# The Effects of the Atmosphere and Weather on the Performance of a mm-Wave Communication Link

Predict the effects of moisture and atmospheric gases on a signal path

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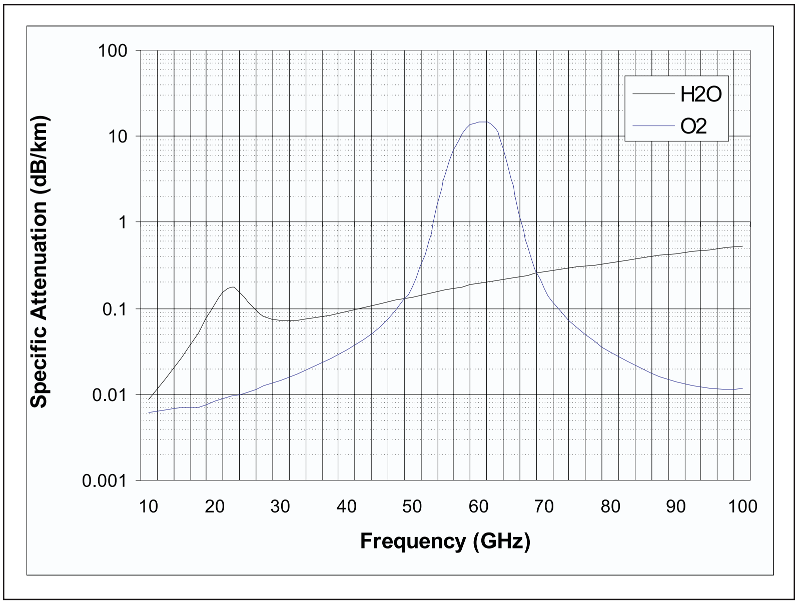
The Friis free-space propagation equation is commonly used to determine the attenuation of a signal due to the spreading of the electromagnetic wave. For frequencies between 500 MHz and 10 GHz this model provides a good estimate of the propagation loss. However, for frequencies above 10 GHz, there are several additional factors that affect propagation including (a) absorption due to gases or water vapor and (b) attenuation due to mist, fog, or rainfall. An understanding of these is important so that sufficient design margin can be allocated to ensure the link's integrity under changing weather and atmospheric conditions.



▲ **Figure 1. The Specific Attenuation due to water and oxygen calculated at a pressure of 1013 millibars, a temperature of 300 K, and water vapor content of 7.5 grams per cubic meter.**

This article presents a methods for calculating the losses due to molecular resonance and various types of precipitation. For the dominant contributors, $O_2$ and $H_2O$ at millimeter wave, an empirical model is presented to estimate the absorption.

## Transmission Losses

The total transmission loss for a millimeter link is given by Freeman [1] as:

$$\mathit{Attenuation}\ (\mathrm{dB}) = 92.45 + 20\cdot\log_{10}(f_{\mathrm{GHz}}) + 20\cdot\log10(D_{\mathrm{km}}) + a + b + c + d + e$$

where,

a = excess attenuation (dB) due to water vapor
b = excess attenuation (dB) due to mist or fog
c = excess attenuation (dB) due to oxygen ($O_2$)
d = sum of absorption losses (dB) due to other gases
e = excess attenuation (dB) due to rainfall

There are many atmospheric gases and pollutants that have absorption lines in the millimeter bands (such as $SO_2$, $NO_2$, $O_2$, $H_2O$, and $N_2O$), however, the absorption is primarily due to water vapor and oxygen [2]. Due to their low density, the absorption loss due to other gases is negligible (d~0).

### Molecular resonance of $H_2O$

Water vapor is a polar molecule with an electric dipole resulting in two absorption lines in the microwave region at 22.235 GHz and 183.31 GHz. Although there are additional absorption lines in the far-infrared region above 300 GHz these lines are negligible below 100 GHz. For frequencies below 100 GHz, the total water absorption coefficient can be expressed as [3] (in dB/km):

$$\kappa_{H_2O} = 2f^2 p_v \left(\frac{300}{T}\right)^{1.5} \gamma_1 \left[\left(\frac{300}{T}\right) e^{\frac{-644}{T}} G + 1.2\times 10^{-6}\right]$$

where,

$$G = \frac{1}{\left(494.4 - f^2\right)^2 + 4f^2\gamma_1^{\,2}}$$

$$\gamma_1 = \left(\frac{P}{1013}\right)\left(\frac{300}{T}\right)^{0.626}\left(1 + 0.018\frac{p_v T}{P}\right)$$

For the previous equation, $f$ is frequency in GHz, $T$ is temperature in kelvins, $p_v$ is the water vapor content in grams per cubic meter, and  is the atmospheric pressure in millibars. The amount of water vapor in the atmosphere at sea level can vary from 0.001 grams per cubic meter in a cold, dry climate to as much as 30 grams per cubic meter in hot, humid climates. An average water vapor [4] content is 7.72 grams per cubic meter corresponding to mid-latitudes, around 45° N.

### Molecular resonance of $O_2$

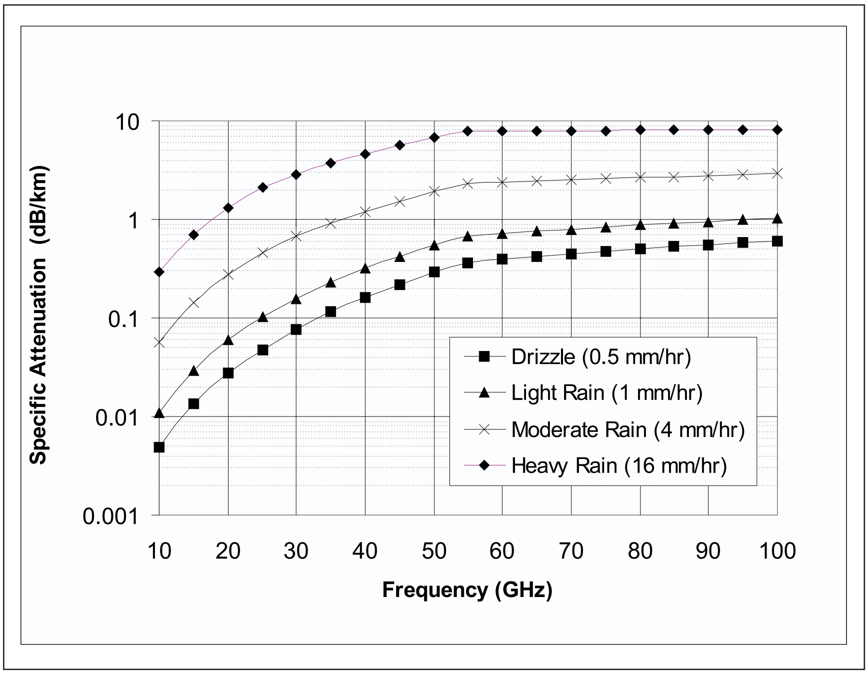
Unlike water vapor, the oxygen molecule has a permanent magnetic moment that produces a family of absorption lines that spread out between 50 and 70 GHz [5]. In the lower earth atmosphere, these blend into a broad absorption band around 60 GHz. There is an additional absorption line at 118.75 GHz. For frequencies lower than 45 GHz, an adequate approximation can be found by replacing the family of absorption lines with a single line at 60 GHz and neglecting the effects of the 118.75 absorption line yielding [6] (in dB/km):

$$\kappa_{O_2} = 0.011 f^2 \left(\frac{P}{1013}\right)\left(\frac{300}{T}\right)^2 \gamma \left(\frac{1}{\left(f - f_0\right)^2 + \gamma^2} + \frac{1}{f^2 + \gamma^2}\right)$$

where,

$$\gamma = \gamma_0 \left(\frac{P}{1013}\right)\left(\frac{300}{T}\right)^{0.85}$$

$$\gamma_0 = \begin{cases} 0.59 & P \geq 333\ \text{mbar} \\ 0.59\left[1 + 0.0031(333 - P)\right] & 25\ \text{mbar} \geq P \geq 333\ \text{mbar} \\ 1.18 & P \leq 25\ \text{mbar} \end{cases}$$



▲ **Figure 2. Specific Attenuation Versus Frequency for Various Rainfall Rates including: (a) Drizzle, (b) Light Rain, (c) Moderate Rain, and (d) Heavy Rain.**

(In the above expression, frequency is expressed in gigahertz and the single absorption line, $f_0$, is at 60 GHz.)

### Precipitation

At frequencies above 10 GHz, the effects of precipitation can be significant. The rainfall rate is commonly expressed in millimeters per hour and normally relates to a percentage of time that the specified rate is not exceeded. For example, in the mid-Atlantic region of the United States, peak values of 108 millimeters per hour may be expected for very short periods (less than 0.001 percent or 5.26 minutes per year [7]), however, over 95 percent of the year there is no rainfall. Therefore, link margin can be related directly to link reliability (or percent outage) based on the individual rainfall rate patterns.

The attenuation due to rainfall is dependent on the size and distribution of the water droplets. Models are generally created empirically based on nominal sizes and distributions. The attenuation rate (dB/km) due to a specified rainfall rate can be approximated based as [8]:

$$\kappa_{rain} = aR^b$$

where,

$$a = \begin{cases} 4.21 \times 10^{-5} f^{2.42} & 2.9\text{ GHz} \le f \le 54\text{ GHz} \\ 4.09 \times 10^{-2} f^{0.669} & 54\text{ GHz} \le f \le 180\text{ GHz} \end{cases}$$

$$a = \begin{cases} 1.41 f^{-0.0779} & 8.5\text{ GHz} \le f \le 25\text{ GHz} \\ 2.63 f^{-0.272} & 25\text{ GHz} \le f \le 164\text{ GHz} \end{cases}$$

where $R$ is the rainfall rate in millimeters per hour. Since snowfall rates are generally less than rainfall rates, propagation is less affected by snowfall. For attenuation due to ice particles in the atmosphere (such as with hail and snow) the attenuation at 0° C is given [9] as:

$$\kappa_{snow} = \frac{0.00349R^{1.6}}{\lambda^4} + \frac{0.00224R}{\lambda} \qquad \text{dB/km}$$

where $R$ is the snowfall rate in millimeters per hour of melted water content and $\lambda$ is the wavelength in centimeters. For clouds and fog, the attenuation rate at 180 C is given as:

$$\kappa_{fog} = \frac{727.1d^{1.43}}{\lambda^2} \qquad \text{dB/km}$$

where $d$ is the optical visibility in feet and $\lambda$ is the wavelength in centimeters. (For both snow and fog, the attenuation loss is a function of temperature and can vary by a factor of 3 between 0° and 40° C [10].)

## Summary

Propagation of radio waves above 10 GHz through the atmosphere is greatly influenced by effects of molecular resonance and precipitation. Empirical models have been presented for calculating the attenuation due to oxygen and water vapor. Further, approximation for calculating the losses due to various form of precipitation including rain, snow, and fog were presented. ■

## References

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3. Ulaby, Moore and Fung, pp. 270-271.

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## Author Information

Thomas L. Frey, Jr. received a Bachelor of Science in Electrical Engineering from Texas A&M University. He earned his Master of Science and Ph.D. in Electrical Engineering from the University of Texas at Arlington. He is currently a systems engineer for Lockheed Martin Tactical Aircraft Systems in Fort Worth, Texas. Dr. Frey is a registered Professional Engineer and a Senior Member of the IEEE. His e-mail address is thomas.l.frey@lmco.com.

Tropospheric weather conditions, "conventional" weather occuring in the lower 10 km of the atmosphere, can also cause losses in signals propagating between satellite and ground stations. Water vapour is particularly damaging to signals above about 2 GHz, causing absorption of signals which becomes greater as the frequency increases. K-band signals (10-20 GHz) are particularly susceptible, and precipitation in the vicinity of satellite ground stations can cause total loss of signal.Â  There are a number of strategies that may be taken to minimise the effects of space weather on satellite communication systems. As far as the satellites themselves are concerned, the first step should occur in the design phase prior to launch. References 1. T. L. Frey, Jr., The Effects of the Atmosphere and Weather on the Performance of a mm-Wave Communication Link, Applied Microwave and Wireless Magazine, February, 1999, pg. 76-80. 2. R. L. Freeman, Telecommunication Transmission Handbook, Third Edition, John Wiley & Sons Inc., 1991, pg. 494. 3. A. M. Alevy, Antenna Fundamentals for Microcellular Applications, Base Station/Earth Station Magazine, January/February 1999, pg.