

Electromagnetic Noise Studies of Severe Convective Storms in Iowa : The 1970 Storm Season

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ABSTRACT

Electromagnetic noise from six convective storms in Iowa has been studied at a variety of frequencies from 0.67 to 144 MHz, with the majority of the data being recorded at 53 MHz. The quasi-static atmospheric electric field was also studied. Twelve tornadoes, numerous funnel clouds and several hailstorms occurred during these storms. Eleven of the tornadoes appear to correlate with some type of enhancement of the recorded electromagnetic pulse rate. A spectacular peak in pulse rate during Storm No. 5 is attributed to a brief but destructive tornado at 38 km; the event is discussed in detail. One tornado at long range, the longest lived of the season, showed no correlation and is thought to represent a minority class of tornadoes which exhibit little electromagnetic noise generation. Good time correlation is also achieved between data events and several hailstorms and funnel clouds. Except for the closest events (<20 km), the region above 1 MHz appears to be a better indicator of tornadic activity than that portion of the radio spectrum below 1 MHz. The data also reveal a number of pulse-rate peaks which could not be correlated with known severe weather events.

Four and possibly five types of radio noise observed from severe storms are described, along with some initial suggestions about the possible mechanisms involved. The lack of understanding of the basic physics involved is indicated and the need for more observational data is emphasized.

1. Introduction

Our interest in the study of radio noise from severe local storms was originally stimulated by reports that tornadoes could be detected by the use of a television receiver [see, for example, Waite and Weller (1969)]. The most straightforward interpretation of such an effect is that unusual radio noise pulses in the very-high-frequency (VHF) region of the spectrum were being emitted by the storm. We decided to embark on an experimental investigation of electromagnetic pulses generated by severe storms, to determine, if possible, answers to the following questions:

- 1) Does some fraction of tornadoes and/or other severe weather events (such as hailstorms, windstorms, etc.) in fact produce electromagnetic radiation of different character than that of ordinary thunderstorms?
- 2) If so, in what ways is the radiation different (power spectrum, pulse rate, polarization, etc.)?
- 3) What fraction of tornadoes does not emit such characteristic radiation?
- 4) What fraction of events would be false indicators of severe weather?
- 5) What is the physics of the phenomena?

Accurate answers to the above questions can only be ascertained after studying a large number of severe weather events. In this paper, we present the results of our study of six severe convective storm systems that

occurred in Iowa during the 1970 storm season. While this season produced only about half the usual number of tornadoes in Iowa, at least twelve tornado events occurred, along with a number of reported funnel clouds and several intense hailstorms during the storms for which we were able to record and study radio noise. The present paper provides results which, while they are only one season's studies and thus cannot give complete answers, are a serious initial attempt at a more quantitative understanding of the phenomena.

Several good review articles have appeared on the investigation of general radio noise from thunderstorms (Horner, 1964; Pierce, 1969; Uman, 1969). Thunderstorms producing tornadoes often display unusually intense lightning. A number of authors have discussed the electrical effects associated with tornadoes (e.g., Wilkins, 1964; Silberg, 1966; Brook, 1967; Colgate, 1967; Vonnegut and Weyer, 1966). While a great number of articles exist in the literature concerning electromagnetic noise generation at very low frequencies (i.e., near 10 kHz), it has been shown that storm noise energy in this region of the spectrum is due primarily to large-scale electrical strokes (for example, the cloud-to-ground stroke), and is not as good an indicator of tornadic activity as higher frequencies. Jones (1951, 1959) studied tornadoes at 10 and 150 kHz and found during most of the events he observed that the higher frequency was the better indicator of such activity. Kohl (1962) and Kohl and Miller (1963) observed an

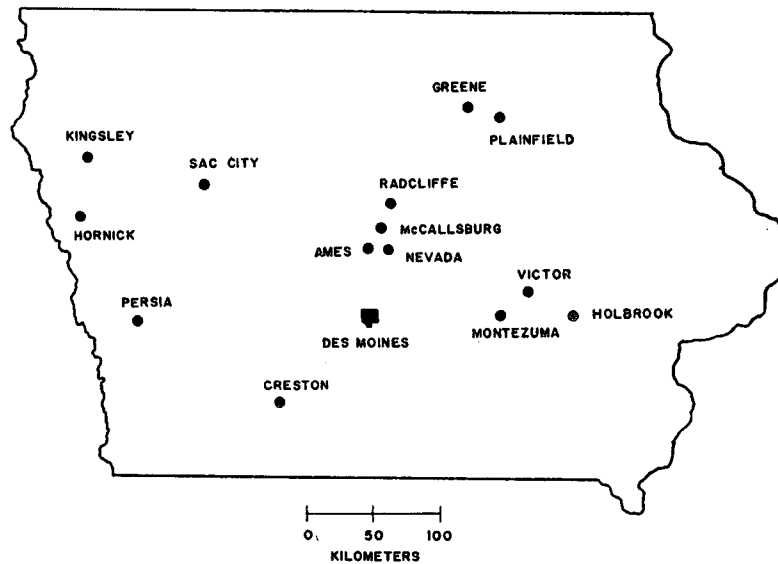


FIG. 1. Map of Iowa showing relative locations of severe weather events studied in this investigation.

increase in "sferic" pulse rates coincident with several tornadoes at 500 kHz. The term "sferic" in the literature denotes any radio noise pulse of atmospheric electrical origin. Ward *et al.* (1965) also studied sferic pulse rates at 500 kHz from severe storms in Oklahoma. They reported correlation with several tornadoes, but in general found the pulse rate quite variable with respect to severe weather events, many changes in the data not resulting from severe storm events. More recently, Hughes and Pybus (1970) have recorded the emission spectrum from two tornadoes at six frequencies in the range 10–250 kHz. They find the upper end of their spectrum to be the best indicator of tornado activity. On the other hand, they also show that increased pulse rates can often be associated with convective uplift processes. They also report sferic rate increases that do not correlate with hail or tornado events.

Our investigation, run for this first year on a small research budget, utilized frequencies of 670 kHz, 53 MHz and 144 MHz. The quasi-static atmospheric electric field was also recorded. The last storm, No. 6, was also studied at 11 MHz. We believe the results presented in this paper to be the first detailed report of a quantitative investigation of electromagnetic noise from severe convective storms at frequencies above 1 MHz. As will be discussed, we believe this region of the spectrum to be a better indicator of tornadic development than that below 1 MHz.

2. Experimental apparatus

The main antenna system is mounted on a specially designed tower located on top of the Iowa State University physics building. Two six-element yagi antennas with 24-ft booms are tuned to 53.25 MHz. One yagi is horizontally polarized, the other vertically. Two ten-

element yagi antennas tuned to 144 MHz are mounted above the 53-MHz system. Again, one yagi is horizontally polarized and the other vertically. All the 53 and 144 MHz data in this paper were obtained from the horizontal yagi. The 53 and 144 MHz antennas are approximately 110 and 120 ft above ground level, respectively. Both antenna arrays are capable of rotation of 360° in the horizontal plane, and are controlled and monitored to $\pm 3^\circ$ from the laboratory within the building. The time required for one complete revolution is ~ 1 min. A 5-ft whip mounted on the roof, 85 ft above ground level, serves as the antenna for the 670-kHz receiver.

At 670 kHz, a broadcast-band automobile receiver was used, while at 53 and 144 MHz, nuvistor preamplifiers were utilized in front of converters feeding into a communications receiver at 28 MHz. Only one of the two high frequencies could be utilized at a time, because only a single communications receiver was available. The low- and high-frequency receiver outputs were fed to the two channels of a Sony tape recorder, where the data were recorded on magnetic tape for later analysis. Only the envelope of the rf signal was recorded, the receiver bandwidths being ~ 5 kHz. The two signals were also simultaneously observed on a dual-trace oscilloscope.

The atmospheric electric potential gradient was also monitored. The probe consists of a two-plate capacitor mounted on the roof of the physics building, 85 ft above ground. The plates are 1 ft² in area and 2 cm apart, filled with paraffin. A coaxial cable connects the plates to a high-impedance vacuum-tube voltmeter, the output of which was amplified and displayed on a chart recorder as a function of time. Corrections for disturbing effects of the building have not been made, the potential

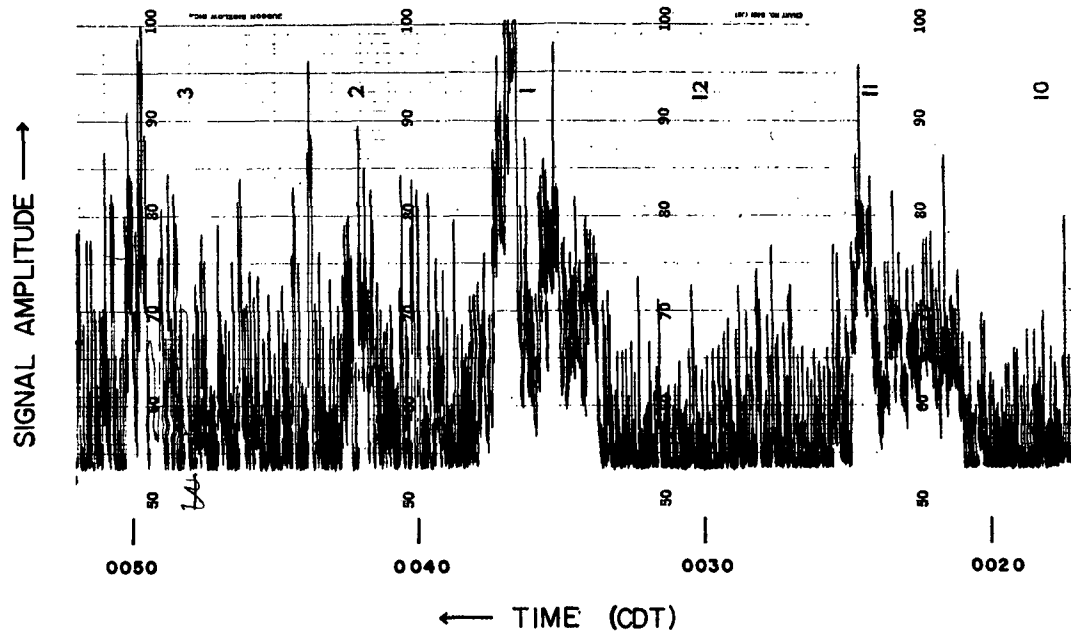


FIG. 2. Strip chart-record of 670-kHz signal amplitude vs time for the time interval including the Ames tornado of 11 May 1970. The time constant for this system was primarily that of the recorder, ~ 0.5 sec.

gradient recordings being utilized only as a relative indicator of quasi-static electric field changes during severe weather.

The last storm, No. 6, was also studied at 11.2 MHz. A 10-ft vertical antenna, tuned to 11 MHz with a low Q inductor, was mounted on the roof. This was fed to a second communications receiver. The 11.2-MHz data were also recorded on magnetic tape.

Later data analysis included counting the pulse rates recorded on magnetic tape by an electronic frequency counter. The pulse rates obtained were a function of counter threshold voltage. As will be discussed, several storms were studied at a variety of threshold voltages. The pulse rate data obtained in this manner were then displayed in histogram fashion vs time, the counting times generally being 20 sec.

The majority of the storms were monitored on the WOI-TV weather radar by closed-circuit television. This often helped identify areas of maximum storm intensity.

3. Experimental results

a. Storm No. 1

Early in the storm season, the brief touchdown of a tornado was reported near Ames (Fig. 1). This event occurred at 0037 (all times CDT) on 11 May 1970, approximately 5 km from our apparatus. At that time, the equipment was not yet completed and we were unable to record the data on magnetic tape. (Subsequent storm data were so recorded.) A strange pulse rate was noted on 53 MHz, described as sounding like a "swarm of bees" and lasting for several minutes. A strip-chart

record of the 670-kHz signal amplitude is reproduced in Fig. 2. Note the intensity peaks at the time of the tornado touchdown. The earlier noise burst at 0021–0025 is unaccounted for, and could possibly correspond to an earlier unreported funnel, although there is no way of knowing. The quasi-static atmospheric electric field was also monitored during this period, starting at 0025. The chart record for this period is shown in Fig. 3. At the time of the intense 670-kHz noise, a corresponding change in the atmospheric electric field can be seen. The rest of the record is typical of that for an intensely electrified storm. It is apparent that while the atmospheric electric field changes during the tornado are noticeable, they are not spectacular and can only be reliably identified after the fact.

b. Storm No. 2

Fig. 4 shows the count rate intensity during the period of approximately 2130–2230 for the storm of 12 May 1970. About half of the intensity peaks correlate in time with confirmed funnels or brief tornadoes. All the data in Fig. 4 were obtained at 53 MHz with the exception of a 4-min time interval from 2157–2202 when the 144-MHz antenna and converter were connected to the communications receiver. The drop to zero counts at 2157 marks the time of changeover. The changeback, which required a shorter time, is marked by the dip at 2202. It will be seen that the 144-MHz data reveals a minute or so of counts at 110–150 per second, and then at about 2159 the counting rate jumps by an order of magnitude for a period of ~ 2 min. It was at 2200 that the brief touchdown of a tornado was

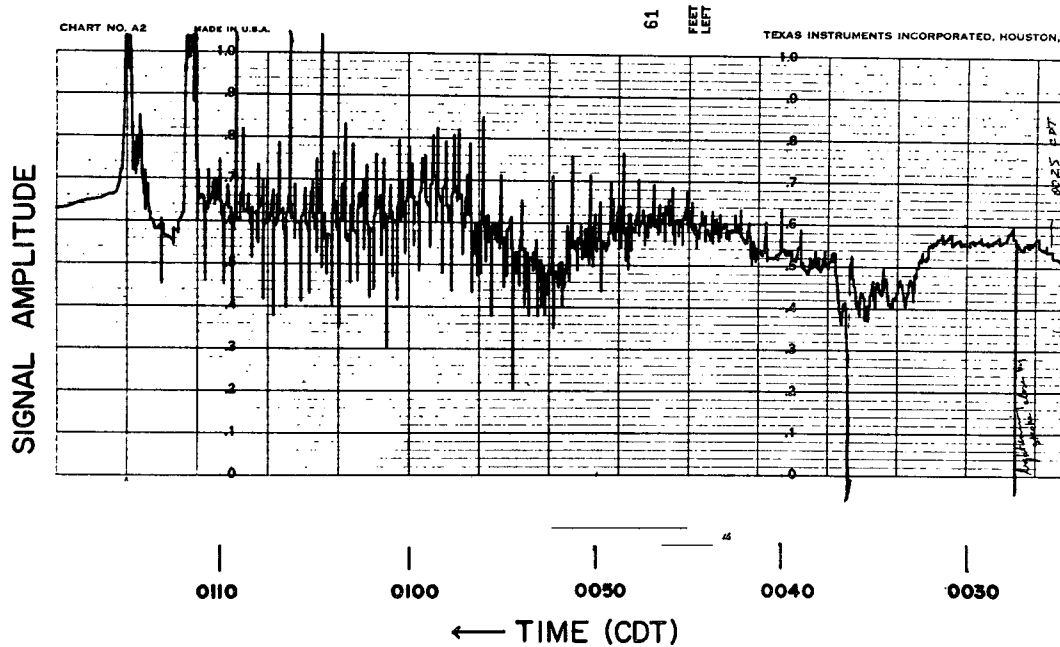


FIG. 3. Strip chart of the quasi-static atmospheric electric field for the time interval including the Ames tornado of 11 May 1970.

reported near Nevada, Iowa, about 20 km from our apparatus. Another brief tornado, reported moving across farm land near McCallsburg, Iowa (25 km distant) at 2215 appears to correlate with the 53-MHz intensity peak recorded at about that time. The times on the graph are uncertain by probably 2-3 min. The

other intensity peaks probably also signify intense convective activity, but whether these relate to unreported funnels or tornadoes is not known. It does not seem necessary to the authors that every intensity peak be related to tornadic development, although there is independent evidence to suggest that they may signify

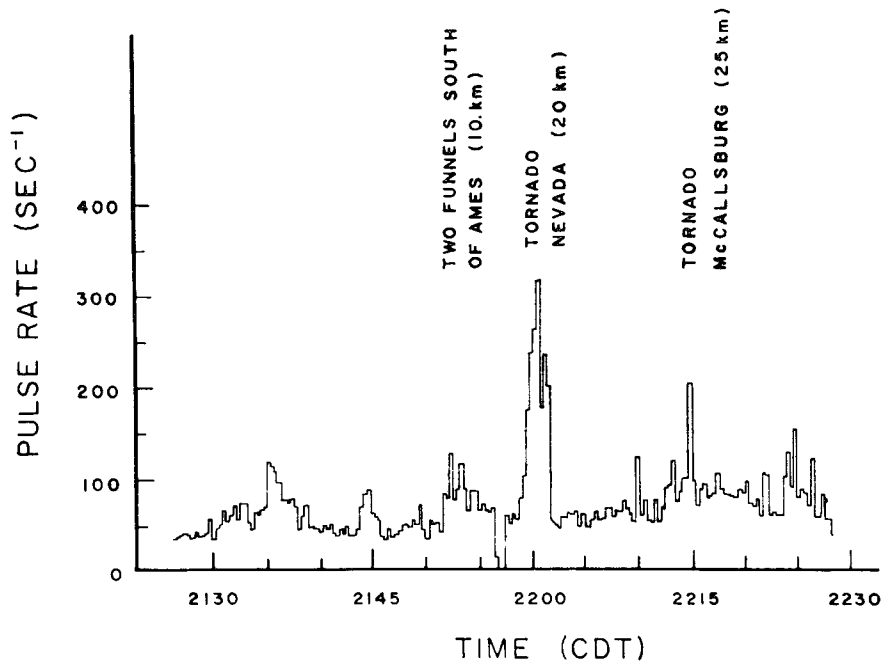


FIG. 4. Electromagnetic pulse rate vs time for Storm No. 2 of 12 May 1970. The pulse rates have been averaged over 20 sec.

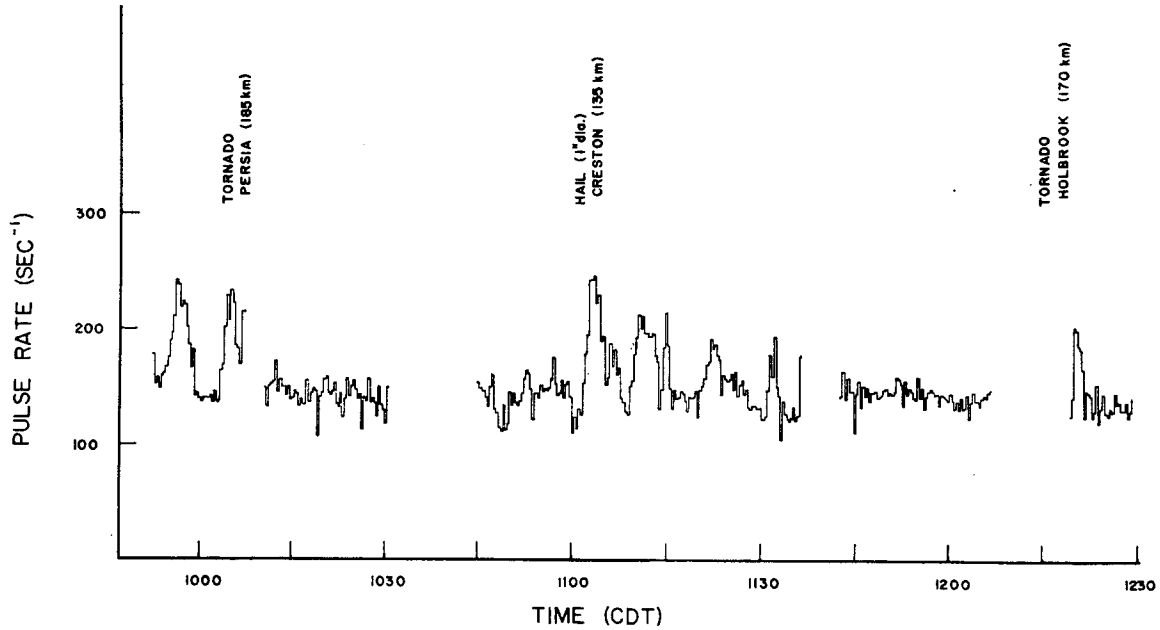


FIG. 5. Electromagnetic pulse rate vs time for Storm No. 3 of 17 June 1970. The pulse rates have been averaged over 20 sec.

some type of strong convection process. This will be discussed further in Section 4.

c. Storm No. 3

Fig. 5 shows the 53-MHz pulse rate recorded for the storm of 17 June 1970, the gaps in the data indicating times when the equipment was not operating. Two of these shutdowns unfortunately occurred near two tornadoes, at Persia and Holbrook. Although at great range, pulse rate peaks (unknown at the time) are indicated just before or after the equipment was tem-

porarily shut down. The hailstorm at Creston (135 km) appears to correlate with the start of a series of quasi-periodic pulse-rate peaks observed between 1100 and 1130. The two well-defined peaks around 1100 may also be part of a series of related peaks. Such a series of almost periodic data peaks was also recorded during confirmed severe weather events in Storm No. 4.

d. Storm No. 4

Fig. 6 shows the 53-MHz count rate record taken during a post-midnight severe storm that developed in central Iowa and swept eastward across the state on 3 July 1970. Fig. 6 shows an almost periodic surge in counting rate between approximately 0200 and 0240. Four distinct peaks are seen in the data, each with a duration of ~5 min, occurring regularly about 9 min apart. By personal telephone conversations, we learned that at least two severe weather events occurred during the time interval depicted in Fig. 6. At approximately 0200 a tornado of narrow width destroyed a barn on a farm near Montezuma, Iowa. A narrow path of twisted trees could be seen in a nearby timber. Witnesses stated that they heard a roar like a freight train and that the lightning preceding the tornado was the most intense seen in many years. This event occurred at a range of 105 km from our apparatus. At roughly 0230, the roof of a restaurant near Victor, Iowa, was blown off by what witnesses believe was a tornado. A large truck was also overturned at the same location. An adjacent campground was essentially unaffected; this was 115 km from Ames. The geographic location of the two events with respect to the storm and the time interval between

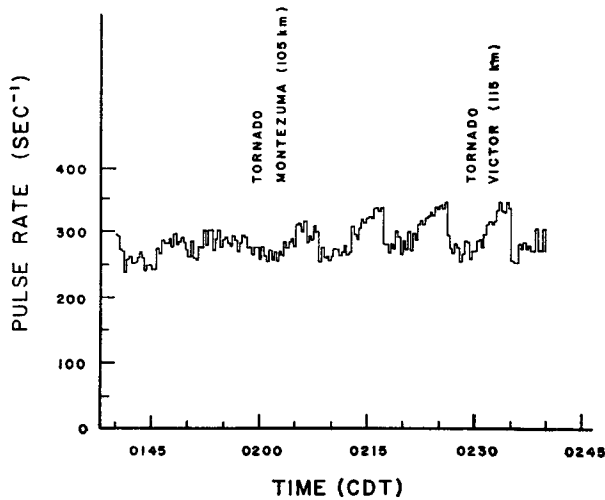


FIG. 6. Electromagnetic pulse rate vs time for Storm No. 4 of 3 July 1970. The pulse rates were obtained by averaging over 20 sec.

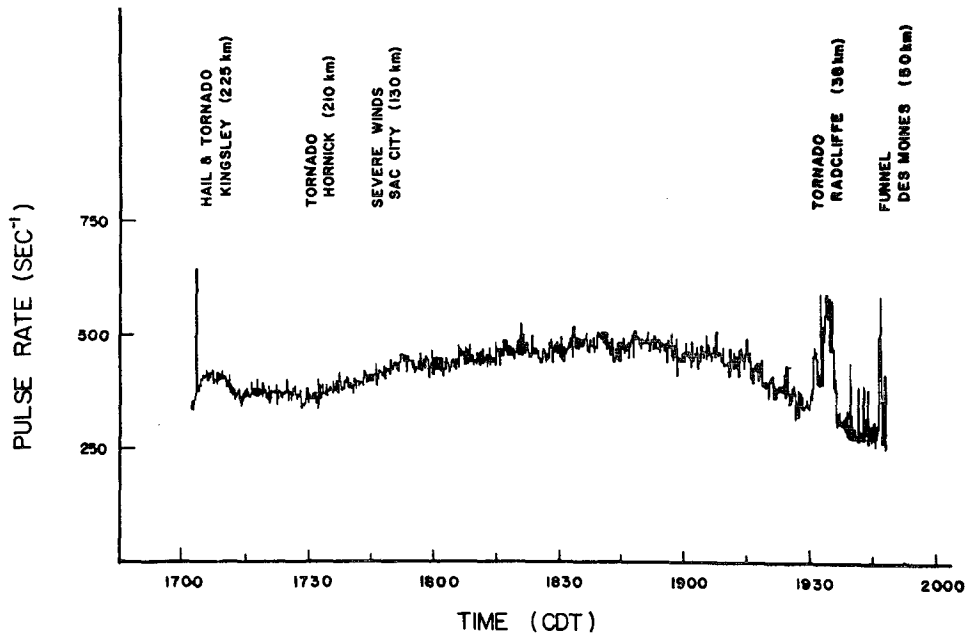


Fig. 7. Electromagnetic pulse rate vs time for Storm No. 5 of 14 July 1970. The pulse rates were obtained by averaging over 20 sec.

them make it likely that they were independent, short-lived severe weather events. A possible interpretation of the repeating data peaks is discussed in Section 4.

e. Storm No. 5

On the afternoon and early evening of 14 July 1970, a major storm formed and swept from west to east across most of central Iowa. This was the most severe storm in Iowa during the 1970 storm season. Our monitoring of this storm, shown in Fig. 7, began about 1700, just as an extensive and severely damaging hail storm, along with a brief tornado near Kingsley, was occurring in far western Iowa at a range of ~ 225 km from our apparatus. The broad electromagnetic pulse rate peak at approximately this time likely correlates with this combined severe weather event. Around 1730, the longest-lived tornado of the 1970 season in Iowa occurred, with a 10-mi track starting near Hornick, Iowa (210 km). As can be seen from Fig. 7, no electromagnetic pulse rate enhancement was observed from this tornado. This will be discussed further in Section 4.

From approximately 1730–1800, Fig. 7 shows a slow build-up in the pulse rate, which is then nearly constant for approximately an hour. At 1845 an unusually severe windstorm moved into Sac City, Iowa (130 km from Ames). No funnel clouds were verified, but winds of over 100 mph were experienced, with damage to nearly every structure in the community. Photographs of the city reveal large-scale devastation in what was the worst storm in the history of the community. The electromagnetic pulse rate during this time (Fig. 7) is distinct from that of the other storms observed in 1970, the 14 July storm having a nearly steady “background”

pulse rate approximately twice that of the other storms. This seems to have been an indicator of unusually severe convective activity.

After 1900, Fig. 7 shows that the storm appears to have diminished in intensity. (The storm began passing over Ames at approximately 1900, so some of the decreased count rate of Fig. 7 could conceivably be due to the insensitivity of our 53-MHz antenna to incident EM radiation at high incident angles.)

Shortly after 1930 a spectacular enhancement of the pulse rate occurs, and for a shorter duration, again at approximately 1950. These two events correlate very closely with a brief but powerful and destructive tornado at Radcliffe, Iowa, and with a funnel sighted north of Des Moines, respectively. We will now discuss these two events in some detail.

We have ascertained by personal interviews with eye witnesses that the Radcliffe event correlated with the observed peak in 53-MHz pulse rate between 1930 and 1940, and that the event was definitely tornadic. Because the interpretation of the Radcliffe event is of crucial importance in the understanding of our data, we list the reasons for believing that it was a true tornado: 1) heavy destruction: two farms practically destroyed, several others damaged; 2) a damage path several (3–4) miles long but of relatively narrow width: at one point a narrow path of destruction about 20–25 ft wide was observed in a corn field, leading directly to one of the devastated farm building complexes; 3) distinct stump evidence that large trees between 1–2 ft in diameter were twisted off; 4) a blunt piece of window glass was driven like a sword 1 inch into a tree trunk as were numerous fragile oat straws; 5) observation of the

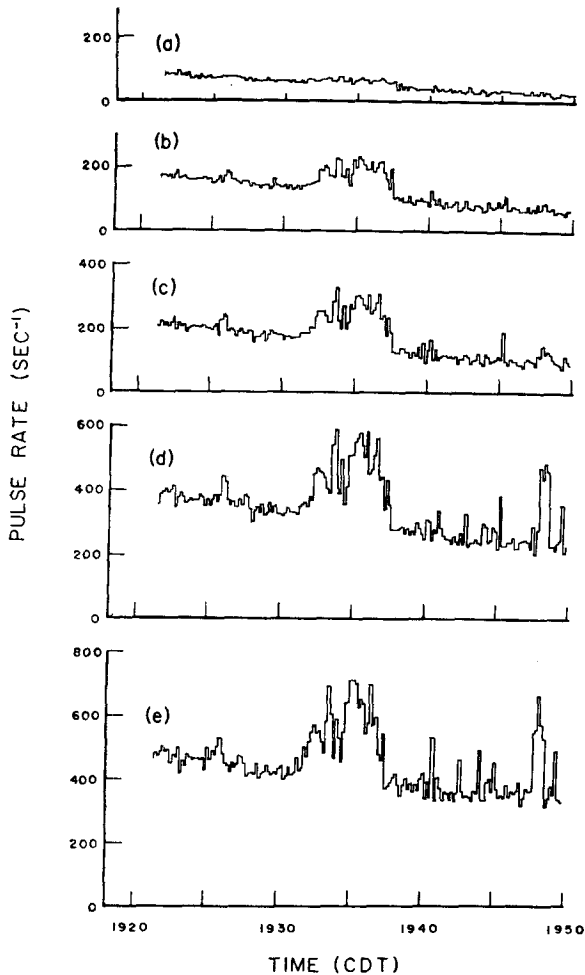


FIG. 8. Electromagnetic pulse rates averaged over 10 sec for the time period including the Radcliffe tornado and the Des Moines funnel, analyzed at different pulse heights: (a) 3.0 V, (b) 1.5 V, (c) 1.0 V, (d) 0.4 V, (e) 0.2 V.

funnel by several eyewitnesses from adjacent farms. This tornado occurred 38 km north-northeast of our apparatus (see Fig. 1).

Fig. 8 shows on an expanded time scale the electromagnetic pulse rate recorded at 53 MHz around the time of the Radcliffe tornado. Figs. 8a-e are the pulse rates obtained when the recorded data were analyzed for pulse-height thresholds of 3.0, 1.5, 1.0, 0.4 and 0.2V, respectively. These voltages are those of the envelope of the 53-MHz pulses, after amplification by the apparatus. A system gain of approximately 10^4 was measured with a calibrated 53-MHz pulse of ~ 40 msec duration and $10 \mu\text{V}$ amplitude. The data shown in Fig. 8 were obtained by counting the pulses from the magnetic tape recording for intervals of 10 sec. The integrated counts over this time span were then plotted in histogram fashion vs time. The counting rates actually heard through the receiver by ear are more nearly represented by Fig. 9, which is analogous to Fig. 8 but with counting times of 1 sec each.

Fig. 8e is the counting rate obtained when the majority of storm pulses are counted. Here the Radcliffe tornado and the Des Moines funnel cloud have roughly the same count rate. Our 53-MHz antenna array is fairly directive, with a front-to-back power ratio ≥ 20 db. At the time of the recording of the data in Figs. 7 and 8, the antenna was aimed slightly east of north, that is, directly at Radcliffe, and with its backside to the Des Moines event (see Fig. 1). It is thus not surprising that as the triggering threshold is increased, from Fig. 8e to Fig. 8a, the Des Moines event is lost in the noise, while the Radcliffe tornado is not. This is, in fact, further evidence that the correlation of the two data peaks with these two severe weather events is indeed correct.

The signal-to-noise ratio of the Radcliffe tornado is approximately independent of counter triggering level in Fig. 8. This indicates that the 53-MHz pulses from the tornado (at 38 km) and those from the rest of the storm (overhead in Ames at the time) were of roughly the same amplitudes, at least on the recording. The character of the signals are different, as shown in Fig. 10. The 53-MHz signal during the height of the Radcliffe tornado is depicted in Fig. 10a, while that of the general storm noise a few minutes later is shown in Fig. 10b. It is possible that strong pulses from relatively close lightning are overloading the receiver or the recorder, and that this partially accounts for the fact that the (less frequent) close-in storm noise pulses do not appear to be much greater in amplitude than the Radcliffe tornado noise. On the other hand, the data would also be consistent (at least in part) with the hypothesis that the mechanism generating the electro-

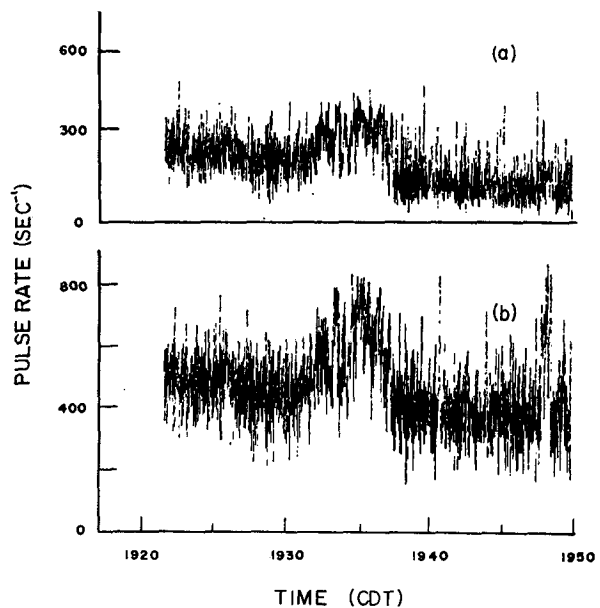


FIG. 9. Electromagnetic pulse rate during the Radcliffe and Des Moines events of 14 July 1970. The pulse rate has been averaged over 1.0 sec and for thresholds of (a) 1.0 V, (b) 0.2 V.

magnetic pulses at 53 MHz within the tornado produces noise of larger amplitude than ordinary storm processes at 53 MHz and at the same range from the apparatus. Fig. 2 would also be consistent with this interpretation. More observational data on tornadoes at various radio frequencies are clearly needed.

The magnetic tape channel on which was recorded the 670-kHz pulse information was also utilized as a voice-information channel. While the 670-kHz information was thus lost during part of the Radcliffe tornado due to voice recording, a strip-chart recording of the signal amplitude vs time was made, similar to that of Fig. 2. However, at the time of the Radcliffe tornado, the general storm background noise on this lower frequency was so intense that the chart recorder sensitivity had been greatly reduced, and only a very slight peak is observed in the data around 1930–1940. Although inconclusive, it appears that this frequency gave considerably less indication that the tornado had occurred. We are led to conclude that the difference between the 670-kHz behavior for the Radcliffe tornado (38 km) and the Ames tornado (5 km) of Storm No. 1 is probably accounted for by the considerably greater range to the Radcliffe event. An alternate possibility, that the two tornadoes had different energy content at this frequency, cannot be ruled out on the basis of the present data. In spite of admittedly poor statistics, this may be evidence that VHF portions of the radio spectrum are better than the region below 1 MHz for discriminating tornado noise from general storm noise. Again, the need for more observational data is emphasized.

Fig. 11 shows the atmospheric potential gradient taken during this period. There is clear evidence (after the fact) that a charge buildup occurred for the short period of time during the Radcliffe tornado. At the time of the Des Moines funnel some slight structure is seen in Fig. 11, covered partially by close lightning (large-amplitude spikes). Whether this structure is related to the Des Moines funnel is debatable. Unfortunately, the potential gradient apparatus was changed after this storm and the sign of the field buildup during the tornado cannot now be directly ascertained. The noticeable effect at a range of 38 km may imply considerable electrostatic charging effects during the formation of the tornado. In the absence of a charge distribution model for tornadic storms, attempts at estimating charge magnitudes appear unwarranted.

Finally, Fig. 12 shows outlines of the 14 July storm at various times. The outlines were obtained from photographs made of the Des Moines weather radar screen.¹ This will be discussed further in Section 4.

¹ We are indebted to Mr. W. C. Caldwell and Mr. C. E. Lamoreaux of the Des Moines Weather Bureau for the use of their radar photographs.

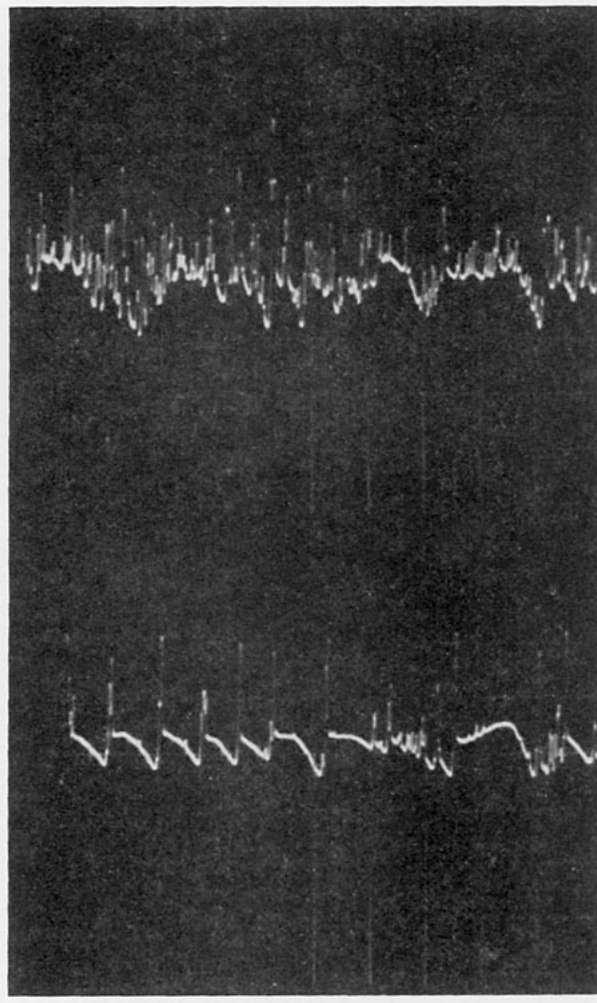


FIG. 10. Oscilloscope photograph of 53-MHz noise. Horizontal scale: 10 msec per large division; vertical: 1 V per large division. The upper trace was taken during the Radcliffe tornado; the lower trace consists of general storm background taken a few minutes later. Time increases from right to left.

f. Storm No. 6

On 9 September 1970, thunderstorms initiated in western Iowa swept northeast across most of the state. Several severe weather events were reported as this storm system passed over northeast Iowa. Fig. 13 shows the electromagnetic pulse rates recorded during a portion of this storm with sections (a) and (b) representing the 11.2-MHz signal with high and low counter triggering levels, respectively, while (c) and (d) are for 53 MHz, again with high and low triggering levels, respectively. Several features are noteworthy. A broad peak is seen in all the data, centered around 1430, as the storm intensified. Between 1500 and 1600, at least six prominent data peaks are seen. During this period the main storm cells had passed out of the Ames area, but isolated cells were occasionally overhead. Strong electrification overhead cannot thus be completely ruled out, although corona discharge on the antennas is not thought to be

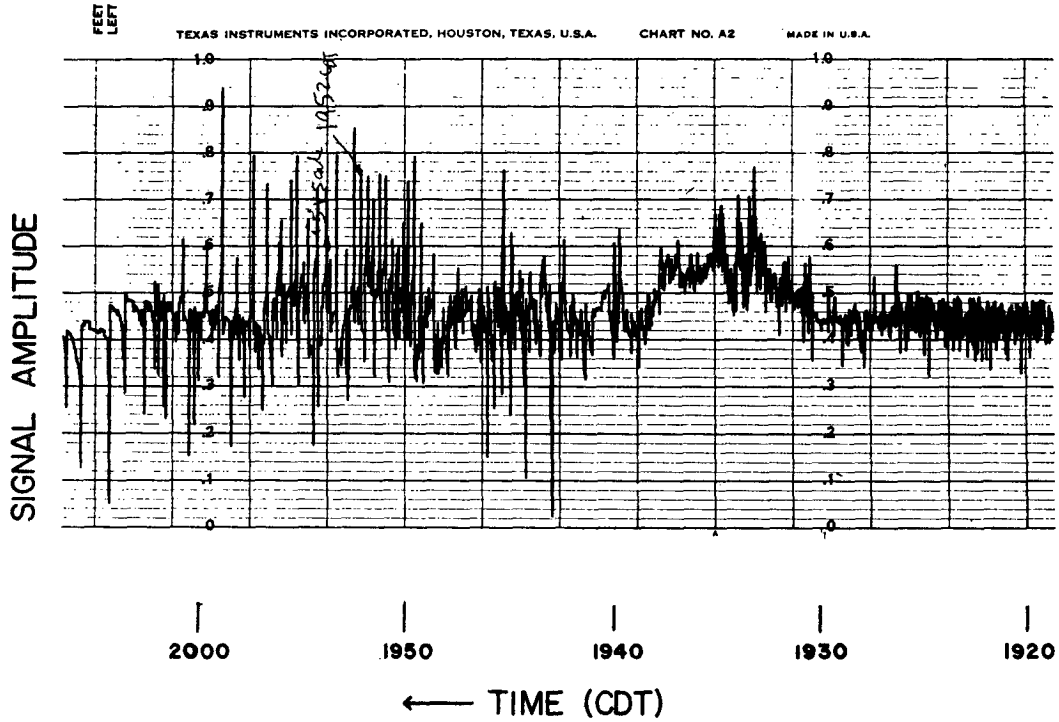


FIG. 11. Atmospheric electric field (in relative units) for the time period including the Radcliffe and Des Moines events of 14 July 1970.

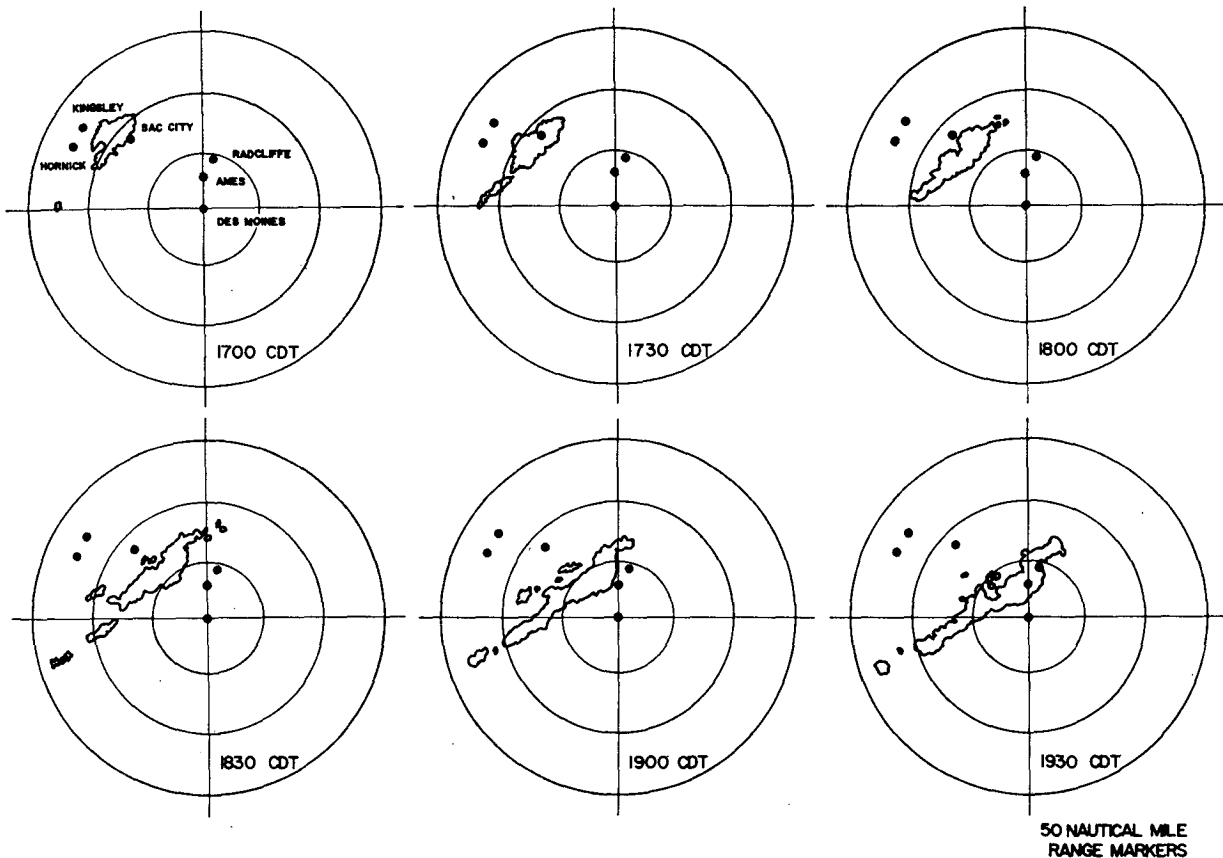


FIG. 12. Outlines of Des Moines radar pictures for Storm No. 5 of 14 July 1970.

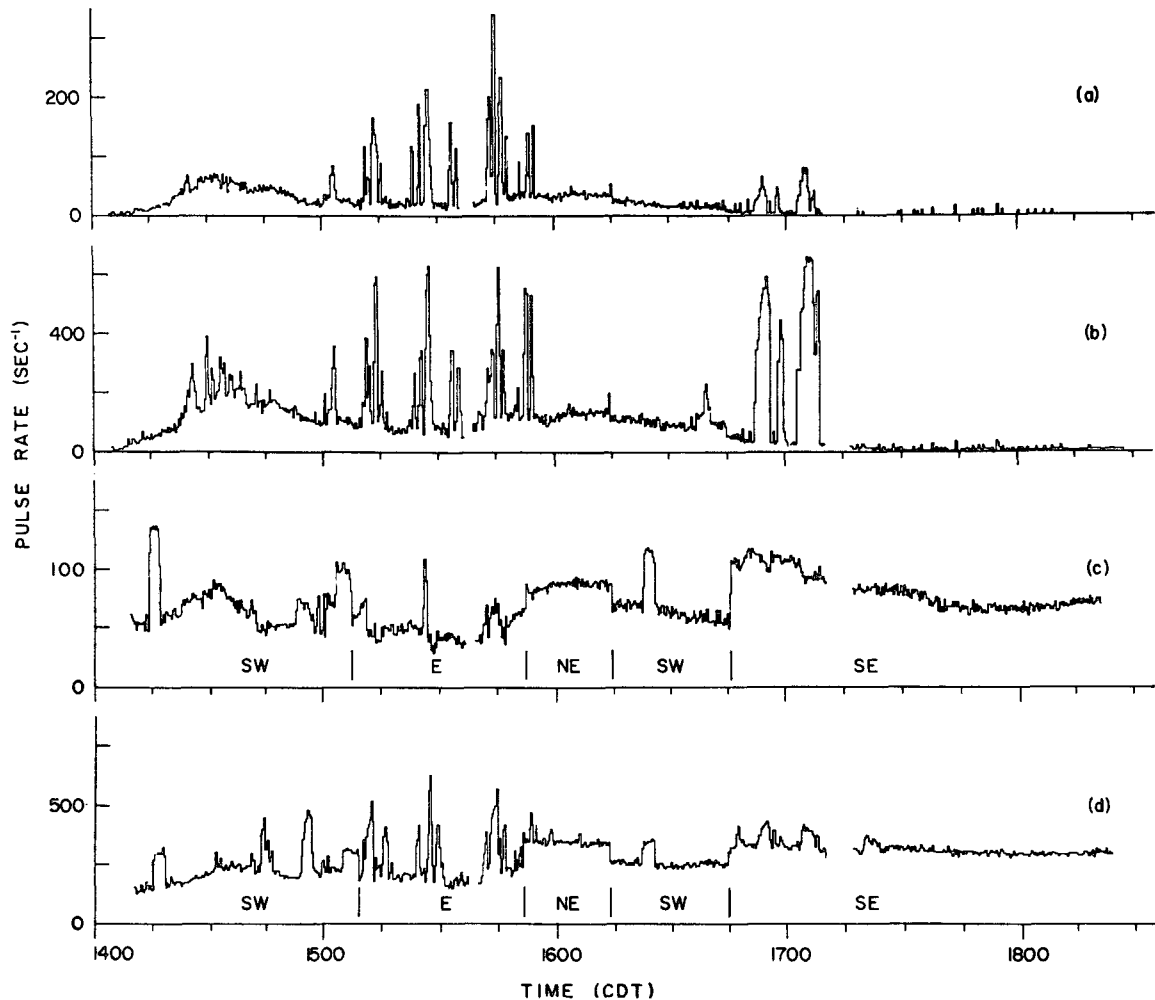


FIG. 13. Electromagnetic pulse rates vs time for a portion of Storm No. 6 of 9 September 1970: (a) and (b), 11.2-MHz pulses at high and low thresholds, respectively; (c) and (d), 53-MHz pulses at high and low thresholds, respectively. The 53-MHz antenna direction for various times is denoted below each trace.

the explanation of all six data peaks. At 1542, two funnel clouds were sighted near Greene, Iowa (130 km). One of the funnels touched down in the open countryside, causing damage to the corn crop. An observer stated that the tornado stayed on the ground ~ 5 min, causing "big balls of fire" to drop to the ground when it hit high power lines. There is good time correlation between this tornado and the largest of the six data peaks, which (according to Fig. 13) started at approximately 1542 or 1543 and lasted 5–6 min. At the higher triggering threshold (Fig. 13c) the 53-MHz peak is reduced with respect to the general background. This indicates that the 53-MHz antenna was not aimed directly at the event. The antenna was pointing east [as indicated by the letters under sections (c) and (d)] until approximately 1550. At this time it was directed to the northeast, directly at the event (see Fig. 1). The general noise-background rate increases considerably at this time. These facts are consistent with the assignment of the largest data peak to the Greene tornado.

Shortly before 1600, a number of funnels were sighted at Plainfield (135 km), with up to five separate funnels being reported. According to one eyewitness, three funnels coalesced into one, touching down and damaging at least three farms near Plainfield. As nearly as we can ascertain from telephone conversations, this event occurred at approximately 1550, apparently correlating with the data peak occurring in Fig. 13 at about that time. At nearby Greene, Iowa, eyewitnesses watched a tornado touch down and destroy a barn at 1515. This appears to correlate with the second of the six data peaks in Fig. 13a.

The other data peaks in Fig. 13 remain uncorrelated with known severe weather events. They could represent unseen or unreported tornadic activity or they could represent "noise." Such unexplained pulse rate peaks should be further investigated to determine their validity as indicators of severe weather.

The 670-kHz signal amplitude was recorded on a strip-chart recorder for this storm. Little indication of

the severe weather events are observed on the chart record, suggesting that higher frequencies provide a better indication of tornadic development.

4. Discussion

a. Types of phenomena observed

An examination of our data reveals that several possibly different types of electromagnetic radiation phenomena are being observed from severe storms:

1) Radiation is observed from "ordinary" lightning stroke processes. These are usually distinguished by their strong amplitude and isolation from other pulse trains.

2) A gradual buildup of pulse rate over 15–30 min is often observed, probably connected with convective processes occurring during storm intensification. The close connection between electrification and major convective processes is well known. See, for example, Vonnegut (1963) and Vonnegut *et al.* (1966). Phenomena 1) and 2) are probably due to the same physical mechanism, that of radiation from acceleration of charges during the lightning process (cloud-to-ground strokes, cloud-to-cloud strokes, intracloud strokes, etc.). These processes, although much studied, are incompletely understood (Uman, 1968).

3) Occasionally, pulse-rate peaks occurring almost periodically in time are observed spaced by times on the order of 10 min. On the basis of the occurrences of a number of these events near in time to known severe weather events (Figs. 5 and 6), we tend to think these series of peaks are associated with unusually severe convective motions in the giant storm. The data are not sufficient to allow a statement about whether the microscopic physical mechanism producing this radiation is different from that of phenomena 1) and 2).

4) Counting-rate peaks apparently directly associated with tornadic activity have been observed. Our best documented example of this is the Radcliffe tornado in Fig. 7. The physical mechanism responsible for this phenomena is unknown (and extremely interesting). It may be due to corona-type discharges within a highly electrified funnel cloud. The pulse rates would be consistent with such a corona process. Also consistent with this idea are eyewitness reports of the observation of nearly continuous lightning occurring within the tornado bore [quoted in Justice (1930)]. There is no way of knowing what percentage of funnels exhibit this effect, since not many people have looked up into the bore of a funnel cloud and lived to tell about it. An unambiguous answer to the origin of this effect requires further studies on the frequency spectrum and polarization of a large number of tornadoes. Our present studies, with their admittedly poor statistics, appear to suggest that the majority (but not all) of tornadoes do emit electromagnetic noise pulses at high radio fre-

quencies which are different in some ways from those emitted by ordinary thunderstorms.

5) Sharply defined pulse-rate peaks are frequently observed during storms which do not appear to correlate with known severe weather events (see Figs. 4 and 13, for example). Some of these events may correspond to funnel clouds or tornadoes of which we are unaware. Others of these events may be due to processes related to short-lived severe convective motion, as in 3) above. Hughes and Pybus (1970) have also reported similar uncorrelatable rate peaks for storms studied at lower frequencies (10–250 kHz). Although closer correlation with public reports and increased (and more accurate) statistics may minimize events of type 5), they presently constitute a major source of difficulty: How can true tornadic events be distinguished?

b. Bandwidth and pulse-counting consideration

The bandwidth of the receiving equipment used was ~ 5 kHz. Our data exhibit pulse rates of generally less than 500 sec^{-1} when integrated over periods of 20 sec, with occasional bursts to $1.5 \times 10^3 \text{ sec}^{-1}$ on a 0.2-sec time scale. Since a bandwidth-to-pulse rate ratio of 10 is known to introduce little distortion into the shape of amplified pulses, it does not appear that our 5-kHz bandwidths caused a loss of appreciable amounts of storm information.

An independent investigator, using wider bandwidth equipment, has studied several Oklahoma tornadoes and obtained pulsing rates (for the megacycle frequency range) of the same order of magnitude as ours.² Kohl (1969) and Hughes and Pybus (1970) have also found counting rates of the same order of magnitude, at frequencies of 500 and 10–250 kHz, respectively. In this regard, it should be realized that the counting rates are unlikely to agree exactly between any two storms or any two observers. The reasons are that storms are quite variable in nature, and that the pulse rate obtained depends critically on antenna characteristics, apparatus gain, and the pulse-height threshold used for counting. The latter effect is exhibited by our Fig. 8.

c. Propagation effects

Horner (1953) investigated high-frequency radio noise bursts from 10–20 MHz for thunderstorms at various ranges. He concluded that 100 km represents approximately the range where the ground wave signal disappears and beyond which signals usually are propagated by ionospheric reflections. Also, beyond 100 km, line-of-sight view subtends increasingly smaller segments of the upper-most portions of a storm. These

² William Taylor, private communication. We were grateful for the opportunity to discuss Mr. Taylor's preliminary results with him prior to their publication.

Note added in proof. Taylor has now found that counting rates one to two orders of magnitude larger sometimes occur for brief periods.

reasons perhaps account for much of the difference in character of radio noise associated with close and distant (>100 km) tornado events.

d. Periodic noise rate peaks

The repeating peaks in the data of Storm No. 4 (Fig. 6) are intriguing and not understood. The antenna was rotated during the middle of the first peak, which occurred at approximately 0205 CDT. Had the antenna been aimed continuously at the event, the peak would have undoubtedly been stronger. Two of the four peaks in Fig. 6 may correspond to the Montezuma and Victor events. The other two peaks could conceivably be attributed to unobserved or unreported funnel developments. However, the long range and the regularity of the four peaks suggest an alternative explanation. Although the physics of the phenomenon is unexplained, there is mounting evidence to suggest that such counting-rate peaks may be correlated with strong vertical convection in cumulonimbus development (Hughes and Pybus, 1970). Newton (1962) has suggested that a connection exists between individual tornadoes and bursts of convection in the mother cloud, possibly associated with new cell formation. The peaks in Fig. 6 could thus be indicators of strong convective growth of cells at regular intervals as the storm intensified. For example, Vonnegut (1963) shows data for the altitude of cloud tops revealed by radar for a New Mexico thunderstorm. The convective process produced a series of vertical cloud development growth and decay, separated regularly in time by ~ 10 min. The order of magnitude of time periodicity of the events in Fig. 6 is thus consistent with an interpretation relating high electromagnetic pulse rate with strong cloud convective activity. Utilizing low radio frequencies (500 kHz), Kohl (1964) has also found correlation between the intensity of convective storms and the electromagnetic pulse rate.

e. The Hornick tornado

From Fig. 12, it appears that the Hornick tornado, at approximately 1730, occurred well behind the main storm precipitation outline. It should be realized at this range that the Des Moines radar would be mainly sensitive to the upper portions of the storm, due to effects of the earth's curvature. The radar beam would also be attenuated behind the storm. Nevertheless, the tornado occurred at some distance from regions of high radar reflectivity.

f. Corona effects

Local sources of noise, such as corona discharge on the antenna during periods of intense electric field buildup, are certainly a problem in interpreting the data. Corona discharges were often observed on our antenna system, but the noise during the Radcliffe

tornado, for example, was of different character than that from the more obvious local point discharges. The latter tended to be more coherent, while the former was quite incoherent (at 53 MHz). Some of our data peaks are almost certainly due to corona, such as that at 1425 in Fig. 13c, and perhaps the large peaks around 1700 in Fig. 13b. Also, we have been unable to uncover further evidence for the reported Nevada tornado of Fig. 4, and it is possible that the peak at 2200 could have been corona-induced. Distinguishing between local and distant noise sources remains a serious problem. We hope to provide better discrimination during future investigations.

5. Conclusions

There is definite evidence that the majority (but not all) of tornadoes emit electromagnetic noise which is distinguishable from the associated storm background noise. Hail and violent windstorms were also found to correlate with noise peaks. Other radio noise effects are observed from severe thunderstorms, some resembling those from tornadoes, but seemingly uncorrelated to any known severe weather events. At present, only speculations can be made about the physics of the various noise phenomena observed. There is a clear need for more observational data.

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