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RAIN ATTENUATION EFFECTS ON SIGNAL PROPAGATION AT W/V-BAND FREQUENCIES

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By

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B.E. Electrical Engineering,
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THESIS

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DEDICATION

To my hero and the most important person in my life,

my mother Madeleine

To my support system,

my sister Aline and my brother Jihad

I cannot thank you enough for everything

you have done for me

Love you

ACKNOWLEDGMENT

I would like to thank Dr. Christos Christodoulou for the continuous support and kindness he offered me throughout the past years. Dr. Christos is the kind of person to look up to.

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ABSTRACT

The current frequency spectrum congestion in space is begging for the exploration and utilization of a new range of frequencies. The W/V-band Terrestrial Link Experiment (WTLE) project run jointly by AFRL, NASA and the University of New Mexico, focuses on using higher frequencies for satellite communications, more precisely, at 72 GHz and 84 GHz.

In this thesis, the rain effect on the propagating signal is studied. First, instantaneous comparisons between the experiment and two different models, the ITU-R and the Siva-Mello, is presented. Second, the WTLE link was analyzed statistically over a period of approximately 10 months, and the ITU-R model was tested accordingly. Third, a shorter prototype of the WTLE experiment was established spanning a distance of only 0.56 Km and operating at 84 GHz. In this experiment the weather factors affecting any signal attenuation are better known than the longer version of the WTLE experiment. Therefore, the shorter link is used to examine the validity and the accuracy of the ITU-R model for rain attenuation for the region of Albuquerque, New Mexico.

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Chapter 1 – Introduction

The millimeter wave spectrum occupies the 30 GHz to 300 GHz frequency band. When compared to microwaves, millimeter waves have many advantages some of which are broader bandwidth, smaller components in the system, reduction in the multipath effects, and selective atmospheric attenuation. However, the propagation in the millimeter wave band is highly affected by climate conditions, and rain in particular [1]. Many models have been used to predict rain attenuation effects on signal propagation for lower frequencies [2]. However, the W/V-band windows have recently emerged as viable communication bands and are currently under consideration for being used for satellite communication purposes. Thus, existing models [7, 9, 12] have not been tested or proven to work on these frequencies of operation. In order to have a clear understanding about the climate conditions effects on the communication in the W/V-band, specifically at 72 GHz and 84 GHz, the WTLE (W/V-band Terrestrial Link Experiment) was created. The ultimate goal of this experiment is to determine if existing rain models, would predict accurately the attenuation based on the rain conditions, or if there is a need to create a new model designed specifically for this experiment.

Many rain attenuation models have been developed throughout the years, and after careful consideration, the ITU-R model for rain attenuation and the Silva-Mello model were selected for the purpose of comparison with our WTLE experiment.

Chapter 2 - Experiment Setup and Data Manipulation

The WTLE experiment was set up and started running on September 3rd, 2015. It represents a communication link having a transmitter on the Sandia Peak at an altitude of 3.225 km above sea level, and a receiver on the top of the COSMIAC building at the University of New Mexico at an altitude of 1.619 km above sea level. Both are located in Albuquerque, NM. The path length between the transmitter and the receiver is 23.5 km, with a resulting slant angle of 4.16°. The overall path geometry is shown in Figure 2.1.

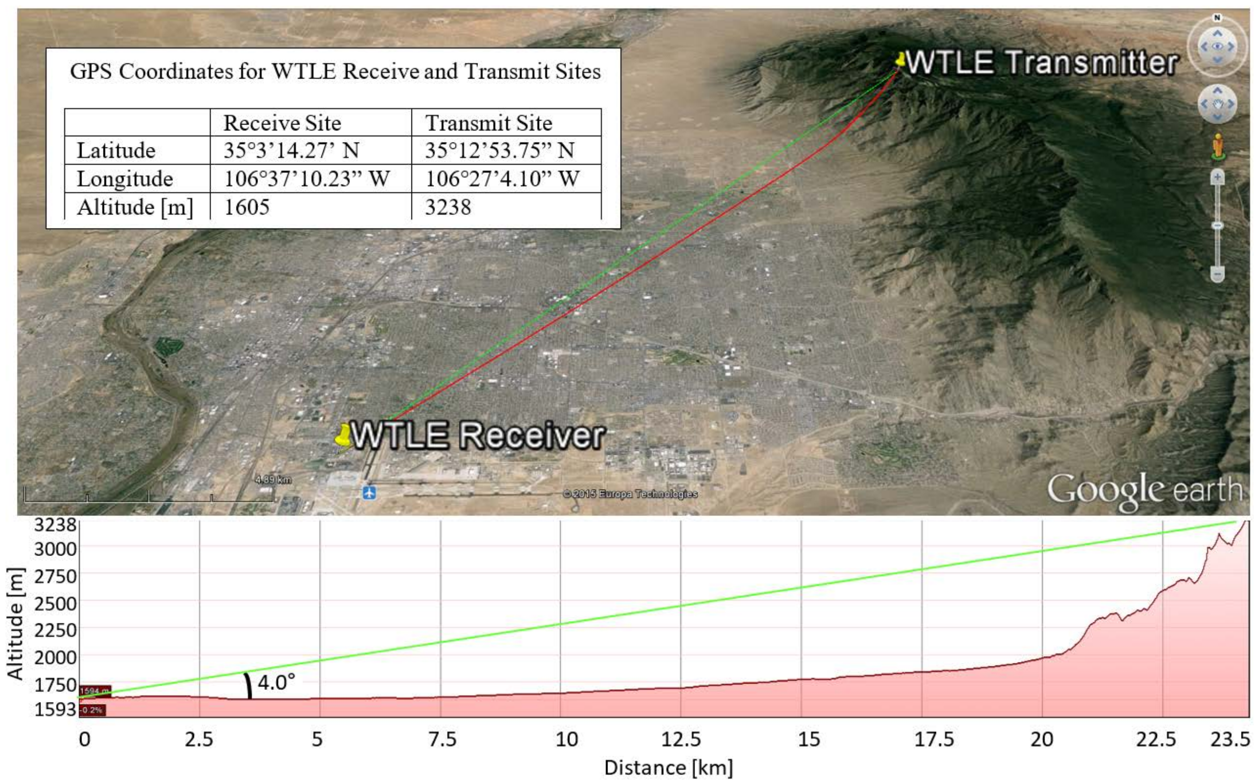

Figure 2.1. WTLE Experiment Path Geometry

The transmitter and the receiver both operate at two different channels to allow the comparison of the 72 GHz and the 84 GHz bands under the same climate conditions. A weather station, and a disdrometer were installed at the receiver station as well. A signal is sent from the transmitter station, and the power received is recorded at the receiver station. The availability of all these different types of data is key for analyzing the experiment and understanding the climate effects on the propagating signals, as well as checking the validity of the models selected with regards to predicting attenuation.

Transmitter

The technical specifications of the transmitter located at the top of the Sandia Mountains are given in Table 2.1 [3].

Parameter	**V-Band**	**W-Band**
Operating frequency	72 GHz	84 GHz
Antenna Diameter	8.89 cm	8.89 cm
Polarization	LHCP	LHCP
Antenna Gain	33 dB	34 dB
Antenna Half-Power Beamwidth	3.6° (E/H)	3.2° (E) / 3.0° (H)
Effective Isotropic Radiated Power (with 5 dB Attenuator)	41.1 dBm	40.4 dBm

Table 2.1. Transmitter Specifications

The transmitter used in the experiment is shown in Figure 2.2, and the overall transmitter site with all the equipment used is shown in Figure 2.3.

Figure 2.2. Transmitter

Figure 2.3. Transmitter Site

Receiver

The technical specifications of the receiver located at the top of the COSMIAC Building are given in Table 2.2 [3].

Parameter	**V-Band**	**W-Band**
Operating Frequency	72 GHz	84 GHz
Antenna Diameter	0.6 m	0.6 m
Polarization	LHCP & RHCP	LHCP & RHCP
Antenna Gain	50.9 dB	52.2 dB
Antenna Half-Power Beamwidth	0.486	0.417
Measurement Rate	10 Hz	10 Hz
Noise Floor	-75 dBm	-80 dBm

Table 2.2. Receiver Specifications

The receivers used in the experiment are shown in Figure 2.4, and the overall receiver site with all the equipment used is shown in Figure 2.5.

Figure 2.4. Receiver

Figure 2.5. Receiver Site

Disdrometer

By definition, a disdrometer is an equipment used to measure the drop size distribution and the velocity of rain particles [4]. In the experiment, the disdrometer is used to collect raw rain rate data (mm/hr) at the receiver side. The disdrometer used in the WTLE experiment is shown in Figure 2.6.

Figure 2.6. Disdrometer

Albuquerque's Weather Characteristics

To study different case scenarios and understand the effect of rain on the WTLE communication link, it is important to distinguish first the different rain classes. Table 2.3 shows the different categories of rain rates [10].

Description	**Rain rate (mm/hr)**
Light Rain	0 – 2
Moderate Rain	2 – 10
Heavy Rain	10 – 50
Violent Rain	> 50

Table 2.3. Rain Rates Categories

Over the last 30 years, Albuquerque has noted an average rainfall of 240.03 mm (9.45 inches). To understand better the significance of this average number, it is 76% less than the average rainfall in the United States, and 38% less than the average rainfall in New Mexico [11]. However, this average is the accumulation over the entire year for 30 years, so a better approach to understand the climate regime is to analyze the average rainfall per month.

The distribution of the rainfall rate per month in Albuquerque over the last 30 years is shown in Table 2.4 [11].

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
Average (mm)	9.652	12.192	14.478	15.494	12.7	16.764	38.1	40.132	27.432	25.908	14.478	12.7

Table 2.4. Rainfall Distribution According to Months in Albuquerque

Therefore, Albuquerque is at the lower bound of the heavy rain category, since for most of the months, the rain average is slightly greater than 10 mm/hr. The rain is mostly intense only between July and October.

Chapter 3 – Instantaneous Analysis of the WTLE Link

Overview

Since the experiment was fairly new, the first approach to analyze its aspects was to study instantaneous rain event moments, that is, choose specific days, hours, and minutes of the day where rain was recorded by the disdrometer. However, as mentioned earlier, the disdrometer gives information for the region around the receiver only, thus the rain conditions along the 23 Km path were unknown except for the receiver area. Therefore, external references such as the Next Generation Radar (NEXRAD) [5] and the National Oceanic and Atmospheric Administration (NOAA) weather and climate toolkit [6] were used to check the rain conditions throughout the path. The challenge was to find specific points in time when it was actually raining only in the vicinity of the receiver, and not raining anywhere else along the path, to match the rain event recorded by the disdrometer with the rain conditions along the path, which would allow an accurate test of the models.

To elaborate more on this matter, one of the major inputs for the ITU-R model and the Silva-Mello model is the rain rate, so the rain rate used was the one recorded by the disdrometer. On the other hand, the attenuation measured at the receiver side was used to test the accuracy of the attenuation calculated using the models. However, the attenuation measured is affected by all the rain events throughout the path, not only the ones caught by the disdrometer. So to make sure that the rain rate recorded by the disdrometer describes accurately the rain rate affecting the signal, specific points in time where the rain was concentrated around the receiver only should be used. Figure 3.1 shows a scale to describe the rain distribution of most interest and most value to the experiment.

Figure 3.1. Region of Interest for the Rain Distribution

Theoretical Model

ITU-R Model

The ITU-R P.838-3 “Specific attenuation model for rain for use in prediction methods” [7] was applied. The model uses the rain rate (mm/hr) to calculate the specific attenuation (dB/km) according to the following equation:

$$\gamma_R = kR^{\alpha} \tag{1}$$

Where R is the rain rate (mm/hr), and the coefficients k and α are a function of the frequency. The ITU-R model [7] provides a method to calculate the k and α coefficients for the frequencies between 1 GHz and 1000 GHz. First, the horizontally polarized and the vertically polarized components of the k and α coefficients are determined. To simplify the task, The ITU-

R model gives a table for these values at every frequency. However, these coefficients are proven to be sufficiently accurate for attenuation prediction for frequencies up to 55 GHz only [8]. Second, these values are used to calculate k and α using the following equations:

$$k = [k_H + k_V + (k_H - k_V)cos^2\theta \cos\ 2\tau]/2 \tag{2}$$

$$\alpha = [k_H\alpha_H + k_V\alpha_V + (k_H\alpha_H - k_V\alpha_V)cos^2\theta \cos\ 2\tau]/2k \tag{3}$$

Where θ is the path elevation angle and τ is the polarization tilt angle relative to the horizontal. τ is equal to 45^{o} for circular polarization.

Silva-Mello Model

Unlike the ITU-R model that is based on the equivalent rain cell concept, the Silva-Mello model uses the complete rainfall rate cumulative distribution to calculate the attenuation due to rain. The Silva-Mello model uses the path reduction factor and effective path length concepts [9]. The rain attenuation (dB) according to the Silva-Mello model is given by:

$$A = \gamma d_{eff} = k[R_{eff}(R,d)]^{\alpha} \frac{d}{1 + \frac{d}{d_o(R)}} \tag{4}$$

Where

$R_{eff} = 1.763\ R_p^{(0.753+0.197/d)}$	is the effective rain rate,
$d_o = 119R_p^{-0.211}$	is the equivalent cell diameter,
d	is the actual path length (km),
R_p	is the rain rate (mm/hr), and

The coefficients k and α are calculated using equations (2) and (3) similar to the ones used in the ITU-R model.

Comparisons and Results

Different case studies were selected to try to cover as many weather variables as possible, to understand the effect of each factor on the signal attenuation. At this first stage of the experiment, and since approximate comparisons were studied, the clear air received power is assumed to be -12 dBm at 72 GHz and -16 dBm at 84 GHz. Later in the analysis, accurate calculations based on a larger range of data set will be shown to determine the clear air attenuation at 72 GHz and 84 GHz.

Case One

Description

The first case selected corresponds to October 10, 2015 at 04:05 GMT. The rain rate recorded at that time was 4.908 mm/hr thus it corresponds to a moderate rainfall rate. The experimental measured attenuation relative to clear air is 24.9 dB at 72 GHz, and 24.2 dB at 84 GHz. NOAA's weather and climate toolkit [6] was used to get a radar image of the link showing the climate conditions at that time. As shown in Figure 3.2, light to medium rain was concentrated around the receiver region, and dry snow and ice crystals existed over almost half of the path from the side of the transmitter.

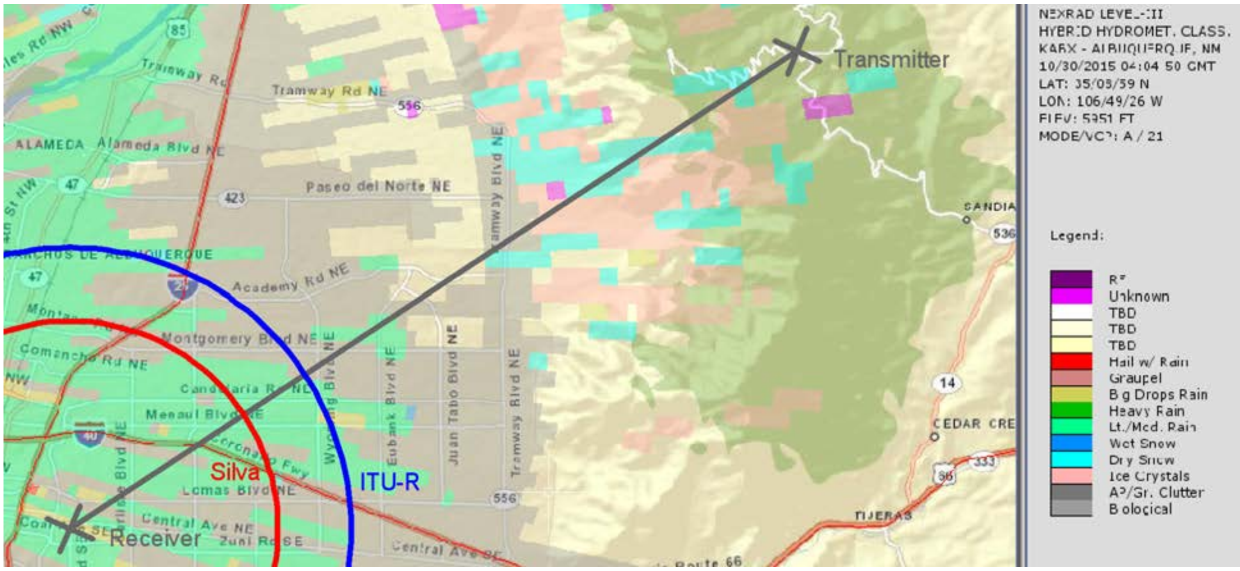

Figure 3.2. Radar Image on October 10, 2015 at 04:05 GMT. The blue circle corresponds to the 7.438 Km ITU-R radius, and the magenta circle corresponds to the 5.509 Km Silva-Mello radius.

The 4.908 mm/hr rainfall rate was used as an input for both the ITU-R model and the Silva-Mello model. To consider the worst case scenario, this rainfall rate was assumed to be consistent all over the path, i.e. that it was raining over the 23 Km path with a rainfall rate of 4.908 mm/hr. For the purpose of this analysis, only the 72 GHz frequency was studied. The attenuations calculated based on the ITU-R model and the Silva-Mello model are shown in Figure 3.3. Note that the 84 GHz frequency was not taken into consideration in some cases because the same conclusions apply to both 72 GHz and 84 GHz.

The goal was to test if the expected rain cell radius resulting from the models calculations matches the real rain cell diameter shown in the radar image in Figure 3.2.

First, according to the model calculations plots, the distance of the path covered by rain that would result in a 24.89 dB attenuation, which is the experimental measured attenuation relative to clear air, was found. In other words, considering continuous uniform rainfall all over the path, what is the quantity of rain that would result in a 24.89 dB attenuation relative to clear air? As shown in Figure 3.3 the rain cell radius according to the ITU-R model calculations is 7.438 Km and the rain cell radius according to the Silva-Mello model calculations is 5.509 Km.

Second, the two radii are drawn on the radar image as shown in Figure 3.2 to compare each radius to the actual rain distribution in the area. The blue circle corresponds to the 7.438 Km ITU-R radius, and the magenta circle corresponds to the 5.509 Km Silva-Mello radius.

Result

According to Figure 3.2, the analysis based on the ITU-R model seems to match the experimental results more than the Silva-Mello model since the rain coverage area matches the light/medium rain area showed by the radar more than the Silva-Mello case. However, the dry snow and ice crystals mentioned earlier were not taken into account in the calculations, and at that point it was unknown if these factors had any effects on the attenuation or not.

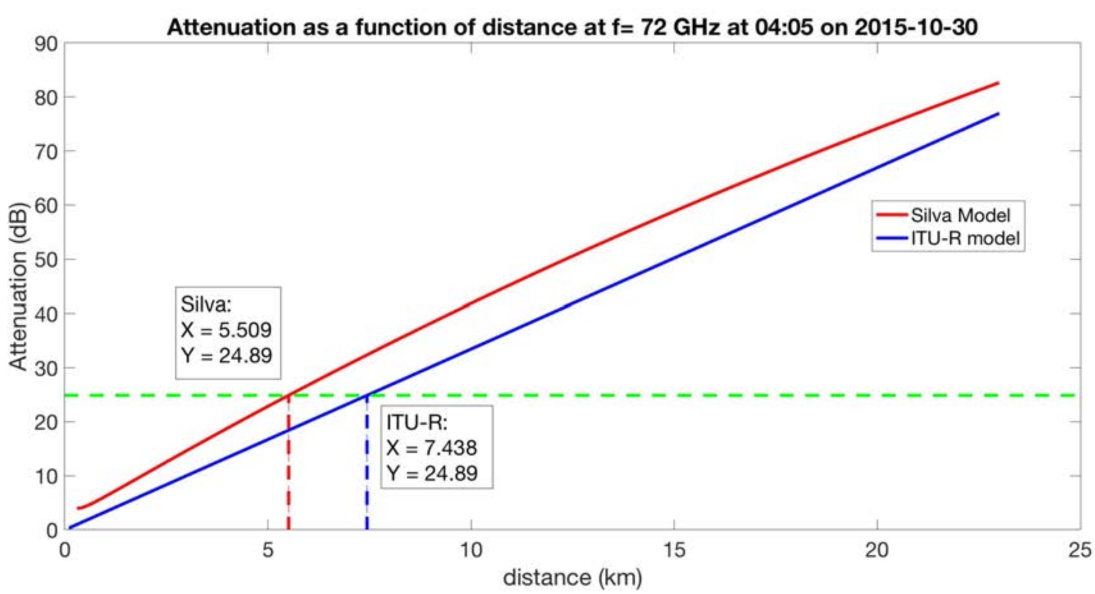

Figure 3.3. ITU-R and Silva-Mello Attenuations at 72 GHz on October 10, 2015 at 04:05 GMT

Case Two

Description

The second case considered corresponds to October 10, 2015 at 01:45 GMT. The rain rate recorded at that time was 0.064 mm/hr thus it corresponds to a light rainfall rate. The experimental measured attenuation relative to clear air is 7.40 dB at 72 GHz, and 6.49 dB at 84 GHz. The same procedure as the one described in case 1 was followed. NOAA's weather and climate toolkit [6] was used to get a radar image of the link showing the climate conditions at that time. The radar image in Figure 3.4, shows that light to medium rain was concentrated around the receiver region, and no other weather factors exist along the path from the transmitter to the receiver.

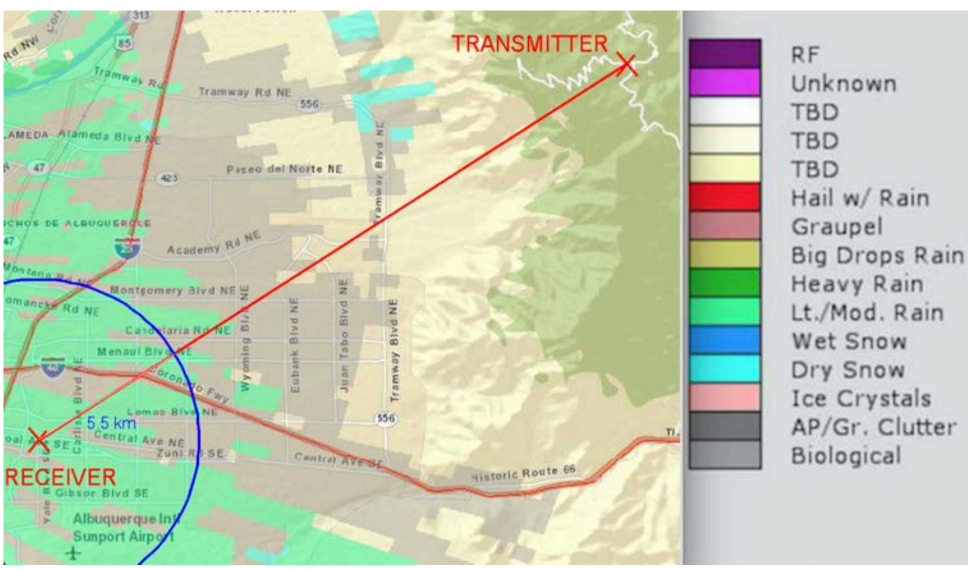

Figure 3.4. Radar Image on October 10, 2015 at 01:45 GMT

Just like in case 1, the 0.064 mm/hr rainfall rate was used as an input for both ITU-R model and Silva-Mello model. Considering continuous and uniform rainfall along the 23 Km path, the attenuations calculated based on the ITU-R model and the Silva-Mello model are shown in Figure

3.5 for the 72 GHz case and in Figure 3.6 for the 84 GHz case.

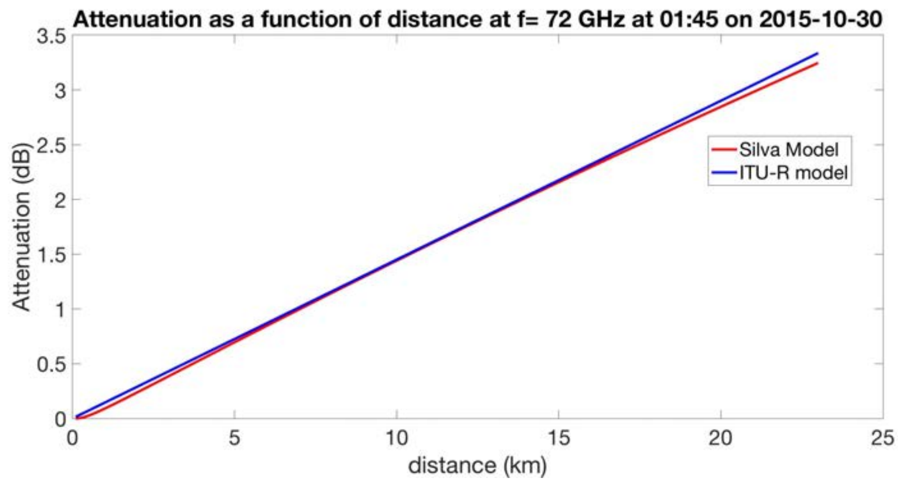

Figure 3.5. ITU-R and Silva-Mello Attenuations at 72 GHz on October 10, 2015 at 01:45 GMT

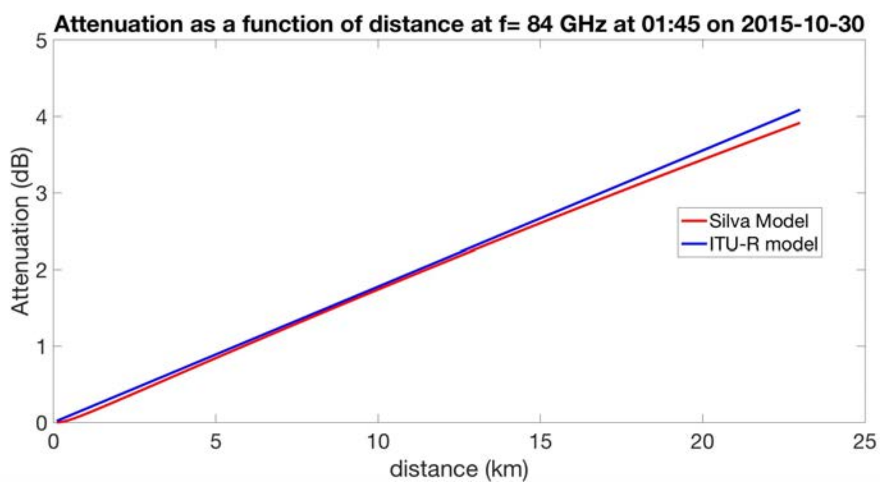

Figure 3.6. ITU-R and Silva-Mello Attenuations at 84 GHz on October 10, 2015 at 01:45 GMT

The plots show that even if it were raining all over the path, the calculated attenuation would not exceed the 3.5 dB at 72 GHz, and would not exceed 4.5 dB at 84 GHz. However, Figure 3.4 shows that in reality the rain cell radius is approximately 5.5 Km, and it was not raining all over the path.

Result

In this case, neither of the models matched the actual experimental results of the WTLE link, or came close to it. Both models underestimated the attenuation value. An explanation for this mismatch could be that even though at the receiver the rain rate was 0.064 mm/hr, a little bit farther, within the 5.5 Km, the rain rate was higher than 0.064 km/hr and it was attenuating the signal more than what was noted in the calculated results. **This case resulted in a very important finding to keep in mind for the overall experiment, which is that the accuracy of the rain rate recorded by the disdrometer at the receiver side can cover a distance that is less than 5.5 Km.**

Case Three

Description

The third case considered corresponds to November 4, 2015 at 22:30 GMT. The rain rate recorded at that time was 8.809 mm/hr thus it corresponds to a moderate rainfall rate. The experimental measured attenuation relative to clear air is 51.72 dB at 72 GHz. The radar image shown in Figure 3.7, shows that light to medium rain was concentrated around the receiver region, and dry snow existed along the path between the transmitter and the receiver.

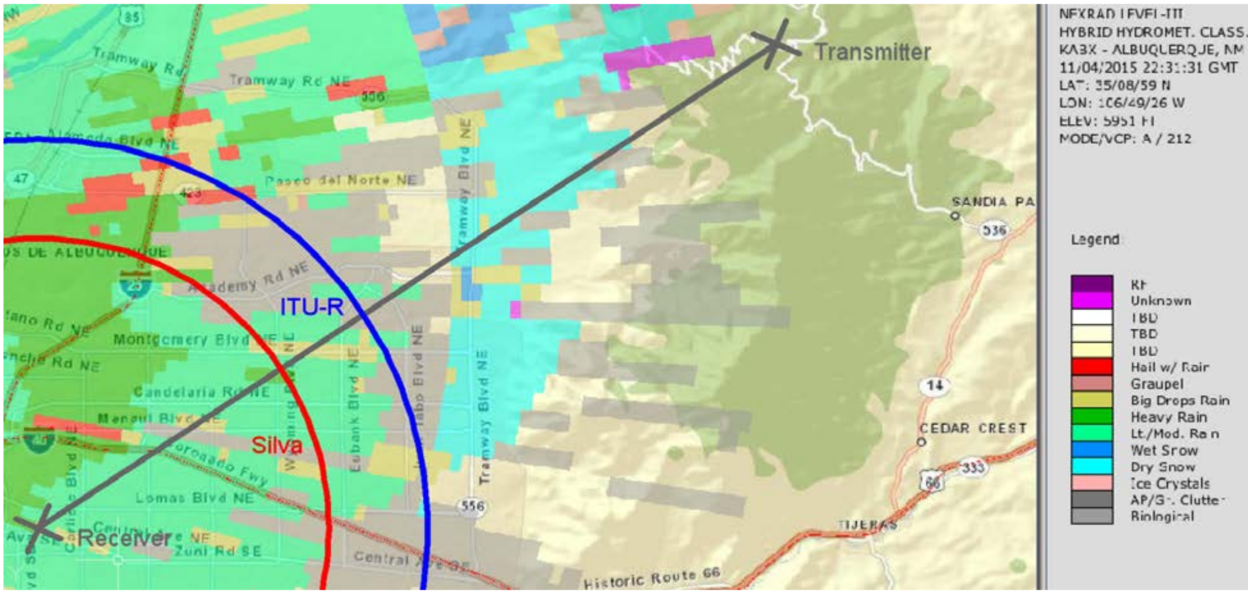

Figure 3.7. Radar Image on November 4, 2015 at 22:30 GMT. The blue circle corresponds to the 10.13 Km ITU-R radius, and the magenta circle corresponds to the 7.556 Km Silva-Mello radius.

Just like in case 1, the 8.809 mm/hr rainfall rate was used as an input for both ITU-R model and Silva-Mello model. Considering continuous and uniform rainfall along the 23 Km path, the attenuations calculated based on the ITU-R model and the Silva-Mello model are shown in Figure 3.8 for the 72 GHz frequency.

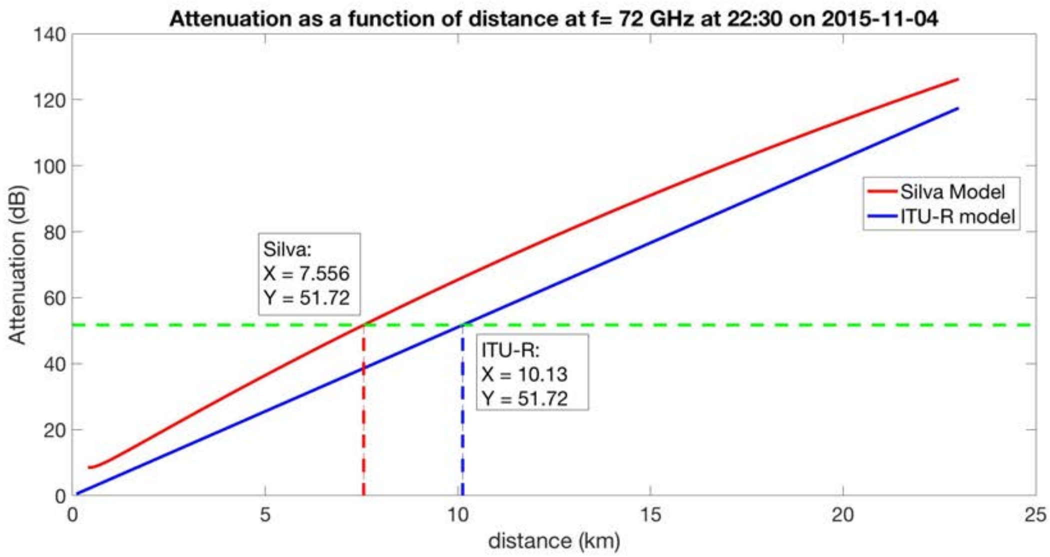

Figure 3.8. ITU-R and Silva-Mello Attenuations at 72 GHz on October 4, 2015 at 22:30 GMT

Applying the same concept described in case 1, the rain cell radius according to the ITU-R model calculations is 10.13 Km and the rain cell radius according to the Silva-Mello model calculations is 7.556 Km. The two radii are drawn on the radar image as shown in Figure 3.7 to compare each radius to the actual rain distribution in the area. The blue circle corresponds to the 10.13 Km ITU-R radius, and the magenta circle corresponds to the 7.556 Km Silva-Mello radius.

Result

According to Figure 3.7, the analysis based on the ITU-R model seems to match the experimental results more than the Silva-Mello model since the rain coverage area matches the light/medium rain area showed by the radar more than the Silva-Mello case. However, the dry snow present along the path was not taken into account in the calculations, and at that point it was unknown if this factor had any effects on the attenuation or not, which leads to analyzing case number four.

Case Four

Description

To understand if dry snow had any effects on the attenuation, the fourth case was considered. This case corresponds to November 17, 2015 at 00:10 GMT. The rain rate recorded at that time was 0.001 mm/hr which can basically be considered as a “no rain” event. The experimental measured attenuation relative to clear air is 17.36 dB at 72 GHz and 22.83 dB at 84 GHz. The same procedure as the one described in case 1 was followed. The radar image shown in Figure 3.9, shows that indeed it was not raining along the path, and the only weather factor present along the path is dry snow.

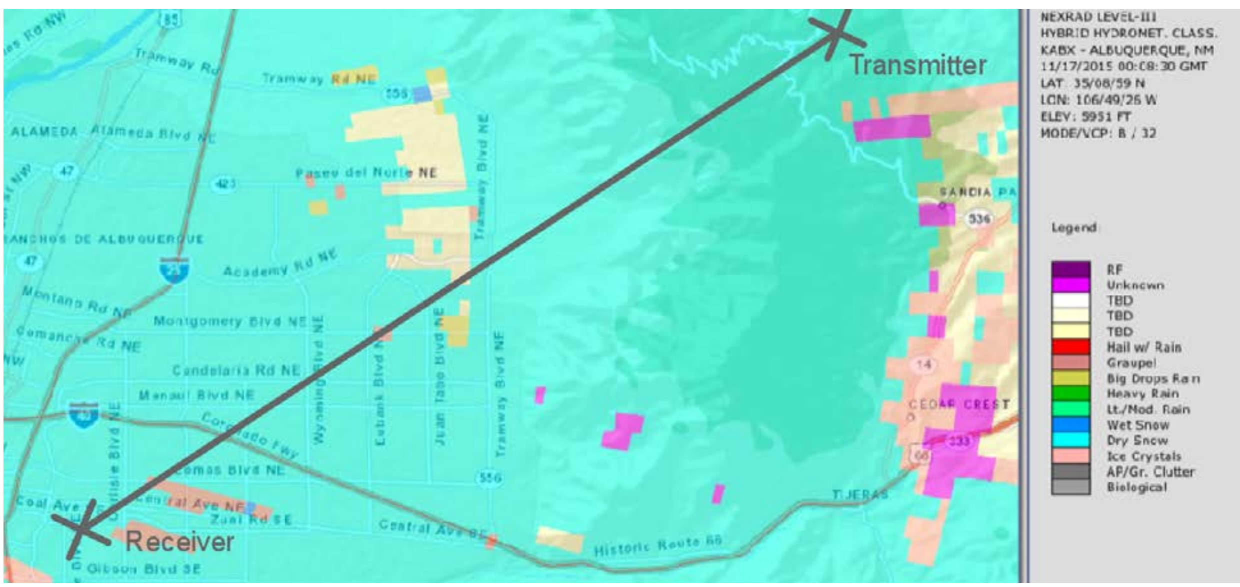

Figure 3.9. Radar Image on November 17, 2015 at 00:10 GMT

Just like in case 1, the 0.001 mm/hr rainfall rate was used as an input for both ITU-R model and Silva-Mello model. Considering continuous and uniform rainfall along the 23 Km path, the attenuations calculated based on the ITU-R model and the Silva-Mello model are shown in Figure

3.10 for the 72 GHz case and in Figure 3.11 for the 84 GHz case. The attenuation based on the two models shows that the rain attenuation was negligible in this case, and the attenuation recorded at the receiver side was due to other factors.

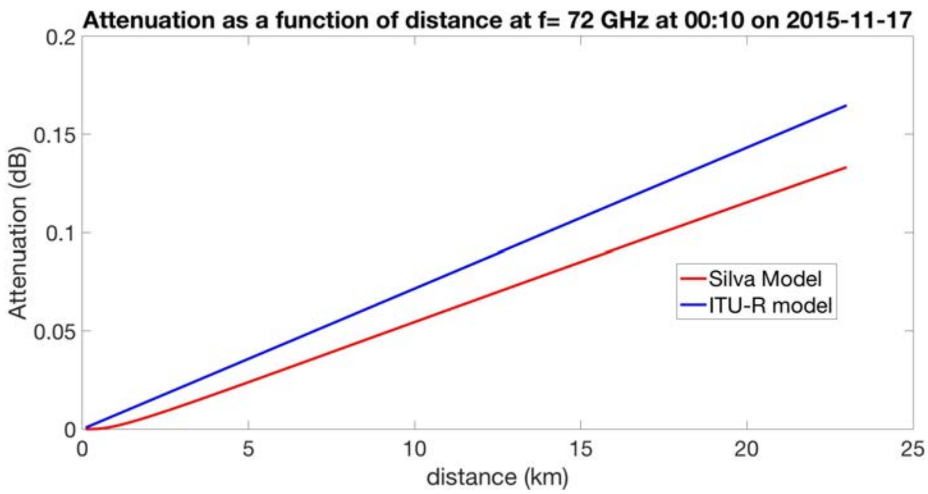

Figure 3.10. ITU-R and Silva-Mello Attenuations at 72 GHz on November 17, 2015 at 00:10 GMT

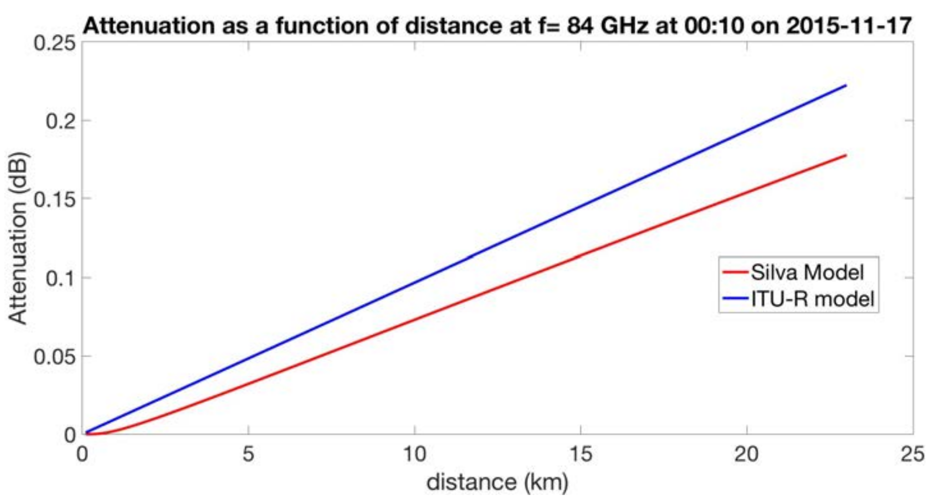

Figure 3.11. ITU-R and Silva-Mello Attenuations at 84 GHz on November 17, 2015 at 00:10 GMT

Result

Since there was no rain, and thus no rain attenuation, and since the only weather factor that existed along the communication link was the dry snow, it can be established that the attenuation relative to clear air was due to the dry snow effects in this case. **Therefore, if dry snow exists along the path (in this case and in the previous cases), it cannot be neglected because it is attenuating the signal.**

Summary

Using the instantaneous analysis, none of the two models showed consistent results for the case studied. Moreover, due to the lack of data availability throughout the link, the data recorded at the receiver was assumed to be consistent all over the path, which was not accurate when compared to the actual climate condition.

A conclusion cannot be drawn based on instantaneous specific cases; thus a better approach would be to analyze the link's behavior over a long period of time and to examine statistical results.

Chapter 4 – General Analysis of the WTLE Link

Overview

After using the instantaneous analysis to understand the different weather factors that might affect the signal, a more general analysis was considered to understand the overall behavior of the link over a certain period of time. The timespan of the following study goes roughly from October 1st, 2015 to July 15th, 2016. The model under consideration was the ITU-R model for rain attenuation [7, 12]. The rain rate (mm/hr) recorded by the disdrometer, and the received power were used to compare experimental and theoretical results.

Several analyses were considered:

1) A Comparison of the measured rain attenuation relative to clear air and the calculated rain attenuation based on the ITU-R model [7, 12] exceeded for 0.01% of the time and 0.1% of the time at 72 GHz.
2) A Comparison of the measured rain attenuation relative to clear air and the calculated rain attenuation based on the ITU-R model [7, 12] exceeded for 0.01% of the time and 0.1% of the time at 84 GHz.
3) A Comparison of the experimental results at 72 GHz and 84 GHz.

Theoretical Model

The ITU-R procedure used for the following part is a combination of two ITU-R models. The first model [7] calculates the attenuation as a function of distance, and the second model [12] computes an effective path length to calculate the total attenuation over the region of interest.

ITU-R P.838-3

The ITU-R P.838-3 model [7] is the same model used in Chapter 3 for the instantaneous comparison. The attenuation (dB/Km) is given by the following equation:

$$\gamma_R = kR^{\alpha} \tag{5}$$

Where R is the rain rate (mm/hr) exceeded for p% of the time,

k and α are coefficients function of the frequency and they are calculated as described previously in Chapter 3.

ITU-R P.530

The ITU-R P.530 model [12] calculates the total attenuation (dB) exceeded for a p% of time by multiplying the attenuation resulting from the ITU-R P.838-3 model [7] by an effective path length as follows:

$$A_p = \gamma_R d_{eff} \tag{6}$$

Where γ_R is the specific attenuation (dB/Km),

$d_{eff} = d \times r$ is the effective path length where d (Km) is the actual path length, and r is a distance factor calculated as shown in equation (7).

$$r = \frac{1}{0.477\, d^{0.633} R_p^{0.073\,\alpha} f^{0.123} - 10.579\,(1 - \exp(-0.024d))} \qquad (7)$$

Where R_p is the rain rate (mm/hr) exceeded for p% of the time,

d is the actual path length (Km),

f is the frequency of operation (GHz)

α is the frequency dependent coefficient.

The characteristics of the ITU-R P.530 model are shown in Table 4.1.

<table>
<tr><th>Method</th><th>Application</th><th>Type</th><th>Output</th><th>Frequency</th><th>Distance</th><th>% Time</th><th>Terminal Height</th><th>Input Data</th></tr>
<tr><td rowspan="8">ITU-R P.530</td><td rowspan="8">Line-of-sight fixed links</td><td rowspan="8">Point-to-point line-of-sight</td><td rowspan="8">Path loss diversity improvement (clear air conditions)</td><td rowspan="8">Approximately 150 MHz to 100 GHz</td><td rowspan="8">Up to 200 Km if line-of-sight</td><td rowspan="3">All percentages of time in clear air conditions</td><td rowspan="8">High enough to ensure specified path clearance</td><td>Distance</td></tr>
<tr><td>Tx height</td></tr>
<tr><td>Frequency</td></tr>
<tr><td rowspan="3">0.001 in to 1 in precipitation conditions</td><td>Rx height</td></tr>
<tr><td>Percentage time</td></tr>
<tr><td>Path obstruction data</td></tr>
<tr><td rowspan="2">Worst month for attenuation</td><td>Climate data</td></tr>
<tr><td>Terrain information</td></tr>
</table>

Table 4.1. ITU-R P.530 Characteristics

Experimental Procedure

Calculated Attenuation

The first part of the experiment was to calculate the total rain attenuation for the WTLE link using the rain rate and the ITU-R model. The calculation was performed according to the following steps:

1) A cumulative distribution function (CDF) of the rain rate was plotted to show the rain distribution at the receiver site from October 1st, 2015 till July 15th, 2016.
2) Using the rain rate CDF, the rain rate exceeded for 0.1% of the time and the rain rate exceeded for 0.01% of the time were found.
3) These rain rate were then inputted simultaneously in equation (3) to calculate the corresponding attenuation in dB/Km.
4) The total rain attenuation exceeded for 0.1% of the time and the total rain attenuation exceeded for 0.01% of the time were calculated according to the ITU-R model [7, 12] by multiplying the attenuation in dB/Km by the effective path length as shown in equations (6) and (7).

Measured Attenuation

The second part of the experiment was to calculate the total rain attenuation for the WTLE link using the recorded received power at the receiver. Since the rain attenuation was calculated relative to the clear air attenuation basis, the power of the transmitted signal does not affect the results and is not a point of interest. The calculation was performed according to the following steps:

1) A cumulative distribution function for the total experimental received power was plotted for the time period of interest. This CDF is plotted using the absolute values of the received power, and all the received powers mentioned in the following analysis are considered to be in absolute values.
2) Using the total received power CDF, the total received power recorded for 90% of the time was found; this received power corresponds to the clear air received power since it can be assumed that for more than 90% of the time no rain events are noted on the WTLE link.
3) Using the total received power CDF, the total received power exceeded for 0.1% of the time and the total received power exceeded for 0.01% of the time were found.
4) The rain attenuation relative to clear air exceeded for 0.1% and 0.01% of the time were calculated by subtracting the clear air received power from the total received powers exceeded for 0.1% and 0.01% of the time correspondingly.
5) The noise floor level is a very important factor to be taken into consideration to make sure that the data used in the experiment are valid. At 72 GHz the noise floor level is -75 dBm and at 84 GHz the noise floor level is -80 dBm. For the purpose of the comparison with the CDF plot, the noise floors are also used in absolute values. Therefore, any recorded value below these two thresholds must be evaluated and must fall into one of the two following categories:

- The value larger than the threshold (in absolute value) was reached during a rain event, thus it must be taken into consideration for the statistical analysis of the experiment as a rain event, however its value was not accurate. In other words, this value was kept in the statistical analysis and was considered as a flat 75 dBm or 80 dBm received power depending on the frequency of operation.
- The value larger than the threshold (in absolute value) was reached suddenly and for a relatively short period of time during a clear day event, which means that it was the result of a failure in the experiment or in the equipment, and thus should be totally neglected and removed from the analysis.

6) Finally, the dynamic range for the rain event at each frequency was calculated by subtracting the noise floor level from the clear air received power. Note that any rain attenuation relative to clear air that exceeded the dynamic range was not a valid value and was not considered in the analysis.

Comparisons and Results

Calculated Attenuation

First, the rain attenuation according to the ITU-R model was calculated.

The CDF for the rain rate is shown in Figure 4.1. The rain rate exceeded for 0.1% of the time is 5.27 mm/hr and the rain rate exceeded for 0.01% of the time is 47.145 mm/hr.

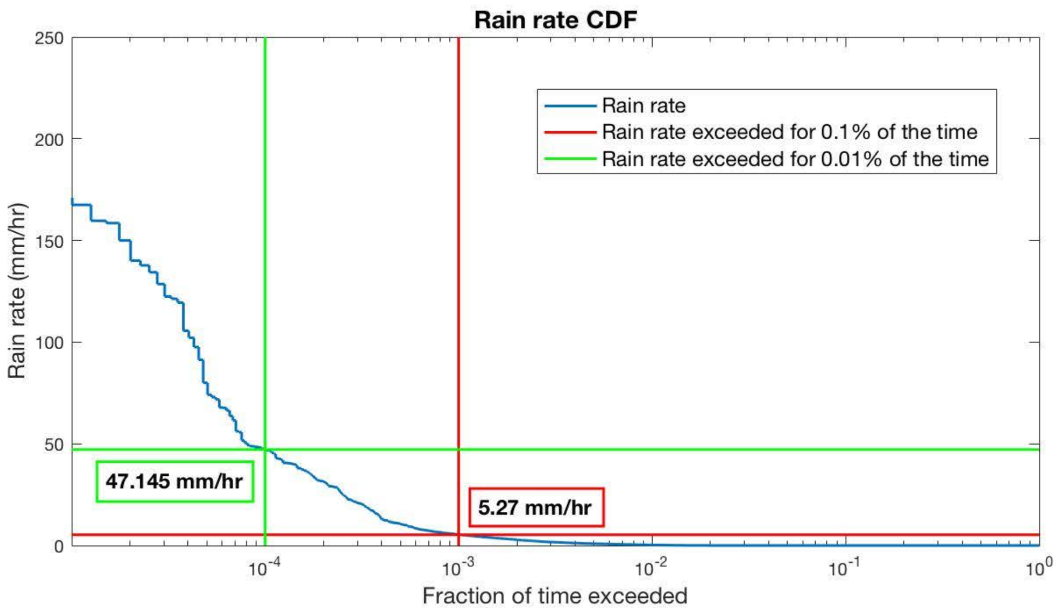

Figure 4.1. WTLE Link Rain Rate Cumulative Distribution Function

Therefore, using the ITU-R model [7, 12] as described earlier, the calculated rain attenuation exceeded for 0.1% of the time at 72 GHz is 42.087 dB and the calculated rain attenuation exceeded for 0.01% of the time at 72 GHz is 145.753 dB. Similarly, the calculated rain attenuation exceeded for 0.1% of the time at 84 GHz is 44.118 dB and the calculated rain attenuation exceeded for 0.01% of the time at 84 GHz is 148.133 dB. The results are summarized in Table 4.2.

Fraction of time exceeded (%)	**Rain rate (mm/hr)**	**Rain attenuation for f = 72 GHz (dB)**	**Rain attenuation for f = 84 GHz (dB)**
0.1	5.27	42.087	44.118
0.01	47.145	145.753	148.133

Table 4.2. WTLE Link Calculated Attenuation Summary

Measured Attenuation

72 GHz Frequency

Second, the attenuation according to the received experimental power was calculated.

The CDF for the total measured received power at 72 GHz is shown in Figure 4.2. The clear air received power seen for 90% of the time is 10.22 dBm. The measured attenuation values that have reached the 75 dBm threshold were not exactly equal to 75 dBm, but this is the largest value that the receiver in the experiment can record. This data was only kept to calculate correctly the probability of the rain events but their exact value (75 dBm in absolute value) does not add any significance to the experiment. Figure 4.2 shows that the 0.01% exceedance value is within these data points, thus this value could not be considered for comparison purposes. The 0.1% exceedance value is just at the edge of the curve's saturation and could be considered for comparison purposes. Therefore, for the 0.1% of the time exceedance rate, the total received power is 75 dBm.

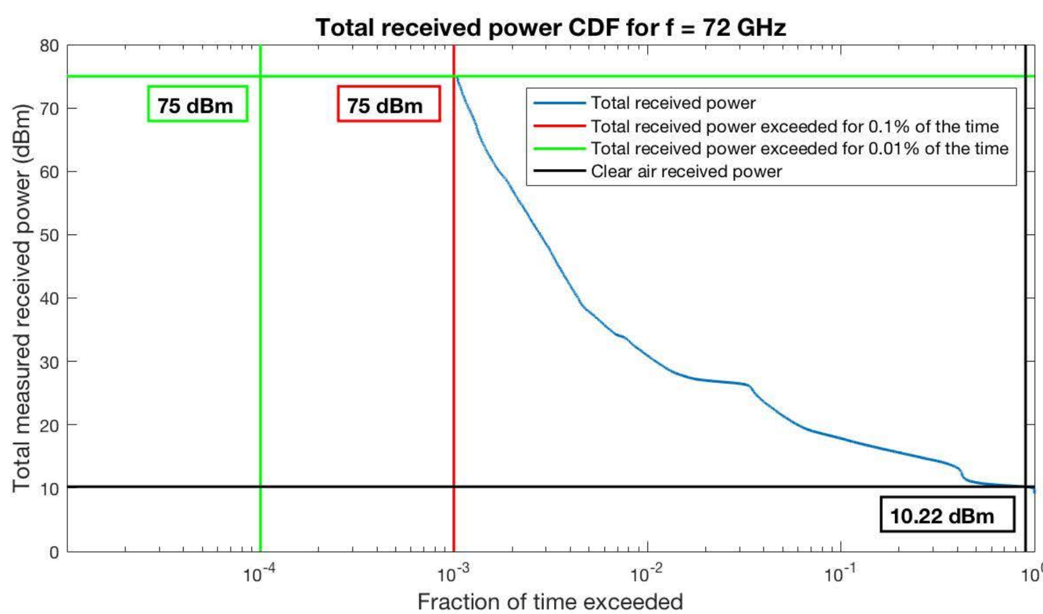

Figure 4.2. WTLE Link Total Measured Received Power Cumulative Distribution Function at 72 GHz

The rain attenuation relative to clear air is calculated as follows:

$$rain\ attenuation\ relative\ to\ clear\ air = total\ received\ power - clear\ air\ received\ power \quad (8)$$

Therefore, the rain attenuation relative to clear air exceeded for 0.1% of the time is 64.78 dB. The results are summarized in Table 4.3.

Fraction of time exceeded	Total received power for f = 72 GHz (dBm)	Rain attenuation relative to clear air for f = 72 GHz (dB)
0.1	75	64.78

Table 4.3. WTLE Link Measured Attenuation at 72 GHz Summary

Finally, the dynamic range of the rain event under consideration is calculated as follows:

$$dynamic\ range = clear\ air\ received\ power - noise\ floor \quad (9)$$

$$dynamic\ range = 10.22 - (-75)$$

$$dynamic\ range = 85.22\ dB$$

84 GHz Frequency

Similarly, the CDF for the total measured received power at 84 GHz is shown in Figure 4.3. The clear air received power seen for 90% of the time is 12.451 dBm. For the same reasons explained for the 72 GHz frequency, the total received power exceeded for 0.01% of the time is ignored and the total received power exceeded for 0.01% of the time is 80 dBm (in absolute value).

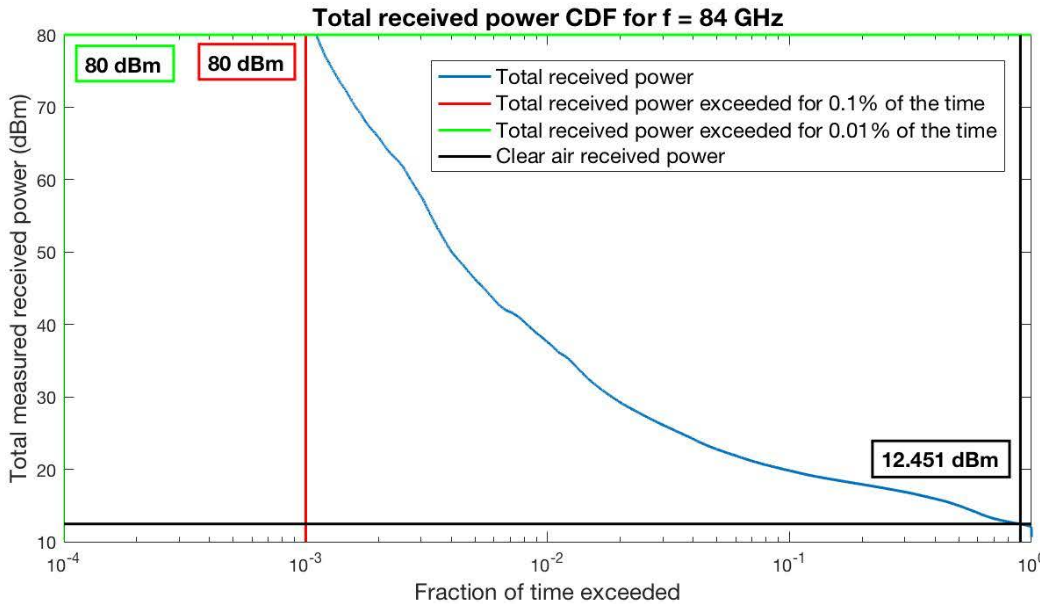

Figure 4.3. WTLE Link Total Measured Received Power Cumulative Distribution Function at 84 GHz

The rain attenuation relative to clear air is calculated using equation (8). Therefore, the rain attenuation relative to clear air exceeded for 0.1% of the time is 67.549 dB. The results are summarized in Table 4.4.

Fraction of time exceeded	Total received power for f = 84 GHz (dBm)	Rain attenuation relative to clear air for f = 84 GHz (dB)
0.1	80	67.549

Table 4.4. WTLE Link Measured Attenuation at 84 GHz Summary

Next, the dynamic range is calculated using equation (9).

$$dynamic\ range = clear\ air\ received\ power - noise\ floor \quad (9)$$

$$dynamic\ range = 12.451 - (-80)$$

$$dynamic\ range = \ 90.451\ dB$$

Results Analysis

The computed rain attenuation using the ITU-R model and the measured attenuation calculated using experimental data were compared to check the validity of the ITU-R model for the WTLE link. The results corresponding to the 0.1% of the time exceedance rate were compared only, because the ones corresponding to the 0.01% of the time exceedance rate showed to be out of bound. The difference is calculated according to equation (10). The results are summarized in Table 4.5 for the 72 GHz values and Table 4.6 for the 84 GHz values.

$$Difference = \ \ Experimental\ rain\ attenuation - ITUR\ rain\ attenuation \quad (10)$$

Rain rate (mm/hr)	**ITU-R rain attenuation (dB)**	**Experimental rain attenuation (dB)**	**Attenuation difference (dB)**
5.27	42.087	64.78	22.693

Table 4.5. WTLE Link Comparison of ITU-R and Experimental Results at 72 GHz

Rain rate (mm/hr)	ITU-R rain attenuation (dB)	Experimental rain attenuation (dB)	Attenuation difference (dB)
5.27	44.118	67.549	23.431

Table 4.6. WTLE Link Comparison of ITU-R and Experimental Results at 84 GHz

For both frequencies of operation, the ITU-R showed optimistic results when compared to the experiment. However, the interesting finding is that, for the same rain rate, the inconsistency of the ITU-R model compared to the experimental results was consistent between the two frequencies of operation. Though, as noted in Chapter 3, the disdrometer is giving information about the rain rate only at the receiver site, and the validity of this data covers much less than 5.5Km of the 23 Km link. This means that the high attenuation recorded by the experiment could be due to more severe rain events that were not caught by the disdrometer, whereas the rain attenuation calculated using the ITU-R model resulted from using the low rain rate noted by the disdrometer. Therefore, this could have caused having the optimistic ITU-R results compared to the experimental ones. More analysis is performed in Chapter 5, to examine the accuracy of the ITU-R model for the WTLE experiment.

72 GHz vs. 84 GHz

The experiment analysis was done for the 72 GHz and 84 GHz frequencies simultaneously. However, if a relation for the signal behavior between these two frequencies is found, the experiment can be done for just one of the frequencies, and the result can be extrapolated for the second frequency, which would consequently save time and resources.

For the purpose of this analysis, only the experimental results were used. In addition, only the results corresponding to the 0.1% of the time exceedance rate were compared because they were the only ones proven to be valid and within the dynamic range of the experiment.

Therefore, two factors were compared for the two frequencies: the clear air received power (Table 4.7) according to equation (11) , and the rain attenuation relative to clear air (Table 4.8). The difference is calculated according to equation (12).

$$Difference = \ Received\ power\ at\ 84\ GHz - Received\ power\ at\ 72\ GHz \qquad (11)$$

$$Difference = \ Attenuation\ at\ 84\ GHz - Attenuation\ at\ 72\ GHz \qquad (12)$$

Received power at f = 72 GHz (dBm)	**Received power at f = 84 GHz (dBm)**	**Received power difference (dBm)**
10.22	12.451	2.231

Table 4.7. WTLE Link Clear Air Attenuation Comparison

Attenuation at f = 72 GHz (dB)	**Attenuation at f = 84 GHz (dB)**	**Attenuation difference (dB)**
64.78	67.549	2.769

Table 4.8. WTLE Link Rain Attenuation Relative to Clear Air Comparison

Table 4.7 and Table 4.8 show that the clear air received power at 84 GHz was larger than the one at 72 GHz by 2.231 dBm, and the rain attenuation relative to clear air at 84 GHz was larger than the one at 72 GHz by 2.769 dB.

Consequently, if the 84 GHz frequency is chosen to perform the experiment, one would confidently say that this would cover the worst case scenario. The rain attenuation value relative to clear air recorded for the 84 GHz link, will be always greater than the one at 72 GHz by about 2.769 dB under the same experimental conditions.

Summary

Using the statistical approach for the WTLE link showed that the ITU-R model does not match with the experiment conducted in Albuquerque, New Mexico. Nevertheless, this conclusion could not be validated due to the lack of data along the communication path. Consequently, further analysis needs to be performed.

Note: Recently, it has been noted that some inconsistencies in the experiment are not permitting a correct estimation for the clear air received power value. However, it is known that once corrections are made, and exact clear air received power value can be calculated, the gap between the theoretical and experimental results will increase. Therefore, since the model does not match with the experiment now, it will absolutely not match with the experiment after the corrections are made. Moreover, the method presented can be applied to any future data collected, so the theory and the procedure would be the same for any data set.

Chapter 5 – Short Link Prototype

Overview

To overcome the ambiguity caused by the missing data over the 23 Km link, and to have better control over the experiment, a short link of 0.56 Km operating at 84 GHz was built. The 84 GHz receiver located at the top of the COSMIAC building that was used for the WTLE experiment was redirected to serve as the receiver for the short link experiment. An 84 GHz transmitter was placed on the top of the Schafer Corporation building. The equipment locations are shown in Figure 5.1. Rain rate and received power are still recorded at the receiver site. In this case, the rain rate seen at the receiver can be assumed to be consistent for the overall link because the communication path is short, and statistical study is under consideration. The data used for the short link analysis spans roughly from August 3, 2016 till September 30, 2016. The same ITU-R model [7, 12] used in the Long link analysis was tested in this short link experiment. Even though the sample size is small, it is sufficient in order to perform a preliminary test to check whether the ITU-R model is accurate for the region of Albuquerque or not.

In this chapter, two analyses were performed:

1) A Comparison of the measured rain attenuation relative to clear air and the calculated rain attenuation based on the ITU-R model [7, 12] exceeded for 0.01% of the time and 0.1% of the time at 84 GHz.
2) A Comparison of the measured rain attenuation relative to clear air and the calculated rain attenuation based on the ITU-R model as a function of the rain rate, and finding new k and α coefficients for the ITU-R model to fit it to the experimental results.

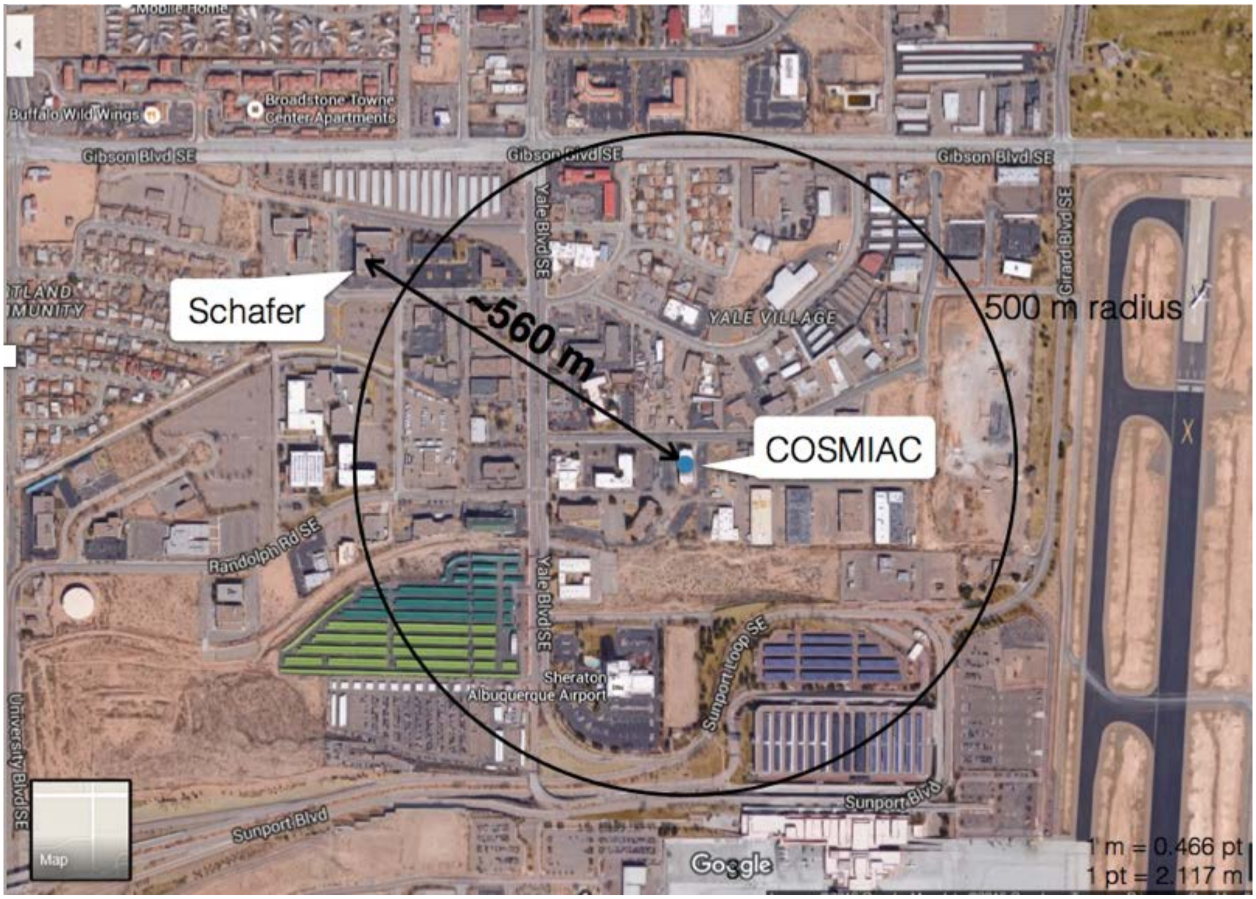

Figure 5.1. Short Link Experiment Location

Comparisons and Results

Calculated Attenuation

First, the rain attenuation according to the ITU-R model was calculated. The CDF for the rain rate is shown in Figure 5.2. The rain rate exceeded for 0.1% of the time is 13.715 mm/hr and the rain rate exceeded for 0.01% of the time is 129.29 mm/hr.

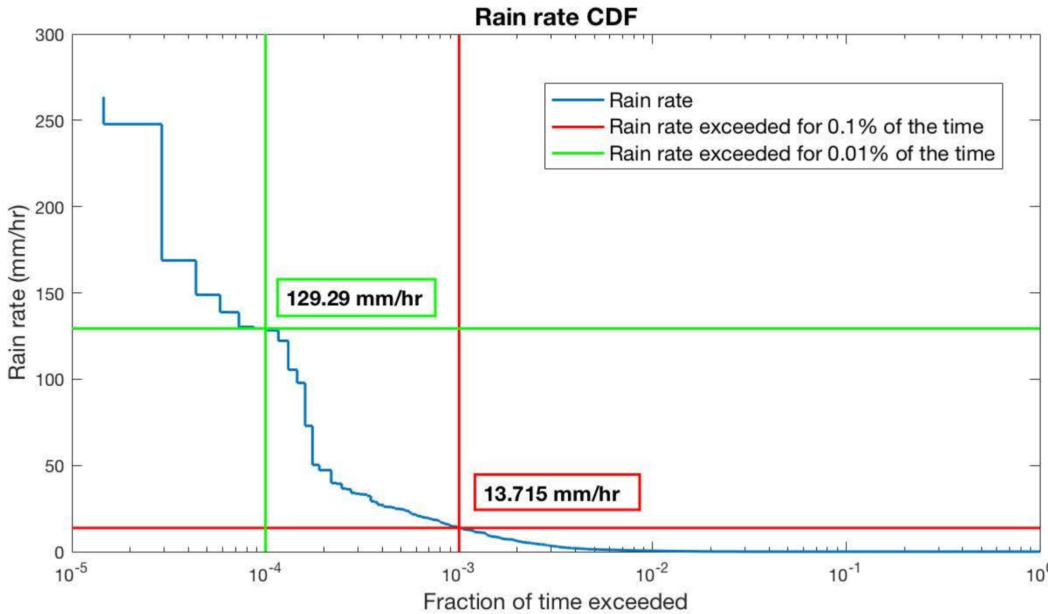

Figure 5.2. Short Link Rain Rate Cumulative Distribution Function

The calculated rain attenuation exceeded for 0.1% of the time at 84 GHz is 8.344 dB and the calculated rain attenuation exceeded for 0.01% of the time at 84 GHz is 34.734 dB according to the ITU-R model.

Measured Attenuation

Second, the attenuation according to the received experimental power was calculated. The noise floor level for the link at 84 GHz is -80 dBm. The same procedure as the one considered for the long link in Chapter 4 was followed to assess which data are useful to keep for the experiment and which data should be deleted due to any failures in the equipment or any improbable events in the experiment. Again, the CDF is plotted using the absolute values of the received power, and all the received powers mentioned in the following analysis are considered to be in absolute values.

The CDF for the total measured received power is shown in Figure 5.3. The clear air received seen for 90% of the time is 20.202 dBm. The total attenuation received power for 0.1% of the time is 43.192 dBm and the total received power exceeded for 0.01% of the time is 58.857 dBm.

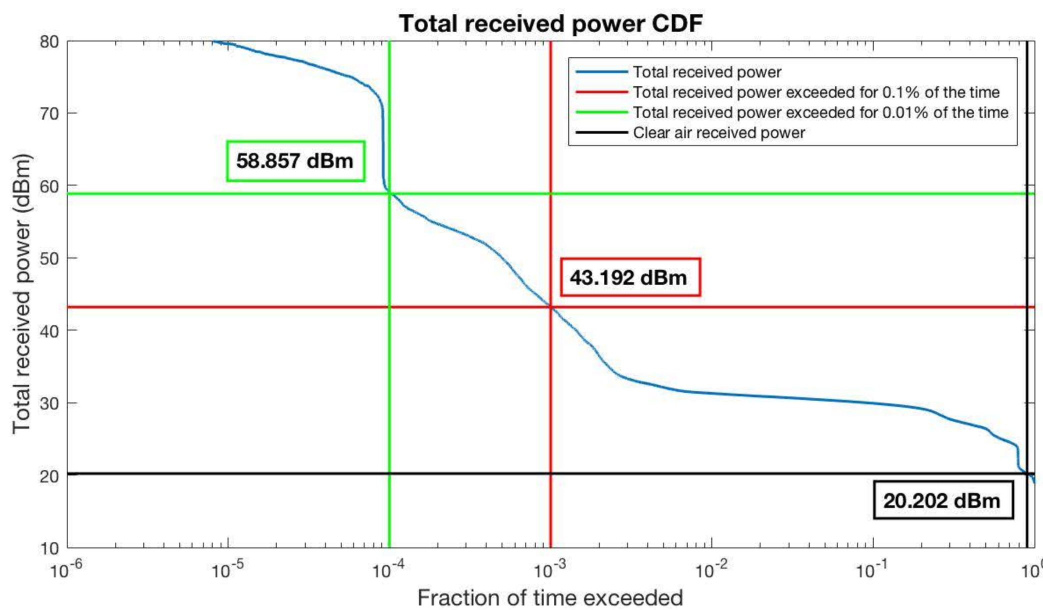

Figure 5.3. Short Link Total Measured Received Power Cumulative Distribution Function at 84 GHz

The rain attenuation relative to clear air is calculated using equation (8). Therefore, the rain attenuation relative to clear air exceeded for 0.1% of the time is 22.99 dB and the rain attenuation relative to clear air exceeded for 0.01% of the time is 38.655 dB.

Next, the dynamic range is calculated using equation (9).

$$dynamic\ range = clear\ air\ received\ power - noise\ floor \tag{9}$$

$$dynamic\ range = 20.202 - (-80)$$

$$dynamic\ range = 100.202\ dB$$

Results Analysis

Once again, the values resulting from the ITU-R model calculations and the experimental results were compared. The difference is calculated according to equation (10). The results are summarized in Table 5.1.

Fraction of time exceeded	Rain rate (mm/hr)	ITU-R rain attenuation (dB)	Experimental rain attenuation (dB)	Attenuation difference (dB)
0.1%	13.715	8.344	22.99	14.646
0.01%	129.29	34.734	38.655	3.921

Table 5.1. Short Link Comparison of ITU-R and Experimental Results

The ITU-R model seems to underestimate the rain attenuation compared to the real values. The difference between the ITU-R model results and the experimental results is more severe at low rain rate than at higher rain rates. Thus, it is obvious that the ITU-R model is not valid for the WTLE experiment conducted in Albuquerque, New Mexico.

Fitting of ITU-R Model

The K and α coefficients used in the analysis so far are given by the ITU-R model. However, these coefficients are highly dependent on climate conditions and cannot be assigned one single value to cover any experiment, independently of the region where the experiment is conducted. Conversely, the climate regime of the region under consideration should be taken into account to find the appropriate values of the K and α coefficients to check if the ITU-R model can correctly estimate the experimental signal attenuation. Therefore, in the following section, the least square error fitting method was used to fit the K and α coefficients in the ITU-R model to the experimental results. As mentioned earlier, the ITU-R model uses the rain rate to calculate the attenuation in dB/Km according to equation (5). Originally, the k and α coefficients given by the ITU-R at 84 GHz are the following:

$k = 1.2164$

$\alpha = 0.6999$

After fitting the experimental values, it turned out that the corrected k and α coefficients, with a 95% confidence bounds, that should be used with the ITU-R model to calculate the attenuation for the WTLE link are the following:

$k = 17.5 \quad (17.18,\ \ 17.82)$

$\alpha = \ 0.06003 \ \ (0.05796,\ \ 0.0621)$

Figure 5.4 shows the measured attenuation as a function of rain rate, the original calculated attenuation using the k and α coefficients suggested by the ITU-R model, and the fitted attenuation corresponding specifically to the short link experiment.

A Korean group tested the ITU-R model for rain attenuation at 73 GHz and 83 GHz over a short 0.5 Km terrestrial link [13]. They proved that the ITU-R model resulted in a good estimate for the rain rates below 100 mm/hr, but it was inconsistent for the rain rates above 100 mm/hr.

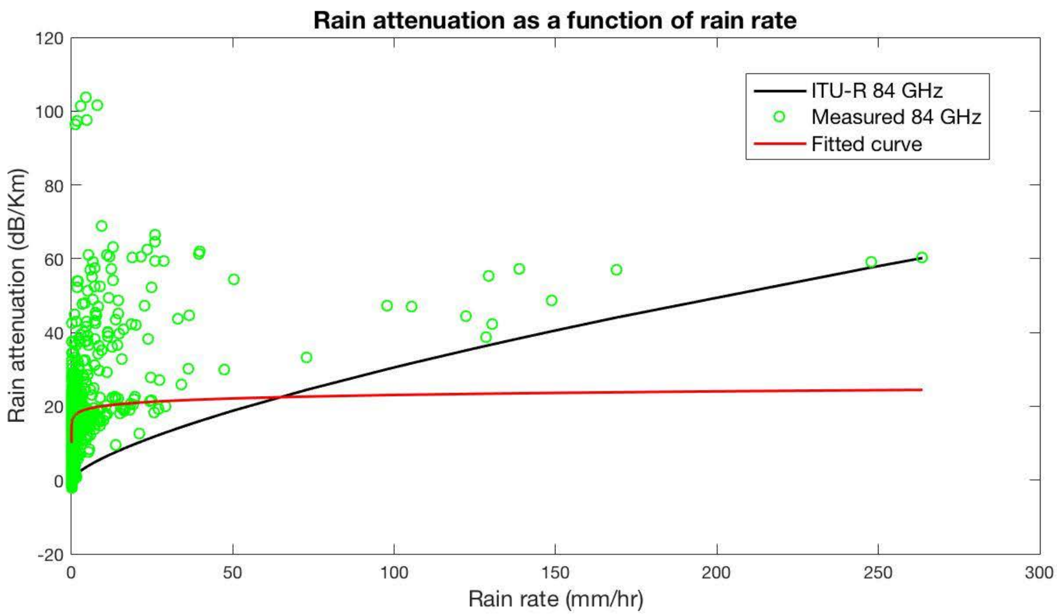

Figure 5.4. Rain Attenuation as a Function of Rain Rate

The attenuation according to the ITU-R model [7, 12] was calculated again using the k and α coefficients found from the curve fitting procedure. The new calculations showed that the calculated rain attenuation exceeded for 0.1% of the time is 26.342 dB and the attenuation exceeded for 0.01% of the time is 29.751 dB. To check if these new coefficients showed some improvement to the ITU-R model, the results are summarized in Table 5.2.

Fraction of time exceeded	Rain rate (mm/hr)	Difference with old k and α (dB)	Difference with new k and α (dB)
0.1%	13.715	14.646	-3.352
0.01%	129.29	3.921	8.904

Table 5.2. Comparison of ITU-R Model before fitting and after fitting

When the rain rate was 13.715 mm/hr, at the lower limit of the heavy rain rate category according to Table 2.3, the fitted curve showed significant improvement in matching the ITU-R model to the experiment compared to the results noted previously when using the original k and α coefficients values. However, when the rain rate was 129.29 mm/hr, which is categorized as violent rain rate according to Table 2.3, the fitted curve coefficients resulted in a worse matching than the one gotten when using the original k and α coefficients with the ITU-R model.

Albuquerque is considered to be slightly in the heavy rain rate category, as mentioned in Chapter 3. Moreover, it is clearly noticeable from Figure 5.4 that the majority of the rain events occurred between 0 and 25 mm/hr. A larger set of data is needed to validate the following theory, however as a preliminary finding, the power law relationship $\gamma_R = kR^{\alpha}$ given by the ITU-R to calculate the rain attenuation cannot be fitted to the real data for the Albuquerque region. A different equation form having a steeper slope for low rain rates and a slope converging to saturation at high rain rates must be generated.

Chapter 6 – Conclusion

The ITU-R model for rain attenuation [7, 12] proved to be invalid for the WTLE experiment. This model depends highly on the k and α coefficients, that in turn depend on the frequency of operation and on the rain regime of the region of interest.

Even when trying to fit these coefficients to the experiment using the least square error, a general result satisfying low rain rates and high rain rates concurrently could not be found. A new form of the equation might be needed to account for the special climate conditions in Albuquerque, New Mexico.

The WTLE experiment is an ongoing project, more resources will be added continuously to help improve the accuracy of the experiment and understand the effects of the weather conditions on the propagating signal in more depth. Some of the expected improvements in the future are, adding disdrometers and weather stations at different locations along the path to have a better understanding of the climate conditions all over the path, and adding a fog sensor at the transmitter site on top of the Sandia Peak to be able to monitor the clouds effect on the signal.

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Appendix A

Matlab Code for the WTLE Link Statistical Analysis

Matlab version: Matlab_R2016a

```
clear all;
close all;
clc;

%--------------------------------------------------------------------------
%Read the attenuation at 72 GHz and 84 GHz from the nids text files and save
them in a single column.
f=input('Input the frequency of operation 72 or 84 (GHz):  ');
if f == 72;
    noisefloor = -75;
else
    noisefloor = -80;
end

if f == 72;
    pathstr = '/Users/nadinedaoud/Documents/UNM/Work/Fall 2016/Long Link/72
GHz attenuation nids files';
    folder_name=uigetdir(pathstr);
    files=dir(fullfile(folder_name,'*.txt'));
    curr_folder=pwd;
    cd(folder_name);
    disp(length(files));
    for i=1:length(files)
        fid=fopen(files(i).name,'r');
        m = textscan(fid,'%*f %*f %*f %*f %*f %*f %*f %*f %f %*f %*f %*f %*f
%*f %*f %*f','delimiter',' ','MultipleDelimsAsOne',1);
        if i==1
            A(:,i)=m{:};
        else
            A = vertcat(A, m);
        end
        fclose(fid);
    end
    save('attenuation72.mat','A');
else
    pathstr = '/Users/nadinedaoud/Documents/UNM/Work/Fall 2016/Long Link/84
GHZ attenuation nids files';
    folder_name=uigetdir(pathstr);
    files=dir(fullfile(folder_name,'*.txt'));
    curr_folder=pwd;
    cd(folder_name);
    disp(length(files));
    for i=1:length(files)
        fid=fopen(files(i).name,'r');
        m = textscan(fid,'%*f %*f %*f %*f %*f %*f %*f %*f %f %*f %*f %*f %*f
%*f %*f %*f','delimiter',' ','MultipleDelimsAsOne',1);
        if i==1
            A(:,i)=m{:};
```

```
        else
            A = vertcat(A, m);
        end
        fclose(fid);
    end
    save('attenuation84.mat','A');
end

%---------------------------------------------------------------------------
%Save the total attenuation at 72 GHz and 84 GHz in two different columns
if f == 72;
    attenuation72=load('attenuation72.mat');
    attenuation72=attenuation72.A;
    Allattenuation = {cat(1,attenuation72{:})};
    Allattenuation = Allattenuation{:};
else
    attenuation84=load('attenuation84.mat');
    attenuation84=attenuation84.A;
    Allattenuation = {cat(1,attenuation84{:})};
    Allattenuation = Allattenuation{:};
end

%---------------------------------------------------------------------------
%Read the rain rate for 72 GHz and 84 GHz from the nids text files and save
them in a single column.
pathstr = '/Users/nadinedaoud/Documents/UNM/Work/Fall 2016/Long Link/Receiver
rain rate nids files';
folder_name=uigetdir(pathstr);
files=dir(fullfile(folder_name,'*.txt'));
curr_folder=pwd;
cd(folder_name);
disp(length(files));
for i=1:length(files)
    fid=fopen(files(i).name,'r');
    m = textscan(fid,'%*f %f %*f %*f %*f %*f %*f %*f %*f %*f %*f %*f %*f %*f
%*f %*f %*f %*f %*f %*f %*f %*f %*f %*f %*f %*f %*f %*f %*f %*f %*f %*f %*f
%*f %*s','delimiter',' ','MultipleDelimsAsOne',1);
    if i==1
        B(:,i)=m{:};
    else
        B = vertcat(B, m);
    end
    fclose(fid);
end
save('rain.mat','B');

%---------------------------------------------------------------------------
%Save the rain rate in an array.
rain=load('rain.mat');
rain=rain.B;
Allrain = {cat(1,rain{:})};
Allrain=Allrain{:};

%---------------------------------------------------------------------------
%Delete all the rain rate values that record a rain rate of 999.999 mm/hr
[rows junk] = size (Allrain);
for i=1:rows
```

```
    if Allrain(rows-i+1) == 999.999
        Allrain(rows-i+1)=[];
    end
end


%Quick exceedance binning exercise

%determine the set size
setsize=length(Allrain);

%exceedance plot resolution
res=0.01;

%determine the number of power steps
ressize=(max(Allrain)-min(Allrain))/res;

%initialize empty array for data
exceedanceplot_rain=zeros(floor(ressize)+1,2);

iterate=0;
start=min(Allrain);
finish=max(Allrain);

%march through the plot
while start+ iterate*res <= finish

exceedanceplot_rain(iterate+1,:)=[sum(Allrain>=(start+res*iterate))/setsize,s
tart+res*iterate];
   iterate=iterate+1;
end

xrain=exceedanceplot_rain(:,1);
yrain=exceedanceplot_rain(:,2);

desiredXValue01=0.001;
xrain01 = find(abs(xrain-desiredXValue01) < 0.00005);
xrain01=xrain01(1:19,:);
desiredYValues=yrain(xrain01);
rainyDesired_01=mean(desiredYValues);

desiredXValue001=0.0001;
xrain001 = find(abs(xrain-desiredXValue001) < 0.000001882);
xrain001=xrain001(1:58,:);
desiredYValues=yrain(xrain001);
rainyDesired_001=mean(desiredYValues);

%generate the plot
fig1=figure;
set(fig1,'name','Rain','numbertitle','off')
semilogx(xrain,yrain)
v=vline(desiredXValue01,'r');
h=hline(rainyDesired_01,'r');
fprintf('\nThe rainfall rate exceeded for 0.1 percent of the time at %i GHz
is %f mm/hr',f, rainyDesired_01);
```

```
v=vline(desiredXValue001,'g');
h=hline(rainyDesired_001,'g');
fprintf('\nThe rainfall rate exceeded for 0.01 percent of the time at %i GHz
is %f mm/hr',f, rainyDesired_001);


%--------------------------------------------------------------------------
%Calculate the attenuation (dB/km) corresponding to the rainfall rate
%exceeded for 0.1% and 0.01% of the time.

[rainattenuation_01,alpha,d] = Rainattenuation(rainyDesired_01,f);
[rainattenuation_001,alpha,d] = Rainattenuation(rainyDesired_001,f);

%--------------------------------------------------------------------------
%Calculate the distance factor r for our link and the effective distance
r_01 = 1/((((0.477*(d^0.633))*(rainyDesired_01^(0.073*alpha))*(f^0.123)))-
(10.579*(1-exp(-0.024*d))));
deff_01 = r_01*d;
r_001 = 1/((((0.477*(d^0.633))*(rainyDesired_001^(0.073*alpha))*(f^0.123)))-
(10.579*(1-exp(-0.024*d))));
deff_001 = r_001*d;

%--------------------------------------------------------------------------
%Calculate the total attenuation exceeded for 0.1% and 0.01% of the time for
the
%overall link
A_01=rainattenuation_01*deff_01;
A_001=rainattenuation_001*deff_001;
fprintf('\nThe total calculated attenuation exceeded for 0.1 percent of the
time at %i GHz is %f dB',f, A_01);
fprintf('\nThe total calculated attenuation exceeded for 0.01 percent of the
time at %i GHz is %f dB',f, A_001);

%--------------------------------------------------------------------------
%Calculate the total measured attenuation

[rows junk] = size (Allattenuation);
Allattenuation = Allattenuation(:,1);
Allreceivedpowertest = Allattenuation;

Allattenuation(Allattenuation<noisefloor) = noisefloor+0.000001;

Allattenuation = 0 - Allattenuation;


%Quick exceedance binning exercise


%determine the set size
setsize=length(Allattenuation);

%exceedance plot resolution
res=0.01;

%determine the number of power steps
```

```
ressize=(max(Allattenuation)-min(Allattenuation))/res;

%initialize empty array for data

arraysize=floor(ressize)+1;
exceedanceplot_atten=zeros(arraysize,2);


iterate=0;
start=min(Allattenuation);
finish=max(Allattenuation);
residual=0;
data=Allattenuation;
h=waitbar(0,'calculating');


while start+ iterate*res <= finish
   mask=data>=(start+res*iterate);
   data=data(mask);
   exceedanceplot_atten(iterate+1,:)=[sum(mask)/setsize,start+res*iterate];
   waitbar((iterate*res+start)/finish)
   iterate=iterate+1;
end
close(h)


xatten=exceedanceplot_atten(:,1);
yatten=exceedanceplot_atten(:,2);

if f ==72
    desiredXValue01=0.001;
    xatten01 = find(abs(xatten-desiredXValue01) < 0.005);
    attenyDesired_01=75;

    desiredXValue001=0.0001;
    attenyDesired_001=75;

    desiredXValue90 = 0.90;
    xatten90 = find(abs(xatten-desiredXValue90) < 0.002);
    attenyDesired_90=yatten(xatten90);

else
    desiredXValue01=0.001;
    xatten01 = find(abs(xatten-desiredXValue01) < 0.0005);
%     xatten01=xatten01(407:478,:);
%     desiredYValues=yatten(xatten01);
    attenyDesired_01=80;

    desiredXValue001=0.0001;
    attenyDesired_001=80;

    desiredXValue90 = 0.90;
    xatten90 = find(abs(xatten-desiredXValue90) < 0.002);
    attenyDesired_90=yatten(xatten90);
end
```

```
%generate the plot
fig2=figure;
set(fig2,'name','Attenuation','numbertitle','off')
semilogx(xatten,yatten)
v=vline(desiredXValue01,'r');
h=hline(attenyDesired_01,'r');
fprintf('\nThe attenuation exceeded for 0.1 percent of the time at %i GHz is
%f dB',f, attenyDesired_01);

v=vline(desiredXValue001,'g');
h=hline(attenyDesired_001,'g');
fprintf('\nThe attenuation exceeded for 0.01 percent of the time at %i GHz is
%f dB',f, attenyDesired_001);

v=vline(desiredXValue90,'k');
h=hline(attenyDesired_90,'k');
fprintf('\nThe clear air attenuation at %i GHz is %f dB',f,
attenyDesired_90);

rainattenuation01 = attenyDesired_01-attenyDesired_90;
fprintf('\nThe rain attenuation relative to clear air exceeded for 0.1
percent of the time at %i GHz is %f dB',f, rainattenuation01);
rainattenuation001 = attenyDesired_001-attenyDesired_90;
fprintf('\nThe rain attenuation relative to clear air exceeded for 0.01
percent of the time at %i GHz is %f dB',f, rainattenuation001);

dynamicrange = attenyDesired_90-noisefloor;
fprintf('\nThe dynamic range for this rain event at %i GHz is %f dB',f,
dynamicrange);
```

Appendix B

Matlab Code for the Short Link Statistical Analysis

Matlab version: Matlab_R2016a

```
clear all;
close all;
clc;

f=84;
noisefloor = -80;
%----------------------------------------------------------------------------
%Read the attenuation at 84 GHz from the nids text files and save them in a
single column.

    pathstr = '/Users/nadinedaoud/Documents/UNM/Work/Fall 2016/Short
Link/NEW_20161004/84GHz nids files';
    folder_name=uigetdir(pathstr);
    files=dir(fullfile(folder_name,'*.txt'));
    curr_folder=pwd;
    cd(folder_name);
    disp(length(files));
    for i=1:length(files)
        fid=fopen(files(i).name,'r');
        m = textscan(fid,'%*f %*f %*f %*f %*f %*f %*f %*f %f %*f %*f %*f %*f
%*f %*f %*f','delimiter',' ','MultipleDelimsAsOne',1);
        if i==1
            A(:,i)=m{:};
        else
            A = vertcat(A, m);
        end
        fclose(fid);
    end
    save('attenuation84.mat','A');

%----------------------------------------------------------------------------
%Save the total attenuation at 84 GHz in a single column
    attenuation84=load('attenuation84.mat');
    attenuation84=attenuation84.A;
    Allattenuation = {cat(1,attenuation84{:})};
    Allattenuation = Allattenuation{:};


%----------------------------------------------------------------------------
%Read the rain rate for 84 GHz from the nids text files and save them in a
single column.
pathstr = '/Users/nadinedaoud/Documents/UNM/Work/Fall 2016/Short
Link/NEW_20161004/Receiver rain rate nids files';
folder_name=uigetdir(pathstr);
files=dir(fullfile(folder_name,'*.txt'));
curr_folder=pwd;
cd(folder_name);
```

```
disp(length(files));
for i=1:length(files)
    fid=fopen(files(i).name,'r');
    m = textscan(fid,'%*f %f %*f %*f %*f %*f %*f %*f %*f %*f %*f %*f %*f %*f
%*f %*f %*f %*f %*f %*f %*f %*f %*f %*f %*f %*f %*f %*f %*f %*f %*f %*f %*f
%*f %*s','delimiter',' ','MultipleDelimsAsOne',1);
    if i==1
        B(:,i)=m{:};
    else
        B = vertcat(B, m);
    end
    fclose(fid);
end
save('rain.mat','B');

%---------------------------------------------------------------------------
%Save the rain rate in an array.
rain=load('rain.mat');
rain=rain.B;
Allrain = {cat(1,rain{:})};
Allrain=Allrain{:};

%---------------------------------------------------------------------------
%Delete all the files when we have missing data during the day
C = [A B];
[rows junk] = size (C);
for i=1:rows
 [Arows junk] = cellfun(@size,A,'uni',false);
end
for i=1:rows
    if Arows{rows-i+1} ~= 86400;
    C(rows-i+1,:)=[];
    end
end
D=C;
[rows junk] = size (D);
for i=1:rows
shortB{i,1} = D{i,2};
end
for i=1:rows
 [Brows junk] = cellfun(@size,shortB,'uni',false);
end
for i=1:rows
    if Brows{rows-i+1} ~=  1440;
    C(rows-i+1,:)=[];
    end
end

AA = {cat(1,C{:,1})};
AA=AA{:};
BB = {cat(1,C{:,2})};
BB=BB{:};
%---------------------------------------------------------------------------
%Calculate the mean of each 60 consecutive rows (because every 60 seconds are
equal to 1 minute.
%Then store the resultant means in an array.
%I am interested in every 1 min data not every 1 second data to be able to
%assign every 1 min received power to every 1 min rain rate.
```

```
[rows junk]=size(AA);
lastelement=60*floor(rows/60);
indices= lastelement+1:rows;
AA(indices,:)=[];
meanAA = mean(reshape(AA,60,[]));
meanAA=transpose(meanAA);
CC=[meanAA BB];

%-----------------------------------------------------------------------------
%Delete all the rain rate values that record a rain rate of 999.999 mm/hr
[rows junk] = size (Allrain);
for i=1:rows
    if Allrain(rows-i+1) == 999.999
        Allrain(rows-i+1)=[];
    end
end

%Quick exceedance binning exercise

%determine the set size
setsize=length(Allrain);

%exceedance plot resolution
res=0.01;

%determine the number of power steps
ressize=(max(Allrain)-min(Allrain))/res;

%initialize empty array for data
exceedanceplot_rain=zeros(floor(ressize)+1,2);

iterate=0;
start=min(Allrain);
finish=max(Allrain);

%march through the plot
while start+ iterate*res <= finish

exceedanceplot_rain(iterate+1,:)=[sum(Allrain>=(start+res*iterate))/setsize,s
tart+res*iterate];
   iterate=iterate+1;
end

xrain=exceedanceplot_rain(:,1);
yrain=exceedanceplot_rain(:,2);

desiredXValue01=0.001;
xrain01 = find(abs(xrain-desiredXValue01) < 0.00005);
xrain01=xrain01(1:162,:);
desiredYValues=yrain(xrain01);
rainyDesired_01=mean(desiredYValues);

desiredXValue001=0.0001;
xrain001 = find(abs(xrain-desiredXValue001) < 0.000002);
xrain001=xrain001(98,:);
```

```
desiredYValues=yrain(xrain001);
rainyDesired_001=mean(desiredYValues);

%generate the plot
fig1=figure;
set(fig1,'name','Rain','numbertitle','off')
semilogx(xrain,yrain)
v=vline(desiredXValue01,'r');
h=hline(rainyDesired_01,'r');
fprintf('\nThe rainfall rate exceeded for 0.1 percent of the time at %i GHz
is %f mm/hr',f, rainyDesired_01);

v=vline(desiredXValue001,'g');
h=hline(rainyDesired_001,'g');
fprintf('\nThe rainfall rate exceeded for 0.01 percent of the time at %i GHz
is %f mm/hr',f, rainyDesired_001);




%--------------------------------------------------------------------------
%Calculate the attenuation (dB/km) corresponding to the rainfall rate
%exceeded for 0.1% and 0.01% of the time.

[rainattenuation_01,alpha,d,k] = Rainattenuation(rainyDesired_01,f);
[rainattenuation_001,alpha,d,k] = Rainattenuation(rainyDesired_001,f);

%--------------------------------------------------------------------------
%Calculate the distance factor r for our link and the effective distance
r_01 = 1/((((0.477*(d^0.633))*(rainyDesired_01^(0.073*alpha))*(f^0.123)))-
(10.579*(1-exp(-0.024*d))));
deff_01 = r_01*d;
r_001 = 1/((((0.477*(d^0.633))*(rainyDesired_001^(0.073*alpha))*(f^0.123)))-
(10.579*(1-exp(-0.024*d))));
deff_001 = r_001*d;

%--------------------------------------------------------------------------
%Calculate the total attenuation exceeded for 0.1% and 0.01% of the time for
the
%overall link
A_01=rainattenuation_01*deff_01;
A_001=rainattenuation_001*deff_001;
fprintf('\nThe total calculated attenuation exceeded for 0.1 percent of the
time at %i GHz is %f dB',f, A_01);
fprintf('\nThe total calculated attenuation exceeded for 0.01 percent of the
time at %i GHz is %f dB',f, A_001);

%--------------------------------------------------------------------------
%Calculate the attenuation due to rain relative to the no rain received
%power.
%Neglect the extreme cases where we suspect that there is something wrong
%with the recorded data (below noise floor level)

[rows junk] = size (Allattenuation);
Allattenuation = Allattenuation(:,1);
Allreceivedpowertest = Allattenuation;
```

```
for i=1:rows
    if Allattenuation(i)<noisefloor;
        Allattenuation(i)=noisefloor;
    end
end

Allattenuation = 0 - Allattenuation;

 %-----------------------------------------------------------------------------
-
        %Plot the received power as a function of time.

        figtest=figure;
        timetest=linspace(0,100,length(Allreceivedpowertest));
        set(figtest,'name','Test','numbertitle','off')
        plot(timetest,Allreceivedpowertest)

set(gca,'XTickLabel',{'0','10','20','30','40','50','60','70','80','90','100'}
)
        xlabel('Time')
        ylabel('Received power (dBm)')
        title(['Received power as a function of the time at ' num2str(f) '
GHz']);



%Quick exceedance binning exercise


%determine the set size
setsize=length(Allattenuation);

%exceedance plot resolution
res=0.01;

%determine the number of power steps
ressize=(max(Allattenuation)-min(Allattenuation))/res;

%initialize empty array for data

arraysize=floor(ressize)+1;
exceedanceplot_atten=zeros(arraysize,2);


iterate=0;
start=min(Allattenuation);
finish=max(Allattenuation);
residual=0;
data=Allattenuation;
h=waitbar(0,'calculating');


while start+ iterate*res <= finish
   mask=data>=(start+res*iterate);
```

```
   data=data(mask);
   exceedanceplot_atten(iterate+1,:)=[sum(mask)/setsize,start+res*iterate];
   waitbar((iterate*res+start)/finish)
   iterate=iterate+1;
end
close(h)


xatten=exceedanceplot_atten(:,1);
yatten=exceedanceplot_atten(:,2);

    desiredXValue01=0.001;
    xatten01 = find(abs(xatten-desiredXValue01) < 0.00005);
    xatten01=xatten01(40,:);
    desiredYValues=yatten(xatten01);
    attenyDesired_01=mean(desiredYValues);

    desiredXValue001=0.0001;
    xatten001 = find(abs(xatten-desiredXValue001) < 0.000003);
    xatten001 = xatten001(1:4,:);
    desiredYValues=yatten(xatten001);
    attenyDesired_001=mean(desiredYValues);

    desiredXValue90 = 0.90;
    xatten90 = find(abs(xatten-desiredXValue90) < 0.002);
    xatten90 = xatten90(2,:);
    attenyDesired_90=yatten(xatten90);


%generate the plot
fig2=figure;
set(fig2,'name','Attenuation','numbertitle','off')
semilogx(xatten,yatten)
v=vline(desiredXValue01,'r');
h=hline(attenyDesired_01,'r');
fprintf('\nThe attenuation exceeded for 0.1 percent of the time at %i GHz is
%f dB',f, attenyDesired_01);

v=vline(desiredXValue001,'g');
h=hline(attenyDesired_001,'g');
fprintf('\nThe attenuation exceeded for 0.01 percent of the time at %i GHz is
%f dB',f, attenyDesired_001);

v=vline(desiredXValue90,'k');
h=hline(attenyDesired_90,'k');
fprintf('\nThe clear air attenuation at %i GHz is %f dB',f,
attenyDesired_90);

rainattenuation01 = attenyDesired_01-attenyDesired_90;
fprintf('\nThe rain attenuation relative to clear air exceeded for 0.1
percent of the time at %i GHz is %f dB',f, rainattenuation01);
rainattenuation001 = attenyDesired_001-attenyDesired_90;
fprintf('\nThe rain attenuation relative to clear air exceeded for 0.01
percent of the time at %i GHz is %f dB',f, rainattenuation001);

dynamicrange = attenyDesired_90-noisefloor;
```

```
fprintf('\nThe dynamic range for this rain event at %i GHz is %f dB',f,
dynamicrange);



%--------------------------------------------------------------------------
%From this part till the end of the code, I am going to compare the
%calculated attenuation according to the ITU-R model and the measured
%attenuation recorded at the receiver side, as a function of the rain rate.
%--------------------------------------------------------------------------



%--------------------------------------------------------------------------
%Calculate the attenuation (dB/km) corresponding to the rainfall rate
%exceeded for 0.1% and 0.01% of the time.

CCsorted = sortrows(CC,2);
measuredattenuation = CCsorted(:,1);
[rows junk] = size (measuredattenuation);
for i=1:rows
    if measuredattenuation(i)<noisefloor;
        measuredattenuation(i)=noisefloor;
    end
end

measuredattenuation = 0 - measuredattenuation;
measuredattenuation = measuredattenuation-attenyDesired_90;
measuredattenuation_Km = measuredattenuation/0.56; %gives the measured
attenuation in dB/Km
rainrate = CCsorted(:,2);
[rainattenuation,alpha,d] = Rainattenuation(rainrate,f);


fig5=figure;
set(fig5,'name','Attenuation comparison as a function of rain
rate','numbertitle','off')
plot(rainrate,rainattenuation,'k')
hold on;
scatter(rainrate,measuredattenuation_Km,'g')
xlabel('Rain rate (mm/hr)')
ylabel('Attenuation (dB/Km)')
title(['Attenuation comparison as a function of rain rate  at ' num2str(f) '
GHz']);
legend('ITU-R 84 GHz','Measured 84 GHz')

fittedcurve = fit(rainrate+0.0001,measuredattenuation_Km,'power1')
hold on;
plot(fittedcurve,rainrate+0.0001,measuredattenuation_Km)
legend('ITU-R 84 GHz','Measured 84 GHz','data','Fitted curve')

%--------------------------------------------------------------------------
%Testing the ITU-R model with the new K and alpha coefficient

result = coeffvalues(fittedcurve);
k = result(1);
alpha = result(:,2);
```

```
[NEWrainattenuation_01,d] = RainattenuationAlphaK(rainyDesired_01,f,alpha,k);
[NEWrainattenuation_001,d] =
RainattenuationAlphaK(rainyDesired_001,f,alpha,k);

r_01 = 1/((((0.477*(d^0.633))*(rainyDesired_01^(0.073*alpha))*(f^0.123)))-
(10.579*(1-exp(-0.024*d))));
deff_01 = r_01*d;
r_001 = 1/((((0.477*(d^0.633))*(rainyDesired_001^(0.073*alpha))*(f^0.123)))-
(10.579*(1-exp(-0.024*d))));
deff_001 = r_001*d;


A_01=NEWrainattenuation_01*deff_01;
A_001=NEWrainattenuation_001*deff_001;
fprintf('\nThe NEW total calculated attenuation exceeded for 0.1 percent of
the time at %i GHz is %f dB',f, A_01);
fprintf('\nThe NEW total calculated attenuation exceeded for 0.01 percent of
the time at %i GHz is %f dB',f, A_001);
```