

Effects of Propagation Delay on Signal Transmission.

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ABSTRACT

As radio signals are propagated through the atmosphere, they are affected mostly by variability in refractive index which, in turn, leads to a decrease in their speed of propagation. This will eventually bring about a delay called propagation delay. Propagation delay could be viewed in various forms, but this paper has concentrated on ionospheric and tropospheric propagation delays. These delays must be properly estimated so as to be able to determine the efficiency of the transmitting and receiving antenna systems to be used. This paper therefore reviewed the theory of propagation delay caused by some atmospheric constituents.

(Keywords: tropospheric delay, troposphere, ionospheric delay, ionosphere, refractive index, propagation speed)

INTRODUCTION

As radio signals pass through any medium, they experience some delays. As a result, radio signals passing through the earth's atmosphere and received by an antenna located on the surface of earth do experience a decrease in their speed of propagation and as a result they deviate their path from a straight line. This effect is generally known as propagation delay. Dry air, water vapor, hydrometeors, and other particles (sand, dust, moisture, volcanic ash etc.) in the atmosphere are among the factors that introduces these delays [1]. Other environmental factors that can lead to delay are refraction, reflection, diffraction, and ducting. For example, the ground, mountains, and buildings will reflect a traveling wave. Waves are also refracted as they pass through layers of the atmosphere, which have differing densities or differing degrees of

ionization. Also electromagnetic wave may be diffracted around tall, massive objects. In addition, they may interfere with each other [2].

The delay introduced by the atmosphere depends on the refractive index along the actual path traveled from the radio source in space to the ground receiver. This propagation delay is commonly described by the refractivity (N) through the relationship:

$$N = (n - 1) \times 10^6$$

where n = varying index of the atmosphere. In the ionosphere for example, there are the D, E, F₁ and F₂ layers with varying refractive indices n₁ n_x.

The excess path length of the signal (ΔS) due to the propagation delay is thus given by:

$$\Delta S = 10^{-6} \times \int N ds$$

It can be seen that a model to determine the integral of refractivity along the path will be required so as to be able to estimate the propagation delay in the atmosphere.

The propagation media affects radio signals at all frequencies and causes refraction with a time delay of the arriving signal [3]. Focus is made on these propagation media encompassing the ionosphere and troposphere. The ionosphere is the upper of the two layers, ranging between approximately 100km to 1000km above the Earth's surface and containing free electrons.

Ionospheric propagation or sky wave propagation is the mode used for short-wave communications (from 3 MHz to 30 MHz) enabling signals from all over the world to be picked up on a short-wave receiver. During the day, reception is best at

higher frequencies (say above 10 MHz). While at night, reception is best at lower frequencies (say below 10MHz).

The troposphere is the region below this, extending from the earth's surface to a height of about 50km, in which most of the common climatic variations occur. Tropospheric propagation or line of sight propagation is used for signals above 30 MHz.

THEORETICAL CONSIDERATION

It is an established fact that electromagnetic signals propagated through the neutral atmosphere are affected by the constituent gasses. The fact that their combined refractive index is slightly greater than unity gives rise to a decrease in the signal's velocity. This increases the time taken for the signal to reach the receiver's antenna, also increasing the equivalent path length. Both effects are often referred to as the "Delay".

Refraction also bends the raypath and thereby lengthens it, thus further increasing the delay [4]. Because the bulk of the delay occurs within the troposphere, the whole delay is often referred to solely as the "Tropospheric Delay".

By assuming that the neutral atmosphere is both horizontally stratified and azimuthally symmetric, the tropospheric delay can be modeled in two parts: the delay experienced in the zenith direction and the scaling of that delay to the delay experienced at the zenith angle of the raypath. This can lead to a formulation of zenith delay and mapping function. Such formulation of the tropospheric delay can be expressed as:

$$d_{trop} = d_{hyd}^z \cdot m_{hyd} + d_{wet}^z \cdot m_{wet}$$

where d_{hyd}^z , d_{wet}^z are hydrostatic and wet zenith delays, m_{hyd} , m_{wet} are hydrostatic and wet mapping functions.

The total delay d_{trop} , is a function of the delays in the zenith direction caused by the atmospheric gasses in hydrostatic equilibrium and by those gasses not in equilibrium. The mapping functions are usually described as functions of the satellite elevation angle, which is the complement of the zenith angle.

Tropospheric Delay

The error of tropospheric delay can be well simulated by attempting to model the refractivity of the atmosphere along the signal path. For proper accuracy, the tropospheric delay can be explicitly written as the contribution of a hydrostatic (dry) and a wet component. Each one consisting of the product of the delay experienced in the zenith direction and a mapping function that models the elevation angle dependence of the tropospheric delay. As stated earlier:

$$d_{trop} = d_{hyd}^z \cdot m_{hyd} + d_{wet}^z \cdot m_{wet} \quad (1)$$

Now, the delay experienced by radio signals in the zenith direction is:

$$d_{trop}^z = 10^{-6} \int_{r_a}^{r_s} N dr \quad (2)$$

The limit of integration here is from r_a to r_s ,

where:

N , refractivity

r_s , radius of the receiving antenna

r_a , radius of the top of neutral atmosphere.

$$N = K_1 [P_d/T] + K_2 [e/T] + K_3 [e/T^2] \quad (3)$$

K_1, K_2, K_3 , refractivity constants

P_d , partial pressure due to gas.

E , water vapor pressure

T , temperature.

The first term on the right hand side of Equation (3) does not depend on water vapor content of the atmosphere and is therefore known as **dry component** of the refractivity. The remaining terms represents **wet component**. If we assume that the air behaves as an ideal gas, then $P_d = p - e$, then Equation (3) can be rewritten as:

$$N = K_1 [P/T] + (K_1 - K_2)e/T + K_3 e/T^2 \quad (4)$$

Consequently, Equation (2) can be rewritten in terms of wet and dry component as:

$$d_{trop}^z = 10^{-6} \int N_h dz + 10^{-6} \int N_w dz \quad (5)$$

or it can be represented symbolically as:

$$d_{trop}^z = d_h^z + d_w^z \quad (6)$$

where d_h^z represents the hydrostatic zenith delay and d_w^z represents the wet zenith delay. Now, as regards the hydrostatic component we have:

$$d^2 z_h = 10^{-6} K_1 R_d \int \rho dz \quad (7)$$

where:

R_d , specific gas constant for dry air
 ρ , density of the moist air

REFRACTION

When a radio wave is transmitted into ionized layers, it is always refracted or bent. This bending of radio waves is called refraction. Such situation causes the wavefront to acquire a new direction in the second medium and is followed by a change in wave velocity. Now, if a wave move from a medium and enters a denser medium of charged ions, its upper portion will move faster than the lower portion. The abrupt speed increase of the upper part of the wave causes it to bend back towards the earth.

As shown in Figure 1, AC is the ray path for the incident. Without refraction, it must follow the path CCi. Contrary to that, it follows the path CD which has been lengthened further from CCi. Thus refraction causes further lengthening of the ray path and as such increases its propagation time which results in a delay before getting to destination.

Now observing this refraction in the tropospheric region, the refractivity N is defined by the relation:

$$N = \frac{77.6 p}{T} + 3.73 \times 10^5 \frac{e}{T^2}$$

where:

P = Pressure

T = Temperature

e = water vapour pressure.

The constants 77.6 and 3.73×10^5 are empirical values using the analysis of Bevis et al., 1992.

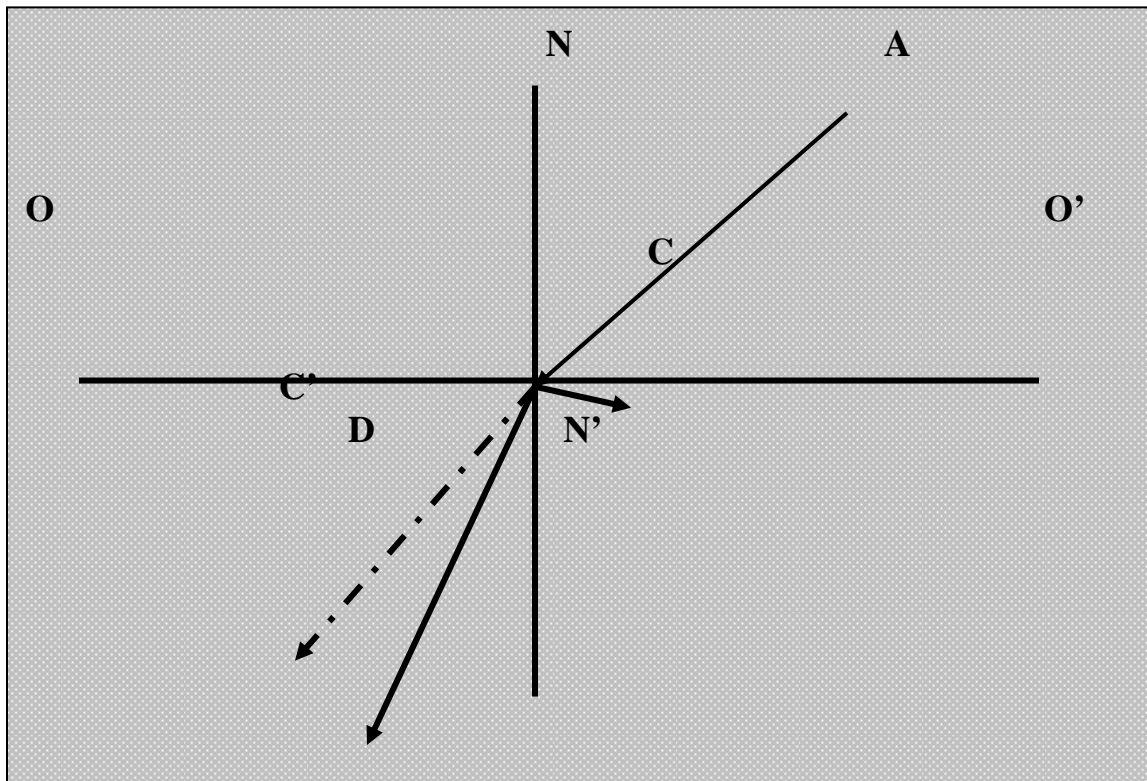


Figure 1: Illustration of Signal Raypath.

To estimate the delay analytically, it is possible to break down the refractivity (N) into sum of dry refractivity (N_{dry}) and wet refractivity (N_{wet}). Thus, the total delay is obtained by integration of the refractivity along the raypath.

$$\text{Total Delay (T.D)} = \underbrace{\int N_{dry} ds}_{D_{dry}} + \underbrace{\int N_{wet} ds}_{D_{wet}}$$

PHASE DELAY INDUCED BY WATER VAPOR

The second and largest contributor to tropospheric delay after hydrostatic constituents (gases) is water vapor. It is also the most highly variable component of delay. Delays as a result of water vapor are caused due to the polar nature of the water molecules in the atmosphere. Phase delays induced by cloud droplets can be approximated using calculations based on permittivity. Apart from phase delay, the presence of water vapor in the atmosphere can lead to absorption of transmitted signal. In the presence of high humidity, or if there is fog, rain, or snow, a high rate of absorption and reflection from rainwater drops may take place. For example, a

radar system operating at 10GHz may have a transmission range of 75km in dry air, but this can drastically reduce to about 25km in moderate rain. This shows effectively how precipitation can cause severe absorption at microwave frequencies.

It must be mentioned here that such absorption is insignificant at lower frequencies, except over long path. The major consequence of this absorption is attenuation of the propagated signal. Figure 2 below shows various degrees of attenuation at different frequencies as a result of water vapor in the atmosphere. At higher frequencies, there are high rates of absorption leading to signal attenuation.

SIMULATION

For practical analysis and better understanding of the concept of propagation delay, consider a directional antenna used to transmit a VHF signal. By virtue of the frequency, SA at this region, almost all weather phenomena occurs (e.g., the temperature decreases rapidly with altitude, formation of clouds are possible and also there may be a lot of turbulence because of variation in temperature, pressure and density). Assume the signal to be propagated with the speed of light (i.e., 3×10^8 m/s) through a distance of 3000km.

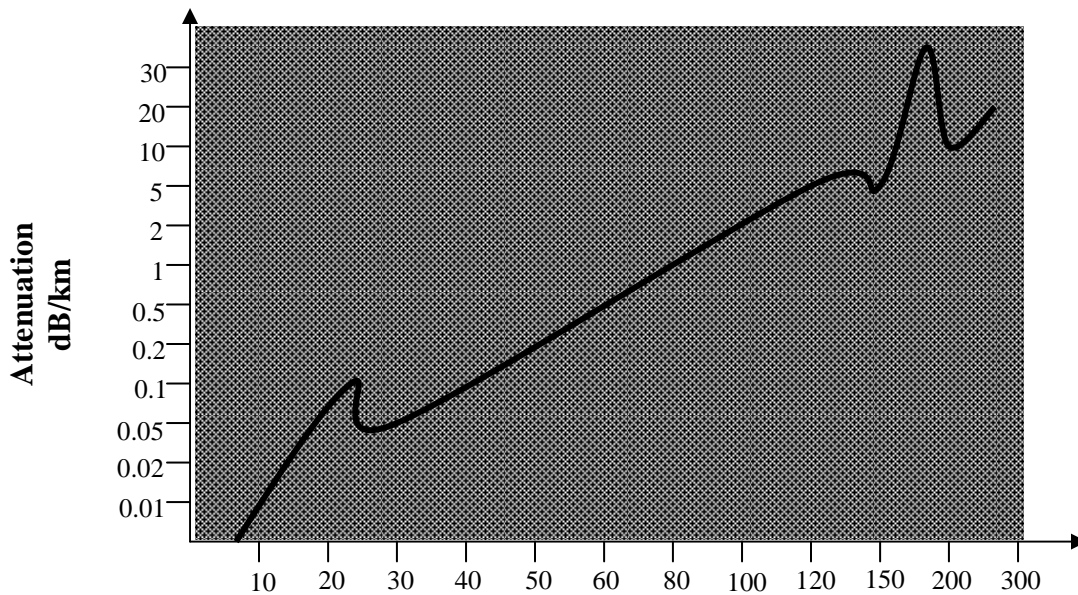


Figure 2: Atmospheric Absorption of EM Waves.

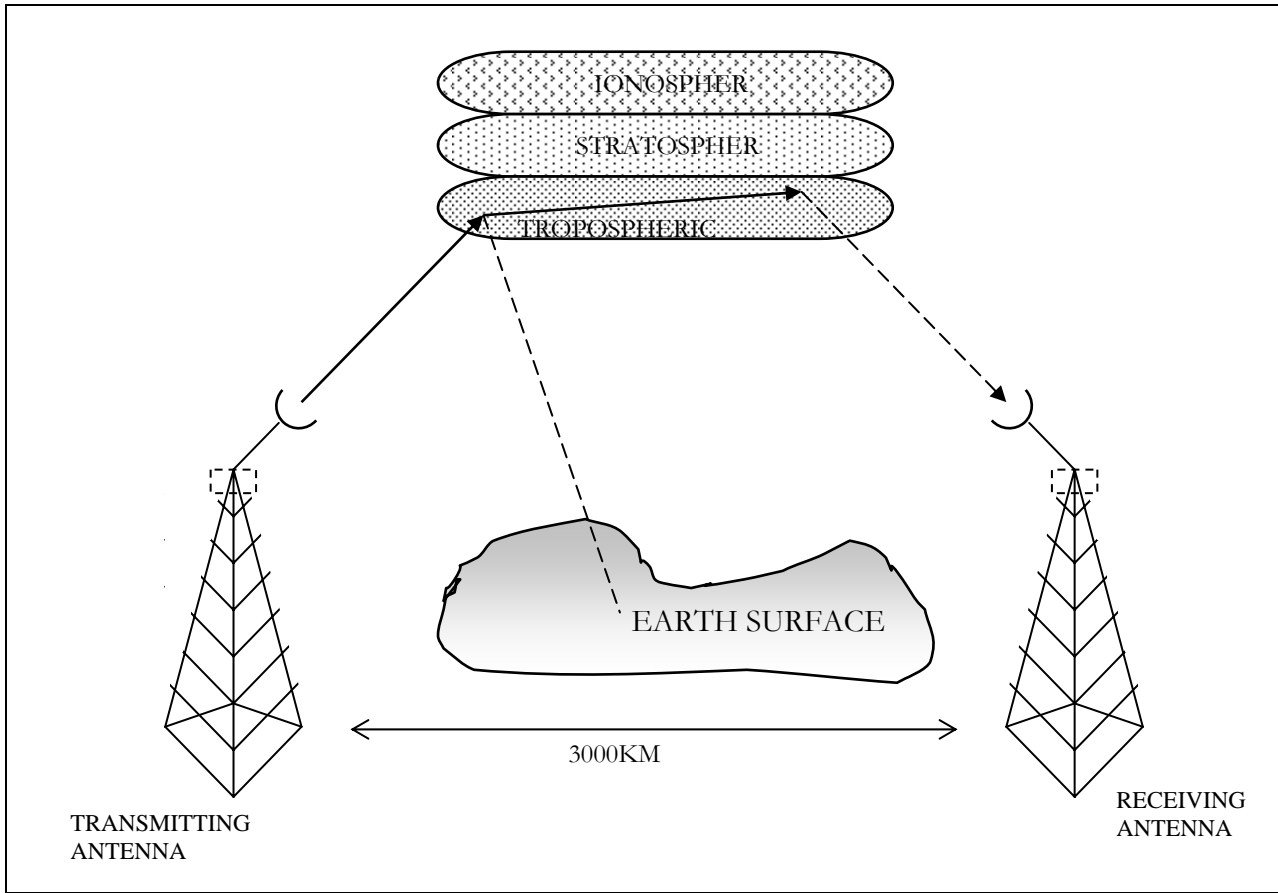


Figure 3: Raypath Between Transmitting and Receiving Antenna.

From Figure 3, Antenna A is transmitting while Antenna B is receiving. It was positioned 3000km away from the transmitting antenna. Also, as the raypath enters the tropospheric region, it experiences refraction. Its upper portion tends to move faster than the lower portion. This abrupt speed disparity lengthens the raypath and subsequently decreases its propagation velocity. The major consequence of this is that its propagation time is increased which in turn delays the arrival time as estimated below.

Assuming free space condition:

C = speed of light = 3×10^8 m/s

S = distance between transmitting and receiving antenna = 3×10^6 m

$$\text{Arrival time} = \frac{3 \times 10^6}{3 \times 10^8} = 0.01 \text{ sec} \quad (8)$$

When taking into consideration the tropospheric effect whereby the speed of propagation is reduced by a value V m/s, the arrival time is thus,

$$\frac{3 \times 10^6}{3 \times 10^8 - V} \text{ sec} \quad (9)$$

This value (2) is obviously greater than (1) above since its denominator is reduced by a factor of V . Hence, the delay in arrival time caused by tropospheric effect is:

$$t_{PD} = \frac{3 \times 10^6}{3 \times 10^8 - V} - \frac{3 \times 10^6}{3 \times 10^8} \quad (10)$$

$$\frac{1}{10^2 - \frac{V}{3 \times 10^6}} - \frac{1}{10^2}$$

writing 3×10^6 in x gives:

$$\frac{x}{100x - V} = \frac{1}{100} \quad (11)$$

This further dissolves to

$$t_{PD} = \frac{V}{10^4 x - 100V} \quad (12)$$

introducing back the value of x gives the following expression:

$$t_{PD} = \frac{1}{10^{-2} \left\{ \frac{3 \times 10^8}{V} - 1 \right\}} \text{secs.} \quad (13)$$

The above which gives the delay time will hold for all signals transmitted with the speed of light when the reduction in speed due to the effect of troposphere is known.

RESULTS AND DISCUSSION

As shown in our presentations it is evident that there is definitely a delay when signals are propagated through the atmosphere. This delay is being caused by the presence of dry air, water vapor, hydrometeors, sand, and dust in the air.

Atmospheric delays induced by dry air (i.e. hydrostatic components) are relatively large and depend on slowly varying pressure fields which could be easily modeled. Water vapor is the second largest contributor to propagation delay. Propagation delay due to water vapor is normally due to the polar nature of water molecules.

As contained in our simulation, once the frequency of propagation is established, the medium of propagation could be known. Whether ionosphere or troposphere, the fact is that the signal will acquire a new speed (Vm/s) which will be lesser than the initial propagation speed. If this is substituted for in Equation (13), the exact time delay in seconds could be estimated.

CONCLUSION

Using the assumption of free space condition, any signal propagated through the atmosphere will arrive at the destination exactly at the estimated time. But as we have seen in this paper, it has been demonstrated that there are differences in

arrival time of signals based on atmospheric conditions. The obvious reason for this is the influence of atmospheric constituents on transmitted signals. When signals are propagated, there are possibilities of the signals experiencing a decrease in their speed of propagation and as a result their paths deviate from a straight line. This deviation further lengthens the ray-path, thereby increasing the propagation time.

The increase in propagation time leads to late arrival time of the signals and it is this that results in what we called propagation delay. Also, these delays are further accentuated by the amount of particles which constitutes the atmosphere at that particular point. So, for proper correlation of the transmitting and receiving circuits, it is recommended that the amount of delay introduced be properly estimated as formulated in our simulation. Conclusively, further research in this area will lead to proper estimation of delays introduced by each region of the atmosphere.

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