W/V-Band Propagation Modeling

Nolan Rebernick

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W/V-Band Propagation Modeling

by

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B.E., Electrical Engineering, University of Minnesota, 2022

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Abstract

Enhancing the accuracy of atmospheric loss modeling holds the potential to significantly refine estimations of received power, thereby enhancing the overall quality of satellite communication links. This study aims to pioneer and validate an innovative modeling framework to reliably predict atmospheric attenuation along satellite-to-ground propagation paths, particularly focusing on portions of the W-band (81-86 GHz) and V-band (71-76 GHz). By leveraging meteorological data, this approach will encompass various weather scenarios, including clear skies, cloud cover, and diverse forms of precipitation. Utilizing the generated time domain data, the research aims to construct complementary cumulative distribution functions, enabling the analysis of satellite links with heightened precision and reliability. The hypothesis of this research is that such a model can provide reasonable statistics for an annual period, despite (1) radiosonde data only being available twice per day, (2) the uncertainty of cloud formation, and (3) the limitation of only having point-measurements of precipitation events (as opposed to distributed measurements along the propagation path). This model is validated using radiometer and beacon measurements obtained in collaboration with the Air Force Research Laboratory, Space Vehicles Directorate.
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1 INTRODUCTION

The goal of this research is to develop and validate a novel modeling approach to predict atmospheric attenuation for a satellite-to-ground propagation path for W-band (particularly 81-86 GHz) and V-band (particularly 71-76 GHz) that can be used to model fade statistics for satellite communications links. The model uses meteorological data (i.e., temperature, pressure, and relative humidity), disdrometer data (for precipitation), and radiosonde data (which provides information on the vertical profile of the atmosphere). The model output is time-domain estimates of path attenuation due to gaseous constituents (primarily oxygen and water vapor), clouds (condensed water droplets and ice), and precipitation (liquid and frozen). Time domain data are used to generate a complementary cumulative distribution function (CCDF, also referred to as an exceedance plot) that can be used to design and analyze the satellite link (particularly, the power and aperture needed to meet availability requirements). The hypothesis of this research is that such a model can provide reasonable statistics (i.e., CCDF’s) for an annual period, despite (1) radiosonde data only being available twice per day, (2) the uncertainty of cloud formation, and (3) the limitation of only having point-measurements of precipitation events (as opposed to distributed measurements along the propagation path). This novel modeling approach does not require radiometer data or beacon data to reasonably estimate annual statistics for a given ground site location. This model is validated using radiometer and beacon measurements obtained in collaboration with the Air Force Research Laboratory, Space Vehicles Directorate.

1.1 Background
The world has come to rely on satellite communications at all levels. New sensor systems require higher capacity wireless communication links to enable timely data exploitation. Currently, much of the high-data-rate satellite communication systems rely on K-band (~20 GHz) and Ka-band (30 – 40 GHz) spectrum. Satellite communication at these frequency bands is subject to degradation from interference – both intentional and unintentional.

Government, military, and commercial use of K-band (and higher) was made possible in large part by the NASA Advanced Communications Technology Satellite (ACTS), a mission that was launched in September 1993 [1-6]. ACTS was the first all-digital communications satellite. It carried a propagation experiment package with 20.2 GHz and 27.5 GHz beacons. Propagation experiments were designed to acquire attenuation statistics for use in propagation model development and verification. Data was collected at seven sites specifically selected to cover a broad range of meteorological zones and elevation angles. Each site included meteorology instrumentation to measure rain-rate, temperature, humidity, pressure, wind speed and wind direction. ACTS served as a testbed for NASA Glenn researchers for more than 6 years. Characterizing signal propagation and atmospheric effects at 20.2 GHz and 27.5 GHz was critical for commercial development of next generation satellites using K-band and Ka-band.

Airbus and the European Space Agency (ESA) designed and built AlphaSat, which was launched in July 2013 [7]. AlphaSat carried four technology demonstration and science payloads, one of which was the Aldo Paraboni Q/V Communications and Propagation Experiment. The goal of the Q/V (i.e., 38 GHz / 48 GHz) experiment was to collect data to enable commercial expansion into these new frequencies, resulting in more bandwidth availability and less need for large user terminals. This is analogous to the NASA ACTS
mission. Figure 1.1 presents the specific attenuation for a standard atmosphere at sea level computed using the International Telecommunications Union (ITU) model [8]. Given the strong atmospheric attenuation at 60 GHz that results from oxygen interaction, the next higher frequency atmospheric window for electromagnetic signals is about 70-90 GHz. The ITU Radio Communications Sector has designated a portion (i.e., 71-76 GHz) of the V-band for satellite communication downlinks, and a portion (i.e., 81-86 GHz) of the W-band for satellite communication uplinks [9]. This includes both fixed and mobile satellite service. Thus, there is 10 GHz of spectrum reserved for satellite communications that is currently unused.

![Specific Attenuation for a Standard Atmosphere at Sea Level](image)

**Figure 1.1: Specific Attenuation for a Standard Atmosphere at Sea Level**

Here, “attenuation” refers to the loss of signal power as the signal propagates through the medium, which is in general moist atmosphere, which may or may not include frozen particulates, and may or may not include precipitation. This is also commonly referred to as the signal “extinction” or “loss” in reference texts. At these frequencies, scattering is not
significant. Therefore, attenuation is primarily due to absorption. If frozen particulates are present, there will likely be signal loss due to de-polarization, e.g., loss of co-polarization signal strength to cross-polarization – from pure right-hand circular to partial right-hand circular plus left-hand circular. So, “attenuation” can be used interchangeably with “loss”, “absorption”, and “extinction” – and typically has units of dB. The term “specific attenuation” refers to attenuation per unit length. The atmosphere causes signal attenuation. Thus, we say that the atmosphere has “opacity”. Atmospheric opacity is a function of wavelength, temperature, dry air pressure, water vapor pressure, clouds, precipitation, and propagation path length.

Before future satellite communication systems can utilize these spectrum bands, fundamental research must be conducted to statistically characterize signal propagation and atmospheric effects, as was accomplished by the NASA ACTS mission for K-band and Ka-band, and as currently underway by the ESA AlphaSat mission for 38 GHz / 48 GHz. It is necessary to develop and validate modeling tools to predict path attenuation based on limited data, such as point-measurements of temperature, pressure, humidity, rain-rate, or spatially broad measurements from weather radars. Signal propagation at these frequencies is strongly affected by weather, and measured data is expected to vary statistically as does the weather. Rainfall and attenuation models used to determine ground-to-satellite radio frequency (RF) link availability and margins are based on cumulative distribution functions (CDF’s).

The Air Force Research Laboratory (AFRL) contracted Northrop Grumman Aerospace Systems (NGAS) to develop, test, and deliver a dual-tone, W/V-band beacon payload that is hosted at geostationary earth orbit (GEO). The beacon payload will be operated for ~5 years, allowing AFRL to collect propagation data at these frequencies that can be used to validate
models and enable design of future operational military satellite communication systems. This effort is known as W/V-band Satellite Communications Experiment - Beacon (WSCE-B). Figure 1.2 provides an illustration of the WSCE-B concept of operations. The beacon payload is controlled via the Host Spacecraft Operations Center. Science data is collected at multiple ground terminals located in the field-of-view of the beacon payload. Data is relayed to the Experiment Operations Center for analysis and archiving. Data from the WSCE-B experiment for the ground receiver located at Albuquerque, NM were made available to the University of New Mexico to validate the model developed during this research project.

![Figure 1.2: Overview of WSCE Concept of Operations](image)

### 1.2 Overview

This work presents the development of attenuation modeling due to weather events for satellite-to-ground communication. The experiment setup and the sensors utilized are detailed to provide insight into the methodology employed alongside a comprehensive description of data processing of measurements from the experiment and its sensors. Results are presented,
offering a comparison between model estimates and measured data, thereby validating the effectiveness of the developed model. Finally, conclusions are drawn based on the findings, and recommendations are provided for further research or practical applications.

2 THEORY

The foundation of modern satellite communication systems relies on the ability to accurately predict and model the propagation of electromagnetic signals through the Earth's atmosphere. This is crucial for ensuring the reliability and efficiency of satellite-to-ground communication links. In this section, we will delve into the theoretical explanation of various topics essential for the comprehensive analysis of such communication systems. Topics include link budgets, atmospheric effects, data measurements, and data processing.

2.1 Link Budget Model

Wireless communications encompass various methods of transmitting information between systems without direct physical connections. While multiple techniques exist, radio and microwave signals have emerged as prevalent modes of wireless communication. The analysis of such systems, such as the one shown in Figure 2.1, often involves interpreting data through frameworks like the Friis transmission equation and link budgets. This section will explore the concepts behind these analytical tools and elucidate their practical applications in the work of researchers and engineers.
2.1.1 Friis Transmission Equation

The Friis Transmission equation is used to calculate the power received by an antenna in a communication link and is given by,

\[
P_r = P_t G_t G_r \frac{\lambda^2}{(4\pi R)^2}
\]  

(1)

where \( P_r \) is the power received and \( P_t \) is the power transmitted both in watts. \( G_t \) and \( G_r \) are antenna gains for the transmit antenna and receive antenna respectively. \( R \) is the distance between the transmit and receive antennas. \( \lambda \) is the wavelength of the frequency of the link. This equation can be manipulated to calculate transmitted power as well. Free space path loss, also known as spreading loss, is represented by the inverse of the squared term \([11]\),

\[
L_{FS} = \frac{(4\pi R)^2}{\lambda^2}
\]  

(2)

and can also be represented in decibels (dB) as

\[
L_{FS} = 20 \log_{10} \left( \frac{4\pi R}{\lambda} \right)
\]  

(3)

To achieve a more complete transmission equation, we consider polarization loss factor (PLF), which is shown as

\[
PLF = |\hat{p}_w \cdot \hat{p}_a|^2 = |\cos \psi_p|^2
\]  

(4)
where $\hat{\rho}_w$ and $\hat{\rho}_a$ are unit vectors for the transmitted wave and the receiver antenna, respectively. The angle between the two vectors is given by $\psi_p$. PLF is a measurement of how well the transmit and received antennas are pointed. For example, if the antennas are perfectly pointed ($\psi_p = 0$) PLF will equal 1 or 0 dB having no effect on the transmission equation [10]. The updated equation is shown as

$$P_r = P_t G_t G_r \frac{\lambda^2}{(4\pi R)^2} |\cos \psi_p|^2 \tag{5}$$

There are many other forms of losses we can add to the transmission equation, however it is much more convenient to represent these losses in a link budget versus accounting for them in the transmission equation.

### 2.1.2 The Link Budget

For satellite communication links, it is vital that a link budget is created for that specific link. These link budgets account for all gains and losses in signal transmission and can be used for estimating received signal power. Common parameters that can be found in link budgets are antenna gain, transmission line loss (insertion loss), and path loss. These parameters are used in combination with the transmit power to estimate the received power. Gains and losses are represented as decibels (dB) and powers are represented as milliwatt decibels (dBm) in the link budget. Table 2.1 shows a generalized link budget [11].
Table 2.1: Generalized Link Budget for Satellite Communications

<table>
<thead>
<tr>
<th>Component</th>
<th>Symbol</th>
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</thead>
<tbody>
<tr>
<td>Transmit Power</td>
<td>$P_t$</td>
</tr>
<tr>
<td>Transmit antenna line loss</td>
<td>$(-) L_t$</td>
</tr>
<tr>
<td>Transmit antenna gain</td>
<td>$G_t$</td>
</tr>
<tr>
<td>Path loss</td>
<td>$(-) L_{FS}$</td>
</tr>
<tr>
<td>Atmosphere attenuation</td>
<td>$(-) L_{atm}$</td>
</tr>
<tr>
<td>Receive antenna Gain</td>
<td>$G_r$</td>
</tr>
<tr>
<td>Receive antenna line loss</td>
<td>$(-) L_r$</td>
</tr>
<tr>
<td>Polarization loss factor</td>
<td>$(-) PLF$</td>
</tr>
<tr>
<td>Receive power loss</td>
<td>$P_r$</td>
</tr>
</tbody>
</table>

To arrive at received power loss, all gains and losses must be added together along with the transmitted power. Signals can be added since they are represented logarithmically:

$$P_r = P_t - L_t + G_t - L_{FS} - L_{atm} + G_r - L_r - PLF$$

(6)

Following the calculation of received power loss, a comparison can be made with the anticipated noise power, enabling the determination of the signal-to-noise ratio (SNR). In characterizing wireless communication links, the carrier-to-noise ratio (CNR) is frequently preferred over SNR. Regardless, they are important metrics for a satellite link budget. Energy-per-bit to noise power spectral density ratio can be derived from either the SNR or CNR, which can be used to predict the probability of bit error for a digital communication link. Improved modeling of atmospheric losses will result in better estimates of the received power and therefore performance of the communications link.

It can be seen in this equation why link budgets are so useful in satellite communications. The ability to easily understand and track the impact of components or effects on a transmitted signal is essential for optimizing communication system performance and ensuring reliable signal reception.
2.2 Modeling Atmospheric Propagation Effects

In this section, we delve into the intricate modeling of atmospheric propagation effects, offering a comprehensive exploration of the various factors contributing to attenuation. These effects include attenuation due to gases, clouds, and precipitation. The end of the section will touch on the necessary calculations to calculate signal path through each of these weather events.

2.2.1 Wave Propagation

The oscillation of a time varying magnetic and a time varying electric field that are normal to each other will result in the propagation of an electromagnetic (EM) wave. The wave propagates in the direction of the cross product of the electric and magnetic field and is known as the Poynting vector. Waves propagate though different types of media which can be classified as lossless or lossy media. The effect of lossy media is known as attenuation and corresponds to power loss [12]. A plane wave though lossy media is given by:

\[ E(z) = E_0 \exp(-\gamma z) \]  

(7)

where \( z \) is the direction of propagation and \( \gamma \) is the propagation constant,

\[ \gamma = \alpha + j\beta \]  

(8)

\( \alpha \) is the absorption constant, and \( \beta \) is the phase constant both of which are dependent on the material that the plane wave is propagating though. The power intensity (flux) for a plane wave is given by

\[ S(z) = S_0 \exp(-\kappa_e z) \]  

(9)

where \( \kappa_e \) is the extinction coefficient and is given by sum of the absorption (\( \kappa_a \)) and scattering (\( \kappa_s \)) coefficients. For propagation of a wave in the frequency range 70-90 GHz, the scattering
coefficient can be ignored during clear day atmosphere conditions, however this may not be the case for other atmospheric conditions. With this assumption, the absorption coefficient is shown as:

$$\kappa_a = 2\alpha$$  \hspace{1cm} (10)

and is given as nepers (Np) per unit length. Typically, absorption coefficients are expressed as $dB/km$ and can be converted using the following method:

$$\kappa_a = 1000 \times \log_{10}(e^1) \times \kappa_a$$  \hspace{1cm} (11)

The absorption coefficient is commonly referred to as the specific attenuation. The following section will discuss how to calculate specific attenuation of a gaseous (clear day) atmosphere.

### 2.2.2 Gaseous Attenuation

EM waves interact with the particles in the atmosphere causing attenuation of the propagating wave. The main particles that cause this signal degradation are water vapor and oxygen molecules. These molecules interact with signals differently depending on the EM wave’s frequency. This section will dive into how signal loss is accounted for in a gaseous atmosphere.

#### 2.2.2.1 Standard Atmosphere Model

The standard atmosphere model is a recommendation published by the ITU to give representation to the mean global temperature and pressure at altitudes ranging from sea level to 100 km as shown in Figure 2.2.
The standard atmosphere model is incorporated here purely as a means to explain methods for calculating attenuation, rather than to deviate from the section's primary focus. To maintain clarity and conciseness, we will refrain from delving deeply into the calculation intricacies of these models. For details regarding the determination of temperature and pressure profiles, please refer to reference [13].

2.2.2.2 Specific Attenuation Calculation, Optical Thickness, and Opacity

The International Telecommunication Union (ITU) has synthesized a model to accurately predict the absorption of these gases. ITU-R P.676-13 *Attenuation by atmospheric gases and related effects* offers a method to calculate specific attenuation, which is the unit length measurement of attenuation (dB/km). This model uses temperature, pressure, and humidity along with spectroscopic data for oxygen and water vapor to predict specific attenuation. The
ITU recommendation denotes these spectroscopic data sets as spectral lines and provides 35 lines for water vapor and 44 lines for oxygen.

Following the recommendation provided by the ITU we can calculate the specific gaseous attenuation as follows:

\[
\gamma = \gamma_o + \gamma_w = 0.1820f \left( N''_{\text{oxygen}}(f) + N''_{\text{water vapor}}(f) \right) 
\]

(12)

where \( \gamma_o \) and \( \gamma_w \) are the specific attenuation of oxygen and water vapor respectively and \( f \) is frequency in GHz. \( N''_{\text{oxygen}}(f) \) and \( N''_{\text{water vapor}}(f) \) refer to theimaginary parts of the frequency dependent complex refractivities:

\[
N''_{\text{oxygen}}(f) = \sum_{i=0}^{35} S_i F_i + N''_D(f) 
\]

(13)

\[
N''_{\text{water vapor}}(f) = \sum_{i=0}^{44} S_i F_i 
\]

(14)

\( S_i \) and \( F_i \) refer to the line strength and the line shape respectfully for both oxygen and water vapor spectral lines. These variables change with every line and are summed to calculate their respective refractivites. \( N''_D(f) \) is the dry continuum due to pressure-induced nitrogen absorption and the Debye spectrum, and it is only included with the calculation of the oxygen complex refractivity.

Line strength is given by:

\[
S_{io} = a_1 \times 10^{-7} p \theta^3 \exp[a_2(1 - \theta)]
\]

\[
S_{iw} = b_1 \times 10^{-1} e \theta^{3.5} \exp[b_2(1 - \theta)]
\]

(15)  

(16)

where \( p \) is the dry air pressure and \( e \) is the water vapor partial pressure. The sum of dry air pressure and the water vapor partial pressure is the total barometric pressure. \( \theta = 300/T \) where \( T \) is the temperature in Kelvin.

The line-shape factor is given by:
\[ F_i = \frac{f_i}{f_i} \left[ \frac{\Delta f - \delta(f_i - f)}{(f_i - f)^2 + \Delta f^2} + \frac{\Delta f - \delta(f_i + f)}{(f_i + f)^2 + \Delta f^2} \right] \] (17)

where \( f_i \) is either the oxygen or water vapor line frequency and \( \Delta f \) is the width of the line:

\[ \Delta f_o = a_3 \times 10^{-4} (p\theta^{0.8 - a_4} + 1.1e\theta) \] (18)

\[ \Delta f_w = b_3 \times 10^{-4} (p\theta^{b_4} + b_5e\theta^{b_6}) \] (19)

The correction factor \( \delta \) is only needed for oxygen lines and this is due to interference effects.

\[ \delta = (a_5 + a_6\theta) \times 10^{-4} (p + e)\theta^{0.8} \] (20)

The dry air continuum arises from the non-resonant Debye spectrum of oxygen below 10 GHz and a pressure-induced nitrogen above 100 GHz. It is denoted as:

\[ N_D''(f) = f * p * \theta^2 * \left[ \frac{6.14 + 10^{-5}}{d*(1 + \left( \frac{f}{d} \right)^2)} + \frac{1.4 + 10^{-12}p*\theta^{1.5}}{1 + 1.9*10^{-5}*f^{1.5}} \right] \] (21)

where \( d \) is the width for the Debye spectrum:

\[ d = 5.6 \times 10^{-4} (p + e)\theta^{0.8} \] (22)

The spectroscopic data for oxygen is shown in Table 2.2 and the spectroscopic data for water vapor is shown in Table 2.3 [8].
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Table 2.2: Spectroscopic Data for Oxygen Attenuation
Table 2.3: Spectroscopic Data for Water Vapor Attenuation

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Following the equations outlined in this section we arrive at the following plot shown in Figure 2.3 which shows the specific attenuation across frequencies up to 500 GHz at different altitudes.

![Specific Attenuation vs Frequency for Different Altitudes](image)

**Figure 2.3: Specific Attenuation vs Frequency for Different Altitudes**

As one would expect, as you reach higher and higher altitudes, specific attenuation decreases across all frequencies. This is due to less water vapor and oxygen particles in the atmosphere at those altitudes. This effect can be better seen in Figure 2.4, which shows the specific attenuation as a function of altitude at 72 GHz.
2.2.3 Cloud Modeling

EM waves interact with hydrometers, things such as particles in clouds, rain, and snow, differently than that of oxygen gas and water vapor previously discussed. These interactions between waves and particles depend heavily on the particle’s shape, size, density, and dielectric properties along with the frequency of the wave. This section will dive into the necessary methods to predict clouds and calculate the extinction coefficients necessary to calculate their attenuations.

2.2.3.1 Critical Relative Humidity Curve

Without constant observation of the sky, it can be difficult to know when a cloud is present along the propagating path. For this, the relative humidity from radiosondes can be referenced.
and then applied to what is called a critical relative humidity curve. A critical relative humidity curve is a function of altitude and relative humidity and predicts a cloud when measured relative humidity exceeds the critical value at that specified altitude.

**Figure 2.5: Critical Relative Humidity Curve for Albuquerque, New Mexico**

Figure 2.5 shows a critical relative humidity curve for the Albuquerque New Mexico, which was synthesized by comparing observations to radiosonde data. There are existing models such as the Decker or Solomon models that give critical relative humidity curves, however these are synthesized to fit with global cloud occurrences. This relative humidity curve was created for Albuquerque with observations from Albuquerque and is an attempt to improve cloud predictions for the location. In addition to cloud occurrence, length of propagation path through clouds as well though the critical relative humidity curve can be approximated.
2.2.3.2 Double-Debye Dielectric Model

The double-Debye dielectric model was initially developed with seawater in mind, however by setting the salinity equal to zero it can be used to calculate dielectric constant for pure (distilled) water [14]. This model was chosen over the much simpler single-Debye model because of the frequency range that it can be used with. The single-Debye model can only be used with frequencies up to 50 GHz while the double-Debye model can approximate the dielectric constant of water for frequencies up to 1000 GHz.

For calculation of the dielectric constant \( \varepsilon \) though the use of the double-Debye model, we must calculate the real and imaginary components separately where,

\[
\varepsilon_w = \varepsilon'_w - j\varepsilon''_w \tag{23}
\]

It follows for this model that,

\[
\varepsilon'_w = \varepsilon_{\infty} + \frac{\varepsilon_0 - \varepsilon_1}{1 + (2\pi f \tau_1)^2} + \frac{\varepsilon_0 - \varepsilon_{\infty}}{1 + (2\pi f \tau_2)^2} \tag{24}
\]

\[
\varepsilon''_w = \frac{2\pi f \tau_1 (\varepsilon_0 - \varepsilon_1)}{1 + (2\pi f \tau_1)^2} + \frac{2\pi f \tau_2 (\varepsilon_0 - \varepsilon_{\infty})}{1 + (2\pi f \tau_2)^2} + \frac{\sigma_i}{2\pi \varepsilon_0 f} \tag{25}
\]

where \( \varepsilon_0 \) is the permittivity of free space and \( \sigma_i \) is the ionic conductivity for the water solution.

For this research, we assume that all hydrometers are pure water, \( \sigma_i = 0 \). This causes equation 25 to reduce to

\[
\varepsilon''_w = \frac{2\pi f \tau_1 (\varepsilon_0 - \varepsilon_1)}{1 + (2\pi f \tau_1)^2} + \frac{2\pi f \tau_2 (\varepsilon_0 - \varepsilon_{\infty})}{1 + (2\pi f \tau_2)^2} \tag{26}
\]

If \( f \) is evaluated in GHz, then the relaxation coefficients, \( \tau_1 \) and \( \tau_2 \) must be computed in nanoseconds (ns) to achieve correct unit cancelation. The parameter functions are:

\[
\varepsilon_{w0} = 87.85306 \times \exp - 0.00456992T - a_1 S - a_2 S^2 - a_3 ST \tag{27}
\]

\[
\varepsilon_{w1} = a_4 \exp - a_5 T - a_6 S - a_7 ST \tag{28}
\]

\[
\tau_{w1} = (a_8 + a_9 S) \exp \left( \frac{a_{10}}{T + a_{11}} \right) \text{ns} \tag{29}
\]
\[ \tau_{w2} = (a_{12} + a_{13}S) \exp\left(\frac{a_{14}}{T + a_{15}}\right) \] ns

(30)

\[ \varepsilon_{w\infty} = a_{16} + a_{17}T - a_{18}S \]  

(31)

\[ \sigma_i = \sigma * P * Q \]  

(32)

where,

\[
\sigma = 2.903602 + 8.607 \times 10^{-2}T + 4.738817 \times 10^{-4}T^2 - 2.991 \times 10^{-6}T^3 + 4.3041 \times 10^{-9}T^4
\]  

(33)

\[
P = S^{\frac{37.5109+5.45216S+0.014409S^2}{1004.75+182.2835+5S^2}}
\]  

(34)

\[
Q = 1 + \frac{a_0(T-15)}{T+a_1}
\]  

(35)

\[
\alpha_0 = \frac{6.9431+3.2841S+0.099486S^2}{84.85+69.0425+5S^2}
\]  

(36)

\[
\alpha_1 = 49.843 - 0.2276S + 0.00198S^2
\]  

(37)

The coefficients \(a_1\) through \(a_{18}\) are found in Table 2.4. This semi-empirical model represents the dielectric constant of water within 3% for frequencies between 30 and 100 GHz.

**Table 2.4: Coefficients for Parameter Functions for the Double-Debye Dielectric Model**

<table>
<thead>
<tr>
<th>(a_1)</th>
<th>(a_{10})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.46606917 \times 10^{-2}</td>
<td>0.58366888 \times 10^{3}</td>
</tr>
<tr>
<td>(-0.26087876 \times 10^{-4})</td>
<td>0.12684992 \times 10^{3}</td>
</tr>
<tr>
<td>(-0.63926782 \times 10^{-5})</td>
<td>0.69227972 \times 10^{-4}</td>
</tr>
<tr>
<td>0.63000075 \times 10^{1}</td>
<td>0.38957681 \times 10^{-6}</td>
</tr>
<tr>
<td>0.2624202 \times 10^{-2}</td>
<td>a_{14}</td>
</tr>
<tr>
<td>(-0.42984155 \times 10^{-2})</td>
<td>a_{15}</td>
</tr>
<tr>
<td>0.34414691 \times 10^{-4}</td>
<td>a_{16}</td>
</tr>
<tr>
<td>0.17667420 \times 10^{-3}</td>
<td>a_{17}</td>
</tr>
<tr>
<td>(-0.20491560 \times 10^{-6})</td>
<td>a_{18}</td>
</tr>
</tbody>
</table>

The water permittivity and loss factor can be seen in Figure 2.6.
2.2.3.3 Dielectric of Pure Ice

Now we must consider the dielectric constant of pure ice, denoted as $\varepsilon_i$, which has the same structure as equation 24. $\varepsilon_i'$ is essentially independent of frequency from 10 MHz to 300 GHz, and exhibits a weak temperature dependence as shown:

$$\varepsilon_i' = 3.1884 + (9.1e - 4) \times T$$  \hspace{1cm} (38)

where $T$ is the temperature in °C and must lie between -40°C and 0°C. The loss factor, $\varepsilon_i''$ is given as:

$$\varepsilon_i'' = \frac{\alpha_0}{f} + \beta_0 f$$ \hspace{1cm} (39)

where $\alpha_0$ and $f$ are in GHz and $\beta_0$ is in (GHz)$^{-1}$. The coefficients $\alpha_0$ and $\beta_0$ are given by the expressions:

$$\alpha_0 = (0.00504 + 0.0062\theta) \times exp(-22.1\theta)$$  \hspace{1cm} (40)
\[ \beta_0 = \frac{B_1}{T_K} \frac{\exp(b/T_K)}{[\exp(b/T_K)-1]^2} + B_2 f^2 + \exp[-9.963 + 0.0372(T_K - 273.16)] \]  

(41)

where \( T_K \) is the temperature in kelvin, \( B_1 = 0.0207 \, K/\text{GHz}, B_2 = 1.16 \times 10^{-11} \, \text{GHz}^{-3}, b = 335K, \) and

\[ \theta = \frac{300}{T_K} - 1 \]  

(42)

The frozen water permittivity and loss factor can be seen in Figure 2.7.

**Figure 2.7: Permittivity and Loss Factor against Frequency at 0° C**

### 2.2.3.4 Cloud Specific Attenuation Coefficient

Using the particle dielectric coefficients calculated in the previous section, we can use the Rayleigh approximation to the Mie solution for a single particle to calculate the extinction coefficient (specific attenuation) for a cloud [16]. The Rayleigh approximation is used here because the particles interacting with the wave are assumed to be much smaller than the
wavelength. The full solution to the Mie scattering coefficients is used to calculate the scattering and absorption efficiencies for rain and will be discussed in more detail in coming sections. The specific attenuation for a cloud shown as

$$\kappa_c = \kappa_L m_v$$  \hspace{1cm} (43)

where $\kappa_c$ is the cloud volume extinction coefficient, $\kappa_L$ is the liquid extinction coefficient, and $m_v$ is the water content of the cloud. The liquid extinction coefficient is given by:

$$\kappa_L = \frac{6\pi}{\rho_L \lambda_0} \Im \{ -K \}$$  \hspace{1cm} (44)

$\rho_L$ is the liquid water density. $K$ is a function of the dielectric properties of the water contents of the cloud and is also an approximation to the Mie solution. It is given by the equation:

$$K = \frac{(\varepsilon' - \varepsilon'') - 1}{(\varepsilon' - \varepsilon'') + 2}$$  \hspace{1cm} (45)

Let it be known that $\kappa_L$ is in $\frac{Np}{m} \frac{1}{(g/m^2)}$ and can be converted to $\frac{dB}{m} \frac{1}{(g/m^2)}$. This is shown in the equation below,

$$\kappa_L = 4.3429 \frac{6\pi}{\rho_L \lambda_0} \Im \{ -K \}$$  \hspace{1cm} (46)

$m_v$ is the liquid water content (LVC) of the cloud, which is found by summing the volumes of each of the droplets and multiplying it by the liquid water density,

$$m_v = \rho_L \sum_{i=1}^{N_v} \frac{4\pi r_i^3}{3}$$  \hspace{1cm} (47)

This can be estimated as the mass density of liquid of a cloud by a unit volume of air,

$$m_v = \frac{m}{V}$$  \hspace{1cm} (48)

when substituting $\kappa_L$ and $m_v$ into the equation for $\kappa_c$ and solving for the summations, we arrive at

$$\kappa_c = 4.3429 \frac{6\pi}{\rho_L \lambda_0} \Im \{ -K \} * m_v$$  \hspace{1cm} (49)
This is considering that all particles in the cloud are liquid water, however this is not the case. Ice particles are found in clouds all the time and they must be accounted for. This can be done by swapping the density for water for the density of ice, \( \rho_i \), into the calculation of liquid extinction coefficient to transform into ice extinction coefficient. K is also calculated with the dielectric constant for ice. The equation is shown as:

\[
\kappa_I = 4.3429 \frac{6\pi}{\rho_i \lambda_0} m \{ -K \}
\]

The extinction coefficient can be swept across frequency to display the difference in interaction between ice and water clouds and EM waves. This is seen in figure 2.8.

![Figure 2.8: Cloud Extinction Coefficient for Liquid and Solid Water](image)

### 2.2.4 Precipitation Modeling

The most detrimental form of weather that microwave signals encounter is rain. The main cause for this is the similarity between the EM wavelength and the water droplet diameter. In
this section, we will discuss two models: (1) the ITU power model, and (2) the Mie scattering solution and compare the two. In addition to rain, ice particles’ effect on a propagating signal will also be discussed.

### 2.2.4.1 ITU Model

The ITU model uses the power law relationship with rain rate and frequency dependent constants to calculate specific attenuation \([17]\). The relationship is shown as

\[
\gamma_R = kR^\alpha
\]  

(51)

where \(R\) is the rain rate, and \(k\) and \(\alpha\) are frequency dependent constants. Depending on the polarization of the wave, the calculations for \(k\) and \(\alpha\) differ. The ITU outlines methods for computing vertical, horizontal, linear, and circular polarized waves. Equations for \(k\) and \(\alpha\) are given as:

\[
\log_{10} k = \sum_{j=1}^{4} \left( a_j \exp \left[ - \left( \frac{\log_{10} f - b_j}{c_j} \right)^2 \right] \right) + m_k \log_{10} f + c_a
\]

(52)

\[
\alpha = \sum_{j=1}^{5} \left( a_j \exp \left[ - \left( \frac{\log_{10} f - b_j}{c_j} \right)^2 \right] \right) + m_\alpha \log_{10} f + c_a
\]

(53)

where \(f\) is frequency in GHz and spans from 1 to 1000 GHz. \(k\) is either \(k_H\) or \(k_V\) and \(\alpha\) is either \(\alpha_H\) or \(\alpha_V\) depending on if the polarization is horizontal or vertical respectively. Coefficients \(a\), \(b\), and \(c\) are polarization dependent and are given in tables found in the ITU reference. Circular and linear polarized constants are calculated with both vertical and horizontal components of \(k\) and \(\alpha\) along with the addition of the path elevation angle, also known as the angle from zenith, and the polarization tilt \(\phi_{tilt}\) which is relative to the horizontal \((\phi_{tilt} = 45^\circ\) for circular polarized waves). The coefficients for linear and circular polarized waves are computed as follows
\[ k = [k_H + k_V + (k_H - k_V)\cos^2\theta\cos2\phi_{tilt}] / 2 \]  \hspace{1cm} (54)

\[ \alpha = [k_H\alpha_H + k_V\alpha_V + (k_H\alpha_H - k_V\alpha_V)\cos^2\theta\cos2\phi_{tilt}] / 2k \]  \hspace{1cm} (55)

Using the equations displayed above we can look at the specific attenuation against frequency for various rain rates. The signal is circular polarized and has a polarization tilt of 45 degrees.

![ITU Extinction Coefficient vs Frequency for Various Rain Rates](image)

**Figure 2.9: ITU Extinction Coefficient vs Frequency for Various Rain Rates**

This gives insight into how well higher frequencies perform in rain compared to lower frequencies while precipitation is present. According to this model, it appears that frequencies perform very similar to each other up until approximately 10 GHz regardless of rain rate. After this we can see a large deviation in the extinction coefficient regarding rain rate. This is better illustrated when looking at a single frequency and sweeping it across multiple rain rates.
This exhibits the power rule very well. One can see the exponential change with increasing rain rates at 72 GHz. This goes to show how detrimental heavy rainstorms can be to a high frequency signal’s power.

2.2.4.2 Mie Scattering and Absorption

Mie coefficients are used to describe the extinction and absorption of EM waves through a dielectric sphere of a given radius [18]. These parameters are calculated through the use of,

$$\chi = \frac{2\pi r}{\lambda_0} \sqrt{\varepsilon_b}$$ \hspace{2cm} (56)

and

$$n = n' - n'' = \Re\{\varepsilon^{1/2}\} - \Im\{\varepsilon^{1/2}\}$$ \hspace{2cm} (57)
where \( \chi \) relates to the normalized circumference and \( n \) to the relative index of refraction. The calculation of the normalized circumference references the dielectric properties and radius of the sphere coupled with the wavelength of the EM wave.

The Mie coefficients are given by [19]:

\[
a_l = \frac{\left( \frac{A_l + l}{n + \chi} \right) \Re\{W_l\} - \Re\{W_{l-1}\}}{\left( \frac{A_l + l}{n + \chi} \right) W_l - W_{l-1}} \tag{58}
\]

and

\[
b_l = \frac{\left( \frac{nA_l + l}{n + \chi} \right) \Re\{W_l\} - \Re\{W_{l-1}\}}{\left( \frac{nA_l + l}{n + \chi} \right) W_l - W_{l-1}} \tag{59}
\]

where

\[
W_l = \left( \frac{2l}{\chi} \right) W_{l-1} - W_{l-2} \tag{60}
\]

with

\[
W_0 = \sin \chi + j \cos \chi \tag{61}
\]

and

\[
W_{-1} = \cos \chi - j \sin \chi \tag{62}
\]

and

\[
A_l = - \frac{l}{n \chi} + \left[ \frac{l}{n \chi} - A_{l-1} \right]^{-1} \tag{63}
\]

with

\[
A_0 = \cot n \chi \tag{64}
\]

The solutions of these coefficients can bring us to the calculation of the efficiencies for extinction and scattering [20].

The Mie extinction efficiency for a sphere is given by:

\[
\zeta_e(n, \chi) = \frac{2}{\chi^2} \sum_{l=1}^{\infty} (2l + 1) \Re\{a_l + b_l\} \tag{65}
\]
The Mie scattering efficiency for a sphere is given by:

$$\zeta_s(n, \chi) = \frac{2}{\chi^2} \sum_{l=1}^{\infty} (2l + 1)(|a_l|^2 + |b_l|^2)$$ (66)

The efficiencies can be used to calculate the cross section ($Q$) of the dielectric spheres for both extinction and scattering and is given by the volume of a sphere multiplied by the respective efficiencies:

$$Q = \pi r^2 \zeta$$ (67)

With the cross-section along with the drop size distribution, $p(r)$, we arrive at the calculations of the rain volume extinction and scattering coefficient for a given rain rate,

$$\kappa = \int_{r_{min}}^{r_{max}} p(r) Q(r) dr$$ (68)

This is where $r_{min}$ and $r_{max}$ represent the minimum and maximum droplet radii. Using the Marshall Palmer distribution, rain volume extinction coefficients can be calculated for different rain rates across multiple frequencies. This can be seen in Figure 2.11.
Figure 2.11: Liquid Extinction Coefficient Calculated using the Mie Solution

The same calculations can be made for a solid particle if the dielectric is changed to calculate the normalized circumference and the index of refraction. This is seen in Figure 2.12.
By comparing the liquid and solid extinction coefficient curves for frequencies under 100 GHz, liquid precipitation is much more detrimental to signal propagation than solid precipitation.

2.2.5 Path Length

For all models discussed in this section, it is imperative that path length is calculated. Path length directly corresponds to the opacity, $\tau$, calculation which is the amount of attenuation a signal encounters along a path,

$$\tau = \gamma \times \ell$$

(69)

where $\ell$ is the path length. This section will discuss how path length is calculated and approximated for each model.
2.2.5.1 Path Length for Clear Day

To calculate the path length for a satellite communication link it is imperative that the coordinates of both the ground station and the satellite are known. This includes the altitudes of each. Typically, these coordinates are given in latitude and longitude format, however for these calculations they must be converted to cartesian by the equations below:

\[ x = R \cdot \cos(lat) \cdot \cos(long) \]  
\[ y = R \cdot \cos(lat) \cdot \sin(long) \]  
\[ z = R \cdot \sin(lat) \]

where \( R \) is the radius of the Earth. Now consider a ground station at position \((x_g, y_g, z_g)\) and a satellite at \((x_s, y_s, z_s)\) where \((x, y, z)\) are rectangular coordinates. If \(x_g = x_s\) and \(y_g = y_s\) then the satellite is directly over head also known as zenith and the path length is the difference between \(z_s\) and \(z_g\). In situations where the satellite is not directly overhead of the ground station, the path length is calculated as:

\[ path\ length = \sqrt{(x_s-x_g)^2 + (y_s-y_g)^2 + (z_s-z_g)^2} \]  

In cases where the satellite is not at zenith, the angle from zenith or the angle of arrival must be considered. This is the angle between the propagating path of the satellite and the ground station and the normal vector of the ground station. The angle of arrival, \( \theta \), is calculated as:

\[ \cos\theta = \frac{a \cdot b}{||a|| \cdot ||b||} = \frac{(x_g, y_g, z_g) \cdot (x_s-x_g, y_s-y_g, z_s-z_g)}{\sqrt{x_g^2 + y_g^2 + z_g^2} \cdot path\ length} \]

A visualization of path length can be seen in Figure 2.13.
2.2.5.2 Path Length for Clouds

The path length for the cloud model is dependent on how many relative humidity measurements exceed the critical relative humidity curve. For each point that exceeds the curve, path length would increase by the resolution ($\Delta h$) of the measured relative humidity. For example, if there are 10 points that exceed the critical relative humidity curve and the resolution of the measurements was 10 m, the path length through the cloud would be 100 m. This is then multiplied by the secant of the angle of arrival.

2.2.5.3 Path Length for Precipitation

Calculating precipitation path is very similar to that of gaseous attenuation as discussed. However, the difference between the two is that it is not raining along the entire path of the communication link, and this must be considered. Precipitation begins at the cloud floor, so the path that encounters rain can be estimated as the path from the antenna to the cloud floor. To approximate the cloud floor, upper atmosphere soundings (radiosonde) are required to find
when temperature reaches 0°C (or the lifted condensation level, as appropriate). This is noted as the 0° isotherm and is visualized in Figure 2.14.

![Figure 2.14: Visualization of 0° Isotherm and Propagating Path through Precipitation](image)

Applying basic geometry, we arrive at the calculation for the path for precipitation as:

$$\text{pathlength} = \sec(\theta) (h_{iso} - h_g)$$  \hspace{1cm} (75)

where $h_{iso}$ is the altitude of the 0° isotherm from atmospheric soundings, and $\theta$ is the angle of arrival discussed in previous sections. If the rain is heavy, then the path length should be reduced, because heavy rain cells are more localized than stratiform rain cells.

### 2.2.6 WSCE-B Description and Link Budget

The W/V-Band Satellite Communication Experiment - Beacon (WSCE-B) was launched into geostationary orbit in 2021. The beacon is a dual-tone beacon, meaning it is configured to transmit two signals at 72 and 84 GHz to ground terminals located across the United States. The purpose of this experiment is to collect data to statistically characterize atmospheric effects (particularly rain-fade) on electromagnetic signal propagation at 72 GHz and 84 GHz.
In addition to scientific data, general payload telemetry, tracking, and control (TT&C) data is also recorded. This includes things such as satellite health and location in orbit. These are received in a separate location via a host communication link before being relayed to the experiment’s data collection site. This host link also gives the opportunity to communicate with the satellite.

As discussed in Section 2.1.2, satellite communication links can be expressed as link budgets. The link budget for WSCE-B is shown in Table 2.5.

**Table 2.5: WSCE-B Link Budget**

<table>
<thead>
<tr>
<th>WSCE-B Link Budget</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmit Antenna Gain</td>
<td>~30 dB</td>
</tr>
<tr>
<td>Free Space Propagation Loss</td>
<td>~220 dB</td>
</tr>
<tr>
<td>Pointing Loss</td>
<td>~3 dB</td>
</tr>
<tr>
<td>Polarization Mis-match Loss</td>
<td>~4 dB</td>
</tr>
<tr>
<td>Receive Antenna Gain</td>
<td>~50 dB</td>
</tr>
<tr>
<td>T-line Loss</td>
<td>~3.5 dB</td>
</tr>
<tr>
<td>LNA Gain</td>
<td>~30 dB</td>
</tr>
<tr>
<td>Other RF Components Gain</td>
<td>~30 dB</td>
</tr>
<tr>
<td>Attenuation due to weather</td>
<td>x dB</td>
</tr>
</tbody>
</table>

### 2.2.7 Beacon

As stated earlier, the beacon is a dual tone beacon with the ability to transmit tones at 72 GHz and 84 GHz. Located in geostationary orbit at approximately 110 degrees W, the beacon transmits these tones on to the United States. With the beacon being in geostationary orbit, scientists and engineers can receive tones and have communications with the beacon at all
hours of the day, since the satellite rotates with the earth. Geostationary orbit also aids with the ground station pointing, making it easier for the transmit and receive antennas to be aligned. The beacon is outfitted with solid-state power amplifiers, allowing for signal reception up to approximately -40 dB of atmosphere attenuation before loss of signal (i.e., a dynamic range of 40 dB). In addition to the power amplifiers, filters are placed strategically before and after the signal to ensure no unwanted signals are transmitted or amplified along with the desired tones. Finally, signals are transmitted through a horn antenna. The combination of these components in their correct order is known as the RF front-end. The block diagram for the RF front-end for WSCE-B is illustrated in Figure 2.15.

![Figure 2.15: Block Diagram of WSCE-B RF Front-end](image)

**2.2.8 Receiver**

Ground stations, noted as the receiver terminals in Figure 1.2, are outfitted with a variety of different meteorological sensors along with the receiver antennas. These sensors include weather stations, disdrometers, and radiometers.
The receiver shown in Figure 2.16 receives both V-band and W-band tones from the beacon. Immediately after reception, signals are fed into a low noise amplifier. This is to ensure that signals are amplified before passing through more noisy components that could introduce more noise and alter our received data. The signal is then filtered and then down converted to a frequency which a microcontroller can sample the received signals. This circuitry is the RF front-end for the receiver (Figure 2.17). Let there be a note for both receiver and transmitter front-ends that all components are connected through transmission lines.
2.3 Data Measurement and Processing

Now that the models and experiment have been discussed in detail, the focus shifts to the foundational stage of data measurement and preprocessing. Given that the models under consideration utilize data collected throughout the entirety of 2023, it becomes imperative to thoroughly scrutinize the collected data for irregularities and errors. This section delves into the multifaceted process of data collection for the experiment and sheds light on the meticulous preprocessing steps undertaken to ensure the integrity and reliability of the dataset before its utilization by the models.

2.3.1 Beacon Signals

With regards to preprocessing beacon data, there are occurrences that we must remove as they do not reflect the atmosphere effects. These things consist of maintenance events, pointing errors, and satellite maneuvers / momentum dumps. Figure 2.18 shows the measured beacon data from the receiver on a day where there is no rain or clouds.
When beacon data is received, it can be interpreted as a very noisy signal. In order to draw accurate conclusions between our models and the received data, the received data must be “cleaned up”. This can be done by a smoothing filter. These filters take a window of samples and apply an averaging filter to them. With the right resolution, the noise can be smoothed out from the sampled data. An example of the smoothing filter can be seen in Figure 2.19. Here a random signal is generated and then smoothed by the same gaussian filter used to preprocess the beacon data.
Figure 2.19: Random Data with a Smoothing Filter Applied

The filter does an excellent job of smoothing out any fluctuations in the randomly generated signal. If we apply this same filter to the data shown in Figure 2.18, it is much easier to interpret the measurements (Figure 2.20).
Next, the unusual drop in signal power around 1330 Universal Time Coordinated (UTC) must be addressed. When a geostationary satellite drifts out of its position, it must be corrected. The satellite is outfitted with torque rods and reaction wheels to correct itself. Every now and then, the built-up momentum must be “dumped” – or “zeroed out” by a space vehicle maneuver (i.e., thruster firing), which results in the “spike” that is seen at about 1330 UTC. Since this research focuses on the signal loss due to weather events and not satellite drift, these data points must be removed. Space vehicle attitude pointing error is captured in telemetry data, as seen in Figure 2.21. “attitude” error, not altitude error…
In Figure 2.21, there is a large spike in space vehicle pointing error around 1330 UTC just as there is a drop in signal power at 1330 UTC in Figure 2.20. This error is significant enough for preprocessing. To account for this, a linear interpolation is performed, as is done when preprocessing radiosonde data, across the beacon data when the error occurs. To note, this is done instead of the alternative of removing the data completely. This is to maximize the quality of useful data. The processed beacon data can be seen in Figure 2.22 superimposed on to the attitude error.
Figure 2.22: Processed Beacon Data & Attitude Error vs Time for January 6th, 2023

We must also discuss maintenance events performed on the ground terminal. During these events, the receiver is turned off for certain amounts of time and no data is being gathered. To account for this time, a linear interpolation can be used to replace corrupt or lost data, in some circumstances. “Peak pointing” events are another event that must be accounted for. These are conducted to optimize antenna alignment to the space vehicle. Any data corruption resulting from the peak pointing event must also be removed.

In order to compare our model to our beacon experiment, we first must perform calculations on our received signal to convert it into a loss (i.e., attenuation) value. This can be done with the WSCE-B Link Budget in Table 5. As discussed in previous sections, the gains and losses of a link budget are summed to calculate what would be the received power. However, if the received power is known (i.e., measured), we can solve for another variable in the link budget such as the loss due to the atmosphere or weather. This can be seen in the equation below,
\[ L_{\text{weather}} = P_r + P_t - L_t + G_t - L_{FS} + G_r - L_r - PLF \]  

(76)

Here the link budget is manipulated to solve for the loss due to weather, \( L_{\text{weather}} \), which is the focus for the model. In Figure 2.23, the comparison between the processed beacon data and the estimated loss due to weather data is shown. During clear-day periods, we can “calibrate” our relative beacon measurements to the absolute gaseous attenuation as measured by a radiometer. Thus, measured beacon signal power can be expressed as measured atmospheric attenuation (valid up through the 40 dB of dynamic range).

![Figure 2.23: Power and Weather Loss for WSCE-B in Albuquerque NM](image)

2.3.2 Radiometer Data

Radiometers measure atmospheric emissions at narrow frequency bands. From this, the “brightness temperature” of the atmosphere at a given frequency band can be estimated. The concept is illustrated in Figure 2.24. The brightness temperature can then be used to estimate
atmospheric absorption (attenuation) at the measured frequency bands. This is because, for atmosphere at thermal equilibrium, emissions must equal absorption.

\[ T_b(r) = T_0 e^{-\tau(0,r)} + \int_0^r k_e(r') [(1 - a)T(r') + a T_{sc}(r')] e^{-\tau(r',r)} dr' \]

**Figure 2.24: Illustration of Radiometer Concept**

The radiometer used is the Radiometer Physics model RPG-LWP+72+82 as shown in Figure 2.25. This is a four-channel radiometer that measures brightness temperatures at 23.8 GHz (for integrated water vapor (IWV) calculations, gaseous water vapor), 31.4 GHz (for liquid water path (LWP) calculations, due to clouds), 72.5 GHz, and 82.5 GHz. The radiometer provides accurate estimation of clear-weather opacity (attenuation), but its dynamic range is limited to about 10 – 15 dB.
The radiometer measures atmosphere noise power at each frequency band simultaneously with selected integration times, typically 1 second. The data collection is continuous, except for occasional gain-calibrations and maintenance events. Radiometer properties are summarized in Table 2.6.
Table 2.6: Radiometer Properties

<table>
<thead>
<tr>
<th>Radiometer:</th>
<th>RPG Model LWP+72-82 (G5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (GHz):</td>
<td>23.8 31.4 72.5 82.5</td>
</tr>
<tr>
<td>Antenna Beamwidth (deg):</td>
<td>3.7 2.8 1.5 1.3</td>
</tr>
<tr>
<td>Accuracy (K):</td>
<td>0.2 0.2 0.2 0.2</td>
</tr>
<tr>
<td>Resolution (K):</td>
<td>0.2 0.2 0.2 0.2</td>
</tr>
</tbody>
</table>

The radiometer cannot provide attenuation measurements for rain events. In Figure 2.26, the instrument saturates during rain events (i.e., the attenuation exceeds the instrument’s dynamic range). Because of this, data from the radiometer can only be used to validate gaseous and cloud models (where attenuation is less than ~ 10 dB).
The radiometer, as stated earlier, is a great tool for estimating attenuation when there is no weather present. This can be used to “calibrate” the link budget estimation for loss due to weather. This is called the gain offset and is calculated as:

\[ \text{Gain Offset} = \tau_R - L_{\text{weather}} \]  

(77)

and applied to the WSCE-B data to compute gaseous+cloud+precipitation attenuation as shown in Fig 2.23 (bottom).

### 2.3.3 Radiosonde Data

Radiosondes, also known as weather ballons, have a variety of different uses spanning from weather forecasting to climate research. These instruments gather data about the atmosphere’s temperature, pressure, and relative humidity at various altitudes in the atmosphere, which is vital to the generation of this research’s models.
These instruments consist of a helium or hydrogen filled balloon, radiosonde instrument to gather weather data, a transmitter to relay the data in real time, and a parachute. According to the NOAA these instruments can reach heights exceeding 30 km before the balloon bursts, and can take two hours to do so. The balloons have also been reported to drift several kilometers from the launch site during their ascent. Launches typically occur twice daily, once at 0000 UTC and 1200 UTC [21].

Radiosonde data files are publicly accessible and can be retrieved from online archives such as https://weather.uwyo.edu/upperair/sounding.html. Figure 2.27 shows a typical sample from the archive. The surface altitude is 1619 meters above sea level for this launch from Albuquerque airport, which is located within a few miles of the location of the ground terminal of the experiment. Inspecting the altitude at which the samples were taken, the change in altitude is not consistent for the samples. This is true for all radiosonde measurements.

<table>
<thead>
<tr>
<th>PRES</th>
<th>HIGHT</th>
<th>TEMP</th>
<th>DWP</th>
<th>RELH</th>
<th>MIXR</th>
<th>DRCT</th>
<th>SKNT</th>
<th>THTA</th>
<th>THTE</th>
<th>THTV</th>
</tr>
</thead>
<tbody>
<tr>
<td>hPa</td>
<td>m</td>
<td>C</td>
<td>C</td>
<td>%</td>
<td>g/kg</td>
<td>deg</td>
<td>knot</td>
<td>K</td>
<td>K</td>
<td>K</td>
</tr>
<tr>
<td>1000.0</td>
<td>81</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>835.0</td>
<td>1619</td>
<td>11.4</td>
<td>1.4</td>
<td>50</td>
<td>5.10</td>
<td>260</td>
<td>8</td>
<td>299.6</td>
<td>315.1</td>
<td>300.5</td>
</tr>
<tr>
<td>830.0</td>
<td>1669</td>
<td>10.8</td>
<td>-0.2</td>
<td>47</td>
<td>4.56</td>
<td>256</td>
<td>10</td>
<td>299.5</td>
<td>313.4</td>
<td>300.3</td>
</tr>
<tr>
<td>823.0</td>
<td>1739</td>
<td>10.0</td>
<td>0.0</td>
<td>50</td>
<td>4.67</td>
<td>250</td>
<td>13</td>
<td>299.4</td>
<td>313.6</td>
<td>300.2</td>
</tr>
<tr>
<td>817.0</td>
<td>1799</td>
<td>9.6</td>
<td>-0.2</td>
<td>50</td>
<td>4.62</td>
<td>245</td>
<td>15</td>
<td>299.6</td>
<td>313.6</td>
<td>300.4</td>
</tr>
<tr>
<td>788.0</td>
<td>2093</td>
<td>7.6</td>
<td>-1.4</td>
<td>53</td>
<td>4.39</td>
<td>250</td>
<td>16</td>
<td>300.6</td>
<td>314.0</td>
<td>301.4</td>
</tr>
<tr>
<td>768.0</td>
<td>2383</td>
<td>6.2</td>
<td>-2.3</td>
<td>54</td>
<td>4.23</td>
<td>235</td>
<td>17</td>
<td>301.3</td>
<td>314.3</td>
<td>302.0</td>
</tr>
<tr>
<td>759.0</td>
<td>2399</td>
<td>5.6</td>
<td>-2.7</td>
<td>55</td>
<td>4.16</td>
<td>245</td>
<td>16</td>
<td>301.6</td>
<td>314.4</td>
<td>302.3</td>
</tr>
</tbody>
</table>

Figure 2.27: Snippet of Radiosonde Data from January 1st, 2023

This data can be read into Matlab for analysis. In Figure 2.28, the raw readings from the radiosonde are plotted against altitude.
As stated earlier, the launches are within a few miles of the ground terminal at the Albuquerque airport. If the launches were to occur further away, they might not be representative of the atmosphere surrounding the experiment site. This could cause the model to suffer. Thankfully, this is not the case for this research.

2.3.3.1 Preprocessing of Radiosonde

In order to make the radiosonde data suitable for this research, extensive processing is required. This involves tasks such as interpolating, incorporating weather station data, and scrutinizing soundings.
As discussed in earlier sections, radiosonde ballons are launched twice daily at 0000 UTC and 1200 UTC and takes upwards of two hours of measurements before ballon burst. An assumption we make here is that all radiosonde measurements are instantaneous. The assumption that the weather ballons do not drift is also made. These two assumptions must be made because there is no tracking data reported with the radiosonde data.

Two interpolations are made to synthesize a full day’s worth of data from two daily samples. The first is linear spatial interpolation along the height vector of the radiosonde sample. This is to set up a temporal interpolation of the temperature, pressure, and relative humidity vectors between the two daily radiosonde samples and the first sample of the following day. This is done at each interpolated height at a resolution of one minute. The formula for a linear interpolation is shown as:

\[ y = y_0 + (x - x_0) \frac{y_1 - y_0}{x_1 - x_0} \]  

(78)

where \((x_0, y_0)\) and \((x_1, y_1)\) are known points and \((x, y)\) is the desired interpolated point. Application of these interpolations yields a data set from 0000 UTC to 0000 UTC of the next day. This is shown in Figure 2.29.
Figure 2.29: Temperature vs Time for Interpolated Radiosonde Data at Three Altitudes

From inspection, the synthesized weather data between radiosonde measurements has no fluctuations as we would expect weather to act. This can be compensated for with the use of weather data gathered at the ground station (also a resolution of one minute) though the use of the exponential decay function. The radiosonde interpolations at the surface altitude (i.e., temperature, pressure, relative humidity) are simply corrected (i.e., adjusted) to the values measured by the ground station. In my model, I applied an exponential decay (with altitude) to the correction:

$$x_{adj} = x + \Delta \times \exp \left( \frac{-(h-h_0)}{h_0} \right)$$  \hspace{1cm} (79)

where $x_{adj}$ is the new adjusted weather value (temperature, pressure, relative humidity), $\Delta$ is the difference in the weather station data and the radiosonde value at the surface, $h$ refers to
the height, and \( h_0 \) is the surface altitude. Applying this to the temperature profiles seen in Figure 2.29 yields the temperature profile shown in Figure 2.30.

![Temperature vs Time for Interpolated Radiosonde Data at Three Altitudes and Adjusted Temperature Profile](image)

**Figure 2.30: Temperature vs Time for Interpolated Radiosonde Data at Three Altitudes and Adjusted Temperature Profile**

With the application of the weather data, we can synthesize real-time weather fluctuations into our interpolated radiosonde data, thereby providing more realistic model simulations.

### 2.3.4 Disdrometer

A disdrometer uses lasers and optics to analyze precipitation as it falls. A 785-nm infrared laser source produces a parallel light beam. A photodiode and lens are located at the receiver side and transform optical intensities into electrical signals. When a particle (i.e., liquid or solid water droplet) passes though the parallel light beam, the signal in the receiver is reduced in
amplitude. An onboard digital signal processor analyzes these values. Statistical comparison to a collection of all particle types, diameters, and velocities provides identification of the particle, and the result is checked against the temperature of the particle to provide reliability.

**Figure 2.31: Thies Clima 5.4110.00.100 Disdrometer**

The ground terminal in Albuquerque, New Mexico is outfitted with the Thies Clima 5.4110.00.100 Laser Precipitation Monitor (LPM) as shown in Figure 2.31. Properties are listed in Table 2.7. This unit measures rain drop size distribution (DSD), rain-rate, identifies precipitation type, precipitation intensity, and the precipitation spectrum. Particles above 9 degrees C are automatically accepted as liquid except for hail, while particles below -4 degrees C are automatically accepted as solid particles. The precipitation spectrum output consists of binned particles with 22 diameter size classes up to 8 mm, and 20 particle velocities for each diameter class up to 10 m/s, as listed Table 2.8. Precipitation measurements made by the disdrometer can be seen is Figure 2.32.
Figure 2.32: Liquid and Solid Precipitation Rates Against Time

Table 2.7: Disdrometer Properties

<table>
<thead>
<tr>
<th>Disdrometer:</th>
<th>Thies Clima LPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle size (mm):</td>
<td>0.16 to 8.0</td>
</tr>
<tr>
<td>Rain Intensity (mm/h):</td>
<td>0.005 to 250</td>
</tr>
<tr>
<td>Integration time (min):</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Data</th>
<th>Description</th>
<th>Unit</th>
<th>Format</th>
<th>Sampling Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RR</td>
<td>Rain Rate</td>
<td>mm/h</td>
<td>xxx.y</td>
<td>60</td>
</tr>
<tr>
<td>DS</td>
<td>Number of drops/ bin (22 bins)</td>
<td>#</td>
<td>xxx.y</td>
<td>60</td>
</tr>
<tr>
<td>DSD</td>
<td>Number of drops at a specific velocity/bin (20 bins)</td>
<td>m/s</td>
<td>xxx.y</td>
<td>60</td>
</tr>
</tbody>
</table>
Table 2.8: Disdrometer Class Binning for Particle Diameter and Velocity

<table>
<thead>
<tr>
<th>Particle diameter class</th>
<th>Particle speed class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class</td>
<td>Diameter [mm]</td>
</tr>
<tr>
<td>1</td>
<td>≥ 0.125</td>
</tr>
<tr>
<td>2</td>
<td>≥ 0.250</td>
</tr>
<tr>
<td>3</td>
<td>≥ 0.375</td>
</tr>
<tr>
<td>4</td>
<td>≥ 0.500</td>
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<tr>
<td>5</td>
<td>≥ 0.750</td>
</tr>
<tr>
<td>6</td>
<td>≥ 1.000</td>
</tr>
<tr>
<td>7</td>
<td>≥ 1.250</td>
</tr>
<tr>
<td>8</td>
<td>≥ 1.500</td>
</tr>
<tr>
<td>9</td>
<td>≥ 1.750</td>
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<td>11</td>
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<td>≥ 5.500</td>
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<td>≥ 6.000</td>
</tr>
<tr>
<td>19</td>
<td>≥ 6.500</td>
</tr>
<tr>
<td>20</td>
<td>≥ 7.000</td>
</tr>
<tr>
<td>21</td>
<td>≥ 7.500</td>
</tr>
<tr>
<td>22</td>
<td>≥ 8.000</td>
</tr>
</tbody>
</table>

2.3.5 Meteorology Station

The Albuquerque ground terminal includes a meteorology station in addition to the disdrometer. A meteorology station includes temperature sensor, relative humidity sensor, barometric pressure sensor, wind monitor, and rain bucket. Weather monitoring sensors are
wired directly to a serial interface/convertor. Signals are then sent to the LabVIEW data acquisition system. Samples are collected every minute at a 1/60 Hz sampling rate.

2.3.5.1 Ambient Temperature and Relative Humidity Sensor

R.M. Young model number 41382VC Temperature/Relative Humidity Sensor measures ambient temperature and relative humidity, shown in Figure 2.33. A platinum resistance temperature detector (RTD) measure temperature in the range of -50 to +50 C with output voltage of 0-5 VDC. A Rotronic Hygrometer measures relative humidity in the range of 0-100% relative humidity with output voltage of 0-5 VDC.

![Figure 2.33: R.M. Young 41382VC Temperature/Relative Humidity Sensor](image)

2.3.5.2 Barometric Pressure Sensor

R.M Young model number 61302V barometric Pressure Sensor measures barometric pressure shown in Figure 2.34. An electronic barometer measures barometric pressure in the range of 500-1100 hPa with output voltage of 0-5 VDC.
2.3.5.3 Wind Monitor

R.M. Young model number 05103V Wind Monitor measures both wind direction and speed shown in Figure 2.35. A 10k ohm precision conductive plastic potentiometer measures wind direction in the range of 0 to 360 degrees heading from north with an output of 0 to 5 VDC. A centrally mounted stationary coil on the propeller measures wind speed in the range of 0 to 100 m/s with output voltage of 0 to 5 VDC.
2.3.5.4 Rain Bucket

R.M. Young model number 52203 Tipping Bucket Rain Gauge measures the amount of rain fall, shown in Figure 2.36. A tipping bucket mechanism in the form of a magnetic reed switch measures 0.1 mm per tip of the mechanism. The voltage pulse output is registered and counted by the Young 32400 Serial Interface. Rain bucket data is used to confirm disdrometer measurements and provides redundancy in case the disdrometer fails.

Figure 2.36: R.M Young 52203 Tipping Bucket Rain Gauge

2.3.5.5 Serial Interface

R.M. Young model number 32400 Serial Interface receives all sensor inputs and creates on serial output for interfacing with the data logger, shown in Figure 2.37. Voltage inputs accommodate temperature, relative humidity, and barometric pressure. Wind speed and direction are reserved inputs, and the tipping bucket rain gauge is managed using a combination of a voltage input with a pull-up resistor on a separate voltage excitation channel. A power
output on the serial device provides power to all active sensors. All meteorological data are recorded at a sampling rate of once per minute.

Figure 2.37: R.M. Young Model Number 32400 Serial Interface

An example of the samples gathered and logged by these instruments can be seen in Figure 2.38 for March 16, 2023.
3 RESULTS

For the results section of this thesis, model performance over the course of 2023 will be examined. The method that will be used to compare the integrated model to beacon data is a complementary cumulative density function also known as CCDF. Conclusions for this comparison will be drawn qualitatively from how well the model and measured data’s CCDFs line up against one another.

Time-domain optical thickness calculations will also be presented in this section as well. Although not the central focus of this thesis, these calculations will serve as a supportive element in understanding the formulation of the CCDFs pertaining to the modeled attenuation.
3.1 Optical Thickness Calculated During Clear Conditions

The optical thickness, $\tau$, is the integration of specific attenuations along the propagating path and is represented as $-L_{atm}$ in Table 2.1. The calculation of opacity is positive, however the effects on a link are negative. This is best illustrated by the integral:

$$\tau(h_g, h_s) = \sec\theta \int_{h_g}^{h_s} \gamma(H) \, dH$$  \hspace{1cm} (80)

When the angle of arrival is equal to 0, the zenith optical thickness is represented by the integral:

$$\tau_0(h_g, h_s) = \int_{h_g}^{h_s} \gamma(H) \, dH$$  \hspace{1cm} (81)

Optical thickness can also be calculated as a sum through the trapezoidal rule:

$$\tau = \sec\theta \sum_{i=1}^{i=N} \left( \frac{\gamma_i + \gamma_{i+1}}{2} \right) \Delta h$$  \hspace{1cm} (82)

The layer thickness is noted at $\Delta h$ and $N$ is the number of layers. The quality of the calculation is determined by the size of $N$. To increase $N$, we must decrease $\Delta h$ which improves resolution.

**Figure 3.1: Visualization of Atmosphere Profiles that a Signal Passes Through**
In Figure 3.1 we can see the different atmosphere profiles the communication link must pass through. Attenuation must be calculated for each one of these layers and then summed to achieve the total instantaneous attenuation for the path. With the processed radiosonde data discussed earlier, we can calculate the attenuation due to a gaseous atmosphere for a full day’s worth of data. As seen in Figure 3.2, attenuation for V-band seems to fluctuate around 0.5 dB of attenuation while W-band fluctuates around 0.4 dB for weather profiles shown in Figure 3.3.

![Figure 3.2: Gaseous Attenuation for March 16th, 2023, for Albuquerque, NM](image)

Figure 3.2: Gaseous Attenuation for March 16th, 2023, for Albuquerque, NM
In Figure 3.4 we can see relative humidity radiosonde measurements for a day in Albuquerque, New Mexico. For altitudes from approximately 3 km to 13 km, we assume that a cloud is present along the propagation path.
Using the methods discussed in Section 2.2.3 along with the temperature profile shown in Figure 3.5, we can calculate specific attenuation for clouds and then sum this over the path. This is seen in Figure 3.6.
Figure 3.5: Temperature Profile Overlayed with Cloud Levels
3.3 Optical Thickness Calculated During Precipitation Events

In Section 2.2.4, specific attenuation due to precipitation was discussed and a standardized drop size distribution was used as a method to illustrate how the models perform. For the calculation of specific attenuation, the measurements gathered by the disdrometer will be used to generate the drop size distributions to be used instead of the standardized Marshall-Palmer Distribution.

3.3.1.1 Drop Size Distribution

As discussed earlier, the Thies Clima disdrometer measures raindrop size, velocity, and frequency. The raindrop size distribution is given by

$$N(D_i, T) = \sum_{j=1}^{22} \frac{n_{ij}(T)}{V_j \cdot A \cdot T \cdot \Delta D_i}$$

(83)
where \( n_{ij} \) is the number of drops in the \( i^{th} \) and \( j^{th} \) bin, \( V_j \) is the velocity of the raindrop in the \( j^{th} \) bin, \( A \) is the measurement area of the disdrometer, \( T \) is the sample period, and \( \Delta D_i \) is the \( i^{th} \) bin width [22]. Using this new distribution, the specific attenuation equation reduces to

\[
\kappa = \int_{r_{\text{min}}}^{r_{\text{max}}} N(r)Q(r)dr
\]  

(84)

3.3.1.2 Optical Thickness

With the specific attenuation along with our pathlength calculations discussed in Section 2.2.5, we can calculate the optical thickness for a liquid precipitation event (Figure 3.7).

![Figure 3.7: Optical Thickness due to Precipitation](image)

Using the same methods, optical thickness can be found for solid precipitation as well. This is seen in Figure 3.8.
3.4 Integrated Model

Up to this point only individual attenuation models have been discussed. However, all models must be considered when discussing the attenuation along the entire path. We will call the combination of all the weather models the integrated model (Figure 3.9).

Figure 3.8: Optical Thickness due to Solid Precipitation

Figure 3.9: Block Diagram of Integrated Model
The integrated model is the sum of modeled attenuations for each weather event that the propagating path passes through. It is a function of time and wavelength with inputs of meteorological, radiosonde and disdrometer data. The output of this model is specific attenuation which can be used to compute the opacity (attenuation) of the link. This is visualized in Figure 3.10 and expressed as $\gamma_{total}$. Note that Figure 3.10 is not to scale. Typically, there would be more gaseous atmosphere than there would be rain and clouds and the cloud layer wouldn’t be this uniform at all times.

$$\gamma_{total} = \gamma_r + \gamma_c + \gamma_g$$ (85)
The attenuation calculated for $\gamma_r$ can be interpreted as $\gamma_r + \gamma_i$ where $\gamma_r$ is the attenuation due to rain and $\gamma_i$ is the attenuation due to ice. Using this integrated model, we can approximate the signal loss for a full day due to weather events though the use of radiosonde and disdrometer data. The time domain plot for the integrated model is show in Figure 3.11.

![Time domain plot for the integrated model](image)

**Figure 3.11: Integrated W and V Band Attenuation Model for March 16th, 2023, in Albuquerque, New Mexico**

### 3.5 Model Validation - Comparison of Simulation to Measured CCDFs

As previously stated, the model will be validated against beacon data using what is called a complementary CCDF which provides an “on average” visualization of the data. Qualitative results will be drawn from inspection of how well the modeled CCDF curve replicates the measured curve prior to saturation.
Cumulative distribution functions (CDFs) are generated by sorting the data set into bins corresponding to their values. Once the data is sorted, the percent chance that value occurs can be calculated by dividing the number of data points in the bin by the total number of samples. This percent chance is then plotted against the bin values to arrive at a CDF curve. The CCDF is simply calculated as $1 - CDF$. An example of a CCDF plotted with its respective histogram (CDF) can be seen in Figure 3.12.

Let us consider the point of the mean, 50, on the CCDF. By examining the CCDF plot we can interpret that 50% of the values of this data set are 50 or greater and 50% of the values are less than 50. We can improve the accuracy of this curve by decreasing the size of the bins thus improving the resolution.
3.5.2 Model CCDF

The minute-by-minute results from the integrated model will be used to generate the CCDF and can be seen for both V and W band in Figure 3.13.

![Model CCDF for V and W Bands for Albuquerque, NM in 2023](image)

**Figure 3.13:** Modeled CCDF for V and W Bands for Albuquerque, NM in 2023

We can also generate a histogram for the full years’ worth of modeled data, which is shown in Figure 3.14.
3.5.3 Beacon CCDF

The measured beacon data with the link budget calculations applied will be used to generate the CCDF of measured attenuation along the link. The CCDFs and their corresponding histograms are shown in Figure 3.15 and 3.16 respectively.
Figure 3.15: Measured CCDF for V and W Bands for Albuquerque, NM 2023

Figure 3.16: Measured Histogram for V and W Bands for Albuquerque, NM 2023
Let it be noted that we see a saturation around 40 dB for both V and W band beacon measurements. This is due to limitations in the RF frontend. Because of this, our model can only be validated up to that saturation point. In Figure 3.17 we can see the model CCDF superimposed onto the beacon CCDF.

Figure 3.17: Modeled and Measured CCDF for V and W Bands for Albuquerque, NM 2023

Qualitatively, the CCDF curves of the modeled and measured data exhibit a similar shape up to the saturation point. This alignment is anticipated given how both the model and the beacon respond to various weather conditions, or their absence. For example, on clear days we would expect very little attenuation and in Albuquerque, being such a dry climate. This causes the high occurrence of attenuation values in the range of 0 to 3 dB. On the contrary, because of
Albuquerque’s dry climate, we see very few occurrences of precipitation where attenuation exceeds 20 dB.

How closely the model matches to the measured curves is how much the model is over or under estimating. For instance, in the range of less than 10 dB or to the left of the intersecting point in Figure 3.17, on average we see the model over predicting when compared to the measured attenuation. This discrepancy can be reduced by optimizing the cloud attenuation model. For attenuation greater than 10 dB, on average the model under predicts attenuation. This discrepancy can be reduced by optimizing the precipitation attenuation model.

4 CONCLUSIONS AND RECOMMENDATIONS

In conclusion, this research introduced and validated a modeling methodology aimed at accurately predicting atmospheric attenuation along satellite-to-ground propagation paths, particularly in W-band (81-86 GHz) and V-band (71-76 GHz) frequencies. By incorporating meteorological data, disdrometer data for precipitation, and radiosonde data for atmospheric profiling, the model generates time-domain estimates of attenuation due to gaseous atmosphere, clouds, and precipitation, both solid and liquid. Despite challenges such as limited radiosonde data availability, uncertainties in cloud formation, and the reliance on point-measurements for precipitation events, the hypothesis posits that this model can provide robust estimates, demonstrated through complementary cumulative distribution functions (CCDFs). Notably, this approach doesn't necessitate radiometer or beacon data, making it a practical tool for designing and analyzing satellite communication links, aiding in determining the required power and aperture to meet availability criteria for specific ground site locations.
To enhance the robustness of the research, it is recommended to incorporate data from multiple years of atmospheric models to capture seasonal variations and long-term trends accurately. By analyzing data over extended periods, researchers can better understand the dynamics of the atmosphere and EM wave’s response to them. Furthermore, increasing the frequency of radiosonde launches and utilizing ceilometers to measure cloud floor heights can provide a more comprehensive understanding of atmospheric conditions, especially in regions where cloud cover plays a significant role in weather patterns. This additional data will not only improve the accuracy of the models but also enhance our ability to predict cloud events with greater precision. The addition of more precipitation sensors along the signal’s path would also improve CCDF generation as it would better characterize a storm cell’s size and severity. As precipitation impacts signal power the most out of all the weather events discussed in this research, improvements to the characterization of these events are most vital.

In addition to expanding observational methods, conducting experiments in diverse environmental settings can help validate findings across different contexts, thereby increasing the reliability and applicability of the research outcomes. Overall, integrating these recommendations into future studies will advance our understanding of atmospheric dynamics and contribute to more effective signal modeling methods.
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