JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 103, NO. D12, PAGES 14,109-14,115, JUNE 27, 1998

Leader properties determined with triggered lightning techniques

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Abstract. This paper presents current and electric field measurements from two triggered lightning flashes, 9519 and 9516, initiated by the "classical" and "altitude" technique, respectively, at Camp Blanding, Florida, in 1995. The current measurement for flash 9519 shows that the upward positive leader, initiated at the top of the grounded wire unreeled by the triggering rocket, propagates in a discontinuous pattern made of successive current pulses of tens to a few hundreds of amperes and separated by intervals of 20–25 μs. The downward negative leader in flash 9516, initiated from the electrically floating conductor, has a velocity greater than 1.3×10^5 m s^{-1}, a stepping interval of 18 μs, and step length of about 3–5 m; the associated peak currents inferred from the electric field steps are at least 600 A.

1. Introduction

Understanding the mechanisms of leader inception and propagation is one of the main issues in the problem of protection of structures against lightning. When the ambient electric field under the thunderstorm is positive (negative charge overhead), the leader phase of a lightning flash could be of two types. It is an upward developing positive leader if lightning is triggered by the tops of tall ground structures, or it is a downward stepped negative leader if lightning is natural and starts in the cloud.

Using triggered lightning techniques, both kinds of leaders can be investigated. The experiments reported here were carried out during the summer of 1995 at Camp Blanding, Florida. Specific measurements were performed to study the development of the different types of leaders involved in different types of triggered flashes. The aim of the present paper is to describe the basic phenomenology of these leaders, including their inception and propagation, as deduced from electrical field measurements, current measurements, and streak photography.

2. Techniques of Triggered Lightning Initiation

2.1. Classical Triggered Lightning

The sequence of major events occurring when using the "classical" triggering technique is depicted in Figure 1. When the ambient electrostatic field E_0 at ground due to the thunderstorm cloud reaches a critical value of 10 kV m^{-1}, a small rocket that spools out a thin copper wire connected to the ground is launched. When the wire reaches a critical length (typically in excess of 100 m), the electrostatic field enhancement at the rocket tip is high enough for inception and development of an upward positive leader. This leader propagates toward the cloud and initiates a continuous current, typically for a few hundred milliseconds. After cessation of the initial continuous current, several downward leader/upward return stroke sequences usually follow. Positive leader properties are investigated here by analyzing the current flow through the wire during the discharge development as measured by a 1 mΩ shunt installed at the rocket launcher. The length of wire spooled out at the leader inception is determined by a still photograph.

2.2. Altitude-Triggered Lightning

The "altitude-triggered" lightning technique is illustrated in Figure 2. The rocket first spools out 50 m of grounded wire, followed by 400 m of insulating Kevlar, and finally, a second (triggering) copper wire is extended. When this last wire has been unreeled over a sufficient length, a bidirectional leader initiates from its extremities [*Laroche et al.*, 1991]. A positive leader is initiated from the top of the triggering wire or the rocket tip and propagates toward the cloud. A few milliseconds later, a downward negative leader is initiated from the bottom

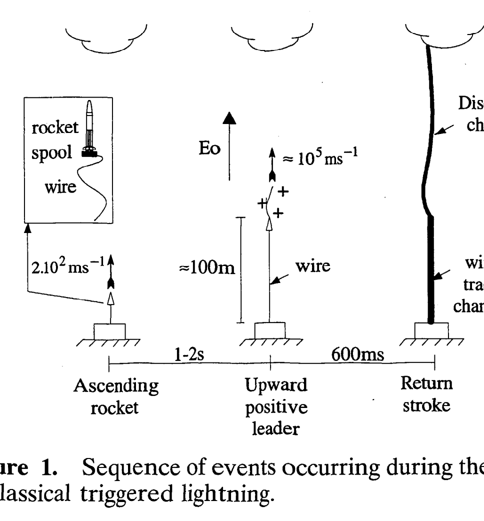

Figure 1. Sequence of events occurring during the formation of classical triggered lightning.

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Paper number 97JD02492.
0148-0227/98/97JD-02492$09.00

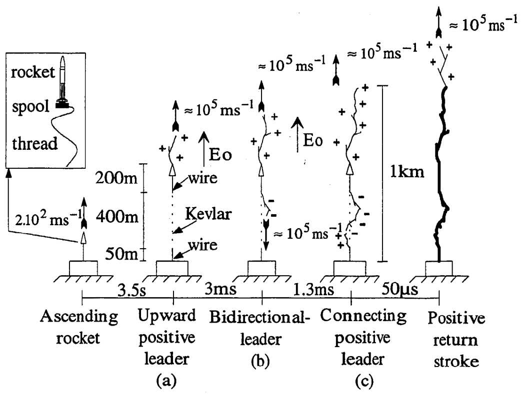

Figure 2. Sequence of events occurring during the formation of the first return stroke in altitude-triggered lightning.

of the triggering wire and propagates toward the ground. Its connection to the ground is produced by an upward connecting positive leader initiated from the lower grounded wire.

The current flowing through the 50-m-long wire attached to ground was measured by a 1 mΩ shunt. The fast electric field variations were measured by two capacitive antennas, A_1 and A_2, located 50 m from the lightning channel. Measurement of magnetic field variations associated with the return stroke phase was made by a sensor at a distance of 55 m from the launch site. A streak camera was also used to film the last phase of propagation of the downward stepped leader, just before the connection.

3. Results

3.1. Classical Triggered Lightning

In the present paper, the description of the triggered flash will be limited to the leader phase; that is, we disregard all following lightning processes. Current measurements can be used as a guide to analyze the main chronological sequence of events which occurred before the first return stroke in flash 9519. The first measured current appears as isolated oscillating pulses separated by quiet periods of 5 ms average duration (Figure 3). At t = 0, 7.53 ms after the last isolated pulse (occurring at −7.53 ms in Figure 3), the current measurement indicates that the discharge enters into a stable propagation regime without any interruption. At that time the wire length is about 115 m (see the photograph in Figure 4). After the assumed actual leader inception (t = 0 ms in Figure 5), the measured current is initially composed of a sequence of regular pulses (Figures 5b and 5c). These current pulses, first oscillating and later (after 200 μs of leader propagation) unipolar in shape, gradually disappear, while the continuous current grows (Figure 5a) and reaches 200 A after a few tens of milliseconds. The first return stroke occurred 600 ms after positive leader inception.

3.2. Altitude-Triggered Lightning

Electric field and current measurements performed on flash 9516 have been used to derive the main chronological sequence of events which occurred before the first return stroke (Figure 6). From time t_0 (t = 0 ms) to t_1, the electric field at ground increases slowly with a mean slope of 30 kV m^{-1} s^{-1} (Figure 7a). As discussed in section 4, this field variation is related to a positive leader extending from the top of the wire.

At time t_1, two small field steps (about 3.5 V m^{-1} each, unresolved in Figure 7a) are superimposed on the continuous field increase. If these field steps are assumed to be due to the sudden appearance via corona of a point charge (or a roughly spherical region of charge), and if height and approximate range from the sensor to that charge are available, the magnitude of the charge can be determined through application of a simple electrostatic formula. The field steps, occurring at time t_1, are consistent with a charge ΔQ of about 40 μC placed at 450 m above ground. They can be either associated with isolated negative coronas or to the first two steps of an aborted negative stepped leader.

From time t_1 to t_2, a further slow field variation is observed,

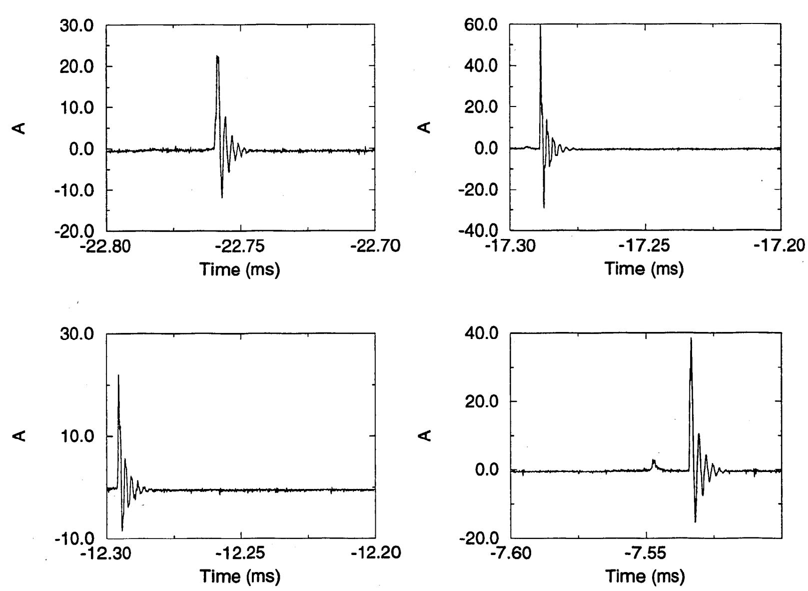

Figure 3. Oscillating pulse current associated with the attempted inception of upward positive leader in classical triggered lightning 9519. Time t = 0 ms is associated with the beginning of the stable propagation phase of the positive leader. This phase corresponds to the beginning of the continuous current phase.

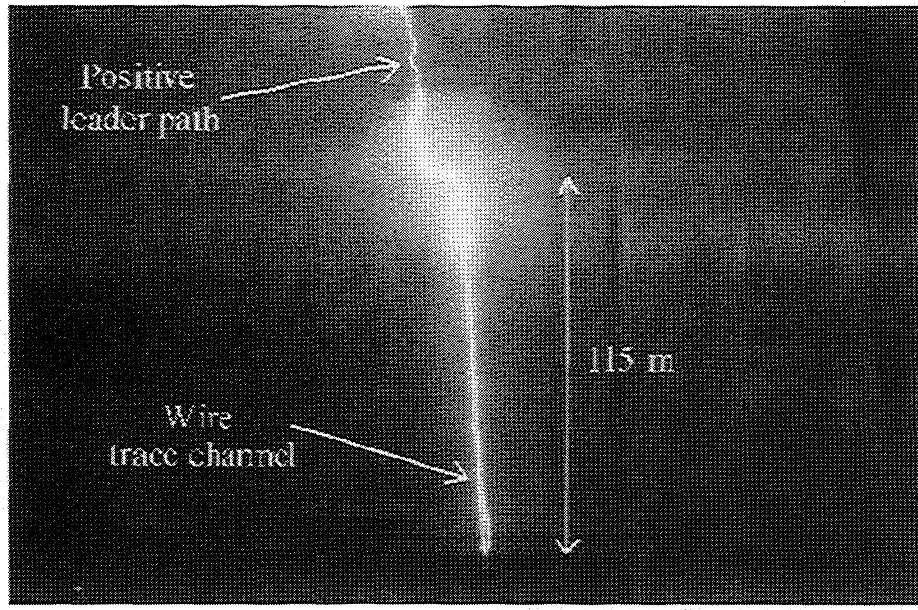

Figure 4. Still photograph of classical triggered lightning 9519.

similar to the one measured from t_0 to t_1, with a mean slope varying from 30 to 49 kV m^{-1} s^{-1} (Figure 7a; t_2 is labeled in Figure 7b).

From time t_2 to t_3, a fast stepped electric field variation is detected which is attributed to negative leader inception at the lower end of the wire (Figure 7b). Each step is of about 15 V m^{-1} and is consistent with a charge of about 170 μC at 450 m above ground. After eight steps, at time t_3, the negative leader development appears to pause. As reported in Figure 6, it is likely that the positive leader exhibits a continuous upward development, while the negative leader starts and stops a few times (around time t_1 and between time t_2 and t_3).

From time t_3 to t_4, the positive leader apparently continues, as indicated by the further field increase after t_3 (Figure 7a; t_3 is labeled in Figure 7b). The increase of the electric field slope after t_3 (121 kV m^{-1} s^{-1}) relative to the slope prior to t_2 (30–49 kV m^{-1} s^{-1}) suggests that the positive leader accelerated following the downward negative leader inception.

After time t_4 (Figure 7a), the negative leader resumes with a mean step field variation equal to 23.5 V m^{-1} (consistent with ΔQ = 270 μC at 450 m) with a time interval of 18.5 μs (Figure 7c). Current measurement at the bottom of the grounded wire indicates that an upward connecting positive leader starts at time t_5 from the top of the grounded wire (Figure 8b), 1 ms after the negative stepped leader onset at t_4. At the time of inception of this upward connecting positive leader, the electric field at ground reaches 10 kV m^{-1} (Figure 8a). During its propagation, this leader exhibits pulses sepa-

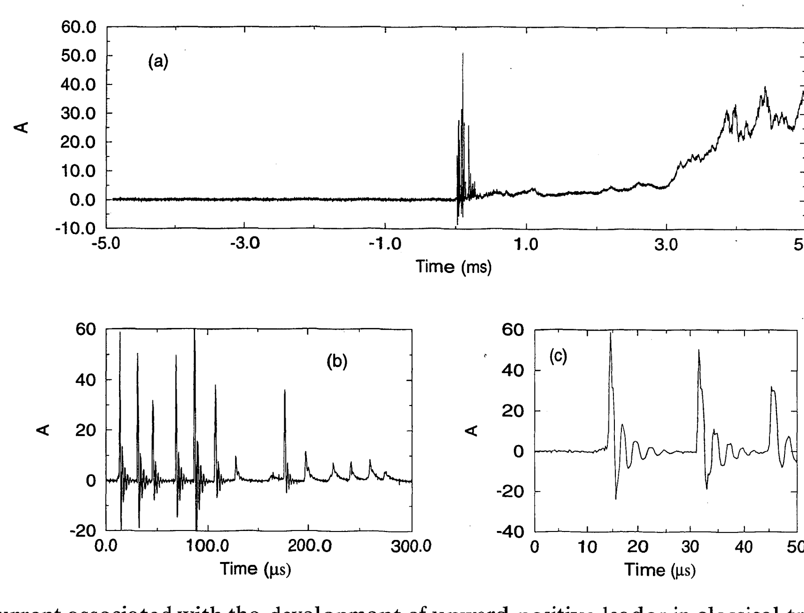

Figure 5. Current associated with the development of upward positive leader in classical triggered lightning 9519. Time t = 0 ms is the same as in Figure 3 and corresponds to the beginning of the stable propagation of the positive leader.

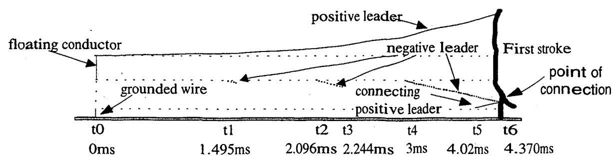

Figure 6. Chronological sequence of events during altitude-triggered lightning 9516 as inferred from electric field measurements for the bidirectional leader and from current measurement for the connecting positive leader.

rated by 20 μs or so (Figure 8b). At time t_5 the streak photography (Figure 9a) shows that there are two main branches of the negative leader whose lower tip is at 120 m above the ground. The axial velocity of the downward negative leader is measured to be 1.3×10^5 m s^{-1}, which is obviously lower than the actual three-dimensional velocity. From the streak photography, the negative step lengths are about 3–5 m with a mean stepping period of 21 μs (Figure 9b).

At time t_6 the contact between the negative stepped leader and the upward connecting positive leader is established. From the photograph in Figure 10, the estimated length of the connecting positive leader at this time is about 20 m. The current rapidly increases to 5 kA (Figure 11a), at the beginning of the return stroke process, and the electric field decreases from 44 to 37 kV m^{-1} (Figure 11b).

The current is cut off after t_7 (Figure 11a) because of the high impedance of the exploding 50-m lower wire, indicating that the lightning channel is disconnected from the ground. At this time, the E field (Figure 11b) increases again as if the "disconnected channel" extended to the ground through the wire residue channel at a speed of 10^7 m s^{-1}. At time t_8 the connection occurs, allowing the return stroke to continue (Figure 11a). It is worth noting that the first return stroke in the altitude-triggered flash is an unusual one, composed of two unipolar pulses separated by an interval of 5 μs, with the first pulse (5 kA) smaller than the second one (12 kA). After this first return stroke, three more return strokes initiated by dart leaders from the cloud, with peak currents of few kA, are observed.

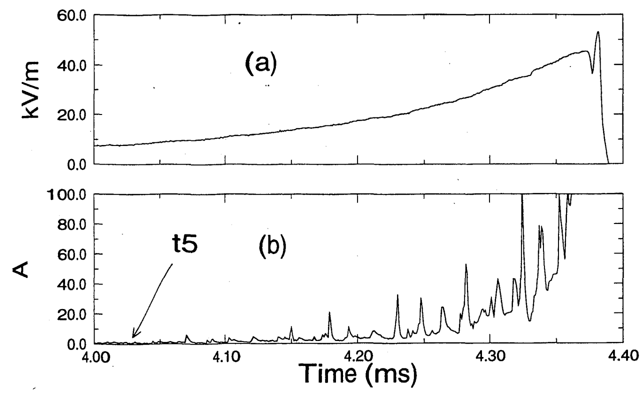

Figure 8. Plots of altitude-triggered lightning 9516 showing (a) electric field variation measured by antenna A_2 at 50 m from the lightning channel and (b) current produced by the upward connecting positive leader from the grounded 50 m wire.

4. Analysis and Discussion

4.1. Properties of Positive Leaders Initiated From Grounded Conductors

The triggered lightning techniques presented in this paper allow the investigation of the propagation of positive leaders initiated from grounded conductors in different ambient field conditions, generated either by the thunderstorm or by the approach of a downward negative leader.

In the classical triggering technique the rocket spools out the wire in a quasi-stationary field E_0 produced by the thundercloud. The positive leader inception and development are directly related to the electric field distribution at and above the rocket tip. This distribution depends on the wire length, the

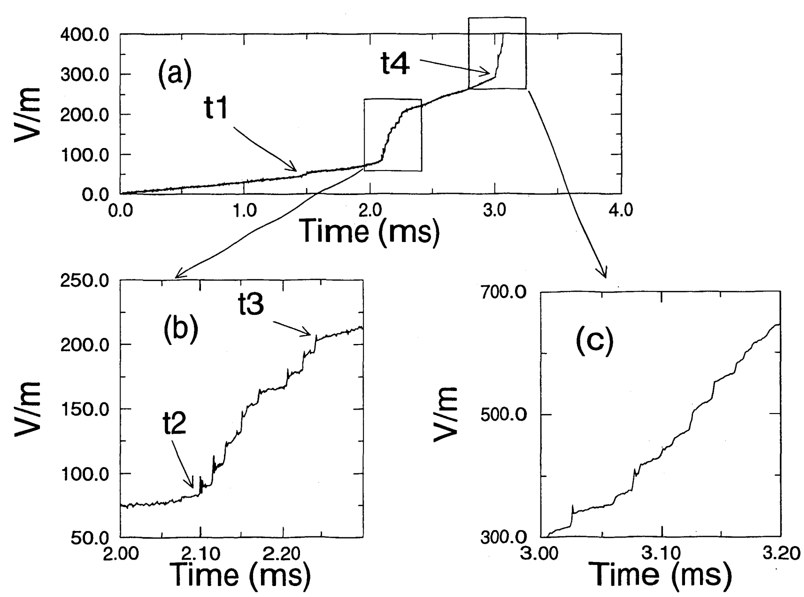

Figure 7. Electric field variation measured by antenna A_1 at 50 m from lightning channel (9516).

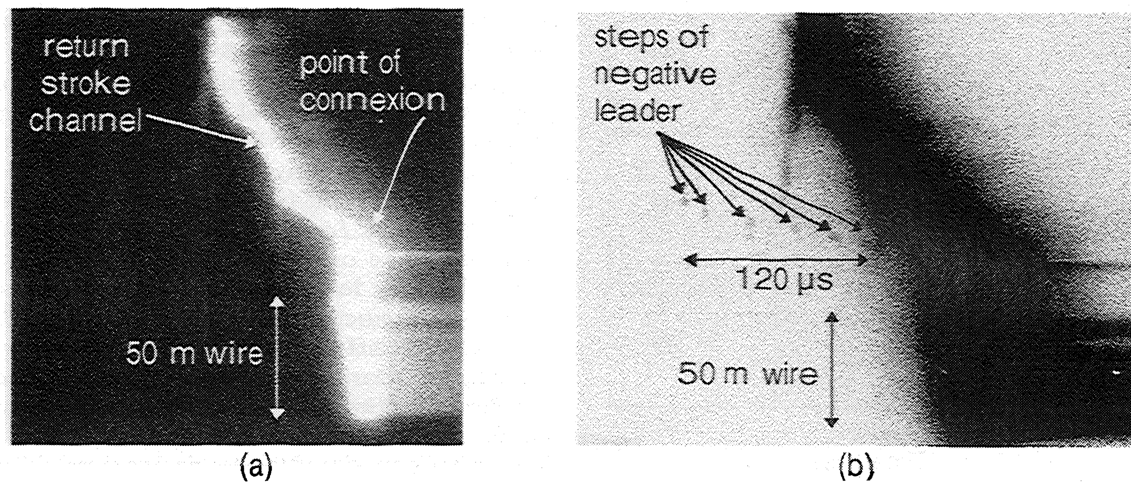

Figure 9. Streak photograph of altitude-triggered lightning 9516: (a) streak photograph of the first return stroke and (b) negative of the streak photograph shown in Figure 9*a*. The contrast of the negative is strongly increased to accentuate the steps of the negative leader. Note that horizontal and vertical scales are the same for the two photos.

ambient field E_0 and, eventually, on the presence of space charge at the rocket tip.

In this case, the generation of isolated current pulses in the first phase of the discharge is attributed to a series of aborted streamer-leader inceptions due to values of electric field at and above the rocket tip being insufficient to sustain stable propagation. Each isolated current pulse corresponds to a charge of several tens of microcoulombs. In the laboratory these values of positive corona charge always lead to the development of a positive leader [*Les Renardieres Group*, 1972], so we can assume that these isolated current pulses are associated to a positive leader development which stops after few meters of propagation.

The interval between isolated current pulses around 5 ms can be attributed to space charge effects. Indeed, in a long air gap submitted to positive impulse voltages, a "field shocking effect" is observed, due to the injection of positive space charge due to the first corona development at the rod. This reduction of local field inhibits the development of subsequent coronas unless the electric field is restored because of the applied voltage [*Les Renardieres Group*, 1972]. In rocket-triggered lightning, as positive ions drift slowly in the local field (average velocity around 100 m s^{-1} [*Badaloni and Gallimberti*, 1972]), the field at the rocket tip can be only restored by the ascending motion of rocket (rocket velocity 200 m s^{-1}), which leaves the space charge behind. If a simple spherical approximation is used for the space charge geometry, it can be shown easily that the space charge effect becomes negligible when the

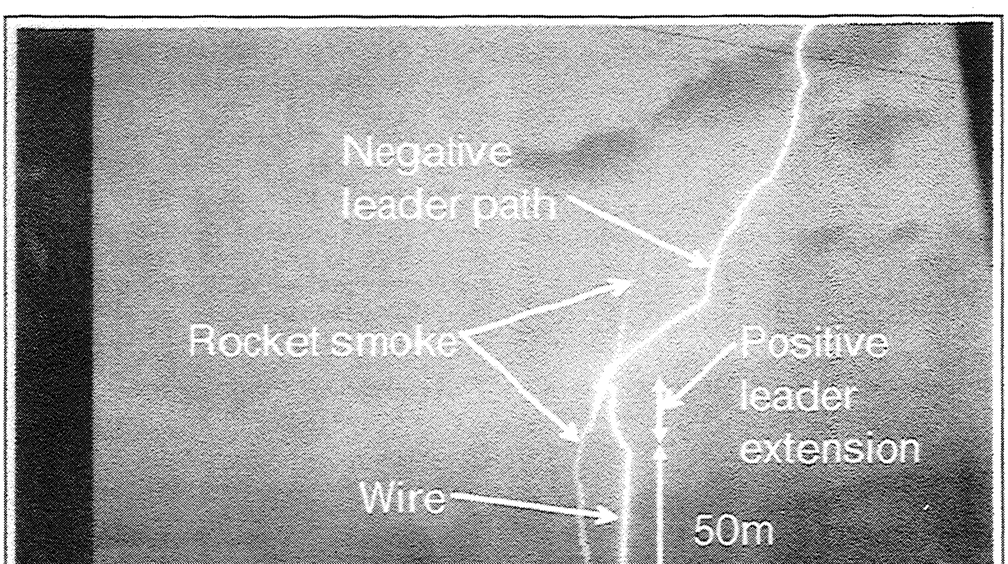

Figure 10. Still photograph of altitude-triggered lightning 9516.

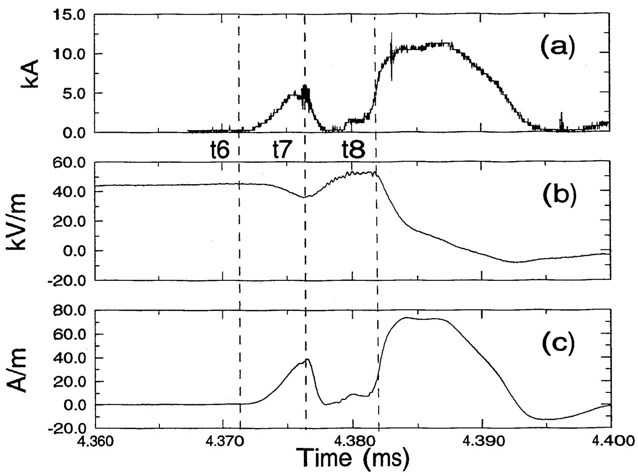

Figure 11. Plots of altitude-triggered lightning 9516 showing (a) current of the first return stroke, (b) electric field variation measured by antenna A_2 at 50 m from the lightning channel, and (c) magnetic field at 50 m from the lightning channel.

rocket tip has moved through half of the space charge extent (or less when considering more relevant geometries for the space charge, such as ellipsoid [*Gallimberti et al.*, 1982]). Since the time separation between pulses is around 5 ms, the distance covered by the rocket, during that time, is equal to 1 m. This is consistent with the interpretation inferred from streak photography of an upward positive leader triggered in similar conditions which gave a minimum corona length of 5 m [*Idone*, 1992].

In altitude-triggered experiments the grounded wire has a constant length (50 m) and the E field variation is produced by the approaching negative leader: the positive upward connecting leader reaches the conditions for its stable propagation in a much shorter time without going through the preliminary phase described above.

In both experiments the actual leader onset (at time $t = 0$ ms in Figure 5 and time $t_5 = 4.02$ ms in Figure 8) is associated with series of current pulses with a repetition period ranging from 20 to 25 μs. In previous experiments [*Laroche et al.*, 1988] using the classical triggering technique, streak photographs of the discharge tip have also indicated that the discharge propagates in a discontinuous pattern made of successive restrikes of similar time period, although the leader was optically undetectable until it reached a height of about 1000 m. This discontinuous propagation mode is specific for lightning leaders, as it is generally not observed in laboratory long sparks, except for slowly varying applied voltages.

The analysis of the shape of the current pulses must take into account the filtering effect of the wire and the lengthening leader channel that may be considered, in first approximation, as a resistance inductance capacitance (RLC) transmission line with time dependent parameters. It has been shown [*Bondiou et al.*, 1994] that the oscillating shape of initial pulses similar to those in Figure 5 is associated with the response of the wire to fast rising current pulses produced at the discharge tip (in the case of altitude-triggered lightning, the grounded wire is of shorter length, the current amplitude is lower, and this effect is not detectable). This oscillating shape progressively disappears because of the high resistance of the growing leader channel.

4.2. Properties of the Bidirectional Leader Produced in Altitude-Triggered Lightning

The altitude-triggering technique offers a unique opportunity to study the bidirectional leader process similar to one involved in aircraft-initiated lightning [*Mazur*, 1989]. It is worth noting that the time delay between inception of the positive and negative parts of the bidirectional leader is around 3 ms (6 ms in the work by *Laroche et al.* [1991]); this value is in the same range as the one existing between the onset of the positive and negative leaders involved in the initial phase of the aircraft striking process [*Mazur*, 1989; *Boulay*, 1991]. This delay is related to the difference in inception thresholds for positive and negative polarities observed in laboratory experiments [*Les Renardieres Group*, 1972, 1981]. The coupling between the two leaders is likely evidenced by the acceleration of the positive leader (increasing of the electric field slope) following the negative leader inception. This is attributed to an enhancement of the electric field at the tip of the positive leader aloft due to the lowering of the potential of the floating conductor (wire) caused by the downward propagation of a negative discharge from the bottom of the wire.

The E field measurements enable the investigation of the main parameters of the negative part of this bidirectional leader. This negative leader shows the main characteristics of a stepped discharge as observed in laboratory and in natural lightning. The stepping period is around 21 μs, and the average velocity is higher than 1.3×10^5 m s^{-1}, these parameters being in the range of those observed for natural stepped leaders. The mean step charge is deduced from the E field variations associated with an individual step: an average charge of 300 μC. In the laboratory this value of charge is associated with a negative leader step whose peak current is about 600 A. We can note that this charge is measured at the beginning of the downward negative leader propagation. As the negative leader approaches the ground, this charge value and the peak current are likely to increase.

5. Conclusion

The two triggered lightning techniques presented in this paper have been used to analyze specific properties of leaders of both polarities. The results will be used in the development of self-consistent models based on theoretical analysis of the different discharge phases investigated in laboratory long sparks [*Bondiou and Gallimberti*, 1994]. Furthermore, the altitude-triggered lightning technique appears to be a valuable tool to study the connection process between a negative downward leader and an upward positive leader originating from a grounded conductor.

Acknowledgments. The Camp Blanding experiments were made possible through the efforts of many French and U.S. organizations, in particular, through the support of the Camp Blanding Army National Guard Base (Charles Golden). We are also grateful to DRET, which partly funded this experiment, and to IREQ, which provided data acquisition equipment.

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(Received November 28, 1996; revised August 26, 1997;
accepted August 29, 1997.)