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LARGE-SCALE RAINFALL DIVERSITY FOR ACTS

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Abstract *- From the NOAA 15 minute precipitation file for the US, data were selected for a set of 23 stations spanning a 5 year period. The selection covers the spot beam locations for ACTS and the propagation experiment sites. There is a 2% probability of having any simultaneous rain at 3 or more stations, but this reduces to less than 0.001% at a rainfall rate of 40 mm/hr.*

Introduction

Satellite communications systems operating at frequencies above 10 GHz are vulnerable to rain attenuation. For elevation angles above about 10° this effect is performance limiting and therefore has to be well understood, both from the perspective of the systems operator, the user, as well as the designer. Much work has already been performed to measure and model satellite propagation through rain [1] in order to develop reliable outage predictions or fade mitigation techniques for currently operating satellites.

The advent of the next generation of satellites at K-Band, such as Olympus, ACTS, and others invites a study of the large scale statistics of rain attenuation, because these satellites introduce new technologies that can make use of the fact that rainfall at any time is limited in spatial extent and has location dependent probabilities on a continental scale. Two examples of these techniques are beam-shaping for satellites with CONUS coverage, such as broadcast satellites, and uplink power control and adaptive transmission rate control for multi-beam communications satellites. An example of the latter is ACTS, which will offer a certain amount of pooled resources to overcome, on demand, rain fading in a limited number of its beam locations [2].

The objective of this study is to predict the probable demand on shared rain fade mitigation resources of multi-beam satellites operating in the CONUS region. Similar to studies that have been pursued in Italy, the UK, and Japan [3-5], the investigation is based on available rainfall data. In order to derive ACTS specific information, precipitation data for 23 stations were extracted from the NOAA 15 minute precipitation data base. The stations are either at locations served by the ACTS spot beams, or are at sites chosen for beacon propagation experiments. The data base yielded 5 years of concurrent information, covering the period of Jan. 1, 1984 to Dec. 31, 1988. The data were used to determine individual rain statistics, as well as joint statistics for pairs and triplets of stations as a function of separation. The number of stations with rainfall rate exceeding a given threshold was also determined. In order to assess the effect of the integration time of the rainfall on the results, four years of rain gauge data obtained in Austin, Texas were used to derive scaling parameters. Where appropriate, the results are compared to those found for Italy.

Precipitation Data Base

Description

Rainfall data with the highest resolution collected in the US are those in the NOAA data file TD 3260. It contains 15 minute precipitation information. According to NOAA, the data were taken by qualified observers at primary, secondary, and cooperative stations operated by the National Weather Service and the Federal Aviation Agency. Approximately 2,700 stations have recorded precipitation data in the file, although not all stations cover the entire period starting in 1970. The data are in the form of variable length ASCII records, giving each station's accumulated rainfall for 15 minute intervals, the daily total, and error flags. For most of the stations rainfall is quantized in increments of 0.1 inches. Error flags indicate abnormal conditions, such as deleted, incomplete, or missing data. The files, a total of about 275 MBytes, are available on magnetic tape. The stations are listed by station identification numbers only, therefore another data tape, the Station Historical File (TD 9767), is also needed for location and operations information.

Selection of Stations

The selection of ACTS stations is summarized in Table 1 and their location (with the exception of the Alaska station) has been plotted in Figure 1. The selected stations include the seven Class I propagation experiment sites, namely:

Fort Collins, Colorado; Tampa, Florida; Baltimore, Maryland; White Sands, New Mexico; Oklahoma City, Oklahoma; Blaine, Washington; and Fairbanks, Alaska.

The other 16 selected stations are covered by ACTS spot beams. In Table 1, the column labeled BAD% gives the percentage of defective records in the data base for each station.

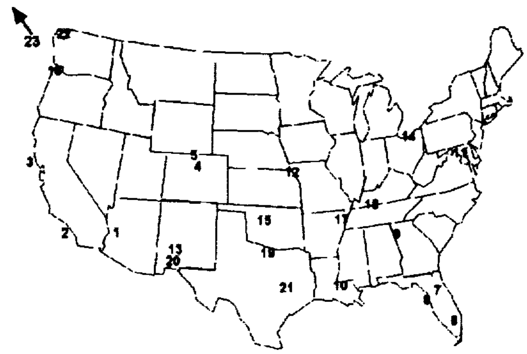

Fig.1 Location of the 23 stations selected for ACTS coverage.

Table 1: Stations Selected For ACTS Prediction

NO	ID	CITY	STATE	BAD %	LAT(°)	LON(°)	ELEV(m)
1	026481	PHOENIX WB AP	ARIZONA	0.0%	33.26	112.02	111
2	047740	SAN DIEGO WB AP	CALIFORNIA	0.0%	32.44	117.10	2
3	047772	SAN FRANCISCO WB CITY	CALIFORNIA	0.0%	37.47	122.25	5
4	052220	DENVER WB AP	COLORADO	0.0%	39.46	104.53	529
5	053005	FORT COLLINS	COLORADO	12.5%	40.35	105.05	500
6	085663	MIAMI WB AIRPORT	FLORIDA	0.0%	25.49	80.17	1
7	086628	ORLANDO (MC COY AFB)	FLORIDA	0.0%	28.26	81.19	10
8	088788	TAMPA WB AIRPORT	FLORIDA	0.0%	27.58	82.32	2
9	090451	ATLANTA WB AIRPORT	GEORGIA	0.2%	33.39	84.25	98
10	166660	MOISANT INT AP	LOUISIANA	0.0%	29.59	90.15	0
11	180465	BALTIMORE WB AIRPORT	MARYLAND&DC	0.0%	39.15	76.32	2
12	234358	KANSAS CITY WSMO AP	MISSOURI	0.0%	39.17	94.43	101
13	299686	WHITE SANDS NATL	NEW MEXICO	12.3%	32.47	106.10	400
14	331657	CLEVELAND WB AP	OHIO	0.0%	41.24	81.51	79
15	346661	OKLAHOMA CITY WB AP	OKLAHOMA	0.0%	35.24	97.36	128
16	356751	PORTLAND WB AP	OREGON	0.0%	45.36	122.36	2
17	405954	MEMPHIS WB AP	TENNESSEE	0.8%	35.03	89.59	26
18	406402	NASHVILLE WB AP	TENNESSEE	0.0%	36.07	86.41	58
19	412242	FORT WORTH INTL WSO	TEXAS	0.9%	32.50	97.03	54
20	412797	EL PASO WB AP	TEXAS	0.0%	31.48	106.24	392
21	414300	HOUSTON WSMO AP	TEXAS	1.5%	29.58	95.21	10
22	450729	BLAINE	WASHINGTON	5.1%	48.59	122.45	4
23	502968	FAIRBANKS WB AP	ALASKA	0.3%	64.50	147.43	44

Rain Statistics for Selected Stations

The probability of having rain for each of the 23 stations has been plotted in Figure 2. In this plot the area of the circle is proportional to the average annual rain probability, defined as the number of 15 minute intervals with precipitation divided by the number of quarter hours per year. The largest value in this selection is 2.37% for Station 16 (Portland, Oregon), and the smallest is 0.34% for station 13 (White Sands, New Mexico). The average annual rain amount for the stations has been plotted in Figure 3, in which the area of each circle is proportional to the rain amount.

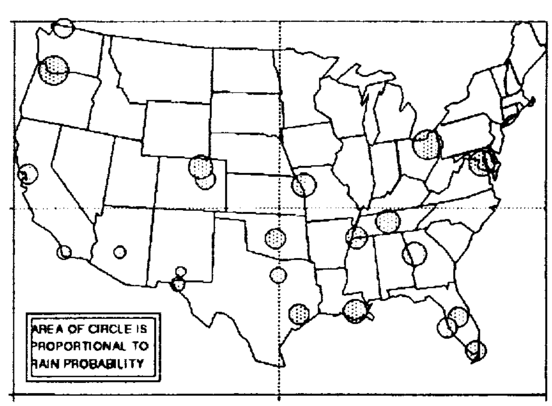

Fig. 2: The probability of having rain at the 23 ACTS stations derived from five years of precipitation data.

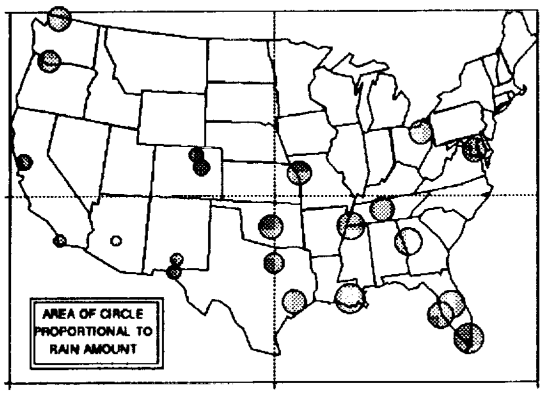

Fig. 3: The average annual rain amount at the 23 ACTS stations.

The site at New Orleans, Louisiana, had the most rain, with 60.03", while Phoenix received the least amount, with only 9.21". By comparing the relative size of the circles for individual stations, one can get some indication about the typical rain intensity. In the case of Florida vs. the Northwest, for instance, the probability of having rain is smaller in Florida, but the total amount at both locations is similar. This is due to Florida's heavy showers and the Northwest's frequent drizzle rain.

Despite the fact that only 23 stations are in the ACTS station set, occasionally a significant fraction of these stations can experience rain at the same time. An example of this is shown in Figure 4, which demonstrates simultaneous rain (within

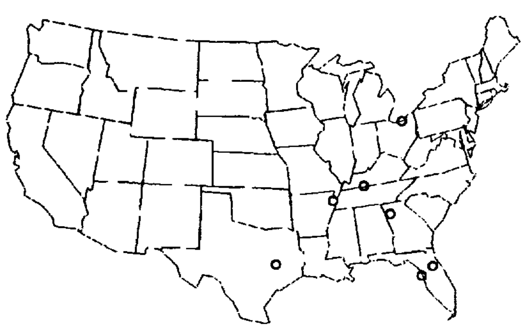

Fig. 4: Due to the structure of weather fronts, on rare occasions many stations report rain during the same 15 minute interval. In this case, 7 stations have precipitation.

the same quarter hour) at 7 of the stations. The statistical significance of this event will be characterized in the following section.

Simultaneity of Rain

Station Count

For a satellite system with many beams and spare capacity for fade mitigation, the most important quantity is the probability that rainfall above a given rate threshold is observed simultaneously at several stations. The count of stations with simultaneous rainfall from 0 to 10 mm/quarter-hour for the ACTS set of 23 stations has been plotted in Figure 5.

The probability that two or more of these stations have simultaneous precipitation of ≥ 2.5 mm/quarter-hour was found to be 0.5%. Increasing the rainfall rate threshold to 10 mm/quarter-hour decreases that probability to 0.02%. Comparing these results to the case in which 128 approximately equal-distant CONUS stations were selected, one finds that for the lower rainfall rates the probability of simultaneous precipitation at a given number of stations is larger in the ACTS case.

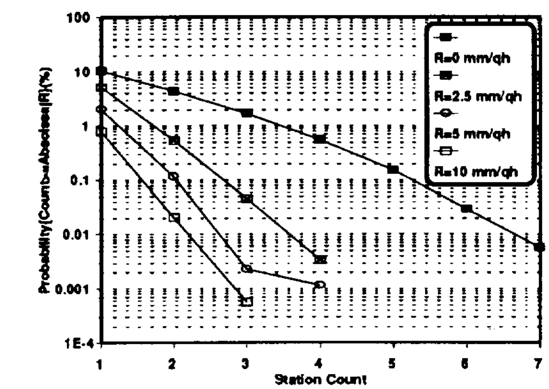

Fig. 5 The probability that rainfall above a threshold rate occurs simultaneously at several of the 23 ACTS stations, for rainfall rates of 0, 2.5, 5, and 10 mm/quarter-hour.

For example, 5% of the ACTS stations have rain exceeding 2.5 mm per quarter-hour for 5% of the time, as opposed to only 1% of the 128 station set. This difference is caused by the large spatial correlation between rainfall events. Both sets of stations are distributed all over the US, but because of the higher density for the set of 128, there is more correlation among the set of 23. Therefore, no linear scaling of the station count is found. This result also indicates that 128 stations are a sufficient number to characterize the large scale behavior of precipitation.

A second difference between the results from the two sets of stations can be attributed to the fact that the National Weather Service has changed the resolution of the rain gauges from 0.1" to 0.01". Most of the 128 station data is based on tenths of inch resolution, whereas the ACTS rain data mostly have 0.01" resolution. This explains the difference in probability between the two station sets. For the 128 stations, low rates cannot be resolved adequately and the 2.5 and 3 mm/quarter-hour station counts merge. At 10 mm/quarter-hour the resolution is adequate and the probabilities are similar.

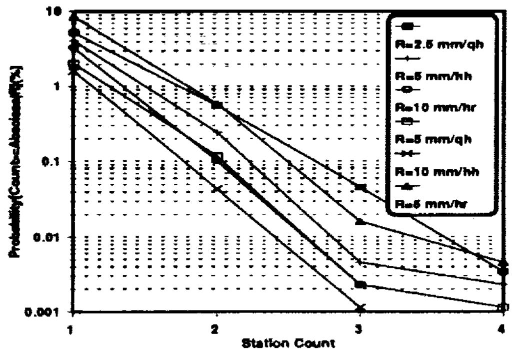

Fig. 6: Comparison of the probability of simultaneity of rain for time bases of 15, 30, and 60 minutes.

Figure 6 displays the probability of rain at several stations for time bases of 15, 30, and 60 minutes. As in the 128 station case, the results for thresholds of 2.5 mm/quarter-hour, 5 mm/half-hour, and 10 mm/hour are not equivalent because most rain events are of short duration.

Joint Probability

More insight is gained into the large scale structure of precipitation when the joint probability of rainfall is determined as a function of station separation. Plotted in Figure 7 are the two-station joint probabilities for rainfall rates in excess of 0, 2.5, 5, and 10 mm/quarter-hour. A probability minimum exists for the case of rain > 0 mm/quarter-hour at a distance of about 1000 to 1500 mile separation, where the joint probability of rain at two of the selected stations is about 0.025%. For the higher rainfall rates, the probabilities are lower and noisier because only 23 stations are considered.

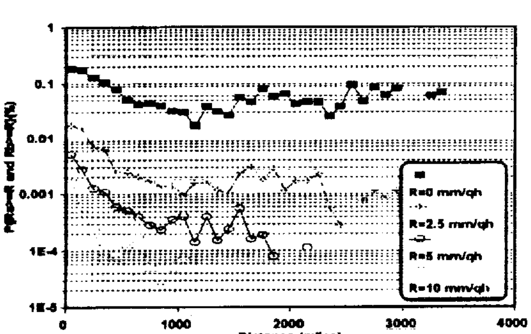

Fig. 7: Joint probability of rain at two of the ACTS stations.

Statistical Dependence

A statistical dependence index has been defined [2] by the ratio of the joint probability to the product of the single station probabilities as

$$\chi = \frac{P_{ab}}{P_a P_b} \tag{1}$$

and

$$\chi = \frac{P_{abc}}{P_a P_b P_c} \tag{2}$$

for 2 and 3 stations, respectively. For the case of statistical independence, $\chi = 1$. If rain at the stations is correlated, then $\chi > 1$. If $\chi < 1$, negative correlation exists.

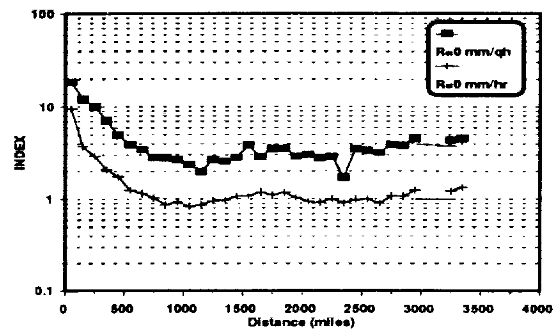

Fig. 9: Average conditional probability of the rain rate at any other station exceeding the threshold value R, given that it rains with rate>R at a specific station.

For the 23 ACTS stations, values of χ for two stations and for rainfall greater than 0 mm per quarter-hour and per full hour have been plotted in Figure 8; the curves for three stations and for R>2.5 mm/quarter-hour are very noisy due the limited set of data and have not been included in the graph. The statistical dependence index has a minimum for pairs of stations separated by 1000 miles and slowly increases for separations greater than 1500 miles, with a peak near 2000 miles, and a second minimum near 2500 miles. The first peak can be explained by the coast-to-coast effect and the second one by the correlation between Alaska and Florida. The result for hourly data is consistent with the 128 station case, but for the quarter hour time base the statistical dependence index is larger. This is a consequence of the typical short duration of rain. If most rain events consist of only 1/4 hour with rain in one hour, then the probability of rain for the 1/4 hour timebase will be 1/4 of the probability for the one hour timebase. The joint probability, P_{ab}, will have the same ratio. Then, according to (1), χ can be up to four times as large for the shorter timebase.

Conditional Probability

Another useful quantity characterizing large-scale rain diversity is the conditional probability of the rainfall rate at any station i exceeding R, given that the rainfall rate at station n also exceeds the same threshold. This can be expressed by

$$P_c(n) = P\{R_i > R \mid R_n > R\} \tag{3}$$

and has been plotted in Figure 9 for the ACTS stations for rainfall rate thresholds of 0, 2.5, 5, and 10 mm/quarter-hour. As expected, the conditional probability decreases with increasing rainfall rate. At the threshold of 2.5 mm/quarter-hour, the conditional probability varies between about 10 to 30% for all the stations. Curiously, some stations have significantly lower conditional probabilities than others, namely stations 5, 13, and 22, i.e., Fort Collins, White Sands, and Blaine, Washington. In the case of station 22, it is furthest removed from all other stations except station 16 and has a lower probability of rain than station 16. The low conditional probability for stations 5 and 13 can be explained with the aid of Figure 7, in which the joint probability of rain is lower for a mid-continent-to-coast geometry than a coast-to-coast one. The reason that neighboring central stations 4 and 20 don't show the same behavior may be that frontal weather systems are more likely to exist near coastlines than mid-continent, making weather in those regions less highly correlated with distance.

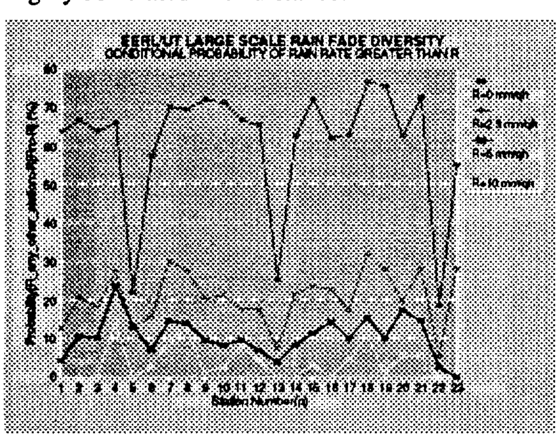

Fig. 9 The average conditional probability of the rain rate at any other station exceeding the threshold value R, given that it rains with rate>R at a specific station.

Conclusions

The NOAA 15 minute precipitation data are the highest resolution rainfall data available for the US for a large number of stations and for a period of about 20 years.

For the 23 ACTS stations, there is a 2% probability of having any simultaneous rain at 3 or more stations, but this reduces to less than 0.001% at a rainfall rate of 40 mm/hr (Fig. 5).

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