9950-711

(NASA-CR-169297) DIVERSITY RECEPTION OF COMSTAR SHF BEACONS WITH THE TAMPA TRIAD, 1978 - 1981 Final Report (GTE Labs., Inc.) 60 p HC A04/MF A01 CSCL 20N

N82-32568

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G3/32 33544

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WITH THE TAMPA TRIAD, 1978-1981

Final Report

by

D.Davidson, D.D.Tang

January 1, 1982

JPL Contract No. 956078

GTE Laboratories Incorporated
40 Sylvan Road
Waltham, MA 02254

This report covers work performed for Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration under Contract NAS7-100.

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Abstract

Tampa, Florida (28°N, 82.5°W), has about 90 thunderstorm days per year, mostly all in summer. These convective events tend to occur in afternoon or early evening. This report presents (1) as background, the results of 19-GHz down-link rain-attenuation diversity measurements in Tampa over a 29-month period (1978-1980), and (2) results of a 29-GHz diversity study during the summer of 1981, using the remaining COMSTAR beacon. At 19 GHz, site separations of 11, 16 and 20 km were used, with reception at high elevation angle (about 57°). At 29 GHz, only the 16-km baseline was employed, with elevation angle about 32°

Almost identical long-term performance of the two longer baselines indicates that for separations above about 15 km diversity improvement was not sensitive to baseline length or direction. Diversity improvement at 29 GHz with the 16-km baseline was similar to that predicted by scaling the 19-GHz results of the previous seasons. Also discussed are the type of attenuation distributions and typical fade durations to be found under persistent convective conditions. For rain climates like Tampa's, site diversity in some form will be required for high-reliability SHF satellite links. The diversity data may be helpful in designing schemes for resource-sharing among numbers of links.

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1. Introduction and Background

Beacon signals on 19 and 29 GHz from the COMSTAR domestic satellites <Cox, 1978> were recorded at Tampa, Florida and also at Waltham, Massachusetts (42.4°N, 71.3°W) during the period 1977-1980. In Tampa three sites forming a diversity reception configuration called the Tampa Triad (Figure 1) began operation in 1978. Two remote sites, Lutz (L) and Sweetwater (S), at exchange buildings of General Telephone Company of Florida, received only the 19-GHz "vertically" polarized (19V) carrier signal, while the 19V, 19H, and 29V carriers were recorded at the University of South Florida (U). Baseline lengths were: LU, 11 km; SU, 16 km; LS, 20 km. Baseline directions were chosen so that baseline SU lay almost exactly in the direction of the D-1 satellite (originally at 128°W), while the LU baseline lay almost at a right angle to that of SU. (See Tables 1 and 2.)

Since at about the time the Triad was established D-1's 19-GHz beacon transmissions were of variable quality, reception was transferred to D-2 beacon during its lifetime, followed by that of D-3. Since the respective elevation angles were 55° and 57° merging the two sets of attenuation data was relatively straightforward. At these high elevation angles, signal attenuation during rainfall is produced in an interaction region close to the receiving site.

The Waltham (W) station, a replica of that at U, was located about 20 km west of Boston, and for part of the period supported a receiving terminal for the 12-GHz CTS beacon (116°W). <Nackoney, Davidson, 1978>. Waltham elevation angles for D-2 and D-3 were 35.5° and 38.5°, respectively.

At each receiving site, at least one rain gauge was also in operation. For part of the reporting period, one or more sites in Tampa each had two rain gauges, one a capacitance rain-rate gauge (Belfort manufacture), the other a standard tipping-bucket (0.01 in) gauge (Weathermeasure manufacture).

In the original reception configuration,19-GHz signal acquisition is made via carrier phase-lock together with phase lock to the 1-kHz polarization modulation of the 19 GHz emission. The 29-GHz receiver channel simply slaved to the 19-GHz channel, taking advantage of the coherent relationship (3/2) of the emissions. Highlights of terminal characteristics are given in Appendix B.

The National Climatic Center's Bulletin, Local Climatological Data, says of Tampa: "On the average, the station has near 90 days with thundershowers occurring mostly in the late afternoons of June, July, August and September. The resulting sudden drop in temperature from about 90° to 70°F induces an agreeable physiological reaction. Between a dry spring and a dry fall, some 30 inches (about 60 percent of the annual) rain falls during the four summer months." Since in the 1978 and 1979 experience with the Tampa Triad May too was an important rain-producing month the summer season has been taken in some of the studies to comprise up to five months in the years 1978-1980.

COMSTAR satellite D-4, launched in February 1981, was maneuvered to longitude 127°W in May to replace aging D-1 which had previously been moved to about 95°W for paired operation with D-2 (also aging). (Cf Table 1.) The Tampa Triad was then to record 19 GHz emissions, but in mid-May, just a few days after the Triad had begun data collection, the 19-GHz beacon failed and all restoration attempts by COMSAT General were unsuccessful. Fortunately the design of the GTE Laboratories receiving terminal is such that by diverting the two-frequency feedhorn canister from Waltham to Sweetwater, and switching USF to lock on 29 GHz, data collection using the SU 29-GHz pair was made possible through August 31, 1981, when the D-4 beacon package was deactivated by COMSAT General according to spacecraft power conservation plans.

The work under the present contract, JPL No. 956078, covers the 29-GHz diversity results for the summer of 1981 (June, July, August). To facilitate understanding and interpretation, this report presents in Section 2 a review of Tampa's rainfall history to indicate the seasonal nature of the rainfall and whether months in the years 1978-1981 were average or not. Section 3 includes the salient 19-GHz diversity attenuation distributions, and the principal conclusions that may be drawn from the 29-month investigation. Section 4 discusses diversity improvement (advantage) as derived from the distributions, and its spacing dependence. Section 5 gives details of the time block incidence of attenuation for single sites and with diversity, for the summer months. The 29-GHz results for summer 1981 are then given in Section 6. Section 7 contains a summary of the mean fade duration measurements, for the years 1978-1980. Section 8 presents conclusions and recommendations, along with acknowledgements. Appendix A contains a discussion (with tables and a figure) on the dependence of the attenuation ratio (29 to 19 GHz) on drop size distribution. Appendix B gives a summary of receiving terminal characteristics. Appendix C contains a selection of paired analog recordings of both rain rate and attenuation from sites S and U from the summer, 1981.

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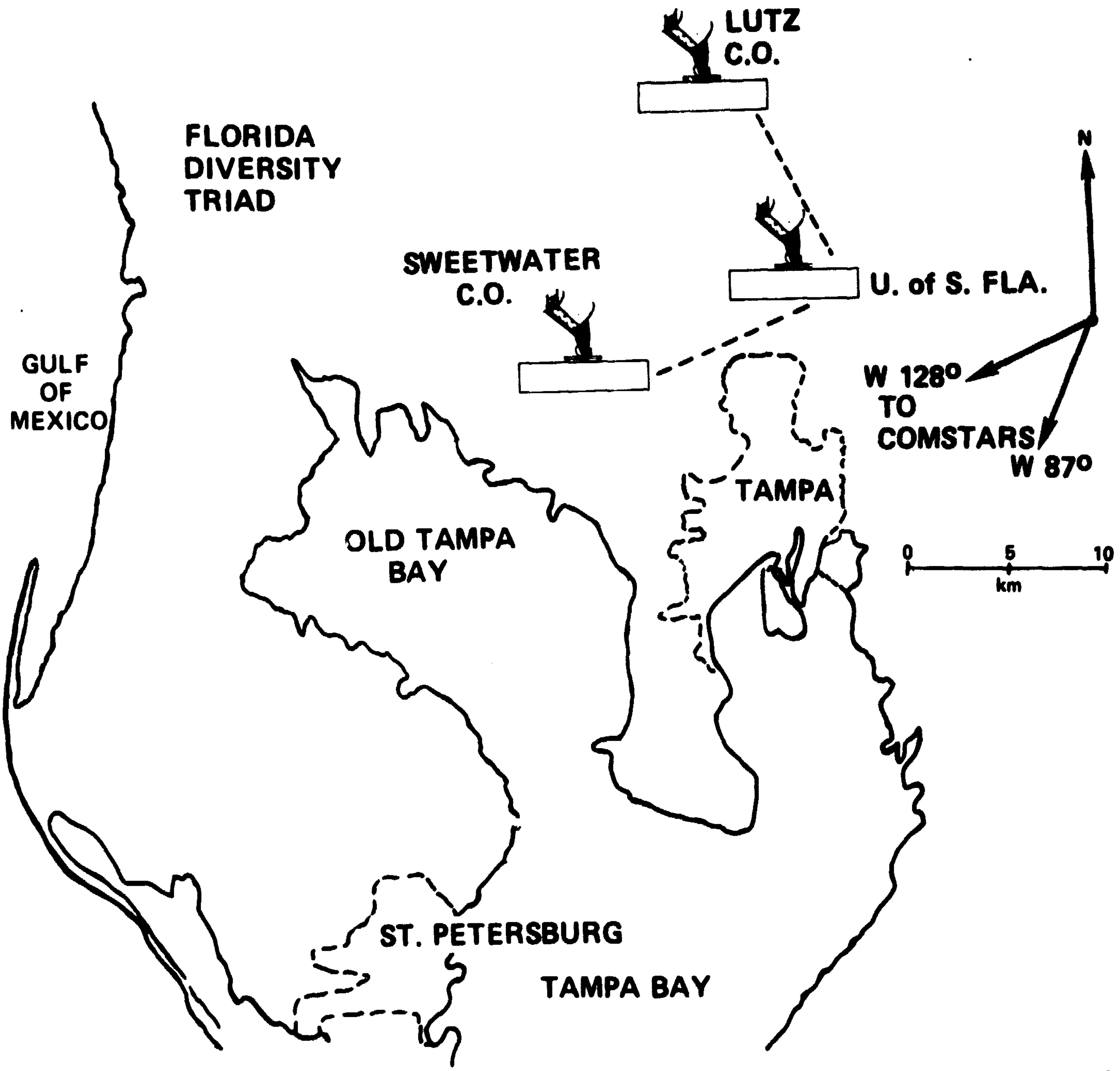

Figure 1 Map showing location of Tampa Triad

Table 1. History of COMSTAR 19/29 GHz Beacons

Satellite	Operational Period on Station (19/29 GHz)
D-1	May '76 - August '78
D-2	July '76 - August '78
D-3	September '78 - August '80
D-4	May '81 - August '81 (See note)

Note: D-4's 19-GHz beacon failed on May 18.

Table 2. Tampa Triad Particulars

Baseline	Length	Direction (from more northern site)
LU	11 km	157.4° TN
SU	16	244.4
LS	20	209.9

(Angle between LU and SU baselines: 93.7°)

Satellite	Position	Elevation Angle	Azimuth (°TN)
D-1	128°W	30.9°	245.2°
D-2	95	54.6	205.2
D-3	87	57.0	189.4
D-4	127	31.7	244.4

2. Tampa's Rainfall History

Figure 2 shows the official 47-year rainfall history (1934-1980) for Tampa; it indicates that a sampling of two or three consecutive years may sometimes include large deviations from long-term means. The large variability can also be appreciated by considering Figure 3, which covers a similar period, but in which the solid circles indicate monthly means for years since 1890, broken lines show monthly rainfalls occurring in years 1978 - 1981. The unusual rainfalls of May, August and September, 1979 are also manifested in the beacon attenuation experience in Tampa. Rainfall in the first nine months of 1981 was below average except for February and June. July 1981 was unusually dry. (Data shown is from Tampa International Airport, about 2 km from Sweetwater, as published by the National Weather Center, Asheville NC, in Local Climatological Data for Tampa.)

3. 19-GHz Cumulative Attenuation Distributions, Tampa: 29 months.

3.1 Distributions

Attenuation distributions were prepared by scaling analog recordings at 2-dB intervals within the 30-dB recorder scale. Beacon was acquired by phase lock of the 19V signal; loss of lock could occur for a fade of around 30 dB.

(The 29-GHz channel, slaved to the 19V lock, could actually track fades of up to 50 dB, but the recording range was truncated at 30 dB). In 1981, the switch to 29 GHz involved the same range till loss of lock.

Figure 4 shows the cumulative single-site and diversity distributions for Tampa for the 29-month period. Data collection in the summer of 1980 was shortened because D-3 beacon was turned off at end of August to conserve spacecraft battery.

3.2 Principal Conclusions Regarding Diversity (1978 - 1980).

The following conclusions may be drawn from the 29-month distributions of Figure 4:

1. Distributions for individual sites are very much alike, indicating that the observed month-to-month differences are sifted out, that sites tend "to catch up with each other". Thus no significant climatic differences appear among the sites in the Tampa Triad, at least for the period reported.

2. The shortest pair (LU, 11 km) was the poorest diversity performer.

3. Very little difference in diversity performance appears between the SU (16-km) and the LS (20-km) baselines, indicating an insensitivity to baseline length greater than about 15 km.

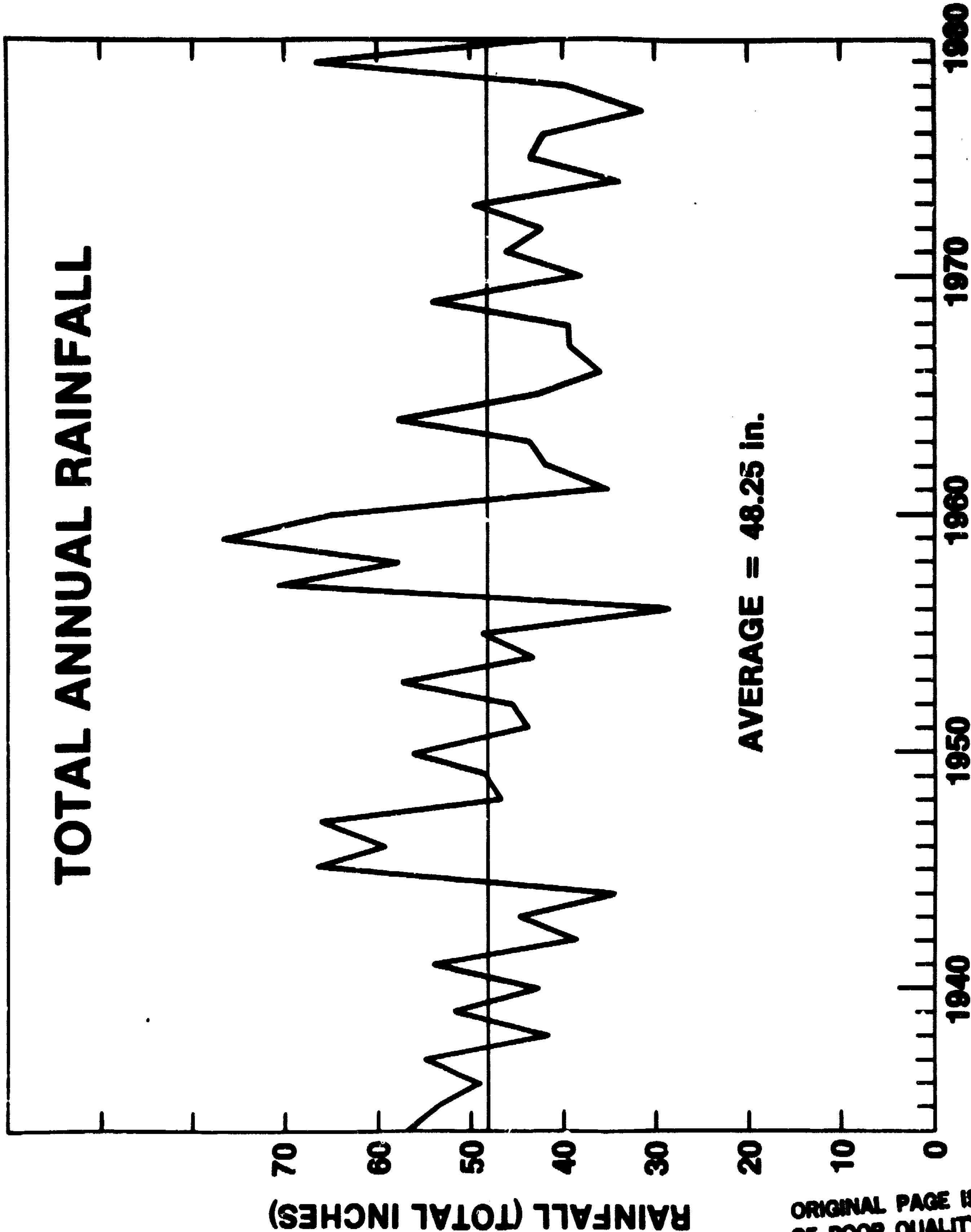

Figure 2 Total annual rainfall in Tampa 1934-1980

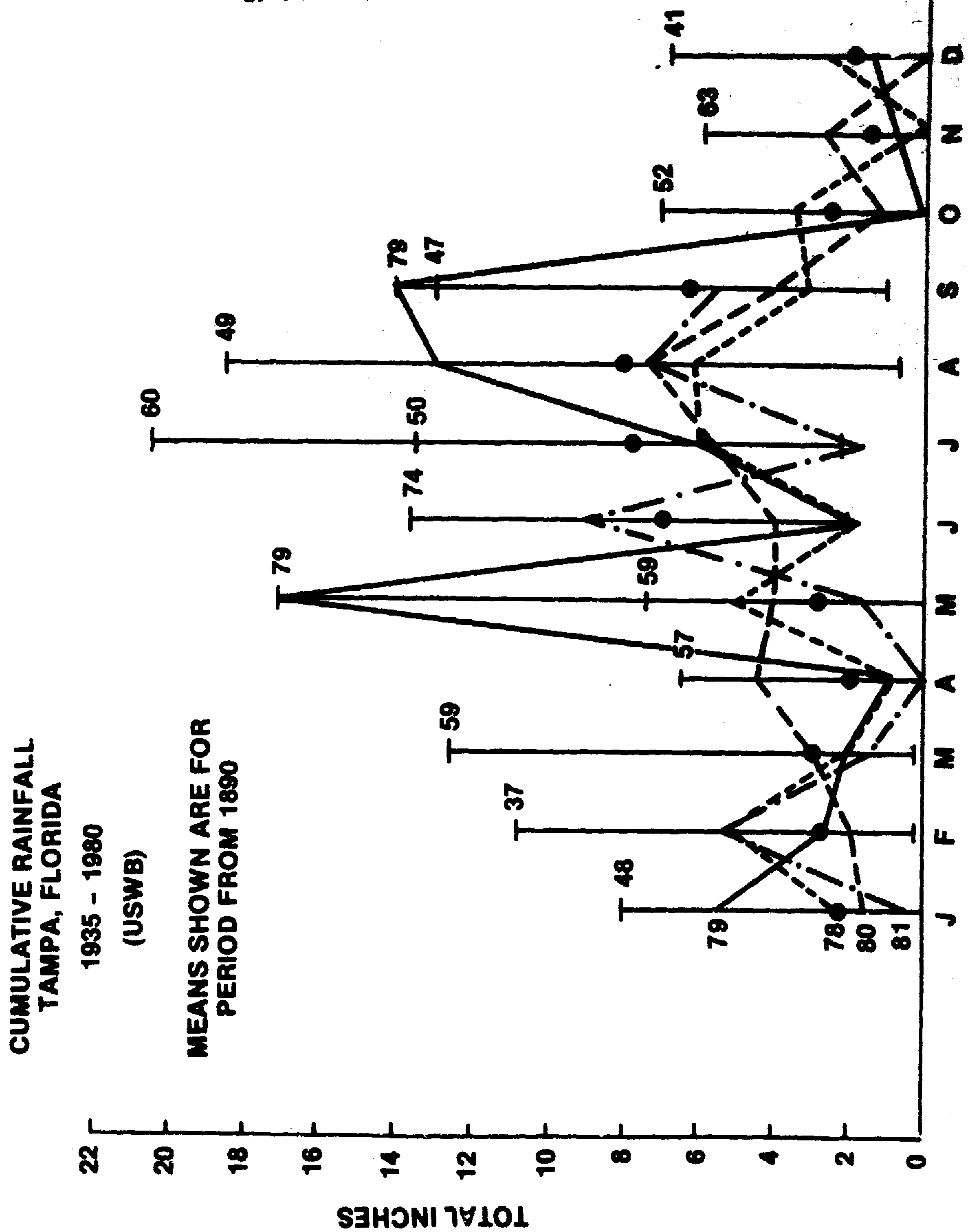

Figure 3 Means and extremes of monthly rainfall, Tampa

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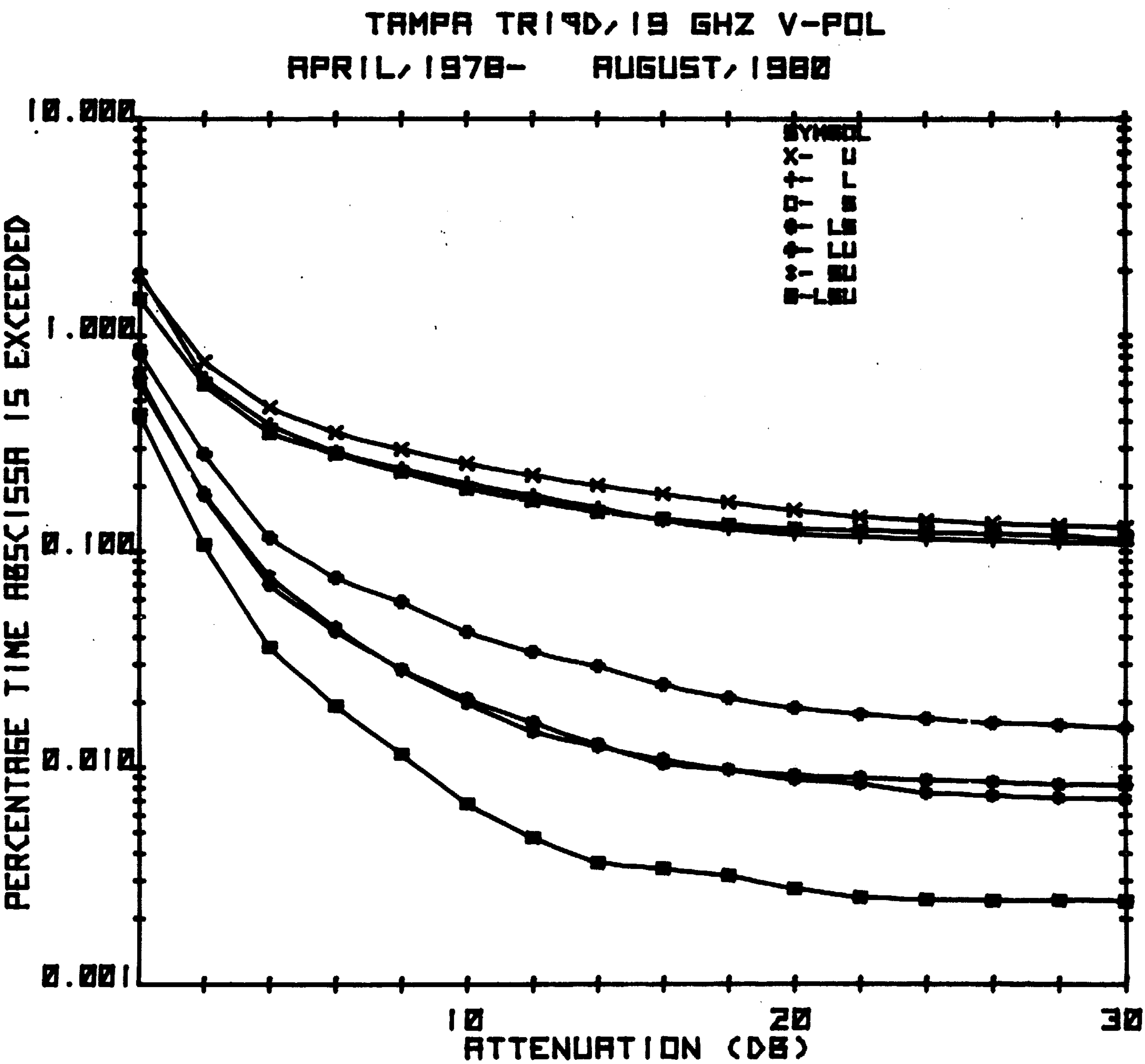

Figure 4 19-GHz attenuation distributions, Tampa Triad, 29 months

4. With the high elevation angles used to view D-2 and D-3 beacons, baseline orientation is unimportant, at least for lengths above about 15 km. This result should facilitate diversity site selection since 12/14 or 20/30 GHz satellite system service to the southeast will surely involve orbit positions giving relatively high elevation angle.

5. Beyond an attenuation of about 10 dB, the single-site distributions show an almost flat tail. This characteristic arises from the precipitate nature of rainfall onset for summer convective rain cells in Tampa. Figure 5 reproduces a 19V analog attenuation recording paired with the local rain rate recording, and shows how steep is the rainfall onset. Figure 6 shows a typical summer month distribution to be contrasted in the tail region with that for November 1979 (Figure 7). Also contrast Figure 8, the 1979 19-GHz attenuation distribution for Waltham.

6. Because of the flat tails in the attenuation distributions, attempting to provide system downlink fade margins in excess of 10 dB at 19 GHz in Tampa's type of rain climate will likely be unproductive. There are of course other reasons why downlink attenuation margin greater than 10 dB may be impractical.

7. For rain climates like Tampa's (e.g. other locations along the coast of the Gulf of Mexico, or locations along the southeast Atlantic coast, typified by Rain Climate G, <Crane, 1980>), link outages (annual) of 0.01 percent with 10-db fade margins cannot be achieved with single-site operation; diversity operation must therefore be considered for high-availability applications like trunking systems. Note: Florida has been reclassified into Rain Climate N according to CCIR Draft Report 563-1 (Mod F). See CCIR Doc. 5/5049-E (10 September 1981). Only one other rain climate, Rain Climate P, is defined that exceeds N in rainfall intensity. Rain Climate N is characterized by rain rates 5, 35, and 95 mm/h for 1, 0.1, 0.01% of an average year, respectively.

8. Three-site diversity operation is very successful.

Other aspects of diversity performance can be gleaned by transforming attenuation distributions to display a measure of diversity effectiveness or improvement.

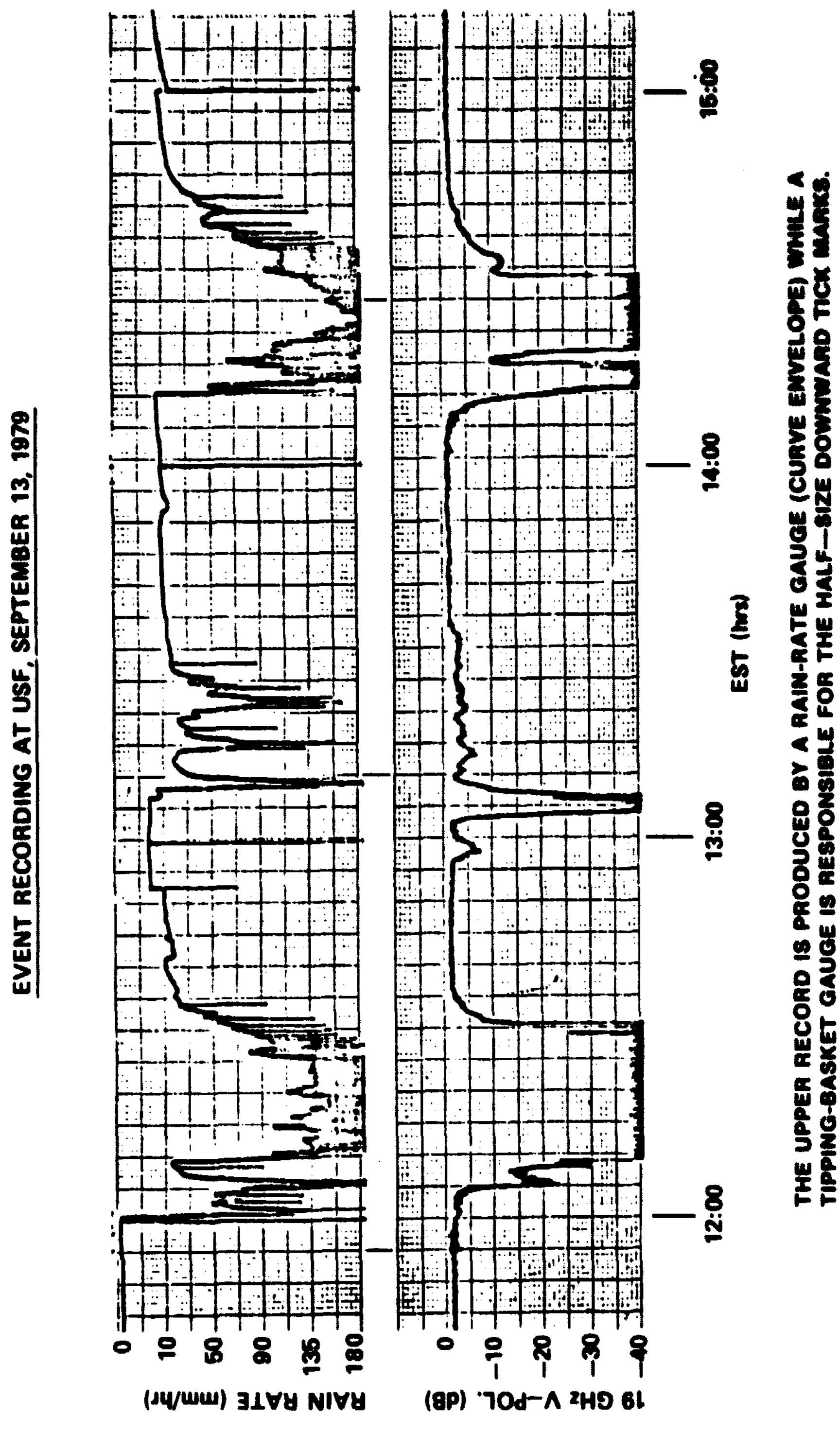

Figure 5 Analog recording at USF showing example of steep onset

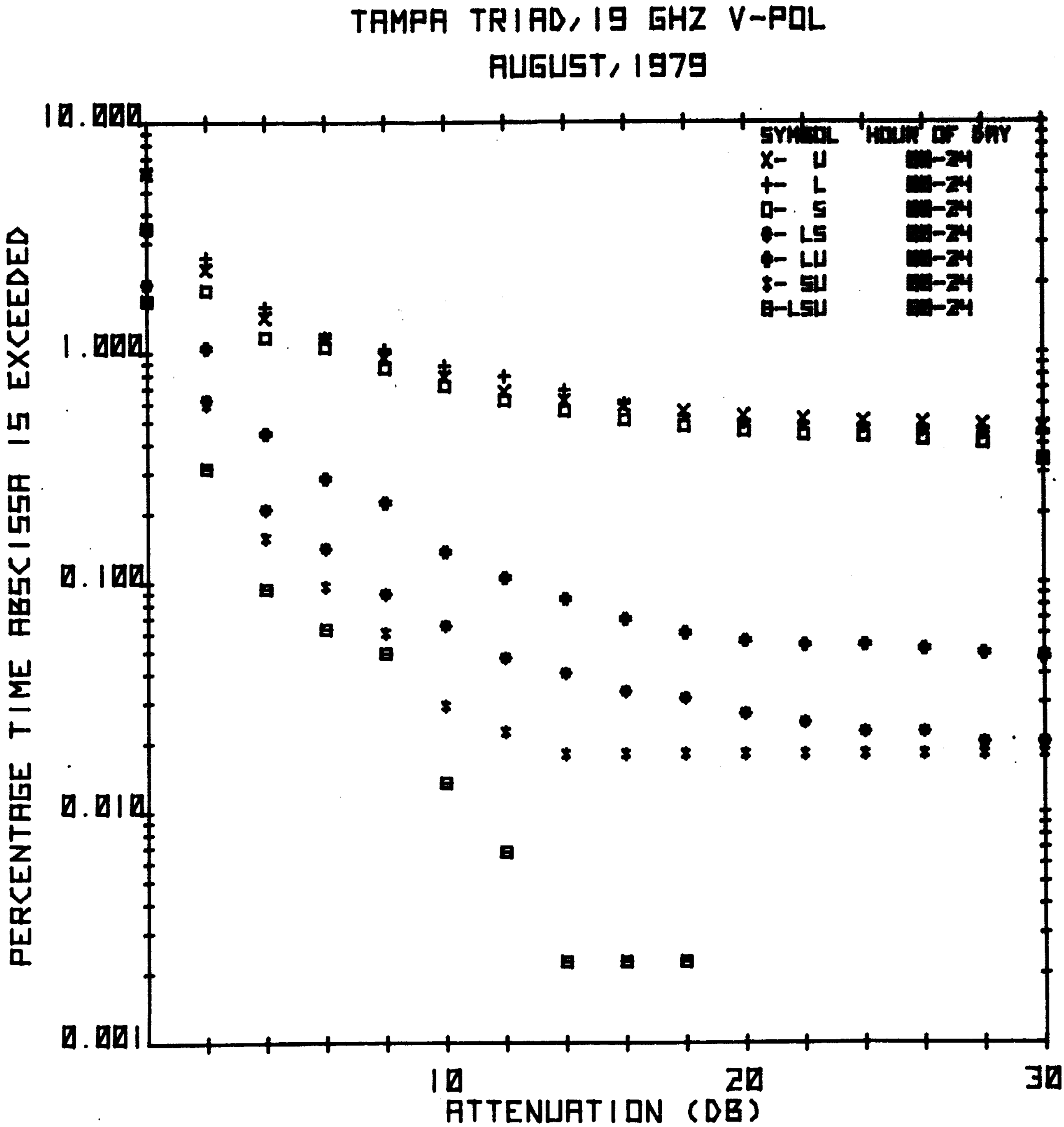

Figure 6 19-GHz attenuation distributions, August 1979, Tampa

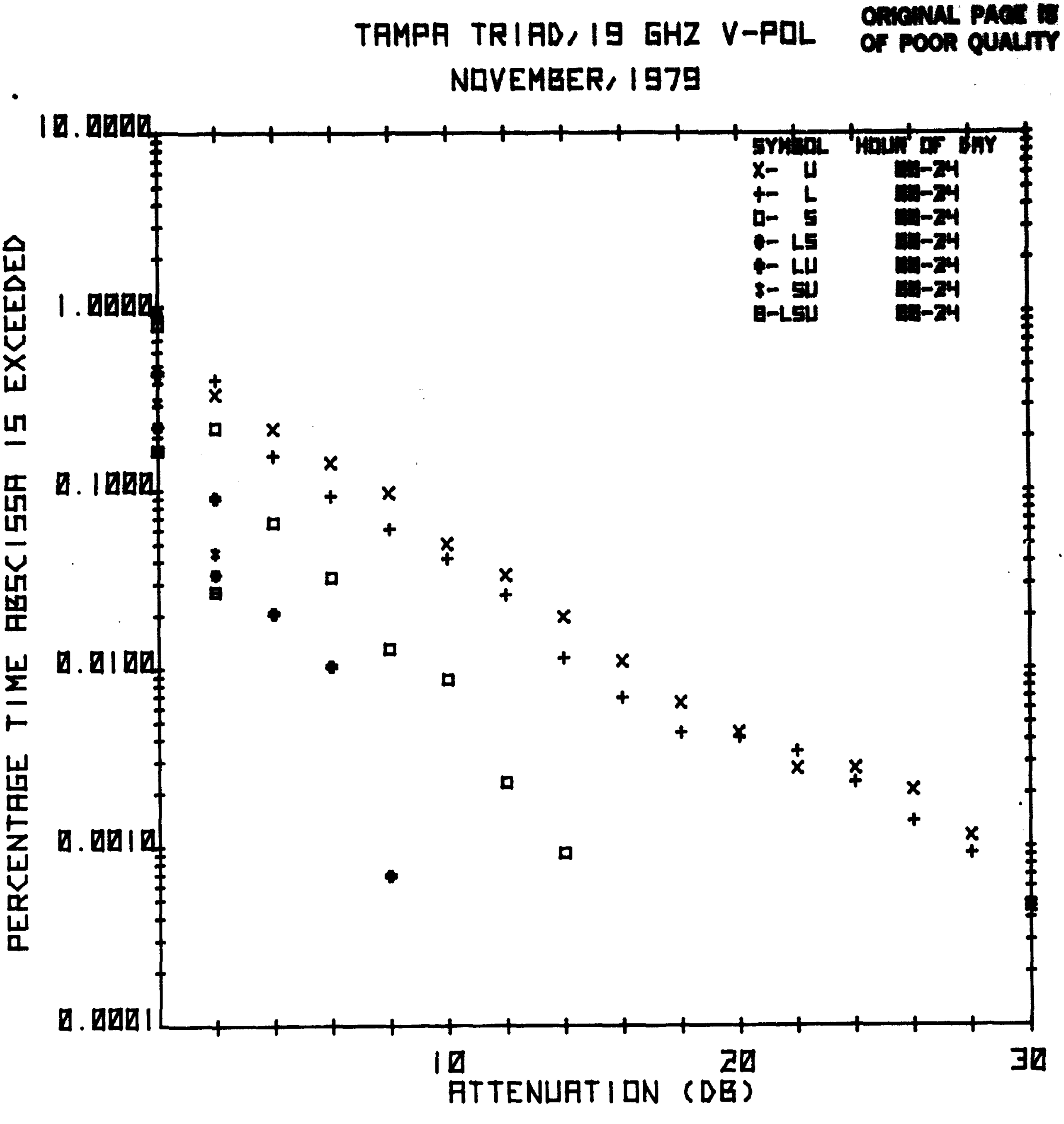

Figure 7 19-GHz attenuation distributions, November 1979, Tampa

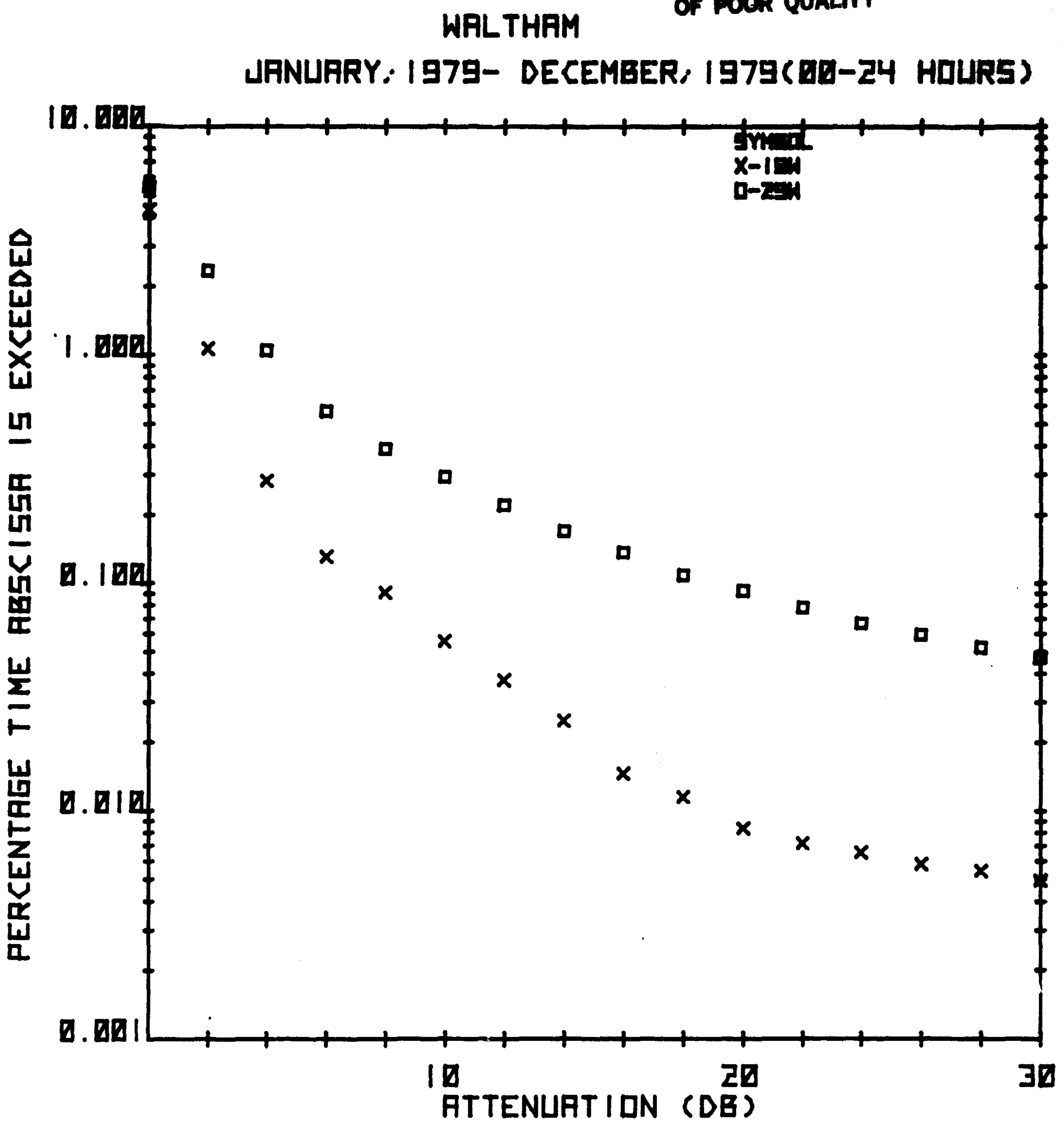

Figure 8 19 and 29 GHz attenuations, Waltham, 1979.

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4. Diversity Improvement

4.1 Definitions

Diversity improvement can be measured by examining the ratio of outage times at given attenuation level ("diversity advantage"), or by noting the reduction in attenuation for a fixed pecentage of time ("diversity gain"). For flat-tail distributions like those found in Tampa, the only practical measure is diversity advantage. (The Tampa diversity gains involved are very large or indeterminate for attenuations of 10 dB or more. This problem is addressed in the NASA Propagation Effects Handbook, Chapter 6. <Kaul et al, 1980>). Diversity advantage has the merit of affording comparisons under the same prevailing rain regime (largely convective here), and is particularly useful when two baselines share a common site. It is also the criterion regularly used in the telephone industry to evaluate diversity.

The diversity advantage, to be identified by the symbol I, is shown in Figure 9 for each of the three dual-diversity configurations for the 29-month period. In calculating diversity advantage, we have chosen as reference the (geometric) mean single-site attenuation probability (at specified attenuation level). If P_1 and P_2 are the cumulative single-site probabilities then the diversity advantage, I, is

$$I = (P_1 \, P_2)^{1/2} / P_{12} \qquad (1)$$

where P_{12} is the joint (diversity) probability. (Other references that may be employed are the arithmetic mean single-site probability, and the smaller probability).

If rain attenuation is uncorrelated at two sites (correlation coefficient ρ=0), then

$$I = 1/(P_1 \, P_2)^{1/2} \qquad (2)$$

which is a simple form, arising from our choice of reference.

If fading is perfectly correlated $P_{12} = P_1$ or P_2, whichever is smaller; I can then be greater than unity with our definition if $P_1 < P_2$.

Figure 9 shows clearly that there is little difference between baselines SU and LS over the 29-month period. At the 10-dB level, uncorrelated fading would lead to I≈333; actual LS and SU values are about I=10.

4.2 Diversity Advantage, Month by Month.

Table 3 lists the measured 10-dB diversity advantage (at 19 GHz) for the 29-month period, April 1978 - August 1980, using the D-2 and D-3 beacons. These figures represent the reduction in outage over mean single-site operation, and are useful in projecting performance of particular systems.

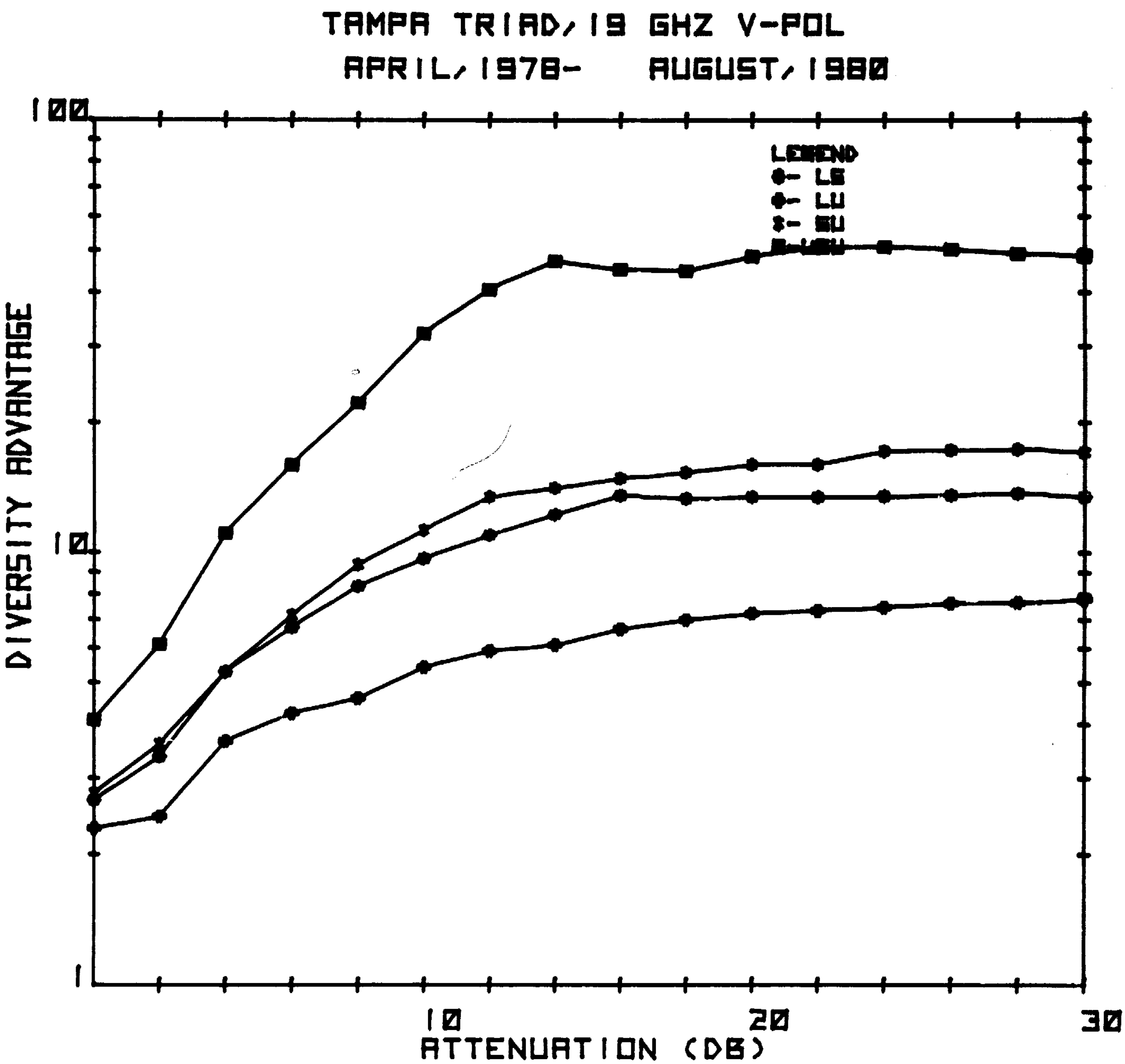

Figure 9 Diversity advantage, 29 months (1978-1980), Tampa Triad

COMPARISON OF DIVERSITY ADVANTAGE IN 1978 and 1979
AT 10-dB ATTENUATION LEVEL, TAMPA TRIAD

Month	LS			LU			SU			LSU		
	1978	1979	1980	1978	1979	1980	1978	1979	1980	1978	1979	1980
January	X	7.5	∞	X	∞	∞	X	∞	∞	X	∞	∞
February	X	5.8	15.7	X	6.1	8.6	X	17.0	∞	X	∞	∞
March	X	∞	22.9	X	∞	6.9	X	∞	4.0	X	∞	∞
April	∞	∞	∞	∞	∞	38.0	2.6	∞	22.4	∞	∞	∞
May	3.3	7.9	17.8	2.2	3.5	3.6	2.0	5.5	36.1	5.6	14.1	41.6
June	∞	∞	10.1	∞	9.2	16.0	∞	∞	27.7	∞	∞	∞
July	72.0	16.6	13.0	21.0	12.0	4.9	174.0	5.4	39.1	∞	∞	∞
August	3.8	12.0	4.8	2.6	6.0	4.4	6.8	26.0	7.1	9.6	60.0	∞
September	5.6	18.0	X	11.5	6.0	X	∞	80.0	X	∞	80.0	X
October	∞	∞	X	∞	∞	X	∞	∞	X	∞	∞	X
November	NR	∞	X	NR	∞	X	NR	∞	X	NR	∞	X
December	9.8	∞	X	6.4	∞	X	∞	∞	X	∞	∞	X

NOTE: NR = No Rain; X = System Not in Operation.

The competing performances of LS and and SU stand out. But it is also clear that in isolated rainy months, such as August 1978 and August 1980, diversity can be disappointing. This is undoubtedly due to the prevalence of organized bands of rain cells, often seen in the scans of local weather radars. The entries for May 1979 are virtually all due to one extraordinary event, that of May 8, discussed below in some detail.

4.3 Application to Link Resource-Sharing.

Acampora <1981> proposed a SHF TDMA link resource-sharing scheme to provide additional downlink reception slots, from a reserve pool, for rain-affected stations. Two critical parameters were identified: α, the ratio of number of hours in a year to the number of thunderstorm hours in a region; and β, manifesting the conditioned correlation of thunderstorm attenuation events for a given pair of stations in a climate region.

Acampora shows that the required relationship is

$$P_{12} = k\,P_1 P_2 \tag{3}$$

where P_1 and P_2 are single-site annual probabilities of given attenuation, P_{12} is the annual joint probability of that attenuation, and $k = \alpha\beta$.

In Figure 4, for SU, $P_1 \approx P_2 \approx 0.3\%$, while $P_{12} \approx 0.02\%$. Thus $k \approx 38$. For the long-term mean there are 88 thunderstorm days in Tampa, and estimating an average of 4 hours per thunderstorm period gives $\alpha = 25$, which is close to Acampora's assumed $\alpha = 24$. Then $\beta = 38/25 = 1.5$, which is slightly higher than Acampora's most favorable geographic condition $\beta = 1$. Thus $\beta = 2$ might be a realistic estimate for the 20/30 GHz band at the 10-dB level in the southeast, for site separations of at least 16-20 km. Note that β can be usefully related to the diversity advantage as defined earlier by

$$\beta = 1/(\alpha I \sqrt{P_1 P_2}) \tag{4}$$

or

$$\beta = I(\rho{=}0)/\alpha I \tag{5}$$

4.4 Spacing Dependence

Morita and Higuti <1979> using suntracker diversity measurements in the 16-17 GHz range chose to characterize diversity performance by an assumed power-law relating joint to single-site probability P_s

$$P_{12} = a(P_s)^b \tag{6}$$

For one-year's measurements in the Tokyo area they found

$$a = a(S) = 1.374\,/S^{0.49} \tag{7}$$

$$b=b(S)=0.9586 - 0.104\ S^{0.5} \tag{8}$$

valid for $10 < S < 50$ km. Suntracker data represents performance over a wide range of elevation angles.

For diversity advantage I the related form is

$$I = C(\ P_s\ )^D \tag{9}$$

where $C = 1/a$ and $D = 1 - b$.

For the Tampa Triad 29-month operation at high elevation angle

$$C = -0.405896 + 0.295135\ S - 0.00727\ S^2 \tag{10}$$

and

$$D = 1.70103 - 0.32722\ S - 0.010194\ S^2 \tag{11}$$

These are valid only for spacing S between 11 and 20 km. C continuously increases with S, while D has its maximum at 16 km.

5. Attenuation Severity Within Local Time Blocks

To indicate the temporal nature of downlink rain attenuation, the 1979 summer 19-GHz data (both single-site and diversity) were grouped according to six-hour local time blocks: 00-06, 06-12, 12-18, 18-24 hours (Eastern Standard Time). Figures 10 and 11 show the percentage of time per block that 10-dB attenuation was exceeded during the five-month rainy period, May - September.

The 00-06 h time block shows the lowest outage percentage. For the single sites, maximum outage occurred between noon and 18 h. Maximum outage was as high as ten times the minimum outage. Inter-site differences within the worst time blocks can be appreciable. With diversity, the time blocks of maximum outage differed according to diversity combination: For LS, maximum outage occurred in 06-12 h; for LU, 12-18, much like a single site; for SU, 18-24 h; and finally, for LSU, 12-18 h, reflecting the influence of the LU combination. Note, too, that in some time blocks, especially 18-24 h, the short baseline LU outperformed SU and was about as good as LS.

Indicated also in the figures are the 00-24 h outage percentages. Note that L and S had almost identical outage percentages.

These results indicate that even with the significant overall diversity performance, a satellite downlink operating in southeastern USA could experience difficulty in the summer during the post-noon period. With diversity, depending on the pair, the period of highest outage may be shifted to the less-busy (telephone) hours of the day.

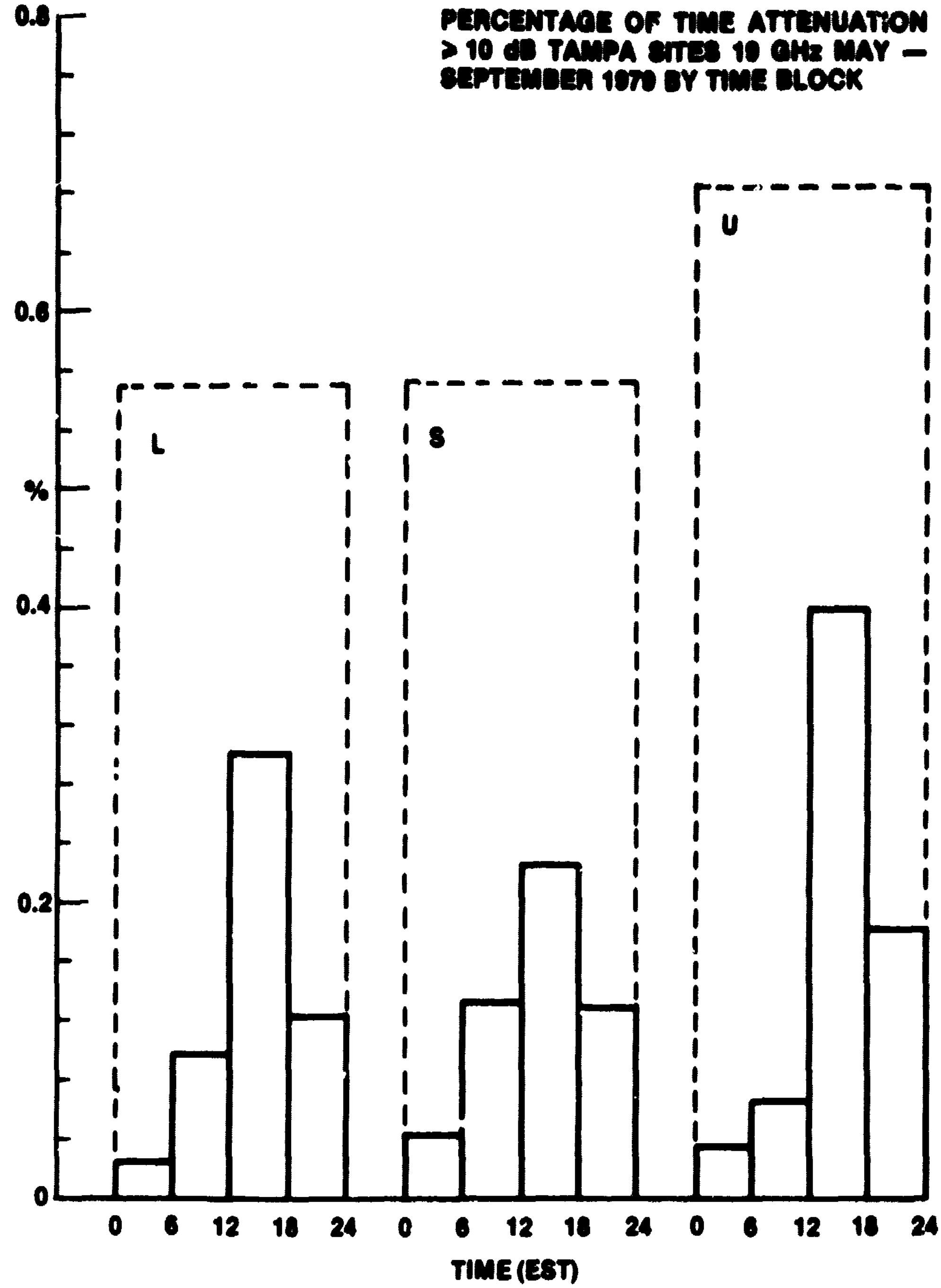

Figure 10 Time block distribution of attenuation, (U,S,L), summer 1979

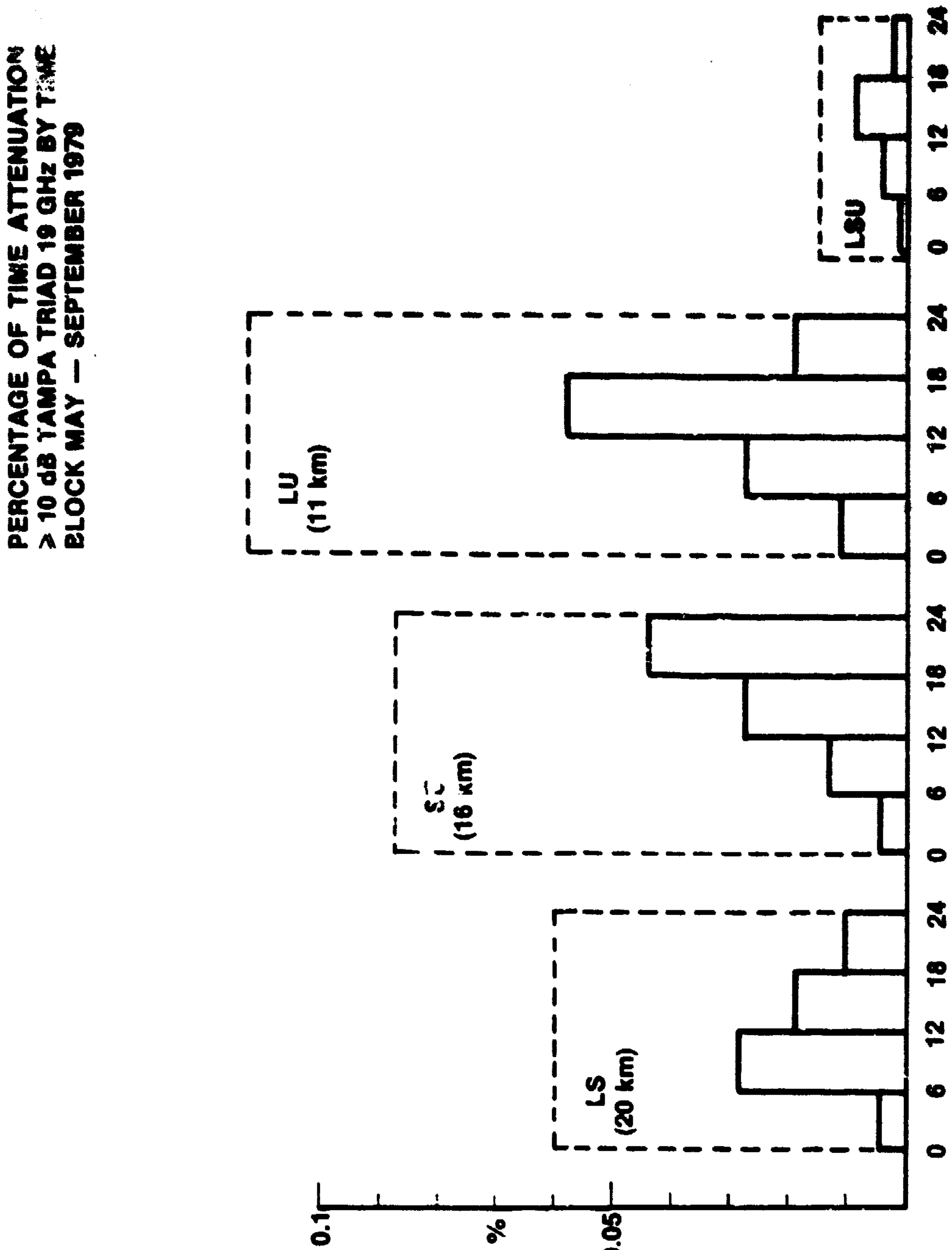

Figure 11 Time block distribution with diversity, summer 1979

6. 29-GHz Diversity, SU Baseline. Summer, 1981.

6.1 Distributions

COMSTAR satellite D-4, launched in February 1981, was maneuvered to longitude 127°W in May, to replace aging D-1 which had been moved to 95°W for paired operation with D-2. But in mid May, just a few days after the Triad had begun 19-GHz D-4 data collection, the 19-GHz transmitter ceased transmitting and could not be restored. By diverting the two-frequency feedhorn assembly from Waltham to S, 29-GHz diversity data collection for SU was made possible through August 31, 1981, the date the D-4 beacon transmissions were terminated according to plan by Comsat General, the space segment operator.

SU was chosen because its baseline direction coincided with the direction to D-4 (See Table 2) and also because SU had show good diversity performance at 19 GHz for the three prior summers. The elevation angle was 32°.

Attenuation distributions for S, U and SU for the entire period are shown in Figure 12, and for the individual months, in Figures 13, 14, 15. The corresponding diversity advantages are shown in Figure 16. The plot for July 1981 shows a steep transition between 12 and 14 dB attenuation because July was an unusually dry month and most of the attenuation events were low but one event caused sudden severe loss of lock. This behavior can also be seen in Figure 14.

Of interest are predictions of SU (29-GHz) summer distributions made by scaling up 19-GHz results of prior years. For a given period of observation, the scaling factor is statistical, relating attenuations at the same exceedance percentage. Employing the basis of the Crane <1980> model but with rain rates from Dutton and Dougherty <1979>, and adjusting for the different elevation angle used in 1981, the scale-up factor averages about 3.57 for the range of attenuation (also rain rates) involved. Note that the path- averaged rain rates producing up to 30-dB attenuation at 29 GHz at an elevation angle of 57° are less than about 25 mm/h. Clearly then, since extreme rain rates in convective storms reach 75-120 mm/h in Tampa, a 29-GHz link is sensitive to the onset and waning phases of a convective storm and will be noticeably affected during widespread rain.

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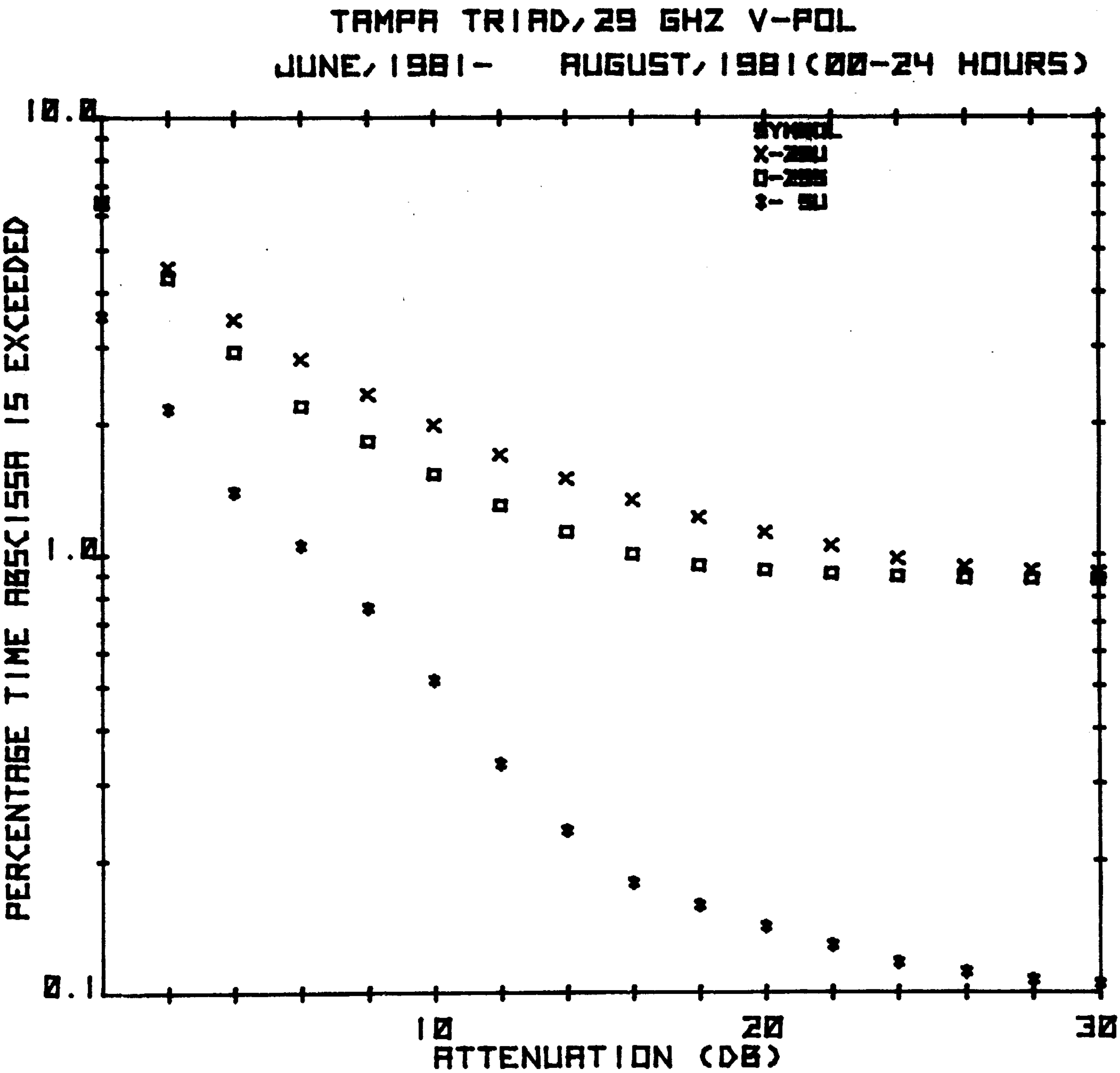

Figure 12 29-GHz S, U, and SU distributions, June-August 1981

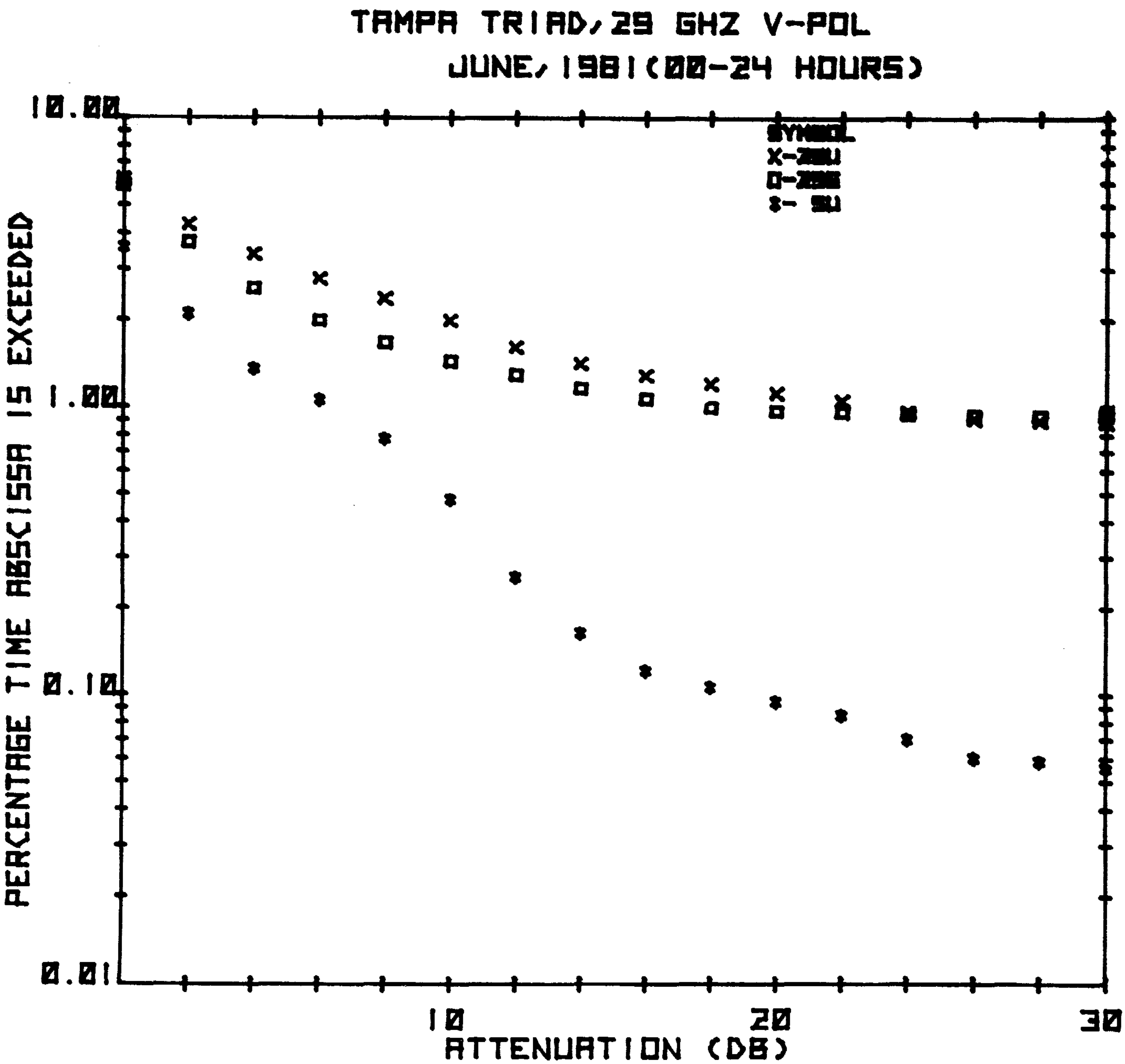

Figure 13 29-GHz S, U, and SU distributions, June 1981

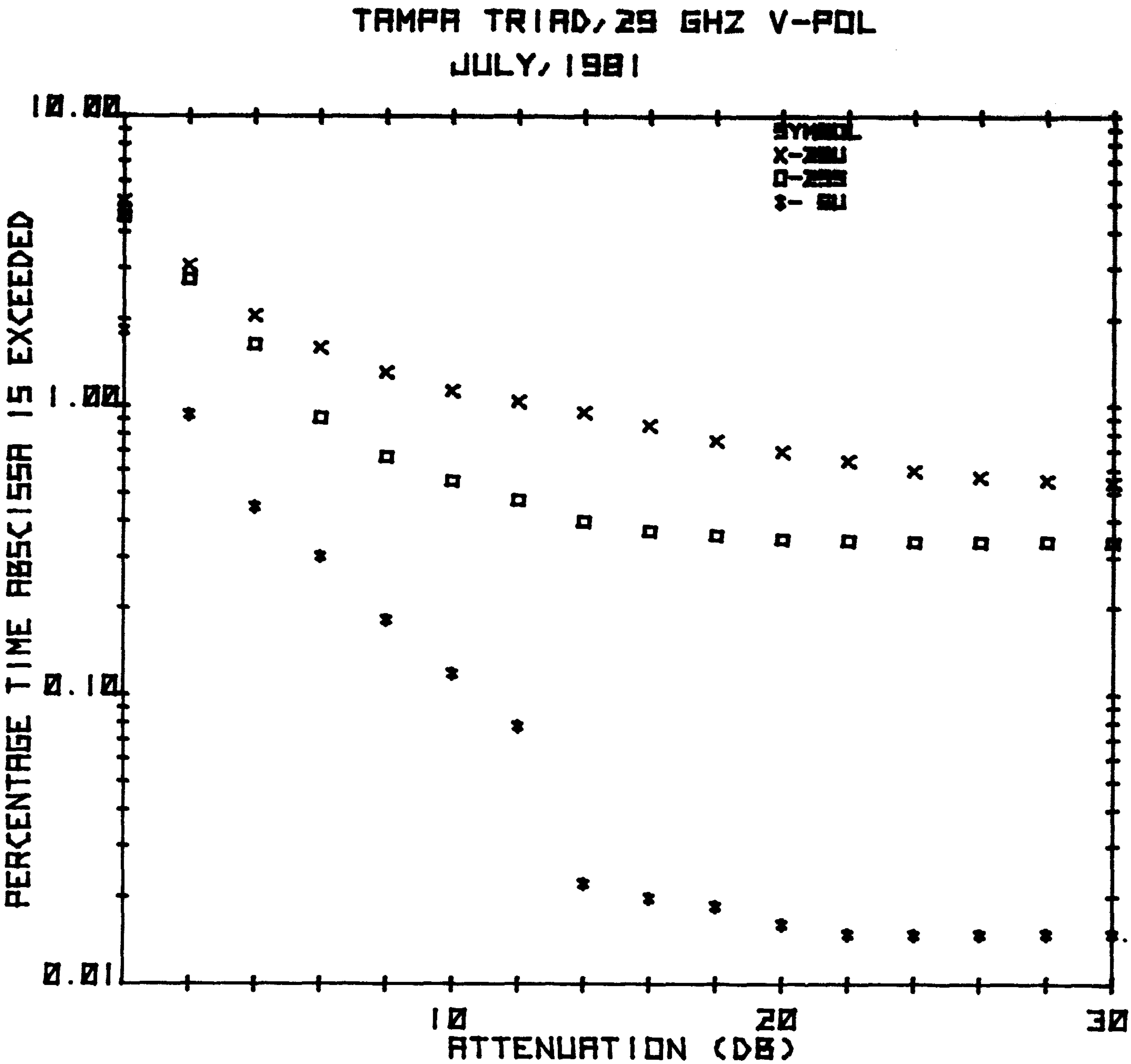

Figure 14 29-GHz S, U, and SU distributions, July 1981

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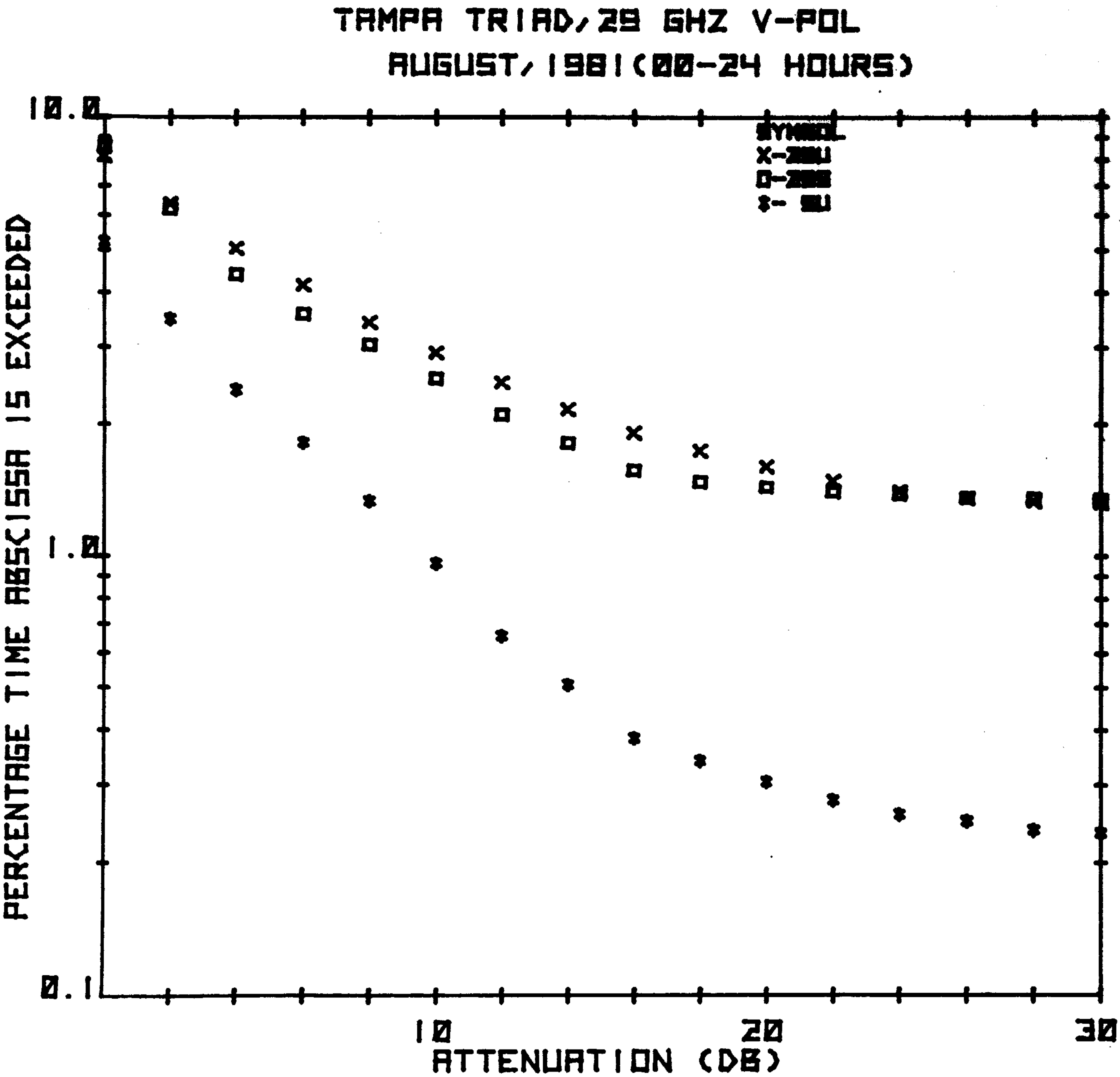

Figure 15 29-GHz S, U, and SU distributions, August 1981

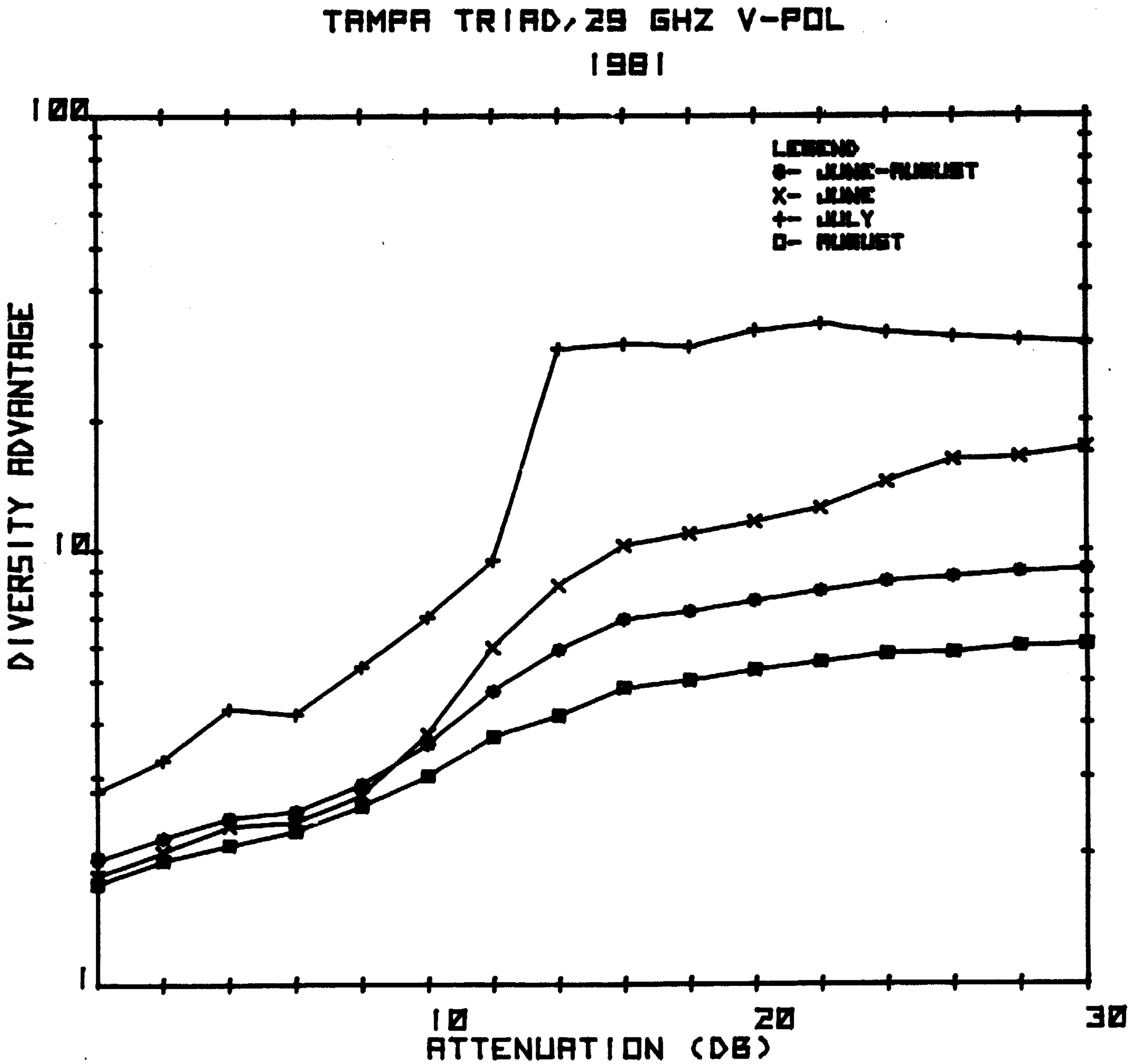

Figure 16 SU diversity advantage, 29-GHz, summer 1981

Figure 17 shows the 29-GHz SU attenuation distribution for June through August 1981, along with four synthesized distributions: (1) Summer 1980 19-GHz SU distribution scaled up to 29 GHz; (2) Summer 1979, scaled up similarly; and a scaled-up 29-month 19-GHz SU distribution (3) unadjusted for seasonal dilution, and (4) adjusted by a factor reflecting the average fraction of rainy months in the 29-month period. <Summers of 1979 and 1980 in these distributions included May through August; May 1979 was an extremely rainy month, Figure 3.> In the region below 12 dB, the 1981 SU percentages are higher than the higher predictions, but are fairly close beyond that level. These high percentages for relatively low attenuation stem from the strong influence of weaker disturbances. A cull of the individual attenuation events at S and at U (Table 6-1) reveals that well over 50% of the events had attenuations significantly under 30 dB, and 12% (U) and 20% (S) of the events with weak attenuation were unaccompanied by on-site rainfall.

It must be emphasized that the prediction curves in Figure 17 are statistically derived and therefore have only limited value in suggesting the range of compensation that would be needed in an uplink power-control scheme. Actual experience both at Tampa and at Waltham with dynamic attenuation-ratio measurements during the course of numbers of rain events shows that the ratio can have such wide scatter that power control within the narrow limits demanded in high-performance systems may be difficult to achieve <J.E.Allnutt, private communication, 1981>. Thus, site diversity and link resource-sharing are serious candidates for uplink management in the 20/30-GHz satellite bands.

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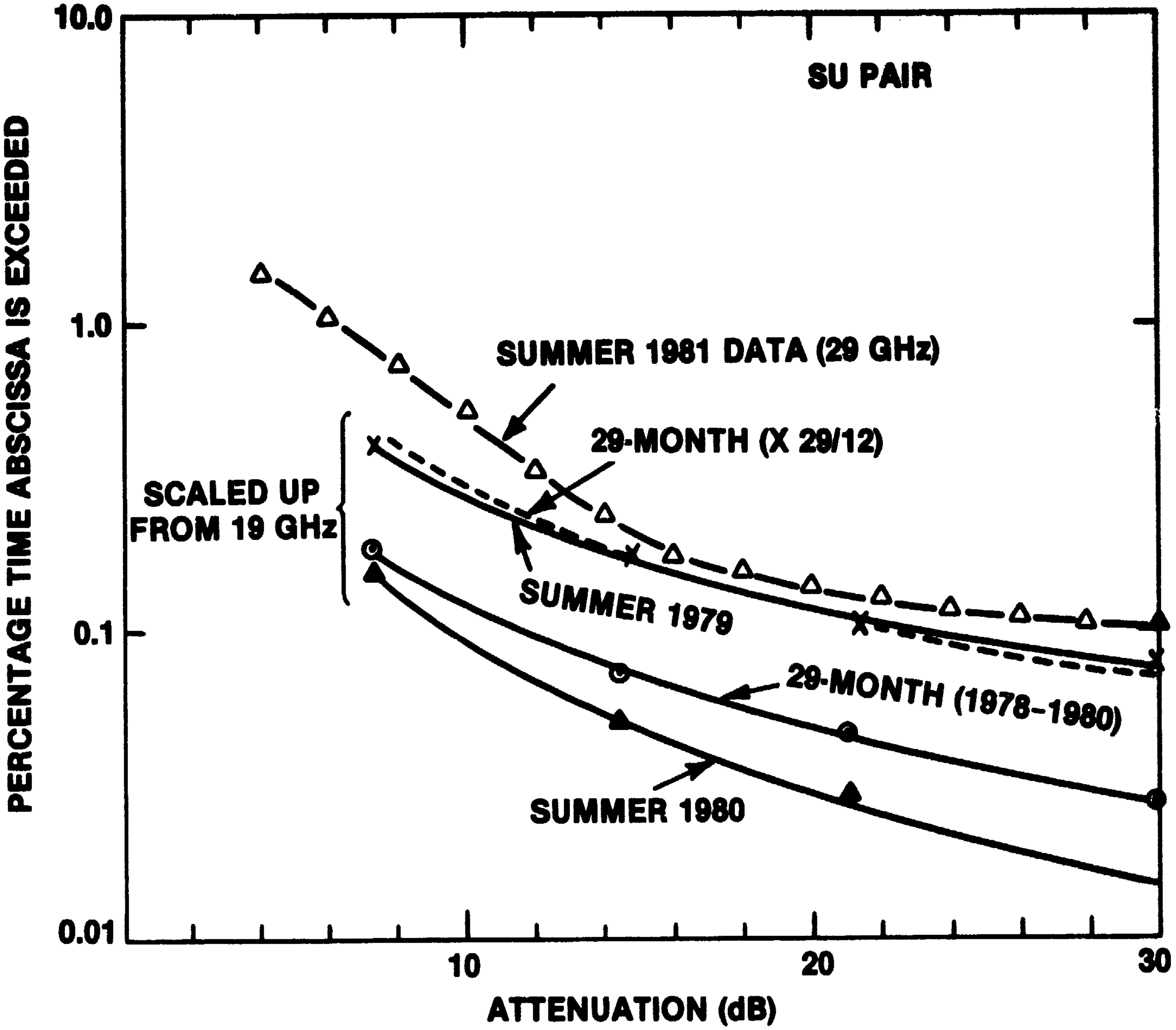

Figure 17 SU Summer Distribution, and Predictions Based on Prior Seasons

6.2 Character of the Rain Events: June 5 through August 31, 1981.

Distinct rain or rain-attenuation events at sites S and U were catalogued sequentially through the recording period June 5 through August 31, 1981. There were 107 separate events at U and 110 at S. On the analog recordings each event comprises the attenuation history together with its associated local rain gauge indication. Each resolvable event can be characterized broadly according to the nature of the attenuation and whether there is an associated local rainfall. In Table 4 are the distributions at the sites as characterized. Symbols have the following meaning:

Associated with local rain:

b	a complete loss of lock, for less than 10 min
bl	like b, but of long duration
w	weak attenuation (no loss of lock)
ws	like w, but long duration, suggesting widespread rain

No association between local rain and attenuation:

nc/w	like w, but no rainfall
nc/o	rainfall, but no attenuation
nc/sc	scintillation, but no rainfall

(The totals indicated in the table differ slightly from the recorded number of identifiable events because some events were compound, and some had incomplete recordings.)

Although site L had no 29-GHz receiver, the rain gauge recording was maintained throughout the period. At L only 84 rain-gauge events were identified, but it is likely that more attenuation/rain events would have been identified had the terminal been in operation; this can be inferred by noting the number of events characterized by the symbols nc/w and nc/sc. Thus for the three-month period the three sites in the Triad each had about the same number of events, though these were not all associated among the sites.

Note that the distributions are not vastly different, except for nc/w events. Note too that all b and bl events had local rainfall; it seems therefore that local rainfall is a requirement for loss of lock (fade of about 30 dB at 29 GHz). In the b or bl cases we found the rain onset may precede or follow the attenuation event as well as commence along with it. At an elevation angle of 31.7° this is to be expected.

Table 4

DISTRIBUTION OF RAIN/ATTENUATION EVENTS ACCORDING TO CHARACTER

Sites S and U........June 5 through August 31, 1981

Character of Event	At S	%	At U	%
b	14	13.1	26	23.2
bl	21	19.6	18	16.0
w	34	31.8	33	29.5
ws	9	8.4	11	9.8
nc/w	21	19.6	13	11.6
nc/o	5	4.7	3	2.7
nc/sc	3	2.8	8	7.1
Total	107		112	

Legend:

b	loss of lock, duration around 10 min or less
bl	long loss of lock
w	weak attenuation, relatively short duration
ws	weak attenuation, long duration
nc/w	weak attenuation, no local rain
nc/o	local rain but no attenuation
nc/sc	scintillation but no local rain

In Table 4 loss-of-lock events account for around a third of the events. Most of the other events had attenuations of about 20 dB or less. At 29 GHz at 31.7° elevation at Tampa model calculations show that 16 mm/h will produce about 30 dB attenuation. Clearly the weak events will be associated with widespread rain, or grazing of convective cells, or cumulus clouds (scintillation); these events are associated with left-hand portion of the attenuation distribution and the rising phase of the diversity advantage distribution.

7. Fade Durations

Lin <1974> has shown statistically that rain fades are characterized by log-normal distributions. An important parameter is the mean fade duration at specified attenuation. Figure 18 shows mean 19-GHz fade durations as a function of attenuation for the three Tampa sites for the period each site was operational, encompassing between 400 and 600 rain events per site. The three distributions are nearly alike, and are representable by a power-law dependence on attenuation. Standard deviations of the logarithm of mean fade duration are also alike, but are practically independent of the attenuation level. Thus for Tampa, while the mean 10-dB fade duration was two minutes, within one standard deviation the mean duration lay between 0.4 to 10 minutes.

Diversity fade durations are not so simply represented. Figure 19 shows the diversity means as a function of attenuation. The dependence tends to be bi-modal, possibly indicative of a change in rain regime. The LSU data, lying all below 10 dB in attenuation, are essentially uni-modal.

With pair diversity of the two longer baselines, mean fade duration was around 0.3 minute, with SU slighly better than LS. The range corresponding to one standard deviation was 0.04 - 2.4 minutes. Thus, at 19 GHz at the 10-dB level in Tampa, with high elevation angle to the satellite, the diversity advantage I = 10, and fades are typically one-sixth as long as at a single site.

For the two-site combinations the bi-modal break point for mean fade duration is at about the 10-dB level, while for three sites it occurs at 4-dB conceivably because thunderstorm rain very rarely hits all three sites at once.

For the pairs, the mean fade duration is inversely dependent, approximately, on the square of attenuation, while with triple diversity a cubic inverse dependence is a good description. Seemingly therefore, the exponent is representable by the order of the diversity (number of sites involved).

Fades at 29 GHz will obviously longer, although at the higher levels, say over 10 dB at 19 GHz corresponding to over 20 dB at 29 GHz, the durations should be very similar.

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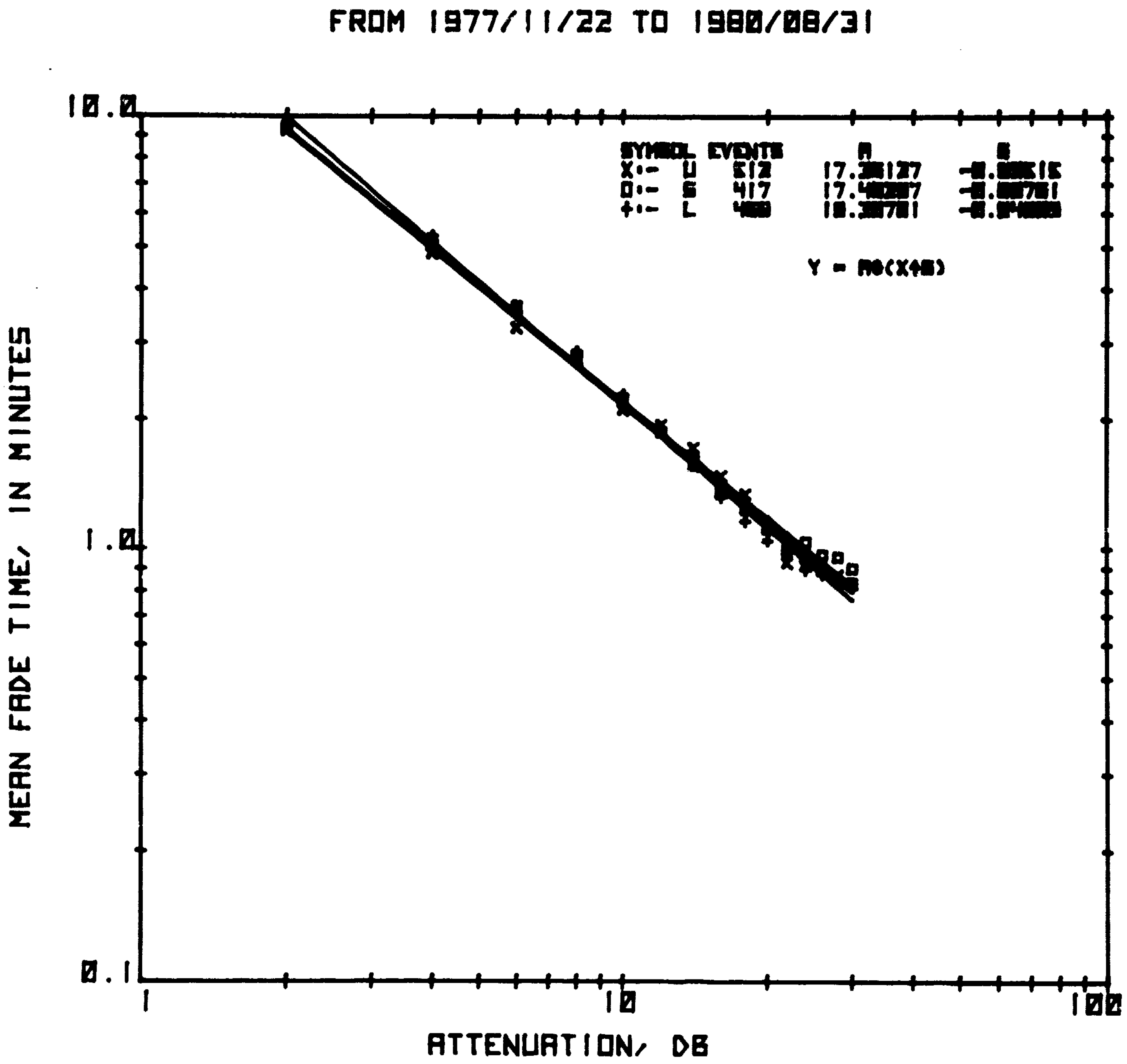

Figure 18 Mean fade duration, single sites, Tampa, 1977 - 1980

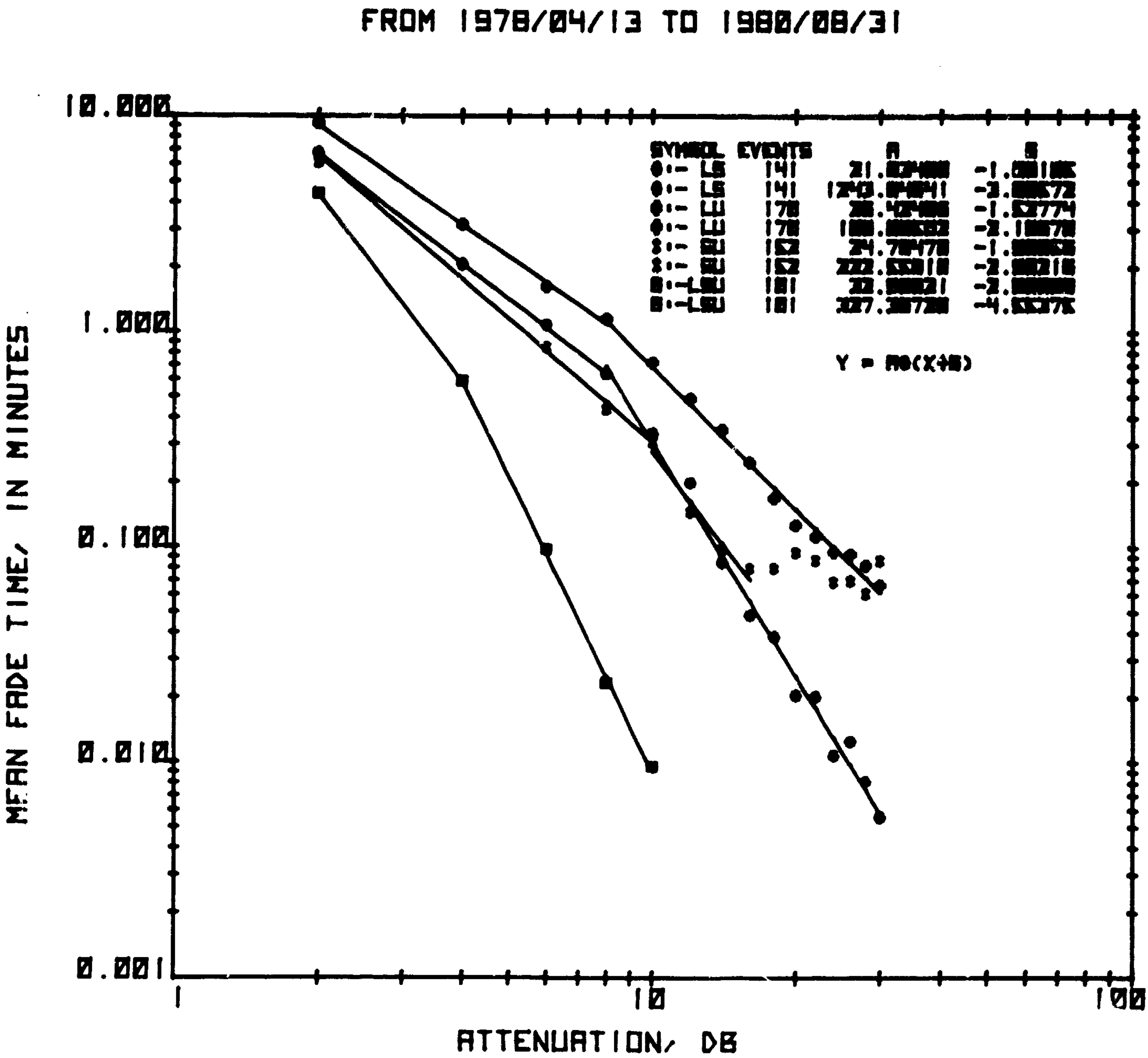

Figure 19 Mean fade duration, diversity, Tampa, 1978 - 1980

8. Conclusions and Acknowledgements

Site diversity with spacings of at least 16-20 km will be required if high-reliability SHF links are to be designed for USA's southeast coast and the coast of the Gulf of Mexico, according to the evidence of 29-month's reception of the COMSTAR 19/29 GHz beacons and reception at 29 GHz during the summer of 1981. To keep attenuation as low as possible for these regions, the satellites to be employed should be positioned to provide high-elevation-angle reception, for which case the data indicate that baseline direction is unimportant. The intense rain events cluster in the afternoon and early evening of the summer months. Fade durations (10-dB level) in these periods typically ranged from 0.4 to 10 minutes, with reduction to 0.04 to 2.4 minutes with diversity. Tampa Triad data should be useful in assessing the feasibility of TDMA link-resource sharing for mitigating rain attenuation effects among single sites in an area. The Tampa data may be scaled to estimate statistically attenuation severity at other SHF frequencies.

The Tampa Triad operations were made possible through the kind cooperation and agreement of the University of South Florida and the General Telephone Company of Florida. The experiment was sponsored in part by GTE Satellite Corporation. The 1981 summer continuation was supported partly by Jet Propulsion Laboratory, California Institute of Technology (Contract 956078), within the framework of NASA's SHF Propagation Experiment, under the leadership of Dr. L. J. Ippolito.

Appreciation is extended to:

Prof. S. C. Bloch, Physics Department, University of South Florida, who led the University's participation in the program, was reponsible for general oversight of the Triad operations, and made valuable contributions to the project.

Mr. Robert Cole, GTE Laboratories, who as chief technician was responsible for construction, check-out, and readiness; he was instrumental in the accomplishing the rapid conversion of the SU pair to 29-GHz operation upon failure of the D-4 19-GHz beacon.

Ms. Kathy Giles, GTE Laboratories, who was in charge of data quality evaluation, logging, reduction and plotting.

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Appendix A

Attenuation ratio for uniform raindrop distribution

For a uniform raindrop distribution,

$$R = 15.08\ v(a)a^3 n(a)$$

where
R = rain rates, mm/hr.
a = drop radius in cm.
$v(a)$ = terminal velocity of rain drops in m/s.,
$n(a)$ = number of drops/m.

Table A-1 lists n(a) as a function of R, and a.

TABLE A-1 n(a) for different rain rate and raindrop sizes

R,mm/hr		0.25	1.25	2.5	12.5	25.0	50.0	100.0	150.0
a,cm	v,m/s								
0.025	2.1	505.20	2526.2	5052.4	25262	50524	101048	202197	303145
0.050	3.9	34.0	170.0	340.0	1700	3400	6801	13603	20404
0.075	5.3	7.4	37.0	74.0	370	741	1483	2966	4449
0.100	6.4	2.6	13.0	26.0	130	250	518	1036	1554
0.125	7.3	1.2	5.8	11.6	58	116	232	465	698
0.150	7.9	0.62	3.1	6.2	31	62	124	249	373
0.175	8.35	0.37	1.9	3.7	19	37	74	148	222
0.200	8.7	0.24	1.2	2.4	12	24	48	95	143
0.225	9.0	0.16	0.8	1.6	8	16	32	65	97
0.250	9.2	0.12	0.58	1.15	5.77	11.53	23.1	46.1	69.2
0.275	9.35	0.090	0.43	0.85	4.3	8.5	17.1	34.1	51.2
0.300	9.5	0.0646	0.323	0.65	3.2	6.5	12.9	25.9	38.8
0.325	9.6	0.05	0.252	0.5	2.5	5.0	10	20	30

For uniform raindrop size distribution, the specific attenuation, at frequency f is given by

$$A = 8.686\lambda_0 n(a) \mathrm{Im} F_v(K_1,K_1)$$

where $F_v(K_1,K_1)$ is the forward (complex) scattering coefficient, and A is in dB/Km.

The ratio r, of attenuation at f_2 to that at f_1 is:

$$r = (\lambda_{02}/\lambda_{01})(F_2/F_1).$$

Tables A-2 and A-3 are obtained using scattering coefficients from Oguchi and Hososya <1974>. Tables A-4 and A-5 use results given by Fang and Lee <1978>.

The attenuations as a function of the radius of rain drops at 34.8 and 19.3 GHz, (Oguchi and Hosoya), are plotted in Fig. A-1. Note the sharp peak at radius 1 mm at 34.8 GHz. Fig. A-2 shows the attenuation ratio as a function of the radius of rain drops, including results given by Medhurst <1965>. Examination of Table A-2 reveals that various ratios are possible for the same attenuation level at 19 GHz. For instance, for attenuation levels between 9 to 10 dB at 19 GHz, the ratio can vary from 1.1 to 2.71. In view of this, it is not surprising that a wide range of ratio is observed at any fixed attenuation level at 19 GHz. Though the maximum of the ratio computed varies according to author, the minimum approaches unity, which is logically consistent.

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TABLE A-2 SPECIFIC ATTENUATION AT 19.3 GHZ AND 34.8-19.3 GHZ ATTENUATION RATIO

		RAIN RATE,MM/HR							
a,cm	RATIO	0.25	1.25	2.50	12.50	25.00	50.00	100.0	150.0
0.025	3.71	0.009	0.047	0.094	0.468	0.935	1.87	3.74	5.60
0.050	4.56	0.01	0.05	0.10	0.51	1.02	2.05	4.10	6.14
0.075	3.66	0.017	0.084	0.17	0.84	1.68	3.37	6.74	10.11
0.10	2.71	0.24	0.12	0.24	1.21	2.33	4.83	9.66	14.5
0.125	2.58	0.024	0.11	0.24	1.18	2.36	4.70	9.44	14.17
0.150	2.21	0.022	0.11	0.22	1.12	2.25	4.49	9.02	13.52
0.175	1.72	0.024	0.12	0.23	1.16	2.25	4.51	9.01	13.52
0.200	1.36	0.23	0.11	0.23	1.14	2.29	4.57	9.05	13.62
0.225	1.18	0.022	0.11	0.22	1.1	2.19	4.39	8.91	13.3
0.25	1.11	0.022	0.10	0.21	1.04	2.08	4.16	8.30	12.46
0.275	1.09	0.020	0.094	0.19	0.94	1.86	3.75	7.48	11.23
0.30	1.098	0.015	0.081	0.17	0.81	1.65	3.28	6.58	9.86
0.325	1.11	0.014	0.086	0.14	0.71	1.43	2.86	5.72	8.58

TABLE A-3 SPECIFIC ATTENUATION AT 34.8 GHz

	RAIN RATE,MM/HR							
a,cm	0.25	1.25	2.5	12.5	25.0	50.0	100.0	150.0
0.025	0.035	0.173	0.347	1.733	3.467	6.93	13.87	20.80
0.050	0.047	0.234	0.467	2.335	4.670	9.34	18.67	28.03
0.075	0.062	0.308	0.615	3.077	6.162	12.33	24.66	36.99
0.100	0.066	0.329	0.657	3.285	6.317	13.09	26.18	39.27
0.125	0.063	0.304	0.607	3.035	6.070	12.14	24.33	36.53
0.150	0.050	0.249	0.497	2.485	4.970	9.94	19.96	29.90
0.175	0.039	0.199	0.387	1.985	3.865	7.73	15.46	23.19
0.200	0.031	0.155	0.311	1.553	3.107	6.21	12.30	18.51
0.225	0.026	0.129	0.258	1.289	2.577	5.15	10.47	15.62
0.250	0.024	0.116	0.230	1.153	2.304	4.62	9.21	13.83
0.275	0.022	0.103	0.204	1.032	2.040	4.11	8.19	12.29
0.300	0.017	0.089	0.181	0.893	1.813	3.60	7.22	10.82
0.325	0.016	0.080	0.159	0.796	1.593	3.19	6.37	9.56

TABLE A-4 SPECIFIC ATTENUATION AT 19 GHz AND 28-TO-19 GHz ATTENUATION RATIO

		RAIN RATE MM/HR							
a,cm	RATIO	0.25	1.25	2.50	12.50	25.00	50.00	100.0	150.0
0.025	2.266	0.011	0.055	0.110	0.548	1.097	2.190	4.39	6.58
0.050	2.582	0.010	0.052	0.104	0.520	1.040	2.080	4.15	6.23
0.075	2.613	0.015	0.075	0.150	0.750	1.498	3.000	6.00	9.00
0.100	2.223	0.022	0.109	0.217	1.090	2.090	4.33	8.65	12.98
0.125	2.216	0.025	0.121	0.243	1.21	2.43	4.85	9.73	14.61
0.150	2.105	0.027	0.134	0.267	1.34	2.67	5.35	10.74	16.09
0.175	1.672	0.031	0.157	0.305	1.57	3.05	6.1	12.21	18.31
0.200	1.269	0.034	0.170	0.341	1.70	3.41	6.82	13.49	20.31
0.225	1.031	0.034	0.172	0.343	1.72	3.43	6.86	13.94	20.81
0.250	0.930	0.035	0.167	0.331	1.66	3.32	6.66	13.29	19.95
0.275	0.913	0.032	0.154	0.303	1.54	3.03	6.1	12.17	18.28
0.300	0.933	0.027	0.136	0.274	1.35	2.74	5.44	10.92	16.36
0.325	0.959	0.024	0.123	0.244	1.22	2.44	4.87	9.74	14.62

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TABLE A-5 SPECIFIC ATTENUATION AT 28 GHZ

	RAIN RATE MM/HR							
a,cm	0.25	1.25	2.5	12.5	25.0	50.0	100.0	150.0
0.025	0.025	0.124	0.248	1.242	2.485	4.97	9.94	14.91
0.050	0.027	0.134	0.268	1.34	2.68	5.36	10.72	16.08
0.075	0.039	0.195	0.391	1.955	3.914	7.83	15.67	23.50
0.100	0.048	0.241	0.483	2.414	4.642	9.62	19.24	28.86
0.125	0.056	0.269	0.538	2.689	5.377	10.75	21.56	32.36
0.150	0.056	0.281	0.563	2.814	5.629	11.26	22.61	33.86
0.175	0.051	0.262	0.51	2.62	5.10	10.21	20.41	30.62
0.200	0.043	0.216	0.433	2.163	4.327	8.65	17.13	25.78
0.225	0.035	0.177	0.354	1.77	3.54	7.08	14.38	21.46
0.250	0.032	0.155	0.308	1.547	3.09	6.19	12.36	18.55
0.275	0.029	0.140	0.277	1.401	2.769	5.57	11.11	16.68
0.300	0.025	0.127	0.256	1.259	2.557	5.08	10.19	15.26
0.325	0.023	0.118	0.234	1.168	2.336	4.67	9.34	14.02

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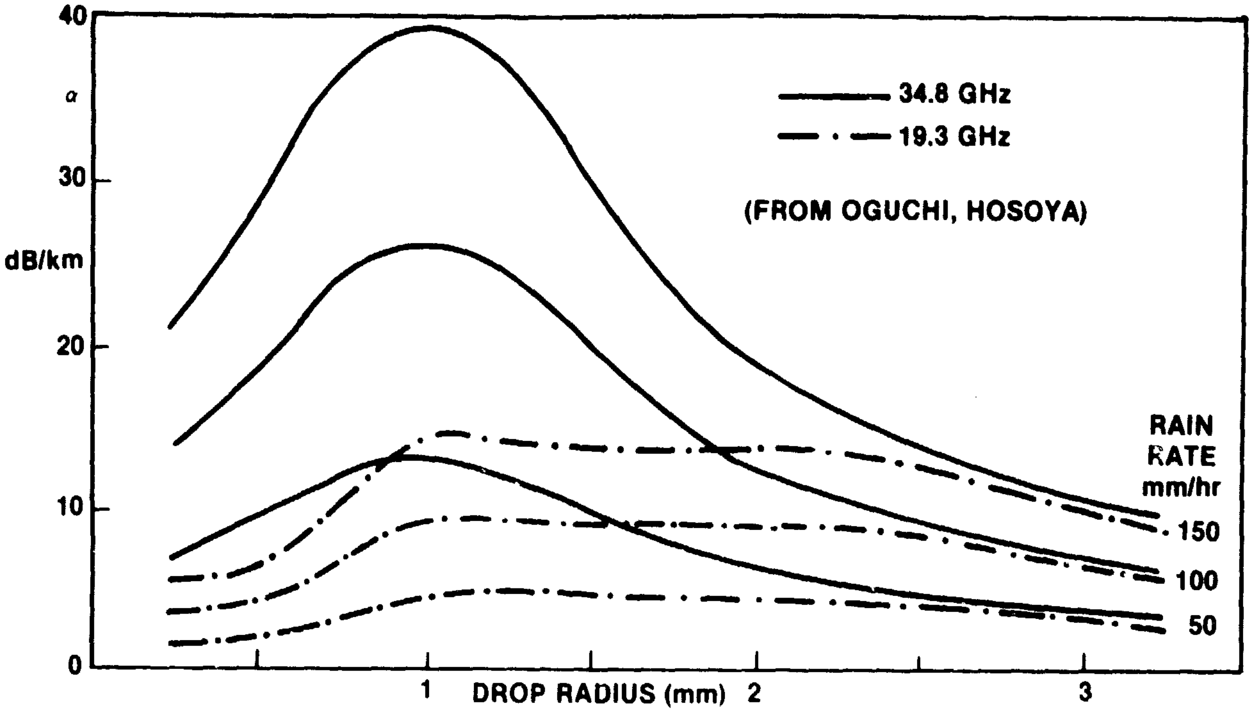

Figure A-1 Attenuations vs drop radius (from Oguchi and Hosoya)

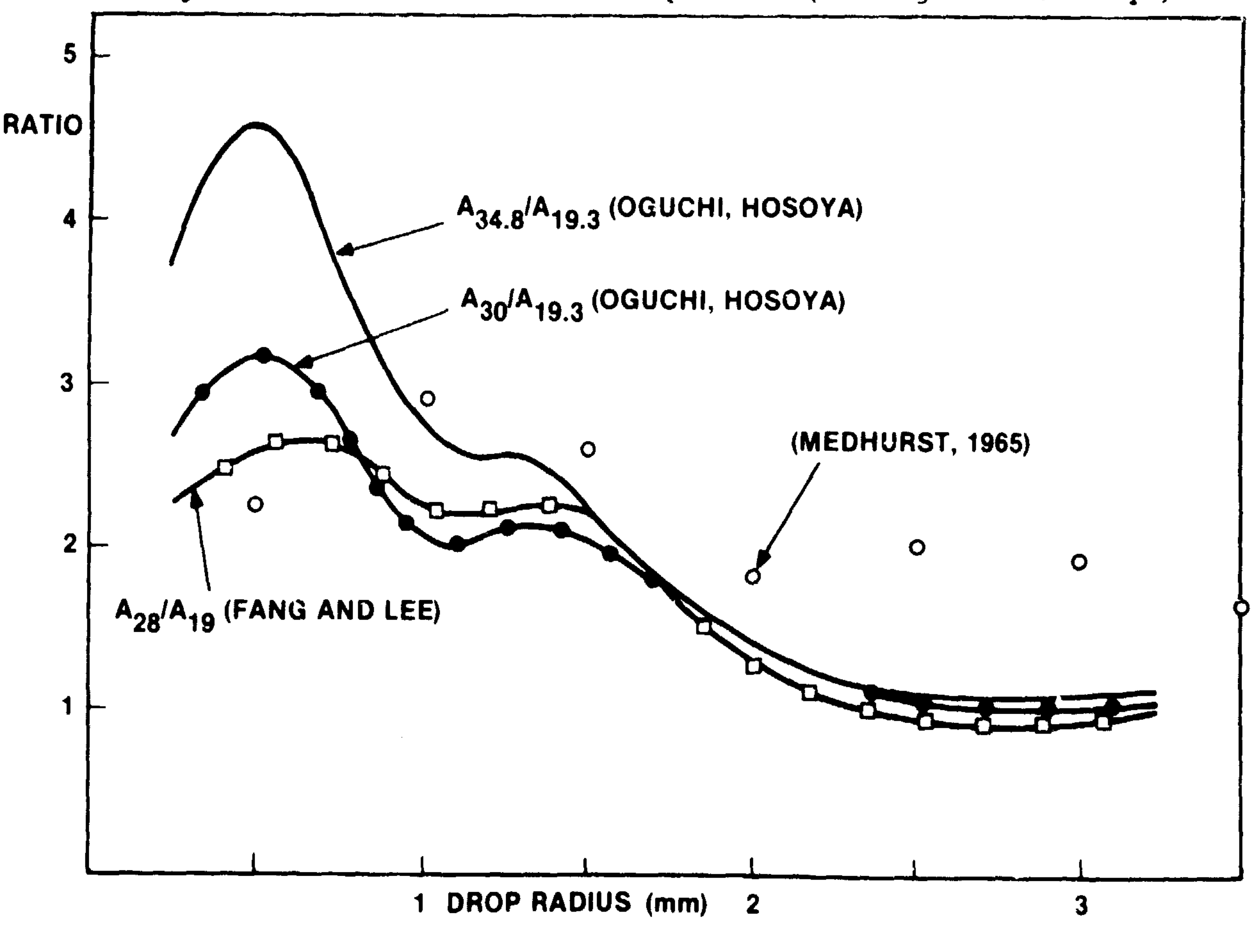

Figure A-2 Attenuation ratios vs. drop radius

Appendix B

Some characteristics of the GTE Laboratories COMSTAR beacon terminals

Nominal Radio Frequency	19 GHz	29 GHz
Satellite (D-2) EIRP at Tampa	18 dBW	22 dBW
Path loss incl. spreading, absorption	209.8 dB	213.7 dB
Receiving antenna gain, dBi	51.7	54.6
Temperature	1000K	1500K
CNR (clear sky), dB-Hz	58.5	59.7
3-dB beamwidth, degrees	0.44	0.29
Maximum sidelobe level, dB	<20	<20
Peak cross-polarization, dB	-30	-30

- -

Carrier-loop noise bandwidth, Hz	43
Loop natural frequency, Hz	13
Damping factor	0.707
Hold-in range, Hz	230.8
Lock-in range, Hz	18
Pull-in range, Hz	2.9 kHz
Maxiumum sweep rate	714 Hz/sec
Overall receiver gain, 19 GHz	123 dB
Overall receiver gain, 29 GHz	129 dB

Appendix C

Selected paired S and U analog recordings

Rain rate and attenuation at 29 GHz

Summer, 1981, events:

Date	Time
8 June	1200 - 1500
11 June	1800 - 2300
18 June	1900 - 2100
19 June	1600 - 2330
24 June	1600 - 1900
25 June	1800 - 2100
26 June	1900 - 2400
6 July	1800 - 2200
8 July	1500 - 2100

The rainfall recording is the output of two gauges:

Envelope = output of capacitance (rain rate gauge), and

Tick marks = output of tipping-bucket gauge (0.01 inch)

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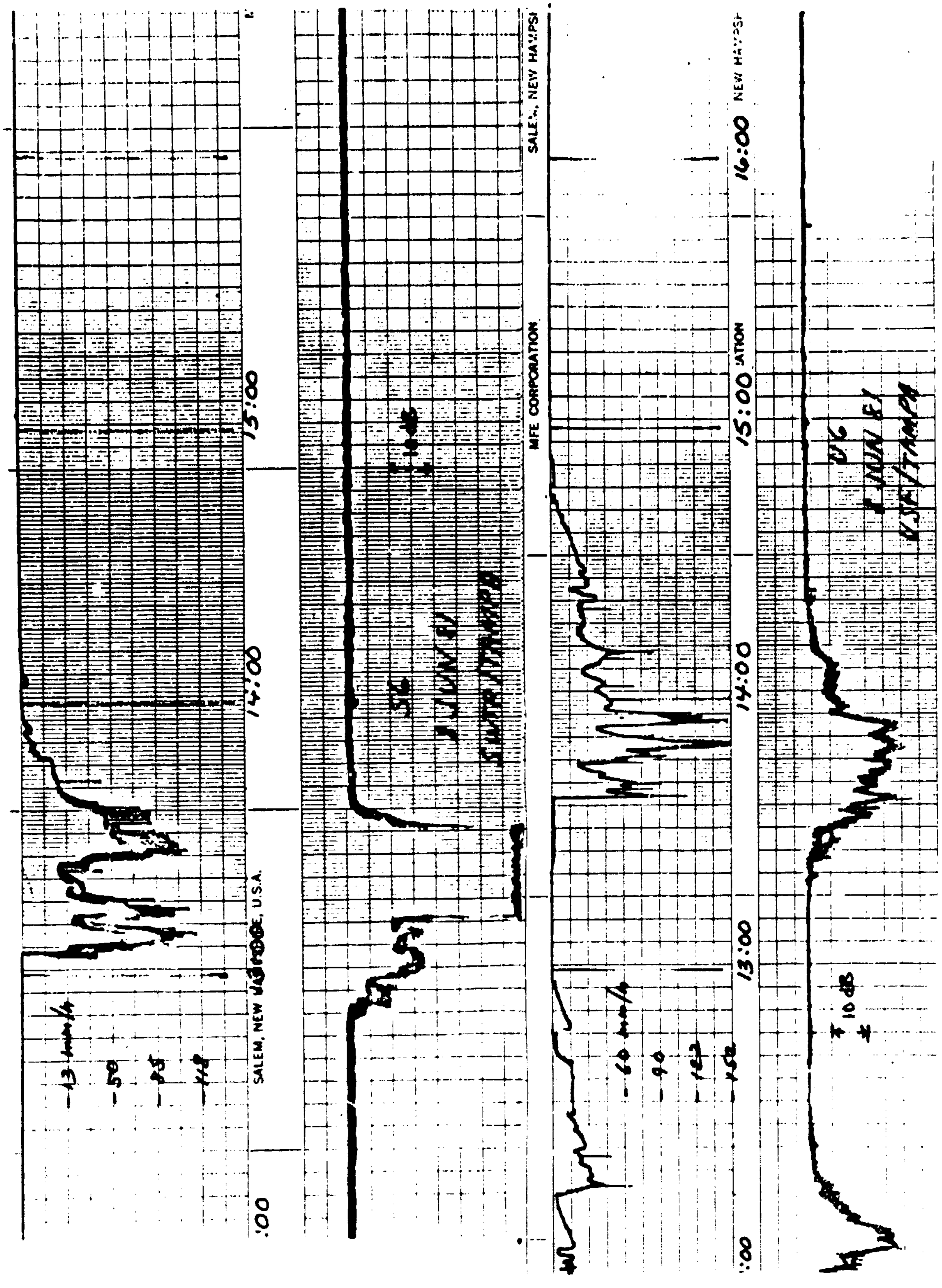

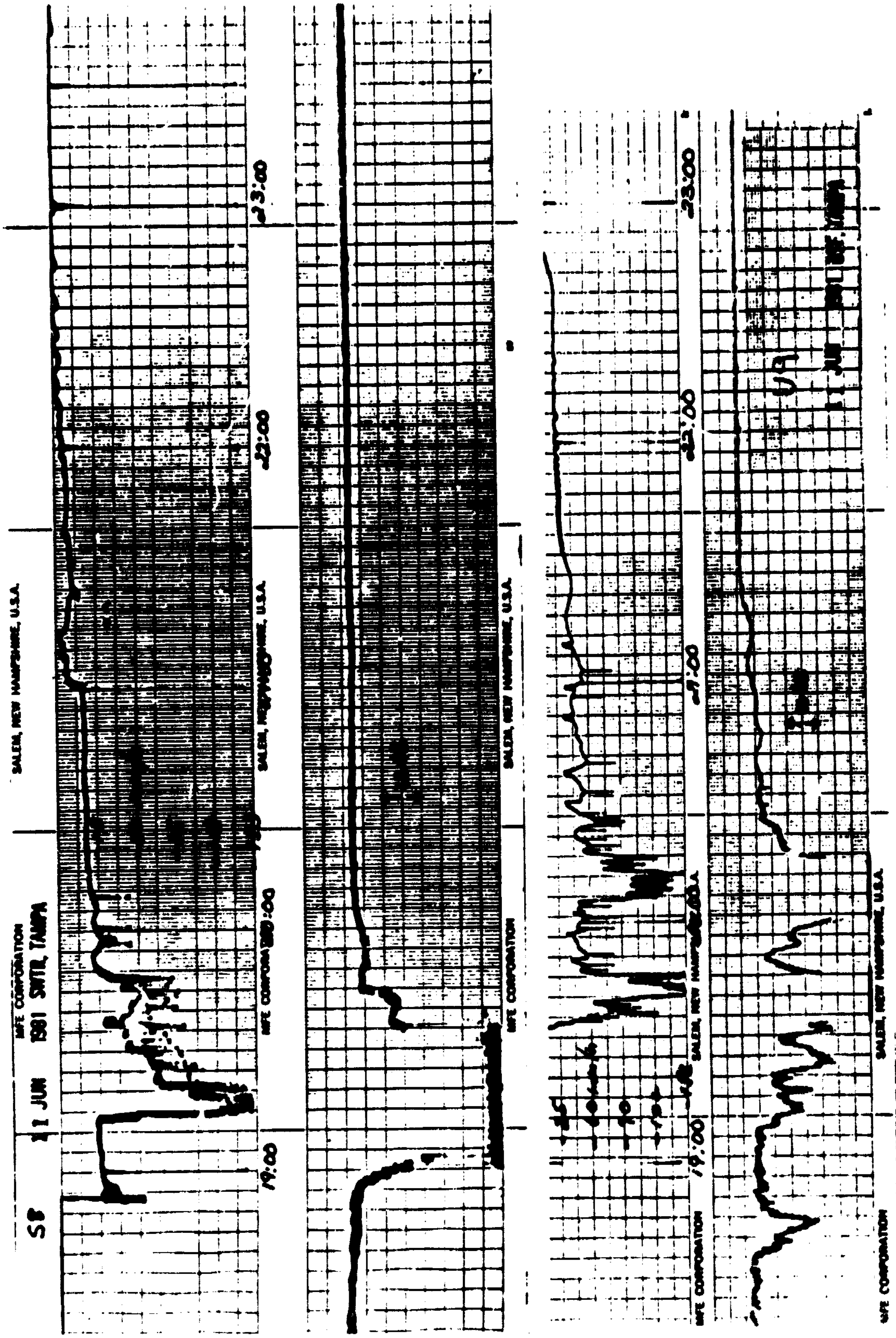
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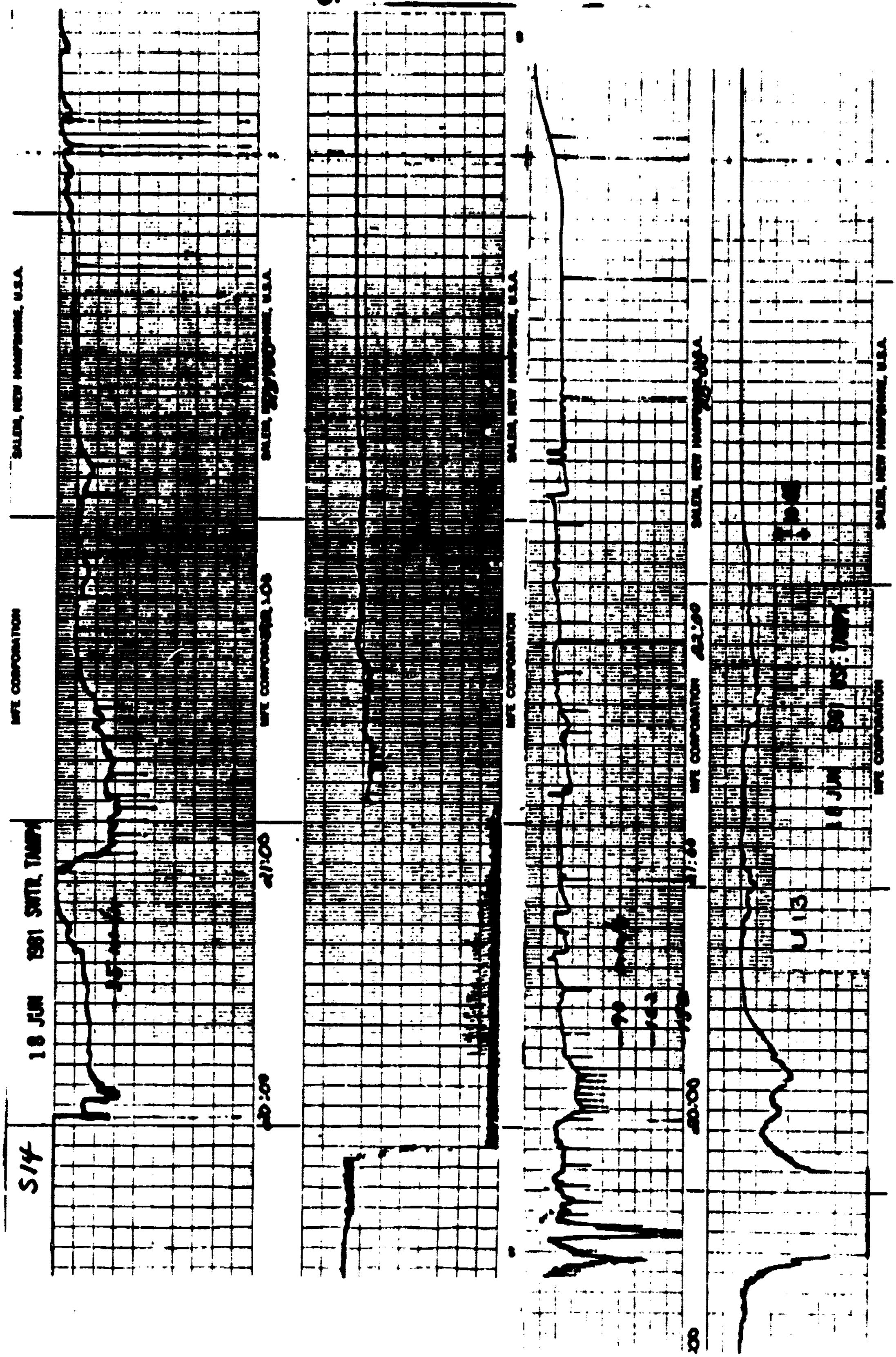

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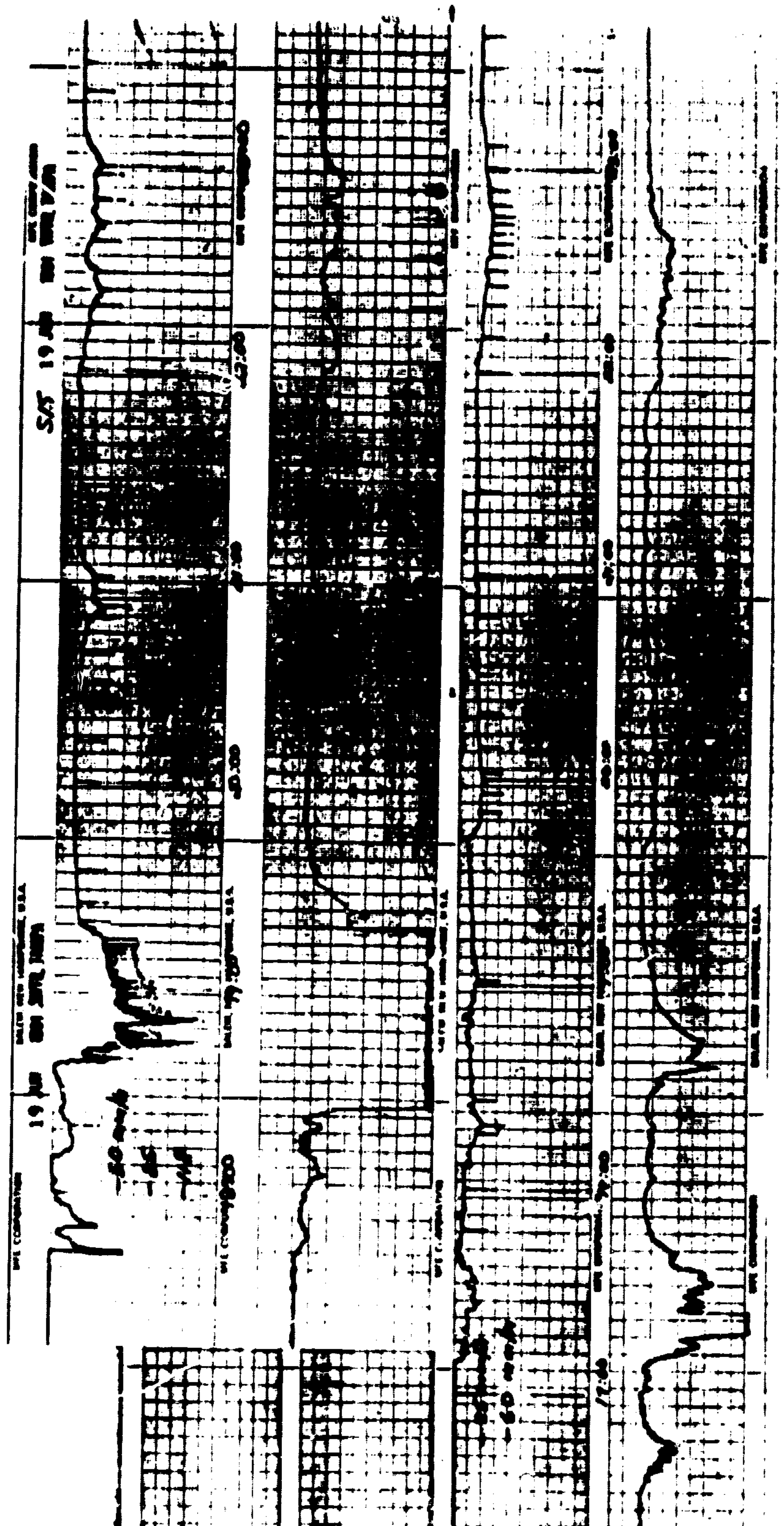

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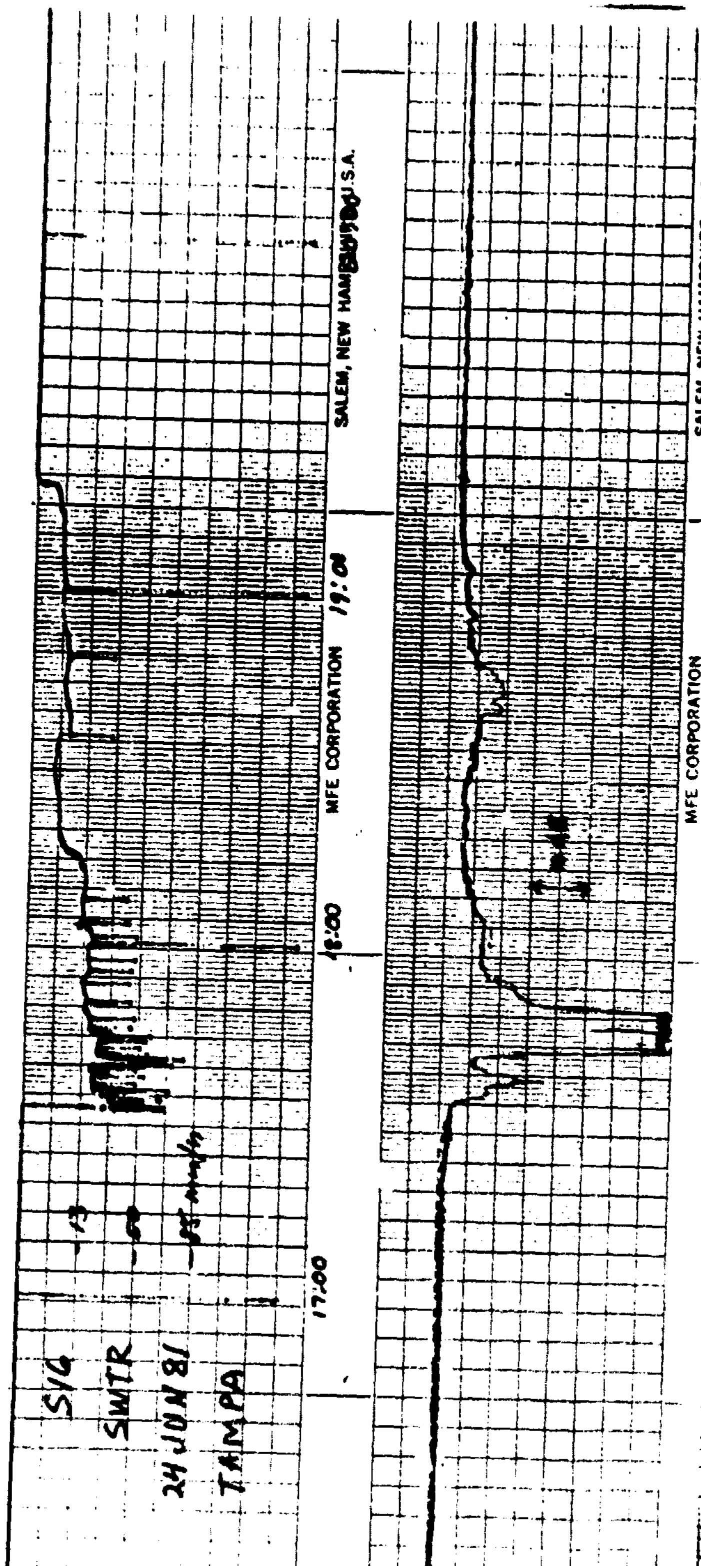

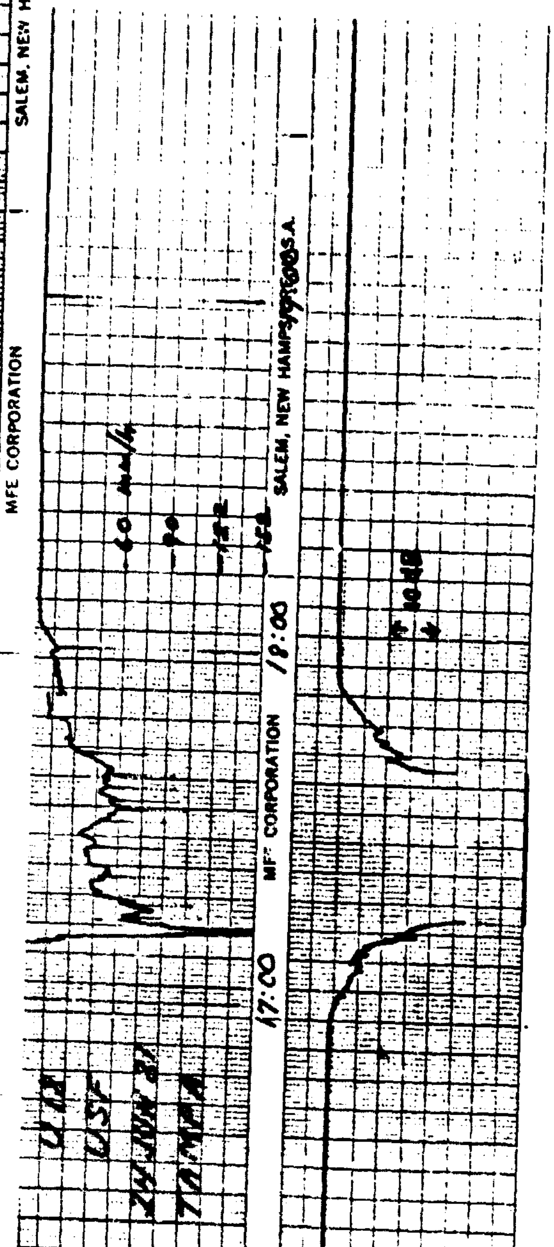

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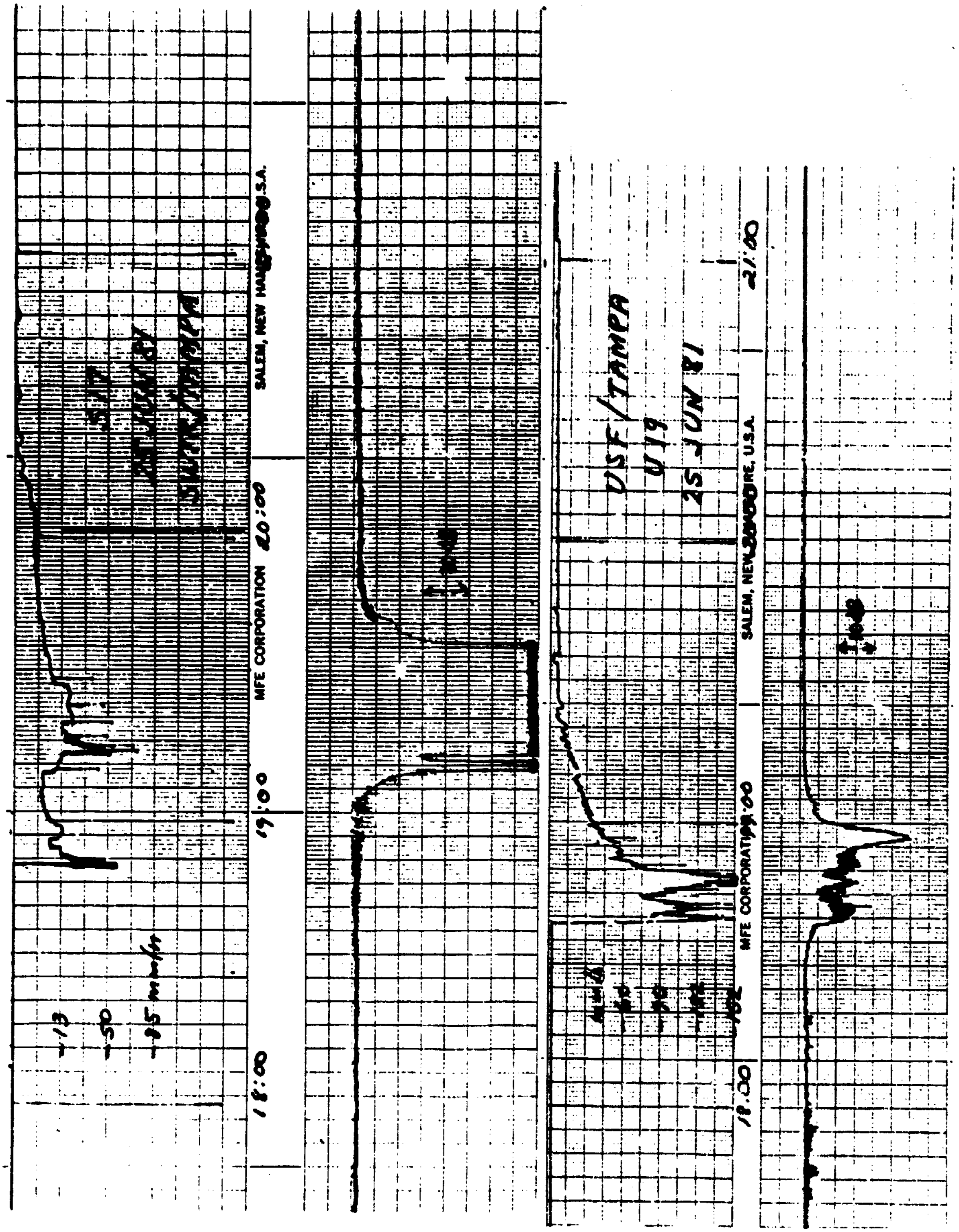

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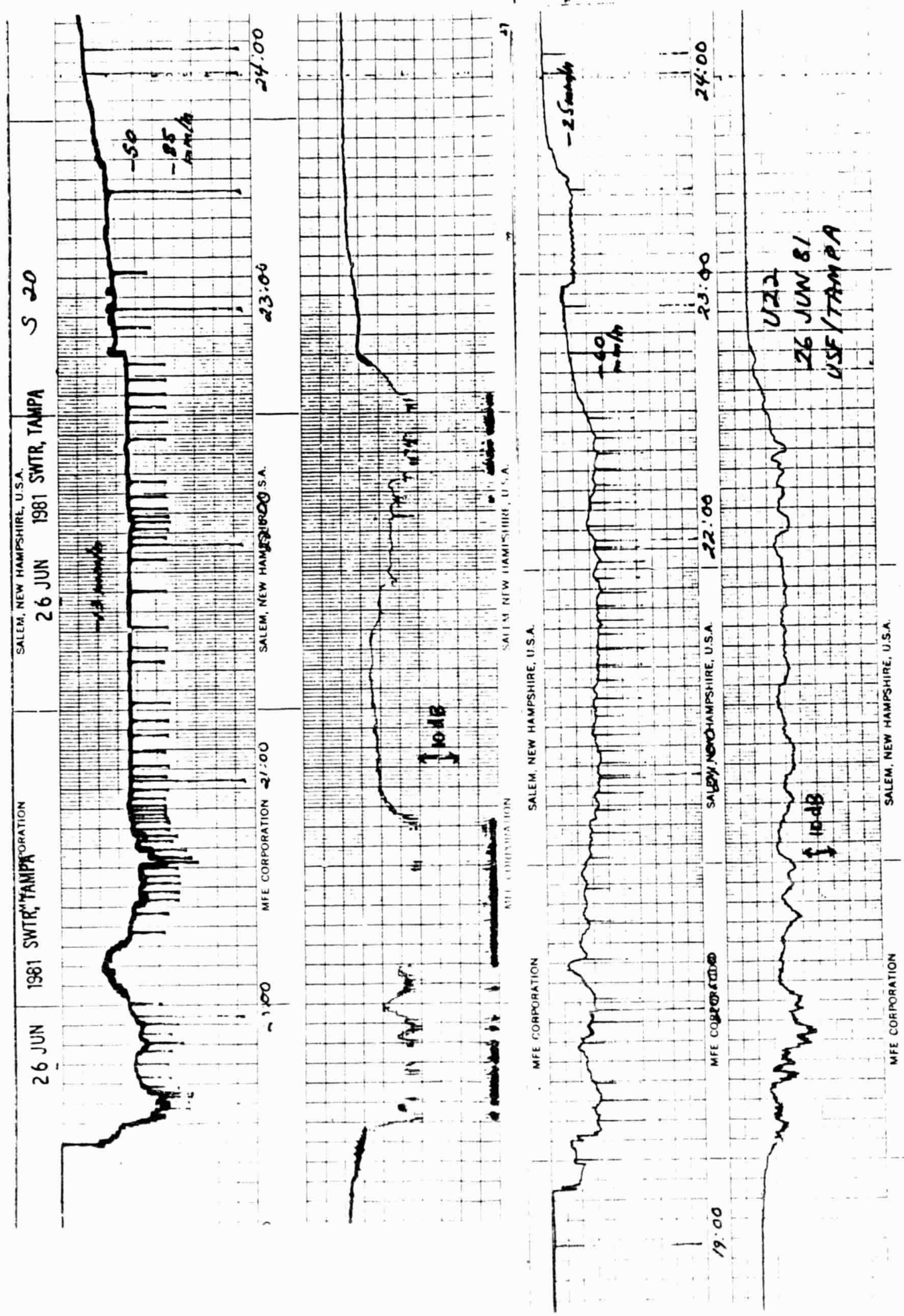

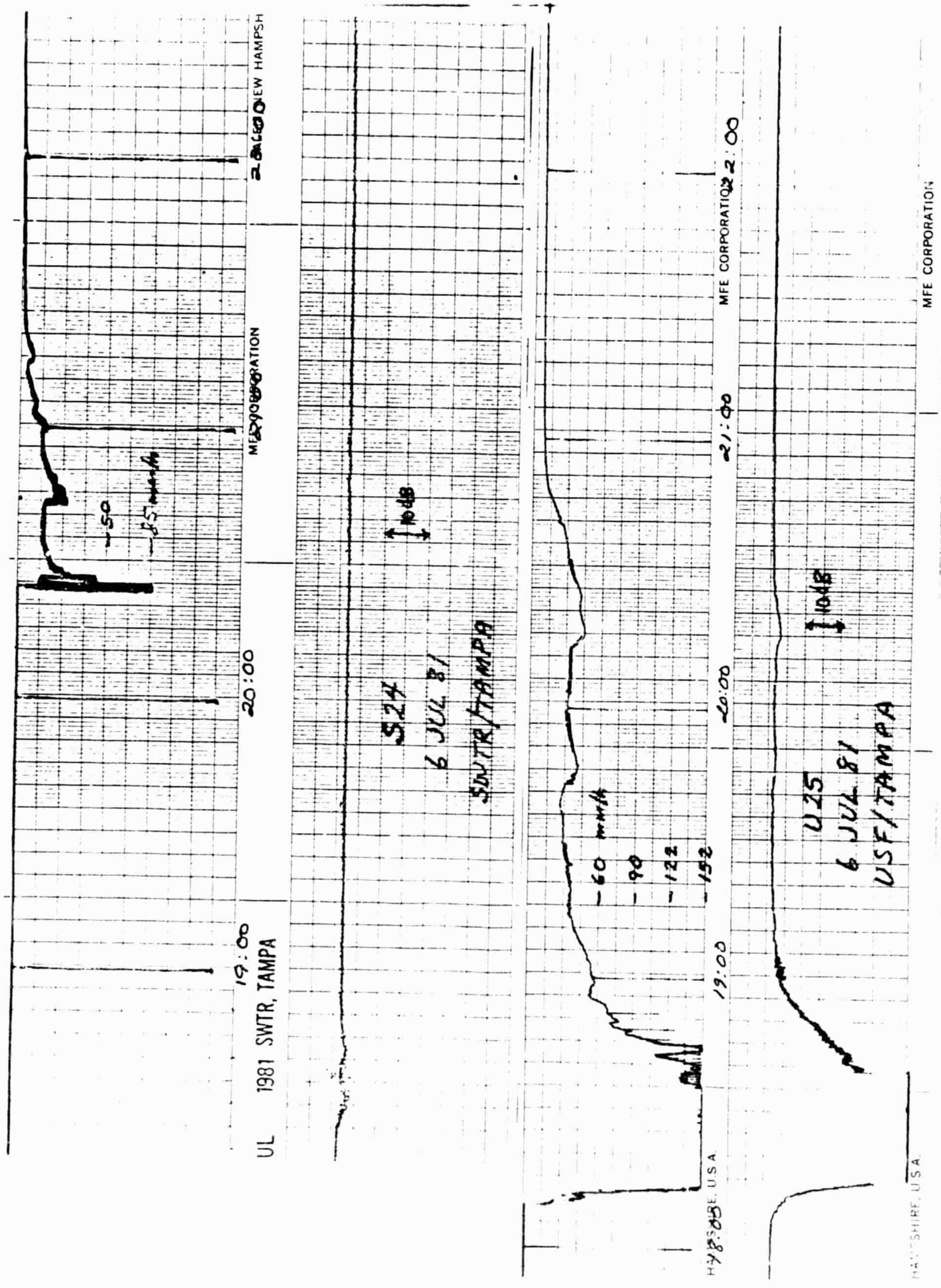
UL 1981 SWTR, TAMPA
19:00
20:00
21:00
22:00
-50
-85 mm/h
10dB
S24
6 JUL 81
SWTR/TAMPA
-60 mm/h
-90
-122
-152
10dB
U25
6 JUL 81
USF/TAMPA
MFE CORPORATION
MFE CORPORATION

ORIGINAL PAGE IS
OF POOR QUALITY