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# OBSERVATIONS OF LIGHTNING PROCESSES USING VHF RADIO INTERFEROMETRY

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## ABSTRACT

A single-station, multiple-baseline radio interferometer has been used to locate the direction of VHF radiation from lightning discharges with microsecond time resolution. Radiation source directions and electric field waveforms have been analyzed for various types of breakdown events. These include initial breakdown and 'K'-type events of in-cloud activity, and the leaders of initial and subsequent strokes to ground and activity during and following return strokes. Radiation during the initial breakdown of a flash and in the early stages of initial leaders to ground is found to be similar. In both instances the activity consists of localized bursts of radiation that are intense and slow-moving. Motion within a given burst is unresolved by the interferometer. Radiation from in-cloud K-type events is essentially the same as that from dart leaders; in both cases it is produced at the leading edge of a fast-moving streamer that propagates along a well-defined, often extensive path. K-type events are sometimes terminated by fast field changes that are similar to the return stroke initiated by dart leaders; such K-events are the in-cloud analog of the dart leader-return stroke process.

Radiation from the above processes is produced exclusively by negative-type breakdown, in agreement with the findings of other investigators. Radiation during return strokes initiated by dart leaders sometimes progresses away from the top end of the leader channel as an apparent positive streamer. These streamers appear to establish channel extensions or branches that are later traversed in the opposite direction by negative-polarity streamers of K- and dart-leader events. Finally, a new phenomenon has been identified whose electric field waveform resembles that of a highly branched, initial-type leader, but which transports negative charge horizontally and slowly away from the eventual channel to ground. The breakdown is observed to be terminated by a fast dart leader to ground from the source region of the activity.

## INTRODUCTION

Radio interferometry is continuing to provide a powerful technique for studying lightning discharge processes. The use of interferometric techniques for studying lightning has been discussed in detail by other investigators (e.g. Hayenga [1979], Richard and Auffray [1985], Rhodes [1989]). In this paper we present results from a two-dimensional interferometer system of different types of breakdown processes that occurred during two multiple-stroke discharges to ground, one of which was preceded by extensive intracloud activity. The discharges occurred over Socorro, New Mexico, during the 1988 summer thunderstorm season.

## THE INTERFEROMETER SYSTEM

Interferometeric techniques determine the direction of arrival of radiation signals by measuring the phase differences of the radiation incident upon an antenna array. The array used in this study consisted of five antennas configured to form short- and long-baselines along each of two orthogonal directions in a horizontal plane. The long baselines were $4\lambda$ in length and provided accurate but ambiguous estimates of the source direction. The short baselines were $\lambda/2$ in length and provided coarse but unambiguous determinations of the source direction that were used to resolve the ambiguity of the long-baseline measurements.

The interferometer operated at a center frequency of 274 MHz with a 6 MHz bandwidth and a time resolution of 1 microsecond. Phase data from each of the short and long baselines was continuously recorded on a high density digital recorder along with separate measurements of the logarithmic RF power and fast electric electric field change. The electrostatic (slow) field change was sampled with 20 $\mu$s time resolution and recorded along as part of serial housekeeping information. The decay time constant of the fast and slow electric field change measurements was 0.1 ms and 10 s, respectively. Data from lightning flashes of

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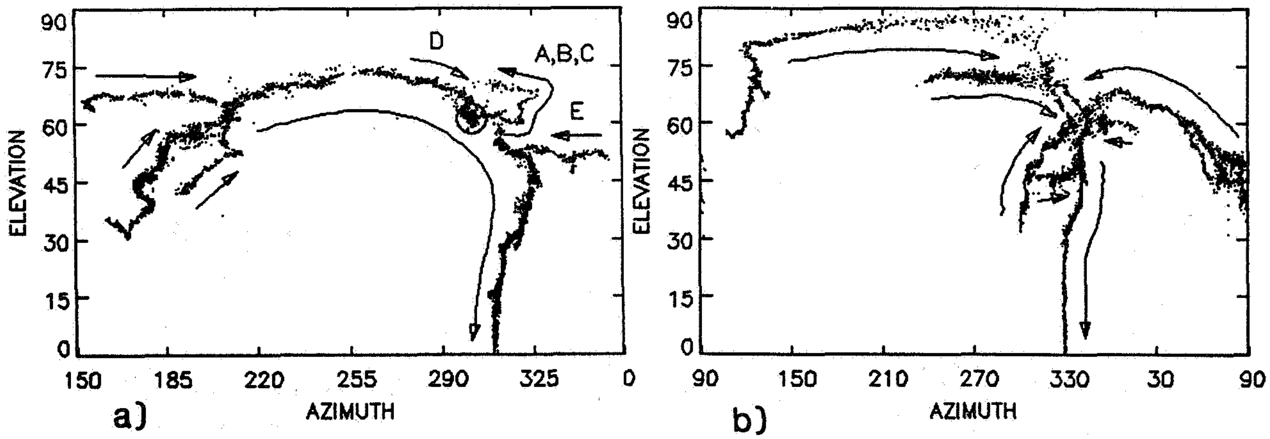

**Figure 1: a.) Overview of Flash 153844. Composite of a K-event during the preliminary intracloud activity, dart leaders for strokes 3, 4, and 5, and several in-cloud streamers between stroke 4 and 5. b.) Overview of Flash 155325. Composite of leaders for strokes 3, 4, 7, 8, 9, and several streamers after continuing current stroke 8.**

interest were played into an analysis computer where they were analyzed in detail using interactive graphics software.

## DATA AND RESULTS

Figure 1 shows composites of selected results for the two flashes, which occurred at 15:38:44 and 15:53:25 on Day 236 (August 23), 1988. Flash 153844 lasted about 1.2 seconds and consisted of 360 ms of intracloud activity followed by 5 strokes to ground. Flash 155325 lasted about 1 second and began with the initial leader to ground; it produced 9 strokes down the same channel. Both discharges went to ground 5-10 km north of the interferometer site and had in-cloud channels which developed toward and on the opposite side of the interferometer. The strokes of both flashes were of normal polarity, i.e. they lowered negative charge to ground.

The composites provide an overview of most of the channels and branches of each flash. The figures show the source directions in azimuth-elevation format and graphically depict the channel to ground. Cloud base was between 20° and 30° elevation along the vertical channel to ground, so that the channels above this point were inside the storm. The discharges are seen to have been substantially branched inside the cloud. Flash 153844 (Figure 1a) began at the location denoted by the circled region and established channels A – E during the intracloud phase of the flash. The initial leader to ground began near the flash start point and established the channel followed by subsequent leaders and strokes. The third stroke initiated a continuing current that originated along the D and E segments. Later strokes originated farther along the main left-hand channel on the other side of the interferometer.

Flash 155325 exhibited substantial and complicated branching into the top of the vertical channel to ground. The branches were followed by different strokes of the flash and by k-events late in the flash. The left branch extended overhead and past the interferometer site; other branches connected into the channel to ground from different directions.

### INITIAL BREAKDOWN

Flash 153844 began with a long interval of in-cloud breakdown that lasted about 360 ms and culminated in the development of an initial leader to ground. Figure 2(a) shows radiation source locations for the initial 70 ms of the in-cloud activity, termed interval A. Radiation during the first 60 ms of A (labelled A1) consisted of series of bursts whose sources drifted slowly in the direction of increasing azimuth, as indicated by the arrow. During each burst the radiation sources were localized and their extent or motion was not resolved by the interferometer, but the centers of successive bursts continually moved in the direction

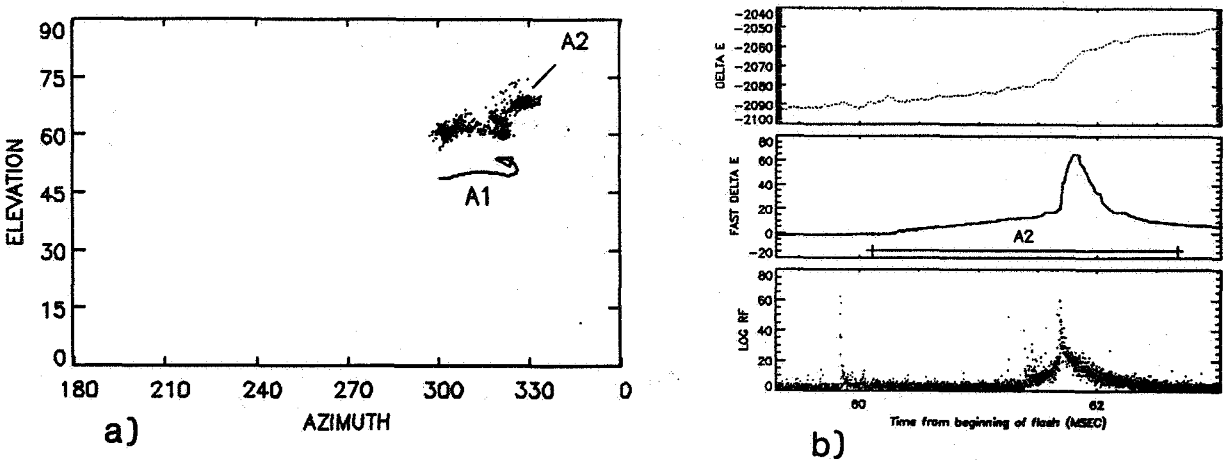

**Figure 2: a.) Activity during the initial 70 ms of breakdown for Flash 153844. b.) Radiation and electric field waveforms for event A2 that completed the initial A activity.**

**of progression. The activity culminated with a strong burst of radiation just beyond the end of the *A*1 activity, labelled A2.**

**Figure 2(b) shows time waveforms for the A2 event. The event began with a brief burst of radiation from a localized region on the edge of A2 closest to A1. The electric field subsequently increased at a steady rate until, 1.5 ms later, radiation developed just beyond the region of the initiating burst and increased in intensity until a large, rapid electric field change occurred. During this time the radiation sources continued to be displaced away from the location of the initial burst and continued the overall progression of breakdown away from the flash start point.**

**The electric field change was positive during the entire A event, indicating that negative charge was transported away from the observation site, or, equivalently, that positive charge was transported toward the site. Later results for the flash show that the A activity progressed away from the observation site; the activity therefore transported negative charge in its direction of progression. (The negative-going change at the end of fast electric field record in Figure 2b was due instrumental decay, of 0.1 ms time constant.)**

**Assuming that the preliminary activity was 5-6 km above ground level (AGL), as found by Krehbiel et al. [1979] in a similar storm from the same area, and noting that the sources were at about 60° elevation, we infer that the initial activity was about 3 km plan distance from the interferometer. From this and from the angular extent of the source motion, the projected extent of the A progression was about 1 km. The projected average speed of progression was therefore about $1.5 \times 10^4$ m/s.**

## K-TYPE EVENTS

**Figures 3 and 4 show results for two K-type events which occurred 212 and 231 ms into Flash 153844. Both events retraced the path of the A activity of Figure 2 and extended the A path. The first K-event is labelled C and is shown in Figure 3. It began with 500 $\mu$s of localized radiation in the flash start region (C1) and continued after a brief lull with a well-defined streamer (C2, the first streamer of the flash) that rapidly retraced the path of the A activity and extended the far end of the channel upward in elevation and backward in azimuth. The electric field increased continuously during the C2 streamer progression, again indicating the transport of negative charge away from the interferometer. As the streamer reached the end of its extent the radiation dropped abruptly in amplitude and the fast electric field signal saturated. Lower-amplitude radiation persisted for about 100 $\mu$s at the far end of the streamer path, then a final burst of radiation (C3) progressed backward along the vertical segment midway along the streamer channel. The entire event lasted about 1 ms, typical of K-events.**

**Results for K-event D are shown in Figure 4. This event substantially extended the breakdown to the left of the flash start region. Two precursor events, D0 and D1, occurred at a distance beyond the flash start region and were directed toward the flash start region. D0 was a short streamer that propagated into the starting point of D1; D1 was a slightly longer and more intense streamer that propagated into**

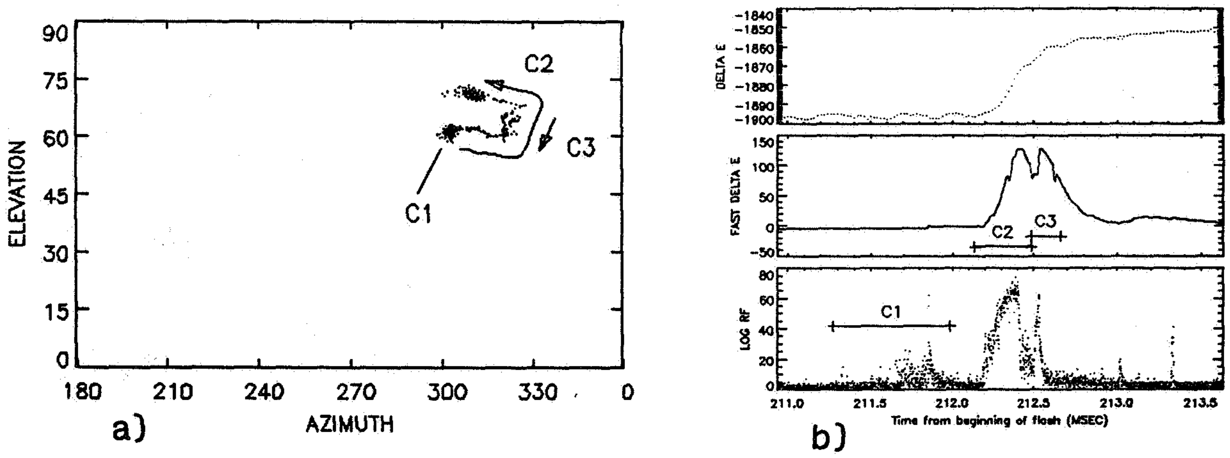

Figure 3: K-event C, 212 ms into the preliminary activity of Flash 153844.

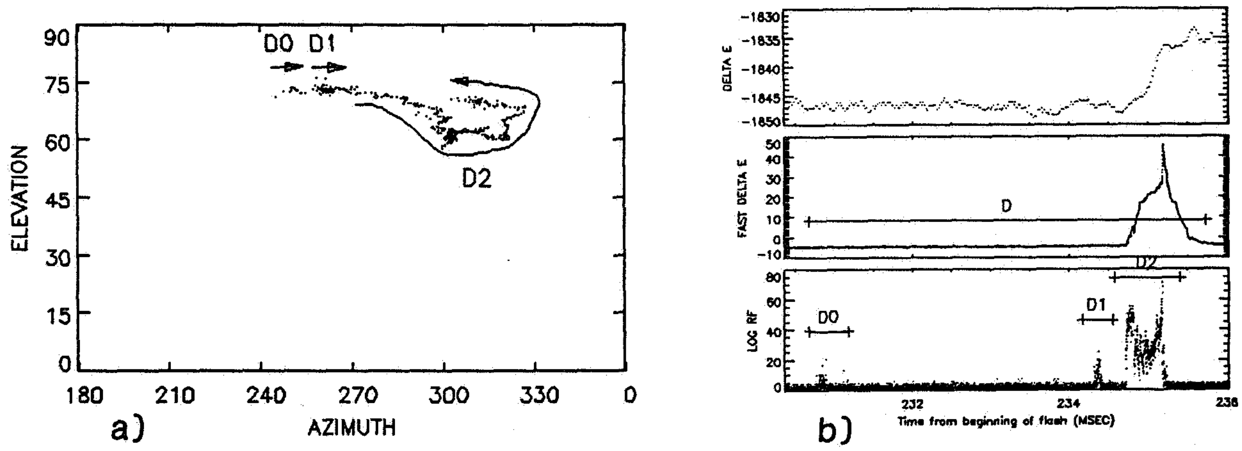

Figure 4: K-event D, 231 ms into the preliminary activity of Flash 153844.

the starting point of the final D2 streamer. D2 progressed rapidly into the flash start region and (without pause) along the full extent of the C channel. When D2 reached the end of its extent, a fast field change occurred and the the radiation abruptly dropped in amplitude. The fast field change indicates that the current rapidly increased along the D channel.

Event D enables the polarity of the streamers to be clearly established. As will be seen later, the channel extension to the left of the flash start point (D0, D1, and the initial part of D2) was traversed in the same direction by negative-polarity dart leaders later in the flash. The electric field change of the dart leaders had the same polarity as the D streamers, indicating that the C and D streamers (as well as the A activity) were also of negative polarity. Knowing the polarity of the C and D streamers, the fact that each produced a positive field change implies that they progressed away from the interferometer site. The fact that the elevation angle of the streamers increased at their far end therefore indicates that they developed vertically upward in the cloud, or had an upward component. (The alternate possibility, that the elevation increase was caused by horizontal motion toward the interferometer, would have produced a field change of the opposite polarity.)

Assuming that the total length of the C streamer was 2-3 km, its velocity is inferred to have been $1 - 1.5 \times 10^7$ m/s, several orders of magnitude greater than that of the A activity. The velocity of the D streamer was comparable to that of C.

Event D is significant for another reason. A careful analysis of the observations prior to D has shown that no radiation occurred along the channel extension established by D0, D1, and the initial part of D2.

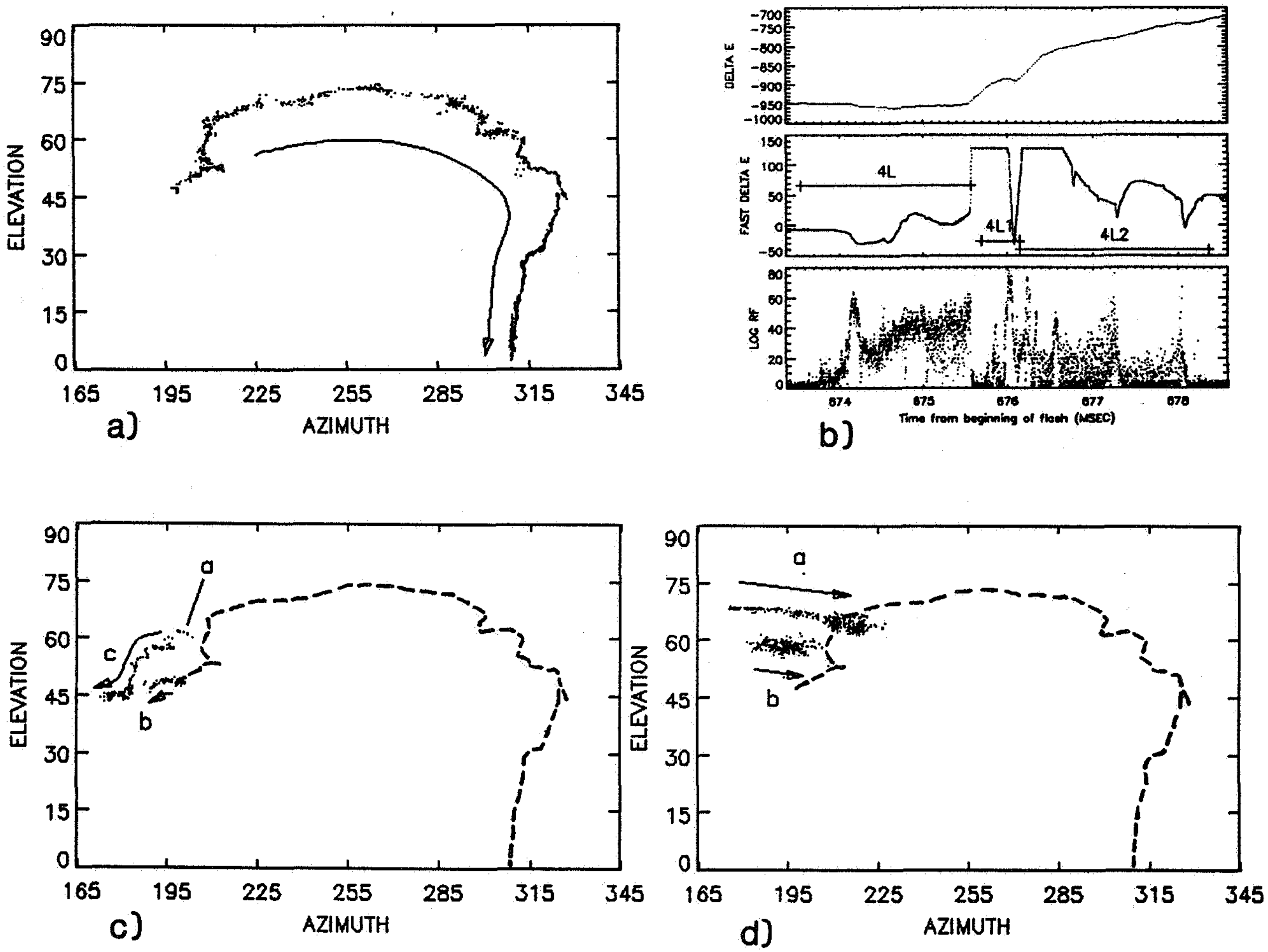

Figure 5: Results for the 4th stroke of Flash 153844. a.) Radiation sources for the dart leader; b.) time waveforms; c.) radiation sources at the end of the return stroke; d.) radiation sources following the return stroke.

The channel appeared to be extended by breakdown which began at a distance from previously-detected activity, and the extension streamer was fast even though no prior radiation was detected along the first half of its path. It is significant that several breakdown events preceded the final streamer; each appeared to enhance the local electric stress for the subsequent event.

## DART LEADERS AND RETURN STROKES

Figure 5a shows radiation sources of a typical dart leader, in this case for the leader of the fourth stroke to ground of Flash 153844. Time waveforms for the leader are shown in Figure 5b. Dart leaders radiate strongly at their advancing tip and usually progress continuously along a well-defined channel to ground. In this instance the leader required 1.7 ms to reach ground and propagated over a substantial horizontal distance within the cloud before turning vertically downward to ground. The leader began south of the interferometer and propagated overhead and to the north, reaching a maximum elevation of about 75° while passing overhead. The radiation ceased at the beginning of the return stroke, whose electric field change saturated the fast field change channel.

During the return stroke the radiation remained quiet for about 200 $\mu$s, after which time three radiation bursts occurred of increasing intensity (interval 4L1). The radiation sources for the bursts are shown in Figure 5c and progressed rapidly away from the far end of the leader channel. The field change of the final burst was strongly negative, indicating that positive charge was transported along the channels away from the interferometer. The events are therefore inferred to have been positive-type streamers and appeared to

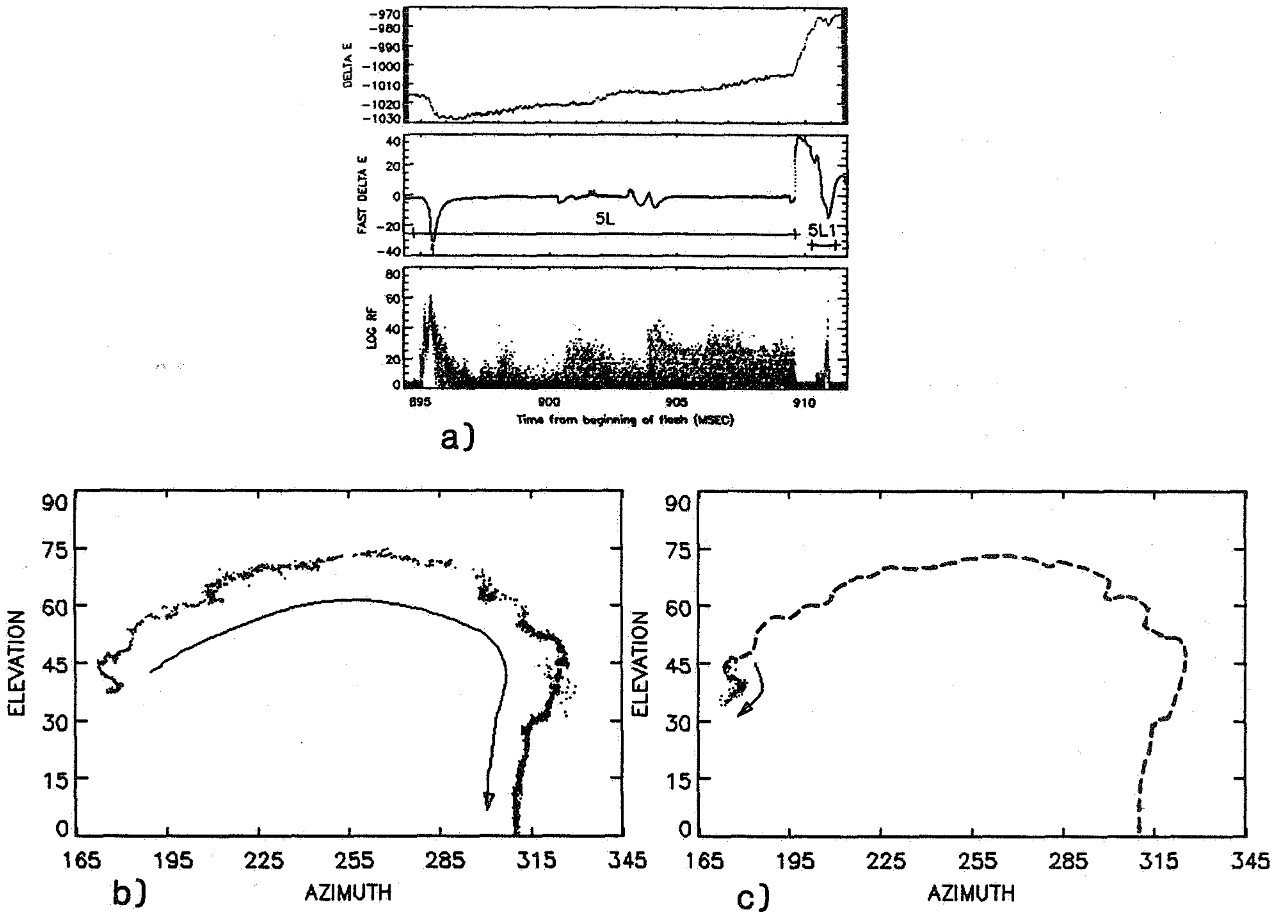

**Figure 6: Results for the 5th stroke of Flash 153844. a.) Time waveforms, b.) radiation sources for the leader, c.) radiation sources at the end of the return stroke.**

occur when the return stroke arrived back in the source region of the leader. Careful analysis of the activity prior to the fourth stroke indicates that no radiation occurred along the *a–c* branch or the *b* extension; therefore the streamer events appeared to create the branch and the channel extension. As we later show, the *a–c* branch was traversed by the next stroke of the flash.

Figure 5d shows radiation source locations for the remainder of the stroke (interval 4L2). For about 2 ms following the 4L1 bursts, negative-type streamers repeatedly propagated along two other branches into the channel of the dart leader and return stroke. These branches had been active during the interstroke interval between the third and fourth strokes. The electric field records of Figure 5b show that these events renewed the current flow in the channel and indicate that charge transported into the channel by the streamer events went all the way to ground. That no radiation was detected along the main channel during the return stroke or during the 4L2 events is typical and indicates that radiation is not produced by current flow along already conducting channels, but predominantly by breakdown processes.

The total length of the 4th-stroke leader is estimated to have been about 20 km, and the average speed of the leader as about 1–1.5 $\times 10^7$ m/s. This is similar to the speeds of the K-streamers. The return stroke is estimated to have taken 200 $\mu$s to travel back along the channel (equal to the duration of the quiet period), and therefore travelled at a speed of about $1 \times 10^8$ m/s.

Figure 6 shows results for the fifth and final stroke of Flash 153844. The leader for the stroke was initiated 220 ms after the fourth stroke and took a relatively long time to progress to ground (14 ms). The leader travelled rapidly (about $10^7$ m/s) until reaching its approximate mid-point, close to the highest elevation angle, and then progressed more slowly (less than $10^6$ m/s) to ground. The initial segment was along the a–c branch established at the end of the fourth stroke; this channel was retraced and extended

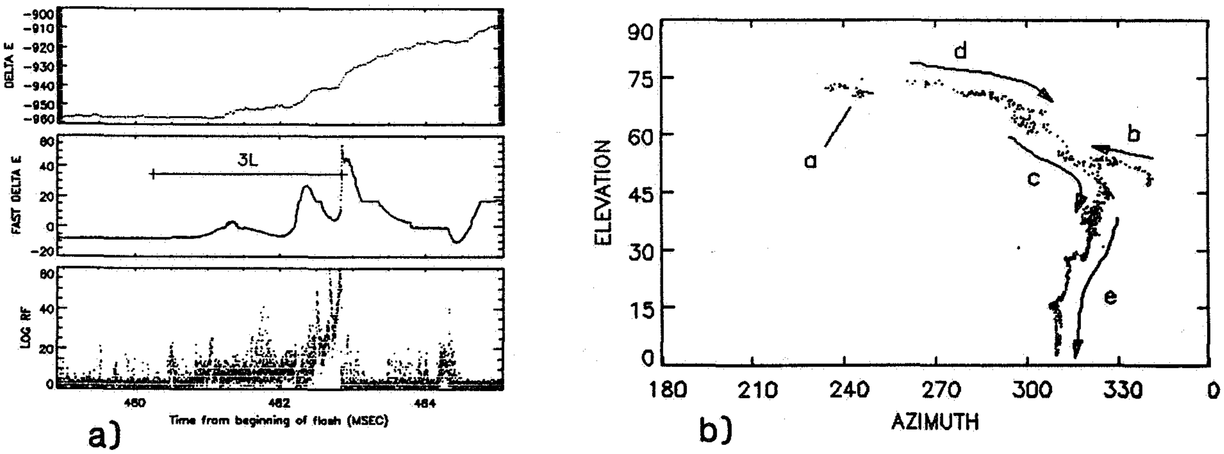

Figure 7: Results for the 3rd stroke of Flash 153844, which initiated a continuing current. a.) Time waveforms, b.) radiation sources for the leader.

numerous times during the intervening interstroke interval. The return stroke was less intense than the fourth stroke and did not saturate the electric field records. It was accompanied by a quiet period of about 1 ms duration in the radiation waveform, and then by a single burst of radiation back in the leader source region. As during the fourth stroke, the radiation sources of the burst progressed away from the source region of the leader and produced a field change indicative of a positive streamer. Assuming that the streamer was initiated by the arrival of the return stroke back in the source region, the speed of the return stroke was about $2 \times 10^7$ m/s, a factor of five slower than the speed of the previous, more energetic stroke.

Figure 7 shows results for the leader of the third stroke of Flash 153844, which initiated a continuing current discharge to ground. The leader lasted about 2 ms and was comprised of an unusually complex sequence of breakdown events. The time sequence of the events is as indicated in the figure. Upon contacting ground, the radiation decreased in amplitude but, unlike the later strokes, did not become quiet. Rather, it radiated intermittently during the beginning of the return stroke, from successively higher points along the channel as the upward-moving return stroke encountered apparent branch points on the channel. Several M-type events occurred during the continuing current, the first of which can be seen just after 484 ms in Figure 7a. Radiation from this M-event began at a distance to the right of the right-hand branch and progressed into the branch, indicating that this was the charge source for the increased current flow to ground. Later M-events originated from the far end of the left-hand branch. The continuing current was therefore supplied with charge along both leader branches. Branching or leader complexity is not a necessary component of continuing current discharges, however, as a continuing current event during Flash 155325 was initiated by a simple dart leader.

Figure 8 shows results for one of the dart leaders of Flash 155325 and illustrates another type of post-leader radiation that was observed in several strokes of that flash. In particular, the radiation dropped abruptly in amplitude at the beginning of the return stroke but otherwise continued through the time of the return stroke, uninterrupted by quiet periods. After the leader reached ground, the radiation source switched immediately to region $a$ to the left of the top of the leader. 150 $\mu s$ later, at about 100.9 ms, two larger-amplitude bursts occurred at the top of the leader channel ($b$) that signified the arrival of the return stroke at this location. (The time delay corresponds to a return stroke velocity of about $0.5 - 1 \times 10^8$ m/s.) Because the $a$ radiation preceded the arrival of the return stroke at the top of the channel and was smaller in amplitude than the final leader radiation, it appeared to be produced by breakdown that was concurrent with the leader and that was revealed only when the stronger radiation of the descending leader was extinguished. No direction of progression or charge transfer could be determined for the $a$ activity, as the source locations were dominated by scatter and the fast electric field record had saturated. The $a$ branch became the path of the leader for the next stroke of the flash; this is similar to results obtained for the stroke of Figure 5 with the difference in this case that the path was established as part of the leader activity, rather than by the return stroke.

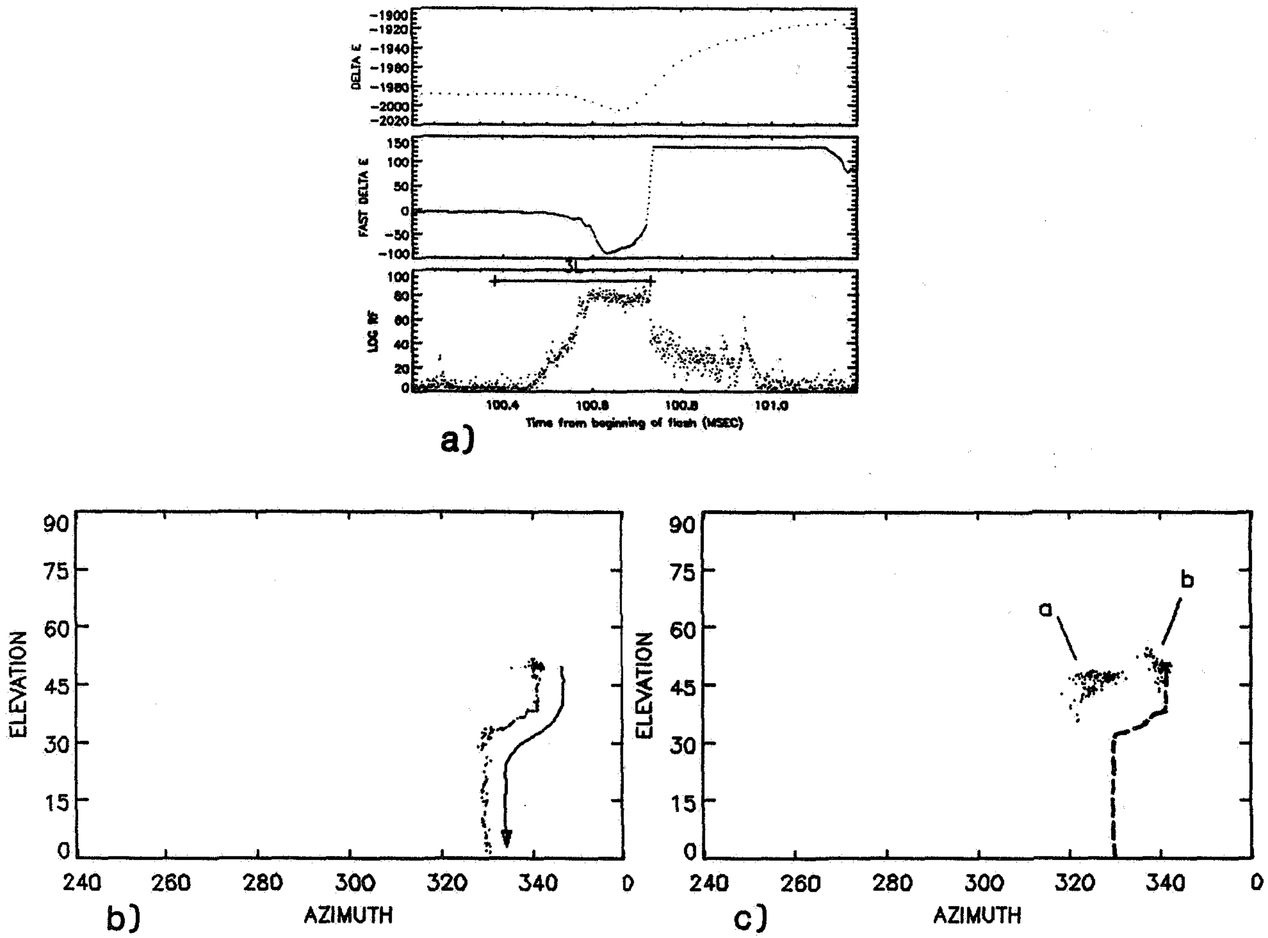

Figure 8: Results for the leader and return stroke of the 3rd stroke of Flash 155325. a.) Time waveforms, b.) radiation sources for the leader, c.) post-leader radiation sources.

## INITIAL LEADER AND RETURN STROKE

Figure 9 shows time waveforms and radiation source locations for the initial leader to ground of Flash 153844. The total duration of the leader was 50 ms. The leader began abruptly with intense and localized bursts of radiation that began in the start region S and progressed slowly but steadily away from the start region along a relatively well-defined channel. As in the initial breakdown of Figure 2a, the extent or motion of the sources during a given burst was unresolved by the interferometer. About halfway through the leader, when the sources had moved down to about 30° elevation, the bursts increased in frequency and the radiation became continuous and more widespread. The radiation continued in this manner, increasing in intensity until reaching ground. The increased width of the channel below 30° elevation is indicative of branching; this is confirmed by results for the subsequent strokes of the flash, whose dart leaders delineated several slightly different branches along the lower channel to ground.

Superimposed on the main leader activity were a number of fast streamers that progressed into the leader start region, as shown in Figure 9b. The occurrence of these events can be seen in a time plot of the phase data, shown in Figure 9c. The streamers funneled negative charge into the developing leader along several channels that were established during the preceding intracloud activity.

The average speed of progression of the initial leader to ground is estimated to have been about $1.5 \times 10^5$ m/s. It is not known when the leader became stepped, as the electrostatic component of the field change dominated over the radiation component due to the close proximity of the flash. Waveforms similar to those of Figure 9 are obtained for the initial leaders of other flashes (e.g. Rhodes and Krehbiel [1989]).

Figure 10 shows expanded time waveforms and source locations for a 2 ms time interval at the end

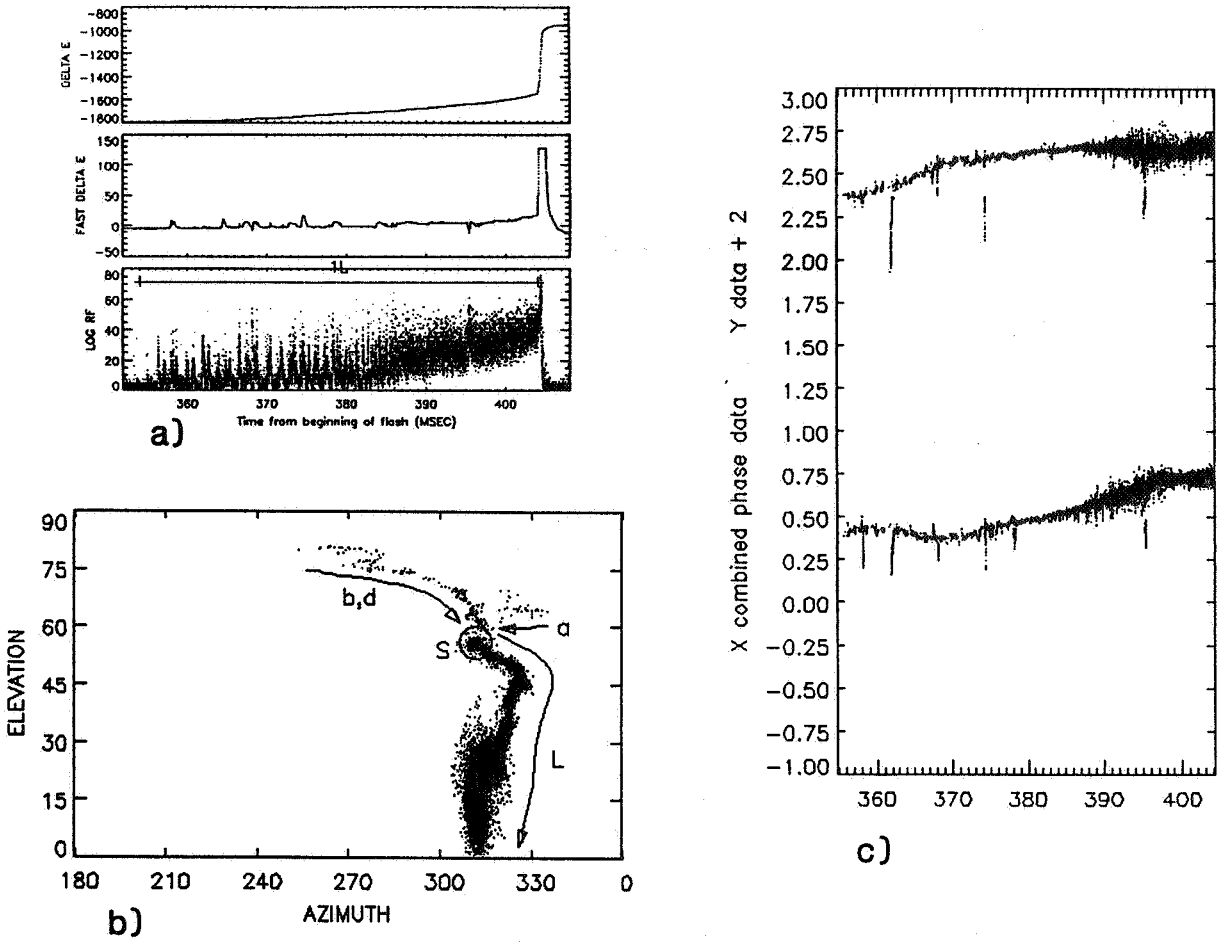

**Figure 9: Results for the initial leader to ground of Flash 153844. a.) Time waveforms; b.) radiation source locations; c.) phase data vs. time.**

**of the initial leader through the time of the return stroke. The return stroke field change lasted about 0.6–0.7 ms and had several components. At its beginning, the fast field record shows the occurrence of a 20 $\mu$s precursor change, indicative of an upward-moving streamer that completed the connection to ground. The ensuing return stroke quickly saturated the fast field change record, but, as seen on the less-sensitive slow field change record, produced only a small electrostatic field change. A larger stroke occurred 200 $\mu$s later, simultaneous with a noticeable increase in the radiation intensity.**

**At the onset of the return stroke, the radiation amplitude did not change significantly from that of the leader but the source locations indicate that a sequence of two upward-moving events (*b* and *c*) occurred along the lower part of the channel. These are seen just after 404.1 ms in the elevation–time plot of Figure 10c, and initiated the small-amplitude initial return stroke. The larger-amplitude stroke just after 404.3 ms was accompanied by even stronger radiation that also moved rapidly up the lower part of the channel (*d*). The radiation moved up to about 30° elevation in about 100 $\mu$s; after this it abruptly switched to higher elevation and progressed backward along the right-hand feeder channel of the leader (*e*, *f*). No radiation was detected along the unbranched upper half of the leader channel. The concentrated sources labelled *a* at the bottom of the channel in Figure 10b were produced at the end of the leader; no source motion was detected during the final connection event.**

## A NEW TYPE OF HYBRID LEADER EVENT

**Figure 11 shows results obtained for the leader of the 6th stroke of Flash 155325. The static electric field change for this leader resembled that of a second initial-type leader along a new channel to ground, in**

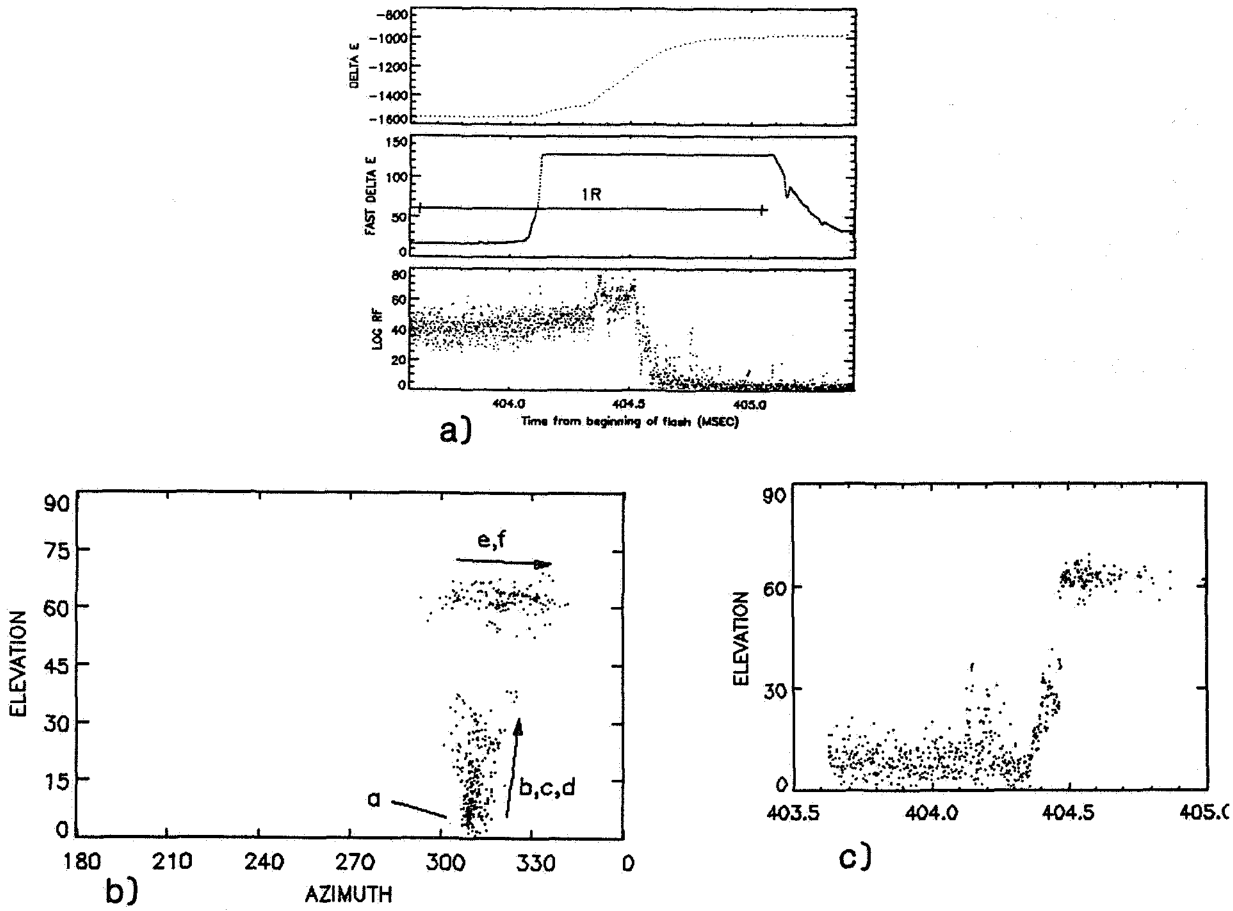

Figure 10: Radiation sources during the initial return stroke of Flash 153844: a.) Time waveforms, b.) radiation source locations, c.) elevation angle vs. time.

that it was long in duration and increasingly negative leading up to the return stroke (Figure 11a). But the radiation sources for the event show that it was a totally different and new type of phenomenon (Figure 11b). In particular, widespread, continous radiation began at a low elevation angle in the direction of the previous channels to ground and progressed slowly and continously toward and past the interferometer along an apparently horizontal path. The sign of the electric field change indicates that the breakdown transported negative charge in its direction of progression, i.e. that it was negative-type breakdown.

After about 60 ms, a dart leader originated back in the source region of the slow breakdown and progressed rapidly in the opposite direction to ground. The dart leader and stroke were also of negative polarity, therefore both the slow activity and the dart leader/stroke transported negative charge away from their common source region. We speculate that the slow moving radiation was produced by the highly-branched and slow-moving 'finger' type discharges that are sometimes observed to propagate horizontally through the base of older storm complexes. Further study is required for a better understanding of this hybrid phenomenon.

## SUMMARY AND DISCUSSION

VHF radiation from lightning typically occurs in bursts and and can be classified as falling into one of two categories: a) that produced by fast-moving streamer events which propagate along well-defined channels during a given burst, at typical velocities of about $10^7$ m/s, but sometimes down to $\sim 10^6$ m/s, and b) localized, intense radiation whose motion within a burst is not resolved but whose centroid moves slowly from burst to burst. In both cases, the breakdown is predominantly negative, i.e. negative charge

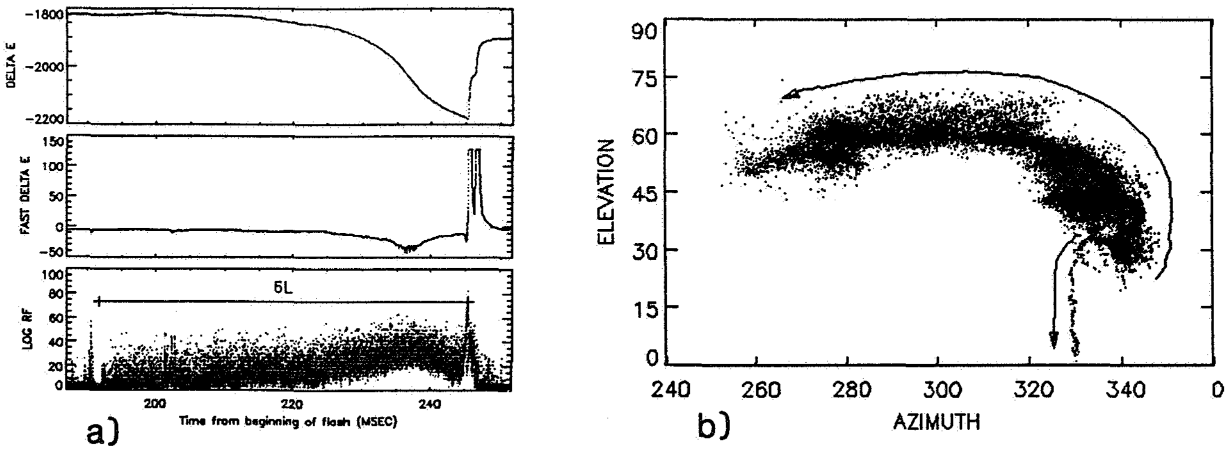

Figure 11: Results for the leader of the 6th stroke of Flash 155325: a.) Time waveforms, b.) radiation source locations.

is transported in the direction of progression; in agreement with the results of other studies (e.g. Proctor [1981, 1988], Richard et al. [1985]). Radiation is sometimes observed from positive breakdown events, however, as discussed later.

Fast-moving streamers are a feature both of in-cloud 'K' events and of dart leaders to ground, and appear to be the same process in both instances. Some K-events are terminated by fast field changes (Figure 4), which indicate a rapid increase in current along the streamer channel and are analogous to the return stroke initiated by a dart leader. Many K-streamers do not produce a fast field change, however, but simply die out after traveling some distance. Although not shown in this paper, aborted dart-type events are observed which also die out before reaching ground (Figure 8, Richard et al. [1986]; Rhodes [1989]). This essentially eliminates any distinction between the dart- and K-type events.

Localized, slow-moving radiation is observed during the initial breakdown of a flash and during initial leaders to ground (Figures 2 and 9, respectively). In these instances the speed of progression is on the order of $10^5$ m/s. During initial leaders the radiation often becomes more widespread with time, indicating the occurrence of branching. A new type of hybrid breakdown event has been identified which resembles an initial-type leader in that the radiation sources are slow-moving and widespread, but which progresses horizontally within the storm and is observed to spawn a dart leader in the opposite direction to ground (Figure 11).

Several types of radiating events are observed during and after return strokes. For initial strokes, the radiation is observed to *increase* in amplitude during the return stroke and to progress rapidly up the lower part of the channel, either in one well-defined event or, in more complex situations, as a sequence of several upward-propagating events (Figure 10). Radiation later in the return stroke is observed from or beyond the source region of the leader.

For strokes initiated by dart leaders, the radiation is observed usually to *decrease* in amplitude when the leader ends and the return stroke begins. Often there is a quiet period of little or no radiation during the return stroke, as has been noted by other investigators (e.g. Hayenga, [1984]; Richard et al. [1986]). The quiet period is terminated by a burst or bursts of radiation back in the source region of the leader. Two types of post-quiet period bursts have been identified: those which travel away from the top end of the leader channel and those which travel into it. The former appear to be launched when the return stroke arrives at the upper end of the channel. From their direction of progagation and from the sign of their electric field change, these appear to be positive-type streamers. The streamers are fast and extend the channel or develop new branches that are sometimes followed by the leaders of subsequent strokes (Figure 5c). Bursts which travel into the top end of the leader channel do so as negative streamers that appear to renew the current flow along the entire channel to ground (Figure 5d).

Other strokes initiated by dart leaders do not have a quiet period during the return stroke. In these instances, also noted by Takagi [1969] and Hayenga [1984], the radiation continues with decreased amplitude after the leader contacts ground (Figure 8). The radiation occurs from breakdown adjacent to the leader source region. Because the radiation is continuous and precedes the arrival of the return stroke back in the source region, it is likely that it is from breakdown that developed simultaneous with the leader and that is revealed only when the stronger radiation from the descending leader tip is extinguished. The polarity of the breakdown has not been established, but the breakdown appears to establish new channels or branches followed by subsequent activity. Delayed radiation is also observed which is associated with the arrival of the return stroke back in the source region of the leader.

Finally, radiation is sometimes observed which moves up the channel to ground during return strokes initiated by dart leaders (Rhodes [1989], Figure 7). In this instance, the radiation occurred at apparent branch points along the lower to middle part of the channel as the return stroke reached the branch points.

We turn now to a discussion of how new channels develop and extend during intracloud activity, prior to the occurrence of cloud-to-ground strokes. This happens either as a result of slow-moving negative breakdown, as in Figure 2, or in a retrograde manner by negative streamers which begin at a distance from previously detected activity (Figure 4). The retrograde streamers are observed to propagate at a fast speed ($10^7$ m/s) even though no radiation has been detected along the extension path. This leads to the question whether the streamers have been preceded by other breakdown which was not detected – in particular by a positive streamer or streamers which propagated *away* from the earlier (negative) activity. The existence of such streamers has been proposed by Mazur [1989a] on the basis of gaps observed in the development of extensive intracloud discharges by Richard et al. [1985], and on the basis of observations of bi-directional breakdown in aircraft-triggered lightning. Mazur proposed that the disconnected, retrograde negative streamers were recoil events along the channels of VHF-invisible positive streamers that develop as part of a bi-directional breakdown process.

Other than the speed of the streamer, there is no indication that the D extensions of Figure 4 followed the path of invisible positive breakdown. Several points argue against the invisible streamer hypothesis. The first is that the extending D streamer required three breakdown attempts to get started. If it were a recoil event along a positive streamer channel it might be expected that one of the earlier attempts at the recoil would have been successful. Rather, the observed sequence of events behaved more like the local triggering of breakdown in enhanced fields generated at a distance from the prior activity. Second, positive streamers appear to be observed at other stages of a flash, as described earlier, that do radiate. This leads one to question the assumption that positive streamers in virgin air would be invisible at VHF. In the case of K-changes and dart leaders, it is the initiating (negative) streamer that radiates and the recoil (positive) event that does not radiate.

Event A2 of Figure 2 provides a possible example of a different kind of non-radiating positive streamer. For 1.5 ms between the initial and final radiation bursts of this event, the electric field increased steadily as if positive charge were being transported toward the interferometer site, but little or no radiation was produced. Then a final radiation burst occurred from negative breakdown which progagated away from the interferometer. This suggests sequential bi-directional breakdown away from the initial A2 burst location that is analogous to case 2) of aircraft-triggered lightning in the study by Mazur [1989b]. If this explains the observations, it is likely that the positive streamer progressed along the path established by the preceding A1 activity. The lack of radiation is then explained as being due to the existence of prior breakdown along the positive streamer path.

The streamer events of Figure 5c and Figure 6c are examples of (rapid) positive streamers that radiate and have not been preceded by detected breakdown. Positive streamers also occur at the beginning of rocket-triggered lightning (e.g. Laroche et al.; Nakamura et al.; this conference) that are not preceded by other breakdown, and it should be relatively easy to determine if these radiate detectably.

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