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# A Planar Earth Model for Studying the Effect of Ground Wave Propagation on Antennas Performance

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**Abstract**

Ground wave propagation is one of the modes in which wireless network signals transmit. The ground wave signals are impaired by certain factors such as poor conducting grounds and antennas height. In order to mitigate the loss of signal or poor signal quality, a propagation model that incorporates these factors is required. In this paper therefore studies the effect of ground wave propagation on antennas performance. We implement the study by simulating a generic planar earth model. Simulation results show that increase in antennas height and phase angle reduces the ground wave propagation loss, thereby improving the signal power quality at the receiver's end.

**Keywords:** planar earth equation, phase angle, surface wave, antenna height, numerical distance, propagation loss.

## Introduction
Wireless transmission propagates in three modes namely the ground wave, sky-wave and Line of Sight (LOS) [1]. Ground wave propagation follows the earth's contour, while sky-wave propagation uses both earth and ionosphere reflection and LOS propagation requires the transmitting and receiving antennas to be within LOS of each other (no obstacles between them). The dominance of a propagation mode depends on the frequency of the underlying signal. Examples of ground wave and sky-wave communications are the AM radio and International broadcasts such as BBC. Above 30MHz, neither ground wave nor sky-wave propagation operate, therefore, the communication is definitely through LOS.

Ground wave propagation involves the transmission of radio signals along or near the earth's surface. These surface waves are also referred to as Norton surface waves, Zenneck waves, Sommerfield waves or Gliding waves [2]. The following are the three components of a ground wave:

(i) The direct wave, which travels from one antenna to another in what is called the LOS mode. The maximum LOS distance depends on the antenna's height above the ground. Hence, the higher the antenna, the further the maximum LOS distance. Because the radio signal travels in the air, any obstruction (such as mountain) between the antennas can block or reduce the signal.

(ii) The reflected waves, which reflects off the earth in going from the transmitting antenna to the receiving antenna. The reflected wave and the direct wave are called the space wave.

(iii) The surface wave, which travels along the earth's surface. It is the usual means of ground wave communication. The surface wave depends on the type of surface between the two antennas. With a good conducting surface, such as seawater, long ground wave distances are possible. If there is a poor surface between both antennas, such as a sand or frozen ground, the expected distance for the surface wave is short. The surface wave range can also be limited by heavy vegetation or mountainous terrain.

An antenna is an electrical conductor or a system of conductors that radiates/collects (transmits or receives) electromagnetic energy into/from space. An idealized isotropic antenna radiates uniformly in all directions. The directivity of an antenna is captured by its beam width; it is the angle within which power radiated is at least half of that in the most preferred direction (i.e. half of the maximum power).

When an electromagnetic wave arrives at an object surface, two waves are created: one enters the dielectric and the other is reflected. If the object is a conductor, the transmitted wave is negligible and the reflected wave has almost equivalent amplitude as the incident wave. When the object is a dielectric, the fraction reflected depends (among other things) on the angle of incidence. When the angle of incidence is small (i.e., the wave arrives almost perpendicularly) most of the energy transverses the surface, and very little is reflected. When the angle of incidence is close to $90^o$ (grazing incidence), almost all the wave are reflected.

Most of the electromagnetic waves emitted to the ground by antennas at moderate angles (say $< 60^o$) of incidence enter the earth and are absorbed (lost). But waves emitted at grazing angles to the ground, far from the antenna, are almost totally reflected. At grazing angles, the ground behaves as a mirror. The quality of reflection depends on the nature of the surface. When the surface's irregularities are smaller than the wavelength, the reflection is good. This scenario is represented in Figures 1 and 2. In Figure 1, the reflected wave by the earth can be considered as emitted by the antenna's image.

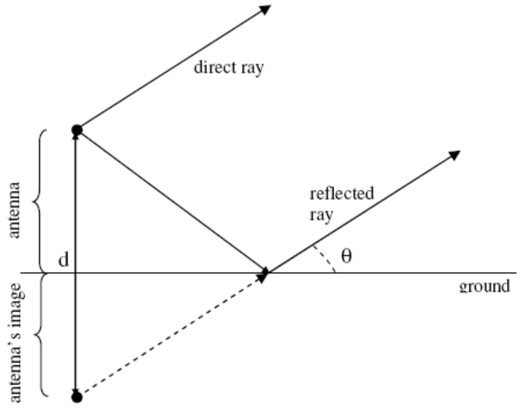


**Figure 1:** Emission of electromagnetic waves by antenna.

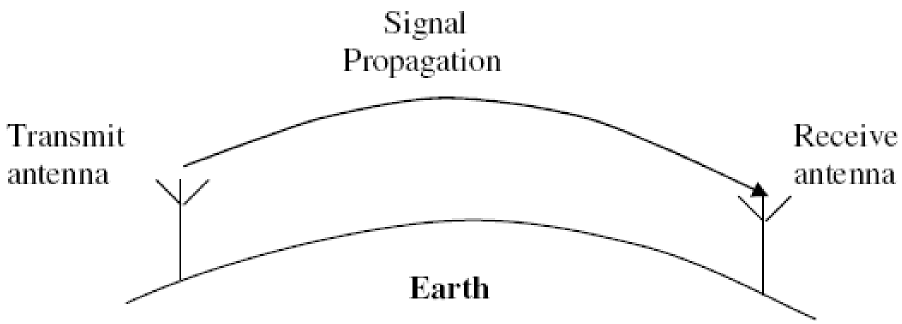


**Figure 2:** Ground wave propagation.

## Statement of Problem

The antenna provides a means for radiating radio frequency energy into space. At the receiver's location, it provides a means of intercepting (picking up) the radiated frequency energy. If the receiver is tuned to the same frequency as the transmitted radio frequency energy (signal), intelligence is made available. In transmission, the antenna operates as a load to the transmitter. It also operates as a signal source to the receiver during reception (i.e. when receiving). The gain of the antenna, whether transmitting or receiving, depends on the signal. The type of antenna, the site and the type of ground used are paramount in radio communications. Four factors which limit electromagnetic wave transmissions are: attenuation, distortion, dispersion and noise.

Below 30KHz, signals can penetrate below the water and underground, thus providing communications for submarines and mines, as well as aircraft and vessel navigation beacons. Because wavelengths are electrically very close to the interface between the earth and the air, the range is affected by ground conductivity, which varies considerably, being influenced by the soil type, degrees of moisture and salinity and by the nature of land development. Dry soils and urban locations are less favourable, while salt water exhibits the highest conductivity, being in the region of 5,000 times more conductive than dry ground [3][4]. As the waves travel over the ground, energy is absorbed into the earth. The signal is attenuated or loses strength and gradually tilts over in the direction of propagation, causing the electrical field to be eventually shorted out or distorted.

The most pervasive form of noise is thermal noise, which is often modeled using an additive Gaussian model. Thermal noise is due to thermal agitation of electrons and is uniformly distributed across the frequency spectrum [1]. The thermal noise found in 1Hz of bandwidth is:

$$N_0 = KT \frac{W}{Hz} \tag{2}$$

where T is the absolute temperature of the medium (conductor) and K, the Boltzmann's constant (1.3803 X $10^{-23}$ Joules/Kelvin). The amount of thermal noise in BHz of bandwidth is simply $N_0B$.

# Materials and Methods

## Ground Wave Model Parameters

### *Antennas*

Antennas are typically designed to operate in a relatively narrow frequency range. The design criteria for receiving and transmitting antennas differ slightly, but generally an antenna can receive and transmit equally well. This property is called reciprocity [5].

If a real antenna generates more than the direct and reflected waves, a correction term must be included. This term has a complex dependence on both distance and height, which is not easily classified. For transmitting and receiving antennas at heights above the earth's surface (which are small relative to the wavelength), direct and earth reflected signals cancel (since the path lengths are equal and the reflection coefficient is -1), leaving only the ground wave component in the received field. Attenuation of the ground wave along the interface is partly due to power loss through the conductivity of the earth's surface, so that more poorly conducting grounds lead to more rapidly attenuating ground waves.

These properties make ground wave contributions to received field intensities important, when both transmitting and receiving antennas are sufficient (such that the direct and reflected rays still cancel); and when the imaginary part of the ground dielectric constant is large. These conditions are typically met at lower frequencies (around a few MHz or less), since raising antennas above hundreds of meter wavelengths at these frequencies is not practical in most situations. However, at these frequencies, the ionosphere often propagates signals much more efficiently. So the ground waves mechanisms should only be considered when ionosphere propagation can be neglected. In most situations, consideration of the ionosphere shows that ground wave contributions dominate local reception of signals in the HF and LF bands, while ionosphere propagation dominates for long distance paths. At frequencies band higher than HF, antennas must be very near to the ground for the ground wave mechanism to be appreciated.

***The Planar Earth Equation***

The Sommerfield's Planar Earth ground wave equation [2] is given as:

$$\underline{E}^{tot} = \frac{E_0}{d}\left(e^{-jk_0R_1} + \underline{\Gamma}e^{-jk_0R_2}\right) \quad (3)$$

where $\underline{E}^{tot}$ is the electric field strength

$E_0$ is the permittivity of free space

$d$ is the distance between the transmitting and receiving antenna.

$j$ is a unit vector

$R_1$ represents the distance to the source location.

$R_2$ represents the distance to the image location

$\Gamma$ is the Fresnel reflection coefficient for the appropriate polarization.

By approximating $\frac{1}{R_1} = \frac{\cos\varphi_1}{d}$ and $\frac{1}{R_2} = \frac{\cos\varphi_2}{d}$ as $\frac{1}{d}$, where $d$ is the horizontal distance between the two antennas, and neglecting any variations in the antennas which occur in angle. The next equation shows a more accurate version for the $z$ component of the radiated field strength, which removes the assumptions.

$$\underline{E}_z^{tot} = \frac{E_0}{d}\left(\cos^3\varphi_1 e^{-jk_0R_1} + \underline{\Gamma}\cos^3\varphi_2 e^{-jk_0R_2}\right) \quad (4)$$

where a directivity pattern of $\cos^3\varphi$ for the $z$ component fields radiated by the source has been assumed. This pattern corresponds to that of a short vertical dipole antenna as would be encountered for the lower frequency ranges when ground wave calculations are appropriate. The total electric field in equation (4) will vanish as the source and receiving antenna heights above the interface become small compared to the wavelength. This is because the phase difference related to $R_1$-$R_2$ becomes small for small antenna heights and the Fresnel reflection coefficients approach -1. However, in this case an appreciable ground wave field is still observed. An improved version of equation (4) that includes the ground wave contributions is

$$\underline{E}_z^{tot} = \frac{E_0}{d}\left(\cos^3\varphi_1 e^{-jk_0R_1} + \underline{\Gamma}\cos^3\varphi_2 e^{-jk_0R_2} + (1-\underline{\Gamma})\cos^3\varphi_2 e^{-jk_0R_2}\,\underline{\tilde{F}}(R_2,\underline{\varepsilon})\right) \quad (5)$$

The final term in equation (5) represents the ground wave. Note that its form appear similar to that of the reflected wave but an additional complex factor $\underline{\tilde{F}}(R_2,\underline{\varepsilon})$ is included that can significantly modify both the amplitude and phase of the ground wave relative to the reflected wave.

When the transmitting and receiving antennas are very close to the ground due to grazing paths, only the ground wave term is required and the received field becomes

$$\underline{E}_z = \frac{2E_0}{R_2}\underline{\tilde{F}}(R_2,\underline{\varepsilon})e^{-jk_0R_2}$$

Replacing $R_2$ with $d$, we have

$$\underline{E}_z = \frac{2E_0}{d}\underline{\tilde{F}}(d,\underline{\varepsilon})e^{-jk_0d} \quad (6)$$

where $\underline{\varepsilon}$ is the permittivity of the ground with

$$d = \frac{2h_1 h_2}{d_r - d_g}$$

where

$d$ is the distance between the transmitting and receiving antennas

$h_1$ is the height of the transmitting antenna.

$h_2$ is the height of the receiving antenna

$d_r$ is the distance between the transmitting and receiving antenna in free space.

$d_g$ is the distance between the transmitter and the ground surface.

The field amplitude thus varies with distance as

$$\frac{\underline{\tilde{F}}(d,\underline{\varepsilon})}{d}$$

Studies have shown that $\underline{\tilde{F}}(d,\underline{\varepsilon})$ depends on a single variable $\underline{P}$, a function of $d$ and $\underline{\varepsilon}$ , when the transmitting and receiving antennas are in close proximity, since $\underline{P}$ depends on both variables ($d$ and $\underline{\varepsilon}$), $\underline{\tilde{F}}(d,\underline{\varepsilon})$ can be re-written as $\underline{\tilde{F}}(\underline{P})$ and the description of the ground wave propagation is great if considered in terms of the "numerical distance", $\underline{P}$. The equations which define $\underline{P}$ for vertically and horizontally polarized sources respectively are

$$\underline{P} = -j\frac{k_0 d}{2\underline{\varepsilon}}\left(\frac{\underline{\varepsilon}-1}{\underline{\varepsilon}}\right) \tag{7}$$

for vertical polarization, and

$$\underline{P} = -j\frac{k_0 d}{2}(\underline{\varepsilon}-1) \tag{8}$$

for horizontal polarization

The numerical distance is thus related to the actual distance, $d$, divided by the electromagnetic wavelength (since $k_0 = \frac{2\pi}{\lambda}$) scaled by a function of $\underline{\varepsilon}$. For a fixed actual distance, $d$, the amplitude of $\underline{P}$, will increase with frequency. Also, since values of $\underline{\varepsilon}$ will typically have very large, negative imaginary parts when ground wave effects are important, the quantity in parenthesis in equation (7) is approximately unity, so that $\underline{P}$ is approximately inversely proportional to $\underline{\varepsilon}$, for vertical polarization. For a fixed distance and frequency, the vertical polarization amplitude of $\underline{P}$ will therefore decrease as the ground becomes more conducting. For fixed distance and frequency, values of $\underline{P}$ for horizontal polarization, will always be much larger than those for vertical polarization. These dependencies (on frequency and polarization) are very important for understanding ground wave propagation.

Notice that the amplitude of $\underline{P}$, is a function of both *d* and $\underline{\varepsilon}$, while the phase of $\underline{P}$ depends only on $\underline{\varepsilon}$. A commonly used notation defines the phase of $\underline{P}$ as *b* through

$$\underline{P} = | p | e^{-jb} \tag{9}$$

where *b* is the phase degree and depends on $\underline{\varepsilon}$.

***Dependence on Distance***

The function $\underline{F}(\underline{P})$, which determines the ground wave dependence on distance, does not have a simple form. A series of expansions which is useful for $|\underline{p}|$ less than approximately 10 is deduced by

$$\underline{F}(\underline{P}) = (-j\sqrt{\pi}\rho e^{-\rho}) - 2\underline{p} + \frac{(2\underline{p})^2}{1.3} - \frac{(2\underline{p})^3}{1.3.5} + \ldots \tag{10}$$

where additional terms in the series follow the pattern of the final two terms above. For larger values of $|\underline{p}|$, another expansion is more appropriate

$$\underline{F}(\underline{P}) = \frac{-1}{2\underline{p}} - \frac{1.3}{(2\underline{p})^2} - \frac{1.3.5}{(2\underline{p})^3} - \ldots \tag{11}$$

A compressed form of equation (11) is

$$\underline{F}(\underline{P}) = -\left[\sum_{n=1}^{\infty}\left(\frac{\prod_{i=1}^{n}(2n-1)}{(2\underline{p})^n}\right)\right] \tag{12}$$

Notice that the series expansion of equation (12) is an asymptotic series that does not obtain a uniform convergence rate. Additional terms in the series (*n*) should not be added if their successive amplitudes begin to increase rather than decrease. For $|\underline{p}| > 20$, a single term in equation (12) will provide an accuracy better than 10%.

From equation (12) we shall compare two parameters group $(\underline{F}(\underline{P}), \underline{p})$ and $(\underline{F}(\underline{P}), b)$, where $\underline{p}$ and *b* are the numerical distance and phase degree respectively. A plot of $|\underline{F}(\underline{P})| vs |\underline{p}|$ will help illustrate the behaviour of ground wave propagation.

***Dependence on Numerical Antenna Height***

For transmitting and receiving antennas sufficiently close to the ground surface, the ground wave contribution dominates, the received field $(1-\underline{\Gamma})$ is approximately 2, and the field amplitude is $\frac{2E_0}{d}|\underline{F}(\underline{P})|$. However, as the transmitter and receiver heights are increased, direct and reflected wave contributions must be included, and the ground wave contribution is slightly modified. For vertical antennas sufficiently close to the ground, the ground wave is quantified using the "numerical antenna heights", $q_1$ and $q_2$ as

$$q_{1,2} = \frac{K_0 h_{1,2}}{\sqrt{|\underline{\varepsilon} - 1|}} \tag{13}$$

where $h_1$ and $h_2$ are the transmitter and receiver heights respectively. Numerical antenna heights are similarly defined for horizontal antennas, but the above definition of $q$ is multiplied by $|\underline{\varepsilon}|$. Again, the antenna heights depend on both frequency and $\underline{\varepsilon}$ and are scaled versions of the actual heights. Here antenna elevation effects can be neglected for cases with $q_1 + q_2 < 0.01$

For elevated antennas, Spherical Earth theory shows that the Planar Earth theory considered in equation (5) becomes invalid if either actual antenna heights $h_{1,2}$ becomes larger than approximately $610 / f_{MHZ}^{2/3} m$. For antenna heights within these limits and for distances less than $80 / f_{MHZ}^{1/3} m$, the Planar Earth theory remains valid, with a slight modification of the ground wave contribution. The ground wave function $\underline{F}$ is computed as $\underline{F}(\underline{P})$, where $\underline{P} = \frac{4\underline{P}}{(1-\underline{\Gamma})^2}$. Computing this against distance is very tedious and requires computer programming. An approximation for the total field exist for cases where $\underline{P} > 20$, $\underline{P} > 10, q_1, q_2$ *and* $\underline{P} > 100(q_1 + q_2)$. Here the resulting total field amplitude is that of the ground wave alone, multiplied by the "height-gain" functions $f(q_1)$ and $f(q_2)$, where

$$f(q) = \left[1 + q^2 - 2q\cos\left(\tfrac{\pi}{4} + \tfrac{b}{2}\right)\right]^{1/2} \tag{14}$$

This equation simplifies calculations for elevated antennas falling into an applicable region.

## Simulation Results and Discussion

Figure 3 gives the numerical results of $F(\underline{P})$ as a function of the numerical distance with varying phase angle ($b$). The ground wave propagation loss in Figure 3 is observed to transmit between a near constant behaviour for small values of $P$ to larger values of $P$. Small values of $b$ show a more constant behaviour for far distances, indicating stronger ground wave propagation for vertical polarization and more conducting grounds. Larger values of $b$ produce a more rapid transition to the $\frac{1}{P^2}$ dependence for final field values.

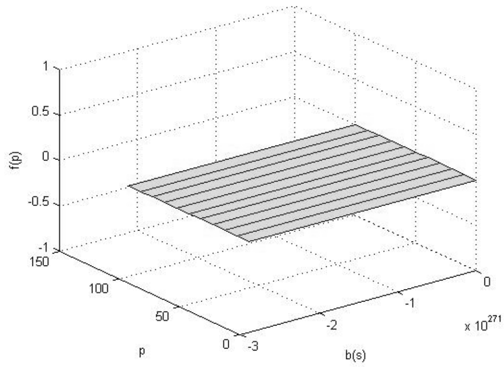


**Figure 3:** Mathlab plot of F(P) vs p for varying values of *b.*

Shown in figure 4 is a function of ground wave propagation loss against phase angle. As can be observed from the graph, *F(P)* lies steadily along (0-60) degrees. The reason for this is that for highly conducting grounds, the electric field strength reduces.

Figure 5 shows a plot of *F(q)* versus *q* for varying values of *b*. Notice that increase in antenna height typically results in increase in received power. Although there are some combinations of *q* and *b* for which reduced power is direct and reflected waves as antenna heights increase is compensated by decreased power in the ground wave field, particularly for smaller values of *b*.

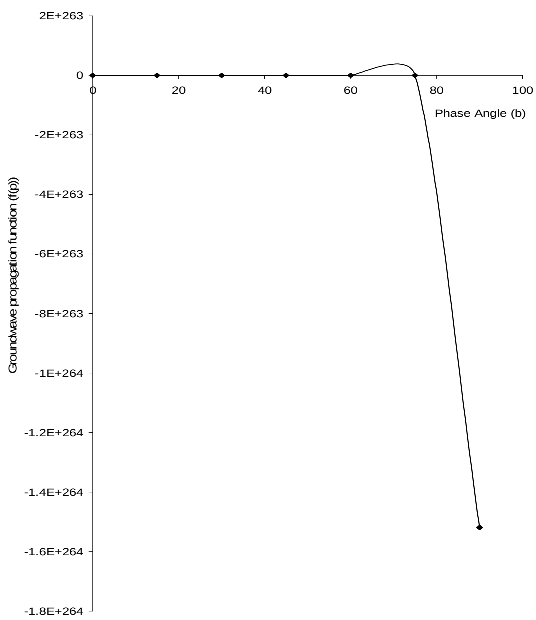


**Figure 4:** A Plot of F(P) vs *b.*

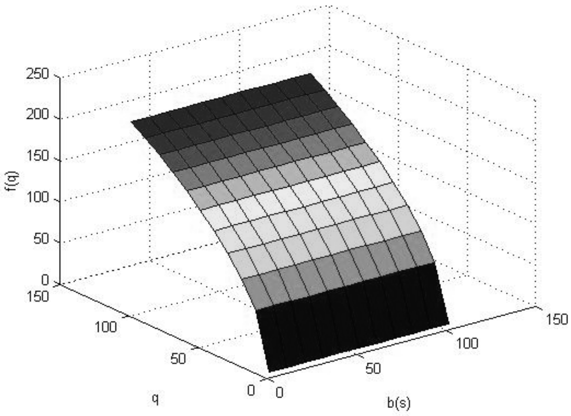


**Figure 5:** Mathlab plot of *F(q)* vs *q*.

## Conclusion

This paper has shown so far that when antennas are close to the ground and are located in non conducive grounds, the performance of the antenna reduces. The planar earth ground wave propagation model has provided a means of enhancing antenna performance. Further research on this topic is recommended, as ground wave propagation literatures are scanty.

Conclusively, any antenna located in a favorable ground with large distance and height above most obstacles like walls, heave vegetation, etc, will perform better.

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