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Rain Attenuation Measurements at 28.8, 57.6, and 96.1 GHz on a 1-km Path

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TABLE OF CONTENTS

LIST OF FIGURES

FIGURE		PAGE
21	Cumulative distributions of the 28.8-, 57.6-, and 96.1-GHz signal attenuation of received signals during rain at Gasquet, CA, in January, February, and March 1985.	31
22	Signal attenuation versus rain rate as a function of frequency from a cumulative distribution analysis of a 115-hour sample of rain data at Gasquet, CA.	32
23	A comparison of measured and predicted specific attenuation.	34

RAIN ATTENUATION MEASUREMENTS AT 28.8, 57.6, AND 96.1 GHz ON A 1-km PATH

R. H. Espeland, E. J. Violette, and K. C. Allen*

An experimental millimeter-wave propagation link was installed on a 1-km path in the northern California area (Gasquet) to compare rain rate and attenuation at 28.8, 57.6, and 96.1 GHz. During the monitoring period (January 26 through April 14), rain occurred on 27 days with an accumulation of 514 mm (20.25 in.). For periods when the rain rate exceeded 5 mm/h, both VV (vertical polarization at the transmitter and vertical polarization at the receiver) and VH (vertical polarization at the transmitter and horizontal polarization at the receiver) signals were recorded. Maximum rain rates exceeded 50 mm/h and maximum attenuations of 4, 10, and 17 dB were observed on the 28.8, 57.6, and 96.1 GHz channels, respectively.

Key words: attenuation; measurement; millimeter-wave; multifrequency; rain rates

1. INTRODUCTION

With the increasing importance of millimeter-wave systems to telecommunications applications, the Institute for Telecommunication Sciences (ITS) has maintained an experimental program for the development and validation of models for predicting millimeter-wave system performance. In fiscal years 1983 and 1984, ITS measured telecommunication systems parameters in the frequency range 30 to 100 GHz under realistic and varying conditions on a 27-km terrestrial link near Boulder, Colorado (Espeland, et al, 1984).

In fiscal year 1985, the millimeter-wave experimental program was expanded to develop and begin initial operation of a millimeter-wave atmospheric probe that will provide data for the evaluation of these telecommunication propagation models in varying climatic environments. The millimeter-wave probe is transportable in order to obtain measurements in varying meteorological and topographical conditions.

Because rain poses the greatest threat to link reliability at millimeter-wave frequencies, the first priority in the FY85 plan was to characterize the effects of rain on link performance. Thus the intent of this segment of the program was to utilize the atmospheric probe in a region of high annual rainfall to evaluate the probe as an experimental link and to collect rainfall data that could be used for future model and link analyzes and for comparison of rainfall and propagation characteristics in various climates.

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Parameters measured and presented in this report are the received signal levels at 9.6, 28.8, 57.6, and 96.1 GHz and the simultaneously recorded rain rate. At rain rates above 5 mm/h, cross polarization data were also recorded at 28.8, 57.6, and 96.1 GHz. These measurements were made in January, February, March, and April of 1985 at Gasquet, California. The recieved signals were coherently detected by phase locking a local reference oscillator at the receiver to the 9.6 GHz signal. The attenuation by rain at 9.6 GHz was small because of the short path and was not used in the analysis.

This report describes the millimeter wave instrumentation used in the experiment, the test site, the rain characteristics, and the attenuation characteristics. Subsequent reports will provide additional analysis of the data and compare the measured results with the predictions model.

A second set of rain attenuation measurements similiar to those recorded at Gasquet, were made at Boulder, Colorado. These new data are not included in this report, but will be a part of the analysis of the experimental measurements in the next report.

2. EQUIPMENT DESCRIPTION

The millimeter-wave measurements link operates at 9.6, 28.8, 57.6, and 96.1 GHz. At both the transmitting and receiving terminals, the 9.6, 28.8, and 57.6 GHz units are contained in a common enclosure and the 96.1 GHz units are seperate. A functional diagram of the 9.6, 28.8, and 57.6 GHz segment of the transmitting terminal is shown in Figure 1. All radio frequencies (rf) are derived from a 100-MHz temperature-compensated crystal oscillator (TCXO). A phased-locked, cavity-tuned (X96) multiplier is used to feed 20 mW at 9.6 GHz to an 18-in (45.72 cm) parabolic reflector antenna. An identical (X96) multiplier drives a varactor tripler that injection locks an 85 mW Gunn source at 28.8 GHz through a high isolation ferrite circulator. The Gunn power is fed to a directional coupler providing 20 mW to a 24-in (60.96 cm) parabolic-reflector antenna and the remaining power drives a varactor doubler. The output of the doubler provides 12 mW of power at 57.6 GHz to a 12-in (30.48 cm) parabolic-reflector antenna. This segment of the transmitter is mounted in a temperature-controlled enclosure that is held at 45°C ± 1°C to reduce power variation to less than 0.5 dB in the worst case.

A block diagram for the 96.1 GHz transmitter is shown in Figure 2. A phase-locked IMPATT oscillator provides 28 mW of power to a linearly-polarized 12-in (30.48 mm) parabolic-reflector antenna. The output of the TCXO shown in Figure 1 is used as the reference source for this transmitter and is multiplied to 96 GHz

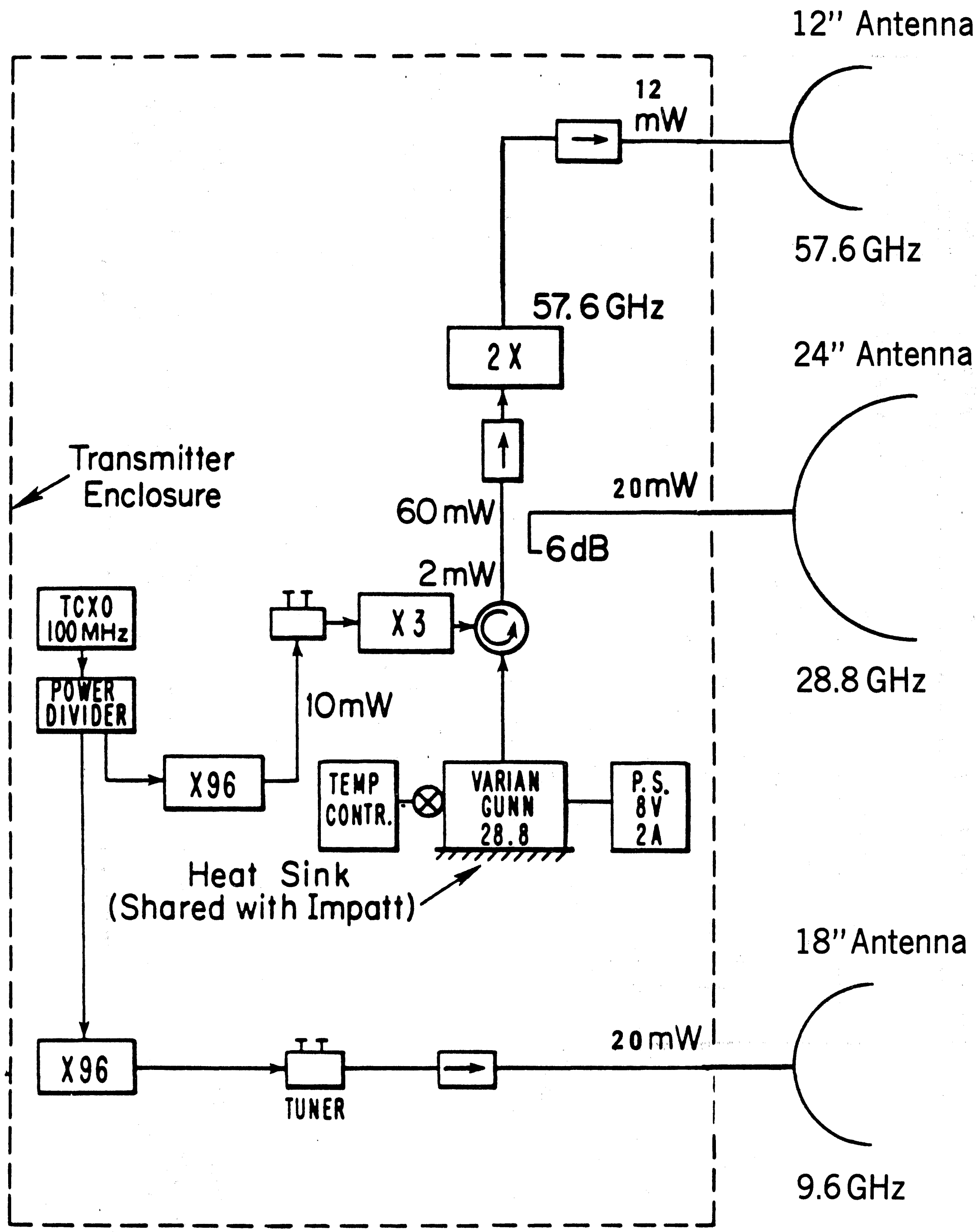

Figure 1. A functional diagram of the 9.6-, 28.8-, and 57.6-GHz transmitting terminal.

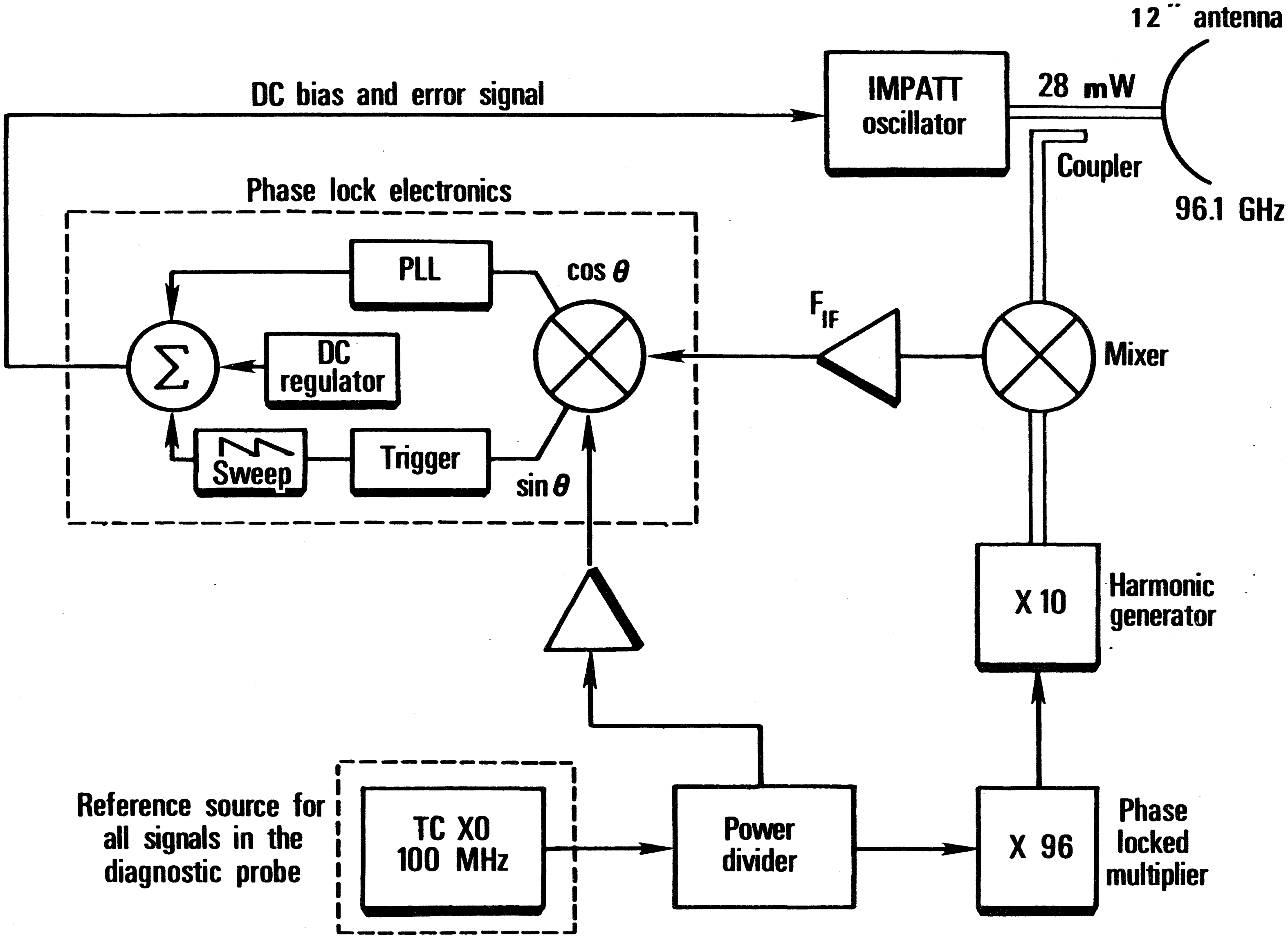

Figure 2. A block diagram of the 96.1-GHz transmitter.

by successive phase-locked stages for comparison to the output of the IMPATT oscillators through an rf balanced mixer. The phase-lock electronics generate an error signal that is added to the direct current (dc) bias voltage supplied to the IMPATT. If the IMPATT is not in a locked state, a voltage sweep is triggered and added to the dc bias supply until the IMPATT frequency is the same as the multiplied TCXO signal at which time the error signal takes control to hold the IMPATT in lock.

The following table summarizes the power output, antenna gain, and antenna beamwidth parameters at the transmitter terminal.

FREQUENCY	OUTPUT (to antenna)	ANTENNA size	GAIN	BEAMWIDTH
9.6 GHz	20 mW	18-in	31 dB	5°
28.8 GHz	20 mW	24-in	43.1 dB	1.25°
57.6 GHz	12 mW	12-in	43.1 dB	1.25°
96.1 GHz	28 mW	12-in	47.5 dB	0.75°

Manual azimuthal and elevation adjustments are provided at the antenna and enclosure mounts for accurate alignment of the antennas. The transmitter terminals require only a housing or stand for mounting and 120-Vac power with a minimum current capacity of 3 A.

A functional diagram of the 9.6, 28.8, and 57.6 GHz segment of the receiving terminal is shown in Figure 3. The incoming signals are received with parabolic-reflective antennas. At the 9.6 GHz frequency, the antenna is coupled directly to a low-noise down converter. At 28.8 and 57.6 GHz, the received signals are fed through orthomode transducers and waveguide mechanical switches and then to low-noise down converters. The transducers and switches allow for selection of either the vertically or horizontally polarized component of the incoming signals. The switching action is controlled by the data acquisition computer. The computer is programmed to drive the switches when the rain rates exceed a specified threshold, recording both the vertical and horizontal components. Below the threshold, only the vertical component is recorded.

The receiver noise figure is determined by the input down converter. At 9.6 GHz, the double-balanced mixer produces a 7.5 dB double sideband noise figure. The 28.8 and 57.6 GHz input mixers are of the stripline-waveguide-junction balanced type with double sideband noise figures of 5.5 and 6.0 dB, respectively. All local oscillator (LO) signals are generated from a voltage-controlled crystal oscillator (VCXO) that is phase-locked to the 9.6 GHz received signal with a 5 MHz reference offset frequency. The multipliers for the voltage-controlled 100 MHz reference

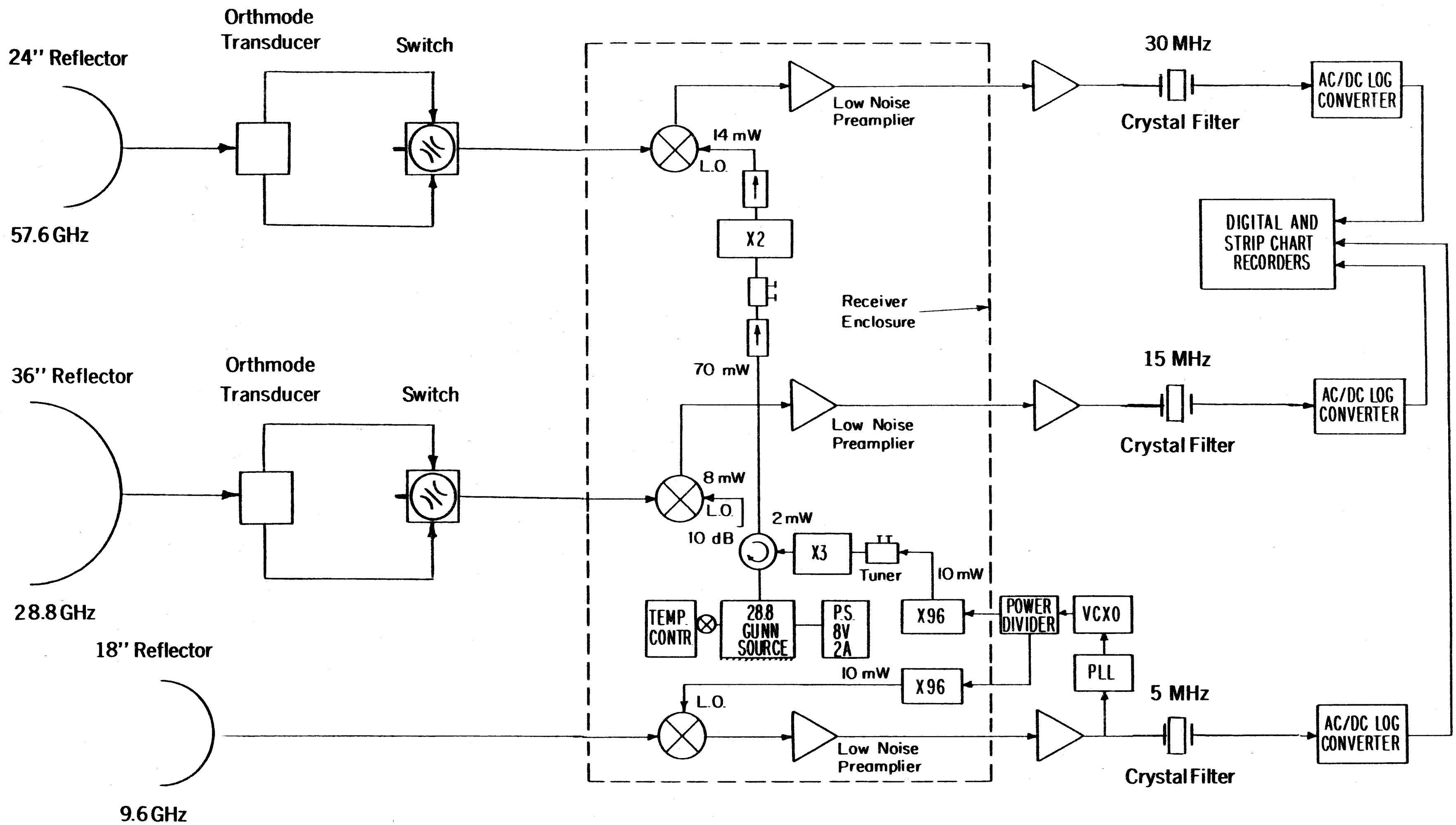

Figure 3. A functional diagram of the 9.6-, 28.8-, and 57.6-GHz receiving terminal.

($\pm$IF/multiplying factor), to derive the LO injection signals, are identical to the scheme used for the transmitter sources. The long-term (weeks) gain stability for each reciver is better than $\pm$ 0.1 dB.

The three intermediate frequencies (IF) of 5, 15, and 30 MHz are down converted from 9.6, 28.8, and 57.6 GHz, respectively; fed to low-noise preamplifiers through narrow-band crystal filters, and then fed to ac-to-dc log converters. The IF signals are converted to dc levels that are logarithmically related to the rf signal amplitude. The dc levels are scanned and read with a digital voltmeter. The dynamic range of the log-amplifiers (log-converters) is 80 dB with linearity of $\pm$0.5 dB.

A block diagram of the 96.1 GHz receiving terminal is shown in Figure 4. The incoming signal is received with a scalar horn lens antenna and fed through the orthomode transducer and the waveguide mechanical switch to the down converter (balanced mixer). A Gunn oscillator is used as the LO source in place of an IMPATT because of superior low-noise performance resulting in a better receiver noise figure.

The received signals are coherently detected as a result of phase locking the VCXO frequency to the 9.6 GHz IF signal. As in the transmitter, all timing, and the IF and rf sources are derived from a single reference; a VCXO that is phase locked to the received signal. Phase-locking of the Gunn sources uses electronics similar to that used in the transmitter to lock the IMPATT. The 96.1-GHz channel is locked at an IF of 250 MHz, a number that results from the phase-lock electronics set to provide twice the 100-MHz reference signal plus the IF of the 9.6 GHz reference channel (5 MHz) multiplied by the ratio of 96.1/9.6. The IF bandpass filter for the 96.1 GHz channel is on the order of 0.4% of the center frequency (250 MHz).

The following table summarizes the antenna gain, antenna beamwidth, receiver noise figure, and receiver sensitivity for all channels at the receiver.

	ANTENNA			RECEIVER	
FREQUENCY	SIZE	GAIN	BEAMWIDTH	NOISE FIGURE	SENSITIVITY
9.6 GHz	18-in	27.5 dB	7.5 °	7.5 dB	-130 dBm
28.8 GHz	36-in	46.6 dB	0.84°	5.5 dB	-130 dBm
57.6 GHz	24-in	49.1 dB	0.63°	6.0 dB	-130 dBm
96.1 GHz	*12-in	49.3 dB	0.75°	6.5 dB	-108 dBm

*This antenna is a scalar horn lens with approximately 90% efficiency, thus the gain is nearly 2 dB greater than the parabolic antenna used at the transmitter.

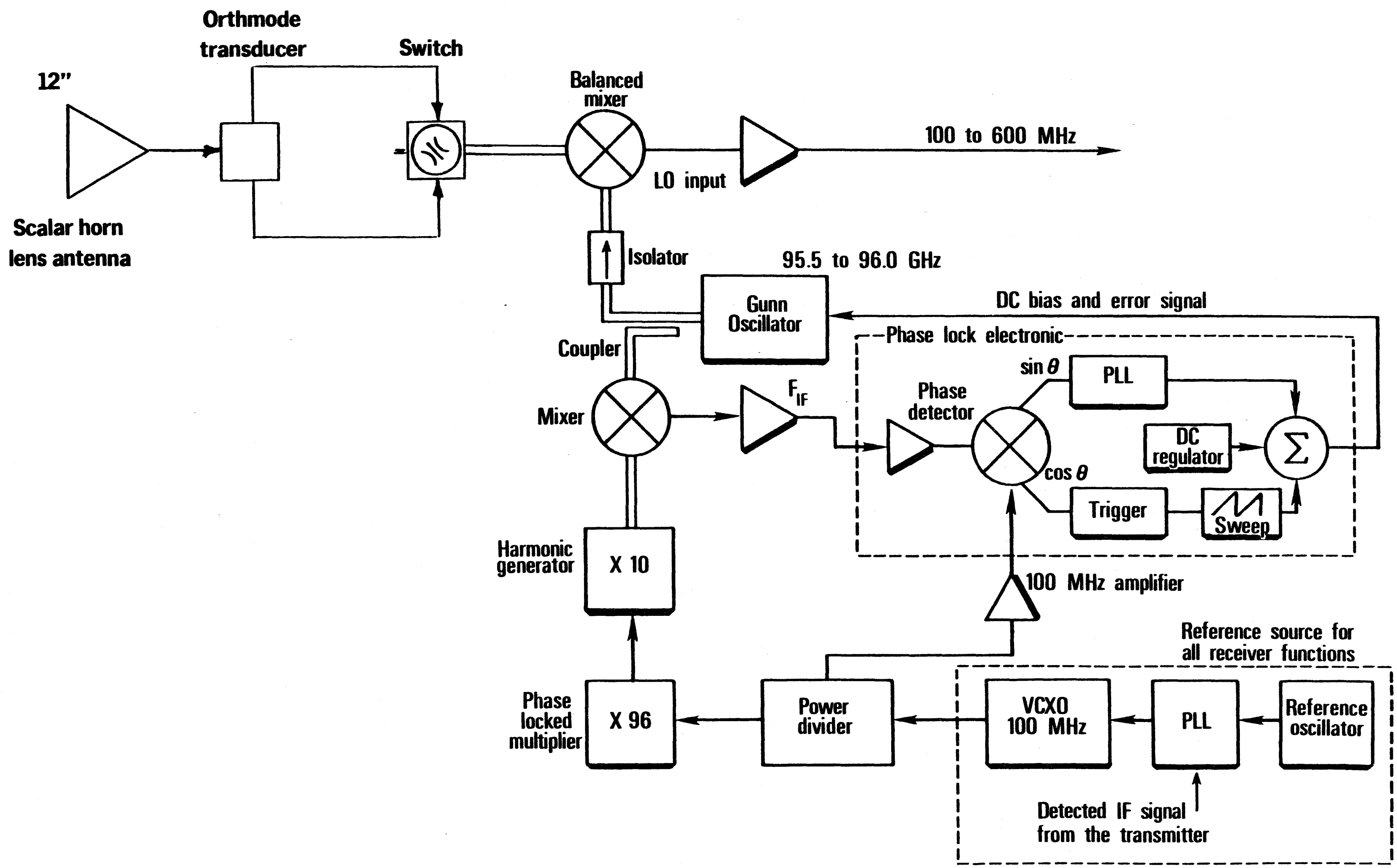

Figure 4. A block diagram of the 96.1-GHz receiver rf stage and local oscillator source generator.

As with the transmitting terminal, manual azimuthal and elevation adjustments are also provided at the receiving terminal. The complete receiver electronics and antenna package is housed in a rain-proof enclosure that is attached to the mobile van. The mobile van thus provides a platform for the receiving terminal and housing for the IF electronics, and data acquisition and recording system.

A desk-top computer is utilized for system control and data acquisition and a disk drive is used for data storage. The drawing in Figure 5 is a diagram of the data acquisition, data recording, and control system. The log-converted signals for the 9.6, 28.8, 57.6, and 96.1 GHz channels and the dc signals corresponding to temperature and rain rate are fed to the channel scanner. These values are read at 6-sec intervals and stored as two sample (12 sec) averages in the computer memory. At the end of each hour, these data are recorded on disk. The monitor screen of the computer, at the operator's option, displays either each line of data as sampled or a 24-h graphic display of the data. At the end of each day, a copy of the file number, start and stop time for each file, the number of samples, and the maximum recorded rain rate in the file is printed and a copy of the graphics for the day is also printed.

The normal operating mode is with the transmitter antenna set to transmit with vertical polarization and the receiving antenna set to receive the vertical componet of the incoming signal (VV mode). The waveguide switch control segment of the computer program contains a preset rain-rate level. When this level is exceeded, the computer activates the waveguide switches and both the vertical and horizontal (VH mode) components of the incoming signals are sampled. The 9.6 GHz channel is not equipped with a waveguide switch. When the rain-rate drops below the preset level, the switching action stops and again only the VV components are sampled.

3. TEST SITE

The millimeter-wave probe van was made transportable in order to obtain realistic estimates of the millimeter wave telecommunication system parameters in varying meteorological and topographical conditions. The first site chosen for rain attenuation measurements was Gasquet, CA. Factors considered in selecting this site were annual and seasonal rainfall, availability of a clear path (at least 1 km in length) and the availability of local personnel to help with the monitoring.

Gasquet, CA, is in a narrow valley along the Smith River at a location approximately 12 km from the Pacific Ocean and 10 km from the California/Oregon border. It is geographically situated in the Pacific Northwest coastal region as indicated in Figure 6. A topographical map of the site and surrounding area is shown in

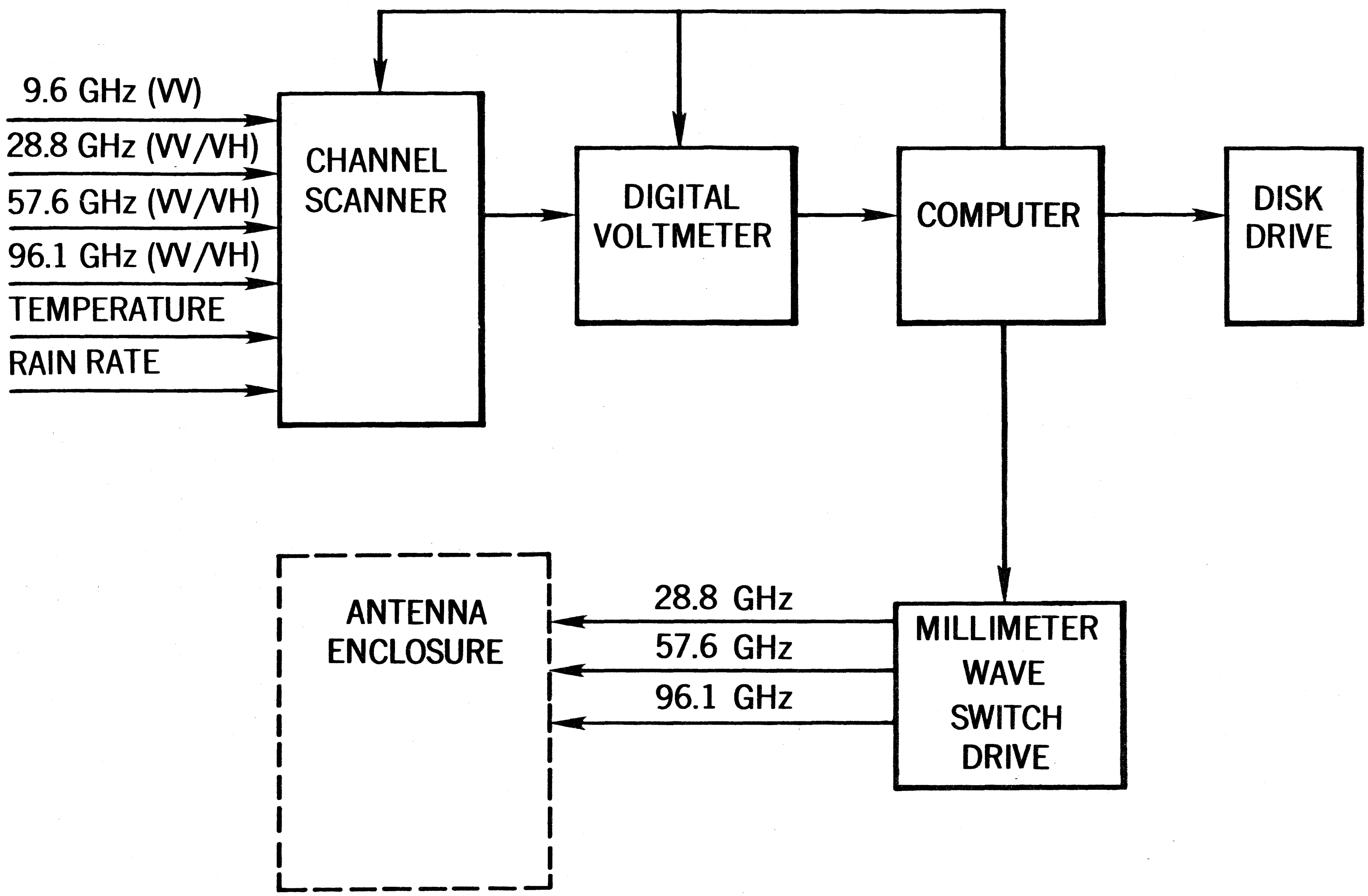

Figure 5. A diagram of the data acquisition, recording and control system.

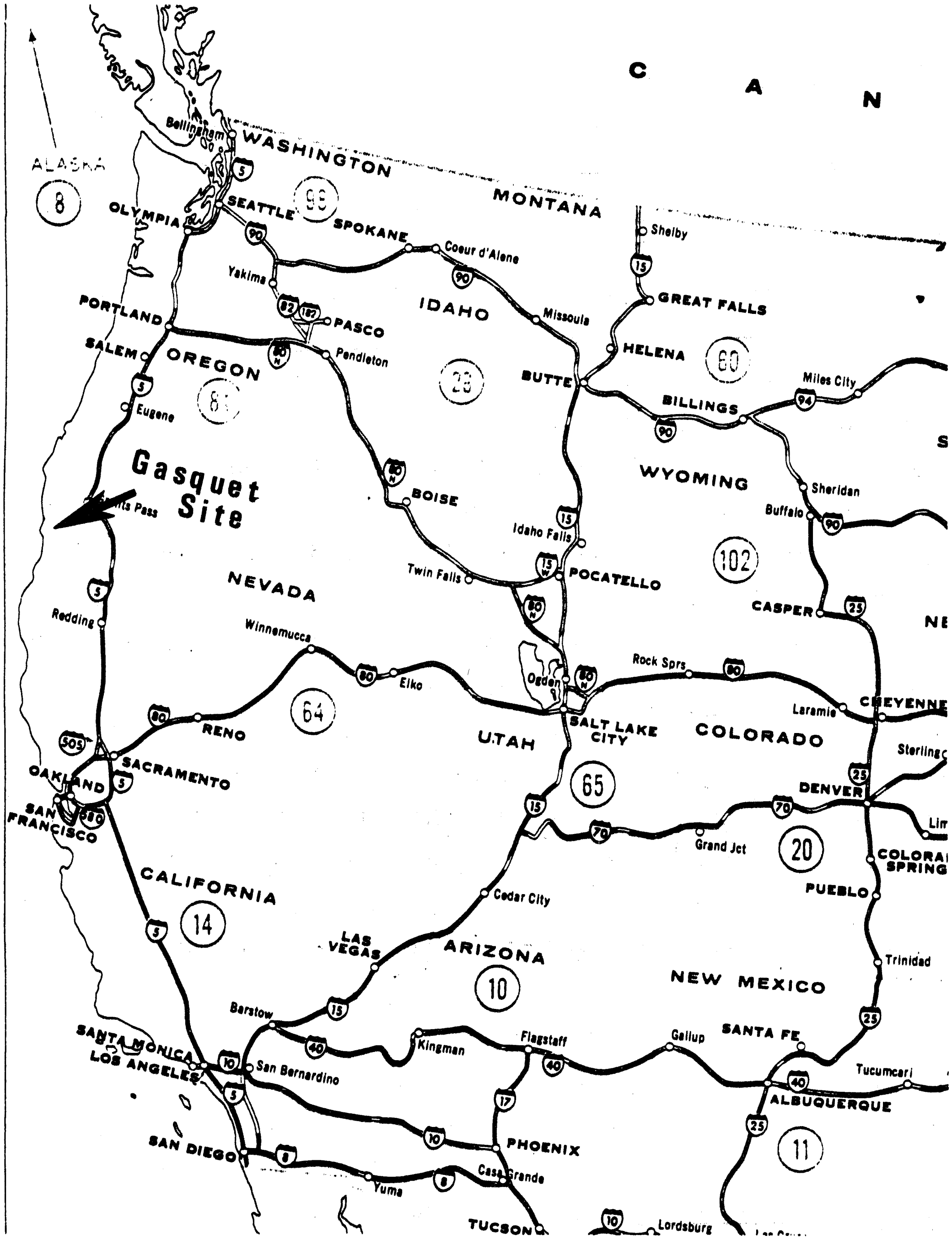

Figure 6. A map of the northwest United States.

Figure 7. The transmitter was set in a clearing off the edge of the Ward Field runway and the receiver van was located in the parking lot of the Gasquet fire station. These terminal locations provided a path length of 1003 meters. The elevation of the air field is 390 ft (119 m); however, the surrounding area (within 2 km) reaches 2000 ft (610 m).

The long-term average annual rainfall measured at the Gasquet Ranger Station (.5 km from the receiver) is 95 inches (241.3 cm), of which approximately 90 inches (228.6 cm) falls in the 8 months from October through May. The precipitation records in Figure 8 show the annual average by month from July through June and the precipitation record from July, 1984, through April 15, 1985.

The photographs in Figure 9 are of the transmitting and receiving terminals and the test path at Gasquet, CA. The transmitter enclosures and antennas shown in Figure 9A are positioned on a 15-ft (4.57 m) scaffold, which provides ground clearance between the transmitting and receiving terminals. The respective antennas for the 9.6, 28.8, 57.6 and 96.1 GHz transmitters are indicated in the picture. Figure 9B shows the receiving van and antenna enclosure. The respective receiving antennas are labeled also. After the terminals were positioned and properly secured, each antenna was carefully aligned for maximum received signal level. The photograph in Figure 9C was taken from the top of the transmitter scaffold and shows the receiver location in the center (indicated by the arrow). The photograph in Figure 9D was taken from in front of the receiver van and shows the transmitter terminal location near the center (also indicated by an arrow).

4. RAIN CHARACTERISTICS

During the 80-day monitoring period that included the last 7 days of January, all of February and March and the first 14 days of April in 1985, the measured rainfall was 20.25 inches (51.43 cm). The data in Table 1 show the weekly distribution of the rainfall measured during the monitoring period.

The capacitive bridge rain-rate gauge was located at the receiving terminal on the propagation path. The rain rate and the received signal levels (RSL) were recorded at 12-sec intervals. The data in Figure 10 are examples of recorded rain events that represent some of the higher and more sustained rain rates. Additional examples displayed with the simultaneous recordings of the RSL are shown in the next section.

The curve in Figure 11 shows the cumulative distribution of the measured rain rate based on 115 h of data selected from a total of 221 h of rain during the 80-day monitoring period at Gasquet. During the sample period (115 h), 290 mm (11.4 in) of

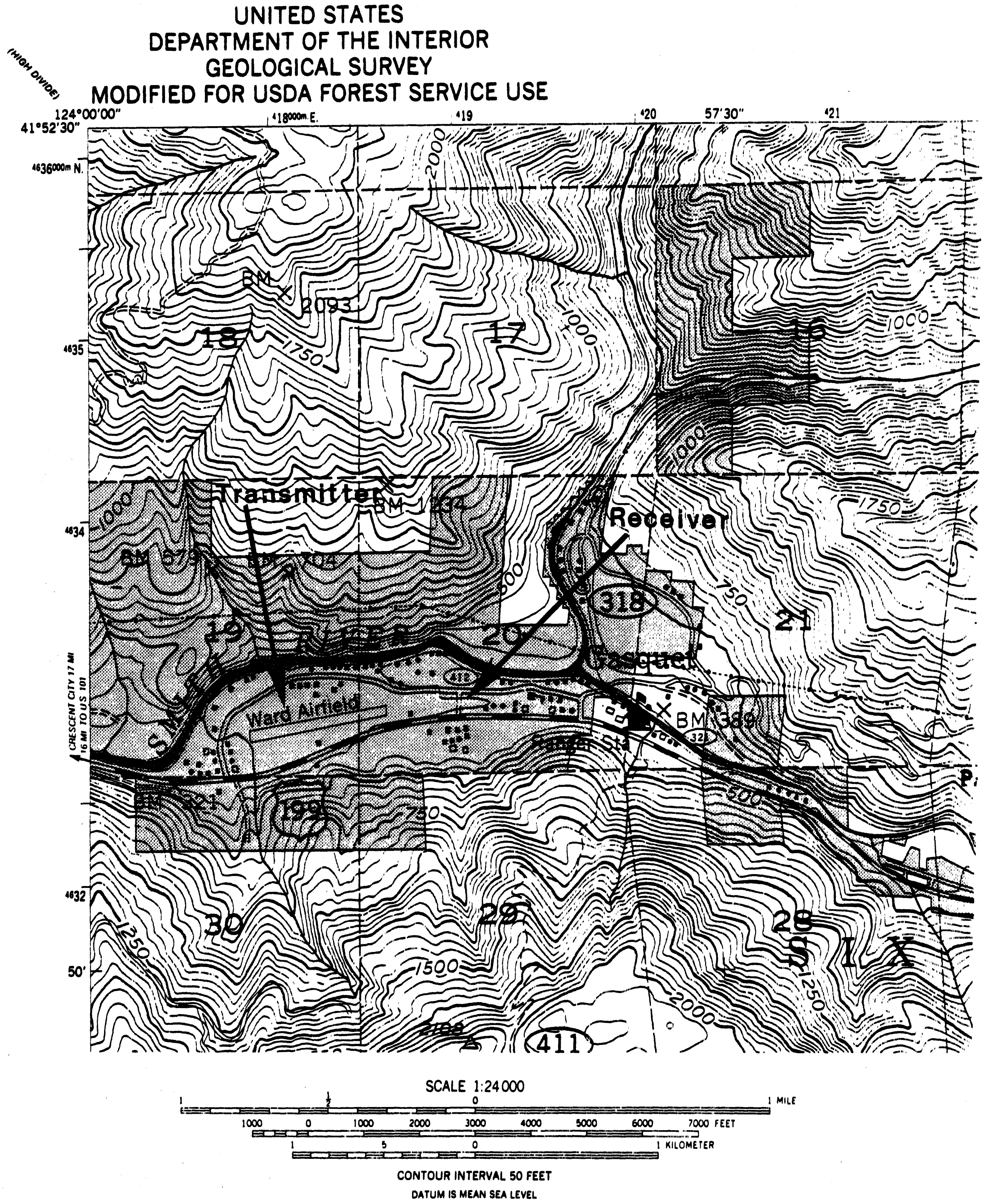

Figure 7. A topographical map of the Gasquet, CA site.

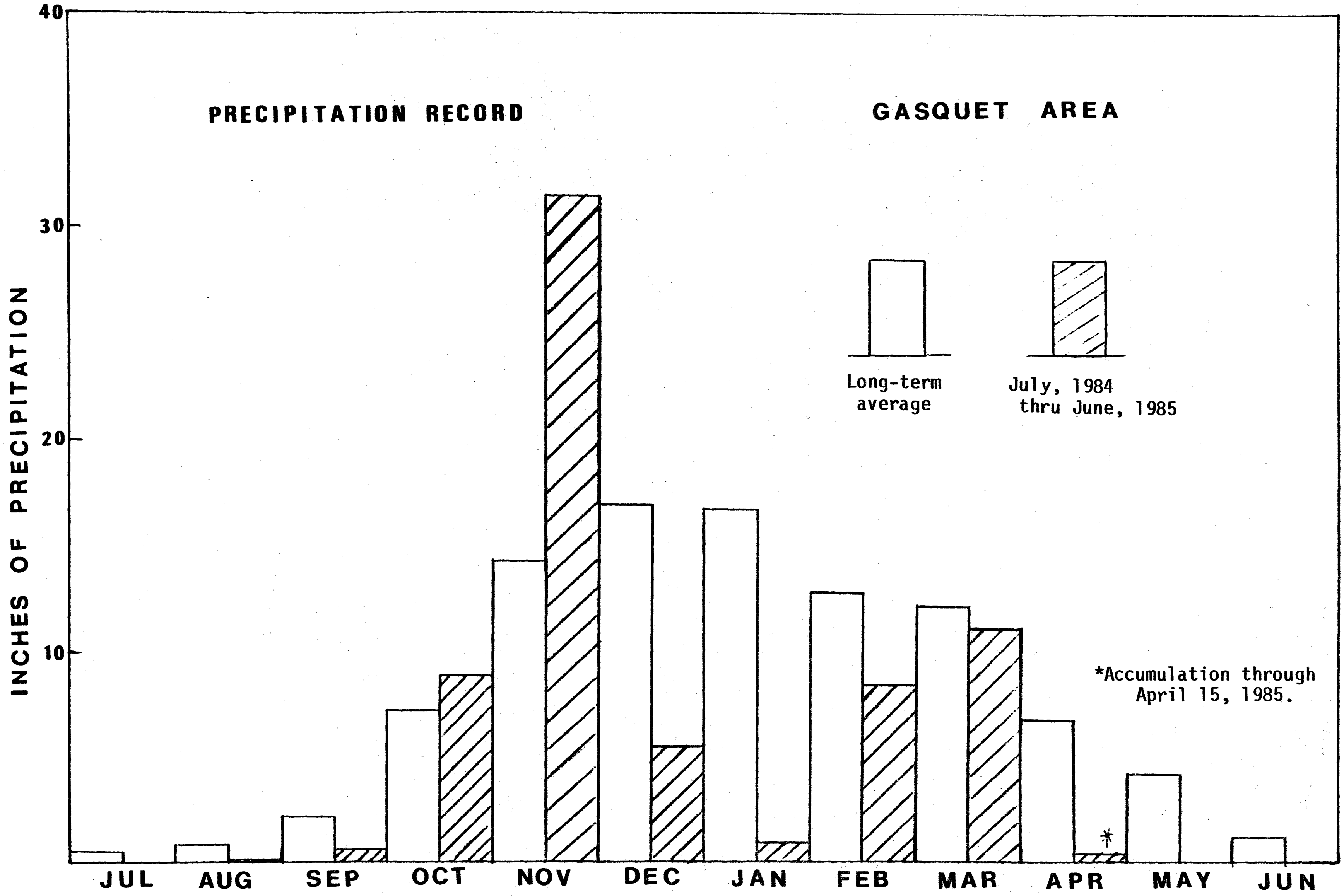

Figure 8. Precipitation records from the Gasquet, CA area.

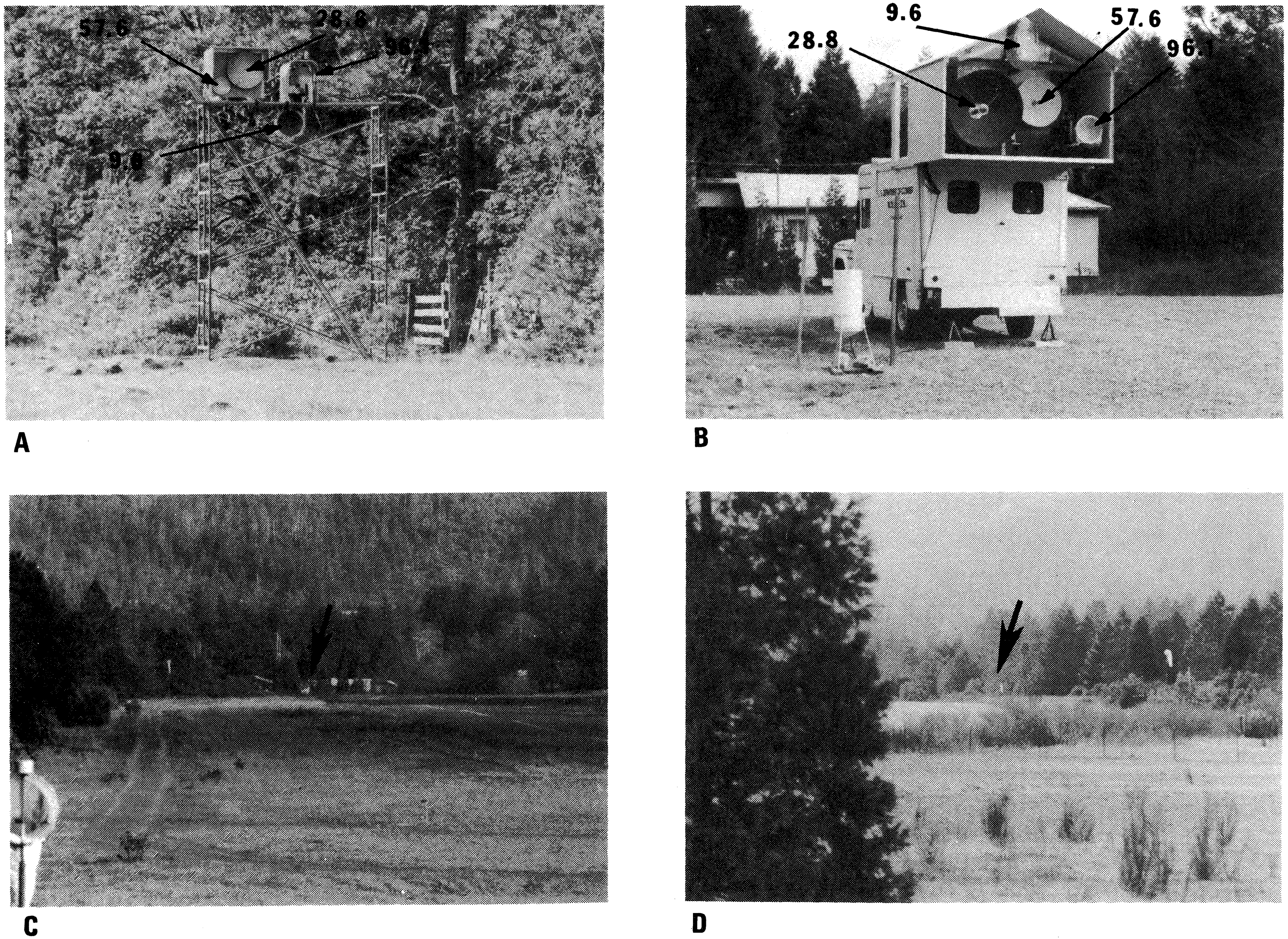

Figure 9. Photographs of the Millimeter-wave system terminals and path at Gasquet, CA.

Table 1. Accumulated Rain at the Gasquet Ranger Station (1/22-4/15/85)

WEEK OF (1985)	MEASURED RAINFALL* (mm)	(INCHES)
1/22 -- 1/29	14.0	0.55
1/29 -- 2/5	16.5	0.65
2/5 -- 2/12	190.5	7.50
2/12 -- 2/19	---	---
2/19 -- 2/26	5.1	0.20
2/26 -- 3/5	53.3	2.10
3/5 -- 3/12	20.3	0.80
3/12 -- 3/19	---	---
3/19 -- 3/26	139.7	5.50
3/26 -- 4/1	67.3	2.65
4/1 -- 4/8	---	---
4/8 -- 4/15	7.6	0.30
TOTAL	514.3	20.25

*The tipping bucket gauge at the ranger station measured the accumulative rain in inches.

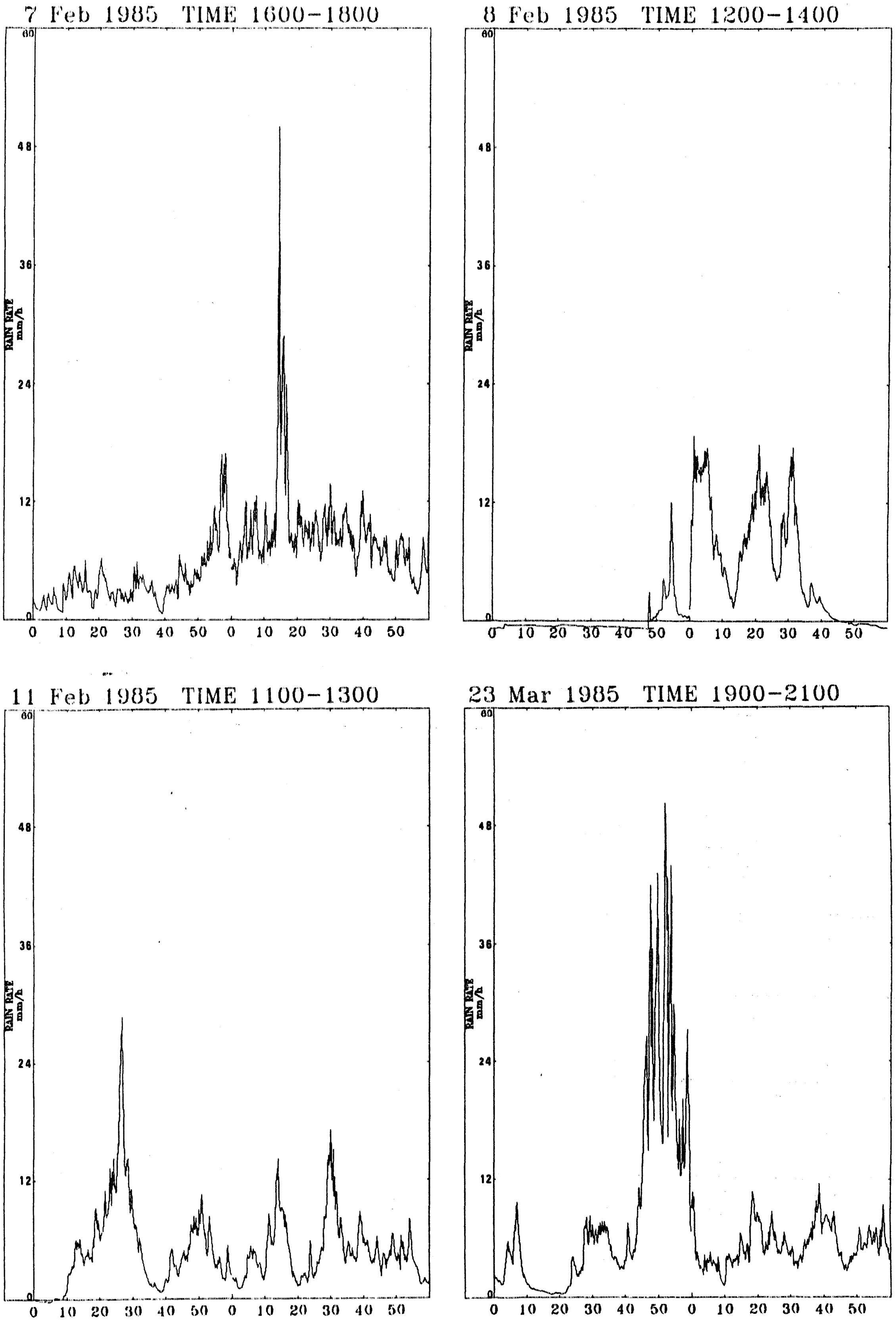

Figure 10. Plots of rain-rate data recorded at the Gasquet, CA field site.

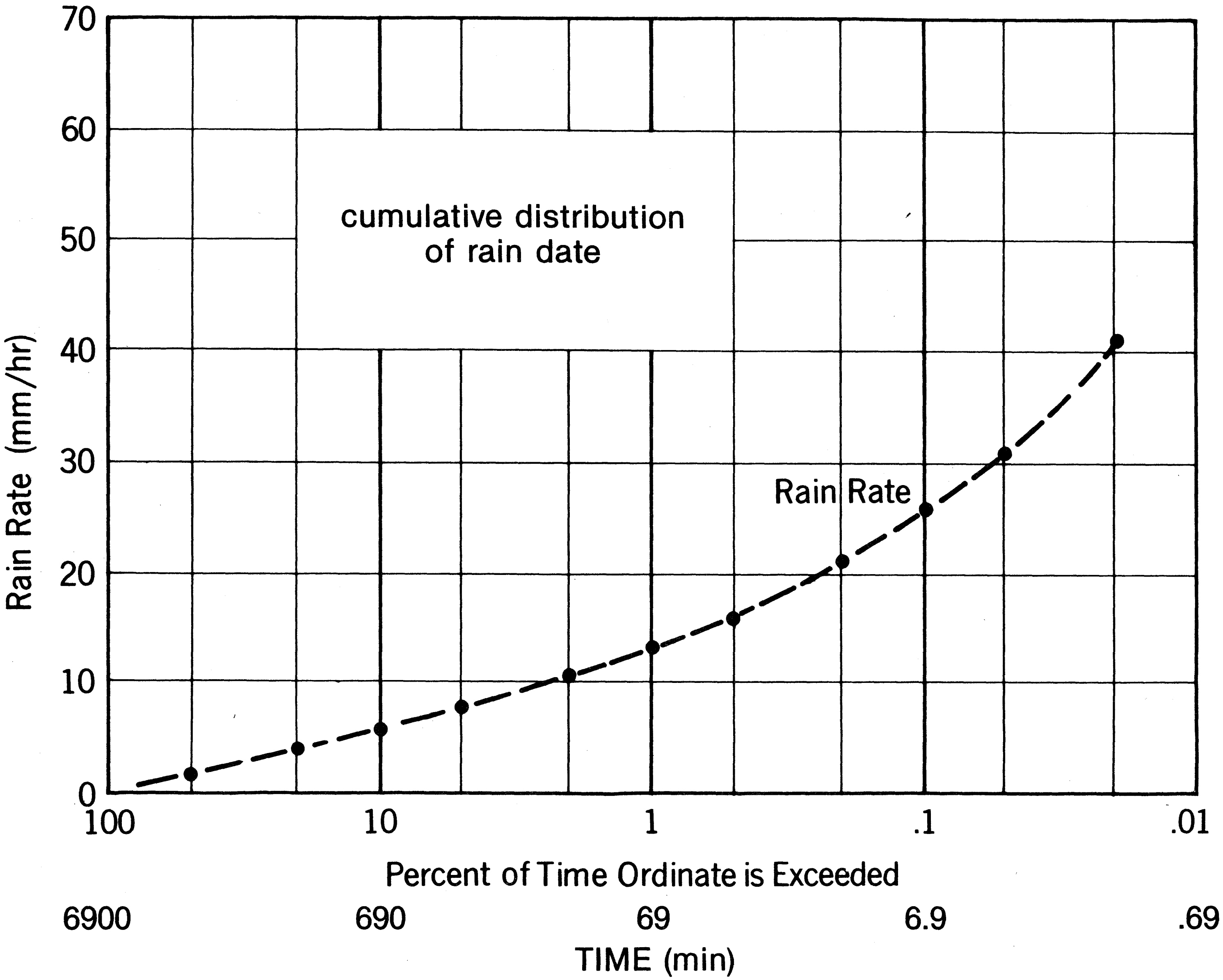

Figure 11. A cumulative distribution of the rain rate recorded at Gasquet, CA in January, February, and March of 1985.

rain fell compared to the total 514 mm (20.25 in) measured for the monitoring period. The sample represents approximately 56 percent of totals for both the rain accumulation and the hours during which rain fell. The basis for selecting this particular sampling was that during these hours, all channels of data (rf and rain rate) were recorded and were free of measurement error. Those segments of the total data that were omitted from this analysis were recorded during periods when one or more channels of data were missing or in error. Factors contributing to the incomplete data sets were power outages at the transmitter or receiver terminals, contamination of the rain-rate gauge (which produced erroneous readings), and the failure of a waveguide switch (which resulted in an incomplete set of rf data). The 115-h sample of rain rate and corresponding RSL data is considered typical of rain events occurring this time of year at the Gasquet site. The dates, hours, and accumulated storm rainfall for this sample are shown in Table 2.

The 221 h of rain represent slightly more than 10 percent of the total monitor period and the maximum observed rain rate during this period was approximately 50 mm/h for the 12-sec samples.

5. ATTENUATION CHARACTERISTICS

The millimeter-wave link was operated continuously at the Gasquet site from January 25 through April 14, and except for outages, the following data were recorded:

1. rain rate (mm/h)
2. 9.6 GHz VV (dB)
3. 28.8 GHz VV (dB)
4. 28.8 GHz VH (dB)
5. 57.6 GHz VV (dB)
6. 57.6 GHz VH (dB)
7. 96.1 GHz VV (dB)
8. 96.1 GHz VH (dB)
9. ambient temperature (°C)

NOTE: VV = vertical transmitter antenna polarization and vertical receiver antenna polarization

VH = vertical transmitter antenna polarization and horizontal receiver antenna polarization

Table 2. Gasquet Rain Data Bank.
(Date, hours and accumulated storm rainfall)

DATE	HOUR	RAINFALL
Jan 27	1900-2300	0.55"
Jan 28	0000	
Feb 1	1100-1600	0.45"
Feb 6	1700-2300	0.85"
Feb 7	0000-1900	2.60"
Feb 8	0900-1300	0.75"
	1500	
	1800-2300	
Feb 9	0200-0400	0.35
	1100-1400	
Feb 11	0400	1.85"
	0700-2300	
Feb 12	0000	0.20"
	0100	
	0500	
	0600	
Feb 19	1300-1600	0.20"
Mar 20	1300	0.20"
	1400	
	1800	
Mar 21	1000	0.10"
	1100	
	1300	
Mar 23	1300-2200	2.00"
Mar 24	0000-0200	0.50"
	0900-1300	
	1700	
Mar 26	0600-1200	0.80"
Totals	115	11.35"

One-day samples (24 h) of these data are shown in Figures 12 and 13. An example of the same data from a day for which there was no rain is shown in Figure 14. A comparison of these data shows that the principal signal attenuation is caused by rain on the path. These data are the 12-sec average values as recorded at the field site. All channels are recorded continuously except the VH RSL, which are recorded only when the rain-rate exceeds 5 mm/h.

The data in Figure 15 are recordings for February 7, for the hours from 0000 through 2000. This record and the expanded 2-hour segment of the same day in Figure 16 show the strong correlation between VV and VH RSL as a function of rain rate. Cross-polarization isolation for clear air was measured at -22 dB, -22.5 dB, and -27.5 dB, for the 28.8, 57.6, and 96.1 GHz channels, respectively. Closer observations show that at 57.6 and 96.1 GHz, the VH channels were attenuated slightly more than the corresponding VV channels at the higher rain rates. The records in Figure 17 show data similar to Figures 15 and 16, except the time period is between 1100 and 1500 on February 11.

The data in Figures 18, 19, and 20 are the RSL for 28.8, 57.6, and 96.1 GHz (VV) and rain rate from select hours on February 8, March 23, and March 24. Full scale attenuation for the three channels is 5, 10, and 15 dB, respectively, and the observed attenuations were coarsely in this ratio. Departures from this ratio and variations in attenuations as a function of rain rate were also observed. Note that the rain-rate measurement was recorded at the receiver terminal; thus, it is a point sample of the rain rate for a 1-km path.

The curves in Figure 21 show cumulative distributions of the attenuation for received signals at 28.8, 57.6, and 96.1 GHz during rain for the 115-h selected data base used for the cumulative distribution of rain rate shown in Figure 11. These data, of course, represent percentages of time for which an attenuation value is exceeded during rainy periods and does not include the clear-air time periods. For example, during one percent of the 221 h that it rained at Gasquet during the monitor period, the distribution indicates that the attenuation on the 28.8, 57.6, and 96.1 GHz VV rf channels exceeded 1.5 dB, 6 dB, and 9 dB respectively.

The curves in Figure 22 show attenuation of the received signals at 28.8, 57.6, and 96.1 GHz as a function of rain rate based on the cumulative distributions. Naturally, in these cumulative distributions the percentage of time that an exceedance level (attenuation or rain rate) is exceeded decreases as the level increases, so that the fraction of the observation data that determines the correspondence between exceedance level and percentage of time exceeded decreases. Thus, the cumulative distribution curves become less significant in a statistical sense for the higher

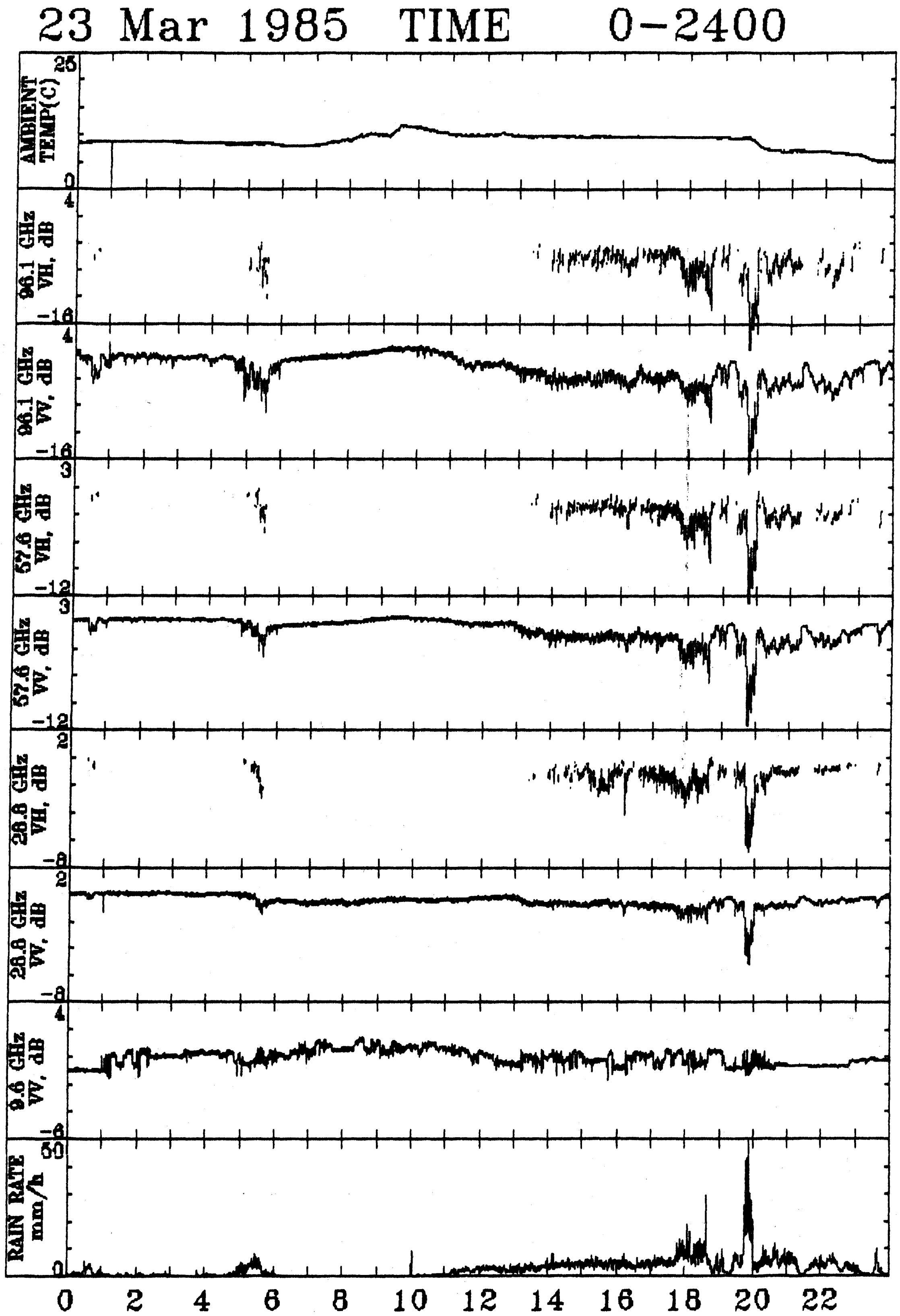

Figure 12. A copy of all the channel data recorded on March 23, 1985.

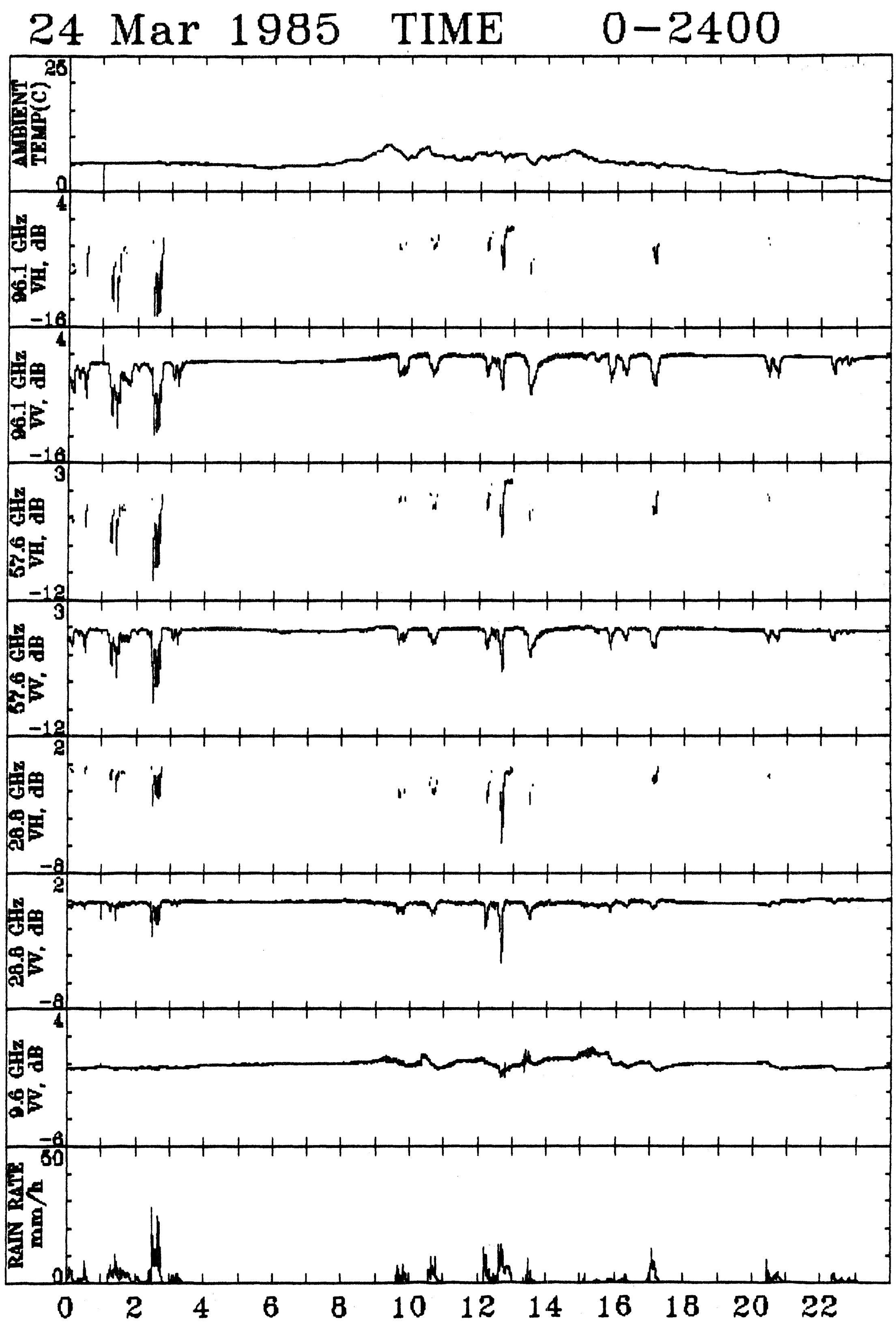

Figure 13. A copy of all the channel data recorded on March 24, 1985.

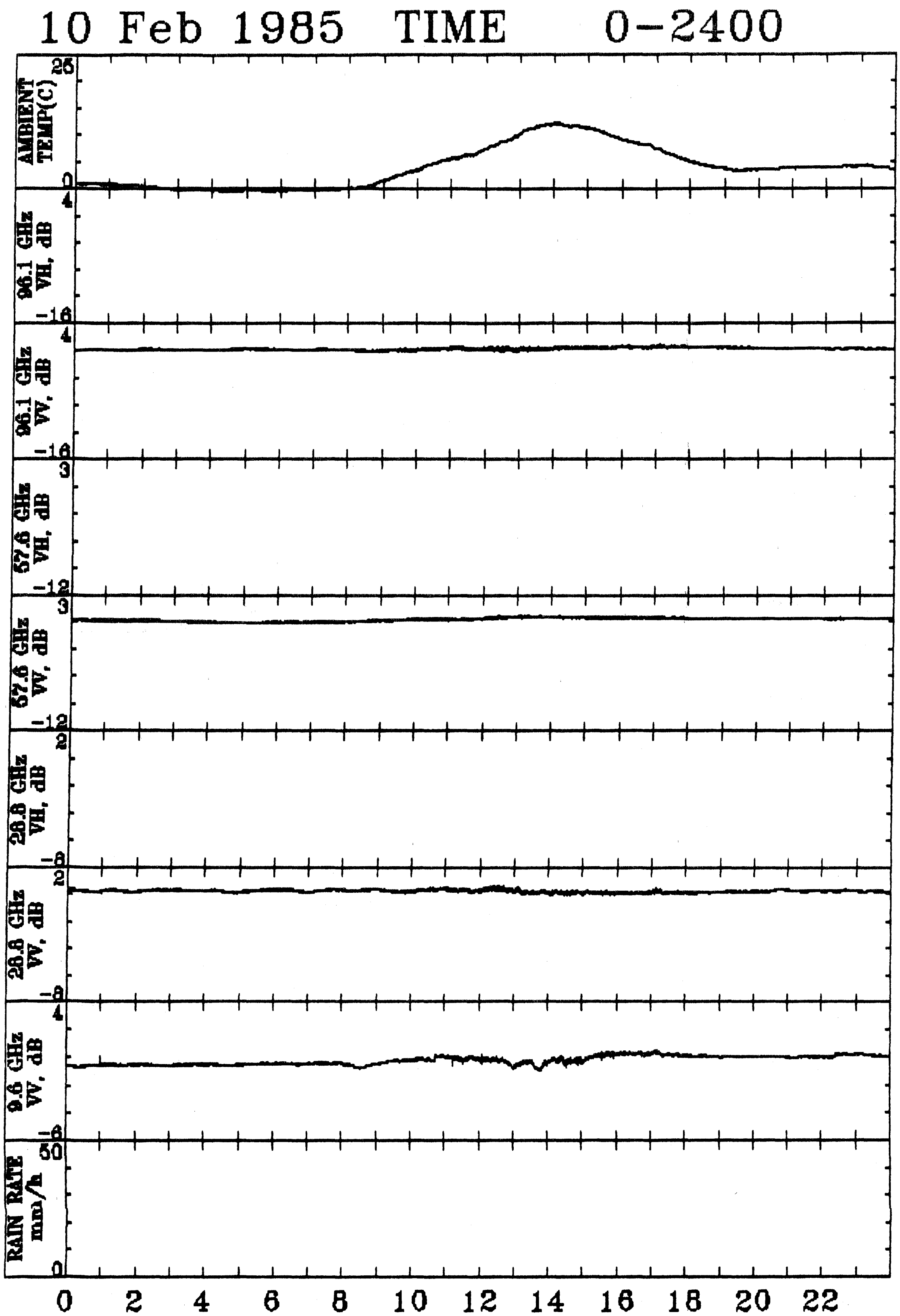

Figure 14. A copy of all the channel data recorded on February 10, 1985.

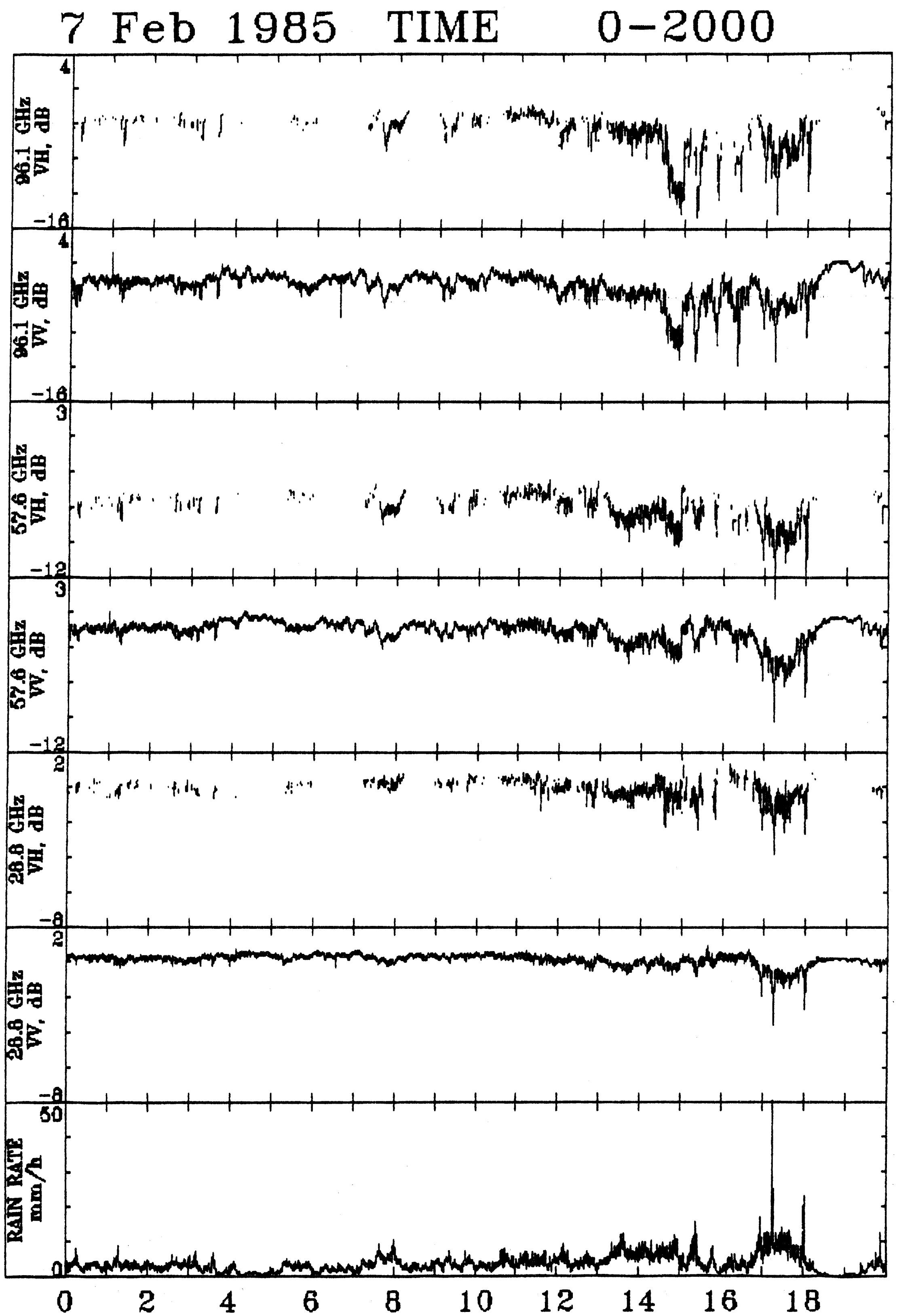

Figure 15. Partial records from the data recorded on February 7, 1985.

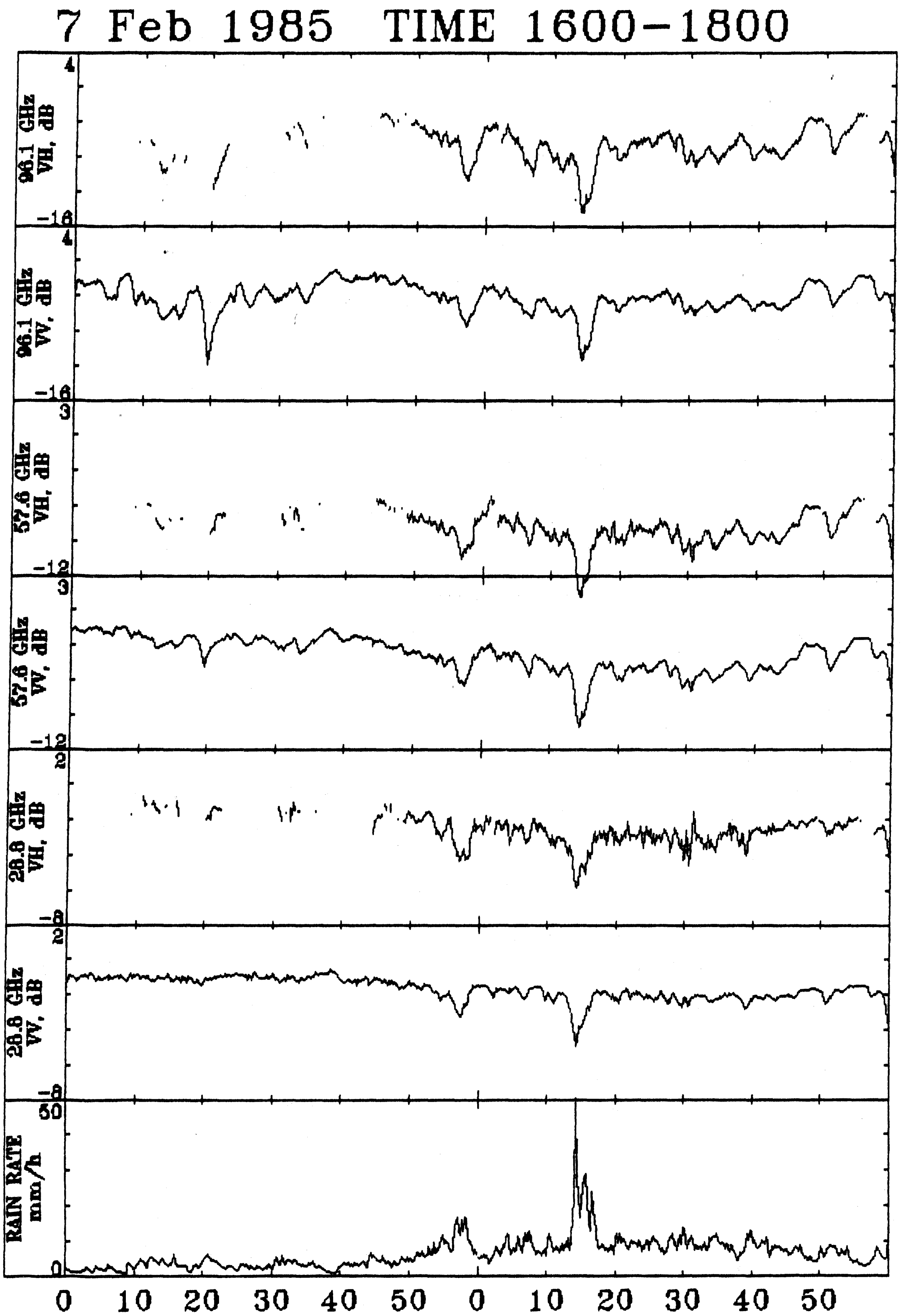

Figure 16. Partial records from the data recorded on February 7, 1985.

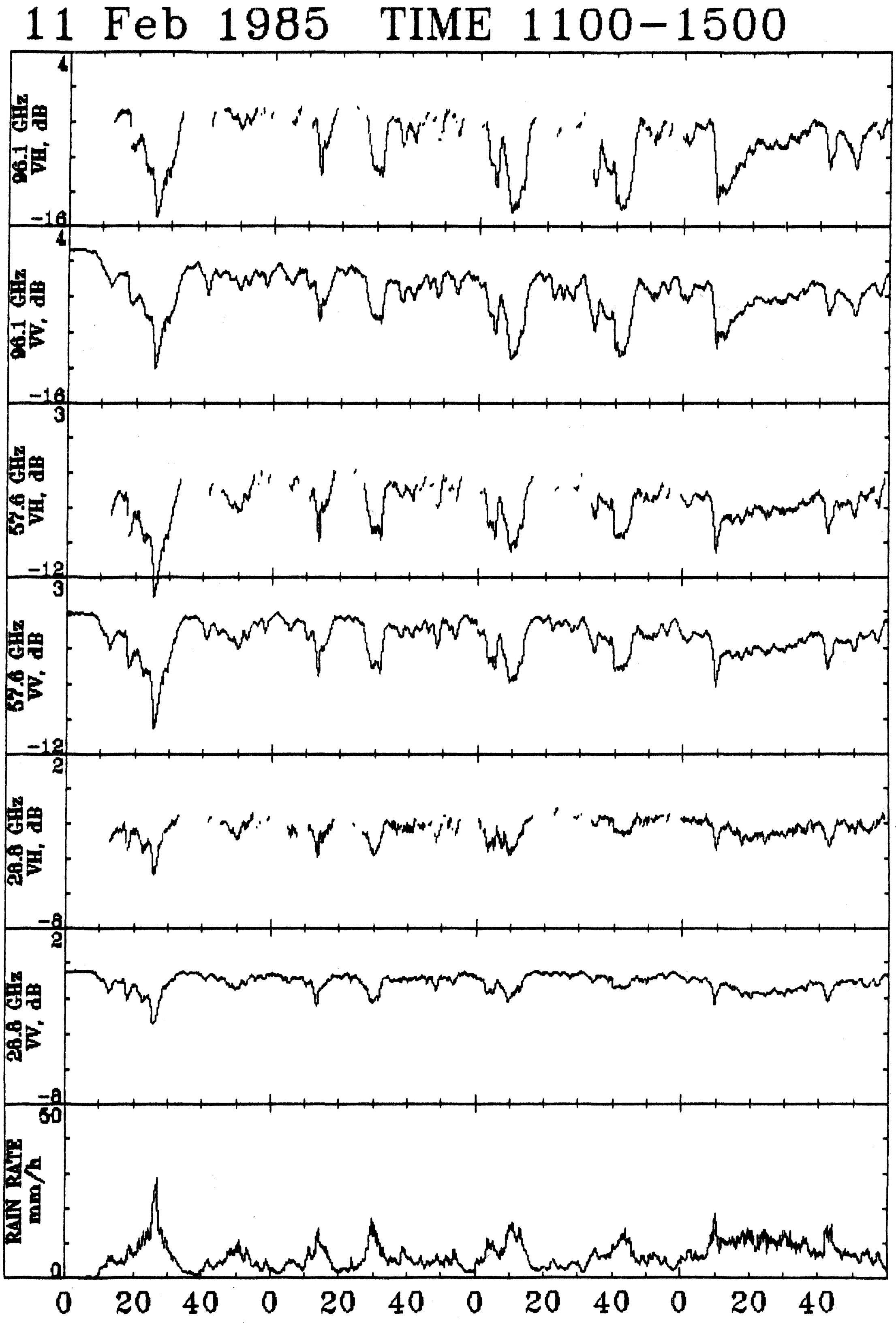

Figure 17. Partial records from the data recorded on February 11, 1985.

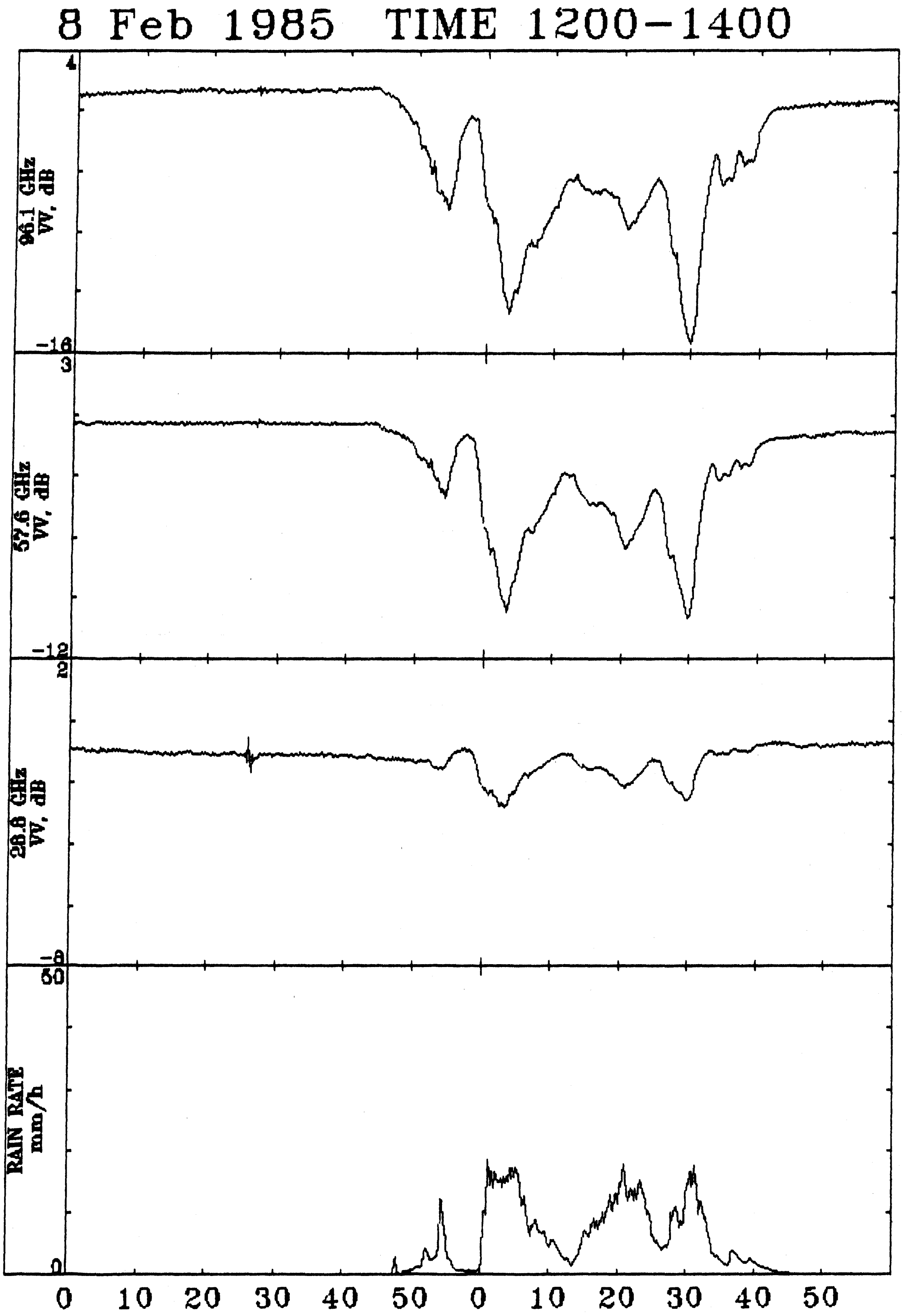

Figure 18. Records of received signals from the 28.8-, 57.6-, and 96.1-GHz VV Channels and rain rate on February 8, 1985.

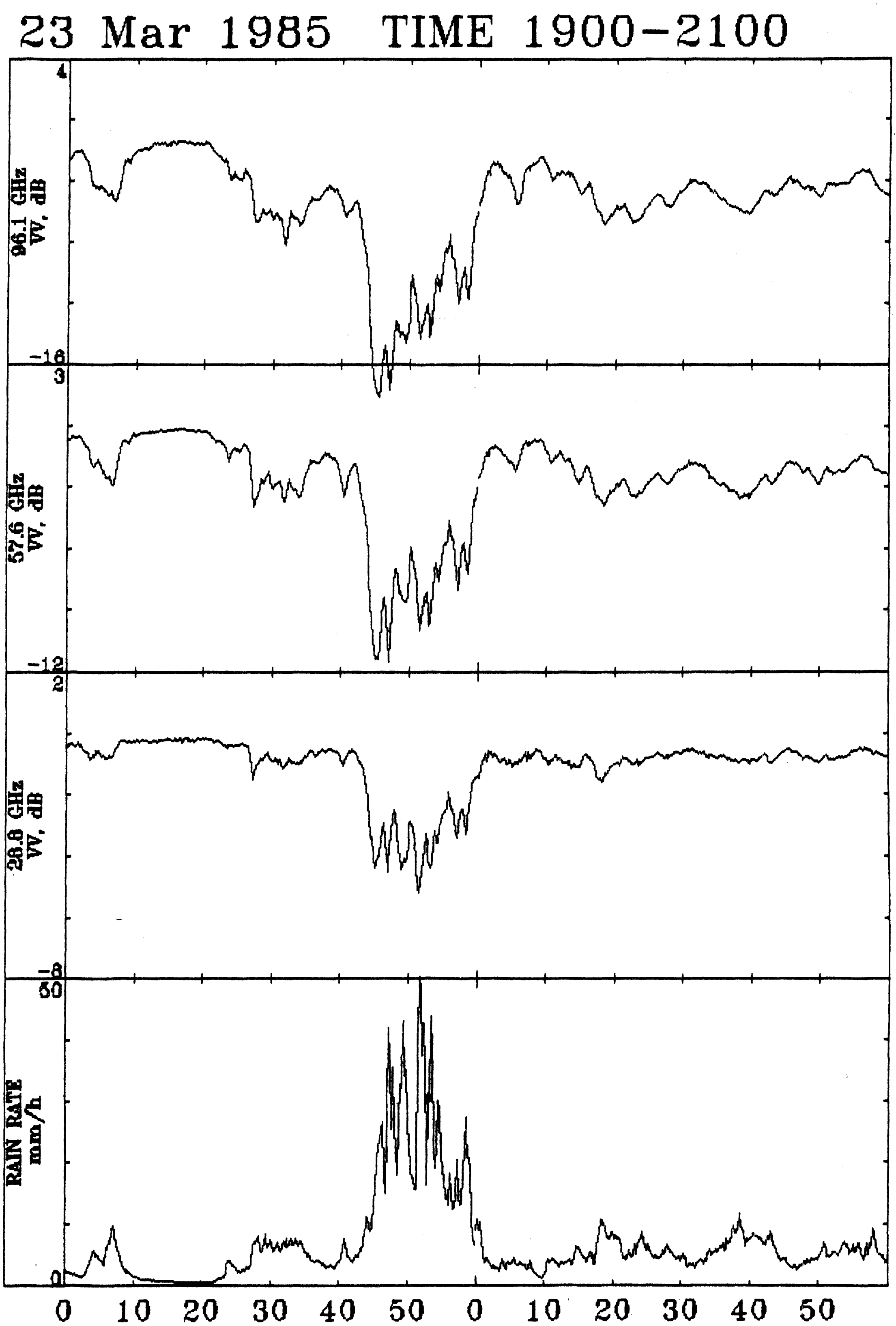

Figure 19. Records of received signals from the 28.8-, 57.6-, and 96.1-GHz VV Channels and rain rate on March 23, 1985.

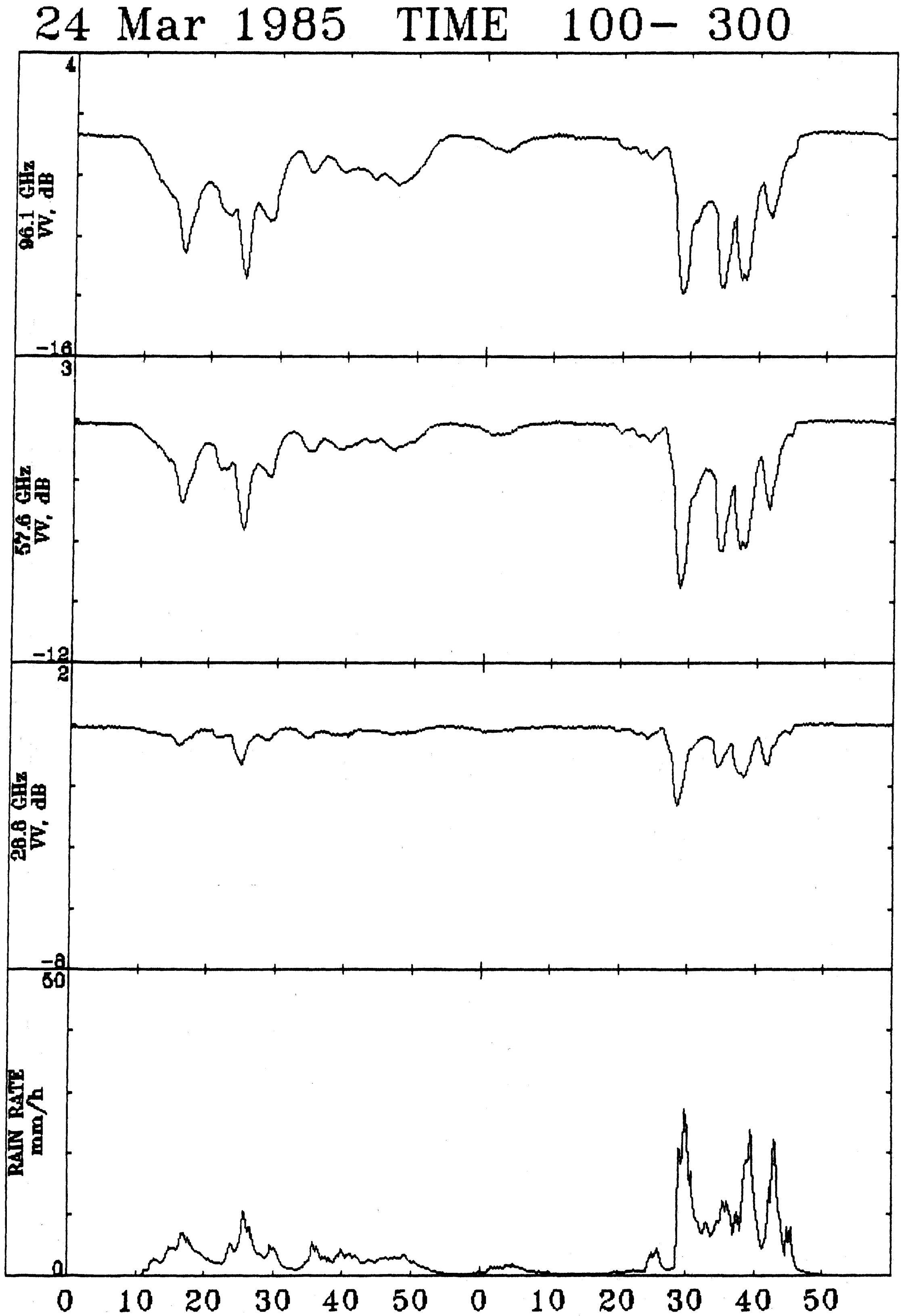

Figure 20. Records of received signals from the 28.8-, 57.6-, and 96.1-GHz VV Channels and rain rate on March 24, 1985.

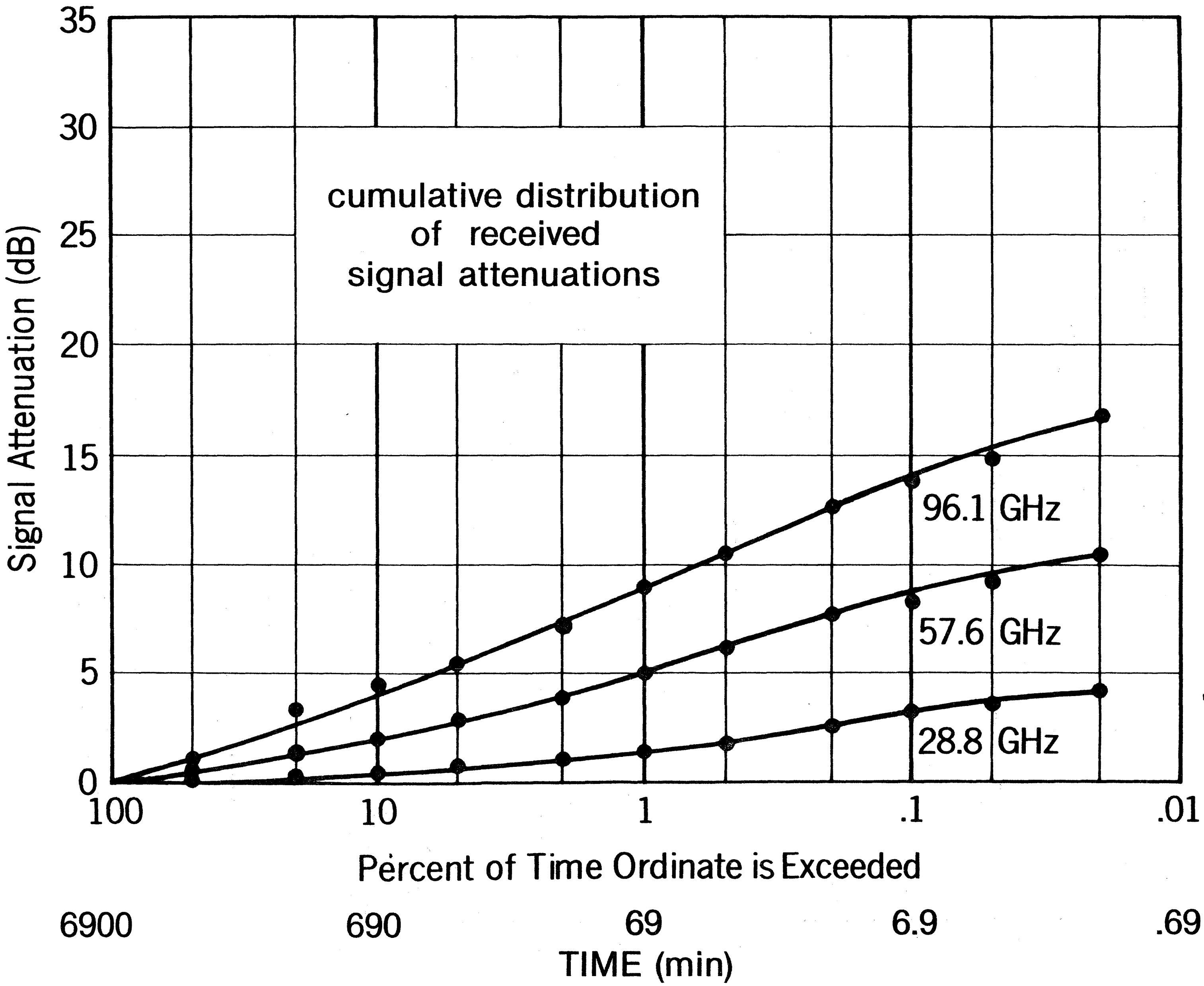

Figure 21. Cumulative distributions of the 28.8, 57.6, and 96.1 GHz signal attenuation of received signals during rain at Gasquet, CA in January, February, and March, 1985.

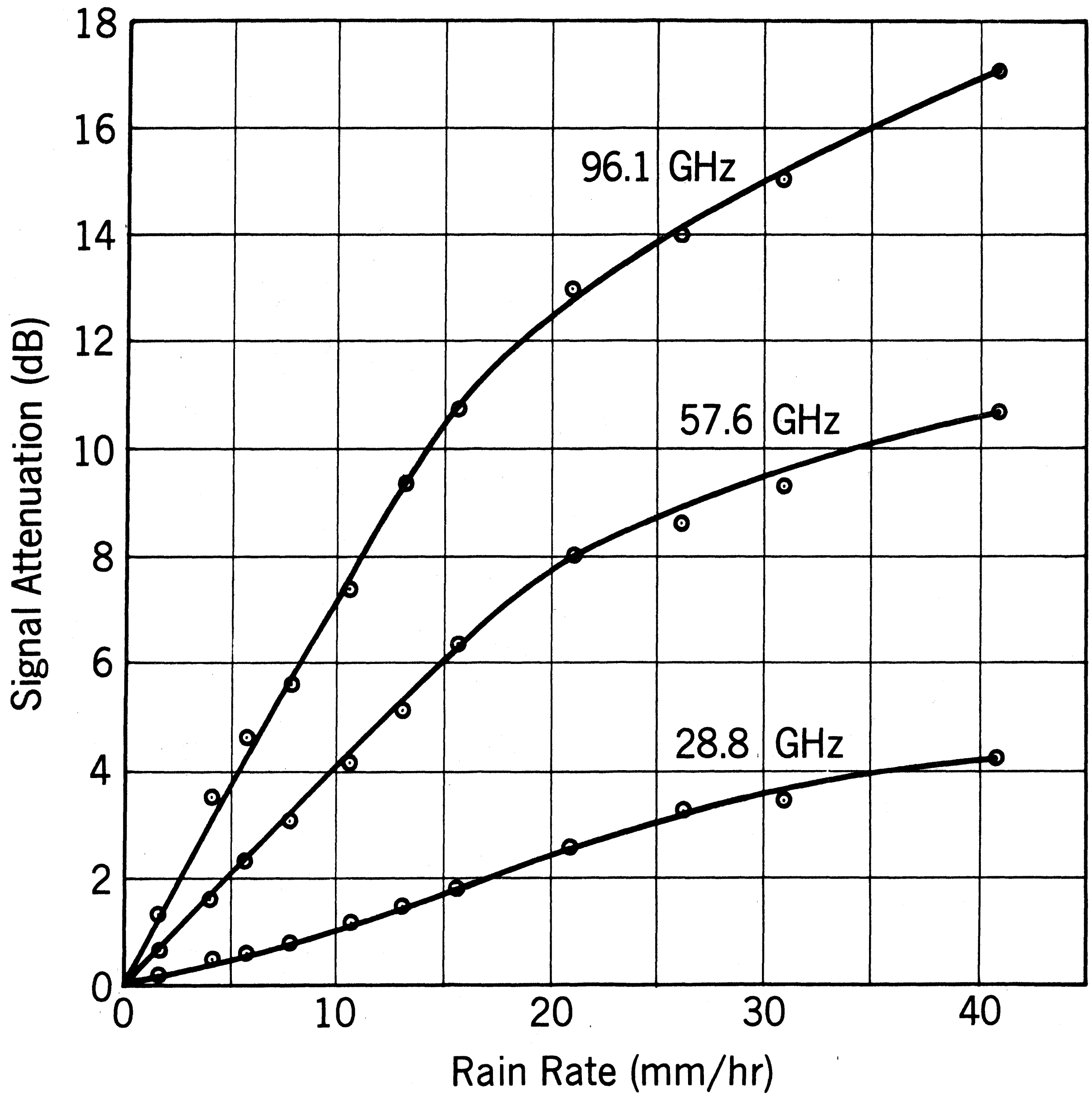

Figure 22. Signal attenuation versus rain rate as a function of frequency from a cumulative distribution analysis of a 115-hour sample of rain data at Gasquet, CA.

rain rates and attenuations. Only 14 minutes of data correspond to rain rates greater than 20 mm/h. Fourteen minutes is such a small sample size that the portions of the attenuation versus rain rate curves of Figure 22 for rain rates above 20 mm/h are not statistically significant.

The relationship between attenuation and rain rate is usually modeled using

$$\alpha = aR^b \quad (1)$$

where α is the attenuation in dB/km and R is the rain rate in mm/h. The parameters a and b depend on the radio frequency and the temperature and drop-size distribution of the rain. For frequencies above 10 GHz the temperature dependence is not significant, however. The published results of Olsen et al (1978) have become the standard reference for the values of a and b. Values of a and b interpolated from their tables for 0° C and the Laws and Parsons (1943) dropsize distribution, low rain rate, (one of the most popularly used) are given below.

Frequency	a	b
28.8 GHz	0.148	1.069
57.6 GHz	0.617	0.864
96.1 GHz	1.057	0.747

In Figure 23, the relationship (1) using the parameter values from the table above are compared to the data previously presented in Figure 22. The data for 28.8 GHz show less attenuation than the model. At 57.6 GHz the model and data match very closely. For 96.1 GHz the data show greater attenuation than the model. The relationship (1) appears to satisfactorily model the data but the parameter a is too large at 28,8 GHz and too small at 96.1 GHz. This is presumably due to a difference between the Laws and Parsons drop-size distribution and the actual drop-size distribution of the observations.

6. SUMMARY

The millimeter-wave experimental link established to measure the effects of rain rate on several propagated rf signals was operated on a 1-km path in Gasquet, CA. The monitoring period (January 26 through April 14) lasted 80 days. Rain fell for approximately 221 h of this time, during which 514 mm (20.25 in) of rain accumulated.

Millimeter-wave signal levels at 28.8, 57.6, and 96.1 GHz, and rain rate were recorded continuously. These rf channels utilized vertical antenna polarization

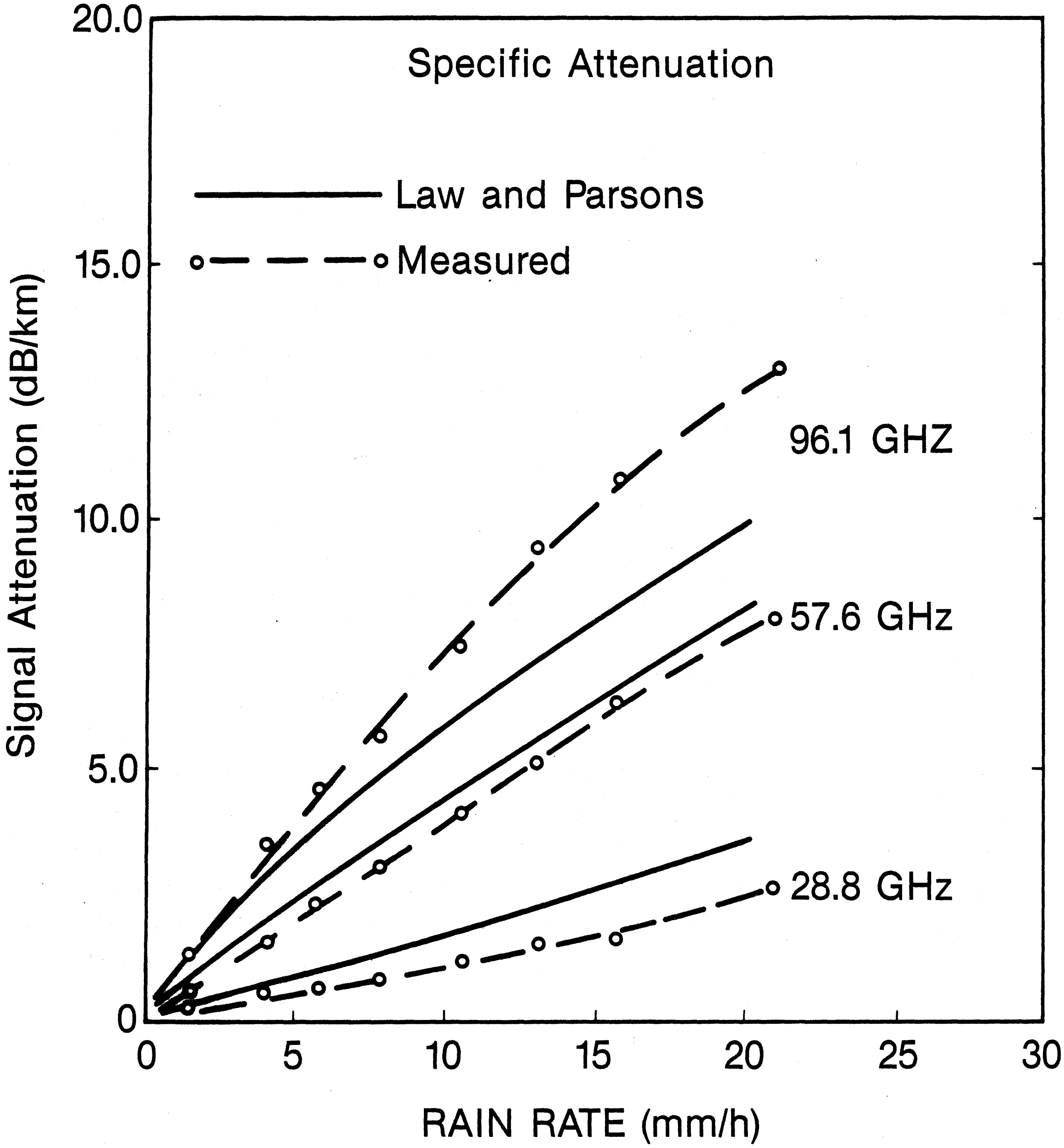

Figure 23. A comparison of measured and predicted specific attenuation.

for both transmitter and receiver (VV). When rain rates exceeded 5 mm/h, VH signals (vertical polarization at the transmitter and horizontal polarization at the receiver) were also recorded for the 28.8-, 57.6-, and 96.1-GHz channels.

A sample period consisting of 115 h during which 290 mm (11.4 in) of rain fell was selected as characteristic of the rainfall patterns for the Gasquet area during these months. This specific sample was selected because it represented times for which all channel data were recorded without measurement error.

Maximum rain rates greater than 50 mm/h were observed during this monitoring period that caused attenuations exceeding 4 dB, 10 dB, and 17 dB for the 28.8-, 57.6-, and 96.1-GHz channels, respectively.

Cumulative distributions of rain rate and signal attenuation at 28.8, 57.6, and 96.1 GHz based on the 115 h sample are presented. A comparison of the measured specific attenuation at these frequencies is compared to predicted values based on the Laws and Parson's dropsize distribution model.

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15. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

An experimental millimeter-wave propagation link was installed on a 1-km path in the northern California area (Gasquet) to compare rain rate and attenuation at 28.8, 57.6, and 96.1 GHz. During the monitoring period (January 26 through April 14), rain occurred on 27 days with an accumulation of 514 mm (20.25 in). For periods when the rain rate exceeded 5 mm/h, both VV (vertical polarization at the transmitter and vertical polarization at the receiver) and VH (vertical polarization at the transmitter and horizontal polarization at the receiver) signals were recorded. Maximum rain rates exceeded 50 mm/h and maximum attenuations of 4, 10, and 17 dB were observed on the 28.8, 57.6, and 96.1 GHz channels, respectively.

16. Key Words *(Alphabetical order, separated by semicolons)*

attenuation; measurement; millimeter-wave; multifrequency; rain rates

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