# ATS-6 ATTENUATION DIVERSITY MEASUREMENTS AT 20 AND 30 GHz

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16. Abstract

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# PREFACE

The results of data obtained at The University of Texas at Austin in conjunction with the ATS-6 millimeter wave experiment are presented. Attenuation measurements at 30 GHz and sky-noise data at 20 GHz were obtained simultaneously at each of two sites separated by 11 km. Space diversity reduces outage time for a system in Austin, Texas with a 10 dB fade margin at 30 GHz from 15 hours to 16 minutes per year. The maximum cloud height shows a good correlation to the maximum attenuations measured.

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# I. INTRODUCTION

## A. General

Satellite-terrestrial communication systems depend upon the propagation of electromagnetic waves through the atmosphere. A successful design of such a system is one that meets realistic specifications. These must be based on the knowledge of any limitations introduced by the atmosphere. At millimeter wave frequencies for elevation angles above about 15° mainly two mechanisms exist that introduce limitations: (1) the absorption and reradiation of radio waves by oxygen and water vapor and (2) the absorption and scattering of radio waves by precipitation. While the first can be essentially determined (Straiton, 1975) the second one requires that propagation measurements be made. This is so because while the interaction can be theoretically analyzed if the physical parameters of the precipitation are known (Vogel et al. 1973) the frequency of occurrence and the severity of precipitation events are not well enough defined to allow a purely theoretical prediction.

For this purpose and in anticipation of the future need of satellite systems operating at 20 and 30 GHz NASA's ATS-6 satellite included a millimeter wave experiment. The signals from the 20 and 30 GHz transmitters could be used by participating experimenters for pertinent measurements. This report describes the efforts by the Electrical Engineering Research Laboratory, The University of Texas at Austin.

B. Experiment Objectives

The information to be presented here has been obtained in three ways.

1. Statistical data has been collected on the attenuation due to the atmosphere for the transmission from the satellite at both 20 and 30 GHz. The 30 GHz data has been taken by using the satellite signal and the 20 GHz data has been obtained by radiometric means. From the 20 GHz data the 30 GHz attenuation could be estimated for the times during which the satellite signal was not received because of the unavailability of the transmitter or rare failure of the receiver.

2. Space diversity studies have been carried out by having a radiometer and a receiver located at Balcones Research Center and a second radiometer and a second receiver located on the Main Campus of The University of Texas at a distance of 11 km to the south. This distance was selected on the basis of the results of the ATS-5 satellite experiments which indicated that thunderstorms that produced attenuation of a severe nature were commonly less than 12 km in diameter. The thunderstorms whose width is less than the separation of the terminals would not be covering both stations at the same time.

3. Data obtained from the Weather Bureau both by radar and by other techniques have been compared to the measured attenuations. This has the objective of trying to extrapolate the measurements made in Austin to other sites which might later be used for ground terminals

and for which similar meteorological data are available. For this extrapolation an understanding of the nature of the thunderstorm is important background information. The results of measurements made on the ATS-5 satellite indicated that severe attenuations were experienced only during the periods of very severe thunderstorms. The area around Austin, Texas has a relatively high number of thunderstorms per year and, therefore, provides a location where this effect can be studied thoroughly.

### C. Organization of Paper

In Chapter II the ground station instrumentation and the operational procedures and statistics will be described. Chapter III is devoted to the meteorological characterization of Austin. Besides a general climatology it includes various relevant statistics published by the U. S. Weather Bureau and explains where and how the weather data were obtained. The results of the measurements are given in Chapter IV both from a single site point of view and a diversity one. Conclusions are presented in Chapter V.

## II. GROUND STATIONS

### A. Instrumentation

#### 1. Antennas

The two ground stations had different antenna systems. The northern site at the Balcones Research Center of The University of Texas (UTBRC) utilized two 3 m parabolic dishes attached side by side to one azimuth-elevation steerable converted ballistic radar mount. The pointing of these antennas was controlled by the observer with setting accuracy within .03°. Both antennas had prime focus feeds. For this purpose each had a 30 cm long aluminum cylinder with 23.5 cm diameter mounted at the focus which served as universal receiver box. The side pointed towards the dish was covered by a half sphere plexiglass radome of 7.5 cm radius with the focal point at its center. The thickness was selected to achieve a quarter wave match at either 20 or 30 GHz. This wasy reflections off the radome were minimized. The outside was coated with water repellant (Silanox 101) causing immediate beading and runoff to any water on it. The antenna for the second site on the Campus of The University of Texas (UTCAM) was a 1.5 m converted searchlight. It was outfitted with a stepping motor and digital shaft encoders to allow automatic pointing in azimuth and elevation to within .02°. This antenna had a prime focus feed support structure. For the simultaneous operation at 20 and 30 GHz the feeds were placed into the focus side by side. This caused the two beams to be divergent by approximately 1°. The front of the antenna was covered with a plexiglass plate (matched to 20 GHz and coated with water repellant), enclosing both the antenna and the receiver box.

To prevent condensation refrigereated air was blown into this cavity. Minimum elevation angles at BRC were 15° to the east and west because of the structure of the mount and about 35° on Campus because of adjacent buildings.

2. Satellite Receivers

The 30 GHz satellite receivers had superheterodyne front ends in which 28.95 GHz crystal multiplier local oscillators were mixed with the signal from the feed into a 1.05 GHz IF. This allowed the utilization of back ends built for the ATS-V experiment by Martin-Marietta. These receivers have been documented elsewhere (Martin-Marietta, 1969). They are phase-locked loop receivers in which the down converted carrier is locked to a 10 MHz crystal oscillator. The noise bandwidth of these receivers is 50-100 Hz. With the typical 12 dB SSB noise figure of the mixers the noise power of the receivers $P_N = kTB$ is -142 dBm. To improve the reliability of the local oscillators in continuous operation even during the hottest summer weather all active front end components were mounted on a water cooled plate. This could be inserted into the focal cylinder of the 3 m antenna or the support structure of the 1.5 m antenna. Fig. 1 gives a block diagram of the satellite receivers. The fade margins when the satellite was pointed at Rosman, N.C. and was transmitting through the 30 GHz horn antenna were better than about 33 dB for both receivers. The only small difference between the 3 m and 1 5 m antenna systems can be explained by the fact that the 3 m dish is degraded at 30 GHz and the mixer with the better noise figure was used for the smaller antenna.

3. Radiometers

The 20 GHz sky-noise radiometers were Dicke switched receivers. Their local oscillator frequency was chosen to coincide with the first lower sideband frequency of the 20 GHz satellite transmitter at 19.82 GHz. Thus it was ensured that the 30 MHz IF (total bandwidth =

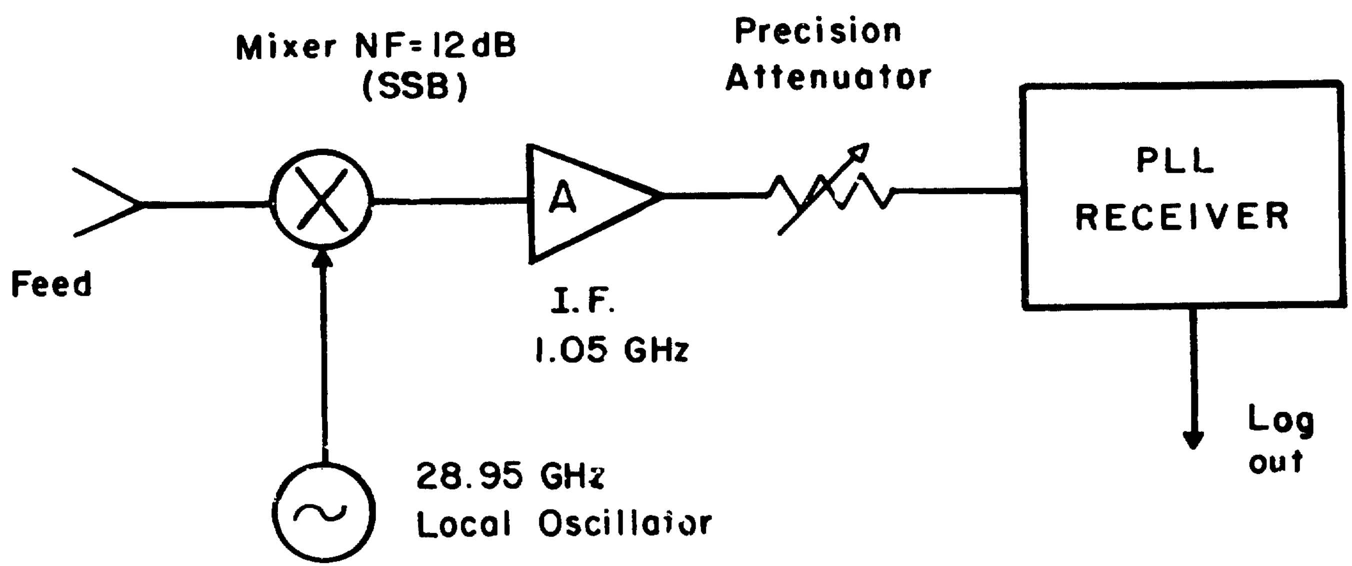


Fig. 1 SATELLITE RECEIVER BLOCK DIAGRAM

20 MHz) would not allow any satellite signals to introduce errors into the measurements. For additional isolation the radiometers were approximately cross-polarized to the satellite signals. Even during clear air propagation conditions no satellite signals were ever noted in the radiometer outputs. A plot of the spectrum is given in Fig. 2.

The sensitivity of the radiometers was about 1°K with a 1 sec integration time. Their block diagram is given in Fig. 3. The components were mounted on a water-cooled plate. For the searchlight system they shared the plate with the satellite receiver.

4. Station Location

Site 1 at the Balcones Research Center (UTBRC) was located at the northern edge of Austin, Texas. Its coordinates are shown in Fig. 4. Site 2 on the Campus of The University of Texas (UTCAM) was 11 km to the south. Figure 5 gives the relevant data and shows that the two sites were almost aligned along the direction of the satellite.

B. Calibration

1. Satellite Receivers

Because of weight and space limitations for the front end all calibrations were performed by attenuating the satellite signal with a calibrated attenuator during periods when no rain was in the propagation path. Since the attenuation was introduced in the IF (1.05 GHz BRC site; 60 MHz Campus site) noise generated in the front end was attenuated too. Therefore the attenuation at 30 GHz has to be related to the attenuation at the IF level by

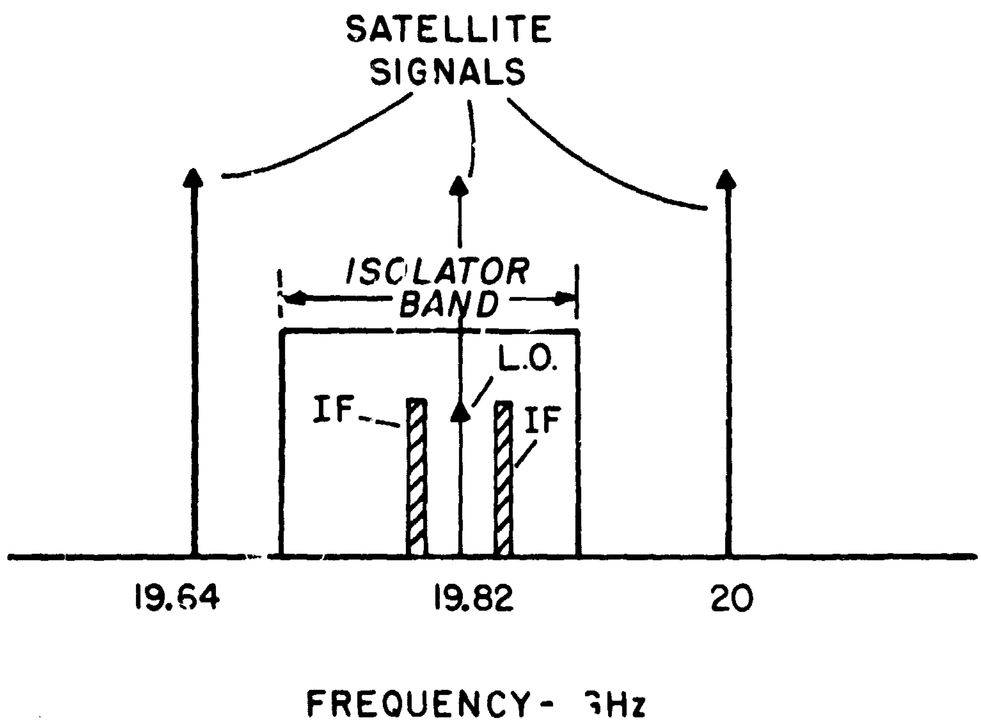


Fig. 2 SPECTRUM FOR 20 GHz RADIOMETER

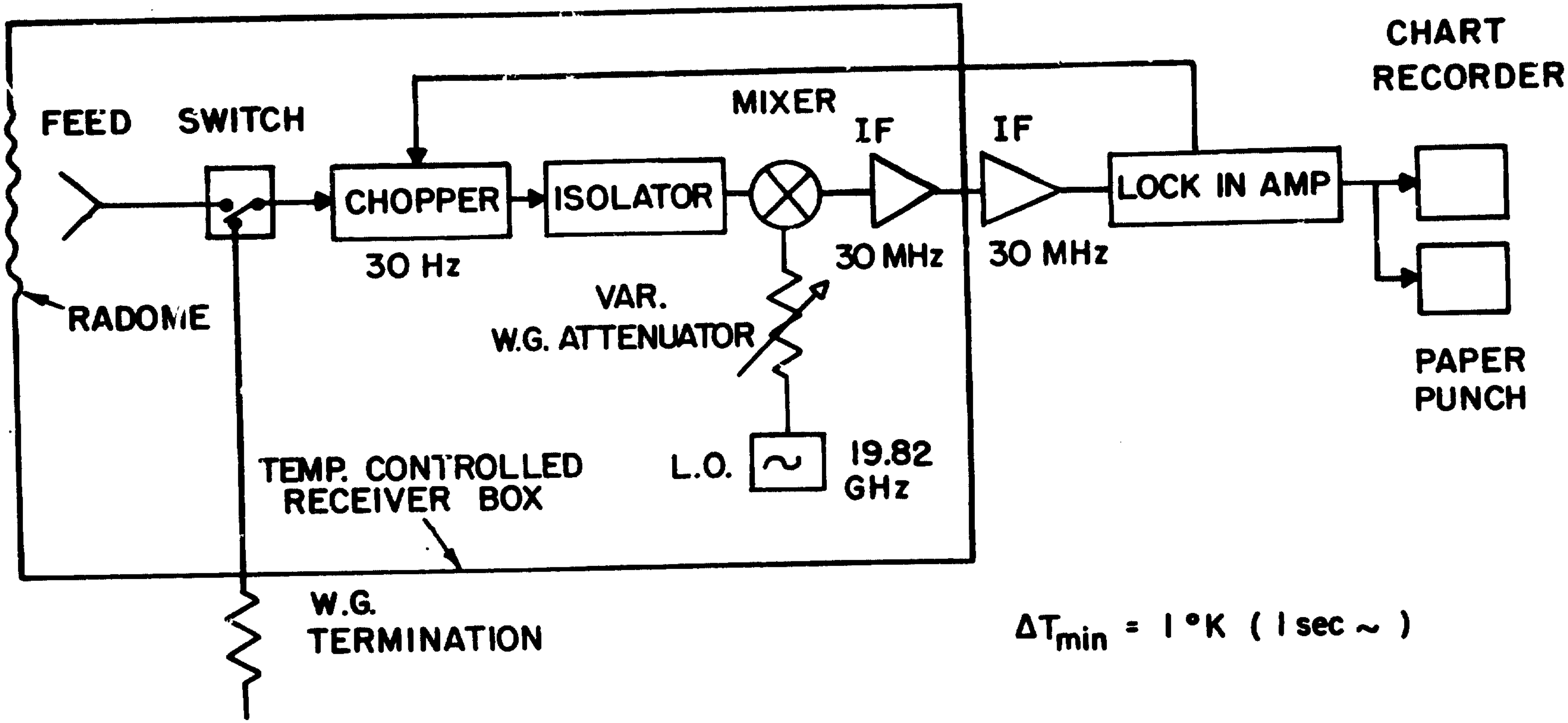


Fig. 3 20 GHz RADIOMETER SYSTEM SIMPLIFIED BLOCK DIAGRAM

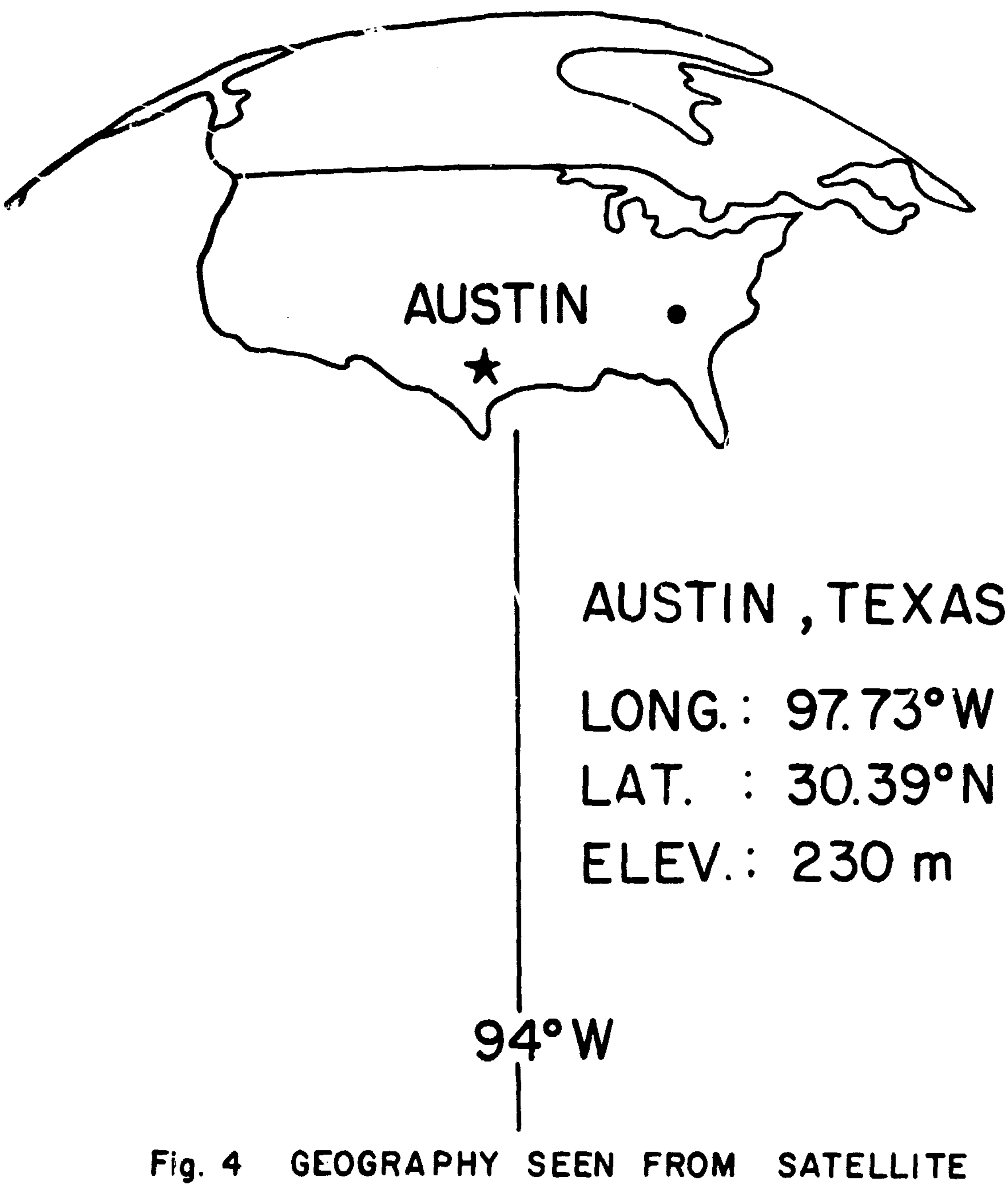


Fig. 4 GEOGRAPHY SEEN FROM SATELLITE

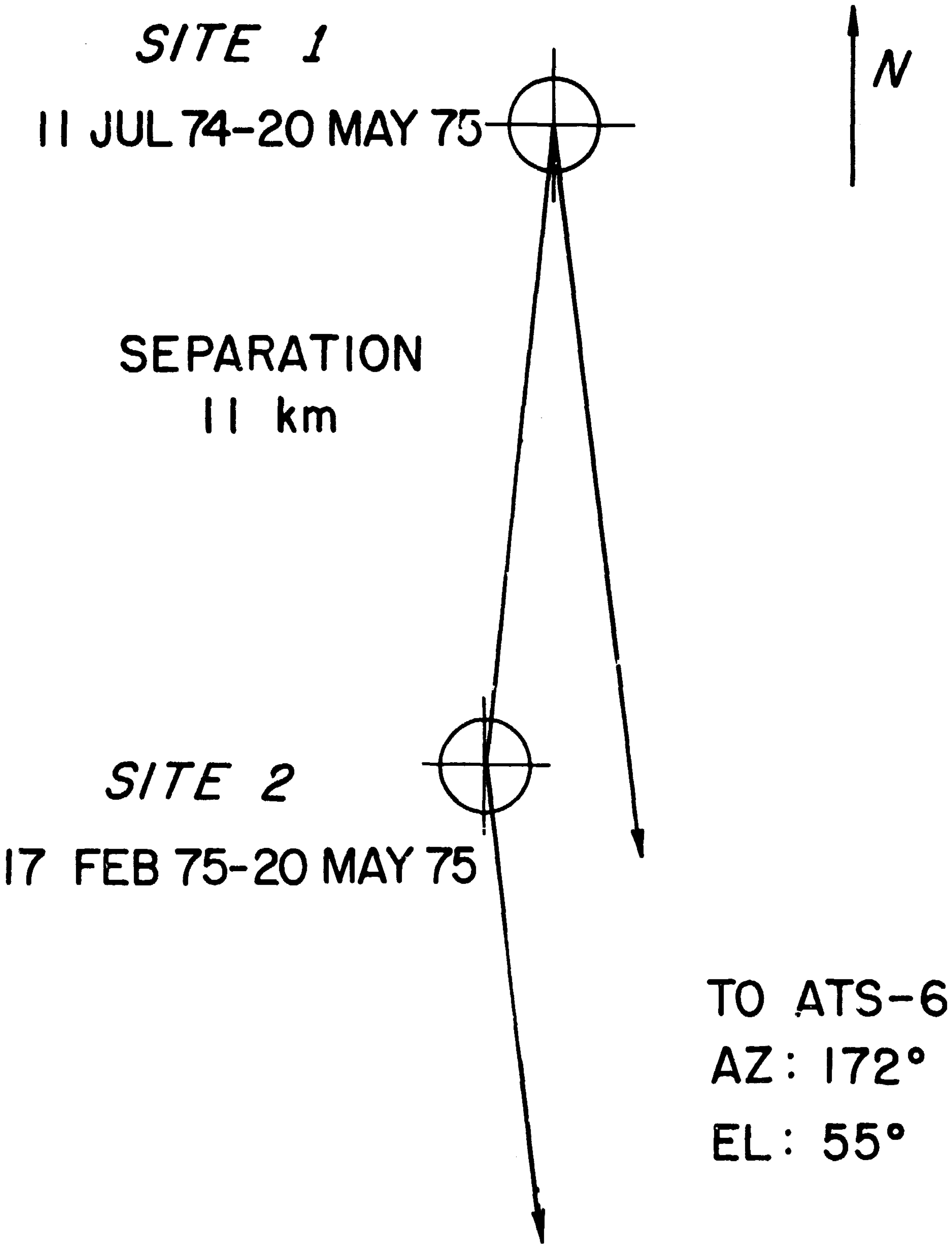


Fig. 5 STATION LAYOUT IN AUSTIN, TX.

$$L_{RF} = L_{IF} + \left\{ SNR - 10 \log\left(10^{\frac{SNR}{10}} - 10^{\frac{L_{IF}}{10}} + 1\right)\right\}$$

where SNR is the signal-to-noise ratio in dB under clear weather transmission conditions. $L_{RF}$, $L_{IF}$ are the RF and IF attenuation in dB. Because of the difficulty in exactly measuring the SNR of the phase locked receiver for all the possible clear-air levels which existed for the many combinations of pointing and mode of the spacecraft, the data analysis was restricted to a maximum fade depth of 25 dB. For these levels the above relation simplifies to

$$L_{RF} \approx L_{IF}.$$

Calibrations were performed as frequently as the weather and the operation of the satellite allowed. At the BRC station this was typically at least once for each turn-on period and each spacecraft pointing. At the automated receiver site on Campus calibrations were made typically once during days with attenuation events. The accuracy of the calibrations is estimated to be ±.5 dB.

2. Radiometers

The radiometers were calibrated about once a week during cloudless periods. Since they operated in a temperature controlled environment of about 40°C the "hot" point was found by disconnecting the IF preamplifiers from the IF amplifier. The output then corresponds to a zero signal level at the chopper frequency and equals the temperature of the chopper, typically 313°K. The second point to define the linear relationship between sky temperature and radiometer output voltage was found by calculating the clear air sky-noise temperature from a measurement of the absolute ground humidity, resulting in typically between 15 and 25°K. This method of calibration has the advantage that the losses from the input of the antenna to the output of the feed need not be measured. It is estimated that the absolute accuracy of the calibrations is ±5°K at low sky temperatures and ±2°K at high sky temperatures.

3. Clocks

Since the data from each of the two stations has to be compared, another calibration was required, consisting of synchronizing a 60 Hz clock at each site. This was done with a WWV receiver and over the telephone. The clocks were checked regularly and discrepancies were kept to less than 1 sec.

C. Operation

Regular observations of the 30 GHz satellite signal started at the UTBRC site on 11 July 1974 and lasted until 20 May 1975 for a total of 314 days. The 20 GHz radiometer at this site was put into operation on 30 October 1974 and continued until 20 May 1975 for a total of 203 days. During the period from 11 July 1974 to 30 October 1974 the station could be made operational in about the time it took to have the satellite transmitter turned on. This fact combined with a relative high priority assured that few attenuation events were missed. The geographical location of Austin (see Fig. 4) proved to be of significant advantage. Regardless of the pointing of the spacecraft including Alaska we almost always stayed within the 3 dB beamwidth of the 30 GHz horn. Therefore we could utilize the transmitter while other experiments were conducted (as long as no other restrictions on the satellite prevented this). All systems, except the antenna drive were in continuous operation or standby. This allowed monitoring of the system, eliminated warm-up problems and assured instantaneous response to the weather. The antenna was pointed manually for satellite observations with the pointing coordinates supplied to us by ATSOCC and peaked regularly.

The second station, on the Campus of The University of Texas, was in operation from 17 February 1975 to 20 May 1975 for a total of 93 days. This station operated fully automated. The antenna was kept pointed at all times by the antenna controller which also used the ATSOCC supplied pointing data as input. The PLL receiver continuously searched over a range of ±12 kHz around the 30 GHz carrier and locked on to the signal if present. The outputs from the radiometer and the receiver were sampled every 10 min. in clear weather and every 20 sec if the sky temperature exceeded 80°K. The data, with the time and rain gauge information were then punched out on paper tape.

## III. METEOROLOGY OF AUSTIN

### A. Thunderstorm Climatology for Central Texas

High attenuation events were always associated with thunderstorms in the Austin area. The storm climatology is given to help in the interpretation of the attenuation data.

Information on thunderstorms in Central Texas is given in Table I. The frequency of occurrence refers to the mean over a thirty year observational period and was obtained from Local Climatological Data for Austin, Texas. The other information was obtained from Mr. William Hare, Meteorologist in Charge at the National Weather Service Meteorological Observatory, Radar Center, Hondo, Texas. Data obtained from the radar at Hondo (which includes Austin in the scope area) for the two years this site has been in operation were used. These data should be fairly representative of the Austin area. Cloud (thunderstorm) tops are given in kilometers above mean-sea-level, the translational speed of the individual rain cells is given in km/hr, and the direction of movement of the rain cells is given as the direction from true north from which the cell is moving. It should be pointed out that when the showers are arranged in a line (a squall line) as they frequently are in the spring (March through May) the line usually moves from 300° to 310° (i.e. from the northwest). The individual shower cells within the line, however, move in the direction as indicated in the Table.

Thunderstorm frequency is bimodal, as shown in the Table. May and August have the highest observed mean frequencies (though the standard deviation is very large throughout the year). Maximum cloud tops occur almost concurrently with maximum frequency. Translational speed of individual cells is at a maximum in early spring (March) when mean wind speeds within the troposphere at this location are at a maximum. Minimum

Table I

MEAN VALUES OF THUNDERSTORM PARAMETERS

FOR CENTRAL TEXAS BY MONTH OF YEAR

| Month | Frequency of Occurrence | Height of Cloud Tops km | Cell Speed (km/hr) | Direction of Movement (degrees) |
|---|---|---|---|---|
| Jan | 1 | 8.5 | 46 | 240 |
| Feb | 2 | 9.1 | 56 | 250 |
| Mar | 3 | 11.6 | 65 | 270 |
| Apr | 5 | 12.2 | 56 | 250 |
| May | 7 | 12.8 | 46 | 240 |
| Jun | 4 | 10.7 | 37 | 180 |
| July | 4 | 9.8 | 28 | 170 |
| Aug | 5 | 9.8 | 28 | 150 |
| Sept | 4 | 12.2 | 46 | 230 |
| Oct | 3 | 11.6 | 46 | 230 |
| Nov | 2 | 9.1 | 46 | 240 |
| Dec | 1 | 8.5 | 46 | 240 |

speeds are observed in late summer. The direction of movement of individual cells has a strong southwesterly to westerly component most of the year, except in the summertime when cells move from the south (June) to southeast (August).

B. Meteorology for 11 July 1974 - 20 May 1975

The 40 year mean rainfall for 11 July - 20 May is 78.84 cm with a standard deivation of 22.25 cm. The amount measured for 11 July 74 - 20 May 75 was 87.63 cm. During this 314 day period there were 54 days with more than .25 cm total precipitation. Significant attenuation events, defined by the 30 GHz attenuation exceeding 3 dB and/or the 20 GHz sky temperature exceeding 80°K were measured on 50 days.

A total of 37 thunderstorms occurred. The direction from which the rain cells were moving and their speed are given in Fig. 6. The mean direction was 233° and the mean speed was 37.7 km/hr. The tops of the clouds extended from 3 to 5 km. Their relation to the measured attenuations will be given later.

Another quantity obtainable from the Weather Bureau is the grid value. It is a numerical indication, manually derived from a weather radar, of the rain intensity and percent coverage of the grid. The grid including Austin is a square with 80.47 km sides. The grid values are the integers 0 through 9. Their interpretation is given in Table II. The last column in the table gives the percentage of time (based on the hourly reporting intervals by the Weather Bureau) each value was assigned to the Austin area.

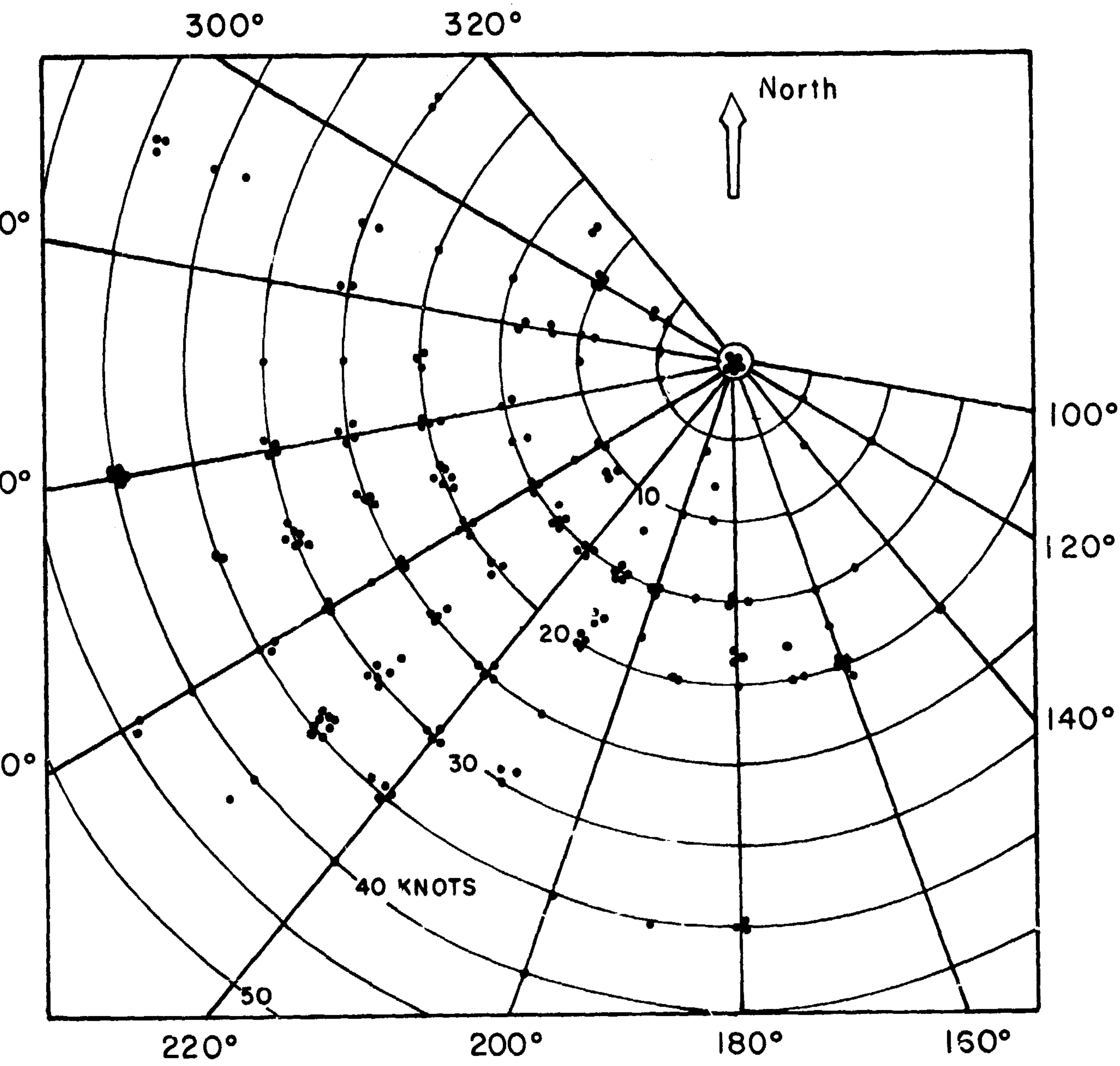


Fig. 6 DIRECTION FROM WHICH STORM CELLS MOVED AND THEIR SPEED (11 JULY 74–20 MAY 75)

## TABLE II

| Grid Value Code No. | Maximum Observed VIP Level | Coverage in Box | Rainfall Rate in/hr | Intensity Category | Austin Grid % Time |
|---|---|---|---|---|---|
| 0 | No echoes | | | | 85 |
| 1 | 1 | Any VIP1 | <.1 | Weak | 5.4 |
| 2 | 2 | ≤1/2 of VIP2 | .1-.5 | Moderate | 3.7 |
| 3 | 2 | >1/2 of VIP2 | | | |
| 4 | 3 | ≤1/2 of VIP3 | .5-1 | Strong | 1.1 |
| 5 | 3 | >1/2 of VIP3 | | | |
| 6 | 4 | ≤1/2 of VIP3 and 4 | 1-2 | Very Strong | .73 |
| 7 | 4 | >1/2 of VIP3 and 4 | | | |
| 8 | 5 or 6 | ≤1/2 of VIP3 4, 5 and 6 | >2 | Intense or Extreme | .35 |
| 9 | 5 or 6 | >1/2 of VIP3 4, 5 and 6 | >2 | Intense or Extreme | |

(Ignore additional coverage by weak echoes for all DR code numbers above 1. Intensity categories and rainfall rates correspond to maximum observed VIP levels.)

Priority for additive data group giving row-column position of blocks with present or past severe weather or lines is: 1) +, 2), 3) /. No box shown more than once, group in left-to-right, top-to-bottom order.

## IV. RESULTS

### A. Single Site

The 20 GHz sky noise temperature and the 30 GHz attenuation of the satellite signals are shown in Fig. 7 as they were recorded on paper charts during one typical rain storm. One notes that a general agreement between crests and valleys exists. The sky temperature curve seems to be relatively smoother, however. The primary reason for this is that the 30 GHz transmitter is effectively a point source whereas the 20 GHz sources (the raindrops) are distributed, the effective source size being the result of the receiving antenna pattern. In addition, both emission and attenuation strongly influence the radiometer input causing the apparent sky temperature to level off for high attenuations. Also, changes in the drop size distributions would be expected to have a little greater effect on the higher frequency.

Assuming the rain to be an absorbing, non-scattering medium with a physical temperature of 284°K, the measured noise temperature $T_{sky}$ can be converted to attenuation A with

$$A = 10 \log \left[\frac{284}{284 - T_{sky}}\right] \text{ dB}.$$

This formula can be derived from the theory of radiative transfer (e.g. Kraus, 1966). It can be used with reasonable accuracy for attenuations of up to about 10 dB. Fig. 8 shows the measured 30 GHz attenuation plotted versus the calculated 20 GHz attenuation for the BRC site. Each point represents a sample taken at one minute intervals for most of the periods for which such simultaneous data were available. In the average the ratio between the two

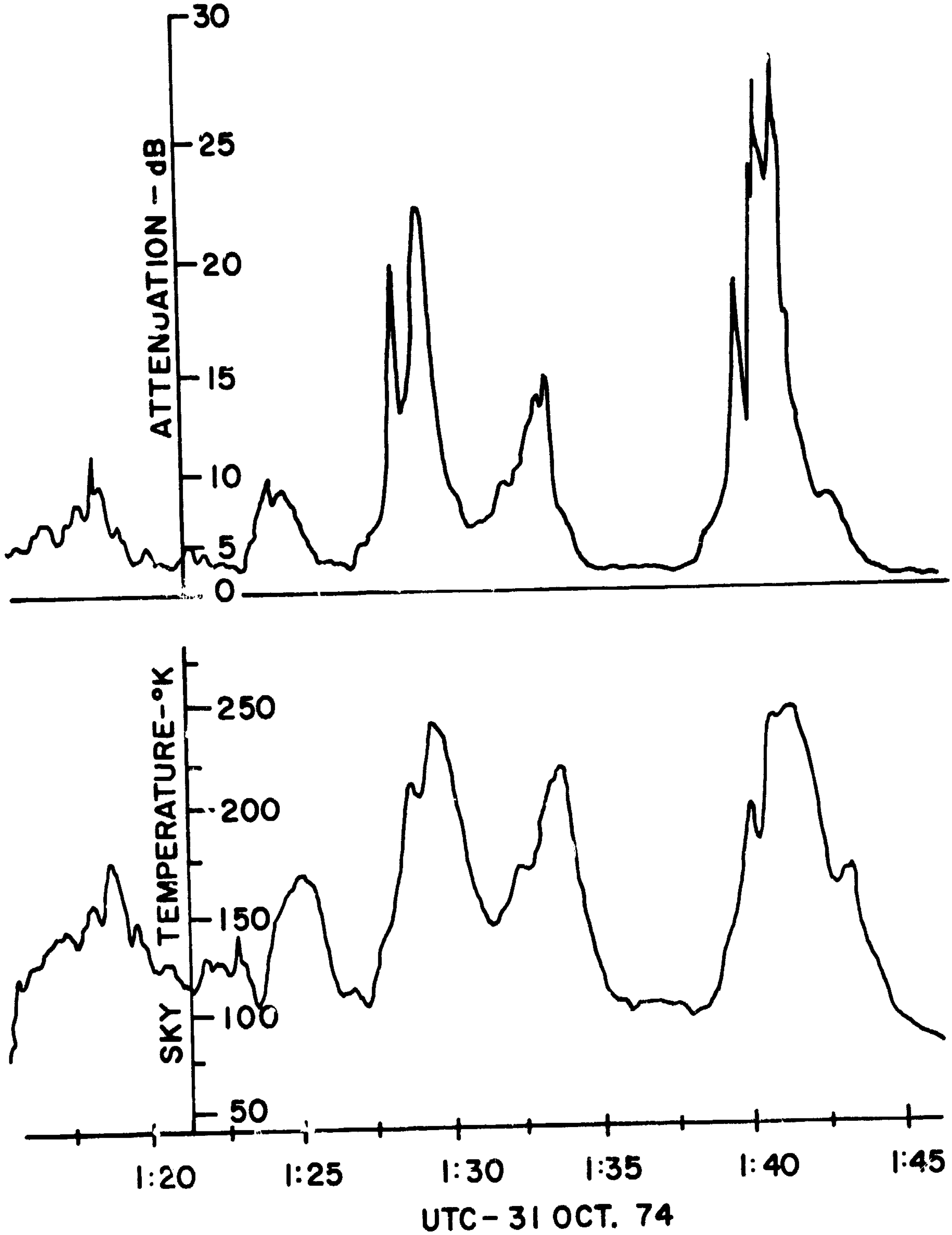


Fig. 7 30 GHz ATTENUATION AND 20 GHz SKY TEMPERATURE UTBRC — ATS-6

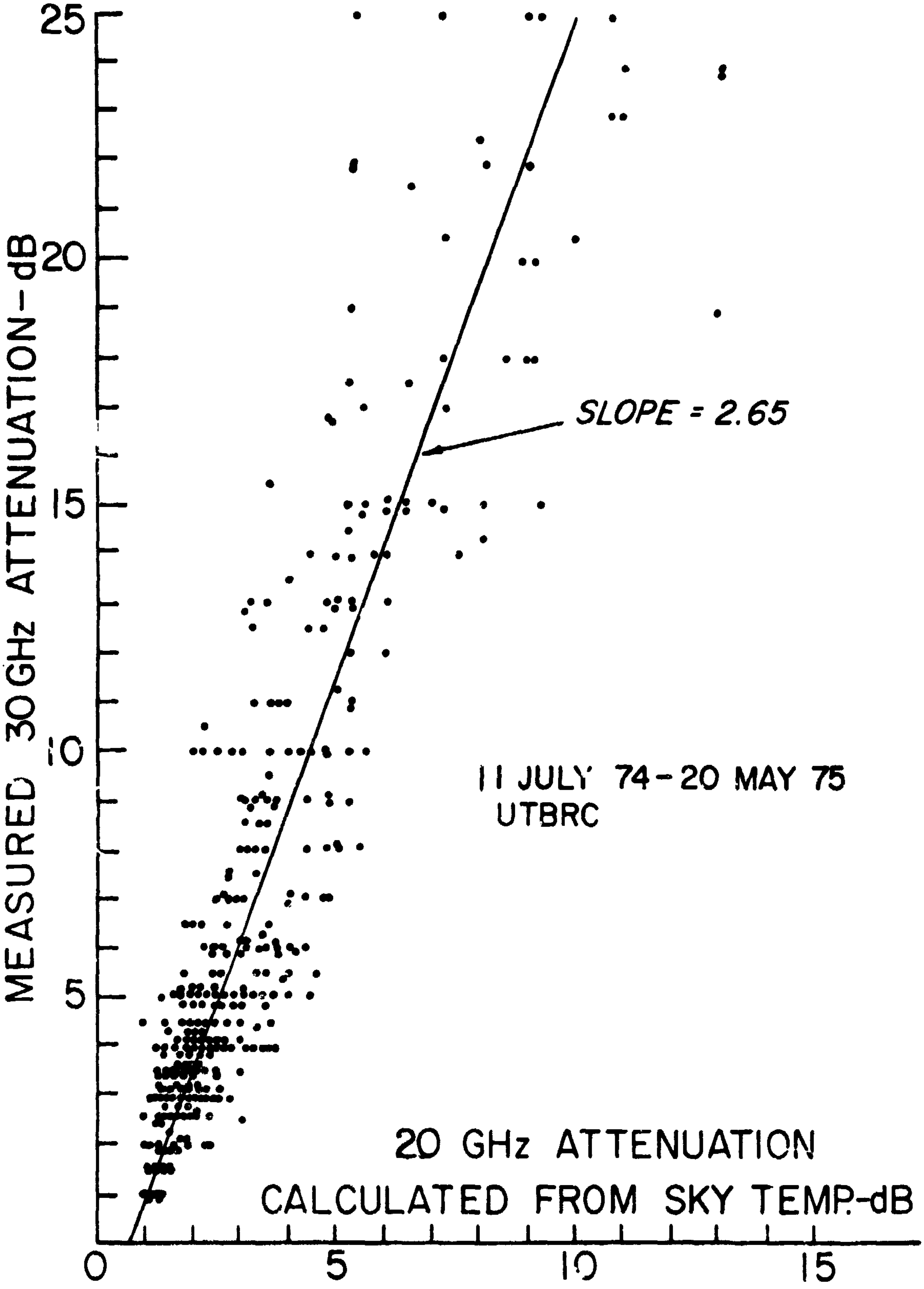


Fig. 8 20 GHz VERSUS 30 GHz ATTENUATION

attenuations is 2.65 with extremes ranging from 2 to 4. The straight line drawn through the points does not intercept at (0, 0) because the 30 GHz values do not includes the attenuation caused by oxygen and water vapor because of the way this system was calibrated. The 30 GHz attenuations include these losses because they contribute to the sky noise temperature. Therefore the attenuation ratio due to precipitation is taken as the slope of the median line. Fig. 9 shows the same kind of plot for data collected on 28 April 75 at the UTCAM site with essentially the same slope. The spread of the points in Fig. 8 is larger than in Fig. 9 because the values at the UTBRC site were taken from strip chart recordings which could not be read as accurately as the digital recordings at the UTCAM site, particularly at times when the signal was changing rapidly. It is felt that the relationship between the 20 GHz and the 30 GHz values is well enough defined to allow an estimation of the 30 GHz attenuation from 20 GHz sky temperature data.

The fade histogram for the 30 GHz attenuation at the BRC site from 11 July 1974 to 20 May 1975 is given in Fig. 10. The dark areas were derived from direct measurements and the light ones are based on the 20 GHz sky temperature for times when the satellite was not available.

The 5 dB level, for instance, was exceeded for a total of 18.17 hours while the satellite was on and 11.45 hours while it was off. Table III summarizes these results. A fade that exceeds 15 dB must also exceed 10 dB but it will be of longer duration in the latter case.

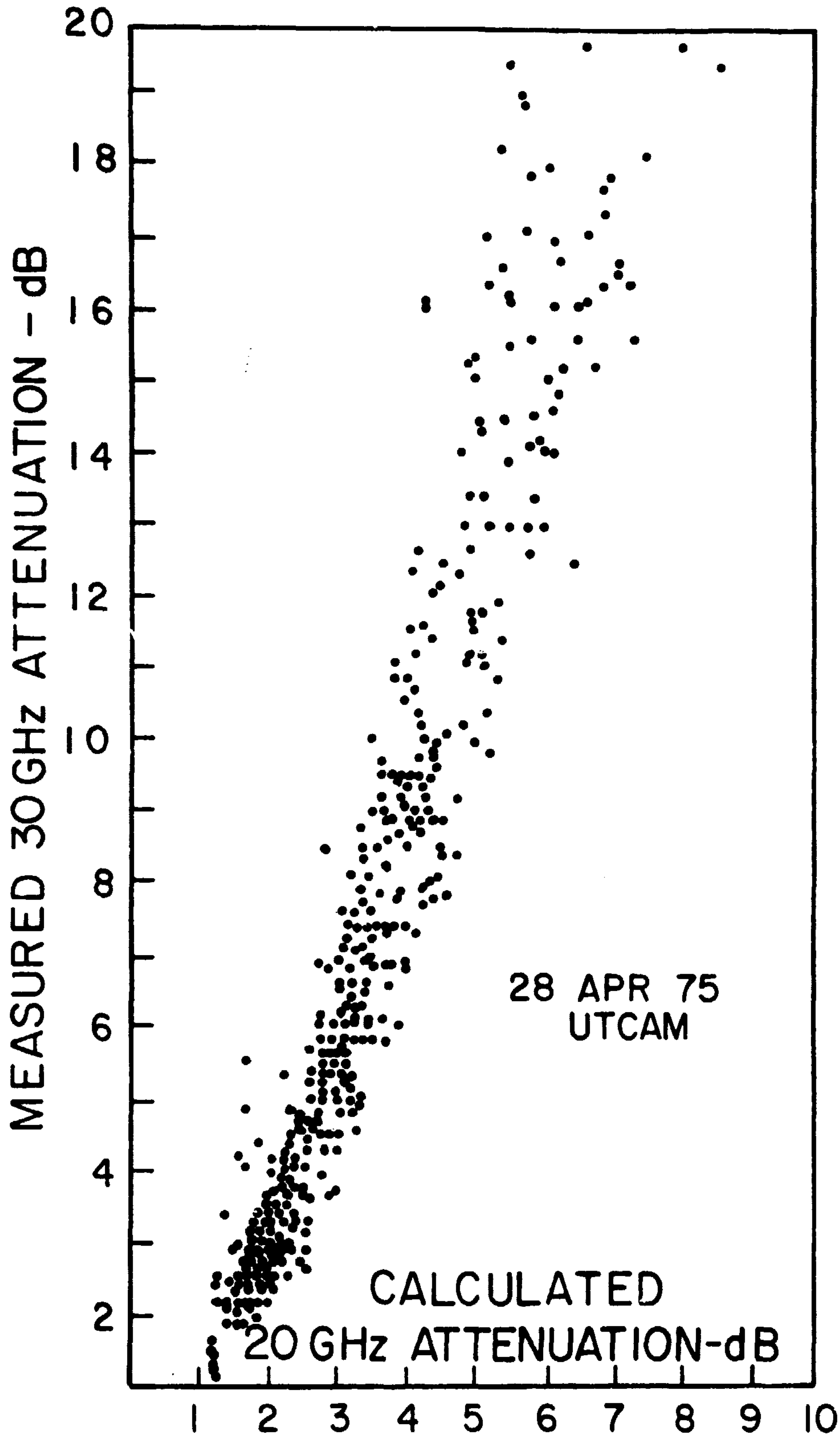


Fig. 9 20 GHz VERSUS 30 GHz ATTENUATION

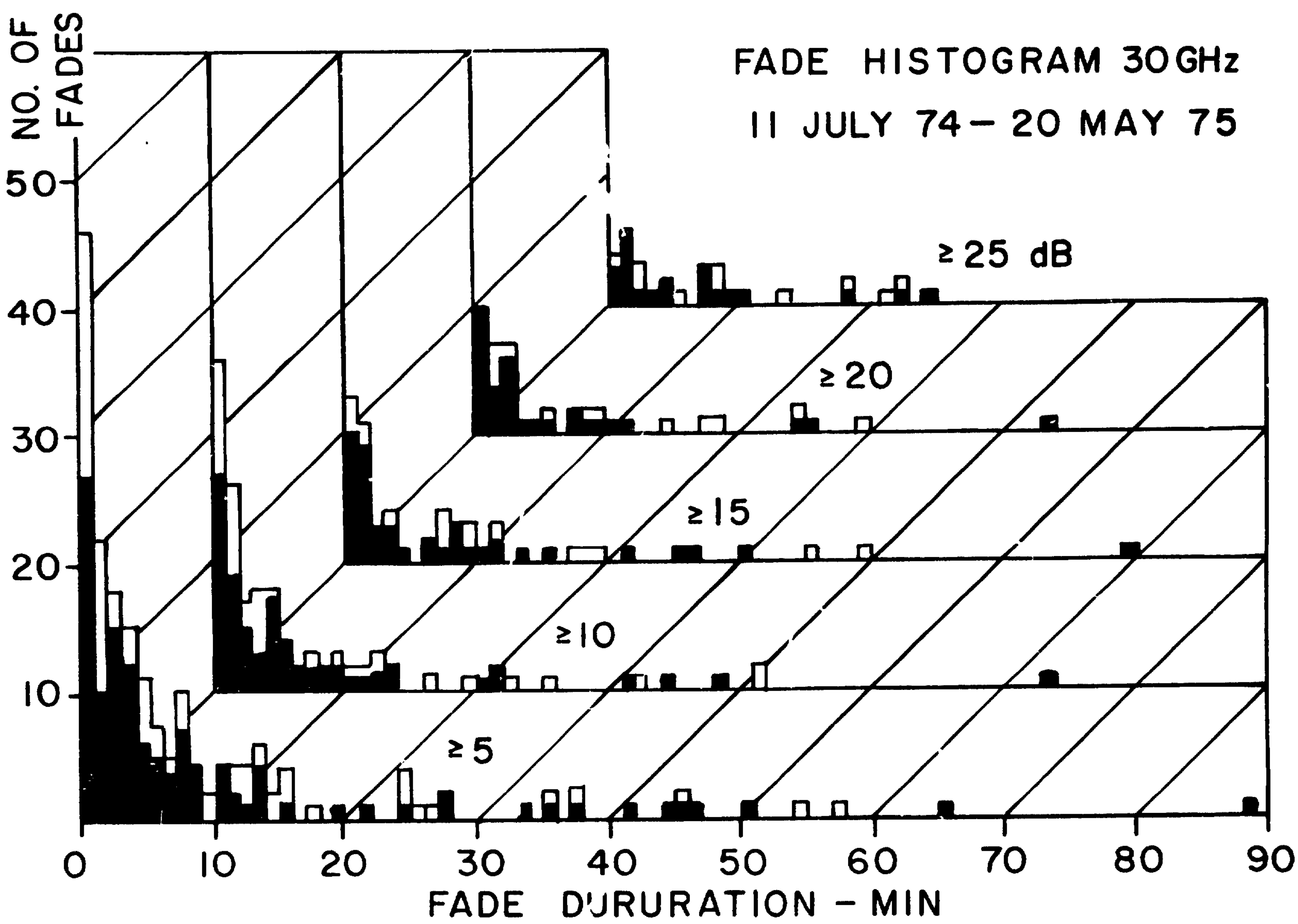


Fig. 10 FADE HISTOGRAM

TABLE III

| Attenuation exceeded at 30 GHz: | Time (hrs) Satellite on | off | Total (hrs) |
|---|---|---|---|
| 5 dB | 18.17 | 11.45 | 29.62 |
| 10 | 8.45 | 4.33 | 12.76 |
| 15 | 5.73 | 3.33 | 9.07 |
| 20 | 3.37 | 2.35 | 5.72 |
| 25 | 2.55 | 1.82 | 4.37 |

The satellite was available for an average of 61.4% of the measured attenuation events. The availability was much higher before November 1974 than afterwards.

The cumulative probability in percent of time the 30 GHz attenuation exceeds a certain fade depth is given in Fig. 11 for fades between 5 and 25 dB. It can be seen that in Austin, Texas 10 dB attenuation is exceeded at 30 GHz for .17% and 25 dB for .058% of the time. This corresponds to about 15 and 5 hours respectively, on an annual basis.

A comparison of rain rates (measured with one tipping bucket at the antenna) with the attenuation at 30 GHz as given in Fig. 12 shows that it is not possible to predict the fade depth from point rain data. This confirms conclusions reached previously (Straiton, et al. 1971). The effective path lengths L that have been added to the plot are based on the theoretical relationship between rain rate and attenuation for homogeneous rain. They vary over an order of magnitude for a given rate. A statistical comparison of these data has been made also. For this purpose the attenuations A and rain rates R for equal cumulative probabilities were compared. The effective cloud heights were then derived with

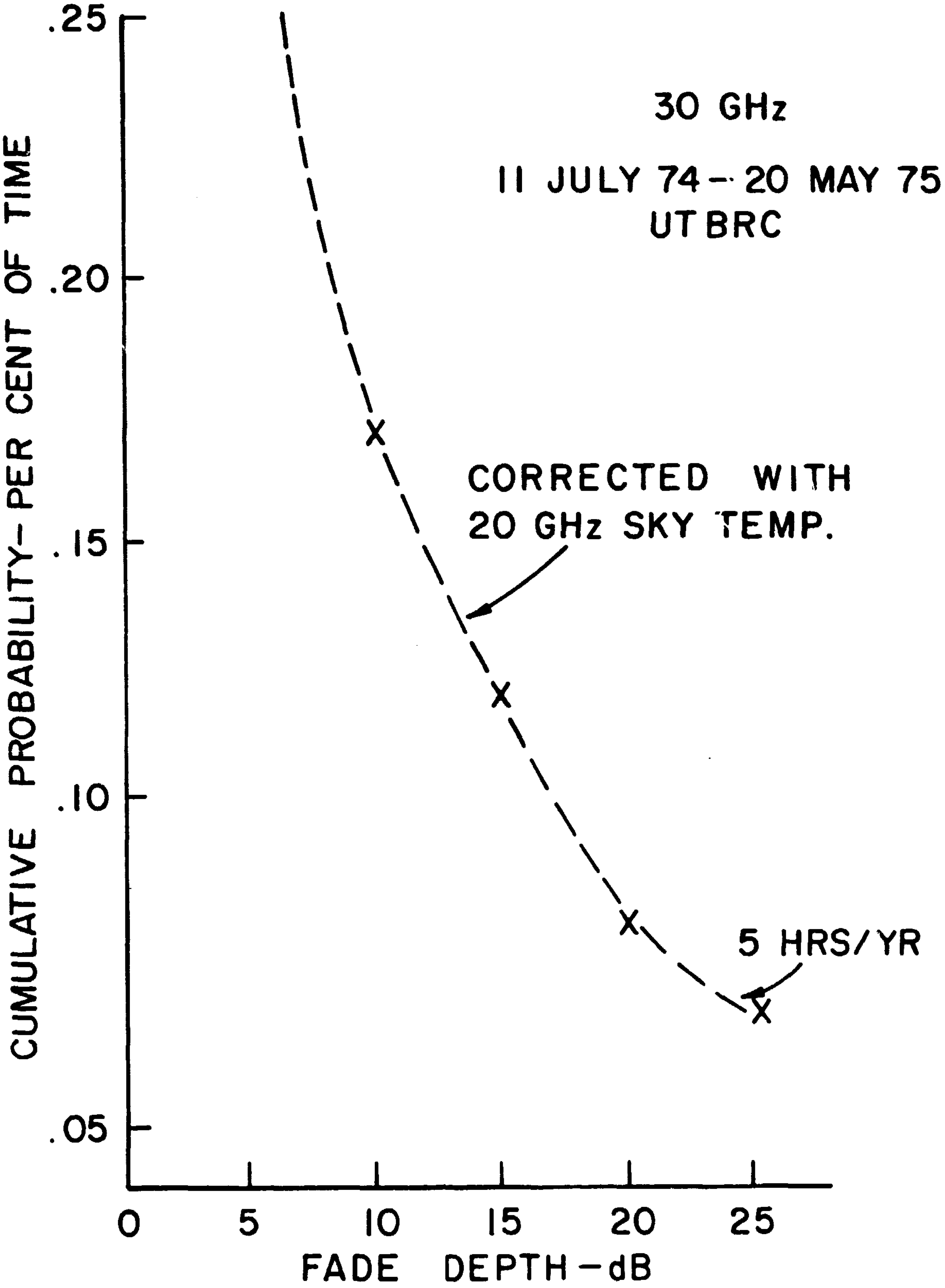


Fig. 11 CUMULATIVE FADE PROBABILITIES AT 30 GHz

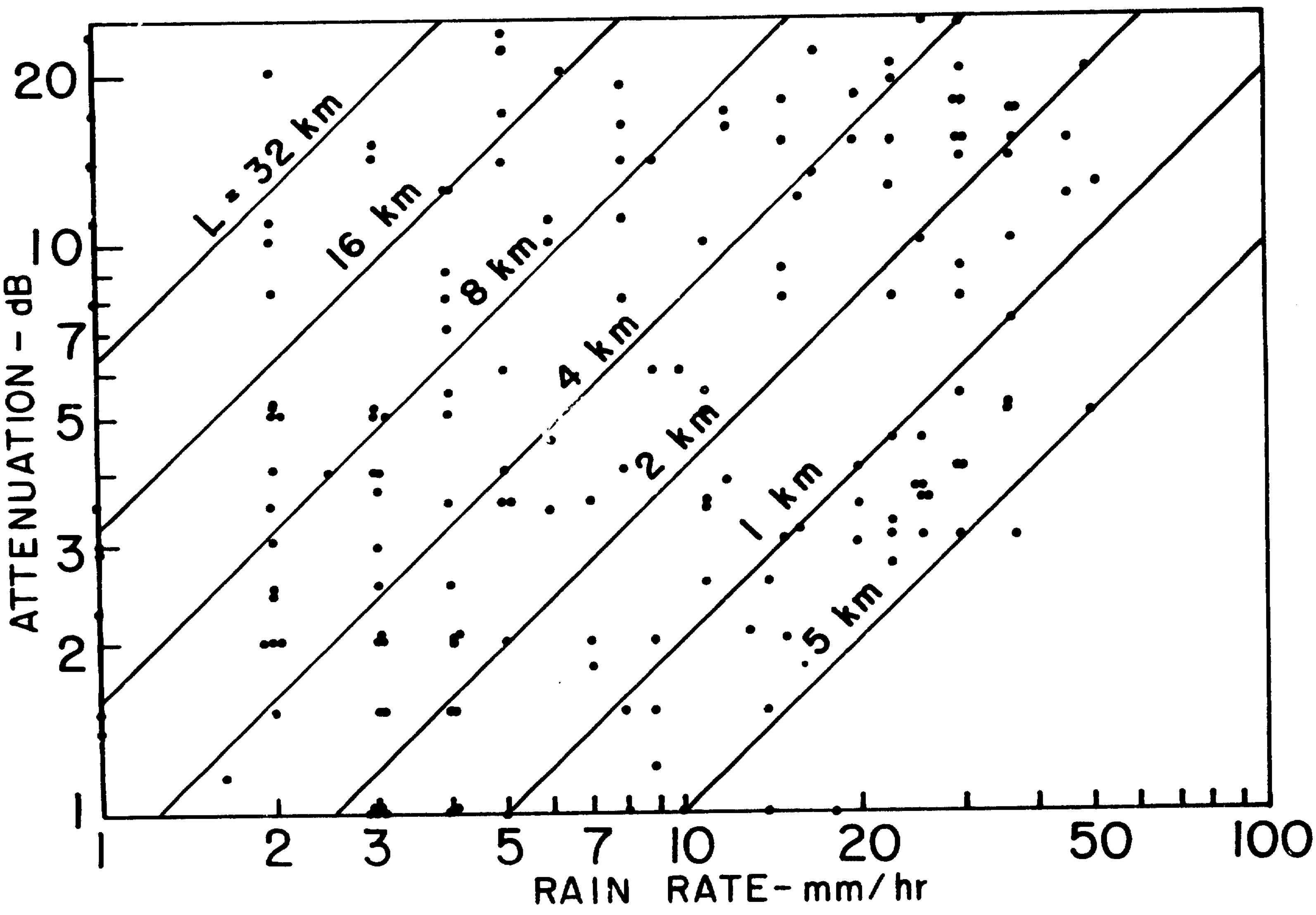


Fig. 12 ATTENUATION VS. POINT RAIN RATE

$$H_{eff} = \frac{A}{A_{theoretical}(R)} \times \sin(\text{angle of elevation})$$

The results are given in Table IV.

Table IV

Probabilistic Effective Cloud Heights

| Attenuation dB exceeded for equal percentage | Rain rate mm/hr | A Theor. dB/km | Effective cloud top height km |
|---|---|---|---|
| 5 | 3.4 | .6 | 6.8 |
| 10 | 7 | 1.3 | 6.3 |
| 15 | 9.6 | 1.75 | 7.0 |
| 20 | 17.5 | 3.2 | 5.1 |
| 25 | 24 | 4.4 | 4.7 |

From these data one would conclude that the highest attenuation occurs when the clouds are lowest. It should be emphasized, however, that these cloud heights are effective heights which have been derived from the attenuation data and not from meteorological measurements. The data, in Table IV, are in apparent contradiction to the results from the ATS-V experiment, where a direct correlation of attenuation with cloud heights was found (Straiton, 1971). Fig. 13 shows the maximum height for maximum attenuations in hourly intervals for 30 GHz. The cloud data were obtained from the Hondo, Texas Weather Station and apply to the area covered by a radius of approximately 400 km. It is noted that all of the points fall above a straight line from the origin to an attenuation of 25 dB for cloud heights of 12.2 km. This line establishes the minimum cloud height which was observed to produce

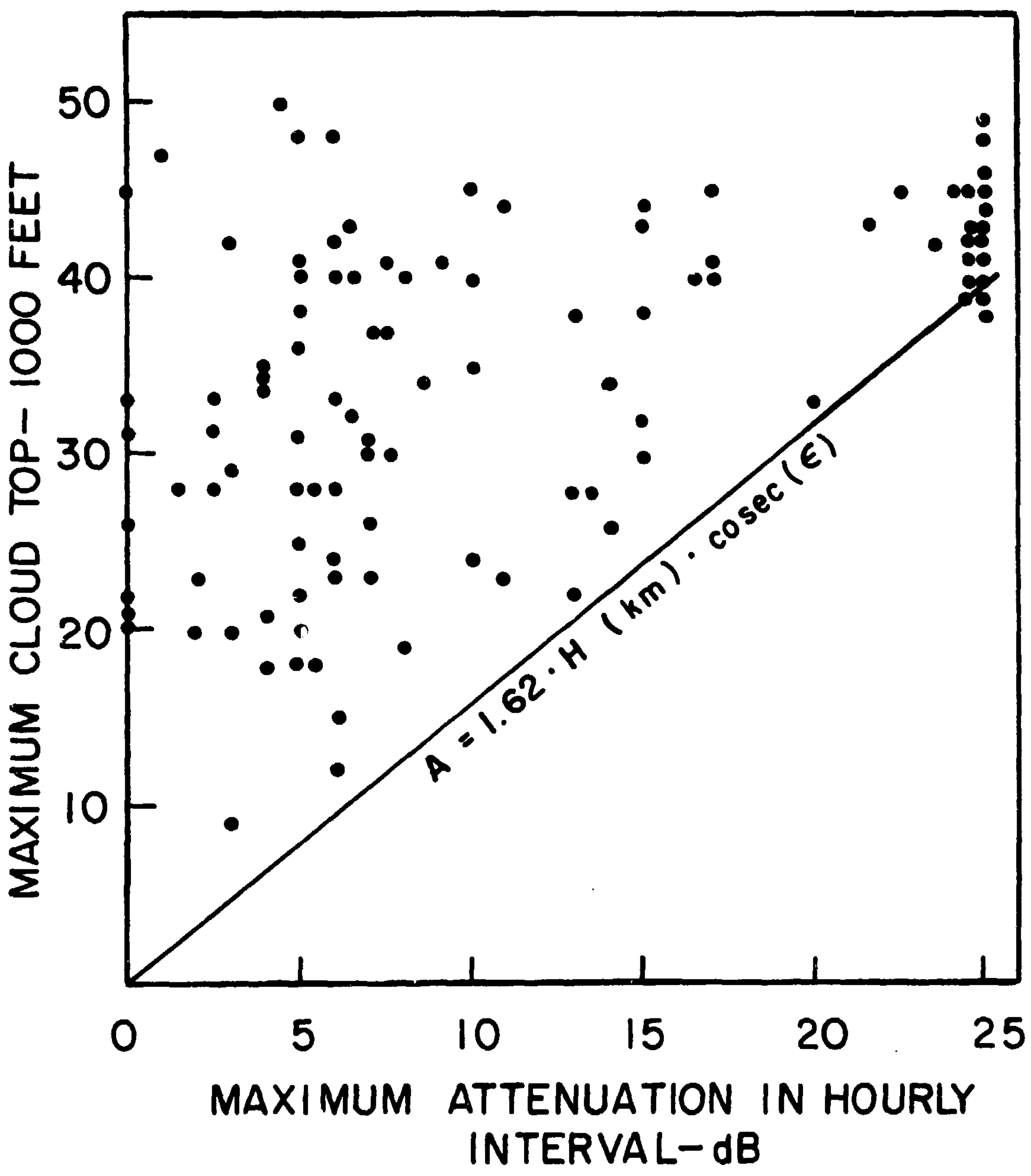


Fig. 13 CLOUD TOP HEIGHT VS. ATTENUATION AT 30 GHz

the noted attenuation. One can certainly attribute a considerable portion of the latter of points above this line to the maximum cloud height not always occurring along the path toward the satellite, but differences in structure of clouds having the same height would also contribute. The relation between attenuation and cloud height suggested by Fig. 13 is roughly

$$A = 1.62 \cdot H \cdot \text{cosec}(\epsilon) \text{ dB}$$

where H is the cloud height in km and $\epsilon$ is the angle of elevation.

Fig. 14 shows a plot of the attenuation versus the associated values assigned by the Weather Bureau radar at Hondo for the Austin grid. Because of the areal extent of the grid, a correlation of attenuation versus grid value is not apparent.

B. Space Diversity Results

The measured cumulative probabilities of the fade depth for the single sites and the joint probability for the pair of satellite receivers operating at 30 GHz have been plotted in Fig. 15. In these plots use has been made of the 20 GHz sky temperatures to augment the fade data for times of satellite unavailability. For the single sites the 93 day UTCAM statistics and the 314 day UTBRC statistics agree very closely. The 93 day UTBRC probabilities deviate from the other two for the higher fades. This difference is probably just the result of the relatively short period of sampling. In this plot 100% of the time represents the total 93 days of common operation. The product of the single site probabilities is much less than the measured point probability. This indicates some correlation of attenuation at the two sites. Naturally during the extended periods of clear

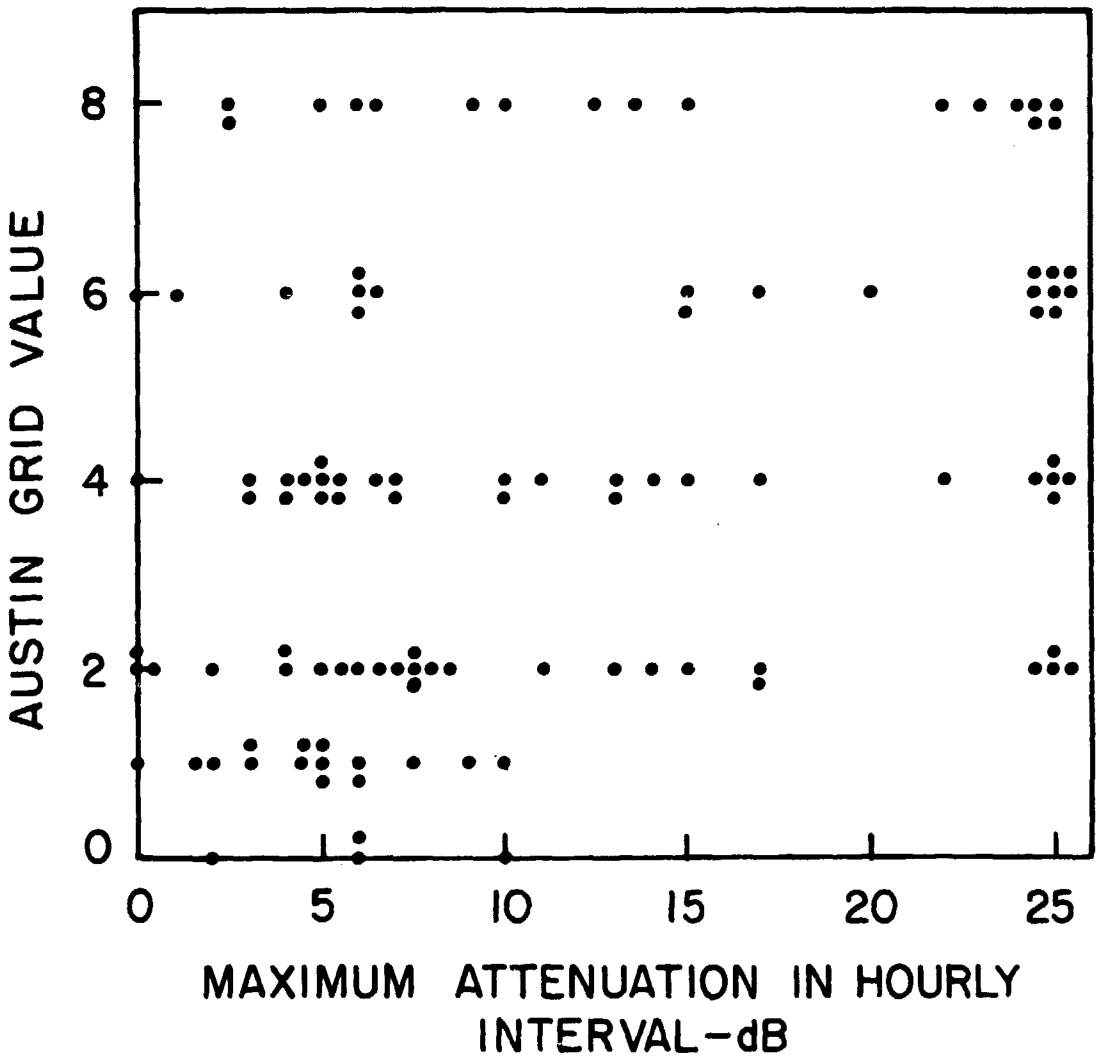


Fig. 14 GRID VALUE VERSUS ATTENUATION AT 30 d Hz.

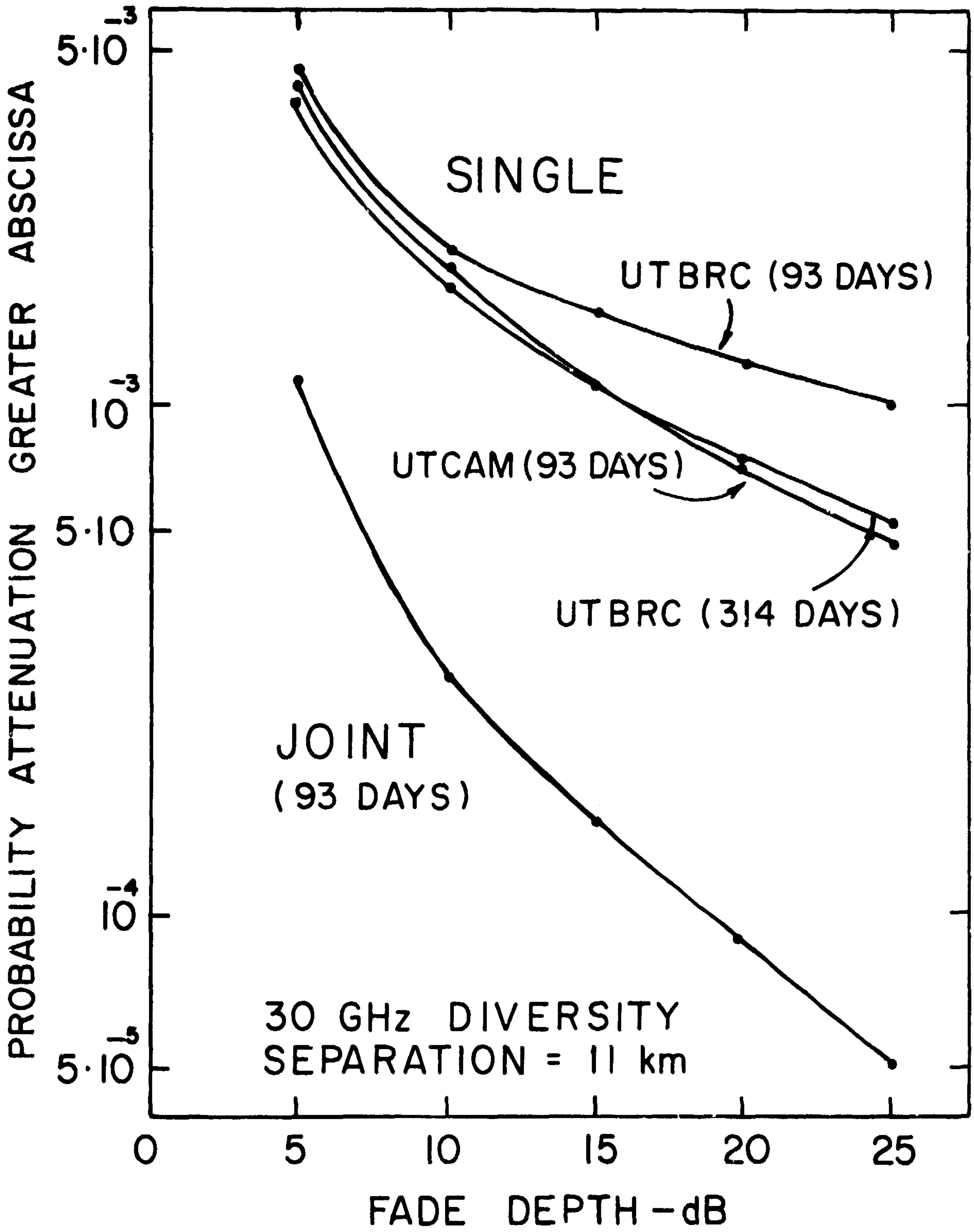


Fig. 15 DIVERSITY RESULTS

weather both stations are correlated. Therefore the curves have been redrawn in Fig. 16 as conditional probabilities. The 100% time base is now the time during which the attenuation exceeded 2 dB at either station, thereby eliminating the correlated clear weather data. It can be seen that the joint probability is in fairly good agreement with the squared single site probability much closer. Naturally the result would differ if one conditioned the probabilities on another fade level. The diversity gain has been defined by Hodge (1973) as the reduction in fade depth for equal probabilities. This gain has been plotted in Fig. 17 versus the single station attenuation. The points lie on a straight line defined by

Diversity Gain in dB = (.7) (Single Path Attenuation in dB)

Another way of looking at the data is to determine the diversity advantage which is the factor by which the probability that simultaneous fades exceed a certain level is decreased. In our case this value varies between 3 and 11 for attenuations between 5 and 25 dB. The curve is given in Fig. 18.

## V. CONCLUSIONS

Satellite propagation experiments that require unscheduled transmission in response to the weather while all other experiments sharing the spacecraft can be scheduled ahead are at an obvious disadvantage when it comes to full coverage of all fade events. Nevertheless, nearly complete coverage was achieved in Austin for the following reasons: (1) The geographical location of the stations and the type of measurements made allowed reception largely independent of the spacecraft pointing and (2) the simultaneous operation of

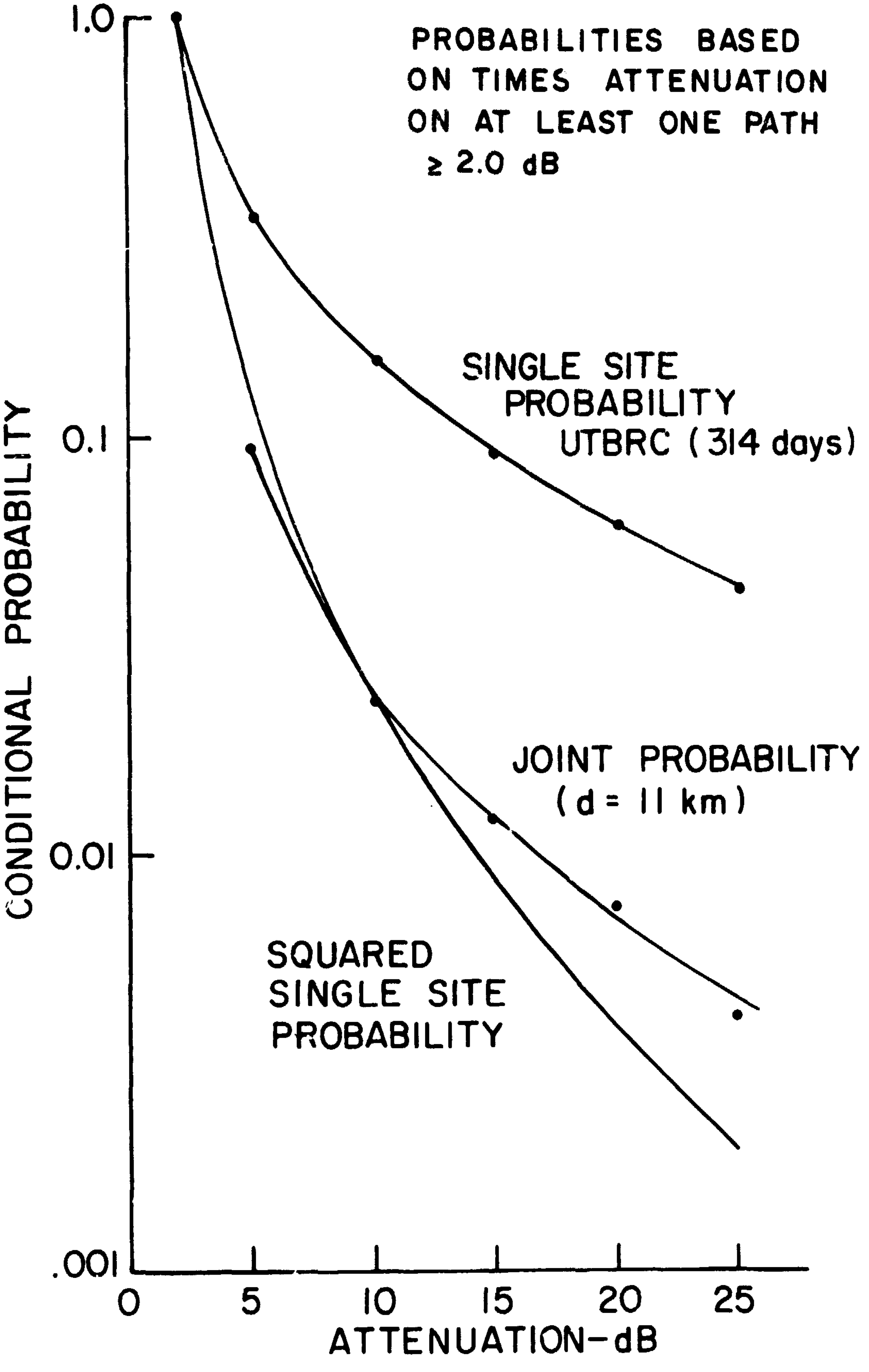


Fig. 16 CONDITIONAL SPACE DIVERSITY FOR A ≥ 2 dB

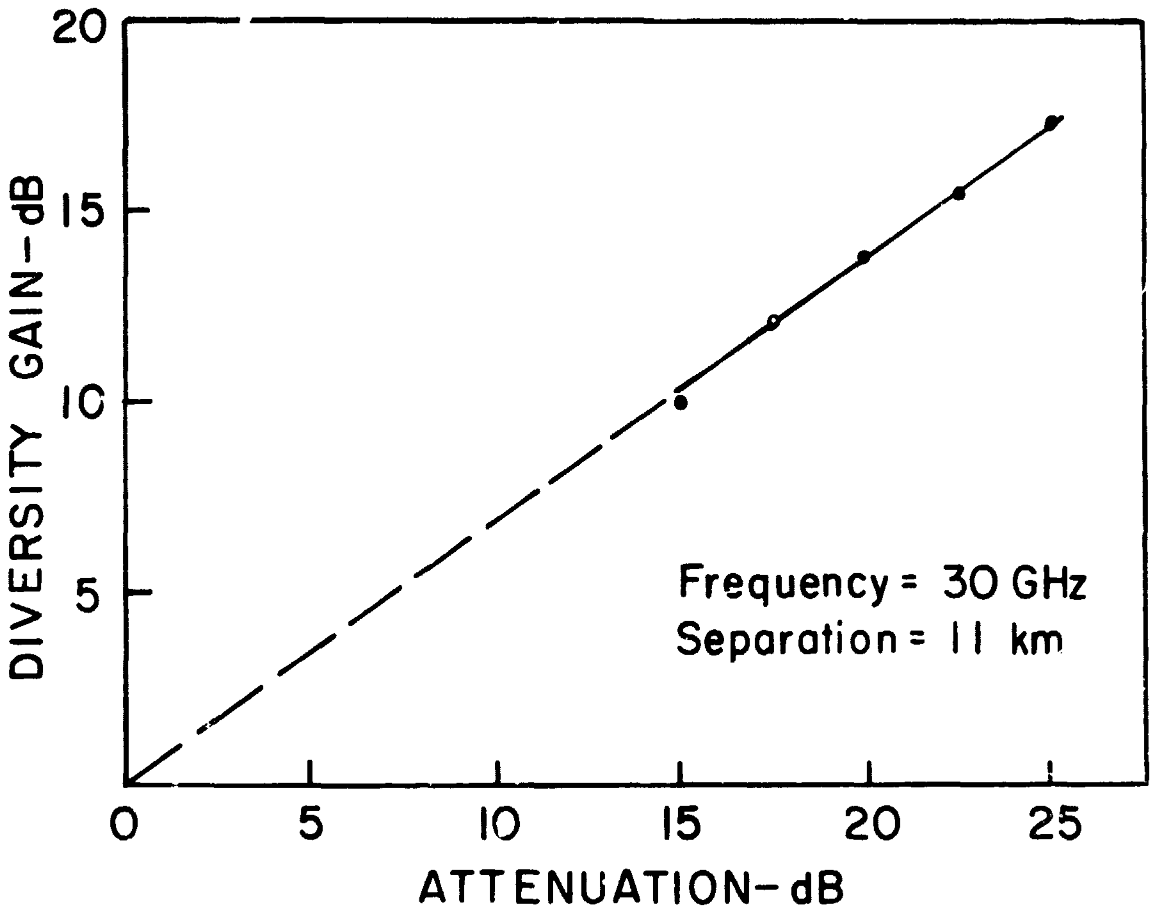


Fig. 17 DIVERSITY GAIN AS A FUNCTION OF SINGLE SITE ATTENUATION

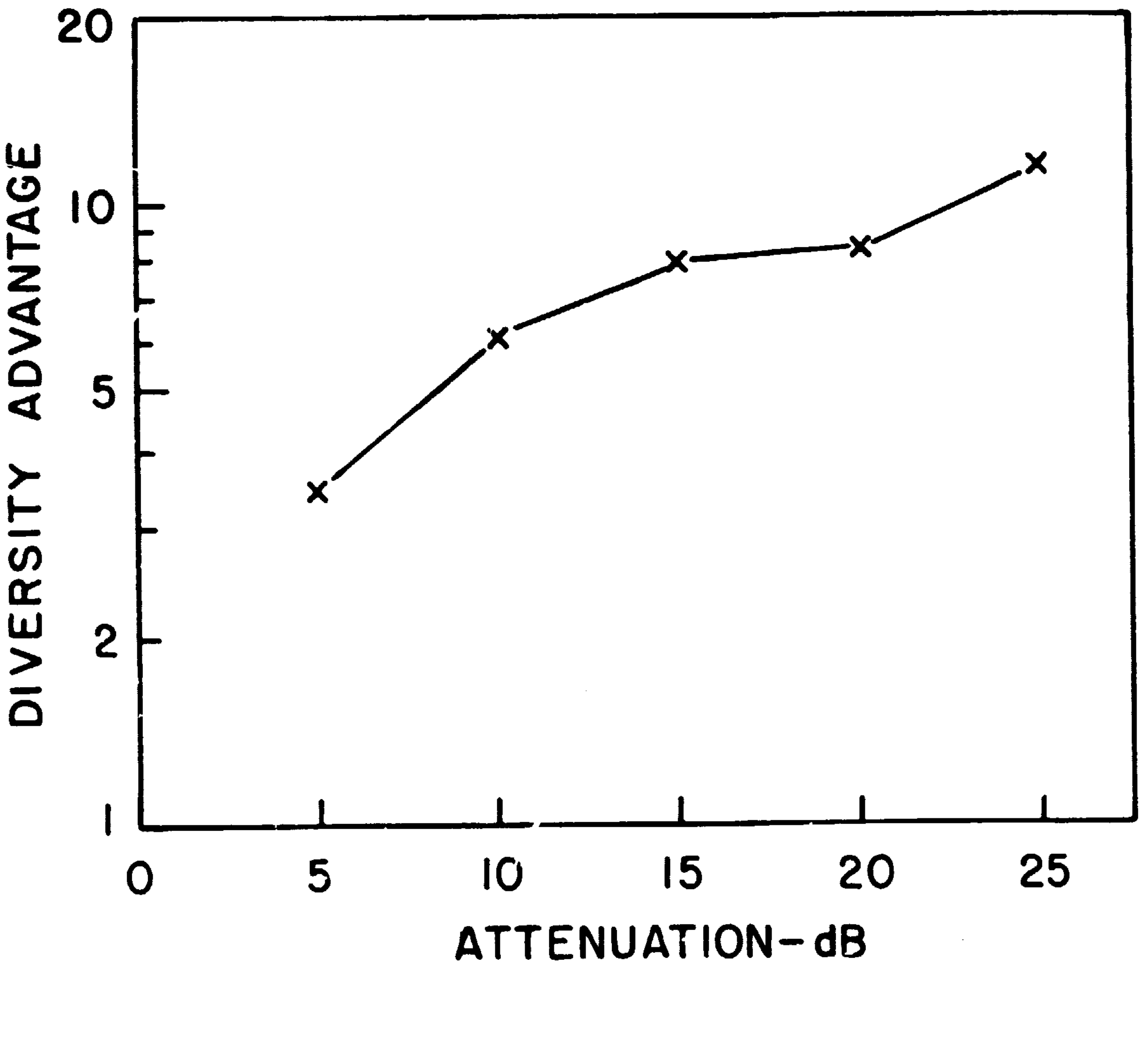


Fig. 18 THE DIVERSITY ADVANTAGE OF TWO RECEIVER SITES AT 30 GHz.

20 GHz radiometers served both as an effective way of judging if the conditions required a request of the satellite transmitter and, if the request was denied, the sky temperature data could be used to derive the 30 GHz attenuation.

If commercially operating satellite communication links are restricted to a 10 dB fade margin (for economic reasons for instance) then our measurements show that one station in Austin would achieve 99.83% reliability and a diversity pair with 11 km separation would achieve 99.997% reliability, as far as weather influences are concerned. To achieve the same reliability with only one station the fade margin would have to be increased by over 20 dB.

Of all the types of weather data obtained from the U. S. Weather Bureau the maximum height of cloud tops show the best correlation to the attenuation data. It should be worthwhile to make such measurements directly at the site of a propagation experiment to exclude the points in Fig. 13 not relating directly to the experiment site. A linear relation between attenuation and cloud height is suggested by the data. Other weather parameters, such as rain rate or grid value show very little promise of allowing an estimate of attenuations. Many of the Weather Bureau data are qualitative rather than quantitative and are not well suited for analysis.

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