PROPAGATION RESULTS FROM THE ADVANCED COMMUNICATIONS TECHNOLOGY SATELLITE (ACTS) AND RELATED STUDIES

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1. Introduction

The National Aeronautics and Space Administration (NASA) launched the Advanced Communications Technology Satellite (ACTS) in September 1993, primarily to demonstrate advanced satellite communication technologies at Ka-band. Beacons at frequencies of 20.2 and 27.5 GHz on ACTS served both for adaptive impairment control and as a source for signal level measurements. Propagation measurements with the ACTS beacons, augmented with radiometric skynoise measurements at the same frequencies and various types of meteorological data, were performed for the five calendar years 1994-1998 at seven sites in North America [1].

ACTS Propagation Terminals (APTs) developed for NASA by Virginia Polytechnic Institute and State University [2], were used to collect the data. Uniform system-calibration, data-collection and data-processing procedures and software, prescribed and developed by the NASA Propagation Experimenters (NAPEX) Group, promoted commonality among the data sets and facilitated comparison of results from the various sites. The APT sites were selected to sample a variety of North American climate regions and the associated propagation features with a view to obtaining information for the development of improved prediction methods and impairment-mitigation techniques.

Statistical results from the propagation measurements are presented and compared to the predictions of prediction models. Other aspects of the measurements, including unusually strong antenna-wetting effects observed with the APTs, plus analyses related to impairment dynamics, rain-rate modeling, and clear-air effects, are discussed. Results of related studies conducted as part of the ACTS program are also noted.

2. Experiment Design and Implementation

Prior to launch, NASA convened several meetings of propagation specialists to evaluate the capabilities of ACTS for propagation measurements, and to design experiments to take advantage of these capabilities. Goals were established regarding investigation of fundamental propagation phenomena and fade-mitigation algorithms, the corresponding configuration of the propagation terminals, and novel experiments that might be performed with the ACTS communications package [3]. These recommendations served as guidelines to develop the APTs, and influenced the selection of experiment sites and propagation measurements to be performed with the terminals. Collection of Ka-band propagation data in varied climate regions, some previously unsampled, was considered an important element of the campaign. Features of the seven selected APT sites are summarized in Table 1, along with respective climate designations for the Crane rain zone classifications and the previous ITU-R zone designations [4], recently replaced by a new model based on geographic parameters [5].

The ACTS data sets are also valuable for evaluation of climate effects on model performance. Fairbanks experiences a complex mixture of snow and rain influence on path attenuation and the high-latitude location tests the freezing-level dependence of models. The Colorado and New Mexico sites, at almost 1.5 km above mean sea level, test the rain-height assumptions of prediction models. Previous Ka-band fade statistics collected at the Florida location were in time percentage "gaps" of the ITU-R data banks; the new data fill these gaps. The Virginia site provides a good reference for data collected during prior propagation campaigns. The Las Cruces (White Sands), New Mexico, data stress the ITU-R rain zone scheme and have few independent rain/fade events, testing the statistical stability of prediction models. Oklahoma is a region where rain zones are closely spaced, allowing the effects of spatial variation of rain climate to be examined. At Vancouver, the rainy season occurs in winter, contrary to the (summer) rain height assumed by most models, providing yet another test of freezing-level assumptions.

Table 1. *ACTS Propagation Terminal (APT) locations and their path/climate characteristics.*

	Location	**Coordinates (N lat, W long)**	**Path Elevation and Az. (CWN)**	**Station Ht. (m)**	**Rain Zone ITU-R**	**Rain Zone Crane**
AK	Fairbanks, Alaska	64.85°, 147.82°	8.1° / 129.3°	180	C	B1
BC	Vancouver, BC	49.25°, 123.22°	29.3° / 150.5°	110	B/D	B1
CO	Greeley, Colorado	40.33°, 104.61°	43.1° / 172.8°	1460	E	B2
FL	Tampa, Florida	28.06°, 82.42°	52.0° / 214.0°	50	N	E
NM	Las Cruces, N Mex	32.54°, 106.61°	51.5° / 167.8°	1460	M	F
OK	Norman, Oklahoma	35.21°, 97.44°	49.1° / 184.4°	420	M	D2
VA	Reston, Virginia	38.95°, 77.33°	39.2° / 213.3°	80	K	D2

Automated calibration and beacon signal reference-level determination provided signal loss estimates with a statistical uncertainty of less than 0.2 dB (one standard deviation) and a peak uncertainty of less than 0.5 dB [6]. Two types of data were archived for the experiment: continuous 1-sec average calibrated beacon and radiometer attenuation data, with 1-min supporting meteorological data and all associated calibration and reference level determination information; and 10-min high-data-rate segments of beacon data collected at a rate of 20 samples per sec. Continuous 1-sec data are available for the complete experiment on CD-ROMs. Annual *empirical distribution functions* (EDFs) for attenuation, skynoise temperature, fade duration, interfade interval, and rain rate are posted on the internet at <http://rossby.ou.edu/~actsrain/>. High-data-rate observations are available for ten minutes in each hour for selected sites and seasons.

Data acquisition began 1 December 1993 and ceased at the end of 1998. Calibrated data are available for all seven sites for the five calendar years 1994-1998, except Reston, which collected data from March 1994 through February 1999 due to late receipt of an APT. Three sets of attenuation statistics were generated: 1-sec average attenuation relative to free space loss, AFS; 1-min average AFS; and 1-min average attenuation relative to clear sky, ACS (or AFS minus attenuation due to gaseous absorption). Attenuation due to gaseous absorption was estimated for each minute using a statistical estimation procedure and surface meteorological data [6].

Path Attenuation Measurements

Attenuation EDFs for the five years of observations are presented for 20.2 GHz and 27.5 GHz, respectively, in Figs. 1a and 1b. The EDFs include the effects of attenuation due to rain and clouds, but are corrected to remove estimated losses due to water on the antenna reflector and feed window, and antenna mismatch at 27.5 GHz caused by lack of a feed isolator at the higher frequency. (The antenna effects are discussed in the next section.)

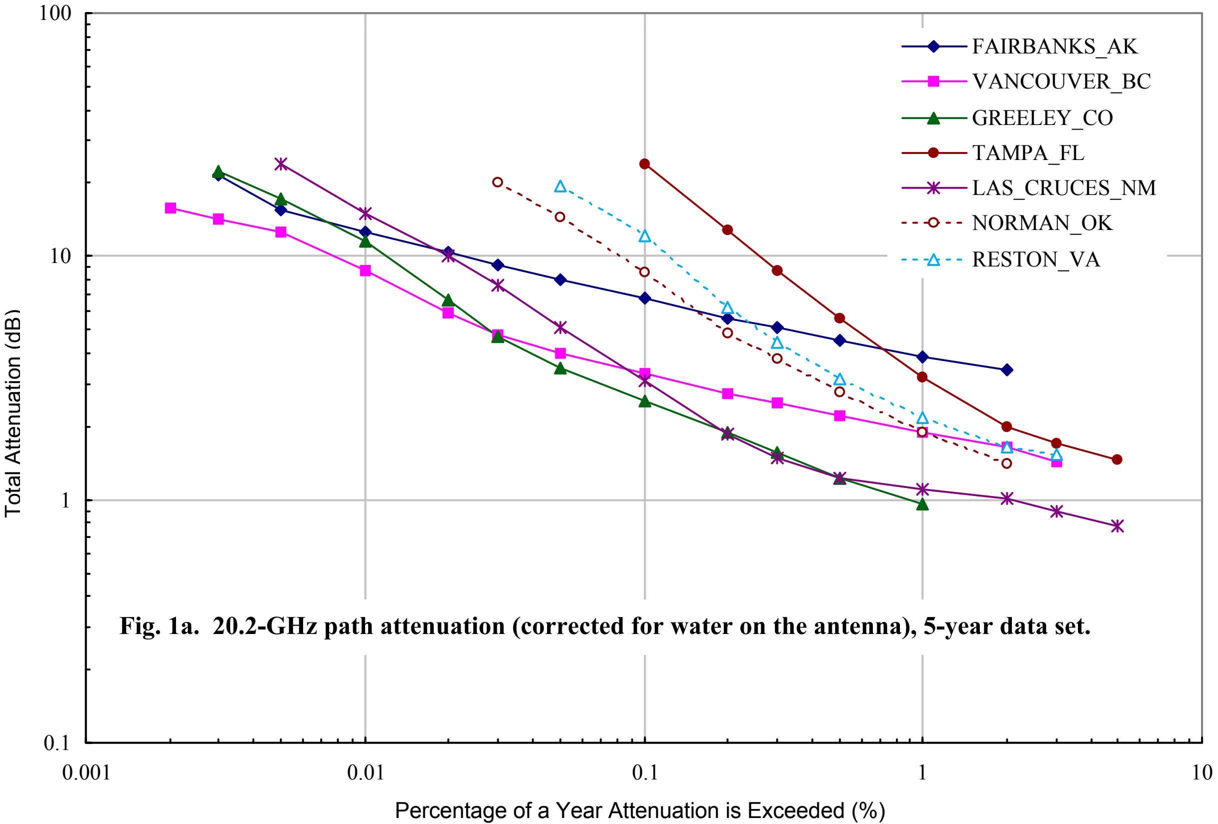


Fig. 1a. 20.2-GHz path attenuation (corrected for water on the antenna), 5-year data set.

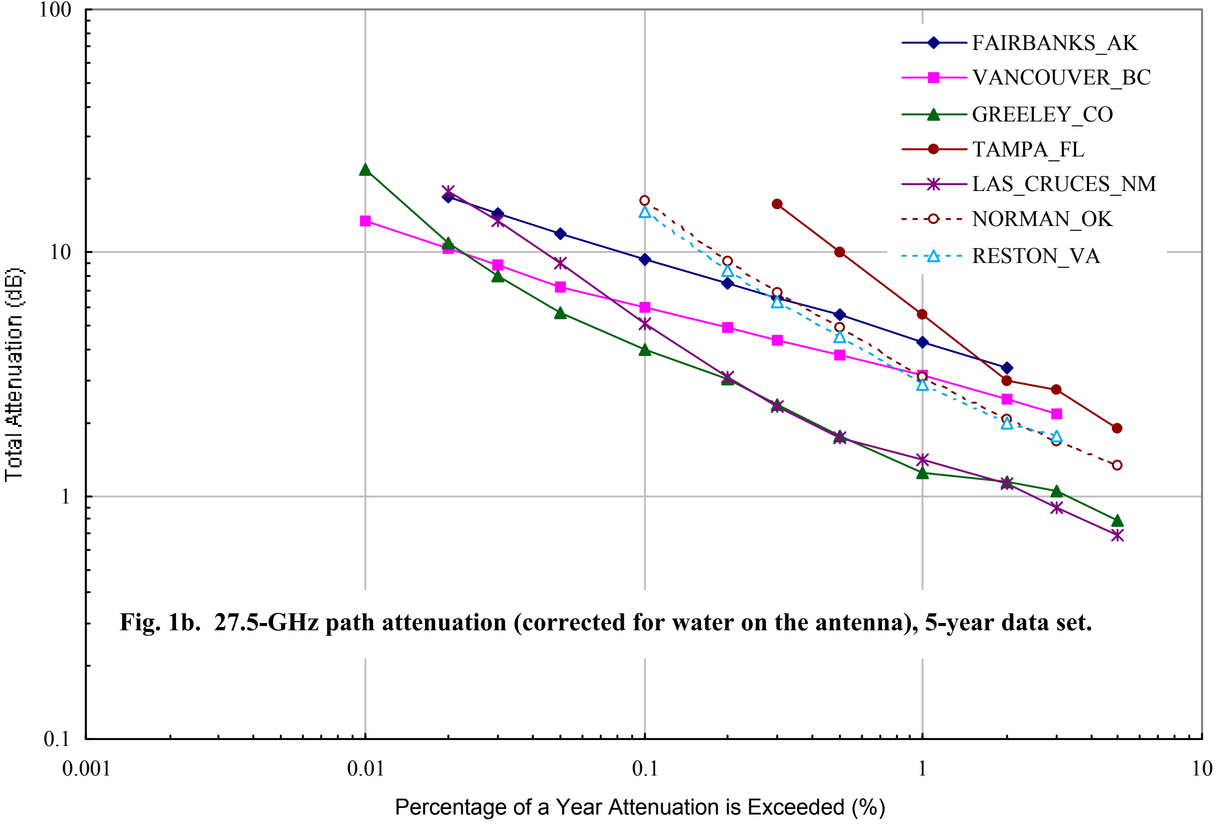


Fig. 1b. 27.5-GHz path attenuation (corrected for water on the antenna), 5-year data set.

General characteristics of the attenuation distributions are consistent with the climatic features noted above. Tampa's convective rain regime displays the most attenuation, while the maritime rain climate of Vancouver shows least attenuation for high fade levels, but more attenuation than some other sites for low fade values. The Oklahoma and Virginia statistics are similar, expected with Crane's zonal classification but not from the previous ITU-R zones [4]. The EDFs for Colorado, Alaska, and New Mexico reveal less attenuation, mainly due to the high site altitude in the first instance and less precipitation in the latter two cases.

Crane's revised Two-Component model [7] predicts the effects of both rain and clouds accompanying the rain. With this model, the prediction biases for the first four annual EDFs for Norman are 3% at 20.2 GHz and 2% at 27.5 GHz. Root mean square deviations (RMSDs) between model predictions and observations are 22% at 20.2 GHz and 18% at 27.5 GHz based on a lognormal model for year-to-year variations in the EDFs. These results show a combined model consistency with measurements at the 0.1 (10%) significance level; i.e., use of the model cannot be rejected based on this test.

3.2 Wetting of Antenna Reflector and Feed Surfaces

During the ACTS Propagation Experiment, a strong sensitivity of the APT antenna to dew and rain water on both the antenna reflector surface and the feed window was discovered. In sprayer tests, the wet antenna could produce as much as 8 dB additional loss. The high losses are caused mainly by: 1) a dielectric coating over the metal screen reflector, which is roughened by the manufacturing process, thus retarding the flow of water down the reflector surface while providing a spacer between the water layer and the primary reflecting surface; and 2) the feed window orientation necessitated by the offset feed design. Existing hydrophobic properties of both surfaces were found to be quickly lost after field installation through natural weathering.

Several experimenters examined these effects and proposed correction procedures [8]-[11]. A physical model [8] developed to estimate the loss caused by wet surfaces predicts the antenna-wetting losses for the APT sites, presented for 27.5 GHz in Fig. 2 as a function of time percentage relative to the corresponding rain rate at the antenna. The predictions were made for the specific elevation angle and polarization orientation of each antenna. An additional design problem affects the 27.5 GHz observations. Water on the feed window produces a mismatch between the antenna and the receiver LNA due to lack of an isolator in the 27.5 GHz channel. The mismatch produced as much as 2 dB additional loss at the higher rain rates.

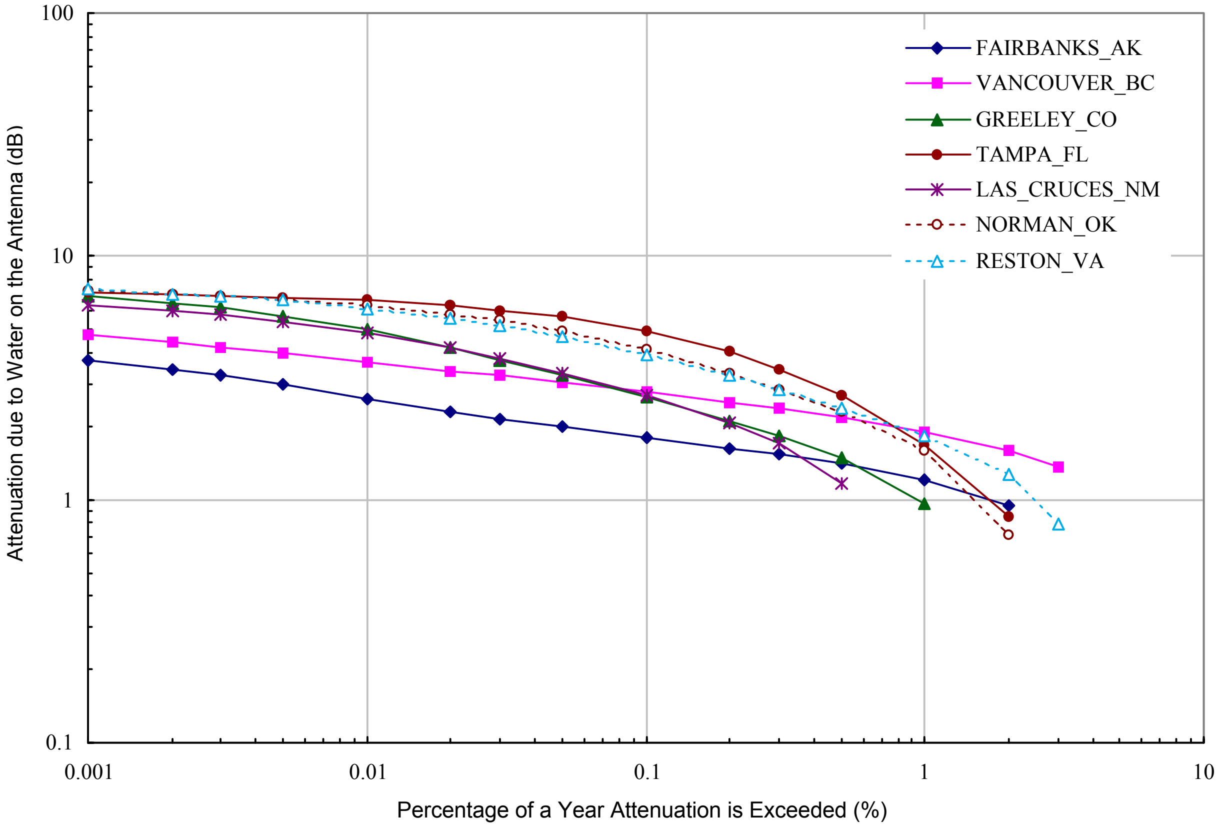
From empirical knowledge of AFS and ACS and model estimates of antenna-wetting loss as a function of rain rate at the antenna, the EDFs can be decomposed into the various fading components (see Fig. 4), important elements of the propagation modeling efforts still in progress.

3.3 Microwave Brightness Temperature Measurements

The radiometric measurements for each site were primarily used for beacon signal level calibration. As an interim step in the calibration process, the microwave brightness temperatures were estimated for each beacon frequency for every minute of observations. For additional calibration verification, brightness temperature measurements at the Oklahoma site were compared with concurrent values calculated from nearby rawinsonde observations.

One application where the radiometrically-derived attenuation statistics have proved quite valuable is in the analysis of rain fade durations [12]. These data are less susceptible to signal fluctuations induced by the equipment and are independent of tropospheric scintillations, thus are particularly useful for study of rain attenuation durations in isolation from other fading effects.

Fig. 2. Wet-antenna correction at 27.5 GHz relative to rain rate time percentage for each



site.

3.4 Impairment Dynamics

Fade duration and interfade interval statistics were compiled for each day, month and year of observations. The automated data preprocessing program generated the duration and interfade interval data for the four attenuation thresholds of 3, 5, 7 and 10 dB; these levels were subsequently corrected for antenna wetting. Unfiltered 1-sec averaged data were used for this analysis. The observations were extrapolated through each calibration interval (20 sec every 15 min) by instantaneous frequency scaling based on the attenuation values from the other beacon. The calibration times for the two frequencies were staggered so that frequency scaling could be used. The frequency-scaling coefficients were dynamically adjusted using the two-frequency observations from the prior minute. The fade duration data were compiled for each day. Fading events that continued across midnight were ignored. Interfade intervals were only computed between rain attenuation events that occurred on the same day. The complete EDFs could not be modeled by simple lognormal, exponential, or power-law CDFs. Similar results were obtained for fade duration and interfade interval EDFs from all the APT sites.

3.5 Clear-Air Effects

The preprocessing program generated EDFs for the standard deviations of within-a-minute fluctuations of the beacon signal levels and radiometer attenuation estimates. The beacon data display variations produced by scintillation due to clear-air turbulence, to attenuation due to clouds and rain, and to the increased effect of receiver noise at low signal-to-noise values during a rain fade. The radiometer data do not show clear-air scintillation but do reveal the fluctuations caused by rain and clouds. Differences between the beacon and radiometer EDFs can be used to estimate the EDFs for scintillation intensity.

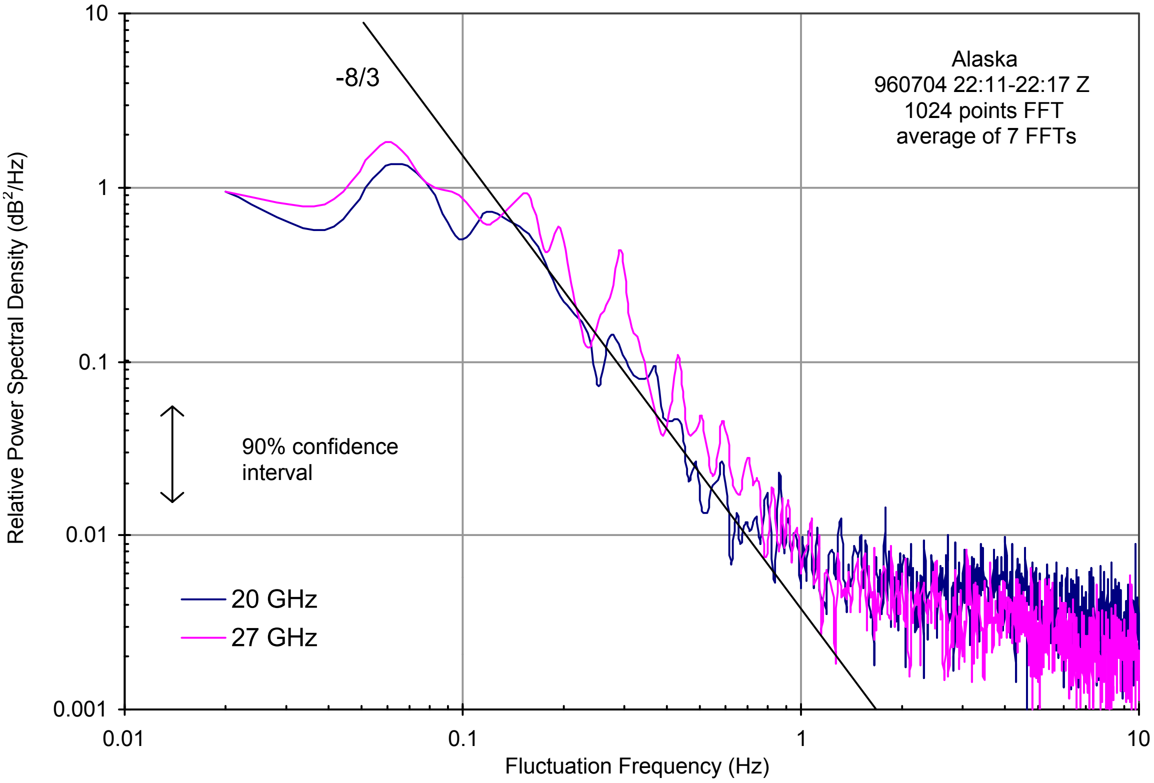


Fig. 3. Spectral density derived from Fairbanks, Alaska, data.

During clear-air periods the high-rate data produce power spectra that display the classic segmented power-law shape expected for clear-air turbulence, as illustrated in Fig. 3 for data collected at the Fairbanks, Alaska, site (path elevation angle of 8.1°). During periods of rain the spectra display the characteristics of a slowly varying flat fading channel with a relative increase in noise caused by the lower signal-to-noise ratio.

4. Comparison to Model Predictions

The prediction errors for the revised Two-Component model [7] and Dissanayake, Allnutt, and Haidara (DAH) model (rain attenuation only) [13] were compared to the annual EDFs for each site. The rain-rate distributions were predicted using the Two-Component local rain model [14]. Wet antenna effects were determined using calculations as presented in Fig. 2. The wet antenna attenuation at 27.5 GHz was also corrected for mismatch.

Each model was subjected to a hypothesis test at the 0.1 (10%) significance level. Calculated RMSD values were tested against the expected value for year-to-year fluctuations at a single location [7] using a chi-square test. The revised Two-Component model can be rejected for three of the seven sites. The DAH model can be rejected for five sites. A closer examination of the observations from the three sites with data not consistent with either model reveals significantly higher year-to-year variability in the EDFs than expected, which exists even if the median observed EDF is used for the prediction model. The model for variability was originally based primarily on 4- and 5-year measurement sets collected in Italy. The number of rain events that occur at two of the sites (Colorado and New Mexico) is significantly smaller than at the Italian sites or at the other ACTS sites. Given its larger intrinsic variability, the attenuation prediction model may be applicable for the Colorado location (at this site the average prediction is unbiased). Performance of the DAH model was improved by using rain rates predicted with the Rice-Holmberg model.

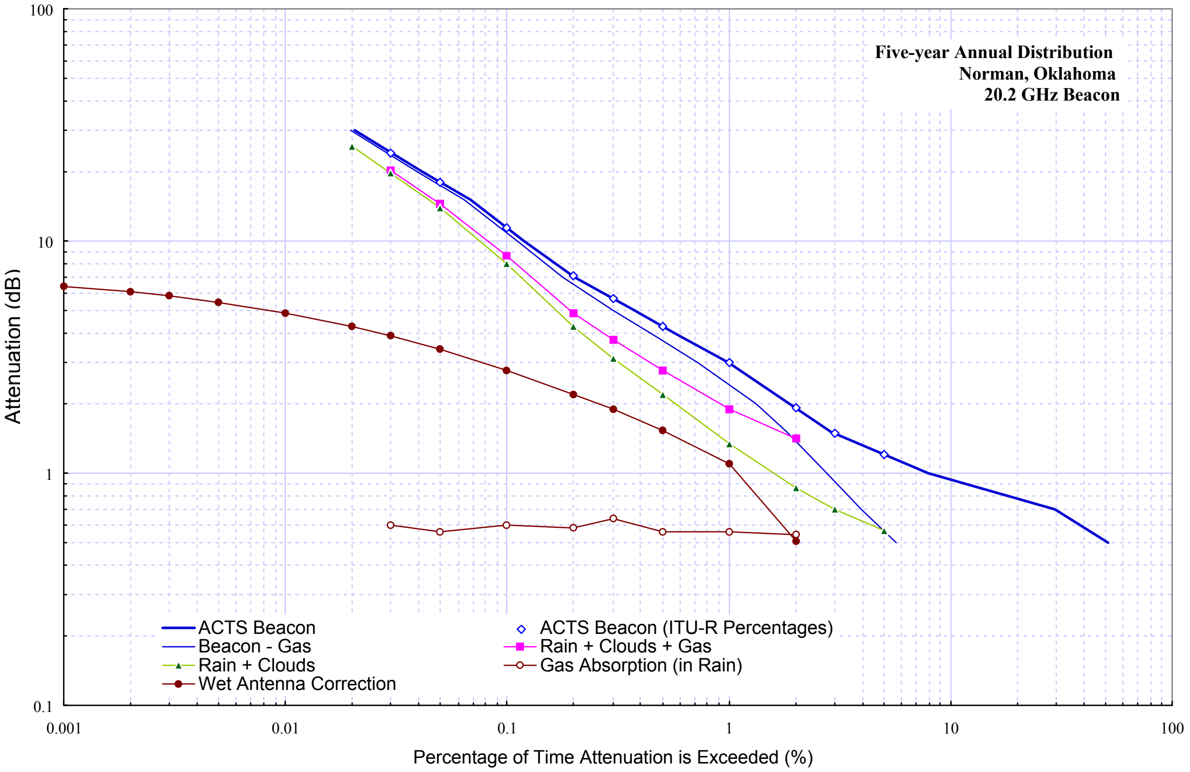


Fig. 4. Attenuation phenomena at 20.2 GHz illustrated for Norman, Oklahoma, site.

The model predictions for British Columbia produce significantly higher attenuation values than were observed. For this site, the rain occurs predominantly during the winter months. If the rain height is reduced by a factor of two to mimic wintertime height profiles, the observations and predictions are in satisfactory agreement (not rejected at the 0.1 significance level for the revised Two-Component model).

The revised Two-Component model for predicting the attenuation EDFs uses a complete description of the rain-rate distribution. Both the DAH and former ITU-R [15] models rely only on rain-rate predictions at 0.01% of a year. The former ITU-R model postulates a universal distribution shape; i.e., all the EDFs should be parallel. The DAH model (recently adopted as the current ITU-R model) provides minor adjustments in shape with elevation angle and latitude (but not rain climate). As the observed EDFs show a significant departure from parallel curves, these results bring into question one of the tenets of models dependent on predictions at only one probability level and the use of a universal adjustment to extend those predictions to other probabilities.

5. Conclusions

Initial comparisons between the ACTS measurements and model predictions concluded that none of the models tested provided a superior fit to the data. Overall, the DAH model combined with the Rice-Holmberg model performed best. The wet antenna problem was noted. Two new models for attenuation prediction, the local Two-Component rain rate model [14] and the wet antenna model [8], have been developed. The effect of water on the antenna was successfully analyzed and good agreement between model estimates and predictions was achieved.

The ACTS propagation campaign has proven to be a valuable undertaking, particularly with the current intense interest in Ka-band satellite systems for a variety of fixed- and mobile-satellite applications, in spite of the difficulties posed by the unexpectedly strong antenna-wetting effect (which however also became an important research topic). Uniform procedures specified and adopted by the experimenters for system calibration, data collection, and analysis yielded an important data set for the characterization of Ka-band propagation, the development of prediction models, and the development and evaluation of adaptive impairment-mitigation schemes.

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