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Aircraft-Triggered Lightning: Processes Following Strike Initiation that Affect Aircraft

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The analysis of airborne electromagnetic records of seven lightning strikes to the FAA CV-580 instrumented airplane during the 1987 field campaign and eleven strikes to the French C-160 airplane during the 1988 Transall campaign was aimed at revealing and interpreting processes taking place during the intracloud propagation of lightning strikes initiated on or intercepted by the airplane. It is shown that intracloud development of the strike may consist of recoil streamers, dart leader/return stroke sequences, and the secondary initiations of new discharges. These processes, with their high current-pulse amplitudes, may present greater threat to aircraft than current pulses during strike initiation. The latter are presently considered by the technical community to be the primary lightning threat to aircraft.

Introduction

MOST previous investigations of lightning strikes to aircraft with in-situ measurements have focused on interpretation of lightning interaction with aircraft,[1–3] as well as on quantitative measurements of lightning strike characteristics during the initial period of lightning attachment.[4–7] The initial encounter of aircraft with lightning (usually several ms long) is believed to produce the most severe electromagnetic effects resulting from high current amplitudes and fast current rise times. Such a view is not, however, verified by experimental measurements. The processes following strike initiation and associated with its intracloud development (junction stage) for hundreds of ms have not been investigated, with the exception of Reazer et al.[7] and Mazur et al.[8] During the junction stage, the aircraft remains a part of the lightning structure and continuous current keeps flowing in the channel. Evidence of the presence of continuous current is found in the continuous luminosity of the attached channel that lasts for hundreds of milliseconds.[3] Thus, processes during intracloud development of a lightning strike may adversely affect aircraft, and these processes need to be included in an appropriate fashion in the definition of the lightning threat to aircraft in the current SAE document.[9]

The primary objective of this paper is to characterize and interpret lightning processes during the junction stage of lightning strikes to aircraft. We analyzed the airborne records of electromagnetic waveforms of seven lightning strikes to be instrumented FAA CV-580 airplane and eleven strikes to the French C-160 airplane at altitudes below 6 km during storm penetrations in the 1987 field campaign in the United States and the 1988 Transall campaign in France, respectively. No comments are made regarding quantitative measurements of electromagnetic waveforms, because of the frequency-limited recordings and an insufficient dynamic range of the recorders, which often produced signal saturation.

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Definitions of Lightning Processes Involving Aircraft

Interpretations of lightning strikes to aircraft are based on the following four definitions of the processes that compose a lightning flash. They are known from the literature on lightning[10] and have been verified for lightning-aircraft interaction.[3]

1) A positive leader is a continuously propagating ionized channel, in which current amplitude increases with channel length. Its speed of propagation is about 10^4 m s^{-1}. When initiated on an aircraft, the positive leader is followed by a decrease in the aircraft's electrical potential, noticed as a negative change of the local electric field (E-field).

2) A negative stepped leader is a series of current pulses with a pulse duration of a fraction of a microsecond, a pulse amplitude of hundreds to thousands of amperes, and a pulse rate of several pulses per ms. The average propagation speed of the negative stepped leader is 10^5 m s^{-1}. When initiated on an aircraft, the negative stepped leader is followed by an increase in the aircraft's electrical potential, noticed as a positive change of the local E-field.

3) A recoil streamer is a negative current pulse originating in a cloud, possibly near the tip of the positive leader and traversing the ionized channel of the positive leader toward the region of flash initiation. Recoil streamers occur later in the flash, usually during the junction stage of the discharge. Recoil streamers deposit a negative charge on the aircraft; the speed of propagation is about 10^7 m s^{-1}.

4) A dart leader/return stroke sequence characterizes multistroke cloud-to-ground flashes (CG). Like a recoil streamer, a dart leader is a negative current pulse originating in the cloud, having all the other features of recoil streamers, but terminating on the ground rather than in the cloud. A return stroke in a negative CG flash is a positive current pulse originating from the ground, thus depositing a positive charge on the aircraft. A dart leader/return stroke sequence may be recognized in airborne records by a different polarity of charges deposited on the aircraft by two pulses and by the short (a few milliseconds) interval between them. With the propagation speed of both dart leaders and return strokes changing with the distance from the source,[11] the average speed is assumed here to be at least half of their maximum speed near the ground; i.e., 0.5×10^6 m s^{-1} and 0.5×10^7 m s^{-1} for dart leaders and return strokes, respectively.

Positive leaders are recognized by slow negative variation of the E-field, produced by continuous current, while negative leaders and streamers are recognized by a single negative pulse or a series of pulses. The only current pulses that produce positive changes in the E-field record are from return strokes.

Data Presentation

The sign convention for lightning currents on the CV-580 airplane is shown in Fig. 1. In the records of the three current shunts included in the analysis, a positive output is produced by a positive charge flowing into the tail boom and wing tips or by a negative charge flowing off the tail boom and wing tips. The sign convention for the E-field is as follows: the positive sign corresponds to the positive aircraft electrical potential; the positive E-field change corresponds to the positive polarity electric field derivative ($\dot{D}$) pulse, and vice versa.

Signal ranges of the CV-580 data recorders are 1) currents (I_{RW}, I_{LW}, I_{VS}): range 10 A–1.6 kA, frequency range DC-500 kHz; 2) E-field (J_{nff}): range 2.25 kV m^{-1} – 2.25 MV m^{-1}, frequency range 0.5 Hz–500 kHz; and 3) electric field derivative ($\dot{D}$) ($\dot{J}_{nff}$): range 3.54×10^{-8} – 8.85×10^{-6} C m^{-2}, frequency range 400 Hz–2 MHz.

The current pulses initiated on the aircraft and those traversing the aircraft have distinctly different signatures in the E-field record. For the former, the E-field value makes a step to a new level during the duration of the pulse and remains at this level until the next pulse. For the latter, the E-field returns to the prepulse value after the pulse exits the airplane, so that the variation resembles a pulse.

Following are several examples of processes during the intracloud development of a lightning strike. The time reference in the descriptions is given in ms of absolute time.

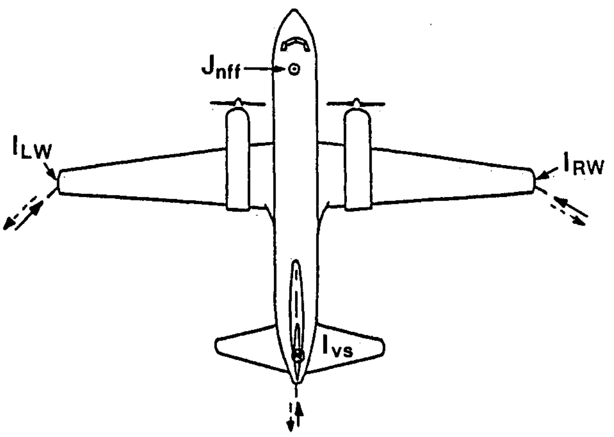

Fig. 1 Sign convention of current flows producing a positive response in the current shunt records on the CV-580. Solid and dashed arrows indicate positive and negative charge flows, respectively. J_{nff}—an electric field sensor, I_{RW}, I_{LW}, and I_{VS}—are current shunts on tips of the right wing, left wing, and vertical stabilizer, respectively.

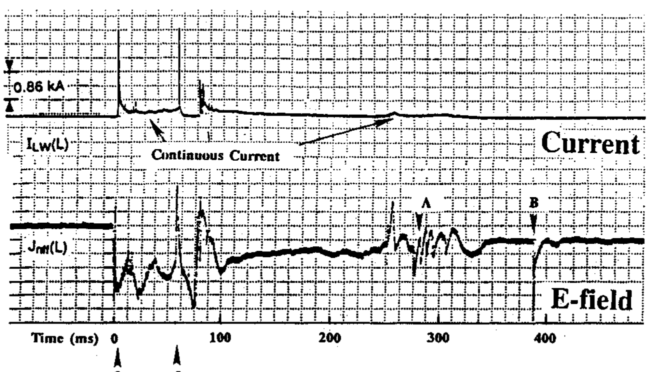

Fig. 2 Strike 1, day 87197, start time 1444:02.068 UT, duration 388 ms: Current and E-field records on the left wing of the CV-580. The time axis is in relative time.

Cloud-to-Ground Flashes Initiated on the Aircraft

Strike 1 (day 87197, start time 1444:02.068 UT) is initiated on the CV-580 (arrowhead at 2, Fig. 2). The initiation process is depicted in the waveforms shown in Fig. 3. Decrease of the aircraft electrial potential during period T1, 1.6 ms prior to the first negative leader pulse, corresponds to the emergence of the positive leader from an aircraft extremity.[3] A negative stepped leader is seen as a series of current pulses superimposed on the continuous current of the positive leader. Negative change of the E-field during period T2 results from the continuous current of increasing amplitude.

The current pulse at about 59 ms later (at 127.9 ms, arrowhead at 3, Fig. 2) produces a positive change in the local E-field (Fig. 4). The presence of continuous current at the left wing prior to the pulse (Fig. 2) is evidence of the continuous attachment of the lightning channel to the aircraft after

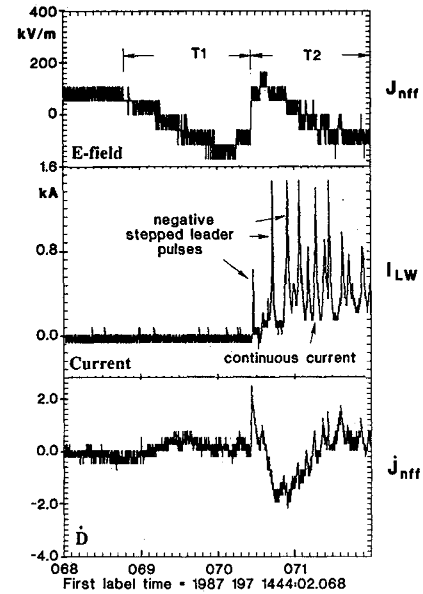

Fig. 3 Strike initiation process on the CV-580 for strike 1. Data correspond to arrowhead 2 in Fig. 2. T1-period of positive leader development prior to occurrence of the negative stepped leader. T2-part of the negative stepped leader process. Notice the correspondence of current pulses and $\dot{D}$ pulses in the negative stepped leader. Their rate is about 10 per ms. Continuous current (about 160 A) seen in the record produces the negative E-field change.

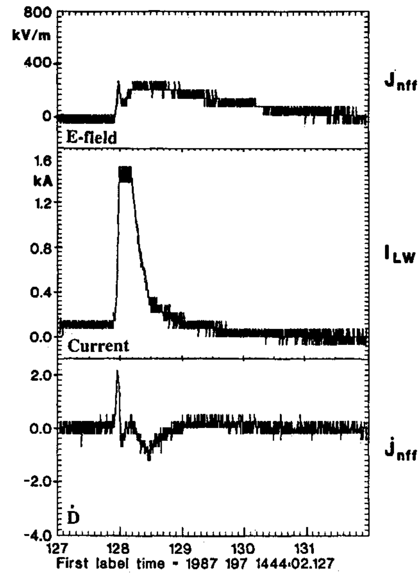

Fig. 4 Return stroke intercepting the CV-580, after traversing the channel from the ground, during strike 1 on the CV-580. Data correspond to arrowhead 3 in Fig. 2.

initiation. Therefore, the only possible interpretation of the current pulse, which deposits a positive charge on the aircraft, is that it is a return stroke of a CG flash. With this assumption, the stepped leader will take about 60 ms to reach the ground from a flight altitude of 6 km, and less than 1 ms for the return stroke that traverses the stepped ladder channel to reach the aircraft. Notice that the magnitude of the return stroke current is greater than that of the negative stepped leader.

For strike 4 (day 87216, start time 2253:01.074 UT), the E-field and $\dot{D}$ records at 75 ms are typical of the lightning initiation process on an aircraft and are similar to those shown in Fig. 2. At 326 ms (251 ms after the initiation), there is a pair of current pulses intercepting the aircraft. The first pulse deposits a negative charge and the second pulse deposits a positive charge, as indicated by both the E-field changes and the polarity of the $\dot{D}$ pulses (Fig. 5). The pair of pulses matches the dart leader/return stroke sequence both in terms of the order of pulses (first negative, then positive) and the 3-ms interval; this time interval is sufficient for the dart leader/return stroke to cover the distance from the aircraft to the ground twice, assuming appropriate propagation speeds. Thus, the CG flash developed following the intracloud propagation of a lightning strike that was initiated on the aircraft. For this CG flash, the dart leader amplitude is greater than that of the return stroke (see Fig. 5).

Recoil Streamers

Recoil streamers usually take place tens of ms after strike initiation. During strike 4, mentioned earlier, the series of current pulses deposited a negative charge (see polarity of $\dot{D}$ pulses, Fig. 6) on the aircraft, starting at 147 ms (73 ms after the initiation). The rate of these pulses (about 0.46 per ms) is considerably lower than that in negative stepped leaders (several pulses per ms).[3] The pulse-like E-field changes indicate that recoil streamers intercepted the aircraft. The largest of these recoil streamers, at 191 ms, has a current amplitude greater than 1.5 kA (record saturation level). Continuous current accompanies the pulse series for about 38 ms, starting at 155 ms. The duration of the individual recoil streamers is measured in hundreds of μs, usually not exceeding 500 μs.

Later in strike 4, at 213 ms, a new series of pulses carrying negative charges exists the right wing tip (Fig. 7). The rate of pulses is about 3 per ms, which is a rate typical of stepped leaders. However, the pulse-type of E-field variation suggests that pulses intercepted the aircraft. A surge of continuous current during this series, seen as a low frequency envelope in the current record, is at least of 400 A maximum value, and lasts for about 7 ms. This series of negative current pulses may be a series of rapidly branching recoil streamers or a negative stepped leader initiated somewhere in a cloud. The durations of individual pulses are, however, much greater than those in negative stepped leaders and correspond to durations of recoil streamers. Unfortunately, a definite distinction between these two processes cannot be made with airborne records alone.

Strike 5 (day 87216, start time 2254:00.082 UT) also is triggered by the aircraft. The two recoil streamers that intercepted the aircraft at about 227 ms are separated by less than a 1-ms interval (Fig. 8), and the current amplitude of one of them is above 1.5 kA. Such a short time interval between recoil streamers is frequently observed in the CV-580 data..

Figure 9 shows an example of the magnetic and electric field records of recoil streamers during lightning attachment

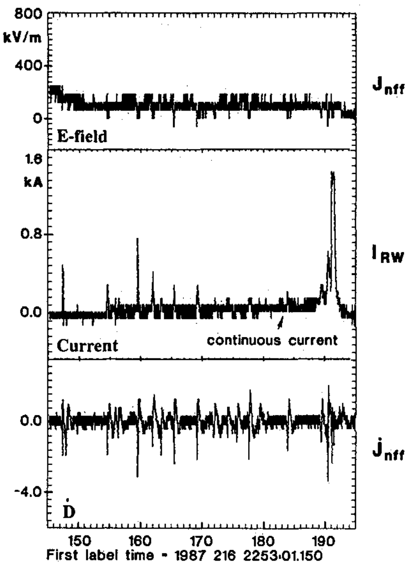

Fig. 6 Series of recoil streamers intercepting the CV-580 during strike 4. Notice presence of continuous current and correspondence of current pulses to negative $\dot{D}$ pulses and pulse-like changes in the E-field record.

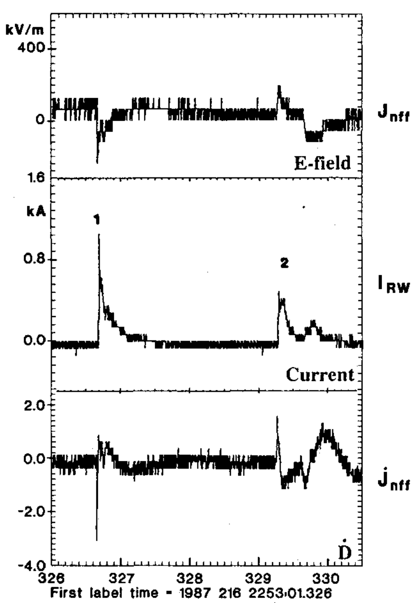

Fig. 5 Sequence of a dart leader/return stroke intercepting the CV-580 during strike 4. Notice pulse-type E-changes and $\dot{D}$ pulses of opposite polarity indicating interception rather than initiation of pulses. 1—a dart leader pulse, 2—a return stroke pulse.

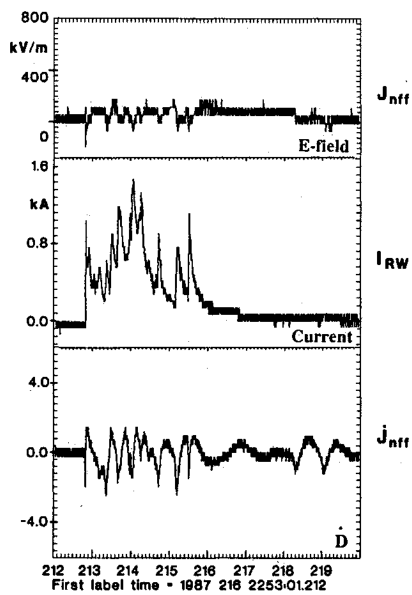

Fig. 7 Group of negative pulses (branching recoil streamers or a stepped leader) intercepting the CV-580 during strike 4. Notice continuous current present between 213–219 ms.

to the C-160 airplane. Time intervals between recoil streamers measured during the Transall 88 campaign are usually several milliseconds in length.

New Lightning Initiation Processes

Strike 3 (day 87211, start time 1925:00.045 UT) is a classic case of lighning initiation on an aircraft. At about 165 ms of UT (120 ms after initiation), there is a negative E-field change (lasting 0.5 ms) (arrowhead at 3, Fig. 10) that is not accompanied by current pulses (Fig. 11). The entire process resembles the initiation of lightning on aircraft (Fig. 3), but with 1) a shorter than usual decrease of the aircraft's potential prior to the first negative leader pulse; and 2) fewer than usual negative pulses. Notice the step-like E-field changes during the occurrence of pulses 1 and 2, which suggest emergence from the aircraft (Fig. 11). Three recoil streamers intercepted the aircraft immediately following the new initiation process. Supporting such an interpretation are the negative $\dot{D}$ pulses and the pulse-type changes in the E-field record, both of which characterize an interception. A group of recoil streamers separated by intervals of 2, 4, and 6 ms (Fig. 12) conclude the process. A continuous current surge associated with development of the positive leader (Fig. 10, arrowhead 3; and Fig. 12) lasts for at least 25 ms. The gradual negative change of the aircraft's potential (the local E-field) during this period is caused by the positive continuous current emerging from the aircraft.

Strike 6 (day 87223, start time 1934:00.058 UT) is an example of intercepted natural lightning (Fig. 13). At 252 ms (arrowhead at 4, Fig. 13), a new initiation process begins (Fig. 14), with positive leader development (negative E-field change) preceding the occurrence of the negative stepped leader at the right wing tip of the CV-580 airplane. This process is similar to the process in strike 3 (Fig. 11), and to the lightning initiation process in strike 1 (see the resemblance between the bracketed part in the $\dot{D}$ and current record of Fig. 14, and those in Fig. 3). Two recoil streamers follow shortly (Fig. 14).

A new initiation process on the C-160 airplane is depicted in Fig. 15 in the magnetic and electric field records. The process starts with a short negative E-field change associated with a positive leader initiation. The high rate pulses that

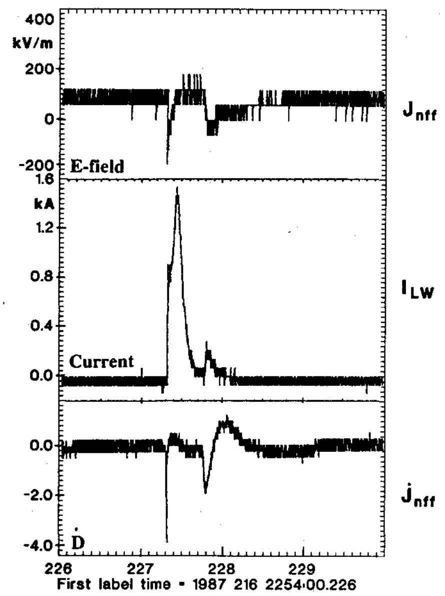

Fig. 8 Two recoil streamers intercepting the CV-580 during strike 5.

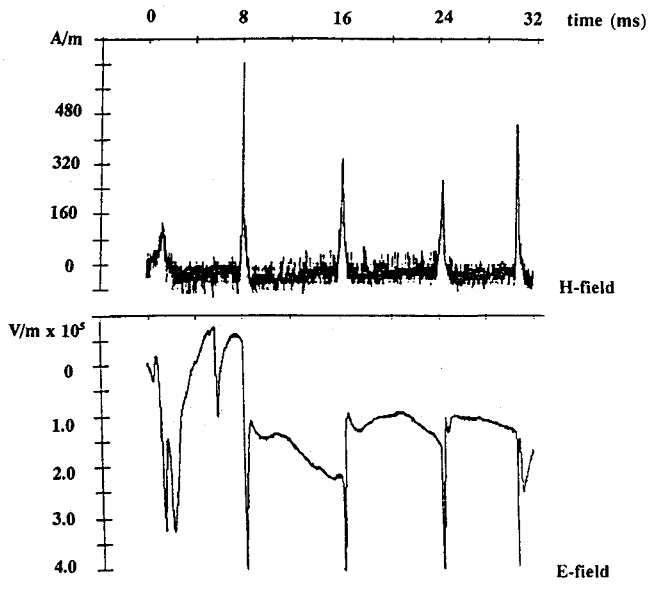

Fig. 9 Recoil streamers intercepting the C-160 airplane; H- and E-field records.

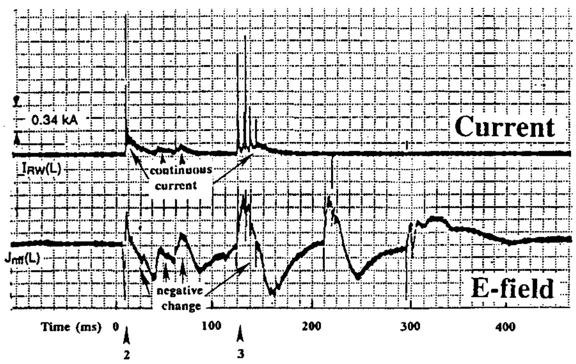

Fig. 10 Strike 3, day 87211, start time 1925:00.045 UT, duration 406 ms: Current and E-field sensor records on the right wing of the CV-580. The time axis is in relative time. Notice time correspondence between periods of continuous current flow and periods of negative E-field changes. At the end of these periods, the aircraft's potential reaches its highest negative value.

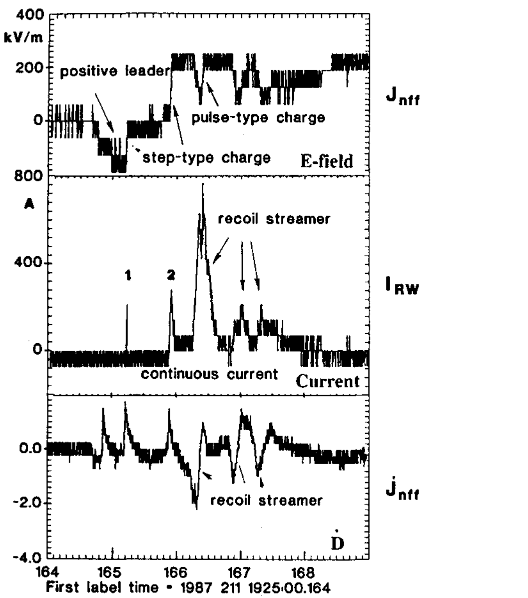

Fig. 11 New initiation process on the CV-580, followed by a series of recoil streamers during strike 3. Data correspond to arrowhead 3 in Fig. 10. Notice negative E-field change corresponding to positive leader development, then step-type positive changes corresponding to stepped-leader pulses (1, 2) emitted from aircraft, and pulse-type changes from intercepted recoil streamers.

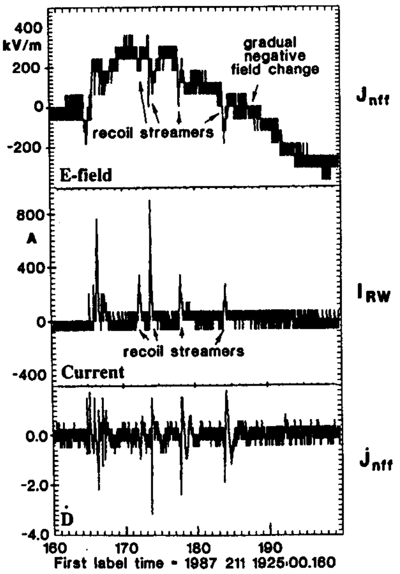

Fig. 12 Series of recoil streamers following the new lightning initiation depicted in Fig. 11 (strike 3, CV-580). Recoil streamers occur during the gradual negative E-field change. This period corresponds to the period of continuous current in Fig. 10.

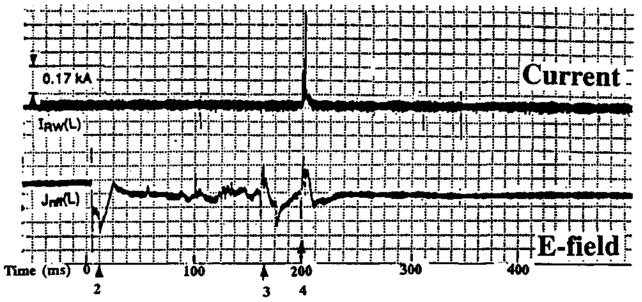

Fig. 13 Strike 6, day 87223, start time 1934:00.058 UT, duration 210 ms: Current and E-field sensor records on the right wing of the CV-580. The time axis is in relative time.

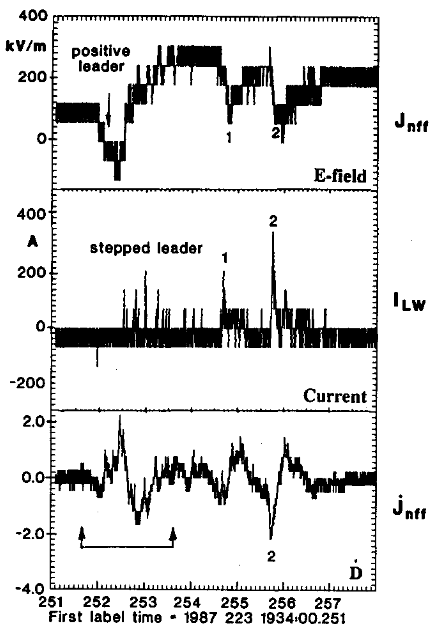

Fig. 14 New initiation process of a secondary discharge during strike 6 on the CV-580. Notice features typical of a positive leader and a stepped leader (in brackets). This initiation process is followed by recoil streamers, marked 1 and 2. Data correspond to arrowhead 4 in Fig. 13.

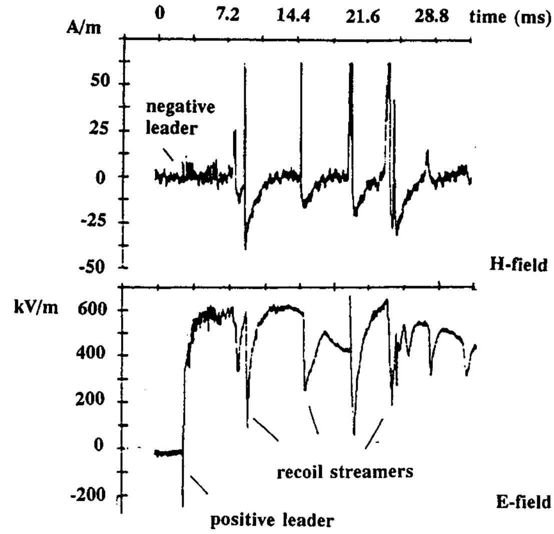

Fig. 15 Example of a new initiation process on the C-160 airplane: H- and E-field records.

immediately follow in the magnetic field record are from the negative stepped leader. As was the case in strike 3 to the CV-580 airplane (Figs. 11 and 12), recoil streamers occur within several ms after the negative leader.

Discussion and Conclusions

Several novel observations have resulted from the analysis of the entire airborne electromagnetic records of lightning flashes that were either triggered or intercepted by the CV-580 and the C-160 aircraft. For example, evidence was obtained that recoil streamers occur both as a single pulse and as a series of pulses separated by less than 1-ms intervals. The presently accepted idea of recoil streamers considers them as single pulses.[12] The hypothesis is advanced that "bunches" of recoil streamers are associated with rapidly branching channels. This suggestion must be confirmed with simultaneous high-speed video and electromagnetic measurements.

Another observation is that the amplitude of recoil streamers are usually much larger than those of negative stepped leaders during the initiation process. This should be taken into consideration for a new definition of the lightning threat to aircraft. A comparison of stepped leaders in natural lightning flashes with those in strikes to aircraft should not be made, however. Such a comparison is not valid because of the possible dependence of the stepped leader in an aircraft-triggered flash on a given aircraft's size and shape. Recoil streamers, on the other hand, being less influenced by aircraft, are similar to those of natural lightning flashes. Therefore, recoil streamers may be measured unambiguously on an instrumented airplane.

It is also shown in this study that lightning strike following initiation on the aircraft (in cases of storm penetration below 6 km altitude) frequently turns into a cloud-to-ground flash. In three of seven strikes to the CV-580, a CG flash developed after the strike initiation on the aircraft, and in one case after the aircraft was intercepted by a natural flash. As previously observed in a case of a multistroke CG flash to the NASA F-106B airplane,[8] and also demonstrated by this study, return stroke currents at flight altitudes are much smaller in amplitude than those measured on the ground, and are usually smaller than current pulses of dart leaders and recoil streamers. This observation strongly indicates the need for reexamining the threat to aircraft from return strokes.

During the intracloud development of a lightning strike, processes resembling a new initiation process of a secondary discharge on the aircraft were discovered. These processes have much shorter durations of both positive and negative leaders than those observed during initiation of the original flash. Initiation of the secondary discharges on the aircraft was observed to take place more than once during the course of a strike. We speculate that reinitiation occurs when intracloud development of the flash stops, continuous current flow ceases, but the aircraft is still in the high ambient electric field that originally produced the strike.

Acknowledgments

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