Propagation Path and Related Tropospheric, Phenomena on the Satellite-Earth

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Abstract

Attenuation is a major drawback for the field of satellite communication which we can not ignore, but, ofcourse can try to mitigate at an instant. In this project, my focus is on the attenutaion part. I am trying to explain the types of attenuation which is being faced by the signal at tropospheric region. We will see how the signal changes its properties when it passes through tropospheric region. Different type of models is being used by the research scientist for measurement of the attenuation impact over the signal. Many times the models has given the fruitful result but some time they are failed as per different location. I took the Ku-band signal from NSS-6 (geostationary 950E) at an elevation angle of from Kolkata. My result outcome shows that the ITU-R model is the best model out of them and it makes the best predictions for different tropical climates. Based on my experimental result, I am trying to show that the ITU-R model is the best option for our climate. On the other side, I have explained through my project that how much signal depolarized at the different percentage of time at one-minute rain rate distribution.

Keywords: Propagation Path, Tropospheric, Phenomena, Satellite-Earth.

INTRODUCTION

Now days, increasing demand in the field of satellite communication, the 14/11 GHz and 14/12 GHz brought into the limelight. This is actually called Ku band. It is used for fixed and broadcast services, and for specific applications such as NASA's Tracking Data Relay Satellite used for both space shuttle and International Space Station (ISS) communications. We know that tropospheric effects such as rain and atmospheric irregularities, particularly at low elevation angle, significantly affect radio waves above the 10 GHz frequencies. Since, passing the 10 GHz frequency limit rises to signal fading. If the larger fade margin creates not feasible either technically or economically. Under these conditions, it is difficult for satellite system to satisfy the availability and quality of service (QoS) specification recommended by ITU-R. Attenuation causes in electromagnetic waves through the process of absorption and scattering; rainfall attenuation is a phenomenon relative to the rainfall rate and frequency which results in increasing path loss, limiting the coverage area, and consequently degrading the system performance. In recent years, the rapid development of technology for wireless communications, especially in developing countries, causes the frequency bands to reach a saturated level. Because of this issue, telecommunication systems engineers are exploring the frequency band above the 10 GHz (Ku band) in order to meet the rapidly growing request for wide bandwidth for transformation of the tricky radio access network. The frequency band above 10 GHz is advantageous because it provides a wider spectrum, potential repeated use of frequencies and compact size of antenna and equipment. Rainfall rate data for a given time percentage is required in the prediction of rain attenuation for that time percentage. International Telecommunication Union Radio communication Sector (ITU-R) is an organization which standardized the rule for telecommunication and provides a step by step approach for prediction of rain attenuation on any earth-satellite radio link; however, this model does not perform well in tropical region and at high rainfall rate since average radius of raindrop in tropical region is greater than that in non-tropical and data for ITU model is based on data collected from temperate region of the world. Technically to design the satellite links as determined by the fade margin of the link the study of different tropospheric phenomena is important. So these factors are studied and some experimental measurements are carried out to indicate how these factors affect the signal such that an appropriate fade mitigation technique can be adopted. In this project various tropospheric effects on a Ku-band signal is studied. We obtain the Ku-band signal from NSS-6 (geostationary 950E) at an elevation angle of from Kolkata. Studied mainly three effects viz. attenuation, rain depolarization and rain rate distribution and the observation are used to validate the existing models.

It is well known that precipitation adversely affects the transmission performance of radio communication systems. The increase in the attenuation of the signal has, until recently, been the major concern, but with the introduction of the concept of frequency reuse employing orthogonal polarizations, the depolarization properties of the transmitted medium have become important. To describe such propagation characteristics as attenuation and cross polarization of rain-filled media, the scattering from an assemblage of many particles must be considered.

TROPOSPHERE

The troposphere is the lowest layer of Earth's atmosphere and site of all weather on Earth.

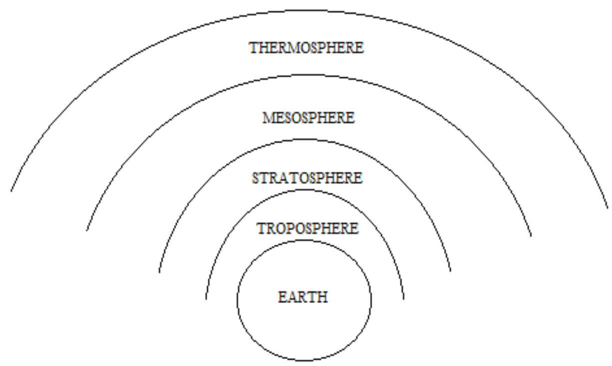

Fig:1 Earth Atmosphere

The troposphere is bonded on the top by a layer of air called the tropopause, which separates the troposphere from the stratosphere and on bottom by the surface of the Earth. The troposphere is wider at the equator (10mi) than at the poles (5mi).

(i) Enhanced conditions-Under certain conditions the radio propagation conditions provided by the troposphere are such that signals travel over even greater distances. This form of "lift" in conditions is less pronounced on the lower portions of the VHF spectrum, but is more apparent on some of the higher frequencies. Under some conditions radio signals may be heard over distances of 2000 or more kilometers with distances of 3000 kilometers being possible on rare occasions. This can give rise to significant levels of interference for periods of time. These extended distances result from much greater changes in the values of refractive index over the signal path. This enables the signal to achieve a greater degree of bending and as a result follow the curvature of the Earth over greater distances. Under some circumstances the change in refractive index may be sufficiently high to bend the signals back to the Earth's surface at which point they are reflected upwards again by the Earth's surface. In this way the signals may travel around the curvature of the Earth, being reflected by its surface. This is one form of "tropospheric duct" that can occur. It is also possible for tropospheric ducts to occur above the Earth's surface. These elevated tropospheric ducts occur when a mass of air with a high refractive index has a mass of air with a lower refractive index underneath and above it as a result of the movement of air that can occur under some conditions. When these conditions occur the signals may be confined within the elevated area of air with the high refractive index and they cannot escape and return to earth. As a result they may travel for several hundred miles, and receive comparatively low levels of attenuation. They may also not audible to stations underneath the duct and in this way create a skip or dead zone similar to that experienced with HF ionospheric propagation.

(ii) Fading- When signals are propagated over extended distances as a result of enhanced tropospheric propagation conditions, the signals are normally subject to slow deep fading. This is caused by the fact that the signals are received via a number of different paths. As the winds in the atmosphere move the air around it means that the different paths will change over a period of time. Accordingly the signals appearing at the receiver will fall in and out of phase with each other as a result of the different and changing path lengths, and as a result the strength of the overall received signal will change. Any terrestrial signals received at VHF and above will be subject to the prevailing propagation conditions caused by the troposphere. Under normal conditions it should be expected that signals will be able to be received beyond the normal line of sight distance. However under some circumstances these distances will be considerably increased and significant levels of interference may be experienced. One useful form of radio communications technology for applications where path lengths of around 800 km are needed is known as tropospheric scatter or troposcatter. It is a reliable form of radio communications link that can be used regardless of the prevailing tropospheric conditions. Although reliable, when using troposcatter, the signal strengths are normally very low. Accordingly troposcatter radio communications links require high powers, high antenna gains and sensitive receivers.

Troposcatter is often used for commercial radio communications applications, normally on frequencies above 500 MHz for over the horizon links. It is ideal for remote telemetry or other links where low to medium rate data needs to be carried. Where viable, troposcatter provides a means of communication that is much cheaper than using satellites.

ATTENUATION

Attenuation is a general term that refers to any reduction in the strength of a signal. It occurs with any type of signal, whether digital or analog. Sometimes called loss, attenuation is a natural consequence of signal transmission over long distances.

(i) Tropospheric Attenuation- Some issues related to W/V-band propagation are primarily due to the effects of the Earth's atmosphere and their impact on system availability and margin. Distortions due to multipath propagation do not affect the millimeter wave. However, some atmospheric effects at the millimeter wavelengths are rain attenuation, cloud attenuation and gaseous absorption. Rain attenuation has the most dominant contribution to the total propagation loss when dealing with higher frequencies. Cloud attenuation at the W/V bands can contribute to significant loss (> 10 dB). Gaseous absorptions are mainly due to atmospheric gaseous components (predominantly oxygen and water vapor) and typically have a small contribution to the total path attenuation in the W/V band.

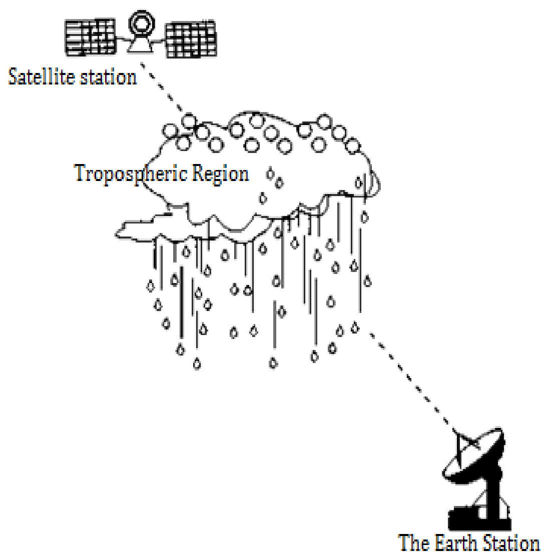

Fig.2 Signal path between the earth-satellite stations through troposphere region

(ii) Tropospheric Scintillation-The process of scintillation is one of luminescence whereby light of a characteristic spectrum is emitted following the absorption of radiation. The emitted radiation is usually less energetic than that absorbed. Scintillation is an inherent molecular property in conjugated and aromatic organic molecules and arises from their electronic structures. Scintillation also occurs in many inorganic materials, including salts, gases, and liquids. Troposphere scintillation is the rapid fluctuations in the refractive index of owing to turbulence and produces random fades and enhancements of the received signal amplitude. This phenomenon can seriously affect satellite-earth links at frequencies above 10 GHz and at very low elevation angles (<=5 degrees). It will because the signal degradation in satellite communication with low fade margin. To analyze tropospheric scintillation, we should obtain current data from a satellite link installed at any location all over the world. Due to demand for higher bandwidth, tropospheric scintillation is receiving more attention. Higher-frequency bands, that causes the rapid fluctuation of the magnitude and phase of radio waves.

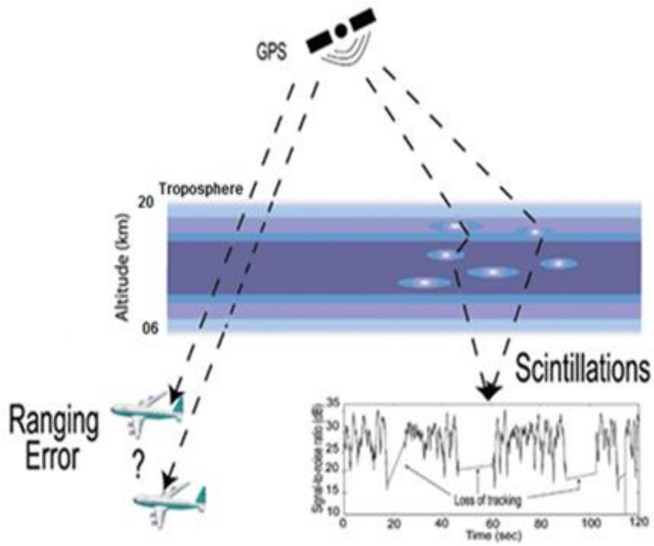

Fig.3 Tropospheric Scintillation

These fluctuations called scintillations. Tropospheric scintillation depends on the season and daily weather conditions.

(iii) Signal Depolarization-Differential phase shift and attenuation caused by non-spherical scatters (e.g. raindrops and ice crystals) cause signal depolarization. Although this may affect a little for single polarized satellite systems, its effect becomes significant for systems reusing frequency by transmitting two orthogonally polarized signals for optimum RF utilization. In this case, depolarization results in cross polar interference, i.e. part of the transmitted power in one polarization interferes with the orthogonally polarized signal i.e. cross talk occur. Rainstorms are the most common cause of depolarization as well as of attenuation. According to most of the models of depolarization due to rain, the medium has two principal planes and the characterization parameters are the canting angle of these planes and the differential attenuation and differential phase shift between planes. From the measured depolarization data during rain events, these characteristics of the depolarizing mechanism of the rainstorms can be obtained and some of the existing models can be verified. Ice crystals present in clouds above the can also cause severe depolarization. The depolarization is mainly caused by differential phase shift and not by differential attenuation. Depolarization due to ice crystals does not coincide with significant co-polar attenuation. If a rainstorm and ice cloud are present on the propagation path at the same time, the both can cause an amount of depolarization which cannot easily be separated in rain and ice depolarization. Since generally the two media do not have the same axes of symmetry, the assumption of two principal planes of the whole medium is no longer valid. In melting layer, where ice crystals are in the process of forming raindrops, hydrometers consist of a mixture of ice and water. Also this area can cause differential attenuation and differential phase shift between two principal planes, resulting in some degree of depolarization. Alternatively, dust particles can also cause depolarization of microwaves in desert areas. Since, we are measuring these phenomena in the tropical region, ice crystal effects can be omitted because this has practically no impact on depolarization. The rain event has the most significant effect on depolarization. The experimental study has shown that the depolarization due to raindrops depends on:

i. Orientation and Shapes of falling raindrops,

ii. Number of raindrops in the propagation path, and

iii. Polarization and operating frequency of RF waves

iv. Rain rate

v. Rain cell size

vi. Distribution of canting angles that the raindrops acquire during their descent to ground.

When rain fall occurs the attenuation and signal depolarization occur simultaneously and it is generally observed that the attenuation is significant at some certain rainfall and at the same time the cross-polar signal rises to some dB value. The degree of depolarization may be represented by the radio cross-polarized to co-polarized signals at the receiver. We may define two kinds of cross-polarization factors:

i. Cross-polarization discrimination (XPD), and

ii. Cross-polarization isolation (XPI).

$$XPD_H = 20\log_{10}|\Delta E_V/E_H| \quad (1)$$

$$XPD_V = 20\log_{10}|\Delta E_H/E_V| \quad (2)$$

$$XPI_H = 20\log_{10}|\Delta E_H/E_H| \quad (3)$$

$$XPI_V = 20\log_{10}|\Delta E_V/E_V| \quad (4)$$

where, E_H and E_V are the co-polarized received electric fields in the direction $E^{\circ}{}_H$ and $E^{\circ}{}_V$, ΔE_H is the cross-polarized received electric field in the direction E_H transferred from E_V, and ΔE_V is the cross-polarized received electric field in the direction E_V transferred from E_H.

While XPD arises in the transmission measurements where a single-polarization transmitter and a dual-polarization receiver are used, XPI describes the interference in each of the two signal lines of the dual-polarization frequency-reuse communication systems. Depolarization is the maximum for horizontal propagation path and is the minimum for vertical path when the axes of raindrops are in the vertical direction. The maximum acceptable level of cross-polarization factors is considered to be around -25dB to -30 dB depending on the communication systems. Now it is said earlier that in microwave communication links above 10 GHz the employment of frequency reuse in orthogonal polarizations is limited b cross-polarizations. The total cross-polarization signal in the receiver of a radio link is the sum of these components, their phase relationship, and hence the result of their addition should be estimated. For cross-polarization experiments that aim at measuring cross-polarization generated by the atmosphere it is of primary importance that the equipment components be reduced as far as possible.

RELATION BETWEEN CO-POLAR ATTENUATION & CROSS-POLARIZED DISCRIMINATION

Theoretically as well as empirically, it has been shown that there is a certain co-relation between depolarization and the attenuation due to rain. This relation is studied here because it provides a practical prediction tool for depolarization.XPD statistics may be derived from attenuation statistics. Furthermore, combined statistics of XPD and attenuation are necessary to assess the margins of both parameters required for a certain system outage probability. In this section, attenuation is indicated with the symbol CPA (co-polar attenuation). Different experiments have derived expressions for the relation between XPD and CPA. These expressions have been derived from calculations, using different theories of EM wave scattering by raindrops (e.g. Mie scattering, point-matching technique) and using different models of rain drop size distribution and raindrop shape and orientation. The various resulting models are very similar and only differ in neglecting and approximating several dependencies. All models were formulated in the form of the following expression:

$$XPD = S + C\log f + I(\delta, \sigma_\theta) - G\log\cos\varepsilon - V(f)\log CPA(dB) \quad (1)$$

Where

f = frequency (GHz);

= polarization tilt angle (measured from the horizontal);

=temporal standard deviation of the canting angle of the medium ( );

= elevation angle;

= polarization improvement term (dB);

S, C, G, V = characterizing parameters, which are different for each proposed model and depend on raindrop size distribution and raindrop shape model (S also depends on the effective path length through rain L and on the spatial distribution of the rain drop canting angles).

(i) The essential Parameters-From the above expression we see that XPD depends upon several parameters. The system parameters are the frequency of operation (f), the elevation angle of the slant path (ε) and the tilt angle (τ) of the linearly polarized electric field related to horizontal ($\theta\ is\ positive\ upward\ from\ horizontal$) and standard deviation (σ_θ), when we assume raindrop distribution to be Gaussian distributed. Now here we briefly describe the concept of canting angle. The basis for the calculation of the canting angle is the following assumption. The mean orientation of the axis of rotational symmetry of the drop is always parallel to the direction of the airflow around the drop. It is therefore always necessary to consider the direction of airflow relative to the drop. The inclination of that airflow with respect to vertical is equal to the canting angle of the drop.

From these considerations it becomes clear that wind as such is not a cause of raindrop canting. If the wind speed is constant and independent of height, the drop will assume the same horizontal speed as the surrounding air particles and the airflow relative to the drop will have a horizontal component; the resultant airflow around the drop will be inclined and the drop will cant accordingly. However the component of the drag force on the drop will accelerate or decelerate the drop in the horizontal direction until its horizontal speed is equal to the wind speed again. A nonzero mean canting angle will exist only during acceleration or deceleration of the drop. A drop which initially had the same horizontal speed as the air, and which is falling through this region, will be constantly decelerated and will show a canted orientation as illustrated below in fig.4.

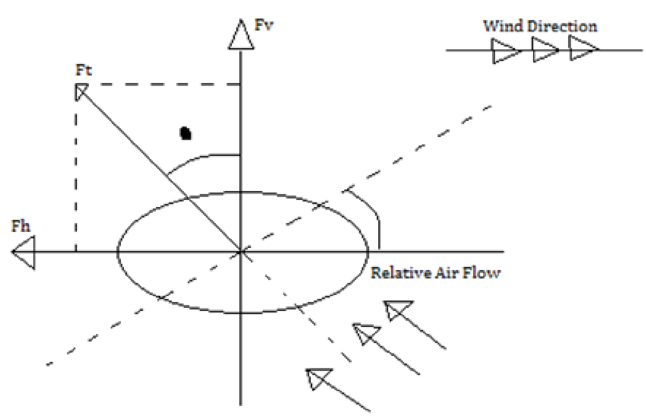

Fig.4. Raindrop Canting; Ft is the total drag force on drop, Fh is horizontal and Fv is vertical component

Referring from the fig.4

$$\tan\theta = \frac{F_h}{F_v} = \frac{m(dV_h)/(dt)}{m\,g} = \frac{U - V_h}{V_v} \qquad (2)$$

Where

θ=canting angle;
V_h=horizontal drop speed;
V_v=vertical drop speed (assumed to be constant and equal to be terminal speed in stagnant air);
U=wind speed at the position of the drop;
g=gravitational constant.

Now we come to the point of other parameter. The shape distribution is assumed to be bimodal with fraction F_0 being spheroidal and the remaining fraction $(1-F_0)$ spherical. The mean orientation angle of the raindrops and polarization of the radio wave can be combined since it is only the orientation of the electric field relative to the medium. To do this we use the angle,

$$\delta = \begin{cases} |\tau-\theta| & for\ linear\ polarization \\ 45^\circ & for\ circular\ polarization \end{cases} \quad (3)$$

The path length and the rain rate distribution profile along the propagation path play a dominant role in the predictive modeling of total path attenuation and *XPD* when calculated as a function of point rain rate. However, the dependence of *CPA* and *XPD on* path length is similar in the frequency range of 10 GHz to 30 GHz. Because of this the *XPD* versus *CPA* relationship is relatively insensitive to the rain rate distribution, Calculations of *XPD* with a multiple scattering model for uniform and exponential rain rate distribution revealed that for fixed values of attenuation the *XPD* was invariant for varying path parameters from 10 GHz to 30 GHz. Therefore, in calculation type studies we can use any responsible rain rate distribution and can exclude parameters associated with the rain rate distribution (such as path length and from factors for a spatial profile).
There are following parameter which has needed to explore our research:

a) XPD=cross-polarized discrimination
b) CPA=co-polar attenuation
c) δ =polarization tilt angle(measured from the horizontal)
d) ε = elevation angle
e) S,C,G,V =characterizing polarization parameters of waves, which are different for each model and depend on rain drop size & rain drop shape model
f) σ_θ = temporal standard deviation of the canting angle of the medium (in degree);
g) "σ^{ref}" is the standard deviation of the signal amplitude,
h) "*f*" is the operational frequency,
i) "*g*(*x*)" is the antenna averaging factor,
j) "θ" is the antenna elevation angle,
k) "*H*" is the surface humidity,
l) And "t" is the surface temperature (°C).

CONCLUSION

In the present study the phenomena of depolarization at a topical location, Kolkata has been investigated. To investigate depolarization we have used five standard models and our whole experiment process is carried out in comparison with ITU-R Model which is globally accepted and it is shown that the models do not deviate much in case of low co-polar attenuation. The depolarization caused by rain has been measured in terms of the degradation of XPD. This is because the cross-polar attenuation can be best understood by the terms of XPD. Since, proper measurement of XPD is difficult to express XPD in terms of its degradation is advantageous.

REFERENCES

1. Satellite Communication" 2nd Edition by T.Pratt, C Bastian & J.Allnutt, pg. 295-340.
2. Warren L. Stutzman and Donald L Runyon (1984): The Relation of Rain Induced Cross-Polarization Discrimination to Attenuation for 10-30 GHz Earth

Space Radio Links, IEEE Transactions on Antenna and Propagation ,vol. AP-32, pp 705-709
3. Gert Brussaard (1976): A meteorological Model for Rain-Induced Cross-Polarization, IEEE Transactions on Antenna and Propagation ,pp 5-7
4. Van de Kamp: Climatic Radiowave Propagation Models for the design of Satellite Communication Systems, pp 1-92
5. Polat Kaya (1980): A Model for Calculating the Depolarization of Microwave Signals Propagating Through Rain, IEEE Transactions on Antenna and Propagation ,vol. AP-28, pp 154-155
6. Oguichi T (1960): Attenuation of electromagnetic wave due to rain with distorted raindrops, J. Radio Res Labs, vol 7, pp 467-485
7. M.J. Singh, Abdulla M & Tariqul M, "Development of new tropospheric scintillation prediction model for country in tropical climate".
8. C.Y Chen and M.J Singh "Comparison of tropospheric scintillation prediction models of the Indonesian climate".
9. Van de Kamp M J L,J K, Salonen E T, Poirares Baptista J P V; "Improved models for long-term prediction of tropospheric scintillation on slant paths".
10. Oei Wei Chun and Jit Singh Mandeep; Empirical methods for converting rainfall rate distribution from several higher integration times into a 1-minute integration time in Malaysia; GEOFIZIKA VOL. 30 2013, Original scientific paper, UDC 551.508.85.
11. Chieko Ito and Yoshio Hosoya, the Thunderstorm ratio as a Regional Climatic Parameter:
12. Its effects on different-integration-time rain rate conversion, rain attenuation,
13. Site-diversity and rain depolarization.
14. Y.Sulochana, P.Chandrika & S.Vijaya Bhashkar Rao,"Rain Rate & Rain Attenuation Statistics for Different Homogeneous Regions of India", Indian Journal of Radio & Space Physics ,Vol 43,August – October 2014,pp 303-314.
15. Agunlejika O, Raji T.I and Adeleke O.A "Tropospheric Scintillation Prediction for Some Selected Cities in Nigeria's Tropical Climate", International Journal of Basic & Applied Sciences IJBAS-IJENS Vol: 09 No: 10.
16. Martin Hall, Les Barclay, Propagation of Radiowaves, 2nd edition, The Institute of Electrical Engineers, London, UK.
17. ITU-R Recommendation P.676-5, Attenuation by atmospheric gases, 2001.
18. ITU-R Recommendation P.618-7, Propagation data and prediction methods required for the design of Earth-space
19. telecommunication systems, 2001.
20. ITU-R Recommendation P.834-4, Effects of tropospheric refraction on radiowave propagation, 2003.
21. ITU-R Recommendation P.837-5, Characteristic of precipitation for propagation modeling, 2007.
22. Dong Y.Choi, Rain attenuation prediction model by using the 1- hour rain rate without 1-minute rain rate conversion, IJCSNS
23. Iinternational Journal of Comp. Science and Network Security, March 2006, Vol. 6 No. 3A.
24. ITU-R Recommendation, P.618-8, Propagation data and prediction methods required for the design of Earth-space
25. telecommunication systems, 2003.
26. Glen Feldhake, Estimating the attenuation due to Combined Atmospheric Effects on Modern Earth-Space Paths, IEEE
27. Antennas and Propagation Magazine, August 1997, Vol. 39, No. 4.
28. CCIR, Report 719, Attenuation by atmospheric gases, Recommendations and reports to the CCIR, 1978, Vol. 5, pp.
29. 97-102.
30. Hany E. Green, Propagation Impairment on Ka-band SATCOM links in Tropical and Equatorial Regions, IEEE Antennas and Propagation Magazine, April 2004, Vol. 46, No.2.
31. Shkelzen C., Kresimir M., Rain Attenuation at Low Earth Orbiting Satellite Ground Station, Presented in 48 th
32. International symposium ELMAR-2006, 07 09 June 2006, Zadar, Croatia.
33. ITU-R Recommendation P. 838-1, Specific Atteuation model for Rain for use in Prediction Methods, Geneva, 1992.
34. Louis J. Appolito, Radio Propagation for Space Communication Systems, In Proceedings of the IEEE, June 1981, Vol. 69, No.6.
35. T. S. Chu, Rain Induced Cross-polarization at centimeter and millimeter wavelengths, Bell. Sys. Tech. J., Oct. 1974, Vol. 53,
36. no.8, pp. 1557-1579.
37. Teschl, F., Schoenhuber, M., Perez-Fontan, F., Valtr, P., Hovinen, V., Kyröläinen, J., Prieto-Cerdeira, R., "Channel Characterization Studies at GNSS C-Band Frequencies", in 4th ESA Workshop on Satellite Navigation User Equipment Technologies, Navitec 2008, Noordwijk, The Netherlands, December 2008.
38. Béniguel, Y., Adam, J.-P., Jakowski, N., Hoque, M., Cueto, M., Radicella, S., Nava, B., Lannelongue, S., Prieto-Cerdeira, R., "Ionospheric Propagation Impairments for GNSS at C Band" in 4th ESA Workshop on Satellite Navigation User Equipment Technologies,
39. Navitec 2008, Noordwijk, The Netherlands, December 2008.
40. European Space Agency / European GNSS Supervisory Authority: "Galileo Open Service Signal In Space Interface Control Document (OS SIS ICD) Draft 1", GAL OS SIS ICD/D.1, Iss.Draft, Rev.1, February 2008
41. Orus, R.; Arbesser-Rastburg, B.; Prieto-Cerdeira, R.; Hernandez-Pajares, M.; Juan, J.M.; Sanz, J.; "Performance of Different Ionospheric Models for Single Frequency Navigation Receivers", Beacon Satellite Symposium 2007, Boston, June 2007.
42. Orus, R.; Prieto-Cerdeira, R., "GIOVE-A Experimentation Campaign: Ionospheric Related Data Analysis", in 4th ESA Workshop on Satellite Navigation User Equipment Technologies, Navitec 2008, Noordwijk, The Netherlands, December 2008.
43. Tossaint, M., Binda, S., Hahn, J., Falcone, M., Prieto-Cerdeira, R., Giuntini, F., "Galileo Initial Validation Step: GIOVE Navigation Message", in ENC-GNSS08, Toulouse, France, April 2008.
44. Hernandez-Pajares, M., Juan, J.M. and Sanz, J., "New approaches in global Ionospheric determination using ground GPS data". Journal of Atmospheric and Solar Terrestrial Physics, Vol 61, pp 1237-1247, 1999
45. Prieto-Cerdeira, R., Arbesser-Rastburg, B., Orus, R. et al "Ionospheric modelling and validation for Satellite Based Augmentation Systems: the European EGNOS System example", in 1st Colloquium Scientific and Fundamental Aspects of the Galileo Programme, Toulouse, France, October 2007.
46. Beniguel, Y., "Global Ionospheric Propagation Model (GIM): a propagation model for scintillations of transmitted signals", Radio Sci., May/June 2002
47. Thompson, P., Prieto-Cerdeira, R., "Consideration of Ionospheric Scintillation in the Design of C-Band VSAT Systems", in Radiowave Propagation Models, Tools and Data for Space Systems Workshop, Noordwijk, The Netherlands, December 2008.
48. Perez-Fontan, F.P., Vazquez-Castro, M., Cabado, C.E., Garcia, J.P. and Kubista, E., "Statistical modeling of the LMS channel", IEEE Transactions on Vehicular Technology, 2001.
49. Lehner, A., Steingass, A., "A Novel Channel Model for land mobile satellite navigation" in Proceedings of the 18th International Technical Meeting of the Institute of Navigation Satellite Division (ION GNSS 2005), Long Beach, California, USA, 2005.
50. Schubert, F., Prieto-Cerdeira, R., Steingass, A., "GNSS Software Simulation System for Realistic High-Multipath Environments", in 4th ESA Workshop on Satellite Navigation User Equipment Technologies, Navitec 2008, Noordwijk, The Netherlands, December 2008.
51. A. Maitra, K. Chakravarty, S. Bhattacharya, and S. Bagchi, "Propagation studies at Ku-band over an earth-space path at Kolkata", Indian J Radio & Space Phys., 36, 2007, pp. 363-368.
52. A. Maitra, A. Adhikari and A. Bhattacharya, "Some characteristics of earth-space path propagation phenomena at a tropical location", Indian Journal of Radio & Space Physics, 41, 2012, pp. 481-487.
53. A. Maitra and K.Chakravarty, "Rain depolarization measurements on low margin Ku-band satellite signal at a tropical location", IEEE Antennas and

Wireless Propag. Lett., 8, 2009, pp. 445-448.
54. Adhikari et al., 2012 A. Adhikari, A. Bhattacharya and A. Maitra, “Rain Induced Scintillations and Attenuation of Ku-band Satellite Signals at a Tropical Location”, IEEE Geoscience Remote Sensing Letters, 9(4), 2012, pp. 700-704.
55. J. S. Mandeep, and J. E. Allnutt, “Rain attenuation predictions at Ku-band in South East Asia countries”, Prog. Electromagn. Res., PIER 76, 2007, 65–74.
56. J. S. Mandeep, S. I. S. Hassan, M. F. Ain, and K. Tanaka, “Rainfall propagation impairments for medium elevation angle satellite-to-earth 12 GHz in the tropics”, Int. J. Satell. Commun. Network., 26, 2008, 317–327.
57. K. Chakravarty and A. Maitra, “Rain attenuation studies over an earth-space path at a tropical location”, J. Atmos. Solar Terr. Phys., 72, 2010, pp. 135-138.
58. B. Arbesser-Rastburg, N. Jakowski, Effects on satellite navigation, Chapter 13, in Space Weather – Physics and Effects, ed. by V. Bothmer, I. Daglis (Springer, Berlin, 2007).
59. L. Castanet, Influence of the Propagation Channel on Satellite Communications – Channel Dynamic Effects on Mobile, Fixed and Optical Multimedia Applications (Satnex E-book, Shaker, 2007).
60. G. Maral, M. Bousquet, Satellite Communications Systems, 5th edn. (Wiley, Chichester, 2009).