

LARGE SCALE RAINFALL DIVERSITY AND SATELLITE PROPAGATION

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Abstract - From the NOAA 15 minute precipitation file for the US we selected data for 128 stations covering a 17 year period and calculated the probability of simultaneous rainfall at several stations. We assumed that the chosen stations were located in separate beams of a multi-beam communications satellite with shared fade mitigation resources. In order to estimate the demands made on these resources, we determined the number of stations at which rainfall rates exceeded 10 to 40 mm/hr. We found a 1% probability that at least 5 of the 128 stations have rain at or over 10 mm/hr in any 15 minute interval. Rain at 2 stations was found to correlate over distances less than about 600 miles.

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 /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], we base our investigation on available rainfall data. For this purpose, we have selected data for 128 stations and 17 years, from 1972 through 1988, from the NOAA 15 minute precipitation data base. These were used to determine the 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 is also determined. In order to assess the effect of the integration time of the rainfall on the results, we also used four years of rain gage data obtained in Austin, Texas and derived 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 stations 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 needed for location and operations information.

Selection of Stations

Of the total number of stations, 793 were identified as having data available for the entire Jan. 1, 1972 - Dec. 31, 1988 period. From these, 128 stations were selected for the diversity analysis for an average station-to-station spacing of about 200 miles. This number was chosen to represent a reasonable beam size for a future multi-beam satellite system. The selection criteria were that (1) less than 12.5% of each station's records should have any error flags, and (2) the stations should be approximately evenly distributed across the US. The first criterion was met by only 309 stations. From these, 128 stations were culled using the second criterion and are shown in Figure 1.

Rain Statistics for Selected Stations

The annual number of quarter-hours with precipitation for each station is given by the area of the circles around each station. The graph shows that rainfall is less frequent in the western center than the eastern center and along both coasts. The average annual rain amount, depicted in Figure 2, is a similar function of location. 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 comparable. This is due to Florida's heavy showers and the Northwest's frequent drizzle rain.

An example of a particular 15 minute snapshot is given in Figure 3, in which 9 stations reported rain simultaneously within a 15 minute period. Several distinct clusters of rainfall activity can be observed, one comprised of 5 adjacent stations in the Northwest due to widespread rain, one isolated event in Idaho, and one cluster along a line from Louisiana to New York State, probably part of a frontal system. Other snapshots with comparable station counts show similar clustering.

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. Figure 4 displays the probability that this number of stations exceeds a value in the range from 1 to 10. At least 5 stations with a rainfall rate exceeding 2.5 mm/quarter-hour can be observed to exist 1% of the time. The probability of having such rain at 10 or more stations is less than 0.001%, however.

Curves for rainfall rate thresholds of 3, 5, and 10 mm/quarter-hour have also been drawn. Note that results for the former two are almost identical. This is due to the fact that most of the rainfall data are given in increments of 0.1 inches (2.5 mm). As long as thresholds are selected to match multiples of the rather coarse quantization, reliable answers can be obtained, however. As the rainfall rate threshold is increased to 10 mm/quarter-hour, it becomes much less likely to find many simultaneous events. At the 0.001% level, only three stations will be affected.

We know from diversity studies that events with high rainfall rates are decorrelated over a distance of about 15 km. At low rates, significant correlation exists for separations of up to several hundred miles, however. If each beam contains many ground stations, more 15 minute intervals in each beam will be affected by precipitation. Lowering the rainfall threshold rate to 2.5 mm/hr effectively enlarges the area of integration and results in higher estimates of simultaneity, with 10 or more stations at the 1% level and 18 at 0.001%. Therefore, 5% to 8% of the ground stations will experience fading simultaneously with a 1% probability.

In Figure 5 we compare the probabilities for rain at several stations using a quarter-hour, half-hour, and full-hour interval for rain rate determination. Simultaneous rainfall is observed at 5 or more stations with a probability of 1%, 0.009%, and 0.003% for the three time-bases, respectively. Data with an equivalent rain rate of 10 mm/hr produce different answers because of the short duration of most rain events. From Figure 6 it can be seen that about 90% of the rainfall data consists of a single 2.5 mm increment observed in any of the three intervals. As higher rainfall rates generally are not sustained over more than 15 minutes, it is misleading to calculate rain rates from longer time bases. The effect of the integration time on the measurement of rainfall rates is examined in greater detail further on.

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. We have calculated the probability that the rainfall rate exceeds 10, 20, and 40 mm/hour, based on quarter-hour intervals, and plotted it versus distance in Figure 7. For 10 mm/hr (2.5 mm/quarter-hour) a minimum exists in the joint probability at a distance of about 1000 miles. For larger

distances, i.e. coast-to-coast, the joint probability rises again. At the higher rain rates, even though there are fewer cases and the curves are therefore noisier, no minimum is obvious.

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

$$\chi = P_{ab} / P_a \cdot P_b$$

and

$$\chi = P_{abc} / P_a \cdot P_b \cdot P_c$$

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. In Figure 8 the average statistical dependence index has been plotted versus station separation, where a condition of equidistance ($\pm 20\%$) has been imposed on the 3 station case. We observe that the index for 2 stations decreases to 1 at about 750 miles, is below 1 at 1000 miles, and increases slightly for separations of 2000 miles. Three stations start out with high correlation at close distance, but are decorrelated at about 450 miles separation. For larger distances, the index continues to decrease. This reflects the fact that the joint probability for three equidistant stations is most often zero. In Figure 10 we compare our results to those derived for Italy [2] at a rainfall rate of 5 mm/hr. For station pairs the results are quite similar up to the 600 mile maximum, for station triplets, however, the index decreases much faster in the US than in Italy. It is not clear whether this is due to differences in climate or data processing.

Integration Time and Quantization

The NOAA precipitation data have an integration time of 15 minutes and a quantization of 2.5 mm. Propagation models for rain fade prediction require rates based on a 1 minute integration time. It has been shown [6] that the prediction error is very small when rates based on variable integration times are used instead. Such data are generated by tipping bucket rain gages. Tipping bucket rainfall data collected in Austin, Texas, over a 46 month period have been converted using integration times of 1, 5, 15, 30, and 60 minutes to estimate the effect of using the 15 minute integration data for the large scale diversity study. Figure 10, a summary plot of the rainfall rate exceedances, shows the variation of the distributions with rainfall rate and integration time. At low to intermediate rates (10 to 40 mm/hr), where simultaneous events are most likely, the 15 minute integration distribution is quite close to the 1 minute curve. This means that the temporal dynamics of precipitation are still reasonably well represented by 15 minute data. Predictions have to be based on rates matched to the quantization level, however.

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. Although many of the entries contain errors, 128 stations were found to give representative coverage for a hypothetical multi-beam satellite using fade mitigation techniques supplied from a shared pool of satellite resources. While a data base with 1 minute integration time and 0.01 inches resolution would have been preferred, most fades impeding systems performance at K-Band happen at low to medium rain rates, where the available data are adequate. We found that rain tends to occur in clusters (Fig. 3). There is a 1% chance of having rain of 10 mm/hr simultaneously affecting at least 5% of stations in any 15 minute period, but 8% or more stations will be affected at that rate threshold in the same quarter hour only once per year (Fig. 4). The joint probability for precipitation at 10 mm/hr at two stations decreases to a minimum at 1000 miles distance and slowly increases at larger separations, probably due to the distance between the two coasts (Fig. 7). The average statistical dependence index for 2 stations was found in agreement with published data from Italy, but for 3 stations significant differences were noted to exist (Fig. 9).

Bibliography

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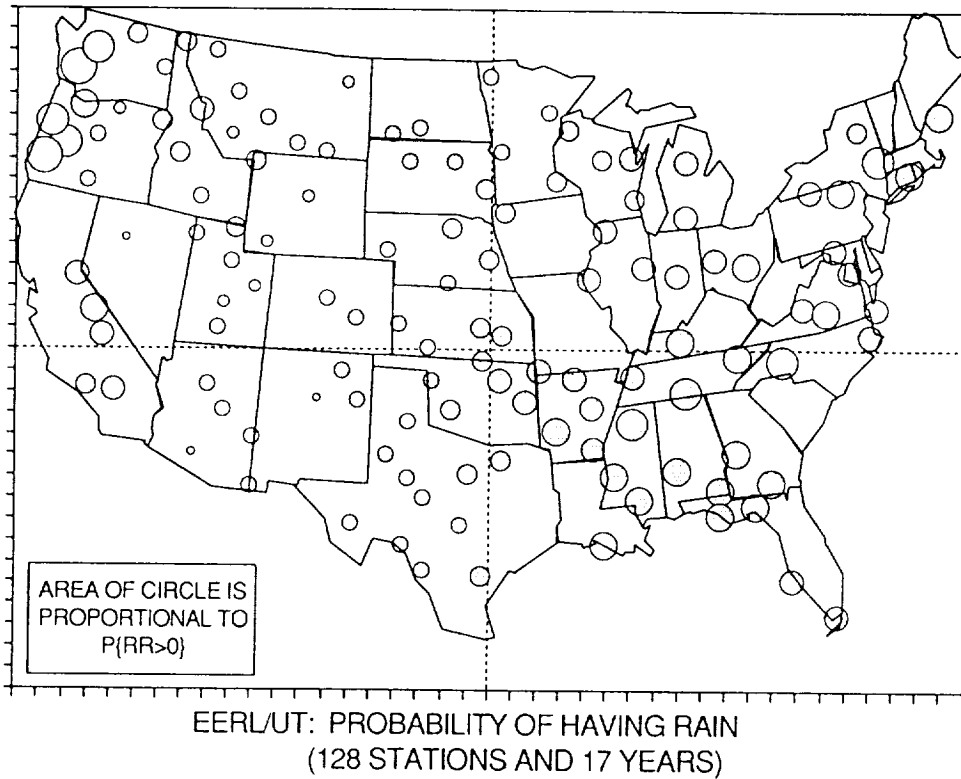
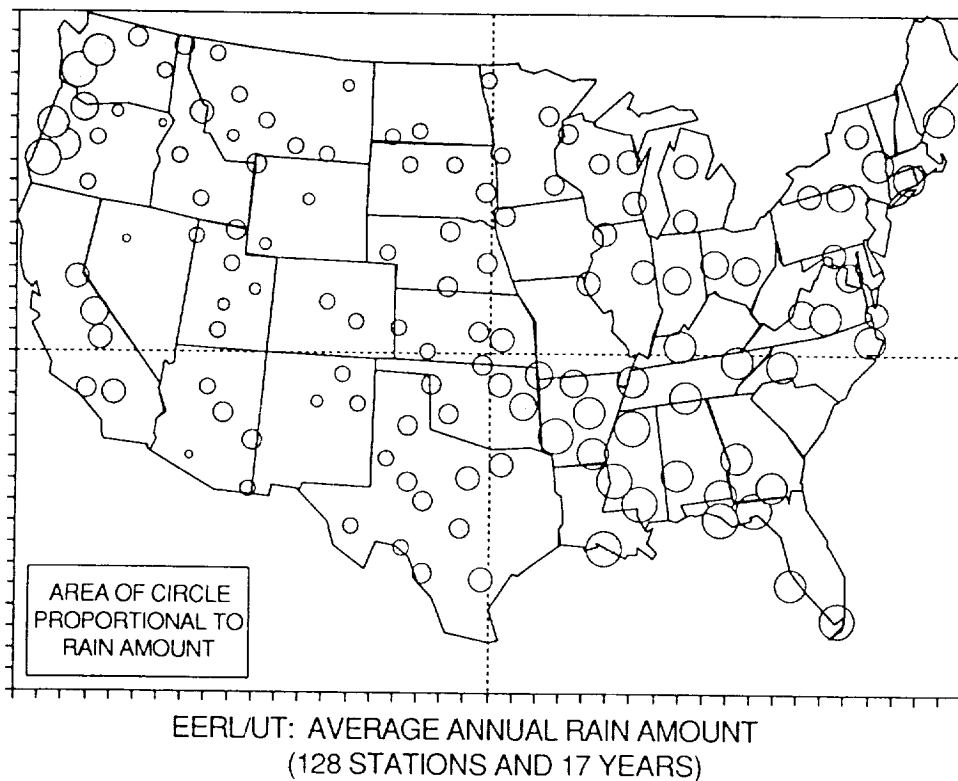


Figure 1: The probability of having a precipitation event (2.5 mm) in a 15 minute period for 128 stations across the US, based on 17 years of data.

Figure 2: The average annual rain amount for 128 stations across the US, based on 17 years of data.



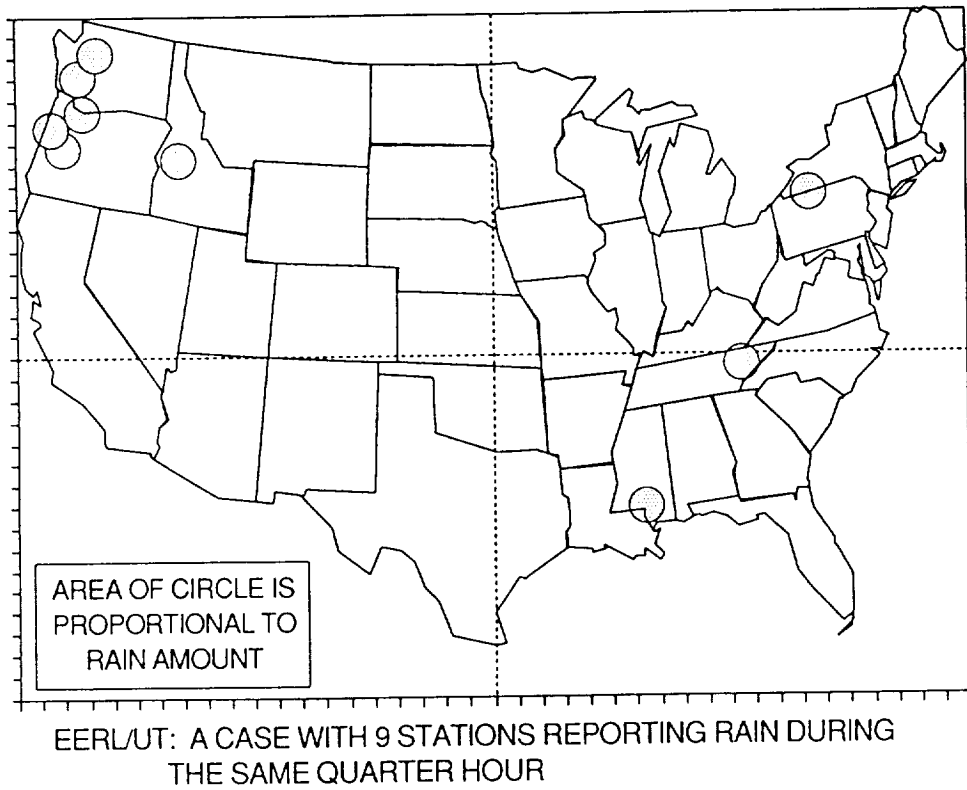
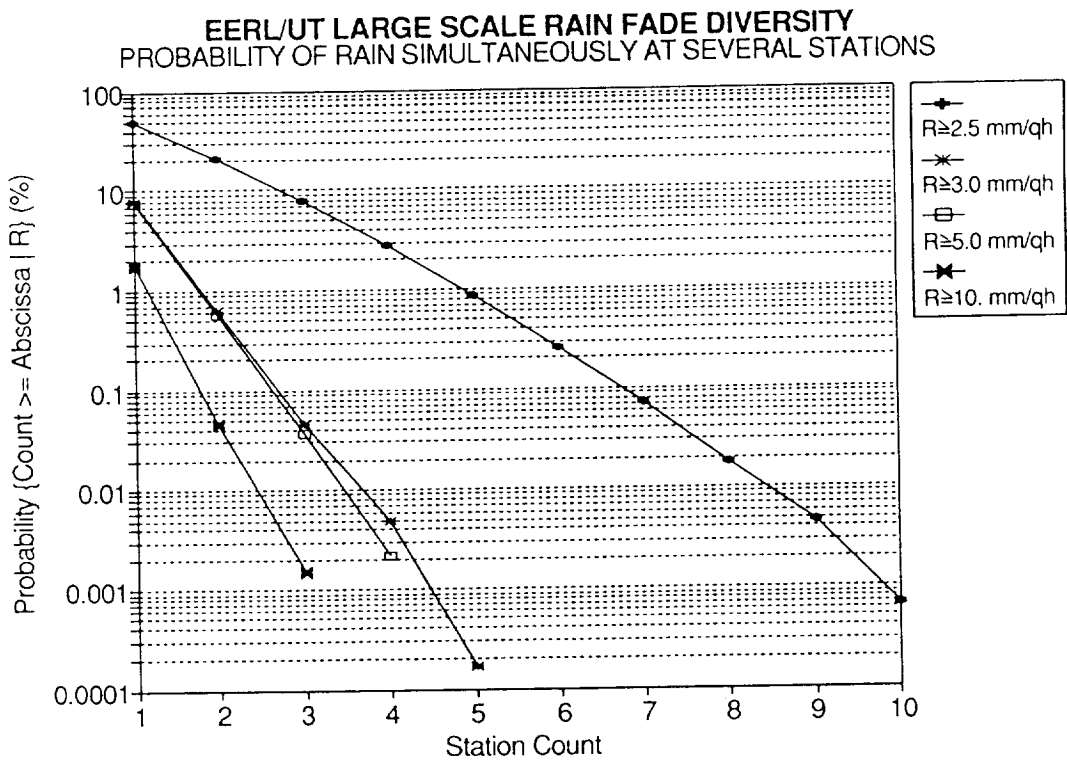


Figure 3: Precipitation frequently shows a structure of clusters.

Figure 4: The probability that rainfall above a threshold rate occurs simultaneously at several stations, for rainfall rates of 2.5, 3., 5., and 10 mm/quarter-hour.



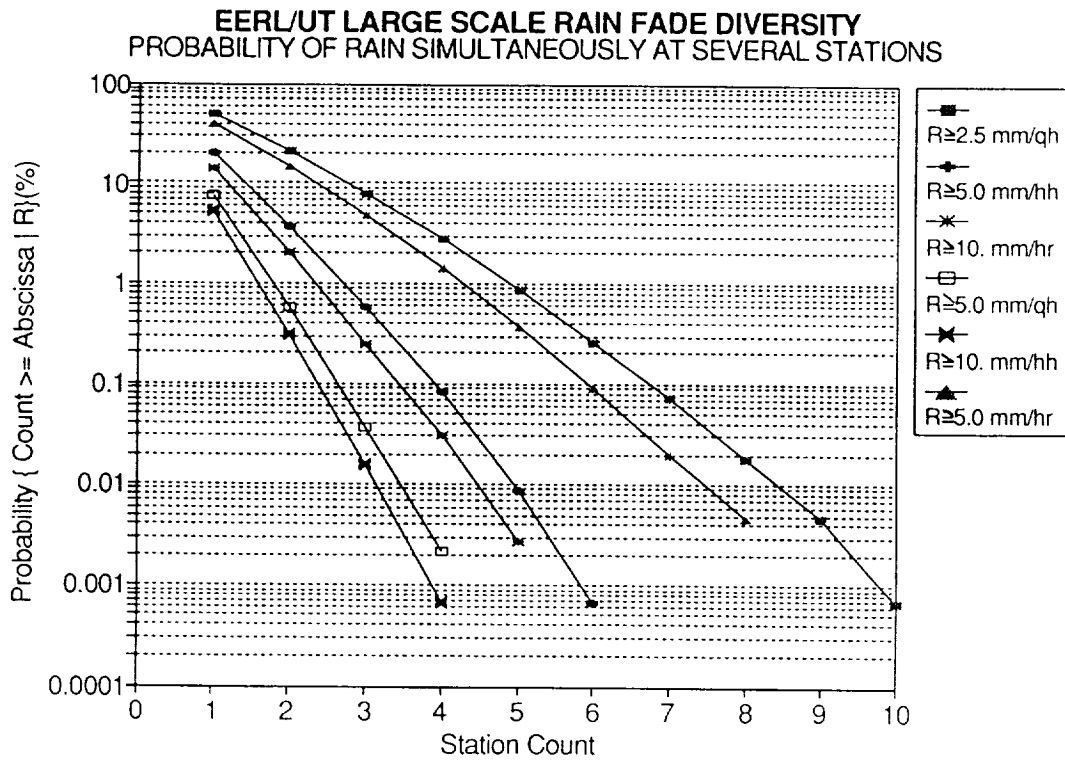
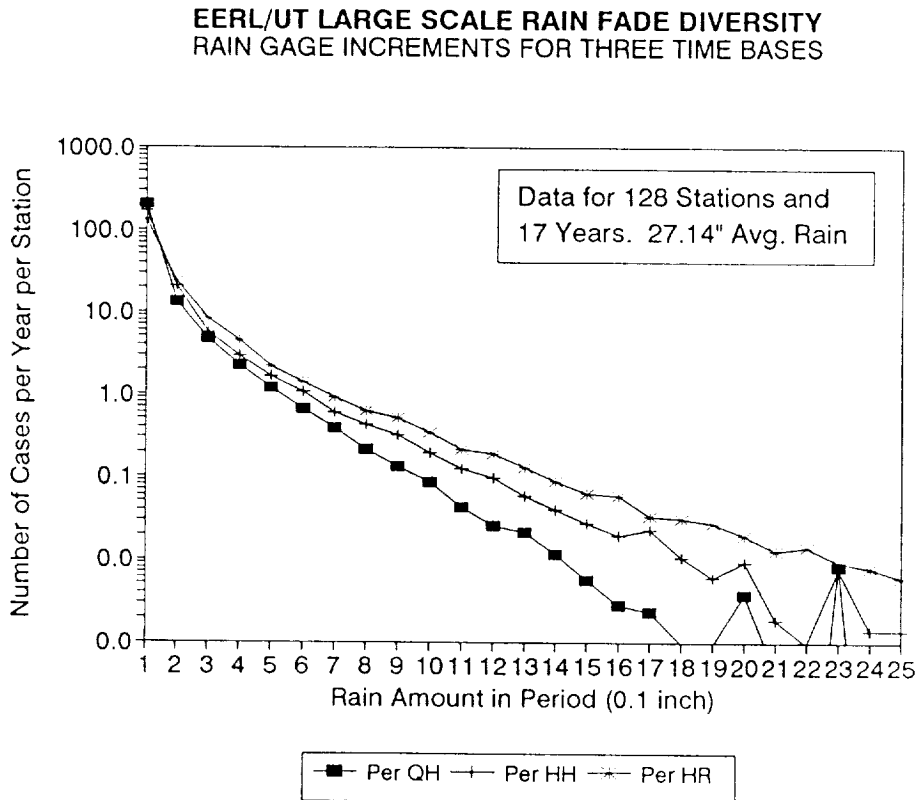


Figure 5: Comparison of the probability of simultaneity for several time bases.

Figure 6: A great majority of rain events have a single rainfall increment (2.5 mm) in intervals from 15 minutes to 1 hour.



EERL/UT: LARGE SCALE RAIN FADE DIVERSITY
2 STATION JOINT PROBABILITY VERSUS DISTANCE

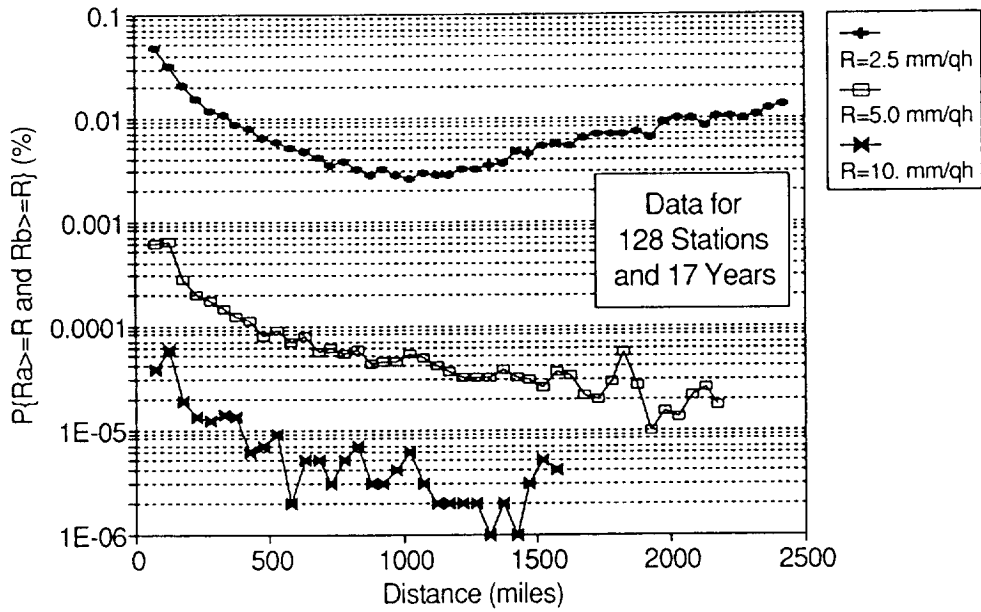
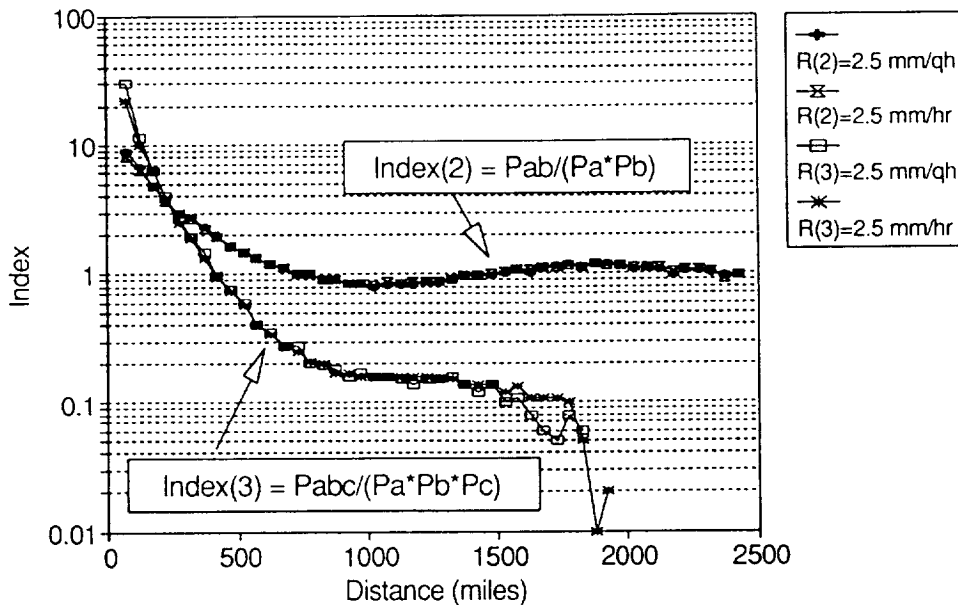


Figure 7: The joint probability of rain at two stations as a function of distance.

Figure 8: The average statistical dependence index for station pairs and triplets as a function of separation.

EERL/UT: LARGE SCALE RAIN FADE DIVERSITY
2 AND 3 STATION STATISTICAL DEPENDENCE INDEX



EERL/UT: LARGE SCALE RAIN FADE DIVERSITY
STATISTICAL DEPENDENCE INDEX AT 5 mm/hr RAIN RATE

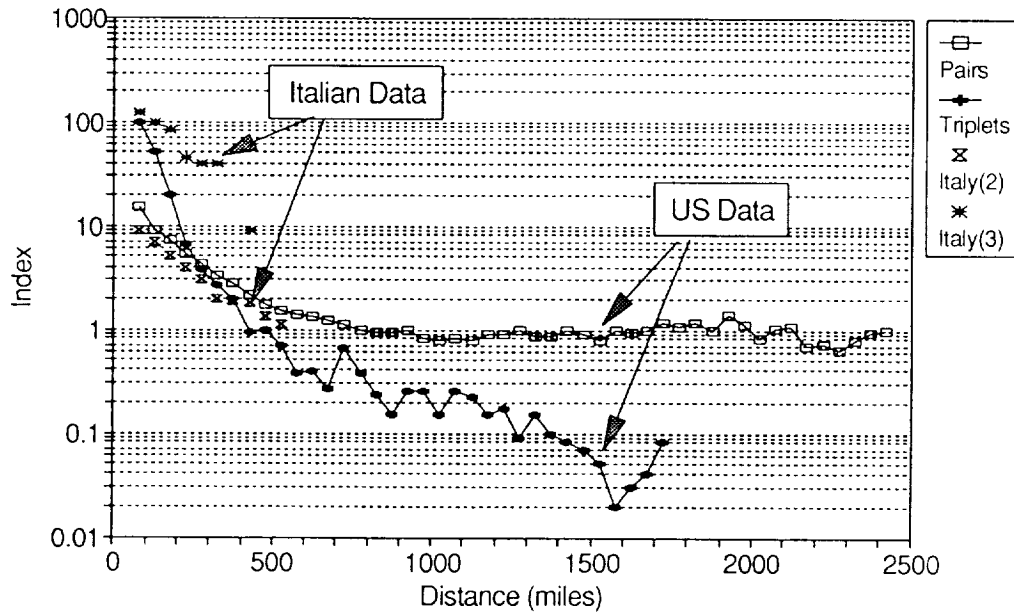


Figure 9: A comparison of the average statistical dependence index derived for Italy and U.S.

Figure 10: The influence of the rain gage averaging time on the probability distribution of the rainfall rate for averaging times from 1 to 60 minutes, derived from 46 months of tipping bucket rain gage data measured in Austin, Texas.

EERL/UT: LARGE SCALE RAIN FADE DIVERSITY
INFLUENCE OF RAINGAGE AVERAGING TIME

