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**VIRGINIA PRECIPITATION
SCATTER EXPERIMENT —
EXPERIMENT DESCRIPTION**

AUGUST 1972

GSEC

— GODDARD SPACE FLIGHT CENTER —

GREENBELT, MARYLAND

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Computer Sciences Corporation

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ABSTRACT

This experiment provided a year's statistical data for the purpose of refining existing coordination procedures for the sharing of common frequency allocations between terrestrial and space services. The measurement program was conducted between October 3, 1970, and October 2, 1971, to empirically determine the cumulative distributions of scattering cross section per unit volume of hydrometeors at heights up to 9 km above the surface and of rain rate at the surface. The measurements were made in southeastern Virginia using a bistatic, continuous-wave (cw), vertically polarized radar system operating at S- and X-band frequencies and tipping-bucket rain gages. The bistatic radar system was configured to represent an interference situation between a radio-relay system and a space communication system Earth terminal; the results may be interpreted as measured distributions of transmission loss for interference due to rain. This report contains a description of the experiment and equipment; the data analysis is covered in a companion report (ref. 13).

The experiment was conducted in two parts: the first (October 3, 1970, to June 3, 1971) emphasized exploration and the second (June 4, 1971, to October 2, 1971) emphasized high accuracy and reliability. The total measurement year spanned 8760 hr during which 119 rain-scatter events occurred. An event was defined as the occurrence of a 1-min averaged rain rate in excess of 1 mm/hr at the surface or an equivalent reflectivity in excess

of 22 dBZ (163-dB transmission loss, which, for this experiment configuration, corresponds to the threshold for interference recommended by the International Radio Consultative Committee (CCIR) for Earth terminal receivers operating in the 3.4- to 4.2-GHz frequency band). Rain scatter of sufficient intensity to qualify as an event was measured for at least 1 min of each of a total of 568 hr of the measurement year for the scattering volume at a 3-km height and of 128 hr at a 6-km height. During the measurement year, 7 hr of rain-scatter data were lost due to system outage and 42 hr of rain-gage data were lost due to snow. The overall measurement accuracy varied throughout the year and was ± 3 dB for the bistatic radar measurements and ± 10 percent for the rain-rate measurements made during the important summer months.

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VIRGINIA PRECIPITATION SCATTER EXPERIMENT-- EXPERIMENT DESCRIPTION

1 INTRODUCTION

1.1 BACKGROUND

Interference between centimeter- or millimeter-wave communication systems operating at the same frequency and beyond each other's radio horizon may be caused by one or more of several propagation mechanisms: tropospheric scatter, terrain diffraction, ducting, and rain scatter. The procedures used to assess the possibility of interference (the coordination procedures in effect prior to the revisions prepared at the 1971 World Administrative Radio Conference for Space Telecommunications (1971 WARC-ST)) paid little attention to rain scatter. Early theoretical work by W. Gordon (ref. 1) predicted that rain scatter would cause a higher signal level on a troposcatter path than would atmospheric turbulence for frequencies above 100 MHz and rain rates above 1 mm/hr. Measurements in 1958 by Doherty and Stone (ref. 2) showed the prediction to be substantially correct. Doherty continued the investigation of bistatic scattering by rain using a short path with a scattering volume just above the surface. He found (ref. 3) that the scattering cross section could be statistically related to the rain rate at the surface. Under NASA sponsorship, Dennis (ref. 4) and the Central Radio Propagation Laboratory (now the Institute for Telecommunication Sciences (ITS)) (ref. 5) made investigations of forward scatter by rain to assess the importance of this phenomenon in causing interference. More recently, both the Federal Communications Commission (FCC) (POPSI experiment, ref. 6) and Comsat (ref. 7) conducted long-duration measurement programs to determine the cumulative distributions of transmission loss due to rain. These programs have shown that rain scatter can cause interference in communication systems (ref. 8). In 1967, the Office of Telecommunications Management (now Office of Telecommunications Policy (OTP)) requested NASA, with the support of the FCC, to begin a study of rain interference with the goal of improving coordination and interference prediction techniques.

The NASA program to study rain-caused interference included (1) the preparation of methods for the estimation of cumulative distributions of surface rain rates (refs. 9 and 10) for use in estimating interference levels, (2) an experimental investigation of the bistatic scattering properties of rain using both monostatic and bistatic radars for the assessment of the validity of the approximations used to relate the scattered signal levels to meteorological parameters (ref. 11), and (3) the Virginia Precipitation Scatter Experiment. The common theme of the NASA interference studies is the prediction of transmission loss, hence

interference levels, using the scattering properties of rain and the prediction of the scattering properties using available climatological data. The two-step procedure is used because the transmission loss for a variety of transmitting/receiving antenna configurations may be estimated from a knowledge of the spatial and temporal behavior of the scattering cross section per unit volume of rain. If only transmission loss measurements are recorded, the results are applicable only to situations involving identical antenna orientation configurations. Although transmission loss estimation is the ultimate goal of the program, the bistatic scattering cross section per unit volume, referred to as equivalent reflectivity, is the basic parameter of interest.

1.2 EXPERIMENT APPROACH

The Virginia Precipitation Scatter Experiment had the following goals or objectives:

- (1) Demonstrate that rain scatter may cause interference for terminals sited in accordance with the pre-1971 WARC-ST (ref. 12)
- (2) Provide empirically determined cumulative distributions of transmission loss for a 1-yr measurement period for transmitter/receiver configurations typical of radio-relay space communication system Earth terminal interference problems
- (3) Provide empirically determined cumulative distributions of surface rain rate and equivalent reflectivity Z_e at several heights for use in assessing the effectiveness of estimation procedures established under NASA sponsorship or by other investigators

The first goal was of importance prior to the preparatory meetings for the 1971 WARC-ST; the last goal was of highest priority afterward. The experiment was conducted in three phases: the first or exploratory phase (designated as phase Ia) was directed at goals (1) and (2); the second, transitional phase (phase Ib) covered the time required to reconfigure the experiment for the third phase; and the third or high-accuracy phase (phase II) was directed at goals (2) and (3). Phase Ia was directed by ITS of the Office of Telecommunications with P. Rice as principal investigator. Phases Ib and II were directed by GSFC with R. Crane of MIT Lincoln Laboratory as principal investigator. This report is primarily concerned with the experiment and equipment description. The analysis of the year's results with emphasis on the high-accuracy phase is described in a companion report, *Virginia Precipitation Scatter Experiment—Data Analysis* (ref. 13). The exploratory work has been separately reported by ITS (ref. 14).

The equivalent reflectivity measurements were made with a bistatic radar system operating at frequencies of 3.7 GHz (S-band) and 7.8 GHz (X-band). A 30-ft (9.1-m) vertically polarized receiving antenna oriented at an elevation angle of 13.5° was used to represent a typical Earth terminal in the fixed satellite communication service. Transmitters were located at four sites between 30 and 180 km from the receiving antenna. At S-band, 10-ft (3.0-m) vertically polarized transmitting antennas were used; at X-band, 6-ft (1.8-m) vertically polarized antennas were used. The transmitting antennas were oriented at elevation

angles between 0.3° and 8.4° to represent terminals typical of the terrestrial radio-relay service. A total of 24 transmitter/receiver paths were used to investigate scattering from precipitation at heights of 5000, 10 000, 20 000, and 30 000 ft (1.5, 3.0, 6.1, and 9.1 km; hereafter referred to as 5K, 10K, 20K, and 30K) for scattering angles ranging from 15° to 171° . All 24 paths were used only during the exploratory phase and part of the transitional phase. Data for the measurement year, October 3, 1970, through October 2, 1971, were obtained at S-band using only the 3- and 6-km heights and scattering angles near 90° . Although the bistatic radar system was configured to duplicate communication systems in a typical interference problem, the measurement of interest was the equivalent reflectivity because it allows the results to be extrapolated to other path configurations. Because the basic measurement was reflectivity, the measurement system will be referred to as a bistatic radar system throughout this report. Conversion factors will be given to allow the results to be interpreted as transmission loss. Of the 24 paths, only 18 had antenna beam intersections or common volumes. Of these 18 common volumes, only 11 were small enough to be useful in measuring reflectivity. The other paths were used to represent interference problems with sidelobe-to-mainlobe coupling or coupling via other propagation mechanisms.

Surface rain-rate measurements were made at points below the 5K, 10K, 20K, and 30K scattering volumes for the entire experiment period—and additional gages were used at the transmitter and receiver sites in the high-accuracy phase of the experiment. The data for the entire year and each phase were processed to provide measurements of 1-min averaged rain rate. Additional meteorological data for storm alerts, storm tracking during rain events, and post-test analysis were obtained from an onsite S-band surveillance radar, a National Weather Service (NWS) weather radar, NWS rain gages, NWS upper air soundings (radiosondes), and surface observations made at the transmitter and receiver sites.

Data processing and analysis were accomplished during and after the experiment. Sufficient onsite examination of the data, calibration, and testing were performed to assure data quality. Computer reduction was used for phase Ia data and was performed at ITS. Hand reduction was used for phase Ib, phase II, and rain-gage data and was performed at GSFC. Analysis of the phase Ia data was performed by ITS (ref. 14). Analysis of data for the measurement year and of the auxiliary meteorological support data was performed at MIT Lincoln Laboratory (ref. 13).

1.3 SUMMARY OF RESULTS AND CONCLUSIONS

The experiment and equipment described in this report provided for the measurement of equivalent reflectivity and surface rainfall rates for a period of 1 yr. From these measurements cumulative distributions were prepared and analyzed (ref. 13). Of the 119 known rain events (either scatter level or rain rate above threshold) that occurred during the year, bistatic radar data were recorded and processed for a total of 107 events and rain-gage data for 82 events. A summary of the operating record of the primary measurement systems is given in table 1-1. Because of equipment and path redundancy, the only bistatic data loss occurred when the receiver was not functioning (with the exception of 1 hr, for the 3-km height, when transmitters malfunctioned simultaneously at the Eastville and Fort Lee sites). This occurred for a total of 7 of

Table 1-1.—Operating Performance Summary

Measurement period	Hours with measurements above event criteria and system operational			Hours not operational			Event hours with equipment not operational			Total duration of rain events, hr	Total measurement-period hours
	Bistatic		Gage	Bistatic		Gage	Bistatic		Gage		
	3 km	6 km	Surface	3 km	6 km	Surface	3 km	6 km	Surface		
Phase Ia	176	10	154	1	1	12	1	0	12	256	2904
Phase Ib	249	23	192	36	39	30	4	4	30	395	2952
Phase II	143	95	121	95	95	0	2	2	0	247	2904
Entire measurement year	568	128	467	132	135	42	7	6	42	898	8760

Table 1-2.—Equipment Accuracy Summary

System	Site	Path	Accuracy, dB ^a	
			Phase I	Phase II
Bistatic radar system	Eastville	10K	4.0, -5.0	±3.5
		20K	6.9, -4.9	5.8, -2.8
	Fort Lee	10K	9.9, -4.9	8.8, -2.8
		20K	9.9, -4.9	±3.0
	Best composite	10K	4.0, -5.0	±2.9
Rain-gage system	5K, 10K, 20K Langley, Eastville, Fort Lee	20K	6.9, -4.9	±3.0
			±1.6 ^b , ±1.8 ^c	±1.6 ^b , ±1.7 ^c
			Not used	±0.7 ^b , ±0.7 ^c

^aWhen applied to the rain gage system, dB refers to the maximum value for rate measurements expressed in dBZ using $Z = 200R^{1.6}$ or $\text{dBZ} = 23 + 16 \log R$.

^b12 mm/hr.

^c100 mm/hr.

898 hr of rain events at the 3-km height (99.2 percent reliability) and for 6 of 898 hr at the 6.1-km height (99.3 percent reliability). For the rain-gage system, data were lost only when snow and ice prevented operation of all gages simultaneously. This occurred for a total of 42 of the 898 hr of rain events (95.3 percent reliability). Bistatic radar data were missed during three events because of receiver malfunction. For two of these events, the rain-gage data indicate that only low-level signals were present; therefore, these two events will not affect the cumulative distributions. The other event missed was one of 18 events with surface rain rates exceeding 50 mm/hr. Although the event was significant because of the high rates, events with higher rain rates were observed and the distribution estimation error should be small. The gage data missed because of snow should have only a small effect on the measured cumulative distributions of surface rain rate because the effective precipitation rates in snow are generally quite small.

System measurement accuracy varied throughout the year depending upon the monitoring and calibration equipment available and the number of operating personnel in the field. The system accuracy estimates are summarized in table 1-2. As shown in the table, the accuracy for phase II (high-accuracy phase) is ± 2.9 and ± 3.0 dB for the measurements of equivalent reflectivity for the best composite 10K and 20K paths, respectively. The accuracy estimate for reflectivity Z based upon surface rain-rate measurements made during the same period is ± 0.7 dB. The accuracy of the equivalent reflectivity measurements for the best composite paths used to provide data for 1-yr distributions (phase Ia) is estimated to be $+4.0$ and -5.0 dB for the 10K and $+6.9$ and -4.9 dB for the 20K path. The accuracy of the reflectivity estimate based upon rain-gage data is ± 1.8 dB for the measurement year.

2 EXPERIMENT DESCRIPTION

This section describes the overall characteristics and operation of the Virginia Precipitation Scatter Experiment. It contains sections on experiment design, experiment configuration data processing, and errors and an operation summary. Other sections of this report will describe the bistatic radar and rain-gage systems and data processing in greater detail.

2.1 EXPERIMENT DESIGN CONSIDERATIONS

The Virginia Precipitation Scatter Experiment was designed to provide the cumulative distributions of transmission loss for a variety of transmitting/receiving antenna orientations and distances for use in preparing methods for the estimation of coordination distance for a given transmission loss $L(p)$, which must be exceeded for all but p , the percent of the year. In addition, the experiment was designed to demonstrate that the measured transmission loss values may be less than 162 dB for 0.01 percent of the year or that interference due to rain could occur.

A procedure for the estimation of a coordination distance for rain was incorporated in appendix 28 of the Radio Regulations as adopted at the 1971 WARC-ST (ref. 15). This procedure was prepared from the results of computations based upon single scattering theory, the bistatic radar equation, and the statistical properties of an ensemble of randomly positioned hydrometeors. The equation for transmission loss or the ratio of the interfering signal power transmitted by one system to that received by another used in the preparation of coordination procedures is given by equation (1) of reference 8:

$$L = \frac{P_t}{P_r} = \frac{r_2^2}{C_R G_2(\hat{r}_2) Z_e D} \quad (1)$$

where

L = transmission loss

P_t = transmitter power (mW)

P_r = receiver power (mW)

r_2 = distance from antenna 2 to the scattering volume (km)

C_R = equipment constant $\sim 6 \times 10^{-18}/\lambda^2$, λ = wavelength (cm)

$G_2(\hat{r}_2)$ = gain of antenna 2 in the direction of the scattering volume (Antenna 2 refers to the antenna with the broadest beam at the scattering volume for mainlobe-to-mainlobe coupling or the antenna whose sidelobes are involved in sidelobe-to-mainlobe coupling.)

Z_e = equivalent reflectivity; equal to the value of reflectivity as measured by a radar when the scattering cross section is formally related to Z using Rayleigh theory and the dielectric properties of liquid water (for rain and frequencies below 10 GHz, $Z_e = Z$) (mm^6/m^3)

Z = reflectivity; equal to the sum of the sixth powers of the raindrop diameters in a unit volume and is a meteorological parameter that depends only on rain-rate and raindrop-size distribution (mm^6/m^3)

D = extent of the scattering volume along the mainlobe of antenna 1 as defined by rain-cell size or, in the case of mainlobe-to-mainlobe coupling, the beamwidth of antenna 2 given by $r_2\theta_2/\sin\phi$, whichever yields the smallest value (km)

θ_2 = beamwidth of antenna 2 (radians)

ϕ = scattering angle

Equation (1) (p. 5) is recommended for use at frequencies below 5 GHz because the effect of attenuation has been neglected. For use in estimating coordination distances, the transmission loss required to provide adequate protection against interference must be known. When the specific system parameters are not known, it is recommended that (ref. 15)

$$L(0.01) = 177 - 10 \log T_R \quad \text{dB} \quad (2)$$

be used for the frequency band 3.4 to 4.2 GHz for the protection of fixed satellite system Earth terminals from interference from typical radio-relay systems. In this equation $L(0.01)$ is the transmission loss that must be exceeded for all but 0.01 percent of the year and T_R is the receiver noise temperature in kelvins. For a low-noise receiver system with $T_R = 50$ K, $L(0.01)$ may not be less than 160 dB. The pre-1971-WARC-ST coordination procedure as given in reference 12 also specifies a minimum basic transmission loss for the protection of fixed satellite system Earth terminals. From section 4 of reference 12,

$$L_b(0.01) = P_T - F_S - (P_W + B) - I_C + G_T + G_R \quad (3)$$

where

$$\begin{aligned} L_b(0.01) &= \text{basic transmission loss required for all but 0.01 percent of the year (dB)} \\ &= L(0.01) + G_T + G_R \end{aligned}$$

P_T = terrestrial station transmitter power in a 4-kHz band (dBW)

F_S = site shielding (dB)

P_w = carrier power subject to interference in a 4-kHz band at the receiver input (dBW)

B, I_C = parameters relating to the statistical properties of the interfering signal and the susceptibility of the assumed modulation technique to interference (dB) (See ref. 12.)

G_T = radio-relay (terrestrial) antenna gain (dBi)

G_R = Earth station antenna gain (dBi)

Using the values for $(P_T + G_T)$, P_w , B , and I_C for a 12-channel, angle-modulated satellite communication system and a typical radio-relay system as given in reference 12, and assuming $G_T = 40$ dBi and $F_S = 0$, the transmission loss that must be exceeded for all but 0.01 percent of the year is 162 dB.

An underlying element in the design of the bistatic radar system was to duplicate typical Earth stations and terrestrial microwave radio-relay stations in typical interfering configurations. The frequencies selected were 3.7 and 7.8 GHz, in or near frequency bands allocated for shared space and terrestrial communication system use. A total of 24 transmitter antenna orientation, scattering angle, scattering volume height, frequency, and distance combinations or paths were used. The transmitter sites were positioned and antenna pointing angles adjusted so that on 11 of the paths no measurable received signal could be obtained by nonprecipitation propagation mechanisms in accordance with pre-1971-WARC-ST siting criteria. These paths were used for the bistatic scatter cross-section measurement because they were free of contamination by other propagation modes. For economy, the receiver system multiplexed the 24 combinations into eight receiving recording channels by sampling each of the paths for 1 min out of every 4 (except as noted in table 3-3). During the 1-min sampling interval, continuous-wave (cw) transmission was used. The experiment was operated in this mode for the duration of the exploratory phase (phase Ia, 2904 hr from October 3, 1970, through January 31, 1971).

Acceptance and use of equation (1) (p. 5) implies that sufficient information for testing the statistical performance of transmission loss prediction schemes may be obtained from measurements of Z_e at several heights. The rain-cell-size model used in conjunction with equation (1) in preparing the coordination procedure assumed that all cells have a uniform horizontal size of 3.5 km at the half scattering intensity points. Using a cell size of 3.5 km and typical cell translation velocities of 10 to 20 m/s, the cell would pass through the scattering volume in 3 to 6 min. A sampling sequence that observed the equivalent reflectivity of a scattering volume for 1 min out of 4 was not compatible with the requirement of reliably measuring the cumulative distribution of the short duration scatter phenomena for percentages of the time between 0.001 to 0.01 percent of the year (5 to 53 min) as required for interference prediction. To provide the required measurements and to increase the reliability of the bistatic cw radar system by both simplifying the system and providing redundant measurements, the number of scattering volume heights investigated was reduced to two

(10K and 20K), the number of transmitting sites was reduced to two (Eastville and Fort Lee), the X-band measurements were eliminated, and the sampling sequence was modified. With this reconfiguration, simultaneous observations of scatter from the volume at 3-km height were made using transmissions from both sites. Continuous observations at the 6-km height were made using alternate 1-min-duration transmission from one site and then the other. During the alternate minutes, when the 6-km height was not sampled, the great circle (GC) path was sampled to study both sidelobe-to-mainlobe coupling and other propagation mechanisms. The reconfigured experiment was operated for the duration of the high-accuracy phase (II), 2904 hr from June 4, 1971, through October 2, 1971. The transitional phase (Ib) of the experiment covered the 2952 hr of operation between January 31, 1971, and June 4, 1971, during which time the experiment reconfiguration was accomplished.

A goal of the NASA rain interference study program is the estimation of the statistics of interference levels using available meteorological data. The rain coordination procedure (ref. 15) accomplishes this through the use of rain climate zones, each characterized by a specific cumulative distribution of surface rain rate and specific values for rain-cell height and width (ref. 8). One-min-averaged rain-rate distributions were measured, both under the scattering volumes used in the bistatic radar system and at several of the transmitting and receiving sites. The measurements were made to construct reflectivity distributions for comparison with the measured equivalent reflectivity distributions, the distribution used in reference 15 to characterize the rain climate of southeastern Virginia, and distributions proposed by other investigators. The rain-gage measurements were averaged over a 1-min interval as a compromise between the requirement for a long measurement interval to reduce sampling noise and a short interval to track changes due to cell motion.

Surface rain accumulation measurements were obtained from the NWS gages located in the general area of the experiment to aid in assessing the measurement accuracy of the experiment gages and to provide a tie between the particular measurement year and the climatology of the area. For storm alerting, to track storms in progress, and as an aid in establishing the general synoptic weather conditions for each rain event, weather radar data from the NWS station at Patuxent River Naval Air Station in Maryland were monitored. An onsite S-band radar was also used in this capacity to track rain cells in the vicinity of the scattering volumes and to qualitatively indicate the change of equivalent reflectivity with height. Surface and upper air temperature soundings were required to establish the existence of rain or snow at the surface during the winter months and to indicate hydrometeor state changes with height. The surface data were obtained using meteorographs (an instrument for measuring temperature, pressure, and relative humidity) located at several of the transmitter and receiver sites. Upper air data were obtained from NWS radiosonde measurements.

GC path transmissions were monitored throughout the experiment to aid in assessing the possible contamination of the bistatic radar measurements by signals propagated via other mechanisms. During phases Ib and II, this system used 10-ft (3.0-m) transmitting antennas at both of the transmitter sites and horn antennas at the receiver site. The GC path antennas were oriented at elevation angles below 1° and pointed at each other along a great circle. The GC path transmissions were also monitored via the sidelobes of the 30-ft receiving antenna.

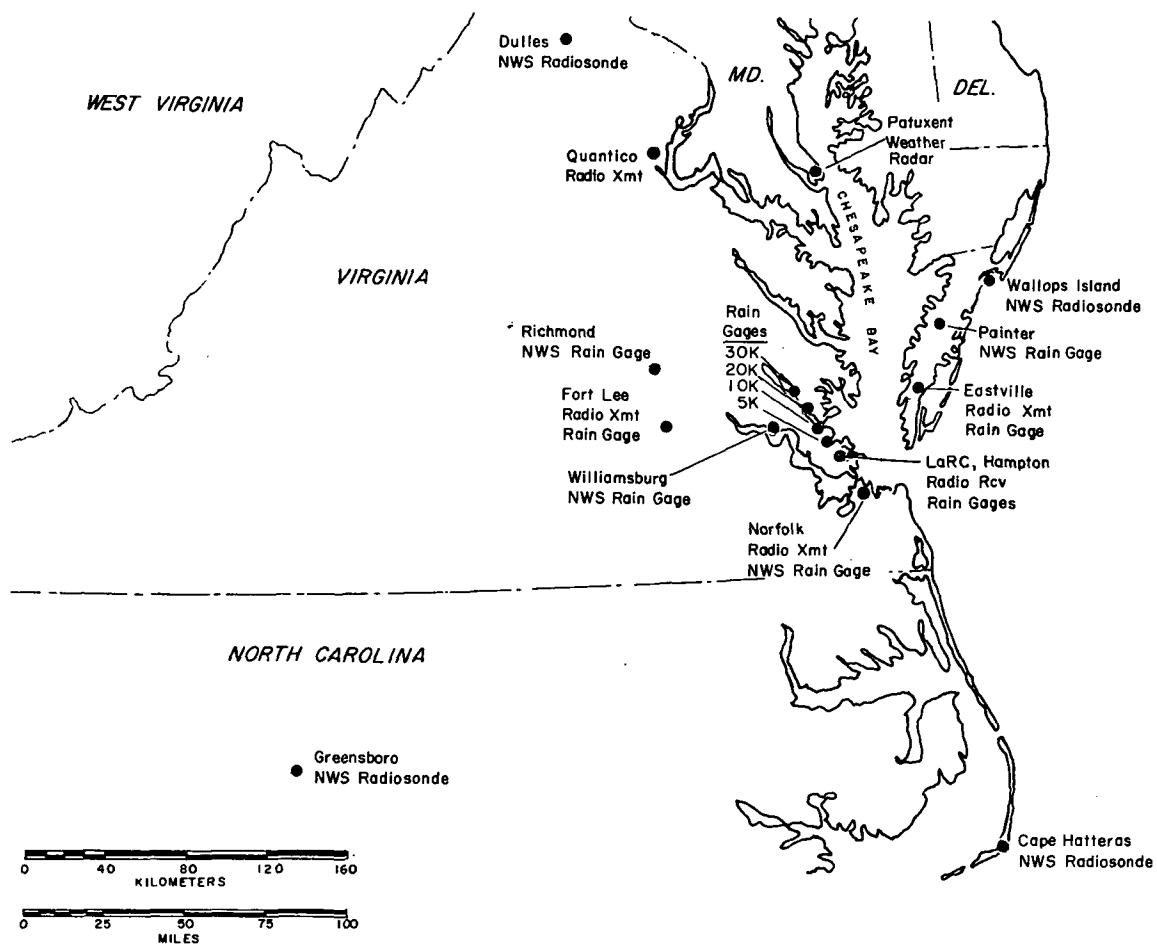


Figure 2-1.—Experiment area map.

2.2 EXPERIMENT CONFIGURATION

The primary measurement systems and auxiliary meteorological support systems were located in southeastern Virginia as shown on the experiment area map, figure 2-1. This area is designated as “rain climate 1” in reference 15 and may be characterized as having relatively more rain of high rates and higher cell heights than other rain climates. Simplified representations of the equipment configuration and path geometry are given in figures 2-2 and 2-3. Table 2-1 itemizes the locations and numbers of each of the measurement systems and their functions, and summarizes the methods used to process the measurements. This table presents the experiment configuration for each of the experiment phases.

2.2.1 Bistatic Radar System

2.2.1.1 Path Geometry

The receiver site was located at NASA Langley Research Center (LaRC) in Hampton, Va. The four transmitter sites were located on the Quantico Marine Corps Base near Triangle, Va.;

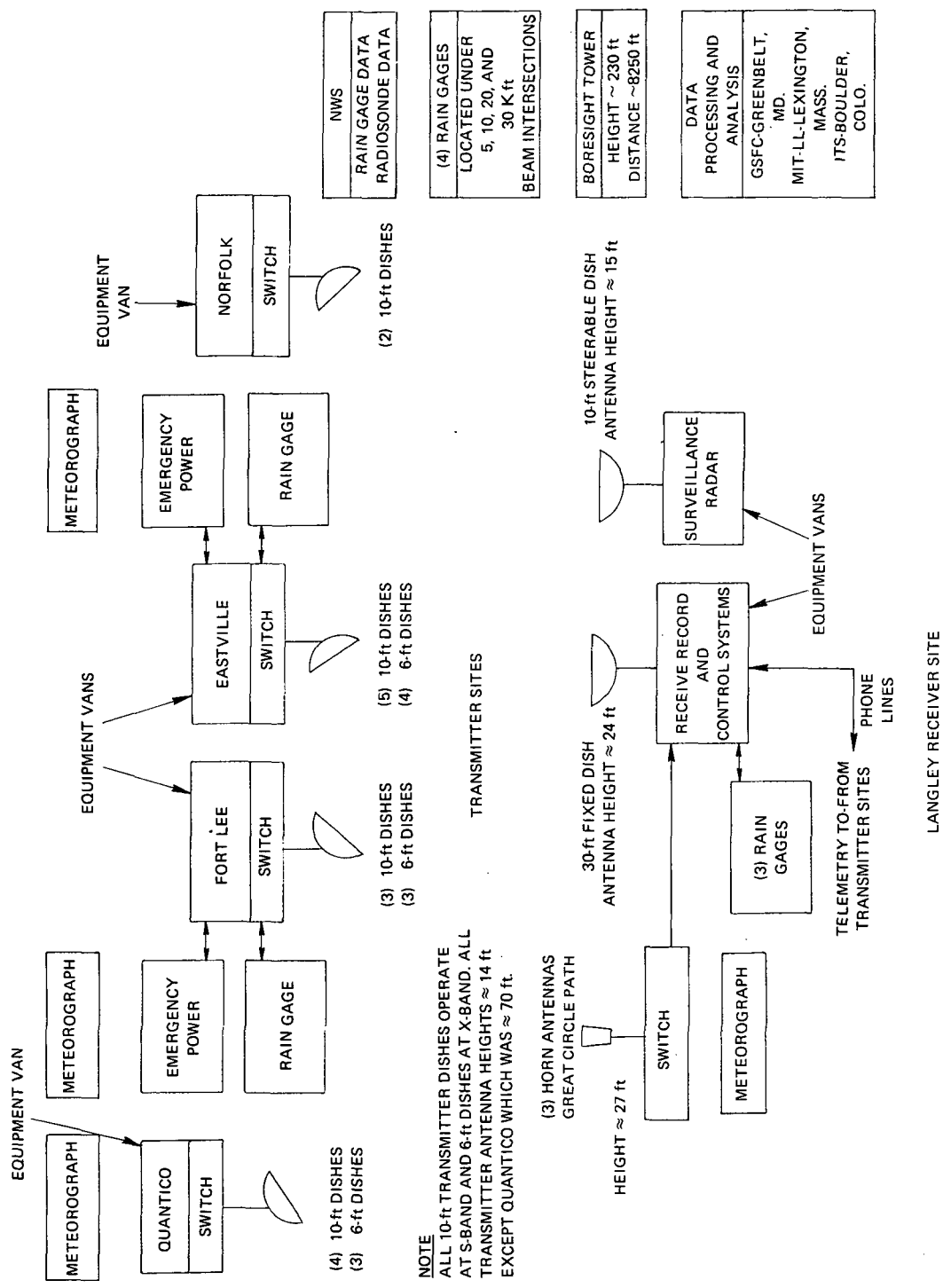


Figure 2-2.--Experiment configuration.

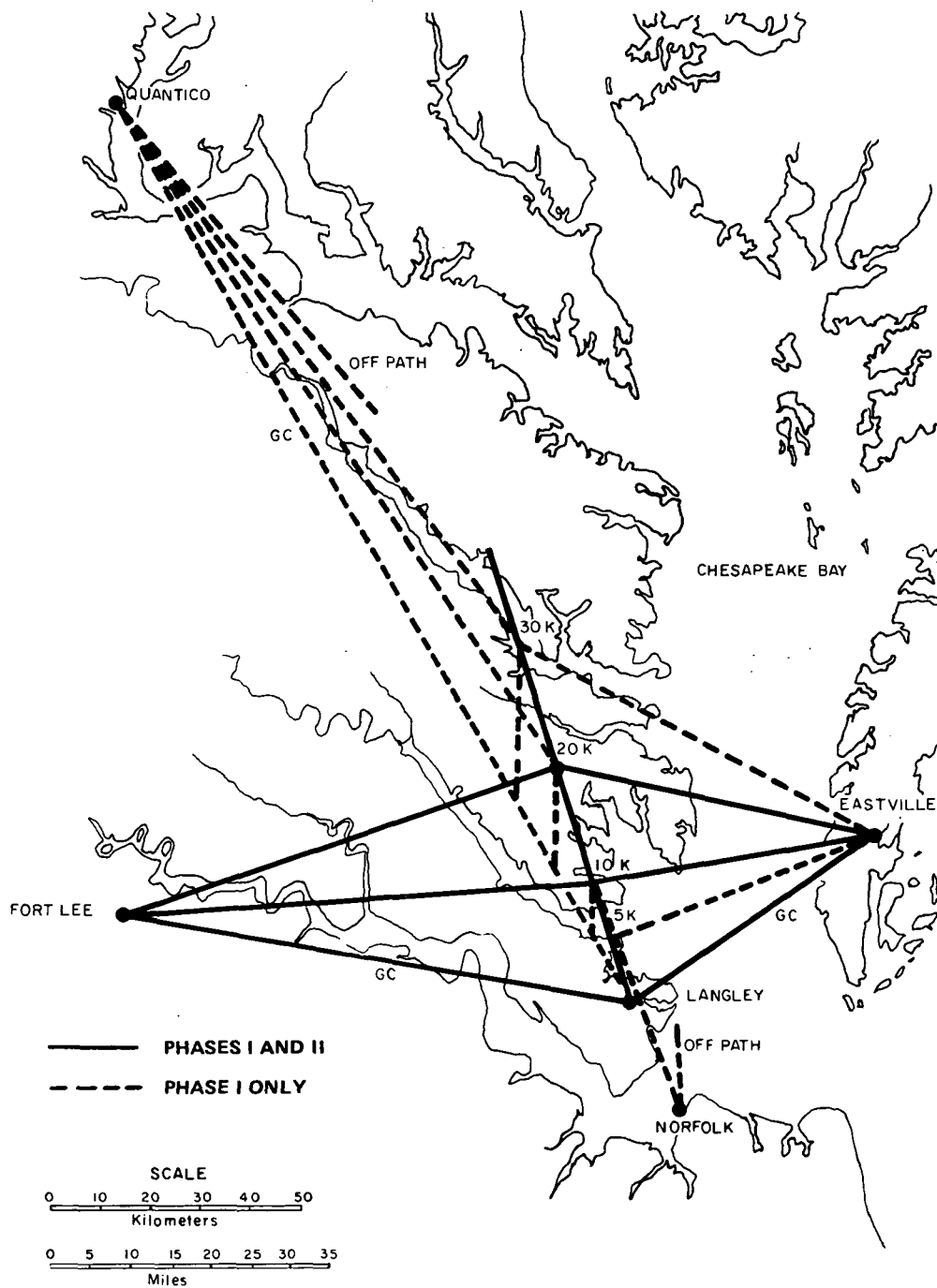


Figure 2-3.—Path geometry.

Table 2-1.—Subsystem Summary^a

Measurement	System	Phase Ia			Phase Ib			Phase II		
		Number of paths	Location	Processing	Number of paths	Location	Processing	Number of paths	Location	Processing
Bistatic radar cross section ^b	Bistatic radar	18	(^c)	Automatic A/D conversion, computer averaged	2	E-10S-L ^d F-10S-L ^d E-20S-L ^d F-20S-L ^d	Manually processed, subjective average Hourly summaries	2	E-10S-L F-10S-L E-20S-L F-20S-L	Manually processed, computer averaged Manually processed, subjective average
GC path transmission loss (side-lobes 30-ft antenna)	Bistatic radar	4	(^c)	Automatic A/D conversion, computer averaged	14 2	(^c) EGCS-L F-GCS-L	Not processed Hourly summaries	2	— EGCS-L F-GCS-L	— Hourly summaries
Nonintersecting beam transmission loss	Bistatic radar	2	(^c)	Automatic A/D conversion, computer averaged	2	(^c)	Not processed	—	—	—
GC path transmission loss (horn antenna)	GC path	—	—	—	2	Q-OPS-L N-OPS-L	Not processed	—	—	—
Surface rain rate ^b	Rain-gage network	4	5K, 10K, 20K, 30K	Manually read, computer averaged	2	EGCS-L F-GCS-L	Not processed	2	EGCS-L F-GCS-L	Hourly summaries
Surface accumulation	Rain-gage network NWS radar	1	T	Manually read, computer averaged	1	Q-GCS-L	Not processed	—	Same as phase Ia	—
Areal structure of rain	S-band	1	—	—	—	—	—	—	—	—
Surface accumulation	NWS gage network	4	Richmond, Norfolk, Williamsburg, Painter	NWS hourly precipitation data, Virginia	—	—	—	4	E8, F8, L8, L19 LC	Manually read computer averaged Manually read
Surface temperature	Meteorograph	12	Gages within 40 miles Langley	NWS climatological data, Virginia supplement	—	—	—	—	—	—
Upper air temperature and wind	Radiosonde	4	Dulles, Wallops Island, Greensboro, Cape Hatteras	NWS data, computer reduced	3	E, F, L	Manually examined	3	E, F, L	Manually examined

^aA/D = analog to digital; E = Eastville; F8, F8, L8, L19 = location of rain gage and orifice diameter in inches; F = Fort Lee, GCs = great circle path, S-band; L = LaRC; LC = accumulating gage at LaRC; N = Norfolk; OPS = Non-intersecting beams, S-band; Q = Quantico; T = bore-sight tower; (5K, 10K, 20K, 30K) = common volume subpoint; 10S, 20S = scattering volume location, S-band.

^bPrimary measurements.

^cSee table 2-2.

^dPrimary paths.

Fort Lee near Petersburg, Va.; the Norfolk Navy Base in Norfolk, Va.; and a NASA site near Eastville, Va. The receiving antenna was directed along the GC toward Quantico at an elevation angle of 13.5° . Antennas at the transmitter sites were directed towards the 5K, 10K, 20K, and 30K scatter volumes on the receiver mainlobe as specified in table 2-2. At Quantico, Eastville, and Fort Lee, antennas were also directed along the GC toward LaRC to provide a reference troposcatter path. The paths from Eastville and Fort Lee to the receiver via the 10K and 20K scatter volumes are considered the primary bistatic radar measurement paths because of (1) their relatively small scattering volume dimensions (2) the relatively large angular distance between the GC and mainlobe azimuth directions (which helps suppress contamination via other propagation mechanisms).

The general terrain in the experiment area over which the scatter paths pass can be characterized as low rolling hills with large areas of water. The paths from Fort Lee to LaRC and the common volumes of intersection are mainly over land; the paths from Eastville are mainly over water. Obstructions along the path are possible only in the immediate foreground of the antennas because of the nature of the terrain and relatively high elevation angles. The photographs in figure 2-4 were taken at Eastville from just in front of the antennas at approximately the antenna height. The ground in front of the antennas is grass covered to the thin row of trees at a fence line approximately 0.3 km from the antennas. Beyond the tree line is cultivated land. To the right under the 30K antenna beam there is a heavy grove of trees. The cross marks the top of the tree line at the antenna azimuth and the circle marks the approximate position and size of the antenna main beam. The angular separation between the obstructions and tree line for the 10K, 20K, and 30K paths is large and, due to the transmitting antenna patterns, the paths may be considered to be unobstructed or have no site shielding. For these paths the maximum sidelobe level in the direction for specular reflection from the flat field in the foreground is -30 dB with respect to the peak of the mainlobe and, assuming a unity reflection coefficient, the maximum effect of surface multipath is to change the signal level at the common volume by less than 0.3 dB. The 5K path has treetops at the center of the mainlobe. The trees are deciduous and in the winter provide a minimum of blockage and attenuation due to scatter. For phase Ia, the path may be considered unobstructed; it was not used during the other phases. The GC path is shown as passing through the trees. This path was not used for quantitative measurements and any blockage effects were ignored.

The foreground of the Fort Lee site is shown in figure 2-5. At this site, the foreground out to the grove of trees is mainly asphalt paving and, for the 10K and 20K paths, is illuminated only by sidelobe levels less than -15 dB with respect to the peak of the mainlobe. For these paths, the maximum sidelobe level for specular reflection is less than -26 dB with respect to the peak of the mainlobe resulting in less than a 0.4-dB change in the signal at the common volume due to multipath. The distance to the trees is about 0.7 km. Both the GC and 10K paths show obstructions by rather dense stands of trees. The trees are coniferous and their electrical properties should change only slightly with season. Using simple knife-edge diffraction theory to bound the possible effect of the obstruction and for the distance, wavelength, beamwidth, and common volume size that apply to this path, the

Table 2-2.—Bistatic Radar System Path Summary

Site	Path		Antenna pointing angle, ^a deg		Scatter volume parameters							System sensitivity			
					Height, km	Distance, km		Scatter, angle, deg	Dimensions		Scale constant, ^b dB	L, dB	Z _e , dBZ		
	Designation	Fre- quency band	Azimuth	Elevation					Along receiving beam, km	Across receiving beam, km				K _L	K _P
						To transmitter	To receiver								
L E	c ₁	All	S, X	333.1	13.5									163	21
	d ₂	GC	S	237.3	.8									163	21
	c ₃	5K	S	245.2	1.6	1.6	50.5	6.6	92.2	1.72	0.079	184	144	163	21
	c ₄	10K	S	252.1	3.6	3.0	51.1	12.9	99.4	1.76	.154	184	144	163	21
	d ₅	20K	S	265.2	6.2	6.1	54.7	25.7	112.7	2.02	.306	184	144	163	21
F	d ₆	30K	S	277.0	8.4	9.3	61.2	39.4	124.6	2.53	.470	184	144	163	21
	c ₇	GC	X	237.9	.8									155	22
	d ₇	5K	X	245.2	1.6	1.6	50.5	6.6	92.2	1.41	.046	177	137	155	22
	d ₈	10K	X	252.5	3.3	3.1	51.2	13.2	99.7	1.45	.092	177	137	155	22
	d ₉	30K	X	277.0	8.4	9.3	61.2	39.4	124.6	2.08	.275	177	137	155	22
	c ₁₀	GC	S	101.5	1.0									163	22
	c ₁₁	10K	S	94.0	2.1	3.0	78.1	12.8	60.4	3.06	.153	185	145	163	22
	c ₁₂	20K	S	84.6	4.4	6.3	72.2	26.8	70.0	2.61	.319	185	145	163	22
	d ₁₃	GC	X	101.1	.8									155	23
	d ₁₄	10K	X	93.7	2.0	3.1	77.9	13.1	60.6	2.50	.091	178	138	155	23
Q	d ₁₅	20K	X	85.0	4.6	6.2	72.4	26.4	69.7	2.16	.184	178	138	155	23
	16	GC	S	152.2	.3	2.8	167.4	11.8	15.4	14.93	.141	183	143	163	20
	17	20K	S	152.2	1.8	6.3	152.8	26.9	16.9	17.89	.321	183	143	163	20
	18	30K	S	152.2	3.3	9.4	140.7	39.7	18.4	15.17	.473	183	143	163	20
	19	Op ^e	S	148.2	.3									163	20
N	20	GC	X	152.2	.3	2.8	167.4	11.8	15.4	13.00	.082	177	137	155	22
	21	20K	X	152.2	1.8	6.3	152.8	26.9	16.9	14.68	.188	177	137	155	22
	22	30K	X	152.2	3.3	9.4	140.7	39.7	18.4	12.45	.277	177	137	155	22
	23	10K	S	337.3	5.8	3.1	29.6	13.2	171.4	6.74	.157	173	133	163	10
	24	Op ^e	S	344.7	.8									163	10

^aThe pointing angles are as originally installed except for the paths used in phase II which are as measured at the end of the experiment. (See table 3-5.)

^bZ_e = K_L - L (in dB, see eq. (7), p. 20); Z_e = K_P - P_r (in dB, where P_r = received power in dBmW).

^cPath used in phase II.

^dPath with small common volumes.

^eOP = off path.

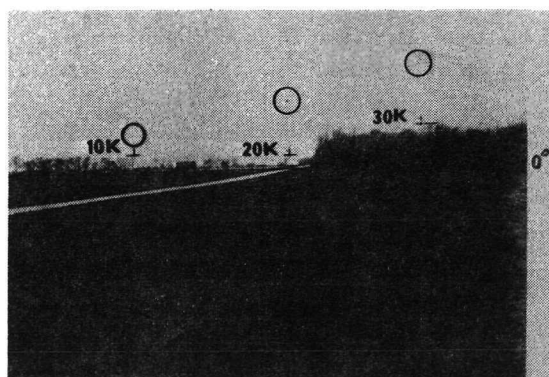
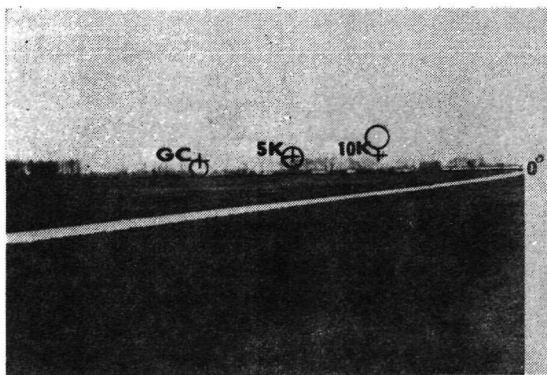


Figure 2-4.—Foreground and horizon at the Eastville transmitter site.

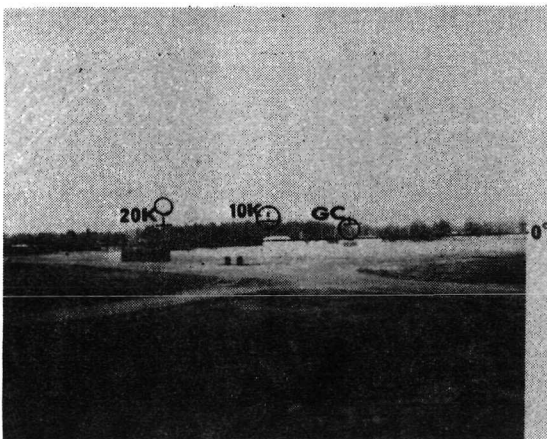


Figure 2-5.—Foreground and horizon at the Fort Lee transmitter site.

effect of the trees is to reduce the size of the common volume by blocking a fraction of the beam. From the photograph it appears that for the pointing angles listed in table 2-2 indicated by the circle, the trees block less than one-third of the beam and the additional path loss is estimated to be between 0 and 2 dB.

The foreground of the receiving antenna is shown in figure 2-6 and is a composite photograph over a 180° arc. The approximate azimuth and elevation scales are marked on the border of the photograph. On the GC path toward Eastville, about 57.7° azimuth, there is a small grove of trees with marsh grass and open water beyond; toward Fort Lee, about 281.7° azimuth, there is a grove of trees in the immediate foreground, then a short open space and more trees. For scattering from the 5K, 10K, 20K, and 30K volumes, no obstructions are evident. For the GC path from Fort Lee, however, blockage does occur due to the trees in the immediate foreground for signals received either by the horn antennas or the sidelobes of the 30-ft antenna. Receiving antenna pattern measurements were made using a source on the boresight tower located at azimuth and elevation angles of 2.4° and 1.4° , respectively. A clump of trees may be seen midway between the antenna and the tower. The trees were just below the line of sight and using simple knife-edge diffraction theory and the signal level at treetop as determined from the pattern of the 30-ft antenna, an error of 0.5 dB may occur in the measurement of antenna gain.

2.2.1.2 System Summary

The bistatic scatter measurements were made using vertically polarized cw transmission from switched antennas at the

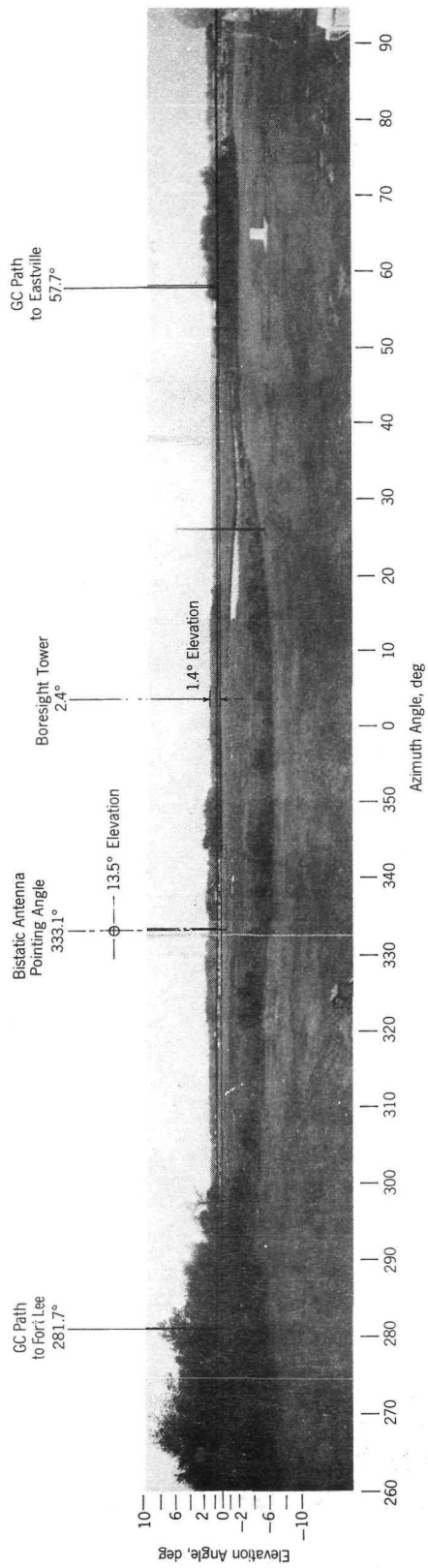


Figure 2-6.—Foreground and horizon at the LaRC receiver site.

transmitter sites and a narrowband, multichannel receiver system. A simplified system block diagram is given in figure 2-7. All transmitter sites were similar, the differences being in the number of antennas, their pointing angles, and the number and frequency of the transmitters (described in sec. 3). The rf frequencies were derived independently from a single standard frequency oscillator at each site having a 24-hr stability of five parts in 10^{10} . The rf output of each transmitter was nominally 10 W and was stabilized by means of an rf leveling loop. The antennas used were 10-ft (3.0-m) parabolic dishes at S-band and 6-ft (1.8-m) dishes at X-band. Radiofrequency monitoring equipment was provided along with a telephone line telemetry system to display the operating status of the transmitters at the receiver site.

At the receiver site a single 30-ft (9.1-m) parabolic dish with a dual-frequency feed horn was used. After rf amplification in a tunnel diode preamplifier with a noise figure of approximately 8 dB, the signals were heterodyned down to 9.6 MHz where they were separated by narrowband crystal filters, each having a nominal bandwidth of 2 kHz. Adjacent channel rejection was approximately 60 dB. Each crystal filter was followed by a log-linear amplifier-detector that had a dc output proportional to the log of the amplitude of the i.f. input signal. The receiver system had a dynamic range in excess of 50 dB. Calibration of the system was automatic and occurred every 2 hr. An override capability was provided for canceling a calibration if desired. This option was exercised on several occasions during periods of strong received scatter signals. Means were provided at the transmitter and receiver sites for monitoring and recording critical signal and voltage levels. A summary of the bistatic radar system characteristics is given in table 2-3. Data from the receiver systems were recorded on an eight-channel strip chart and a 14-channel analog magnetic tape. The data bandwidth for both recording systems was from dc to approximately 100 Hz.

During phase II, the 10K paths from Eastville and Fort Lee were illuminated continuously and an automatic switchover capability was provided so that if the 10K transmitter failed, the GC-20K transmitter would automatically be substituted in its place. The GC-20K paths were sampled alternately (switched) providing a sample of 1 min of every 2 for each path. Timing for the switching cycle was derived independently at each site from the standard oscillator. Temperature stabilization of critical components in both the transmitter and receiver systems was provided to maintain gain stability. The signals received from the 10K intersections were integrated (1.5-s time constant) prior to recording on the strip charts. Spare data recorders were provided. Calibration was performed on one narrowband receiver channel at a time while the other channels operated to maintain continuity of data.

During phase I the automatic switchover capability was not provided, and the 10K paths were switched. The switching sequence provided a sampling of 1 min out of every 4 with the exception of four paths as indicated in table 3-3. Timing for the transmitter switching was controlled from the receiver site via the telemetry system for the period listed in table 3-2. With this method, synchronization would be lost occasionally because of telephone line "hits" and outages. Also, during phase I, a diplexer was used to separate S- and X-band signals and an X-band receiver was provided. Temperature stabilization was not provided. The calibration system was less accurate and required more time. The transmitters were not operated during the entire calibration sequence causing a net loss of 15 min of

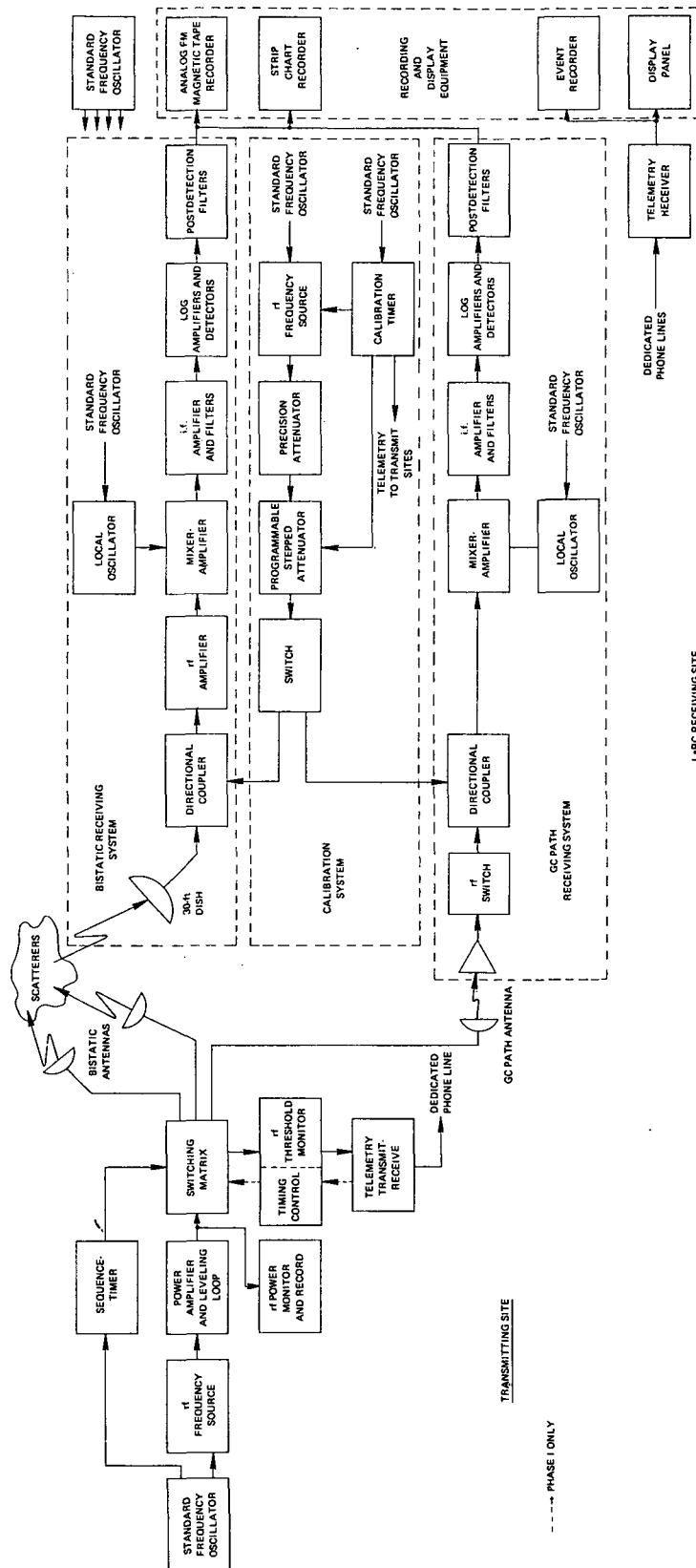


Figure 2-7.—Simplified bistatic and GC system block diagram.

Table 2-3.—Bistatic Radar System Parameters (Nominal)

System parameters	S-band	X-band
Transmitter:		
Antenna diameter	10 ft	6 ft
Antenna polarization	Vertical	Vertical
Antenna gain	38.8 dBi	41.0 dBi
Beamwidth (3 dB)	1.95°	1.6°
Sidelobe levels	-22 dB	-21 dB
Transmission line loss	4.4 dB	3.6 dB
Transmitter output power	10 W	10 W
Frequency	3.672 GHz	7.834 GHz
Frequency stability	5×10^{-10} /day	5×10^{-10} /day
Receiver:		
Antenna diameter	30 ft	30 ft
Antenna polarization	Vertical	Vertical
Antenna gain	48.0 dBi	50.8 dBi
Beamwidth (3 dB)	0.68°	0.40°
Sidelobe levels	-21 dB	-18 dB
System noise figure	8 dB	16 dB
Bandwidth	2 kHz	2 kHz
Dynamic range	50 dB	50 dB
Frequency stability	5×10^{-10} /day	5×10^{-10} /day

data every 2 hr. The 10K path signals also were not integrated nor were spare recorders provided. Detailed differences between the phase I and II systems are given in section 3.

2.2.1.3 Path Loss Computations

The transmission loss due to rain scatter was given by equation (1), page 5. The sensitivity of the bistatic radar system for the measurement of equivalent reflectivity may be determined from this equation and from the nominal transmitter and receiver characteristics listed in table 2-3. From equation (1) for intersecting beams with a common volume filled with hydrometeors, the equivalent reflectivity is

$$Z_e = \frac{r_2 \sin \phi}{LC_R G_2(\hat{r}_2)\theta_2} = \frac{P_r r_2 \sin \phi}{P_t C_R G_2(\hat{r}_2)\theta_2} \quad (4)$$

Using a 10-dB signal-to-noise ratio (S/N) as a criterion for useful signal detection, the received power is found to be

$$P_r = kT_0 Bf(S/N) = 10kT_0 Bf \quad (5)$$

where

k = Boltzmann's constant

T_0 = standard temperature (290 K)

B = receiver i.f. bandwidth (Hz)

f = system noise figure

The equipment constant C_R (ref. 16 and ref. 11, eq. (9) where $C_R = A_R m$ with A_R as defined in ref. 11) is

$$C_R = \frac{1.86 \times 10^{-18} m \theta_1^2 G_1 l_1 l_2 |k|^2}{\lambda^2} \quad (6)$$

for intersecting gaussian-shaped antenna patterns, where

m = polarization mismatch factor (ratio < 1)

θ_1 = half-power beamwidth of antenna 1 (rad)

G_1 = gain of antenna 1 in the direction of the mainlobe (peak)

$l_1 l_2$ = transmission line loss factors for antennas 1 and 2 (ratio < 1)

$|k|^2 = |(\epsilon - 1)/(\epsilon + 2)|^2$; ϵ = complex dielectric constant for liquid water at 0° C for wavelength λ

Using the values in table 2-3 and 0.935 for $|k|^2$ (ref. 11),

$$\begin{aligned} C_R &= \frac{5.3 \times 10^{-18}}{\lambda^2} = 7.9 \times 10^{-20} \quad \text{at S-band} \\ &= \frac{4.1 \times 10^{-18}}{\lambda^2} = 2.8 \times 10^{-19} \quad \text{at X-band} \end{aligned}$$

The computations of minimum detectable Z_e for the primary measurement paths are detailed in table 2-4; results for all the paths that have common volumes are listed in table 2-2. For paths with no common volume, only the minimum detectable transmission loss for $S/N = 10$ dB is given. The transmission loss for all cases is found from the definition of transmission loss (P_t/P_r) and equation (5), page 19. The scale constants K_L and K_P are used to convert from transmission loss L or received power P_r to equivalent reflectivity and are listed in table 2-2. From equation (4) (p. 19),

$$K_L = 10 \log L + \text{dBZ} = 10 \log \frac{r_2 \sin \phi}{C_R G_2 (\hat{r}_2) \theta_2} \quad (7)$$

$$= 166.9 + 10 \log (r_2 \sin \phi) \quad \text{dB, S-band}$$

$$= 160.0 + 10 \log (r_2 \sin \phi) \quad \text{dB, X-band}$$

$$K_P = K_L - 10 \log P_r = K_L - 40 \quad (8)$$

where K_L and K_P are in decibels, $\text{dBZ} = 10 \log Z_e$, and the values for S- and X-bands were obtained from the nominal parameters listed in table 2-3.

Table 2-4.—Minimum Detectable Equivalent Reflectivity for Primary Paths.

Parameter	Value	dB equivalent for each path ^a			
		E-10S-L	F-10S-L	E-20S-L	F-20S-L
System:					
Frequency, GHz	3.672				
Wavelength λ , cm	8.164	18.2	18.2	18.2	18.2
Polarization	Vertical				
Modulation	cw				
Constant ^a	1.86×10^{-18}	177.3	177.3	177.3	177.3
Transmitter:					
Power P_t , mW	10^4	-40.0	-40.0	-40.0	-40.0
Antenna size, m	3.05				
Antenna gain $G_2(r_2)$, dBi	38.8	-38.8	-38.8	-38.8	-38.8
Beamwidth θ_2 , rad	0.034	14.7	14.7	14.7	14.7
Line loss l_2 , dB	-4.4	4.4	4.4	4.4	4.4
Path:					
Distance from transmitter to common volume r_2 , km					
Sine of scatter angle ϕ	-.3	-.1	-.6	-.3	-.3
Polarization mismatch $ \kappa ^2$	0.935	.3	.3	.3	.3
Receiver:	2×10^3				
Bandwidth B , Hz	-174.0	33.0	33.0	33.0	33.0
Noise power/unit B kT_0 , mW/Hz	8	-174.0	-174.0	-174.0	-174.0
Noise figure f , dB	10	8.0	8.0	8.0	8.0
Signal to noise S/N , dB	48.0	10.0	10.0	10.0	10.0
Gain G_1 , dBi	0.0	-48.0	-48.0	-48.0	-48.0
Line loss l_1 , dB	0.12	.0	.0	.0	.0
Beamwidth θ_1 , rad		38.5	38.5	38.5	38.5
Equivalent reflectivity ^b					
Z_e , dBZ		20.9	22.2	21.0	22.2
Rain rate ^b R , mm/hr		^c .7	^c .9	^c .7	^c .9
Transmission loss ^b L , dB	5.0×10^{-13}	163.0	163.0	163.0	163.0
Receiver power ^b P_r , mW		-123.0	-123.0	-123.0	-123.0

^aValues are given as required in eqs. (4) to (8); i.e., the dB equivalent for λ^2 rather than λ is listed; dBZ is found by summing each column.

^bMinimum detectable values for $S/N = 10$ dB.

^cIn mm/hr.

The minimum detectable Z_e results in approximately 22 dBZ for both frequencies. This corresponds to a transmission loss of 163 dB at S-band and 155 dB at X-band. The S-band system has sufficient sensitivity to detect signals corresponding to the interference threshold (162-dB transmission loss) of an Earth terminal receiver system. For optimum

receiver operation, the input signal should, however, be in the range from -114 to -64 dBmW corresponding to the region where the receiver output voltage is linearly related to the logarithm of the amplitude of the input signal. At S-band this corresponds to transmission loss values between 154 and 104 dB and equivalent reflectivity values between 30 and 80 dBZ, respectively.¹ Using the “standard” relationship between equivalent reflectivity and rain rate (ref. 17),

$$Z = 200R^{1.6} \quad (9)$$

where R is in mm/hr, the measurement range is between 3 and 3700 mm/hr, and the minimum detectable rain rate for $S/N = 10$ dB corresponds to 0.8 mm/hr. The minimum detectable rain rate for the primary paths is listed in table 2-4.

2.2.1.4 Operating Procedure

During phase II, all sites were manned during precipitation events and systems were calibrated before and after each event. During clear weather the transmitter systems were checked daily and the antenna pointing positions and radiated power were tested every 2 weeks. (See sec. 3.5.) The receiver site was manned and checked during the day and spot checked at night. At all times a single individual, the “duty officer of the day,” was responsible for monitoring the system and the weather and for calling storm alerts or watches when rain was possible or likely. When this situation existed the duty officer notified designated operations personnel, who went to the sites and calibrated the systems. Operations personnel lived close to the sites and could normally reach them less than ½ hr after notification. On occasion, operating personnel notified the duty officer that local conditions were such that a rain event was likely.

During phase I, the transmitter sites operated unattended. They were checked and calibrated weekly and when the remote status display system indicated transmitter malfunction. The receiving site was manned during the day and all personnel were on standby 24 hr a day. Storm alerts were called by all operating personnel.

2.2.2 Rain-Gage Network

2.2.2.1 System Summary

The rain-gage network consisted of a total of seven tipping-bucket gages—three located beneath the 5K, 10K, and 20K scattering volumes, one at Eastville, one at Fort Lee, and two at LaRC—and a collecting rain gage at the LaRC receiver site for measuring the total accumulation for each event. Three of the four gages used at the sites also had catchment containers for measuring total accumulation. Two additional gages were part of the original installation, one beneath the 30K scatter volume and the other at the boresight tower, but these gages were subject to an excessive number of failures and were not used in the data analysis.

The tipping-bucket gages were used to measure the 1-min averaged rain rate used in constructing rain-rate distributions. The locations and calibration constants for each gage

and experiment phase are shown in table 2-5. Except for the 1829-cm²-collecting-area gage (19-in. diameter) at LaRC, each of the recording gages at the transmitter and receiver sites were adjusted to indicate tips or successive accumulations of approximately 0.25 mm (0.01 in.) of rain. The gages located near the scattering volumes were adjusted to indicate successive accumulations of approximately 0.51 mm (0.02 in.) during phase II and 0.25 mm (0.01 in.) during phase I. The nominal 0.25-mm-per-tip gages had a useful measurement range of between 5 and 100 to 200 mm/hr depending on the gage and the recording system used. The lower rate limit was set by the natural variability of rain and the long time interval between tips that occurs at low rain rates. The higher limit was set by gage calibration error and the recording system. The gages located in the vicinity of the common volumes used a recording system with a chart speed of approximately 1 cm/hr. For these gages, the 1-min averaged rate cannot be determined with precision above about 15 mm/hr primarily because of the 2- to 3-min averaging time inherent in the reading process. The other gages used higher chart speeds and were calibrated over a range of rain rates to provide better estimates of the higher rates. The 19-in. gage was used to extend the measured range down to about 1 mm/hr because it tipped more often at a given rain rate. The 1829-cm² collecting area of the 19-in. gage was obtained by masking a portion of a larger 7316-cm² collecting area (38 in.) on the gage. The larger collection area was not used during the experiment.

2.2.2.2 Gage Siting

The gages were located as shown in figure 2-1 either to provide a measurement in the vicinity of the scattering volume or to provide measurements in the experiment area at

Table 2-5.—Rain-Gage System Summary

Gage no.	Location	Phase or period of recording	Type ^a	Collecting area, cm ²	Calibration, mm/tip
1	L	I, II	Can	324	
2	L	II	I (19 in.)	1829	0.08
3	L	II	I (8 in.)	324	.27
4	E	II	I	324	.29
5	F	II	I	324	.29
6	5K	I	II	324	.25
6	5K	II	III	159	.51
7	10K	I	II	324	.25
7	10K	II	III	159	.51
8	20K	I	II	324	.25
8	20K	II	III	159	.51
9	30K	I	II	324	.25
9	30K	II	III	159	.51
10	T	9/1/70 to 10/20/70	II	324	.25
10	T	10/21/70 to 3/11/71	III	159	.51

^aThe type refers to—

Can = total accumulation measuring gage.

I = tipping-bucket gage as used at the transmitter and receiver sites.

II = tipping-bucket gage used in the vicinity of the common volumes of the bistatic radar system.

III = same gages as II with the collecting area reduced in size.

locations that were operationally convenient. The gages used near the common volumes each had a battery-operated recording system, screens over the sampling orifice to protect against clogging, and a slow chart speed allowing up to 45 days unattended operation. The other gages required power for the recording system, used higher chart speeds, and were not equipped with screens to protect against clogging. These gages had to be inspected periodically and visited after each rain event to measure the total accumulation for each event stored in the catchment container. Because the sites were manned for each event during phase II, these gages were located at the sites.

The gages located at each of the transmitter and receiver sites were in open flat areas with either grass or sparse scrubby growth of height less than gage top and no obstructions. Any object within 60° of the vertical above the gage might shield the gage under adverse wind conditions and is considered an obstacle. These obstacles can cause gage measurement errors either by physically diverting the rain or by modifying the vertical component of the wind field and of the raindrop fall velocities at the gage. The former effect leads to a low estimate of rain rate and total accumulation; the latter effect may either increase or decrease the measured rain rates. At the sites, the closest possible obstructions were either buildings or antennas. At LaRC the tops of the 30-ft antennas were greater than 57 m from the gage, hence the closest obstruction was more than 78° from zenith above the gage. At Eastville a building was 21 m from the gage with an angle of more than 75° from zenith. At Fort Lee the closest possible obstruction was an antenna 12 m from the gage that subtended an angle more than 66° from zenith. The gages located in the vicinity of the common volumes did have obstructions or other possible siting difficulties. The closest obstructions to the 5K gage were coniferous trees located approximately 5 m from the gage with heights of approximately 8 m. The trees provided shielding at zenith angles greater than 30° over an azimuth sector from 130° to 230° . The 20K gage was located on level terrain near a soybean field with a single deciduous tree about 5 m high at a distance 8 m from the gage. The tree provided shielding for zenith angles larger than about 60° at azimuths between 260° and 280° and should be important only in extreme wind conditions. The 10K gage was sited on the roof of a two-story building within 10 m of the edge as shown in figure 2-8. Strong low-level winds may modify the vertical wind field above the gage causing errors in rate measurements. Each of the gages located beneath the common volumes had possible measurement errors due to siting. The magnitude of these errors is estimated in section 4.

2.2.2.3 Operating Procedures

The 5K, 10K, and 20K gages were generally left unattended. The gages were inspected once every 6 weeks prior to January 1971 and every week thereafter; the charts were changed every 6 weeks. The gages, although equipped for winter operation, were not used in this mode. As a result they were inoperable in snow or freezing rain and data for these events were discarded.

The Eastville, Fort Lee, and LaRC gages were operated only during the phase II portion of the experiment. The rain-gage recording systems used with these gages employed chart speeds of 45 in./hr and were designed for unattended operation over a relatively short time



Figure 2-8.—10K rain-gage siting.

period. The recording systems were designed to turn themselves on with the first tip. A “turn on” indication was telemetered to the LaRC site to notify personnel that the gage was operating. The chart recorders had to be shut off manually. An operator was also required to measure the contents and empty the catchment container after each rain event. The collecting rain gage at LaRC was also read manually and emptied after each rain event. The gages were inspected daily in clear weather and calibrated periodically.

2.2.3 Auxiliary Meteorological Systems

In addition to the primary radio and rain-gage systems used in the experiment, the following auxiliary systems were used: surveillance radar; meteorographs; and NWS data including radar weather pictures (facsimile), rain-gage data, and radiosonde data. These are described in the following sections.

2.2.3.1 Surveillance Radar

An S-band surveillance radar (VERLORT) was located at the LaRC receiving site and was dedicated to the experiment. Its primary purpose was storm tracking and propagation mechanism discrimination. It was equipped with both PPI and RHI displays, which were photographed to provide sequential records of the progress of storms and of anomalous propagating situations (extended range, etc.). The radar was operated before, during, and after precipitation scatter events and was capable of providing qualitative information on storm reflectivity.

A simplified block diagram of the radar is given in figure 2-9. As shown, the system used a magnetron transmitter, a pedestal-mounted antenna, and a low-noise traveling-wave-

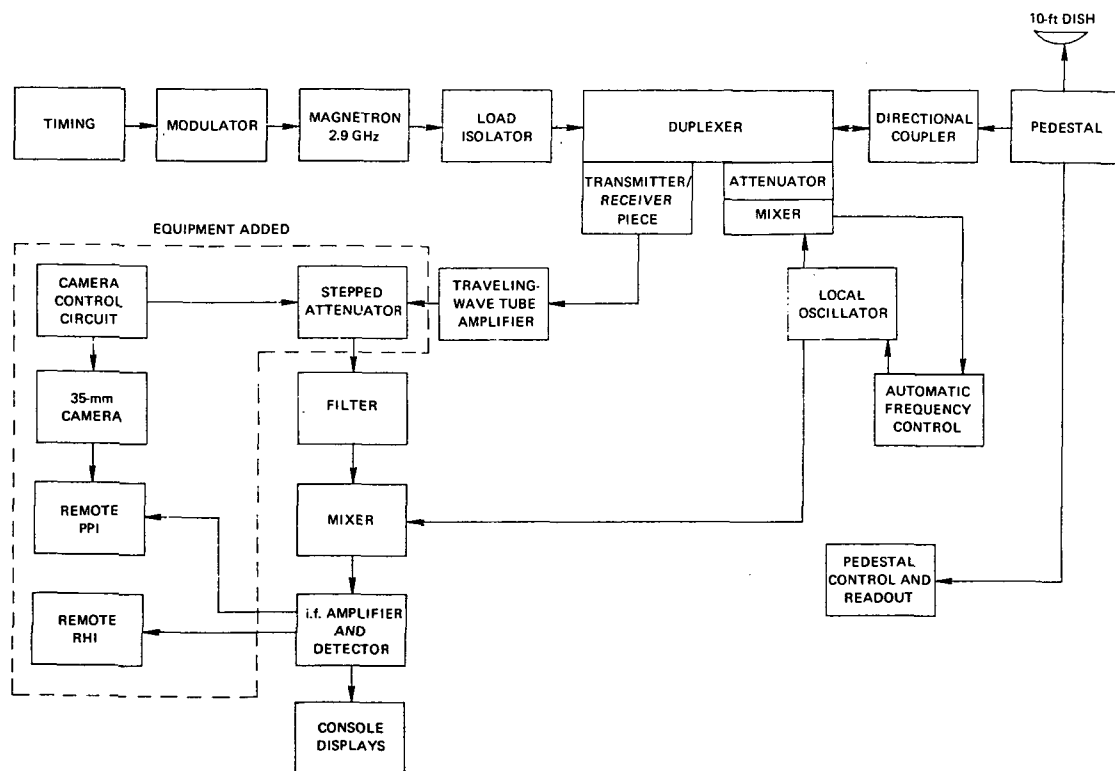


Figure 2-9.—Surveillance radar block diagram.

Table 2-6.—Surveillance Radar Summary

Parameter	Description
Frequency	2.85 GHz
Range	Approximately 125 n. mi.
Antenna:	
Size	10-ft parabolic dish
Height	Approximately 15 ft
Gain	36.8 dBi nominal
Beamwidth	2.5° nominal
Polarization	Linear, horizontal
Transmitter:	
Power	250-kW peak, 100-W average
Pulsewidth	0.8 μ s
Pulse repetition rate	300 to 2000 pps
Receiver:	
Noise figure	4 dB
Bandwidth	3.0 MHz
Sensitivity	-106 dBmW (measured)
Display	PPI, RHI, and A-scope

tube preamplifier in the receiver. The original system was field modified by adding remote PPI and RHI displays and a 35-mm camera. For phase II, an operator-selectable stepped attenuator (HP-33300 programmable attenuator) was provided as an aid in the estimation of cross-section intensity. The characteristics of the radar are summarized in table 2-6.

The radar system was located in a separate equipment van approximately 100 ft from the receiving van. Communications between vans was via an intercom system.

2.2.3.2 NWS Weather Radar Data

Facsimile recordings of a WSR-57 weather radar were received at the LaRC site and used for storm alerting and real-time storm

tracking. The pictures were transmitted continuously from the Patuxent River Naval Air Station located approximately 90 miles north of LaRC and were updated from time to time depending on weather conditions. At the LaRC site, the facsimile recorder picture update interval was under operator control. During nonstorm periods updating was hourly; during storm periods it was at least every 15 min and occasionally continuously.

2.2.3.3 NWS Rain-Gage Data

Rain-gage data were obtained from the NWS for the first-order stations at Norfolk and Richmond and the second-order stations at Painter and Williamsburg. The data from these gages were used for two purposes. First, the occurrence of rain events and the amount of accumulated water were checked and compared with the data recorded by the experiment rain-gage network. This helped insure that all data were used in calculating the cumulative distributions. Second, the rain-rate statistics were calculated for the Norfolk gage data and were compared with the radio and rain statistics obtained by the measurement systems. These distributions are given in reference 13. In addition to these stations, data were examined from 22 other stations located within 100 km of LaRC as a further check on the recorded data.

2.2.3.4 Meteorographs

Three meteorographs, capable of measuring temperature, pressure, and relative humidity, were located at LaRC, Fort Lee, and Eastville. A fourth unit was provided for backup purposes. The units were of the continuously recording type and were inspected, calibrated, and had their charts replaced weekly.

2.2.3.5 NWS Radiosondes

Radiosonde data were obtained from the NWS stations of Dulles, Wallops Island, Greensboro, N. C., and Cape Hatteras, N. C. These data were analyzed to obtain upper air temperature for use in estimating the height of the freezing level.

2.2.4 GC Path System

During the latter part of phase I, a second S-band antenna/receiver system was installed at LaRC to monitor signals arriving along the GC paths. The received signals were used to aid in separating mechanisms and, during periods of high received-signal strength, the frequency (at i.f.) was measured as a check on the transmitter frequency.

The system was made up of three horn antennas, each having a gain of 19 dBi, pointing to Eastville, Fort Lee, and Quantico, which were alternately switched to the receiver. The receiver was identical to the one used in the bistatic radar system. The signals were recorded on strip chart and magnetic tape.

A detailed description of the GC path system is given in section 3.3. The operating procedures for the GC path system were identical to those of the bistatic radar given in section 2.2.1.4.

2.3 DATA PROCESSING

The data obtained from the bistatic radar system and the rain gages were recorded on strip charts and, in the case of the bistatic radar system, on analog magnetic tapes. The recorded data were read and processed preparatory to analysis in several ways. For phases Ib and II the bistatic radar data were hand-scaled from the strip charts (Z-fold) and manually averaged to provide estimates of the 1-min average of the received-signal level. The bistatic radar data for phase Ia were automatically processed using analog-to-digital conversion equipment and computer sorting to provide estimates of the 1-min-median received-signal level. The rain-gage charts were read by hand-scaling the time of each tip, keypunching the tip times for each event, and using a computer to calculate the average rain rate between tips. Data from the auxiliary meteorological sources were obtained in a form ready for analysis. A summary of the data sources and processing techniques is given in table 2-1.

The bistatic radar and rain-gage systems were operated continuously. During most of the time the chart records were blank. The gages tipped only when it rained. The bistatic radar system was configured so that during periods with no rain, with the exception of the GC path from Eastville to LaRC, no signals were recorded. Signals were often received from Eastville over the GC path by terrain diffraction enhanced by superrefraction conditions over the large expanse of water between Eastville and LaRC. The terrain-diffracted signals were not processed. The chart records for both the bistatic radar system and the rain-gage system were edited or examined for an indication of scattering due to rain or rain measured at the surface prior to processing. On the primary measurement paths (10K and 20K, Eastville and Fort Lee), all occurrences of measurable signals were associated with rain events. Only data corresponding to rain events were read either manually or using the analog-to-digital converter and computer system. The editing process was accomplished by tabulating hourly summaries for each hour of the measurement year. This involved choosing the highest of three levels (thresholds) exceeded by a signal recorded in that hour. The threshold levels were chosen so that level 1 approximately corresponded to an averaged signal level equal to receiver noise. Level 2 corresponded to a 10-dB signal-to-noise ratio, which approximates the interference threshold for an S-band Earth terminal receiver system. Level 3 corresponded to a -115-dBmW value, which approximates the minimum useful signal level for measurement. The existence of gage tips and equipment status were also tabulated for each hour of the measurement year. The tabulations or hourly summaries were prepared for the gages and for the GC, 10K, and 20K bistatic scatter paths from Eastville and Fort Lee to LaRC.

The hourly summaries were used to generate a rain-event list. All occurrences of a received signal not obviously due to scatter from an aircraft (a very short duration signal lasting for less than 1 min) with a 1-min averaged value that exceeded threshold level 2 or 3 and all occurrences of a measured rain rate at the 5K, 10K, or 20K gages in excess of 1 mm/hr were used to establish events. Generally both gage and bistatic radar measurements

were obtained during an event. The duration of an event was taken as the number of successive hours the event threshold was exceeded. For events consisting of light rain with occasional event indications, the duration of the event was increased to span all the hours between the first and last hour the threshold was exceeded. If the intervals between event indications exceeded 6 hr, the event indications were assigned different event numbers or considered as belonging to different events. For the measurement year, 119 rain events were identified spanning a total of 898 hr.

Data processing techniques and processing precision are considered in section 5. The description of processing given there is through the stage of determining the 1-min-average received-signal level or rain-rate values. The final step of constructing the cumulative distributions is described in reference 13 because additional correction must be made to adjust for the effect of signal level fluctuations. Only bistatic radar received-signal level data above a threshold value of -115 dBmW were processed and tabulated for use in constructing the final cumulative distributions. The -115 -dBmW threshold was chosen because the receiver characteristics were not logarithmic below that threshold level and correction estimates based upon an analysis of the statistical fluctuations in the received signal (considered in ref. 13) were incorrect below that level. Below -115 dBmW the reading inaccuracies due to scale compression also became large.

2.4 DISCUSSION OF ERRORS

The accuracy, repeatability, and precision estimates given in this report refer to the behavior of the components of the system. When these component estimates are combined, they represent only a part of the possible sources of error in the estimation of equivalent reflectivity. Scatter by rain must be viewed as a statistical process, the scattered signal a random variable, and the components of the bistatic radar system as devices that modify the statistical properties of the random signal. The errors involved in the estimation of the parameters of the random process such as Doppler spread are given in reference 13. Angular errors in antenna alignment are described in section 3.1.4 of this report. The errors in the measurement of equivalent reflectivity caused by antenna misalignment and the resultant change of the scattering volume parameters are considered in reference 13.

Accuracy as used in this report refers to the possible difference between the median value of all the equivalent reflectivity measurements or transmission loss measurements made during the particular time period and the true median value measured with an ideal bistatic radar. The accuracy values given in sections 3 and 4 are estimated from the results of periodic calibration measurements, the variations of critical parameters as noted in the site logs throughout the year, and the manufacturers' specifications on the performance of the test equipment used. The measurement accuracy as quoted is a theoretical estimate because it cannot be measured. The accuracy estimates as given for each of the measurement systems are maximum values obtained by adding the individual accuracy estimates for each of the system components.

Repeatability as used in this report refers to the possible difference between the median value of all the equivalent reflectivity or transmission loss measurements made during a

single rain event and the true median value for that event that may occur in addition to the difference accounted for by the accuracy estimate. The repeatability refers mainly to slow changes or drifts in the components due to, for example, temperature changes that have been compensated for, on average, but that may affect the accuracy of measurements of a single event. The repeatability estimates given in sections 3 and 4 were obtained from the measured variations in parameters observed periodically throughout the year or from measured sensitivities of components to changes in parameters such as temperature or voltage level settings and the variations in the parameters as noted in the site logs. The repeatability estimates for each system component are reported as maximum values. The estimates for particular measurement systems are obtained from the square root of the sum of the squares of the individual component estimates.

Precision is defined as the difference between a single 1-min averaged value of reflectivity and the true value for that minute that may occur in addition to the differences accounted for by the accuracy and repeatability estimates. Precision as used in this report refers to the possible errors involved in a single 1-min measurement due to the data processing or chart reading process. Accuracy or repeatability estimates for the data processing are not given because they depend on the precision of the reading process, the way in which the measurements are combined, and the number of measurements to be combined. This is considered in reference 13.

A goal of this experiment is the construction of the measured cumulative distribution of equivalent reflectivity for a complete year. The purpose in constructing the measured distribution is to provide an estimate of actual temporal distribution of equivalent reflectivity for a single location for use in rain interference prediction and comparison with distribution estimates obtained in other ways. A discussion of the possible differences between the 1-yr measured distribution and the true temporal distribution is given in reference 13.

2.5 OPERATION SUMMARY

The operating summaries displaying the number of hours of the measurement year that data were obtained, that the systems were inoperable, and that data were lost because of system failure are given in tables 2-7 to 2-9. Table 2-7 shows the number of hours during which the threshold was exceeded for at least 1 min. The event duration refers to the total duration of each event as described in section 2.3. The summaries show that significantly more hours of scattering were detected from the 10K scatter volume than from 20K and that the number of hours of scattering from the 10K volume was higher than the number of hours of rain-rate measurement on the surface. The thresholds for recording data occurrences correspond to $S/N = 10$ dB on the bistatic system (level 2 ~ 1 mm/hr) and 1 to 2 mm/hr on the rain-gage system. The operating summaries are given only for the gages and primary paths used throughout the year and for the GC paths that supplied additional information on other propagation mechanisms. The operation of the other paths is discussed in reference 14.

The GC path performance, summarized in the tables, is for reception via the sidelobes of the 30-ft antenna. The occurrences on the Fort Lee-GC path are associated with rain

Table 2-7.—Operating Summary—Number of Hours of Data

Period	Bistatic radar						Rain gage						Total event duration	Number of hours in time period				
	E			F			Composite		Type I			Types II and III						
	20K		GC ^a	10K	20K	GC ^a	10K	20K	Composite	L	E	F	Composite	5K	10K	20K	Com- posite	
	10K	20K	GC ^a	10K	20K	GC ^a	10K	20K										
Oct. 1970	28	4	3	23	—	—	31	4						19	18	18	27	696
Nov. 1970	10	6	55	33	1	2	37	6						37	41	40	54	720
Dec. 1970	42	—	13	34	—	—	42	—						34	34	—	38	744
Jan. 1971	66	—	2	43	—	—	66	—						29	26	22	35	744
Feb. 1971	60	1	26	44	2	—	60	2						32	34	29	43	672
Mar. 1971	56	3	20	23	—	2	56	3						36	42	38	56	744
Apr. 1971	35	1	53	11	—	—	36	1						29	22	5	31	720
May 1971	89	16	43	81	12	10	91	16		20	18	21		34	32	30	61	744
June 1971	42	18	44	31	17	3	42	22		8	8	15	26	5	6	8	11	720
July 1971	35	22	64	35	21	9	35	25		22	14	20	41	15	16	19	28	744
Aug. 1971	30	22	30	30	22	5	31	23		37	23	30	61	—	24	32	38	744
Sept. 1971	25	13	20	26	17	5	26	19		24	19	21	39	25	20	17	27	720
Oct. 1971	15	3	2	15	7	—	15	7		13	5	18	29	7	12	6	18	48
Phase Ia	146	10	73	133	1	2	176	10						119	119	80	154	2904
Phase Ib	246	22	150	164	15	13	249	23		23	18	21		132	131	102	192	2952
Phase II	141	77	152	132	83	21	143	95		101	69	104	196	51	67	82	121	2904
Measure- ment year	533	109	375	429	99	36	568	128		124	87	125	196	302	327	264	467	8760

^aReceived via 30-ft antenna sidelobes.

Table 2-8.—Operating Summary—Number of Hours Systems Were Inoperable

Period	Bistatic radar						Rain gage						Number of hours in time period
	E			F			Type I			Types II and III			
	10K	20K	GC	10K	20K	GC	L	E	F	5K	10K	20K	
Oct. 1970	35	3	3	41	41	41				—	—	—	696
Nov. 1970	376	48	48	1	1	1				—	114	168	720
Dec. 1970	—	—	—	—	—	—				—	64	744	744
Jan. 1971	—	—	—	—	—	—				72	80	302	744
Feb. 1971	3	3	3	3	3	3				16	16	16	672
Mar. 1971	—	—	—	—	—	—				72	72	72	744
Apr. 1971	23	43	43	23	23	23				—	44	613	720
May 1971	31	35	35	34	36	36				293	34	449	744
June 1971	—	—	—	—	—	—	6	6	4	—	—	—	720
July 1971	84	85	85	83	83	83	83	—	83	37	—	—	744
Aug. 1971	4	4	4	4	4	4	—	—	—	744	—	—	744
Sept. 1971	8	8	8	8	8	8	—	—	—	38	—	—	720
Oct. 1971	—	—	—	—	—	—	—	—	—	—	—	—	48
Phase Ia	411	51	51	42	42	42				72	258	1214	2904
Phase Ib	57	81	81	60	62	62				381	126	1150	2952
Phase II	96	97	97	95	95	95	89	6	87	819	—	—	2904
Measurement year	564	229	229	197	199	199	89	6	87	1272	384	2364	8760

events and correspond to scatter by rain over the receiver site. Significantly more data were observed on the GC path from Eastville. Less than 10 percent of these data, however, were associated with rain events, the bulk of the data being associated with superrefraction conditions over the large expanses of water between Eastville and Langley. During these conditions, strong stable signals were observed that were monitored to determine the frequency of the GC and 20K source at Eastville.

The major system changes that occurred throughout the measurement year have been discussed previously and are detailed later in the bistatic radar and rain-gage system description sections. The changes were instituted to increase the accuracy of estimation of the cumulative distribution of equivalent reflectivity. The changes were of two types, one to modify the switching sequences so the paths of interest were continuously sampled rather than sampled for 1 min out of 4. The second type was to increase system reliability. Operating reliability was increased by eliminating switching for the 10K paths; by providing redundant transmitter facilities at each site, standby recording systems at the receiver site, and simplified operations; and by manning all the sites during events. The 10K path was considered the highest priority path and automatic transmitter switching was provided to maintain operation on the 10K path if a transmitter failure occurred. Emergency power was provided at each site to protect against power failure. Automatic switchover to emergency power was provided at the transmitter sites. Both the power supply and transmitter backup switching systems at Eastville had to be used during two major rain events. An engine

Table 2-9.—Operating Summary—Number of Hours Systems Were Inoperable During Ram Events

Period	Bistatic radar								Rain gage							Total event duration		
	E			F			Composite		Type I			Types II and III						
	10K	20K	GC	10K	20K	GC	10K	20K	L	E	F	Com- posite	5K	10K	20K		Com- posite	
Oct. 1970	3	—	—	—	1	—	—	—	—	—	—	—	—	—	—	—	—	44
Nov. 1970	30	—	—	—	1	1	—	—	—	—	—	—	—	1	—	—	—	77
Dec. 1970	—	—	—	—	—	—	—	—	—	—	—	—	—	—	35	—	—	55
Jan. 1971	—	—	—	—	—	—	—	—	—	—	—	—	12	12	17	—	—	80
Feb. 1971	3	3	3	3	3	3	3	3	—	—	—	—	16	16	16	16	16	99
Mar. 1971	—	—	—	—	—	—	—	—	—	—	—	—	14	14	14	14	14	93
Apr. 1971	—	—	—	—	—	—	—	—	—	—	—	—	—	4	17	—	—	51
May 1971	1	1	1	1	1	1	1	1	—	—	—	—	13	—	18	—	—	146
June 1971	—	—	—	—	—	—	—	—	—	—	4	—	—	—	—	—	—	77
July 1971	2	4	4	2	2	2	2	2	2	6	2	—	2	—	—	—	—	54
Aug. 1971	—	—	—	—	—	—	—	—	—	—	—	—	26	—	—	—	—	60
Sept. 1971	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	37
Oct. 1971	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	25
Phase Ia	33	—	—	1	1	1	1	1	—	—	—	—	12	13	53	12	—	256
Phase Ib	4	4	4	4	4	4	4	4	—	—	—	—	43	34	65	30	—	395
Phase II	2	4	4	2	2	2	2	2	2	8	6	6	—	—	—	—	—	247
Measurement year	39	8	8	7	7	7	7	6	—	—	—	—	83	47	118	42	—	898

generator that could be started manually and used to supply power at the receiver site was also provided. The receiver components were not duplicated with a standby receiving system, but parts were available from the GC path system that could be installed if failure was detected.

The measurement system operating record is shown in table 2-8. Only involuntary outages are shown. The transmitter and receiver subsystems were periodically removed from operation for testing and maintenance. This was done when observations and forecasts indicated that rain would not occur. The outages indicated in table 2-8 for phase I were predominantly caused by transmitter failures. The significant loss of data for the Eastville 10K path indicated in table 2-9 is due to a varactor multiplier failure that took 2 weeks to fix. The outages that occurred during phase II were predominantly receiver site malfunction. The data lost in phase Ib occurred because of strip chart recorder failure. These data are stored on magnetic tape and are recoverable. The rain-gage and radar data indicate that the rains were very light and therefore are not expected to cause scattered signals higher than -115 dBmW. Recovery of the data has not been attempted because they do not contribute to the final cumulative distributions. The bistatic radar system and LaRC and Fort Lee rain-gage outages logged in table 2-8 for July were caused by loss of power at the receiver site. All but 4 hr of the outage were caused by a planned power shutdown at LaRC. During this time emergency power was available from the engine generator. It was not used because rain was neither observed nor forecast. The 2-hr loss of data logged for July in table 2-9 occurred later in the month and was caused by a failure in the connector supplying power to the receiver trailer. This occurred during a thundershower that provided one of the major events of the year.

The operating performance of the rain gages is also shown in tables 2-7 to 2-9. Two of the gages, the 30K and tower gages, had unreliable recording systems and were neither used in the tabulations of system performance nor as a source of data. The 10K gage lost data either because of snow or gage malfunction. The 20K gage lost data because of recorder system malfunction in December and January, snow, and misplacement of the April recorder chart prior to data processing. The 5K gage lost data because of snow and recorder malfunction. The site gages lost data either because of power failures at LaRC, misplaced charts prior to processing, or an obstruction in the funnel (Fort Lee, 2 hr in June). Except for the 42 hr of data lost because of snow events, at least one of the common volume gages and one of the site gages were functioning for each rain event.

The experiment operations may be summarized using data from tables 2-7 to 2-9. Rain events occurred during 898 hr or 10.2 percent of the hours of the measurement year. Rain scatter from the 10K common volume (using paths from either Eastville or Fort Lee) was detected for 568 hr or 6.5 percent of the hours of the measurement year and from the 20K volume 128 hr or 1.5 percent of the time. System reliability for each of the 10K and 20K paths taken over the entire year ranged from 93.6 to 97.8 percent. Reliability for the common volume rain gages taken over the entire year ranged from 73.0 to 95.6 percent. Because of path redundancy, the overall bistatic radar system reliability was 98.5 percent for the measurement year (table 1-1). During rain events, the bistatic radar system reliability

was 99.2 percent. Because of the use of several gages, the overall rain-gage system reliability was 99.5 percent for the entire year and 95.3 percent during rain events. The loss of reliability in the rain gages was entirely the result of the occurrence of snow or freezing rain.

3 BISTATIC RADAR SYSTEM

This section describes the equipment used during phases I and II. It includes the bistatic transmit and receive system, the calibration and monitoring systems, the GC path reference system, a configuration history, and equipment error analysis.

3.1 BISTATIC TRANSMIT SYSTEM

The major items making up the transmit system included a standard frequency oscillator, an rf source, a power amplifier and leveling loop, an rf switching matrix, and one or more antennas. A block diagram of the Fort Lee transmitter used during phase II is shown in figure 3-1. The installation at Eastville was essentially identical except for operating frequencies given in table 3-1. The differences in the equipment configurations used in phases I and II are listed in table 3-2. The antenna switching sequences used in each phase of the experiment are shown in table 3-3. As can be seen in figure 3-1 for phase II, the site used two transmitters, identical except for operating frequency. One transmitter (F2) illuminated the 10K common volume intersection on a continuous basis while the other (F3) was switched between the GC and 20K antennas. Both transmitters used a single standard frequency oscillator as the basic frequency source.

3.1.1 Radiofrequency Source

The output of the standard oscillator, at 5 MHz, was applied to the frequency source which consisted of a frequency synthesizer (single frequency), a varactor multiplier, and a variable attenuator. In the synthesizer the standard oscillator frequency was translated to 102.0 MHz using frequency division, multiplication, and heterodyning techniques. Its power output was approximately 10 dBmW. The synthesizer output was routed to a varactor multiplier (X36 for S-band and X80 for X-band) for multiplication to the final operating frequency. The output of the varactor multiplier, at a level of approximately 15 dBmW, was then applied to the power amplifier and leveling section through a variable attenuator (used for level set and calibration purposes).

3.1.2 Power Amplifier and Leveling Loop

The rf signal input from the frequency source was applied to the traveling-wave-tube amplifier (TWTA) through the pin-diode modulator and a 10-dB pad. The pad was provided to eliminate the possibility of overdriving the TWTA during turn-on. In the case of the F3 transmitter, the input power level and the TWTA gain were too low to permit the use of the 10-dB pad. The TWTA had a maximum gain of 40 dB and a maximum power output of 20 W. It was operated near saturation with a gain of approximately 37 dB and a power output of 10 W. The isolator was included to provide a constant load impedance for the TWTA. A

Table 3-1.—Frequency Operation Summary

Frequency code	Phase I		Phase II		
	Location	Paths ^a	Location	Paths	Dates
F1	Q	GC, OP, 20K, 30K	E	GC, 20K	8/9 to 10/2
F2	N	OP, 10K	F	GC, 20K	5/8 to 7/26
				10K	7/26 to 10/2
F3	F	GC, 10K, 20K	F	10K	5/8 to 7/26
				GC, 20K	7/26 to 10/2
F4	E	GC, 20K	E	GC, 20K	5/8 to 7/26
				10K	7/26 to 10/2 ^b
F5	E	5K, 10K, 30K	E	10K	5/8 to 7/26
				GC, 20K	7/26 to 8/9

^aOP = off path.^bFrom Sept. 1 to Oct. 2 the F5 synthesizer was modified to produce F4 and used.

Frequency code	Synthesizer frequency, Hz	Multiplication ratio	rf, Hz	i.f., Hz
F1	101 998 000	36	3 671 928 000	9 528 000
F2	102 000 000	36	3 672 000 000	9 600 000
F3	102 002 000	36	3 672 072 000	9 672 000
F4	101 996 000	36	3 671 856 000	9 456 000
F5	102 004 000	36	3 672 144 000	9 744 000
F6	97 920 000	80	7 833 600 000	9 600 000
F7	97 921 920	80	7 833 753 600	9 753 600
F8	97 918 080	80	7 833 446 400	9 446 400
LO ^a (S-band)	91 560 000	40	3 662 400 000	—
LO ^a (X-band)	97 800 000	80	7 824 000 000	—

Note: Frequency spacing at rf: S-band = 72 000 and X-band = 153 600.

^aLO = local oscillator.

portion of the output of the transmitter was coupled to the thermistor and power meter, which was used as the reference system for the leveling loop. A dc voltage was obtained from the output of the power meter which was proportional to the loop rf output. This dc signal was then amplified and used to control the pin-diode modulator level (variable attenuator) to hold the output of the transmitter constant at 10 W.

3.1.3 Switching Matrix

The rf output from the power amplifier and leveling loop was routed to the switching matrix through a directional coupler used for monitoring, calibration, and recording purposes. The switching matrix was designed to switch or connect the transmitter to the appropriate

Table 3-2.—Equipment Configuration for Phases I and II

System and equipment	Quantity at site (unless otherwise noted)					
	Phase I				Phase II	
	E	F	Q	N	E	F
Bistatic radio system:						
Transmit system:						
Total antennas (= paths)	9	6	7	2	3	3
S-band antennas (10 ft)	5	3	4	2	3	3
S-band transmitters	2	1	1	1	2	2 ^a
X-band antennas (6 ft)	4	3	3			
X-band transmitters	1	1	1			
10K transmitter backup	No	No	No	No	Yes	Yes
10K antenna switching	Yes	Yes	Yes	Yes	No	No
Emergency power units	2 ^b	1 ^b	1 ^b	1 ^b	3	2
Voltage regulation	1 ^b	1 ^b	1 ^b		2	1
Recording equipment	1 ^b	1 ^b	1 ^b	1 ^b	2	2
Antenna switch timing control	Local ^c	Local ^c	Local ^c	Local ^c	Local	Local
Receive system (at LaRC):						
Diplexer	Removed 5/27/71				None	
Receivers	S- and X-band ^d				S-band	
Receiver temperature stabilization	Installed 4/7/71				Yes	
Calibration systems	S- and X-band ^d				S-band	
Calibration standard	Pin-diode attenuator				Programmable attenuator	
Receiver down time during calibration	15 min, 8 min after 2/24/71				2 min	
Magnetic tape recorder	1				1 + 1 spare	
Strip chart recorder	1				1 + 1 spare	
Event recorder	Installed 2/6/71				1	
Temperature recorder	Installed 4/7/71				Digital printer	
Strip chart integration	None				10K paths	
Primary ac power backup	None				Engine generator ^e	
GC path system	Installed 2/5/71				1	

^aUsed Norfolk S-band transmitter.^bInstalled in latter part of phase Ib.^cControlled from LaRC via telemetry from Dec. 15, 1970, to Feb. 14, 1971.^dX-band removed Apr. 11, 1971.^eInstalled July 1, 1971.

antenna and to a pad during automatic calibration. Located in the switching matrix section were various rf power samplers used as sensing devices. If the rf level dropped below a preset threshold, a loss of power was indicated. In the case of the first rf sampler (switch-over) located in the F2-10K system, power loss of the F2 transmitter initiated a switchover sequence that resulted in transmitter F3 being switched to the 10K antenna. The two switches that were activated for this function are shown in figure 3-1 as "auto. switchover."

Table 3-3.—Transmitter Antenna Switching Sequence
for Minutes 1 to 4

Transmitter site	Frequency	1	2	3	4
Phase I:					
Q	F1	GC	30K	OP	20K
	F6	GC	30K	Off	20K
N	F2	10K	OP	10K	OP
F	F3	GC	Off	10K	20K
	F7	GC	Off	10K	20K
E	F4	GC	GC	20K	20K
	F5	Off	30K	10K	5K
	F8	GC	30K	10K	5K
Phase II:					
E	F4	10K	10K	10K	10K
	F1	20K	GC	20K	GC
F	F2	10K	10K	10K	10K
	F3	GC	20K	GC	20K

In the case of the second rf samplers (10K, GC, and 20K), loss of power was relayed to the receiver site via a phone line telemetry link. The calibration switches were controlled from the receiver site via the phone line telemetry system. Control was such that every 2 hr during receiver calibration the output of the appropriate transmitter was switched into the 20-dB pad to prevent possible interference at the receiver. A pad was used rather than a termination to provide an additional monitoring point. The antenna switch, located in the F3, GC-20K system, was used to switch the F3 transmitter output to the GC or 20K antennas. The timing for the GC-20K antenna switch was derived from the standard frequency oscillator (100-kHz output frequency). Stability of the standard oscillator was such that timing inaccuracies were negligible. When it was necessary to reset the timing (for example, after transmitter tests), it was done manually under direction from the receiver site.

3.1.4 Transmission Line and Antennas

The transmission lines used at S-band were either 50- or 100-ft lengths of foam-filled, 7/8-in., 50- Ω , copper-conductor, coaxial cable. The voltage standing-wave ratio (VSWR) of the cable was 1.3 or less. The measured insertion loss values are given in table 3-4 (and in later tables) as changes from the nominal value listed in table 2-3. At X-band the transmission line used was a pressurized, air dielectric, elliptical waveguide (Andrews Corp. model EW-71).

The antennas, 6- and 10-ft parabolic dishes at X- and S-band, respectively, were of standard design using rear-mounted buttonhook sectorial horn feeds guyed to the dish at four points. The VSWR of the antennas was approximately 1.4 or less. Antenna pattern and gain measurements were made before the experiment on one 6-ft and one 10-ft antenna

Table 3-4.—Transmitting Transmission Line Loss

Site	Path			Transmission line		
	No.	Designation	Frequency band	Length, ft	Additional loss with respect to nominal values, ^a dB	
					Measured	Estimated
E	1	GC	S	100	1.1	
	2	5K	S	50		-0.7
	3	10K	S	50		
	4	20K	S	100	- .6	
	5	30K	S	50	1.1	
	6	GC	X	50		- .7
	7	5K	X	50		.0
	8	10K	X	50		.0
	9	30K	X	50		.0
F	10	GC	S	50	.4	
	11	10K	S	50	- .7	
	12	20K	S	50	.5	
	13	GC	X	50		.0
	14	10K	X	50		.0
	15	20K	X	50		.0
Q	16	GC	S	100		1.1
	17	20K	S	100		1.1
	18	30K	S	100		1.1
	19	OP	S	100		1.1
	20	GC	X	100		1.1
	21	20K	X	100		1.1
N	22	30K	X	100		1.1
	23	10K	S	50		- .7
	24	OP	S	50		- .7

^aNominal values are 4.4 dB at S-band and 3.6 dB at X-band and refer to the loss between the output of the power amplifier and leveling loop section and the antenna. Values are for phase 1a. Information for remainder of the year is given in sec. 3.4.

and after the experiment on the 10-ft antennas used for the 10K and 20K paths at Eastville and Fort Lee. All the S-band measured patterns were similar. The preexperiment patterns are given in figures 3-2 and 3-3 for S- and X-band, respectively. The measurements were made at an outdoor antenna test range at LaRC by NASA personnel. The rotating mount had to be strengthened and modified somewhat for this measurement because it had not been designed to handle 10-ft-aperture antennas. As a result of the modification, the center of rotation of the mount was offset somewhat from the radiating phase center of the antenna. The measurement was made with an antenna separation of approximately D^2/λ where D is the dish diameter. The correction factor for gain measurements made at D^2/λ was not included because the accuracy of the measurement was not sufficient to warrant it. For the

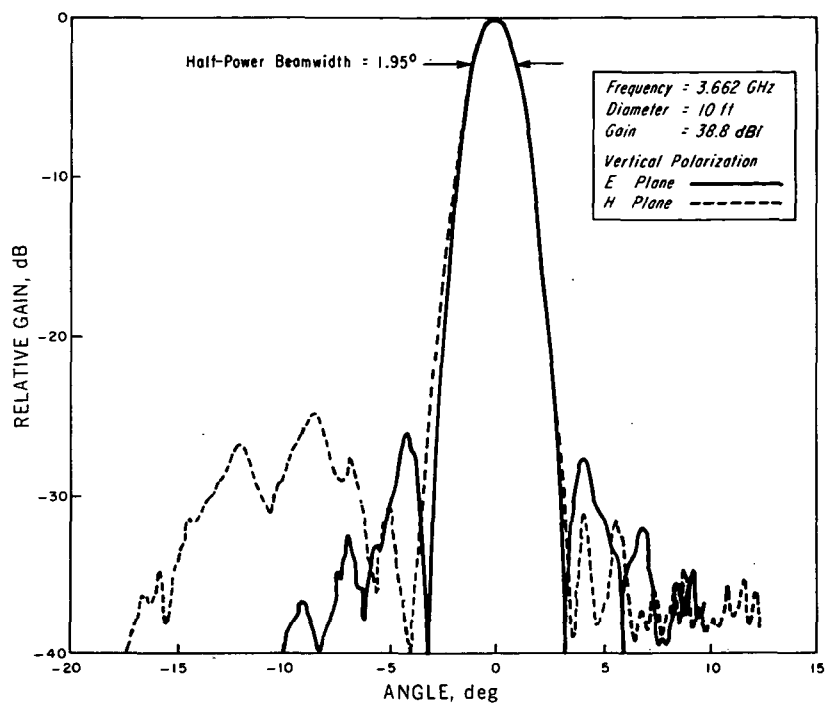


Figure 3-2.—Transmitting antenna patterns—S-Band.

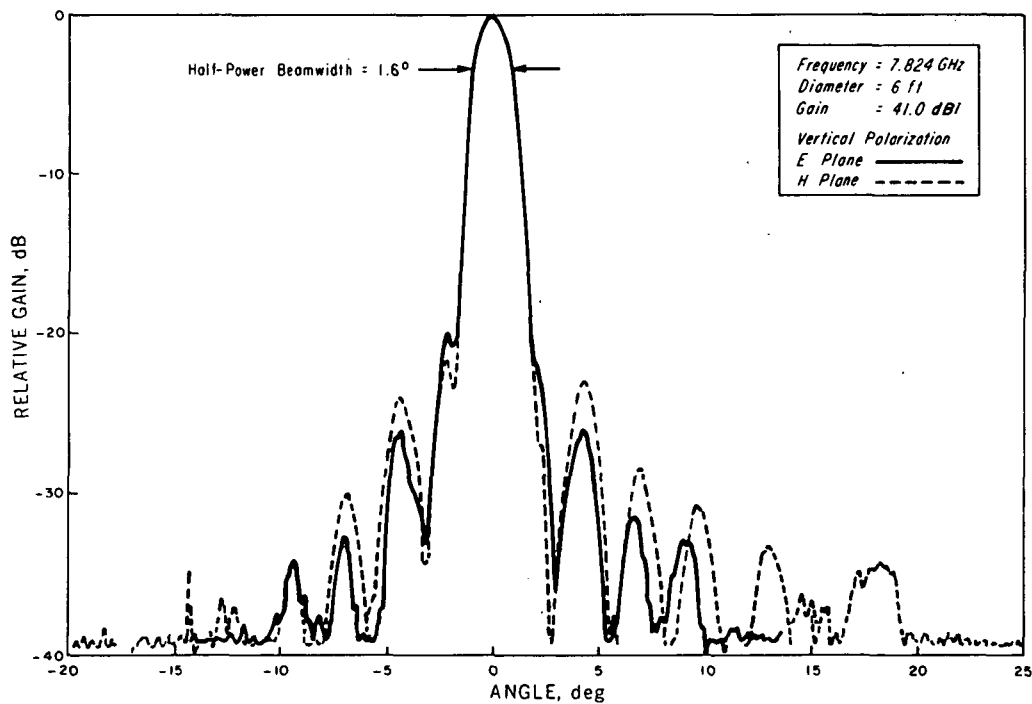


Figure 3-3.—Transmitting antenna patterns—X-Band.

S-band antenna, the gain was measured to be 38.1 ± 0.7 dBi using the substitution method with a horn reference of gain = 17.5 dBi. Postexperiment gain measurements for the 10K and 20K antennas were all within ± 0.2 dB of the nominal 38.8-dBi antenna gain and therefore the 38.1-dBi value is believed to be low. For system calculations the gain measurements made upon completion of the experiment were used. The half-power beamwidth was 1.95° in both E and H planes and the maximum sidelobe level was approximately 24 dB below the peak gain. For the X-band antenna, the gain was measured to be 40.7 dBi, the half-power beamwidth = 1.6° , and the maximum side level was approximately 21 dB below the peak gain.

At the conclusion of the experiment, in situ patterns, gains, and pointing angles were measured for the 10K and 20K antennas at Eastville and Fort Lee. The measurements were made using a crane (cherry picker) at distances of approximately D^2/λ . The direct transmission loss method of gain measurement was used by which the distance and relative power transmitted and received are measured and the gain is calculated. The substitution method could not be used because of multipath problems. The gain of each antenna was measured several times and the results averaged. The gain values for these four antennas are listed in table 3-5. Although an attempt was made to measure the cross-polarized pattern, it could not be measured with the available equipment under field conditions.

The transmit antennas were initially aligned to their prescribed pointing angles by mechanically positioning the plane of the rim of the antenna. The orientation of this plane was established using surveying techniques referenced to the North Star azimuth (corrected value) and transit estimates of horizontal. An estimate of the accuracy of mechanically aligning the antenna is $\pm 0.4^\circ$. The feed horns were installed in accordance with the manufacturer's instructions. It is estimated that the difference in the electrical and mechanical pointing angles (boresight offset) is $\pm 0.3^\circ$. Therefore, the accuracy of the initial alignment values is $\pm 0.7^\circ$. Electrical pointing angle measurements were made before realignment (April 30 to May 5, 1971) and after realignment (May 6, Eastville only) using the broadband radiated power probe (par. 3.5.3) and a transit. The accuracy of the measurements is estimated to be $\pm 0.5^\circ$. Table 3-5 also lists the electrical pointing angle values obtained from the in situ measurements made at the end of the experiment. These measurements have an estimated accuracy of $\pm 0.1^\circ$. The broadband radiated power measurements made during phase II indicated that the antenna pointing angles did not change between May 7 and November 1, 1971. Periodic antenna pointing measurements were not made prior to April 30, 1971. At the time of the April 30 measurements, it was noted that the Fort Lee antenna guys were taut and the Eastville guys were loose. It is expected that the Fort Lee antennas did not move prior to April 30 and that the differences between mechanical and electrical pointing positions can be attributed solely to the installation and measurement technique. The Eastville antennas shifted position, necessitating realignment, and it is estimated that the antennas were pointed within 5° in azimuth and 1° in elevation of their initial values.

Table 3-5.—Antenna Pointing Angles and Gain

Site	Path	Antenna pointing, deg										Gain, dBi
		Desig- nation	Fre- quency band	Initial mechanical alignment		Before realinement (electrical) 4/30/71 to 5/5/71		After realinement, 5/6/71		After experiment, electrical		
					Azimuth	Elevation	Azimuth	Elevation	Azimuth	Elevation	Azimuth	Elevation
L E	All	S, X			333.1	^a 13.5		^b 13.5			333.1	13.5
	1 GC	S			237.9	.8		^c .7				
	2 5K	S			245.2	1.6		2.0				
	3 10K	S			252.5	3.3		3.3				
	4 20K	S			265.8	6.2		^e 6.4				
	5 30K	S			277.0	8.4		^c 7.9				
	6 GC	X			237.9	.8						
	7 5K	X			245.2	1.6		2.0				
	8 10K	X			252.5	3.3		3.0				
	9 30K	X			277.0	8.4						
F	10 GC	S			101.1	.8		1.0				
	11 10K	S			93.7	2.0		1.5				
	12 20K	S			85.0	4.6		4.7				
	13 GC	X			101.1	.8						
	14 10K	X			93.7	2.0						
	15 20K	X			85.0	4.6						
	16 GC	S			152.2	.3						
	17 20K	S			152.2	1.8						
	18 30K	S			152.2	3.3						
	19 OP	S			148.2	.3						
Q	20 GC	X			152.2	.3						
	21 20K	X			152.2	1.8						
	22 30K	X			152.2	3.3						
	23 10K	S			337.3	5.8						
	24 OP	S			344.7	.8						
N												

^aMeasurement referenced to known position and height of boresight tower.

^bMeasured April 5, 1971.

^cMeasured after loose guy wires were tightened.

^dRealined May 7, 1971.

^eNot reset.

3.1.5 Monitoring Capabilities

Transmitter performance was monitored both locally (at the transmitter sites) and remotely (at the receiver site). The remote monitoring was accomplished using a telemetry system that transmitted tones over dedicated phone lines. The presence or absence of rf power at the input to each transmission line leading to an antenna was continuously monitored and recorded remotely at LaRC. By this means, one could tell if rf power was being fed to the antennas and if timing of the switching was correct. The use of the emergency power system was also remotely monitored. The power output of each 10K transmitter was monitored and recorded locally on a continuous basis on strip chart recorders.

During phase II, the reflected rf power, the ac and dc voltages, and the minimum and maximum van temperatures were measured daily and before and after an event. The antenna guy cable tension, the power radiated from the dish antennas, and the constancy of antenna pointing angle were monitored every 2 weeks. The latter measurement is described in detail in section 3.5. No significant changes in antenna pointing or radiated power were observed during this period.

During phase I, the following parameters were measured on a weekly basis: rf loop power, rf power out of the 20-dB pad monitoring point, dc and ac voltages, and minimum and maximum van temperatures.

3.1.6 Installation

Figures 3-4 and 3-5 are photographs of the Eastville and Fort Lee sites, respectively. All antennas, except those at Quantico, were mounted on 6.6-in.-diameter steel pipes with dish centers approximately 14 ft above ground level. The masts were approximately 21 ft high and were guyed at four points. The guys to the sides and to the rear were of steel whereas the one to the front was of Dacron to minimize aperture blockage effects. The

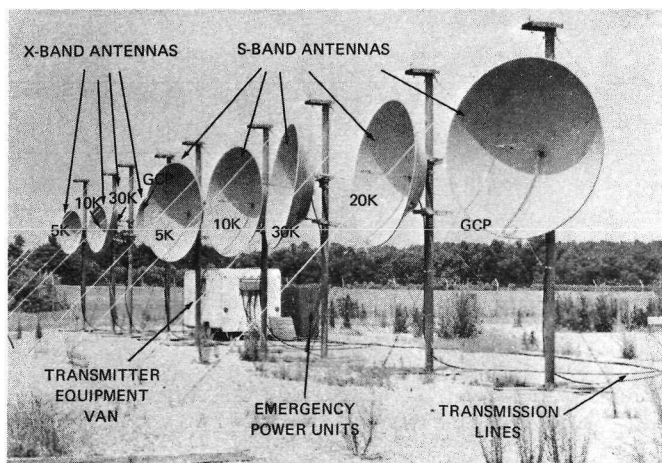


Figure 3-4.—Eastville transmitter site.

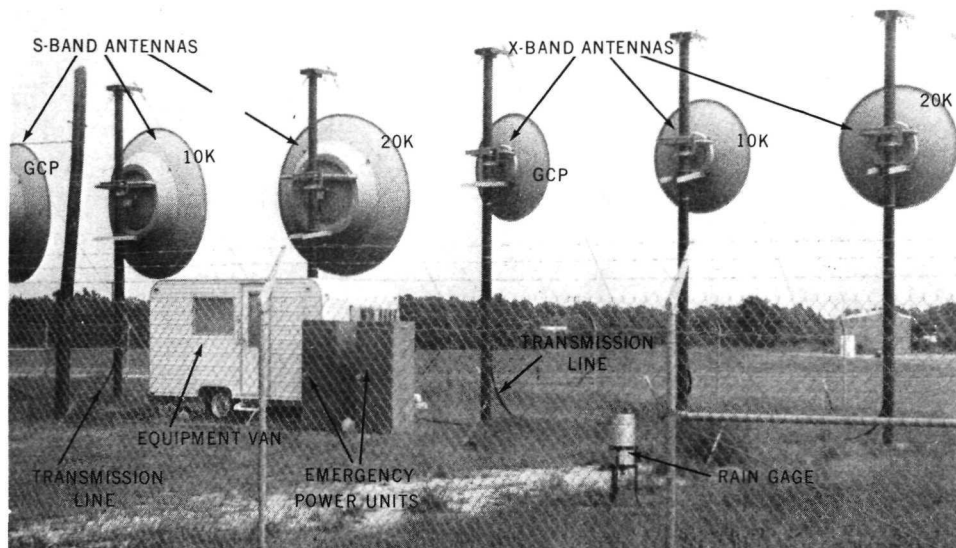


Figure 3-5.—Fort Lee transmitter site.

masts were bolted to crossed 6-ft-long by 15-in.-wide C-channel members that formed the base of the mounting structure. The base rested on the ground and was held in place by the weight of the antenna and structure and the downward force component from the guys. If the guys became loose through buffeting by the wind, settling, or aging of the Dacron guy, the structure was free to move. This apparently happened at Eastville sometime prior to April 30, 1971, necessitating antenna realignment. Consequently, both the guy tension and antenna pointing angle monitoring procedures (wideband radiated power) were required. At Quantico the antennas were mounted on an existing free-standing tower at heights of approximately 70 ft above the ground. All antennas were adjustable in elevation angle by means of a threaded rod and in azimuth by loosening several bolts.

The transmitting equipment was housed in portable camper-type trailers (vans), which provided weather protection; the vans were equipped with air conditioning and heating for temperature control. A thermometer was provided, which indicated the minimum and maximum temperatures reached inside the van. Commercial power was normally used; however, an emergency power unit with near-instantaneous switchover capability was provided that picked up the load when primary power was lost. Voltage regulators were also provided to insure constant voltage to the transmitter components under all conditions.

3.2 BISTATIC RECEIVING SYSTEM (30-FT DISH RECEIVER)

The bistatic receiving system consisted of an antenna, rf, if., detection, and data recording and display sections. The receiver used a single stage of conversion and was assembled, for the most part, from commercially available parts.

3.2.1 Antenna

The receiving antenna was a 30-ft parabolic dish with a dual-frequency prime focus feed horn (S- and X-band) aligned for vertical polarization. Antenna pattern and gain measurements were made at S- and X-band before the experiment and at S-band after the experiment. The before and after S-band measurements were identical to within measurement error and are given along with the X-band results in figures 3-6 and 3-7. The measured gain of the antenna at X-band was approximately 4 dB low and the measured half-power beamwidth was approximately 1.4 times broader than expected for a 30-ft antenna. The departure of the X-band parameters from the expected values may be due to the compromise in feed-horn design needed to achieve simultaneous operation at S- and X-band, defocusing, or measurement error. The measurements were made using a target transmitter with a horn radiator at the top of a tower (boresight tower) 8250 ft from the antenna, which is in the far field ($\geq 2D^2/\lambda$) at S-band and at approximately D^2/λ at X-band. The gain was determined using the direct transmission loss method where the distance, power transmitted, and power received are known (measured) and the gain calculated. The response of the receiving antenna to a cross-polarized field at S-band was checked. On the mainlobe axis the cross-polarized response was down approximately 40 dB relative to the principally polarized field. The principal lobes of the cross-polarized pattern (as measured in the two planes located at $\pm 45^\circ$ with respect to the E- or H-plane) were approximately -25 dB with respect to the mainlobe peak.

At S-band the approximate sidelobe level along the GC path toward Eastville was -50 dB with respect to the mainlobe peak. This value was obtained by comparing the levels received with that of the horn receiving system during periods of high signal strength (enhanced terrain diffraction) when both received signals tracked in detail. Sufficient data were not obtained along the GC path toward Fort Lee to make a similar measurement.

The antenna pointing angles, as measured with respect to the known position of the boresight tower, are given in table 3-5. The antenna was maintained in this position for the full experiment year.

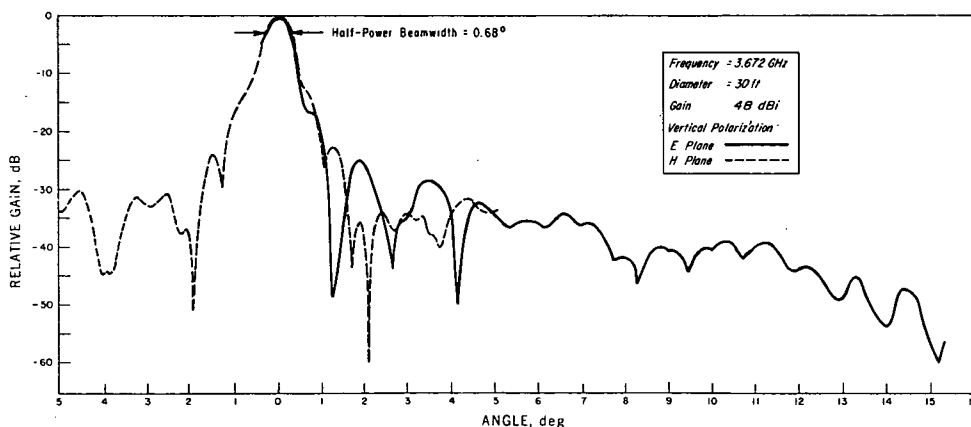


Figure 3-6.—Receiving antenna pattern—S-band.

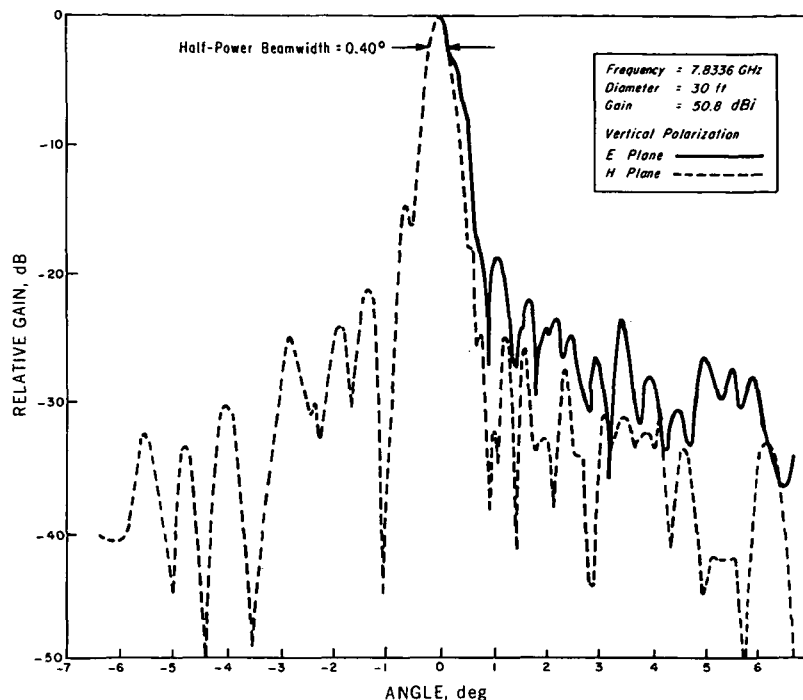


Figure 3-7.—Receiving antenna pattern—X-band.

3.2.2 Radiofrequency Section

A block diagram of the bistatic receiving system used in phase II is shown in figure 3-8. Differences in the phase I and II equipment are given in table 3-2. Incoming signals were routed through the directional coupler (used for calibration) to a low-noise tunnel diode preamplifier (TDA). The TDA had a single sideband noise figure of 5 dB, gain of 20 dB, and a bandwidth of approximately 400 MHz. After amplification, the signal was routed to the mixer stage. Because no image rejection filter was used between the TDA and the mixer, the resulting system noise figure was 8 dB. As indicated in figure 3-8, these components were mounted behind the antenna feed horn in a temperature-stabilized housing. The local oscillator (LO) signal, which provided the second input to the mixer, was derived from a standard frequency oscillator and a frequency synthesizer (single frequency). The synthesizer, which accepted a 1-MHz input signal, used frequency division, heterodyning, and multiplication to convert the incoming signal to the desired frequency of 91.56 MHz. The output of the synthesizer was then split into two parts (one for the bistatic receiver and the other for the GC path receiver) and routed through a pad and approximately 200 ft of coaxial cable to an amplifier located in the antenna-mounted electronics housing. The pad was used to achieve the proper drive level to the amplifier. After amplification (approximately 20 dB) the signal was routed through a varactor multiplier ($\times 40$) and pad to the mixer assembly. The pad was used to obtain the LO power level of 1 to 2 mW required for

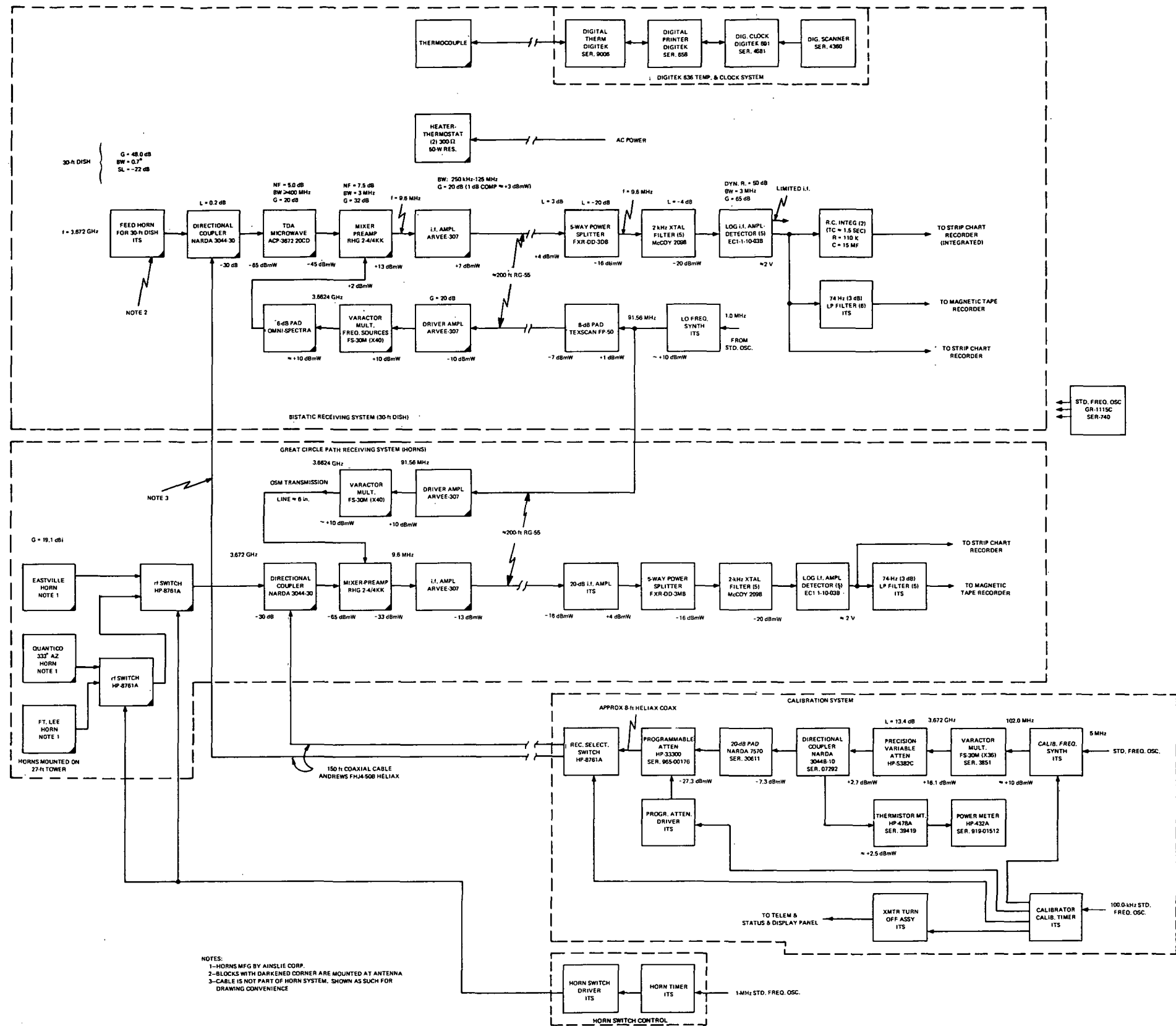


Figure 3-8.—LaRC receiving and calibration systems.

proper mixer operation. The mixer assembly consisted of dual crystal hybrid mixers integrated with low-noise silicon i.f. preamplifiers. The unit had a noise figure of approximately 7 dB, gain of 32 dB (rf - i.f.), i.f. center frequency of 9.6 MHz, and bandwidth of 3 MHz.

3.2.3 Intermediate Frequency and Postdetection Section

The 9.6-MHz i.f. output of the mixer-preamplifier was further amplified (approximately 20 dB) and routed through 200 ft of coaxial cable to a five-way power splitter located in the equipment van. The power splitter was of the resistive type and had a loss of approximately 20 dB. The output of the power splitter was routed to five narrowband crystal filters where all but the desired signal frequency was attenuated. The filters had a 3-dB bandwidth of approximately 2 kHz, a loss of 4 dB, and out-of-band signal rejection of greater than 60 dB. The selected i.f. signals were then applied to the associated log i.f. amplifiers where the signal was amplified and detected. The log i.f. units were similar to those used in radar applications and had a dynamic range of 60 dB with ± 1.5 -dB linearity, an i.f. bandwidth of 3 MHz, a gain of approximately 65 dB, and an output frequency of approximately dc to 1 MHz at a level of 2 V. The output signal, which was proportional to the logarithm of the received rf signal amplitude, was then routed through various filtering circuits (of 100 Hz or less) and recorded on strip chart and analog magnetic tape recorders. The characteristics of the filters and recorders are described in later sections.

3.2.4 Receiver Characteristics

A summary of the characteristics of the S- and X-band receiver systems was given in table 2-3. The results of critical receiver subsystem measurements are given in the following paragraphs.

3.2.4.1 Oscillator Stability

Measurements made of frequency variations during the year were on the order of tens of hertz. The largest offset observed was 22 Hz. This included transmitter offsets, which were measured at the transmitter, as well as receiver offsets (during periods of enhanced terrain diffraction when the received signal was of large amplitude and not fading).

3.2.4.2 Typical Passband Structure

The bandpass characteristics of all components of the receiver were broad compared to that of the i.f. crystal filter. Therefore, the passband structure of the system was basically that of the i.f. filter. The frequency response of the F2 filter is shown in figure 3-9. The center frequency of the received signal was 9.60 MHz. As can be seen in the figure, a frequency offset of 10 or 20 Hz (measured frequency stability) would have little or no effect on the received signal amplitude. The other filters had similar bandpass characteristics with variations of less than ± 0.4 dB within 400 Hz of their center frequencies.

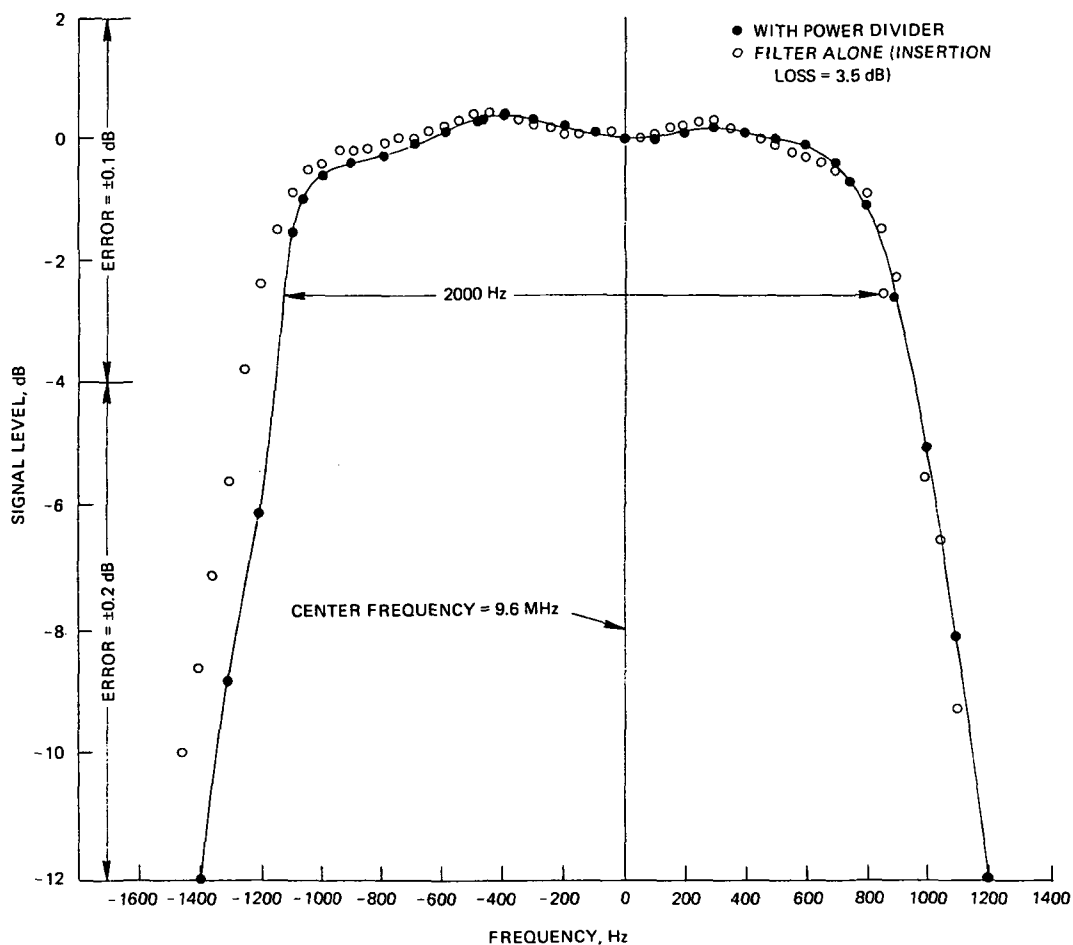


Figure 3-9.—F2 crystal filter frequency response.

3.2.4.3 Receiver Transfer Function

The overall transfer function of the F2 receiver channel is shown in figure 3-10. It is a plot of the dc voltage out of the log amplifier-detector as a function of signal level at the input to the TDA. As can be seen in the figure, the system is linear to within ± 1.0 dB over a 50-dB range.

3.2.4.4 Postdetection Filtering

Two types of postdetection filters were used: 74-Hz (3-dB bandwidth), low-pass and 1.5-s RC time constant filters (integrators). As shown in figure 3-11, all bistatic receiver channels recorded on magnetic tape were routed through the 74-Hz filters. Bistatic signals recorded on the strip chart in phase I were not integrated. During phase II the 10K signals were routed through the 1.5-s integrators prior to strip chart recording. In addition, the strip chart recorder itself acted as a low-pass filter. Its frequency response is given in the following section.

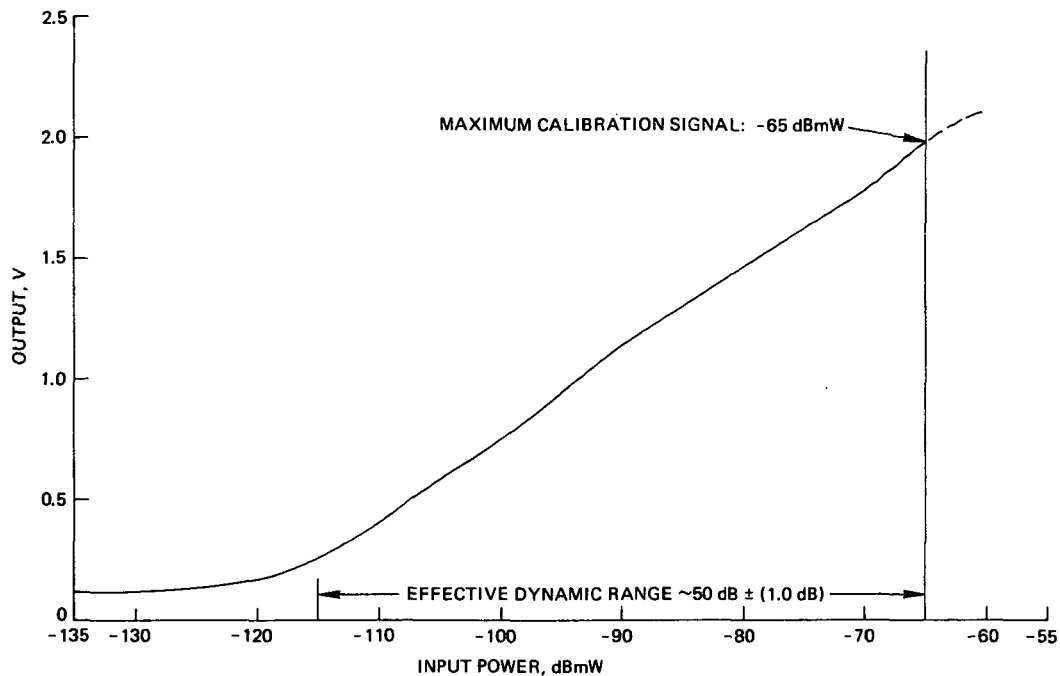


Figure 3-10.—F2 receiver transfer function.

3.2.5 Data Recording and Display

The bistatic radio data and GC path data were recorded on 1-in., 14-channel, analog FM magnetic tape and on an eight-channel strip chart. The strip chart records were used for display as well as data reduction purposes. A block diagram of the recording system, as configured in phase II, is shown in figure 3-11. The differences between the phase I and II configurations are given at the end of this section and in table 3-2. As can be seen in the figure, all bistatic channels recorded on magnetic tape were routed through low-pass filters prior to recording. The characteristics of the filters (and integrators) were given previously. The 74-Hz filters were used to limit the frequency band of the scattered signal to that of the magnetic recorder. The system used FM recording for all channels at a center frequency of 600 Hz with frequency deviation of ± 40 percent. The linearity (best-fit line) over this range was ± 1 percent. Second and third harmonic distortion was less than 1 percent. To achieve these characteristics the recording speed was 0.6 in./s and wow and flutter compensation was used. A new tape reel was required every 13 hr (2400-ft reels) and a total of approximately 795 reels were used during the experiment. The strip chart recorder was of the pressurized ink variety and had two side marker (event) channels in addition to the eight analog channels. Signals from the 10K common volumes were routed through RC integrating filters prior to recording while data from the 20K paths and GC receiver were not. Low-gain dc amplifiers (HP-8820A) were used in each channel to achieve full-scale chart deflections (50 divisions) for a received signal level of -65 dBmW. The frequency response as operated was dc to 150 Hz (3 dB down at 10 divisions), rise time was 3 ms (10 to 90 percent of final deflection) with 4 percent overshoot, linearity was ± 0.25 division, noise and

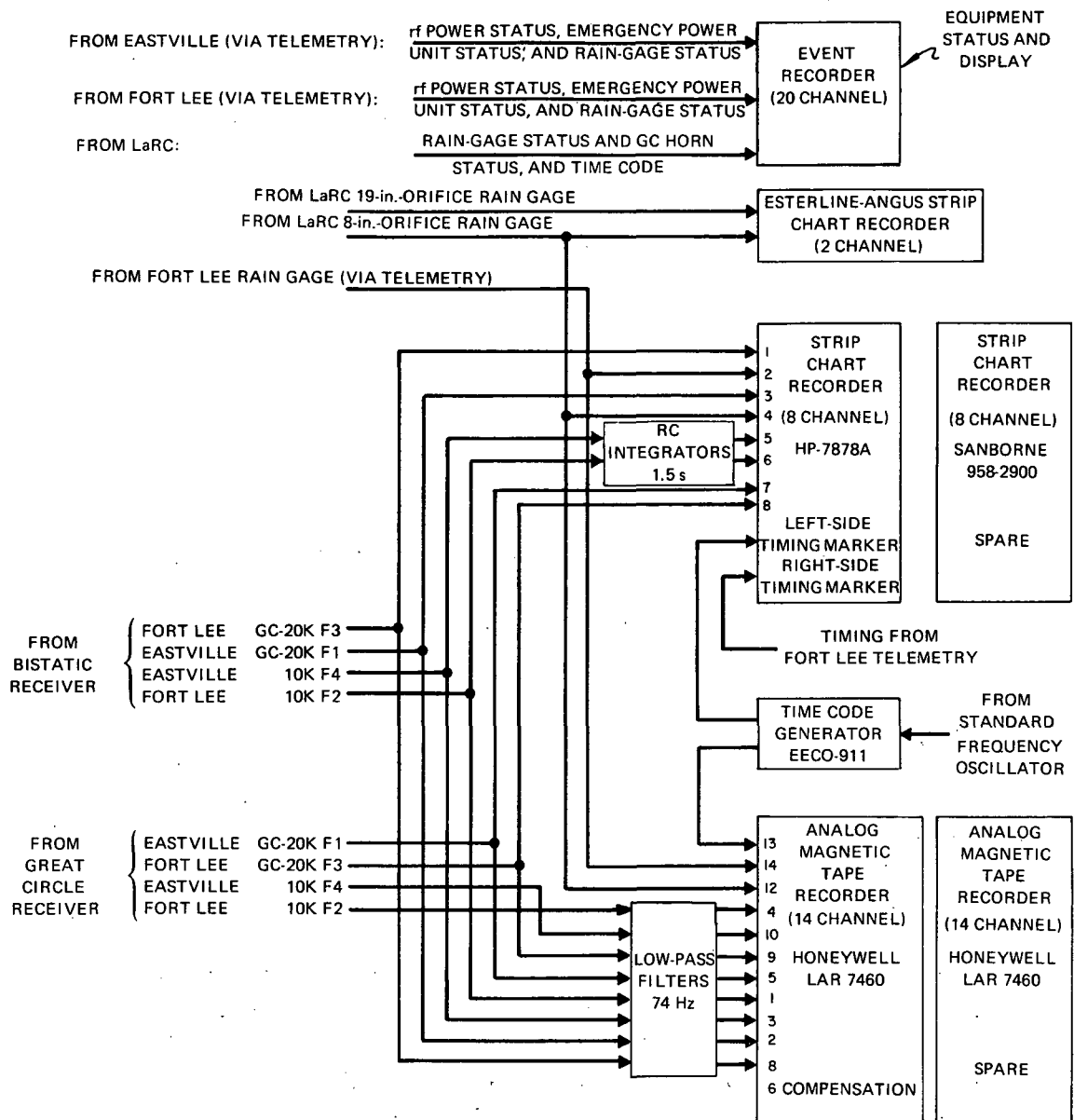


Figure 3-11.—LaRC recording equipment—phase II.

ripple ≤ 0.1 division, gain stability ≤ 0.5 percent per 10°C and ≤ 0.15 percent for ± 10 percent variation in line voltage (around 115 V), drift ≤ 0.5 division per 10°C and $\leq \pm 10$ percent line voltage variation, and channel crosstalk was at least 72 dB down. The side marker channels were used to record local and Fort Lee timing. Timing for the recording systems was from a time code generator that was driven by the standard frequency oscillator. The standard oscillator provided 1.0-MHz pulses to the time code generator which produced a

time code pattern in IRIG-E format. This format uses a 100-Hz carrier, a code frame length of 10 s, and indicates time in days, hours, minutes, and seconds. This code was recorded on channel 13 of the magnetic tape recorder.

In addition to the data recorders described above, a display panel, a 20-channel event recorder, and a digital printer were used for diagnostic and display purposes. As indicated in figure 3-11, the event recorder was used to indicate the status of equipment at Eastville, Fort Lee, and LaRC. The following information was obtained via telemetry from Eastville and Fort Lee: rf power monitor status, rain-gage status, and the emergency power unit status. Also recorded were the status of the LaRC rain gages, LaRC site timing, and the status of the horn antenna switches used in the GC path system. The digital printer recorded the ambient temperature and also the temperature within the antenna-mounted electronics housing as shown in figure 3.8.

During phase I the spare strip chart and magnetic tape recorders shown in figure 3-11 were not available and the 10K strip chart paths were not integrated prior to recording. Also in phase I, the X-band channels were recorded and displayed on the strip chart. The event recorder and digital printer were introduced in the latter part of phase I.

3.2.6 Calibration System

A block diagram of the calibration system used in phase II was given in figure 3-8. The differences between the phase I and II configurations are described at the end of this section and summarized in table 3-2. Calibration of the bistatic and GC receivers was fully automatic and occurred every 2 hr. Timing for the calibration was derived from the site standard frequency oscillator. Approximately 1 min was required to calibrate each channel (frequency) of each receiver. When a particular channel was being calibrated, the corresponding transmitter was turned off (routed to an attenuator) via the telemetry system to prevent the possibility of interference. The automatic calibration signal level was controlled in 10-dB steps over a 70-dB range, from -135 to -65 dBmW, by the calibration timer and programmable attenuator.

The rf signals used for calibration were generated in the same manner as the transmitter frequencies. A standard frequency oscillator was used to feed a frequency synthesizer which in turn fed a varactor multiplier. Because each frequency in the system was calibrated, the synthesizer had a multifrequency capability. The frequencies of the calibration signals were within 22 Hz of the corresponding transmitter frequencies. The output of the varactor multiplier was routed through a precision variable attenuator and a directional coupler to a thermistor and power meter. The precision attenuator served several purposes. It was used (1) in conjunction with the power meter for testing and resetting power levels when required, (2) periodically to check the programmable attenuator, and (3) to provide a finer grained calibration than the 10-dB steps of the programmable attenuator. The other output of the directional coupler was routed through a 20-dB pad to the programmable attenuator which was used as the calibration standard in phase II. The programmable attenuator was calibrated before and after phase II by the Calibration Laboratory of MIT Lincoln Laboratory

and was found to be within ± 0.2 dB over its full range in both accuracy and repeatability. The output of the programmable attenuator was applied sequentially to each receiver via the receiver select switch and directional couplers.

In phase I, an X-band calibration system was provided; a pin-diode attenuator of limited accuracy and repeatability was used as the calibration standard; and all channels were off during calibration which lasted approximately 15 min.

3.2.7 Monitoring Capabilities

The receiver parameters that were monitored in the summer months are given in the following list. Some parameters were monitored before and after radio events and also on a daily basis, whereas others were monitored periodically. Prior to the summer months many of these parameters were measured on an irregular basis.

(1) Daily or preevent and postevent monitoring:

- (a) Minimum discernible signal level (cw using calibration system)
- (b) Receiver and calibration system stability
- (c) Calibration tone levels
- (d) dc power supply voltages
- (e) ac line voltage
- (f) Strip chart recorder calibration
- (g) Minimum and maximum temperatures (van, outside, and antenna-mounted electronics)
- (h) Telemetry system levels

(2) Periodic monitoring:

- (a) System gain stability (temperature)
- (b) Insertion loss and VSWR of calibration system
- (c) Receiver bandwidth and transfer function
- (d) Mixer crystal currents
- (e) Frequency and spectra of calibration tones and LO signal
- (f) Frequency of the FM oscillators in the magnetic tape recorder

3.2.8 Installation

As indicated in figure 3-8, the rf sections and first i.f. amplifier for the bistatic receiver were mounted in a separate housing adjacent to the antenna feed horn. The housing was weatherproof and temperature stabilized. All equipment not mounted at the antenna was

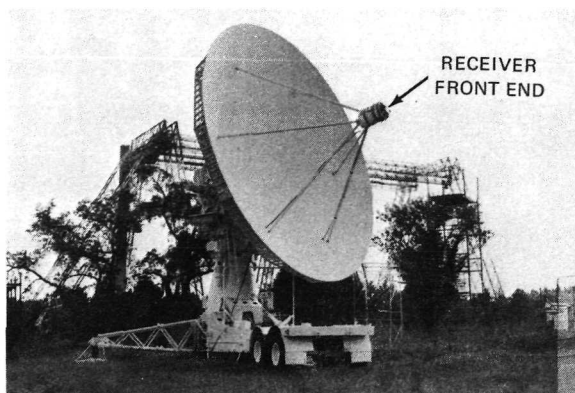


Figure 3-12.—Thirty-foot dish antenna, LaRC receiver site.

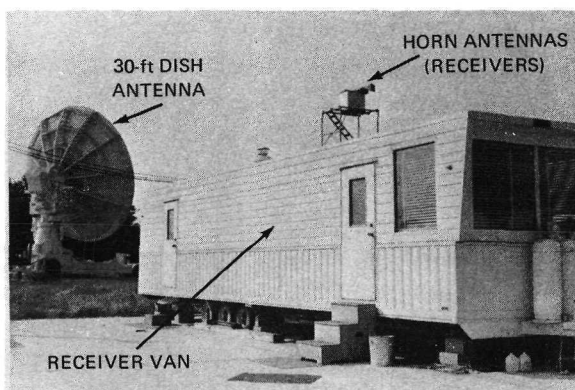


Figure 3-13.—LaRC receiver site.

installed in the equipment van. The van was equipped with air conditioning and heating for temperature control. Commercial power was used. During the summer months an engine generator was provided in case of power failure. Figures 3-12 and 3-13 are photographs of the LaRC site.

3.3 GC PATH SYSTEM

A block diagram of the GC path system is shown in figure 3-8. The system used three horn antennas, each having a gain of approximately 19 dBi mounted on a tower approximately 27 ft above the ground. The Eastville and Fort Lee horn antennas were pointed at those sites at an elevation angle of approximately 0° ; the Quantico horn was pointed in the same direction as the 30-ft dish at an elevation angle of approximately 10° . The antennas were connected to the receiver by two rf switches whose timing was derived from the standard oscillator. After the rf switches, the received signals were routed to the mixer-preamplifier through the directional coupler which was used for calibration purposes. The horn receiving system had

a 10-dB noise figure and was almost identical to that of the 30-ft dish except that a TDA was not used and 20-dB additional i.f. gain was provided as compensation.

The recording equipment for this system as used in phase II is shown in figure 3-11. As can be seen in the figure, the Fort Lee and Eastville GC path signals were recorded, unintegrated, on channels 8 and 7, respectively, of the strip chart recorder and filtered (74-Hz low pass) on tracks 9 and 5, respectively, of the magnetic tape recorder. For phase I, a single horn antenna was used directed at Eastville and the data were recorded on a single-channel strip chart.

3.4 INSTRUMENTATION CHANGES AND EFFECTS

As described in earlier sections, the bistatic radar configuration was changed during the transitional phase. In addition, measurements made on components and subsystems during the year indicated that changes in performance had occurred. These changes are referred to

as “correction factors” and are used to modify the nominal values given in table 2-3. The following categories were considered:

- (1) Attenuator incorrectly set in calibration system
- (2) Calibration standard system change
- (3) Transmission line loss variations
- (4) Transmitter spectrum differences

The specific changes, their effects, and the period over which the situation existed are summarized in chronological order in tables 3-6 to 3-9 for the Eastville and Fort Lee 10K and 20K paths. Changes resulting in corrections of ± 0.1 dB or less are not included. The spectrum corrections were empirically derived using the calibration system as reference. The antenna gain and pointing angles differed from the values used for the path loss computations. Their changes are documented in section 3.1.4.

Table 3-6.—Eastville 10K Path Correction Factors

Period	Change or occurrence	Correction factor, dB
10/3/70 to 5/17/71	The transmission line loss was less than the reference system because there was no directional coupler and fewer rf switches and power monitors in the path.	-0.6
12/8/70 to 6/4/71	An attenuator (pin diode) with more loss than that of the reference system was used in the calibration system.	-1.0
4/5/71 to 10/2/71	The setting of the precision attenuator in the calibration system was in error.	-2.0
7/26/71 to 9/1/71	The F4 and F5 transmitters were interchanged. Subsequent tests showed that the F4 transmitter had poorer spectral characteristics.	1.7

Table 3-7.—Fort Lee 10K Path Correction Factors

Period	Change or occurrence	Correction factor, dB
10/3/70 to 10/2/71	The transmission line loss was more than that of the reference system.	+0.7
12/8/70 to 6/4/71	An attenuator (pin diode) with less loss than that of the reference system was used in the calibration system.	-1.0
4/5/71 to 10/2/71	The setting of the precision attenuator in the calibration system was in error.	-2.0

Table 3-8.—Eastville 20K Path Correction Factors

Period	Change or occurrence	Correction factor, dB
10/3/70 to 8/15/71	The transmission line was twice as long (100 ft) as the reference system and had greater loss.	1.1
12/8/70 to 6/4/71	An attenuator (pin diode) with more loss than the reference system was used in the calibration system.	-1.0
4/6/70 to 10/2/71	The setting of the precision attenuator in the calibration system was in error.	-2.0
8/9/71 to 10/2/71	The F1 transmitter replaced the F5 transmitter during this period; it had poorer spectral characteristics.	1.5
8/16/71 to 10/2/71	A directional coupler was inserted into the transmission path; its loss was 0.2 dB.	1.3

Table 3-9.—Fort Lee 20K Path Correction Factors

Period	Change or occurrence	Correction factor, dB
10/3/70 to 8/10/71	The line loss was measured to be 0.5 dB above that of the reference system.	0.5
12/8/70 to 6/4/71	An attenuator (pin diode) with more loss than the reference system was used in the calibration system.	-1.0
4/6/71 to 10/2/71	The setting of a precision attenuator in the calibration system was in error.	-2.0
7/26/71 to 8/24/71 (except for 8/18/71)	The F2 and F3 transmitters were interchanged; subsequent tests showed that the F3 transmitter had poorer spectral characteristics.	3.0
8/10/71 to 10/2/71	A directional coupler was inserted into the transmission path; its loss was 0.2 dB.	0.7
8/18/71	The frequency synthesizer voltage was misset; this resulted in increased power at the desired frequency.	1.8
8/25/71 to 10/2/71	The voltage on the varactor multiplier was changed for improved spectrum.	2.5

3.5 EQUIPMENT ERROR ANALYSIS

This section describes the equipment errors as estimated for the bistatic radar system. The tests and results that formed the basis for the estimates are discussed as well as the transmitting antenna broadband radiated power tests made in phase II to insure that the transmitting system parameters did not change. Angular errors in antenna alignment are considered in reference 13 based on measurements given in section 3.1.4. All test

equipment was calibrated, in accordance with the manufacturer's specifications, in the Standards and Calibration Laboratory at LaRC by qualified NASA or contractor personnel. The basic measuring instruments used for measuring rf power were HP-432A power meters and HP-478A temperature-compensated thermistor mounts.

3.5.1 Error Budget Summary

Table 3-10 contains the values of measurement accuracy (acc.) and repeatability (rep.) for the components used in the primary transmitting and receiving systems for phases I and II. The definition of measurement accuracy and repeatability as used in this report was given in section 2.4. As described there, system accuracy estimates are obtained by adding component accuracy estimates, whereas repeatability estimates are obtained from the square root of the sum of the squares of the individual component estimates. In general, the accuracy and repeatability values given for the period from October 3, 1970, to May 7, 1971, were based on estimates; those covering May 7 to October 2, 1971, were based both on estimates and measurements. Table 3-10 is organized into three sections:

- (1) A listing of the errors associated with the equipment for each of the primary paths
- (2) A listing of the most accurate 10K and 20K paths for each phase selected by using data from tables 3-11 and 3-12
- (3) The results of the wideband radiated power tests

These data are discussed in this section and in sections 3.5.2 and 3.5.3.

The most accurate 10K path for the year used the Eastville 10K path (F5) from October 3, 1970, through July 26, 1971, and the Fort Lee 10K path (F2) from July 26 through October 2, 1971. (See table 3-11.) For this combined 10K path, the errors were 4.0 and -5.0 dB for phase I and ± 2.9 dB for phase II. Using a similar approach, the most accurate 20K path had errors of 6.9 and -4.9 dB for phase I and ± 3.0 dB for phase II. The pin-diode error summary is given in table 3-12.

The wideband antenna radiated power tests made during phase II indicated that (1) the pointing angles of the antennas did not change; (2) the power received on each path as averaged over the 10 measurements for each path was within ± 0.5 dB of the calculated value; and (3) the variation of the individual measurements around the average was within ± 0.5 dB. These variations were well within the accuracy and repeatability of the measurements themselves and it was therefore concluded that the antenna gain and transmission line loss measurements were correct and did not vary during phase II.

3.5.2 Supportive Data

3.5.2.1 Transmitting Sites

As can be seen in table 3-10, the accuracy of the transmitting systems depended on the leveling loop, line losses, antenna gain, and transmitter spectrum. The error estimate of the

Table 3-10.—Bistatic Radio Equipment Error Summary

System	Phase I errors, dB						Phase II errors, dB					
	E			F			E			F		
	10K		20K		10K		10K		20K		10K	
	Acc.	Rep.	Acc.	Rep.	Acc.	Rep.	Acc.	Rep.	Acc.	Rep.	Acc.	Rep.
Transmitting:												
Leveling loop	0.3	0.4	0.3	0.4	0.3	0.4	0.3	0.2	0.3	0.2	0.3	0.2
Line loss	.2	.3	.2	.3	.2	.3	.2	.3	.2	.3	.2	.3
Antenna gain	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5
Spectrum ^a	.1	.1	+3,-0	.1	+6,-0	.1	.7	.2	+3,-0	.2	+6,-0	.2
Total	1.1	.5	+4,-1.0	.5	+7,-1.0	.5	1.7	.4	+4,-1.0	.4	+7,-1.0	.4
Receiving:												
Antenna gain:	.4	.8										
Line loss (calibration)	.1											
Power meter and transfer	.3											
Pointing accuracy	.1											
Target transmitter	.6											
Gain standard and multi-path												
Subtotal	1.5	.8	±1.5	.8	1.5	.8	1.5	.8	±1.5	.8	±1.5	.8
Calibration:												
Pin-diode attenuator ^b	+1.3,-2.3	1,-4	+1.3,-2.3	1,-4	+1.3,-2.3	1,-4	.2	.1	.2	.1	.2	.1
Programmable attenuator	.1	.4	.1	.4	.1	.4	.1	.4	.1	.4	.1	.4
Reference power meter		3.0		3.0		3.0		.1		.1		.1
Receive gain change within calibrated interval		.1		.1		.3		.1		.1		.3
Spectrum	+1.4,-2.4	+3.3,-5.1	+1.4,-2.4	+3.3,-5.1	+1.4,-2.4	+3.3,-5.1	.3	.3	.3	.3	.3	.3
Subtotal	+2.9,-3.9	+3.3,-5.1	+2.9,-3.9	+3.3,-5.1	+2.9,-3.9	+3.3,-5.1	1.8	.9	±1.8	.9	1.8	.9
Total	+4.0,-5.0	+3.3,-5.1	+6.9,-4.9	+3.3,-5.1	+9.9,-4.9	+3.3,-5.1	3.5	1.0	+5.8,-2.8	1.0	+8.8,-2.8	1.0
Grand total												
Most accurate 10K and 20K path per phase:	+4.0,-5.0		+6.9,-4.9				2.9					
10K path ^{a,b}												
20K path ^{a,b}												
Wideband radiated power tests:												
Calculated received power (dBmW)							6.2		9.1		6.7	
Measured received power (dBmW) ^c							5.7		8.6		7.7	
Calculated minus measured value (dB)							.5		.5		.0	
Variation from average for all measurements (dB)							.5		.5		.2	

NOTE: All values are ± except when given otherwise.

^aSee table 3-11.

^bSee table 3-12.

^cAverage of all phase II measurements.

Table 3-11.—Spectrum Error Summary

Path	Frequency	Period	Accuracy, dB	Repeatability, dB
E-10K	F5	10/3/70 to 7/26/71	^a 0.1	0.1
	F4	7/26/71 to 9/1/71	.7	.2
	F4 ^b	9/1/71 to 10/2/71	.1	.1
F-10K	F3	10/3/70 to 7/26/71	-0, +6	NA
	F2	7/26/71 to 10/2/71	^a .1	.1
E-20K	F4	10/3/70 to 7/26/71	^c -0, +3	NA
	F5	7/26/71 to 8/9/71	.1	.1
	F1	8/9/71 to 10/2/71	.2	.3
F-20K	F3	10/3/70 to 5/7/71	-0, +6	NA
	F2	5/7/71 to 7/26/71	^c .1	.1
	F3	7/26/71 to 8/25/71	^c .2	.2
	F3	8/25/71 to 10/2/71	^c .2	.1

NOTE: Values are $\pm$ unless given otherwise.

^aMost accurate 10K path for this period.

^bF5 was modified to produce F4 for this period.

^cMost accurate 20K path for this period.

Table 3-12.—Pin-Diode Error Summary

Period	Accuracy, dB	Repeatability, dB
10/2/70 to 12/8/70	+0, -2.3	+0, -4
12/8/70 to 1/25/71	1.3	+0, -4
1/25/71 to 4/5/71	.3	1.0
4/5/71 to 6/4/71	1.0	1.0

NOTE: Values are $\pm$ unless given otherwise.

power out of the leveling loop was ± 0.3 dB and was largely from power meter inaccuracy and component uncertainty. Transmission line loss was measured several times during the course of the experiment. Based on the errors associated with these measurements, a value of ± 0.2 dB was believed to be an accurate estimate of error. The accuracy assigned to the antenna gain measurement was ± 0.5 dB and includes multipath effects, uncertainty of gain and pointing of the gain standard, and errors of the precision attenuator used in the measurement. The errors associated with the transmitter spectra were the largest source of transmitter error for many of the transmitters. The problem was that the spectral distribution of power was voltage sensitive and that this was not known until August 26, 1971. The voltage was not accurately measured until August 9, 1971, at Fort Lee and August 18, 1971, at Eastville. Thus, in spite of the fact that the power output of the transmitters was held constant, the power in the 2-kHz receiver bandwidth may have changed. The spectrum errors for the different transmitters are given in table 3-11 and are described in the following paragraph.

The spectra of the F2 and F5 transmitters were not voltage sensitive and very little error was ascribed to them. The F3 transmitter output was quite voltage sensitive. Based on measurements made using the maximum and minimum voltages recorded in site logs and not knowing when the voltage sensitivity problem began, the error was estimated at +6 and -0 dB from October 3, 1970, to July 26, 1971. From July 26 to August 26, 1971, the voltage sensitivity problem was assumed to have existed and because the power supply voltages were accurately measured from August 9 to October 2, 1971, the F3 errors could be corrected, resulting in improved measurement accuracy. The F4 transmitter was also frequency sensitive but not as much as F3. Based on information and measurements similar to those described for F3, the error estimates were lower as shown in table 3-11. There was, however, some uncertainty associated with the basic voltage sensitivity measurements and, because of this, an accuracy of ± 0.7 dB was used from July 26 to September 1. On September 1 the F5 transmitter, which was not voltage sensitive, was modified to produce F4 and was used for the remainder of the experiment. Because it was not voltage sensitive, the error associated with it was ± 0.1 dB. The F1 transmitter, although quite voltage sensitive, had its voltage controlled and monitored when it was used. The accuracy ascribed to it was ± 0.2 dB. The total error estimate for the transmitters is given in table 3-10.

Temperature and voltage drifts were the major source of repeatability errors. At the transmitter sites, the thermistor mount which was part of the leveling loop was temperature sensitive. Based on observations and measurements of this effect, the repeatability estimates were ± 0.4 dB in phase I and ± 0.2 dB in phase II. Transmission line loss variations due to temperature changes are estimated at ± 0.3 dB based on empirical data. A value of ± 0.1 dB was assigned to spectrum repeatability errors due to voltage uncertainty.

3.5.2.2 Receiving System

The accuracy of the receiving system was a function of the antenna and calibration system errors (given in table 3-10). The antenna gain measurement required knowledge of the loss of a transmission line system (calibration) containing many components (see fig. 3-8) whose total loss was approximately 70 dB. Because the dynamic range of the measuring equipment used in the field was limited, the line loss was measured in sections and the results summed. The accuracy estimate was ± 0.4 dB. The above line loss measurement was referenced to a port of a directional coupler and an error of 0.1 dB is estimated for shifting the reference point. The 30-ft antenna had a beamwidth of approximately 0.7° , and an error of ± 0.1 dB is ascribed to pointing it at the target transmitter. The pointing error estimate for the transmitting horn was ± 0.2 dB. This is somewhat higher than one might normally estimate and was due to not using a boresight telescope for pointing. The pointing procedure involved using the strip chart recorder of the receiver to monitor transmission loss and relaying instructions for antenna movement, via radio, back to the boresight tower. An error of ± 0.1 dB is assigned to the target transmitter stability, power meter drift, and transfer of the wideband power reading to a narrowband calibration signal level reading required during the course of the gain measurement. Finally, an error of ± 0.6 dB was estimated for the gain of the transmitting gain standard and multipath effects due to

diffraction by the trees in the foreground as described in section 2.2.1.1. Adding the individual accuracy estimates results in a ± 1.5 -dB accuracy for the gain measurement.

In the calibration system the major source of error during phase I was the pin-diode attenuator (HP-8733B) that was used as the calibration standard. This attenuator was a voltage- and current-controlled analog device, which was driven from a regulated power supply and a bank of dropping resistor networks. For accuracy it was calibrated against the precision attenuator and adjusted periodically. This was done in early September 1970, on December 8, 1970, and on January 24, 1971. The error estimates given in table 3-12 are based on the drifts recorded at these times. On January 25, 1971, the regulated power supply was replaced and a daily calibration procedure was instituted. As a result of the recorded calibrations over the period from January 25 to April 5, 1971, a -1.0 -dB correction factor was applied with an estimated error of ± 0.3 dB. The attenuator was calibrated infrequently between April 5 and June 4, 1971, so that a ± 1.0 -dB error estimate was used. In phase II, a programmable stepped attenuator (HP-33300) was used. It was calibrated before and after the experiment and its accuracy and repeatability was ± 0.2 and ± 0.1 dB, respectively. The other contribution to calibration system error was the frequency source. Although it varied ± 0.4 dB (repeatability) during the experiment, its accuracy was estimated to be 0.1 dB.

The major causes of large repeatability error values were temperature, voltage drifts, and (in phase I) a spurious oscillation in the i.f. amplification stages of the mixer-preamplifier assembly. Measurements and calculations indicated that the calibration transmission line loss variation was ± 0.8 dB and that it was due to temperature. The high value of pin-diode attenuator repeatability error was due to voltage variations. The receiver gain change within the 2-hr calibration interval was caused by temperature variations and the spurious oscillation in the antenna-mounted electronics. The spurious oscillation was at approximately 500 kHz and of large amplitude. The harmonics of the oscillation varied in amplitude and frequency with temperature. One of the harmonics often passed through the narrow receiver passbands during periods of temperature change. When a harmonic of the spurious oscillation was present in the receiver output it typically had a slowly changing amplitude with a peak value as high as -95 dBmW. The harmonic of the spurious oscillation added to the signals being detected, thereby masking lower level signals. The spurious oscillations were also sensitive to power supply voltage level such that changing the voltage level slightly shifted the frequency of the oscillation out of the narrow channel passband of the receiver. The harmonics had a spacing different from the channel frequency separation and only one channel was affected at a time. In data processing, signals were always available from the other channels preventing a loss of data for a particular scattering height. The onset of spurious oscillations (or shift of frequency so it could be detected) was generally accompanied by a 2- to 3-dB change in receiver gain. This happened in a time interval that was short in comparison with the time between calibrations, and the magnitude of the effect is given in table 3-10 as ± 3 dB. The mixer-preamplifier assembly was modified to stop the spurious oscillation on April 19, 1971. Temperature stabilization for the antenna-mounted electronics was installed April 7, 1971. After the mixer-preamplifier modifications

and temperature stabilization the gain change between calibrations was reduced to ± 0.1 dB. The spurious oscillations also caused mixing between the harmonics of the oscillations and the signals to be measured resulting in high cross-talk between channels. Cross-talk levels as high as -20 dB with respect to the level in the primary channel were observed. Because the spurious oscillation and the attendant mixing operation occurred in a wideband section of the i.f. amplifier chain, the calibration tones provide an adequate monitor for receiver operations and it is considered unlikely that a single narrowband channel would experience a loss in gain.

3.5.3 Broadband Radiated Power

Broadband radiated power measurements were performed at both the Fort Lee and Eastville transmitter sites from early May 1971 to the end of the program (October 2, 1971). These measurements were made every 2 weeks and were obtained on the electrical axis of each antenna, to the right and left and above and below this axis. Plots of the measurements obtained on axis are given in figures 3-14 and 3-15 and for the 10K and 20K paths, respectively. The purpose of these measurements was to insure that the antenna pointing angles and radiated power levels remained constant throughout the experiment. The constancy of antenna pointing angle was verified by comparing the on-axis data with the data

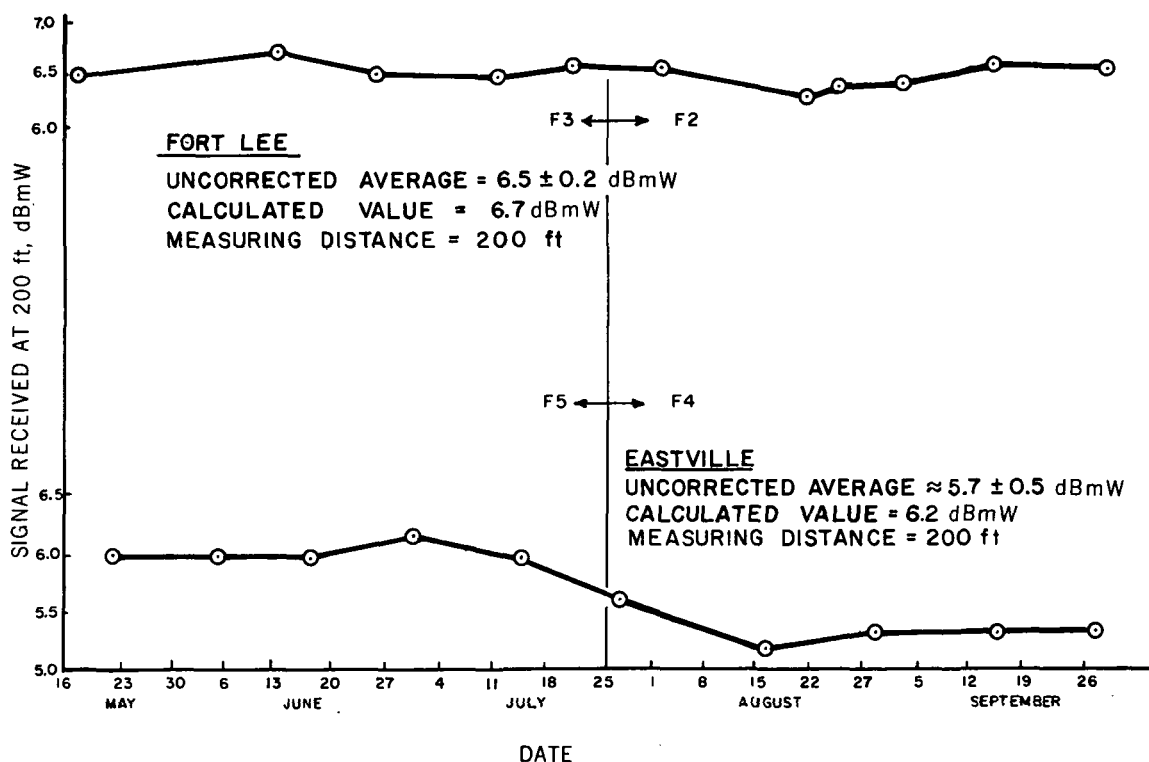


Figure 3-14.—10K antenna broadband radiated power measurements.

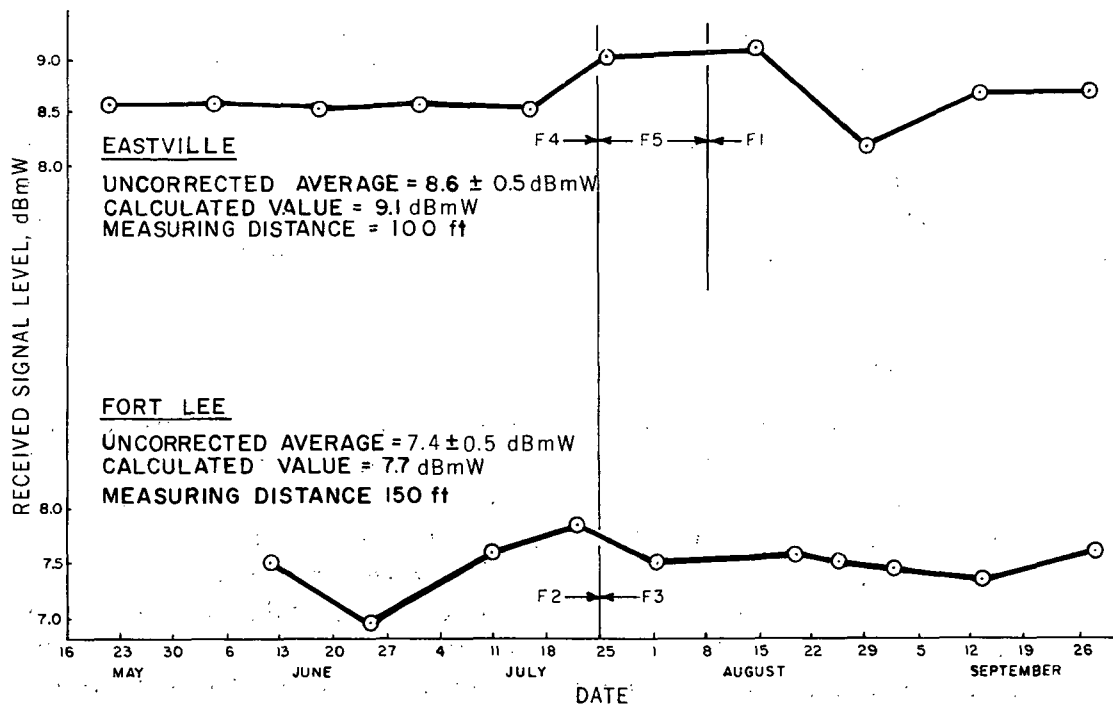


Figure 3-15.—20K antenna broadband radiated power measurements.

obtained off-axis, while constant radiated power was verified by comparing the on-axis readings. It is concluded from these measurements that variations in radiated power levels during the May 7 to September 30 interval were minor and that the pointing angles of the antennas remained unchanged during this interval.

The measurements were performed at distances between 100 and 200 ft using an antenna probe of 12.1-dBi gain, an HP-432A power meter, and an HP-478 thermistor mount. These are broadband measurements, limited by the antenna bandwidth, probably of the order of 10 percent of the transmitter frequency.

3.5.3.1 10K Antennas

The measurements were performed at a distance of 200 ft. The received power level for this measurement, based on the parameters of the nominal system, is calculated to be 6.2 dBmW (includes -0.8-dB quasi-near-field correction). Using the correction factors given in section 3.4, the calculated expected values are 6.7 and 6.2 dBmW, respectively, for the Fort Lee and Eastville sites. Examination of figure 3-14 reveals that the measured average levels at Fort Lee (6.5 ± 0.2 dBmW) and Eastville (5.7 ± 0.5 dBmW) show good agreement with the expected values. The minor discrepancies can be attributed to the accuracy of the measurement, which is approximately ± 0.5 dB. This indicates good corroboration between the wideband radiated power measurements and the measurements of transmission line loss and antenna gain.

3.5.3.2 20K Antennas

The measurements were performed at distances of 100 and 150 ft for Eastville and Fort Lee, respectively. The received power level for this measurement, based on the parameters of the nominal system, is calculated to be 10.3 dBmW and 8.3 dBmW for Eastville and Fort Lee, respectively. To obtain these figures, 2.7 and 1.2 dB were subtracted from the 10-ft dish antenna gain at Eastville and Fort Lee, respectively, because the measurements were not made in the far field of the dish. Using the correction factors given in section 3.4, the calculated expected values are 9.1 and 7.7 dBmW, respectively, for the Eastville and Fort Lee sites. Examination of figure 3-15 reveals that the measured average levels at Eastville (8.6 ± 0.5 dBmW) and Fort Lee (7.4 ± 0.5 dBmW) show good agreement with the expected values. The discrepancies can be attributed to the accuracy of the measurement, which is approximately ± 0.5 dB. The wideband radiated power measurements thus corroborate the measurements of transmission line loss and antenna gain.

4 RAIN-GAGE SYSTEM

The rain-gage network, siting, and operating procedures were presented in section 2.2.2. In this section, the equipment, equipment calibration, and equipment measurement accuracy are discussed.

4.1 COLLECTION AND MEASUREMENT

The tipping-bucket gages used in the experiment were of the standard type consisting of a sampling orifice with a sharp edge and high collar to reduce splashing, a funnel below the sampling orifice to direct the water into the metering cups, and a pair of balanced metering cups mounted below the funnel and on a pivot so one cup emptied while the other cup was being filled. The cup size and weight was adjusted so that the cup being filled moved away from the funnel when a prescribed amount of water was collected. The motion or tip was electrically sensed and displayed as an event mark or a step on a chart recorder. Each tip indicated the accumulation of a fixed volume of water. This is related to rain depth by

$$V = \frac{Ad}{10} \quad (10)$$

where

V = volume of water per tip (cm^3/tip)

A = sampling orifice area (cm^2)

d = depth (mm/tip), a calibration constant

During the experiment, the depth corresponding to a tip was changed for the gages located near the common volumes by changing the orifice area as noted in table 2-5. The rain rate

was obtained as an average rate between tips:

$$R = \frac{d}{t} = \frac{10V}{At} \quad (11)$$

where

R = rain rate (mm/hr)

t = time between tips (hr)

The housings for the gages depended upon the manufacturer. The gages located in the vicinity of the common volumes (types II and III, table 2-5) had a conical shape near the orifice as shown in figure 4-1 and were designed to house heaters for winter operation and a recorder system. The gages were equipped with heaters but the heaters were not operated. The 324-cm² (8-in.) gages located at Eastville, Fort Lee, and LaRC (type I) were cylindrical in shape and the bottom section was enclosed to collect the water dumped by the measuring cups. The water could be drained for measuring total accumulation using a petcock on the bottom of the housing. The 1829-cm² (19-in.) gage at LaRC had a funnel shape and no enclosure for recording apparatus or storing water. Aerodynamic investigations of gage

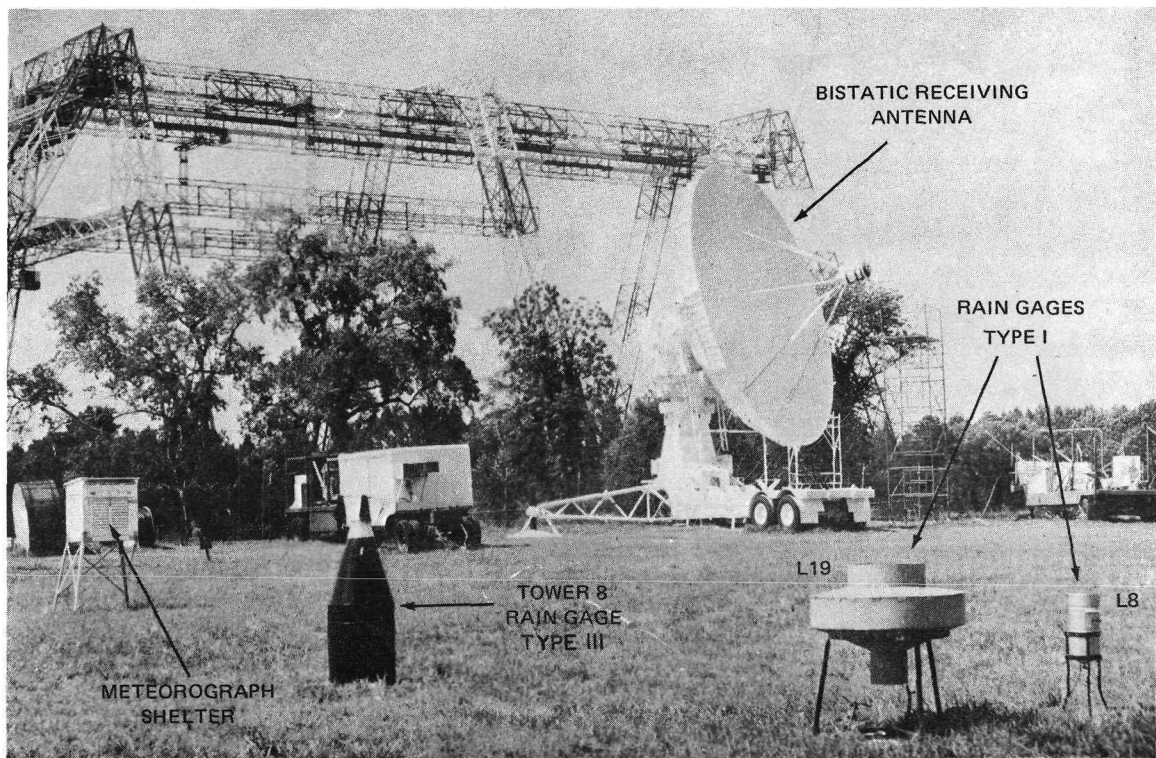


Figure 4-1.—Type I and III rain gages.

shape (ref. 18) have shown that, of the gage shapes used in the experiment, the funnel shape causes the smallest perturbation to the wind field around the gage. The maximum measurement error due to perturbations in air motion over the gage is small and is estimated as less than 3 percent for the cylindrical gages. (See ref. 19 for comparison between gage measurements.) The cone-shaped gages presented a much larger cross section to the wind and the error was estimated to be 5 percent.

4.2 RECORDING SYSTEM

The gages located near the common volumes used portable 45-day chart recorders powered by alkaline type-D-cell batteries. The recorders were installed within the rain-gage housing. The chart was pressure sensitive and was fastened to a drum with a total recording area of 14 by 24 cm. The recording operation was continuous for the complete 45-day period using a chart speed of approximately 1 cm/hr and a stylus motion along the axis of the drum of approximately 3 mm/day. The events were recorded by stepping the recorder stylus up or down for each tip, five steps in each direction (as in fig. 5-5).

At Eastville, a strip chart recorder was used with a chart speed of 45 in./hr (114 cm/hr). Each tip was displayed as a single tick or event mark on the chart. (See fig. 5-4.) The tip event indication was displayed whenever it occurred and the chart drive was turned on at the time of the first tip. The gage operation was manually supervised and the chart recorder was turned off manually after an event or during a long interval with no tips during an event. The operator manually logged the date and time on the chart and each first tip event was automatically telemetered to LaRC and recorded on an event recorder.

The recording system at Fort Lee was identical to the one at Eastville until June 19, 1971. After this date, the tip events were telemetered to LaRC and recorded directly on the Z-fold chart used to record the bistatic radar data.

The recording system at LaRC was similar to that used at Eastville with the exception that two event channels were recorded, one for the 324-cm² gage and the other for the 1829-cm² gage. The larger collecting-area gage was used to turn the recorder on. In addition, the tip events from the 324-cm² gage were recorded on the Z-fold chart used to record bistatic radar data after June 19, 1971. (See fig. 5-2.)

4.3 GAGE CALIBRATION

4.3.1 Type II and III Gages

The gages located in the vicinity of the common volumes were used without extensive calibration. The manufacturer's nominal calibration constant or depth accumulation per tip was used in the data reduction and is listed in table 2-5. A limited number of calibration checks were performed in the field. These checks were made by measuring the quantity of water required to cause a prescribed number of tips. The flow rate used was typically between 10 and 20 mm/hr when making the calibration measurements. Field calibration measurements for the common volume gages were performed using 10 tips for each gage.

The field calibration indicated that the system was operating as expected. The manufacturer's specifications state that the gage calibration constant should be within 0.5 percent of the nominal value at 12 mm/hr and 6 percent at 150 mm/hr. The in situ calibration measurements show that, when the calibration data from each of the gages were averaged, the manufacturer's calibration constant resulted. The maximum uncertainty in the measured calibration constant for a single gage was 12 percent. By virtue of similarity in gage construction and the small error stated in the manufacturer's specifications, the averaged calibration constant was applied to each of the gages. These calibration values apply as long as the tipping measurement cup assembly is maintained in a level state using a bubble spirit level affixed to the assembly. Gage level was periodically checked throughout the measurement and adjusted if required to maintain operation in accordance with the manufacturer's recommendations.

4.3.2. Type I Gages

The gages located at the sites were calibrated at several rain rates prior to installation in the field. Both gages sited at LaRC were calibrated by measuring the average time between two tips for 1000 tips at a fixed flow rate into the gage orifice. The calibration was repeated at a number of flow rates and, knowing the collecting area and using equation (11), page 70, the calibration curves shown in figure 4-2 were obtained. Two curves are displayed

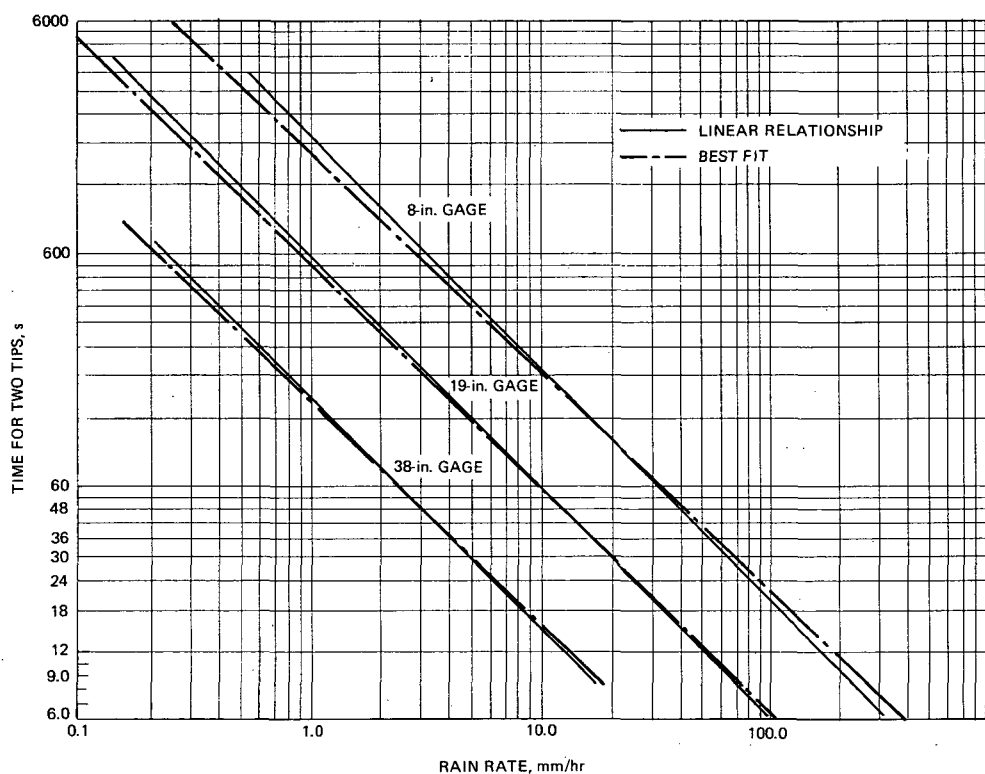


Figure 4-2.—Calibration curves for type I gages.

for each gage: a linear relationship curve implying a single calibration constant that does not depend upon rain rate and a best-fit curve to the calibration data implying a calibration constant that depends on rain rate. The calibration constants given by the linear relationships are listed in table 2-5. The difference between the best-fit calibration and the linear relationship assumed by using a single calibration constant is typical of tipping-bucket rain gages and is responsible for the 6-percent error at 150 mm/hr quoted by the manufacturer of the type II and III gages. The 324-cm² gages located at Eastville and Fort Lee were identical to the LaRC 324-cm² gages in construction. Their calibrations were checked at one rain rate prior to installation and found to be within 10 percent of the LaRC 324-cm² gage. After installation, the gages were periodically calibrated. The in situ calibrations for each gage were made using rates of 10 to 30 mm/hr and 50 tips for each measurement set. The calibration constants derived from the in situ measurements agreed with the preinstallation curve within 9 percent. The estimated accuracy of the in situ measurements is ± 7 percent. The in situ measurements for the LaRC 324-cm² gage agreed with the preinstallation value within 3 percent. Checks for level were made for the site gages during each pre- and post-rain-event calibration.

4.4 ERROR ANALYSIS

Rain-gage measurements are subject to a variety of errors, including calibration, aerodynamic effects, and siting. The errors are listed in summary form in table 4-1. The accuracy values are listed both as a percent error for rain-rate measurement and a decibel error in the estimation of dBZ where equation (9), page 22, is used to convert rain rate to Z. Repeatability estimates were also made for the gage system but not for the individual elements shown in the table. Measurement accuracy probably changed as a function of surface wind conditions and perhaps other parameters. Comparisons between the accumulations for each event measured with the closely spaced common volume gages showed differences as large as 47 percent on two occasions under conditions of widespread, long-duration rain (where one would expect reasonable agreements). For these events the accumulation of the 10K gage was 46 or 47 percent low when compared with the averaged

Table 4-1.—Rain-Gage Accuracy and Repeatability Estimates

Errors	Type I, 324- and 1829-cm ² area						Type II, 324-cm ² area						Type III, 159-cm ² area					
	Accuracy				Repeatability		Accuracy				Repeatability		Accuracy				Repeatability	
	12 mm/hr		100 mm/hr				12 mm/hr		100 mm/hr				12 mm/hr		100 mm/hr			
	Percent	dB	Percent	dB	Percent	dB	Percent	dB	Percent	dB	Percent	dB	Percent	dB	Percent	dB	Percent	dB
Calibration	7	0.5	7	0.5	—	—	12	0.8	16	1.0	—	—	12	0.8	14	0.9	—	—
Aerodynamic	3	.2	3	.2	—	—	5	.3	5	.3	—	—	5	.3	5	.3	—	—
Siting	—	—	—	—	—	—	7	.5	7	.5	—	—	7	.5	7	.5	—	—
Total	10	.7	10	.7	5	.3	25	1.6	29	1.8	47	2.7	25	1.6	27	1.7	47	2.7

NOTE: All values are $\pm$. Percentages refer to the maximum value as a percent of rain rate; decibel values refer to the maximum value for rate measurements expressed in dBZ using $Z = 200R^{1.6}$ or $\text{dBZ} = 23 + 16 \log R$.

accumulations of both the 5K and 20K gages. The 5K and 20K accumulations agreed with each other within 3 percent. Using this difference to estimate repeatability for the type II and III gages as sited, a value of ± 2.7 dB was obtained for the estimate of Z . Measurements of the variability of total accumulation were also made using the two LaRC tipping-bucket rain gages, counting tips, and the calibration constants for the 10- to 20-mm/hr range. The results show differences ranging between 0 and 5 percent. The maximum deviation of 5 percent was taken as an estimate of repeatability as shown in the table.

The accuracy of gage calibration was determined using the in situ measurements just described. The calibration errors for the common volume type II and III gages are shown as rain-rate dependent as specified by the manufacturer. The other gages have a change in calibration constant with rain rate as shown in figure 4-2. Data taken with these gages were converted to rain rate using the calibration curve after adjustment to match the in situ calibration values at rates between 20 and 30 mm/hr. The calibration accuracy for type I gages, therefore, is not rate dependent.

The aerodynamic errors are due to perturbations in the wind field as caused by the gages and were discussed previously. The siting errors were due to obstructions or to the gage being sited on and near the edge of a building as discussed in section 2. The effects of siting cannot be obtained from a description of the area. The siting errors as listed were obtained from a comparison of total gage catch with the catch of gages in the nearby area. The LaRC, 5K, and 10K gages were sited along a line toward Quantico. The 5K gage was 6.4 km from LaRC and the 10K gage was 12.8 km from LaRC. The 20K gage was 12.4 km along the same line from the 10K gage. The Williamsburg NWS gage was approximately 20 km from the 10K and 35 km from the LaRC gages as shown on figure 2-1. For 10 generally widespread rain events between July and October 1971 when all but the 5K gage were in operation and all gages caught measurable quantities of rain, the total accumulation for each gage was calculated and compared with each other. The accumulations for the tipping-bucket gages were computed by counting tips and multiplying by the gage calibration constant that was determined for rates between 10 and 20 mm/hr. The LaRC gage accumulations were also computed by integrating the rate measurements obtained using the calibration curves. The LaRC 1829- and 324-cm² gages agreed with each other within 3 percent and the two different accumulation computation techniques agreed with each other within 2 percent. The LaRC 324-cm² catch was within 2 percent of the 236-mm catch of the Williamsburg gage. The 10K and 20K gages, although closer to Williamsburg, had significantly less catch, being about 30 percent low. The Fort Lee, Eastville, and Norfolk NWS gages all had catches within 15 percent of the Williamsburg gage.

The catch comparisons show that the type II and III gages in the vicinity of the common volume have significantly lower catch than the other gages in the area. Some of the variability may be due to natural changes in the total rainfall. As a second estimate of siting error, the catch of the 10K gage was compared with the NWS gages at Norfolk and Richmond. Data for phase I and the entire year were used. The 10K gage was used because it was the only gage in service for the entire measurement year. The comparison between the 10K gage catch and the average of the catches at the Norfolk and Richmond gages showed the 10K

gauge accumulation to be 25 percent low for the year and 7 percent low for the winter months. The total catch comparison includes the effect of siting, aerodynamic gauge errors, and calibration errors. Because the siting errors will vary over the year due to changes in the prevailing wind conditions for summer and winter storms, it is concluded that the total error for the 10K gauge should be 25 percent in agreement both with the year measurements and the 10-storm comparison with the Williamsburg gauge allowing for local changes in rain accumulation. Working the accuracy estimation budget backward, the error for siting is 7 percent. It is noted that the small siting errors are due to the offsetting effect of the rather large gauge calibration errors that resulted from the limited field calibration effort for the type II and III gauges. The average of the limited number of calibration attempts for these gauges was within 0.5 percent of the manufacturer's specifications; and, if his accuracy estimate of 0.5 percent was used, the siting error numbers would be 18 percent, which more realistically describes the severity of the siting problem. In comparing the 10K gauge data with the NWS data, it is noted that the year's accumulation at Richmond was within 8 percent of the accumulation for Norfolk with Norfolk registering 1099 mm. For the winter months, the Richmond and Norfolk NWS accumulations were within 6 percent. In making these comparisons and the comparison between their average with the 10K data, data for snow events were not used.

For the months of October 1970 through March 1971 both the 5K and 10K gauges were operable. During this time period, the accumulation for the 5K gauge was 9 percent below that of the 10K gauge, presumably because of the additional shielding caused by the coniferous trees near the gauges. The Richmond and Norfolk gauges were within 4 percent of each other with Norfolk registering 405 mm. The 5K gauge was 20 percent below the average of the two NWS gauges and the 10K gauge 10 percent below. Although the effect of shielding is obvious, the extent to which it degrades measurement accuracy is not. Because of the change in prevailing surface wind during the year, the 5K gauge may well register a higher catch than the 10K gauge for some period of the year as was observed during several widespread rain events in the summer. The accuracy estimate for the 5K gauge is assumed to be the same as for the 10K gauge as given in the table because better information is not available. Similarly, the 20K gauge is assumed to have the same siting error. In estimating the accuracy error budget, the overall error value obtained from comparison with NWS gauges is attributed to the 12-mm/hr case because only a very small part of the total accumulation is contributed by rates above this value. No siting error was attributed to the type I gauges because no obstacles were present and the comparisons with nearby gauges were within the estimated measurement error.

The accuracy estimates as given are for the measurement devices as installed in the field. Errors in measurement are also caused by chart reading uncertainties. These errors are particularly large for the type II and III gauges. The change in collecting area converting type II to III was made in an attempt to reduce the reading errors. These errors are discussed in the data processing section, section 5.

These accuracy estimates assume that the rain rate to be measured does not vary during the time required for a bucket tip. At rates above 15 mm/hr (31 mm/hr for the type III

gage and 5 mm/hr for the 1829-cm² type I gage), one or more tips occur within a 1-min interval and changes in rain rate during the time to accumulate the tip do not affect the final 1-min averaged rain rate. At rates below this threshold, the time between tips is larger than the 1-min integration time desired. The 1-min rate values may be in considerable error for rates below 2 to 5 mm/hr (4 to 10 mm/hr for type III and 1 to 2 mm/hr for 1829-cm² type I) because 3 to 6 min are required to accumulate sufficient rain for a tip; during this time interval a shower may have passed having a rate that is several times the indicated value but a duration that is small compared with the time between tips. The threshold value of 2 to 5 mm/hr for adequate gage measurements corresponds to Z values between 28 and 34 dBZ, which is approximately equal to the bistatic radar system measurement threshold imposed by the transfer characteristics of the logarithmic detector.

5 DATA PROCESSING

The types of data and associated processing techniques were summarized in section 2. The data were edited, scaled, and averaged as depicted in figure 5-1. The editing process used the hourly summary data as described in sections 2.3 and 2.5. The data sources and recording modes are shown in figure 3-11. This section describes in detail the reading and averaging techniques used to handle the bistatic radar and rain-gage data. The precision of the reading and correction factors required to estimate a true average value are also considered. Accuracy and repeatability estimates for data processing are considered in reference 13.

5.1 BISTATIC RADAR DATA REDUCTION

The bistatic radar system was described in sections 2 and 3. The data provided by this system were recorded both on magnetic tape and on eight-channel strip charts (Z-fold). As discussed in section 2.3, the data were edited prior to reading to reduce the amount of data to be scaled. Scaling was done only for the primary measurement paths and was accomplished by using a card containing the calibration levels prepared from the periodic calibration data on the Z-fold charts, placing the card on the chart at the selected time for a value to be read, estimating the level in dBmW for that time, and listing the value rounded to the nearest decibel. The scale card was constructed using a linear interpolation in decibels between each 10-dB calibration step.

A sample Z-fold recording for phase II from the rain event on September 11, 1971, is shown in figure 5-2. The eight channels recorded include two for the 324-cm² rain gages at

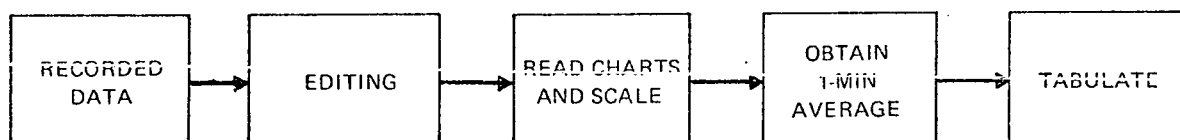


Figure 5-1.—Data processing flow diagram.

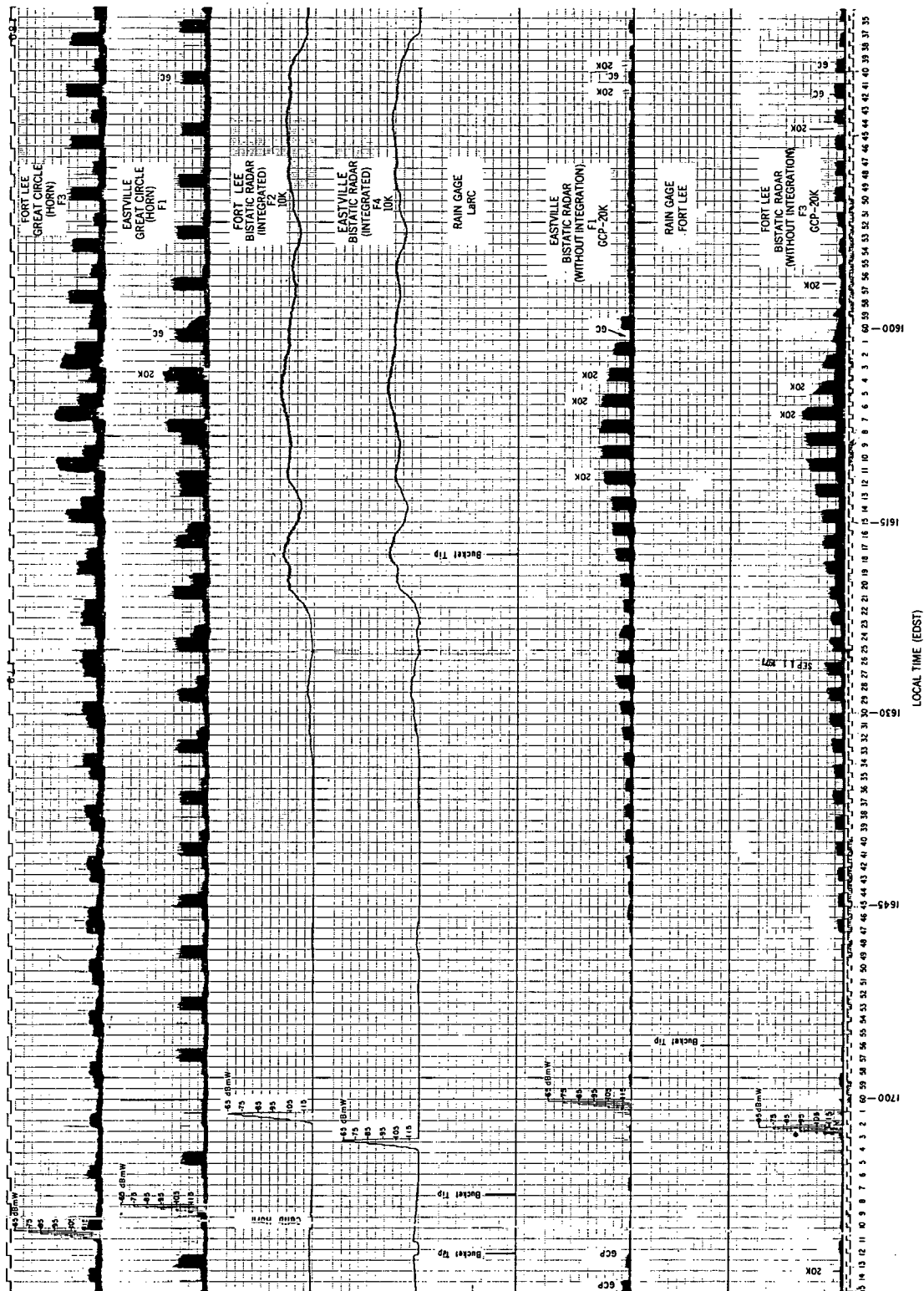


Figure 5-2.—Sample strip chart recording—phase II, September 11, 1971.

LaRC and Fort Lee; two for the GC path system receivers for Eastville F1 and Fort Lee F3; and four for the F1, F2, F3, and F4 frequencies for the bistatic radar system (30-ft antenna). Two of the bistatic radar channels recorded integrated (1.5-s time constant) data from the Eastville and Fort Lee 10K paths and two recorded switched data (without integration) alternately from the 20K and GC paths. The data for each minute for the switched paths are labeled on the sample Z-fold. The two types of bistatic radar data that must be scaled can readily be seen. The integrated 10K data provide a clean trace that may be readily hand scaled. The 20K and GC data are not integrated and present a solid smear because of rapid fading that is difficult to read. A summary of the reading techniques and their precision is given in table 5-1. The event pens on the edge of the strip chart were used to indicate time. The event pen above the Fort Lee F3 horn channel alternated position every minute and indicated to which antenna the F3 transmitter at Fort Lee was connected. The event pen below the Fort Lee F3 30-ft channel provided LaRC site timing information by being in one state for 40 s and the other state for 20 s. This timing pattern was inverted every hour to mark hours on the chart. The antenna switching used on the Eastville 20K and GC paths

Table 5-1.—Bistatic Radar Data Processing Summary

Method	Reading technique	Phase	Precision estimate, dB		Correction factors, ^a dB
			10K	20K	
A	Integrated, 10-s sampling	II	±1		0
B	Integrated, subjective average	II	±3		0
C	Subjective estimate of upper bound of fading signal ^b	II		±3	-10
D	Subjective estimate of upper and lower bounds of fading signal, average of decibel values ^b	II		±4	+2
E	Subjective estimate of upper and lower bounds of fading signal, scaled midpoint of distance on chart ^b	Ib	±5	±5	+2
F	Subjective estimate of upper bound of fading signal, scaled midpoint of distance upper bound to lower edge of display area on chart ^b	Ib	±7	±7	(^c)
G	Automatic analog-to-digital conversion and computer sorting to find median ^b	Ia	±1	±1	-0.5

^aEmpirically derived correction factors. To be added to the scaled values to provide an estimate of the average of the logarithm of the received signal level.

^bPrecision estimates apply after empirical or statistically derived factors have been used to correct the data.

^cCorrection factor depends on signal level. See sec. 5-1.

and the GC horn receiver system was synchronized with the Fort Lee 1-min timing marks so the data could be identified with the correct path.

The data were read using scales prepared from the calibrations that occurred every 2 hr. Generally, the calibration closest to the data was used. The calibration signal was stepped between -65 and -135 dBmW in 10-dB steps. As noted on the calibration sequences on the Z-fold, the scale was not linear in decibels and severe compression occurred for signals below -115 dBmW. Received signal levels between the 10-dB points were estimated by linear interpolation. For signal levels above -115 dBmW, the maximum deviation of the actual scale as determined using 2-dB steps from the scale obtained by linear interpolation was less than 0.8 dB (as shown on fig. 3-10). The degree of curvature changed slightly from calibration to calibration, and 1.5 dB represents the maximum deviation from the piecewise linear calibration scales.

The 10K integrated data were read in two different ways. For data from rain events between June 4 and June 22, 1971, the 1-min average was subjectively estimated and the average position was scaled (method B, table 5-1). For data obtained during the rest of phase II, the scaling and averaging were accomplished by reading the signal level every 10 s, transforming the logarithmic level to a linear value, averaging six successive values, and expressing the result in decibels (method A, table 5-1). A sample of 10-s-sampled and processed data for September 11, 1971, is shown in figure 5-3. The 10-s-sampling rate is below the Nyquist rate and the errors resulting from processing in this manner must be evaluated statistically (ref. 13). Data for one event were processed both by subjective average estimation and the 10-s-sampling methods. A comparison of 1-min estimates of the averaged value obtained using both techniques differed by as much as 4-dB maximum and 1-dB rms. In the comparison it was noted that if the signal changed little within the minute, the two methods differed by less than 1 dB; but, under conditions of large change within the minute, the results differed markedly. The data as scaled were rounded to the nearest decibel. The 10-s-sample and average process had a precision of ± 0.3 dB using 10-s readings quantized in 1-dB steps. The result of the averaging was also rounded to the nearest decibel and quantized in 1-dB steps with a precision of ± 1 dB. The subjectively averaged reading also was quantized in 1-dB steps and had a precision of ± 3 dB. The precision estimates as quoted do not include the effects of scale nonlinearity.

The rapidly fading 20K data appear as a smear on the strip chart. The data were read by subjectively determining the 1-min average position of the upper and lower edges of the smear, scaling the upper and lower edge values, and tabulating both the upper edge value and the average of the upper and lower edge decibel values. The upper and lower edge values were estimated using the positions on the chart where the heavy inking stops. Only a few fluctuating signal spikes appear above that apparent level. For a limited period between May 5 and June 22, 1971, the 10K channels were recorded with and without integration. A comparison of both reading techniques was made using data obtained during this time interval. It was empirically determined that for normal inking or ink flow from the recorder pen and the normal 0.1 mm/s chart speed, the average difference between the average of the upper and lower edge values (method D, table 5-1) and the integrated, 10-s-sampling and

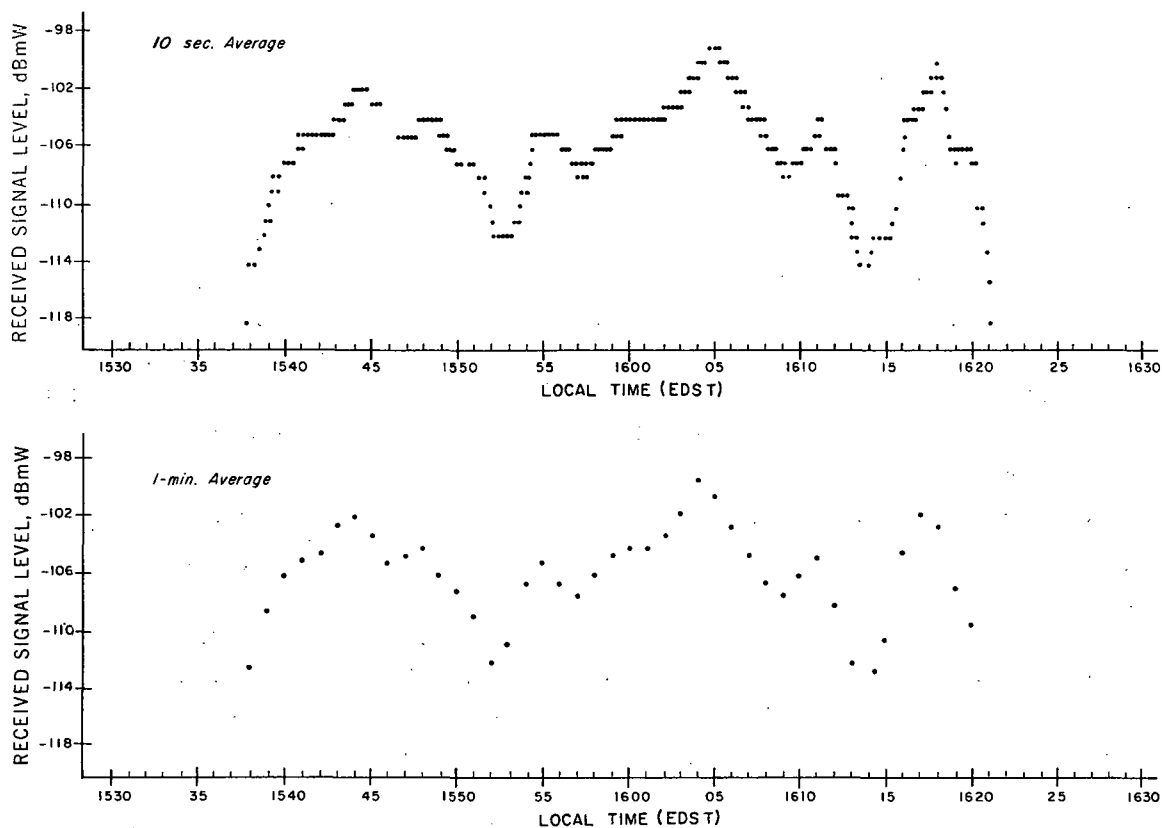


Figure 5-3.—Sample of processed radio data—Eastville, September 11, 1971.

1-min averaging values (method A) was 2.3 ± 0.6 dB. Using this empirically determined average difference as a correction factor, the precision of method D was, after quantization, ± 4 dB. Readings based only on the upper value on the chart (method C), after correction by an empirically determined factor of -9.9 ± 0.3 dB, had an estimated precision of ± 3 dB.

Data for the 10K paths from phase Ib were not integrated, except for the period between May 5 and June 4, 1971. The phase I switching sequence was used prior to April 17, 1971, so that data for each path were measured for only 1 min out of every 4. Two scaling methods were used during the time period prior to May 5, 1971. The first method consisted of estimating the 1-min average value by subjectively picking a point physically halfway between the upper and lower edge of the smear on the chart (method E). The second method used a point halfway between the upper edge and the bottom edge of the display area for the channel (method F). For signals with estimated average values below about -112 dB, both methods were identical because the bottom edge corresponds to the lowest possible display value. For signals above that level the two methods produce different values. Above -100 dBmW, method E is identical to method D because the scales become approximately linear in decibels at higher signal levels. An estimate of the precision of scaling using method E, including the differences in performance of the personnel reading the charts, and correcting by the 2.3-dB factor is ± 5 dB for levels above -100 dBmW. The required correction factor for signal level estimates below -100 dBmW is signal level dependent. Because of

compression, the correction factor becomes smaller at lower signal levels, being about 1 dB at -115 dBmW. The precision of the measurement also increases as the signal gets weaker because the bottom edge becomes better defined as a result of scale compression. At signal levels near -115 dBmW, the precision is estimated at ± 4 dB. For ease in data correction, the correction factor for method E is assumed to be 2 dB for all signal levels above -115 dBmW and the precision is assumed to be ± 5 dB.

The other reading technique (method F, table 5-1) uses the bottom edge of the display area and has a signal level dependent correction factor that continuously increases in magnitude for indicated signal levels above -112 dBmW although the precision of the measurement remains constant and at ± 5 dBmW provided the correction is known. The estimation of the midpoint between the upper edge of the smear and the bottom of the chart used in this reading process requires only an estimate of the position of the upper edge. The correction factor required for this scaling process must include both a factor relating the estimated value to an estimate of the position of the upper edge and the -9.9-dB upper edge to average correction factor. The precision of this correction factor, however, depends upon calibration stability because the physical distances will vary from calibration to calibration. Calibration stability amounted to an additional ± 1.6 dB during phase Ib. The precision of the resultant signal level correction scheme therefore has a poorer precision value, estimated at ± 7 dB.

Phase Ia data were read using the automatic analog-to-digital converter and computer at ITS (method G). The automatic reading system played back the FM analog recording tapes at high speed (25 times faster than the recording speed), sampled the data without integration at a rate equivalent to 80 samples per second at the rate as recorded (2000 samples per second at the fast playback rate), and recorded the analog-to-digital converted values on digital magnetic tape for computer sorting. The analog magnetic tape system had a low-pass prerecording filter with 74-Hz bandwidth, and the analog-to-digital sampling rate was below the Nyquist rate. The computer sorted the data for each channel and minute to provide distributions of analog-to-digital units within the minute. The median and mean values for each distribution were selected, scaled from analog-to-digital units to received signal levels using the calibration data, and printed for subsequent use. The calibration records were read in a manner similar to data. The median analog-to-digital unit value for each calibration was assigned the received signal level value for that calibration minute. Calibration curves were constructed by linear interpolation in decibels between the 10-dB-stepped analog-to-digital unit calibration values. For long data runs, the calibration levels were linearly interpolated in time between calibrations (to improve accuracy). For short runs close in time to calibrations or long runs with skipped calibration, the set of calibrations closest in time were used. The computer printouts were used to provide 1-min median signal level values. These levels were corrected by subtracting 0.5 dB to provide an estimate of the average value. The analog-to-digital converter and computer-processed data have a precision after correction of ± 1 dB.

Several of the Z-fold charts for phase Ia events were also hand-scaled using method E. With a 2-dB correction factor, the results were within ± 4 dB of the computer-generated

values for signal level values (corrected) ranging from -115 to -105 dBmW. These results are in reasonable agreement with the empirical precision estimates given above (± 5 dB).

5.2 RAIN-GAGE DATA REDUCTION

The rain-gage data were recorded as event marks on strip charts as discussed in section 4. The rain rate was determined by reading the time of each tip from the recorded charts, key-punching the times for entry into a computer, and using the computer to calculate the average rain rate between tips and the 1-min averaged rates. The average rate between tips was computed using the calibration curves given in figure 4-2 for type I data or equation (11) (p. 70) for type II and III data. The 1-min average rates were computed from the between-tip average rates by

$$R = \frac{\sum_{k=1}^n t_k M_k}{60} \quad (12)$$

where

R = 1-min averaged rain rate (mm/hr)

t_k = time interval in seconds within the minute that corresponds to the averaged rate M_k

M_k = averaged rain rate between tips (mm/hr)

n = number of between-tip averaged rates that exist in the 1-min interval

The 1-min averages start with the time in seconds of the first tip and are recorded for successive 60-s intervals.

The reading precision for a rain-gage chart is expressed as the error in estimating the time interval between tips. The error in rain rate is related to the error in time interval estimation by

$$\frac{\Delta M_k}{M_k} = \frac{M_k \Delta t}{d} \left(1 + \frac{M_k \Delta t}{d} \right)^{-1} \quad (13)$$

where

ΔM_k = rain-rate error (mm/hr)

Δt = time interval estimation error (hr)

d = calibration constant (mm/tip)

For the 1-min averaged values the rain-rate error ΔR is estimated by

$$\Delta R = \frac{\sum_{k=1}^n \Delta M_k}{n(n-1)^{1/2}} \quad (14)$$

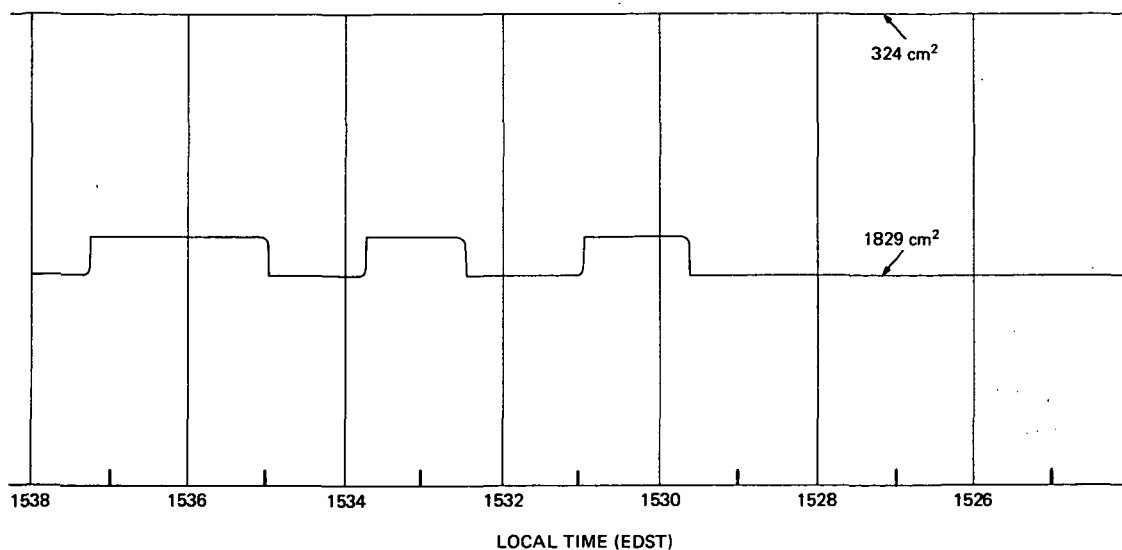


Figure 5-4.—Sample recording of LaRC type I rain gages—September 11, 1971.

or, if $n = 1$, $\Delta R = \Delta M$.

Two types of charts were used. For the type I gages, the data were recorded at 45 in./hr chart speed with single event marks as shown in figure 5-4 for a sample of data from the rain event on September 11, 1971. Type I gage data were also recorded on the Z-fold charts and tip indications were shown in figure 5-2. Type II and III data were recorded on 45-day charts. An entire chart for September 2 through October 6, 1971, is shown in figure 5-5. The tips on the 45-day charts are indicated by step level changes.

The time of a tip on the Z-fold chart was read to the nearest second with a position uncertainty of ± 2 s. Time of tips on the other type I Esterline-Angus (EA) strip charts were read to the nearest second with a ± 1 -s precision. For scaling using the Z-fold data, the precision is ± 2.4 percent at 12 mm/hr and ± 8.0 percent at 100 mm/hr. Scaling from the type I EA strip charts yields a precision for the 324-cm²-gage data of ± 1.2 percent at 12 mm/hr and ± 4.0 percent at 100 mm/hr and for the 1829-cm²-gage data of ± 4.0 percent at 12 mm/hr and ± 12 percent at 100 mm/hr. Converting these estimates to decibels using equation (9), page 22, the precision is ± 0.2 dB at 40 dBZ and ± 0.5 dB at 55 dBZ for the Z-fold charts and ± 0.1 dB at 40 dBZ and ± 0.3 dB at 55 dBZ for the EA type I 324-cm²-gage charts. The precision estimates are summarized in table 5-2.

The times of the tips on the type II and III chart records were read to the nearest 0.01 hr or 36 s with an accuracy of ± 0.01 hr for rates below 12 mm/hr. At higher rates the measurement was made by counting the number of tips in a 60- to 180-s interval, measuring the time between the first and last tip in the interval, determining the average interval between tips, and assigning times for each tip so they are uniformly distributed between the first and last tip. The scaling process for type II data is estimated to have a precision of

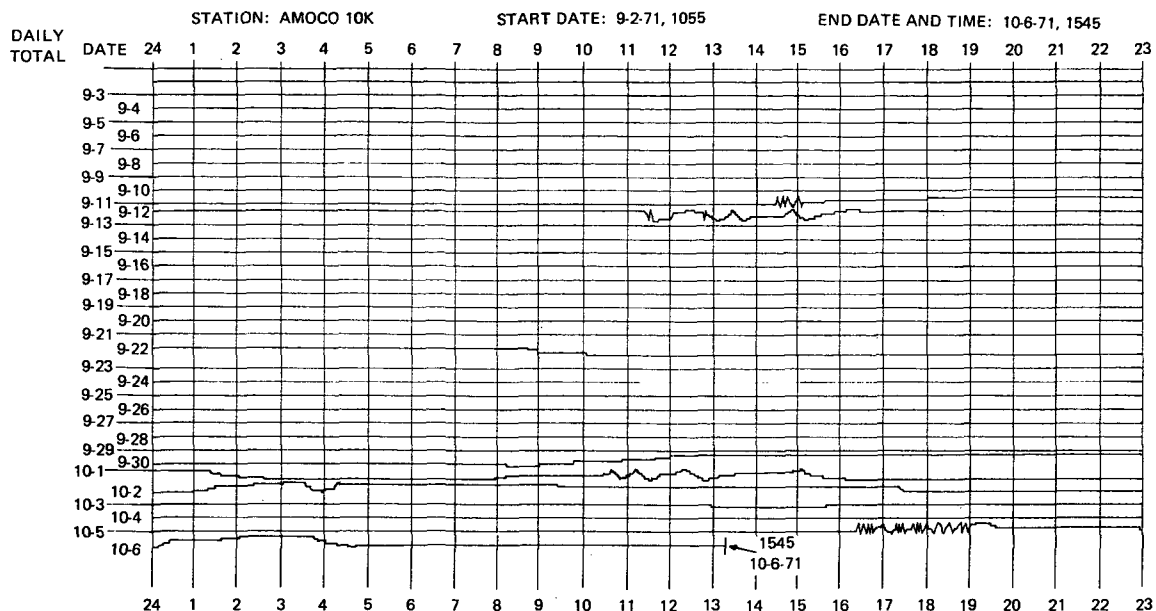


Figure 5-5.—Sample recording of type II and III gages—September 2 to October 6, 1971.

± 17 percent at 5 mm/hr, ± 32 percent at 12 mm/hr, and ± 36 percent at 100 mm/hr. These precision estimates apply to the 1-min average values provided by the computer although the reading process averaged the rate over a 1- to 3-min interval. Additional errors may occur because the data do not represent a true 1-min average because the effective integration time is larger than 1 min. An analysis of the latter type of error is given in reference 13.

Type III data used a smaller collecting area in an attempt to increase reading precision. With the collecting area halved, the resultant precision is estimated to be ± 9 percent at 5 mm/hr, ± 19 percent at 12 mm/hr, and ± 30 percent at 100 mm/hr. An example of type III processed data for September 11, 1971, is given in figure 5-6. Both the between-tip averaged rates M and the 1-min averaged rates are shown. The effect of quantization of the tip duration is evident in the discrete rate value displayed in the between-tip averaged data. The 1- to 3-min averaging between tip intervals is also evident in the several minute constant rain-rate estimates at rates above 25 mm/hr.

The computer program provided clock 5-min and clock 60-min average rain rates in addition to the 1-min averaged data. The clock 5- and 60-min averages were computed in the same manner as the 1-min averages with the exceptions that the averaging period was 300 to 3600 s, not the 60 s used in equation (12) (p. 82), and the starting time for the 5-min

Table 5-2.—Rain-Gage Chart Reading Precision Estimates

Reading	Type I												Type II, 324-cm ² area, 45-day chart				Type III, 159-cm ² area, 45-day chart			
	324-cm ² area								1829-cm ² area, EA chart											
	EA chart				Z-fold chart															
	12 mm/hr		100 mm/hr		12 mm/hr		100 mm/hr		12 mm/hr		100 mm/hr		12 mm/hr		100 mm/hr		12 mm/hr		100 mm/hr	
	Percent	dB	Percent	dB	Percent	dB	Percent	dB	Percent	dB	Percent	dB	Percent	dB	Percent	dB	Percent	dB	Percent	dB
1-min average	1.2	0.1	4.0	0.3	2.4	0.2	8.0	0.5	4.0	0.3	12.0	0.8	32.0	2.0	36.0	2.1	19.0	1.2	30.0	1.8
Clock 5-min average	.6	.04	2.0	.1	1.2	.1	4.0	.3	2.0	.1	6.0	.4	16.0	1.0	18.0	1.2	9.5	.6	15.0	1.0
Clock 60-min average	.2	.01	.6	.04	.4	.03	1.2	.1	.6	.04	2.0	.1	4.8	.3	5.4	.4	2.9	.2	4.5	.3

NOTE: All data are $\pm$ values. Percentages refer to the maximum value as a percent of rain rate; decibel values refer to the maximum value for rain rate expressed in dBZ using $Z = 200R^{1.6}$ or $\text{dBZ} = 23 + 16 \log R$.

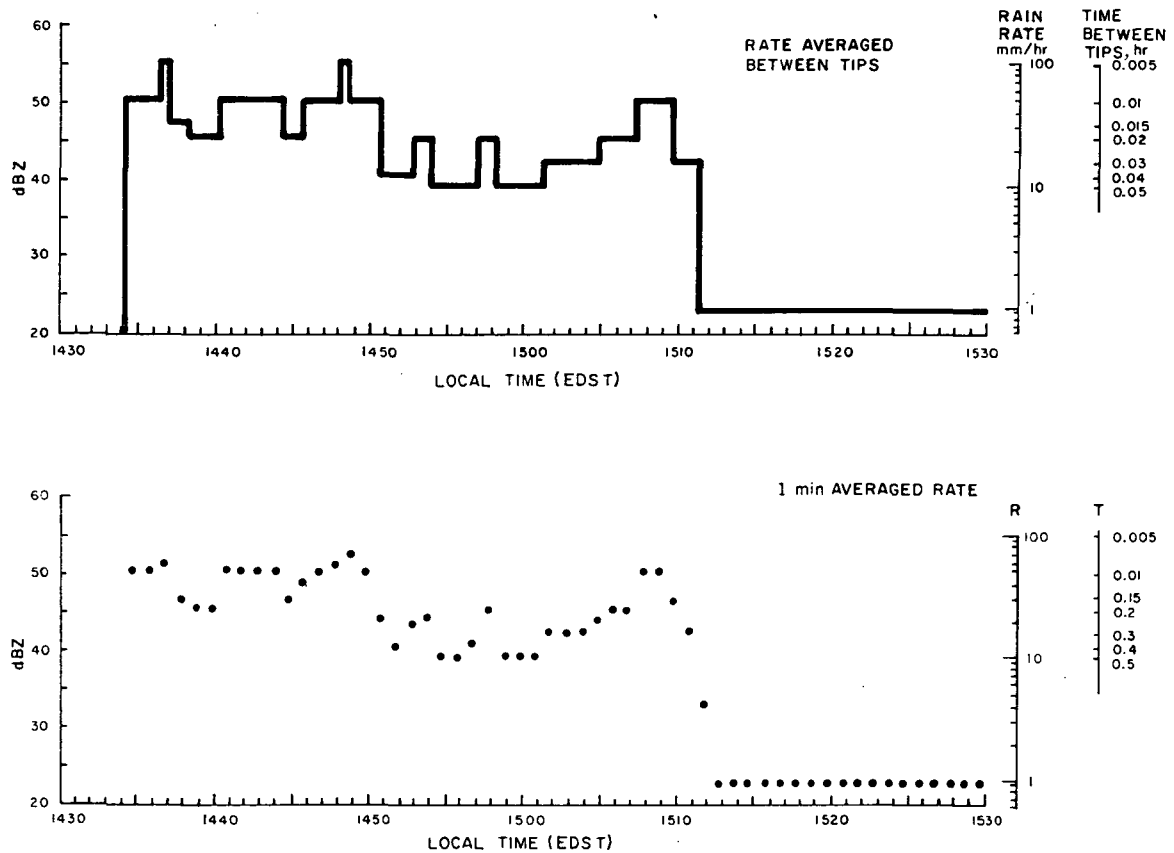


Figure 5-6.—Sample of type III processed rain gage data—September 11, 1971. (To compare with radio data, add 73 min to correct gage recorder data.)

averages was fixed as a multiple of 5 min after the start of the hour and the starting time for the 60-min averages was on the hour. The precision estimates for the clock 5-min and 60-min measurements are shown in table 5-2.

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