The Impact of Dust and Foliage on Signal Attenuation in the Millimeter Wave Regime*

Gary Comparetto
Director SATCOM Engineering
Radio Dynamics Corporation
Phone: (719) 266-0046
e-mail: gmc@radyn.com

ABSTRACT

Rain has long been recognized as a principal cause of unwanted signal loss in satellite communications (SATCOM) systems operating in the millimeter wave region (i.e., 3 to 300 GHz). Signal attenuation on the order of tens of dB is possible depending upon the specific characteristics of the rain event. Consequently, a significant amount of research has been expended in developing models to quantify the impact of rain attenuation on communications link performance. In contrast to this, very little work has been done in the area of signal attenuation due to signal propagation through dust and/or foliage. This is probably because the dust and/or foliage laden propagation path was thought in the past to be an unlikely occurrence relative to rain. However, geo-political events of recent years have given rise to an increased likelihood of operations requiring communications links in these types of environments. A good example for communications link requirements through a dust-laden channel was Desert Storm, while potential conflicts involving drug interdiction may result in the need to support communication links through intense foliage typical of South American forests. Consequently, the signal attenuation characteristics of dust and foliage must be well understood in order to ensure adequate communications capabilities in these types of environments.

The purpose of this paper is to discuss the phenomena associated with signal attenuation through dust and foliage and to quantify the impact of these environments on signal propagation. Specifically, models used to characterize dust and foliage attenuation will be described and available experimental data will be presented to support the discussion. It will be shown that the attenuation due to sand and/or dust storms on SATCOM communications links operating in the frequency range investigated is small, with link degradations on the order of .1 dB. However, foliage is shown to be extremely impacting with signal attenuation on the order of 3 to 4 dB per <u>meter</u> of foliage. The conclusions drawn are: (1) satellite communications in the millimeter wave regime through a dust laden communications path can be assured via adequate link design, and (2) communications through any length of foliage should be discouraged and that it is predominantly through operational adjustments and procedures, and not link design, that communications with any degree of confidence can be assured in a foliage environment.

---

* Originally published in J. of Space Comm., Vol. 11, no. 1, pp. 13-20, July 1993

INTRODUCTION

Rain has long been recognized as a principal cause of unwanted signal loss in satellite communications (SATCOM) systems operating in the millimeter wave region (i.e., 3 to 300 GHz). Signal attenuation on the order of tens of dB is possible depending upon the specific characteristics of the rain event. Consequently, a significant amount of research has been expended in developing models to quantify the impact of rain attenuation on communications link performance [1-8]. One of the early pioneers in the area of quantifying the impact of rain attenuation on SATCOM links was Crane. In his paper of 1971, Crane identifies rain as a major contributor to SATCOM system signal degradation at high operating frequencies [1]. Crane's most famous contribution in this area was his paper of 1980 in which he proposed a model for the prediction of attenuation by rain on either terrestrial or slant Earth-to-space propagation paths [2]. The model was developed using geophysical observations of the statistics of point rain rate, the horizontal structure of rainfall, and the vertical temperature structure of the atmosphere. In a later study, Tattelman and Scharr [4] developed a more detailed model for estimating one-minute rainfall rates using stepwise multiple regression analysis. The model included six regression equations to estimate point rain rates that were equaled or exceeded 0.01, 0.05, 0.10, 0.50, 1.0, and 2.0 percent of the time during a single month period at a given location.

The preponderance of rain attenuation studies germane to satellite communications applications in the millimeter wave regions is in direct contrast to the dearth of studies investigating the impact of dust and foliage on the same propagation paths. This is probably because the dust and/or foliage laden propagation path was thought in the past to be an unlikely occurrence relative to rain. However, geo-political events of recent years have given rise to an increased likelihood of operations requiring communications links in these types of environments. A good example for communications link requirements through a dust-laden channel was Desert Storm, while potential conflicts involving drug interdiction may result in the need to support communication links through intense foliage typical of South American forests. Consequently, the signal attenuation characteristics of dust and foliage must be well understood in order to ensure adequate communications capabilities in these environments.

The purpose of this paper is to discuss the phenomena associated with signal attenuation through dust and foliage and to quantify the impact of these environments on signal propagation. Specifically, models used to characterize dust and foliage attenuation will be described and available experimental data will be presented to support the discussion. It will be shown that the attenuation due to sand and/or dust storms on SATCOM communications links operating in the frequency range investigated is small, with link degradations on the order of .1 dB. However, foliage is shown to be extremely impacting with signal attenuation on the order of 3 to 4 dB per <u>meter</u> of foliage. The conclusions drawn are: (1) satellite communications in the millimeter wave regime through a dust laden communications path can

* Originally published in J. of Space Comm., Vol. 11, no. 1, pp. 13-20, July 1993

be assured via adequate link design, and (2) communications through any length of foliage should be discouraged and that it is predominantly through operational adjustments and procedures, and not link design, that communications with any degree of confidence can be assured in a foliage environment.

* Originally published in J. of Space Comm., Vol. 11, no. 1, pp. 13-20, July 1993

DISCUSSION

Sand/Dust Attenuation

Most studies to date concerning the attenuation of SATCOM signals from sand and/or dust have been based upon the assumption that the sand/dust medium results from a nuclear detonation. However, experience gained in the Desert Storm operations have shown that signal attenuation due to sand or dust, where the sand/dust medium results from local storms, should be considered and evaluated in ground-supported satellite communications systems.

First of all, sand storms and dust storms are two quite different phenomena [9]. What are often called sandstorms, because they occur in arid regions, are, in fact, dust storms. Where the surface is alluvial, and not sandy, such as in Iraq or the Sudan around Khartoum, storms called "haboobs" will produce vast dust clouds rising more than 1 km into the air and obscuring the sun for long periods of time [10,11]. True sandstorms, on the other hand, seldom rise above 2 meters in height! In a sandstorm, except at the beginning of the storm, the air will often be clear with the sun shining on top of the heads of those walking around in what appears to be a "sea of sand" [12]. The movement of the sand in a true sandstorm is primarily via saltation, a process through which the sand grains are propelled forward by the wind and, upon impacting the rough surface material at a shallow angle, rebound upwards to be driven further down wind. Due to the low maximum height of sandstorms, they are not typically a factor in satellite communications propagation loss calculations. Consequently, the remainder of this section focuses on the potential impact of dust storms, or haboobs, in the millimeter wave region.

In order to estimate the effects of a dust storm on the performance of a communications link, it is first necessary to develop a representative dust model. The models developed to date have primarily characterized dust in the turbulent and dynamic medium resulting from the strong afterwinds following the fireball phase of a nuclear event.[1] Although the actual particulate makeup of a dust storm may differ significantly from that of a nuclear-induced region, it is still beneficial to study the results of such analyses since the theory applied is similar.

---

[1] The fireball is typically characterized as an extremely hot and highly ionized spherical mass of air and gaseous weapon residues immediately following a nuclear burst. The fireball grows rapidly and, because of its intense heat, some of the soil and other material in the area are vaporized and taken into the fireball. It is the effect of the strong afterwinds, however, that cause most of the dust particulate to be inserted into the propagation path.

* Originally published in J. of Space Comm., Vol. 11, no. 1, pp. 13-20, July 1993

The varying sizes of the dust particles are often represented by a power law probability distribution of the form [13-14]:

$$P(r) = kr^{-p} \tag{1}$$

where r is the particle radius, p is the power law exponent, and k is chosen such that:

$$k \int_{r_{min}}^{r_{max}} r^{-p}\, dr = 1 \tag{2}$$

The nuclear-induced dust cloud is typically modeled by five distinct regions that evolve independently in time and exhibit individual characteristics with respect to region radius, region upper altitude, minimum/maximum average particle size, and particle density distribution. Equation (1) above would be applied to each region and would provide the particulate distribution for that region. The particulate distribution would then be used to quantify the signal attenuation per kilometer of path length.

SATCOM signals incident on dust particulate in the atmosphere undergo both absorption and scattering, the degree of each being dependent upon the size, shape, and complex dielectric constant of the particulate as well as the wavelength (or frequency) of the signal. A complicated expression for calculating the absorption and scattering from a dielectric sphere was first derived by Mie [15]. A Rayleigh approximation is allowable when the size of the dust or sand particle is very small with respect to the signal wavelength; however, the more complicated Mie expressions are required as the dust particles approach the signal wavelength. The signal wavelengths in the millimeter range are, by definition, limited on the lower end by a millimeter. The maximum particle size observed in desert dust storms is on the order of .2 mm or approximately 50 times smaller than the minimum signal wavelength in the millimeter wave regime [9]. Consequently, the Rayleigh approximation is valid to model signal attenuation in dust storms for operating frequencies in this regime.

The Rayleigh approximation technique was applied by Altshuler [13] to generate the data presented in figure 1 showing the signal attenuation due to dust (in dB/km) as a function of operating frequency. The power law exponent used in equation (1) to generate the data in figure 1 was 3.5, the minimum and maximum particle radii were 0.005 and 5 mm, respectively, and the bulk particulate density assumed was 2.6 gram/m^3. As shown, the signal attenuation is a strong function of the operating frequency, increasing with increasing frequency.

* Originally published in J. of Space Comm., Vol. 11, no. 1, pp. 13-20, July 1993

Altshuler also generated data that showed the correlation between signal attenuation and the minimum and maximum radii of the particulate. It was shown that the signal attenuation was a very weak function of the minimum particle radius. However, as shown in figure 2, the data indicate a strong correlation between signal attenuation and the maximum particle radius with an abrupt rise in signal attenuation as the maximum particle radius is increased. The signal attenuation reaches a peak when the maximum particle diameter is on the order of the signal wavelength. For example, the curve for 45 GHz reaches a maximum value at approximately 2 mm and the wavelength of a 45 GHz signal is:

$$\lambda = c/f = 3x10^{8}/45x10^{9} \text{ meters} = \sim 6.5 \text{ mm} \quad (3)$$

The data presented by Altshuler show that the attenuation due to sand can be quite severe, depending upon the maximum particle size. The resulting signal attenuation is on the order of several to 10 dB per kilometer. However, as previously stated, the particulate region modeled in Altshuler's analysis resulted from a nuclear detonation which would exhibit significantly different particulate characteristics from those resulting from a dust storm. For example, using the .2 mm maximum particle size claimed by Rafuse [9] as a representative value for a dust storm, together with the data presented by Altshuler in figure 2, the signal attenuation due to dust is seen to be on the order of .5 dB/km at 45 GHz and .2 dB/km at 20 GHz. Rafuse [9] also claims that the maximum height of a dust storm is 1 to 2 km. Thus, by combining both the Rafuse and Altshuler data, the maximum attenuation due to dust attenuation that one would expect for millimeter regime communications links is approximately .5 to 1 dB.

Rafuse also presents specific attenuation data (in units of dB/Km) for dust using the same bulk particulate density assumed by Altshuler (i.e., 2.6 gram/m^3) [9]. The data presented by Rafuse [9] is significantly more optimistic than Altshuler. For example, the maximum value for signal attenuation due to dust at frequencies as high as 44 GHz is given by Rafuse as .04 dB/km. If this is accurate, dust storm attenuation could be considered insignificant for satellite communications in the millimeter regime since the total impact for a storm up to 2 km in height would be less than one tenth of a dB. However, data measured by Al-Hafid et al. in Iraq for an 11 GHz microwave link[2] during a dust storm indicate a median signal reduction of

---

[2] (U) Note that a microwave link is a terrestrial communications link (i.e., ground-to-ground) as opposed to a satellite communications link (i.e., ground-to-space). The following discussion, while not directly applicable to a satellite communications link, does provide insight into the signal attenuation mechanisms associated with dust storms for ground-supported SATCOM link applications.

2 to 4 dB, with signal fades as high as 10 to 15 dB observed. How can this apparent discrepancy be explained?

Rafuse provides a plausible explanation based upon studies by Lawson [10] and Idso [11]. Since most dust storms are produced by downdrafts from thunderstorms, even though no rain may reach the ground, rain-cooled air is thrust down from the storm and out along the ground under the warm, dry, pre-existing air mass. Very often, because of the manner in which the lobes of the advancing mini-front are generated, large patches of warm air are found imbedded in the cool air behind the front [10]. The mini-frontal structure moves forward at a velocity approximately equal to one-half of the maximum wind speed behind it. Measurements in Khartoum indicate that the mini-frontal structure reaches maximum speeds of advance of 70 to 80 kph so that the maximum wind velocities behind the front can be expected to range up to 160 kph [9]. Similar data has been observed in Arizona haboobs by Idso et al. [11].

The meteorological conditions within the advancing moist, cool air and the surrounding warm air are quite different. Temperature differences of up to 15 degrees Centigrade have been observed within a separation distance of less than 50 meters [9]. Additionally, large differences in percent relative humidity have been recorded For example, data measured by Idso [11] for the Arizona haboob show that the relative humidity internal to the cool, dust-laden air mass was 81 percent compared to 33 percent in the warm, dry external air mass. The refractive index of the atmosphere is a strong function of temperature and water content (i.e., humidity). Rafuse [9] provides a series of calculations supporting the argument that the primary impact on signal attenuation from a dust storm results not from signal attenuation due to scattering and absorption by the dust particulate but from the atmospheric changes in the refractive index and the increased loss in signal power due to water vapor attenuation (which is not typically associated with a dust storm in an arid region). Furthermore, Rafuse states that these impacts are more likely to occur for terrestrial communications links as opposed to satellite communications links. Rafuse concludes that the major cause of fading and median signal level reductions in terrestrial paths traversing dust storms is the significant refractive index changes brought about by the temperature and humidity differentials between the "inside" and "outside" of the dust storm. In addition, significant, small-scale (10 to 20 meters) inhomogeneities in the refractive index that exist inside the storm because of "entrapped" out-side air, coupled with the large excess phase changes, make multipath fading very likely on long terrestrial paths. However, since a satellite/terminal path would only extend a few kilometers through a storm, such a path is less likely to exhibit multipath fading [9].

In conclusion, the signal attenuation due to dust storms for satellite communications links operating in the millimeter wave regime will be small, typically on the order of .1 dB. Terrestrial communications links; however, may exhibit significantly larger signal attenuations due to multi-path fading phenomena resulting from the severe changes in the refractive index throughout the storm region. Additional experiments are needed in this area to increase the accuracy of the dust storm particulate models used, as well as to expand the meteorological database associated with dust storms. The data generated from these experiments will significantly increase the analyst’s ability to adequately quantify the impact of dust storm signal attenuation on communications link performance. With the data currently available, and "after the dust has settled," it does not appear that signal attenuation resulting from operations through dust storms will be a major factor in millimeter wave communications link calculations.

Foliage Attenuation

Of all of the signal propagation effects typically evaluated for communications links operating in the millimeter wave regime, signal attenuation due to foliage is probably the most difficult to accurately quantify. The wide diversity in the types and density of foliage makes the estimate of attenuation highly variable. Most studies performed to date to quantify the impact of signal attenuation due to propagation through foliage have been concerned with horizontal propagation paths (i.e., parallel to the ground) and have only considered lower frequencies than the millimeter wave regime. Typical examples of such studies are found in references [16] through [18], which treat the frequency region below 1250 MHz. In this region, the leaves are small compared to the wavelength and the forest is treated as a homogeneous layer above the Earth. The homogeneity assumption is not acceptable in the millimeter wave regime, where the leaves and the spaces between the leaves are large compared with the signal wavelength.

As one might imagine, the inconsistency in characterizing foliage from one study to another has lead to a great deal of inconsistency in developing empirical models to characterize the limited amount of measured data. For example, Saxton and Lane [19] state that the one-way attenuation resulting from leaf-bearing trees for systems operating in the .1 to 3 GHz frequency range could be characterized by:

$$a\ (\mathrm{dB/m}) = 0.25\ f^{\gamma} \tag{4}$$

where f is the operating frequency in GHz and γ=0.75. LaGrone slightly adjusted the constant and exponent in equation (4) as follows [20]:

$$a\ (\mathrm{dB/m}) = 0.26\ f^{0.77} \tag{5}$$

Perhaps the most pertinent data to this discussion has been generated by Currie, et al., at the Georgia Technology Research Institute (GTRI) [21-23] at discrete frequencies up to 90 GHz. The measurements were performed by radar techniques, using a corner reflector target embedded in the foliage and measuring two-way attenuation. The authors fit the following equation to the data to approximate foliage attenuation per meter of path length:

$$a\ (\mathrm{dB/m}) = 1.102 + 1.48\mathrm{Log}_{10}(f) \tag{6}$$

Finally, the confusion mounts in that there is a school of thought that considers the thickness of the foliage to impact the attenuation; that is, the attenuation per meter is believed to decrease as the distance through the foliage increases. The argument used to explain this peculiar effect is that some of the energy travels above the treetops and is thus unaffected by the trees. McQuate [24] developed the following expression for the attenuation due to foliage as a function of operating frequency, f, and the foliage thickness, d:

$$a\ (\mathrm{dB/m}) = 1.33\ f^{\,0.284} d^{-0.412} \tag{7}$$

The thickness dependence phenomenon is also reported by Flock [25] and Nathanson [26]; albeit with different constants and power coefficients!

Equations (4) through (7) were used to generate the foliage attenuation data shown in table 1 as a function of operating frequency through a foliage thickness of one meter. As shown, the various analytical expressions yield fairly similar results, typically within 1 dB of each other. Also shown in table 1 are the measured experimental data from the GTRI experiments reported in [21,22] for operating frequencies of 16.2 and 35 GHz. These data are within several tenths of a dB from the data generated from the empirically derived expression in column D of table 1.

Finally, the most complete experiments to date in the 44.5/20 GHz operating regime were conducted by Massachusetts Institute of Technology Lincoln Laboratory (MIT/LL) [27,28]. In [27], MIT/LL reported the results of a series of experiments in which a United States Army (USA) SCOTT transportable EHF communications terminal was used to measure the impact of foliage on signal attenuation at 20 and 44.5 GHz. In these experiments, measurements of the received signal were made both before and after the tree (a swamp maple tree) was interposed in the transmission path. The tree was gradually trimmed away until the attenuation was reduced to 3 dB. The experiment was performed on the Lincoln Laboratory Antenna Test Range and was completed as rapidly as possible, lasting about four hours on 17

* Originally published in J. of Space Comm., Vol. 11, no. 1, pp. 13-20, July 1993

August 1981, so that the leaves had little chance to dry out. The averaged results of these experiments are also shown in column F of table 1 at operating frequencies of 20 and 44.5 GHz.

In [28], MIT/LL reported the results of a series of experiments carried out to characterize the attenuation due to foliage of a SATCOM signal operating at a frequency of 20 GHz. Two experimental setups were used: (1) a transportable SATCOM terminal which received a frequency-hopped downlink signal from a satellite at geosynchronous altitude, and (2) a terrestrial setup composed of a transmitter operating at 20 GHz in the continuous wave (CW) mode with a compatible receiver. The conclusions made were as follows:

1. Foliated trees are essentially opaque to 20 GHz signals from a communications standpoint (i.e., it is not practical to design a system with sufficient link margin to overcome the attenuation).

2. The "RF edge" of a tree is roughly equivalent to its "visible edge." Thus, one can expect to receive signals in the gaps between trees if the geometry is correct.

3. Unfoliated trees can also significantly attenuate 20 GHz signals; however, they are not opaque to communications. Diffraction, scattering, and multipath all play a part in the signal loss phenomenon, giving rise to attenuation levels which are highly variable and dependent upon the exact geometry of the received antenna and the tree(s).

Based upon the previous discussion and the data presented, it is clear that foliage attenuation is difficult to accurately quantify. However, it is also clear that foliage attenuation can severely degrade, and potentially preclude, satellite communications in the millimeter regime regardless of the available link margin. The signal attenuation was shown to be on the order of 3 to 4 dB per <u>meter</u> of foliage in the 44/20 GHz operating regime, but significantly less through "holes" in the path through the foliage. The conclusion to be drawn from this discussion is that communications through any length of foliage should be discouraged, and that it is predominantly through operational adjustments and procedures (e.g., operating through holes in the foliage), and not link margin design, that communications through foliage can be assured with any degree of confidence.

SUMMARY AND CONCLUSIONS

The purpose of this paper was to discuss the phenomena associated with signal attenuation through dust and foliage and to quantify the impact of these environments on signal propagation. The models used to characterize dust and foliage attenuation were described and available experimental data was presented to support the discussion.

It was shown that the attenuation due to sand and/or dust storms in the frequency range investigated is small, with link degradations on the order of a tenth of a dB. Terrestrial communications links; however, could exhibit significantly larger signal attenuations due to multi-path fading phenomena resulting from the severe changes in the refractive index throughout the storm region. Additional experiments are needed in the area of dust attenuation to increase the accuracy of the dust storm particulate models used, as well as to expand the meteorological database associated with dust storms, in order to adequately quantify the impact of dust storm signal attenuation on communications link performance.

It was clear based upon the data presented that foliage attenuation is difficult to accurately quantify. However, it was also clear that foliage attenuation can severely degrade, and potentially preclude, satellite communications in the millimeter wave regime regardless of the available link margin. The impact of foliage on millimeter wave communications links was shown to be on the order of 3 to 4 dB per <u>meter</u> of foliage.

The overall conclusions drawn in this study are: (1) satellite communications in the millimeter wave regime through a dust laden communications path can be assured via adequate link design, and (2) communications through any length of foliage should be discouraged and that it is predominantly through operational adjustments and procedures, and not link design, that communications with any degree of confidence can be assured in a foliage environment.

* Originally published in J. of Space Comm., Vol. 11, no. 1, pp. 13-20, July 1993

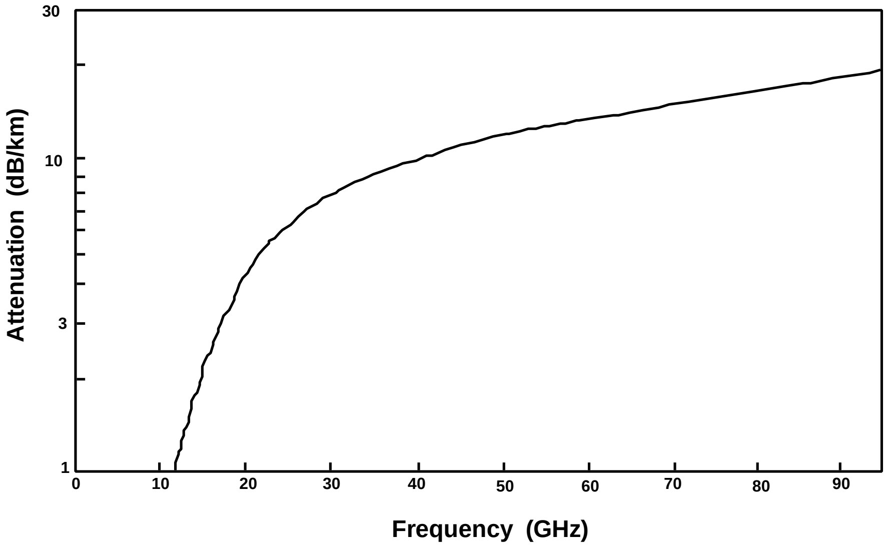

Figure 1. Signal Attenuation Due to Sand as a Function of Operating Frequency

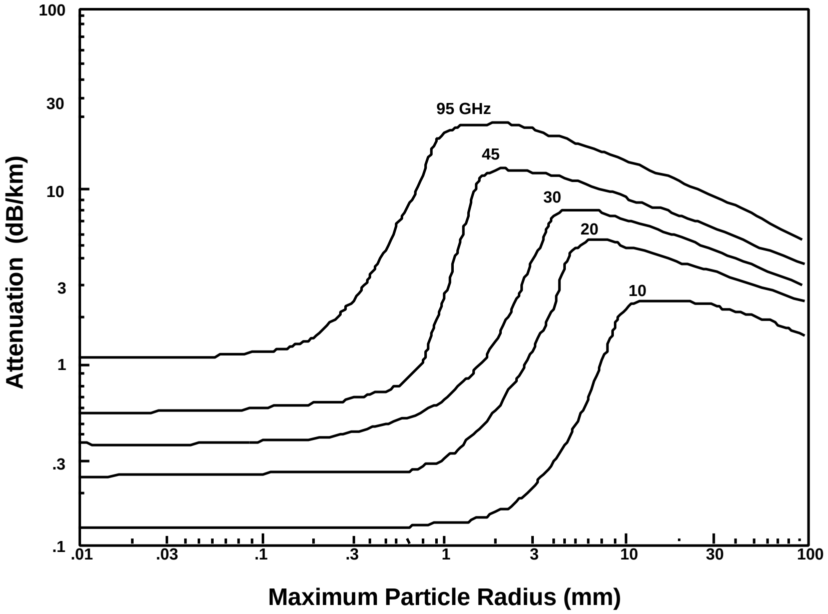

Figure 2. Signal Attenuation Due to Sand as a Function of Maximum Particle Radius and Parameterized by Operating Frequency

* Originally published in J. of Space Comm., Vol. 11, no. 1, pp. 13-20, July 1993

Table 1. Foliage Attenuation Data, a, in dB per Meter of Path Length, for a One-Meter Foliage Thickness

f (GHz)	A	B	C	D	E	F
10	1.41	1.53	2.56	2.54		
16.2	2.02	2.22	2.93	2.84	2.5	
20	3.36	2.61	3.11	2.97		3.4
35	3.59	4.01	3.65	3.33	3.7	
44.5	4.31	4.83	3.91	3.48		3.9
50	4.70	5.29	4.04	3.55		

Key:

A: $a = .25\, f^{.75}$

B: $a = .26\, f^{.77}$

C: $a = 1.33\, f^{0.284} d^{-.412}$

D: $a = 1.102 + 1.44 \mathrm{Log}_{10}(f)$

E: GTRI data (Ref [21,22])

F: MIT/LL data (Ref [27])

* Originally published in J. of Space Comm., Vol. 11, no. 1, pp. 13-20, July 1993

LIST OF REFERENCES

1. Crane, R. K., 1971, "Propagation Phenomenon Affecting Satellite Communications Systems Operating in the Centimeter and Millimeter Wavelength Bands," *Proc. IEEE*, Vol. 59, pp. 173-188.

2. Crane, R. K., September 1980, "Prediction of Attenuation by Rain," *IEEE Trans. on Comm.*, Vol. COM-28, No. 9, pp. 1717-1733.

3. Crane, R. K., 1977, "Prediction of the Effects of Rain on Satellite Communications Systems," *Proc. IEEE*, Vol. 65, pp. 456-474.

4. Tattelman, P. and K. G. Scharr, September 1983, "A Model for Estimating One-Minute Rainfall Rates," *J. of Climate and Appl. Meteor.*, Vol. 22, No. 9, pp. 1575-1580.

5. Tattelman, P., 1989, "New Rain Rate Analyses to Asses Rain Attenuation on Satellite EHF Communications," *Int. J. of Sat. Comm.*, Vol. 7, pp. 23-25.

6. Tattelman, P. and D. D. Grantham, 1985, "A Review of Models for Estimating 1-min Rainfall Rates for Microwave Attenuation Calculations," *IEEE Trans. Commun.*, Vol. COM-33, No. 4, pp. 361-372.

7. Maciel L. R. and M. S. Assis, 1990, "Tropical Rainfall Drop-Size Distribution," *Int. J. of Sat. Comm.*, Vol. 8, pp. 181-186.

8. Manning R. M., 1990, "A Unified Statistical Rain-Attenuation Model for Communications Link Fade Predictions and Optimal Stochastic Fade Control Design Using a Location-Dependent Rain-Statistics Database," *Int. J. of Sat. Comm.*, Vol. 8, pp. 11-30.

9. "Effects of Sandstorms and Explosion-Generated Atmospheric Dust on Radio Propagation," R. P. Rafuse, Technical Report Number DCA-16, Massachusetts Institute of Technology Lincoln Laboratory, 10 November 1981.

10. T. J. Lawson, 1971, "Haboob Structure at Khartoum," J. of Weather, Vol. 26, pp. 105-112.

11. S. G. Idso, et al., October 1972, "An American Haboob," Bull. Amer. Meteor. Soc., Vol. 53, pp. 930-935.

12. R. A. Bagnold, 1941, The Physics of Blown Sand and Desert Dunes, Methuen & Co., Ltd, London, England.

13. Altshuler, E. E., December 1983, "The Effects of a Low-Altitude Nuclear Burst on Millimeter Wave Propagation," *Rome Air Development Center In-House Report*, RADC-TR-83-286.

14. Ellis, J. B., August 1987, "DUCLATORS: A Model for Dust Cloud Attenuation of Radio Signals," MITRE Technical Report, MTR 10291.

15. Mie, G., 1908, "A Contribution to the Optics of Turbid Media, Especially Colloidal Metallic Suspensions," *Ann. Phys.*, Vol. 25, pp. 377-445.

16. Tamir, T., July 1977, "Radio Wave Propagation Along Mixed Paths in Forest Environments," *Trans. App. Phys.*, Vol. 25, pp. 471-477.

17. Horwitz, G. M., May 1979, "Optimization of Radio Tracking Frequencies," *Trans. App. Phys.*, Vol. 27, pp. 393-398.

18. Tewari, R. K., S. Swarup, and M. N. Roy, April 1990, "Radio Wave Propagation Through Rain Forests of India," *IEEE Trans. on Ant. and Prop.*, Vol. 38, No. 4, pp. 433-449.

19. Saxton, J. A., May 1955, "VHF and UHF Reception, Effects of Tree and Other Obstacles," *Wireless World*, pp. 229-232.

20. Lagrone, A. H., June 1960, "Forecasting Television Service Fields," *Proc. IRE*, Vol. 48, pp. 1009-1015.

21. Currie, N. C., F. B. Dyer, and E. E. Martin, October 1976, "Millimeter Foliage Penetration Measurements," Abstracts of the IEEE AP-Society Symposium, pp. 575-577.

22. Currie, N. C., E. E. Martin, and F. B. Dyer, December 1975, "Radar Foliage Penetration at Millimeter Wavelengths," Technical Report No. 4, Contract DAAA 25-73-C-0256, Engineering Experiment Station, Georgia Institute of Technology.

23. Currie, N. C., and C. E. Brown, 1987, Principles and Applications of Millimeter-Wave Radar, Artech House, Norwood, Massachusetts.

24. P. L. McQuate, J. M. Harman, and A. T. Barsis, March 1968, "Tabulation of Propagation Data Over Irregular Terrain in the 230 to 9200 MHz Frequency Range.

Part 1: Gunbarrel Hill Receiver Site," Technical Report No. ERL 65-ITS 58-1, Institute for Telecommunications Science, Boulder, Colorado.

25. Flock, W. L., December 1987, "Propagation Effects on Satellite Systems at Frequencies Below 10 GHz," NASA Reference Publication 1108(02).

26. Nathanson, F. E., 1991, Radar Design Principles, 2nd edition, McGraw-Hill, Inc., New York, New York.

27. Simmons, A. J., September 1981, *EHF Propagation Through Foliage*, Lincoln Laboratory Technical Report TR-594.

28. Greenberg, W. L., J. F. Siemasko, and L. N. Weiner, October 1989, "Foliage Attenuation Measurements Near 21 GHz," Lincoln Laboratory Internal Paper, Sponsored by the Dept. of the Air Force under contract No. AF19628-90-C-002.