5. ANTENNA MODELING

Accurate antenna modeling is necessary to determine the elevation and azimuth gain variability for prediction of the actual gain to be used in launching the sky wave at the appropriate take-off angles, and the ground-wave gain at the horizon angle. The performance of an antenna on or near the surface of the Earth is very dependent on the interaction with the lossy Earth. This is especially true for antennas at MF. Currently available techniques for analyzing antennas over ground with computer algorithms are time consuming and require conversion or normalization for use in system computations. This process will be described in this section. The gain of the antenna is a function of the antenna geometry, materials used, ground conductivity, ground dielectric constant, frequency, elevation angle, and azimuth angle. The gain required for systems performance analysis is usually calculated with respect to an isotropic radiator in free space or some other reference antenna such as a dipole. Conventional methods such as free space analysis could not be used due to the close proximity of the antennas to a lossy Earth. Antenna modeling techniques at medium frequencies must account for the actual gain that launches the ground wave. The end result for the antenna gain described in this paper has been transformed to be referenced to an isotropic radiator in free space.

There are several methods for modeling antennas that are in close proximity to a lossy Earth. Some of these are not valid for an antenna located right on the surface and require that the antenna be 0.2 wavelengths above the surface or the algorithm used in the calculation will not be valid. These algorithms that assume free-space conditions or negligible ground effects should not be used to model antennas that are too close to the Earth, because the results are poor. The model selected for analyzing antennas makes use of extensive method-of moments calculations and is implemented in a computer program titled the Numerical Electromagnetics Code (NEC) [50]. It is an accurate method for analyzing antennas at these low and medium frequencies where the antennas are small or comparable to a wavelength in size. Numerical methods are required to solve this problem and NEC is a good algorithm to use. The NEC program operates using a computation mode that implements a Sommerfeld integral computation for the determination of electromagnetic fields for antenna structures that are buried or penetrate the ground-air interface. This computation technique includes the reflected field below the interface, the field transmitted across the interface, and the fields above the ground-air interface. The algorithms used are also valid for antennas very close to the interface. The NEC program can also model near fields of the antenna very close to the antenna structure, in addition to being able to model the far field and compute antenna gain.

A different antenna gain phenomenon occurs with antennas at medium frequencies as compared to antennas at VHF, UHF and higher frequencies. The antenna principles are the same, but the surface wave becomes more signficant at MF. This is important because it is the surface wave that accounts for practically all of the energy transmitted and received at these frequencies. The concepts of gain and efficiency for antennas close to the surface of the Earth at MF are difficult to comprehend, since a major portion of the power launched by the antenna is absorbed by the lossy Earth. The electric field propagating along the surface of the Earth decreases faster than the usual reciprocal of the distance decay rate. In order to see this phenomenon, it is necessary to examine the Norton expressions [10] for the electric field resulting from an electric dipole above the surface of a finitely conducting Earth. Norton [10] in his effort to simplify the expressions developed by Sommerfeld

[13] came up with equations that clearly show the surface wave and space wave components. Jordan [54] deleted the higher order terms that are inversely proportional to the distance terms of Norton's equations for the vertical and radial directed components of the electric field in cylindrical coordinates. These higher order terms represent the induction and near field of the antenna and diminish in amplitude rapidly with distance. Jordan [54] further reduced the equation complexity by vectorially combining the equations for the vertical and radial directed field components, and then separating the resulting equation into a total space and total surface wave component. The resulting equations are:

$$E_{space} = j30IkL\left(\frac{e^{-jkR_1}}{R_1} + R_v\frac{e^{-jkR_2}}{R_2}\right)\cos\theta \tag{54}$$

$$E_{surface} = j30IkL(1-R_v)A(\rho)\frac{e^{-jkR_2}}{R_2}\sqrt{1-2u^2+u^2\cos^2\theta\,(1+\sin^2\theta/2)^2} \tag{55}$$

where $k=2\pi/\lambda$ as defined previously, $A(\rho)$ is the flat-Earth attenuation function defined previously, I is the peak dipole current amplitude in amperes, L is the length of the dipole in meters, R_1 is the distance between the dipole and the observation point in meters, R_2 is the distance between the dipole image and the observation point in meters, R_v is the complex reflection coefficient for vertical polarization, $u^2=(\varepsilon_r+j\sigma/\omega\varepsilon_0)^{-1}$, and θ is the angle representing the direction of the incident wave measured with respect to the Earth's surface.

The equations (54 and 55) for the electric-field components of the space wave and the surface wave are plotted in Figure 8 for conditions representing MF frequencies with average ground. Examination of an electric-field strength pattern such as that displayed in Figure 8 shows that the electric field due to the space-wave pattern indicates a very small component at the horizon, but this is not what launches the surface wave component of the ground wave. The actual gain that launches the surface wave can be determined from a numerical electromagnetic approach by analyzing the specific antenna geometry. The normal pattern shown in Figure 8 as a dotted line is the electric-field antenna pattern responsible for launching the space-wave component of the ground wave consisting of the direct and reflected ground wave. This is equation (54). It is also responsible for launching the sky wave. The amplitude of the space-wave electric field decreases with distance and is proportional to the reciprocal of the distance. The electric-field pattern that launches the surface wave is shown as a solid line in Figure 8. This is equation (55). It is a plot of the unattenuated surface wave with $A(\rho)=1$ and represents the surface wave close to the antenna. For large numerical distances, the amplitude of the surface-wave electric field decreases as the reciprocal of the square of the distance. Notice that it has a maximum level at the surface and decreases rapidly with increasing elevation angle. For larger elevation angles greater than a few degrees the space wave

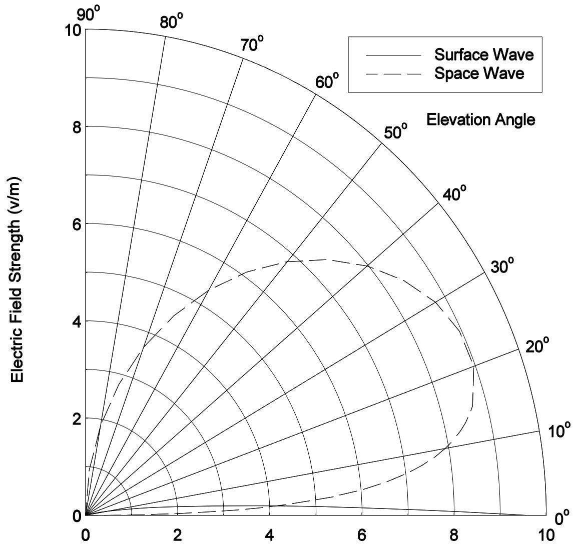


Figure 8. Space wave and unattenuated surface wave components of the ground wave for a vertical dipole at the Earth's surface for average ground conditions at 760 kHz.

contribution becomes more significant and is responsible for the launching of the space wave component of the ground wave and the sky wave. The relative geometry between most transmitters and receivers used for propagating ground-wave signals at MF frequencies will be at very low elevation angles with respect to each other. These elevation angles are on the order of one degree or less. The ground wave for these conditions will consist predominantly of the surface wave with little contribution by the space wave. Correct performance predictions will be obtained only when using this unique electric-field pattern that launches the surface wave to calculate an equivalent gain that correctly represents the magnitude of electromagnetic energy transmission or reception. Both the surface wave and the space wave components are included to represent the total electric field of a dipole or any antenna near a lossy Earth. As one or both antennas are raised in height a distance comparable to a wavelength above the Earth's surface, the surface wave becomes less significant and eventually negligible.

Receiver antennas at MF tend to be small in physical size with respect to a wavelength, and therefore have very low gains due to radiation efficiency considerations. The transmit antennas are usually more efficient since they are comparable to a wavelength in size. The antenna algorithm used to predict the antenna gain for low and medium frequency antennas computes an equivalent gain and represents the effectiveness of the antenna in launching or receiving the surface wave component of a ground wave. The gains for these antennas were derived from behavior analysis of extensive method-of-moments calculations using the Numerical Electromagnetics Code [50,51].

A short dipole was selected as a reference antenna due to simplicity of analysis and convenience in measurement. Many loss calculations in ground-wave analysis are referenced to short dipoles or monopoles. The computer program NEC is used to determine the equivalent gain of a short dipole over a lossy Earth with respect to an isotropic radiator in free space for the appropriate ground conductivities, ground dielectric constants, and frequencies. The relative performance of the subject antenna with respect to the short dipole is then determined using the NEC program. These two factors are then combined to obtain the equivalent gain with respect to an isotropic radiator in free space.

The gain of a short dipole antenna at the surface of a lossy Earth referenced to an isotropic radiator in free space can be derived from some basic relationships. The power density in free space for an isotropic radiator is given by Norton [52,53]:

$$\frac{e^2}{\eta} = \frac{P_r}{4\pi D^2} \tag{56}$$

where $e(V/m)$ is the electric field strength in volts per meter, η $(ohms)$ is the impedance of free space (120π ohms), $D(m)$ is the distance from the antenna in meters, and $P_r(W)$ is the radiated power in watts.

Taking the square root of both sides and rearranging terms, the primary electric field strength from an isotropic antenna is:

$$e(V/m) = \frac{\sqrt{30 P_r(W)}}{D(m)} \tag{57}$$

The primary electric field strength from any antenna in free space is:

$$e(V/m) = \frac{\sqrt{30 P(W) g}}{D(m)} \tag{58}$$

where g is the equivalent antenna gain ratio referenced to an isotropic radiator in free space and P is the transmitter input power in watts. If the units are changed the above equation becomes:

$$e(mV/m) = 173 \frac{\sqrt{P(kW) g}}{d(km)} \tag{59}$$

where $e(mV/m)$ is the electric field strength in millivolts per meter, $P(kW)$ is the transmitter power in kilowatts, and $d(km)$ is the distance in kilometers.

If the antenna is a short vertical dipole element (g=3) at but not touching the surface of a perfectly conducting Earth, then:

$$e(mV/m) = 300\frac{\sqrt{P(kW)}}{d(km)} \tag{60}$$

This is the familiar 300 mV/m at one km for a radiated power of one kW over a perfectly conducting Earth.

The electric field strength for a lossy Earth and an arbitrary gain g is given by Terman [8] as:

$$e(mV/m) = 173 \bullet A \bullet \frac{\sqrt{P(kW)g}}{d(km)} \tag{61}$$

where A is the Norton approximation [9] to the Sommerfeld attenuation function [13]. This attenuation function was described previously in the discussion on ground-wave propagation. If this expression is rearranged to solve for g and the logarithm of both sides is taken, the gain of a short dipole antenna at but not touching the surface of a lossy Earth referenced to an isotropic radiator in free space is:

:

$$G_d(dB) = 10 \bullet \log\left[\frac{e^2(mV/m)d^2(km)}{(173)^2 P(kW) A^2}\right] \tag{62}$$

The effectiveness of an antenna in launching a surface wave which will be referred to as “equivalent gain,” is then determined by first calculating a ratio called the relative communication efficiency for the antenna as a function of the ground constants, frequency, antenna geometry, and azimuthal direction. The relative communication efficiency in decibels (*dB*) is then added to the reference dipole gain. The relative communication efficiency (*RCE*) [53] of an antenna is defined by:

$$RCE(dB) = 10 \bullet \log\frac{(E_t)^2 P_r}{(E_r)^2 P_t} \tag{63}$$

where E_r(*V/m*) is the electric field strength predicted by NEC at reference distance d and input power P_r for a short dipole, P_r (*W*) is the dipole antenna input power from NEC used to compute E_r (*V/m*), E_t (*V/m*) is the electric field strength predicted by NEC at reference distance d and input power P_t for the subject antenna, and P_t (*W*) is the subject antenna input power from NEC used to compute E_t.

The “equivalent gain” $G_a(dBi)$ of the subject antenna over lossy Earth referenced to an isotropic radiator in free space is given by:

$$G_a(dBi) = G_d(dBi) + RCE(dB) \qquad (64)$$

The “equivalent gain” referenced to an isotropic radiator in free space can now be used for communication system analysis. The result is a term similar to power gain that can be defined in the presence of a lossy Earth. A number of antennas were modeled using this technique.

One antenna that was modeled for the DGPS correction signal at 300 kHz consisted of a top-loaded monopole on a ground screen. This antenna is typical of a DGPS antenna that was installed at a site in Appleton, Washington. This site is one of the first installation sites for the DGPS system. DGPS signals radiated from this antenna site were measured extensively [55]. The monopole antenna is a tapered triangular shaped steel tower consisting of steel tubing 1.52 cm in diameter. The monopole length is 91.16 meters which is only 0.0912 wavelength at 300 kHz. The cross section of the monopole is an equilateral triangle measuring 0.61 meters on a side for most of its length and is tapered to a point on each end. There is a copper radial wire ground screen with 120 radials of 0.32 cm diameter that are each 100 meters in length. There are also twelve copper top-loading elements approximately 138 meters in length symmetrically located around the monopole extending from the top of the monopole down to the ground just outside but not touching the edge of the radial wire ground screen. The top-loading elements are 0.95 cm in diameter. Their purpose is to increase the efficiency of the antenna. The antenna is omnidirectional in the azimuth plane. The elevation plane

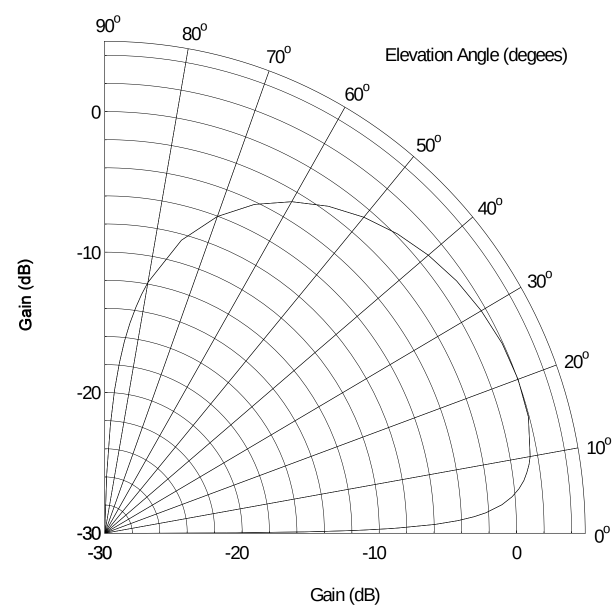


Figure 9. Elevation plane pattern for the space wave antenna power gain for the DGPS transmitter site antenna for average ground conditions at 300 kHz.

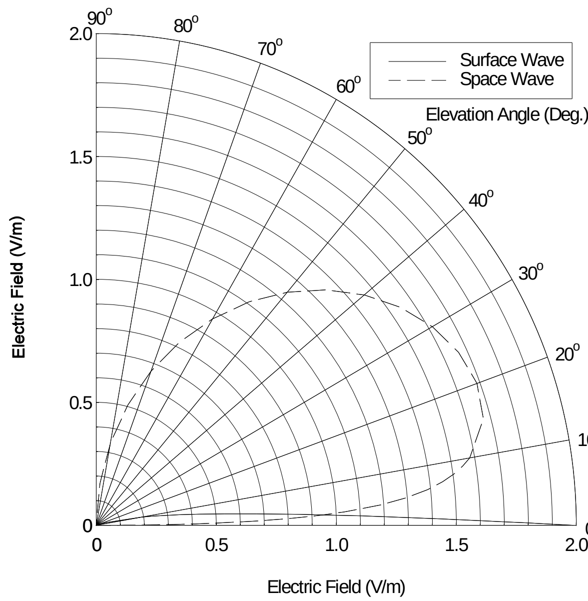


Figure 10. Electric field strength antenna patterns of the space wave and the surface wave for the DGPS transmitter site for average ground conditions at 300 kHz.

pattern for the space wave antenna power gain is shown in Figure 9. Notice the amplitude of the space wave pattern at the horizon. Figure 10 shows antenna patterns in terms of electric field strength for both the space wave and the surface wave for this antenna. The equivalent gain for launching the surface wave component was determined to be 3.2 dBi using the technique described previously, which includes the efficiency factor of 53 percent (-2.75 dB). This antenna gain occurs in all azimuth directions since the antenna is symmetrical in all azimuth planes. This equivalent antenna gain occurs at an elevation angle of zero degrees, and rapidly decreases in amplitude with increasing elevation angle. The loss due to impedance mismatch was assumed to be negligible, since the voltage standing wave ratio (VSWR) was less than 1.5:1. This antenna gain computation was verified by measurement of field strength from the actual DGPS site that uses this antenna [55].

Reception characteristics of a 300 kHz signal from a one meter antenna mounted on a van test vehicle were also determined using the equivalent gain technique. A short whip (one meter in length) on a van test vehicle was modeled to determine the antenna gains to use for system performance calculations. These gains will be much lower than what may be expected for this type of antenna due to the inefficient operation of small (with respect to a wavelength) vehicle antennas. Antennas were modeled at 300 kHz for DGPS and 760 kHz for the AM subcarrier ATIS. The antennas are much shorter than a wavelength and can also suffer from impedance mismatch loss into the receiver. Since the van test vehicle was also much smaller than a wavelength, it was found to have a negligible effect on the antenna as expected. The model for the van consisted of closely spaced metal wires that represented the geometry of the metal surface of the entire test van. There is only a slight pattern asymmetry of a few tenths of a dB created by the van asymmetry. Figure 11 shows the power gain pattern in the elevation plane for the space wave for the one meter whip at 300 kHz mounted in the center of the van roof. Notice the gain amplitude in comparison to Figure 9, even though the patterns have the same general shape. The equivalent gain for launching the surface wave was calculated for this antenna to be -21.3 dB. This gain exists in all azimuth directions since the antenna is symmetrical in this plane. The elevation angle for this equivalent gain is zero degrees

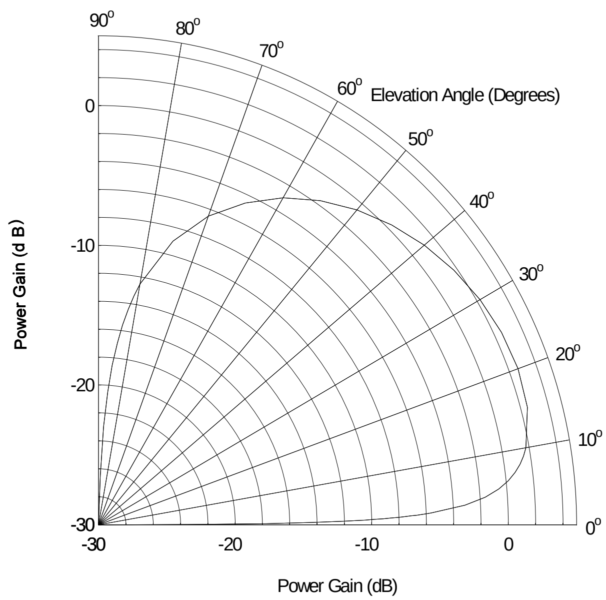


Figure 11. Power gain antenna pattern in the elevation plane for the space wave for the DGPS one meter whip mounted in the center of the van roof for average ground conditions at 300 kHz.

(the horizon). The power gain in the elevation plane of the antenna pattern for the same one meter antenna on the van roof at 760 kHz is shown in Figure 12. The equivalent gain for launching the surface wave was calculated to be -13.1 dB. The impedance mismatch loss can add a significant amount of loss to the antenna gain if the antenna is severely mismatched. If the characteristics of the receiver impedance and the cabling between the receiver and the antenna are known, then the mismatch loss can be calculated and included in the calculation of gain. An impedance mismatch characterized by a VSWR of less than 1.5:1 has been measured, so the impedance mismatch loss for this case is negligible.

A single quarter-wavelength monopole on a large ground screen (120 radials each $\lambda/4$ in length) was also modeled to simulate a broadcast transmitter for an AM radio station at 760 kHz. The monopole has a symmetrical pattern in azimuth. The resulting power gain pattern in the elevation plane at any azimuth angle is shown in Figure 13. The equivalent gain that launches the surface wave was determined to be 4.7 dB for this antenna.

A more complex antenna was also modeled. This antenna is a model of the actual antenna used at station KTLK at 760 kHz in Denver, Colorado. Two configurations are used: one for nighttime

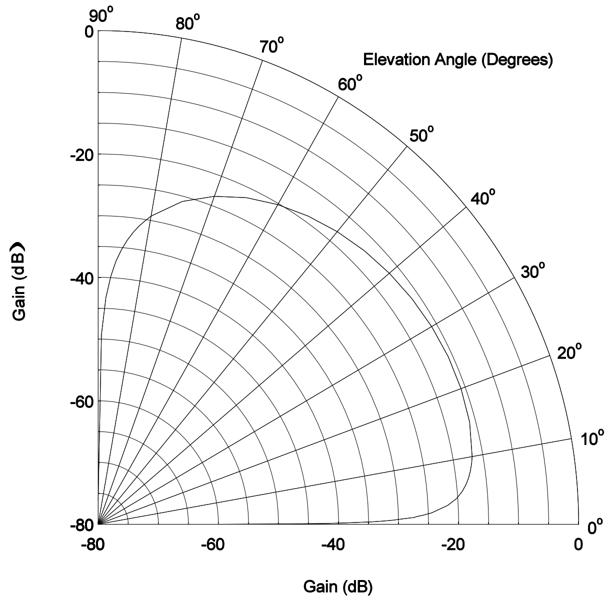


Figure 12. Power gain antenna pattern in the elevation plane for the space wave for the one meter whip antenna mounted in the center of the van roof for average ground conditions at 760 kHz.

operation, and one for daytime operation. The nighttime configuration consists of four monopole towers arranged in a physical array with the geometry and electrical phasing given in Table 2. All antenna tower positions and phasing are relative to tower 1. The azimuth pattern is shown in Figure 14. This pattern is at an elevation angle of zero degrees and represents an equivalent gain that launches a surface wave. It is not the space wave pattern which would have a very low gain at this elevation angle of zero degrees. The daytime configuration consists of two monopole towers arranged in the geometry and phasing given in Table 2. The azimuth pattern is shown in Figure 15. This pattern for the daytime antenna configuration is also the equivalent gain that launches the surface wave.

Figure 16 shows an elevation cut on the azimuth beam maximum at an azimuth angle of 225 degrees for the nighttime KTLK antenna configuration. Figure 17 shows an elevation cut on the beam maximum at an azimuth angle of 195 degrees for the daytime KTLK antenna. Figures 16 and 17 are elevation cuts of conventional antenna patterns of power gain showing the small magnitude of the gain at the horizon and for small elevation angles.

Table 2. Geometry and Phasing for Station KTLK Daytime and Nighttime Antenna Arrays.

Daytime Antenna Array

Tower	Field Ratio	Phase (deg)	Spacing (deg)	Bearing (deg)	Height (deg)
1	1.000	360.0	00.0	00.0	89.0
2	1.350	451.0	134.8	116.5	89.0

Nighttime Antenna Array

Tower	Field Ratio	Phase (deg)	Spacing (deg)	Bearing (deg)	Height (deg)
1	1.000	360.0	00.0	00.0	89.0
2	0.980	462.0	90.0	75.0	89.0
3	0.800	272.0	134.8	116.5	89.0
4	0.820	530.0	90.0	158.0	89.0

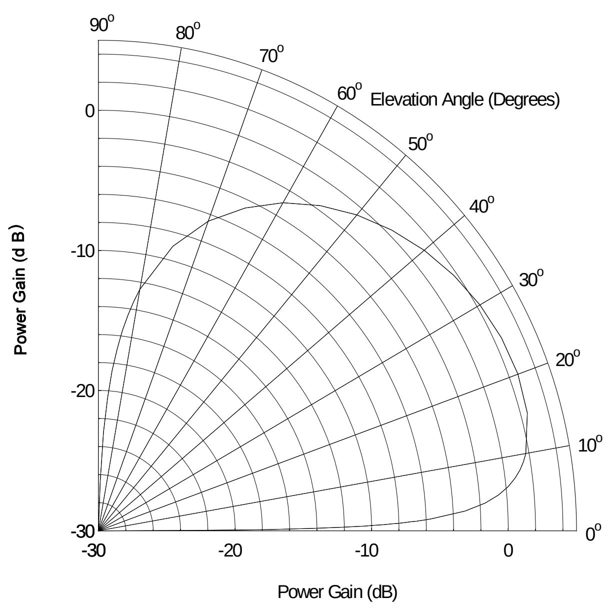
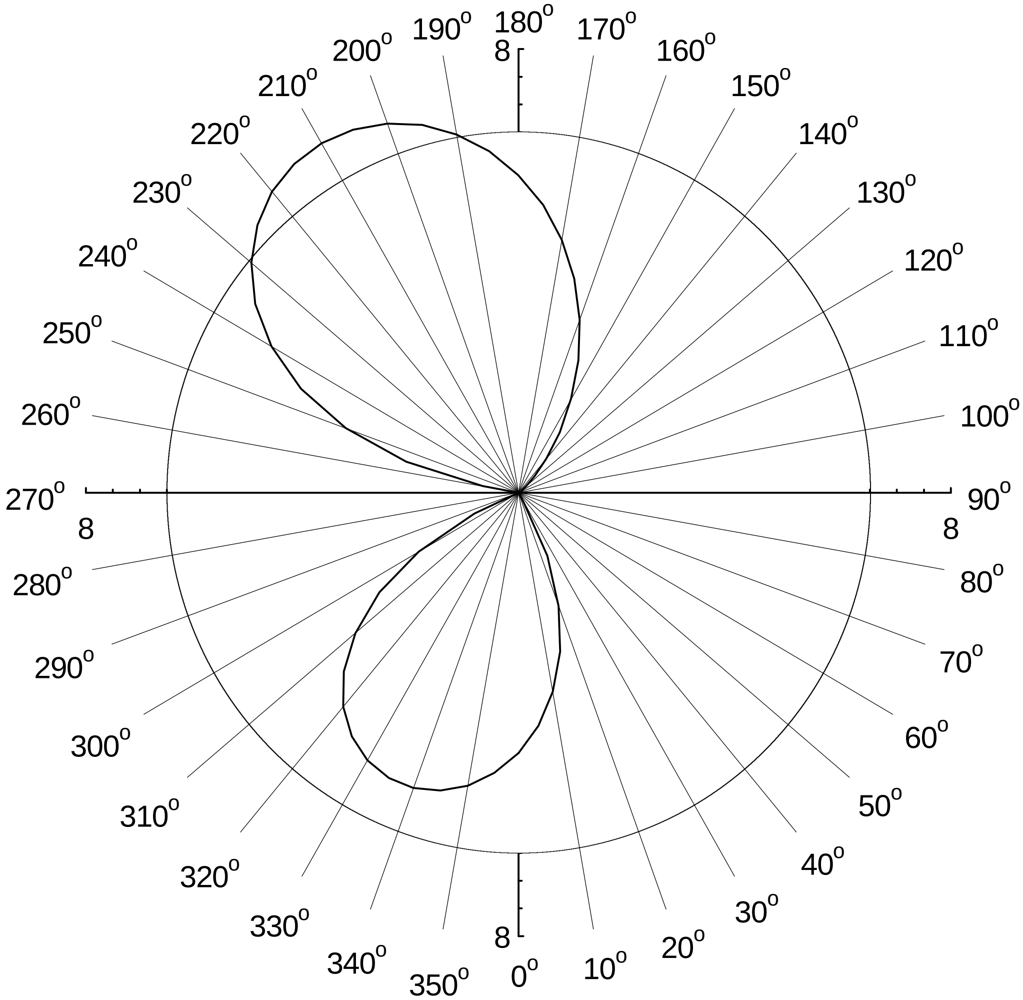
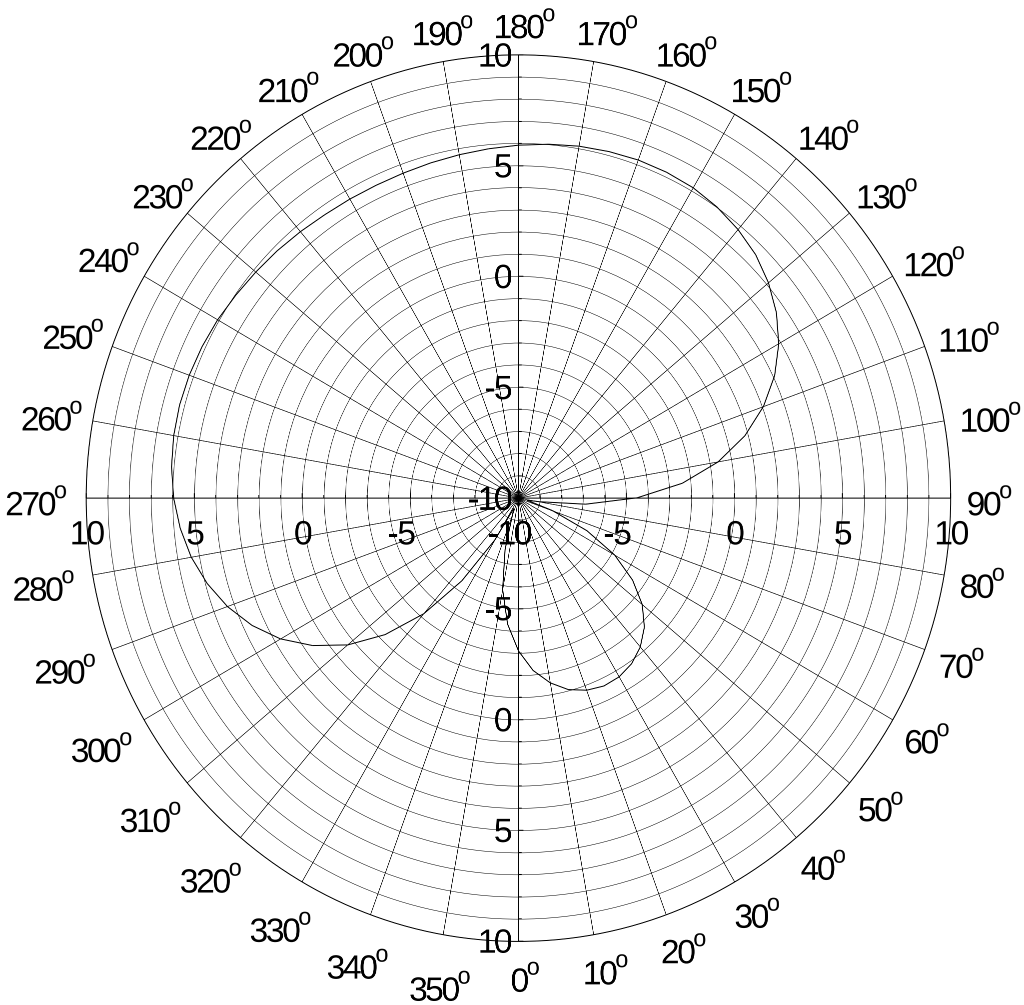


Figure 13. Power gain antenna pattern in the elevation plane for a quarter-wave monopole antenna on a ground screen for average ground conditions at 760 kHz.



Radial Scale is in dBi

Figure 14. Equivalent gain antenna pattern for station KTLK nighttime antenna configuration versus azimuth angle for average ground conditions at 760 kHz.



Radial Scale is in dBi

Figure 15. Equivalent gain antenna pattern for station KTLK daytime antenna versus azimuth angle for average ground conditions at 760 kHz.

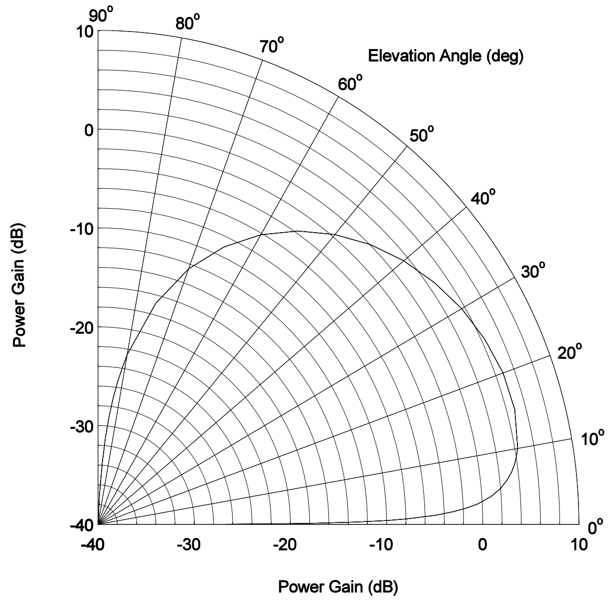


Figure 16. Power gain antenna pattern in the elevation plane on azimuth beam maximum for the KTLK nighttime antenna for average ground conditions at 760 kHz.

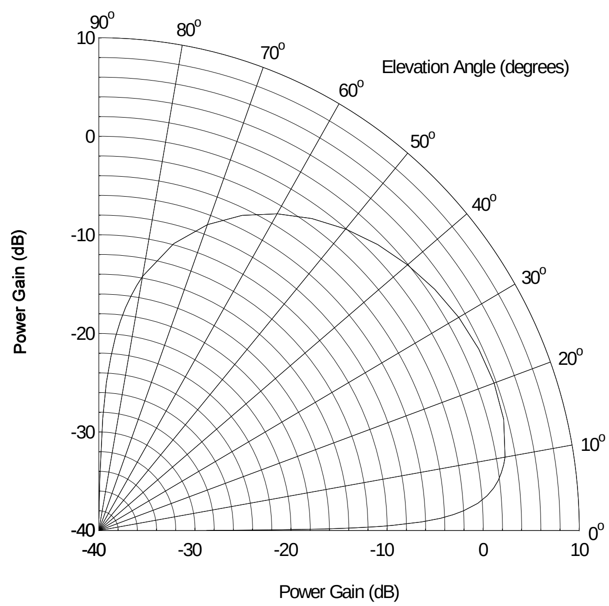


Figure 17. Power gain antenna pattern in the elevation plane on azimuth beam maximum for the KTLK daytime antenna for average ground conditions at 760 kHz.