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On the propagation mode of upward positive leaders initiated from grounded structures

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***Abstract*— From the analysis of typical measurements of negative downward and upward lightning, the common propagation mode of upward positive leaders is discussed. It is shown that there are no elements to support the claim for a stepped propagation of positive leaders. On the other hand, the current records indicate that propagating continuously seems to be the common feature of upward positive leaders. Based on results obtained at Morro do Cachimbo Station, Brazil, and at the Peissenberg Tower, Germany, a comprehensive propagation model of positive upward connecting leaders in negative downward lightning is presented and discussed.**

Keywords—upward positive leaders; continuous propagation mode; stepwise development.

I. INTRODUCTION

The propagation mode of negative leaders in virgin air is well documented in literature, for both laboratory environment and natural lightning. Several works present experimental results of the stepwise propagation of such leaders in real lightning [Biagi et al., 2010; Hill et al., 2011; Petersen & Beasley, 2013; Qi et al., 2016; Tran et al., 2014; Wang et al., 2016a]. In this respect, it is worth mentioning that a step is understood as an abrupt change of the leader geometry. For negative leaders, it corresponds to an instantaneous elongation of the leader caused by the bridging of the gap between the main leader and one or more stems/space leaders established ahead.

Although laboratory experiments indicate that, for most of the humidity conditions, positive leaders propagate continuously [Bazelyan and Raizer, 2000], little is known about this propagation mode outside the laboratory environment. Only recently, a few experimental works presented analysis of the propagation mode of positive leaders based on real lightning data [Kong et al., 2008; Biagi et al., 2011; Wang and Takagi, 2011; Jiang et al., 2013; Sun et al., 2014; Lu et al., 2014; Wang et al., 2016b]. Most of these works present impressive results that led the authors to claim that positive leaders do propagate by steps, in contrast with most of the laboratory experiments.

This paper summarizes and updates the main results presented on a recent work by the authors [Visacro et al., 2017a], which is focused on fundamental aspects of the propagation of positive upward leaders (UPLs). The discussion is based on measurements obtained at Morro do Cachimbo Station (MCS), Brazil, and Peissenberg Tower, Germany. In addition, it is shown that the results presented by all the aforementioned references can be explained by the reasoning presented by the authors.

The discussion begins with the identification of the existence of induced effects on grounded structures and on upward positive leaders by negative leaders propagating in the surroundings. This is very important, since several works do not identify the cause of these effects and associate them to a supposed stepwise development of the positive leaders.

After that, a fundamental difference between patterns of currents of different types of negative upward lightning (self-initiated and triggered by nearby event) is presented as an evidence of the continuous propagation of upward positive leaders.

In the following, a propagation model of the positive upward connecting leader (UCL) in negative cloud-to-ground lightning is presented, based on measurements and video-recordings obtained at MCS. Detailed information about MCS instrumentation can be found in [Guimaraes et al., 2017; Visacro et al., 2017a; 2017b].

II. THE EXISTENCE OF INDUCED EFFECTS ON GROUNDED STRUCTURES AND ON UPWARD POSITIVE LEADERS

The successive disruptions associated to the steps of negative stepped and dart-stepped leaders are able to induce pulses of current in grounded structures and in existing positive upward leaders. This is physically sound and has already been demonstrated by some researches, as discussed in [Visacro et al., 2010; Schoene et al., 2008].

In this context, measurements of the pre-return stroke current in grounded structures struck by lightning demonstrate this reasoning. Figure 1 shows records of current and electric field obtained at MCS, just before the first stroke of a negative downward lightning measured on 25 February 2015, at 20:16:49 (UT).

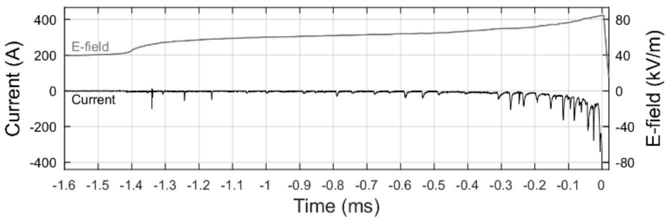

Fig. 1. Current and close electric field (50 m) of the first stroke of a flash measured at MCS on 25 February 2015, at 20:16:49 (UT). Adapted from [Visacro et al., 2017a]

Each current pulse induced along the tower and along the positive UCL (when it is already launched) is caused by the formation of a new step of the downward negative leader. It is worth noting that such pulses are measured along the whole interval, from hundreds of microseconds prior to the initiation of the positive upward connecting leader, at t = -490 µs in the case of Figure 1 [Visacro et al., 2017b], until the beginning of the return stroke. Thus, they cannot be attributed to a stepwise propagation of the positive upward leader, as it is usually done. As discussed in [Visacro et al., 2017a], the uprising continuous current, i.e., the current component that increases exponentially before the initiation of the return stroke, is associated with the sustained development of the UCL.

The intensification of the electric field in the considered interval also indicates that a negative leader approaches the structure. Note that the physics sign convention [Rakov and Uman, 2003] is adopted in the E-field waveforms of this paper.

III. CURRENTS OF NEGATIVE UPWARD LIGHTNING

Currents of upward lightning measured at the Peissenberg Tower (Germany) showed to be very important to better understand the propagation mode of upward positive leaders. Figure 2 shows records of the initial continuous current (ICC) of two types of upward lightning measured there: (a) triggered by nearby lightning and corresponding detail (b); (c) self-initiated and detail (d).

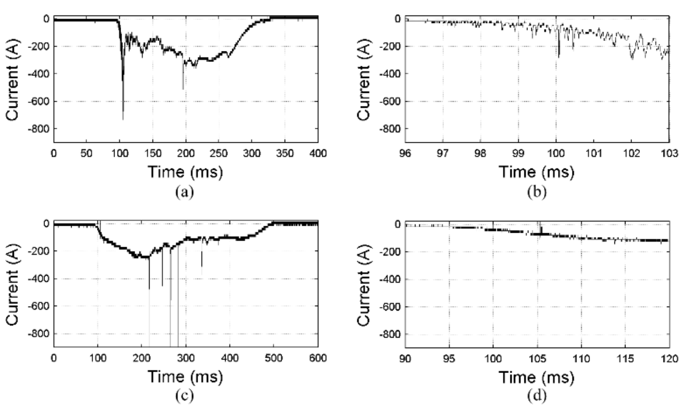

Fig. 2. Records of current of negative upward lightning measured at Peissenberg Tower, Germany: (a) initial stage of an event triggered by a nearby lightning measured on 26 June 1997; (b) detail of the current in the beginning of the initial stage; (c) initial stage of a self-initiated event measured on 17 February 1999; (d) detail of current just before the initial stage. Adapted from [Visacro et al., 2017a], Courtesy of F. Heidler.

The ICC is the initial stage of the negative upward lightning: it comprises the upward leader initiation and development, long before the occurrence of return strokes. In the case of the event depicted in Figures 2a and 2b, a negative leader propagating above the tower induced the unipolar pulses observed in the detail (Fig. 2b). As demonstrated by Heidler et al. [2013], the electric field waveform of this event indicates the approach of a negative leader. Thus, such pulses cannot be strictly attributed to a stepwise development of the upward positive leader.

On the other hand, the absence of pulses in Figure 2d, which is a detail of the current of the self-initiated upward lightning depicted in Figure 2c, shows that *the positive upward leader propagates continuously*, with a corresponding smooth current profile. This is a common feature of all self-initiated negative upward lightning measured at the Peissenberg tower. Moreover, in this kind of event, the corresponding electric field waveform shows no signs of negative leaders approaching.

For the case of the upward lightning triggered by nearby lightning, the record of Figures 2a and 2b is the sole event of this type measured at the Peissenberg tower. However, all upward lightning measured at MSC are triggered by nearby negative leaders and present the same pulses. Figure 3 shows the ICC of a negative upward lightning measured there on 26 January 2015. Current pulses induced by the steps of an approaching negative leader are observed during the whole interval and the corresponding electric field record depicts this approach.

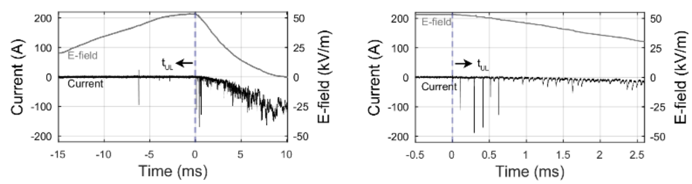

Fig. 3. Current and close electric field (50 m) of the ICC of a negative upward lightning measured at MCS on 26 January 2015. Adapted from [Visacro et al., 2017a]

IV. THE CONTINUOUS PROPAGATION MODE OF UPL AND A COMPREHENSIVE PROPAGATION MODEL

On the two previous sections, evidences of the continuous propagation mode of upward positive leaders were presented. Based on these evidences and on recent results obtained at MCS [Guimaraes et al., 2017; Visacro et al., 2017a; 2017b], a comprehensive model was developed to explain the propagation and corresponding measurement results. This model is exhibited in Figure 4.

Figure 4 shows a sequence of events yielded by the approach of the negative leader to the ground in steps. Each step interval comprises the time required for the formation of a stem/space leader ahead of the negative leader tip (b, d, f, etc.), followed by the bridging of the gap between them (c, e, g, etc.) at the end of the interval. Each stepped elongation of the negative leader causes an E-field pulse shown in the fast E-field curve and an increasing stepped E-field at the region above the grounded structure, as shown in the slow E-field curve.

Under the effect of this increasing E-field in steps, first only pulses of current are induced along the grounded structure, increasing the charge deposited at the structure (4a). After reaching a critical electric field value, positive corona streamers are developed from the structure top (4b), causing the flow of a small corona current. A pulse of current of a few tens of amperes

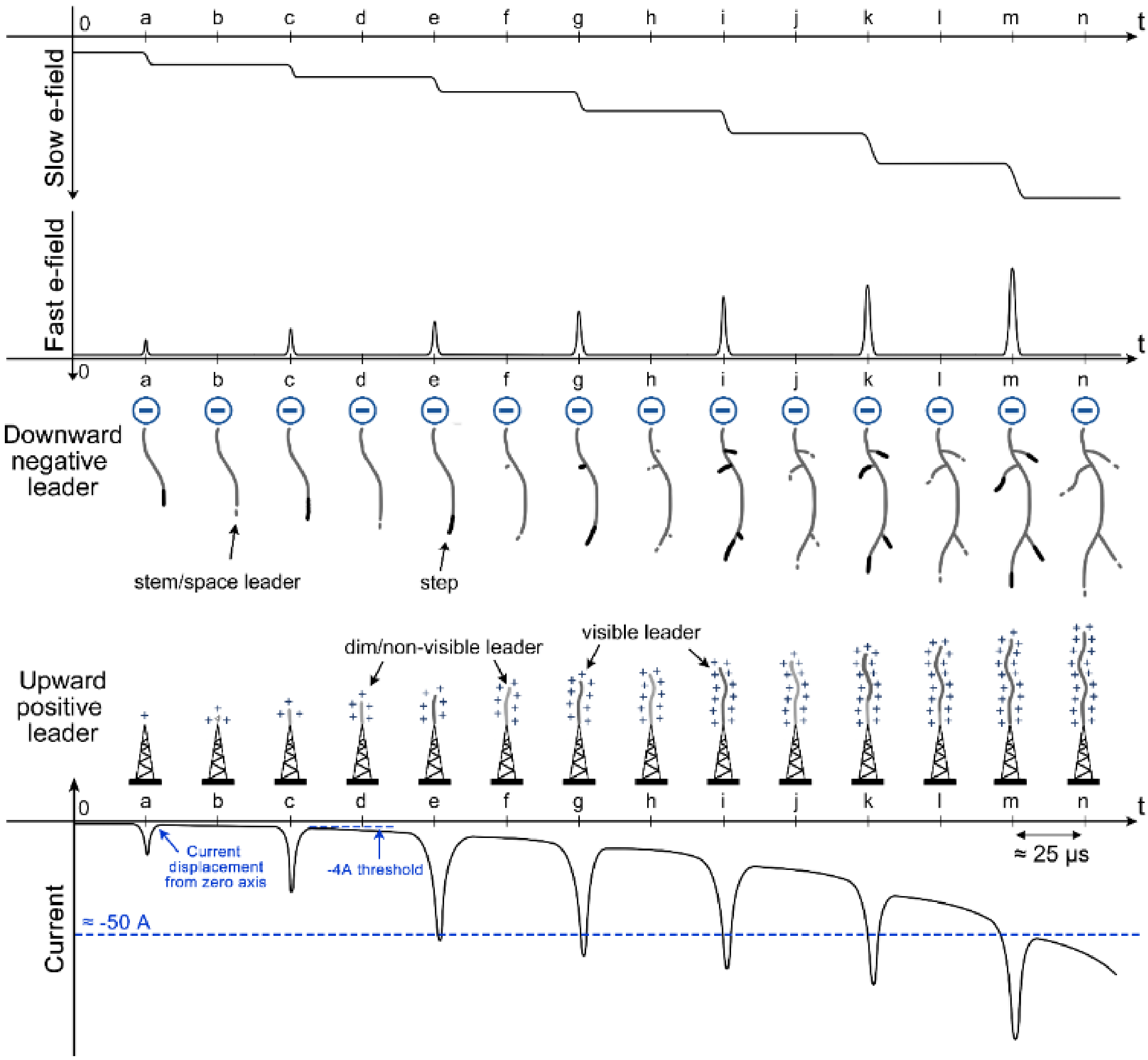

Fig 4. Schematic representation of the continuous propagation of the positive upward connecting leader. Adapted from [Visacro et al., 2017a]

superimposed on a 4-A continuous current is able to initiate a sustained upward positive leader (4c), though it is still under the camera detection threshold. This leader develops continuously (4d) until a new E-field step induces a pulse of current larger than 50 A, which produces a luminous effect detectable by the camera (4e). The positive leader continues to develop without steps (4f to 4j), producing luminous effect when pulses of current larger than 50 A are induced by the steps of the negative leader (g, i) and the continuous current continues to increase. In long upward positive leaders, sometimes the luminosity of the positive leader bottom become too low to be detected by the camera due to the increase of the leader conductivity under the cumulative effect of the current flowing at the leader bottom (k,l). The sequence of this process decreases the distance between the positive and negative leaders and causes the amplitude of both the continuous current and the superimposed pulses of current to increase. This makes the whole positive leader detectable by the camera (4m, 4n). Ultimately, the attachment of the leaders leads to the return stroke.

Final Remarks

The great similarity of the continuous propagation model presented in Figure 4 with recent current measurements and high-speed video recordings obtained at MCS reinforces the conclusion that *propagating continuously is the common feature of upward positive leaders in negative CG lightning*. It also seems applicable to the propagation of positive leaders in general, including those in negative upward lightning and triggered lightning. It is worth mentioning that, under the effect of E-field enhancement during the steps of the approaching negative leader, an increase in the propagation speed of the positive leader is expected, though this does not correspond to a stepwise process.

Regarding the recently-published works that claim for a stepwise development of upward positive leaders, it is important to state clearly that all elements used to support this claim can be, in fact, associated with effects induced by negative stepped or dart-stepped leaders approaching the grounded structure. These effects include pulses of current, electric field, magnetic field, luminosity, and so on.

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