The radar observation of lightning*

MYRON G. H. LIGDA
Department of Oceanography and Meteorology
The Agricultural and Mechanical College of Texas
College Station, Texas

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Abstract—In this paper are reported a series of observations of radar echoes from lightning discharges detected on a horizontally scanning system. The investigation has comprised the development of a practical and convenient method of studying many properties of high-level strokes which heretofore have been inaccessible to observation. Descriptions are presented of the methods of observation used, consideration being given to the physical, geometrical and meteorological factors involved, and the resulting interpretations are explained. A photograph of the echo from a discharge over 100 miles in length is shown, as well as many others exhibiting novel or interesting characteristics.

1. INTRODUCTION

A NUMBER of investigators have reported observing radar echoes from lightning discharges (Ligda, 1950; Browne, 1951; Marshall, 1953; Miles, 1953; Hewitt, 1953; Jones, 1954; Ligda, 1955). The phenomenon is believed to be caused by the reflection of the radio energy by the column of highly ionized gas created by the main discharge. When the discharge ends recombination of the free charges occurs within a few milliseconds and an echo is no longer obtained.

2. EARLIER OBSERVATIONS

Since the entire event from leader stroke to recombination usually takes place in a few tenths of a second, since the direction of the stroke is unpredictable, and also because it is necessary that the radar antenna be pointed directly toward the stroke when it occurs, most investigators have made the observation with a stationary antenna pointing toward the suspected thunderstorm or area of thunderstorms and waiting for a discharge to take place.

Under such conditions the observation may be made either visually or photographically. On the A and R types of radar indicators the echo will appear as a sudden, strong signal, a few miles in length, rising from the baseline as shown in Fig. 1 (Ligda, 1950). On PPI and RHI types of indicators the echo will appear as a bright spot or short radial line since the antenna (and consequently the scope trace) is stationary. Photography of these transient echo signals may be accomplished by: (1) having an observer with a fast reaction time trip the shutter of the camera when he sees the echo (Ligda, 1950); (2) continuously photographing the scope with a conventional or special type of movie camera (which may be wasteful of film if no stroke occurs for some minutes); or (3) using the echo or signal from the stroke to activate the camera shutter or turn on the scope (Ligda, 1950).

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Miles (1952, 1953) employed an ingenious method of photographing such echoes on a PPI scope which avoided excessive consumption of film or use of "fast reaction" observers. Directing the antenna of his radar vertically toward a thunderstorm which was passing directly over his station, he turned on the antenna azimuth drive of his radar. With the antenna directed straight up, the co-ordinates of the PPI scope were transformed from azimuth and range, to height versus time (relative); height being indicated by distance from the centre of the scope, and echo duration being proportional to the angle through which the trace rotated while painting the echo. Thus he was able to make very accurate determinations of the duration of the echoes and their heights above the radar. The appearance of two of his observations is shown in Fig. 2. The same technique could of course be used to detect and study other discharges than those occurring directly overhead by pointing the antenna toward the storm, disconnecting the antenna drive motor, and then allowing the sweep of the PPI scope to rotate. The scope co-ordinates would then be slant range and time.

However, with a stationary beam, discharges cannot be scanned and very little can be learned about their paths in space and their general appearance. To accomplish this, the antenna must be permitted to scan the volume in which the stroke occurs. Since the exact instant and location of a discharge is unpredictable and antennas are too heavy to permit quick pointing, any observations which are obtained will be by chance; the radar beam just happening to be scanning the volume in which the discharge has occurred during its few tenths of a second of existence. The narrower the beam of the antenna and the slower the scanning rate, the smaller will be the chance of detecting the discharge, other factors being equal. A more complete consideration of the probabilities involved is offered in a later section.

Rather low probabilities of having the antenna properly oriented notwithstanding, Marshall (1953) has identified a large number of what to all indications were echoes from lightning discharges on a normal RHI presentation. He was making a photographic exposure of each cycle of the RHI scope scan (which was accomplished every 8 seconds), obtaining many hundreds of consecutive pictures. On a number of these he noted what appeared to be bonafide echoes but which appeared on one frame of the film, only. This meant the target was in the scanned volume for only something less than 8 seconds.* A series of frames showing these echoes is given in Fig. 3. The arrow in the middle picture points toward an echo which does not appear on the other frames. The bright spots which repeat from frame to frame are echoes from the thunderstorm precipitation. They do not change perceptibly for several minutes. Since the antenna was scanning a vertical plane these RHI pictures show a vertical slice through the thunderstorm and lightning discharge. The appearance and height of the lightning echoes suggests that high-level, more or less horizontal cloud-to-cloud (C-C) or in-cloud (I-C) discharges were being observed so that the echo is produced

* Marshall notes that some of these echoes appear on two successive frames. This is undoubtedly the result of persistence of the scope (afterglow) holding a very intense echo long enough for it to be photographed on the following scan. A number of these have also been observed by the writer. In every case the echo on the later frame is much less intense than that on the first frame. "Two frame" echoes are most likely to be observed when the echo is detected just shortly before the film is advanced in the camera.
Fig. 1. R-scope of SCR 615B radar (10 cm) showing lightning echo signal. Four downward marks are range marks two miles apart. Note steep edges of lightning signal. Total range of scope 8 miles (from 60-68 miles from the radar). Lower drawing identifies features shown in photograph. This is the first known radar lightning echo ever purposely photographed. (M.I.T., 20 July 1949.)

Fig. 2. PPI scope photographs (10 cm radar) showing single and paired lightning echoes using MILES’s method of observation at heights of 26,600, 17,400, and 24,400 feet above the radar. The duration of the echoes as indicated by the angle they subtend at the centre of the scope is about 0.3 sec. (Photographs taken at Salisbury, Southern Rhodesia, December (21?), 1951.)

* Radar characteristics: Wavelength, 10 cm; Pulse Length, 1.9 microseconds; Peak Power, 500 kw; PRF, 500/sec; Beamwidth, 3 degrees.
Fig. 3. A series of three successive RHI scope photographs, the middle one of which shows a lightning echo absent on the other two frames. (Photographed by MARSHALL (1953) on a vertical scan 10 cm radar, Montreal, Canada, 5 July 1948.)
Fig. 4. Successive PPI scope photographs showing a lightning echo on the middle frame; note that it does not appear on the preceding and following frames. (AN/ FPS-3 23 cm radar, Tyndall Air Force Base, Florida, 16 May 1955.) Length of arrow is 40 nautical miles. In this and all following PPI pictures, magnetic north is at the top of the scope and the pictures may be scaled from the arrow length indicated in the caption.

Fig. 8. Representation showing theoretical comparative "smearing" of the fine detail of a C-C lightning discharge approximately 10 miles long at a range of 100 miles for a radar with a 2° beamwidth and a pulse length of 2 microseconds. Fig. 8(a) shows the effect obtained when the long axis of the stroke lies on a radius to the radar; Fig. 8(b) shows what might be expected when the axis is at right angles to this position. The photograph in the inset is an actual radarscope picture of such an echo detected at a range of 120 nautical miles. The length of the arrow in the picture is 11 nautical miles and the echo from the precipitation has been dotted for identification.
Fig. 9. Lightning echoes associated with isolated storms, believed to be produced by C-G strokes. (23-cm radar, Amarillo, Texas, 19, 20 June 1955.) Length of arrow 45 nautical miles.

Fig. 10. Arrow points to lightning echo detected in area downwind of main precipitation area. (23-cm radar, Amarillo, Texas, 16 June 1955.) All thunderstorms visible on scope in this situation were moving very nearly from west to east. Length of arrow 45 nautical miles.
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by what might be considered a long rod stretched across the sky. (Subsequently
in this paper cloud-to-cloud, cloud-to-ground, and in-cloud discharges will be
referred to by the symbols, C-C, C-G, and I-C, respectively.)

To obtain a lightning echo while scanning the horizontal plane is somewhat
less probable because the area swept by the beam is much larger and accordingly
cannot be sampled as frequently. There also exists the problem of scanning a
wide range of altitudes. Precipitation present directly above or beneath the
discharge will also give a radar echo which will tend to obscure any echoes from
the stroke. Because of this it is highly improbable that a vertical C-G discharge
whose path lies entirely in heavy precipitation can be detected with conventional
microwave radars. Long, horizontal C-C and I-C discharges which have at
least part of their paths in precipitation-(but not necessarily cloud-) free regions
are however quite possible to detect.

Fig. 4 shows such an echo as it appears on a normal PPI scope. Again, the
arrow in the middle picture points to an echo which does not appear on preceding
or following frames. Space will not be taken here to demonstrate why this signal
cannot be ascribed to such factors as equipment malfunction, flaws in film emul-
sion, nor "atmospherics". All possible alternative explanations have been care-
fully explored and subsequently rejected on one basis or another. Supporting
evidence exists in all cases where checks were made, as surface weather stations
in the vicinity of these echoes were reporting frequent lightning at correspondiHng
times. Visual observations from the radar stations are not available because:
(1) no attempts were made to obtain them; and (2) in most cases the discharge
area was probably too distant for visual observation (usually about 100 miles).
The writer was not at any of the stations when the observations subsequently
to be described in this paper were made.

3. THE SOURCE OF THE LIGHTNING ECHO

It is known that gaseous ions will vibrate under the influence of an impressed
electromagnetic field. These vibrations result in the reradiation of electromagnetic
energy (SKILLING, 1948) at the same frequency as the impressed signal. The
higher the ion density, the greater will be the amount of energy reradiated. For
reflection of the signal to occur, certain ion, or free-charge, densities must be
reached or exceeded for a given frequency. Fig. 5 shows the relationship between
this critical density and signal frequency, and gives the names of those who
have reported lightning echoes at several frequencies. It will be noted that
higher densities are required for reflection of higher frequencies. A familiar
example of this is the well-known phenomenon of reflection of long radio waves
by the ionosphere while short wavelengths pass through it and escape to extra-
terrestrial space. In general, the longer the wavelength, the more efficient will
be the reflection for a given free charge density; also, the reflectivity from pre-
cipitation is less at longer wavelengths.

The ionized column can probably be considered to have a reflecting cross-
section equal to its projected area on a plane normal to the axis of the radar
beam. Since all portions of the ionized column, which are within the effective
limits of the beam and which have a separation in range not exceeding one half
of the pulse length, contribute to the power of the echo received at the radar at a given instant, it is possible to estimate the effective cross-section presented by a hypothetical discharge. Assuming the discharge to have a length of 3 km within the boundaries specified above (which corresponds to a discharge at a slight angle to a 1° beam at 80 miles) and an ionized column 2 cm in diameter, the cross-section presented by such a discharge would be 60 m². These are probably conservative estimates in both dimensions. The average radar cross-section of

\[ \frac{4\pi N_e q^2}{m_0 \omega^2} = 1 \]

where \( N_e \) = number of electrons/cc, \( q \) = charge on electron, \( m_0 \) = mass of electron, and \( \omega \) = angular frequency of the radio wave.

a B-29-type bomber is about 70 m². With modern equipment such a bomber can be detected at over 200 miles range. Accordingly, it may be seen that the lightning discharge presents an excellent radar target with an extremely long detection range which may be primarily limited only by the curvature of the earth.

Another factor which tends to confirm the theory that the echoes, in spite of their gross appearance, are from localized regions of the atmosphere, resides in the absence of any detectable attenuation. If a large portion of the beam were intercepted, echoes from precipitation detected along the same azimuth at greater distances would be reduced in intensity. That this does not happen may be readily confirmed by comparing the precipitation echo-signal intensity in such regions on successive frames of the film, one of which shows the lightning echo. This is illustrated in Fig. 4.
4. **The Geometry of Radar Detection of Lightning**

A. **Height**

With but few exceptions, all investigators who have observed radar echoes from lightning have so adjusted their equipment that the source of the echo was clearly at high altitude (Ligda, 1950; Miles, 1952; Marshall, 1953). Although low antenna-elevation-angle settings were employed in the PPI observations presented in this discussion, this does not necessarily mean that the discharges were at low altitudes. Fig. 6 shows the vertical coverage patterns of the two radar types used predominantly for these observations. It will be noted that, due to vertical beamwidth, the discharges could well have, and in all probability did, occur at reasonably high levels. This supposition is strengthened by the fact that no long discharges have yet been noted at ranges of less than about 40 nautical miles.

B. **Resolution of the Fine Detail**

Most authorities are of the opinion that the diameter of the ionized channel through which the lightning discharge takes place is of the order of a few cm (Loëb, 1948). Estimates range from 2 to 10 cm. Lightning discharges observed visually appear to be much broader because of their great brilliancy which stimulates the rods and cones on either side of the image formed on the retina of the eye, thus giving a false impression of thickness. Strokes observed in broad daylight against a bright background of sky or cloud appear to be much finer and are more difficult to see.

Resolution of fine details of target characteristics by radar is influenced by three factors: (1) the angle subtended by the beam at the position of the target, (2) the pulse length of the radar, and (3) the reflective properties of the target. The radar cannot resolve details of the target which subtend an angle smaller

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**Fig. 6.** Estimated radar coverage diagrams for radars AN/CPB-6B and AN/FPS-10. Contours represent 75% blip-scan ratio for target with scattering cross section of 45 m².
than the effective beamwidth (or are closer together than this angle) or have a dimension in range which is less than half the pulse length. Thus, individual targets which occupy a volume of space defined by the effective beamwidth and half the pulse length, cannot be resolved by the radar. We may consider this volume to be shaped like an elliptical disk as shown in Fig. 7.

Due to the geometry of the PPI scope, all targets detected are presented very nearly as they would appear if projected on a horizontal plane. If the radio beam is on horizontal scan, a transparent map of proper scale may be superimposed over the PPI scope to determine geographical location of targets detected.

![Fig. 7. Approximate shape, position and dimensions of echoing volume (region from which the echoes from all targets are received at the same instant) of the AN/FPS-3 radar at 80 nautical mile range. (Beam limits as defined in Fig. 6.)](image)

By virtue of horizontal beamwidth and pulse length, a "point" target will be presented on the PPI scope as a short arc, subtending an angle at the centre of the scope which is equal to the effective beamwidth or angle which the antenna turns through while receiving a detectable echo from the target. The theoretical minimum thickness of an echo on the scope in range is one half the pulse length. A typical radar such as is used for observations of the kind discussed in this paper has a horizontal beamwidth of about 1.5° and a pulse length of about 600 metres. On a PPI scope of 12" diameter and range setting of 150 miles, the echo from a "point" target (such as an aircraft) at 100 miles range will have theoretical minimum dimensions of \( \cdot38 \times 2.66 \) mm. However, while the electron beam, which brightens the PPI phosphor when a target is detected, can be focused about this sharply, the phosphor behaves somewhat like the retina of the eye and the above dimensions are "smeared" to about \( 1 \times 3 \) mm on even the best adjusted and carefully focused scopes. The stronger the signal, the greater the amount of smearing.

If the echo from the target is very strong, the size of its echo spot will be bigger, just as a bright star appears to be bigger than a faint one. Thus, highly reflective aircraft appear as larger targets on PPI scopes than those of equal
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dimensions which reflect poorly, although both are much smaller than indicated by the size of the echo on the PPI scope. Accordingly, the echoes shown in Fig. 3 could be produced by very small, but highly reflective targets. (The diameter of the dots measures about 3/8 miles according to the scale of the scope.)

Returning to the PPI display, Fig. 8 shows how pulse length (which can be ignored) and horizontal beamwidth (which cannot) smear out the fine details of a discharge 10 miles long at a range of 100 miles for a radar with a 2° beamwidth and a pulse length of 2 microseconds. Fig. 8a shows what would happen if the long axis of the stroke was lying on a radius to the radar; Fig. 8b shows the same stroke as it would be presented if oriented 90° from its former position. The stroke is assumed to be a C-C discharge and therefore approximately horizontal. It can be seen that the effect of beamwidth is to destroy all fine detail at this range and make the echo appear to cover much more area than it actually does.

5. Regions of Storms Where Lightning Echoes May Be Observed

Because heavy precipitation can produce a strong radar echo even at wavelengths of 23 cm, the detection of echoes from lightning in or near areas of very heavy precipitation is virtually impossible. Accordingly, while undoubtedly many discharges occur in such areas, the discussion which follows is confined to those strokes which occur in areas where precipitation echoes are weak, entirely absent, or at the edges of strong precipitation echoes.

A. Cloud-to-Ground Discharges

Although considerably less numerous (Hagenguth, 1951) than C-C discharges, more or less vertical C-G discharges command most of our attention because of the relative ease with which they can be seen, photographed, and studied by the surface observer. Since such discharges usually occur in close conjunction with heavy precipitation and may not have appreciable horizontal extent, it may be deduced that they are inconspicuous and difficult echoes to detect on the PPI scope of a radar. In spite of these limitations, however, a fairly large number of echoes which are ascribed to C-G discharges have been noted. Fig. 9 shows two fairly typical examples, indicated by the arrows.

It will be noted that most of these occur in a portion of the storm where precipitation was evidently light. Aside from the fact that such conditions are well-nigh essential to the detection of the lightning echoes at all, an additional bit of information is provided by these photographs. Apparently the light-precipitation echo is in many cases produced by, or is closely associated with, the anvil top of the cumulonimbus cloud. This conclusion is based upon the manner in which the light-precipitation areas were observed to form; that is, after the intense echo had grown to about maximum size, the light-precipitation echo grew out of the main echo in a high level, downwind direction. In those cases where no precipitation echo can be detected there is usually, but not invariably, a strong precipitation echo upwind from the lightning echo (Fig. 10). Also, in nearly all cases lightning echoes are detected at moderate-to-long ranges. This suggests that the beam (which in search radars is normally broad in the vertical
plane) is at considerable altitude. C-G lightning discharges are not infrequently observed to occur between anvil and ground.

C-G lightning echoes are almost invariably observed when the associated thunderstorm precipitation echoes are large, isolated, and widely scattered. From common observations it is suggested that lightning is but rarely observed unless some portion of the cloud is glaciated. Foster (1950) has described an observation where this was not the case.

B. Cloud-to-Cloud and In-Cloud Discharges

Far more spectacular, interesting, and easy to detect on PPI time-lapse film are the echoes from what are apparently more-or-less horizontal C-C or I-C discharges. These exhibit the same general properties as the C-G discharges, i.e.: they are visible on just one frame of the sequence (unless the PPI phosphor is sufficiently excited so that persistence is strong enough to allow them to be recorded on the following frame); they can be observed only in areas where the echo from precipitation is weak or absent, and the lightning echoes are very strong. It is deduced that the lightning echoes shown in Fig. 11 are C-C or I-C discharges because of their great length.

Long C-C and I-C lightning discharges probably occur along paths which lie through regions of the atmosphere which present relatively low resistance. Accordingly it is natural to expect that they would be found at high levels where the atmosphere is less dense, and in regions of high relative humidity and high liquid-water content (Byers, 1952), the latter two conditions of course implying the presence of clouds. If the path of the discharge lies in clouds, it cannot be observed visually nor photographed. Hence the very long discharge, because of the conditions required for its occurrence, has heretofore been utterly impossible to observe directly. One therefore cannot reject the conclusion that these remarkable echoes are caused by extended lightning discharges on the grounds that in the long history of lightning study and observation, strokes of this length have never before been reported.

(a) Physical location of the discharges

As mentioned above, one would intuitively expect on the basis of atmospheric electrical properties that C-C and I-C discharges would occur only in upper levels of the troposphere. There are additional reasons for expecting this to be true. For one thing, whatever may be the exact charge generation and separation process, two factors, namely, turbulence and freezing, seem to be closely associated with the production of lightning. These physical conditions of course are present at high levels in midlatitude summer thunderstorms. Also, when lightning is observed at night in a distant squall line, the upper parts of clouds seem to be illuminated most frequently. When high-potential charge centres develop at low levels, it is more likely that the discharge will be between cloud and ground.

From the radar observations under discussion, there is compelling evidence that most lightning echoes are obtained from heights of about 20,000 feet. Ligda (1950), Miles (1953), Marshall (1953), and others are all in fair agreement on this point. It is of interest to note that pilots flying for the Thunderstorm Project
Fig. 11. Extended echoes from instability line storm I-C or C-C discharges. All pictures printed to the same scale with arrow 27 nautical miles in length. (a) 23-cm radar, Belleville, Illinois, 27 May 1955; (b) 23-cm radar, Fordland, Missouri, 19 April 1955. Note the “root-like” structure of the echo at its southern end. This short stubby branching in a direction opposite to branches in other parts of the echo has been observed several times and may indicate regions of high charge concentration. (c) 23-cm radar, Fordland, Missouri, 11 October 1954. This is the longest continuous echo yet found. If the lightning echo south of the long echo is part of the long discharge (see Fig. 20), this echo is over 100 statute miles in length. Similar gaps have been noted in other echoes and may be significant. (d) Same storm as (c) but from 10-cm radar, Kirksville, Missouri, 11 October 1954. Note weaker lightning echo relative to precipitation echo.
Fig. 12. Three consecutive frames of PPI scope film showing lightning echoes on each frame. Weather station in discharge area reported continuous C-C, I-C, and C-G discharges, all quadrants in light thunderstorms. Arrow lengths about 15 nautical miles. (23-cm radar, Fordland, Missouri, 11 October 1954.)

Fig. 13. PPI scope presentation of two widely separated discharges on the same frame of film. Length of top arrow about 18 nautical miles. (23-cm radar, Fordland, Missouri, 11 October 1954.)
Fig. 14. Examples of "incomplete" lightning echoes. The incomplete echo may result when the discharge begins or ends while in the radar beam. Note similarity of echo in (a) with the example shown in Fig. 8a. (23-cm radars, (a) at Fordland, Missouri, 11 October 1954, and (b) at Belleville, Illinois, 7 May 1955.) Arrow lengths, 20 nautical miles.
Fig. 15. Instability line of 11 October 1954 as detected by radars on opposite sides of the storm about 1800 CST. Lightning echoes indicated by arrows. Region of common coverage shown by arcs. The northern radar is 10 cm, the southern, 23 cm. Note the more efficient detection of light precipitation by the 10-cm radar. The pictures were taken 6 minutes apart to show lightning echoes in the same region of storm. See also Figures 11c,d.
Fig. 16. Basic types of lightning echoes drawn from photographs of actual discharge echoes. Different patterns are probably a result of difference in charge distribution patterns and conductivity of the atmosphere in the volume in which the discharge took place. See text for descriptions.

Fig. 17. "Static" signals from lightning discharges as observed on 23-cm radar. This is called "spoking" and need not be confined to the direction from which the signal comes, but may find its way to the antenna via a reflected path from some building near the radar antenna.
Fig. 20. Same echo as shown in Fig. 11(e) to illustrate how echoes can be enhanced photographically. This is \textit{not} a retouched picture. See text for explanation.
observed that most strikes on their aircraft occurred near the 15,000-foot level (U.S. Weather Bureau, 1949).

Nearly all extended lightning echoes on PPI scopes have been observed at ranges in excess of about 70 miles, and many are detected beyond the 100-mile range. Under normal atmospheric conditions the radar horizon is about 5000 feet above the surface at 100 miles; however, the top of the beam for the radars used to make these observations at that distance exceeds 30,000 feet of altitude (AN/FPS-3). If the echoes originated at low levels, one would expect to see a fair number of them at close ranges, and vice versa if at high levels, because the radar beam increases in height with increased range due to the curvature of the earth and vertical beamwidth. This reasoning is strongly supported by the weight of observational evidence, thus substantiating the hypothesis of the high-altitude origin of extended lightning echoes. Radar detection of high-level discharges may also be enhanced by the longer persistence of the discharge due to the slower recombination time. However, this may not be a very significant factor.

(b) Probability of detection

Suppose a discharge which follows a more or less straight path ten miles in length occurs at a range of 100 miles from the radar. The radar has an infinitely narrow beamwidth and is scanning at the rate of 5/RPM (30° per second). What are the probabilities that the stroke will be swept by the beam if the discharge lasts for 1/2 second?

It is necessary to consider two situations when computing such probabilities: (1) when the path of the discharge is on a line toward the radar, and (2) when the path lies perpendicular to a line from the radar. In the first circumstance, since the radar scans an angle of 15° every 1/2 second, the chance that the discharge will occur while the radar scans it will be 15/360 or 1 in 24. Another way of saying this is that on the average, 1 out of every 24 such strokes should be observed.

In the second instance, the stroke will subtend an angle of about 6° at the radar. For the radar to scan the whole length of the stroke while it lasts, the probability is 1 in 40. For just some portion of the discharge to be observed during its life, the probability becomes 1 in 10. If the radar has an effective beamwidth in the horizontal of 2°, the probabilities are increased slightly to 1 : 21, 1 : 33, and 1 : 9·5 respectively.

From these probabilities it is seen that in a storm where several hundred discharges occur, the chances are excellent that a number of them will be detected with a scanning radar. Fig. 12 shows three consecutive frames of film on which lightning echoes, indicating a remarkably active storm, are recorded. That this storm was particularly active was verified from a surface station observation in the vicinity of the area from which echoes were received. The station reported continuous C-C, C-G, and I-C lightning in all quadrants, in light (!) thundershowers.

The fact that widely separated discharges appear on the same frame of film (Fig. 13) does not mean that the strokes occurred at the same instant. If such were true, it would strongly imply some common triggering mechanism. From the angle subtended by the two echoes at the centre of the scope and the antenna scanning speed, the approximate interval between two such discharges can be
determined. In Fig. 13 the beam scanned one discharge about 1.3 seconds after the other. In visual lightning observation it is frequently noted that strokes occur in the same general area a few tenths of a second apart. This suggests that the initial discharge alters the electrical characteristics of a large volume of the cloud and triggers other strokes.

If the beam is pointing toward the centre of the discharge when it begins or ends, the entire path will not be observed. Fig. 14a,b shows examples of echoes where this is believed to have happened, the inference being based entirely on the incomplete appearance of the echoes.*

If the antenna is scanning in a clockwise direction (north through east) and echoes are detected which have a flat edge (along a radius to the centre) on the end toward which the antenna first started scanning the area, then the stroke began after the beam was scanning the discharge region. If the flat edge is on the other end of the echo, the discharge was completed before the beam swept the entire discharge. Thus assuming clockwise rotation of the antenna, the echo in Fig. 14(b) ended while the beam was in the discharge region.

The film files from which these examples were taken contain records of situations in which more than one radar scanned the general area where discharges were taking place. While invariably in such cases, both radars detect these echoes in the same general area of the storm, in the study of three or four active storms in which dozens of echoes were detected, we have not yet succeeded in finding a case where both radars observed the same discharge as evidenced by its appearance.

One need not seek far to find the explanation for this. While the chance is small that one antenna will be pointing in precisely the right direction when a discharge occurs, the odds that two of them are both correctly oriented are much smaller. If the antennas are rotating in the same direction, say from north through east, and the discharge area lies roughly between the stations, the antenna of one radar will scan the common area in the opposite direction from the other. While this would not affect the probability of detection of discharges which occurred on a line between the stations, it would work to reduce the probability of simultaneous detection of long discharges which were oriented about normal to this line, since the echoes from most long discharges seem to branch in the direction toward which the antenna is turning. This suggests that these discharges propagate at a relatively slow speed which coincides with the rate the antenna is scanning the area and permits all regions of the discharge to be scanned before recombination occurs. Fig. 15a,b shows different echoes from the same region as detected by radars on opposite sides of the precipitation area at about the same time.

(c) Types of echoes

While the echoes exhibit an infinite variety of shapes and forms, many appear to have certain fundamental characteristics which may be useful as the basis

* Because of the manner in which radar time-lapse cameras operate, if the path of the discharge crosses the azimuth on which film is advanced from one frame to the next, part of the echo will be found on one frame of film and part on the following.
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for a system of classification. The following tentative list of types illustrates some of the common basic features:

Type I.—*Echoes due to essentially vertical cloud-to-ground discharges.* These are small, inconspicuous, and generally lacking in interesting detail. Examples are shown in Fig. 9.

Type IB.—Echoes essentially like those in I but with branches.

Type II.—*Direct, straight-path discharges with long horizontal extents.* These echoes travel in essentially straight paths and exhibit few branches, forks, etc. (Fig. 16a).

Type IIB.—Echoes from extended sources, showing branches (Fig. 16b).

Type IIC.—Single-path discharges which show a high degree of curvature (Fig. 16c).

Type III.—*Discharges which show branches extending in several directions from a common single source.* Branches extend in essentially different directions (Fig. 16d).

Type IIIA.—Echoes of the same type as III above, but with branches extending in the same general direction and more or less parallel (Fig. 16e).

Type IV.—*Echoes showing a number of paths over the same extended area.* These have two localized charge centres (Fig. 16f).

In the examination of lightning echoes presented on PPI displays it must be kept in mind that different portions of the echo may differ considerably in altitude, and that, because of factors previously discussed, some portion of the discharge may be above or below the beam and not be detected. For these reasons attempts are not made here to present theories as to the possible charge centre positions to account for the various forms which have been observed. With more detailed information on heights this problem could be more successfully attacked.

(d) *The static signal*

Soon after these echoes were identified, the reason was sought to explain why a strong signal was not received if the radar pulse was being reflected by the ionized column. In spite of the fact that extremely sensitive receivers with highly directive antennas were being employed, more often than not, no evidence of any radiated signal from the discharge could be detected. Such signals, being unsynchronized with the radar PRF would appear as bright radial lines on a line from the centre of the scope toward the azimuth from which the signal was received.

When attention was focused on this matter, careful inspection of film revealed that in roughly 1/4 of the cases there actually was some evidence of the reception of static noise as shown in Fig. 17. This expressed itself on the photographs in various ways, as radial rows of dots, as one or more short radial lines, or as combinations of these expressions.

It is known that lightning discharges are preceded by at least two distinctly different types of leader strokes, the stepped leader and the dart leader. According to LOEB (1948), the stepped leader advances with remarkable regularity (in any
one stroke) at intervals of about 50 microseconds. The progress of stepped leaders has been observed both by photography and oscillography.

The electron beam of the PPI scope moves a distance corresponding to 10 nautical miles (on the scope) in 126 microseconds. Accordingly, if the advance of the stepped leader is accompanied by detectable signals, discrete intensifications, separated at intervals of about 5 miles in range or half the distance between successive range markers, should be observed. Where dots are visible in line with lightning echoes, this is found to be the case, and it is hypothesized that

![Diagram from Schonland, Hodges, and Collens, of oscillograms of stepped leader strokes of the x type with schematic indication of the events correlated therewith underneath. Potential in the A part of the figure is upward and t is plotted along the axis of abscissae. Note the oscillations produced by each step and the intense oscillation B caused by the return stroke. The occurrences to the right indicate successive strokes with dart leader with no stepping.](image)

the dots are produced either by successive advances of the stepped leader in its channel or the termination of current flow at the advancing tip. This is manifested by intense illumination which can and has been photographed in some discharges.

Successive discharges along the old channels usually are preceded by a dart instead of a stepped leader. The dart leader advances without stepping along the ionized path left by previous main discharges at a velocity of about $2 \times 10^8$ cm/sec or $2 \times 10^3$ km/sec. For a discharge 5 km long, the time required would be about $2.5 \times 10^{-3}$ sec which, if producing a signal, would result in a brightening of the sweep for about 200 nautical miles. Such long spokes have not yet been observed. After the stepped leader has established this channel, the main discharge occurs, advancing with a speed of from $3 \times 10^3$ to $10^{10}$ cm/sec (Loeb, 1948). At this time the main, powerful, static signal is observed as shown in Fig. 18. The speed with which this discharge takes place would serve to emit signal which would brighten the sweep for about 15 nautical miles for a discharge 20 km long and a speed of $10^{10}$ cm/sec. The short dash shown in Fig. 17 is about this length.

There are at least three explanations why such static signals are not frequently observed: (1) radiated power at the radar frequency is too low; (2) the antenna may not be properly oriented; (3) the signal may be received during the scope rest period.
The writer in general favours the third explanation since the proportion of signals noted seems to be of the right magnitude considering this factor alone. The explanation resides in the relationship between pulse repetition frequency and scope range setting. The relationship is such in cases studied that the sweep takes about 1/4 of the time interval between successive transmitted pulses to travel from the centre to the edge of the scope. Any signals received during this time can be presented. After the electron beam reaches the edge, no more signals can be presented until the next pulse is transmitted and the cycle is repeated. With a range setting of 150 nautical miles and a PRF of 200/sec, signals can be presented for about 1.8 milliseconds, and the scope is then inactive for about 3.2 milliseconds until the next pulse is transmitted.

Two factors probably contribute to the somewhat surprising weakness of signals from discharges as observed on PPI scopes. The first resides in the very narrow bandwidths (of the order of 0.5 megacycles) of the receivers employed. Radar receivers are of the superheterodyne type and must be very sharply tuned. Accordingly, only that energy of the lightning signal which lies in this very restricted portion of the spectrum is accepted, amplified, and presented on the scopes. The second factor is that the lightning signal, at least at microwave frequencies, is of a comparatively short duration, and hence it will only brighten a single trace of the electron beam on the PPI scope. The brightness of an echo or signal on the PPI scope is not only a function of the original signal strength, but also the number of times it is displayed at the same position on the phosphor of the scope. This “integration factor” is very important in the presentation and detection of short duration signals (Ridenour, 1947). It should be borne in mind that lightning signals at microwave frequencies will be constrained to travel in the same general paths as those followed by the radar pulses and echoes. Therefore, only those signal-emitting portions of the discharge which are in the radar beam will be detected. These considerations may operate in limiting the range of reception of very high frequency and ultra-high-frequency “sferics,” i.e.: they must originate at a point in the atmosphere above the radio horizon.

6. The Mechanism of the Long Discharge

The reader will perhaps find the concept of discharges 50-100 miles long somewhat difficult to accept. However, if one can conceive of C-C discharges of 5 km across a clear air gap, and such have been observed by Gunn (1954), it is not difficult to demonstrate that high level, I-C discharges of ten times this length are not unreasonable. If the discharge is at high level and its path entirely in clouds, the resistance along the path is appreciably reduced because of both decreased pressure and the presence of liquid water.* Hence lower breakdown voltages are required for the charge to jump between the two centres. In addition to this, Newman (1953) suggests a mechanism by which he was able to produce sparks in the laboratory between two gaps with about 1/50 of the normal breakdown voltage. His suggested circuitry for long discharges is shown in Fig. 19.

It is well known that the great majority of C-G discharges occur between a

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* The breakdown voltage at 20,000 feet is roughly 50% of that at sea level due to decreased pressure (Smithsonian Physical Tables, 1934).
negative cloud base and a positive ground. The leader stroke in such cases progresses from the cloud (which contains a higher concentration of charges and is considered to be a point source) to the ground plane. There are several observations which show that before the tip of the advancing step leader reaches the ground, a positive streamer starts from the ground toward the descending negative leader and meets it at a place called the junction point. Branching occurs in the direction of advance of the leader whether positive or negative.

In a number of photographs of long lightning echoes, distinct branching is evident (Fig. 11c). While these are branches which may be several miles or tens of miles in length, it is suggested that they also indicate the direction of advance of the leader. Where such branching is evident, it invariably appears to be in the direction from heavy to lighter precipitation.

Unfortunately, from the radar observation alone it is not possible to determine whether the leader stroke has its source in a positive or negative charge centre. However, it may be noted that roughly one half of the potential difference is required for electrical breakdown between a positive point and a negative plane than vice versa. This is given as the explanation for the high frequency of lightning strokes on the Empire State Building which permits a high concentration of positive charges to accumulate beneath the negative cloud base so that the building itself acts as a point source. In the case of C-G and I-C discharges we have a charged field rather than a plane, but since the breakdown potential depends upon the resistance offered to the tip of the advancing leader rather than the relative concentration of charges, conditions may otherwise be the same. The theory has been advanced that in isolated thunderstorms the top of the cloud has a

Fig. 19. Newman's (1953) hypothesis of the circuit of long discharges. With such a circuit he was able to produce discharges with about 1/50 the potential difference required for an "open-gap" spark.
positive charge relative to the cloud base, the cloud forming what might be con-
considered a dipole. If the charge-separation process is the same in a line of thunder-
storms, the high C-C and I-C discharges might well originate in positive charge
centres from the tops of the heavy precipitation areas back toward the regions of lighter precipitation, while the negatively charged bases discharge to the
ground.

The cloud droplets must themselves be closely associated with the charge
centres rather than the raindrops; otherwise we would have evidence of C-G
discharges which terminated below the cloud base in the clear air or in the pre-
cipitation column. One also wonders, considering the dipole distribution of
charges in the isolated thundercloud, whether there might not be many discharges
in the cloud from base to top which have heretofore escaped observation.

7. SUGGESTIONS FOR FUTURE WORK

As is to be expected, a discovery such as has been described above, presents
more questions than it answers and opens up a powerful new line of attack on
the subject. If a well-organised programme were set up, the writer is convinced
that significant progress could be made toward the eventual solution of the
following problems:

1. Identification of the regions in clouds where discharges originate. (Locating
these regions would be of great help in explaining mechanisms of charge
separation, etc.) It may be mentioned here that any satisfactory explanation
of the lightning mechanism must provide for the frequency of extended
discharges in the areas of comparatively light precipitation or where only
clouds are present. It would be very interesting to compare the locations
of charge centres as described by REYNOLDS and NEILL (1955) with radar
observations. Certainly good radar observations would be of enormous
assistance in the interpretation of surface observations of the type des-
cribed by REYNOLDS and NEILL (1955). The radar observations may be
made at stations some distance from the surface network.

2. Illumination of the relationships between sferics and the lightning
mechanism.

3. Establishment of the rate of recombination after termination of the main
discharge.

4. Advancement of the understanding of the nature of cloud-to-ionosphere
discharges reported by MALAN (1951) and their relationship to C-C and
C-G discharges.

5. Advancement of knowledge concerning the nature of sferics associated
with tornadoes (JONES, 1951). Though such have not been observable,
the writer believes that many discharges may take place between the top
and base of isolated thunderstorms, perhaps more than go from cloud base
to ground. Suitable radar observations would show this.

There are undoubtedly many other topics which will suggest themselves to
authorities in the field of lightning research. The possibility of detection and
study of corona discharges and hydrogen atom radio energy radiation at 21 cm
wavelength (Bok, 1954) which may accompany lightning discharges is one such.

Fortunately, a well-planned research programme should encounter little difficulty in obtaining large amounts of first class data in a single thunderstorm season. Presently available radar equipment may be slightly modified and observational techniques adapted in the following ways to increase the quality and quantity of data:

1. The pulse length should be shortened as much as possible thus allowing for the maximum increase in the transmitted power. More important, reducing the pulse length serves to reduce the power of the echo from precipitation without appreciably reducing the lightning echo. Accordingly, it would increase the number of observations in areas of light and moderate rain.

2. After the lightning area is located, this region only should be sector scanned by the radar (lightning is usually confined to a fairly restricted zone along a front). If the sector from which lightning echoes are received is 60° wide, by sector scanning, the number of strokes observed may easily be increased by a factor of 5 or 6. The use of off-center PPI scopes is recommended to decrease the scale of the scope and improve resolution.

A simplified method developed in our laboratory for detecting lightning echoes on time-lapse PPI scope film is the following: After the film has been developed, a copy is made of opposite polarity to the original (positive if the original is a negative and vice versa). The two film strips may then be matched together, displaced by one frame, placed in the copying machine with a third, unexposed film strip, and a copy made of the matched strips. The resulting film will be a negative showing very little except the lightning echoes which will be quite dark in contrast with the rest of the scope image. By use of this technique, lightning echoes, which might otherwise be overlooked because of being embedded in regions of relatively intense precipitation echo, may be located with comparative ease. A print from such a film showing one of the lightning echoes observed in Fig. 11 is shown in Fig. 20.

If the video signal during each complete scan of the antenna can be recorded (on tape or memory drum and subtracted from that of the following scan, lightning echoes could be displayed alone on a special long persistence indicator at the time of observation. This would be of use in immediate location of electrically active regions of storms which might be of interest to flyers, forest-fire observers, and meteorologists.

3. The PRF should be increased to the maximum amount commensurate with scope range settings to increase the number of echoes received.

4. The use of auxiliary equipment such as a pulse integrator (Ligda, 1950), drum-type cameras, oscilloscopes, signal analysers, field-strength meters, and sferics equipment, where available, is more-or-less assumed. The effects obtained when special radar circuitry, such as MTI (moving target indication) and FTC (fast-time constant) are used, should be explored. In the opinion of the writer, lightning echoes will be eliminated by MTI techniques.

5. Associated vertically scanning and V-beam radars should be used to obtain height information simultaneously with the PPI displays. The AN/CPS-4 (10 cm) radar which has a fairly broad beam in the horizontal would be a suitable radar to use for this purpose.

The most complex and extended discharges, about which nothing is known,
The radar observation of lightning

seem to be most often observed in connection with line squalls. Probably these could best be studied in the midwestern United States during the spring months of the year. Due to the flat terrain, good radar coverage can be obtained with little difficulty in this area.

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References


Byers H. R. 1953 *Thunderstorm Electricity*, University of Chicago Press, 161, 163, 188.


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<thead>
<tr>
<th>Author/Institution</th>
<th>Year</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newman M. M.</td>
<td>1953</td>
<td>The lightning discharge propagation mechanism effect on atmospheric wave forms, <em>Supplement to the Proceedings of Conference on Radio Meteorology</em>, University of Texas Press, Austin, Texas, V-5.</td>
</tr>
</tbody>
</table>