Ka-Band Propagation Model Based on High Resolution ACTS Data

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Abstract

High rate data transmission is crucial for the success of NASA’s Deep Space missions. The Jet Propulsion Laboratory is going to update its Deep Space Network (DSN). NASA’s Advanced Communications Technology Satellite (ACTS) experiment provides the first contribution of Ka-band data propagation effects. This study performs an extensive analysis on Ka-band degradation phenomena due to weather and atmospheric effects using high resolution data. Detailed case studies at two sites are performed for several typical rain events. Then, statistical studies on properties of signal attenuation and attenuation changes are carried out. Attention will be put on the comparison between high and low resolution measurements and with available models. The resulting models can be applied to low margin downlink systems. Results from this study will help in designing telecommunication and wireless systems, selecting downlink experimental sampling rates, and understanding how signal fluctuation/scintillation is generated by rain and turbulence.
Acknowledgement
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Introduction

As NASA’s Deep Space Network (DSN) downlink data transmission is getting congested, there is an urgent need to increase bandwidth [1], [2]. In order to meet the increasing demands for larger telecommunications capacity, serious investigation is currently being made to increase the DSN ground station receiving capability by two orders of magnitude [3], [4]. Ka-band (30/20 GHz) is attractive due to availability of ample spectrum needed to support multi-megabit links, in addition to other advantages over lower frequency bands. However, a good understanding of the Earth’s atmospheric propagation environment is needed to maximize the benefits of future high rate Ka-band links. Fortunately, the Advanced Communication Technology Satellite (ACTS) provided the first experiment on Ka-band microwave signal propagation effects as shown in figure 1-1.

The Earth’s atmosphere and weather have much larger degradation effects on the Ka-band than other lower frequency bands [4], [5]. The atmosphere affects Ka-band telecommunication in two ways. One way includes increasing water vapor content in the atmosphere that will radiate more intense atmospheric noise, causing a receiver’s noise temperature to increase. The other affect involves atmospheric losses for passing radio signals that can be significantly increased due to gaseous absorption, rain and cloud attenuation, tropospheric scattering, scintillation etc. as displayed below [6], [7], [8].

When the wavelength of Ka-band radio waves is comparable to the Fresnel length of the atmospheric turbulences, the fast scintillation (0.1 - 10 Hz) and scattering become significant [9], [10]. Receiving signals appear highly dynamic at their amplitude and phase. These fast variations on amplitude and phase of signals are different from those slow variations caused by rain or cloud attenuations. Fast variations often superimpose on the top of slow fading, causing the deep fading in a short time. The high time resolution Ka-band data is urgently needed for modeling these fluctuations.

Atmospheric gases, such as oxygen and water vapor, affect higher frequencies dramatically [6], [11]. Below 10 GHz, attenuation due to atmospheric gases is less then 0.01 dB/km, while above 10 GHz, the attenuation starts to increase severely.

Rain is one of the biggest contributors to signal degradation [7], [12]. Signals in the Ka-band can expect to be severely affected depending on the rate of the rainfall and the temperature of the water. The path attenuation caused by heavy rainfall (up to 40 dB) can cause signals to become indistinguishable from the noise signal of the receiver. While higher frequency radio waves are expected to experience higher propagation losses, higher data rates imply a new sensitivity to short term amplitude (SNR) fluctuation. Rain attenuation and fast amplitude fluctuations due to atmospheric turbulences and rain scattering become dominant signal impairment factors.
Attenuation due to clouds and fog also grows with increasing frequency [8]. The size of these very small liquid drops can soon be on the same order as the wavelength of signals with frequencies higher than 10 GHz. Of course the approximate damage needs to take into account elevation angle, temperature, and density of the clouds or fog among other parameters.

Scintillation is produced by turbulent air with variations in the refractive index [9], [10], [13]. These losses are strongly dependent on time percentage, elevation angle, and antenna size. When Ka-band signals pass through a turbulent region and are scattered by the turbulent cells, rapid amplitude changes around the average will occur. The amplitude fluctuation is due to the overlapping of signals from different propagation paths that have
also been phase shifted. Attenuation due to scintillation rapidly increases with increasing frequency.

Using long-term statistics, based on the Water Vapor Radiometer (WVR) alone sometimes may not be sufficient to predict the short term performance, because a few of the fast fluctuations (which cannot be obtained from current WVR data) can knock the receiver out of lock and the receiver needs to take time to recover. A long-term model cannot help us to forecast short-term dynamics. Short term and fading slope models are needed for short term forecasting. The short term statistics provides a basis to assess various operational issues, such as frequency of receiver lock time, recovery time and outrange time, etc.

The ACTS experiment is the first United States experiment for Ka-band study [14], [15], [16]. Between 1993 and 1998, ACTS had 5 years of continued measurements at seven stations across the continental United States. The ACTS propagation terminal (APT) provided the capacity to record simultaneously low data rate (1 sample per second) and high data rate (20 samples per second) data at 20.2 GHz and 27.5 GHz. Low data rate data (LDR) were recorded continuously. High data rate data (HDR) were recorded only occasionally. These data are very efficient in studying atmospheric scintillation effects in signal amplitude variations and spectrum, fading slopes and durations.

The present study will be, for the first time, based on high time resolution data from ACTS, which is designed to provide information on Ka-band propagation phenomena that affect low-margin satellite communication system operation. High data sample rates, narrow beams, and various elevation angles characterize these ACTS experiments.

In this study, both experimental and theoretical studies provide models to evaluate the effects of fast fluctuations and fading on Ka-band link. The purpose is to deliver a tool or model for the short-term variations. This study is also a good complement to an on-going WVR study, together these studies would cover a full spectrum of variations—from slow (days, hours) to fast (min, sec) variations.

An extensive analysis on Ka-band degradation phenomena using these high resolution data will be performed in this study. Because the primary weather effect on the Ka-band is attenuation due to rain, detailed case studies at two sites (Oklahoma and British Columbia) are performed for several typical rain events. Both show fluctuations due to rain fading and fast scintillation due to rain scattering and are examined case by case. Then, the statistical studies on properties of signal attenuation and attenuation changes (fading slopes) are carried out using the high resolution data. A theoretical study based on atmospheric turbulence theory can be used to estimate scintillation intensity, fluctuation power spectrum, scaling factors, etc.

The focus of this study is the detailed comparison between the high and low resolution data in examining their standard deviation, attenuation, power spectra and fading rates, etc. The experimental results from this study are also compared with previous modeling work and theoretical results. Throughout this study, it is found that, as expected, high
time resolution data do appear to have large standard deviation (up to 15 dB) and attenuation levels (up to saturation level of 35 dB). High frequency scintillations can extend up to 10 Hz, even though the rain caused fluctuations dominate low frequency part (< 0.2 Hz). There are much higher attenuation change rates, which mainly correspond to rain caused scintillation and follow a log-normal distribution, for the high resolution rate than for the low resolution data. These resulting models can be applied to a low margin downlink systems such as DSN and wireless communication at Ka-band. It will help in designing all telecommunication systems, in selecting downlink experimental sampling rates, and in understanding how signal fluctuation/scintillation is generated by rain and turbulence.

In chapter 2, we will introduce ACTS experiment, which includes system design, propagation ground terminal, data collection processes, etc. In chapter 3, preprocessing computer software will be described. This software can be used for data calibration and daily statistics. An essential component of this study is in chapter 4: rain case studies for two sites. The study includes daily time series for signal attenuation, standard deviations, power spectra, etc. Comparison is made between low resolution and high resolution data. In chapter 5, the statistics of attenuation and attenuation change are performed using high time resolution data for the first time. Their distribution and fading rates during clear weather and during a rain period are investigated in detail. The last two chapters are results from this study and a summary.
2.0 ACTS Experiment Design

The National Aeronautics and Space Administration designed the Advanced Communications Technology Satellite propagation experiment to obtain slant-path beacon attenuation statistics at frequencies of 20.2 and 27.5 GHz [14], [15], [16]. The system consists of a spacecraft and ground segments. The spacecraft is comprised of a multi-beam communication payload and the spacecraft bus. The satellite has a geosynchronous orbit and is fixed at 100° W longitude well above the continuous United States. Within the communication payload are the multi-beam antenna assembly, the base band processor, and the microwave switch matrix as shown in figure 2-1. These technologies enable high-speed communications and data transfers between smaller dish earth terminals. The spacecraft bus provides altitude control, electric power, thermal control, command reception, telemetry transmissions, and propulsion for station keeping [3]. The ground segments are represented in seven different regions across the United States and Canada.

![ACTS Communication Payload Diagram](image)

Figure 2-1: ACTS Communication Payload

The ACTS propagation terminals (APT) used for all experimental sites are identical, with a 1.2 m dish antenna. Their purpose is to acquire signals from the ACTS satellite. The terminal equipment included computer-controlled beacon receivers and collected total power radiometers operating at the beacon frequencies. The receivers were designed for continuous unattended operation with periodic calibration of the total power radiometers. The data was recorded for postprocessing analysis and archival. Because the receiver systems were identical, a single preprocessing program for first-level postprocessing analysis was used by all the experimenters. These measurements were to be made in different rain-rate climate regions (or zones) within the United States and Canada to provide additional information for the design of low-margin satellite communication systems. Each signal encountered different environmental elements and underwent loss accordingly. The sites were chosen to sample the rain attenuation processes in six different rain-climate zones at the locations presented in table 2-1. In table 2-1, the coordinates of each location are given. The height that the receiving antennas are placed above sea level is also indicated. The elevation angle refers to the angle that the antenna needs to be pointed in order to have contact with the satellite through the atmosphere.
The polarization degree is measured from the horizontal and refers to the tilt of the linear polarization, which indicates the orientation of the electric field. Figure 2-1 illustrates the different locations and global rain zones. This map shows the climate-zone boundaries for the Crane-Global model (A, B1, B2, C, D1, D2, D3, E, F, G and H) [16], [17]. Each location represents a different climate and elevation angle. At the seven different locations, more than five years of low time resolution (1 sample/second) propagation data have been collected. These low-resolution data have been extensively analyzed [13], [15], [16], [17], [18], [19], [20]. In this article, the locations to be analyzed are Norman, Oklahoma and Vancouver, British Columbia.

<table>
<thead>
<tr>
<th>Location</th>
<th>N. Latitude (deg)</th>
<th>W. Longitude (deg)</th>
<th>Height (km)</th>
<th>Global Rain Zone</th>
<th>ITU-R Rain Zone</th>
<th>Elevation Angle (deg)</th>
<th>Polarization deg from horizontal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fairbanks, AK</td>
<td>64.85</td>
<td>147.82</td>
<td>0.18</td>
<td>B1</td>
<td>C</td>
<td>8.1</td>
<td>45</td>
</tr>
<tr>
<td>Vancouver, BC</td>
<td>49.25</td>
<td>123.22</td>
<td>0.01</td>
<td>C</td>
<td>D</td>
<td>29.3</td>
<td>72</td>
</tr>
<tr>
<td>Greeley, CO</td>
<td>40.33</td>
<td>104.61</td>
<td>1.9</td>
<td>B2</td>
<td>E</td>
<td>43.1</td>
<td>84</td>
</tr>
<tr>
<td>Tampa, FL</td>
<td>28.06</td>
<td>82.42</td>
<td>0.05</td>
<td>E</td>
<td>N</td>
<td>52.0</td>
<td>77</td>
</tr>
<tr>
<td>Reston, VA</td>
<td>38.95</td>
<td>77.33</td>
<td>0.08</td>
<td>D2</td>
<td>K</td>
<td>39.2</td>
<td>76</td>
</tr>
<tr>
<td>Las Cruces, NM</td>
<td>32.54</td>
<td>106.61</td>
<td>1.46</td>
<td>F</td>
<td>M</td>
<td>51.5</td>
<td>81</td>
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<tr>
<td>Norman, OK</td>
<td>35.21</td>
<td>97.44</td>
<td>0.42</td>
<td>D2</td>
<td>E</td>
<td>49.1</td>
<td>86</td>
</tr>
</tbody>
</table>

Table 2-1: Locations of APTs

The propagation terminals were provided with meteorological sensors to record the temperature, pressure, relative humidity, wind speed, wind direction, and rain rate continuously at the surface. These data were averaged for one minute and were sampled and recorded in the same files as the beacon and radiometer data.

In addition to the beacon receivers, each APT has two total power radiometers with center frequencies at the beacon frequencies. The radiometers are used to establish the beacon signal reference levels needed for calculating beacon attenuation values. For the combined radiometer and beacon measurement system, the attenuation measurement error was less than a maximum of 1.0 dB and was generally less than 0.3 dB.

The basic recording mode collected beacon and radiometer data for a propagation terminal continuously at one sample per second. These data were combined with a time stamp, meteorological observations, and receiver status information and stored in daily output files.

However, this study focuses on high time resolution data acquired from ACTS. The high time resolution Ka-band experimental data from the Advanced Communications Technology Satellite are exclusively collected by Professor Robert K. Crane. Generally, the site operators were not interested in the high data rate observations. Dr. Crane (through the ACTS experimenter meetings) forced the site operators to collect the data. Then the site operators forwarded the observations to Dr. Crane at the Oklahoma site. Dr. Crane now exclusively has the entire data set.
In the beginning of five years of ACTS mission, high data rate data (HDR) were recorded only occasionally. Toward the end of the experiment period, as used in the study of 1998, an effort was made to record HDR data for 10 minutes once every hour. This recording program was voluntary at the sites and some site operators did not participate consistently. At two of the sites used in the 1998 study, the data were collected whenever the APT was functioning; at the British Columbia site, HDR recording was started in March and then not collected during a two month period in the summer months, June, July and August. Two of the seven APT sites have been selected, British Columbia and Oklahoma, on the basis of the elevation angles to ACTS. Nearly one-year at each site are sufficient for a study of fast fluctuation feature due to weather effects.
3.0 Processing for High Time Resolution Data

All data useful to this analysis was obtained from files created by the ACTS preprocessing programs created by Dr. Robert Crane and D. B. Westenhaver.

There are two types of data. Low-resolution data was taken at one sample per second. High-resolution data was taken at 20 samples per second, but for only 10 minutes of every hour at the Oklahoma site (11th minute – 21st minute of each hour) and 9 minutes of every hour at the British Columbia site (11th minute – 20th minute of each hour).

An extensive “preprocessing” program was developed to calibrate the APT and automatically generate daily LDR statistics. The unprocessed (or raw) daily data files were input to the preprocessing program, which performed the calibration functions, generated attenuation histograms, and prepared one-minute average and standard deviation estimates for beacon signal level, beacon attenuation, radiometer-derived sky brightness temperature, and radiometer-derived attenuation. The preprocessing program also extracted the meteorological, status, and calibration control information from the raw data files. The calibrated one-second attenuation estimates were output to daily preprocessed data files together with time, surface weather, and status data.

The HDR processing program previously developed analyzed the HDR beacon data but did not calibrate the output nor suppress “bad” data sequences. Throughout this study, the intention was to provide verified “good” and calibrated HDR attenuation time series and to generate daily and monthly HDR statistics. Calibration was affected by comparison with the LDR one-minute average summaries. The daily output from the preprocessing program (from ACTSPP76 or a later program version .sum files) was input with the HDR data to calibrate the beacon receivers.

When the data was originally archived, the files were stored in a compressed PC-based format. The low-resolution files had the extension .PD2. The high-resolution files had the extensions .HOK and .HBC as displayed in figure 3-1. In order to make these files useful, they needed to be preprocessed using DOS-based programs provided by Dr. Robert Crane and D. B. Westenhaver.

Using ACTSPP80 to run the low-resolution files and ACTShdr7 to run the high-resolution files, many meaningful files were created, such as .EDF, .LOG, .SEC, etc. These files could then be opened using Microsoft’s Excel program. Excel was then used to interpret these files into plots that could then be analyzed. A block diagram of the processing steps is illustrated in figure 3-1.
.LOG files, created by ACTSPP80, were used to determine which days had the most rain at each location. In the Oklahoma files, the column titled “weather” indicated the weather for each day. Generally, it would specify if the day was rainy, cloudy, or clear. Rainy days also offered the time span and maximum rain rate. In the British Columbia files, the column titled “weather” indicated only if the day was rainy, cloudy, or clear. The column titled “NWS Accum” indicated how many inches of rain was measured that day.

.SEC files, created by ACTSPP80, were used to compare the one second values from the low-resolution data to the twenty samples per second values from the high resolution data. Because only ten minutes were available for each hour of the high resolution data, the same ten minutes of low-resolution data was chosen to be processed.

.SUM files, created by ACTSPP80, were used to plot low-resolution attenuations and standard deviations of both beacons and radiometers for the uplink and downlink frequencies. This file was also used to plot the rain rates for the locations. It is apparent when comparing the rain rate plots to the attenuation plots that there is a direct relationship. These .SUM files were also fed into the ACTShdr7 program in order to form comparison statistics. They were renamed the .AOK and .ABC files.

.MDF files, created by ACTShdr7, were used to plot statistics for both high-resolution and low-resolution data. From this development, it was possible to plot both attenuation
and change in attenuation occurrences. From there, the graphs could be compared to well known statistical models.

.MOK and .MBC files were created by ACTShdr7. They were used to plot the low and high resolution attenuation levels over the course of an entire day. These files also contained the necessary data to plot high-resolution and low-resolution standard deviations against time. It was also useful to compare attenuation with standard deviation for low and high resolution conditions.

.SOK and .SBC files, created by ACTShdr7, were used to plot the beacon fluctuation power spectrum for both frequencies. These power spectra are important for examining the effects of scintillation on the signals.

.VOK and .VBC files, created by ACTShdr7, were used to plot the high-resolution Beacon Attenuation for both frequencies as a function of time. The data from these files were compared with the data from the low-resolution .SEC files and presented in this text.

There are detailed descriptions for both software applications in the appendix. All input and output parameters and formats of the processing applications can also be found in the Appendix. The following case and statistical studies are based on these outputs.
4.0 Case Studies for Rain Attenuation at Two Sites

Rain-induced attenuation on satellite-earth communication links at frequencies above 10 GHz is the dominant signal impairment phenomena. Therefore, many researchers are focusing their attention on establishing a reliable method to predict rain-induced attenuation. It has been known that water droplets can absorb and scatter the energy from the incident microwaves. Attenuation increases exponentially as the frequency increases. Deep and rapid fading (up to 40-50 dB) due to huge storms is commonly seen. Attenuation is also highly dependent on rainfall rate which varies depending on weather, location and seasons.

First of all, it is necessary to determine accurate rainfall-rate characteristics for all sites. The ACTS propagation terminals were provided with capacitor rain-rate measurement gauges and tipping-bucket-type rain gauges. These gauges estimate the rain accumulation in a 10-s interval by measuring the capacitance change produced by a change in the height of a column of rain water collected in a vertical tube. The one-minute average rain rate was estimated by calculating the average rate of change of the rain water column height or the rain water accumulated in the gauge in one minute. The capacitor gauge employed a high-impedance high-gain amplifier that was susceptible to noise, especially if the input was an open circuit. With this gauge, the minimum observable rain rate in 1 min of observations was 2.1 mm/h; the measurement resolution was 0.3 mm/h.

The HDR data (20 sample/sec) are suitable for the study of the short-term attenuation or received signal level fluctuations often referred to as scintillation. The 1-second average LDR data were also used to study scintillation. Scintillation may be produced by different propagation phenomena. Foremost amongst the various phenomena are diffraction by small-scale variations in radio refractivity and fluctuations in path attenuation due to rain and clouds. The dominant phenomenon can be ascertained by comparing the scintillation intensity as measured by the standard deviation of LDR beacon attenuation with the standard deviation of the attenuation values derived from the LDR radiometric observations.

Two sites (Oklahoma and British Columbia) are selected for this case study based on their latitude and rainfall zones. To begin, the Oklahoma site has the most completed data records among the seven APT sites. Because Oklahoma has similar latitude to the DSN Goldstone station (35°), this site is of special interest to NASA. British Columbia has a lower elevation angle (29.3°), but is in the same ITU-R rainfall zone (Zone D) as the Goldstone station. Goldstone, located in California, is one of the three sites operating a 70 meter antenna for the DSN. For both sites, we have selected the entire year of 1998 for the case and statistical studies.

In the first section, the case study of Oklahoma site is performed. This case study includes 5 rainfall events. In section 4.2, three rainfall events from British Columbia are shown. These studies include the time series of attenuations and standard deviations of attenuations for both low and high resolution measurements. The last section is the comparison with model prediction in both attenuation and power spectra.
4.1 Oklahoma Site
4.1.1 Case 1: March 16, 1998
The first day to be evaluated was March 16, 1998 at the Norman, Oklahoma site. The rain rate for that day was described in the 9803OK.LOG file as “rain all the day (30mm/hr, TRG).” From the 980316OK.SUM file, the rain rate was plotted for that day in figure 4-1. Between 02-06 h UT, there was a high rainfall rate, up to 28 mm/hr. This is a good case to be studied for continued rain attenuation.

![Figure 4-1: Rain Rate at Oklahoma site March 16, 1998](image)

The attenuation experienced by the ACTS signal was also gathered from the low-resolution data. Attenuation at 20.2 GHz and 27.5 GHz was plotted for both the beacon and radiometer. Radiometer derived attenuation follows the beacon attenuation at the two frequencies very well, but with slightly higher values during rain storms. The estimated gaseous absorption (which is less than 0.4 dB) is also plotted for reference at the two frequencies.
Figure 4-2: Low Resolution Attenuation Data for Oklahoma March 16, 1998

Figure 4-3: 20.2 GHz LDR and HDR Attenuation Levels, Oklahoma March 16, 1998
Incorporating the high-resolution data of 10 minute intervals for each hour onto the low-resolution plots, we obtain figures 4-3 and 4-4 for the two frequencies, representing the total attenuation over the day. High resolution attenuation values are from one minute averages of the HDR data.

We can see that attenuation from high-resolution data follows the attenuation from the low-resolution data and radiometer very well, but with large variation, especially during large rainfall rate periods.

![Graph showing attenuation levels](image)

**Figure 4-4: 27.5 GHz LDR and HDR Attenuation Levels, Oklahoma March 16, 1998**

It is easy to see the correlation between heavier rain periods and more degradation to the signal. From the low-resolution data, it is hard to see the fluctuation of the attenuation. Focusing on the high-resolution data the fluctuations are more observable.
Figure 4-5: HDR Attenuation Levels, Oklahoma March 16, 1998, 02:11-02:21 UT.

Figure 4-6: HDR Attenuation Levels, Oklahoma March 16, 1998, 04:11-04:21 UT.
Figures 4-5 and 4-6 are a couple examples of 10-minute intervals during the hours of 02 and 04 (Universal Time) taken from the 98031602.VOK and 98031604.VOK high data rate files and the 980316OK.SEC low data rate file. Unfortunately, the ten minutes of available data was predetermined, so many of the more interesting minutes for large rainfall rate changes are not observable. From the expanded time series, we can see that the high-resolution data has very large fluctuations at the two frequencies. It is evident that the low-resolution data is just an average of the high-resolution data. A lot of the detail is lost in the low-resolution data.

We can also calculate standard deviations from the 980316OK.SUM file, it is also possible to obtain a plot of the standard deviation of the signal over the course of the day as shown in figure 4-7 for low-resolution data. This is another way to demonstrate the fluctuation of the signal. The radiometer data shows smaller standard deviation than the beacon data during the low rainfall rate periods.

![Figure 4-7: Low Resolution Standard Deviation Data for Oklahoma March 16, 1998](image)

By superimposing the high-resolution measurements over the low-resolution data, figures 4-8 and 4-9 are generated for each frequency. The first is for the 20.2 GHz frequency and the second is for the 27.5 GHz frequency.
Figure 4-8: 20.2 GHz LDR and HDR Standard Deviation Levels, Oklahoma March 16, 1998

Figure 4-9: 27.5 GHz LDR and HDR Standard Deviation Levels, Oklahoma March 16, 1998
Again, the blue diamond markers signify the one-minute averages from the high-resolution data for ten minutes of each hour. The red circular markers at the same ten minutes of each hour indicate the contribution from scintillation which was generated after noise removal. A spectral analysis calculated the receiver noise level for each ten minutes after the power integration. The 20.2 GHz scintillation data displayed in figure 4-8 was calculated after the noise reduction. As expected, the standard deviation should be correlated with scintillation very well because part of the standard deviation is caused by scintillation. In both figures 4-8 and 4-9, the standard deviations of high-resolution data and scintillation are higher than the low-resolution data at both frequencies by about 0.2 dB.

From the Standard Deviation graph, it is apparent that there is a lot of fluctuation during periods of rain. By comparing the low-resolution attenuation and standard deviation in figure 4-10, below, it is possible to understand that the deviation rises with the rise in attenuation making it positively correlated. It is also observed that the attenuation and standard deviation of the higher frequency is also higher. It generally follows log-linear behavior. Data generally can be divided into two groups. The left part corresponds to the lower attenuation during rainless times, and the right part occurs during rainy periods.

![Figure 4-10: Low Resolution Attenuation Levels with respect to Standard Deviation Levels, Oklahoma March 16, 1998](image-url)
Figure 4-11: High Resolution Attenuation Levels with respect to Standard Deviation Levels, Oklahoma March 16, 1998

Figure 4-12: Power Spectral Density, Oklahoma March 16, 1998, 02:00 UT
Although there are fewer points (1/6 relative to LDR) taken over the course of a day, it is interesting to observe the attenuation and standard deviation correlation from the high-resolution data. This is presented in figure 4-11 which also shows a positive log-linear correlation.

Because both atmospheric turbulence and rain particle scattering can cause rapid fluctuations in signal amplitude, phase, and arrival angle, another parameter of interest was the power spectrum. The scintillation power spectrum is interesting because it is possible to see how the power is distributed across different frequency components. The power spectrums were obtained from the high-resolution files 98031602.SOK and 98031604.SOK for two rainfall periods. These are presented in figures 4-12 and 4-13.

As will be discussed later, the power observed during 02 and 04 UT decreases with increasing frequency without an apparent turning point. With a power law of -5/3, the power spectrum falls over the entire sample windows. This feature shows that rain turbulence with wind convection play a major role during these periods.

![Power Spectral Density](image)

**Figure 4-13: Power Spectral Density, Oklahoma March 16, 1998, 04:00 UT**

### 4.1.2 Case 2: May 26, 1998

May 26, 1998 at the Norman, Oklahoma site was chosen because the day had “rain at 0700-1000 (72mm/hr, TRG)” indicating an isolated rain fall event. Below is a plot of the rain rate from the 980526OK.SUM file.
Figure 4-14: Rain Rate at Oklahoma site May 26, 1998

Figure 4-15: Low Resolution Attenuation Data for Oklahoma May 26, 1998
As shown in figure 4-14, rainfall only occurred from 07-09 h UT. Again, the rain rate can be directly correlated to the attenuation of the signals. We can see that during the two hours, attenuation at both frequencies suddenly increased to more than 35 dB (saturation level). After those hours, it takes several hours to return back to the normal level of only gas absorption effects. This is a good case for studying an isolated storm and its recovery process.

The low resolution attenuation data was obtained from the 980526OK.SUM file and is presented below.

Breaking figure 4-15 into its frequency components, addition of the high-resolution data is possible. This is presented in figures 4-16 and 4-17 for both frequencies. By observing where the high-resolution measurements are taken, it is viable to choose eventful hours for further examination.

![Graph showing attenuation levels](image)

**Figure 4-16: 20.2 GHz LDR and HDR Attenuation Levels, Oklahoma May 26, 1998**

In both figures 4-16 and 4-17, we can see that during the 7th hour, attenuation from the HDR averages rapidly increased from 2 dB to 26 dB. This is further confirmed by the high-resolution time series expansion is figure 4-18.
Figure 4-17: 27.5 GHz LDR and HDR Attenuation Levels, Oklahoma May 26, 1998

Figure 4-18: HDR Attenuation Levels, Oklahoma May 26, 1998, 07:11-07:21 UT
A couple of hours were chosen to examine more closely. The seventh and eighth hours were the most interesting. These were created from the 98052607.VOK and 98052608.VOK high data rate files and the 980526OK.SEC low data rate file. Fortunately, a rapid increase in attenuation due to a huge rain storm is caught during the ten minute high-resolution records (figure 4-18). At about 07:16, the 27.5 GHz signal goes to a saturation level of 35 dB and stays there. This is due to the program being set to a maximum value of 35 dB. When the rain rate got very high, no signal was detectable at that frequency. The 20.2 GHz signal reaches the saturation level later that minute, but doesn’t stay at that state. During the eighth hour (figure 4-19), the rain had decreased and the signal was regained.

An hour later, 08 h UT (displayed in figure 4-19), shows attenuation fluctuations, but gradually goes back to normal as the rain stops.

Figure 4-19: HDR Attenuation Levels, Oklahoma May 26, 1998, 08:11-08:21 UT

The standard deviation over the course of the day is plotted in figure 4-20. This was obtained from the file 980526OK.SUM. During the rainy part of the day, the fluctuations are extremely high, especially from 07-09 UT. It is noted that before the rain, some large fluctuations appeared around the third and fifth hours, which may have been caused by some atmospheric turbulence or clouds. Radiometer measurements support this inference.
Figure 4-20: Low Resolution Standard Deviation Data for Oklahoma May 26, 1998

Figure 4-21: 20.2 GHz LDR and HDR Standard Deviation Levels, Oklahoma May 26, 1998
Figure 4-22: 27.5 GHz LDR and HDR Standard Deviation Levels, Oklahoma May 26, 1998

Figure 4-23: Low Resolution Attenuation Levels with respect to Standard Deviation Levels, Oklahoma May 26, 1998
It is important to look at the correlation of the high and low-resolution data. In figures 4-21 and 4-22, the frequencies are separated for clarity. It is noticed, at times, that the high-resolution data records higher standard deviation than the low-resolution data, especially for 27.5 GHz (at least by 0.2 dB). Radiometer measurements show lower fluctuations than other measurements during no-rain times.

Plotting the attenuation versus standard deviation for low-resolution data in figure 4-23, it is evident that most of the day had relatively good weather with low attenuation and low deviation as shown with the data concentrated in the left side of the figure. For the time that it was raining, the trend was for a rise in attenuation and a rise in the standard deviation of attenuation.

In figure 4-24, the relationship between the attenuation and standard deviation is presented from the high-resolution data. The data distribution shows similar features as in the low-resolution display.

From the 98052607.SOK and 98052608.SOK high data rate files, the power spectra were also obtained and shown in figures 4-25 and 4-26. Because both spectra are taken during the rain storm, they have a rain turbulence power spectra feature. That is, the power in mainly concentrated in the lower frequency portion (<0.2 Hz) with a -5/3 power law. There are no apparent high frequency components (except noise) or turning point of the spectra. Receiver noise dominates at fluctuation frequencies above 8 Hz.
Figure 4-25: Power Spectral Density, Oklahoma May 26, 1998, 07:00 UT

Figure 4-26: Power Spectral Density, Oklahoma May 26, 1998, 08:00 UT
Through this case study, we see a rapid increase in attenuation when a huge storm has just started. We also see a recovery process for about two hours after the storm ends. It takes about four hours for the attenuation levels to go back to a normal level, affected only by gaseous absorption.

4.1.3 Case 3: June 11, 1998
June 11, 1998 at the Norman, Oklahoma site was chosen for evaluation for a single storm event. According to the 9806OK.LOG file, the day had rain “0535-0900 T-storm (106mm/hr, TB).” It is quite similar to the previous case in that the rain was for a short period of time. June 11, however, had heavier rain, with a rain rate of 30 mm/hr more than May 26.

Using the 980611OK.SUM file, all time series for rain rate and attenuation at two frequencies are plotted in figures 4-27, 4-28, and 4-29.

![Oklahoma June 11, 1998](image)

Figure 4-27: Rain Rate at Oklahoma site June 11, 1998

Comparing the rain rate to the attenuation plot, it appears that there were probably some clouds responsible for attenuation before the sixth hour and after the ninth hour. It takes four hours (from 09 – 13 h UT) to return to the normal attenuation level.

Figures 4-29 and 4-30 are the high-resolution and low-resolution attenuation levels on the same plots for 20.2 and 27.5 GHz, respectively.
Figure 4-28: Low Resolution Attenuation Data for Oklahoma June 11, 1998

Figure 4-29: 20.2 GHz LDR and HDR Attenuation Levels, Oklahoma June 11, 1998
Figure 4-30: 27.5 GHz LDR and HDR Attenuation Levels, Oklahoma June 11, 1998

Figure 4-31: HDR Attenuation Levels, Oklahoma June 11, 1998, 06:11-06:21 UT
The sixth, seventh, and eighth hours of the day were plotted (figures 4-31, 4-32, and 4-33) from the high data rate files 98061106.VOK, 98061107.VOK, and 98061108.VOK and the low data rate file 9806110K.SEC. These hours were chosen because they encompass the entirety of the storm. Three time series (each with a ten minute time interval) show a process of starting, evolving, and decaying for both rainstorm and signal attenuation. Figure 4-32, during 07 h UT, shows a tremendous change and saturation.

This graph demonstrates that during these minutes of the storm, only noise was received from the satellite due to heavy rain absorption and scattering.

Figures 4-34, 4-35 and 4-36 show the standard deviations for low-resolution data, radiometer and high-resolution data. From these plots of standard deviation with respect to time, it is again apparent that the highest fluctuations occur during the time of the storm.

Using the high data rate data, the standard deviation is plotted over the low-resolution data plot. It seems that the high-resolution points are consistently higher than the low-resolution data points.

Figure 4-37 is a plot comparing the attenuation to the standard deviation. Because much of the day had no rain, the majority of the measurements are in the lower ranges for attenuation and standard deviation. For the time of the storm, however, the trend was to increase in both respects.

Figure 4-32: HDR Attenuation Levels, Oklahoma June 11, 1998, 07:11-07:21 UT
Figure 4-33: HDR Attenuation Levels, Oklahoma June 11, 1998, 08:11-08:21 UT

Figure 4-34: Low Resolution Standard Deviation Data for Oklahoma June 11, 1998
Figure 4-35: 20.2 GHz LDR and HDR Standard Deviation Levels, Oklahoma June 11, 1998

Figure 4-36: 27.5 GHz LDR and HDR Standard Deviation Levels, Oklahoma June 11, 1998.
Figure 4-37: Low Resolution Attenuation Levels with respect to Standard Deviation Levels, Oklahoma June 11, 1998

Figure 4-38: High Resolution Attenuation Levels with respect to Standard Deviation Levels, Oklahoma June 11, 1998
Figure 4-38, shows the high-resolution relationship between attenuation and standard deviation which has a similar trend to figure 4-37.

From the high data rate files 98061106.SOK, 98061107.SOK and 98061108.SOK, the power spectra were created in figures 4-39, 4-40, and 4-41. In hour 06 UT, the attenuation was relatively low. Fluctuation power generally goes down with increasing frequency. However, between 0.2-1.0 Hz, spectra flatten out. Around 1.0 Hz, there is a turning point, which is probably the corner frequency identified in Ho’s study.[22].

![Power Spectral Density, Oklahoma June 11, 1998, 06:00 UT](image)

In the next two figures, the power spectra show rain turbulence features. This is indicated by the signals falling according to the -5/3 power law.
Figure 4-40: Power Spectral Density, Oklahoma June 11, 1998, 07:00 UT

Figure 4-41: Power Spectral Density, Oklahoma June 11, 1998, 08:00 UT
4.1.4 Case 4: September 22, 1998

September 22, 1998 at the Norman, Oklahoma site was because the day had “severe T-storm@0200-0400, 0720-1300, 1800-2400.” This was an interesting day because there were three substantial rain periods.

From the 980922OK.SUM low resolution data file, rain rate, attenuation and standard deviation plots were constructed. The first two rain periods were very heavy with a maximum rainfall rate of at least 100 mm/hr each as shown in figure 4-42.

![Figure 4-42: Rain Rate at Oklahoma site September 22, 1998](image)

Figure 4-42: Rain Rate at Oklahoma site September 22, 1998

Figure 4-43, 4-44, and 4-45 show attenuation variations during three storm events. The time series clearly show processes of storms and clouds coming and going.

Dividing figure 4-43 into two plots, the addition of high-resolution attenuation data can be made. It is apparent that there are so many hours that could result in interesting outcomes.
Figure 4-43: Low Resolution Attenuation Data for Oklahoma September 22, 1998

Figure 4-44: 20.2 GHz LDR and HDR Attenuation Levels, Oklahoma September 22, 1998
Figure 4-45: 27.5 GHz LDR and HDR Attenuation Levels, Oklahoma September 22, 1998

Figure 4-46: HDR Attenuation Levels, Oklahoma September 22, 1998, 02:11-02:21 UT
From the 98092202.VOK, 98092203.VOK, 98092208.VOK, 98092209.VOK, 98092219.VOK, and 98092221.VOK high data rate files and the 9809220K.SEC low data rate file, the time series for the corresponding hours were reviewed.

Figure 4-46 is the ten minute, high-resolution data for 02 h UT, while figure 4-47 is the ten minute, high-resolution data for 03 h UT, during a storm. Figure 4-48 shows ten minutes of high-resolution measurements during a burst of the storm. Attenuation both progresses and gets saturated. Figure 4-49 shows the trailing part of the storm burst.

To demonstrate the fluctuation a little more clearly, the ninth hour in universal time was expanded for the fourteenth minute. Figure 4-50 is a one-minute expansion of the time series. We further expand the higher resolution data into a 10-second interval as shown in figure 4-51. From the next two graphs, it is easy to see how fast the signal is changing.

Figure 4-52 and 4-53 show signal attenuation caused by a third storm. The graph of standard deviation, shown in figure 4-54, with respect to time is consistent with the previous graphs. It demonstrates much higher fluctuation during periods of three rainstorms.

Figures 4-55 and 4-56 are the high and low-resolution components of the standard deviation for each frequency. The trend followed by the attenuation versus standard deviation is nearly log-linear. This indicates a relationship between increasing attenuation and increasing deviation as shown in figures 4-57 and 4-58 for both types of resolution data.

![Figure 4-47: HDR Attenuation Levels, Oklahoma September 22, 1998, 03:11-03:21 UT](image-url)
Figure 4-48: HDR Attenuation Levels, Oklahoma September 22, 1998, 08:11-08:21 UT

Figure 4-49: HDR Attenuation Levels, Oklahoma September 22, 1998, 09:11-09:21 UT
Figure 4-50: HDR Attenuation Levels, Oklahoma September 22, 1998, 09:14-09:15 UT

Figure 4-51: HDR Attenuation Levels, Oklahoma September 22, 1998, 09:14:00-09:14:10 UT
Figure 4-52: HDR Attenuation Levels, Oklahoma September 22, 1998, 19:11-19:21 UT

Figure 4-53: HDR Attenuation Levels, Oklahoma September 22, 1998, 21:11-21:21 UT
Figure 4-54: Low Resolution Standard Deviation Data for Oklahoma September 22, 1998

Figure 4-55: 20.2 GHz LDR and HDR Standard Deviation Levels, Oklahoma September 22, 1998
Figure 4-56: 27.5 GHz LDR and HDR Standard Deviation Levels, Oklahoma September 22, 1998

Figure 4-57: Low Resolution Attenuation Levels with respect to Standard Deviation Levels, Oklahoma September 22, 1998
Figure 4-58: High Resolution Attenuation Levels with respect to Standard Deviation Levels, Oklahoma September 22, 1998

Relating the high-resolution attenuation data with the high-resolution standard deviation data produces figure 4-58.

The six power spectra are displayed below, each rain storm producing two spectra. They were obtained from 98092202.SOK, 98092203.SOK, 98092208.SOK, 98092209.SOK, 98092219.SOK, and 98092221.SOK high data rate files as shown in figures 4-59, 4-60, 4-61, 4-62, 4-63, and 4-64. The ones corresponding to UT hours 02, 03, and 21 have obvious corner frequencies at 1.0 Hz while the others just show the rain attenuation feature with -5/3 power law. It should also be noted that in the high resolution time series attenuation graphs, these hours had at least a portion of time with attenuation well below 10 dB.
Figure 4-59: Power Spectral Density, Oklahoma September 22, 1998, 02:00 UT

Figure 4-60: Power Spectral Density, Oklahoma September 22, 1998, 03:00 UT
Figure 4-61: Power Spectral Density, Oklahoma September 22, 1998, 08:00 UT

Figure 4-62: Power Spectral Density, Oklahoma September 22, 1998, 09:00 UT
Figure 4-63: Power Spectral Density, Oklahoma September 22, 1998, 19:00 UT

Figure 4-64: Power Spectral Density, Oklahoma September 22, 1998, 21:00 UT
This multiple storm case shows that attenuation is controlled by both rain storms and cloud coverage.

4.1.5 Case 5: October 17, 1998
October 17, 1998 was the last case study for the Oklahoma site. According to the 9810OK.LOG file, the day had “rain@1355-1630 (48mm/hr, TB), 1717-2200 (66mm/hr, TB).” Below (figure 4-65) is a plot of the rain rate from the 981017OK.SUM file.

![Figure 4-65: Rain Rate at Oklahoma site October 17, 1998](image)

The 981017OK.SUM low resolution file is also responsible for the plots of attenuation and standard deviation.

Figure 4-66 displays the low-resolution attenuation data for both frequencies. The next figures, 4-67 and 4-68 present the individual attenuation for each frequency, but also mark the point from the high resolution data.
Figure 4-66: Low Resolution Attenuation Data for Oklahoma October 17, 1998

Figure 4-67: 20.2 GHz LDR and HDR Attenuation Levels, Oklahoma October 17, 1998
Figure 4-68: 27.5 GHz LDR and HDR Attenuation Levels, Oklahoma October 17, 1998

From the 98101717.VOK and 98101718.VOK high resolution data files, the following two time series plots were formed.

Figure 4-69 just caught a rapid rise in attenuation occurring at the beginning of the storm at 17 h UT.

Figure 4-70 shows the attenuation change in the middle of the storm.

The standard deviation of attenuation is displayed in figures 4-71, 4-72, and 4-73. There were many fluctuations the day.

Utilizing the availability of high-resolution data, the standard deviation of each frequency is plotted in figures 4-72 and 4-73.

The graph depicting the correlation between the attenuation and the deviation is provided in figure 4-74. Again, it follows the log-linear pattern that was expected.

The standard deviation with respect to attenuation from the high-resolution data is offered in figure 4-75.
Figure 4-69: HDR Attenuation Levels, Oklahoma October 17, 1998, 17:11-17:21 UT

Figure 4-70: HDR Attenuation Levels, Oklahoma October 17, 1998, 18:11-18:21 UT
Figure 4-71: Low Resolution Standard Deviation Data for Oklahoma October 17, 1998

Figure 4-72: 20.2 GHz LDR and HDR Standard Deviation Levels, Oklahoma October 17, 1998
Figure 4-73: 27.5 GHz LDR and HDR Standard Deviation Levels, Oklahoma October 17, 1998

Figure 4-74: Low Resolution Attenuation Levels with respect to Standard Deviation Levels, Oklahoma October 17, 1998
From the high-resolution data files 98101717.SOK and 98101718.SOK, the two power spectra are presented in figures 4-76 and 4-77. The power spectra show the rain turbulence features at the lower frequency part (<0.2 Hz). Between 0.2 and 1.0 Hz, spectra become flatter. It seems that they are turning around 1.0 Hz. After that, power dampens again to reach the noise level.
Figure 4-76: Power Spectral Density, Oklahoma October 17, 1998, 17:00 UT

Figure 4-77: Power Spectral Density, Oklahoma October 17, 1998, 18:00 UT
4.2 British Columbia Site
4.2.1 Case 1: March 30, 1998
Compared with Oklahoma, British Columbia has a lower elevation angle. Thus, we expected to have a lower signal to noise ratio. March 30, 1998 at the Vancouver, British Columbia site was chosen for evaluation. According to the 9803BC.LOG file, the day had “Rain. 0.456693.” The number represents the amount of rain that was received at the site. Figure 4-78 is a plot of the rain rate from the 980330BC.SUM file. This was the only rain rate data that was available for the days of interest for this study.

![Figure 4-78: Rain Rate at British Columbia site March 30, 1998](image)  

The attenuation and standard deviation for this day are shown from figure 4-79 to 4-87. The rain started after 05 h UT. Because the rainfall rate is so low (between 0.5 and 2.5 mm/hr), signal attenuation is less than 3 dB. The attenuation also did not change very much during the eight hour rain shower.

Observing the high-resolution attenuation data for the same day (figures 4-80 and 4-81), hours 06 and 07 UT appear to have a couple of unexplained recordings. It can be assumed that these were not due to rain, but perhaps a technical malfunction. Figures 4-86 and 4-87 also show these bad data points in the standard deviation.
Figure 4-79: Low Resolution Attenuation Data for British Columbia March 30, 1998

Figure 4-80: 20.2 GHz LDR and HDR Attenuation Levels, British Columbia March 30, 1998
Figure 4-81: 27.5 GHz LDR and HDR Attenuation Levels, British Columbia March 30, 1998

Figure 4-82: HDR Attenuation Levels, British Columbia March 30, 1998, 14:11-14:20 UT
Figure 4-83: HDR Attenuation Levels, British Columbia March 30, 1998, 15:11-15:20 UT

Figure 4-84: HDR Attenuation Levels, British Columbia March 30, 1998, 21:11-21:20 UT
From the 98033014.VBC, 98033015.VBC and 98033021.VBC files, attenuation from the high-resolution data are plotted in figures 4-82, 4-83 and 4-84. Differing from the Oklahoma site is the fact that only 9 minutes of high resolution data was recorded at the British Columbia site. The plots show that this day had relatively smooth attenuation with small fluctuations.

Although there was very little rain and very little attenuation to the signal, the corresponding fluctuation is still noticeable.

![Graph showing standard deviation data for British Columbia March 30, 1998](image)

**Figure 4-85: Low Resolution Standard Deviation Data for British Columbia March 30, 1998**

The time series of standard deviations for both low and high-resolution data are shown in figures 4-85, 4-86 and 4-87. Again, around hours 06 and 07 UT there seems to be event that was not accounted for. However, radiometer measurements show that some clouds might have been passing by during this period and also between 12-13 h UT. It is noticeable in both the low-resolution and high-resolution data sets displaying the standard deviation of attenuation over the day. These standard deviations have relatively small amplitude (~0.1 dB) when compared with Oklahoma measurements.

Observing the deviation with respect to attenuation as shown in figure 4-88 for low-resolution data, it appears that two groups were formed. The group on the left represents the time period where there was no rainfall. The group on the right is indicative of the time period when there was attenuation due to a light rain.
Figure 4-86: 20.2 GHz LDR and HDR Standard Deviation Levels, British Columbia March 30, 1998

Figure 4-87: 27.5GHz LDR and HDR Standard Deviation Levels, British Columbia March 30, 1998
Figure 4-88: Low Resolution Attenuation Levels with respect to Standard Deviation Levels, British Columbia March 30, 1998

Figure 4-89: High Resolution Attenuation Levels with respect to Standard Deviation Levels, British Columbia March 30, 1998
Figure 4-89 shows the link between attenuation and standard deviation using the high-resolution data, which shows similar sections to those seen in the low-resolution data.

From the 98033014.SBC, 98033015.SBC and 98033021.SBC files, power spectra (figures 4-90, 4-91, and 4-92) were generated. They portray the power spectral density for the corresponding hours.

Because there is a relatively small signal to noise ratio, power of the signal fluctuations are very close to the noise floor of the receiver. Figure 4-90 shows the power spectrum before the rain. The lower frequency part is flat, which corresponds to clear air.

Both figures 4-91 and 4-92 show the power spectra during the storm. The lower frequency components show a slope of -5/3 power law, which suggests a 2-dimensional convection turbulence created by a strong wind. Again, signal fluctuation powers almost have the same level as the receiver noise has.

Figure 4-90: Power Spectral Density, British Columbia March 30, 1998, 14:00 UT
Figure 4-91: Power Spectral Density, British Columbia March 30, 1998, 15:00 UT

Figure 4-92: Power Spectral Density, British Columbia March 30, 1998, 21:00 UT
4.2.2 Case 2: May 27, 1998

May 27, 1998 at the Vancouver, British Columbia site is a heavy rain case. According to the 9805BC.LOG file, the day had “Rain. 1.385826772.” The number represents the amount of rain, in inches, that was received at the site. Unfortunately, the rain rate was unavailable for this day at this site.

The 980527BC.SUM files provided data to create plots of the attenuation and standard deviation. Although there is no rain rate data to associate with this attenuation plot, it can be assumed that it was raining from about 02:30-04:00 and from about 05:30-07:00 and perhaps it drizzled throughout the day. It might have reached a maximum rain rate of 15 mm/hr.

While figure 4-93 shows the attenuation due to the low-resolution data, figures 4-94 and 4-95 were obtained by using both high-resolution and low-resolution data. Relatively large attenuation suggests that this was not a light rain case.

Using files 98052703.VBC (figure 4-96), 98052706.VBC (figure 4-97), and 98052708.VBC (figure 4-98), the following three time series were constructed using high resolution data. During the 06 hour UT, there was a little bit more attenuation than the British Columbia site typically saw and many more fluctuations.

The low-resolution standard deviation for this day is shown in figure 4-99.

![Figure 4-93: Low Resolution Attenuation Data for British Columbia May 27, 1998](image-url)
Figure 4-94: 20.2 GHz LDR and HDR Attenuation Levels, British Columbia May 27, 1998

Figure 4-95: 27.5 GHz LDR and HDR Attenuation Levels, British Columbia May 27, 1998
Figure 4-96: HDR Attenuation Levels, British Columbia May 27, 1998, 03:11-03:20 UT

Figure 4-97: HDR Attenuation Levels, British Columbia May 27, 1998, 06:11-06:20 UT
Figure 4-98: HDR Attenuation Levels, British Columbia May 27, 1998, 08:11-08:20 UT

Figure 4-99: Low Resolution Standard Deviation Data for British Columbia May 27, 1998
By combining the 980527.MBC and 980527.SUM files, it was possible to retrieve high and low-resolution data for comparison of standard deviation. This is illustrated in figures 4-100 and 4-101. Both plots show that high-resolution data has a larger standard deviation than low-resolution data. This may be due to higher resolution data having a wider bandwidth.

Scatter plots of the standard deviation versus attenuation for both resolution data are shown in figures 4-102 and 4-103. Comparing the attenuation to the deviation, it is observed that again the log-linear pattern is generally followed.

Looking at the high-resolution attenuation versus standard deviation in figure 4-103, the linear-log relationship again seems evident.

Nine-minute average power spectra are calculated to help characterize the dominant sources of signal fluctuations in the high-resolution data. The 98052703.SBC, 98052706.SBC and 98052708.SBC files are responsible for the creation of the three spectra (figures 4-104, 4-105, and 4-106). They display the power spectral density for the relative hours.

All of the spectra show that rain turbulence are dominant sources in the lower frequency components, up to 0.3 Hz, with a slope of -5/3 power law.
Figure 4-101: 27.5 GHz LDR and HDR Standard Deviation Levels, British Columbia May 27, 1998

Figure 4-102: Low Resolution Attenuation Levels with respect to Standard Deviation Levels, British Columbia May 27, 1998
Figure 4-103: High Resolution Attenuation Levels with respect to Standard Deviation Levels, British Columbia May 27, 1998

Figure 4-104: Power Spectral Density, British Columbia May 27, 1998, 03:00 UT
Figure 4-105: Power Spectral Density, British Columbia May 27, 1998, 06:00 UT

Figure 4-106: Power Spectral Density, British Columbia May 27, 1998, 08:00 UT
4.2.3 Case 3: November 14, 1998

The last case for British Columbia is from November 14, 1998. According to the 9811BC.LOG file, the day had “Rain. 1.677165354.” Where the number represents the amount of rain, in inches, that was received at the site. Unfortunately, the rain rate was also unavailable for this day at this site.

Single day time series for signal attenuation is shown in figure 4-107.

The next two graphs (figures 4-108 and 4-109) relate attenuation with time while incorporating high-resolution data for the two frequencies. Based on the attenuation changes, this seems like a case with continuous rain all day.

The next three figures, 4-110, 4-111, and 4-112 were made utilizing the high-resolution data files created by ACTShdr7 called 98111505.VBC, 98111413.VBC, and 98111414.VBC, respectively.

These three nine-minute time series show the attenuation changes during the rain are relatively smooth.

![Figure 4-107: Low Resolution Attenuation Data for British Columbia November 14, 1998](image)
Figure 4-108: 20.2 GHz LDR and HDR Attenuation Levels, British Columbia November 14, 1998

Figure 4-109: 27.5 GHz LDR and HDR Attenuation Levels, British Columbia November 14, 1998
Figure 4-110: HDR Attenuation Levels, British Columbia November 14, 1998, 05:11-05:20 UT

Figure 4-111: HDR Attenuation Levels, British Columbia November 14, 1998, 13:11-13:20 UT
Figure 4-112: HDR Attenuation Levels, British Columbia November 14, 1998, 14:11-14:20 UT

Figure 4-113: Low Resolution Standard Deviation Data for British Columbia November 14, 1998
While figure 4-113 represents the low-resolution standard deviation of both frequencies, the following two graphs (figures 4-114 and 4-115) split up the frequencies, but integrate the high-resolution data points.

We can see that the radiometer detects larger attenuation changes mainly produced by clouds and rain. For fluctuations caused by clear air (or atmospheric turbulence), the radiometer usually has a lower response. Based on these differences, we can identify which source generates which types of deviations.

High-resolution data show higher standard deviations than the lower resolution data. However, overall, the amplitude of fluctuation is relatively small when compared to that of the Oklahoma cases.

Again, weighing attenuation against its standard deviation as shown in figures 4-116 and 4-117, it is perceived that generally standard deviation increases as attenuation increases, showing a clear positive correlation between attenuation and standard deviation.

From the 98111505.SBC, 98111413.SBC, and 98111414.SBC files, the power spectra were created and plotted in figures 4-118, 4-119 and 4-120. The first one, at 05 h UT, shows two types of fluctuations. At the lower frequency range (<0.2 Hz), rain turbulence is dominant. Between 0.2 and 1.5 Hz, the power spectrum becomes flat. At around 1.5 Hz, there is a turning point corresponding to the corner frequency. It suggests that fluctuations in this frequency range are caused by clear air turbulences.
Figure 4-115: 27.5 GHz LDR and HDR Standard Deviation Levels, British Columbia, November 14, 1998

Figure 4-116: Low Resolution Attenuation Levels with respect to Standard Deviation Levels, British Columbia November 14, 1998
Figure 4-117: High Resolution Attenuation Levels with respect to Standard Deviation Levels, British Columbia November 14, 1998

Figure 4-118: Power Spectral Density, British Columbia November 14, 1998, 05:00 UT
Figure 4-119: Power Spectral Density, British Columbia November 14, 1998, 13:00 UT

Figure 4-120: Power Spectral Density, British Columbia November 14, 1998, 14:00 UT
The next two power spectra show that rain convection is the only source for low frequency fluctuations.

4.3 Model Comparison
4.3.1 ITU Estimation vs. Experimental Measurements
Applying the ITU (International Telecommunication Union)-R rain attenuation models to the frequency band 3 – 30 GHz and calculating the attenuation along horizontal and vertical paths through the rain region. This model shows that total specific attenuation rate, $\gamma_R$, is a function of rain fall rate, $R$, as

$$\gamma_R = kR^{\alpha} \text{ in } dB/km$$

where two coefficients $\alpha$ and $k$ are functions of the signal’s frequency and elevation angle as in the equations below.

$$k = \left[ k_H + k_V + (k_Hk_V)\cos^2 \theta \cos 2\tau \right]/2$$

and

$$a = \left[ k_H a_H + k_V a_V + (k_H a_H k_V a_V)\cos^2 \theta \cos 2\tau \right]/2k$$

where $\theta$ and $\tau$ are elevation angle and polarization tilt angle respectively. The variables are provided from the following table, table 4-1, made available in the ITU-R P.838-1.

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>$k_H$</th>
<th>$k_V$</th>
<th>$H$</th>
<th>$V$</th>
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<td>0.912</td>
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<td>0.00887</td>
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<td>1.099</td>
<td>1.065</td>
</tr>
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<td>25</td>
<td>0.124</td>
<td>0.113</td>
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<td>1.030</td>
</tr>
<tr>
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<td>0.187</td>
<td>0.167</td>
<td>1.021</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Table 4-1: Regression Coefficients for estimating Specific Attenuation

Using the equations above, figure 4-121 was generated using the Matlab program written and attached in Appendix II. The graph shows how dramatically rain affects the transmission of a signal as frequency increases. An elevation angle of 45° was used because it is close to the elevation of the Oklahoma site.
Using the ITU equations and instant rainfall rate measurements, figures 4-123 and 4-125 were created. From the corresponding .MOK files, rain rates were obtained and plugged into the equations above along with the values from the following table (table 4-2).
<table>
<thead>
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<th>Frequency (GHz)</th>
<th>$k_H$</th>
<th>$k_V$</th>
<th>$H$</th>
<th>$V$</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.0691</td>
<td>1.099</td>
<td>1.065</td>
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</tr>
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<td>0.124</td>
<td>0.113</td>
<td>1.061</td>
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<tr>
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<td>0.1555</td>
<td>0.14</td>
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<tr>
<td>30</td>
<td>0.187</td>
<td>0.167</td>
<td>1.021</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Table 4-2: Interpolated Regression Coefficients for estimating Specific Attenuation

In order to convert specific attenuation to attenuation, specific attenuation is multiplied by path length, $L$.

$$A = \gamma_R \cdot L \quad (4)$$

Because the path length is not known, it is estimated to be around 5 km. The rest of the parameters were obtained from the values presented in table 2-1.

Figures 4-122 and 4-124 are reproduced here, are the original graphs created from the low resolution data for the attenuation documented on March 16, 1998 and September 22, 1998 at the Oklahoma site.

Figure 4-122: Low Resolution Attenuation Data for Oklahoma March 16, 1998
Comparing the actual attenuation measurements and model predictions (figures 4-123 and 4-125), it is obvious that there is a direct correlation. It has also been made apparent that rain is not the only parameter affecting the transmission of a signal, although it can be held accountable for the majority of the very detrimental signal loss.

![Oklahoma March 16, 1998 (ITU)](image)

Figure 4-123: ITU Estimated Rain Attenuation for Oklahoma March 16, 1998

The difference between the ITU estimation and the experimental measurements for attenuation are also evident. We can see our predictions using the ITU model only can meet the peak of attenuation measurements. This is because the exact path length during the rain period is unknown. Previous studies have also shown that ITU models do not fit measurements very well. Using an averaging technique might also be helpful to reduce the spikes of figures 4-123 and 4-125.

From these models, it is shown that many more factors need to be taken into account. To get a more accurate estimation, clouds, fog, water vapor, atmospheric gases, etc. need to be incorporated.
Figure 4-124: Low Resolution Attenuation Data for Oklahoma September 22, 1998

Figure 4-125: ITU Estimated Rain Attenuation for Oklahoma September 22, 1998
4.3.2 Power Spectra Model

ACTS high resolution data makes it possible for us to study fast amplitude scintillation for frequencies up to 10 Hz. Scintillation theory [2], [3], [10], [21], [22] predicts that for atmospheric turbulence (clear air scintillation) its power spectrum shows a turning point at the corner frequency, $F_c$, which is proportioned to the ratio between wind draft velocity and the first Fresnel length. Below $F_c$, the spectrum of fluctuation frequencies is flat (mode 1, low frequency approximation). Above $F_c$, the spectrum will fall at a rate of $-8/3$ power law (mode 2, high frequency approximation). This is based on the Kolmogrov turbulence spectrum model. When rain and clouds are present, low frequency fluctuations become dominant. A two-dimension rain turbulence will have a $-5/3$ power law slope.

We have applied these theoretical models into power spectra generated using high-resolution data. We can see that the corner frequency is evident in some of the spectrum graphs. It turns out that during times of clear weather, the corner frequency is obvious and the spectrum obeys current model expectations. The model is labeled Modes 1-4 in the graphs. Mode 1 refers to a slope of zero and corresponds to the clear-air radio refractivity fluctuations that occur for frequencies below the corner frequency. Mode 2 refers to the asymptote after the corner frequency. It has a slope of $-8/3$ and represents clear air scintillation, which is produced for fluctuation frequencies above the corner frequency. Mode 3 refers to another slope of zero and corresponds to the receiver noise levels which are calculated in the spectral analysis program. Mode 4 refers to the asymptote at lower frequencies. It has a slope of $-5/3$ and represents the cloud and rain fluctuation increases, which are higher than the Mode 1 floor. Only two parameters were used to set the model, the drift velocity of the refractivity fluctuations through the first Fresnel zone of each propagation path at the top of the planetary boundary layer (about 1 km above the terrain) and the power spectral density at the cutoff frequency. These two parameters were fit “by eye”. To assist in the interpretation of the spectra, the expected uncertainty bounds for the power spectral density estimates are presented on each figure. All of the mode assessments were made possible with the help of Dr. Crane’s program ‘background’.

Figure 4-126, is an example of model fitting using scintillation theory. The power spectral density at the cutoff frequency was set to 0.09 dB$^2$/Hz and the drift velocity was set to 4.5 m/s. It corresponds to a time period with more affects due to rain. We can see that for this spectrum, the dominant feature due to rain causes low frequency fluctuations with a slope of $-5/3$.

The next two figures represent the power spectra taken during a cloudier time periods. In figure 4-127, the power spectral density at the cutoff frequency was set to 0.025 dB$^2$/Hz and the drift velocity was set to 4.4 m/s. We can see that between 0.2 Hz and 1.2 Hz there are obvious flat parts in the spectra for both frequencies. The corner frequency is identified as 1.2 Hz. This indicates that both rain scattering scintillation and atmospheric turbulence play a role in generating these fluctuations. In figure 4-128, the power spectral density at the cutoff frequency was set to 0.009 dB$^2$/Hz and the drift velocity was set to
4.7 m/s. In this case, we also see an obviously flat spectral part which is between 0.2 Hz and 1.2 Hz.

The last illustration of this section (figure 4-129) has the power spectral density at the cutoff frequency was set to 0.003 dB²/Hz and the drift velocity was set to 4 m/s. It is a plot representative of a time period in British Columbia when there was some rain and clouds. In this spectrum, the noise floor is relatively high. Rain caused fluctuation is the dominant feature below 0.2 Hz. Above it, scintillation caused by atmospheric turbulence is not obvious because it is too close to the noise level to be identical. Further theoretical study is beyond the scope of this study.
Figure 4-127: Power Spectral Density Comparison, Oklahoma June 11, 1998, 06:00 UT

Figure 4-128: Power Spectral Density Comparison, Oklahoma September 22, 1998, 02:00 UT
Figure 4-129: Power Spectral Density Comparison, British Columbia May 27, 1998, 08:00 UT
5.0 Statistical Analysis

In previous studies (see Proceedings of the IEEE in June 1997), the ACTS experiment along with many different parameter analyses of the Ka-band communication systems were discussed. In this study [23], fade slope is defined as “a measurement of the attenuation rate of change with respect to time.” This gives fade slope the unit of decibels per second. After data is filtered to remove scintillation effects, fade slope is calculated by taking the first derivative of the attenuation with respect to time. Fade slope statistics were also presented using low-resolution data collected between December 1993 and November 1995. The annual rate of fade slope is plotted against the number of incidents. Then, the levels of fade slopes are divided into the amount of time spent at different attenuation levels. The cumulative distributions were also submitted for fade slopes indicating the percentage of time that the fade slope was equaled or exceeded. Finally, individual fade levels were evaluated for probability of fade slope. It was determined that fade slope was dependent on location, but the probability of fade-slope was dependent on rain dynamics, although independent of transmission frequency. And last, fade slope at a given fade level is correlated with elevation angle.

In another study of ACTS measurement statistics [24], the Florida, New Mexico and Alaska sites of the ACTS experiment were evaluated for fade durations effecting Ka-band signals. The single sample per second data was utilized for this paper. Fade duration is defined as “the time interval between threshold crossings at a given fade level.” Fade level is referring to the amount of attenuation endured by the signal. The proposed method was to split the fade-duration distribution into two components. The first component was a probability of occurrence dependent on the rain region. The second component was a conditional probability taking the inherent properties of hydrometeor effects. To model the fade-duration statistics over a two year period, a log-normal conditional probability was used which depends on the elevation angle and the size of the data filter used to eliminate scintillation effects. The log-normal distribution represented the normalized actual fade duration very well. It was determined that the two sites with the same elevation angle had nearly the same distribution parameters even though the rain regions were different. The site with the lower elevation angle experienced lower fade depths due to considerably more atmosphere to be traversed.

System designers use fade slope predictions the develop power control algorithms and forward-error correction techniques to minimize the effects of link outages for systems. The evaluation of the effects of rain on a satellite system design requires a detailed knowledge of the attenuation statistics for each ground terminal location at the specific frequency of interest. Direct long-term measurements of rain attenuation for all of the ground terminal locations in an operational network are usually not available, therefore modeling and prediction methods must be used to make a best estimate of the expected rain attenuation for each location. Over the past several years extensive effects have been undertaken to develop reliable techniques for the prediction of path rain attenuation for a given location and frequency, and the availability of satellite beacon measurements has provided a data base for the validation and refinement of the prediction models. Using ACTS low resolution data, a lot of statistical results and models have been produced. However, the high time resolution ACTS data has never been examined in detail for
studying fast fluctuation effects due to rain storms as in this study. Also, when designing a telecommunication system, a system designer likes to find out if the attenuation process follows a Markov model (or process), a probability transition model. We need to find out the probabilities between all possible transition states at any moment for a random process such as a weather system. In the following sections, we will perform such a statistical study to define the probability deviations. In this study, the statistics on attenuation changes include both types of variations; slow-varying rain attenuation and fast-varying scintillations.

5.1 Monthly Statistics
5.1.1 LDR vs. HDR Change in Attenuation Statistics

For the sites at Oklahoma and British Columbia, two months were chosen for processing attenuation statistics. Each month at each site had instances of notable rain, clouds, and clear weather. In this section, it was necessary to make the high-resolution and low-resolution data comparable. Since there was only high-resolution data for ten minutes of every hour, the same ten minutes were taken from the low-resolution data for evaluation. This makes a total of at least twenty times more samples taken for the high-resolution data. Clear, cloudy, and rainy days were also assessed separately from each other for each frequency in addition to the overall evaluation.

The difference in attenuation between each sample was calculated and recorded. The number of times that the attenuation changed by each amount is plotted below. These plots include May 1998 at both sites (Oklahoma and British Columbia) for both types of resolution data (from figure 5-1 through 5-4) and October 1998 at both sites (Oklahoma and British Columbia) for both types of resolution data (from figure 5-5 through 5-8). The data was categorized by the weather conditions and in totality. It is consistent throughout the graphs that data taken during a rain period had the most instances of extreme attenuation fluctuation. At the higher frequency, the change in attenuation was also higher. The clear and cloudy days are almost indistinguishable, but still dependent on frequency. Overall, Oklahoma had more intense rain periods than British Columbia, causing the more dramatic changes in attenuation due to rain.

It is also possible to see the difference between the high-resolution and low-resolution results. The low-resolution results appear to have undergone an averaging effect. Meanwhile, the high-resolution data includes the extreme points. At twenty samples per second, far more fluctuations are observed. It is easy to convert the attenuation changes in this distribution into fading rates (slope) by just diving them by data sample time resolution (1 sec and 1/20 sec).

Comparing two graphs of the low-resolution and high-resolution plots of attenuation changes during the month of May 1998 in Norman, Oklahoma (figures 5-1 and 5-2), it is observed that the graphs have the same trends. However, in the higher resolution graph, there are a few occurrences for the larger attenuation changes (up to ±8 dB). These large changes mostly come from the contribution of rainy days. In the low-resolution graph, these are not observed, indicating that the low-resolution data missed many of the fluctuations that are caught by the higher data rate.
Figure 5-1: Low Resolution Attenuation Changes Histogram, Oklahoma May 1998

Figure 5-2: High Resolution Attenuation Changes Histogram, Oklahoma May 1998
The next two graphs are the low-resolution and high-resolution plots noting the changes in attenuation during the month of May 1998 in Vancouver, British Columbia. In the low-resolution plot it is noticeable that the most dramatic attenuation changes were only by 1 dB. However, in the high-resolution plot, it is observed that a few 2 dB jumps were made during rainy periods.

The next two graphs indicate the number of different changes in attenuation during the month of October in 1998 in Oklahoma. These low-resolution and high-resolution plots are similar to the previous ones obtained from the Oklahoma site. The high data rate plot shows that there are many fluctuations missed by the low-resolution data record.

The last two graphs represent the frequency of the changes in attenuation during the month of October 1998 in British Columbia. The plots of the low-resolution and high-resolution data rates are very similar. It seems that the high data rate has a few more occurrences of higher attenuation changes during the rainy phases.

In summation we find: 1) Low-resolution data have much narrower distributions, with a maximum of about 1.5 dB, while high-resolution data have a wider distribution. 2) Distributions are symmetric for attenuation changes between samples. The same number of increases or decreases occurred between any two consequent samples. 3) Distributions have obvious site dependence. Oklahoma has a different distribution than British Columbia.

Figure 5-3: Low Resolution Attenuation Changes Histogram, British Columbia May 1998
Figure 5-4: High Resolution Attenuation Changes Histogram, British Columbia May 1998

Figure 5-5: Low Resolution Attenuation Changes Histogram, Oklahoma October 1998
Figure 5-6: High Resolution Attenuation Changes Histogram, Oklahoma October 1998

Figure 5-7: Low Resolution Attenuation Changes Histogram, British Columbia October 1998
However, at each site, there are no obvious changes from month to month. 4) There is a significant difference between the two frequencies: 20.2 GHz produces a narrower distribution (<4 dB) while 27.5 GHz produces a wider distribution (<8 dB). 5) Large changes are mainly caused by rain (8 dB with HDR). This is equivalent to a 160 dB/sec fading slope. However, the contribution from rain only accounts for less than 1% of the total distribution. 6) Clouds and clear weather only contribute small changes. At most, 27.5 GHz HDR produces 2 dB changes and 20.2 GHz produces 1 dB changes.

5.1.2 LDR vs. HDR Attenuation Statistics
For the next set of graphs, the number of times that the signals were recorded to have each amount of attenuation was plotted. This was performed for the low-resolution and high-resolution data at each frequency. Each weather condition was evaluated at the British Columbia and Oklahoma sites. Two months of statistics are presented from figures 5-9 through 5-12 for two sites, two frequencies, and two types of data resolution.

These first two graphs are the low-resolution and high-resolution attenuation graphs for the month of May 1998 in Norman, Oklahoma. It is evident that clear and cloudy days don’t have more than 5 dB of attenuation. Rainy days, however, seem to have nearly as many instances of low attenuation as they do high attenuation. In the high data rate graph, the curves are smoother. This is due to the mere fact that there are far more data points to plot. We can see that large attenuation at the two frequencies are mainly due to rain effects, which range from 2 dB to 35 dB.
The next two graphs (figures 5-11 and 5-12) were taken from the data provided for May 1998 in British Columbia. The low-resolution and high-resolution graphs indicate the attenuation level for each weather condition. It is apparent that the rain-induced attenuation is higher than the attenuation caused by cloudy or clear conditions. An appealing observation that can be illustrated with these graphs is the difference between the 20.2 GHz and the 27.5 GHz signals. It is shown that the two frequencies have the same curves, but the higher frequency curve is shifted about 5 dB. The higher frequency has the same peaks as the lower frequency, but at a higher attenuation.

The two graphs in figures 5-13 and 5-14 are taken from data recorded during the month of October 1998 in Oklahoma. From the low-resolution and high-resolution graphs, it is verified that higher attenuations occur with higher frequency and with rainy conditions as opposed to cloudy or clear weather.

The last two plots (figures 5-15 and 5-16) were created from analyzing the data from October 1998 in British Columbia. British Columbia has less recording time, so it is less of a statistical sample than compared to Oklahoma. It has been demonstrated again that rain causes higher attenuation than cloudy or clear weather.
Figure 5-10: High Resolution Attenuation Histogram, Oklahoma May 1998

Figure 5-11: Low Resolution Attenuation Histogram, British Columbia May 1998
Figure 5-12: High Resolution Attenuation Histogram, British Columbia May 1998

Figure 5-13: Low Resolution Attenuation Histogram, Oklahoma October 1998
Figure 5-14: High Resolution Attenuation Histogram, Oklahoma October 1998

Figure 5-15: Low Resolution Attenuation Histogram, British Columbia October 1998
As a summary, we see from both high and low-resolution data that the contribution from the clear air and clouds dominate the distribution of the two frequencies attenuation measurements. At more than 95% of the time, the signals show attenuation between 0-5 dB. Only rain is responsible for the large attenuations which spread from 2-35 dB. These distributions have a site, frequency, and resolution dependence.

### 5.2 Seasonal Statistics

To understand if these distributions have a seasonal dependence, we need to perform a statistical analysis over a larger sampling time. We have chosen Oklahoma with two types of resolution data, at two frequencies, for the four season statistical study. Oklahoma was chosen for processing statistics by seasons because it had the most complete one-year set of data. On the high data rate CD provided by Dr. Robert Crane, the entire year of 1998 was included for the Oklahoma site measurements.

The seasons have been defined as March, April, and May for the springtime months, June, July, and August for the summer months, and September, October, November for the fall months. The winter months are typically defined as December, January, and February, however, in this study they are not consecutive months due to the fact that they all occurred in 1998.

ACTShdr7 was used to gather the monthly statistics for the whole year. They were saved as .MDF files in the yymmPid folders. Because the multiple month option has not yet been incorporated into the ACTShdr7 version of the program, it was necessary to
5.2.1 LDR vs. HDR Change in Attenuation Statistics

Figure 5-17 is the outcome of the low-resolution attenuation changes during the spring months at the Oklahoma site. While the larger attenuation changes are due to rain events, this level of quality does not truly reflect that. To see how many larger changes were made by rain effects, figure 5-18 should be examined. There are a few points that show larger changes and are caused by rain and clouds.

Figures 5-19 and 5-20 represent the changes in attenuation due to the different weather effects during the summer months. From the low-resolution data it appears that clouds and clear conditions are mostly responsible for changes in attenuation. Because of the low-resolution, it is indistinguishable between contributions from cloud rain and clear air. Then analyzing figure 5-20, it is evident that a lot of detail is missed in the low-resolution data. It is interesting how the rain accounts for all the attenuation changes greater than 2 dB during the summer. We see for a summer season, there is a much wider distribution at the bottom. These large changes between samples are solely from rain contribution.
Figure 5-18: High Resolution Attenuation Changes Histogram, Oklahoma Spring 1998

Figure 5-19: Low Resolution Attenuation Changes Histogram, Oklahoma Summer 1998
Figure 5-20: High Resolution Attenuation Changes Histogram, Oklahoma Summer 1998

The following two figures, 5-21 and 5-22, are the statistics for the fall of 1998 in Oklahoma. Figure 5-21 is the low-resolution data compilation results. Figure 5-22 is the high-resolution data compilation results. It is noticed that many more instances of large changes in attenuation are made at 27.5 GHz. In comparing the two graphs, there is a very big difference in detail level. The distributions in the fall season are even wider than those of the summer. At 27.5 GHz, there are some changes greater than 10 dB. This gives a fading slope of 200 dB/sec. Also, there are a few points at the bottom showing that contribution from clouds and clear air can cause large changes (> 2 dB).

The high-resolution and low-resolution data obtained from the winter months is presented in figures 5-23 and 5-24. It is detected that the clouds play an important role in contributing to the large changes in attenuation during these months.

It is also noticed that the spring and winter results are very similar, while the summer and fall results are also comparable. Of course, these observations are site-specific to Oklahoma. As a summary, we find that summer and fall have wider distributions (that is, larger attenuation changes) than the other two seasons. Especially in the fall, some changes have reached to more than a 10 dB 1/20 second sample interval.
Figure 5-21: Low Resolution Attenuation Changes Histogram, Oklahoma Fall 1998

Figure 5-22: High Resolution Attenuation Changes Histogram, Oklahoma Fall 1998
Figure 5-23: Low Resolution Attenuation Changes Histogram, Oklahoma Winter 1998

Figure 5-24: High Resolution Attenuation Changes Histogram, Oklahoma Winter 1998
5.2.2 LDR vs. HDR Attenuation Statistics

This section is where the number of samples of attenuation levels is analyzed. Figures 5-25 and 5-26 signify the attenuation histograms for the spring months of 1998 in Oklahoma. It is clear that the high resolution data in figure 5-26 is more complete than the low-resolution data in figure 5-25. High-resolution data has many more samples (20 times more) and a longer tail of rain attenuation. We can also see a small tail for cloudy days which don’t appear in the low-resolution data.

The two graphs (figures 5-27 and 5-28) are indicative of the attenuation seen in the summer months. The first contains low-resolution results and the second contains high-resolution results. The HDR data doesn’t follow the typical result curve. This can be explained by taking into account the brief, but violent, thunderstorms seen during the summer months in Oklahoma. Contributions from clear air and clouds can reach 5 dB attenuations, while the rain contribution tail stays relatively flat up to 35 dB.

Analyzing the data collected throughout the fall months in Oklahoma, it is seen that the low-resolution data missing the instances of cloud attenuation that is observed in the high-resolution data (figures 5-29 and 5-30, respectively). There are small amounts of large attenuation samples due to clouds in the high-resolution data histogram. Overall, the data is as expected. Rain contribution to large attenuation in the fall distribution is significant.

![Figure 5-25: Low Resolution Attenuation Histogram, Oklahoma Spring 1998](image-url)
Figure 5-26: High Resolution Attenuation Histogram, Oklahoma Spring 1998

Figure 5-27: Low Resolution Attenuation Histogram, Oklahoma Summer 1998
Figure 5-28: High Resolution Attenuation Histogram, Oklahoma Summer 1998

Figure 5-29: Low Resolution Attenuation Histogram, Oklahoma Fall 1998
Figure 5-30: High Resolution Attenuation Histogram, Oklahoma Fall 1998

Figure 5-31: Low Resolution Attenuation Histogram, Oklahoma Winter 1998
During the winter season (see figures 5-31 and 5-32), it is perceived that the 20.2 GHz signal does not attenuate more than 24 dB, while the 27.5 GHz signal attenuation runs all the way up to 35 dB. Cloud contributions also become more significant compared to other seasons.

As a summary, we see that rainy days are responsible for all large attenuation measurements. Without rain, most of the time, attenuation would stay below 5 dB, even though clouds can also generate a few large propagation losses. As shown in previous sections for the fading rate, the fall season shows fewer large rain effects and high attenuation samples.

5.3 Model Comparison
5.3.1 Normal Distribution Model vs. Change in Attenuation Data
The change in attenuation plots can be likened to a probability density function with normal distribution because this is a random weather process. The normal distribution was chosen because it is one of the most widely accepted statistical models. The general formula for this distribution is

\[ f(x) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \]

where \( \mu \) is the location parameter, which shifts the graph left or right, and \( \sigma \) is the scale parameter, which controls the width of the curve. For this study, \( f(x) = \log(y) \) and \( \mu = 0 \) because it is centered around the origin, and a scaling factor \( a \) is also being utilized.
Plugging these factors into the equation, it becomes 
\[ y = 10 \left( \frac{e^{-\frac{x^2}{2\sigma^2}}}{\sigma \sqrt{2\pi}} \right). \]
A sample result is given in figure 5-33.

![Normal Probability Distribution Model](image)

Figure 5-33: Normal Probability Distribution Model

This graph represents three possibilities using the normal distribution function. The blue line is an example of a normal default distribution in which \( \sigma = 1 \) and \( a = 14 \). Using different scaling values, the green and red curves are obtained. For the green line \( \sigma = 0.3 \) and \( a = 4.2 \). For the red line \( \sigma = 3 \) and \( a = 25 \) were chosen. These values seem to create curves very similar to the curves created by the data. Using this distribution function, we can fit all statistical histograms we obtain in section 5.1.1 and 5.2.1 by adjusting these parameters. We also can find probabilities for these distributions above a certain fading rate (i.e. <5 dB/sec).

### 5.3.2 Lognormal Distribution Model vs. Attenuation Data

The attenuation sample distribution plots will be well represented by a probability density function of lognormal distribution. The lognormal distribution was chosen because it is most resembled by the data with positive numbers. The general formula for this distribution is

\[ f(x) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(\ln(x) - \mu)^2}{2\sigma^2}} \] where \( \mu \) is the location parameter, which shifts
the graph left or right and $\sigma$ is the shape parameter, which controls the width of the curve. For this study, $f(x) = \log(y)$ and a scaling factor $a$ is also being utilized.

Plugging these factors into the equation, it becomes $y = 10^{\left(\frac{1}{\sigma \sqrt{2\pi}} \int_{-\infty}^{\infty} e^{-\frac{(\ln(x) - \mu)^2}{2\sigma^2}} dx\right)}$. A sample result is given in figure 5-34.

![Lognormal Probability Distribution Model](image)

Figure 5-34: Lognormal Probability Distribution Model

This graph represents some possibilities using the lognormal distribution function. The blue line is the lognormal default distribution. For this curve $\sigma = 1$, $\mu = 0$, and $a = 90$. The green curve is representative of the cloudy and clear days data, where $\sigma = 0.3$, $\mu = 0.5$, and $a = 7$. The red curve is mostly indicative of the rainy data distribution, where $\sigma = 1$, $\mu = 2.5$, and $a = 9$. By adjusting these parameters, the tail can be shorter or longer. Using this distribution function, we can find the probability for all distributions of attenuation samples when attenuation is greater or less than a certain value. Further model and theoretical studies are beyond the scope of this study.
6.0 Results
6.1 Case Study
We have performed the analysis of two sites, including eight days of rain storm case studies, using ACTS high-resolution data. These rainy days include 3 isolated storm conditions and 5 continuous rain storms. It was observed that before a storm, when clouds are present, signals start to attenuate. At a normal state, attenuation is less than 1 dB, this is due to atmospheric gases. During the storm, the signal degrades proportionally to the rate of the rain up to a saturation value of 35 dB, where the signal becomes indistinguishable from the noise. At the conclusion of the storm, the signal continues to be affected by molecules of water lingering in the atmosphere. It can take anywhere from 2-4 hours for a signal to recover from the effects of rain. Using the International Telecommunication Union model estimation, the attenuation due to rain could be approximated. Substituting the measured rain rate, elevation angle and frequency regression coefficients, comparable attenuation graphs were created. However, we find that by using rainfall rate alone, it is hard to accurately predict the attenuation of a Ka-band signal. To estimate attenuation more precisely, using a combination of rain rate, cloud, water vapor, and other relevant models would be wise.

When observing high-resolution data, it is seen that there are many more fluctuations in the received Ka-band signals than in the low-resolution data. The data rate of the high-resolution data is 20 samples/sec whereas the low-resolution data rate is characterized by 1 sample/sec. These fluctuations are caused not only by atmospheric turbulence, but by rain convection and scattering. Comparing the low-resolution time series to the high-resolution time series for attenuation, we see the fast fluctuations. The low-resolution data tends to only show fluctuations of up 1-2 dB while the high-resolution data shows fluctuations from 4-10 dB.

Next, the standard deviation of the received signals is plotted as a function of time. While there are fluctuations during clear weather hours (0.001 – 0.1 dB), the signal shows far greater fluctuations during rainy hours (0.05 – 8 dB). In this study, it is shown that the radiometer measurements show lower fluctuations than the beacon measurements during the clear weather periods. During the rainy periods, the radiometer measurements spike up to similar measurements of the beacon. From the standard deviation time series, it is possible to determine times that clouds were still present because the radiometer measurements increase.

From the data recorded at the sites in this study (Oklahoma and British Columbia), standard deviation was plotted against the attenuation. It was determined that the standard deviation increases log-linearly with the increase in attenuation. Also, the higher data rate displayed a higher standard deviation than the lower data rate did. However, because the high data rate was taken as an average over each second, the results only shows up to a 0.2 dB increase. The difference between data taken during clear weather and data recorded during the rainy periods were also examined. The results generally fell into two groups. The first group had no rain and would appear on the left side of the graph, where low attenuation was associated with low standard deviation. The second group was found
to the right of the first group and corresponds to the data obtained during a rain storm, which has a positive correlation.

A theoretical model comparison has been made in order to understand the measured power spectrum results. We find that monitoring the power spectra taken from the high-resolution data, it is seen that there are generally two types of power spectra. During periods of rain drifting by, wind, clouds and clear weather, the spectrum follows a \(-5/3\) power law slope for frequencies below 0.2 Hz. Between 0.2 Hz and 1.0 Hz, spectra become flat (with a power law slope of zero), which follows the low frequency approximation of atmospheric turbulence. There is a turning point around 1 Hz that defines the corner frequency, which defines the convection speed and the first Fresnel length. After the corner frequency, the slope turns into a \(-8/3\) power law up to the noise level. The other resulting spectrum is the result taken purely during a rain storm. The power spectra generally follow a \(-5/3\) power law slope until the receiver noise floor is reached with a very slight corner frequency if there is one at all. The power spectral density is determined by how much the rain is affecting the signal. Using the low-resolution data power spectra only frequencies below 0.5 Hz can be seen. With the high-resolution data up to 10 Hz can be evaluated. This is very important since the corner frequencies usually occur from 0.8 – 1.2 Hz. This has provided an important physical insight into the propagation environment. Included are the first Fresnel length, dimensions of the storm, rain rate change, turbulent rain drift speed, wind velocity, rain scattering loss, sample rate, etc.

6.2 Statistical Study
Statistically, the monthly histograms of the changes in attenuation resemble a normal Gaussian probability distribution functions. Two months from each site were chosen for examination: May 1998 and October 1998. Breaking the attenuation change occurrences into weather related categories, rain always has a wider distribution in both attenuation and change in attenuation graphs, while clouds and clear weather have narrow distributions. However, these distributions are site dependant. The low-resolution distributions in Oklahoma display only 2 dB changes (between sample times of one second) in attenuation for rainy periods, while the high-resolution distributions show changes (between sample times of 1/20 second) in attenuation of up to 8 dB, which is equivalent to a fading slope of 160 dB/sec. In British Columbia, the low-resolution data shows less than 1 dB changes while the high-resolution data conveys changes a little over 2 dB occurred. There is also a dependence on frequency. The 27.5 GHz signal encountered more large changes in attenuation than the 20.2 GHz signal.

Histograms for the recorded levels of attenuation were also assessed statistically. It was found that the occurrences of the level of attenuation follow a log-normal probability distribution function. It was ascertained that there is a site and frequency dependence. Higher attenuation levels were achieved for the 27.5 GHz signal than for the 20.2 GHz signal, as expected. British Columbia rarely had instances of attenuation over 15 dB, while Oklahoma had many instance of fully saturated signals (35 dB). Clouds and clear weather were seen to account for the majority of the low-attenuation measurements for both sites, frequencies and resolutions.
Looking into seasonal statistics, it appears that while the summer and fall seasons have similar attenuation change distributions (normal distributions), winter and spring seasons are also similar for the Oklahoma site. This is caused by the resemblance of the weather patterns at these times of the year. Summer and fall are characterized by heavy rain storms occurring for short periods of time, while winter and spring are described by continuous rain storms with lower rain rates. This leads to narrower distributions than for the summer and fall seasons for the graphs associated with the changes in attenuation. The spring and winter seasons exhibit attenuation changes due to rain in the vicinity of 5 – 10 dB. The summer and fall seasons show attenuation changes due to rain in the 10 – 15 dB range. These seasonal statistics were created by compiling all of the monthly statistics assigned to each season. The attenuation levels for each season were also presented. It is seen that nearly all of the large attenuation levels (> 5 dB) occur due to the rain for both frequencies and both resolution levels. Even though rain is the major cause of generating large attenuation and attenuation changes, it only accounts for less than 5% of the time at the Oklahoma site.
7.0 Conclusion

In this paper, an extensive, detailed study outlining the characteristics of weather affects on Ka-band signals using high-resolution data is presented. Through power spectra and fading-rate distributions, the cause of dominant fluctuations has been defined. The primary atmospheric event contributing to the attenuation of these Super High Frequency signals is rain at less than 5% of time.

There are many different scenarios associated with the weather phenomena of rain storms. In this study, many different cases were evaluated. Light and heavy rain rates, consistent rain throughout the day and short violent storms were considered. Throughout this analysis, it is found that, as expected, high time resolution data do appear to have large standard deviations (up to 10 dB) and attenuation levels (up to saturation level of 35 dB). The difference between low and high-resolution standard deviation data may appear to be slight (0.2 dB), but this is only because the high-resolution data has been averaged. Using the existing model provided by the ITU-R which utilizes the rainfall rate to find attenuation levels, it is shown that many more factors need to be taken into account except the rainfall rate. To get a more accurate estimation, clouds, fog, water vapor, atmospheric gases, etc. need to be incorporated.

Power spectra were a vital component of this study. Assessing only minutes before, during, or after a storm, it was determined that the power spectrum fell into one of two groups. During a turbulent rain period, the power spectrum had a power law slope of -5/3. During cloudy or clear weather, the power spectrum displays a power law slope of -5/3 up to about 0.2 Hz, then a slope of zero until the turning point defined as the corner frequency around 1 Hz. Then the spectrum turns into a power law slope of -8/3 until it hits the receiver noise floor. High frequency scintillations can extend up to 10 Hz, even though the rain caused fluctuations dominate low frequency part (< 0.2 Hz). The high data rate made it possible to analyze the spectrum up to 10 Hz. With the low data sampling rate, the spectrum was only visible up to 0.5 Hz. Using the power spectrum, we can understand the rain turbulence, scattering effects, and scintillation and with some modification, we can apply this knowledge to larger antennas such as those in the DSN.

For the first time, high-resolution data has been utilized to study the monthly and seasonal attenuation statistics. Using two months from the Oklahoma site and the same two months from the British Columbia site, the changes in attenuation as well as the attenuation levels were categorized by weather events, resolution and frequency. It has been found that these changes follow a Gaussian random process normal distribution curve, while the attenuation distribution follows a log-normal distribution. Dividing up a year worth of data from the Oklahoma site into the four seasons, the same attenuation statistics were examined for all weather conditions, both frequencies, and both resolutions. Rain was identified as the major contributor to large attenuation changes (> 5 dB). Fade rates of up to 160 dB/sec were also due to rain even though rainy days account for less than 5% of the time. These results seem to be dependent on frequency, sample resolution, and site. Through fitting and adjusting the physical parameters, these models can be used to find the probability of attenuation or the changes in attenuation above a certain value.
These resulting models can be applied to a low margin downlink systems such as DSN and wireless communication at Ka-band. It will help in designing all telecommunication systems, in selecting downlink experimental sampling rates, and in understanding how signal fluctuation/scintillation is generated by rain and turbulence.
8.0 Appendix I: Processing Applications

8.1 ACTSPP80

ACTSPP80 is a PC application created by Robert Crane and David Westenhaver to process compressed low resolution data into readable excel files. CD’s containing the five-year complete data sets are available for each of the ACTS sites.

To begin, it is necessary to create the folders that the program will need. This is illustrated below. The ACTS folder can be created anywhere.

![Folder layout for ACTSPP80](image)

The DOS-based applications fill the EXE folder. When the user starts the ACTSPP80 program, it is understood that the data is in the .Pd2 file format. The program prompts for confirmation which can be made by striking the ‘enter’ key. Then it asks for the location of the .Pd2 files, i.e. D:\9803 if you wanted to process March 1998 from the Oklahoma CD in the D:\ drive of the computer. The program lists all the files available in that directory and numbers them. Then it asks which file number or file name the user would like to access. Generally the file number corresponds with the day of the month. In the case of this study #1 was chosen. The next prompt is for the location of the output subdirectories. Because the ACTS folder was created on the C:\ drive, the input is C:\ACTS.

The next prompt is for the letter assigned to all the functions the program is capable of performing. For this study, ‘o’ was used for the one minute output *.sum file. This option also produces the .log files for each month.

Choosing ‘o’ then causes the program to inquire the number of days to process within that folder (maximum of 31 days). By default the Empirical Distribution Functions are also generated by striking the ‘return’ key again. Then the program processes the selected days and outputs .EDF and .LOG files to the DAYLOGid folders. .SUM files are created within the DATASUM folder. All files are named in the format yymmddid, where yy is the two digit year, mm is the two digit month, dd is the day and id is the two letter abbreviation assigned to each of the APT sites.

In order to obtain the attenuation levels each second instead of the one minute averages, an application called EXTRACT5 is used. It is also provided with the CD set. After declaring the directory containing the data and the file corresponding to the desired day as before, it verifies where the output should be sent. For this study the output was in the folder C:\ACTSI\PCD. Then it prompts the user for a starting and ending time, by hour...
and minute. Because this option provides a second by second account for attenuation levels, it is recommended to process only the hours of interest to conserve space. Excel files have a limit of only 65,536 rows, and there are 86,400 seconds in a day. The next question asks the user for a threshold value in dB for the minutes that are wanted to be processed. The default is zero which returns all minutes. The number of days is also specified before the program runs. For this study, one day was chosen at a time.

8.2 ACTShdr7

ACTShdr7 is a processing program created by Dr. Robert Crane for the purpose of developing meaningful high resolution data files. For the Oklahoma, British Columbia, and Maryland APT sites, high resolution data is available for selected periods of time.

On CD’s provided for the purpose of this study, there are zipped raw data files that need to be unzipped and then processed. Using any unzipping software it is possible to unzip the raw data files. After they have been unzipped, they need to be located in a folder called HDRin, within a folder called ACTS_hdr, as illustrated in figure 8-2. All of the other folders also have to be created manually. yy indicates the two digit year, mm indicates the two digit month, and id indicates the two letter abbreviation associated with each APT site. In this study, the ACTS_hdr folder was created within the C:\ drive. Another step that needs to be taken before the program is ready to be run, is the transfer of the .SUM files into the appropriate yyymmAid folder within the ACTSdata folder.

![Figure 8-2: Folder layout for ACTShdr7](image)

The ACTShdr7 program can be saved anywhere on the computer. After opening the program, it prompts the user for the number of samples for spectral analysis for the purpose of producing statistics. The number input needs to be a 2" number. In this study, 512 was selected providing 44 degrees of freedom. The next prompt is to determine whether the program will process a single day or multiple days, entering a ‘d’ prepares the program for running many days, while any other key strike specifies a single day will be chosen. The program asks for the two letter abbreviation for the site id ie. ok or bc. The next inputs are for the month, start day, and number of days (if ‘d’ was chosen). The program then runs through its computations. If there are files or folders missing, the output screen informs the user.
A typical output screen may look something like this:

Enter number of samples for spectral analysis (max = 4096)
2048 or smaller produces better statistics  512
Number samples:  512 with  44 degrees of Freedom

Multiple days?
(enter d for multiple days or any other letter for normal processing):
 d

Enter site ID
ok

Enter month
3

Start day
1

Number of days
31

03/01/98  0  4  8  12  16  20
03/02/98  0  4  8  12  16  20
03/03/98  0  4  8  12  16  20
03/04/98  0  4  8  12  16  20
03/05/98  0  4  8  12  16  20
03/06/98  0  4  8  12  16  20
03/07/98  0  4  8  12  16  20
03/08/98  0  4  8  12  16  20
03/09/98  0  4  8  12  16  20
03/10/98  0  4  8  12  16  20
03/11/98  0  4  8  12  16  20
03/12/98  0  4  8  12  16  20
03/13/98  0  4  8  12  16  20
03/14/98  0  4  8  12  16  20
03/15/98  0  4  8  12  16  20
03/16/98  0  4  8  12  16  20
03/17/98  0  4  8  12  16  20
03/18/98  0  4  8  12  16  20
03/19/98  0  4  8  12  16  20
03/20/98  0  4  8  12  16  20
03/21/98  0  4  8  12  16  20
03/22/98  0  4  8  12  16  20
03/23/98  0  4  8  12  16  20
03/24/98  0  4  8  12  16  20

03/25/98  0  4  8  12  16  20
03/26/98  0  4  8  12  16  20

Cannot open C:\ACTS_hdr\HDRin\9803Hok\98032420.hok
Cannot open C:\ACTS_hdr\HDRin\9803Hok\98032421.hok
Cannot open C:\ACTS_hdr\HDRin\9803Hok\98032422.hok
03/27/98  0   4   8  12  16  20  
03/28/98  0   4   8  12  16  20  
03/29/98  0   4   8  12  16  20  
03/30/98  0   4   8  12  16  20  
03/31/98  0   4   8  12  16  20  
End of program run time =  2.4 min

From the files generated by this program, it is possible to analyze the high resolution data to the satisfaction of this paper.

Typical Column headers were labeled as follows:

<table>
<thead>
<tr>
<th>Label</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm:ss:00</td>
<td>Time</td>
</tr>
<tr>
<td>hAtten20</td>
<td>hdr Attenuation Value, 20 GHz</td>
</tr>
<tr>
<td>Status</td>
<td>Good or Bad data indicator</td>
</tr>
<tr>
<td>hdrB20</td>
<td>hdr Beacon Value, 20 GHz</td>
</tr>
<tr>
<td>BAAtten20</td>
<td>Beacon Attenuation, 20 GHz</td>
</tr>
<tr>
<td>Shdr20hdr</td>
<td>Beacon Standard Deviation, 20 GHz</td>
</tr>
<tr>
<td>SRadiom20</td>
<td>Radiometer Standard Deviation, 20 GHz</td>
</tr>
<tr>
<td>ARadiom20</td>
<td>Radiometer Attenuation, 20 GHz</td>
</tr>
<tr>
<td>Pres</td>
<td>Air pressure</td>
</tr>
<tr>
<td>TempC</td>
<td>Temperature in degrees Celsius</td>
</tr>
<tr>
<td>wvDen</td>
<td>Water Vapor Density</td>
</tr>
<tr>
<td>nTips</td>
<td>Number of Tips</td>
</tr>
<tr>
<td>rRate</td>
<td>Rain rate</td>
</tr>
<tr>
<td># A20hdr</td>
<td>hdr attenuation value histogram for 20 GHz observations</td>
</tr>
<tr>
<td># A20sec</td>
<td>Histogram for one second hdr attenuation averages, 20 GHz</td>
</tr>
<tr>
<td># A20dsec</td>
<td>Histogram for ten second hdr attenuation averages, 20 GHz</td>
</tr>
<tr>
<td># A20min</td>
<td>Histogram for one minute hdr attenuation averages, 20 GHz</td>
</tr>
<tr>
<td># A20hdr</td>
<td>Histogram for all hdr attenuation values for the month, 20 GHz</td>
</tr>
<tr>
<td># Clear20</td>
<td>Histogram for &quot;clear air&quot; conditions, 20 GHz</td>
</tr>
<tr>
<td># Cloud20</td>
<td>Histogram for cloudy conditions, 20 GHz</td>
</tr>
<tr>
<td># Rain20</td>
<td>Histogram for rainy conditions, 20 GHz</td>
</tr>
<tr>
<td># A20sec</td>
<td>Repeated for one second averages, 20 GHz</td>
</tr>
<tr>
<td>Nrefact</td>
<td>The radio refractivity values in &quot;N units&quot;</td>
</tr>
<tr>
<td># N</td>
<td>Monthly histogram of radio refractivity</td>
</tr>
<tr>
<td>#spectra20</td>
<td>number of spectra used in making a calculation, 20 GHz</td>
</tr>
<tr>
<td>SplusN20</td>
<td>the standard deviation including noise, 20 GHz</td>
</tr>
<tr>
<td>Noise20</td>
<td>the estimated receiver noise contribution, 20 GHz</td>
</tr>
<tr>
<td>#Scint20</td>
<td>the noise corrected scintillation value, 20 GHz</td>
</tr>
<tr>
<td>S/N20 dB</td>
<td>the estimated signal to noise ratio, 20 GHz</td>
</tr>
</tbody>
</table>

Labels for the 28 GHz frequency also exist.
9.0 Appendix II: Matlab code

% This M-file plots specific attenuation of rain according to the ITU

gammaR = zeros (42,12);
fig = [1 2 4 6 7 8 10 12 15 20 25 30];
tau = 0;
kh = [.0000387 .000154 .00065 .00175 .00301 .00454 .0101 .0188 .0306 .0751 .124 .187];
kv = [.0000352 .000138 .000591 .00155 .00265 .00395 .00887 .0168 .0335 .0691 .113 .167];
ah = [.912 .963 1.121 1.308 1.327 1.276 1.217 1.154 1.099 1.061 1.021];
av = [.88 .923 1.075 1.265 1.312 1.31 1.264 1.2 1.128 1.065 1.031];
i=1;
j=1;
theta = [0 10 30 45 60 90].* pi./180

figure
j = i;
for R = [.25 1.25 5 25 50 100 150]
    k = (kh + kv + (kh - kv).*(cos (theta)).^2.*(cos(2.*tau)))./2;
a = (kh.*ah + kv.*av + (kh.*ah - kv.*av).*(cos (theta)).^2.*(cos(2.*tau)))./(2.*k);
gammar = k.*R.^a;
logp4 = polyfit (log10(freq), log10(gammar), 4);
logpred4 = 10.^polyval(logp4, log10(freq));
gammaR((i),:)=logpred4;
i = i+1;
end
newlw = 2;
set (gcf, 'DefaultLineLineWidth', newlw)
loglog(freq,gammaR((j),:),'b',freq,gammaR((j+1),:),'g',freq,gammaR((j+2),:),'r'...
        ,freq,gammaR((j+3),:),'y',freq,gammaR((j+4),:),'m',freq,gammaR((j+5),:),'c',freq,gammaR((j+6),:),'k')
axis ([3 30 .01 50])
grid on
xlabel('Frequency (GHz)')
ylabel('Specific Attenuation, \gamma_R (dB/km)')
title({'[Specific Attenuation \gamma_R Due to Rain, ['for an Elevation Angle of ' num2str(theta.*180/pi) 'circ']}})
newpp = [1.25 1.5 6 8];
set(gcf, 'PaperPosition',newpp)
legend ('.25 mm/h', '1.25 mm/h', '5 mm/h', '25 mm/h', '50 mm/h', '100 mm/h', '150 mm/h')
end
10.0 References


