EVALUATION OF ELECTRIC CHARGES
INDUCED IN THE ATMOSPHERE

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ABSTRACT

An experiment was conducted to investigate the role played by space charge in the electrification of clouds. Eight and one-half miles of fine wire was suspended 30 feet above the ground and charged to a high potential to introduce artificially produced space charge into the lower atmosphere. Three field observatories and an airplane were used to locate the plume of charge from the wire. A CPS-9 and a TPS-10 radar were employed to study the growth of precipitating clouds in the vicinity of the wire and to determine whether or not they were favorably located for becoming charged. Results of the 1960 tests based upon the small line source were inconclusive with respect to the effect of artificial space charge on radar echoes and rainfall. Further tests are recommended utilizing a larger charge source.

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Certain portions of the data analysis were accomplished by other Water Survey staff members. The statistical rainfall analysis was performed by Floyd A. Huff and the first echo analysis by Don Staggs. Consultations in the fields of cloud physics, statistics, and electronics were given by R. G. Semonin, J. C. Neill, and D. W. Staggs and E. A. Mueller, respectively.

Field personnel who contributed to the field program were J. Machado, W. Dunham, and S. Peery. The pilot for the flights was J. William Bullock.

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OTHER REPORTS AND PAPERS PREPARED


5. "Artificial Cloud Electrification Studies" R. G. Semonin for presentation at the Greater St. Louis Chapter, American Meteorological Society meeting at St. Louis, Missouri, on May 18, 1961.

INTRODUCTION

A preliminary study has been made in cooperation with Dr. Bernard Vonnegut and Charles B. Moore of Arthur D. Little, Inc.,* of the initiation and development of convective clouds which have been inoculated with artificially produced space charge. The analysis of much of the airborne data on days with small cumuli will be reported on by Vonnegut, Moore, and others, as listed under the section entitled, Other Reports and Papers Prepared. Results of the analysis of data on days of precipitation which was the prime purpose of the grant are presented in this report.

The mechanisms by which clouds and the atmosphere become electrified are not understood. There is a close association, however, between cloud electrification and precipitation, as all clouds which have an appreciable electric field seem to contain precipitation echoes and to produce rain. Gaston Grenet(1) in 1947, and

*Support for the operation of the energized wire and analysis of data undertaken by the cooperators was made possible through contract NONR 1684 with the Office of Naval Research.
Bernard Vonnegut(2) in 1953, Independently suggested that the accumulation of charge in a cloud is brought about by the transport of charged particles in the convective movements of the cloud, and that the process could be initiated by the fair-weather space charge residing on nuclei in the air beneath the cloud. The Illinois State Water Survey was Invited to participate in the evaluation of this hypothesis, because it had radar equipment available for research and had been studying the natural variability of rainfall for the past 10 years with dense raingage networks.

The evaluation of the effect of induced space charge on clouds was based on data from two major sources, radar and raingages, with supporting data from other sources. It was hypothesized that if the space charge initiated a process which induced precipitation in a cloud that would not naturally precipitate, or caused the formation of precipitation to occur before it ordinarily would have, then the frequency of "first echo" formation downwind from the wire should be greater than the frequency upwind -- and possibly the amount of, rainfall downwind would be greater than the amount upwind. For this paper we define a "first echo" as the initial appearance of a precipitation echo on the CPS-9 radar. Radars were used to compare the frequency of echo formation upwind and downwind from the wire. They were also used to compare the growth, both vertical and horizontal, of echoes that developed over the wire with the growth of those that developed away from the possible influence of the wire. Raingages were used in both the individual case studies and the statistical analysis of the space charge effects on the initiation and quantity of rainfall in the raingage network. An approximate location of the plume of charge from the wire was determined from surface and upper wind measurements for each storm analyzed. The average rainfall downwind of the wire was compared with that in unaffected areas of the raingage network.

INSTRUMENTATION

The experiment was directed from the Illinois State Water Survey's Meteorology Laboratory at the University of Illinois Airport, 6 miles south of Champaign, Illinois. Radar surveillance of the energized area was accomplished at the laboratory by a CPS-9 and a TPS-10 radar, each equipped with a 35-mm camera. The CPS-9 radar with PPI presentation was programmed to scan automatically over 360 degrees from 0 degree to 11 degrees of elevation at 1 degree intervals. During some situations, relative intensity measurements were also made at various elevation angles. The TPS-10 radar with an RHI presentation generally scanned a sector from 200 degrees to 360 degrees centered about the wire. Unfortunately, technical difficulties severely limited the amount of RHI data collected.
The field program was set up, under the direction of Dr. Vonnegut and staff, 30 miles west of the laboratory where 8 miles of wire was suspended 30 feet above the ground in two nearly equal and mutually perpendicular sections as shown in Figure 1. Three observatories were established near the wire: one 3 miles north (N), one 4 miles east (E), and one 2 miles south (S). Each site was equipped with an "all-sky" time lapse camera and instrumentation to record continually the potential-gradient and surface wind speed and direction. The "all-sky" camera consists of a 16 mm camera mounted above and directed toward a spherical convex mirror which reflects the entire sky. A fourth site, the power station (P), located at the north end of the wire, furnished a continuous record of current output to the wire, in addition to the surface wind speed and direction. A Faraday cage at Observatory N measured space charge during part of the study period, balloons (PIBALS) were released from the power station to determine a vertical profile of the wind speed and direction. On several occasions a portable meter was used to measure the potential gradient at a number of locations in the vicinity of the wire. The wire and the observation sites were situated in the southern half of the East Central Illinois Raingage Network, a 400-square-mile network of 49 recording raingages operated by the Illinois State Water Survey.

An example of the influence of space charge on small cumulus clouds is illustrated in Figure 2. Aircraft measurements were made of the potential gradient over the top of three similar clouds at the same geographical location. The cloud at the top of Figure 2 shows an enhanced positive potential gradient on top of the cloud which indicates a concentration of negative charge below the aircraft. The wire was emitting negative charge at this time. A short time after the power was turned off a similar cloud was examined. As shown in the center of Figure 2, these measurements indicated essentially fair-weather potential gradient values of approximately 0.2 to 0.5 volts per centimeter. The wire was then energized positively and a subsequent observation on top of another cumulus showed a concentration of positive charge below the aircraft, as shown at the bottom of Figure 2. Equipment used to measure the potential gradient and space charge is described by Vonnegut and Moore.(3,4)

Examination of the flight data has revealed at least one case where a growing cumulus exhibited electrical properties in agreement with the Vonnegut hypothesis. The wire was emitting negative charge during the time of the flight. It appeared, from the sequence of events, that negative charge was convectively conveyed into the cloud from the wire and a short time later showed a large concentration of positive charge, as illustrated by an enhanced positive potential gradient beneath the cloud. Simultaneously with the observation of a developing positive gradient, light rainfall was observed falling from the base of the cloud.
FIG. I LOCATION OF ENERGIZED WIRE, RADAR, RAINGAGES AND OTHER INSTALLATIONS, 1960
FIG. 2 AIRCRAFT MEASUREMENTS NEAR CHARGING CLOUDS ON JULY 28, 1960
THE PLUME OF CHARGE

The location of the plume and its charge concentration were dependent upon the charge output of the energized wire and upon the atmospheric motions carrying the low mobility ions. Most of the flights indicated that the charge from the line was transported by these motions much like the effluent of a continuous line source of smoke. In regions of convections, the charge was carried aloft into different horizontal wind regimes. On some occasions, the horizontal winds at cloud level and the surface winds were from the same direction and locating the plume of charge was an easy task. The analysis became more difficult, however, when the two winds were from different directions. During periods of considerable convective activity it could not be determined with certainty whether the charge was immediately conveyed aloft near the wire and carried in one direction or carried in a different direction by the surface wind before it was conveyed into a cloud. This situation introduced an element of uncertainty into some of the case studies where precipitation was involved.

The second factor in determining the area of influence of the wire was the fact that, as the charge drifted downwind from the wire, its concentration diminished as it became diffused. The charge could be detected by the airplane from 1 to 8 miles downwind, and on occasion, up to an altitude of 5000 feet. The area of influence then depended on how diffused the charge could be and still be effective.

A typical example of how the fair-weather potential gradient was affected by the artificial space charge downwind of the wire is shown in Figure 3. At 0930 CST on August 18, the surface wind was from the ESE and none of the space charge was passing over Observatory N. At 0938 GST the wind shifted to the south and a few minutes later the potential gradient at Observatory N began reversing and reached a minimum of nearly -4v/cm. At 1158 CST the wind changed to the SE and the potential gradient soon became positive again. The magnitude of the reversal was probably dependent upon, among other things, whether the charge passing overhead was from the north leg of the wire 3 to 5 miles from the observatory or from the east-west leg over 5 miles from the observatory. One of the largest reversals definitely produced by the wire was noted on August 14 when the potential gradient reached nearly -6v/cm at Observatory N. Although readings of -3v/cm were not uncommon at Observatories N and S, readings of -1 or -2v/cm were more typical at Observatory E, 4 miles from the wire, when the wire was emitting negative charge.

It was not known how much artificially produced space charge must be carried into a cloud before the charging mechanism could
FIG. 3 INFLUENCE OF ENERGIZED WIRE DURING CLEAR SKY CONDITIONS ON AUGUST 18, 1960. WIRE ON NEGATIVE CHARGE OUTPUT
operate independent of the wire, or how large the cloud must be to support the mechanism. The amount of charge actually conveyed into the cloud depended upon at least four variables: the amount of charge available from the wire, the area of convective influence of the cloud, the vigorousness of the cloud's updraft, and the length of time the cloud was over the charge source.

OPERATIONS

The wire was operated continuously 24 hours a day from June 11 to September 1, except when it was automatically shut off by the relatively strong electrical fields of approaching storms, or when there were technical difficulties. Negative space charge was produced for most of the summer except for about 15 days when the polarity was reversed; however, during all of the cases discussed in this text the wire was on negative charge output. It was assumed that if positive charge was emitted from the wire, clouds conveying in the charge would form with normal positive polarity, that is, positive top and negative bottom; if negative charge was emitted, clouds forming over the wire would develop a negative polarity. The wire was operated on negative polarity most of the time because the charge output was slightly higher than on positive, and because it was presumed that if a cloud was of negative polarity it would be more easily distinguished from naturally charged clouds.

Normally, radar data collection started about 0830 CST, after a daily briefing meeting, and continued to 1630 CST, at which time it was stopped unless some interesting observations were in progress. On days when the forecast indicated no possibility for cumulus development, the radars were not operated. All field data were collected 24 hours a day, except for the "all-sky" cameras which operated only during the daylight hours. The aircraft was used for potential gradient and space charge measurements in clear air and in the vicinity of fair-weather cumulus on approximately half of the days during the season. Fifty-three flights, as shown in Appendix A, were made in the course of the investigation.

WEATHER CONDITIONS DURING 1960 SUMMER

In general, weather conditions during the 1960 summer were not ideal for the electrification experiments. The month of June was quite cool and wet as numerous squall lines crossed central Illinois. There were 16 days having .01 inch or more of precipitation and thunderstorms occurred on many of these days. July was
also cool but very dry as northerly winds prevailed and skies were clear on 17 days. August was characterized by above normal temperatures but quite dry. It was the third driest August in 60 years at Urbana which recorded 6 days of .01 inch or more precipitation. However, the central raingage of the East Central Illinois Raingage Network recorded precipitation on 9 days. Many of these situations are illustrated in the case study section.

Studies of monthly rainfall maps may often be quite misleading since one storm can greatly affect the monthly precipitation pattern. This is readily illustrated in the section on precipitation analysis. Most of the rains in July and August occurred at night when intense natural electrical fields were present, which automatically shut off the energized wires. However, six rainshowers occurred in August during the period of maximum convection and when the line was energized. The composite rainfall pattern for these six storms shows the maximum rainfall to be generally northeast of the wire. However, detailed study of each individual case would not support the suggestion that there was always a preferred downwind location for greater rainfall, since the storms varied in movement from SW to NW. Other data collected by the Water Survey indicated that there was little hail and no severe windstorms in the area downwind of the energized wire during the operational period.

CASE STUDIES

Individual case studies were made for all dates on which there were small to moderate sizes of radar echoes in the immediate vicinity or downwind of the wire. A few cases of larger weather systems, such as squall lines, were also investigated. New echoes often formed near the wire but it was generally believed that the space charge produced by the wire was insignificant compared to the natural electrification present. The complexity of such situations makes it difficult to ascertain whether electrification was the result of natural conditions or space charge from the wire.

Whenever a small echo passed near or formed near the wire, a study was made to determine if the echo-producing cloud could have been inoculated with artificially produced charge. This was determined by analyzing the surface winds and winds at cloud level. When it was decided that there was a chance the cloud might have been inoculated, a study was made of rainfall from the cloud with respect to the wire. The "all-sky" cameras were helpful in detecting showers too light to register on the raingages and for determining the direction of cloud movements. The potential gradient meters gave an indication of the electrical activity in the clouds. Often, however, it was not possible to determine whether a perturbation in the potential gradient was due to the presence of an electrified cloud overhead, or to space charge between the cloud and earth.
Por all the case studies, a series of PPI radar traces were made showing the positions of the echoes relative to the wire. These traces were studied for changes in area after possible inoculation with charge. Unfortunately, the operation of the RHI radar was sporadic because of mechanical difficulties, but RHI data were collected for a few showers and comparisons were made of echo heights before and after inoculation. Figure 4 is an example of the radar photos of the wire area. The portions of concentric circles are 20-nautical-mile range markers. The canted box is the raingage network with the "T" shaped energized wire enclosed. All radar photos were taken at 1 degree antenna tilt unless otherwise indicated.

July 23, 1960

At 1500 CST on July 23 a thunderstorm was 30 miles north of the wire. By 1700 CST it had reached the northern edge of the raingage network, 15 miles from the wire, as shown in Figure 4. The storm was moving very slowly, but new echoes forming around the edges of the main echo propagated the rainfall southward. The surface winds and the winds aloft in the vicinity of the wire were both light. The wire was emitting negative charge.

At 1709 CST an echo formed near a raingage which recorded 1.59 inches of rainfall about 4 miles NKE of the wire (Fig. 5). Prior to this time the potential gradient at Observatory N was rapidly fluctuating between .5 and 2v/cm which indicated lightning in the nearby storm. When the echo formed over gage #18 the potential gradient at Observatory N gave off-scale deflections of both polarities (fluctuations greater than ±2v/cm). The Observatory N "all-sky" camera showed a large cumulonimbus forming overhead, accompanied by rain. At 1723 CST the wire was automatically shut off by the large natural electrical fields.

The interesting feature of this storm was the 1.59 inches of rain that fell on raingage #18 as shown in Figure 5. The question was, did the wire influence the formation of this isolated precipitation high? Apparently, charge from the wire could not reach the center of maximum precipitation, since the surface winds and the horizontal winds to 400 mb were light due to the flat pressure gradient over central Illinois. Other rains of similar intensity were recorded within 70 miles. There is no direct evidence that the wire caused or influenced the storm that formed over the network.

July 24, 1960

At 1300 CST on July 24, a slow-moving line of echoes formed 4 miles south of the raingage network, and moved slowly northward at 5 knots. The surface winds at Observatory N were from the west
FIG. 4  RADAR FOR JULY 23, 1960

20 NAUTICAL MILE RANGE MARKS
FIG. 5 RAINFALL OF JULY 23, 1960, BETWEEN 1300-2100 CST
at 3 knots until 1330 CST, when they shifted to the NW at 2 knots. At 1330 CST echo #9 was approaching the southern end of the wire (Fig. 6) and, at about the same time, its top collapsed (Fig. 7). There is a possibility that the negative charge may have reached #9 by the time it collapsed.

At 1350 CST the potential gradient at Observatory S began reversing and, by 1400 CST, it reached an off-scale value of more than −2v/cm. The reversal indicated that the cloud which produced echo #11 was of positive polarity, contrary to what would have been expected had the charging processes been initiated by negative space charge from the wire. The potential gradient at Observatory N remained negative until 1440 CST when it increased to greater than +2v/cm for about 8 minutes and then reduced to 1v/cm.

At 1400 CST echoes #6 and #8 were approaching the wire. Echo #8 soon began to collapse and was dissipated by 1420 CST. Echo #6 merged with #7 and later dissipated.

With the close spacing of the echoes in this storm, and the relatively distant spacing of the potential gradient meters, it was not possible to ascertain much about the electrification of the clouds producing the echoes. In this case, the smaller echoes showed a tendency to dissipate when in close proximity to the wire.

August 6, 1960

On August 6 local showers were scattered over the state. At 1330 CST the winds were at 2 knots from the west over the raingage network. Figure 8 shows several radar echoes passing to the south of the hot wire which was emitting negative charge. There were no fluctuations in the potential gradient at Observatory S as the echoes passed over, but immediately afterwards the fair-weather gradient tripled for a few minutes. No rain was recorded on the raingages, but a light sprinkle fell on the Observatory S all-sky camera. The echo analysis revealed no significant change in the height or size of the echo that passed over the charge source.

Forenoon of August 7, 1960

On the morning of August 7 at 0900 CST the surface winds were southwesterly at 2 knots at Observatory E. At 0905 CST five radar echoes formed southwest of the wire and moved EKE at 25 knots (see Fig. 9). Their average maximum height was about 13,000 feet. Echoes #3, #4, and #5 passed south of the wire where #4 and #5 merged. Echo #1 never did develop, for soon after formation it could not be seen on zero-degrees antenna tilt. It persisted for 20 minutes and then, after passing over 2 miles of the wire, dissipated. Echo #2 began developing well, like #3, #4, and #5, until it came to the wire. It then dissipated to about one-third
FIG. 6  RADAR FOR JULY 24, 1960

20 NAUTICAL MILE RANGE MARKS
FIG. 7  ECHO HEIGHTS, JULY 24, 1960
FIG. 8 RADAR FOR AUGUST 6, 1960

FIG. 9 RADAR FOR AUGUST 7, 1960

20 NAUTICAL MILE RANGE MARKS
of its original size and remained that way. This case would also indicate that negative charge from the wire may have had some dissipating effect.

Afternoon of August 7, 1960

On the afternoon of August 7 at 1450 CST, several echoes formed from 5 to 15 miles west of the wire and moved toward the wire at 20 knots, as shown in Figure 10. The surface winds were from the WSW at 7 knots.

Negative charge from the wire was drifting over Observatory E and producing electrical field as large as \(-4\) v/cm. The same type of clouds drifting over Observatory S remained uncharged and were not producing reversals.

The CPS-9 radar was used to determine roughly the growth rate of the echoes. The echoes initially formed at about 5000 feet, but by the time they reached the wire the larger ones had tops to 10,000 feet. No change was noted in the heights of echoes #1 and #3 as they passed over the wire, but light precipitation fell from echo #1 at Observatory E. Echo #2 formed 4 miles downwind of the wire over Observatory E. However, it produced no perturbation in the potential gradient which was still slightly negative. An effort was made to see if #2 was of opposite electrical polarity to those which formed upwind, but the fluctuations in the gradient could not be correlated directly with the passing of clouds over the observatory. This case represents a situation in which random distribution of space charge between the cloud bases and the ground was recorded. Only one echo passed over the wire and no change in character or intensity was noted on the radar record.

August 9, 1960

On the morning of August 9, radar echoes formed 7 miles southwest and 4 miles north of the wire. Later, an echo which appeared to be dissipating, Figure 11, passed over the wire and produced rain at the Observatory E "all-sky" camera. The potential gradient at Observatories N and S was about \(+.8\) v/cm, but there was a small reversal for nearly two hours at Observatory E caused by negative charge from the wire. The cloud that produced the shower did not affect the reversal, however. From the radar it appears that this was a nearly stratified-type echo and probably not very convectively active. No change appeared in the echo. Further downwind, a second echo formed and can be seen 10 miles east of the wire.

August 18, 1960

At 1230 CST on August 18 there was a N-S line of echo activity
FIG. 10  RADAR FOR AUGUST 7, 1960

FIG. 11  RADAR FOR AUGUST 9, 1960

20 NAUTICAL MILE RANGE MARKS
50 miles west of Champaign. This line was moving northward at 30 knots. Figure 12 shows that another N-S line of scattered cells was forming east of the major line, along the eastern half of the raingage network. The surface winds were from the WSW at 10 knots. The raingage rainfall map, Figure 14, shows that most of the rain fell in the eastern half of the network with the high located ENE of the wire.

However, at 1300 CST the potential gradient at Observatory E began increasing in the positive direction until 1325 CST when it suddenly reversed off scale at -2v/cm. At 1400 CST the gradient reduced to a value below instrumental saturation and showed a jagged trace, as it did before it reversed, indicating lightning in the vicinity. The large reversal resembled the type associated with the approach and passage of a cloud of positive polarity, and since the cloud did not develop in the wire area, it undoubtedly became charged naturally. The amount of negative charge which the cloud may have encountered from the line was probably not comparable to the natural charge present. Consequently, it is difficult to see how the wire could have been an influential factor in the formation of the rain.

August 21, 1960

On August 21 an echo, as shown in Figure 13, passed by the northern tip of the wire moving at about 15 knots. Rain fell from the cloud; a trace of precipitation was indicated at gage #26, and .01 inch fell at gage #27, EKE of the wire. No "all-sky" camera data was available from Observatory N so it is not known whether it sprinkled there or not. The potential gradient at Observatory N dropped to two-thirds of its fair-weather value as the echo passed over.

Prior to 1429 CST when the echo passed by the wire, the winds were light at 3 knots and were varying from 250 degrees to 300 degrees. It seems likely that the southern tip of the cloud mass may have been inoculated with negative charge, but it is unlikely that the rest of it was.

The growth and decay of the echo was studied with the TPS-10 radar. The average height of the echo was 10,000 feet with maximum turrets at 14,000 feet. Structurally, it was composed of several individual cells in close proximity. The maximum height of the echo in each of six or seven east-west cross-sections was recorded and plotted for 2-minute intervals over the nearly hour-long life of the echo. This analysis gave data to determine whether or not there was any significant difference in height between the southern and the northern portions of the echo.
FIG. 14 RAINFALL OF AUGUST 18, 1960, BETWEEN 1200-1830 CST
More often than not, the southern portions of the echo were higher than the northern portions. However, this difference was present before the echo reached the wire as well as afterward. The echo as a whole reached and maintained its maximum height about 6 minutes before it reached the wire and, thereafter, remained one or two thousand feet lower, until it decayed. The significance of this reduction in height is questionable primarily because, as mentioned before, it seems doubtful that the cloud as a whole could have become charged. Regardless of the cause, the cloud evidently reached a mature state by the time it passed the wire, because it produced rain soon afterward and later dissipated.

August 29, 1960

On the morning of August 29 the surface winds at the wire were from the west at 4 knots. At 1140 CST about 10 echoes formed within 12 miles of the wire (see Fig. 15). Their tops reached 15,000 feet. Half of these echoes were weak and could not be seen at zero degrees antenna tilt. Most of them dissipated within 30 minutes but the largest echo of those remaining, echo #1, passed over the wire at about 25 knots. Ten minutes after it passed the wire, its area and intensity decreased to about half of what they had been previously. A smaller echo, echo #2, whose bottom did not reach the ground, preceded the large echo over the wire. It dissipated at the same place that the larger one reduced in intensity. Again it appeared that, if anything, the negative space charge released from the wire was having a dissipating effect on the echoes that passed over it.

Summary of Case Studies

The analysis technique employed in the case studies was designed to detect any gross change that may have occurred in small echoes that passed over or near the wire. For the most part, squall line situations were not studied because of the pre-existence of intense natural electrification. In several of the case studies it appeared as if echoes from clouds which may have had the opportunity to convey in space charge, dissipated. However, because of the limited number of echoes involved, it was not possible to determine the probability of the echoes dissipating naturally. There was no indication of an increase in size or number of first echoes or in rainfall downwind of the wire. It is suggested that studies involving a larger source of charge should be pursued in the future to allow more clouds the opportunity of acquiring more charge. Secondly, airborne measurements should be made of the atmospheric electrical variables around large cumulus clouds in the vicinity of the wire to determine the extent of cloud electrification.
FIG. 15  RADAR FOR AUGUST 29, 1960

20 NAUTICAL MILE RANGE MARKS
FIRST ECHO ANALYSIS

As a further study in first echo origin, all the radar data was examined, including rainfall situations that were not selected for case study. The portion of the CPS-9 radar film from an azimuth of 200 degrees to 360 degrees between the 15-mile and 40-mile range markers was examined for the periods of time when the wire was energized. The location of each first echo was determined and plotted as in Figure 16. It should be noted that the data is biased against first echoes from large storms near the wire because, when such a storm approached the wire, the wire was automatically shut off, and further data on that particular storm was subsequently eliminated.

It is evident from Figure 16 that there was not an increase in first echo activity in the immediate vicinity of the wire. This first echo presentation, however, does not discriminate between echoes upwind and downwind from the wire and, therefore, would not necessarily disclose an anomaly that consistently appeared several miles downwind. Further studies which did include the wind direction did not reveal a downwind anomaly.

RAINFALL STUDY

Although the rainfall maps for the case studies give an indication of the distribution of rainfall in the vicinity of the wire, a monthly and seasonal rainfall study was made to compare the rainfall downwind of the wire with that in the surrounding area. The significance of the variations in rainfall upwind and downwind from the wire are discussed in their relation to the natural time and spatial variability of rainfall and their statistical significances.

The natural variability of rainfall in time and space presents a difficult problem whenever rainfall data are employed in the evaluation of cloud modification experiments. The problem becomes especially acute when modification efforts are concentrated on convective precipitation, and when experiments are restricted to a relatively short sampling period of several years.

Huff and Neill have provided considerable quantitative data on the spatial variability of storm rainfall in convective activity, but little data were available on the time and space variability of monthly, seasonal, and annual precipitation at the time the energized wire experiments were initiated in the summer of 1960. Subsequently, studies have been undertaken to evaluate natural variability on a monthly and seasonal basis, with emphasis on the May through September period. These studies have not been
FIG. 16 LOCATION OF FIRST ECHOES - 1960
completed, but certain phases are discussed in the following paragraphs to illustrate the magnitude of the natural variability.

**Time Variability**

Figure 17 shows the frequency distribution of rainfall for the May-September period at a point near the center of the East Central Illinois Raingage Network. This distribution is based upon data for the 50-year period, 1906-1955, collected at cooperative stations of the U.S. Weather Bureau in this region. This frequency curve also provides an estimate of the distribution of areal mean rainfall for the 400-square-mile network, since other studies have shown that the relation between the frequency distribution of point and areal mean rainfall converge rapidly as the length of time incorporated in each observational period is increased. Figure 17 shows that, on the average, the May-September rainfall will equal or exceed 23.0 inches during 20 percent of the years and 29.0 inches during 5 percent of the years. These correspond to increases of 24 percent and 56 percent, respectively, above the normal of 18.5 inches. Viewing the above statistics in another manner, there is one chance in five that an observed May-September rainfall of 24 percent above normal in any given year on a cloud modification target area in central Illinois was due entirely to natural causes, and one chance in 20 that an increase of 56 percent was due only to natural year-to-year variability.

Similar curves for other time periods show that the value at the 5 percent level (one chance in 20) decreases from 56 percent for one year to 36, 28, 21, and 13 percent for 2, 3, 5, and 10 consecutive years, respectively, when based upon May-September rainfall totals. These statistics illustrate the extent to which the effect of the natural time variability in convective rainfall may be minimized by increasing the experimental sampling period.

**Space Variability**

Comparison of the rainfall between target and control areas during a sampling period is the most common method employed in evaluating cloud modification effects on surface rainfall. In this method the natural spatial variability of rainfall is of prime importance. Several analyses are underway to obtain quantitative information on spatial variability under convective conditions in central Illinois. Data on point and areal mean rainfall variability in the 49-gage East Central Illinois Network are being studied, along with point differences between stations with long-term records in the U.S. Weather Bureau Climatological Network.

As one phase of this study, the East Central Illinois Network of 400 square miles was divided into four areas of 100 square miles each. Deviations in areal mean rainfall among the four areas for
the May-September period during 1955-1960 were then compared. The
four areas were divided into various combinations of pairs, assuming
one to be the target area and the other to be the control area. This
procedure provided six independent sets of target-control areas
for each of the six summers or a total of 36 observations. The de-
vviations were expressed in percentages by subtracting the control
area rainfall from the target area total and dividing by the control
area amount. These percentage deviations were then fitted to a fre-
quency distribution, the assumption being made that the 36 samples
over the 6-year period provided a suitable estimate of the popula-
tion distribution. In view of the relatively short sampling period,
the results can only be considered a rough estimate of the true fre-
quency distribution. The calculated frequency distribution gave
values of 19 percent at the 5 percent probability level and 13 per-
cent at the 20 percent probability level. Thus, the results indi-
cate that in a given year there Is one chance in 20 that an increase
of at least 19 percent of target over control rainfall may be ex-
pected for the May-September period within 100-square-mile areas due
to natural spatial variability; there Is one chance in five that an
increase of at least 13 percent may occur in the target area due to
natural variability.

Similar comparisons of target-control differences were made;
between points located at the center of each Of the four areas of
100 square miles. Results indicated values of 36 and 25 percent,
respectively, at the 5 and 20 percent probability levels. These
values are about twice as great as those for the mean rainfall
over areas of 100 square miles, illustrating the desirability of 
areal comparisons In cloud modification experiments.

Other measures of spatial variability, based upon the dense
raingage network, are illustrated in Figures 18 and 19. Figure 18
shows area-depth relations on the network for total rainfall during
May through September in the 6-year period. An area average of
104 inches for the 6-year period is shown. However, over an area
of 25 square miles within the 400 square miles, the average rose
to 112.3 inches or 108 percent of the areal mean. Long-term rain-
fall records indicate that the normal rainfall varies by less than
2 percent within the network.

Figure 19 shows a cross-section of May-September rainfall for
1955-1960 extending from the southwest to northeast corners of the
400-square-mile network. Amounts varied from 99 to 115 inches
along this cross-section during the 6-year period, and resulted in
a ratio of 1.16 between maximum and minimum amounts. These data
further emphasize the great spatial variability in convective rain-
fall, even when integrated over a sampling period of several years.
FIG. 17 FREQUENCY DISTRIBUTION OF MAY-SEPT RAINFALL

FIG. 18 AREA-DEPTH RELATION, MAY-SEPT, 1955-60

FIG. 19 SW-NE CROSS-SECTION OF MAY-SEPT. RAINFALL, 1955-60
Analyses of 1960 Summer Rainfall

Although the number of experiments of electrifying clouds was small and the sampling period relatively short, a comparison was made of rainfall within the plume of the charge area of the energized wire and the rainfall recorded in the raingage network outside the plume area. For this analysis the plume area was determined in still another way. The cross-sectional area of the wire perpendicular to the surface wind was projected downwind a distance equal to that traveled by the surface winds in twenty minutes. Then, using the wind at cloud level, the surface wind projection was itself projected to the edge of the network,. The combination of both areas constituted the plume.

Because of data limitations, analysis was restricted to comparison of monthly and seasonal mean rainfall within and outside of the plume area on the network on days during which the energized wire was in operation and to comparison of the number of storms in which the target and control areas ranked first in mean rainfall. Comparison of rainfall extremes could not be made without restricting the target and control zones to the same size, and this was not done in this preliminary study because of analysis complications involved with the change in target size (plume area) from storm to storm.

Results of the analysis, summarized in Table 1, show that the average rainfall outside of the target area (plume) exceeded that in the target area in all three months by differences of 5 to 40 percent. For the 3-month period, the control-target difference was 14 percent. Also, the control area ranked first in the number of times that each area had the greatest mean storm rainfalls the control area had the greater mean storm rainfall 14 times compared to 6 times for the target area.

The 1960 experiments indicate that no increase in surface rainfall resulted from the electrical charge introduced into clouds over the raingage network. However, the number of samples was too few and the sampling period too short to reach reliable conclusions on the effects of the energized wire experiments. All that can be concluded is that the 1960 experiments did not produce any large-scale effects upon the surface rainfall in the target area. Future experiments may produce different results.
TABLE 1

COMPARISON OF RAINFALL WITHIN AND OUTSIDE PLUME AREA ON EAST CENTRAL ILLINOIS NETWORK, JUNE-AUGUST, 1960

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<td>Average rainfall outside of plume (inches)</td>
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<td>6(3)*</td>
<td>14(11)*</td>
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( )* Excluding days when network average was trace

CONCLUSIONS AND RECOMMENDATIONS

Neither the case studies, the first echo analysis, nor the rainfall study indicated any gross increase in first echoes or rainfall downwind of the wire. In the case studies, it was found that occasionally echoes had a tendency to dissipate as they passed over the wire. The first echo analysis revealed no first echo anomalies in the wire's vicinity. The rainfall analysis indicated 5 to 40 percent less precipitation downwind from the wire, but the sample of data was too small to assign statistical significance to the fact.

It is recommended that in the future the wire be lengthened to allow more clouds the opportunity of becoming charged and to increase the amount of charge available per cloud. Also, the electric field and space charge in the vicinity of a charging cloud should be more thoroughly investigated with aircraft.
BIBLIOGRAPHY


### APPENDIX A

**Research Plights in Tri Pacer 8845D**

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APPENDIX A (cont'd)

Research Plights in Tri Pacer 8845D

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*Crew Listing - All Plights Piloted by J. Wm. Bullock*

CM - Charles Moore  
GES - Glenn E. Stout  
BV - Bernard Vonnegut  
DS - Donald W. Staggs  
HH - Homer Hiser  
WB - Wayne Bradley  
SP - Stanley Peery  
RGS - Richard G. Semonin  
MC - Marcel Kates

LQ - Louis Quam  
AT - Arthur Tuveson  
RE - Ralph Eldridge  
EAM - E. A. Mueller  
DP - D. Palmbaum  
RK - R. Keeler  
EL - Eugene Laska  
NL - Nero Lindblad  
DG - Dr. Gottlieb