Four Years of Experimental Results from the New Mexico ACTS Propagation Terminal at 20.185 and 27.505 GHz

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Abstract—The Advanced Communications Technology Satellite (ACTS) propagation experiment has collected four years of propagation data at 20.185 and 27.505 GHz. The objective of the experiment is to develop long-term statistics and modeling techniques for predicting atmospheric propagation effects in the Ka band. The experiment includes seven identical earth stations at different locations in North America. Each location is meant to characterize a unique rain region. This paper presents the data collected in White Sands, NM. The data from this site provide an excellent resource for validating rain attenuation models due to its unique arid climate with occasional high rain-rate storms. The seasonal and cumulative four-year attenuation statistics for the 20.2 and 27.5 GHz beacons are presented. The Attenuation with respect to Clear Air (ACA) is compared to five different rain attenuation models and seven different frequency scaling models. The results illustrate how well each model predicts rain attenuation in a desert climate region.

Index Terms—ACTS, fade duration, frequency scaling, Ka band, rain attenuation.

I. INTRODUCTION

The Advanced Communications Technology Satellite (ACTS) propagation experiment has collected four years of data from December 1993 through November 1997. The objective of the experiment is to develop statistics and prediction modeling techniques for the Ka band. Since rain fades are the most prominent effect in this band, developing rain attenuation models that best predict data has been the primary concern.

This paper presents the data for the New Mexico ACTS site. The site is one of seven sites, strategically selected to represent unique climate regions throughout North America. The data for the New Mexico site are of particular importance since the data are the only data for a desert in ITU rain region E in the Ka band. The site is an excellent place to test the boundary limitations of gaseous absorption models and rain attenuation models due to its dry climate with occasional high rain-rate storms.

The seasonal and cumulative four-year attenuation statistics for the 20.2 and 27.5 GHz beacons are presented. The cumulative four-year results give the link outage that occurs for a given link margin at 20.185 and 27.505 GHz. The attenuation with respect to clear air is presented and compared to five rain attenuation models: the Crane Global [6], Crane two-component [7], DAH [9], ITU-R [13], and ExCell [3] models. Finally, the data are compared to seven frequency scaling models. The ARS is calculated for each model and compared to the data.

II. ACTS PROPAGATION EXPERIMENT

The ACTS satellite, launched in September 1993, is expected to last for at least five years (through 1999) with an increasingly inclined orbit in the fifth year. The satellite is geostationary at 100° west longitude. For the propagation experiment, the satellite has beacons at 20.185 and 27.505 GHz. The propagation experiment has seven ground stations, strategically located so that various climate regions are represented in the experiment. The ground stations are located at White Sands, NM, Tampa, FL, Clarksburg, MD, Norman, OK, Ft. Collins, CO, Vancouver, BC, and Fairbanks, AK. The ground station receivers are identical, each having a 1.2 m offset feed parabolic antenna, RF head (with LNA’s), digital receiver (IF converters, radiometers, a data acquisition and collection system), weather sensors, uninterruptable power supply, and a personal computer for data collection and temporary storage. The radiometers are used to calibrate the beacon measurements during clear-air time. The total power radiometers operate at 20 and 27.5 GHz. The attenuation measurement is accurate up to 25 dB due to receiver characteristics.

III. NEW MEXICO APT

The New Mexico APT is located at the Goddard White Sands Complex, which is in the Chihuahuan Desert. The APT is located at 106°36'48" west longitude, 32°32'40" north latitude, and 1.459 km above sea level. The elevation angle to the satellite is 51°, and the polarization tilt is 79° with respect to the signal. Fig. 1 illustrates a view of the New Mexico APT.

IV. CUMULATIVE PROPAGATION EXPERIMENT RESULTS

The Attenuation with respect to Free Space (AFS) is a statistical distribution representing the attenuation due to all of the atmospheric propagation effects—gaseous absorption, clouds, scintillation, and precipitation. The four-year cumula-
The percent time that a given attenuation is equaled or exceeded is on the ordinate, and the attenuation is on the abscissa. The percentage of time represents the outage time for a given link budget. For example, if 10 dB is allocated for atmospheric losses in a link budget, the 27 GHz link will be out 0.03% of the time, and the 20 GHz link will be out 0.02% of the time. This corresponds to an availability of 99.97 and 99.98%, respectively.

At higher percentages (>3%), gaseous absorption is the primary cause of the attenuation. In this region, the 20 GHz beacon is attenuated more than the 27 GHz beacon due to the water vapor absorption peak at 22.3 GHz. Since the 20 GHz beacon is near the top of the absorption peak, and since the 27 GHz beacon is at the trailing end of the peak, the attenuation due to gaseous absorption is greater for 20 GHz than for 27 GHz. For lower percentages of time (<3%), rain is the primary cause of the attenuation.

The total amount of power needed to overcome atmospheric losses for a given availability varies significantly from year to year. Figs. 3 and 4 compare the attenuation values at 99.9 and 99.99% availability for each year to the attenuation values from the cumulative four-year distribution. The attenuation values represent the amount of power in decibels needed to obtain the specified availability for that year.

V. CUMULATIVE SEASONAL STATISTICS

Seasonal variations have the largest effects on a given statistical distribution. Link outages are not evenly distributed throughout the year. For New Mexico, the majority of large fade outages occur during the summer months. The cumulative distributions for each season are given in Figs. 5–8. The plots are the combined statistics from each winter, summer, fall, and spring that occurred during the four-year period.

In New Mexico, the winter months are quite cold and dry compared to the rest of the year. The cold, dry winter weather indigenous to the region minimizes the effects of gaseous absorption. Typically, only two or three high rain-rate storms occur during the winter months. The cumulative winter AFS plot is given in Fig. 5.

The AFS plot for spring is given in Fig. 6. The plot is smoother than the winter AFS plot due to the larger number of rain events occurring in the spring. The spring is characterized by medium rain-rate attenuation events that occur more frequently than in the winter. The gaseous absorption is typically lower than in the summer.

The summers in New Mexico are characterized by extremely hot days with higher water vapor density than in other seasons. Since the site is in the desert, the humidity is relatively low compared to most other climates. The AFS plot for summer is given in Fig. 7. The majority of the rain events occur in the summer months. The statistical distribution for the summer months illustrates that high-attenuation events occur more frequently in the summer than in any other season.

Finally, in the fall, the rainy season is dying down, and the statistical distribution is similar to the spring statistics. The AFS plot for fall is given in Fig. 8. The relative humidity begins to decrease to the winter values. The gaseous absorption is similar to what is seen in the spring.

In summary, the tables in Figs. 9 and 10 compare the attenuations at 99.9 and 99.99% availability for each season to the four-year values. The highest attenuations occur in the summer, and the lowest attenuations occur in the spring.

VI. FADE DURATION STATISTICS

The four-year fade duration statistics are illustrated in Figs. 11 and 12. Fig. 11 illustrates the 20.2 GHz fade duration, and Fig. 12 illustrates the 27.5 GHz fade duration. The ordinate is the number of fades, while the abscissa is the fade duration. Each line is a cumulative distribution for the four-year fade depth statistics at a specified fade depth value. A 10 s moving average was implemented for these calculations. From Figs. 11 and 12, the New Mexico APT recorded fewer deep (high-attenuation) events than low-attenuation events, and the deep fades are typically short in duration. The shallow (low-attenuation) events occur much more frequently and were much longer in duration.
VII. COMPARISON TO RAIN ATTENUATION MODELS

Rain attenuation is the largest atmospheric effect on a link in the Ka band, particularly for high-availability links. To separate the effect from gaseous absorption, the gaseous absorption is removed from the distribution. Typically, rain models are compared to the attenuation with respect to clear air (ACA) distribution:

\[ \text{ACA} = \text{AFS} - \text{AGA} \ \text{dB} \]

where AGA is the attenuation due to gaseous absorption. This section compares the New Mexico data to five rain attenuation models: the Crane Global [6], Crane two-component [7], DAH [9], ITU-R [13], and ExCell [3] models.

The Crane Global [6] model is an empirically based model that uses data from geographical regions to develop a relationship between the path average rain rate and the point rain rate. The path average rain rate is assumed to have a power law relationship to the point rain rate. The path averaged rain rate is fully determined if the point rain rate and horizontal path length are known.

The Crane two-component [7] model breaks the statistical distribution for rain attenuation into two parts. The first part gives the probability of occurrence of convective storms, and the second part gives the probability of occurrence for lighter rain rate storms.

In 1991, A. Dissanayake, J. Allnutt, and F. Haidara developed the DAH [9] model. The model was developed to characterize low-latitude, high-rainfall regions for frequencies \( \geq 10 \) GHz. This empirically based model stems from the ITU-R model. The model applies a log-normal distribution.

The ITU-R [13] model is the empirically based model recommended by the International Telecommunications Union (ITU). The model calculates the attenuation due to a rain rate that occurs 0.01% of the time. Then the model uses a reduction factor and an interpolation procedure to determine the rest of the distribution. The model is based on point rainfall statistics.

The ExCell [3] model is loosely based on the CCIR [5] model (the old version of the ITU-R model). The ExCell [3] model utilizes the concept of spatial distribution of rain cells. The structure of a rain cell is assumed to be exponential and characterized by its peak intensity and the cell radius.
The following ACA distributions were calculated on an instantaneous basis using the Leibe model with on-site weather data to subtract out attenuation due to gas. The Crane [6], [7] models were calculated using Crane’s rain region maps, and all other models were calculated using the ITU rain region maps. The models underpredict the attenuation for a given outage. The comparisons are given in Figs. 13 and 14.

The plots illustrate that the Crane Global [6] model best predicts the data for outage times less than 0.01%, and the DAH model best predicts the data for outage times greater...
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than 0.01%. The attenuation is greater than that predicted by the models for all availabilities. The majority of the error is due to error in the rain rate statistics predicted by the ITU and crane rain maps, indicating that more precise maps are needed. Such maps are critical to system designers who probably do not have measured rainfall distributions for each planned downlink. The remaining error is probably due to wet antenna effects. Experiments and simulations conducted through the ACTS experiment show that the water on the feed and antenna dish can cause significant signal attenuation [1], [8]. The experimental data suggest that the feed attenuation is much greater than the attenuation due to water on the reflector.
Fig. 9. Attenuation for 99.9 and 99.99% availability at 20 GHz for each season.

Fig. 10. Attenuation for 99.9 and 99.99% availability at 27 GHz for each season.

The attenuation due to water on the feed is believed to increase with the age of the feed, due to weathering of the feed surface [8]. Preliminary simulations, conducted by Dr. Crane, show a high correlation between the data and the models when the models are corrected for wet antenna effects.

VIII. COMPARISON OF ACA TO FREQUENCY-SCALING MODELS

Frequency scaling models provide an alternative to rain attenuation models when data are available for a site. These methods are extremely useful since they tend to be excellent predictors, and provide a means for determining what to expect at a frequency for which there is no data. The 27 GHz data are compared to the data scaled from 20 to 27 GHz using seven different frequency scaling models: the ITU-R [13], CCIR [5], Hodge [12], Simple [10], Kheirallah [15], Rue [20], and Battesti [2] models.

The ITU-R [13] frequency-scaling model is currently considered the most accurate method for predicting attenuation when it is applicable. The method is valid in the frequency range 7–50 GHz. The method gives the statistical attenuation ratio (ARS) as

$$\frac{A_2}{A_1} = \left( \frac{\varphi_2}{\varphi_1} \right)^{1-H(\varphi_1, \varphi_2, A_{pl})}$$

where

$$\varphi(f) = \frac{f^2}{1 + 10^{-\frac{\gamma}{20}} f^2}$$

and

$$H(\varphi_1, \varphi_2, A_{pl}) = 1.12 \times 10^{-3} (\varphi_2/\varphi_1)^{0.25} (\varphi_1 A_{pl})^{0.25}.$$  

The CCIR [5] model is an older version of the ITU-R frequency-scaling model. The method gives the statistical attenuation ratio (ARS) as

$$\text{ARS} = \frac{A(f_U)}{A(f_L)} = \frac{\varphi(f_U)}{\varphi(f_L)}$$

where

$$\varphi(f) = \frac{f^{1.72}}{1 + 3 \times 10^{-7} f^{3.44}}.$$  

The Hodge [11] model assumes that the rain rate along the path on a given link is a Gaussian function. The model begins by calculating the instantaneous attenuation from

$$A = \int_0^L a[R_0 e^{-\left(\varepsilon x/l_0\right)^2}]^b dx$$

where $R_0$ is the peak rain rate along the link path length $L$, $l_0 \gg L$ is a measure of the cellular rain structure, and $x$ is the distance measured from the maximum rain rate intensity point. The attenuation ratio is then calculated from

$$\frac{A_2}{A_1} = \frac{k_2}{k_1} \sqrt{\frac{\alpha_1}{\alpha_2}} \left( \frac{A_1}{k_1} \right)^{\frac{\alpha_2}{\alpha_1} - 1}$$

where $k_1$, $k_2$, $\alpha_1$, and $\alpha_2$ are the attenuation coefficients [3].

The Simple [10] frequency-scaling model is a power-law scaling model based on the assumption that the attenuation ratio is directly proportional to the ratio of the frequencies squared. Due to its simplicity, this method is very useful for making estimates. The method gives the statistical attenuation ratio (ARS) as

$$\frac{A_2}{A_1} = \left( \frac{f_2}{f_1} \right)^2.$$  

The method is derived from the more general relationship

$$A(f_U) = A(f_L) \left( \frac{f_U}{f_L} \right)^n.$$  

Various values of $n$ have been proposed for different frequency ranges. Ro [19] and Drafuca [10] proposed that $n = 1.72$ for frequencies between 11.2 GHz and 18.7 GHz. In 1980, Owolabi and Ajayi [18] investigated specific attenuation for a Laws and Parson drop size distribution, and found that the relationship holds over the 10–20 GHz range for $n = 2$. They also noticed a trend of decreasing $n$ with increasing rain rate.

Kheirallah’s [15] frequency-scaling model stems from the ITU rain attenuation model by assuming that the parameters $L$ and $r$ are the same at both frequencies so that

$$\frac{A_1}{A_2} = \frac{\gamma r_2 L \alpha_1 r_1}{\gamma r_2 L \alpha_2 r_2} = \frac{\gamma r_1}{\gamma r_2}$$

where $\gamma$ is the specific attenuation (dB/km), $R$ is the rain rate (mm/h), $L$ (km) is the effective path length through the rain, and $k$ and $\alpha$ are tabulated parameters dependent on frequency and the drop size distribution (DSD). Then the specific attenuation is given by

$$\gamma = k R \nu_i$$

and

$$\frac{A_1}{A_2} = \frac{\gamma r_1}{\gamma r_2} = \frac{k_1 R \nu_i}{k_2 R \nu_i}.$$
By making some approximations, Kheirallah [15] concluded that

The Rue [19] model stems from a simplification of the Misme–Fimbel [17] rain attenuation model. Using the Rue model, the attenuation is calculated from

\[ A_2 \approx k_2 \left( \frac{A_1}{k_1} \right)^{\alpha_2/\alpha_1} \]

\[ A_2 = k_2 5^{\alpha_2} D + 3k_2 \left( \frac{A_1 - k_3 5^{\alpha_3} D}{3k_3} \right)^{\alpha_2/\alpha_1} \]

where \( \alpha_1, k_1, \alpha_2, \) and \( k_2 \) are the attenuation coefficients [3].
and

\[ D = \begin{cases} \frac{L_3 \text{ km}}{27}, & \text{for } L < 27 \\ 27, & \text{for } L \geq 27 \end{cases} \]

where \( D \) is the portion of the slant path length through a cylindrical rain cell with a diameter of 3.0 km. The Misme–Fimbel [17] model, a model most applicable for high rain rates of \( \geq 20 \text{ mm/h} \), is based on a log-normal approximation to the cumulative rain-rate distribution. The model assumes that a rain cell is a compact core of constant rain rate surrounded by a much larger area of light residual rain. Rue’s [20] model is a simplification of this model in which the residual rain rate is assumed to be 5 mm/h, and the cylindrical rain core is assumed to be 3.0 km in diameter.
The Battesti [2] method, proposed in 1981, suggests that, for terrestrial links, the attenuation is proportional to a linear function of the frequency. The method was obtained by examining the specific attenuation for spatially uniform rain events with a typical DSD. His study resulted in the following relationship:

\[
\text{ARS} = \frac{A(f_U)}{A(f_L)}
\]

where \( f_U \) is the upper frequency and \( f_L \) is the lower frequency.

In Fig. 15, seven frequency-scaling models were used to scale the 20 GHz data to 27 GHz. The comparison illustrates that all of the frequency-scaling models are good predictors of the data. The ITU-R model predicts the lowest attenuation, and the simple frequency-scaling model predicts the highest attenuations. All of the other models fall in between. The frequency-scaling techniques described here do not include wet antenna effects. From the results illustrated in Fig. 15, the frequency-scaling models do not appear to have been affected much by the wet antenna effect. This may be an indication that the frequency dependence of the wet antenna effect is similar to the frequency dependence of rain, or it may indicate that frequency dependence of the wet antenna effect is small.

Exactly how frequency scaling is affected by attenuation due to a wet antenna has not yet been determined.

The frequency-scaling models can be used to predict the attenuation ratio from statistical distributions (ARS),

\[
\text{ARS} = \frac{A_{27}}{A_{20}}
\]

where \( A_{20} \) is the 20 GHz ACA attenuation and \( A_{27} \) is the 27 GHz ACA attenuation at a given availability (outage). Some models predict a constant ARS value for all attenuation values, while others predict an ARS value that is dependent on the value of the attenuation. The calculated value of ARS changes with the value of the attenuation; thus, the models having varied ARS values are expected to be better predictors of the data. Fig. 16 compares ARS for each model to ARS computed from the data. The slope of the line represents the value of ARS at a given attenuation.

The average value of ARS predicted by each model is compared to the average calculated value in Fig. 17.
IX. CONCLUSION

This paper has presented the cumulative four-year distributions and seasonal distributions at 20 and 27 GHz from the New Mexico ACTS terminal. The cumulative four-year distributions give the link budget needed for atmospheric attenuation as a function of link outage time. The seasonal distributions illustrate that the majority of the high attenuations occur during the summer months in New Mexico.

The ACA distributions were compared to rain attenuation models. The models were found to largely underpredict the data. The Crane Global [6] model was found to best predict the data for less than 0.01% outage, and the DAH [9] model was found to best predict the data for greater than 0.01% outage. All of the models underpredict the data significantly, most of the error is due to the inaccuracy of the ITU and crane rain maps in predicting the rain rate distribution, indicating a need for more accurate maps. The additional attenuation is probably caused by water on the reflector and feed surfaces [1], [8].

The 20 GHz ACA data were scaled to 27 GHz using seven frequency-scaling models. The scaled data from each model were compared to the 27 GHz ACA data. The data scaled using the ITU-R frequency-scaling model [12] were the closest match to the actual 27 GHz data; however, the scaled data matched closely with the 27 GHz ACA data for all models. The frequency-scaling models did not appear to be significantly affected by the wet surface effects, however, greater differences may have been noticed if the frequencies had been further apart. Exactly how frequency scaling is affected by attenuation due to a wet antenna has not yet been determined.

The results of the rain model comparison indicated that the wet antenna effect is a significant attenuator, and should be included in a link budget. From the results of the frequency-scaling comparison, the frequency-scaling models appear to be affected very little by the wet surface effects. From Fig. 2, the four-year ACTS New Mexico receiver terminal 99.9% AFs availability margins for 20.2 and 27.5 GHz are 5.4 and 8.4 dB, respectively. The final goal of the ACTS propagation experiment is to develop long-term statistics and prediction modeling techniques for advanced system planning and design. The experiment is expected to run through November 1999, collecting a total of five years of data.

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