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Analysis of the charge distribution and leaders inside the cloud for upward flash initiation

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***Abstract*— Upward flash initiation has been observed in Rapid City and in Brazil. All upward flashes observed in both locations were triggered upward flashes (more details about the characteristics from the flashes can be found in Saba et al. 2016). The mechanisms observed for upward leader initiation and case studies are described in “Upward Lightning Triggering Study (UPLIGHTS): Project Summary and Initial Findings” in the 2018 ILDC/ILMC conference by Warner et al. This paper aims to discuss the charge structure and leader propagation inside the cloud for the upward flash initiates in addition to these mechanisms. The leader from the triggering event modifies the charge equilibrium in the cloud and promotes the sudden change necessary for the initiation upward leaders. Essentially, when a flash occurs in the area of a tall structure, the positive downward flash brings negative charge to the main positive charge center. This offers a sudden change on the environmental electric field, making the shielding layer more dominant on the resultant electric field. This theory was based on the observations of high-speed videos, radar and LMA data electric field data. Each of the equipment data was analyzed and evidence that contributes for this theory will be presented and discussed in this paper.**

Keywords— Upward flashes; Initiation; cloud structure; triggered initiated.

I. INTRODUCTION

The stages involved in upward lightning flashes are well-known – they have been observed in both current measurement and video observations (Diendorfer, 2009, Saba et al 2016). These stages are schematically described in Figure 1. While these stages are well understood, the reason why leaders initiate from the top of a tall tower is still uncertain.

There are two types of upward lightning flashes: self-initiated and triggered-initiated (Wang, 2008). Triggered-initiated upward flashes are caused by some prior lightning activity (such as a cloud to ground flash or in-cloud activity) in the vicinity of the tower. A triggered upward flash requires a sudden change in the electric field nearby the tower (Wang, 2008). A prior event (cloud-to-ground or cloud-to-cloud) can cause the neccesary change in the electric field over the tower, even it is tens of kilometers away.

The initiation of upward flashes, based on high-speed video observations, radar data, LMA data and fast-eletric field measurements, will be presented and discussed in this paper.

II. Background

Upward flahses are observed on tall towers around the world. In Japan, Wang et al., (2008) presented 14 cases where 4 self-initiated upward flashes and 10 triggered-initiated upward flashes from wind turbines were observed. Another study (Wang and Takagi, 2012) discussed 53 upward flashes recorded during winter where 53% of the cases were triggered-initiated. Zhou et al., (2012) showed that only 14% of 205 upward flashes were triggered-initiated and Jiang et al. (2014) presented 4 triggered-initiated upward flashes. In Germany, triggered-inititated upward flashes were recorded at the Peissenberg tower - one in 2013 and three in 2014 (Heidler, 2013, 2014). Saba et al (2016) presented a large dataset of 100 triggered-initiated upward flashes.

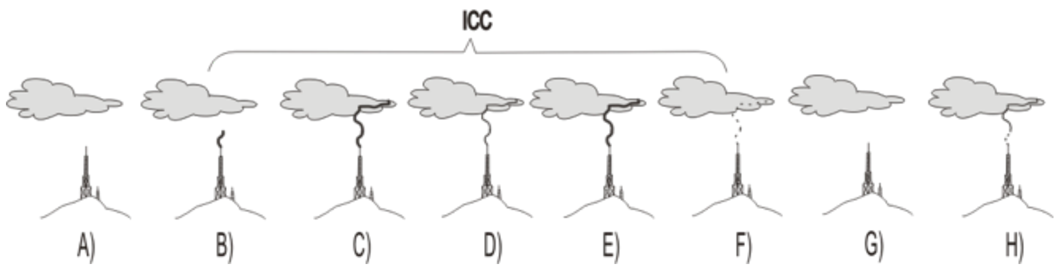

Fig. 1. Upward flash stages of development: Initial Continuing current, Pulses, no- current interval, subsequent return strokes.

1) *Charge Structure*

As 3D-mapping techniques improve, the study of the charge structure in thunderclouds yields more information. Weiss et al. (2012) showed that a main positive center, a main negative center and a small center of positive charge on the base of the cloud can be observed during the convective part of the cloud. As the thunderstorm progresses, the cloud dissipates and the main positive charge center begins to drop in altitude. Being mainly positive charge, the screening layer is predominantly negative.

2) *Bi-directional leader*

Another important concept is that of the bi-directional leader, first presented by Kasemir (1960). When immersed in an electric field, a leader develops in two directions each with opposite polarity. The positive downward leader exits the cloud and moves towards the ground but the negative leader develops inside the cloud and continues to propogate (leader extension). This has implications for triggered-initiated upward flashes and the mechanisms described in Warner et al. (2018) explain the connection between the triggering event and the upward leader initiation from the tower.

III. Hypothesis

The measured ambient electric field before a flash (defined as E_o) will be different to the measured ambient electric field after a flash (defined as E_f), due to the arrangement of charge in the cloud.

The critical value of electric field measured to produce an upward flash is defined as E_c. This critical value is dependent on the tower characteristics (e.g. material, height) as well as the characteristics of the relief of the region (e.g. ground, mountain height) and will therefore be different for each tower. In this paper, E_c is described as a function of these characteristics (φ) (first presented Schumann phD thesis, 2015) such that:

$$E_c \leq E_f \quad (1)$$

$$E_c \leq E.\varphi \quad (2)$$

In the case of self-initiated upward flashes, E_o will be so close to the E_c that even the slightest difference in the environment (wind, the distance of a cloud center from the tower) will be enough to initiate an upward leader. Figure 2 presents a schematic of the self-initiated upward flash.

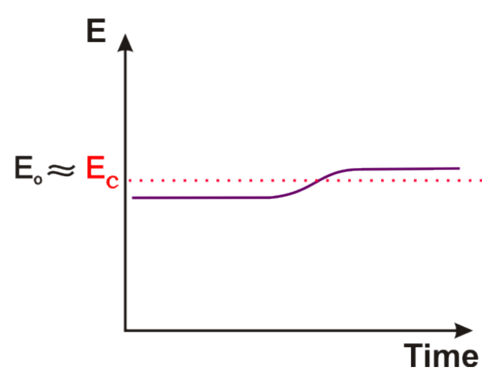

Fig. 2. Self-initiated upward flashes. The environmental electric field is very close to the critical electric field for upward leader initiation.

In the case of triggered upward flashes however, it is necessary to take into account any activity prior to the upward flash as described by Warner et al. (2018) Three different situations prior to an upward flash can be considered:

- First situation - return stroke
- Second situation – leader due to CC
- Third situation – only leader

Figure 3 shows a description of the first situation - a leader approaches a tall tower but without an upward leader inititating from the tower. Then, as the cloud-to-ground return stroke occurs and charge flows, the channel re-illuminates the leader over the towers (intensifying them). When this happens, the upward leader can be initiates from the tall tower.

In the second situation, the charge flowing during the return stroke does not initiate an upward leader but rather the propagation of the bi-directional leader inside the cloud during the continuing current phase of the prior event approaches the tall tower and initiates an upward leader (figure 4).

Lastly, in the third situation, just leaders propagting over the tall tower may initiate a upward leader as described in figure 5.

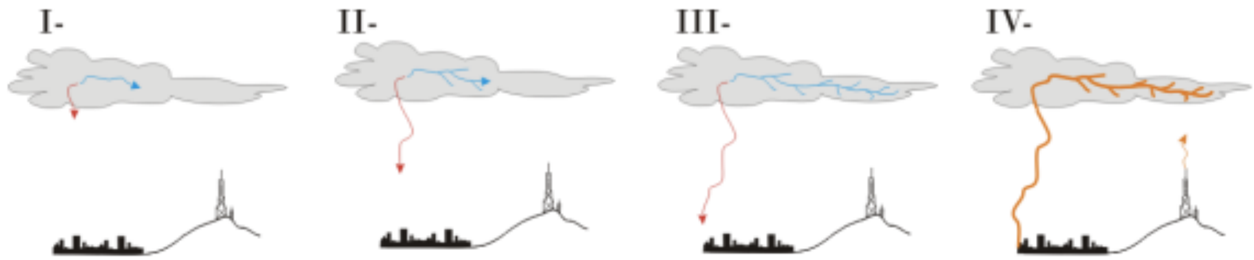

Fig. 3. First situation is due the intensification of the leader due to the return stroke , also called as instantaneous triggering.

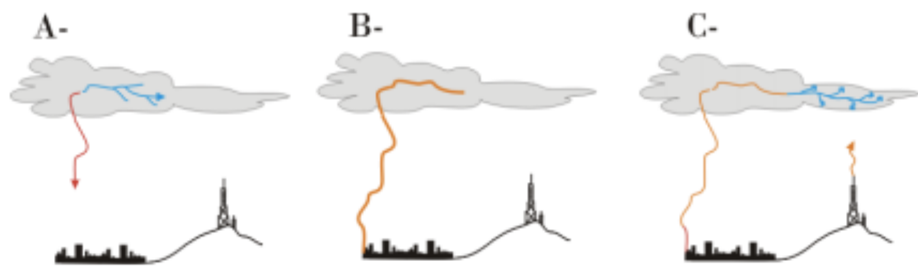

Fig. 4. The leader extension from continuing current phase of the triggering flash.

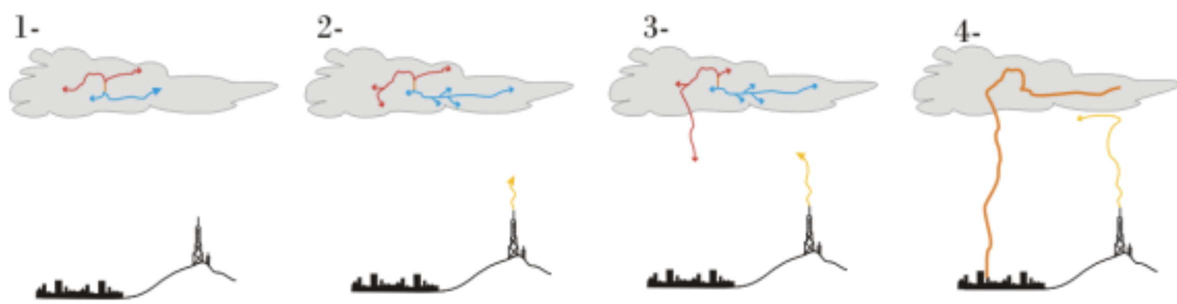

Fig 5. Leader over the tower is enough to trigger upward leader (IC or CG).

These findings suggest that it is necessary to account for a leader inside the cloud (ΔE_l) nearby the towers in the electric field equations. Each leader inside the cloud has characteristics (e.g. charge, height, distance) that may provide the environment for an upward leader initiation. A variation in the electric field due prior activity adds to the intitial electric field (E_o). This, coupled with φ will make upward leader initiation possible. This is summarised as a set of inequalities:

$$E_c \leq E_f$$

$$E_c \leq E.\varphi$$

$$E_c \leq (E_0 + \Delta E).\varphi$$

where:

$$\varphi = f(\varphi_r, \varphi_t)$$

φ_r - Function intensification of electric field due to the **relief**.

φ_t – Function intensification of the electric field due to the **tower's characteristics** (height, grounding system, material, etc).

This leader inside cloud might cause a large variation (figure 6a) or if the initial electric field is high enough, a small variation could initiate the upward leader (figure 6b). This can all be summarised as in figure 7.

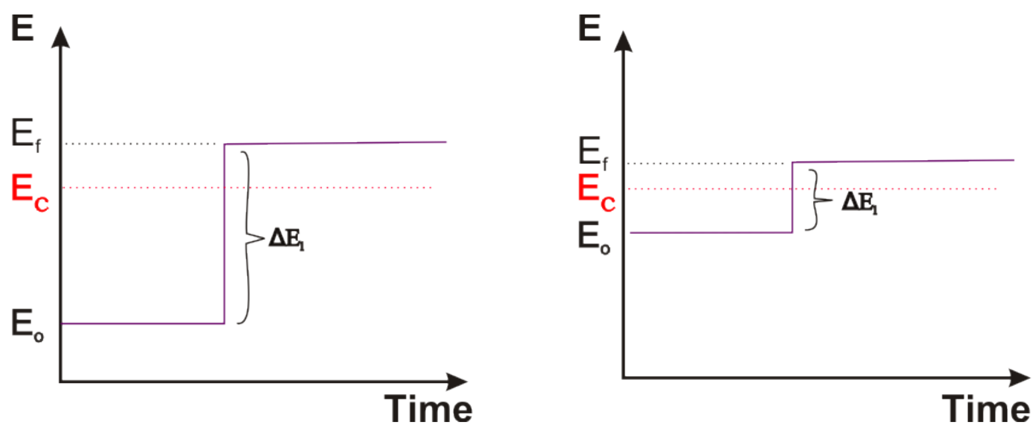

Fig 6. Triggered upward flash – (a) low initial electric field and large leader variation – (b) high initial electric field and small leader variation; both conditions would be able to provide propitious environment to upward leader initiation.

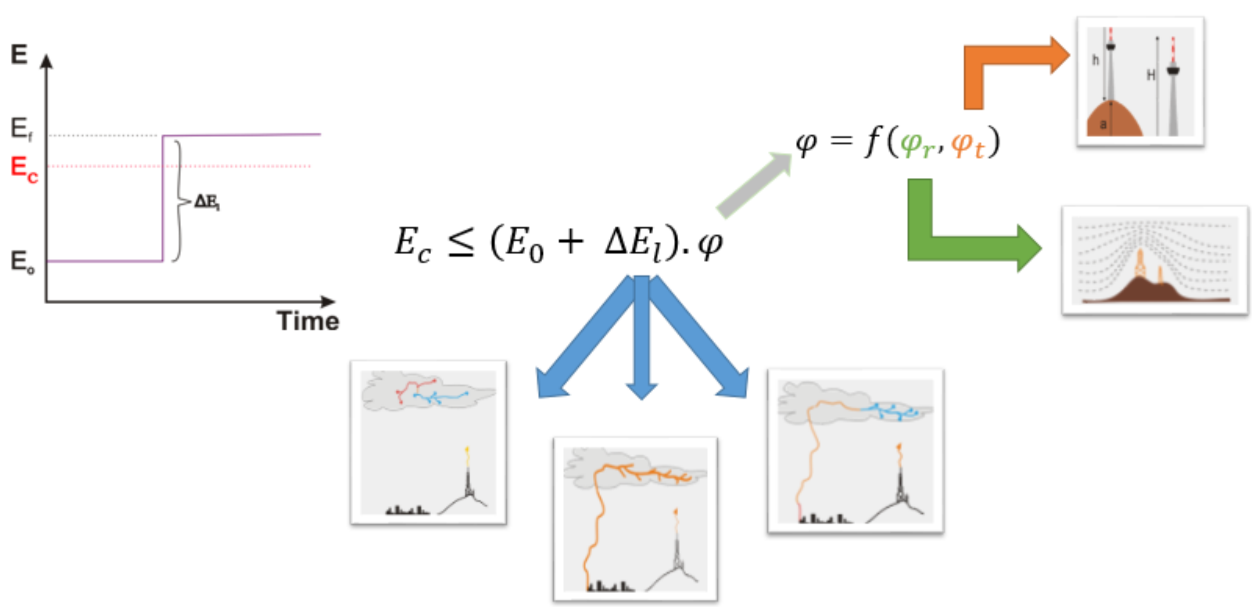

Fig 7. Summary of ambient electric field inequality (hypothesis) and the meaning of each term.

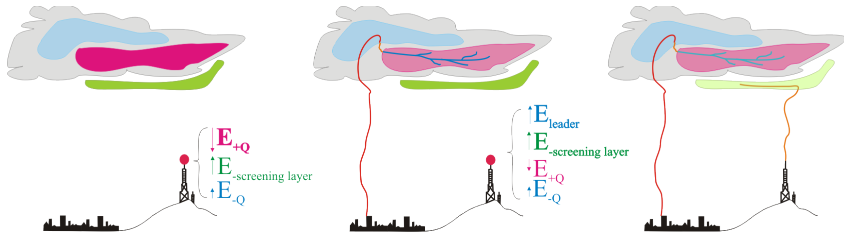

Fig 8. Schematic of the regions that the leaders from different polarities propagate in.

Considering *Kasemir's* bi-directional leader, with two leaders of opposite polarity. The opposite polarity is induced by the ambient electrostatic field with the negative charge at the tip of leader propagating towards the ground while the positive tipped leader develops inside the cloud (in the negatively charged region). The opposite occurs for a positive flash. The total net charge of leader equal a zero.

In the case of positive cloud-to-ground triggering flashes, the positive downward leader moves towards the ground and negative leader develops inside the cloud (leader extension). The leader extension inside the cloud neutralizing the charge in cloud.

When a flash occurs in the area of the tall structures, the positive downward flash neutralises charges in the main positive charge center, offering a sudden change in the environmental electric field making the screening layer more dominant in the resultant electric field. This is shown in figure 8.

IV. Data, Equipment and Methodology:

The study presented here utilizes two datasets – 23 triggered-initiated upward flashes recorded in Rapid City, USA and 49 triggered-initiated upward flashes recorded in São Paulo, Brazil. In both Rapid City and São Paulo, the flashes were recorded with high-speed cameras. The camera models used were the Phantom: v711, v12, v7.1, v310 and Miro4. The frame rate ranged from 1,000 to 100,000 fps. GPS time-stamping of the images allowed for correlation with the Lightning Location Systems (LLSs) and Lightning Mapping Array (LMA) data. All upward flashes (in both locations) were recorded in the later stage of the thunderstorms and were all negative upward flashes (keeping in mind that negative upward flashes have the upward leader tip positively charged).

In order to classify the high-speed footage of upward lightning events as triggered-initiated, LLS data was used to determine if there were any lightning events prior to the the timestamp of the filmed upward flash. More details on the two LLS networks can be found in Naccarato and Pinto (2012) and in Cummins and Murphy (2009). The the recorded triggering events found from the LLSs were either positive cloud-to-ground flashes or intra-cloud flashes.

While all the flashes were recorded with high-speed cameras, only 22 were recorded with LMA. The LMA sensors were installed during two different campaigns: the CHUVA Campaign in 2012 (more details in Bailey et al., 2011) where 10 upward flashes were recorded in Sao Paulo; and during the UPLIGHTS campaign where 12 upward flashes were recorded in Rapid City in 2014.

V. Results:

The results for this paper are presented as follows: firstly, the high speed video observations of the three situations described in above. Secondly, the LMA investigation where some questions remained from the high speed video observations.

A. Video investigation:

In all of the high-speed video recordings, leaders were observed approaching the towers (Figure 9). The three situations described in the hypothesis, where it is possible to identify the leaders associated with the triggering flash, were observed

1) First situation - Return stroke:

The situation in which the return stroke of a nearby triggering event illuminating the leader propagating in the cloud and initiating an upward leader was observed in 13 out of the 72 cases. In this situation, the time interval between the upward leader initiation and the return stroke (triggering flash) is short.

2) Second situation - Leader due to CC:

In the majority of the cases, there are no leaders in the proximity of the towers when the triggering flash occurs. The field change produced by the return stroke of the triggering flash is not strong enough to initiate upward leaders from the tower. However, the associated leader inside the cloud propagates during the continuing current phase, approaching the tower and providing the condition required to start an upward leader from the towers. In this situation, 54 out of the 72 cases were observed to be this situation.

3) Third situation - Leader:

In this situation, the approach of the leader inside the cloud to the towers is sufficient to trigger upward leaders. These can develop a downward cloud-to-ground flash after the upward event or stay inside the cloud. The triggering mechanism in this situation is the in-cloud leader associated with an IC or CG flash and 5 out of the 72 filmed upward flashes were associated with this triggering mechanism.

Figure 9: Video of leaders inside cloud approaching tower location.

B. LMA investigation:

While leaders could be seen approaching tall towers in 72 high-speed videos, 22 of these cases (10 in Sao Paulo and 12 in USA) were registered by the LMA.

1) Analysis of the leader inside cloud approaching towers

Figure 10 shows a plot of absolute horizontal distance between the location of the tower and the location of each reported LMA source. The horizontal distance from the source (prior to upward leader initiation) to the towers ranged from 1.1 to 4.2km (average of 2.1 km). It is possible to observe the approach of the sources to the tower location. The red line indicates the time when the upward leader began and the blue arrow indicates the approach of the leader (radio sources) inside the cloud.

This observation of leaders approaching a tall structure (by video and LMA) leads to the question: Will we always have an upward leader initiating from a tall tower when leaders from a triggering flash propagate over the tower?

2) Analysis of the thunderstorm day with LMA

To answer this question, LMA data for the thunderstorms was analysed. The criterion used is: (1) only thunderstorms where upward flashes were recorded; (2) time window of 1 hour prior to the first upward flash up to 1 hour after the last recorded upward flash; (3) all flashes that had sources inside 40 km x 40 km area around the towers; (4) classified by LLS (CG positive or CG negative or IC). A total of 5724 flashes occurred in these thunderstorms, 371 had sources over the tower region, 70 positive CG, 60 negative CG and 241 were intra-cloud flashes. The number of the cases separated by country are in Table 1.

Table 1: Analysis of the thunderstorm day with LMA

Rapid city	5 Thunderstorms		
	272 had sources over the tower region		
Type:	+CG	-CG	IC
Number	17	48	207
Sao Paulo	4 thunderstorms		
	99 had sources over the tower region		
Type:	+CG	-CG	IC
Number	53	12	34

C. Radar Informations:

Saba et al (2012) showed that almost all upward flashes recorded in São Paulo occurred in thunderstorms associated with a cold front. Souza (2015) studied the radar data from the thuderstorms that upward flashes were recorded in São Paulo.

Based on radar and reflectivity of radar the results of this analysis are:

- All thunderstorms but one presented the bright band in the radar data.
- During the time of upward flash occurrence, the radar data showed stratiform precipitation over the location of the tower.

The bright band is associated with the period of the thunderstorm where positive flashes occur (Füllekrug et al., 2006).

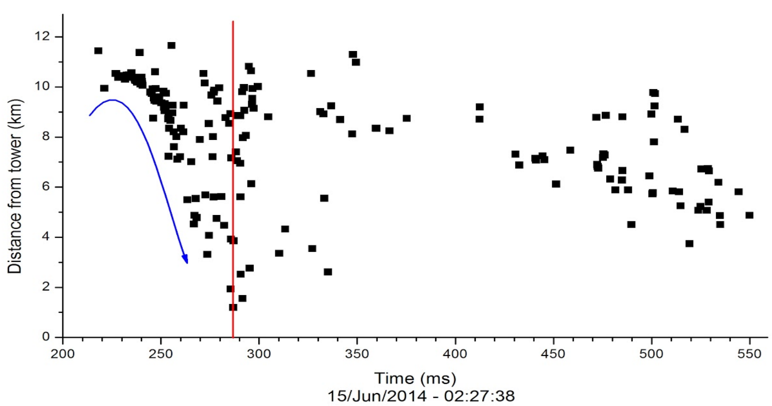

Figure 10: LMA and approximation of the sources. The red line indicates when the upward leader began and the blue arrow indicates the approximation of the source inside the cloud.

VI. CONCLUSION:

All triggered-initiated upward flashes (72 cases) recorded in Sao Paulo and in Rapid City were analysed and the triggering components could be identified.

In the first situation, an upward leader starts from the tall towers after leaders approaching the tower right after a return stroke which almost always saturates the image. In the second situation, the brightness of the return stroke happens, leaders are seen propagating inside the cloud and approaching to the tower. Finally, in the third situation, the leader inside the cloud is close to the tower and an upward leader initiates from the towers. Leaders over the towers are the common reason why the upward leader initiates but there are three different processes. These three different components from the triggering flashes are responsible for the modification of the ambient electric field on the tower surroundings.

From the analysis of LMA data correlated with the high speed videos the question of whether leaders over a tall tower will always initiate an upward leader was answered - the conclusion of this analysis is that leaders over tall towers are necessary but not sufficient to trigger an upward flash. Negative flashes do not trigger upward flashes from towers.

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