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Atmospheric influences on satellite communications

***Abstract**. Among other atmospheric regions, ionosphere, which is ionized region of the atmosphere, is considered to impose serious limitations on satellite communication. At higher frequencies, radio waves pass through the ionosphere and are attenuated due to the free electrons present in ionosphere. This paper discusses atmospheric effects on high frequency radio waves illustrating the attenuation and losses it may come across like attenuation due to atmospheric gases, rain, clouds, beam spreading loss and noise temperature. Data used to summarize the influence of atmospheric phenomena is obtained from ITU-R models and processed using MATLAB.*

***Streszczenie.** Spośród różnych warstw atmosfery szczególnie jonosfera wpływa niekorzystnie na komunikację za pośrednictwem satelitów. Przy wyższych częstotliwościach fale radiowe są silnie tłumione w jonosferze. Artykuł przedstawia analizę wpływu czynników atmosferycznych w jonosferze na tłumienie i straty w radiowej komunikacji wysokoczęstotliwościowej. (**Wpływ atmosfery na jakość komunikacji satelitarnej**)*

Keywords: Radio propagation, Ionosphere, Rain attenuation, cross polar discrimination.
Słowa kluczowe: propagacja fal radiowych, komunikacja satelitarna

Introduction

The ionosphere is the upper part of the atmosphere where sufficient ionization exists to influence radio wave propagation. The ionosphere usually consists of two layers: the E layer which is about 80 to 113 km above the earth's surface and reflects radio waves of lower frequency. Above E layer is F layer which reflects higher frequency radio waves. The F layer is then further sub divided into F1 and F2 layers. The F1 layer is lower portion of F layer and exists from 150 to 200 km above the earth's surface, whereas F2 layer is the upper portion and exists at a height of 200 to 500 km. F2 layer is mainly responsible for reflection of HF waves during day and night. Since the ionization is mainly caused by solar radiations, it is dependent on location, time of the day, season and sunspots [1].

Radio waves propagating through ionosphere experience different attenuation mechanisms such as absorption, reflection, refraction, scattering, polarization, group delay and fading/scintillation. In the region other than ionosphere i.e. troposphere, stratosphere etc. radio waves loses its energy mainly due to absorption, cloud and rain attenuation, attenuation due to snow, hail and fog. Rain is considered to be the major cause of attenuation at frequencies above 10 GHz.

As reported in literature atmosphere contains free electrons, ions, and molecules and their interaction with radio waves depend strongly on frequency, so as the frequency increases, the effect of attenuation also increases.

Rest of the paper is organized as follows: Section II discusses attenuation due to atmospheric gases. Section III discusses attenuation due to precipitation and clouds. Section IV describes beam spreading loss. Section V describes cross polarization at different rain rates, elevation angles and tilt angles. Finally, Section VI gives the conclusion.

Attenuation due to Atmospheric Gases

Attenuation by atmospheric gases at microwave and millimetric frequencies is mainly due to oxygen and water vapor absorption. Oxygen possesses a permanent magnetic moment and because of the interaction of this moment with the magnetic field of the wave, absorption of wave energy takes place [1].

At frequencies below 3 GHz, path attenuation due to atmospheric gases, rain and clouds is small and is often neglected. Whereas oxygen and water vapour in the lower atmosphere significantly affect path attenuation 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.

In most countries, water vapour density is not available for propagation interest; hence it can be calculated from concurrent measurements of temperature and relative humidity using:

$$\rho = (U/5.752)\left[\theta^{6}.10^{(10-9.834\theta)}\right] \quad (1)$$

where U is the relative humidity in percent. θ is the inverse temperature constant, given by:

$$\theta = 300/T_0$$

T_0 is the temperature at the surface in Kelvin [8].

The total gaseous attenuation in the atmosphere A over a path length r_0 (km) is given by:

$$A = \int_0^{\beta_0} \{\beta_0(r) + \beta_w(r)\} dr, dB \quad (2)$$

where β_0 and β_w are the attenuation coefficients (in decibels per kilometer) for oxygen and water vapour, respectively [9].

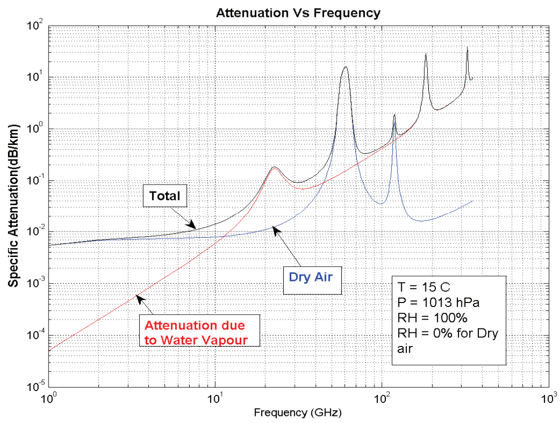

Fig 1: Specific Attenuation due to atmospheric gases for a standard atmosphere in UHF, SHF and EHF bands.

As shown in Fig-1, dry air has an oxygen absorption line at 60 GHz. The first absorption band at 22.2 GHz is due to water vapour, followed by absorption at 60 GHz due to dry air and at 118 and 123 again due to water vapour. The 'Atmospheric windows' between these absorption bands are available for practical earth-space communications.

It is evident from Fig-1 that below 22.3 GHz, the specific attenuation increases with frequency tremendously and it can be more than 10 times higher at 15 GHz than at 2 GHz. Also, the gaseous absorption is less than 1 dB for most paths below 100 GHz as indicated in Fig.1.

Taking into account the relative contribution, it is obvious that there will be more attenuation in presence of water vapour than in dry air because of the presence of more molecules in water vapour. Water vapour is a polar molecule with an electric dipole resulting in two absorption lines in the microwave region at 22.2 GHz and 183.3 GHz, where as Oxygen molecule has a permanent magnetic moment that produces multiple absorption lines that spread out between 50 and 70 GHz.

In conclusion, Atmospheric oxygen and particularly atmospheric water vapour cause a minor level of attenuation to satellite signals. The effects generally increase with frequency and are greatest near lines in the absorption spectra for each molecule. The line of most interest normally is the water absorption line at 22.3 GHz as we normally use the SHF band i.e. 3 to 30 GHz. Besides frequency the amount of absorption depend on the humidity (water vapour concentration), the elevation angle, pressure and temperature.

Attenuation due to Precipitation and Clouds

The strength of satellite signal may be degraded or reduced under rain conditions; in particular radio waves above 10 GHz are subject to attenuation by molecular absorption and rain [5]. Presence of rain drops can severely degrade the reliability and performance of communication links. Attenuation due to rain effect is a function of various parameters including elevation angle, carrier frequency, height of earth station, latitude of earth station and rain fall rate. The primary parameters, however, are drop-size distribution and the number of drops that are present in the volume shared by the wave with the rain. It is important to note that, attenuation is determined not by how much rain has fallen but the rate at which it is falling [10].

The propagation loss due to rain is given by:

$$L = 10\log\frac{P_r(0)}{P_r(r)}, \quad (3)$$

where P_0 is the signal power before the rain region, P_r is the signal power after the rain region, and r is the path length through the rain region.

The propagation loss due to rain attenuation is usually expressed by specific attenuation γ, in decibels per kilometre, so propagation loss is:

$$L = \gamma l_r \quad (4)$$

where γ is specific attenuation in dB/km and l_r is rain path length in km.[11]

Based on ITU-R specific attenuation model [12] it is found that γ depends only on rainfall rate, measured in millimetres per hour. From this model, the usual form of expressing γ is:

$$\gamma = aR^b\,[dB/km] \quad (5)$$

where a and b are frequency dependent coefficients.

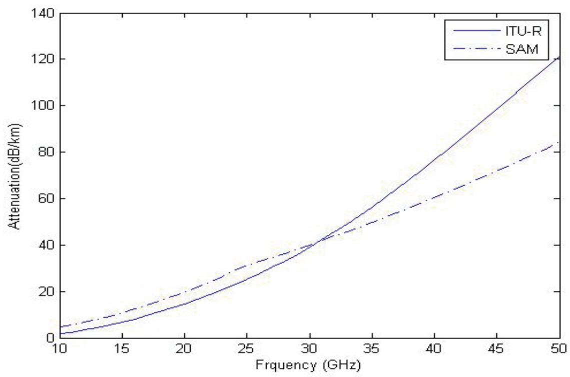

Fig 2: Rain attenuation as determined by ITU-R model and Simple Attenuation Model (SAM) at frequencies above 10 GHz.

Rain attenuation is a key limiting factor in using high frequency bands in satellite and terrestrial microwave systems [1]. Rain drops both absorb and scatter radio-wave energy. Very intense rain rate may cause link outage. If the rain drop size approaches half the wavelength of the signal in diameter, the signal will be attenuated. Higher frequencies exhibit more attenuation than lower frequencies due to smaller wavelength as shown in Fig. 2.

Clouds are also an important source of attenuation at higher frequencies. Due to diverse nature of clouds, attenuation of different intensities may occur. Each type of cloud has different water droplet concentration. Clouds having ice crystals cause less attenuation. Non precipitating clouds are also not very significant as the liquid content is too low to cause much absorption of energy, and the droplets are too small to scatter the energy and also they are spherical so they can not cause cross polarisation. In warmer climates the clouds are thicker so cloud attenuation may be higher.

Rain degrades the performance of a satellite communication system by increasing the noise temperature of the earth station antenna. [7] While raining it receives thermal radiation from rain drops which cause an increase in the overall noise temperature.

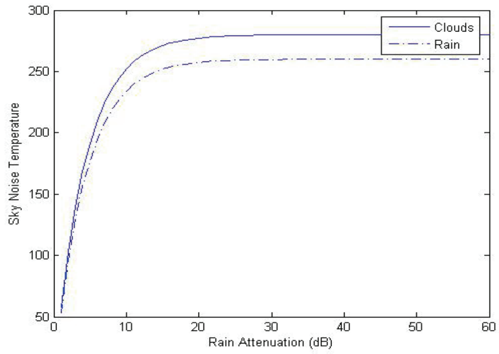

Fig 3: Sky noise temperature as seen by the antenna.

The antenna collect noise from ground, atmosphere (whether cloud or rain), and extraterrestrial sources. Antenna noise temperature varies with elevation angle antenna size, frequency and weather conditions.

Beam Spreading Loss

Due to the regular decrease of the radio refractive index of the atmosphere with height, downward ray bending is produced, which increases by reducing the elevation angle of the ray. The effect is significant at elevations below about 3° [4].

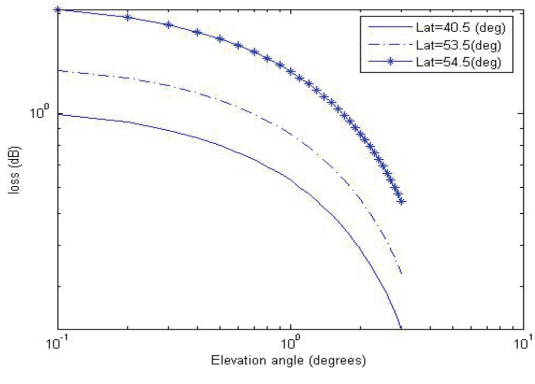

Fig 4: Loss with respect to elevation angle as a function of latitude.

Rays at the top and bottom of the antenna main beam travel 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. There is no increase in the divergence of the beam in horizontal plane.

In satellite communications, beam-spreading loss results from the spreading of the earth-satellite signals as they pass through the earth's atmosphere. Beam spreading loss is maximum at lowest elevation angle and decrements by increasing the elevation angle as shown in Fig. 4. At 3°, the loss becomes constant. It is also clear from the figure below that the loss is comparatively smaller if the antenna is closer to the equatorial region than the one which is far from equator.

Cross Polarization Discrimination

Large raindrops in the rain are not spherical but flatten and fall with their major axis almost horizontal. The horizontal component of the wave is thus more attenuated when it propagates through the rain. If we recombine the horizontal and vertical components at any point to reconstruct the wave, we will see that its polarization has rotated towards the component. Thus, a cross polarization component has come to existence [3].

Depolarization is induced by two factors: a) Rain and b) multipath propagation. Multipath induced depolarization is generally limited to terrestrial links. The major depolarization on satellite paths is caused by rain and ice. The wave while passing through the anisotropic medium exhibits attenuation and phase shift and thus its polarization state is altered, such that power is transferred from desired polarization state to the undesired orthogonal polarization state, resulting in interference.

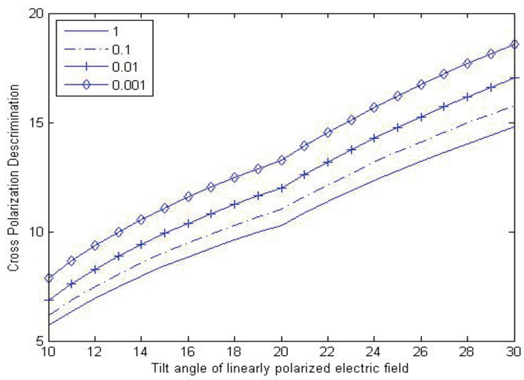

Fig 5: Variation of XPD with frequency and percentage of an average year.

Cross polarization Discrimination (XPD) depends upon attenuation which mainly depends upon the amount or the volume of water present in the atmosphere [3].

(6) XPD = U – V $\log_{10}$ (A) dB

Where: U = 30 log(f) – 40 log(cos ε) – 10 log ½ [1 – cos (4τ) $e^{-k_m^2}$ and and: ε - is the satellite elevation angle, τ - is the local polarisation tilt angle, k_m^2 relates to the variance of the canting angle distribution ($k_m^2 = 0.0024\,\theta_m^2$).

As it can be seen from Fig. 5 that Cross Polarization Discrimination increases with the increase in frequency and decreases with the percentage time of an average year.

Consider two orthogonally polarized linear waves are passing through a volume of canted oblate spheroids as shown in Fig-6. The drops are canted at an angle φ at the horizontal in the directions I and II, with minor and major axes as a and b, respectively. Equations (7-13) determine XPD for both vertical and horizontal polarization transmitted waves [13]. The transmitted waves are:

(7)
$$E_{T1} = E_1 \cos\varphi - E_1 \sin\varphi$$
$$E_{TII} = E_1 \sin\varphi + E_2 \cos\varphi$$

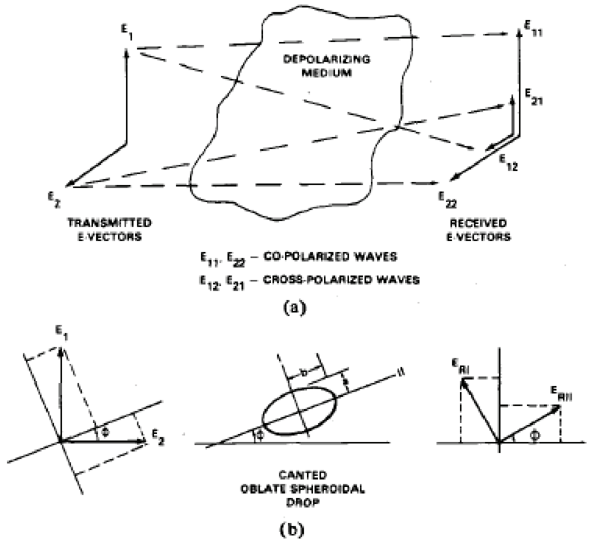

Fig.6 Vector relationship for a depolarizing medium. a) co- and cross-polarized waves for linear transmission and b) classical model for a canted oblate spherical rain drop. [13]

The transmission characteristics of the oblate spheroids is specified by transmission coefficients in the I and II directions as:

(8)
$$\chi_I = e^{-(A_I - i\Phi_1)L}$$
$$\chi_{II} = e^{-(A_{II} - i\Phi_{II})L}$$

where A_I and A_{II} are attenuation coefficients, and Φ_I and Φ_{II} are phase coefficients in I and II directions respectively.

The received waves are then:

(9)
$$E_{RI} = \chi_I E_{TI}$$
$$E_{RII} = \chi_{II} E_{TII}$$

The resulting received waves in the directions 1 and 2 can be obtained by combining (7), (8) and (9):

(10)
$$E_{R1} = \beta_{11}E_1 + \beta_{21}E_2$$
$$E_{R2} = \beta_{12}E_2 + \beta_{22}E_2$$

Where β_{11}, β_{21}, β_{12} and β_{22} are polarization coefficients defined by

(11)
$$\beta_{11} = \chi_I \cos^2\phi + \chi_{II}\sin^2\phi$$
$$\beta_{22} = \chi_I \sin^2\phi + \chi_{II}\cos^2\phi$$
$$\beta_{12} = \beta_{21} = \left(\frac{\chi_{II} - \chi_1}{2}\right)\sin^2\phi$$

The XPD's for vertical and horizontal transmission will then be

(12)
$$XPD_v = 20\log\frac{|\beta_{11}|}{|\beta_{12}|} = 20\log\frac{1 + \frac{\chi_{II}}{\chi_1}\tan^2\phi}{\left(\frac{\chi_{II}}{\chi_1} - 1\right)\tan\phi}$$

(13)
$$XPD_H = 20\log\frac{|\beta_{22}|}{|\beta_{21}|} = 20\log\frac{\frac{\chi_{II}}{\chi_1} + \tan^2\phi}{\left(\frac{\chi_{II}}{\chi_1} - 1\right)\tan\phi}$$

Both χ_{11} and χ_{22} are independent of ϕ, and since $\chi_{12} = \chi_{21}$, the cross polarized components resulting from positive and negative canting angles will cancel out each other.

The XPD for circular transmitted polarization (right hand or left hand circular polarization) is expressed in terms of polarization coefficients as [13],

(14) $$XPD_c = 20\log\left(\frac{|\beta_{11}|}{|\beta_{12}|}\bigg|_{\phi=45^o}\left|\overline{e^{i2\phi}}\right|\right) = 20\log\left(\frac{\chi_{II}+\chi_I}{\chi_{II}-\chi_I}\left|\overline{e^{i2\phi}}\right|\right)$$

where $\overline{e^{i2\phi}}$ is the mean of $e^{i2\phi}$ taken over the canting angle distribution.

As, higher the value of XPD, less will be the depolarization factor and better will be the received signal. So increase in frequency increases the received signal quality in this case.

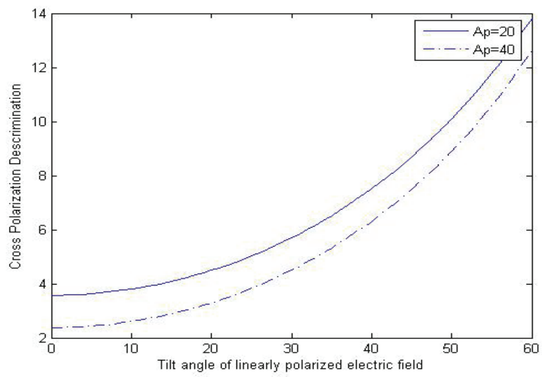

Fig 7: XPD varies with path elevation angle and the rain attenuation exceeding the required percentage of time (Ap)

Increasing tilt angle decreases the cross polarization component as long as it is below 45° as shown in Fig. 8. Since Cross polarization discrimination is a function of copolar attenuation, it degrades by increasing attenuation. Also it degrades at a given attenuation with increasing frequency. XPD for vertical polarization shows significantly good results than for horizontal polarization. Similarly, XPD is better for linear polarization than circular polarization [3].

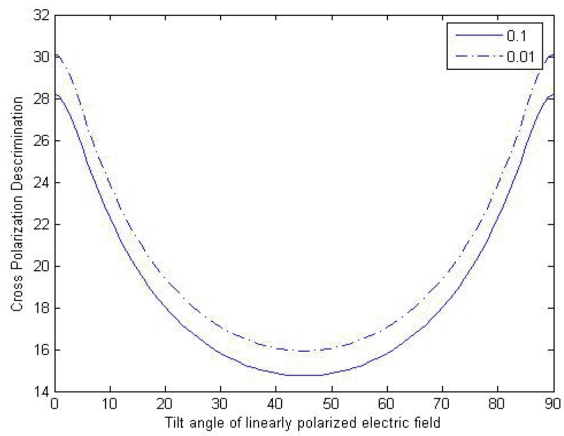

Fig 8: XPD vs. tilt angle of linearly polarized electric Field.

Conclusion

This paper describes how radio propagation is affected by various factors in stratosphere and ionosphere. Both ITU-R and SAM models were used to determine the influence of atmosphere on radio waves in different weather conditions.

The ITU-R model suggests that a 1-min interval must be used to measure rain fall in order to determine rain fall rate, which is very difficult in practice if we want to maintain 1-min data for several years. Furthermore, the 1-hr rain rate data need to be converted to 1-min rain rate data so that it can be applied to the existing rain attenuation models. To overcome these problems a model is needed to be designed to use 1-hr data without converting to 1-min rain rate data.

The results of both models are sometimes not consistent due to the reason that these models are originally designed for Europe and America, so we can rely only on these models where real data is not available. For more accurate results, data from local meteorological departments can be obtained and based on the empirical data local model should be designed which will be more consistent with real time statistics in the region.

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