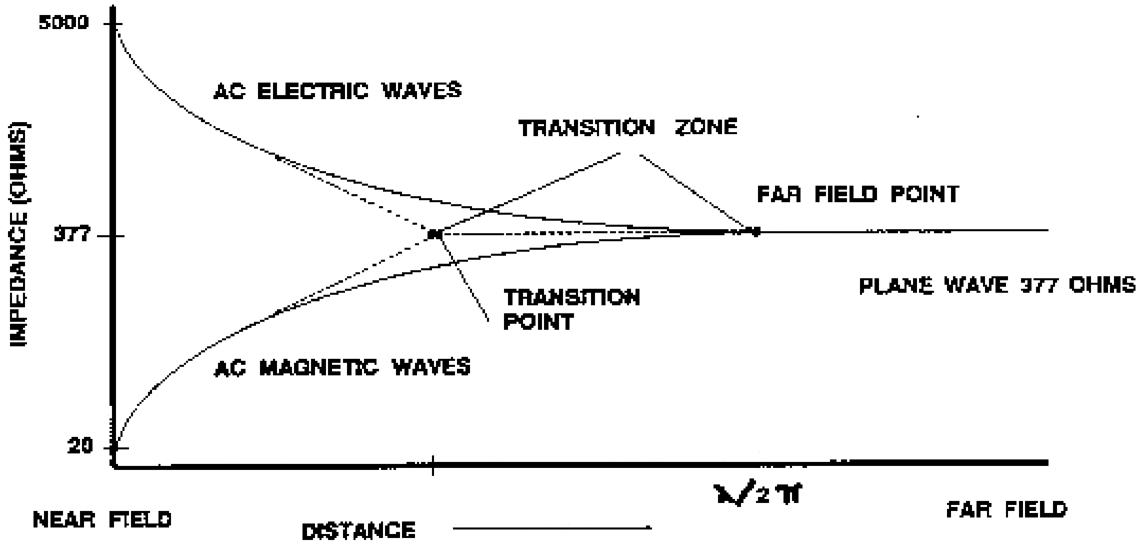
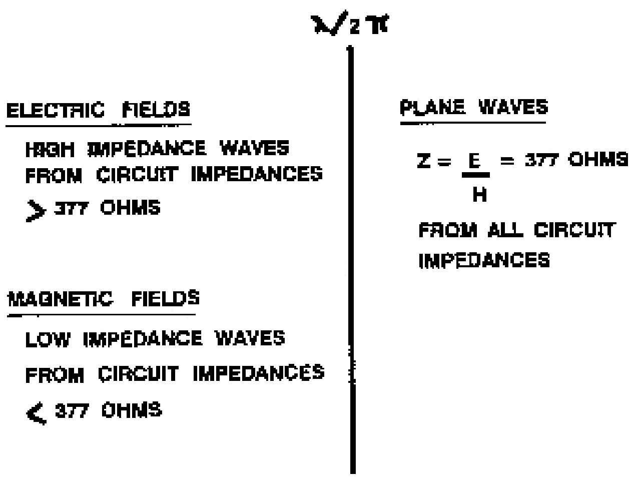


Figure 6 - Near and Far Field Conditions



IMPEDANCE AND POLARIZATION

Propagation is based on the ability to deliver power to an object that is loaded with respect to free space impedance.

For power transmission, antenna's are used to match the impedance of the transmission source to that of free space.

Polarization is determined by the direction of the lines of force that make up the E-field.

Maximum antenna pickup results when the antenna is oriented in the same direction as the radiated field.

Figure 7 - Near and Far Field Impedance Relationships

Polarization of a radiated wave is determined by the direction of the lines of force that make up the E-field. Maximum antenna pickup results when the antenna used is oriented in the same direction as the E-field components. To evaluate power transfer, it is convenient to use, as a standard antenna, one that has a length that is small compared to the wavelength, designated as a doublet. Doublets can be used for both transmitting and receiving. In free space, optimum transmission is achieved when the two doublets are parallel to each other and perpendicular to the line connecting their centers. If their distance apart, d, is large compared to the wavelength, the ratio of power transmitted to maximum useful power received is found from:

$$\frac{P_2}{P_1} = G_1 G_2 \left[\frac{3\lambda}{8\pi d}\right]^2$$

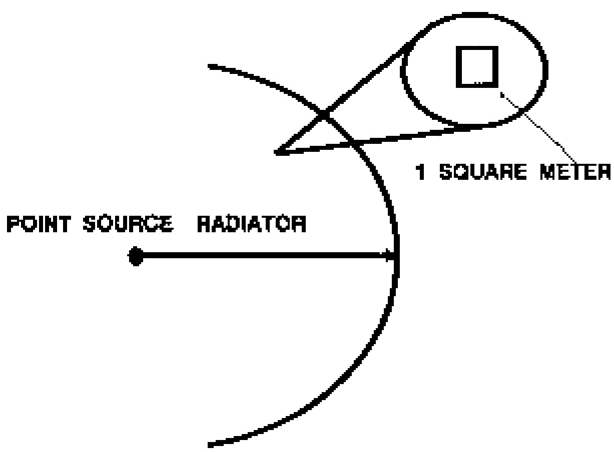


Figure 8 - An Isotropic Radiator

P_2 (P_r) is the power delivered to a matched load at the output terminal of the receiver, and P_1 (P_t) is the power fed to the transmitting antenna. Gain for a directive antenna is the ratio of the power transmitted by a doublet to the power transmitted by the antenna to produce the same response in a distant receiver when both antennas are adjusted for maximum power transfer. Gain can be expressed in relation to a doublet, or relative to a hypothetical isotropic radiator, a lossless radiation source with the same power density in all directions. An isotropic radiator is shown in Figure 8.

If transmission takes place over a conductive body (ground) or in a refracting atmosphere, etc., the power ratio is expressed as:

$$\frac{P_2}{P_1} = G_1 G_2 \left[\frac{3\lambda}{8\pi d}\right]^2 A_p^{\,2}$$

In this case, G_1 and G_2 are the antenna gains of the transmitting and receiving systems, and A_p is the "path factor" relating to the physical characteristics of the transmission path. A nomogram for free space transmission when $G_1 = G_2 = A_p = 1$ is provided at the end of this paper.

John Pierce developed the following equation for path loss over the ground with no structures between transmitter and receiver.

$$\mathbf{P_r = P_t + G_t + G_r + [-32.45\ dB - 20\log d - 20\log f]}$$

P_r = received power (dB) relative to 1 Watt
P_t = transmitted power (dB) relative to 1 Watt
G_t = transmitting antenna gain over isotropic in dB

G_r	= receiving antenna gain over isotropic in dB
d	= distance (km) between transmitting and receiving antennas
f	= frequency in MHz

The part of the equation between the brackets is the actual path loss. The 32.45 dB is a constant that relates the distance in km and frequency in MHz.

Isotropic Radiator Example

Assume a perfect isotropic radiator is driven with 1 watt of power. Determine how much power is present at a distance of km away. Figure 9 shows Figure 8 modified to describe the problem.
Solution: If the space between the radiator and the surface of the imaginary sphere is a vacuum or clear air, all the power radiated (1 watt) will impinge on the sphere's inner surface uniformly. The expression for the surface area of a sphere is:

$$Area\,(A) = 4\pi R^2$$

In the example, A = 4π x 1000 x 1000 = 12,566,368 sq. meters.

1 watt from an isotropic radiator produces 1/1257.3667 =
7.96×10^{-8} watts per square meter at 1 km, or - 70.99 dBW/m.

A sphere with a radius of 2 km would have four times as many cubic meters of surface area, and only one-fourth the power per square meter. Power density falls of inversely as the square of distance.

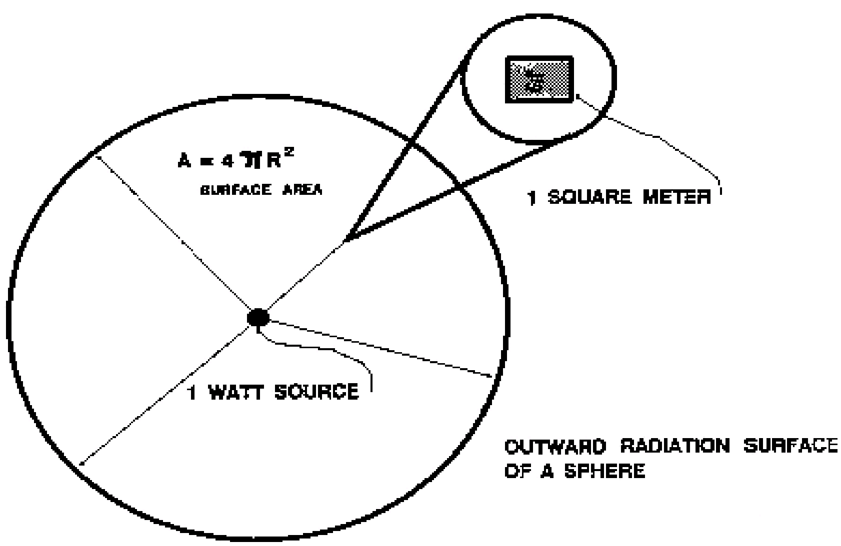


Figure 9 – Perfect isotropic Radiator Driven With 1 Watt

The effective area of an isotropic receiving antenna is equal to the wavelength squared divided by four pi. Since frequency is inversely proportional to wavelength, power received by an isotropic antenna is inversely proportional to the square of frequency (-20 log f). Figure 10 described an isotropic receiving antenna.

To use the expression for power density at the receiving site equal to electric field strength squared divided by the impedance of free space, the free space impedance must be calculated from:

$$Z_v = \sqrt{\frac{\mu}{e}}$$

$\mu = 4\pi \times 10^{-7}$ Henrys per meter $= 1.257 \times 10^{-6}$ H/m

$e = \frac{1 \times 10^{-9}}{36\pi}$ Farads per meter

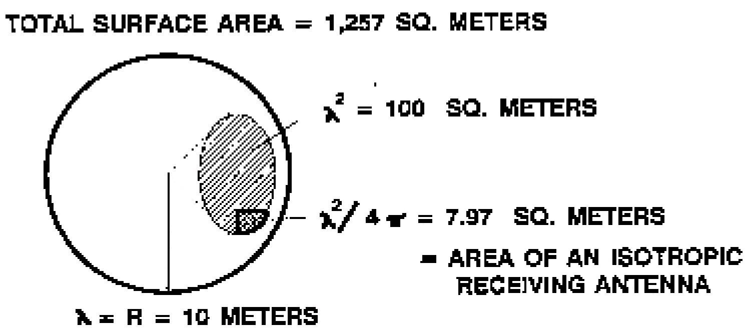


Figure 10 - Isotropic Receiving Antenna

$= 8.842 \times 10^{-12}$ F/m

This value is approximately 377 (376.7) ohms. In a sense, an antenna can be considered to be a transformer, transforming the impedance of free space to the impedance of its output terminals.

The electric field strength at the receiver is given by:

$$E = \frac{3\sqrt{5}}{d}\sqrt{P_1 G_1}\, A_p$$

where E is in volts per meter, and Pt is in watts. If E is known, the power delivered by the receiving antenna to a matched load is:

$$P_2 = \frac{E^2}{120\pi}\frac{3\lambda^2}{8\pi}G_2$$

For the isotropic radiator fed with one watt, the field strength at 1 km would be:

$E = \sqrt{PD * 120\pi}$

$E = \sqrt{7.96 \times 10^{-8} \times 376.7} = 5.48$ mV/m

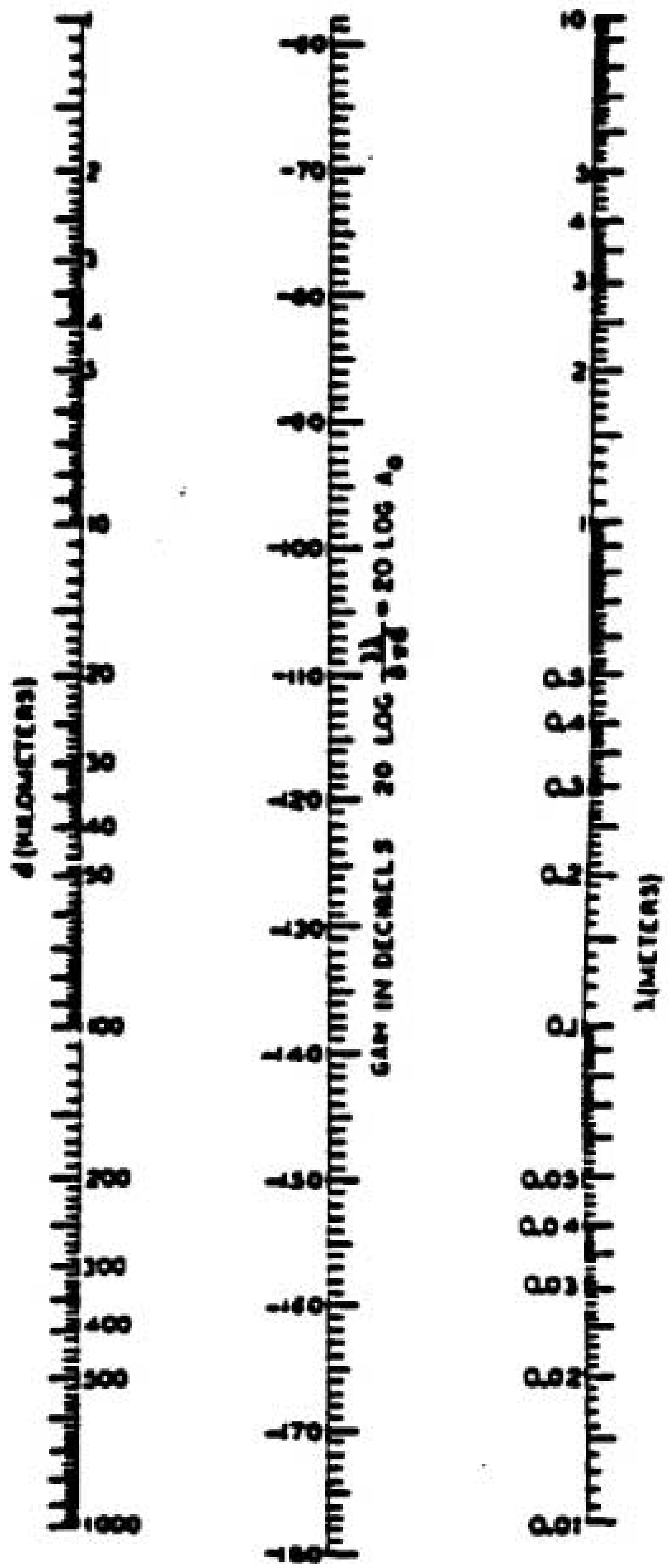
A graph of field strength as a function of distance to transmitter os included at the end of this paper.

Conclusions

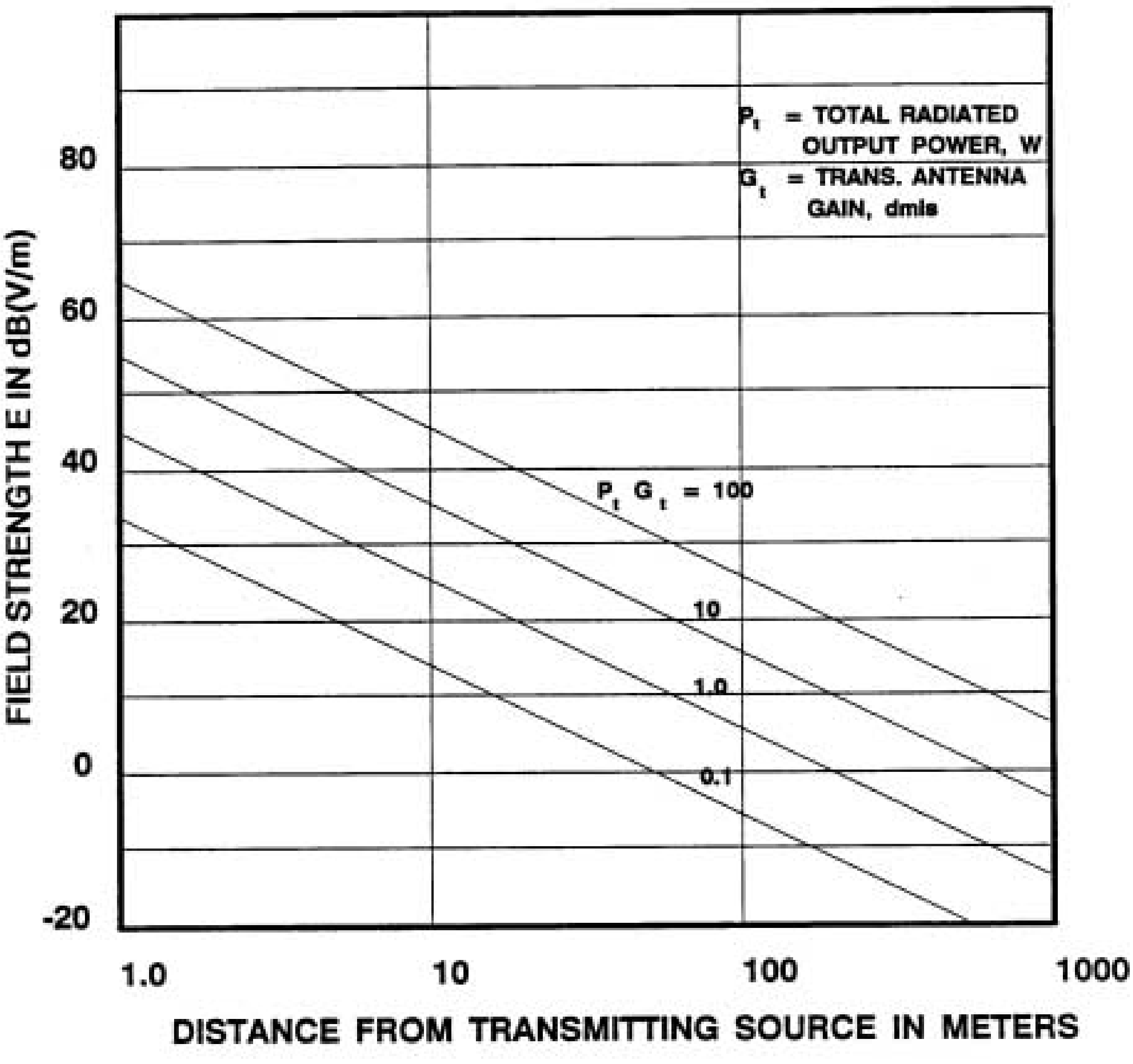
Energy propagates into space based on the impedance mismatch between the transmission line source and the load on the line. If the transmission line is only slightly mismatched, as is the case with the majority of sensitive emission problems encountered, only small higher frequency signals will propagate into space. However, if the mismatch is large, such as unterminated, or if the wire is terminated by an antenna, then significantly more energy radiates into the outside world.

References

Burrows, C.R., and Attwood, S.S., Radio wave propagation, Academic Press, Dec, 1948.
Tendick, C., Understanding Freespace Propagation, MSN & CT Magazine, October 1987.



Nomogram for Free Space Transmission Between Parallel Doublets



P_t = TOTAL RADIATED OUTPUT POWER, W
G_t = TRANS. ANTENNA GAIN, dmls
P_t G_t = 100
10
1.0
0.1
80
60
40
20
0
-20
FIELD STRENGTH E IN dB(V/m)
1.0
10
100
1000
DISTANCE FROM TRANSMITTING SOURCE IN METERS