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A critical review on attenuation of radio waves due to variation in electron density of ionosphere

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ABSTRACT

This paper critically examines the causes of attenuation of radio waves when it is propagating through ionosphere. The electron density of ionosphere affects the propagation of radio waves. We have reviewed thoroughly the reasons of variation of electron density due to scintillation effect, Sudden ionospheric distribution, Polar cap, Auroral effects, etc. At high frequency the propagation of radio waves through ionosphere is severely affected.

Keywords**:** Attenuation, Ionosphere, Electron density, Electron collision frequency, Multipath, Beam Spreading Loss, Cross polarization, Scintillation, Faraday rotation, Sudden Ionospheric disturbance

1. INTRODUCTION

The upper part of the atmosphere- ionosphere influences the radio wave propagation due to remarkable ionization [1-6**]**. The ionosphere plays vital role for communication and navigation systems. The ionosphere generally consists of three layers – D, E and F.

Absorption, reflection, refraction, scattering, polarization, group delay and fading/scintillation are different attenuation mechanisms of radio waves when it is propagating through ionosphere. Absorption, cloud and rain attenuation, attenuation due to snow, hail and fog are the causes of loss of energy of the radio waves in the regions other than ionosphere.

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Rain is thought to be the main reason of attenuation at frequencies above 10 GHz. With the increase of frequency, the effect of attenuation increases due to the increased interaction of electrons, ions, and molecules present in the atmosphere with radio waves [7]. Fading of radio waves at microwave and millimetric frequencies is due to atmospheric gases which contains oxygen and water vapour absorption is going on there.

The magnetic field of the wave interact with permanent magnetic moment of the oxygen which results in absorption of wave energy. The path attenuation due to gases present in atmosphere, rain and clouds is small and is so generally neglected below 3 GHz frequencies. But the effect due to oxygen and water vapour in the lower atmosphere is significant at higher frequencies. As the effect is highly frequency dependent so the attenuation due to atmospheric absorption in some frequency bands is much greater than in others.

The propagation in very low frequency and low frequency band uses wave-guide mode [8-10]. A channel bounded by the ground and the lower ionosphere at about 70 to 90 km height is used for radio wave propagation. Higher frequency radio waves in the low frequency, medium frequency and high frequency bands, up to about 30 MHz, can travel either directly along the Earth's surface (ground-wave propagation) or by successive reflections between the Earth and the ionosphere (sky-wave propagation).

The services like radio navigation and broadcasting has limited range at the higher frequencies and over land whereas sky-wave propagation can provide medium- to long-range communication at medium frequency band and high frequency band. The frequency of the wave compared with the critical frequency of the layers of the ionosphere plays vital role along with the absorption, noise etc. The radio waves above frequencies 30 MHz are used for both Earth-space communication as well as for terrestrial communication because they can travel directly from point to point at these frequencies. Sporadic-E, meteor-trail or auroral ionization can cause higher ionospheric ionization than normal. Sky wave propagation can be caused by this higher ionospheric ionization above 30 MHz frequency.

At ultra-high frequencies and above it, the Earth-space services must cope with additional ionospheric effects [11]. These effects are due to the total electron content along the path, leading to absorption, depolarization, group delay, dispersion and scintillation of the signal.

2. ANALYSES AND RESULTS

2. 1. Electron density

The electron density of the ionosphere plays a vital role in propagation of radio waves through it. Modern communication systems like Radar, mobile, satellite etc. depends to a greater extent on ionosphere's electron density. Due to the ionization from the Sun's rays, the free electron densities of 10^{11} – 10^{12} electron/m^3 are produced in the ionosphere [12]. The vertical layers of the ionosphere with higher densities are called as D, E and F layers on the basis of rate of ionization with altitude and change in the atmospheric neutral composition. O_2^+, N_2^+ and NO^+ are predominantly available in D and E region [13]. The electron density is maximum in F_2 layer.

The radiation from the Sun is the main source of ionization in the ionosphere.

The energetic charged particles of solar and magnetospheric origin and galactic cosmic rays are other sources of ionization [14-20]. The rate of ionization is decided by the intensity of the radiation from Sun. The rate of ionization is maximum when the Sun is overhead.

The ionization loss processes are counter – balanced by the creation of free ionization due to solar radiation. By considering the solar ionizing flux, vertical distribution of neutral atmospheric constituents, their absorption efficiency and solar zenith angle, the distribution of ionization can be explained mathematically.

The transportation of ionization plays crucial role at the height of the F2 layer caused due to the diffusion, neutral atmospheric winds and electromagnetic drift [21-25].

2. 2. Electron collision frequency

The collisions between electrons and neutral particles are also important in the attenuation of radiowaves [26-30]. The collision frequency within the 50-90 km region is very high. The cause of high collision frequency in this region is due to the changes with season and latitude. Sometimes, the cause of high collision frequency in this region is due to the solar activity. An exponential decrease in electron collision frequency with height, to about 140 km, and above that height the collision frequency decreases more slowly with height due to electron-ion collisions in the height range 100 - 200 km, whereas in night the collision frequency increases by six to seven times in summer and by three to four times in winter over daytime values [27].

2. 3. Fading of the waves

To measure the fading of the waves the simplest parameters - fading speed (number of maxima/hour) and the depth of fading are used. Both of these parameters depends on frequency, transmission distance, time of day and ionospheric conditions.

The diurnal changes in both amplitude and phase are readily apparent when the amplitude and phase of VLF/LF signals are observed as a function of time [31-34]. The changes in the reflection coefficients, height of the ionospheric reflection or focusing or defocusing of the wave by the ionosphere can be the cause of random variations. The other cause of random variation may be the interference between the many waves reaching to the receiver. The energy reaching to a receiver comes from an elliptical area in the ionosphere not from a point in the ionosphere, so, during the discussion of the reflection of waves from the ionosphere, the fading of the signals and the effects of small local changes in ionospheric properties must be considered. It is already estabished through different studies that the Fresnel zone at Low frequency can be very large. So, it can be concluded that the fading is the result of ionospheric parameters due to the formation of irregular and non-stationary Fresnel zones. Fading appears either as amplitude fading or as a Doppler-frequency shift. Dispersion in both time and frequency may be caused due to amplitude fading. The cause of Doppler shifts is due to motion of the transmitter, receiver or ionospheric reflector. Generally, multipath signals have differing amplitudes and frequency shifts. During the daytime, the amplitude of the sky-wave is less regular at frequencies near the upper end of the Low frequency band. The amplitude of the sky-wave fades in an irregular manner whereas the phase fading is always very less [35]. The dominant phase change is due to reflection height changes.

At night time, the sky-wave field is comparatively less regular. The fluctuations in the phase contains a random component superimposed on the component due to bodily movement of the reflection height.

2. 4. Types of fading

1) Free-Space Loss/Attenuation

2) Ionosphere's Attenuation
3) Attenuation due to Atmospheric Gases
4) Attenuation by Rain
5) Attenuation Due to Multipath
6) Reflection
7) Scattering
8) Diffraction
9) Attenuation by Buildings
10) Attenuation due to noise Effects

2. 5. Main reasons of fading

Following are some of the causes of attenuation of electromagnetic waves when it is propagating through the ionosphere:

1) Precipitation and clouds
2) Atmospheric gases
3) Beam spreading loss
4) Cross polarization discrimination
5) Effects due to ionization irregularities
6) Interference fading due to movement of the ionosphere, and multipath changes.
7) Faraday rotation
8) Seasonal variation
9) Variation with solar and magnetic activity
10) Sudden ionospheric Disturbance (SID's) associated with solar X-Ray events
11) Effect of latitude

2. 6. Fading due to precipitation and clouds

The strength of radio signals degraded due to raindrops specially above 10 GHz frequency [36-40]. Mainly the process of absorption and scattering are responsible for attenuation in radio waves due to rain. The effect of absorption becomes significant at higher frequencies near to 22 GHz and 60 GHz due to water vapor and oxygen [41-42].

The reliability and performance of the modern communication systems can be severely affected by raindrops. Attenuation due to rainfall is a function of various factors like - elevation angle, carrier frequency, height of earth station, latitude of earth station and rate of rain fall.

The primary parameters are drop-size distribution and the number of drops that are present in the volume shared by the wave with the rain. The rate of rainfall is more important than amount of rainfall in determining the attenuation in radio signal [43].

2. 7. Fading due to atmospheric gases

The gases present in atmosphere like oxygen, water vapour etc. have the capability to absorb the radio signals especially microwave signals at higher frequencies. Attenuation due to these gases have more effect on microwave and millimeter-wave propagation. The path attenuation due to atmospheric gases below 3GHz is small whereas oxygen and water vapour in the lower atmosphere can affect path attenuation at higher frequencies [1, 44]

2. 8. Beam Spreading loss

With the height, the radio refractive index of the atmosphere decreases regularly results in downward ray bending. The downward ray bending increases reducing the elevation angle of the ray. The effect is significant at elevations below about 3° [1, 45]. The rays at the top and bottom of the main beam of the antenna travels with slight different elevation angles and an additional divergence of the beam is produced in the vertical plane due to the resulting differential ray bending. In horizontal plane, the increase in the divergence of the beam in not seen. The beam spreading loss is maximum at lowest elevation angle [1, 46**]**.

2. 9. Cross polarization discrimination

Due to the flatten structure of the larger raindrops they fall with their major axis almost horizontal which results in more attenuation of the horizontal component of the radio waves. To reconstruct the wave if both (horizontal and vertical) components are recombined, then the polarization of the wave will rotate towards the horizontal components. Thus, a cross polarization component appears here. Rain and multipath propagation are responsible for induction of this depolarization [47-51] Depolarization induced by multipath is generally limited to terrestrial links. The depolarization on the paths of satellite is caused by rain and ice.

When the radio wave passes through the anisotropic medium it got attenuated and it faces phase shift. Due to attenuation and phase shift, the polarization state of the wave is altered such that the power is transferred from desired polarization state to the undesired orthogonal polarization state which results in interference.

2. 10. Effects due to ionization irregularities - Scintillation effects

Ionospheric scintillation can severely disrupt the signal along a trans-ionospheric propagation path for signals from VHF to C-band. Due to forward scattering and diffraction, small-scale irregular structures in the ionization density produces the scintillation phenomenon [52]. The steady signal at the receiver is replaced by one which is fluctuating in amplitude, phase, and apparent direction of arrival in scintillation effect [53]. Irregularity strength, layer thickness, signal frequency, season, local time, solar and magnetic activities and the angle between the ray path and the magnetic field of the earth are responsible for scintillations [54].

The two intense zones of scintillations exist - one at high latitudes and the other within ±20° of the magnetic equator on the basis of geographical locations [55-56]. In these two regions severe scintillations have been recorded up to gigahertz frequencies. In the middle latitudes scintillations mainly affect VHF signals. There is a pronounced night-time maximum of the activity in all sectors [57-58].

In the auroral region, the scintillation effect is observed due to geomagnetic storms. During the period of low activity of the Sun, the anomaly and polar region observe less fading. In ±20° of the magnetic equator scintillation may become problem for GPS systems after sunset. Scintillation can affect all the GPS systems. The errors of pseudo range and carrier phase range can be increased due to scintillation effect. This increased error can affect the high precision positioning [59].

Scintillation can degrade the contrast and resolution of images in remote sensing and astronomical systems whereas ionospheric and interplanetary scintillations can lead to image wander, degradation of image contrast, pulse broadening of pulsar signals, angular broadening of point sources results in degradation of the resolving power of radio telescopes [60].

2. 11. Interference fading due to movement of the ionosphere, and multipath changes

In interference fading, the resultant field intensity may vary over wide range for a few seconds to fraction of second. The interference between sky-wave and ground-wave, multiple reflected sky-waves, the ordinary and extraordinary waves and the different scattered signals from irregularities can result in the loss of energy of the resultant electromagnetic wave. The two or more waves coming from different paths to the receiver's point, interferes, results in fading of the signal.

The movement of the ionized regions can cause frequency dependent fading. At high frequencies, the fading is faster than at low frequencies due to the remarkable phase-shift on the shorter wavelength for a given movement in the ionosphere. The motion of the ionized regions can change the path length and the Doppler shifts of frequency of every contributing signal component.

This type of fading may also be caused due to multipath propagation at high frequency.

Due to the tropospheric reflection and refraction, obstacles like mountains, vegetation, buildings, water bodies and other terrestrial bodies, the electromagnetic signal reaches to receiver through different paths [61]. The multiple copies of the electromagnetic wave are produced due to multipath and these radio waves reaches with varying delays and phase causes destructive interference at receiver. This interference can corrupt the signal and also multipath can lead to inter-symbol interference [62].

2. 12. Faraday rotation

A rotation of plane of polarization is observed in radio signal during its propagation through ionosphere due to the presence of the geomagnetic field and the anisotropy of the plasma medium [63-66]. Electron density, geomagnetic field strength and frequency of the signal decides the magnitude of Faraday rotation. As the electron density in the ionosphere varies daily and it also depends on solar activity, so the magnitude of Faraday rotation is changing.

This effect is always proportional to square of the wavelength. Due to this effect the polarization of the short wave signal after reflection from the ionosphere can't be predicted although the polarization of the radio transmitting antennas are known. This effect becomes less dominant with increase of frequency.

The research of faraday effect in Ionosphere started in around 1958 by Browne et al. in which reflected radio waves from moon were used to measure the rotation of plane of polarization of the radiowave in ionosphere [67].

2. 13. Seasonal variation

In low frequency, medium frequency and high frequency band, the field strengths show a consistent seasonal absorption pattern with maximum occurring in summer months and minimum in winter months whereas in VLF band it shows opposite trend [68]. The winter-to-summer ratio is typically 10 dB to 20 dB [56]. With the change in season, the relative position of the Sun changes from one hemisphere to other results in seasonal variations [69-70]. The ionization density of D, E and F1 layers changes with season and it is maximum in summer due to highest angle of the Sun. However, the ionization of F2 layer is maximum during winter and least in Summer, results in requirement of higher operating frequencies of F2 layer in winter than in the summer.

2. 14. Variation with solar and magnetic activity

Several studies have revealed the effect of solar activity on radio propagation through ionosphere. It has high impact on medium frequency signal propagation than on low frequency signal propagation through the ionosphere. The night-time sky-wave field strengths of medium frequency signal decreases with solar activity. This decrease in field strength depends on distance, geomagnetic latitude and sunspot number. At low latitude it is taken to be negligible but at high latitudes the decrease in signal strength is high. The reason may be excess absorption associated with magnetic storm and post-storm effects [71-72]. The field strength maximum tends to occur in the year immediately after sunspot minimum [73-74]. The effect of solar activity decreases with passage of time after sunset [56].

2. 15. Sudden ionospheric Disturbance (SID's) associated with solar X-Ray events

Sudden ionospheric disturbance (SID) have great impact on radio wave propagation through ionosphere. It occurs only in Sunlit zones of the earth. Sudden phase anomaly (SPA), sudden field anomaly (SFA), sudden enhancement of atmospherics (SEA)) are caused due to SIDs associated with solar flare X-Ray events [56]. The X-Rays due to SID produces more number of electrons in most of the ionospheric layers which increases the electron density there.

The impact of increased electron density depends on frequency of operation. The increased electron density can be the cause of total loss of the signal in high frequency band whereas in VLF band the signal intensity may be enhanced.

2. 16. Effect of latitude

The geomagnetic fields run horizontally over the magnetic equator. These geomagnetic fields can cause electromagnetic forces which influences the low latitude regions on both sides of the magnetic equator. Due to the high electrical conductivity, the general form of the ionosphere got distorted. Near the equator, the scintillation peak activity occurs at vernal as well as autumnal equinox mostly after the ionospheric sunset and events can last from 30 min to hours. In high latitude regions, the status of the ionosphere is more complex as the electromagnetic fields runs nearly vertical. At these, latitudes the ionosphere becomes dynamic which can worsen the radio wave propagation. In high latitude regions which is also auroral zone, the rate of ionization is increased to a greater extent due to the solar effect. Absorption of radio signal can occur due to auroral events and polar cap [75-76]. The disturbance in the signal transmission in this range is for a period of time as the polar cap and aurora occurs at random intervals, lasts for different interval of time, and their effects are functions of the locations of the terminals and the elevation angle of the path [77].

3. CONCLUSIONS

The attenuation of radio waves of LF to ULF and above that also depends on electron density. The electron density varies with precipitation and clouds, atmospheric gases, beam spreading, cross polarization, ionization, irregularities, due to movement of the ionosphere, and multipath changes, Faraday rotation, seasonal variation, variation with solar and magnetic activity, sudden ionospheric disturbance (SID's) associated with solar X-Ray events, latitude etc. So, it can be concluded that the propagation of radio waves is affected due to all these reasons and the modern technological system should be made advanced by using software and hardware that they can function well in these situations. With increasing frequency, the attenuation increases due to the increased interaction of electrons, ions, and molecules present in the atmosphere with radio waves. Along with that, we should have better Prediction and warning systems which can predict about the geomagnetic activities in advance.

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