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METEOROLOGICAL FACTORS IN EARTH-SATELLITE PROPAGATION

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A 5-meter paraboloidal antenna operated at 28 GHz showed gain changes of 2 dB due to rain. While precise estimation of the corresponding angle-of-arrival changes is difficult, they appear to have been on the order of 0.02 degrees.

The attenuation at 28.6 GHz inferred from radiometry agreed well with that measured simultaneously over a satellite/earth link at the same frequency. The radiometers so calibrated have been used to add to the available site-diversity data base using a 9 km baseline.

An improved empirical model of site diversity gain was obtained by applying regression techniques to available published data.

A brief review of the literature has led to suggestions for two experimental programs, one dealing with multi-frequency radiometry and the other with the effects of the stochastic properties of precipitation on wide-band data transmission.

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SECTION 1

INTRODUCTION

This report describes experimental and theoretical studies performed over the time period March 12, 1981 to June 30, 1983 as part of a NASA research program on earth-satellite propagation.

One experiment measured the apparent change in gain of a 5-meter (diameter) paraboloidal reflector antenna due to precipitation at 28.6 GHz. A second experiment evaluated the utility of using two earth-station sites to increase the reliability of satellite communications relative to single-site operation at the same frequency. Part of this study involved the validation of using radiometry as an experimental tool instead of direct signal transmission. This was accomplished, in part, by comparing radiometrically inferred signal attenuation against that actually measured directly between a satellite-borne beacon and our receiver. Another approach was to measure the precipitation rate along the satellite-earth path with a meteorological radar, calculate the attenuation to be expected along the earth-satellite path, and compare this with the attenuation inferred from the radiometry.

The results of these experiments are statistical in nature, and reliable unattended operation is required to achieve the almost continuous operation desirable for gathering the statistics. The data acquisition system in use for approximately a decade became increasingly unsatisfactory for this purpose, and it has been replaced with a more reliable system.

In connection with the path diversity study, a literature search was performed and used to form a mathematical model for path-diversity gain by regression analysis.

Finally, attention has been given to the remaining problems that may be anticipated with future satellite communications systems, with a view to formulating experiments that may be useful to resolve potential difficulties. The effect of phase scintillations on the transmission of data at high data rates in relatively short bursts, as for example in a time-division multiple access (TDMA) mode, appears particularly worthy of attention at this time. The use of multiple-frequency radiometry to predict bulk attenuation also appears worthy of investigation.

The results of the research under this contract are reported in annual reports, of which this is the second and final one, and in technical reports which summarize completed tasks in more detail. A listing of reports issued under this contract will be found in Section IX. Part of the work begun under this contract is being continued under Contract No. 956528. Reports being prepared under the successor contract are also listed there.

SECTION II

THE GAIN DEGRADATION EXPERIMENT

A. The Experiment

A proposed method of overcoming the attenuation due to rain is to use antennas with more gain and therefore larger apertures. A possible difficulty with this approach is that the gain of large antennas may not be realized fully during rain periods because of the perturbation of the phase front arriving at the antenna by scattering from the hydrometeors. One experiment therefore consisted of measuring the degradation of the gain of an antenna having a diameter of 5 meters. The signal source for this experiment was the Comstar D/4 geo-synchronous satellite beacon at 28.56 GHz. This satellite was launched on 11 March 1981 and was slowly moved to its permanent location, where it arrived in May 1981. Data was obtained on an essentially continuous basis from May 14, 1981 to September 1, 1981 at which time the beacon was turned off. The satellite location, viewed from Columbus, Ohio, was at an azimuth of 236.4° and an elevation of 25.6°. The experiment consisted of switching a single receiver every thirty seconds between a 5-meter (diameter) Cassegrainian paraboloidal reflector antenna and a focal-point-fed paraboloid of 0.6 meter diameter located on the same axis in front of the Cassegrainian subreflector. Figure 1 shows a block diagram and Figure 2 a photograph of the experiment. The gain of the small reflector antenna would be expected to be affected only slightly by variations

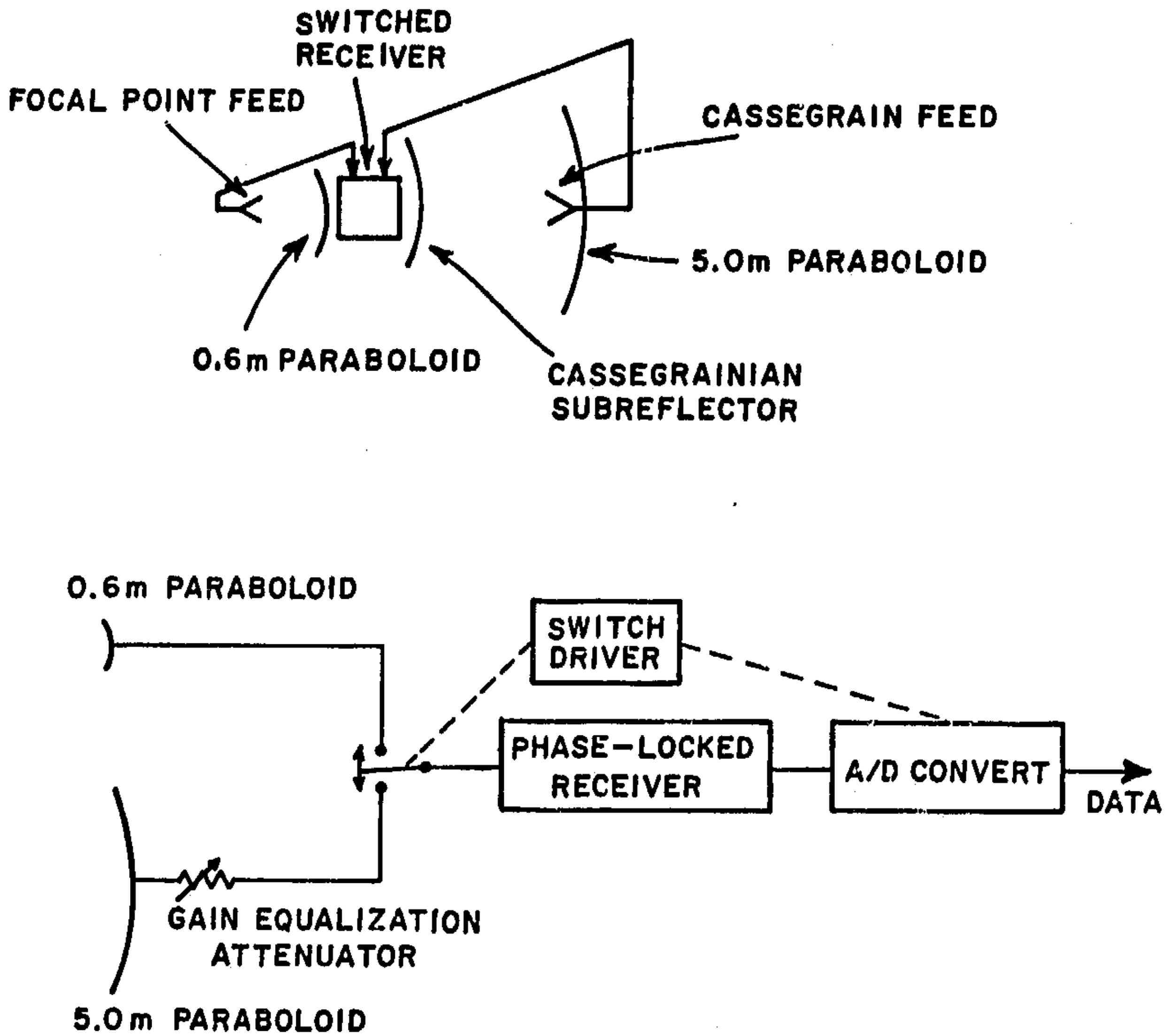

Figure 1. Gain-degradation experiment concept.

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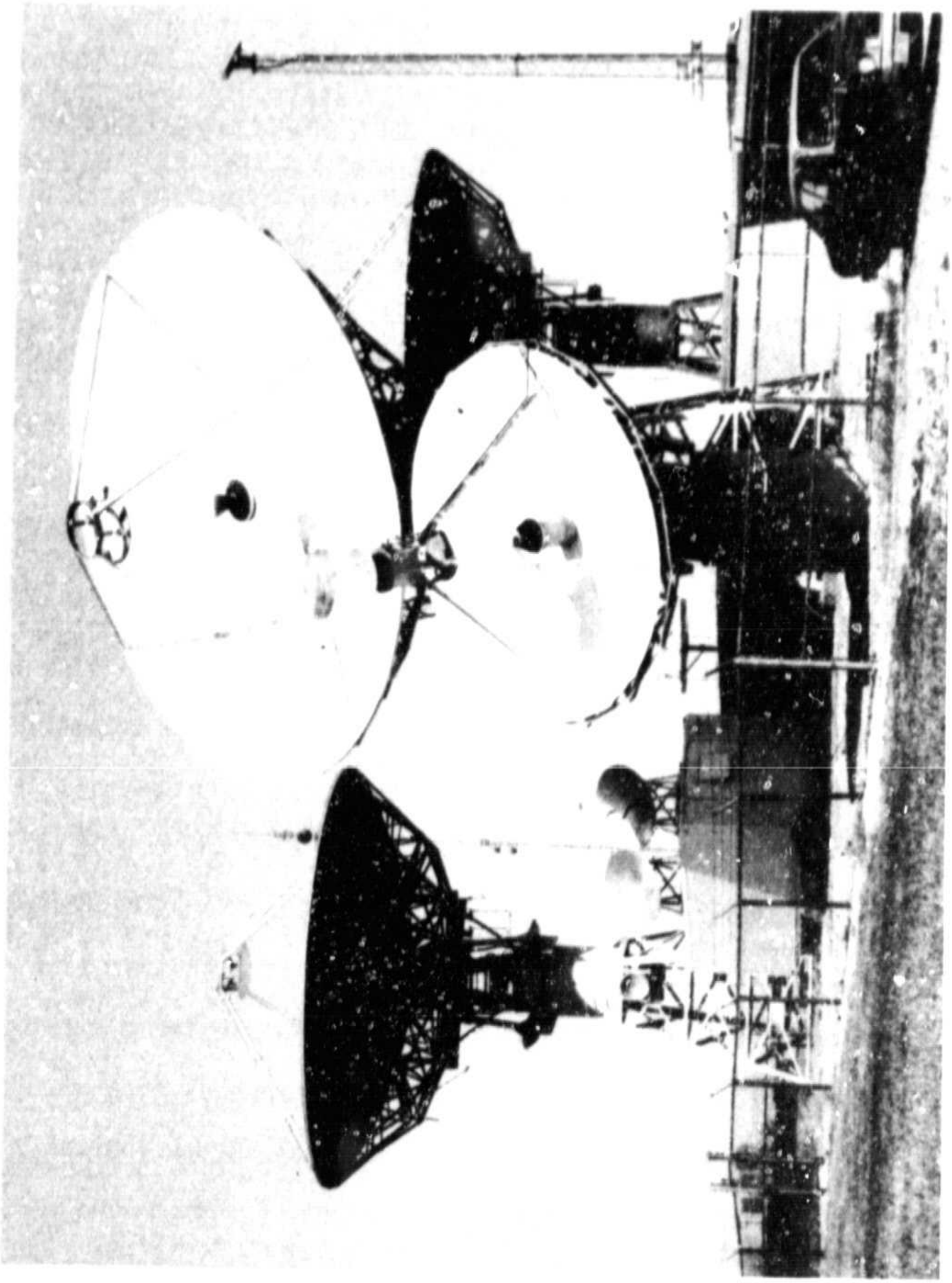
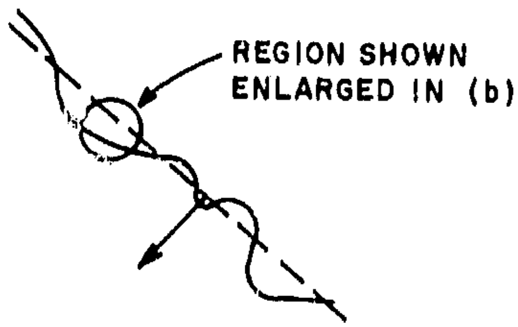


Figure 2. Experimental Facility. The closest antenna structure is the gain-degradation experiment consisting of 15' and 2' coaxially mounted antennas. The 30' antenna immediately behind belongs to the meteorological radar. The more remote of the two antennas atop the trailer belongs to the "local" 28.56 GHz radiometer of the site-diversity experiment; the closer one pertains to a 8.5 GHz radiometer. The antenna atop the mast at right belongs to an X-band radar used for observing the path of storms and precipitation.

of the arriving phase front; in effect, the experiment therefore compares the gain of the large antenna with that of the small antenna used as a standard.

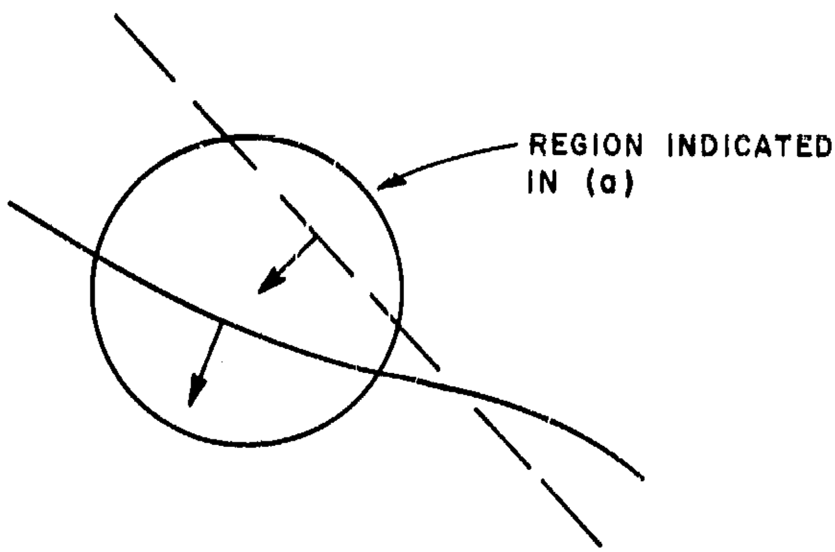
The experiment is, in concept, similar to one performed by Arnold, Cox, and Hoffman at Bell Laboratories [1], but with an important distinction. In the Bell Laboratories experiment, the antenna computer-tracked the satellite quite precisely, while the antennas in our experiment were adjusted to the best of our ability to point at the average location of the satellite in its diurnal motion. This was necessitated in part because our antenna mount was not sufficiently robust to allow tracking during heavy weather; with the pointing fixed for substantial time periods, a mechanical shim could be bolted in place to remove the load from the gears. However, there are compensating advantages, as will be shown.

To first order, a phase-front disturbance due to precipitation appears as a change in angle-of-arrival. This is illustrated in Figure 3, where Figure 3(a) shows a "crinkled" phase front and Figure 3(b) an enlargement of a portion of it: locally it appears that the phase front is still nearly plane, but that the normal, which indicates the direction of arrival, has changed. The effect of this on two antennas, one of which is pointed precisely at the signal source while the second is mispointed slightly, is shown in Figure 4. For small angle-of-arrival changes the effect is very slight for the pointed antenna and considerably larger for the mispointed antenna. In other words, mis-pointing the antenna makes the experiment more sensitive.



(a)

(a) macroscopic view. Dashed line shows undisturbed wavefront, solid line disturbed wavefront. The circled portion is shown enlarged in (b).



(b)

(b) Enlargement of part (a). For the part of the front within the circle, the direction of arrival appears to have changed, as indicated by the arrows normal to the wavefronts.

Figure 3. Relationship between phase-front degradation and angle-of-arrival changes.

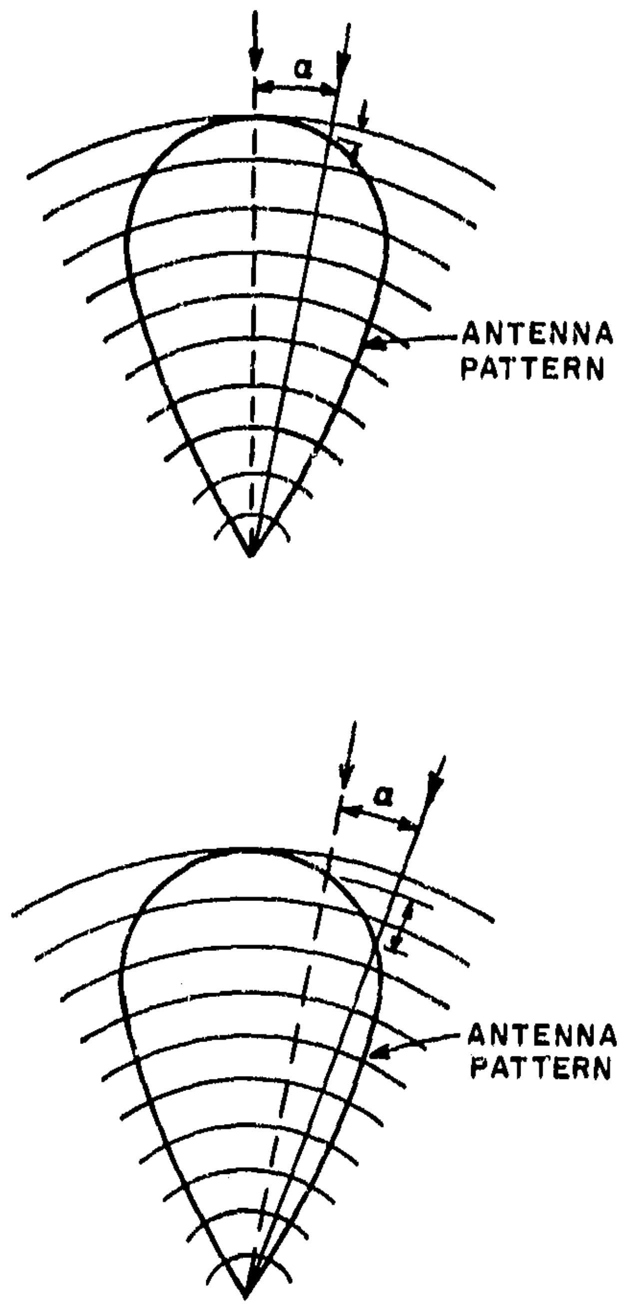


Figure 4. Gain degradation enhancement due to mispointing. The antenna pattern is shown in both parts as a polar graph, with the undisturbed incidence direction of the signal shown by the dotted line and arrow. The incidence direction for angle-of-arrival change α is shown by the solid line and arrow. The gain change, shown by the line segment with two arrows, is larger for the mispointed antenna.

B. Data Reduction

In interpreting the experimental results, care must be shown to remove several experimental artifacts. The first of these is a slow signal variation due to the diurnal motion of the satellite source. Because of its regularity, it can be removed by computation. The effectiveness of the algorithm used for this purpose was verified by applying it to clear days, when the diurnal motion was the only likely source of apparent gain variation. As a result, the residual errors due to this cause can be estimated confidently as less than 0.2 dB. The second difficulty arises from the fact that the receiver is switched between the two antennas: they are not sampled simultaneously. The advantage is, of course, that use of a single receiver makes the experiment insensitive to receiver-gain drift. On the other hand, allowance must be made for the non-simultaneous sampling. This was accomplished by first comparing the signal from the large antenna with a value obtained for the same time from polynomial interpolation of adjacent values for the small antenna, and then reversing the procedure, i.e., comparing the adjacent small-antenna signal with the interpolated signal of the large antenna for the same instant. If the two differential gain values agreed within 0.2 dB, the latter was used as the correct value. Discrepancies arose very infrequently, in fact generally only when the fading was so severe that the receiver lost lock. In case of such a discrepancy, the particular sample was discarded.

Great care must be taken to prevent precipitation particles from adhering to the antenna and, if this should occur, to avoid interpreting the resulting signal variations as propagation effects. The surfaces of the reflectors, the cover of the feed-horn for the large antenna, and the exterior of the waveguide feed for the small antenna were coated with Silibond, a hydrophobic material. Two spray tests were conducted, one early in the experiment and one after its termination, to see whether the signal strength could be changed by wetting the antennas. Both had negative results. Nevertheless, on one occasion a sudden decrease in the signal from the small antenna made the operator suspicious, and it was found that a small drop blocked the end of the feed of the small antenna. On another occasion, after the 28.6 GHz radiometer had become operational at the same site, it was found that after a particular point in time during heavy rain the radiometric data no longer agreed with the small antenna signal but did agree with that of the large antenna. Evidently, for just the right drop size, the combined effects of the hydrophobic material, gravity, and surface tension were such that a drop could be suspended in the feed opening of the small antenna. Since we were unable to reproduce the condition by spray-testing, it must have been a rare occurrence. Nevertheless, the entire data set was re-examined in conjunction with rain-gauge data showing local rain, and with available radar and radiometer data. Any data which might have been due to blockage of the small antenna feed were eliminated. It became quite evident that the great majority of observed relative gain change events were not due to wetting of the antennas or feeds. It should be noted in this connection that gain changes were observed occasionally at times not associated with any precipitation, sometimes under conditions of heavy overcast, and sometimes associated with temperature inversions under clear-sky conditions.

C. Results

A few examples of observed gain variations are shown in Figures 5 and 6. In each case, the graphs labeled "Mean" show the signals received on the two antennas, and the graph labeled "Gain Difference" shows the difference in the relative gains after correction for the diurnal motion. A positive gain difference indicates a loss of gain of the large antenna, i.e., a direction-of-arrival shift away from the antenna axis. Heavy convective rain was observed during the events of Figure 5, while no precipitation occurred during those of Figure 6.

When the attenuation statistics for each antenna are computed on a monthly basis, it is found that those for June through August are quite consistent, but that those for May differ substantially. The reason becomes apparent upon examining the original data: in May the satellite had just been placed in its permanent position, which was still being "fine-tuned", and our antenna was not pointed well toward the "average" satellite position.

The probability density distribution of observed gain changes is shown in Figure 7 for May and in Figure 8 for June through August 1982. During June to August, the median level of the antenna directivity

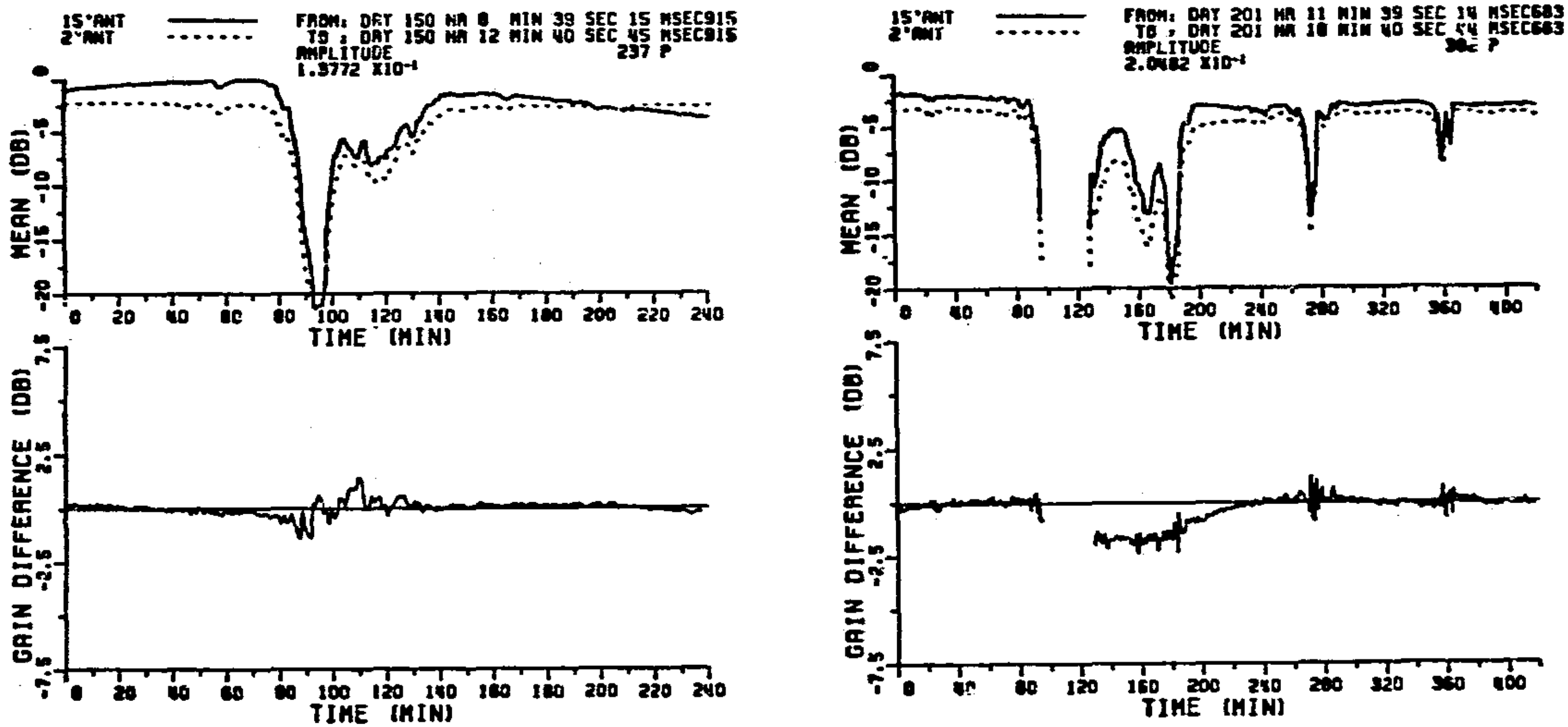
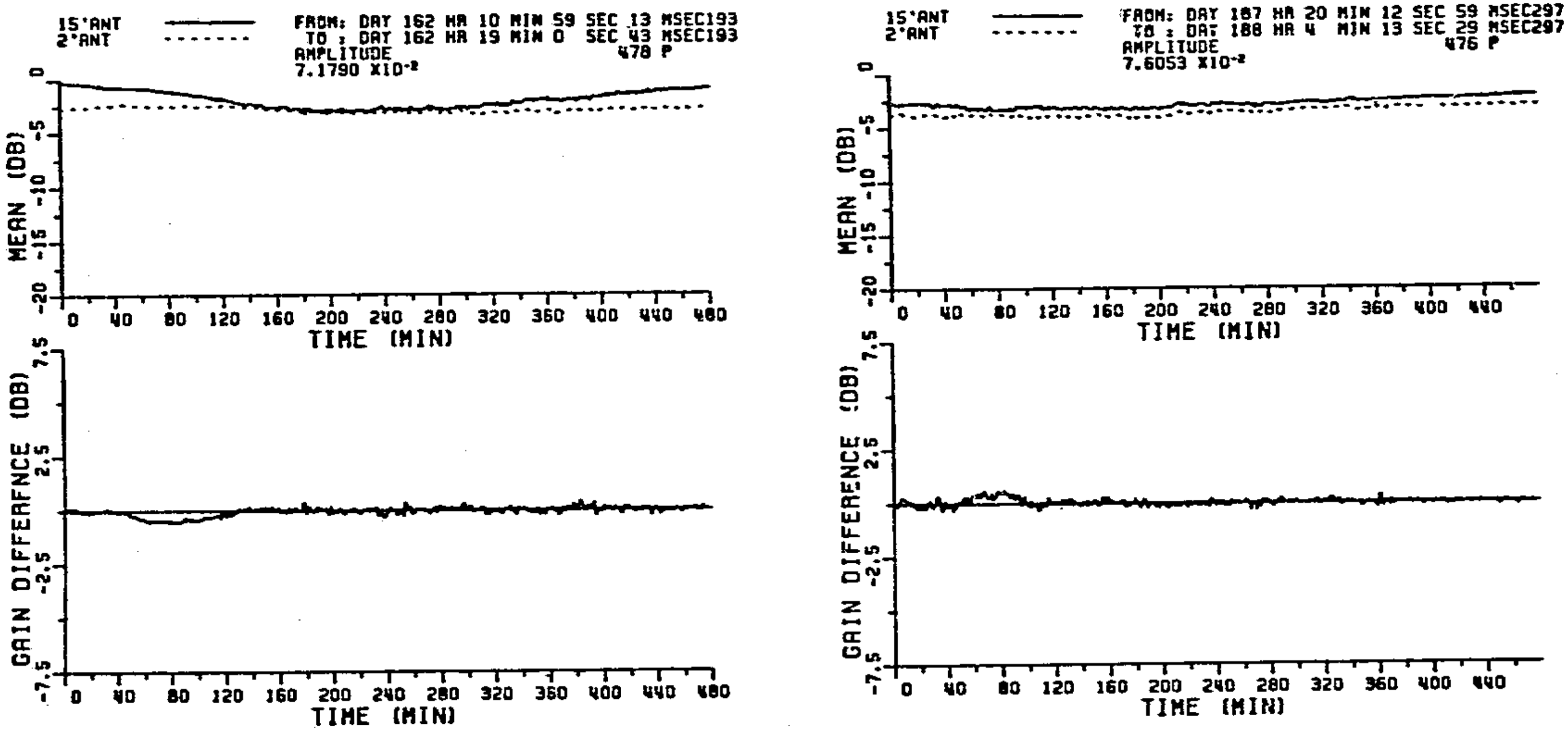


Figure 5. Gain changes during convective rain. The time is given as Julian day 1982 and Universal Time UT.



(a) During heavy overcast

(b) During a temperature inversion near sunrise on a clear morning.

Figure 6. Gain changes during periods of no precipitation.

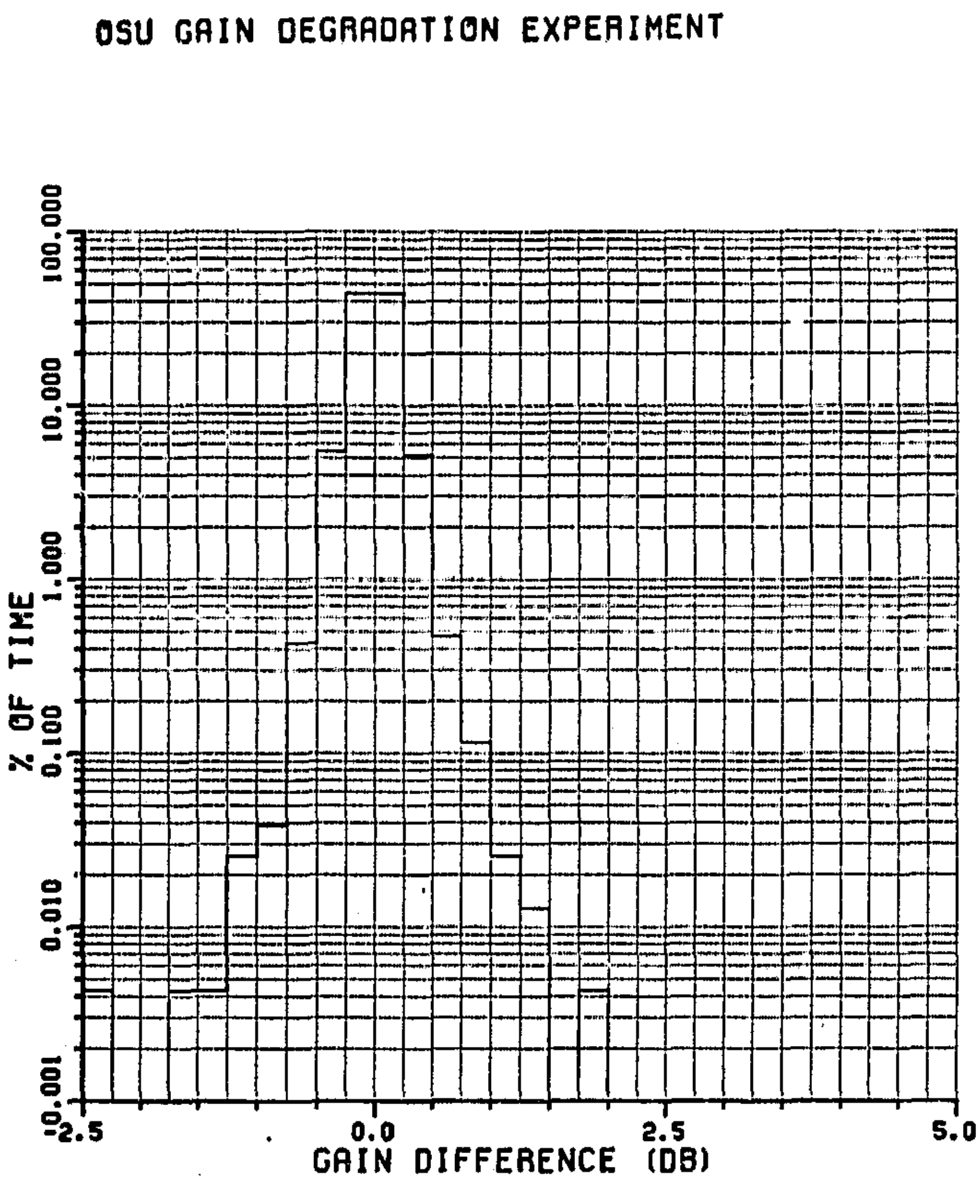


Figure 7. Probability density distribution histogram of relative gain changes for May 1982. Positive gain changes mean a loss of gain of the large antenna.

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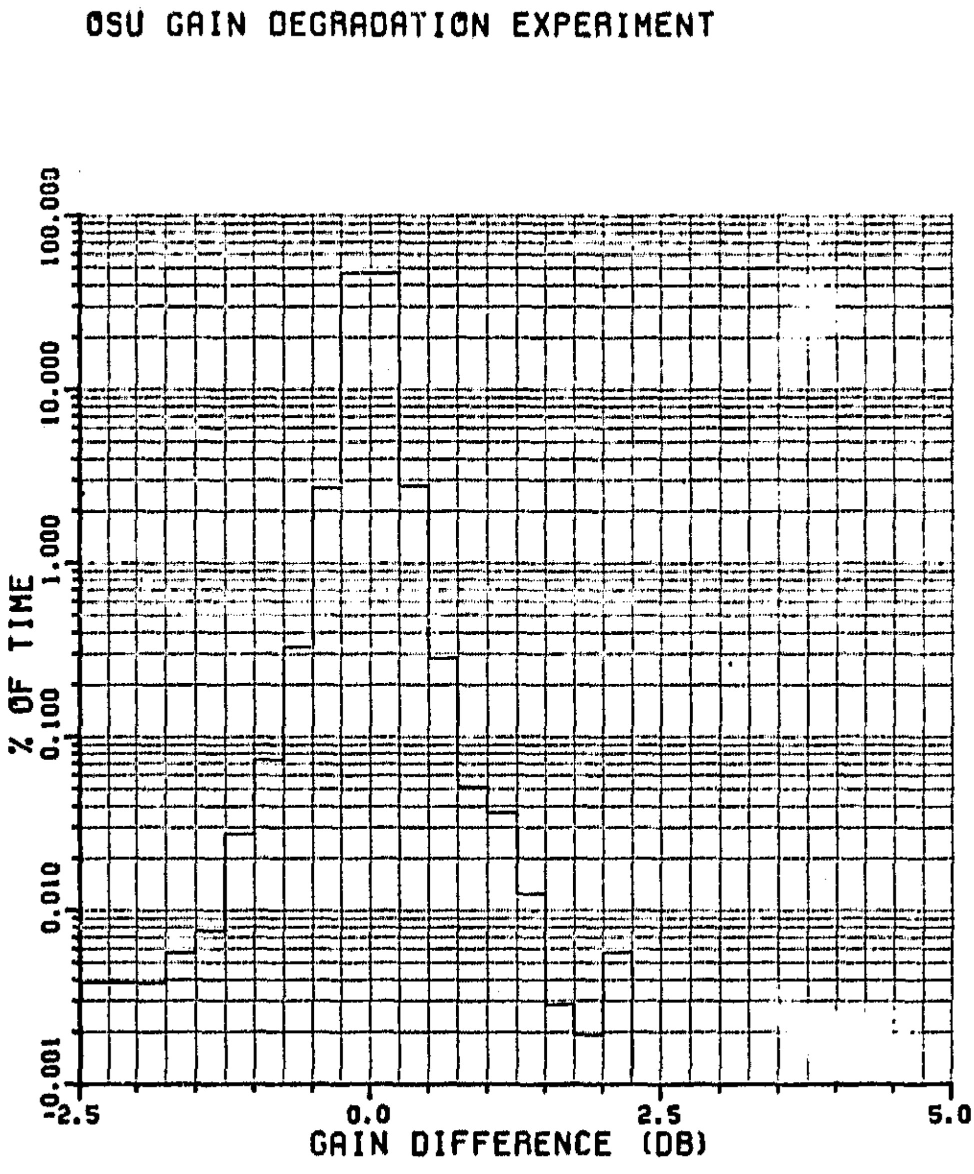


Figure 8. Probability density distribution histogram of relative gain changes for June-August 1982. Positive gain changes mean a loss of gain of the large antenna.

pattern at which the signal was received appears to have been approximately -3 dB. A 2 dB gain change at this level corresponds to a direction-of-arrival change of 0.02°. Thus, our data does not seem inconsistent with the Bell Laboratories experiment [1]. It does appear to be inconsistent with a previous angle-of-arrival experiment conducted at this Laboratory [2].

The data processing has continued under the successor contract. It now appears that the gain-statistics can be translated into more meaningful angle-of-arrival statistics, from which the gain changes for arbitrary antennas can be predicted. In this form the statistical difference between May data and later data appears to vanish, as might be expected. This part of the data reduction is just being concluded and will be included in a technical report, which describes this experiment in much more complete detail.

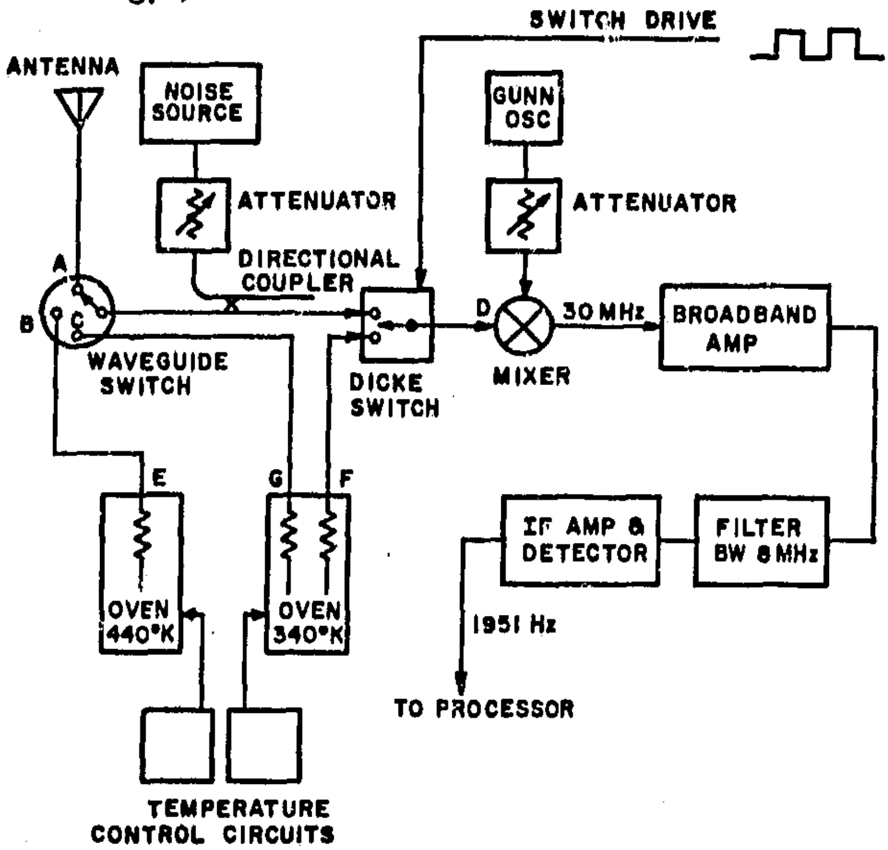
SECTION III

THE PATH-DIVERSITY EXPERIMENT

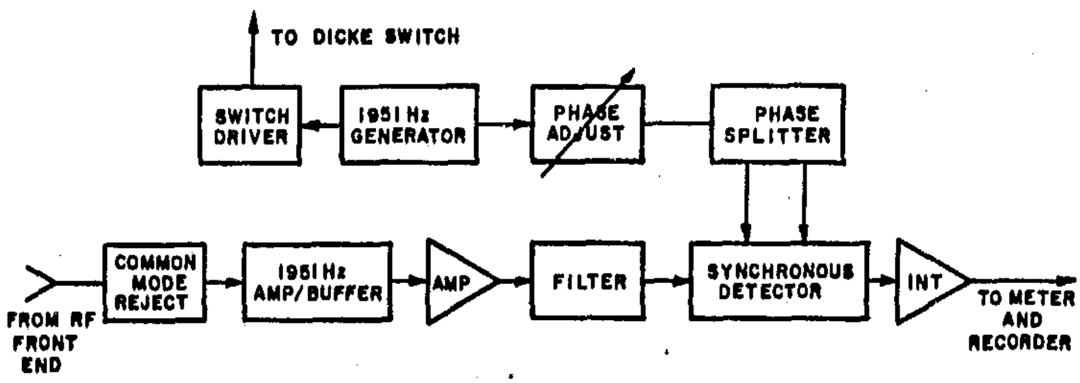
A. The Experiment

A second task under the contract was to instrument two identical radiometers at 28.56 GHz, to calibrate at least one instrument by operating it for some time in conjunction with the gain-degradation experiment which monitored the transmission from the Comstar D/4 28.56 GHz beacon, and then to obtain diversity-reception data by means of the two radiometers over as long a time period as possible. The timing of this task was paced by the expected availability of the D/4 beacon, which ceased operation on 1 September 1981, only 5 1/2 months after the start of the contract. The short availability period of the beacon was, of course, what had led to the decision for a radiometric experiment in the first place: the time was deemed long enough to calibrate the radiometric measurement against a direct transmission measurement, but it was clearly not sufficient to obtain long-term statistical data.

A block diagram of the two radiometers, which were substantially identical, appears in Figure 9. One was located at the main satellite-communications site of the ElectroScience Laboratory, and the other near the University Airport (Donn Scott Field) with a separation of approximately 9 km, as shown in the map of Figure 10. A leased telephone line brings the signals from the remote (airport) site to the main site for recording on magnetic tape. A more detailed description of the experiment appears in the first annual report [3].



(a) Radio-frequency circuits



(b) Processor

Figure 9. 28.56 GHz radiometer block diagram.

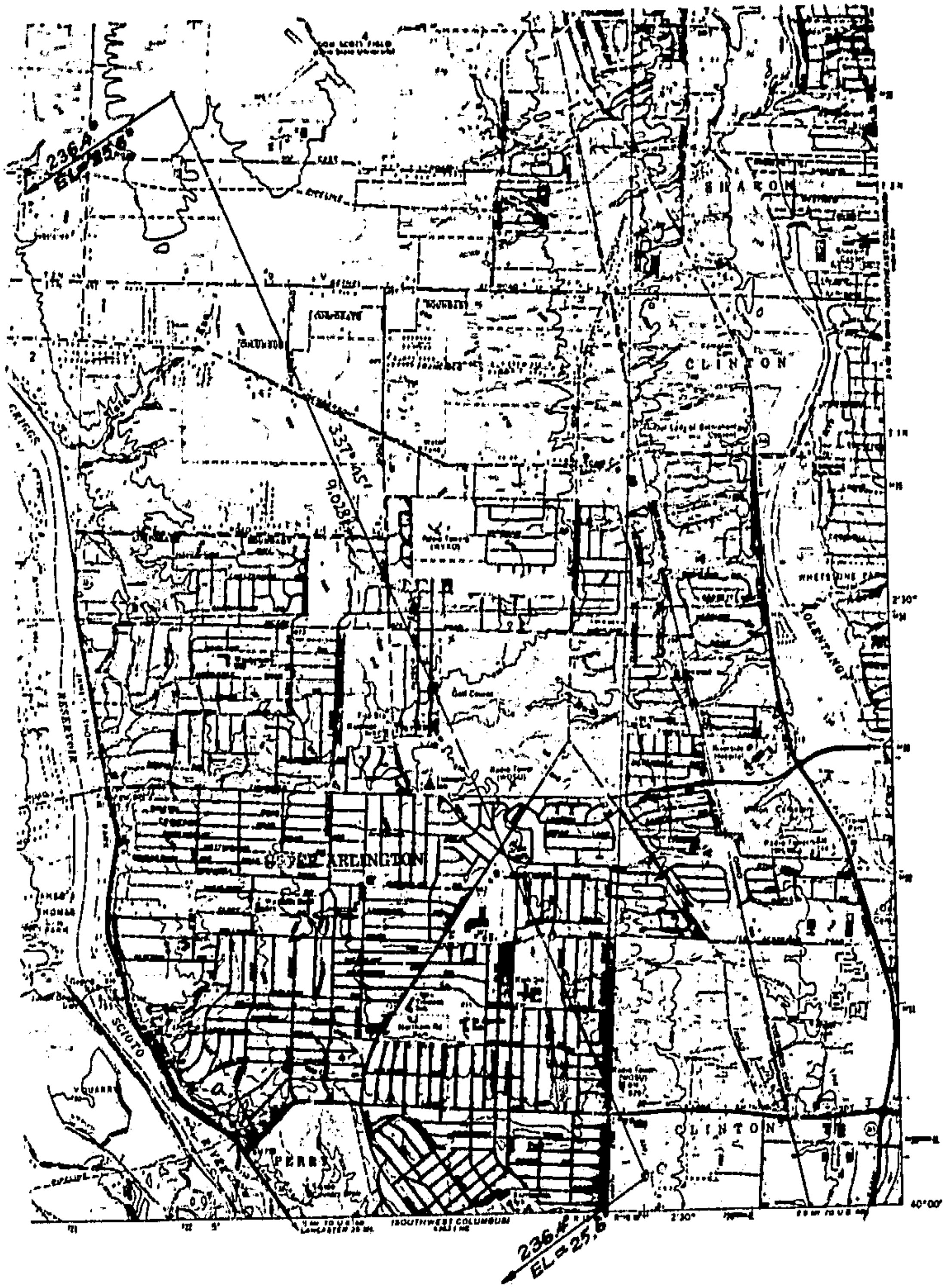


Figure 10. Locations of the two diversity sites.

B. Theoretical Considerations

A radiometer measures directly the sky brightness, not the attenuation (or extinction) of a plane or spherical wave. The attenuation can only be inferred from the sky brightness. When the hydrometeors are sufficiently small compared to a wavelength, scatter from them is much less important than absorption. Under these circumstances, the attenuation can be obtained from the brightness temperature by

$$A = 10 \log_{10} [T_m/(T_m - T_b)] \quad , \tag{1}$$

where T_b denotes the sky brightness temperature, T_m a weighted mean temperature which can be estimated and which is in the vicinity of 270-280 K for most conditions, and A is the equivalent attenuation over the atmospheric path in decibels. This expression neglects scattering and is therefore suspect at 30 GHz for moderate or heavy rain because the scattering and absorption cross sections, averaged over reasonable drop-size distributions, become comparable in magnitude [4]. Calculations to estimate the resultant error have been made by Zavody [5] using a multiple-scattering technique and by Tsang, et. al. [6] and also by Ishimaru and Cheung [7] using radiative transfer calculations. The results depend not only on frequency and rain rate, but also on the viewing angle, cloud layer thickness, and temperature profile, as well as the rain-drop distribution model. They are, therefore, not easily interpreted in general terms. In general, they indicate that near vertical viewing the beam is "brightened", i.e., more energy is scattered into the beam than out of it, while at very large angles from the vertical the beam is "darkened". The calculations by Tsang, et al., show that for a 1 km thick layer of 12.5 mm/hr. rain at 30 GHz the two effects nearly balance near 65° from the vertical, which is the viewing angle of our experiment. The effect is rather broad: for the same rain at 94 GHz the angle at which no brightening or darkening occurs is about 58°, and for 1-km thick cloud at 94 GHz, it is about 55°. Thus, there exists a theoretical basis for hoping that Equation (1) may be used for our experiment.

It should also be said that the experimental community has exhibited considerable faith in the use of this equation [8,9]. It was used in interpretation of experiments concurrent with measurements on the CTS satellite with good results [10].

In the present case, the local radiometer was operated concurrently with the gain-degradation experiment. Both antennas were pointed at the Comstar D/4 beacon. A substantial amount of data was obtained during two rain events occurring in July and August 1982 totalling over 5 hours with widely varying attenuation. The results of this calibration are shown in the scatter plot of Figure 11, where a mean temperature of 280 K has been employed in Equation (1). The points at the top represent data points when the receiver lost phase-lock. The reason for the lone point below the aggregate is not known. It is clear that statistics generated from

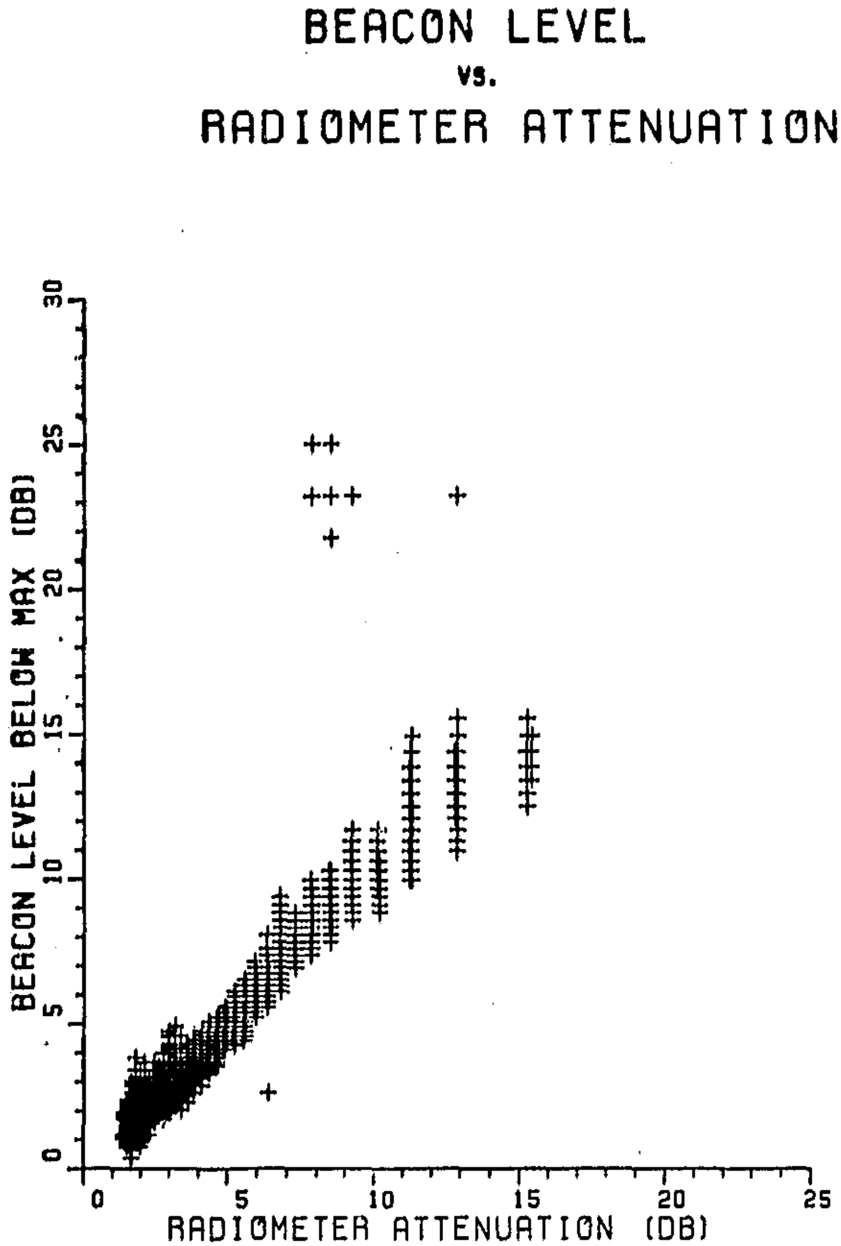


Figure 11. Radiometer calibration scatter plot.

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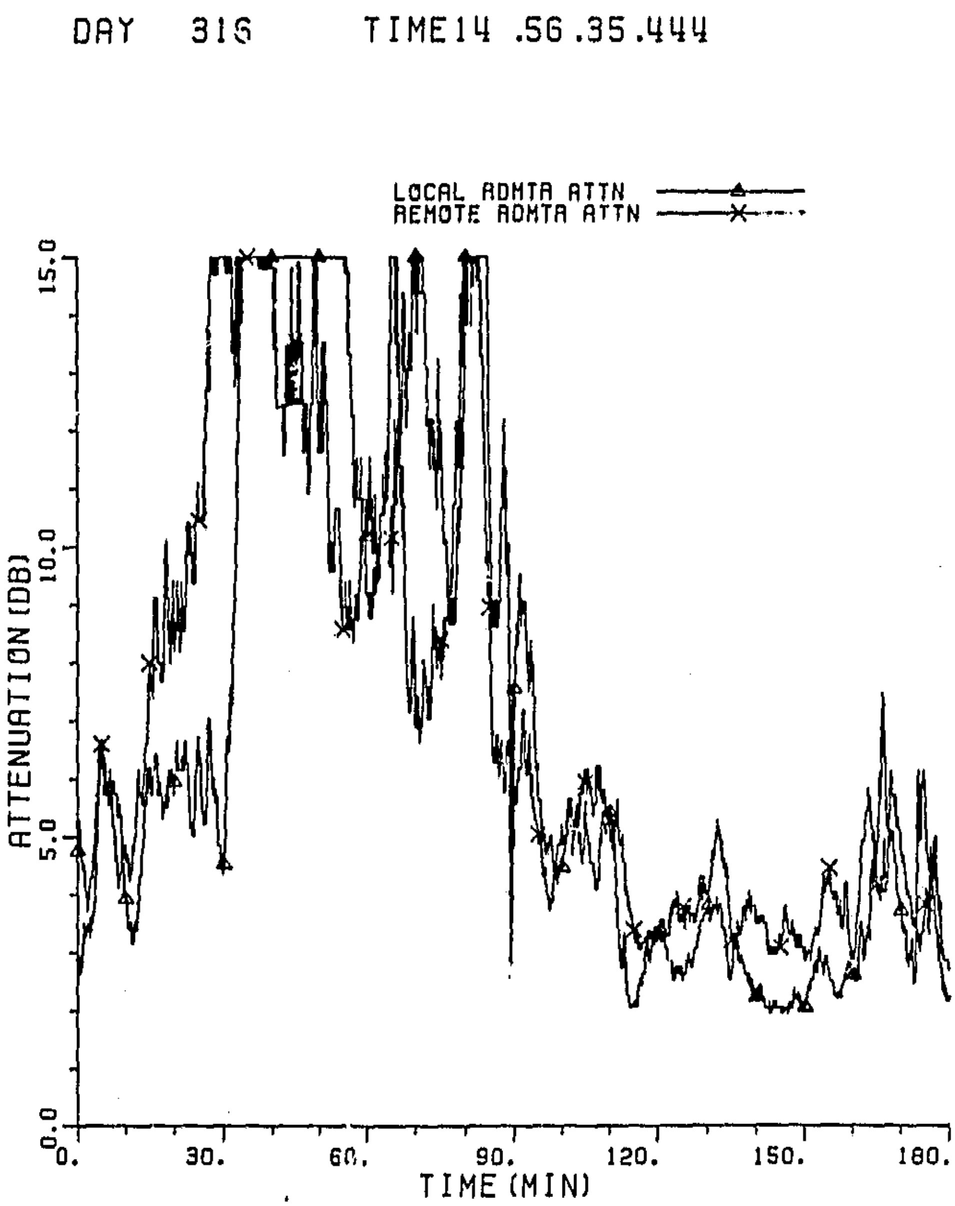

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Figure 12. (Continued).

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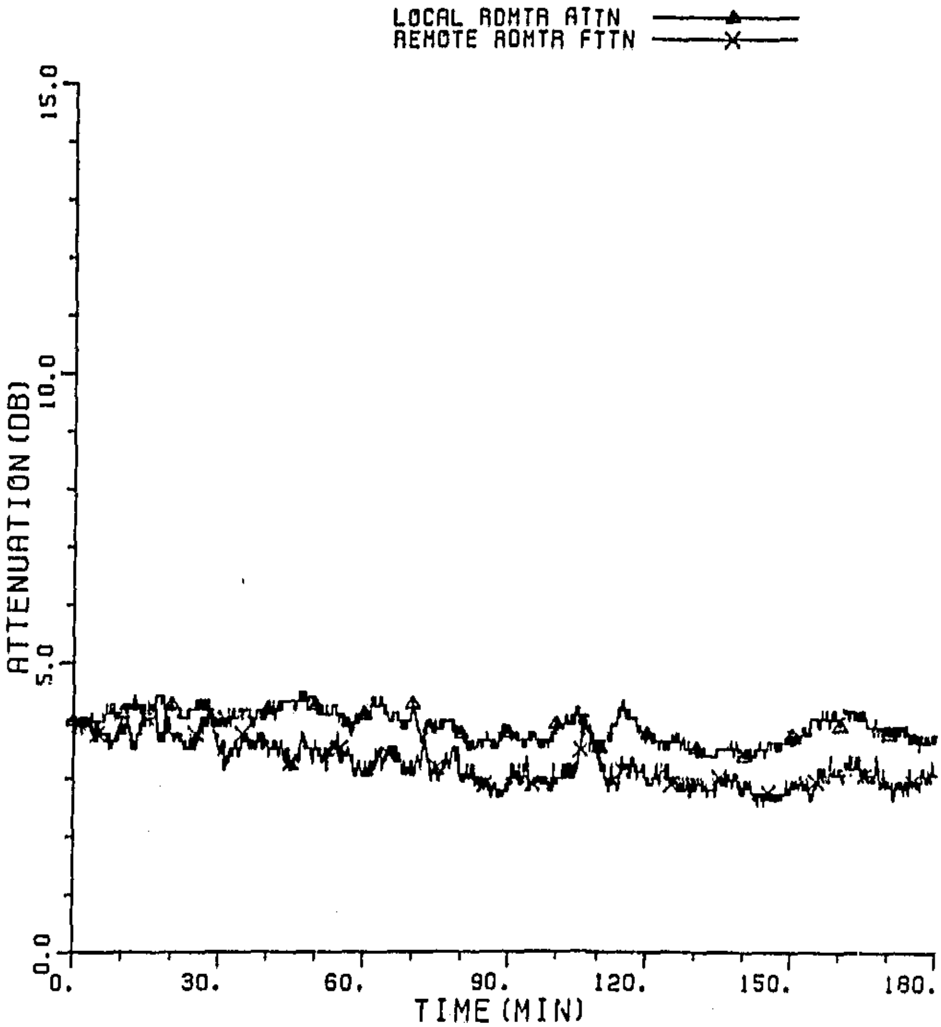

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Figure 12. (Continued).

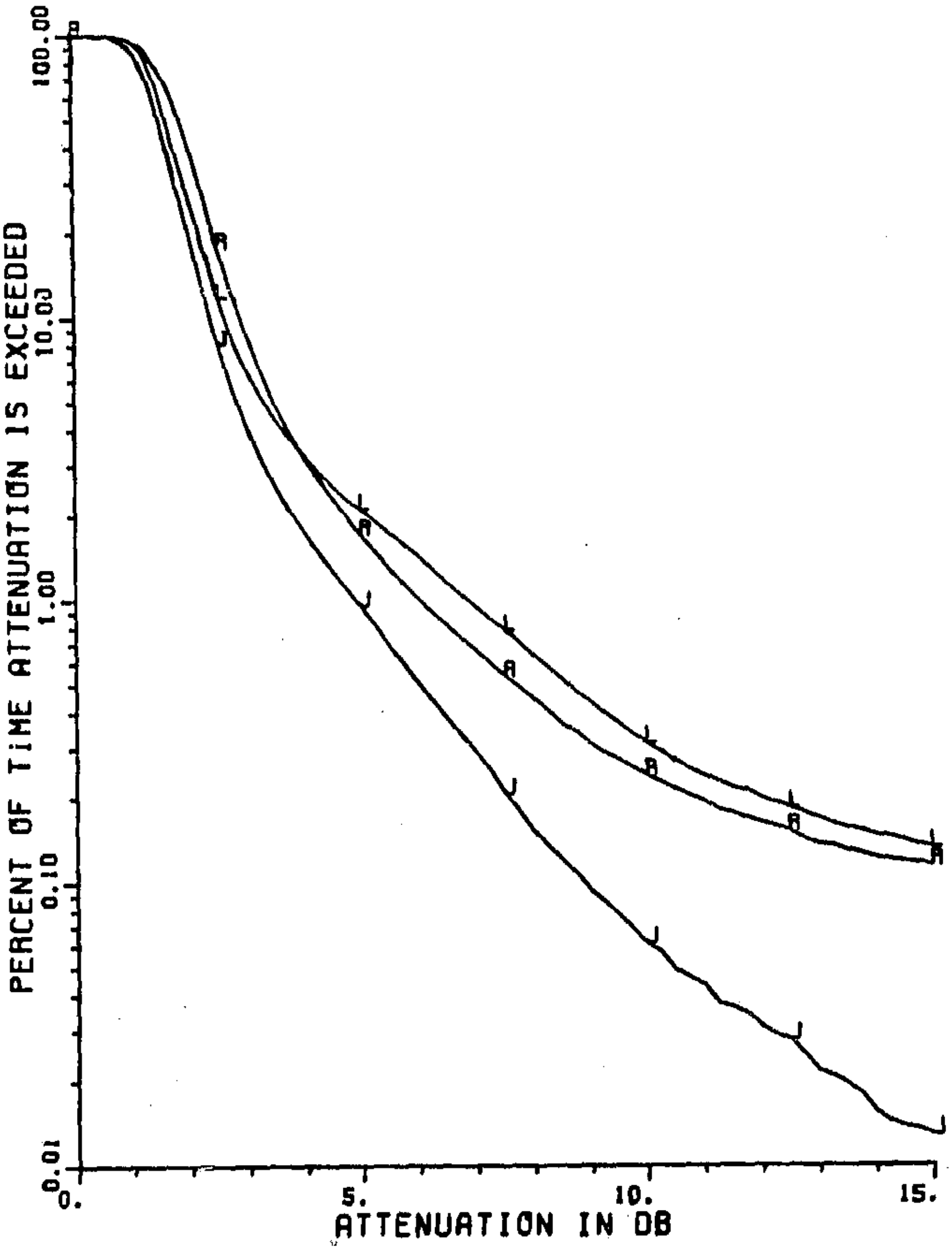


Figure 13. Cumulative single-site and joint attenuation statistics for 224 operational days out of the 284-day period 8 August 1982 to 20 May 1983. L refers to the local site, R to the remote site, J to the joint distribution obtained by always using the better of the two.

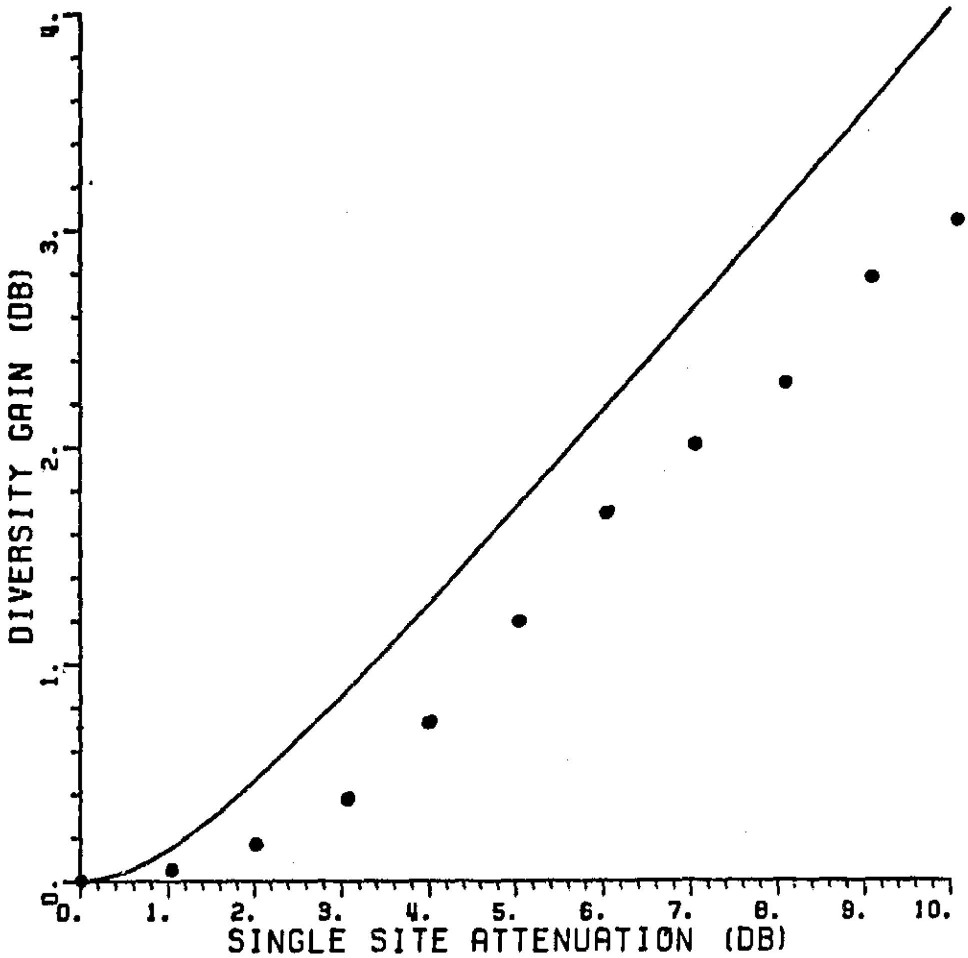


Figure 14. Site diversity gain vs. single-site attenuation. Dots show experimental values. The curve represents Hodge's empirical model [12].

A more detailed technical report on the site-diversity radiometry experiment is planned on the successor contract. It will include data obtained after June 30, 1983, and also it will consider other definitions of diversity gain. It appears to us that the present definition has two drawbacks. First, it presupposes instantaneous switching in its implementation, i.e., the switching must be accomplished and significant switching transients must have disappeared in a time much less than that required to transmit one bit. At proposed information-transmission rates of many hundred megabits per second, this poses a significant problem. Secondly, the switched antenna approach utilizes only the performance of the best antenna, not the best signal-to-noise ratio available from the combination of all antennas. Optimum post-detection linear combining of the signals would have neither of these disadvantages. We intend to compare the two methods for the signals of this experiment.

SECTION IV

A PATH-DIVERSITY MODEL

Part of the work on this contract entailed a literature-search of path-diversity experiments, both direct and radiometric, and the development of an empirical model from these data. The model is summarized in the previous annual report [3] and given in detail in a technical report and in the open literature [12].

SECTION V

RADAR RESULTS

A meteorological radar operating at 3.064 GHz was used as a supplemental data source in all the experiments described above, but on a limited basis. The radar was pointed in the same direction as the other antennas, i.e., toward the location of the Comstar D/4 beacon in August 1982, see Figure 2. The radar reflectivity factor Z observed by the radar was converted to equivalent attenuation coefficient (dB/km) for each range-resolution cell of 150 meters along the path by means of the equation

$$\alpha_i = a_\alpha \, a_Z^{-(b_\alpha/b_Z)} \, Z_i^{(b_\alpha/b_Z)} \qquad (2)$$

where

α_i is the specific attenuation of the i^{th} cell,

Z_i is the reflectivity of the i^{th} cell,

a_Z, b_Z are the constants of the power law relationship for reflectivity at 3.064 GHz, and

a_α, b_α are the constants of the power law relationship for rain attenuation at 28.56 GHz.

Equation (2) is derived from the approximate power laws [13]

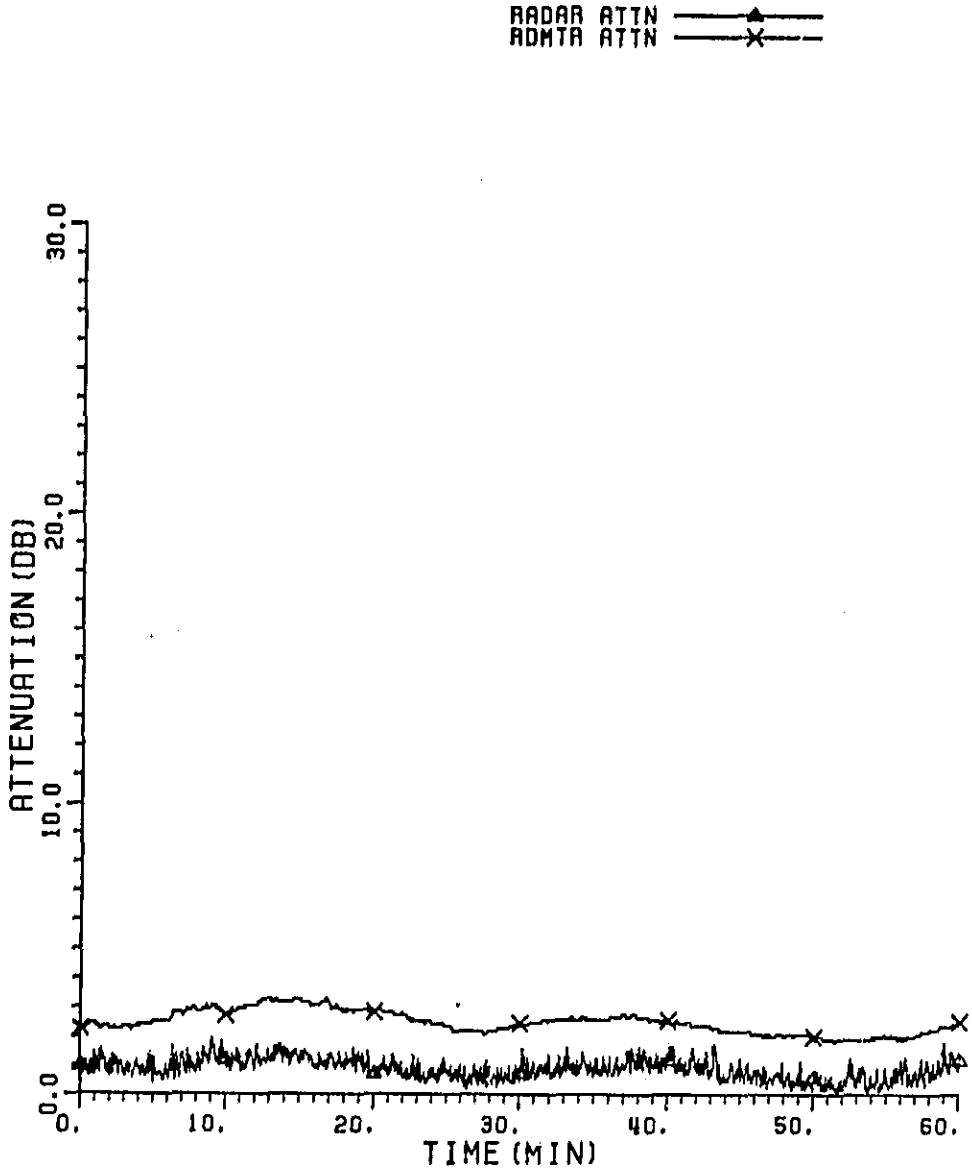
$$Z_i = a_Z R_i^{b_Z} \quad , \qquad (3)$$

$$\alpha_i = a_\alpha R_i^{b_\alpha} \quad , \qquad (4)$$

where

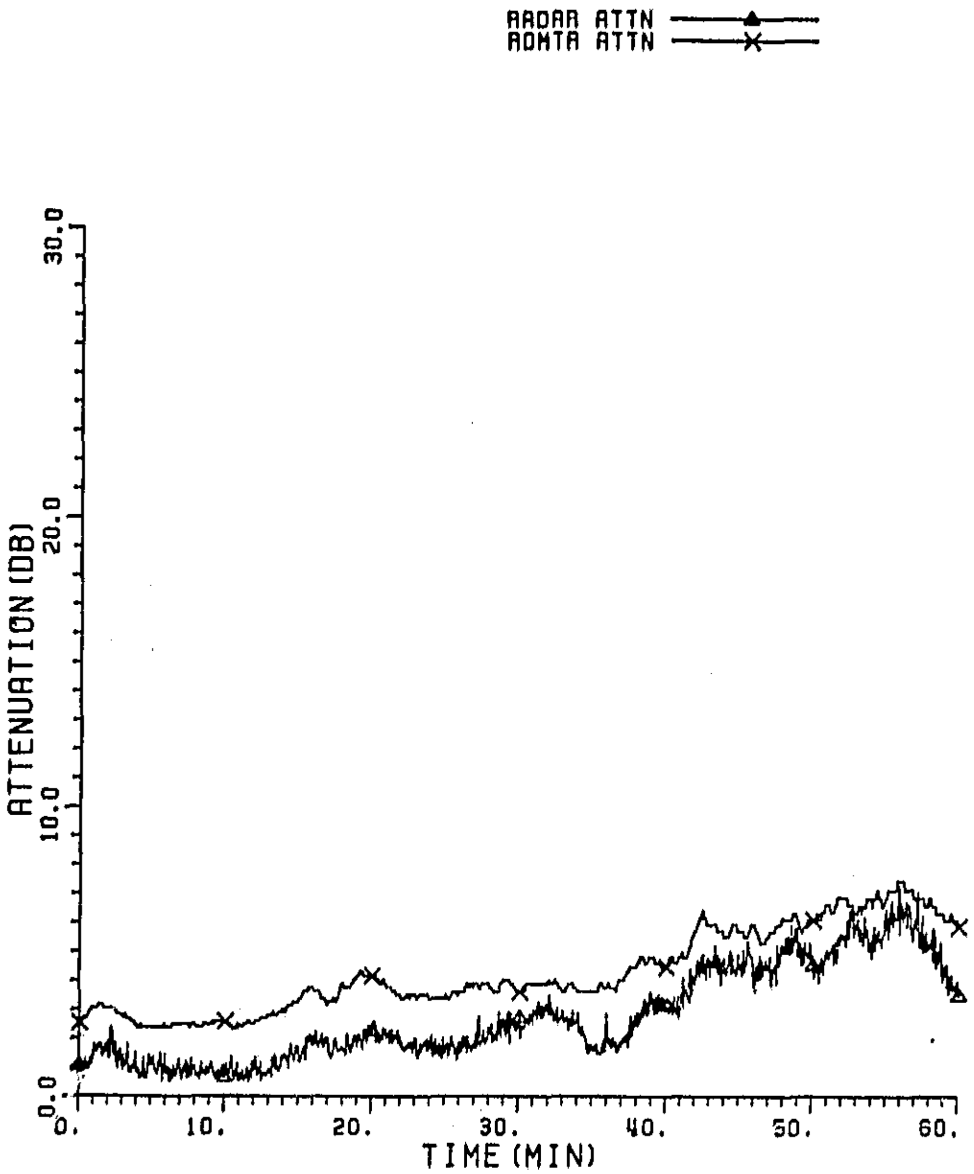
R_i is the rain rate of the i^{th} cell.

The total attenuation at 28.56 GHz was then obtained by integrating along the path between the ground and the melting layer, as shown by the bright band on the radar returns. Typical plots of the total equivalent attenuation over the path at 28.6 GHz obtained by use of Equation (2) are plotted in Figures 15 to 17. The three parts of Figure 15 represent one continuous event on 12 April, 1983. During most of the time the radiometer recorded an attenuation of approximately 1 dB above that of the radar. Approximately 0.5 dB would be expected on a 25.6° elevation path for gaseous absorption on the basis of a Standard U.S. Atmosphere profile [14]. Since the relative humidity is likely to be above that of such a profile during a precipitation event, the observed 1 dB is deemed to be in good agreement. At times the radar-inferred attenuation approaches and even exceeds the radiometrically inferred value, as for example in Figure 15(c) at time 35 minutes. Usually this is associated with a sudden change, sometimes the disappearance, of the bright band. This makes it difficult to estimate the melting layer accurately. In Figure 16 between 60 and 100 minutes the radiometrically inferred attenuation exceeds that calculated from the radar by approximately 8 dB. While the precise value depends on the value of T_m used, it is clear that the radiometer sees a much greater equivalent attenuation than the radar for this period. The event is a convective storm in mid-November. Such occurrences usually are caused by the mixture of intruding moist air masses from the Gulf of Mexico with cold arctic air from Canada. Often sleet is observed at ground level, and it is likely that sleet-like hydrometeors exist at higher altitudes even when they are not observed on



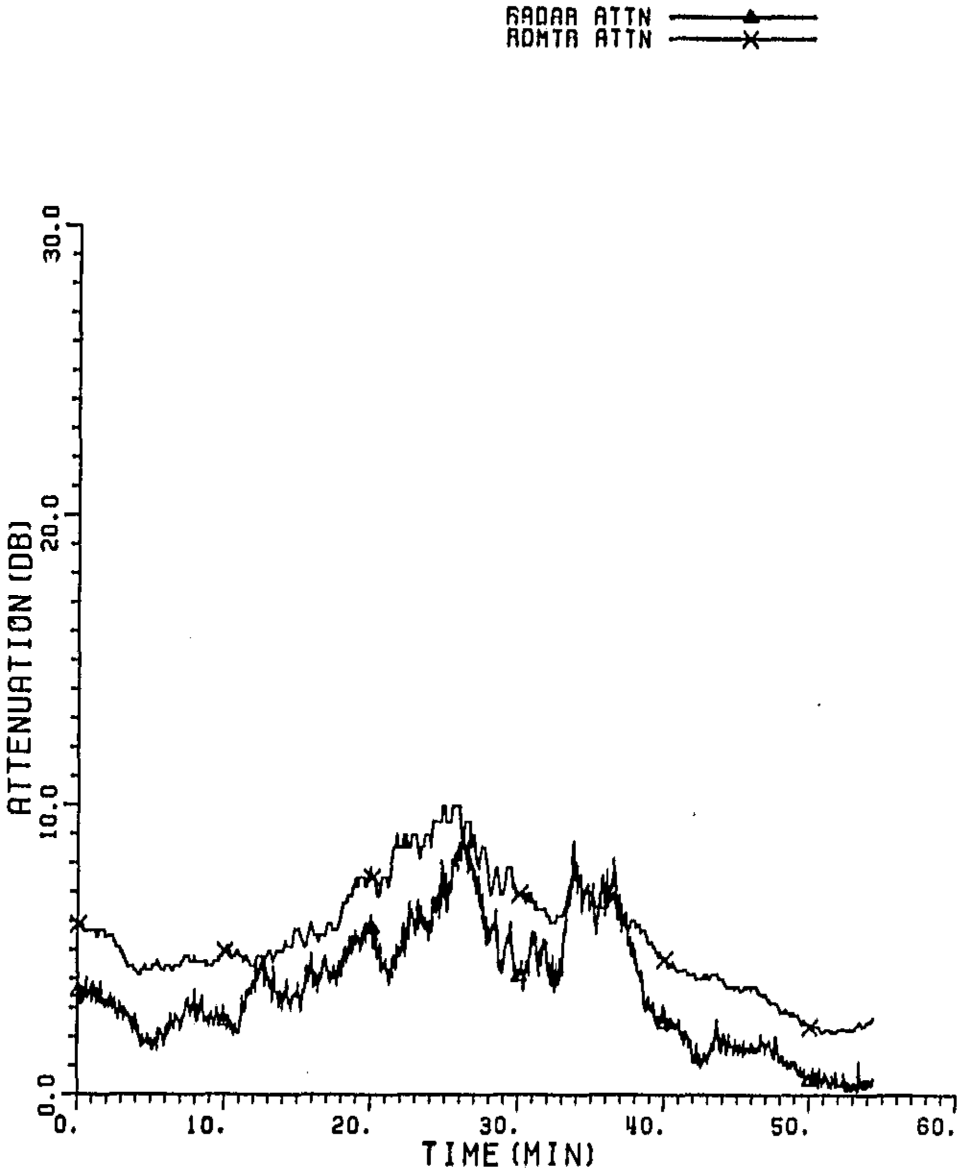
(a) one hour beginning at 12:09 UT

Figure 15. Comparison of equivalent 28.56 GHz attenuation as calculated from 28.6 GHz radiometric and 3.064 GHz radar data. DATE: April 13, 1983, time is Universal time.



(b) next hour

Figure 15. (Continued).



(c) next hour

Figure 15. (Continued).

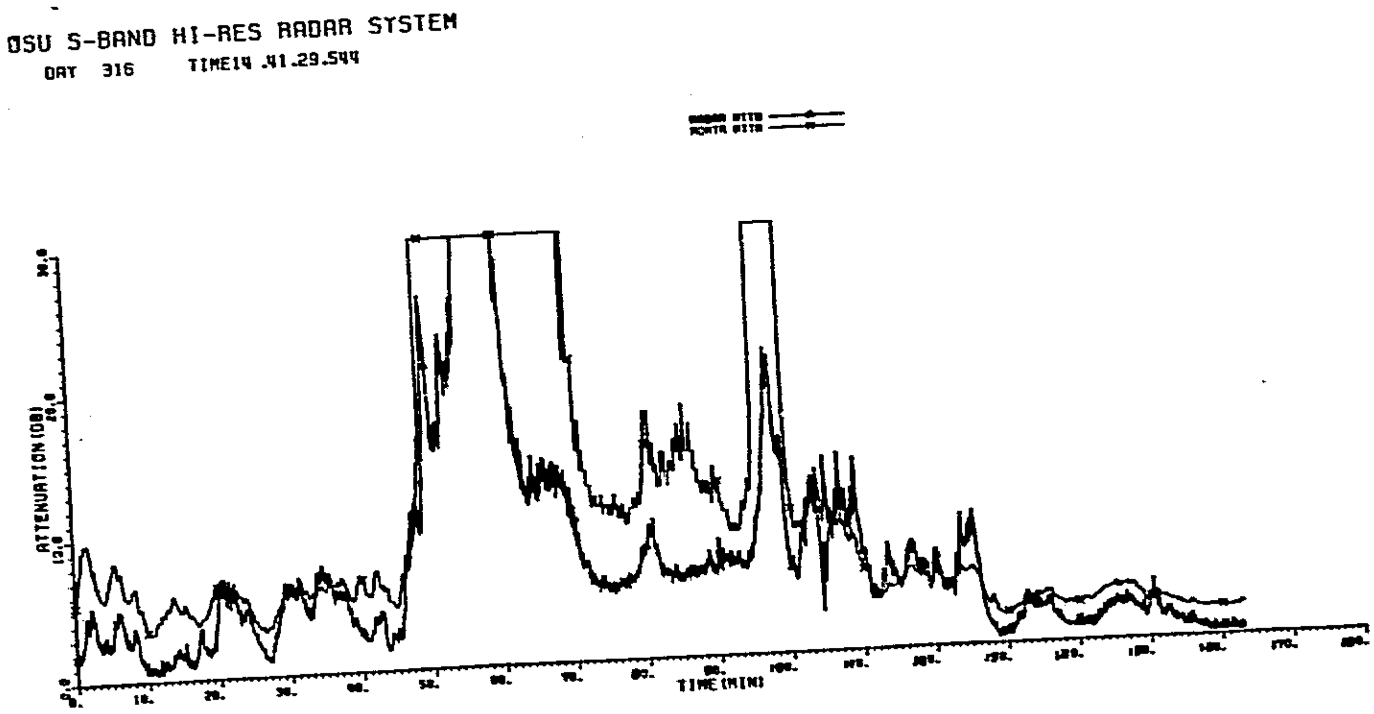


Figure 16. Same as Figure 15. DATE: 12 November 1982.

the ground. The transformation of the radar reflectivity data to equivalent 28.6 GHz attenuation is based on the characteristics of water droplets and would not be expected to hold in such cases. The effect is definitely not an artifact of the experiment, such as a water droplet in the 28.6 GHz local radiometer feed, since the remote radiometer observed attenuations quite in line with those of the local radiometer and also much greater than those obtained from the radar. Figure 17 corresponds to a snow event. Again the radar-inferred attenuation, which is "in the noise" in this case, is too low.

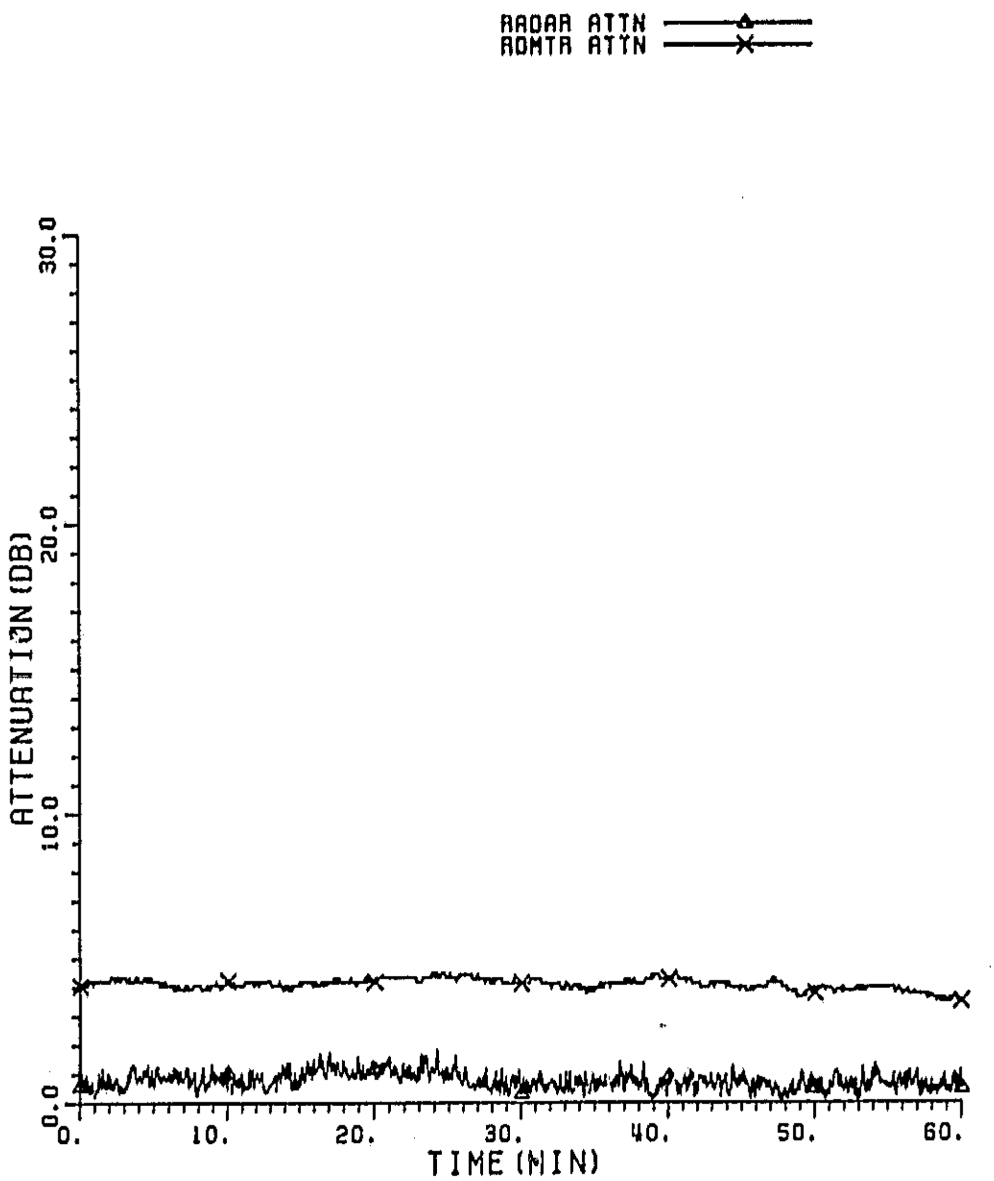


Figure 17. Same as Figure 15. DATE: 15 December 1982.

SECTION VI

A NEW DATA ACQUISITION SYSTEM

The data acquisition system in use at the beginning of the contract period was built around a LSI-2 minicomputer and Pertec Model FT 8840A-9F-45 magnetic-tape drive which were becoming increasingly unreliable and difficult to maintain. The ideal solution would have been to buy a modern mini-computer based system with enough redundancy to ensure reliability, e.g., a pair of DEC 11/23 systems with associated tape drives. The finances of the contract and of the University in a period of severe retrenchment precluded such an elegant solution.

The problem was solved by building a new system around a Hewlett-Packard Model 2116B minicomputer and Model 202 option 7970B magnetic tape drive which were donated to the University. The ElectroScience Laboratory already owns several HP 2116 minicomputers which have been found to be highly reliable. They come with an excellent diagnostic software package which helps isolate problems when they do occur. Also, we have a complete spare HP-2116B minicomputer and most of the interface cards; we are trying to acquire the few for which we do not have duplicates. On the negative side, the HP-2116 is no longer supported by Hewlett-Packard service, and we still have only one reliable magnetic-tape unit. However, we are looking into the possibility of interfacing a magnetic disk unit for emergency data storage. Most of the software for the system was written in FORTRAN for clarity and ease of modification. This was, of course, not feasible for the software drivers for peripheral devices; these were written in HP Assembler language.

The program is designed to service the experimental inputs on demand from the experiments, but also to allow the operator to exercise control. This is achieved by a simulated multi-tasking: control is transferred at frequent intervals (on the order of a second) between two subroutines. The SAMPLER subroutine gathers data, formats it into logical records, and causes these to be written to magnetic tape. The USER subroutine searches for tele-type inputs from the operator and causes the system response to be modified accordingly. For example, it may define new inputs to be sampled by the SAMPLER, in effect placing new experiments into the data stream; it may cause the system status and certain data from the remote site to be displayed; it may be used for diagnostic purposes.

The system is housed in a standard rack (Figure 18), which allows easy interchange between the computer currently in use and the back-up unit in case of failure. It has been in operation for several months with no major problems. It constitutes a M.Sc. thesis and will therefore be documented in complete detail, but the documentation was not entirely complete at the end of the contract and will be completed under the successor contract.

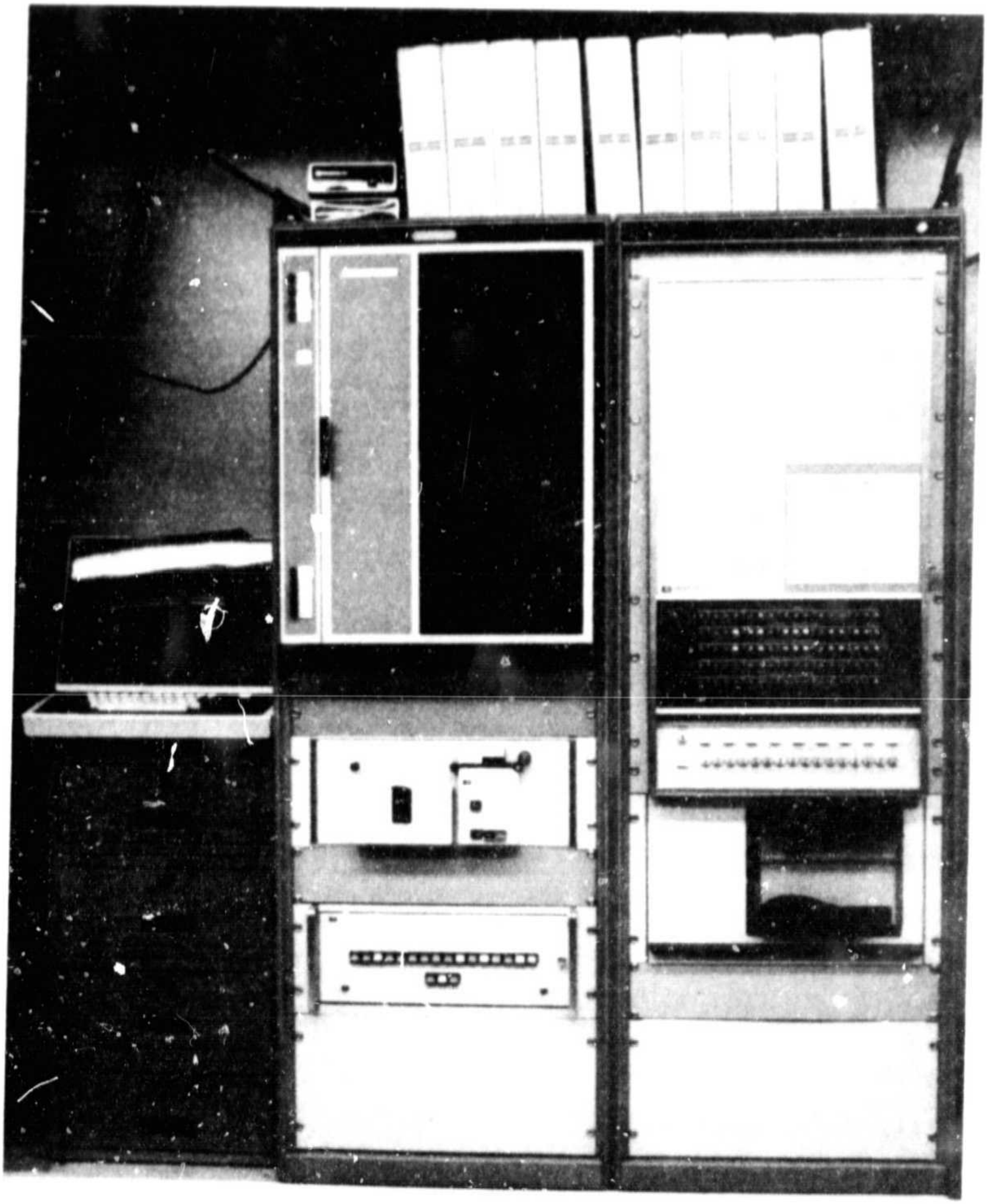


Figure 18. Data Acquisition System.

SECTION VII

PROPAGATION SURVEY AND EXPERIMENT PLANNING

A. Introduction

A task under the contract was to study past experiments to determine areas where more experimental work is needed and to formulate an initial proposal for a flight experiment. After initial consideration, two areas of potential interest were identified. The first deals with the prediction of bulk attenuation due to precipitation on a global basis; the second with the effect of precipitation as a stochastic medium on high-data rate signals.

B. Global Estimates of Attenuation

Bulk attenuation is, of course, the dominant effect of precipitation on earth-satellite signals at frequencies above 10 GHz. By "bulk" attenuation we mean attenuation which persists over time periods much longer than a typical message unit, in contradistinction with stochastic properties which imply changes over time periods comparable with a typical message unit. Bulk attenuation has received by far the most attention of any propagation effect at EHF for earth-space paths so far, and rightfully so. A bibliography of experiments in this area would be a substantial undertaking in itself. Space diversity has been a small subset of experiments dealing with bulk attenuation; thus, the bibliography given for space diversity experiments in our report on the space diversity model [12] would be a small subset of a bibliography on bulk attenuation measurements.

As a result of this body of experimental data, several methods for predicting attenuation statistics have evolved [15-23]. Some of these are based on climate models from which precipitation statistics are deduced, either explicitly or implicitly, and attenuation statistics are then calculated by use of an assumed rain drop-size distribution. Others allow the input of local precipitation statistics directly. Such methods are very useful in overall planning, e.g., in frequency and orbit coordination on an international basis, but they are often inadequate for planning specific links. The reason is that the link performance depends not on a regional climate but on the local microclimate of the earth stations. Microclimates can vary greatly over relatively short distances, primarily due to orographic effects or the presence of large bodies of water. For example, the precipitation statistics of the Erie-Buffalo region may be expected to differ substantially from those of the Youngstown-Warren region, and those of Asheville, NC from those of Charlottesville, VA, because of the influence of Lake Erie in one case and of the Great Smoky Mountains in the other. Such differences are not always well documented even in developed nations, but in many parts of the world applicable data are scarce indeed. There also exist substantial questions on the applicability of the commonly used rain-drop size distributions to tropical and monsoon regions. Finally, none of the current predictive methods take account of ice, e.g., snow, graupel, sleet, or hail. As shown by Figure 17, significant attenuation can result from snow at 30 GHz. It should be noted that ice is frequently present at higher altitudes even when it is not present at the ground; it is almost always present in convective storms.

C. Bulk Attenuation Experiments

For these reasons it appears to us that it would be useful to develop instrumentation for measurements at many geographical locations, which would allow better prediction of attenuation on earth-satellite links. A direct satellite measurement is precluded because beacons at EHF are not sufficiently available, and especially not in the less developed regions. We propose therefore instrumentation based on multi-frequency radiometry, with a flight experiment to calibrate the method as the Comstar D/4 28.56 GHz beacon was used to calibrate the radiometric experiment reported in Section III of this report.*

The central point here is that the effects of scattering and absorption are different at different frequencies. Thus, it should be possible to separate out the effects of water and various ice forms by simultaneous radiometric observation at several frequencies. Also, with respect to liquid water, observation at relatively high frequencies (e.g., 30 GHz) are most useful for light and moderate rain but tend to saturate for heavy rains, for which lower frequencies can give better information. Thus it will take several radiometers at different frequencies to obtain information which might be used to predict the performance of satellites in all frequency bands for a given location.

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*This idea was first suggested to us by Dr. Nathaniel E. Feldman of the Aerospace Corporation.

What has been proposed, then, is a system of radiometers which could be used at many geographic locations to collect the precipitation information for predicting satellite-link attenuation performance at any frequency of interest. Radiometers require relatively small antennas and can be constructed relatively simply and inexpensively; thus deploying many such systems on a world-wide basis is a distinct possibility. In a sense, the intent here is to explore the meteorological troposphere analogously to the exploration of the ionosphere by means of widely distributed ionospheric sounders in the early 1960's.

Substantial theoretical and numerical work will be required to validate this concept and to determine the frequencies at which the radiometers should operate. Also, verification against actual satellite data will be needed. For this purpose we would propose multi-frequency beacons which might be piggy-backed on satellites for other primary purposes, as was done, for example, with the Comstar satellites. These beacons would not need to be operative over time periods longer than a few months, although extended operation would, of course, be desirable.

It should be noted that there exists at present at least one set of satellite sources which might be used to guide the development of such a system through some preliminary experimentation. These are the LES-8 and LES-9 satellites which have the capability to transmit at 38.0 and 36.8 GHz, respectively [24-26]. Their geostationary-radius ecliptic-plane orbits make them visible from most of the continental United States for much of the time, with substantially varying elevation angles (see Figure 19). Their lifetime is expected to extend at least to 1988 or 1989.

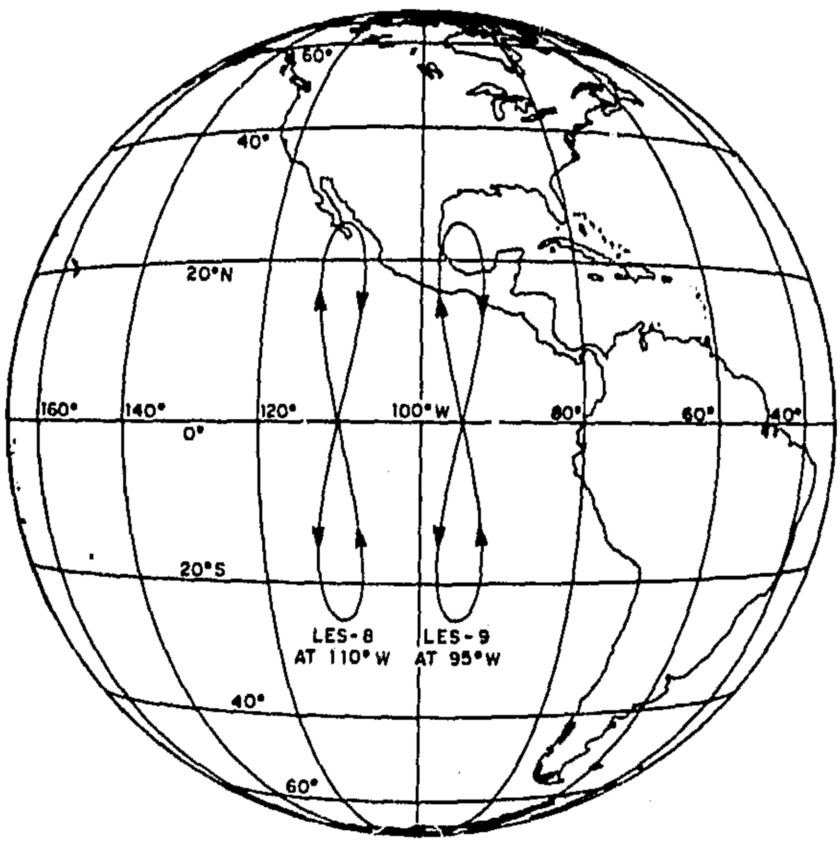

Figure 19. Permanent stations for LES-8/9 (from Ref. 19).

D. Stochastic Effects of Precipitation Satellite Communications

1. Rain as a Turbulent Medium

At frequencies above 15 GHz the diameter of a typical raindrop becomes comparable to the wavelength, and in this frequency domain water is a lossy medium. As a result, both absorption and scattering become significant, and there is substantial attenuation (or extinction) due to rain. Since raindrops are in continual motion due to wind and the dynamics of cloud physics, rain is a spatially and temporally random medium, in other words, a turbulent medium. Investigations of rain effects have, in the past, focused primarily on the averaged effects. The averages are taken over seconds or minutes, i.e., periods which are much larger than the time scale typical of atmospheric effects or that of information-symbol duration. In part, this procedure was justified because the average or bulk attenuation is, of course, a very important consideration. In part, however, the emphasis on the steady part of the signal seems due to the fact that averages are both easier to measure and to calculate than the statistical properties. The misinterpretation, as it seems to us, of such averaged measurement and calculation results has led to a false sense of security that the time-varying effects, especially the phase scintillations, will not affect satellite communications systems seriously until attenuation is already so excessive that other effects are immaterial.

2. Systems Implications of the Randomness of Rain

Some confusion may arise out of the use of the term "averaged" in the discussion to follow. An average over a period of many symbol durations and also over a time period which allows the raindrop positions to change appreciably may require only a fraction of a second. To put it graphically, in terms of a typical strip-chart record, "average" does not imply a level line drawn through the "middle" of the trace; rather, each point on the chart is itself an average as far as a communications system would be concerned. Since many experiments in this frequency range have been performed with CW beacons rather than with actual communications systems, this point is not always appreciated even by propagation experimenters.

The expectation that scintillation effects will be of minor importance, even for systems employing high data rates and wide bandwidths, seems to be based primarily on a lack of appreciation for the role of averaging in available theories and in experiments. A few examples will be given. Although phase-modulated system designs are by far more prevalent, the propagation of pulses will also be considered here, since data on phase modulation is scarce and amplitude and phase scintillations are related.*

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*For example, for clear-air turbulence, Tatarskii showed that the log-amplitude χ and phase S have structure functions related by $D_\chi(\rho) + D_S(\rho) = 0.73\ C_\varepsilon^2\ k^2\ L\rho^{5/3}$. While the same precise law would not be expected to hold for rain, the derivation shows that the interrelationship between amplitude and phase statistics is a general property [5].

An early paper by Crane [27] is sometimes cited as evidence that the atmosphere can "support a bandwidth" of several Gigahertz at carrier frequencies above 10 GHz [28]. The paper deals with coherent pulse transmission through rain, where "coherent" is defined in the paper as the average of an infinite number of identical pulses. In the next section, it will be shown that such an average of many pulses is indeed highly resistant to degradation by atmospheric scintillations, but that the individual pulses are not. Since a reasonable communication system depends on one pulse, or at most a very few, to communicate an information bit, the interpretation of Crane's results in terms of available system bandwidth should be approached very cautiously, in our view. It should be noted that the paper in question modeled the rain as a lossy and dispersive, but time-and space-invariant medium; thus, the very model precluded the calculation of scintillation effects which may affect the "supported bandwidth".

More recent theoretical treatments are based on statistics [29,30], but they are also not fully adequate representations for estimating communications performance. To understand why, we need to contrast the state of the art of rain calculations with that of similar calculations for clear-air turbulence.

In the clear-air turbulence case, the departure point is the structure function, a measure of the spatial correlation of the refractive index [31]. By similarity theory it was shown that this function has a 2/3 power-law, corresponding to a one-dimensional spatial spectrum obeying a -5/6 power law [32]. This spectrum enters into the calculation of the statistical properties of the signal propagating through the medium. From a physical viewpoint, the power law discloses that clear-air turbulence involves eddies with a continuous size distribution, but that the effects of the larger eddies predominate in the atmosphere, with profound effects on the "graininess" in time and space of the received signal.

In contrast, little is known about the structure of rain, and rather severe assumptions are required to obtain analytical solutions. Thus, one paper models rain as a collection of drops of uniform size falling with uniform velocity, with the position of each drop quite uncorrelated with that of other drops [33]. None of these assumptions is representative of the physical situation: the drop-size distribution is known to be more or less exponential [34-36], the velocity is known to depend on the drop size [37], and common experience indicates a marked degree of spatial correlation: if it is raining hard at one location, it is quite likely to be raining hard a few meters away. These comments should not be taken as a criticism of the theory or the paper; at the present state of the art, such crude assumptions are quite necessary in order to obtain any solutions at all. The problem arises when these results are taken by system designers as reliable predictors of actual system performance.

Experimental results are also in need of careful interpretation. Since wide-band satellite signal sources at EHF have been scarce, some experiments have utilized a satellite signal consisting of a carrier and phase-coherently generated sidebands and ground-based receivers which detected these signals phase-coherently [38,39]. The phase dispersion is then calculated from the relative phase differences measured in the various sideband channels relative to the carrier; bandwidths on the order of 1 GHz have been reported. However, it should be noted that the receivers in these experiments integrated the signals over a period on the order of a second. It is not clear how this result should be related to a system which has a bit-rate of, say, 10^8 per second. Substantial phase variations on a time-scale comparable to many bit durations might well average to small variations over the period of a second. In other words, in the absence of good information on the spectra of scintillations due to rain at EHF, it seems risky to base estimates of their effects on measurements which average over periods on the order of a second.

3. Evidence of Systems Effects Due to Rain Turbulence

First, we shall now examine experiments which directly address the points raised in the preceding section.

The ATS-5 satellite failed to despin; consequently, its 15 GHz beacon antenna beam swept across the Earth surface. An Earth-based receiver, therefore, perceived the signal as a train of pulses with the pulse shape determined by the satellite antenna pattern. In order to recover information on the pulse distortion due to scintillations, the following procedure was used at The Ohio State University [40]. First, sets of 40 consecutive received pulses were superimposed in time and averaged to recover the undistorted pulse shape. This shape turned out to be indeed independent of meteorological conditions. The result was then subtracted from each pulse to yield the distortion of that pulse due to amplitude scintillations. Figures 20a to 20c show both the averaged pulses and samples of the individual pulses for clear air, clouds, and hard rain, respectively. The averaged pulse is hardly affected by the rain, but the distortion of the individual pulses by amplitude scintillations is evident. The deviations are much larger than can be accounted for by a simple decrease in signal-to-noise ratio. Thus, the experiment corroborates Crane's theoretical demonstration that the "coherent" (averaged) pulse is highly resistant to degradation, but it also demonstrates that this should not be taken to imply that individual pulses, which carry information, will not be degraded severely.

An interesting experiment, which bears on the bandwidth experiments discussed above, was performed on a ground link in the Washington, D.C. area in 1967-68 [41]. The frequency of transmission was stepped in discrete amounts about a center frequency in the 27-40 GHz range. From the correlation of the amplitudes received at the various frequencies, a bandwidth of at least 6 GHz was inferred for the medium. Data was then transmitted over the same path utilizing DPSK modulation with a 31-bit pseudo-random sequence at a rate of 50 Megabits/second. It was found that the measured bit-error rates greatly exceeded those predicted for a signal in Gaussian noise and that the dependence on carrier-noise ratio was similar to that predicted for a signal in the presence of a weak scattered component. The existence of such effects at a 50 Megabit/sec

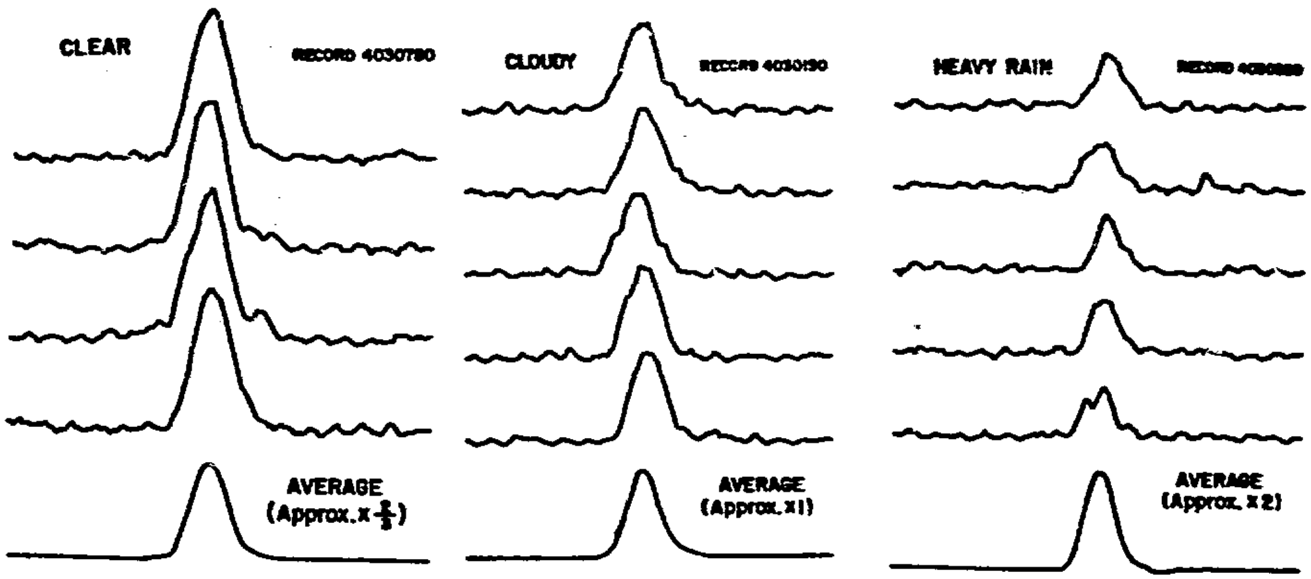

Figure 20. Signal "pulses" received from the ATS-5 satellite as a result of its rotation.

rate casts doubt on the applicability of the "averaged" 6 GHz bandwidth measurement.

The presence of increased amplitude scintillations during rain is familiar to many propagation experimenters at EHF. Figure 21 shows a strip-chart record of amplitude during a rain event; the source was the 28 GHz beacon aboard the Comstar D/4 satellite, and the data was recorded at The Ohio State University. Unfortunately, quantitative digital scintillation data were not taken. This is true of many experiments. The reason is the amount of data required to obtain valid statistical information for a wide variety of rain conditions. In order to end up with a reasonable data volume to be processed, it is customary to average over time periods on the order of a few seconds prior to recording, and the scintillation data is lost in the process.

If phase scintillations of significant amplitude do occur, a knowledge of their spectra under various meteorological conditions will be as important as a knowledge of their statistics because the strategies for overcoming their effects depend strongly on the spectra. For example, if the spectra are highly concentrated toward low frequencies, it should be possible to track the propagation phase changes with a phase-locked loop provided the signal is available continuously. On the other hand, in a time-division multiple-access (TDMA) system, it may be necessary to reacquire phase for each transmission. Therefore, the spectrum of the phase scintillations will be an important factor in deciding to what extent the reacquisition can be accomplished by local phase memory (e.g., a stable oscillator) and to

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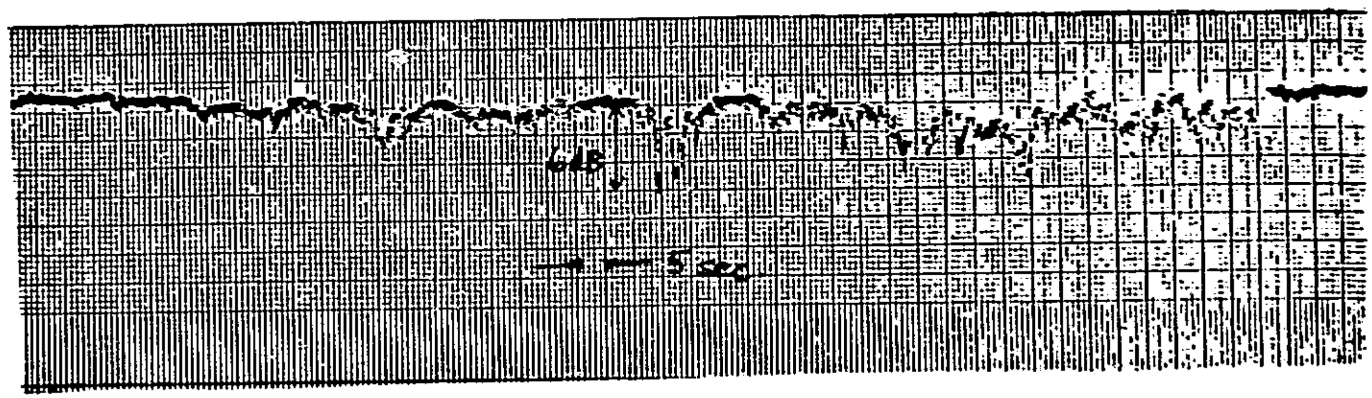

Figure 21. Strip-chart record of Comstar D/4 28.6 GHz beacon signal, showing amplitude scintillations.

what extent the system must depend on other means, such as the transmission of a known code preamble for the purpose of phase reacquisition.

To summarize, there exists substantial evidence that scintillation effects are real, and that system designs may be risky if they are based on theoretical and experimental information which does not take scintillations into account.

4. Preliminary Suggestions for an Experiment

It appears to us, therefore, that a valuable flight experiment would be one in which a known digital bit-stream is transmitted from a satellite and received at earth stations which know the code and therefore can measure the bit-error characteristics, both for continuous reception and for reacquisition simulation purposes. The detailed definition of such an experiment has not progressed beyond this bare concept so far. The performance of the two ongoing experiments, which were linked to the timr of availability of the Comstar D/4 beacon, and the analysis of the data from these experiments were deemed to have priority.

SECTION VIII

CONCLUSIONS

Definite gain changes (up to 2 dB) were observed in the gain degradation experiment. These were magnified by the inevitable mispointing of a non-tracking antenna; they would have been observed at best marginally with a tracking antenna. Translated into equivalent angle-of-arrival variations, these were on the order of 0.02 degrees.

Attenuation inferred from radiometry showed good agreement with that measured directly over an earth-satellite link at 28.6 GHz for summer convective rain. The satellite link was not available for other types of precipitation. Attenuation inferred from single-polarization radar measurements agreed well with that inferred from radiometry for convective rain for which a well-defined bright band was observed. Good agreement could generally not be obtained under other rain conditions and in the presence of sleet and snow.

A significant amount of site-diversity data at 28.6 GHz has been added to the available data base. Alternative definitions of diversity gain are being explored for maximum utility with potential system implementations.

A survey of the site-diversity experimental literature has yielded an improved empirical model by means of linear regression techniques.

A new data acquisition system was required for the ongoing experiments, has been completed, and is operating satisfactorily.

A necessarily brief survey of the very extensive literature on earth-satellite link experiments has led us to propose two areas for experimentation. The first is the development of a radiometrically based instrument for evaluating potential earth-station sites. Satellite sources would be utilized to guide this investigation and verify its results. The second deals with the statistics and spectra of phase scintillations.

SECTION IX

REPORTS

The following reports have been distributed under this contract.

1. Hodge, D.B., An Improved Empirical Model for Diversity Gain on Earth-Space Propagation Paths. [12]

2. Levis, C.A. et. al., Meteorological Factors in Earth-Satellite Propagation: Annual Report, March 12, 1981 to March 31, 1982. [3]

3. Pigon, Brett, A. and Levis, C.A., Radiometrically Inferred Attenuation at 28.6 GHz: Calibration and Initial Results. [11]

Some of the work begun under contract 956013 has been continued under contract 956528. Technical reports reporting on this work and in the process of preparation are:

1. Lin, K.T. and Levis, C.A., Angle-of-Arrival Variation Observations Over an Earth-Satellite Path at 28.6 GHz,

2. Weller, A.E., III and Levis, C.A., A Data Acquisition System for Earth-Satellite Propagation Experiments,

3. Leonard, Richard E. and Levis, C.A., Calculation of the Mean Path Temperature in Radiometrically Inferred Attenuation, and

4. Lin, K.T., Levis, C.A. and Damon, E.K., A Radiometric Path-Diversity Experiment at 28.6 GHz.

SECTION X

NEW TECHNOLOGY

The following may constitute new technology:

Title: Site-diversity receiver utilizing post-detection optimum linear combining of the diversity signals

Innovator: Curt A. Levis

Where reported: This report, page 29

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