MODELLING OF THE LIGHTNING CONNECTION PROCESS TO A GROUND STRUCTURE

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Abstract - This paper describes a self consistent model of the attachment of a negative stepped leader to a ground structure. The computed results are compared with current and electric field measurements obtained during a triggered lightning campaign performed at Camp Blanding (Florida) in summer 1995.

1. Introduction

Since 1990, ONERA and University of Padova have developed a set of self consistent models in order to simulate the "bi-leader" process involved in the aircraft striking [1][2]. These models, based on the numerical simulation of physical laws, compute the time evolution of the main discharge parameters (current, velocity, channel internal field, ...); they have been used and validated in the case of long air gap discharges under positive [3] and negative [4] polarities.
Recently, the numerical codes were adapted to simulate atmospheric discharges and were tested in both configurations of "classical" [5] [6] and "altitude" [7] triggering techniques.
The latter technique, used in summer 1995 in Florida, was designed to study the lightning connection between a downward negative stepped-leader and an upward positive leader initiated from a grounded structure, equipped with a current sensor.
The first part of this paper describes the experimental set up and results. The second part deals with the numerical simulation of the lightning connection. The results of the simulation are discussed and compared with the experimental data.

2. Experimental data

2.1. Experimental set-up

The altitude triggering technique is used to study the bi-directional leader. A small rocket is launched and spools out first 400m of kevlar, followed by a triggering copper wire. When the latter wire has been trailed out over a sufficient length a bi-directional leader discharge is developed from its two ends. An upward positive leader is initiated from the tip of the rocket and propagates toward the cloud (figure 1a). A few milliseconds later, a downward negative stepped leader is developed from the bottom of the triggering wire and propagates toward the ground (figure 1b).
A specific set-up, which consists in adding 50m of copper wire at the lower end of the kevlar thread (figure 1c), is used to direct the connection of the negative stepped leader to an equipped grounded structure; in this case, the junction process is realised by an upward connecting positive leader initiated from the tip of the 50m copper wire (figure 1c).

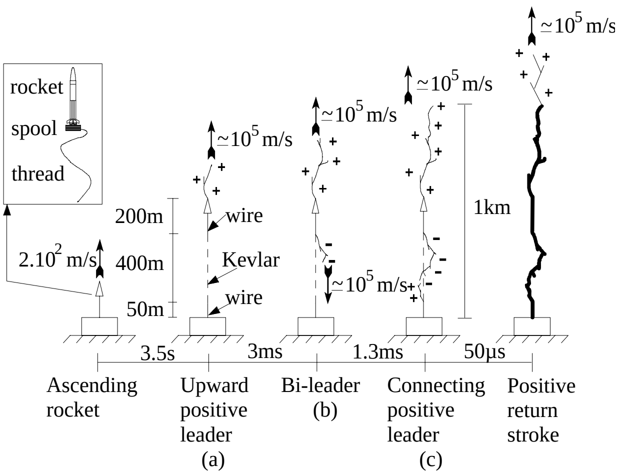

Figure 1 : sequence of events occurring in altitude triggered lightning.

Experiment diagnostics include measurements of the current flowing through the 50m long wire, using a 1mΩ shunt and E-field at 50m from the lightning channel, using two capacitive antennas; the first one (A_1) was calibrated to detect the bi-leader onset, while the second (A_2) was calibrated to record the electric field variation of the return stroke. An image converter camera was placed at 400m distance.

2.2. Experimental results

2.2.1. bi-leader onset and development

Electric field measurements can be used as a guide to infer the main chronological sequence of events which occurs before the first return stroke (fig. 2).

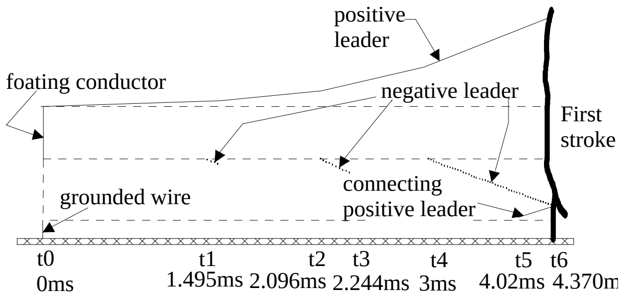

Figure 2: Chronological events measured during an altitude triggered lightning

- From time t_0 to t_1, the electric field at ground increases slowly with a mean slope of 30 kV/m/s (fig. 3a). This field rise at ground is most probably related to a positive leader extension from the top of the wire.
- At time t1, two small pulses (about 3.5 V/m each ; unresolved in fig. 3a) are superimposed to the continuous field increase. These pulses are consistent with a charge ΔQ of about 40 µC placed at 450 m above ground. They may therefore be associated with negative coronas inception at the lower end of the wire.
- From time t_1 to t_2, a further slow field variation is observed, similar to the one measured from t_0 to t_1, with a mean slope varying from 30 kV/m/s to 49 kV/m/s (fig. 3a).
- At time t_2, a fast stepped electric field variation is detected which can be attributed to a negative leader inception at the lower end of the wire (fig 3b). Each step is of about 15 V/m and is consistent with a charge of about 170 µC at 450 m above ground. After 8 steps, at time t_3, the negative leader development appears to pause.
- From time t_3 to t_4, the positive leader apparently continues as indicated by the further field increase after t_3 (fig. 3a). The increase of the electric field slope after t_3 (121 kV/m/s) relative to the slope prior to t_2 (30 to 49 kV/m/s) suggests that the positive leader accelerated following the downward negative leader inception.
- From time t_4, a negative leader resumes with a mean step field variation equal to 23.5 V/m (consistent with $\Delta Q = 270\ \mu C$ at 450m) with a time interval of 18.5 µs (fig. 3c).

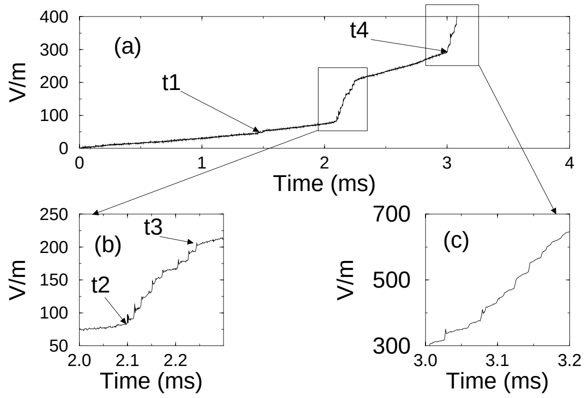

Figure 3: Electric field variation during the bi-directional leader onset (antenna A_1)

2.2.2. Connection process

The current measurement at the bottom of the grounded wire indicates (figure 4b) that a positive upward leader starts at time t_5, 1ms after the stable negative stepped leader onset. At that time the electric field at ground reaches 10kV/m. The positive leader development current exhibits pulses separated by 20µs. The pulse crest values increase up to 200A a few microseconds before the return stroke while the E-field reaches 45kV/m at ground.

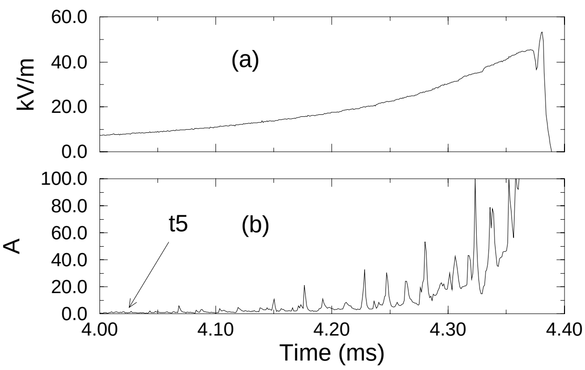

Figure 4: (a) Electric field variation measured by capacitive antenna A_2 placed at 50m from the lightning channel; (b) current produced by the upward connecting positive leader from the grounded 50m long wire.

3. Numerical simulations

3.1. General principles of the modelling

The simulation code is composed of three majors coupled sections which calculate at each time step:

(1) the development of the bi-directional leader from the floating wire. The code computes the advancement of each leader based on a simplified electrostatic description: both channels are represented as uniformly charged lines propagating axially.

(2) the field and potential distributions using the Charge Simulation Method (CSM) [8]; they result from the superposition of three components:

- ambient field (assumed to be vertical and deduced from measurements) distorted by the presence of the floating wire and the 50m grounded conductor.
- E-field due to the bi-leader development calculated with the simplified model described in 3.3.
- local field associated with the propagation of the connecting positive leader (this includes the effects of leader channel and the space charge of corona envelope). This component is calculated within the self consistent model described in 3.2.

(3) the propagation parameters of the positive leader initiated from the 50m wire:

- electric field threshold for corona inception
- leader tip and corona front position
- injected current at the leader tip
- space charge distribution

3.2. Physical basis of the positive leader modelling

A schematic representation of the discharge propagation is given on figure 5. The main physical processes involved in the spark development are the following:

* Corona region. The streamer advancement mechanism is related to the concentration of positive ions at their tips (fig. 5); the space charge field becomes high enough for self sustained ionisation and electron avalanche formation; the propagation is guided by the external field and, for a specific value ("stability field"), an energetically stable condition can be obtained [9][10].
* Leader head. The current injected by the corona region into the leader channel induces the Joule heating of the gas in the transition region in front of its head (fig. 5); as a consequence the conductivity greatly increases due to thermal detachment of negative ions [11]. The leader head appears as a propagating thermal transition wave, which converts the cold diffuse glow of the corona into a hot channel.
* Streamer-leader system. The stable propagation of the whole system results mainly from the coupling between the corona and leader advancement processes. The ionisation activity at the front of the corona streamers supplies the current and energy input necessary to sustain the thermal transition at the leader head; conversely, the conductive leader channel advancement sustains the field at the streamers front, allowing their continuous propagation [12, 13].

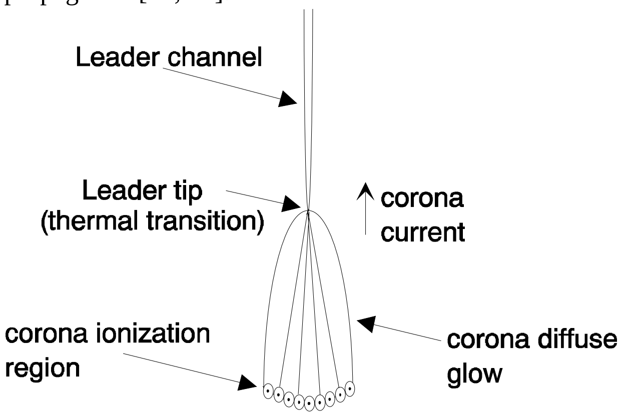

Figure 5: Schematic representation of the positive streamer-leader system with indication of the main regions of discharge.

As opposed to the laboratory case, the positive atmospheric discharge proceeds by discontinuous propagation, as indicated by current measurements (figure 4b). This phenomenon is also observed in "classical" triggering technique (where the thread spooled out by the rocket is only made of copper wire) which is widely used to investigate the upward positive leader inception and development from tall structures (more than 100m) [5]. The proposed model predicts this specific propagation and allows a satisfactory interpretation of the discontinuous behaviour. In atmospheric discharges, the external ambient field (50kV/m) is relatively lower than in the laboratory case (one order of magnitude); as a consequence, the field at the corona front is mainly produced by the distortion produced by the leader tip; when the leader corona streamers develop, they propagate at a very high speed and extend rapidly far from the leader tip, in the region where the field drops to the low ambient value. Then, the front ionisation processes stop, the leader corona cannot reach an equilibrium condition and the discharge is arrested. If the field at the leader tip is high enough, a new corona-streamer can develop and the leader-corona system can restart.

3.3. Simulation of the bi-leader development

At the beginning of the development of the bi-directional leader, the charge per unit length of leader elements is fixed to 50µC/m for positive and 100µC/m for negative in agreement with laboratory measurements. Then, in order to reproduce the electric field variations measured at ground, the value of the negative leader velocity is fitted to be consistent with the measurement of the discharge propagation duration. This constraint leads to increase the values of the charge per unit length of both leaders, which can be justified by the formation of branches that leads to an increase of the total charge.

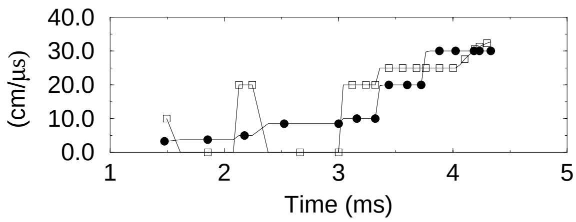

Figure 6: Computed time evolution of the velocity of the positive (filled circle) and negative (square) leaders.

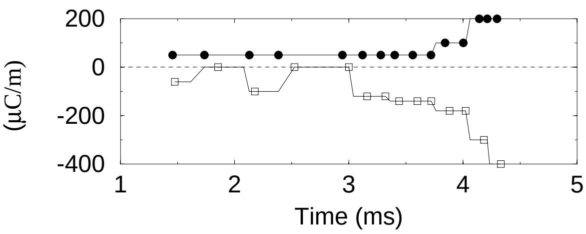

Figure 7: Computed time evolution of the charge per unit length of positive (filled circle) and negative (square) leaders.

Figures 6 and 7 show the time evolution of these two parameters. During time intervals t_1 to t_2 and t_3 to t_4 when the negative leader propagation is arrested, the associated charge and velocity are obviously zero.

The positive leader acceleration associated with the successive negative leader inceptions can be attributed to the coupling between the two discharges through the floating potential of the wire conductor [2].

At the instant of final jump, the last part of the negative leader has a charge of about 400µC/m. The total charge produced by the two leaders is presented figure 8, while the time evolution of their position is given in figure 9.

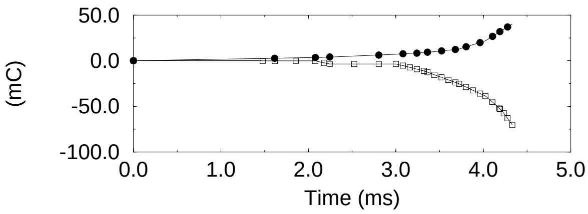

Figure 8: Time evolution of the space charge of the positive (filled circle) and negative (square) leaders.

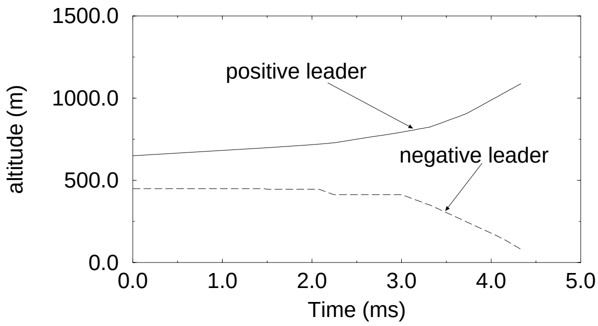

Figure 9: Computed head positions of the bi-directional leader development

The result of the E-field best fit is illustrated in figure 10: the electrostatic simulation is in good agreement with the measurements, except few microseconds before the first stroke; the last computed point in figure 9 corresponds to the simulation of the E-field after the first return stroke: the total lightning channel is here assumed to be equivalent to a 1100m long wire, and the attenuation of the cloud to ground ambient field by this conductor is taken into account.

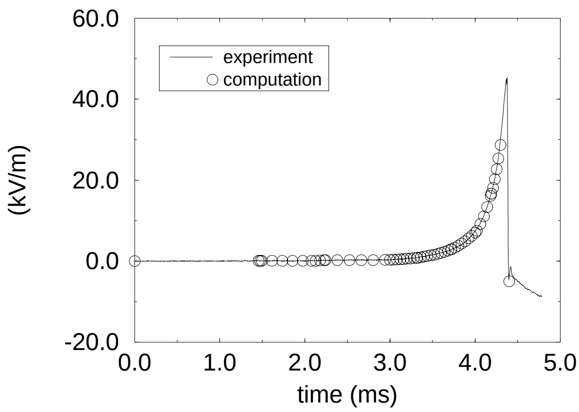

Figure 10: Time evolution of the electric field at ground at 50m of the lightning channel. Comparison between measured and calculated E-field.

3.4. Simulation of the positive connecting leader

In this electric field distribution, the self consistent model is used to simulate the conditions of formation of

the connecting positive leader from the 50m grounded wire. The inception electric threshold is reached at 4.19ms (figure 11), which corresponds quite well to the beginning of significant pulse currents recorded by the experimental measurements (figure 4b).
The connection is realised 150µs later. The time interval between calculated current pulses (22µs) is in quite good agreement with the measured time. Moreover the peak current values are consistent with the measured ones.
The actual computation doesn't take into account the inductive current component generated by the E-field variation and the filtering of the leader current by the 50m long wire. A better agreement could be obtained by these additional calculations.
At the junction, the positive leader is of about 15m long, while the corona front is about 25m long, which is in good agreement with data deduced from the camera recordings (figure 12).

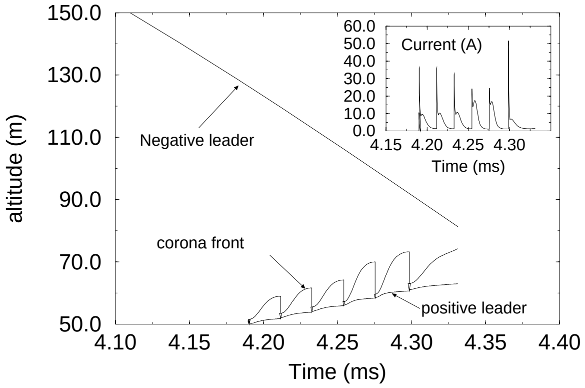

Figure 11: Computed development of the connecting positive leader; evolution of the current flowing through the leader tip.

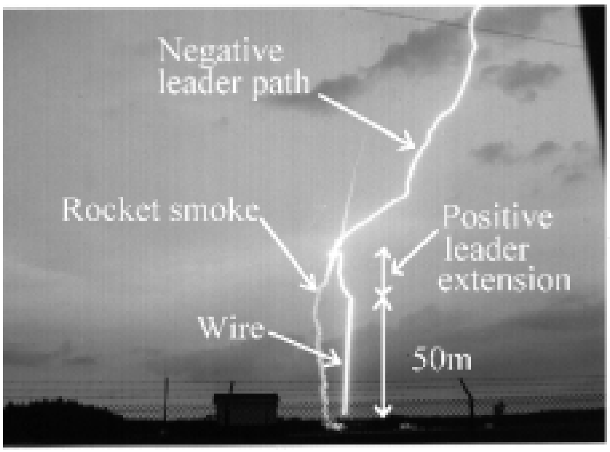

Figure 12: Photograph of the altitude triggered lightning

4. Conclusion

The altitude triggering technique has made possible the investigation of the negative downward flash and the processes occurring just before its connection to ground.
The self consistent model used to simulate the connecting positive leader gives results in very good agreement with the experimental data. This model can be extended to compute lightning protection parameters, such as the striking distance and the attractive radius.

Acknowledgements

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